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REAL-TIME ANALYSIS OF GAMMA-RAY TRANSIENTS: DEVELOPING SOFTWARE AND STATISTICAL METHODS FOR THE CTAO

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*Dedicato alla mia Famiglia, che mi
mostra ogni giorno cosa vuol dire
essere forti, e a Salvatore Puglisi,
nonno superman e sarto sopraffine,
che continua sempre ad essere
la mia Stella Polare...*

Abstract

The Cherenkov Telescope Array Observatory (CTAO) is going to be the major global observatory for very high-energy astrophysics in the next decade and beyond. It is going to be a uniquely powerful instrument for the exploration of the violent and variable Universe thanks to its unprecedented sensitivity to short timescale phenomena. The CTAO will be equipped with a real-time analysis pipeline, the Science Alert Generation (SAG) pipeline, which will perform scientific monitoring of the observed field of view and generate candidate Science Alerts when it detects transient phenomena.

We developed the scientific pipeline of SAG, called **SAG-SCI**, that performs high-level analysis of gamma-ray data using traditional analysis methods. We developed the **SAG-SCI** software respecting the CTAO code quality requirements and scientific strategies to optimise the analyses on different types of target sources and generate candidate Science Alerts. We used **SAG-SCI** to analyse CTAO simulated data under several observational scenarios, that allow us to validate the software algorithms, investigate systematic uncertainties and present an overview of the most relevant applications of **SAG-SCI**.

When the analyses must be performed in a *low-photon-statistics* regime, the traditional methods are not valid, thus we developed a *Burst Analysis* that is statistically valid in this regime. We applied the Burst Analysis to observations of SGR 1935+2154, a Galactic magnetar, performed with the CTAO Large-Sized Telescope Prototype, LST-1. We searched for a possible TeV counterpart of its X-ray persistent and burst emission. While neither persistent nor transient emission was detected in our search, we could provide, for the first time, TeV upper limits to the emission of a short magnetar burst simultaneous to its soft gamma-ray signal.

Our development of the **SAG-SCI** software will allow the CTAO to become a fundamental facility for time-domain astrophysics, and enable multi-wavelength and multi-messenger approaches that will lead to a deeper understanding of the Universe. Our development of the *Burst Analysis* will allow CTAO to analyse several interesting classes of fast transients in the *low-photon-statistics* regime.

Keywords— [Gamma-ray astronomy \(628\)](#) – [Time domain astronomy \(2109\)](#) – [Transient sources \(1851\)](#) – [Observational Astronomy \(1145\)](#) – [Astronomy Data Analysis \(1858\)](#) – [Astrostatistics \(1882\)](#) – [Astronomy Software \(1855\)](#) – [Computational Astronomy \(293\)](#) – [Computational Methods \(1965\)](#) – [Magnetars \(992\)](#) – [Soft gamma-ray repeaters \(1471\)](#)

Sommario

Il Cherenkov Telescope Array Observatory (CTAO) sarà uno dei principali osservatori per l'astrofisica delle alte energie nei prossimi decenni. Sarà un potente strumento per indagare i fenomeni variabili e violenti dell'universo grazie alla sua sensibilità senza precedenti su brevi tempi scala. Il CTAO sarà dotato di una pipeline di analisi in tempo reale, la Science Alert Generation (SAG) pipeline, che eseguirà analisi dati nel campo visivo osservato e genererà candidati per Allerte Scientifiche quando rileva fenomeni transienti.

Abbiamo sviluppato la pipeline scientifica di SAG, detta **SAG-SCI**, che esegue analisi di alto alto livello sui dati astrofisici gamma usando metodi di analisi tradizionali. Abbiamo sviluppato il software **SAG-SCI** rispettando i requisiti di CTAO sulla qualità del codice. Abbiamo sviluppato strategie per ottimizzare le analisi scientifiche su diversi tipi di sorgenti, e per generare i candidati per Allerte Scientifiche. Abbiamo adoperato **SAG-SCI** per analizzare dei dati CTAO simulati sotto diversi scenari osservativi, che ci permettono di validare gli algoritmi software, stimare le incertezze sistematiche e presentare una panoramica dei principali casi di utilizzo di **SAG-SCI**.

Quando le analisi devono essere eseguite in un regime di *bassa statistica*, i metodi tradizionali non sono più validi, e pertanto abbiamo sviluppato un metodo di *Analisi per Transienti Brevi* statisticamente valido in questo regime. Abbiamo applicato l'analisi per Transienti Brevi alle osservazioni della magnetar Galattica SGR 1935+2154 effettuate con il Large-Sized Telescope Prototype di CTAO, LST-1. Abbiamo cercato una possibile controparte TeV della sua emissione persistente e transiente nei raggi X. Non abbiamo rilevato emissione persistente o transiente nella nostra ricerca, ma per la prima volta abbiamo determinato i limiti superiori all'emissione TeV di brevi burst di magnetar simultanei all'emissione di segnale nella banda soft-gamma.

Il nostro sviluppo del software **SAG-SCI** permetterà a CTAO di diventare un osservatorio cruciale per l'astrofisica transiente, e permetterà di intraprendere studi multi-wavelength e multi-messaggero che porteranno a una comprensione più profonda del nostro universo. Il nostro sviluppo dell'*analisi per transienti brevi* permetterà a CTAO di analizzare diverse interessanti classi di transienti brevi che fanno parte di un regime di *bassa statistica*.

Keywords— [Gamma-ray astronomy \(628\)](#) – [Time domain astronomy \(2109\)](#) – [Transient sources \(1851\)](#) – [Observational Astronomy \(1145\)](#) – [Astronomy Data Analysis \(1858\)](#) – [Astrostatistics \(1882\)](#) – [Astronomy Software \(1855\)](#) – [Computational Astronomy \(293\)](#) – [Computational Methods \(1965\)](#) – [Magnetars \(992\)](#) – [Soft gamma-ray repeaters \(1471\)](#)

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Introduction

Gamma-ray astronomy is currently undergoing a golden age, thanks to the work of space satellites and ground-based facilities, that increased our knowledge on the most energetic and extreme processes of the Universe. The major discoveries of the last ten years in gamma-ray astronomy are connected to time-domain astrophysics and transient events, and have greatly benefited from a multi-wavelength and multi-messenger approach.

The Cherenkov Telescope Array Observatory (CTAO, Cherenkov Telescope Array Consortium et al. 2019) is being developed in this scientific context. The CTAO is going to be the major global observatory for very-high-energy astrophysics in the next decade and beyond, capable to transform our understanding of the high-energy Universe and explore questions in physics of fundamental importance, such as: understanding the origin, role and acceleration of cosmic rays; probing extreme environments and transients in the Universe; exploring frontier topics in physics like the nature of Dark Matter. The first Large-Sized Telescope Prototype of the CTAO, called LST–1, is located at the *Observatorio del Roque de los Muchachos*, in the island of La Palma, Canary Islands, Spain. LST–1 started performing astronomical observations in November 2019, during its commissioning phase, and it has been taking data since then (CTA-LST project et al. 2023).

The CTAO is going to be a uniquely powerful instrument for the exploration of the violent and variable universe thanks to its unprecedented sensitivity to short timescale phenomena, wide field of view and broad energy range. To maximise its scientific return, the CTAO will be equipped with a low-latency, effectively *real-time analysis* pipeline which will monitor the field of view for variability on a wide range of timescales. The pipeline, called the *Science Alert Generation* (SAG) system, will issue the production of *Science Alerts* when detecting a gamma-ray flare within 60 s from the acquisition of the data (Bulgarelli et al. 2024).

In this thesis, we present **two** main new results. The first one is the development of the **SAG-Science** (SAG-SCI) software, the sub-system of SAG dedicated to the statistical, high-level analysis of reconstructed gamma-ray, with the goal of performing *scientific monitoring* of the observed sources and generating candidate *Science Alerts*. In particular, I developed: the **gammapy** wrapper, a set of classes and scripts that analyse gamma-ray data using the namesake **python** library; the **DatabaseManager**, a tool to efficiently create, modify and delete Databases for SAG-SCI; a major part of the Test suites that ensure SAG-SCI respects all the standards of professional software development. I contributed to the development of all the other components of SAG-SCI. We present here for the first time detailed strategies to optimise SAG-SCI analyses to the scientific target observed, to improve its performance and to issue candidate Science Alerts. We crafted several observational scenario and simulated CTAO data that we analyse with SAG-SCI. The simulations allow us to validate the scientific and computing performance of the software, estimate systematic errors, present an overview of the main scenarios in which SAG-SCI will operate and generate candidate Science Alerts.

A first release of **SAG-SCI** was tested on the LST–1 in October 2023 during an official CTAO testing campaign, and lead to the detection of the Crab Nebula. We also deployed a stand-alone version of **SAG-SCI** on the LST–1, that analyses the telescope’s data every observation night, and reports the results in a GUI monitored by the shifters. The **SAG-SCI** pipeline will allow the CTAO to become a crucial instrument for time-domain astrophysics and enable multi-wavelength and multi-messenger approaches that will lead to a deeper understanding of the broad-band non-thermal properties of target sources.

SAG-SCI employs traditional analysis methods to perform its analyses, that rely working under a *high-photon-statistics* regime ($\gtrsim 10$ photons). There are several classes of gamma-ray transients showing burst emission on very short time scales ($\lesssim 10$ s), such as short Gamma-Ray Bursts, Magnetar bursts, Magnetar Giant Flares, and possibly Fast Radio Bursts, which may fall under a *low-photon-statistics* regime and that cannot be analysed with the traditional methods. The second main result of this thesis is the development of a **Burst Analysis** statistically valid in the *low-photon-statistics* regime, under short time scales. We applied the Burst Analysis to the case study of the Soft Gamma Repeater (SGR) 1935+2154, a Galactic magnetar that is known to occasionally emit ~ 0.1 s bursts at keV – MeV energies. We used the CTAO LST–1 to search for a TeV counterpart of the soft gamma-ray bursts of SGR 1935+2154, and we present the first TeV upper limits to the emission of a short 0.1 s magnetar flare simultaneous to its soft gamma-ray emission.

This thesis is structured as it follows. Chapter 1 introduces the field of **Gamma-ray astrophysics**. We describe it within the larger context of High-Energy Astrophysics, we discuss the main emission mechanisms of gamma-rays and their deep connection to cosmic rays, and we present an overview of the main sources of gamma-rays in the Universe. In Chapter 2 we describe **Cherenkov Astronomy**. We present the mechanisms for the creation of Extended Air Showers from gamma-rays entering the atmosphere, the emission of Cherenkov radiation, and the main ground-based detectors of gamma-rays. We also describe the Imaging Atmospheric Cherenkov technique, the Reconstruction of Cherenkov data (Low-Level analysis), and the traditional methods of statistical analysis of reconstructed gamma-ray data (High-Level analysis). The High-Level analysis methods are the theoretical algorithms that **SAG-SCI** must implement. In Chapter 3 we describe the context of multi-wavelength, multi-messenger and **Time Domain Astrophysics**, and an extraordinary case study: the detection and analysis of GRB 221009A with the AGILE satellite to which I personally contributed (Tavani et al. 2023). We also introduce the **CTAO**, its Key Science Projects, its suitability for time-domain astrophysics, and the LST–1. We also introduce the *Science Alert Generation* system. Chapter 4 is dedicated to the description of the **SAG-SCI** software, my development work and the strategies to issue the generation of candidate Science Alerts. In Chapter 5 we show the main **Results** of our tests of **SAG-SCI** on several observational scenario crafted to assess its performance and highlight its main functionalities. We also discuss strategies for the optimisation of the analyses. In Chapter 6 we discuss the development of the **Burst Analysis** and its application on SGR 1935+2154. We describe the context of magnetars in general, the importance of SGR 1935+2154, the LST–1 observations on the source and the traditional analysis of its persistent emission. We describe then the Burst Analysis both from a theoretical and the implementation point of view. We obtain the upper limits on the TeV emission of SGR 1935+2154 and discuss their scientific implications. Finally, we **conclude** this work by summarising and discussing our results and future perspectives in Chapter 7.

Chapter 1

Introduction to Gamma-ray Astrophysics

Gamma-ray astrophysics is the branch of astrophysics that studies the gamma-ray band of the electromagnetic spectrum. It is also a branch of *High-Energy astrophysics*, which underwent a different development with respect to other branches of astronomy, due to its strict connection to *Particle physics*. This chapter offers an overview of the main themes and concepts of gamma-ray astrophysics. A detailed discussion of the topics explored in this chapter can be found in the main sources adopted for this chapter: Longair (2011) and Spurio (2018) are classic books on high-energy astrophysics, Degrange and Fontaine (2015), Funk (2015), and De Angelis and Mallamaci (2018) offer reviews on the main topics and science cases of gamma-ray astrophysics, Murase and Bartos (2019) focuses on multi-messenger astrophysics, Bose et al. (2022a) offers an overview on the sky at TeV energies, and Carosi and López-Oramas (2024) focuses on the transient sources.

Section 1.1 focuses on the development of High-Energy astrophysics and compares it to other branches of astrophysics. As gamma-ray radiation is usually produced by accelerated particles, section 1.2 offers an overview on *Cosmic Rays*. The following sections focus on the production mechanisms of gamma-rays. In particular, section 1.3 describes the *Leptonic emission scenario*, where gamma-rays are produced by accelerated electrons via Synchrotron Self Compton emission. Section 1.4 describes the *Hadronic emission scenario*, in which gamma-rays are produced following collisions of protons and the decay of neutral pions. Section 1.5 offers an overview of potential mechanisms to produce gamma-rays from *Dark Matter* particles, as the search for such signals is one of the most relevant topics in the field. Section 1.6 describes the main sources of gamma-rays, that can be broadly classified in Galactic or extra-galactic, steady or transient sources.

1.1 High-Energy Astrophysics

High-Energy astrophysics studies the astrophysical sources emitting high-energy photons, particles and the radiation processes leading to their emission (Longair 2011). It is one of the disciplines developed after the Second World War thanks to the revolutionary development of new technologies and techniques of astronomical observation from the ground, from space, and high speed computers. Some examples of problems in high-energy astrophysics today

entail understanding the physics of *extreme environments*, such as the interiors of neutron stars and the supermassive black holes which are present in the nuclei of active galaxies, the *acceleration* of charged particles to extreme energies and frontier topics on *fundamental physics* such as the nature and distribution of Dark Matter and the limits of the Standard Model of Particle physics and General Relativity. High-Energy astrophysics allows us to study the properties of matter and the application of the laws of physics under physical conditions that cannot be reproduced in laboratory. High-Energy processes, in general, are described by non-thermal spectra, i.e. their emission is not due to black body radiation, but to violent processes, such as shocks, capable to accelerate particles at very high energies (see section 1.2 for details, and section 1.6 for the main astrophysical sources of interest).

High-Energy astrophysics is a complex field that combines approaches, experimental techniques and know-how of different scientific communities (Spurio 2018). It covers *X-ray* and *Gamma-ray astrophysics*, that study electromagnetic radiation in the X-ray and Gamma-ray bands as messenger of information, *astroparticle physics* that adopts techniques similar to those used in high-energy physics to detect charged Cosmic Rays and Neutrinos, *multi-wavelength astronomy* that combines information from different instruments covering a wide part of the electromagnetic spectrum (from radio to X-rays and gamma-rays). Methodological differences between the communities of astronomers and particle physicists lead to adopting different definitions for observable quantities (see section 1.1.2), separate research journals and even different research framework: astronomers usually prefer *observatories*, that publicly release their data (according to specific terms), while particle physics *experiments* usually restrict data access to collaboration members and publish results only. Today, distance between these communities is decreasing and there is a larger exchange of information and methodology. The joint effort of these communities created one of the currently most active fields in astrophysics, *multi-messenger astrophysics*, that connects observations of the same astrophysical event or system carried out using several messengers: electromagnetic radiation, cosmic rays, neutrino and gravitational waves. Another joint effort of the communities is leading to the construction of the *Cherenkov Telescope Array Observatory* (CTAO, see section 3.2).

1.1.1 Gamma-ray Astronomy

Gamma-ray astrophysics studies the electromagnetic emission of gamma-rays (or γ -rays), the most energetic band of the electromagnetic spectrum. γ -rays are photons with energies $\gtrsim 0.1$ MeV, produced by non-thermal emission processes. Gamma-ray astrophysics covers a large range of energies and can be roughly divided into sub-fields according to the covered energy band: *soft gamma astrophysics* covers the MeV energies, *High-Energy* (HE) *astrophysics* covers the GeV energies, *Very High-Energy* (VHE) *astrophysics* covers the TeV energies, *Ultra High-Energy* (UHE) *astrophysics* covers the PeV energies. Each of these bands require different experimental setup and analysis techniques. The Earth's atmosphere is not transparent to high-energy photons (see figure 1.1), so they have to be detected either from space or by exploiting the production of *air showers*, i.e. cascades of secondary particles produced when a gamma photon interacts with the atmosphere (see chapter 2.1). Observations in the MeV-GeV bands are *space-based*, carried out by satellites such as Swift, Integral, Fermi, AGILE (until 2024), COSI (upcoming NASA mission). Observations in the TeV-PeV band are *ground-based*, as the γ -ray flux is too low to be detected by the typical effective areas of satellites; they are carried out by *Imaging Atmospheric Cherenkov Telescopes* (IACTs), such

as MAGIC, HESS, VERITAS, CTAO, and *Water Cherenkov Detectors*, such as HAWC and LHAASO (see chapter 2.2).

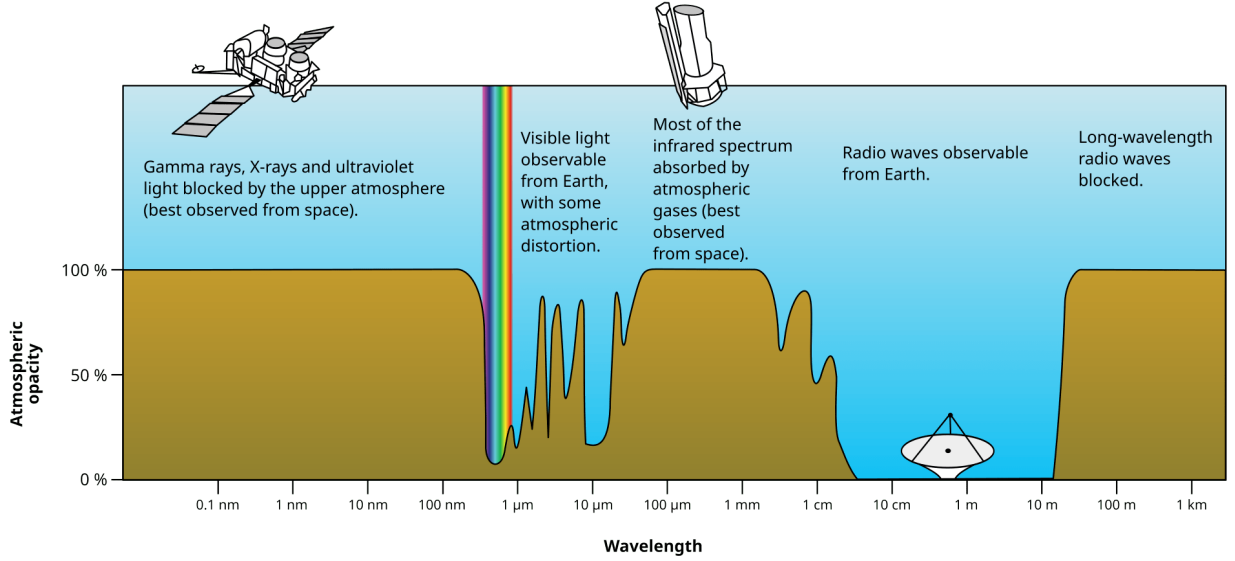


Figure 1.1 – Atmosphere opacity as a function of the wavelength of an incoming photon. Opacity is the percentage of electromagnetic radiation not reaching the ground. We note that high-energy photons, with lower wavelengths, cannot be directly detected from Earth. Credit: NASA.

1.1.2 Observable Quantities in High-Energy Astrophysics

The historical differences between traditional and high-energy astronomy, the latter being influenced by the methods of particle physics, can be also seen in the main observable quantity used to describe the electromagnetic radiation, the *flux*.

Traditional Astronomy. In most fields of astrophysics, electromagnetic emission is detected through its wavelike nature, as incoming radiation over a given range of photon energies. Data collected at different frequencies ν are compared through their **spectral flux density**:

$$F(\nu) = \frac{\delta E}{\delta \nu \delta A \delta t}. \quad \text{Units: erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}. \quad (1.1)$$

It is the amount of energy δE transferred by electromagnetic radiation through a real or virtual surface δA per unit surface area, unit time δt and unit frequency $\delta \nu$. In radioastronomy, it is usually expressed in *Jansky* ($1 \text{ Jy} = 10^{-23} \text{ erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$).

The **Spectral Energy Distribution** (SED) of a source is usually expressed as:

$$J(\nu) = \nu F(\nu). \quad \text{Units: erg s}^{-1} \text{cm}^{-2}. \quad (1.2)$$

The integral version of equation (1.1) is the **flux density**:

$$J_{(\nu_1, \nu_2)} = \int_{\nu_1}^{\nu_2} F(\nu) d\nu. \quad \text{Units: erg s}^{-1} \text{cm}^{-2}. \quad (1.3)$$

$\nu F(\nu)$ and $J_{(\nu_1, \nu_2)}$ have the same dimensions and both of them can be used to represent the SED of an object. If a data point is defined in a small frequency band $[\nu_1, \nu_2]$, i.e. $\nu_1 \approx \nu_2 \approx \nu$,

then $\nu F(\nu)$ is an approximation of the flux density $J_{(\nu_1, \nu_2)}$. If the data point is an average value computed over a large frequency band, the flux density $J_{(\nu_1, \nu_2)}$ is the proper value to use in the SED.

High-Energy Astronomy. In high-energy astrophysics, photons (X-rays and γ -rays) are detected through their particle nature: it is possible to detect individual photons and estimate their individual characteristics: energy, detection time, sky position. Spectral bands are usually addressed in terms of energy (E) rather than frequency (ν) thanks to their direct proportionality through the Planck Constant $h = 6.626 \cdot 10^{-34}$ J s (e.g. Tiesinga et al. 2021):

$$E = h \nu. \quad (1.4)$$

The observed radiation flux can be expressed in several standard formats (e.g. Nigro et al. 2021a):

1. **Differential photon flux.** It is defined as the number of photons δn per unit of time δt , effective area $\delta A(E)$ (geometrical collection area times the detection efficiency at energy E) and energy interval δE :

$$\frac{dN}{dE}(E) = \frac{\delta n}{\delta E \delta A(E) \delta t}. \quad \text{Units: s}^{-1} \text{cm}^{-2} \text{eV}^{-1}. \quad (1.5)$$

It is also referred to as the *spectrum*, as spectral models that describe the emission of a source are usually represented by this quantity.

2. **Photon flux.** It is the integral of equation (1.5) in a given energy band $[E_1, E_2]$:

$$\Phi_{(E_1, E_2)} = \int_{E_1}^{E_2} \frac{dN}{dE}(E) dE. \quad \text{Units: s}^{-1} \text{cm}^{-2}. \quad (1.6)$$

3. **Differential energy flux.** It is defined from equation (1.5) as:

$$J(E) = E^2 \frac{dN}{dE}(E). \quad \text{Units: erg s}^{-1} \text{cm}^{-2}. \quad (1.7)$$

It is often used to express the *Spectral Energy Distribution* (SED) of a source, being the high-energy equivalent of $\nu F(\nu)$, when frequencies are converted into energies using equation (1.4).

4. **Energy flux.** It is defined from equation (1.5) as:

$$J_{(E_1, E_2)} = \int_{E_1}^{E_2} E \frac{dN}{dE}(E) dE. \quad \text{Units: erg s}^{-1} \text{cm}^{-2}. \quad (1.8)$$

It is the high-energy equivalent of the flux density described in equation (1.3), when frequencies are converted into energies using equation (1.4).

If a data point is defined in a small frequency band, $E^2 \frac{dN}{dE}(E)$ is an approximation of the energy flux $J_{(E_1, E_2)}$; if the data point is an average value computed in a large energy band, the energy flux $J_{(E_1, E_2)}$ is the proper value to use in the SED.

1.2 Cosmic Rays and Production of Gamma-rays

Primary **Cosmic Rays** (CRs) are high-energy and stable particles originating in astrophysical environments (e.g. Swordy 2001). CRs are $\sim 87\%$ protons, $\sim 11\%$ nuclei of He (α -particles) or heavier elements, and $\sim 2\%$ leptons (electrons or positrons). Leptons are easily decelerated by their motion in local magnetic fields (see section 1.3.1) and make up a small fraction of the CRs flux. A fraction of the CRs radiation can interact at astrophysical sites producing secondary particles that can be either charged or neutral, particles or antiparticles (mainly positrons and antiprotons), and particles like gamma-rays and neutrinos that are considered different *astrophysical messengers*. CRs produced during the propagation of primary CRs or produced on their arrival in the Earth's atmosphere are called *secondary cosmic rays*. Secondary CRs were historically the first type discovered, at the beginning of the 20th century, when electroscopes would naturally discharge without any apparent reason (Millikan 1926).

The energy spectrum of primary CRs (see figure 1.2), is measured in the range from 10^6 eV to 10^{20} eV. Low-energy particles, below few GeV, are of Solar origin, while the rest of CRs originate outside the solar system and the physical properties of the Galaxy (dimension, matter density, magnetic fields) impact their distribution. The spectrum of cosmic rays is described by *Power Law* functions (e.g. Blümer et al. 2009) with index ≈ -2.7 , up to a transition point called the *knee* at $\approx 3 \cdot 10^{15}$ eV, that is thought to indicate the maximum acceleration energy of Galactic sources. At higher energies, the flux is suppressed and the power law index becomes ≈ -3.1 , up to a second transition point called the *ankle* at $\approx 10^{19}$ eV, beyond which the spectrum flattens again returning to ≈ -2.6 . The flux of CRs is suppressed at $\approx 10^{20}$ eV, and this can be ascribed either to an intrinsic limit of sources and their acceleration mechanisms or to energy losses during propagation, the so-called *Greisen-Zatsepin-Kuzmin* (GZK) effect. According to this effect, when a CR with energy $\gtrsim 10^{20}$ eV interacts with the *Cosmic Microwave Background* (CMB) Radiation, they produce hadrons through Δ resonance (see section 1.4), limiting the maximum distance that they can travel to 50 Mpc (Greisen 1966; Zatsepin and Kuz'min 1966).

Acceleration of Cosmic Rays. The observed spectrum of CRs depends on the acceleration processes in the astrophysical sources and the propagation mechanisms of CRs in the interstellar medium (ISM) of the Galaxy, which can alter the spectral shape. After leaving their origin sites, CRs diffuse in the Galactic magnetic field. The *Galactic diffusion model* (Spurio 2018) explains the observations on energy spectra, chemical compositions and isotropy level of CR detections, providing also the basis for the interpretation of the X-ray and gamma-ray emission. It predicts that the spectrum of CRs at their acceleration sites has index ≈ -2 . Furthermore, CR electrons are subject to synchrotron energy losses (see section 1.3) near the electron accelerators and when they propagates in the Galactic disk, resulting in a diffuse emission.

There are several processes that may be responsible for the acceleration of CRs over the wide range of energies observed. The most popular one is the *Fermi acceleration mechanism* (Fermi 1949), in which charged particles can gain energy stochastically via multiple scatter interactions. Typical scenarios that can enable Fermi acceleration processes are astrophysical shocks. In this *diffusive shock acceleration* mechanism, a fraction of the energy of the bulk flows can be converted into the non-thermal energy of cosmic rays (Drury 1983; Blandford

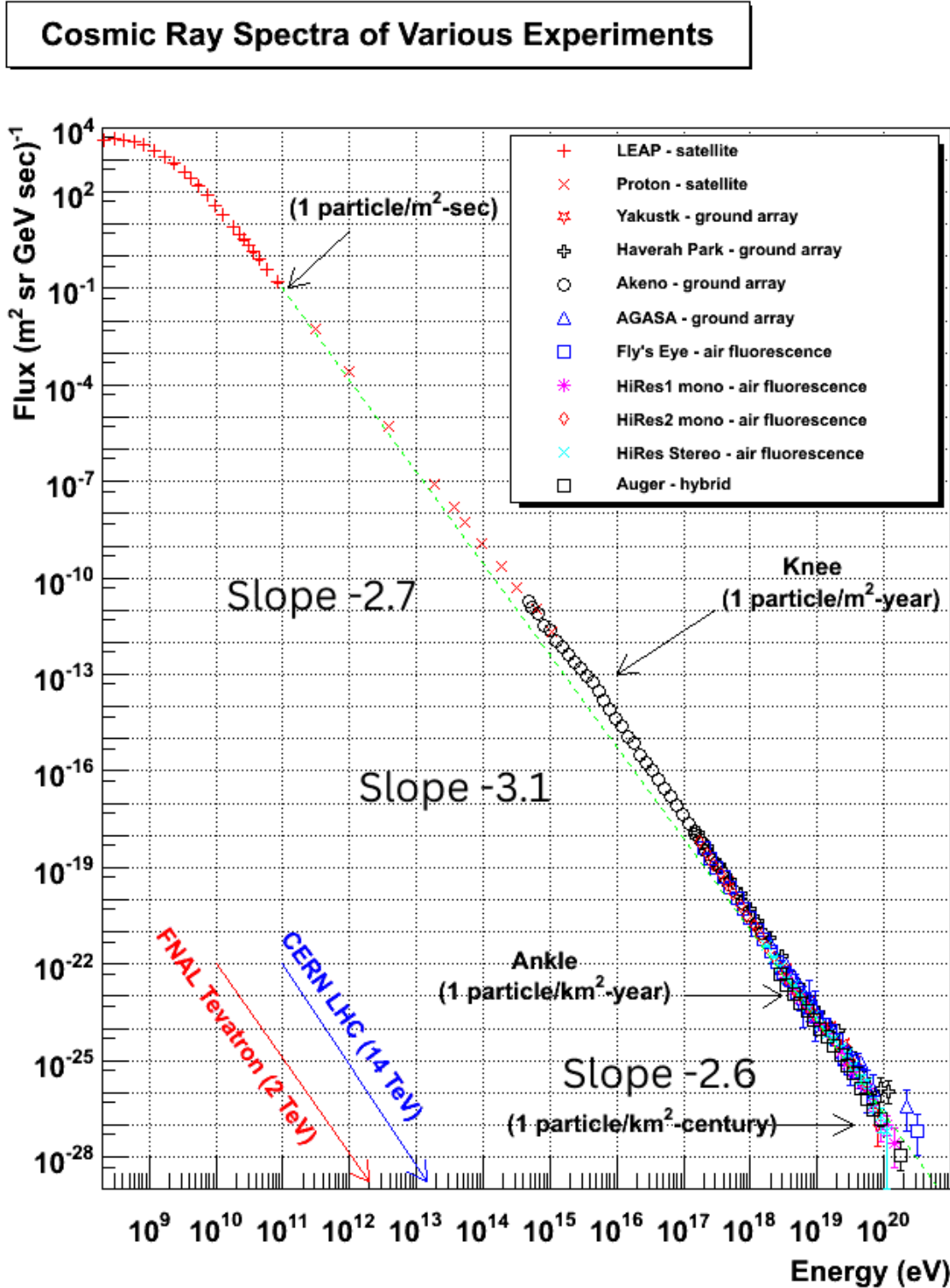


Figure 1.2 – Differential energy spectrum of cosmic rays over eleven decades of energy. The spectrum is remarkably continuous over the whole energy interval and covers more than 30 decades in flux. Credit: Hanlon (2008), <https://web.physics.utah.edu/~whanlon/spectrum.html>

and Eichler 1987). Other possible mechanisms are stochastic acceleration by turbulence or magnetic reconnections. The maximum energy that can be acquired by a particle in a system is defined by the *Hillas condition* (Hillas 1984):

$$E < Z e R B (v/c), \quad (1.9)$$

where E is the energy of the accelerated CRs, e the charge of an electron, so the product $Z e$ is their charge, R is the system size, B the magnetic field strength, v the characteristic velocity of the acceleration mechanism, c the speed of light in a vacuum. For relativistic sources, R and B must be expressed in the comoving system and v/c must be replaced by the Lorentz Factor Γ . Detailed computations require taking into account the cooling processes, but equation (1.9) can be used to highlight that only sources with powerful central engines in extreme conditions, e.g. neutron stars (NS) or black holes (BH), can accelerate cosmic rays to the highest energies (Murase and Bartos 2019).

The study of CRs above 1 PeV is challenging due to their low flux and the magnetic deflection of CRs during their propagation through the Galactic and/or intergalactic medium, which makes it impossible to reconstruct the direction of observed CRs. For this reason, studies on particle acceleration are usually carried out indirectly by observing the gamma-rays and neutrinos produced by CRs, as they are not deflected by magnetic fields.

Production of Gamma-rays. The production of γ -rays cannot be explained in terms of thermal processes. *Thermal processes* describe the emission of radiation from an emitter with a population of particles in thermodynamic equilibrium, whose velocity follows the Maxwell-Boltzmann distribution. The *black body* radiation, emitted by an isolated body in equilibrium, and *thermal bremsstrahlung* radiation are prime examples of thermal processes. **Non-thermal processes** describe the emission of radiation from emitters with a population of particles not in equilibrium, accelerated by magnetic fields and usually with a power law energy spectrum. Non-thermal processes occur in the most violent and extreme environments in the Universe, such as near neutron stars and black holes, where it is possible to accelerate charged particles to high energies. The *Synchrotron*, *Inverse Compton* and *Relativistic Bremsstrahlung* are the main non-thermal types of radiation observed. As γ -ray radiation is usually non thermal, most γ -ray sources can be used to probe the sites of cosmic rays acceleration. For this reason, the *origin of Cosmic Rays*, their *acceleration mechanisms*, and the *physics of extreme environments* are some of the main topics of γ -rays astrophysics.

The main models explaining the production of γ -rays are *bottom-up* models, where the acceleration of charged particles emitted from astrophysical sources causes the production of γ -rays with non-thermal processes (e.g. De Angelis and Mallamaci 2018). Bottom-up models where the charged particles are electrons and the emission processes are synchrotron and inverse Compton, are called *Leptonic models* (see section 1.3). *Hadronic models* (see section 1.4) are bottom-up models where γ -rays are produced by decay of charged and neutral pions generated by proton-proton collisions, or by interaction of CR protons with low-energy photons surrounding astrophysical sources (e.g. gamma-rays photo-production from the interaction of CRs and CMB radiation). Alternative models are the *top-down* models, where the observed radiation is the decay product of exotic dark matter particles, see section 1.5.

1.3 The Leptonic Emission Scenario

The emission of gamma rays from a population of relativistic electrons or positrons occurs when the astrophysical environment is permeated by a magnetic field. The most common cosmic accelerators of electrons, and sites of leptonic emission, are pulsars and Active Galactic Nuclei (AGN), that inject the astrophysical medium with charged particles whose energy distribution follows a power law $\propto E^{-\alpha}$ with $\alpha \approx 2$. Accelerated electrons are then subject to relevant energy loss processes, which cause distortions of their injection energy spectra. The main process is the emission of *Synchrotron radiation*, which can be detected by high-energy detectors (Spurio 2018). Additional processes are due to further interaction with matter and radiation (excitation/ionisation, bremsstrahlung).

1.3.1 Synchrotron Radiation

Synchrotron radiation is electromagnetic radiation generated by charged particles accelerated along a curved orbit due to a magnetic field. The radiated power emitted by a particle with charge q and acceleration a is given by the relativistic *Larmor's equation* (Jackson and Fox 1999), that in the *International System* (SI) of units is:

$$P = -\dot{E} = -\frac{dE}{dt} = \frac{q^2 a^2}{6\pi\epsilon_0 c^3}, \quad (1.10)$$

where E is the energy of the particle with electric charge q , acceleration a , c is the speed of light in a vacuum, ϵ_0 the vacuum electric permittivity. For an electron with charge $q = -e$ and using *Gaussian-cgs* units, equation (1.10) becomes:

$$P = -\frac{dE}{dt} = \frac{2e^2 a^2}{3c^3}. \quad (1.11)$$

The particle acceleration a can be retrieved from its relativistic definition as the derivative of the momentum p with respect to proper time $\tau = t/\Gamma$ over the rest mass of the electron m_e . Here t is the observer's time and Γ the Lorentz factor

$$\Gamma = \frac{1}{\sqrt{1 - (v/c)^2}}. \quad (1.12)$$

The acceleration, neglecting time dependence of Γ , is

$$a = \frac{1}{m_e} \frac{dp}{d\tau} = \frac{1}{m_e} \Gamma \frac{d}{dt} [\Gamma m_e v] = \Gamma^2 \frac{dv}{dt} = \Gamma^2 \frac{v^2}{R}, \quad (1.13)$$

where $\frac{dv}{dt}$ represents the centripetal acceleration $\frac{v^2}{R}$. The radius is given by the relativistic *Larmor radius* $R = r_L$, which is described by the motion of a charged particle subject to Lorentz's force when moving through a magnetic field $\mathbf{B}$. The Larmor radius for a relativistic ($v \simeq c$) electron is:

$$r_L = \frac{v}{\omega_L} = \frac{v}{\frac{qB}{\Gamma m_e c}} \simeq \frac{\Gamma m_e c^2}{eB}, \quad (1.14)$$

where ω_L is the Larmor angular frequency. Equation (1.11) becomes then:

$$-\frac{dE}{dt} = \frac{2e^2}{3c^3} \left(\Gamma^2 \frac{v^2}{r_L} \right)^2 = \frac{2e^2}{3c^3} \Gamma^4 \frac{v^4}{r_L^2} \simeq \frac{2e^4}{3m_e^2 c^3} \Gamma^2 B^2 = \frac{\sigma_T}{4\pi} c \Gamma^2 B^2 \quad (1.15)$$

where $\sigma_T = \frac{8\pi}{3} \frac{q^4}{m^2 c^4}$ is the *Thomson cross-section*.

We can use the relativistic definition of energy

$$E = \Gamma m_e c^2 \quad (1.16)$$

to find the radiation power, i.e. the power loss of the charged particle:

$$-\frac{dE}{dt} = \frac{\sigma_T}{4\pi} c \frac{E^2}{m_e^2 c^4} B^2 \sin^2 \psi, \quad (1.17)$$

where the $\sin^2 \psi$ factor is a generalisation when the electron velocity is not perpendicular to the direction of the magnetic field, hence the electron moves in a spiral path with a constant pitch angle ψ . Averaging equation (1.17) over a constant distribution of pitch angles and using the definition of energy density of the magnetic field $U_B = B^2/8\pi$, the **synchrotron radiation power** of an electron can finally be expressed as:

$$-\dot{E} = -\frac{dE}{dt} = \frac{4}{3} \sigma_T c U_B \Gamma^2 = \frac{4}{9} c \frac{e^4}{m_e^4 c^8} B^2 E^2. \quad (1.18)$$

The synchrotron radiation power is $\propto E^2 B^2 m^{-4}$, we note that:

- A particle with higher energy emits more radiation power and loses its energy.
- The strength of the magnetic field is proportional to the observed synchrotron power.
- Particles with a large mass, such as protons, have smaller power loss and emit less synchrotron radiation than electrons. For this reason, observed synchrotron radiation is usually ascribed to the acceleration of leptons, and observing a synchrotron spectrum provides evidence of relativistic electrons accelerated in the source region.

Synchrotron radiation is beamed along the particle direction, in a cone with aperture angle $\sim 1/\Gamma$. The synchrotron radiation spectrum of a single particle is sharply peaked near the critical frequency ν_c with a narrow dispersion. The critical frequency is approximately given by

$$\nu_c \simeq \Gamma^2 \nu_g = \frac{E^2}{m_e^2 c^4} \frac{eB}{2\pi m_e c}. \quad (1.19)$$

where ν_g is the classical gyrofrequency. It depends on the particle's mass, charge, energy and the magnetic field strength.

Synchrotron spectrum of a particle population. Let us now assume we have a population of electrons with a power law energy spectrum, i.e. the number density of electrons in the energy interval E to $E + dE$ is given by:

$$\frac{dn}{dE} dE = \kappa E^{-\alpha_e} dE, \quad (1.20)$$

where κ is the normalisation of the power law and α_e the spectral index. The spectral flux density, as defined in (1.1), is the energy radiated in the frequency range $[\nu, \nu + d\nu]$ that can be attributed to electrons with energies in the range E to $E + dE$. It can be found by multiplying the radiation power of a single electron (1.18) by their energy distribution (1.20):

$$F(\nu)d\nu \propto - \left(\frac{dE}{dt} \right) \left(\frac{dn}{dE} \right) dE. \quad (1.21)$$

The particle energy can be expressed through equation (1.16) as a function of Γ , that depends on the synchrotron photon frequency and magnetic field through equation (1.19) as $\Gamma \propto \nu^{1/2} \nu_g^{-1/2} \propto \nu^{1/2} B^{-1/2}$. Thus,

$$-\frac{dE}{dt} \propto B^2 \Gamma^2 \propto B \nu, \quad (1.22)$$

$$\kappa E^{-\alpha_e} \propto \kappa \nu^{-\alpha_e/2} B^{\alpha_e/2}, \quad (1.23)$$

$$dE \propto B^{-\frac{1}{2}} \nu^{-\frac{1}{2}} d\nu, \quad (1.24)$$

and by multiplying them we get the **spectrum of a synchrotron emission**:

$$F(\nu)d\nu \propto \kappa \nu^{-\frac{\alpha_e-1}{2}} B^{\frac{\alpha_e+1}{2}} d\nu. \quad (1.25)$$

A power law electron distribution with index α_e produces a power law synchrotron spectrum with index:

$$\alpha = \frac{\alpha_e - 1}{2}, \quad (1.26)$$

thus equation (1.27) can be written as:

$$F(\nu) \propto \kappa \nu^{-\alpha} B^{\alpha+1}. \quad (1.27)$$

Figure 1.3 shows the synchrotron emission from single electrons, peaked around their critical frequency, and the combined emission from a population of particle with a power law energy spectrum, which results in a power law synchrotron emission (Carroll and Ostlie 2017).

If an electron moves in presence of a *curved* magnetic field, the emission process is called **synchrotron curvature emission**. The curvature radiation spectrum for a populations of electrons with a power law spectrum is a power law with index $\alpha = \frac{\alpha_e - 1}{3}$ (Bose et al. 2022a). This mechanism is thought to be responsible for the high-energy emission of pulsars, which have a strong curved magnetic field.

Synchrotron self-absorption

For a typical $\alpha_e \approx 2$, the synchrotron spectrum (1.27) is $\sim \nu^{-1/2}$, which diverges at low frequencies (*infrared catastrophe*). This non-physical behaviour is solved by taking into account the **synchrotron self-absorption** mechanism. The presence of matter in the region where the magnetic field is present modifies the emission spectrum: the photon cross-section increases at small frequencies and the source becomes *optically thick*, which suppresses the flux at low frequencies.

The *optical depth* of a source with number density n (cm^{-3}) is defined as

$$\tau = \int \frac{ds}{\ell} = \int n \sigma(\nu) ds, \quad (1.28)$$

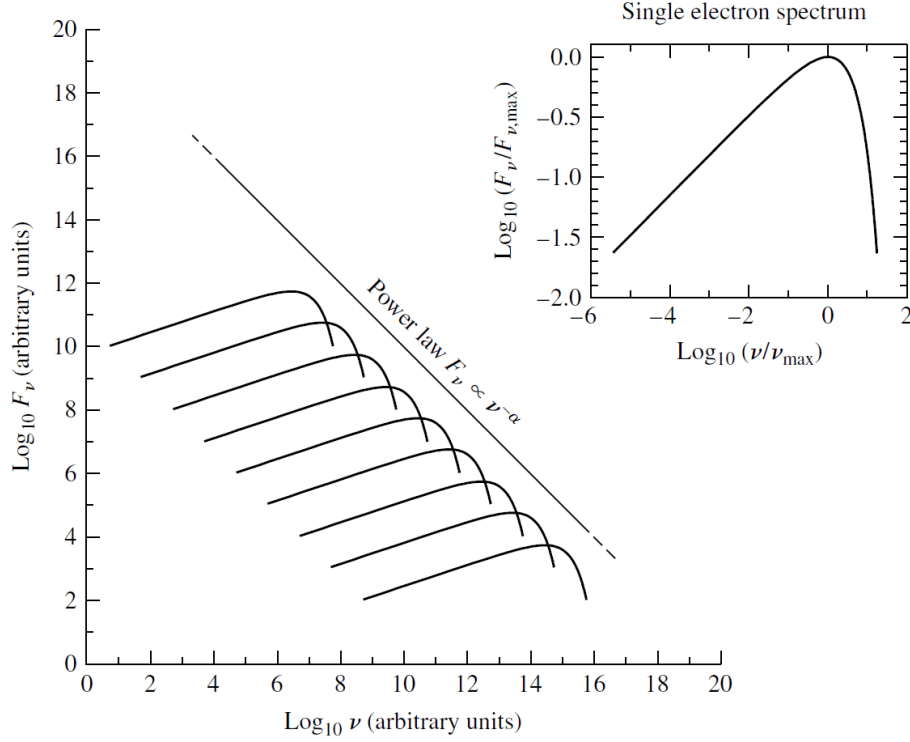


Figure 1.3 – Synchrotron emission from a population of electrons distributed with a power law energy spectrum. It results in a power law synchrotron emission. The emission spectrum of a single electron, peaked around the critical frequency, is shown at the top. Credit: Carroll and Ostlie (2017).

where ds is a small particle path, the integral is over the source extension before the photon escape, ℓ is the free mean path of a photon with frequency ν . The mean free path is defined $\ell = \frac{1}{n\sigma(\nu)}$ (cm), where $\sigma(\nu)$ is the interaction cross-section of a photon with frequency ν in a medium with number density n (cm^{-3}). Thus,

$$\text{if } \tau(\nu) \ll 1 \text{ the source is optically } \textit{thin}, \quad (1.29)$$

$$\text{if } \tau(\nu) \gg 1 \text{ the source is optically } \textit{thick}, \quad (1.30)$$

for an homogeneous source of scale dimension R , $\tau \simeq n\sigma R$.

Inside an optically thick medium, matter is able to absorb part of the radiation. According to the principle of detailed balance (Spurio 2018), for every emission process (e.g. synchrotron emission), there is a corresponding absorption mechanism (synchrotron self-absorption). We can associate an *effective kinetic temperature* T_e to the accelerated electrons population, even if they follow a power-law energy distribution and are not in thermal equilibrium:

$$\Gamma m_e c^2 = 3k_B T_e, \quad (1.31)$$

where k_B is the Boltzmann constant, and from which

$$T_e = \frac{m_e c^2}{3k_B} \Gamma \simeq \frac{m_e c^2}{3k_B} \left(\frac{\nu}{\nu_g} \right)^{1/2} \sim \nu^{1/2} B^{-1/2}. \quad (1.32)$$

We can define the *brightness temperature* T_b of the radiation emitted with a process with *monochromatic intensity* $I(\nu)$ [$\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}$], using the intensity of *black-body* radiation:

$$I(\nu) = \frac{2h\nu^3}{c^2} e^{-(h\nu)/(k_B T_b - 1)} \simeq \frac{2k_B}{c^2} T_b \nu^2, \quad (1.33)$$

where the last equality holds in the Rayleigh-Jeans limit. The brightness temperature is then:

$$T_b = \frac{c^2}{2k_B} \nu^{-2} I(\nu). \quad (1.34)$$

For a source with self-absorption processes, the brightness temperature of the radiation T_b is equal to the effective kinetic temperature of the emitting electrons T_e defined in equation (1.32), hence equation (1.33) becomes:

$$I(\nu) \simeq \frac{2k_B}{c^2} \frac{m_e c^2}{3k_B} \left(\frac{\nu}{\nu_g} \right)^{1/2} \nu^2 \propto \nu^{5/2} B^{-1/2}. \quad (1.35)$$

The flux is proportional to the intensity times the angular dimension of the source. It does not depend on the particle density κ defined in equation (1.20): the more electrons are present, the larger the emission, but also the larger the absorption. The synchrotron spectrum is $\propto \nu^{5/2}$ at low frequencies where the source is optically thick, according to equation (1.35). At higher frequencies, the source is optically thin and the spectrum is $\propto \kappa \nu^{-\alpha} B^{\alpha+1}$ according to equation (1.27). The separation between the two regimes is found when their ratio is ≈ 1 :

$$\frac{F_{\text{thin}}(\nu)}{F_{\text{thick}}(\nu)} \simeq \frac{R \kappa \nu^{-\alpha} B^{\alpha+1}}{\nu^{5/2} B^{-1/2}} \simeq R \kappa \nu^{-\alpha-5/2} B^{\alpha+3/2} \approx 1. \quad (1.36)$$

If the source dimension R and the normalisation κ are fixed, the *self-absorption frequency* ν_t can be obtained, and the synchrotron spectrum peaks close to ν_t .

1.3.2 Inverse Compton Radiation

Inverse Compton (IC) scattering is a non thermal process in which ultra-relativistic electrons scatter low energy photons, that gain energy at the expense of the kinetic energy of the electrons¹.

Let us suppose we have a radiation field with energy density u_{rad} (erg cm⁻³) in the reference frame of the observer. Its energy density in the rest frame of a relativistic electron with Lorentz factor Γ is $u'_{\text{rad}} = \Gamma^2 u_{\text{rad}}$ (Spurio 2018). The power loss of the electron, i.e. the **Inverse Compton radiation power** of an electron is:

$$P = -\dot{E} = -\frac{dE}{dt} = \frac{4}{3} \sigma_T c \Gamma^2 u_{\text{rad}}, \quad (1.37)$$

where $\frac{4}{3}$ arises from averaging over the possible directions between the electrons and the photons and σ_T is the *Thomson* cross section, that can be used due to having low-energy photons and high-energy electrons. The IC radiation power, equation (1.37), is formally similar to the synchrotron radiation power, equation (1.18). Their main difference is that synchrotron power is proportional to the energy density of the magnetic field $U_B = \frac{B^2}{8\pi}$, while the IC power is proportional to the energy density of the radiation field u_{rad} . This is because the electron energy rate loss depends only the acceleration of the electron in its rest frame, see equation (1.11), and it does not change if the acceleration is produced by motion

¹Although in this section we focus on the non-thermal IC scattering, we mention that thermal Compton scattering plays a role in the emission of X-rays from AGN.

through the magnetic field (as in the synchrotron radiation) or by the electric fields of the electromagnetic waves incident upon the electron (as in the inverse Compton scattering).

The average energy that a photon acquires after IC scattering, over all photon-electron relative directions, in the *Thomson regime* $\epsilon \cdot \Gamma \ll m_e c^2$, is:

$$E_\gamma = \frac{4}{3} \Gamma^2 \epsilon, \quad (1.38)$$

where ϵ is the photon's initial energy and Γ the electron's Lorentz Factor. The energy of photons scattered by ultra-relativistic electrons increase by a factor Γ^2 . Usually in astrophysical environments $\Gamma \sim 10^{2-3}$, although in some extreme environments $\Gamma \sim 10^6$ can be reached. Radio photons can be scattered up to the ultraviolet range, infrared radiation can reach the X-ray keV band, optical photons can become γ -rays in the MeV band, and high-energy photons can be scattered up to the GeV-TeV range. IC scattering is a non-thermal process that can effectively create very high-energy photons and reduce the energy of relativistic electrons. Equation (1.38) is valid only in the Thomson regime. In the *Klein-Nishina* regime, the ultra-relativistic limit where $\epsilon \cdot \Gamma \gg m_e c^2$, the average photon energy after IC scattering is:

$$E_\gamma = \frac{1}{2} E_e. \quad (1.39)$$

Inverse Compton spectrum of a particle population. If we assume to have a population of electrons with a power law energy spectrum as in equation (1.20), the spectral flux density can be found by multiplying the radiation power of an electron times their energy distribution, as in equation (1.21):

$$F(\nu) d\nu \propto - \left(\frac{dE}{dt} \right) \left(\frac{dn}{dE} \right) dE. \quad (1.40)$$

The particle energy can be expressed through equation (1.16) as a function of Γ . Let us assume that the radiation field is uniform and monochromatic, composed by photons with energy $\epsilon = h\nu_0$. In the Thomson regime, equation (1.38) yields $E_\gamma \propto \Gamma^2 \epsilon$, thus $\nu \propto \Gamma^2 \nu_0$ and $E \propto \Gamma \propto (\nu/\nu_0)^{1/2}$. We can use this proportionality to study the terms of equation (1.40):

$$-\frac{dE}{dt} \propto u_{\text{rad}} \Gamma^2 \propto u_{\text{rad}} (\nu/\nu_0), \quad (1.41)$$

$$\kappa E^{-\alpha_e} \propto \kappa (\nu/\nu_0)^{-\alpha_e/2}, \quad (1.42)$$

$$dE \propto \nu_0^{-1} (\nu/\nu_0)^{-\frac{1}{2}} d\nu, \quad (1.43)$$

and by multiplying them we obtain the **spectrum of the Inverse Compton emission**:

$$F(\nu) d\nu \propto \kappa \left(\frac{\nu}{\nu_0} \right)^{-\frac{\alpha_e-1}{2}} \frac{u_{\text{rad}}}{\nu_0} d\nu. \quad (1.44)$$

The IC spectrum is a power law with the same slope of the synchrotron radiation, see equation (1.25) and equation (1.26). This is because both IC and synchrotron single electron spectra peak at a typical frequency that is a factor Γ^2 larger than the starting energy seed.

If the radiation field is not monochromatic, the spectrum in equation (1.44) needs to be integrated over the field frequencies ν_0 . The radiation flux u_{rad} considered is the energy

density per unit of frequency, in $\text{erg cm}^{-3} \text{ Hz}^{-1}$:

$$F(\nu) \propto \kappa \nu^{-\frac{\alpha_e-1}{2}} \int_{\nu_{\min}}^{\nu_{\max}} \frac{u_{\text{rad}}(\nu_0)}{\nu_0} \left(\frac{1}{\nu_0} \right)^{-\frac{\alpha_e-1}{2}} d\nu_0. \quad (1.45)$$

The result of the integral is a constant with respect to frequency. If the electron population that produces the Inverse Compton is the same that produces the Synchrotron emission, i.e. we are in the *Synchrotron Self Compton* scenario of section 1.3.3, then $\propto \ln(\nu_{\max}/\nu_{\min}) = \ln \Lambda$ and:

$$F(\nu) \propto \tau_c \nu_c^{-\alpha} \ln \Lambda, \quad (1.46)$$

where $\tau_c = \sigma_T \cdot R \cdot \kappa$ depends on the Thomson cross-section, on the source dimension R and on the electron number density κ .

1.3.3 Synchrotron Self Compton model

The basic interpretation in the Leptonic model for the production of high-energy photons is the *Synchrotron Self Compton* (SSC) mechanism, where the synchrotron photons emitted from electrons moving in a magnetic field interacts with their own parent electron population through Inverse Compton scattering. This mechanism leads to the creation of a region where accelerated electrons coexist with high-energy photons. Synchrotron spectra usually peak from radio to X energies, while the IC emission peak in GeV-TeV energies. In a SSC scenario, the strength of synchrotron and IC emission are correlated, as an increase in the first increases the energy density of the IC photon field. At equilibrium, we can assume that the ratio between the rates of energy loss of an ultra-relativistic electron by synchrotron and IC radiation is constant:

$$\frac{\dot{E}_{\text{IC}}}{\dot{E}_{\text{sync}}} = \frac{u_{\text{rad}}}{B^2/8\pi}, \quad (1.47)$$

derived from the ratio of equations (1.37) and (1.18). At equilibrium, a higher magnetic field can suppress the IC radiation as most of the electrons' energy becomes synchrotron emission.

The SSC SED (figure 1.4) shows a typical double peak structure, where the lower energy peak is due to synchrotron and the higher energy one to IC (Ghisellini 2013). In the synchrotron peak, the self-absorption frequency ν_t defines the transition between optically thick and thin source for the radiation, while the drop at large frequencies is due to a cut-off in the energy distribution of parent electrons. The IC peak shows the same slope of the synchrotron power law, damped by a factor $\tau_c \ln \Lambda$, up to high energies where the spectrum is dumped due to a cut-off in the energy distribution of parent electrons. Many γ -ray sources can be modelled with SSC emission, though models depend on the initial assumptions, such as a stationary flux of radiation. These assumption may not always held and more sophisticated modelling may be required, taking into account source time variability, relativistic bulk motions of the source regions, the presence of external radiation fields such as the CMB Radiation which can trigger external IC radiation.

1.4 The Hadronic Emission Scenario

In the Hadronic emission scenario, γ -rays are produced by the decay of accelerated particles through multiple mechanisms (Bose et al. 2022a).

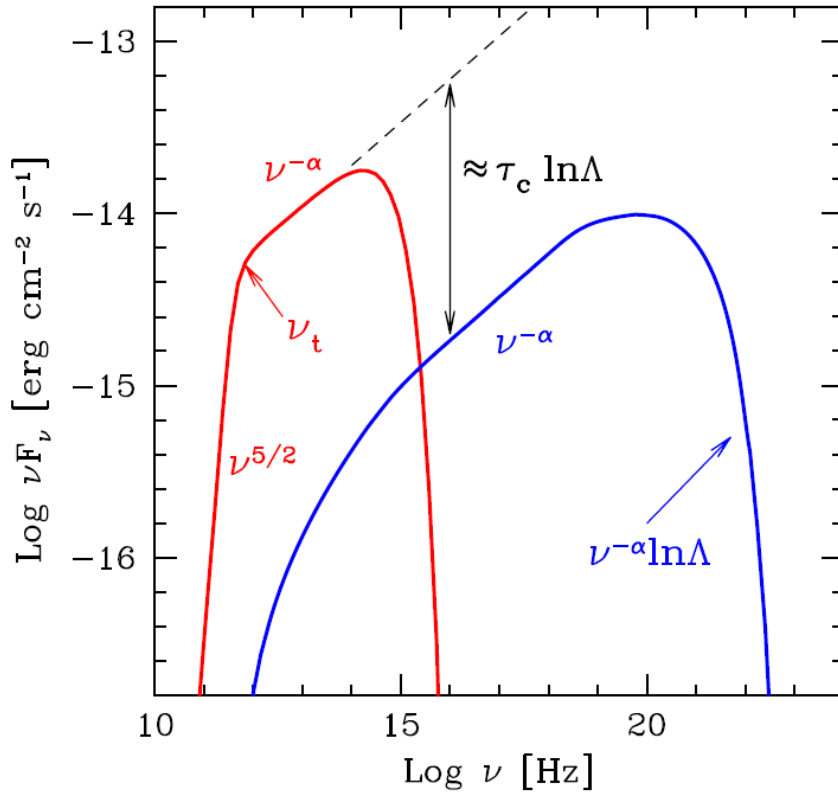


Figure 1.4 – Example of a SSC SED, with the double peak structure corresponding to synchrotron and IC emission, with the same slopes. High-Energy cut-offs are due to the electrons’ cut-off energy. Synchrotron low-energy cut-off at ν_t is due to self-absorption. Credit: Ghisellini (2013).

Hadron-nucleon collisions, or *pp interactions* when only protons are involved, are one of the main hadronic emission processes; they occur when an accelerated hadron collides with an astrophysical target of nucleons, e.g. a molecular cloud. The collision initiates a hadronic cascade with the production of charged and neutral pions (π^+ , π^- , π^0). The neutral pion has a mass of $135 \text{ MeV } c^{-2}$, a mean lifetime of $8.5 \cdot 10^{-17} \text{ s}$ and its dominant decay mode is into two photons (Particle Data Group 2020):

$$\pi^0 \rightarrow \gamma + \gamma. \quad (1.48)$$

The **neutral pion decay** is one of the main interactions that can produce γ -rays in the hadronic models.

Gamma-rays can also be produced in *photoproduction* interactions, i.e. the interaction between protons and an astrophysical radiation field, arising for instance from synchrotron radiation or bremsstrahlung of accelerated electrons. Photoproduction is relevant in environments where the photon density is higher than the matter density, and it occurs via Δ^+ resonance:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n, \quad (1.49)$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p, \quad (1.50)$$

where Δ^+ is a baryon made up by two up quarks and a down quark. The second process is twice as likely as the first one and leads again into *neutral pion decay* and the production of gamma-rays if the pions have enough energy. Approximately, $E_\gamma \sim E_p/10$. Example of radiation fields that may cause photoproduction are the CMB radiation and fields of *ambient*

photons surrounding astrophysical sources at different energies, from radio to ultraviolet. The protons produced by Δ^+ resonances are usually constrained by the existence of magnetic fields, while neutrons can escape the acceleration region and further decay into protons and neutrinos: $n \rightarrow p + e^- + \bar{\nu}_e$. Charged pions can undergo further decay chains:

$$\pi^+ \rightarrow \nu_\mu + \mu^+ \quad (1.51)$$

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \quad (1.52)$$

The energy that escapes an acceleration region through hadronic processes is thus divided between gamma-rays, cosmic rays and neutrinos. The energy partition can be observed if the source is transparent enough, i.e. if its size is much larger than the proton mean free path, but smaller than the meson interaction length. For these sources, protons have a large probability of interacting once, and most secondary mesons can decay. Under these conditions, the energy spectra of CRs, γ -rays and neutrinos are expected to have similar indices, thus γ -ray measurements can provide crucial information on primary CRs and help constraining the expected neutrino flux (Spurio 2018).

The spectrum of γ -rays produced through neutral pion decay shows a bump with a low-energy cut-off at 67.5 MeV, half the rest energy of π^0 . This feature, called the **Pion bump**, is almost independent of the π^0 and proton parent populations, and it is considered as a spectral signature of hadronic processes (Funk 2015). We report an example of hadronic emission in figure 1.5. The identification of pion bumps is one of the main challenges in high-energy astrophysics today. Hadronic processes that produce charged pions result in the production of *neutrinos* due to $\pi^\pm$ decay, which may be detected in a *multi-messenger* context: a simultaneous detection of gamma-rays and neutrinos is an important feature of hadronic models.

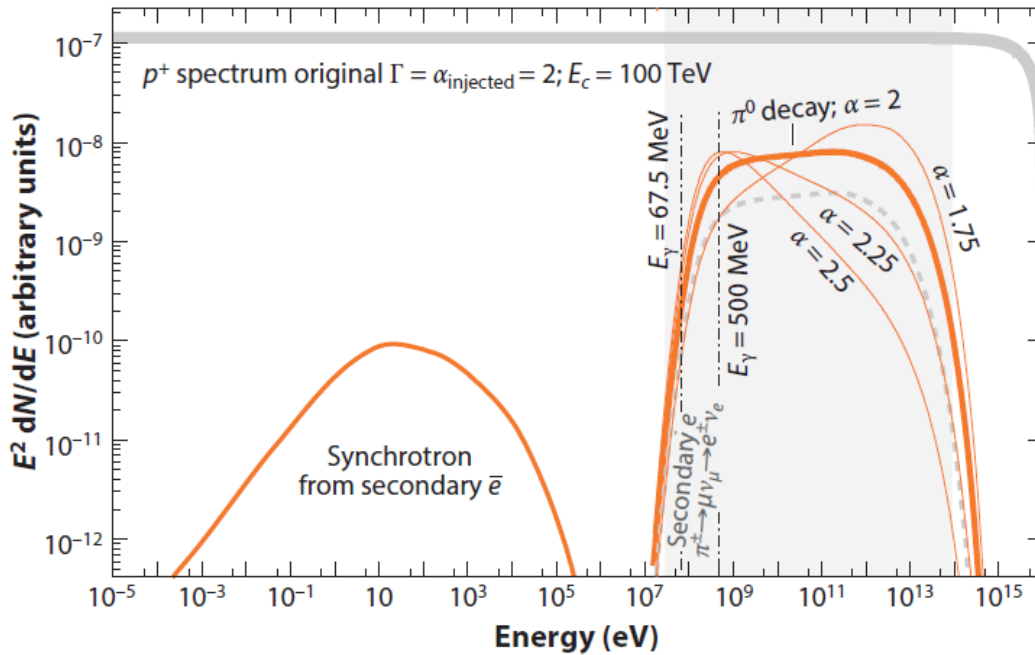


Figure 1.5 – SED of accelerated protons with a power law spectrum with cut-off and γ -rays resulting from their collision with interstellar material. The dominant emission occurs via neutral pion decay (solid orange curves), which is shown in a typical *pion bump* with low-energy turnover at 67.5 MeV. The dashed curved line shows the decay channel of $\pi^\pm$. The plot also shows synchrotron emission from the secondary electrons. Credit: Funk (2015).

1.5 The Dark Matter Emission Scenario

Cosmological dark matter (DM) contributes for $\approx 26\%$ to the total energy content of the universe, but its nature remains unknown. The most often discussed explanation is that of a hypothetical elementary particle different from those included in the Standard Model of Particle Physics (Particle Data Group 2020). A significant number of *exotic* particle candidates have been proposed in literature, and a promising way to test their existence is to look for the gamma rays produced from the *annihilation* or *decay* of these exotic particles, as predicted by *top-down* scenarios for the production of gamma rays (The CTAO Consortium 2024).

The expected signal from DM processes depends on the particle model assumed. The *Weakly Interacting Massive Particles* (WIMPs) are among the most popular DM candidates, with masses and coupling strengths at the electroweak scale and electrically neutral. The expected flux of gamma rays from annihilation processes would be proportional to the line-of-sight integral of the squared DM density distribution, which motivates the search for such signals in targets with density enhancements such as the Galactic Centre, Galaxy Clusters and nearby dwarf spheroidal galaxies. Gamma-rays produced by WIMPs are expected to mostly produce a signal broadly distributed in energy, that would require a very detailed characterisation of the background signal.

Rarer types of WIMPs decay or different DM candidates may instead produce *smoking gun* signatures, clearly distinguishable from the background emission, such as:

1. **Line signals.** Monochromatic spectra may be produced when DM particles annihilates to a pair of final states containing one electrically neutral particle and at least one photon. The CTAO Consortium (2024) discusses example of DM candidates where strong line signals are expected in CTAO's energy range.
2. **Internal bremsstrahlung.** Internal bremsstrahlung radiation may be produced when DM particles annihilates to a final state containing two charged particles and at least one photon. The photons produced with this type of mechanisms would create a spectral feature at an energy similar approximately similar to the DM particle energy.
3. **Box signals.** If DM particles annihilate into a pair of new, long-lived neutral states, their decay into photons may result into a constant spectrum defined in a proper energy range.

The smoking gun signatures are expected to occur at lower rates than typical WIMPs annihilation, but they could provide a clearer discovery of the Dark Matter if detected. We report in figure 1.6 expected models of line, internal bremsstrahlung and box signals in the VHE range (The CTAO Consortium 2024). The details of the spectrum could thus allow us not only to discriminate DM signals from background components, but also provide insights about the underlying particle physics model.

1.6 The Gamma-ray Sky

The γ -ray sky contains thousand of sources belonging to several classes of astrophysical objects, all showing aspects of the violent, energetic, non-thermal phenomena that occur in

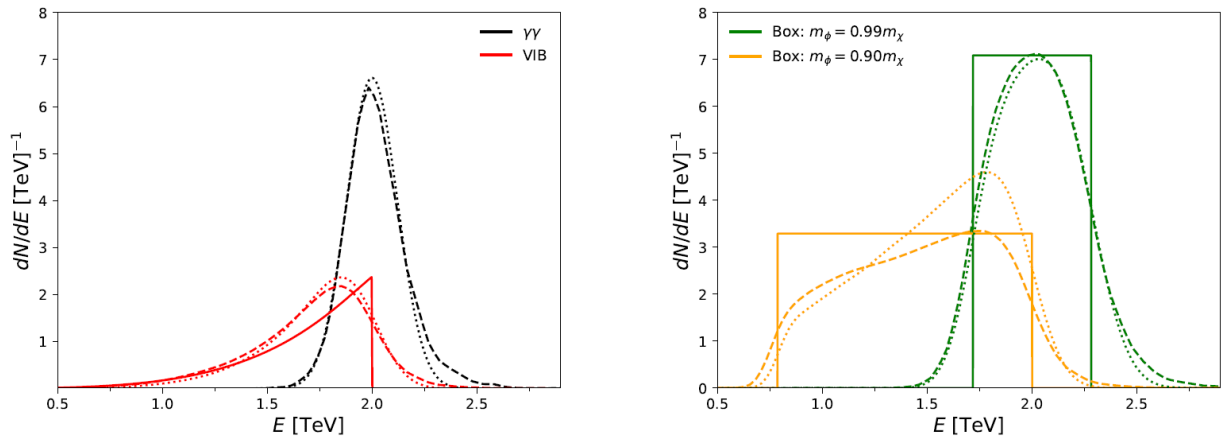


Figure 1.6 – Typical DM signal spectral model. Solid lines are physical spectra, dotted lines show the spectra convoluted with a Gaussian kernel, dashed lines show the observed signal expected using the *Instrument Response Functions* (IRFs) of CTAO. The left panel shows the signal from a monochromatic line in red, and the signal from internal bremsstrahlung in black. The right panel shows two box scenarios with different energy windows. Credit: The CTAO Consortium (2024).

the Universe. An overview of the HE sky as it is known today can be seen in figure 1.7. It shows 12 years of data > 1 GeV acquired by Fermi’s *Large Area Telescope* (LAT) in galactic coordinates, and contains thousands of point-like and extended sources. The most prominent feature is a bright, diffuse central glow that marks the Galactic plane. Most of the point-like sources close to the Galactic plane are pulsars, while most sources outside it are AGN. A similar image of the VHE sky is not available, due to the fact that space satellites are not sensitive to these energies, and *Atmospheric Imaging Cherenkov Telescopes* (IACTs) are needed to detect sources. IACTs today cannot observe the full sky and their background characterisation is strongly affected by the different atmospheric conditions of each observation, hence no full map of the sky has been produced. One of the main perks of the CTAO is going to be a full-sky coverage thanks to having two sites, one in the Canary Islands and the other in Chile, and it will perform the first thorough survey of the VHE sky. The distribution of the known TeV sources is recorded in the *TevCat* catalogue (Wakely and Horan 2008), shown in figure 1.8 superimposed to Fermi’s sky. There are a few hundreds of VHE sources known today, mainly AGN in the extra-galactic sky and pulsars, *Pulsar Wind Nebulae* (PWNe) and *Supernova Remnants* (SNRs) in the Galactic plane. Due to the low number of sources discovered today, the search for VHE counterparts of known sources or completely new ones is one of the main goals driving observations, making γ -ray astrophysics one of the fields of astronomy mostly involved in multi-wavelength and multi-messenger astrophysics.

The astrophysical sources of VHE gamma rays can be roughly divided in *Galactic* or *Extra-galactic* sources, *Steady* or *Transient sources*.

1.6.1 Galactic Sources of Gamma-rays

Here we present an overview on the main Galactic sources of gamma-rays.

Galactic diffuse high-energy emission. Diffuse radiation is seen at all Galactic latitudes in the GeV sky, but it dominates at the Galactic plane. This emission is produced by CR

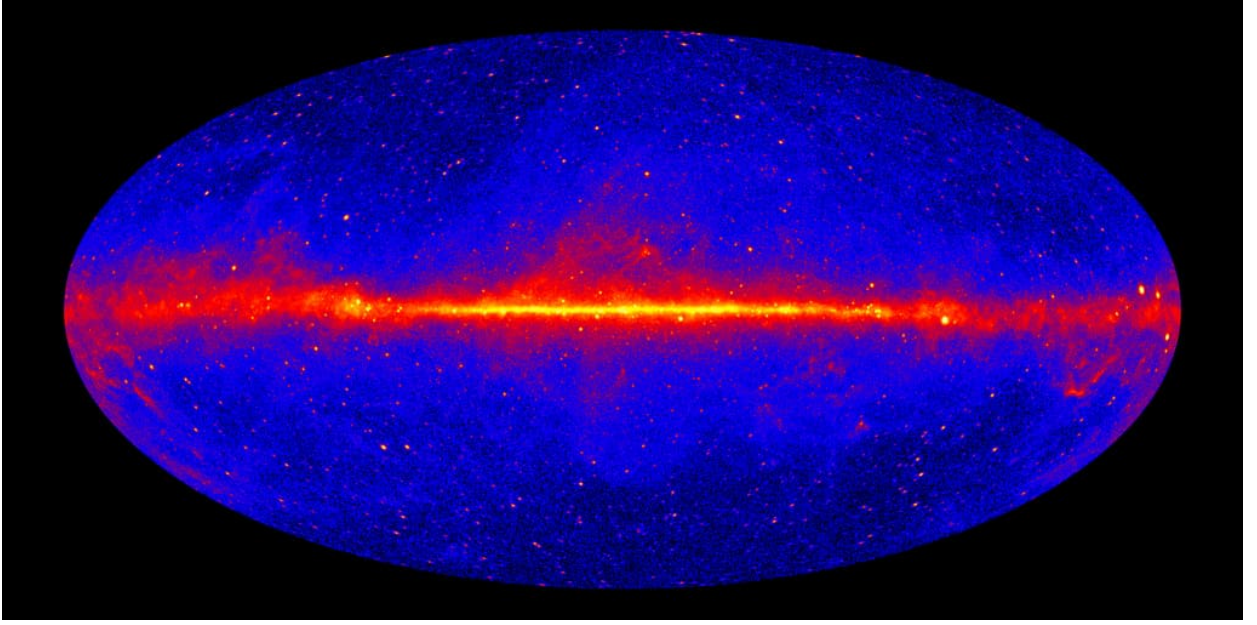


Figure 1.7 – Gamma-ray sky > 1 GeV as seen by Fermi’s Large Area Telescope, using 12 years of observations published in the Fourth Fermi-LAT catalogue (Abdollahi et al. 2022).

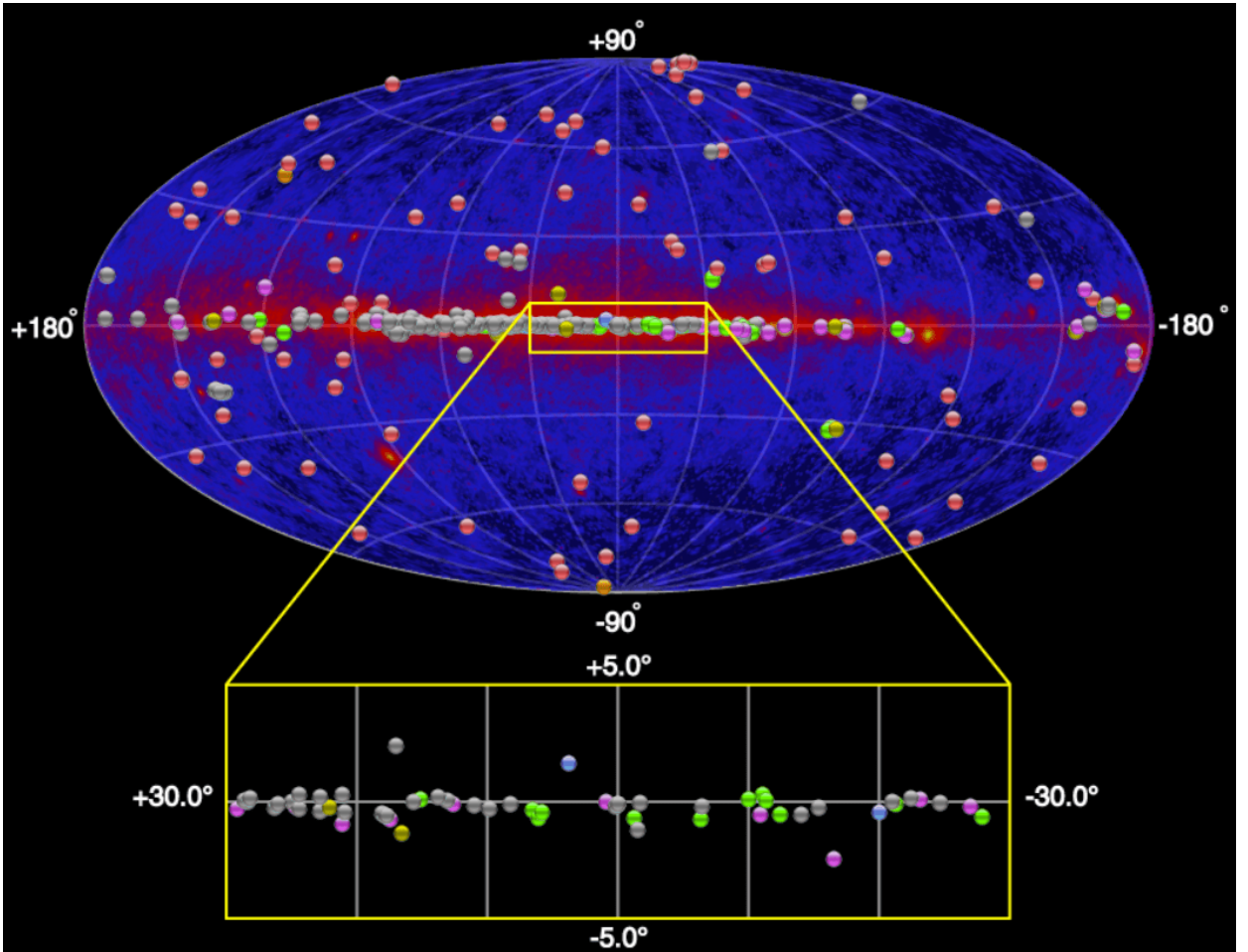


Figure 1.8 – Distribution of the known gamma-ray sources at TeV energies registered in the *TeVCat* catalogue (Wakely and Horan 2008), superimposed to Fermi LAT’s sky. Red points are AGN and GRBs. Orange points are Starburst (SB) galaxies. Green points are SNRs. Violet points are PWNe or TeV Halo candidates. Blue points are Star Forming Regions or Globular Clusters. Yellow points are pulsars, novae or binaries. Grey points are sources of unclear classification.

hadrons and electrons interacting with the interstellar gas and photon fields in the Galaxy. Emission mechanisms entail both hadronic and leptonic processes, such as neutral pion decay, IC of electrons with the optical and infrared Galactic photon fields, bremsstrahlung from the interaction of high-energy photons and interstellar gas (Spurio 2018).

Galactic Centre. The centre of our Galaxy hosts the supermassive black hole *Sgr A**, a source of gamma-rays up to 10 TeV. The high density of the sources with respect to the angular resolution of HE and VHE current instruments does not allow us to resolve the sources of the Galactic centre.

Supernova Remnants. High-mass stars ($\gtrsim 8 M_{\odot}$) end their life with a supernova explosion. Their inner core collapses into a compact object, a neutron star or a black hole, while the outer layers are blown off into the ISM creating a Supernova Remnant (SNR). According to the theory of diffuse shock acceleration, particles in SNRs can be accelerated into high-energy CRs and emit gamma rays. SNRs are thought to be the main accelerators of Galactic CRs. Several SNRs have been detected both in the HE and VHE ranges, and some of them showed a pion bump, supporting the scenario of hadronic acceleration (Bose et al. 2022a).

Pulsars. Pulsars are rapidly rotating neutron stars with strong magnetic fields and rotation periods from few milliseconds to few seconds. Pulsars dissipate their rotational energy by throwing out relativistic winds of accelerated electrons and positrons focused into jets, inside the ISM. If the magnetic and the rotation axes are misaligned, the jet sweeps, and if they point towards Earth, they can be detected with a periodic signal. The main emission mechanism is thought to be synchrotron curvature radiation. Several pulsars have been detected in the GeV range, and Crab and Geminga in the TeV energies. A schema of the emission process is reported in figure 1.9 (MAGIC Collaboration 2008).

Pulsar Wind Nebulae. The magnetosphere of pulsars contains not only the jets, but also a relativistic plasma of electrons, positrons and possibly ions that can be accelerated into a wind by the magnetic field. If this component is energetically relevant, it creates a nebular structure called Pulsar Wind Nebula (PWN). The particles injected into the nebula produce synchrotron emission peaking at optical to X-rays energies, and IC emission by scattering with low-energy photons (usually from CMB or IR fields). PWN are considered to be the source of leptonic CRs in the Galaxy. They differ from SNRs as the bulk of the emission is provided to the nebula by the rotation energy of the pulsar, not by diffuse shocks, and is mostly leptonic. The PWN terminates in a shock when it collides with the surrounding nebula. The size of the nebula is lower at higher energies due to cooling processes. A schema of the emission process is reported in figure 1.10 (Aharonian et al. 2012). The most famous PWN is the Crab Nebula, one of the main sources in gamma-ray astrophysics, a standard candle in VHE and HE prior to the discovery of the Crab flares by the AGILE satellite (Tavani et al. 2011).

Compact binary systems (gamma-ray binaries). X-ray binaries are binary star systems composed by a compact object, either a neutron star or a black hole, accreting matter from a companion star. There are several classes of X-ray binaries due to different accretion

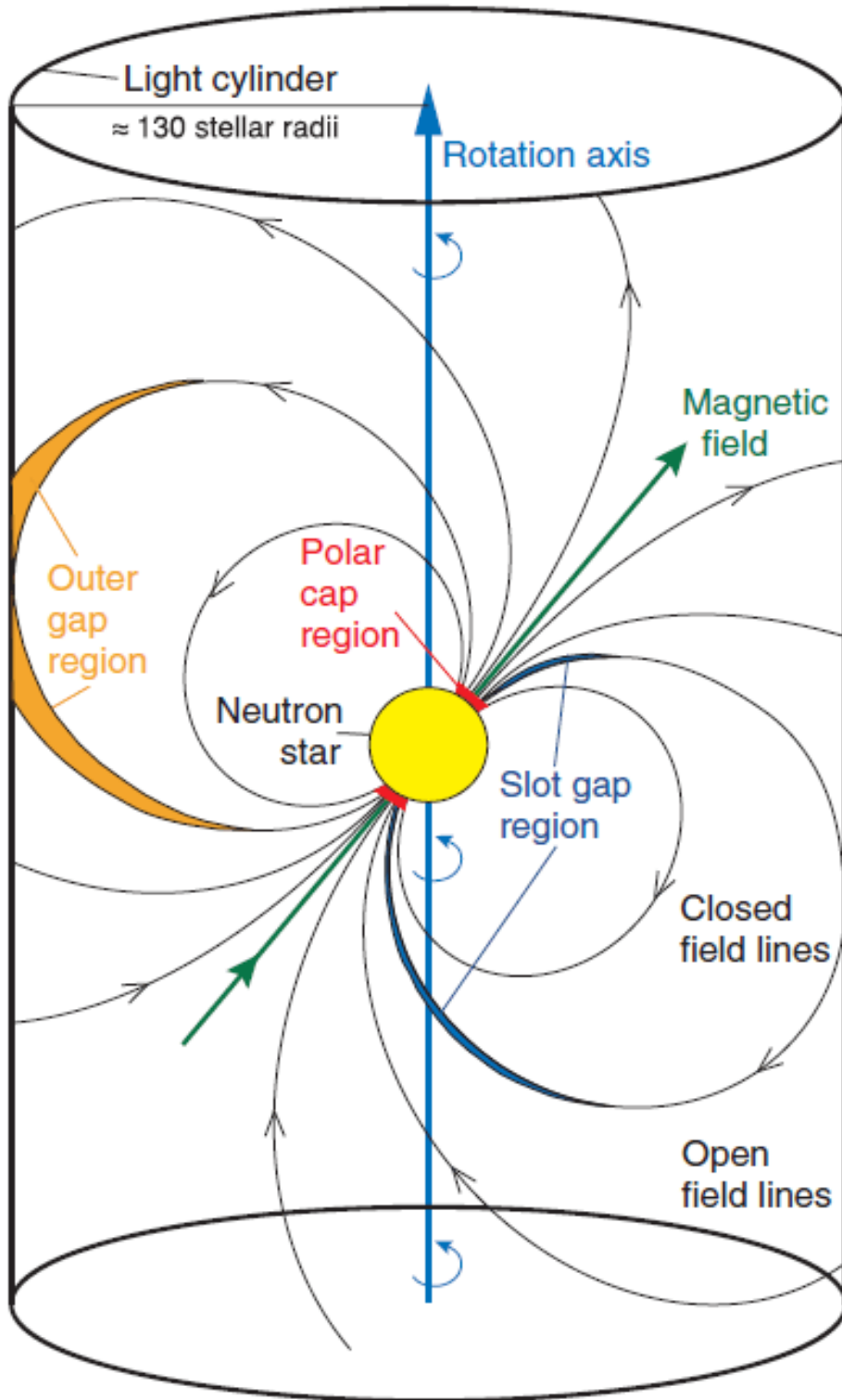


Figure 1.9 – Schematics of the magnetosphere of the Crab pulsar. Electrons are accelerated along the lines of the magnetic field and emit synchrotron curvature radiation. The magnetosphere has regions, called vacuum *gaps*, that can be filled with a plasma capable to accelerate electrons to very high energies. The emitted high-energy γ -rays get absorbed by magnetic pair production and photon-photon pair production. Magnetic pair production dominates close to the surface of the neutron star, and generates a cut-off of the spectrum at few GeV. Photon-photon collisions dominate in the outer magnetosphere and produce exponential cut-off in the spectrum at energies > 10 GeV. Credit: MAGIC Collaboration (2008), on the Crab Nebula.

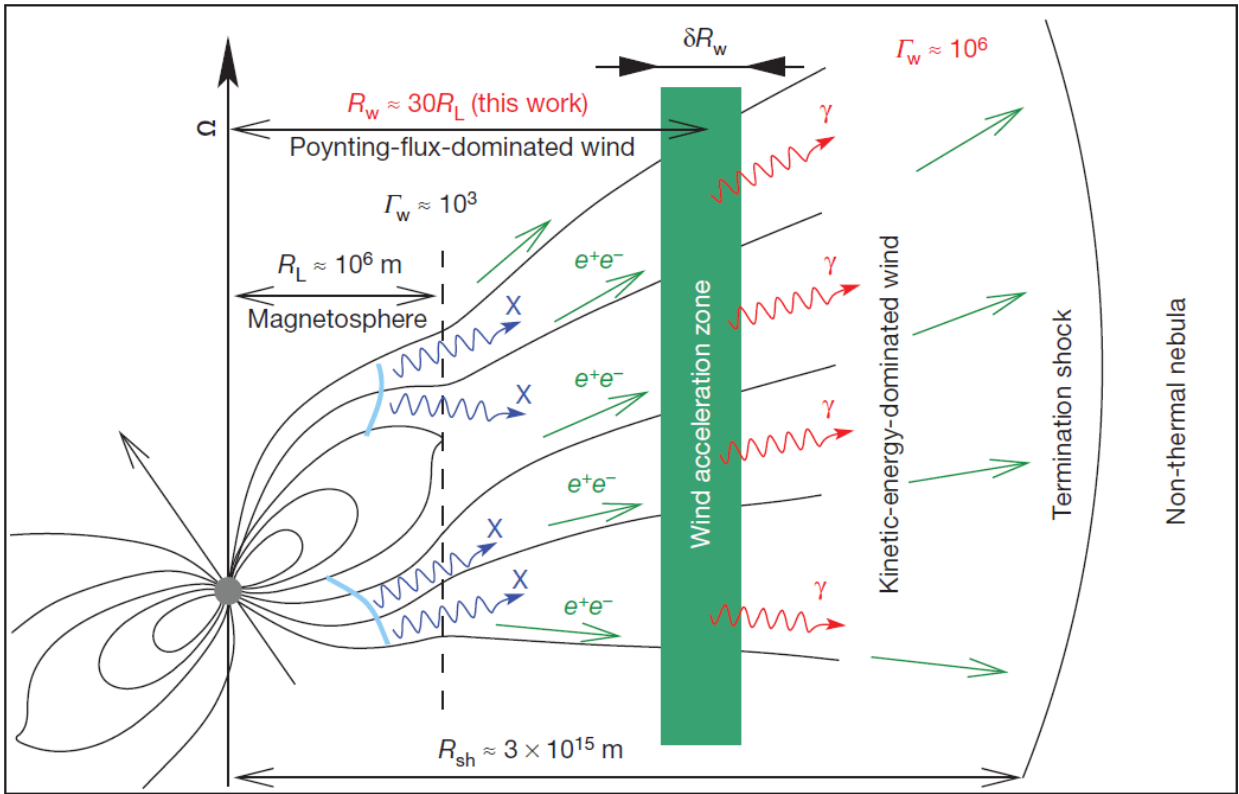


Figure 1.10 – Schematics of VHE γ -ray emission process in a PWN. The rotational energy lost by the pulsar is converted into electromagnetic energy, a flux of photons that in the magnetosphere creates a plasma of electrons and positrons through pair production. Leptons are accelerated by the magnetic field and emit *gamma*-rays through synchrotron curvature radiation. The wind terminates with a shock when it reaches the nebula surrounding the pulsar. The radiative cooling of electrons through synchrotron and IC processes results in an extended non thermal source, the PWN. Credit: Aharonian et al. (2012), on the Crab Nebula.

mechanisms (accretion disks, winds, and so on), and in some cases, namely the *microquasars*, even jets can arise from these objects. A small fraction of X-ray binaries emits VHE γ -rays, and there are three main scenarios for the production, reported in figure 1.11 (Mirabel 2012). If the compact object is a pulsar and its companion is a Be star, i.e. a B star with emission lines, the pulsar wind interacts with the ions in the Be star disk. In the microquasar scenario, γ -rays can be produced by electron-proton or electron-photon interactions. In the third scenario, where the compact object is a pulsar, its wind can interact with the UV field of a massive companion star and reach γ -ray energies by IC scattering.

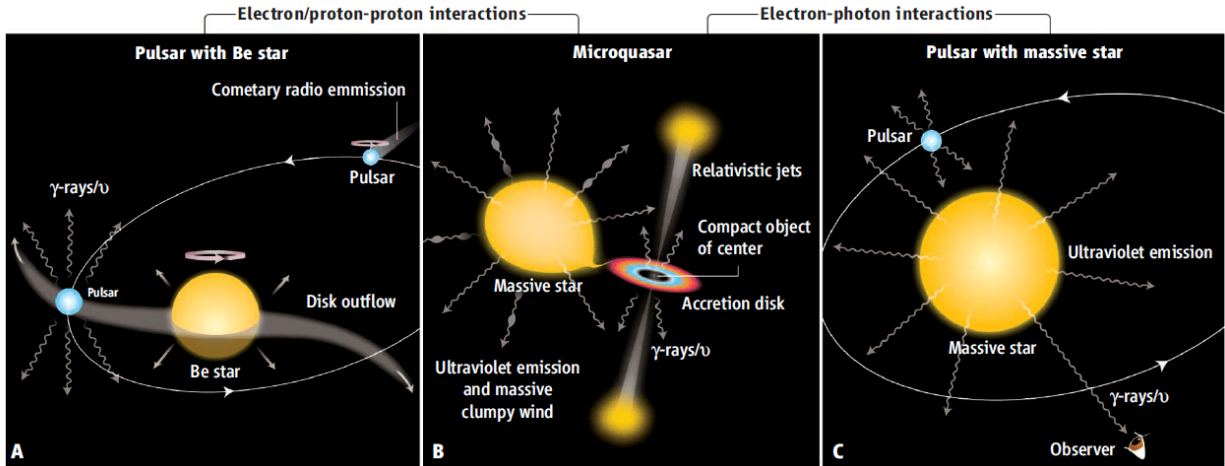


Figure 1.11 – Schematics of VHE emission process in γ -ray binaries. Scenario (A) shows γ -rays produced by the interaction of pulsar wind particles with the outflowing protons in the disk or envelope of a Be star. Scenario (B) is the microquasar, where γ -rays are produced in the jets. Scenario (C) shows γ -rays produced by the interaction of pulsar wind particles with UV photons from a massive star. Credit: Mirabel (2012).

1.6.2 Extra-galactic Sources of Gamma-rays

Here we present an overview on the main Extra-galactic sources of gamma-rays.

Active Galactic Nuclei. Active Galactic Nuclei (AGN) are distant galaxies with a nuclear region that outshines the emission from the rest of the galaxy. They are powered by the accretion of matter from the host galaxy into a central supermassive black hole ($M_{\text{BH}} = 10^6\text{--}10^9 M_{\odot}$) (Bose et al. 2022a). The accreting matter spirals around the black hole, forming an accretion disk, usually surrounded by an obscuring torus of dust and gas regions of moving clouds (forming *Broad* and *Narrow Line Regions*). Relativistic radio jets are emitted from the region close to the disk, though the exact formation mechanism is uncertain. According to the *AGN unification model* (Antonucci 1993), the underlying physics of AGN is the same, but differences in orientation and luminosity create a large ensemble of different observational classes, such as quasars, blazars, radio galaxies, Seyfert galaxies. We show a schema of the AGN structure in figure 1.12. VHE emission has been detected mostly from *blazars*, AGN whose jets have a small angle with respect to the line of sight that are dominated by the emission of the jets. The broadband SEDs of blazars typically show two broad peaks of non-thermal radiation: a synchrotron emission peaking between radio and X-rays due to relativistic electrons being accelerated in the jets, and a high-energy bump whose emission

mechanism is still up to debate. It could be a leptonic bump due to IC scattering of low-energy photons, either from the jet or from outside regions, or hadronic if neutral pions are produced, or having mixed contributions. Hadronic models may be needed to explain associations of blazars with high-energy neutrinos (IceCube Collaboration 2018). The SED of blazar PKS 2155-304 is shown as an example in figure 1.13 (H. E. S. S. Collaboration 2012). Other research areas for blazars include understanding how jets are launched and how they are collimated, what is the acceleration mechanism of particles in the jet, e.g. diffusive shock acceleration, magnetic reconnection.

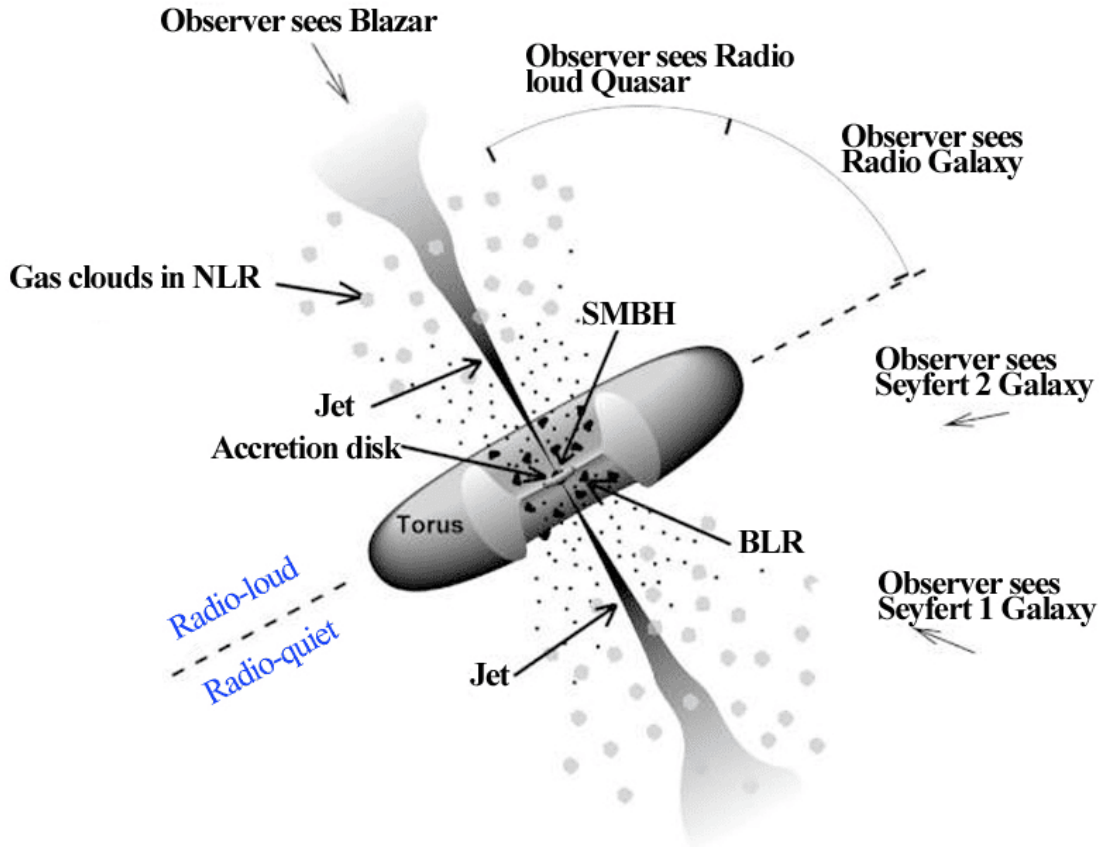


Figure 1.12 – Representation of AGNs according to the AGN unification model. Credit: NASA at <https://fermi.gsfc.nasa.gov/science/etev/agn/>.

Starburst galaxies. Some galaxies such as the Small and Large Magellanic Clouds, and the starburst galaxies M82, NGC253 are detected in the HE range, yielding information on the production of CRs beyond our Galaxy. The emission from these galaxies is similar to the one of the Galactic diffuse emission, arising from the interaction of hadrons and electrons with matter and photon fields of that galaxy.

1.6.3 Transient Sources of Gamma-rays

Here we present an overview on the main transient sources of gamma-rays.

Flares of PWNe. *PWNe* can exhibit flares, the most relevant episode being the discovery of the Crab nebula flare in 2010, which challenged the scenario of the Crab being a constant

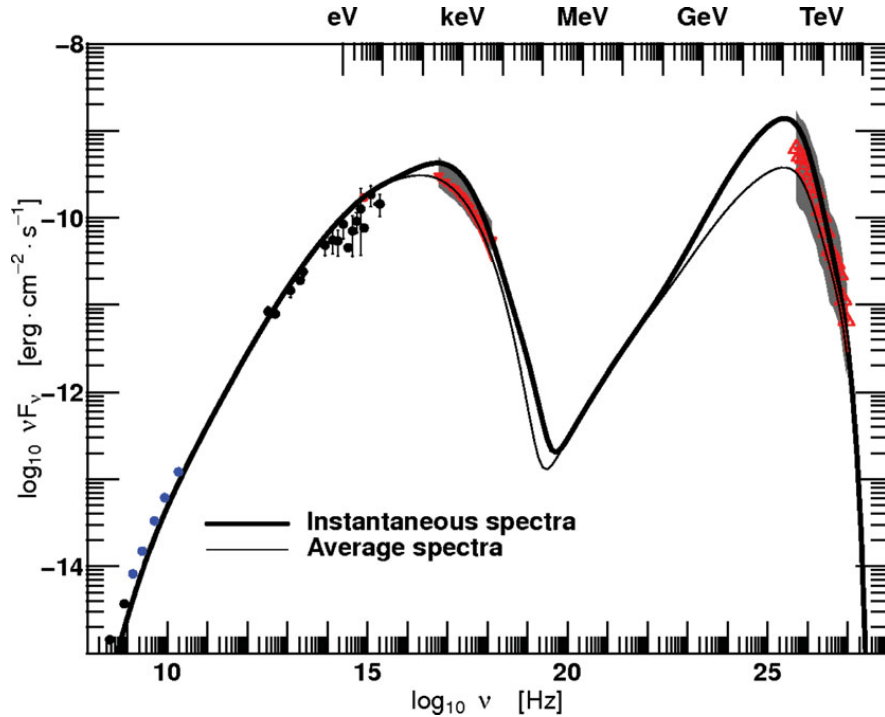


Figure 1.13 – Example of SED emission of the blazar PKS 2155-304 during its 2006 active state. Red points show nightly average spectra from Chandra and H.E.S.S. data, while the grey band indicates the varying spectra. Thin and thick solid lines present time dependent synchrotron-self-Compton models. Credit: H. E. S. S. Collaboration (2012).

flux standard candle for gamma-ray astronomy (Tavani et al. 2011). Flaring episodes show timescales of few hours, can last for several days/weeks, increase the flux by factors 3 – 30 and show variability in spectral index. No variability in the flux of the pulsar is observed during these episodes, and no variability in the synchrotron component in the radio, infrared or X-ray bands. The flaring emission may extend to TeV energies as a synchrotron tail or due to the IC component of a SSC process, but no variability has been observed by IACTs up to now up to ~ 10 TeV. Understanding the emission process of flares is not an easy task. A possible scenario is synchrotron emission by electrons in a shocked pulsar wind, but flares are higher than the expected model values. Other possibilities are IC emission, but flares seem to have shorter timescales than expected (Carosi and López-Oramas 2024), and magnetic reconnection events in a highly magnetised plasma.

Flares of gamma-ray binaries. Several *gamma-ray binaries*, like LSI +61 303 (Archambault et al. 2016) and HESS J0632+057 (Adams et al. 2021), have shown flaring episodes. As both systems include massive Be stars with a circumstellar disk, flares may originate from clumps in the stellar wind or their interaction with the pulsar wind. Only two *microquasars*, Cygnus X-1 and Cygnus X-3, have been detected with transient emission in the HE band. Both of them host a high-mass companion star, and no flares have been detected from microquasars with low-mass companions, the *low-mass X-ray binaries*, *LMXBs*. No microquasar flares have been detected in the VHE band.

Supernovae. During supernovae (SNe) explosions, the outer shells of massive stars are ejected into the interstellar medium and subject to acceleration. Both thermonuclear and core-collapse SNe are expected to produce HE and VHE gamma-rays due to the acceleration

of protons in the blast wave, but no significant signal has been detected yet, probably due to absorption processes of gamma-rays (Carosi and López-Oramas 2024).

Novae. *Novae outbursts* are thermonuclear explosions occurring on the surface of a white dwarf (WD) accreting material from a companion star. When enough material is accumulated on the WD surface, hydrogen burns in degenerate conditions, and once a critical mass is reached, the system undergoes a thermonuclear runaway. Ejecta materials expand at velocities reaching $\sim 10^3 \text{ km s}^{-1}$ and can interact with the surrounding material, if present. Novae are classified into *classical*, where the companion is a main sequence star and accretion occurs via Roche-lobe overflow, or *symbiotic*, where the companion is a Red Giant (RG) star and the WD accretes directly from the RG wind. Novae explosions do not disrupt the binary system and can occur in cycles. Typical classical novae cycles last $\approx 10^{4-5} \text{ yr}$, though some systems known as *recurrent novae* have displayed more than one eruption in a human lifetime. They have WD with masses close to the Chandrasekhar limit ($M \gtrsim 1.2 M_{\odot}$) and high accretion rates ($\dot{M} \approx 10^{-7} M_{\odot} \text{ yr}^{-1}$) (Schaefer 2010). The first nova detected in HE was V407 Cyg by Fermi-LAT in 2010 (Fermi LAT Collaboration 2010), the first one detected in VHE was RS Oph by H.E.S.S. (H. E. S. S. Collaboration et al. 2022) and confirmed by MAGIC and LST-1. The emission is due to particle acceleration in the blast wave of the nova, a shock created by the ejecta expanding in the surrounding medium and the RG wind. Observations suggest that an hadronic scenario for the emission, with novae being proton accelerators.

Fast Radio Bursts and magnetar flares. Magnetars are a class of slowly rotating ($P \sim 1 - 12 \text{ s}$), isolated NS with a strong magnetic field of the order of 10^{14} G to 10^{15} G , about 3 orders of magnitude higher than that of regular NS (Olausen and Kaspi 2014; Kaspi and Beloborodov 2017). The magnetic field acts as the main energy source of the emission, that can be distinguished in two categories: the *persistent* emission from the pulsar (and the surrounding nebula if present), detected in the keV energy range, and a *transient* emission made up by outburst episodes with bursts or flares on different timescales, detected in the keV – MeV energy range, likely caused by crustal fractures and/or rearrangements of the magnetosphere (Beloborodov and Thompson 2007; Mereghetti et al. 2015; Carosi and López-Oramas 2024). Magnetar bursts are one of the possible explanations for *Fast Radio Bursts* (FRBs), a class of $\sim \text{ms}$ radio transient events of (mainly) extra-galactic origin. The first evidence for the FRB-magnetar connection was provided on April 28th, 2020, when bursts emitted by the *Soft Gamma Repeater* (SGR) 1935+2154 were simultaneously detected in the radio with properties similar to those of FRBs (CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020), and X-ray bands (Mereghetti et al. 2020; Ridnaia et al. 2021a; Li et al. 2021; Tavani et al. 2021). This discovery gave a strong support to the classes of FRB models based on the presence of a magnetar and raised the interest for multi-wavelength observations of SGR 1935+2154. Both HE and VHE facilities searched for magnetar emission, but none has been found up to now. In the context of this work, we searched for SGR 1935+2154 VHE emission with LST-1 (see Chapter 6).

Tidal disruption events. Tidal disruptions events (TDEs) occurs when a star is disrupted by tidal forces when approaching a massive BH. They are one of the less studied classes of events in high-energy astrophysics, but they are gaining importance in the context of multi-messenger astrophysics. The disruption of a stellar object may trigger the launch of a

relativistic jet able to shock-accelerate particles from the star remnants, including ultra-high-energy Cosmic Rays (UHECR $> 10^{20}$ eV) and neutrinos (Farrar and Piran 2014; Guépin et al. 2018; Guépin et al. 2020). No significant VHE emission has been found for these events.

AGN Flares. AGN are known to show variability on different time scales, from minutes to years, across all energy bands. Flux variations can be significant enough to be characterised as *AGN flares*. Blazars in particular can have strong enhancement of their flux, even by an order of magnitude, thanks to the Doppler boosting of the relativistic jet emission that boosts the flux and shortens the variability timescale in the observer’s frame (Bose et al. 2022a). One of the main explanations of blazar variability is the *shock-in-jet* models that predicts internal shocks when different parts of the jet moves at different speeds and collide. The shock front created by the collision may accelerate particles to high energies and emit non-thermal radiation. Day-scale variability is consistent with this scenario, though sub-hour variability challenges it and may require more sophisticated models (e.g. turbulence, multi-zone emission, magnetic reconnection and so on).

Gamma-ray Bursts. Gamma-ray Bursts (GRBs) are short and intense bursts of gamma radiation that occur a few times per day in the detectable Universe with an isotropic distribution. Their initial emission, the *prompt*, is detected as a bright, impulsive, irregular signal of soft gamma-rays (10 keV – 10 MeV) with total duration in the range 0.1 s to 10^3 s, with variability timescales of the order of 0.01 s to 1 s, and isotropic equivalent luminosities of $L_{\text{iso}} \sim 10^{50} \text{ erg s}^{-1}$ to $10^{53} \text{ erg s}^{-1}$ (Nava 2021). Example of prompt emission of GRBs are provided in figure 1.14. According to the *fireball* model (Meszaros and Rees 2014), the central engine of GRBs is thought to be a newly-born black hole, with a massive disk of accreting material that causes the formation of two opposite jets of material (see figure 1.15). The accelerated particles in the jets reach ultra-relativistic velocities with bulk Lorentz factor $\Gamma > 100$. The prompt emission is likely caused by the conversion of kinetic or magnetic energy into radiation through internal shocks in the jets, even though the details of this conversion are poorly understood. The prompt emission is followed by an *afterglow* emission attributed to external shocks between the jets and the surrounding medium. The shocks accelerate particles through Fermi processes, and are able to emit from radio to HE and VHE gamma-rays a regular emission that becomes fainter with time and is detectable for days or even weeks. There are two main classes of GRBs: *short GRBs* ($\lesssim 2$ s), due to merger of neutron stars, and *long GRBs* ($\gtrsim 2$ s) likely due to a non spherical collapse of supernovae that enables to formation of a disk and jets (Carosi and López-Oramas 2024). In the VHE band, only the afterglow emission of four GRBs has been detected so far by IACTs (MAGIC Collaboration et al. 2019; Noda and Parsons 2022).

Counterparts of Gravitational Waves. Searching for GRB emission is also relevant in the context of multi-messenger astrophysics, as GRBs are the only detected counterparts of Gravitational Waves (GWs). The first signal of GWs was detected in 2015 by the LIGO and VIRGO scientific collaborations, and attributed to the merger of two stellar-mass black holes (Abbott et al. 2016). We show an example of a typical GW signal in figure 1.16. Just two years later, the first GW signal (GW 170817) from the coalescence of a binary system composed of two NSs was discovered (Abbott et al. 2017), and approximately 2 s after its detection, the Fermi and INTEGRAL satellites detected a sub-threshold short GRB (sGRB), namely GRB 170817A (Goldstein et al. 2017; Savchenko et al. 2017). The identification of a

short GRB as electromagnetic counterpart of a GW signal triggered by a binary NS merger provided the first solid evidence on the nature of short GRB's progenitors, and proved the potential of the *multi-messenger* astrophysics approach.

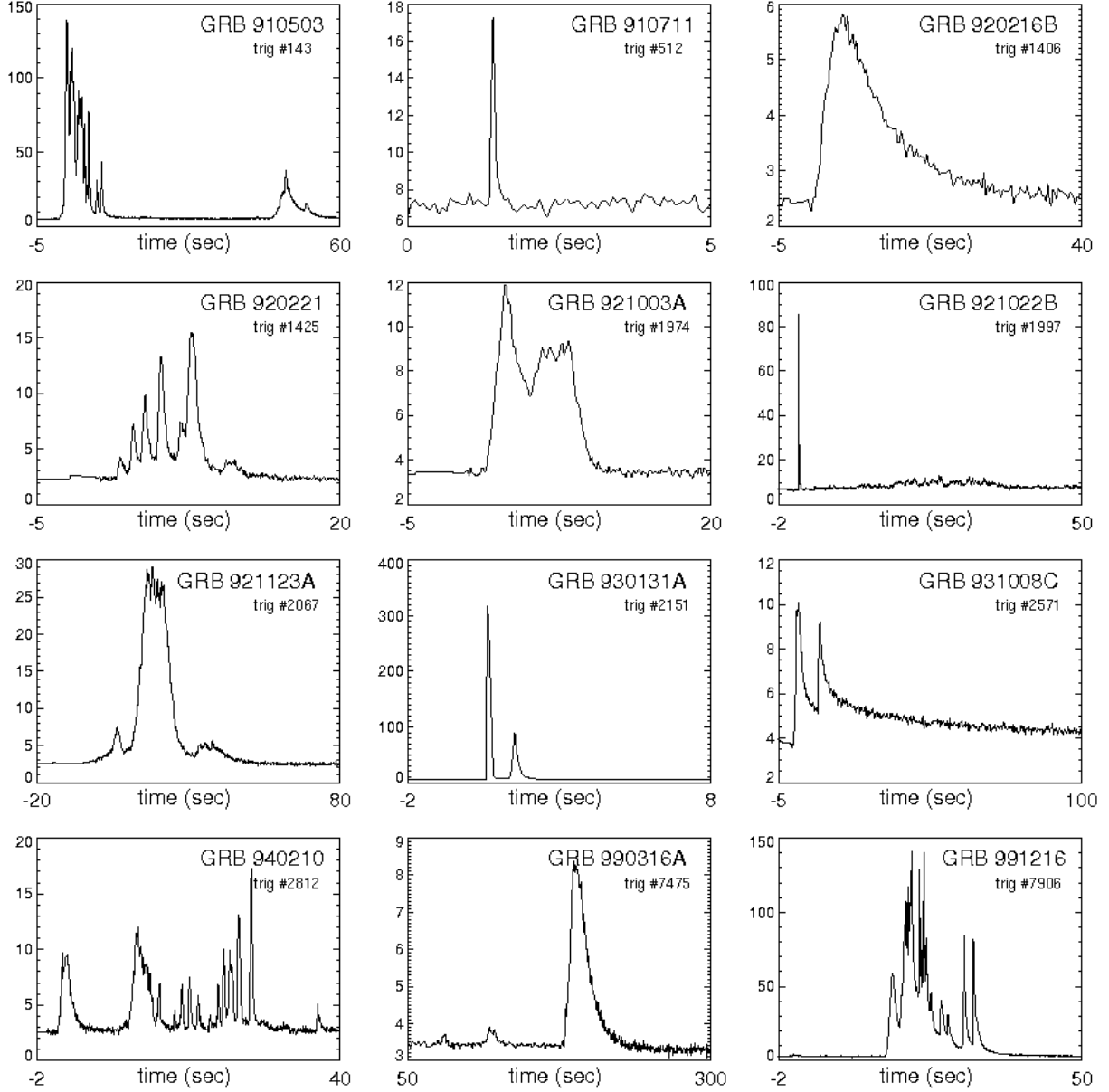


Figure 1.14 – Example of prompt emission of 12 GRBs detected by CGRO-BATSE. Prompt emission light curves show great irregularities in duration, shape, peaks, intensity and are all different from each other. In the fireball model, this variability is explained with internal shocks in the jets when ejected shells with different velocities collide. Credit: D. Perley, public domain.

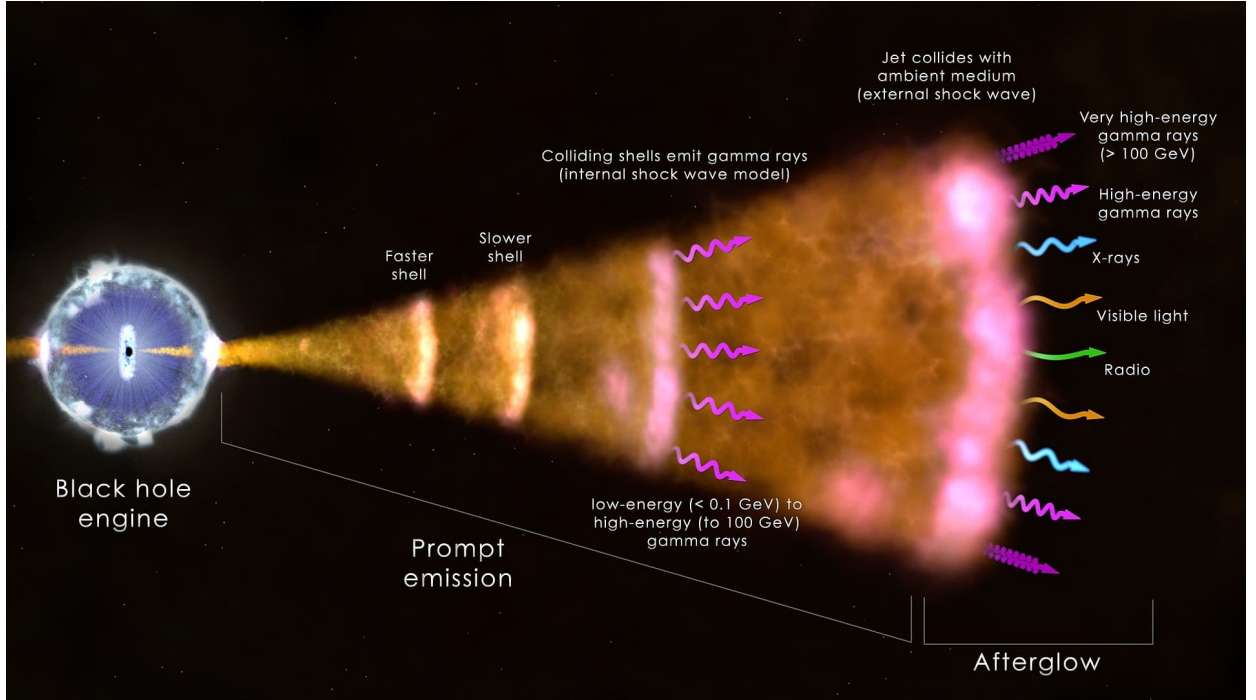


Figure 1.15 – GRB Fireball emission model. The *prompt* is due to internal shocks in the jet, the *afterglow* is due to shocks with the external medium. Credit: NASA’s Goddard Space Flight Center/ICRAR.

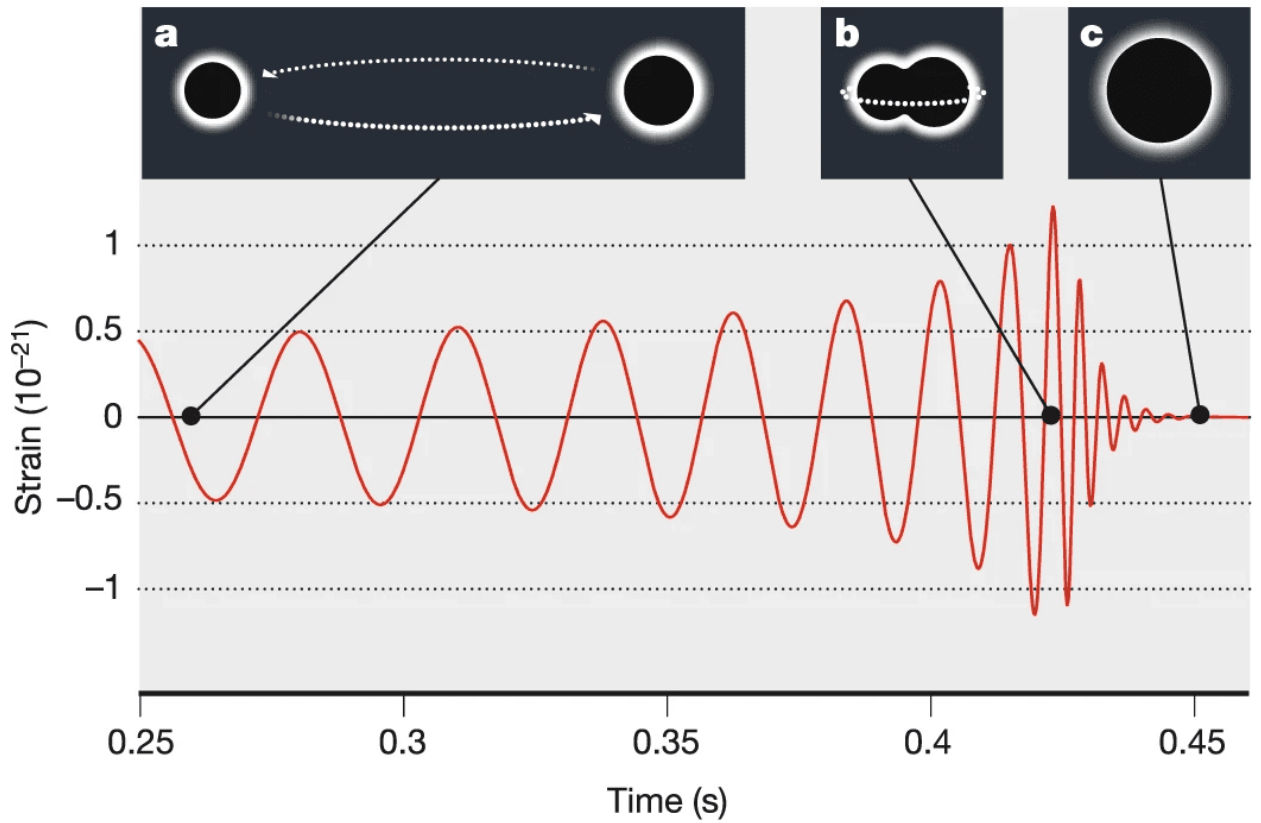


Figure 1.16 – Example of a typical GW signal from the merger of two BHs. Credit: Miller and Yunes (2019).

Chapter 2

Introduction to Cherenkov Astronomy

Very High-Energy (VHE) Gamma-rays ($\gtrsim 0.1$ TeV) cannot be detected from space due to having fluxes too small for the detection area of space telescopes. Only ground-based detectors can reach the large collection areas required to detect VHE gamma-rays, but the Earth’s atmosphere is opaque to high-energy photons (see figure 1.1), as they interact with the atmospheric medium producing a cascade of secondary particles, called an *Extensive Air Shower* (EAS). The products of EASs can be detected with appropriate detectors and used to reconstruct the properties of the primary particle which initiated the EAS, such as direction, energy, arrival time and particle type.

Section 2.1 describes the main types of EASs and the Cherenkov radiation they produce. In section 2.2, we present an overview of ground-based VHE detectors of radiation and particles produced in EASs, with a focus on *Imaging Atmospheric Cherenkov Telescopes* (IACTs). Section 2.3 describes the *low-level analysis* of IACT data, i.e. the *imaging* technique used to visualise Cherenkov radiation and the *reconstruction* technique used to obtain the properties of very-high energy (VHE) gamma-rays from Cherenkov images. Section 2.4 describes the *high-level analysis* of IACT data, i.e. the statistical methods used to estimate the significance of a source and its *scientific* properties, such as its flux.

2.1 Extensive Air Showers and Cherenkov Radiation

When a γ -ray or a CR interacts with atmospheric particles, they initiate the creation of particle cascades called **Extensive Air showers**. The term “shower” is the English translation by P. Blackett of the Italian expression “sciame” first used by B. Rossi (e.g. Rossi 1933). Understanding the physical processes involved in the creation of EASs is fundamental to characterise them and accurately reconstruct the properties of the primary particle (e.g. Anchordoqui et al. 2004). There are two main types of EASs: *Electromagnetic* (EM) showers containing electrons, positrons and photons (see section 2.1.1), and *Hadronic* showers with more complex particle populations and structures (see section 2.1.2). We describe in section 2.1.3 the *Cherenkov radiation* emitted by atmospheric particles during the development of EASs.

2.1.1 Electromagnetic Showers

EM showers contains only $e^\pm$ and γ -rays, mostly created from *pair production* of $e^\pm$ by photons and *bremsstrahlung* emission of photons by $e^\pm$. They are created when a γ -ray or a $e^\pm$ CR interacts with the nuclei of the atmosphere, and they follow a very similar development regardless of the nature of the primary particle. This represents a notable challenge for IACT reconstruction, that must identify and discard EASs initiated by CRs: EM showers initiated by $e^\pm$ constitute a background component difficult to disentangle from a real γ -ray generated shower.

Bremsstrahlung (*braking radiation* in German), is the radiation produced by the deceleration of a free charged particle when deflected by another charged particle, typically an atomic nucleus. The moving free particle converts kinetic energy into radiation and remains free, i.e. not bound to an atomic nucleus, thus bremsstrahlung is also known as *free-free* radiation. Figure 2.1 shows a schema of bremsstrahlung emission.

When a photon has energy $> 2m_e c^2 = 1.022 \text{ MeV}$ (m_e is the $e^\pm$ mass, c is the speed of light in vacuum), **pair production** of an electron and a positron can take place in the electric field of a nucleus. It cannot occur in free space because momentum and energy cannot be conserved simultaneously, and a third body is required to absorb part of the energy or momentum. Figure 2.2 shows a schema $e^\pm$ pair production.

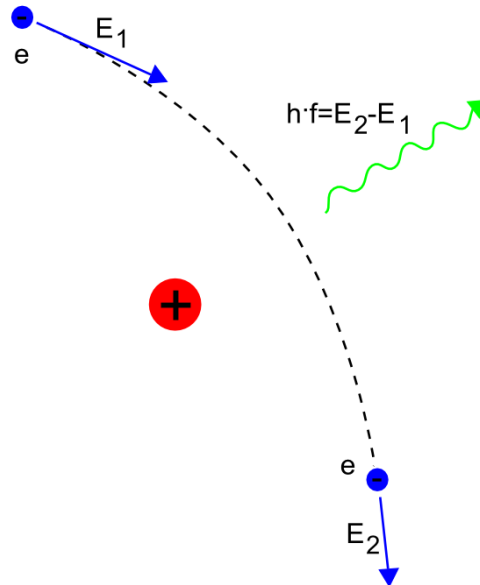


Figure 2.1 – Schema of bremsstrahlung emission. Illustration under public domain.

A simple model to describe EM showers is credited to Heitler (e.g. Heitler 1936; Matthews 2005), in which the evolution of EM cascades is described as a perfect binary tree, where at each step the number of particles doubles through either pair creation or single photon bremsstrahlung. Each of the produced particles has half the energy of its progenitor. In this model, a γ -ray entering the atmosphere with energy E_0 produces $N_k = 2^k$ particles after k generations, each with energy $E_0/2^k$. The development of the shower continues until it reaches the *shower maximum*, for which the energy of the particles drops down the *critical energy* E_c at which radiation losses equal those derived from excitation and ionisation. At such an energy, the multiplication process is not efficient anymore and slows down, as the particles have enough energy to excite atmospheric nuclei, but not enough to produce new

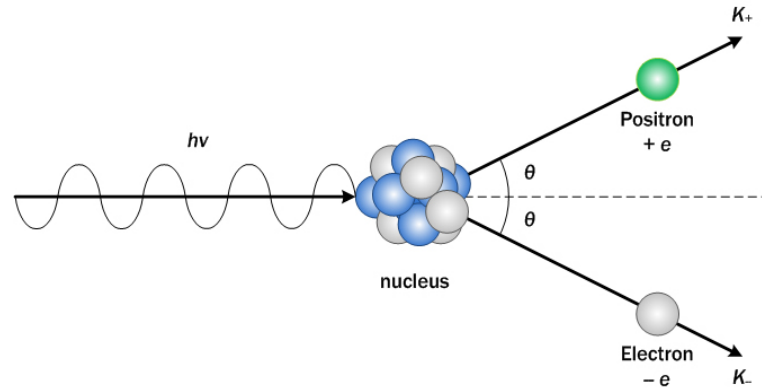


Figure 2.2 – Schema of $e^\pm$ production from a photon in the field of a nucleus. Credit: <http://electrons.wikidot.com/pair-production-and-annihilation>.

particles. The total number of particles created in the shower is given by $\sim E_0/E_c$. Electrons in air have $E_c \approx 86 \text{ MeV}$. The length of the shower and the position of the shower maximum is proportional to the *radiation length*, i.e. the typical length that photons and $e^\pm$ go through in a medium with given density before interacting. For electrons in air it is $\approx 37 \text{ g cm}^{-2}$. Heitler's model describes some basic features of EM showers, but it is overly simplistic for several reasons. The radiation length of γ -rays differs from the one of $e^\pm$, so the cascade is not a perfect binary tree, and the energy of the particle is not perfectly divided in half at every step. Heitler's model overestimates the particle number at maximum by factors of ~ 2 to 3 ; the predicted ratio of $e^\pm$ to photons is 2 , while in reality the ratio is $\sim 1/6$ because multiple photons are emitted during bremsstrahlung processes, and electrons lose energy through additional channels. In addition to bremsstrahlung, electrons are subject to excitation and ionisation energy loss. Figure 2.3 shows a schema of the development of an EM shower according to Heitler's model (Matthews 2005), while we show a more realistic schema in figure 2.4a.

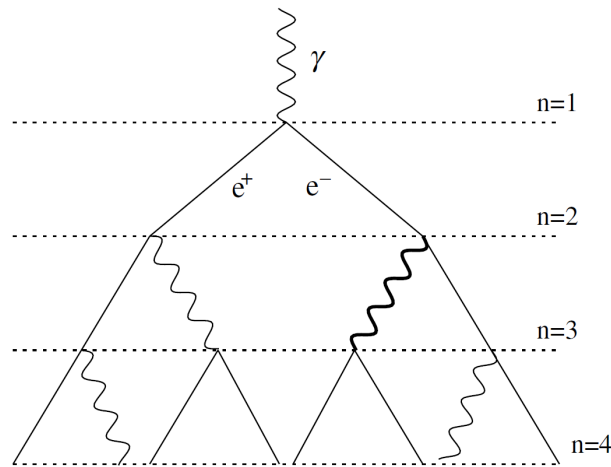


Figure 2.3 – Schema of the development of an EM shower according to Heitler's model of a perfect binary tree. Credit: Matthews (2005).

The main properties of a EM shower can be summarised as:

- The number of particles at shower maximum is approximately proportional to the primary particles' energy.

- The depth in the atmosphere of the shower maximum increases with energy. In the most accurate models, it is proportional to the logarithm of energy.
- In EM showers most particles produced are photons and $e^\pm$. Other particles, such as muons, may be produced by processes with smaller cross section (Spurio 2018) and are at first order negligible.

2.1.2 Hadronic Showers

Hadronic showers have a broader and more complex structure than EM showers, as they involve the production of several types of particles (Anchordoqui et al. 2004). When an hadronic CR interacts with atmospheric nuclei, it produces charged and neutral pions in roughly equal proportions ($\pi^0 : \pi^+ : \pi^- \rightarrow 1 : 1 : 1$), and in smaller fractions ($\sim 10\%$) kaons¹ and light barions ($p, \bar{p}, n, \bar{n}$). According to the mechanisms described in section 1.4, π^0 are able to decay into γ -rays, that initiate EM sub-showers within the main shower, while $\pi^\pm$ produce muons, neutrinos, antineutrinos and $e^\pm$ (which initiates other EM shower components). The protons lose energy by ionisation losses and most of those with energies less than $\approx 1\text{ GeV}$ are brought to rest. Secondary hadrons undergo further collisions, and the shower grows until they reach the minimum energy required for pion production decay ($\approx 1\text{ GeV}$).

The **muons** produced by CRs have very high energies and are highly penetrating, and most of them can be observed at the surface of the Earth and can even penetrate underground, where muon detectors can detect them (e.g., Longair 2011). They play a primary role in monitoring the average intensity and isotropy of the CR flux arriving at the top of the atmosphere. High-energy muons also provide direct evidence for relativistic time dilation and length contraction, as their decay lifetime is $2.2 \cdot 10^{-6}\text{ s}$ in their frame of reference, corresponding to a distance of $\sim 660\text{ m}$ in the atmosphere. To an external observer their lifetime is amplified by the Lorentz factor, see eq. (1.12). As muons are created at an altitude of $\sim 10\text{ km}$, they can reach the surface of Earth if they have a Lorentz factor $\Gamma \gtrsim 20$.

Hadronic showers follow a broader and more irregular development than EM showers, due to the fact that strong interactions provide a larger transverse momentum to secondary hadrons with respect to that of leptons in EM showers. Their timing is also different, as EM showers develop in $\lesssim 3\text{ ns}$, while hadronic showers can take more than 10 ns to develop. Figure 2.4b shows a schema of the development of an hadronic shower in the atmosphere. Figure 2.5 shows simulations of EM and hadronic showers obtained with the software CORSIKA (Heck et al. 1998). Hadronic showers are notably wider and more irregular than EM showers, which in turn are more “beamed”.

2.1.3 Cherenkov Radiation

When a particle moves in a medium with speed larger than the speed of light in that medium it causes the emission of Cherenkov radiation, first proposed by Cherenkov (1934). This mechanism is relevant for EASs, that contain a large number of particles with relativistic speeds, most of which exceed the speed of light in the air (e.g. Blackett 1948; Jelley and Porter 1963).

¹Hadrons composed by strange quarks.

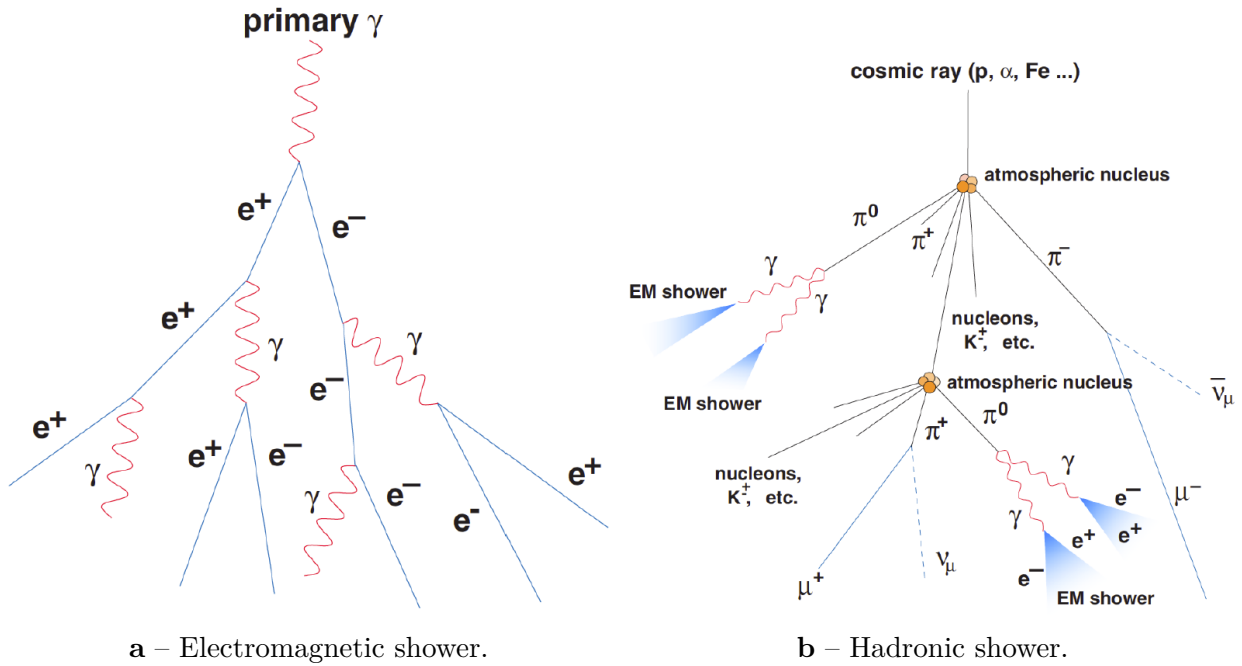


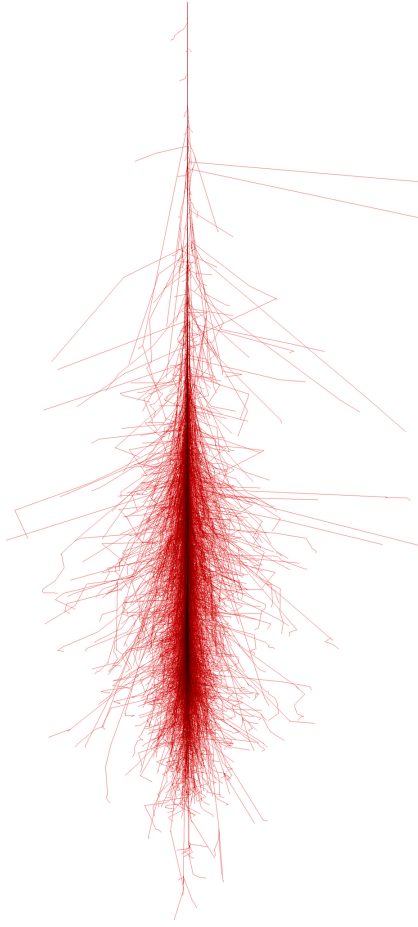
Figure 2.4 – Schematic evolution of EASs in the atmosphere. Panel 2.4a shows an EM shower, panel 2.4b shows an hadronic shower. Credit: Wagner (2006).

Accelerating charged particles in a medium emit electromagnetic waves with spherical wavefronts via Huygens’ principle (Jackson and Fox 1999), that propagate with the phase velocity of the medium $\frac{c}{n}$, where n is the refractive index of the medium. The wavefronts will polarise the atoms of the medium around the charged particle as a response, and when they return to their ground state, they re-emit their excitation energy as photons. If the charged particle moves in the medium with speed $v < \frac{c}{n}$, the polarisation field around it is symmetric and the radiation emitted by the excited medium atoms does not have constructive interference effects and cancels itself out. A schema of this polarisation effect is shown in the left panel of figure 2.6. On the contrary, when $v > \frac{c}{n}$, the charged particle moves faster than its radiation, which causes the polarisation field to have an asymmetric shape elongated along the particle’s direction. A schema of this polarisation effect is shown in the right panel of figure 2.6. The waveforms emitted by excited medium atoms overlaps and constructive interference leads to a cone-like signal at angle θ :

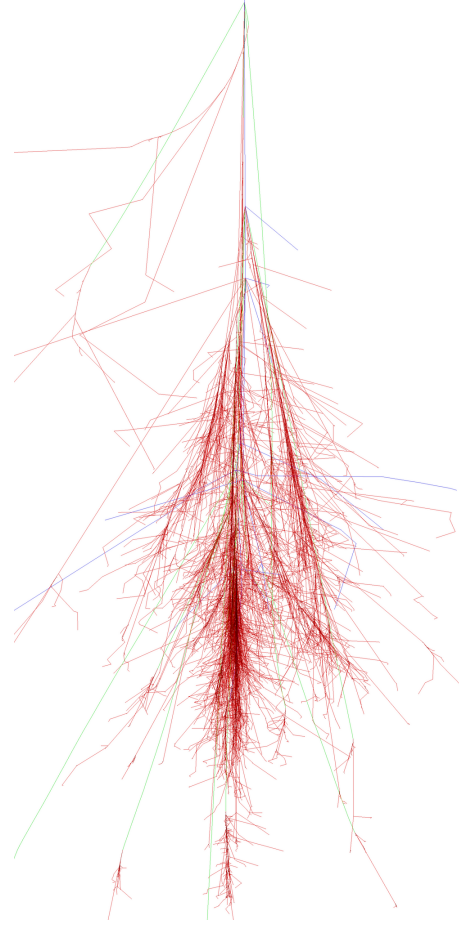
$$\cos \theta = \frac{c}{vn(\lambda)}, \quad (2.1)$$

where $n(\lambda)$ is the refractive index of the medium, which depends on the wavelength λ of the emitted radiation, the Cherenkov light. We show a schematic view of the Cherenkov radiation emitted by a charged particle in figure 2.7.

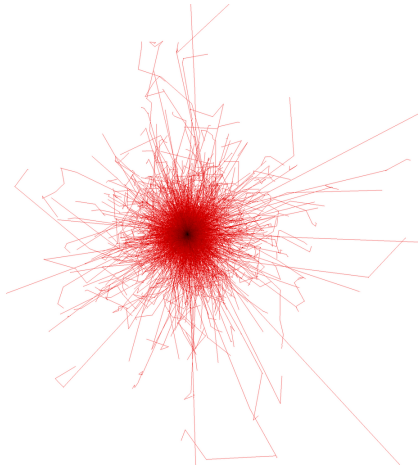
The Cherenkov radiation emitted by EASs appears as a fast flash ($\sim 3\text{--}4$ ns) of ultraviolet (UV) light peaking at ~ 350 nm for a shower emitted at 2000 m above sea level (a.s.l.), with an aperture cone of $\sim 1^\circ$. The properties of the observed Cherenkov spectrum also depends on atmospheric processes: Rayleigh scattering of air molecules, Mie scattering of aerosols, water droplets and dust, UV absorption by ozone molecules, and infrared absorption due to H_2O and CO_2 (Wagner 2006). For a vertical incident gamma-ray of 100 GeV, the Cherenkov photon density is almost constant in a ring with radius ~ 120 m centred in the core of the



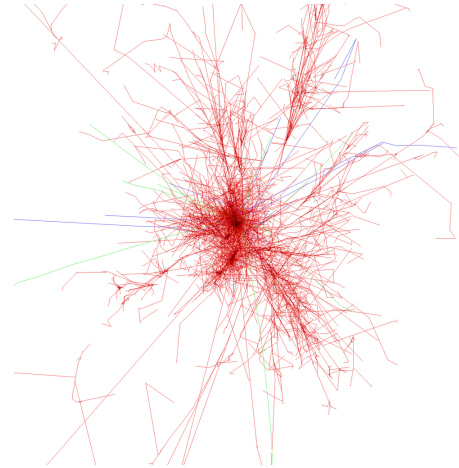
a – EM shower, particle track.



b – Hadronic shower, particle track.



c – EM shower, transversal plane view.



d – Hadronic shower, transversal plane view.

Figure 2.5 – Simulations of EASs. Left panels show the development of an EM shower initiated by a 100 GeV photon, panel 2.5a as viewed from a frontal plane and panel 2.5c as viewed from the transversal plane. Right panels show the development of an hadronic shower initiated by a 100 GeV proton, panel 2.5b as viewed from a frontal plane and panel 2.5d as viewed from the transversal plane. Credit: Heck et al. (1998), latest images at <https://www.iap.kit.edu/corsika/>.

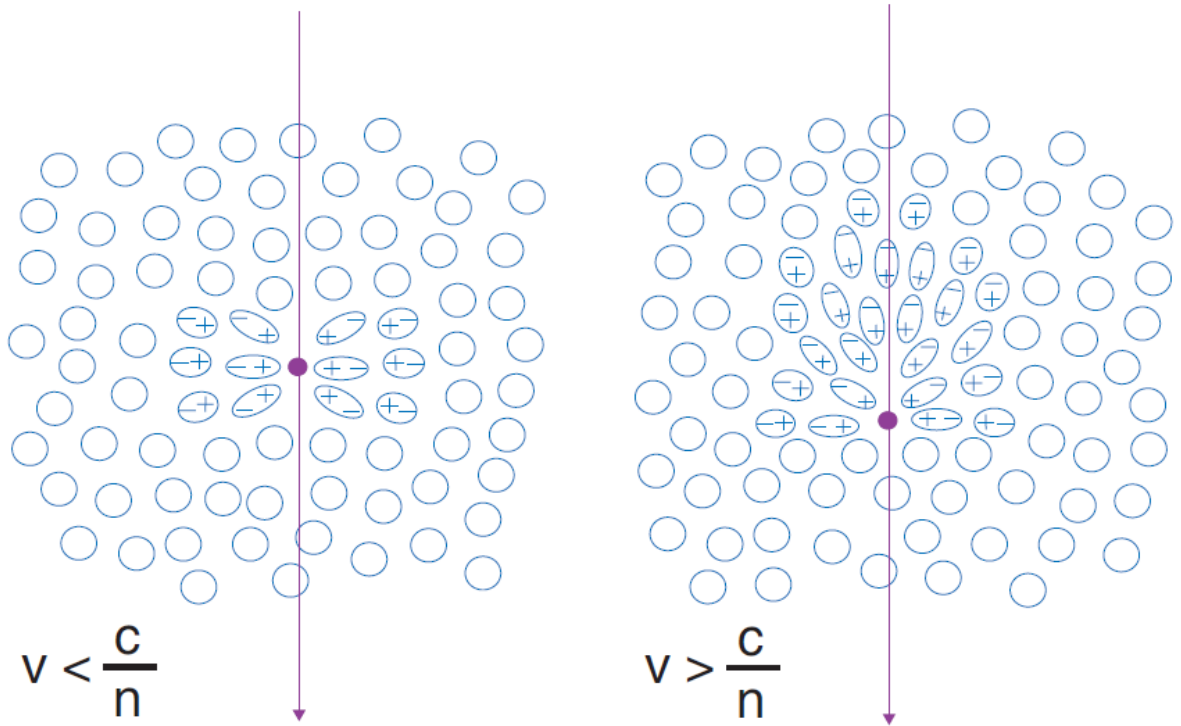


Figure 2.6 – Left panel: symmetric polarisation of a medium crossed by a charged particle moving at speed $v < \frac{c}{n}$. Right panel: asymmetric polarisation of a medium crossed by a charged particle moving at speed $v > \frac{c}{n}$. Credit: Wagner (2006).

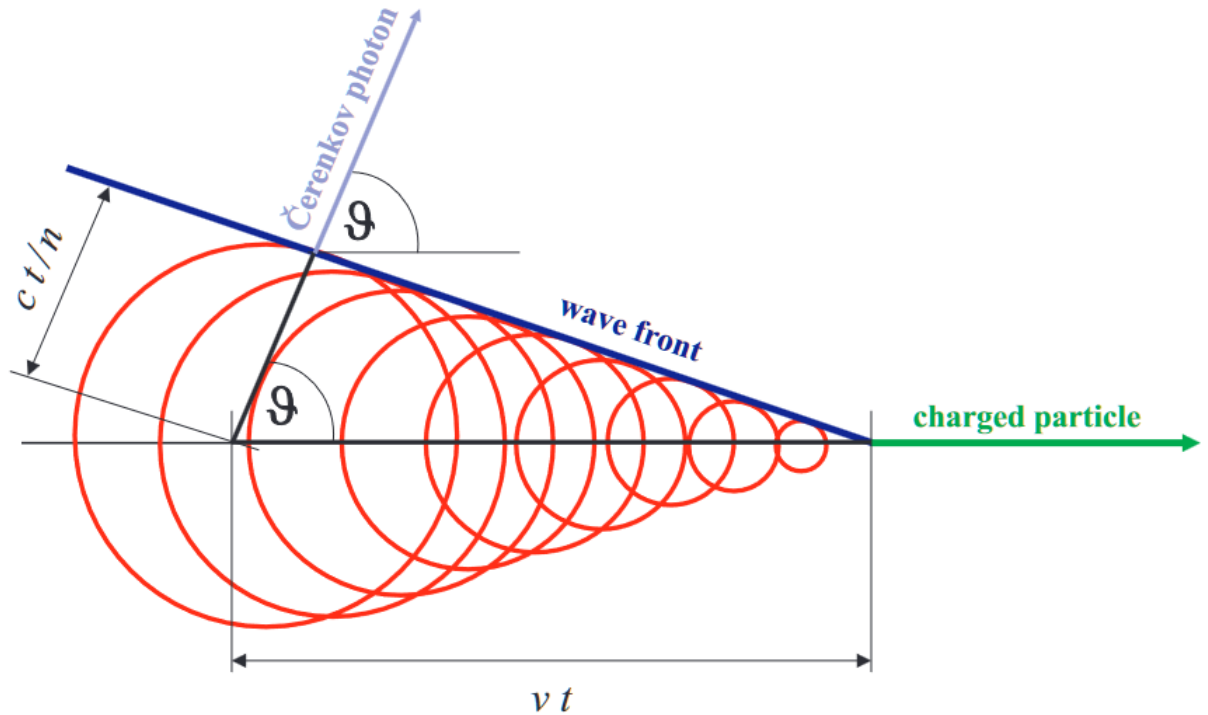


Figure 2.7 – Schematic view of the Cherenkov radiation wavefronts emitted due to the motion of a charged particle in a medium with speed $v > \frac{c}{n}$. The wavefront emits Cherenkov radiation coherently. Credit: Hrupec (2008).

shower, a region often called “Cherenkov light pool”, see figure 2.8.

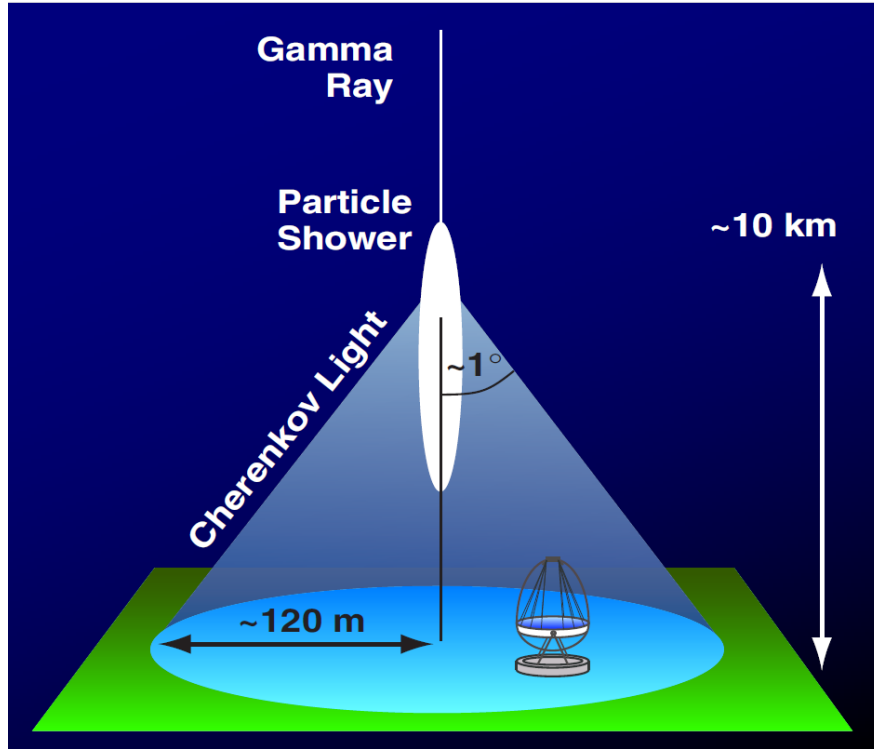


Figure 2.8 – Schematic emission of a Cherenkov light pool following the development of an EM shower in the atmosphere. Credit: Wagner (2006).

2.2 Ground-based Facilities for Very High Energy Astronomy

Several techniques have been developed in the last 70 years to reconstruct the properties of primary particles that triggers EASs (Bose et al. 2022b). The secondary particles of EASs can be directly detected with *Water Cherenkov Detectors* or other particle detectors and can be used to reconstruct the properties of the shower and the primary, see section 2.2.1. Alternative approaches use the Cherenkov radiation emitted in the atmosphere during EASs for reconstruction tasks. An old technique, the *Waveform Sampling*, is described in section 2.2.2. Today, it has been mostly replaced by the Imaging Atmospheric Cherenkov technique used by IACTs. We present an overview of the main IACTs in section 2.2.3, while we describe the technique more in detail in section 2.3.1.

2.2.1 Particle detectors for Extensive Air Showers

Cherenkov light is not the only product of EASs: the charged secondaries can be detected directly and used to reconstruct the properties of the EAS and the primary particle. The detection can be performed according to two techniques. The first one is the **Water Cherenkov Technique**, in which several water tanks are located in a site where EASs develop. When the secondaries enter the tanks, they emit Cherenkov radiation in the water, which can be detected by placing PMTs inside the tanks. In water, the Cherenkov emission angle is

large ($\sim 40^\circ$), thus PMTs can be placed with large spacing between them. The main Water Cherenkov facility today is the *High-Altitude Water Cherenkov* (HAWC, Abeysekara et al. 2017), located on the Sierra Negra volcano in Mexico at an altitude of 4100 m and operative since 2015 (see figure 2.9a for a picture). It is composed by 300 steel tanks covering an area of 2200 m², each containing 4 PMTs. Electrons and positrons present in the shower produce Cherenkov radiation in the water, which is detected by PMTs. The detection of muons is used to distinguish between hadronic and EM showers, as the muon component in EM showers is negligible. The Cherenkov radiation produced by muons is closer to their path than the one produced by $e^\pm$, so they create an excess signal in one PMT, which can be used to discriminate hadronic from EM showers. HAWC succeeded the *Multiple Institution Los Alamos Gamma-Ray Observatory* (MILAGRO), which was operative until 2008 in New Mexico and was composed by a single large water pool of area 60 m $\times$ 80 m.

The second technique used to detect EAS secondaries is the **EAS array** technique, where charged particles are detected by an array of particle detectors, such as scintillation detectors or solid-state detectors spread over a large area. These facilities can also be used as *Cosmic-Ray observatories*. An example is the *Pierre Auger Cosmic Ray Observatory* (The Pierre Auger Collaboration 2015), which uses a combination of surface detectors with water Cherenkov tanks and fluorescence detectors. The latest EAS array developed is the *Large High-Altitude Air Shower Observatory* (LHAASO, see figure 2.9b for a picture), which is being established in Daochen, China (Cao et al. 2019). It is composed of multiple types of detectors, including Water Cherenkov detectors, Muon detectors, electromagnetic detectors capable to perform 3D observations of EASs. LHAASO has unprecedented sensitivity and background rejection power at 1 PeV and has detected several candidate PeVatrons in the Galactic plane with high significance (Cao et al. 2024). The LHAASO Collaboration aims to implement ~ 25 IACTs at its site in the next few years to improve its performance. Most of the existing facilities cover the Northern sky, so the *Southern Wide-field Gamma-ray Observatory* (SWGGO) composed of Water Cherenkov detectors and muon detectors was proposed to be built in the Andes to achieve full sky coverage (Barres de Almeida 2021).

Water Cherenkov Detectors and EAS array must be installed at the same altitude of particle showers, which is higher than most location of IACTs. These facilities complement IACTs: they have higher energy thresholds, detecting γ -rays above some tens of TeV, which makes them particularly suitable for searching PeV sources, the so-called “PeVatrons”, in our Galaxy. They have duty cycles close to 100% as they can operate during the day and are not as strongly affected by weather conditions as IACTs. They have a large field of view, roughly half of the sky. Their sky coverage and large duty cycles makes them useful for the detection of transient sources and sky surveys. On the bad side, the angular resolution of these facilities is usually worse than the one of IACTs.

2.2.2 The Cherenkov Waveform Sampling Technique

An old method to detect Cherenkov radiation from EASs, extensively used in the past but now discarded in favour of using IACTs, is the **Waveform Sampling Technique**. In this method, an array of reflectors with visible-UV photo-multiplier tubes (PMTs) is spread in an horizontal plane. They can detect the wave front of a Cherenkov flash, and measure its arrival time. The arrival direction of the incident γ -ray is computed using the timing information from multiple detectors. PMTs can also measure the photon density and use it to reconstruct the lateral density profile of Cherenkov light in the shower. It gives an estimate

of the total Cherenkov yield of the shower, proportional to the energy of the primary γ -ray. Hadronic showers are rejected due to being off-axis and having higher fluctuations, but the gamma-hadron separation of this method is not as good as in IACTs. At present day, only one wavefront sampling array is operational, the *High-Altitude GAMMA-Ray* (HAGAR) telescope system at Ladakh, India, since 2008 (Saha et al. 2013). Other arrays were operational in the 1990s and 2000s, such as PACT, ASGAT, THEMISTOCLE. The technique was also used by a few Solar array experiments like STACEE, CELESTE and GRAAL: they reflected light from heliostats onto secondary mirrors located inside a tower, which then focused light onto a camera with multiple PMTs.

2.2.3 Imaging Atmospheric Cherenkov Telescopes

IACTs are composed by an array of optical-UV reflectors, i.e. mirrors that collect the Cherenkov light emitted during the development of EASs and focus it into a camera made up by many PMTs. PMTs are the ideal detectors to detect Cherenkov flashes due to their high gain, low noise, ultra-fast response (ns) and sensitivity to the same frequencies of Cherenkov radiation. IACTs are quipped with very fast front-end electronics able to effectively process electrical signals produced by the PMTs.

Past-generation IACTs. *Past-generation* IACTs worked from the 70s to the early 2000s; they detected the most studied VHE sources and established ground-based γ -ray astronomy as legitimate branch of astronomy.

The pioneer of IACTs was the **Whipple** Observatory's telescope, which operated at Mount Hopkins, Arizona, from 1968 to 2006 (see figure 2.9c for a picture). Its data and work were used to lay the foundation of ground-based VHE gamma-ray astrophysics: Hillas (1985) used its data to define the *Hillas parameters* that became the standard parameters used to characterise Cherenkov images, differentiate hadronic and EM showers and reconstruct the primary particle properties (see section 2.3.2). Using this technique, the Crab nebula was detected above 0.7 TeV in 1989 (Weekes et al. 1989) and became the first TeV-emitting source. Whipple also discovered VHE γ -ray emission from several blazars that are now some of the most studied sources in VHE astrophysics, such as Markarian 421 (Punch et al. 1992), Markarian 501 (Quinn et al. 1996), 1ES 2344+514 (Catanese et al. 1998) and H1426+428 (Petty et al. 2002).

Another pioneer of IACTs was the *High Energy Gamma-Ray Astronomy* (**HEGRA**) experiment, located at La Palma in Canary Islands at an altitude of 2200 m a.s.l., that introduced the *stereoscopic reconstruction technique*, using a system of 5 telescopes together to reconstruct the primary particle properties (Pühlhofer et al. 2003). Whipple, HEGRA and other IACTs such as CAT, which first started using pixelated cameras, CANGAROO-I and GT-48 paved the way to the current generation of telescopes.

Current-generation IACTs. The current generation of IACTs started working in the early 2000s, adopting newer technologies to improve the sensitivity and lower the energy threshold to 100 GeV or less, overlapping with satellite-based detectors like Fermi-LAT. The three most notable facilities currently operative are the H.E.S.S., MAGIC and VERITAS experiments, other minor facilities are CANGAROO-III, FACT and MACE.

The *High Energy Stereoscopic System* (**H.E.S.S.**, see figure 2.9d for a picture) is an array of 5 telescopes located at Gamesberg Mountain, Namibia at an altitude of 1800 m a.s.l. (Aharonian et al. 2006). The first four telescopes have a 12 m diameter, while the fifth one was added in 2012 and is the largest Cherenkov telescope in the world, with a 28 m diameter. The angular resolution of H.E.S.S. is ≈ 0.1 deg, it has an energy threshold of 100 GeV and can detect γ -ray flux equivalent to 1% of the Crab nebula flux in 25 h of observation. H.E.S.S. is the only major IACT experiment located in the Southern hemisphere: it discovered more than 100 objects and carried out the first high resolution and sensitive survey of the Milky way in TeV gamma-rays (H. E. S. S. Collaboration et al. 2018a).

The *Major Atmospheric Gamma Imaging Cherenkov* (**MAGIC**, see figure 2.9e for a picture) experiment is composed by two 17 m telescopes located in *El Roque de los Muchachos Observatory* in La Palma, Canary Islands, Spain, at an altitude of 2200 m a.s.l. (Aleksic et al. 2016a; Aleksic et al. 2016b). MAGIC has a Field of View (FoV) of 3.5 deg, an energy threshold of ~ 50 GeV and a sensitivity of $\sim 0.7\%$ of the Crab nebula flux above 220 GeV in 50 h of observations. Its structure is designed to ensure a fast repointing of the telescopes in about 25 s. MAGIC was the first IACT experiment to detect pulsations from the Crab above 25 GeV (MAGIC Collaboration 2008), TeV gamma-ray photons from GRB 190114C (MAGIC Collaboration et al. 2019) and from the candidate neutrino blazar TXS0506+056 (IceCube Collaboration 2018).

The *Very Energetic Radiation Imaging Telescope Array System* (**VERITAS**) is an array of four 12 m diameter IACTs operating at Fred Lawrence Whipple Observatory in southern Arizona, USA (Holder et al. 2008). VERITAS is characterised by a multi-level trigger system that reduce the rate of background events. Triggers work on single-pixel level, checks for pattern of pixels in appropriate time windows and require stereoscopic observations of an EAS event in at least two of the telescopes. VERITAS has an angular resolution of 0.08 deg at 1 TeV and a point source sensitivity of $\sim 1\%$ of the Crab nebula flux in less than 25 h. The main highlights of VERITAS include carrying out the first high-resolution scan of the Cygnus region (Aliu et al. 2013) and the detection of the starburst galaxy M82 (VERITAS Collaboration et al. 2009).

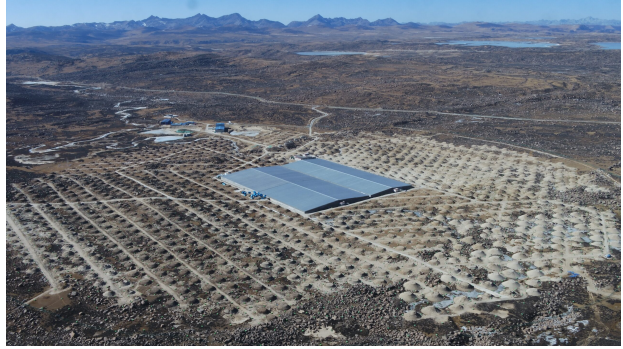
Next-generation IACTs. The success of past and present generation IACTs led to the development of the *next-generation* IACTs: the *CTAO* and the *ASTRI Mini-Array*.

The *Cherenkov Telescope Array Observatory* (**CTAO**) is going to be the major observatory for VHE gamma-ray astronomy over the next decade and beyond (Cherenkov Telescope Array Consortium et al. 2019). It is going to host more than 60 telescopes on two sites, one in the Northern hemisphere and the other in the Southern hemisphere, to ensure full-sky coverage. The Northern Site of the CTAO, located in *La Palma* island (Spain), hosts the first prototype of a CTAO *Large Size Telescope*, called **LST-1**. We will describe CTAO and LST-1 in greater detail in chapter 3.

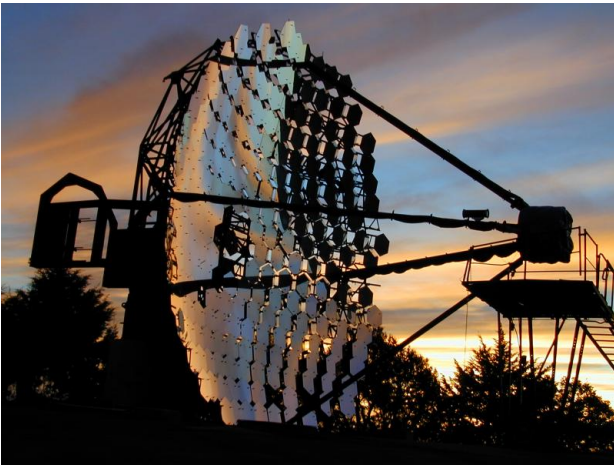
The *Astronomia a Specchi a Tecnologia Replicante Italiana* (**ASTRI**) *Mini-Array* is going to be an array of 9 telescopes located at the *Teide Observatory*, Canary Islands, Spain (Scuderi et al. 2022). It is developed as a “flagship project” funded by the Italian Ministry of University and Scientific Research and led by the Italian National Institute for Astrophysics (INAF). ASTRI is going to detect gamma-rays in the 1 – 100 TeV, complementing the Northern Site of CTAO which will have the best sensitivity in the 0.02 – 5 TeV. A prototype telescope, called ASTRI-Horn, is installed atop Mount Etna, Sicily (see figure 2.9f).



a – HAWC



b – LHAASO



c – Whipple Telescope



d – H.E.S.S.



e – MAGIC



f – ASTRI-Horn

Figure 2.9 – Pictures of several ground-based facilities for the observation of VHE γ -rays described in section 2.2. Credits to the respective collaborations.

2.3 The Reconstruction of IACT Data

IACTs are designed to detect the flashes of Cherenkov light generated during the development of EASs. They are composed of an array of optical-UV reflector telescopes, each of one with a mosaic of mirrors that focus the light into a camera made up by many PMTs. Each PMT represent a pixel of the camera and, when triggered, can register the signal of a Cherenkov flash. The signal recorded by the cameras is visualised into images (see section 2.3.1), which are used to parameterise the EAS and reconstruct the properties of the primary particle (see section 2.3.2). The response of the instrument is evaluated through Monte Carlo simulations that take the characterisation of the atmosphere into account (see section 2.3.3). The final dataset for the scientific analysis is obtained by applying a set of event selection cuts that differentiate hadronic from EM showers (see section 2.3.4).

2.3.1 The Imaging Atmospheric Cherenkov Technique

The *Imaging Atmospheric Cherenkov technique* aims at recording the spatial and temporal information of a Cherenkov flash to produce image that characterises the EAS (Bose et al. 2022b). The cameras of IACTs record a Cherenkov flash (an “event”) when a *camera trigger system* detects an incoming amount of radiation above a predefined threshold for a short time. Trigger systems and thresholds depend on the characteristics of the camera and on the *Night Sky Background* (NSB), the expected level of incoming optical-UV radiation not attributed to Cherenkov flashes, but to sources like stars or the zodiacal light.

The details on the acquisition and elaboration of the signal into a Cherenkov image depends on the specific camera adopted. Older cameras recorded all the signal after a trigger for a fixed amount of time, providing the integrated signal intensity recorded on a pixel in units of *photoelectrons* (p.e.). New-generation cameras that will be used for the CTAO will be able to record the temporal evolution of the electric signal in every pixel by recording its *waveform*, i.e. its shape as a function of time. The LST–1 camera records two 12-bit digitised waveforms in every pixel for every triggered event, each having 40 samples taken at 1 ns intervals (CTA-LST project et al. 2023). One of the recorded waveforms is acquired with low-gain conversion, and the other with high-gain. High-gain waveforms are usually used for further analysis because they characterise the signal with higher resolution. Low-gain waveforms are used to describe high intensity events ($\gtrsim 200$ p.e. per pixel) that may saturate high-gain waveforms. The raw waveforms are calibrated to provide a signal with physical value in *photoelectrons* which is proportional to the recorded optical-UV flux (Kobayashi et al. 2022). In the context of CTAO data flow, the *Calibrated Waveforms* of an event are considered the **Data Level 0** (DL0).

Two images can be created from DL0 waveforms: one records the p.e. charge in every pixel, the other its arrival time. In LST–1, each waveform is integrated in a 8-sample range (1 sample $\simeq 1$ ns) centred around the peak of the waveform (*Local Peak Window Sum* algorithm). For each pixel, the signal arrival time is computed using a charge-weighted average of the sample times (CTA-LST project et al. 2023). In the context of CTAO data flow, the *Charge* and *Time images* of an event are considered the **Data Level 1** (DL1). An example of the DL1 of an event is provided in figure 2.10. The *charge* image of a Cherenkov flash from an EAS has an *ellipse-like* shape, and its major axis points in the direction of the shower central axis. The pixels which do not contain shower signal contain

only photoelectrons from the NSB signal. They can be differentiated by using the *time* image, as NSB pixels have random arrival times, while shower pixels have arrival time that increases along the major axis of the ellipse. Time images can be used to identify the direction of the shower axis, as smaller values are closer to the projection of the shower axis on the ground.

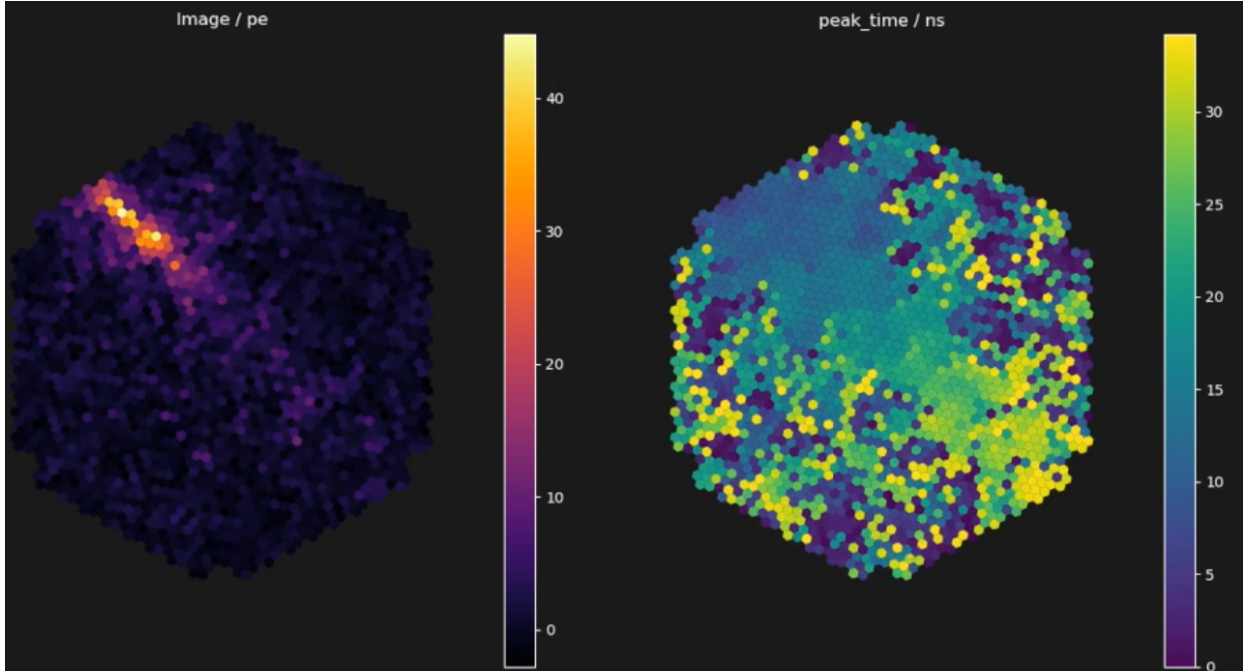


Figure 2.10 – Example of the DL1 of an event in CTAO taken with the LST–1. On the left side, the *charge* image of a Cherenkov flash is recorded in every camera pixel, in units of p.e.. On the right side, the signal arrival time is recorded. Credit: CTAO (2024).

The algorithm used to obtain DL1 images from waveforms (or from raw camera data in older IACTs) depends on the specifics of the system and the camera triggers adopted, and it aims at maximising the signal-to-noise ratio between the Cherenkov light and the NSB, and minimising the background light integration time. The trigger and imaging algorithms impact also the minimum photon energy detectable by IACTs, the so-called *Energy Threshold*, due to the fact that they make it possible to detect faint showers. Faint showers are created by primary particles with lower energy, as they develop into EASs with less secondaries and lower fluxes of Cherenkov light. In fact, the p.e. *intensity* of a Cherenkov image is roughly proportional to the energy of the primary particle. The energy threshold of an IACT can be described as:

$$E_{\text{th}} = \frac{\sqrt{\phi \Omega \tau}}{\epsilon A}, \quad (2.2)$$

where ϕ is the NSB flux, Ω the solid angle of the IACT mirror, τ the integration time of the Cherenkov signal, ϵ the detector efficiency and A is the surface of the mirror. We note that in order to lower the energy threshold of an IACT, we need to have mirrors with a larger area, and have efficient trigger algorithms that can minimise the integration time and discard NSB signal.

The latest algorithms proposed aim to use a **likelihood technique** to characterise the DL0 waveforms of CTAO telescopes. In this technique, a likelihood function is used to describe the waveform of every pixel of an event, and the likelihoods of the pixels are linked by a space-time model that describes the development of the shower image. The likelihoods are fit by maximising the total likelihood over the parameters of the image model, and

the DL1 images are thus obtained integrating the fitted models for the Cherenkov emission instead of the measured data. This technique is still under development, although it shows promising results to improve the sensitivity of LST–1 and CTAO (Alispach et al. 2022).

Different types of showers produce a different morphology of the charge image, as we show in figure 2.11. Panel 2.11a shows the image of an EM shower initiated by a photon, while panel 2.11b shows the image of an hadronic shower initiated by a proton. Images of EM showers, initiated either by γ -rays or by $e^\pm$, are usually more “beamed”, concentrated in elongated ellipses, while images of hadronic showers are wider, more diffuse and with multiple sub-structures. EASs are not the only event capable of creating Cherenkov flashes: isolated CR muons can enter the atmosphere and reach Earth’s surface without creating a particle cascade. Isolated muons create a Cherenkov flash with a characteristic ring-like shape (*muon rings*). It is easy to reconstruct the properties of the muon from the ring, so these images are usually used for calibration purposes. Panel 2.12 shows the image of an EM shower initiated by an isolated muon.

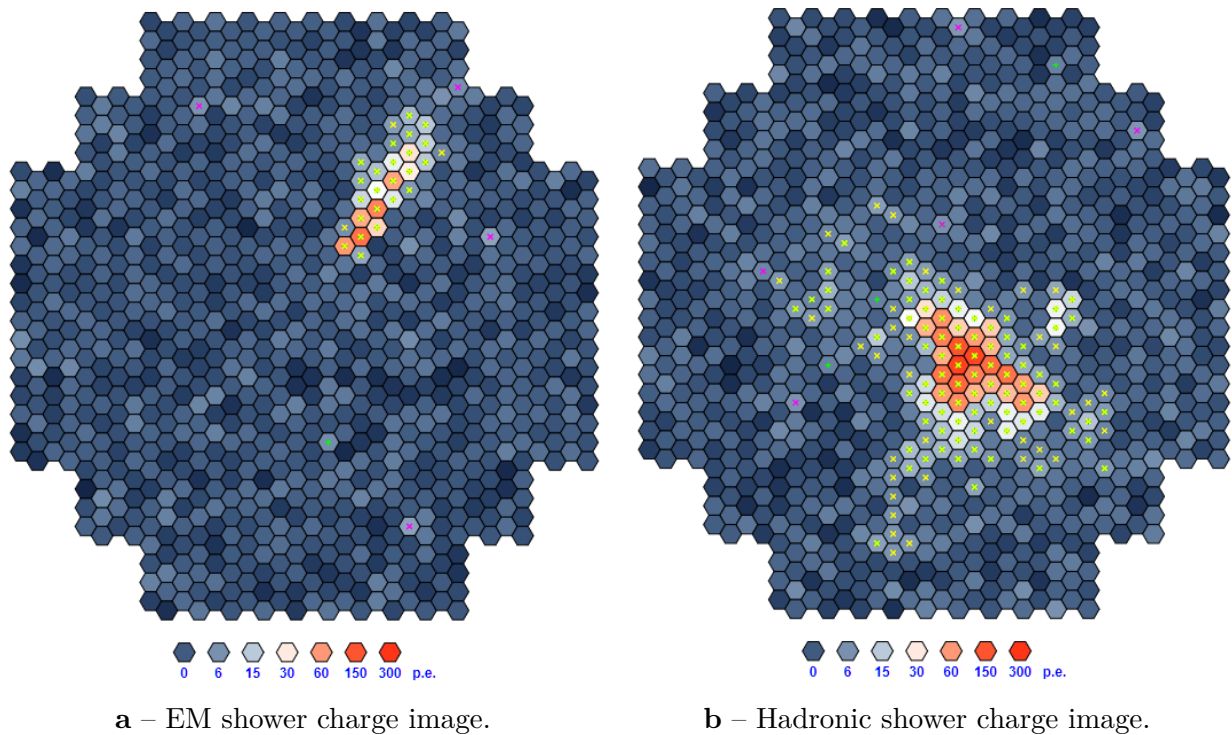


Figure 2.11 – Cherenkov images of showers initiated by different types of particles and detected in a H.E.S.S. camera. Panel 2.11a shows the the charge image of a shower initiated by a photon, while panel 2.11b the one initiated by a proton. Credit: Völk and Bernlöhr (2009).

2.3.2 The Hillas Reconstruction Technique

DL1 charge and time images are used to reconstruct the properties of the primary particle that initiated the EAS. The standard technique used to do so is the *Hillas technique*, which consists of 3 main steps:

1. *Image cleaning*: it consists in removing from DL1 images the pixels without shower information.

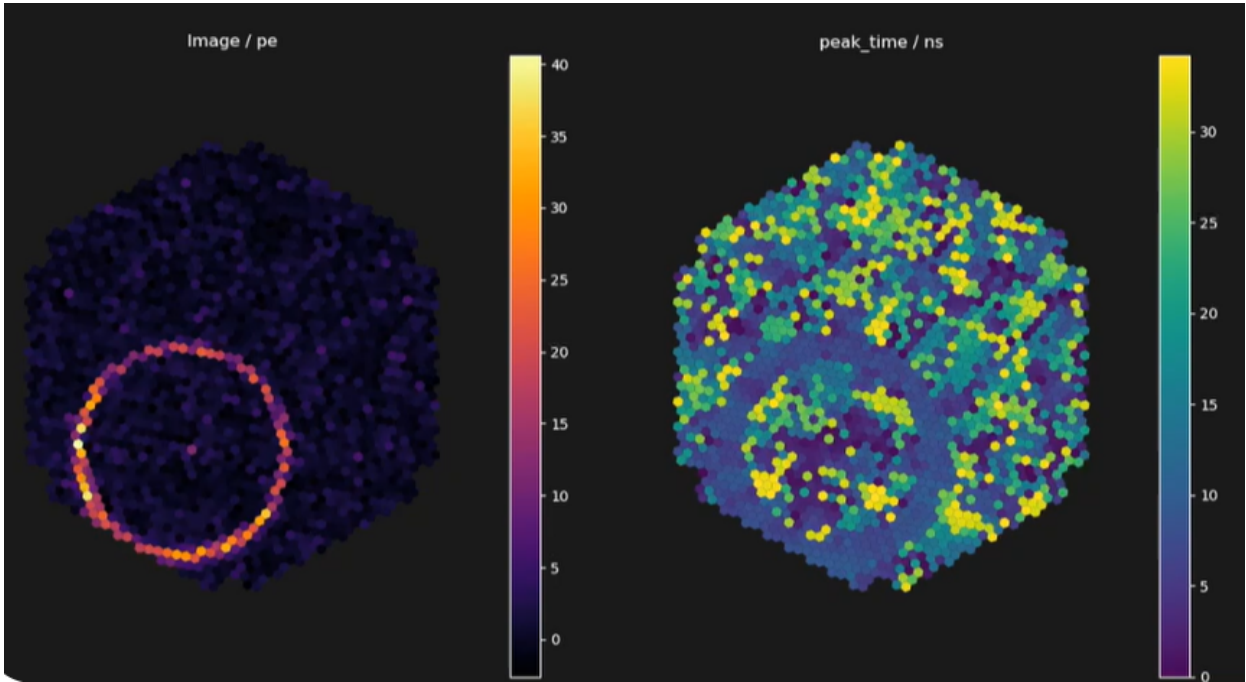


Figure 2.12 – Charge and time images of a shower initiated by an isolated muon, detected on the LST–1. Credit: CTAO at <https://www.ctao.org/emission-to-discovery/science/how-ctao-works/>.

2. *Image parameterisation*: it consists in characterising shower events with a set of parameters extracted from the images that describe the shower event.
3. *Event reconstruction*: it consists in using *Random Forests* to obtain the primary particle position, energy and classification (photon or hadron).

Recently, alternative approaches based on deep learning have been proposed to replace the Hillas technique. The deep learning techniques, used in projects such as **GammaLearn** (Jacquemont et al. 2019) or **CTLearn** (Nieto Castaño et al. 2019), do not perform image cleaning and parameterisation, which remove and simplify the information contained in DL1 images. Instead, they directly apply Convolutional Neural Networks (CNNs) on the DL1 images to reconstruct the properties of the primary particle, using all the information and the morphological features contained in the images. An in-depth discussion of the deep learning approach is beyond the scope of this work. In this section, we will focus on the Hillas technique.

Image cleaning. Most pixels in each camera event contain only fluctuation noise from the NSB and camera electronics. The *image cleaning* procedure selects only the pixels containing a significant amount of signal that can be attributed to Cherenkov light from an EAS. For image cleaning, two charge thresholds are defined, the *picture* and *boundary* thresholds, that discriminate the core of a shower from its tail and from the NSB pixels (Lessard et al. 2001). Default values for the LST–1 are respectively 8 p.e. and 4 p.e. (CTA-LST project et al. 2023), but they can be modified to take into account different values of NSB due to different pointing directions and atmospheric conditions. The level of NSB in a given FoV is measured by acquiring background-only events during observations at a fixed rate (e.g. 100 Hz for LST–1), the so-called *interleaved pedestal* events. Interleaved pedestals are used to estimate the mean $\langle Q_{\text{ped}} \rangle$ and the standard deviation $\sigma_{Q_{\text{ped}}}$ of the reconstructed charge of

every pixel, and to define a modified picture threshold as:

$$Q_{\text{thr}} = \langle Q_{\text{ped}} \rangle + 2.5 \cdot \sigma_{Q_{\text{ped}}}. \quad (2.3)$$

This quantity is computed every few seconds to take into account NSB variations and the presence of bright stars in the FoV. Bright stars might produce few spurious islands of bright pixels in the FoV, that can be removed by using Q_{thr} as picture threshold. The pixel selection is performed applying the following algorithm:

1. If a pixel has Q_{thr} higher than the default value, increase the *picture* threshold to Q_{thr} .
2. Select pixels with charge above their *picture* threshold, and with at least two neighbouring pixels above the picture threshold. These pixels form the *core* of the image.
3. Select pixels with charge above the *boundary* threshold, and with at least one core neighbour. These pixels form the *tail* of the image.
4. Apply a *timing* cleaning step: select pixels that have at least one neighbour with signal arrival time < 2 ns of its own arrival time. This step will remove pixels with high charge value due to NSB fluctuations that are not correlated with the shower event.
5. Select pixels with charge above 3% of the average charge of the three brightest pixels in the image. This step is used as a failsafe for misaligned mirrors, which may produce a faint copy of the shower image in the camera FoV.

An example of image cleaning applied to MAGIC data is shown in figure 2.13.

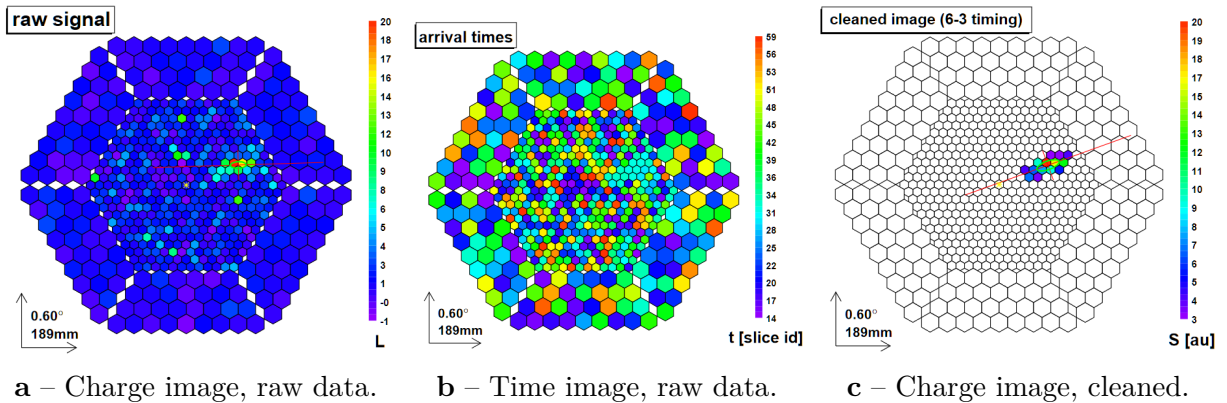


Figure 2.13 – Example of image cleaning on a MAGIC event. Panel 2.13a shows the raw charge image, and panel 2.13b the time image. Panel 2.13c shows the cleaned charge image with only the pixels that survived the cleaning process. The cleaning process for this MAGIC event used a picture threshold of 6 p.e. and a boundary threshold of 3 p.e.. Credit: Aliu et al. (2009).

Image parameterisation. Cleaned charge image can be parameterised with a set of *Hillas* parameters (Hillas 1985). The main parameters used to characterise an image are:

- **Intensity.** Sum of the charges (in p.e.) of the pixels of the image. It is proportional to the energy of the primary particle.
- **Centre of Gravity (x, y).** First-order moments of the charge distribution. They correspond to the coordinates of the image centroid in the camera frame, also known as the centre of gravity of the image.

- **Length, Width.** Second-order moments of the charge distribution along the major and minor axes of the image. They correspond to the length and width of the ellipsoid fitting the image.
- **WL.** Width over length ratio. EM showers produce more elongated images, with smaller WL values than hadronic images.
- **Skewness, Kurtosis.** Third-order and fourth-order moments of the charge distribution.
- **Time RMS.** Root Mean Square (RMS) of the arrival times. EM showers usually produce shorter events than hadronic ones, and their RMS is also smaller.
- **Time gradient.** Gradient of the arrival times computed along the main axis of the image. It is computed using the (cleaned) time image, and it allows to understand the direction of origin of the shower along the image major axis. It is an extremely important parameter to reconstruct the direction of the primary particle in single-telescope systems, and for the angular resolution of the IACT.
- **Leakage.** Fraction of the total charge of the image recorded on pixels at the edge of the camera or their next neighbours. It is useful to define images that are truncated in order to be excluded.
- **Conc(N).** Fraction of the total image charge concentrated in the N brightest pixels. It measures how compact the shower is, and it is usually larger in EM showers.
- **Number of islands.** Number of non-connected pixels that survived the image cleaning. It is usually higher in hadron-induced showers or in noisy images.

These parameters can be used without any assumption on the position of the source. If the position of the target source is known with great precision, it can be used to define additional parameters and perform a **source-dependent** analysis:

- **Dist.** Distance between the centre of gravity and the nominal source position on the camera.
- **Disp Norm.** Distance between the centre of gravity and the point along the major axis closest to the nominal source position.
- **Disp Sign.** It indicates on which side of the image centroid the true source position lies.
- **Alpha (α).** Angle between the ellipse major axis and the line connecting the nominal source position to the image centroid. It is smaller for EM showers as γ -rays are expected to arrive from the nominal source position, while CRs can arrive from multiple directions.

We show the graphical definition of the main Hillas parameters in figure 2.14.

When multiple telescopes are available, the **stereoscopic** approach can be applied to significantly improve IACT sensitivity. A common feature of the stereoscopic approach is the introduction of a *stereo trigger*: IACT cameras record an event only if two (or more) telescopes are triggered. Stereo triggers do not allow to record events caused by background fluctuations that affect only one telescope, and significantly improve the background rejection power of the IACTs. When an event is recorded by multiple telescopes, the charge and time images are slightly different as they see the Cherenkov flash from different angles. Additional *stereoscopic* parameters can be used to characterise the event:

- **Impact point.** Impact point of the shower on the ground, computed from the intersection of the major axes of the shower images and the position of each telescope.

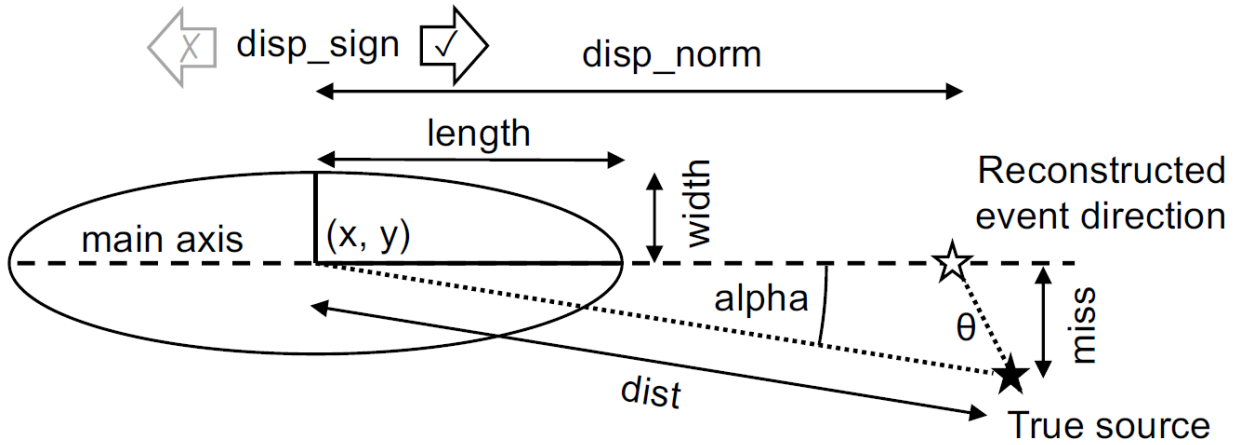


Figure 2.14 – Definition of the main Hillas parameters. Credit: CTA-LST project et al. (2023).

- **Shower axis.** Projection of the impact point on the camera plane.
- **Height of shower maximum.** The shower axis and the angle at which the image centroids are measured with respect to each telescope can be used to estimate the height of the shower maximum. It is inversely proportional to the energy of the primary particle, and it is a powerful γ /hadron discriminator and estimator of the energy.
- **Impact parameter.** Perpendicular distance between the shower axis and the pointing direction of each telescope.

Image cleaning and parameterisation are carried out with dedicated software. In the context of CTAO, cleaned images are usually referred as DL1a and the event parameters as DL1b. CTAO is developing `ctapipe` (Noethe et al. 2022) to perform the reconstruction steps, and LST–1 developed `cta-lstchain` as a pipeline based on `ctapipe` that can execute the Hillas reconstruction steps (López-Coto et al. 2021; Lopez-Coto et al. 2023). Furthermore, the semi-automatic pipeline `lstosa` (LST–1 On-Site Analysis) perform waveform calibration, imaging, cleaning and parameterisation of the LST–1 shower events recorded after the end of the observation night (Ruiz et al. 2022).

Event reconstruction. The event parameters are used as the input data of **Random Forests** (RFs, Breiman 2001) that reconstruct the properties of the primary particle. RFs are machine learning algorithms with two possible goals: classification, i.e. assigning a categorical output variable to the input data; regression, i.e. assigning an output value from a continuous range of values to the input data. RFs operate by constructing a multitude of *decision trees* at training time, that will receive the input data and each of them will evaluate an output. The output of the RF is usually the class selected by most trees for classification tasks, and the average prediction of the individual trees for regression tasks. In the context of IACTs, several RFs models are trained and used to reconstruct the properties of the primary particle. For instance, CTA-LST project et al. (2023) reconstructed the **particle direction** using two models: one regressor for the *Disp Norm* of an event and a classifier for *Disp Sign*. The **particle energy** is usually reconstructed with one RF regressor trained only with simulated γ -ray induced showers, so the energy is a reliable estimate for γ -rays only: if we wanted to study CRs, we would need a different RF trained with simulated hadron-induced showers. Image parameters relevant for the direction and energy reconstruction are: intensity, width, length, wl, skewness, kurtosis, time gradient, leakage.

The **particle type** is reconstructed with a RF that takes in input the Hillas parameters and the reconstructed direction and energy. Its output, for each event, is a *score* in the 0 to 1 range called **gammaness**. It represents how likely it is for the event to be produced by an EM shower (hadron-like event, gammaness 0) or by an EM shower (γ -like event, gammaness 1). In the context of CTAO data flow, the reconstructed *direction*, *energy* and *gammaness* of an event are considered the **Data Level 2** (DL2).

2.3.3 Usage of Monte Carlo Simulations and Atmospheric Monitoring

The atmosphere is a key element of the detection process of IACTs, acting as a *calorimeter*. A calorimeter is a device in which the kinetic energy of an incident particle is converted inside an absorber into a cascade of many secondary particles (the shower). At the end, the energy of the primary particle is dissipated via excitation/ionisation of the absorbing material (Spurio 2018). Several high-energy space telescopes use calorimeters (e.g. AGILE, Tavani et al. 2008) as part of their experimental setup, with the advantage of being able to test and characterise them before launch. The calorimeter of IACTs is the atmosphere. It is not a controlled set-up like the calorimeters of space telescopes, thus it must be continuously monitored and characterised to understand the impact of atmospheric conditions on Cherenkov images (e.g., Spurio 2018). Due to the dependence of the IACT reconstruction on the atmospheric conditions, the analysis of IACT images heavily relies on detailed *Monte Carlo* (MC) simulations of the shower development in the atmosphere and of the response of the telescope. EAS showers produced by photons, electrons and hadrons assuming an atmospheric model can be simulated with dedicated software like CORSIKA (Heck et al. 1998). The response of a camera can also be simulated, resulting in a dataset of simulated shower images. They can be used to *train* the RF models used to reconstruct the properties of real events taken in similar conditions.

Variations in the **atmospheric conditions**, such as the presence of additional cloud layers, may cause variations in the total extinction of Cherenkov radiation (Hahn et al. 2014). Rayleigh and Mie scattering can move the Cherenkov photons away from the FoV of the telescopes, dimming and blurring the images, and making it more difficult to distinguish EM and hadronic showers. Aerosols in the atmosphere may directly absorb Cherenkov light, causing dimmer images. Variations in the vertical profile of the atmospheric density change the refractive index of air, with an impact on the development of the EAS, the number and distribution of secondaries and of the Cherenkov photons produced. In general, the presence of clouds and bad atmospheric conditions reduce the amount of Cherenkov light generated by the showers (Sobczynska et al. 2020). Faint showers may not be able to trigger the telescope camera, thus reducing the detection rate and the effective collection area of the telescopes, which also leads to an increase of the energy threshold according to eq. (2.2). A mischaracterisation of the atmosphere may introduce systematic errors of about $\sim 20 - 30\%$. The most conservative approach to reduce systematic errors is to accurately monitor the atmosphere during observations, and to adopt MC simulations with an atmospheric model close to the measured one. MC simulation are usually computationally expensive, so there are ongoing studies aimed at characterising the atmospheric conditions with a small set of parameters, such as the atmospheric *transmissivity* fraction, and simply apply corrections to standard MC simulations to reproduce the results obtained with weather-degraded MC simulations (e.g. Pecimotika et al. 2021). Atmospheric monitoring can be performed by

using dedicated devices such as LIDARs (Laser Imaging Detection and Ranging), that emit artificial light and detect its absorption. A LIDAR prototype is under development for the CTAO (Zivec et al. 2022).

Monte Carlo simulations need to also take into account the optical **Night Sky Background** of an observation, due to the fact that the Cherenkov radiation is usually faint compared to the NSB. For this reason, IACTs can only be operated at a dark site, away from man-made light pollution, during moonless nights with clear weather. The number of NSB photons is typically $\sim 10^{12}$ ph/m²/s/sr, several orders of magnitude higher compared to the number of Cherenkov photons (Bose et al. 2022b). NSB photons can be distinguished from Cherenkov photons as their spectrum peaks at lower energies and is not coherent. NSB photons can be suppressed by selecting PMTs with quantum efficiency peak in the same range of the Cherenkov flashes, by choosing narrow time windows ($\sim$ few tens of ns) to acquire signal and by using additional trigger algorithms such as the stereo trigger. Nevertheless, NSB cannot be completely suppressed. Once the camera configuration is fixed, it strongly depends on the Moon phase and on the distance of the telescope FoV from densely populated sky regions such as the Galactic disk and the Zodiacal plane. To reach the best analysis performance for an analysis, one needs either dedicated MC simulations, or to *tune* the NSB levels in the training sample of the available MC events to the one of the real data (“noise padding”). It consists in adding some random Poisson noise during the analysis of the MC events (before the image cleaning), to match the average NSB level in the data, that is measured using the *interleaved pedestal events* acquired during real observations (CTA-LST project et al. 2023; Abe et al. 2023b).

2.3.4 Gamma-Hadron Separation Cuts and Sensitivity

DL2 data are composed by the reconstructed direction, energy of the primary particle and a score that evaluates if it is a γ -like or an hadron-like event (*gammaness*). As hadron-like events constitute a source of background for the γ -ray data analysis, they need to be discarded by applying on the data a set of *event selection cuts* or *γ /hadron separation cuts* (Bock et al. 2004), whose goal is to optimise the sensitivity of the analysis to be performed.

The **Sensitivity** of an analysis is defined as the minimum flux from a source with a predefined spectral and spatial model that the telescope is able to detect with a 5σ statistical significance in a given observation time and energy range. Optimisation procedures consist in choosing a subset of the data, evaluating the sensitivity of the analysis scanning a grid of possible cuts values, and choosing the set of cuts that lowers the sensitivity. **Gammaness** is one of the main parameters that needs to be optimised, as only the events with value above the chosen *gammaness cut* (g_{cut}) are considered γ -like events and used for the analysis. Another major parameter that needs to be optimised is **Theta** (θ), i.e. the radius of the circular region that is used to extract the signal of the model source. Photons with angular distance from the nominal position of the source $> \theta_{\text{cut}}$ are not considered to be associated with the source signal. The cuts may change with energy due to the degradation of the angular resolution of the telescopes at high energies and different γ -hadron discrimination power of IACTs in different energy ranges. A cut in image **intensity** (i_{cut}) may be used to discard events near a IACT’s intensity threshold, that are difficult to reconstruct accurately.

The γ /hadron separation cuts must be applied to both simulated and real data. In fact, there is usually a subset of the simulated events that is not used to train the RFs, but only

to test the performance of the IACT system. The simulated events of this *test sample*, for which the attributes of the primary particle are known, are processed through the already trained RFs to obtain a set of simulated DL2 events. The comparison between the simulated and reconstructed properties allows to test the quality of the reconstruction and assess the angular and energy resolution of the telescopes. Applying a set of γ /hadron separation cuts to the simulated data allows to estimate the **Instrument Response Functions** (IRFs) of the analysis, such as the *Effective Area*, the *Point Spread Function* (PSF) and the *Energy Dispersion Matrix* (see appendix A.3 for more details on IRFs). Let us note that the content of the DL2 test sample defines the type of IRFs produced. For instance, a test sample containing only γ -ray events simulated at a fixed offset from the camera centre result in the so-called *Point-like IRFs*, i.e. the effective area convoluted with the PSF at the fixed offset and the energy dispersion matrix. These IRFs cannot be used to analyse sources at different offsets from the centre of the FoV. If the test sample contains γ -ray events simulated across the camera FoV, the *Full-enclosure* IRFs can be produced, containing the effective area and the PSF in a range of possible source offsets. These simulations are usually computationally expensive. If the DL2 test sample contains not only γ -ray events, but also events induced by hadrons and electrons, it is possible to reconstruct the *γ -like Background Model*, i.e. the spectral and spatial distribution of the hadron-like events that survive the γ /hadron separation cuts. Accurate background models are often difficult to obtain due to being strongly dependent on the CR spectrum and the atmospheric processes on the telescope site. For this reason, the background of an analysis is usually estimated directly from the data (see section 2.4).

In order to optimise the γ /hadron separation cuts and evaluate the sensitivity of an analysis, it is necessary to estimate the background and the effective area under a given set of cuts. *Cuts optimisation methods* usually estimate the background from a subset of the real data and the effective area from the MC simulated data, then compute the sensitivity according to the definition of the analysis, and finally compare the sensitivity obtained with different sets of cuts to choose the best one. CTA-LST project et al. (2023) obtained the LST–1 cuts for a “standard” stacked spectral analysis of a point-like source. Stacked analyses integrate the data over a long observation period (see section 2.4). The sensitivity of a standard stacked spectral analysis is defined as the minimum flux from a point-like source that the telescope is able to detect with a 5σ statistical significance in 50 h, calculated in 5 logarithmic energy bins per decade, using an ON/OFF ratio of 0.2, requiring at least 10 detected gamma rays per energy bin, and a signal-to-background ratio of at least 5%. CTA-LST project et al. (2023) optimised the cuts on low-zenith Crab observations, splitting the dataset into two equivalent samples (even- and odd-numbered events). One of the subsets was used to optimise the event selection cuts, by scanning a grid of θ and gammaness cuts, and selecting the cut combination with the best sensitivity for each of the energy bins. In order to avoid biases due to statistical fluctuations in the optimal cuts, they were then applied to the other (statistically independent) subset, that was the only one used for the analysis. The event selection cuts depends on the type of analysis performed and the assumed definition of *sensitivity*. The standard stacked analysis cannot be applied when small integration times are considered, due to working in a regime of *low-photon-statistics* (see section 2.4). In the context of this work, we developed a **Burst analysis** based on Poisson statistics that can be applied when searching for a signal composed of short transient bursts. The analysis requires a dedicated set of *burst cuts* different from the ones used in the standard stacked spectral analysis. We describe the burst analysis and cuts in chapter 6.

In the context of CTAO data flow, the photon lists composed by the γ -like events that survived the cuts and the IRFs of the analysis are considered the **Data Level 3** (DL3).

Estimation of the Energy Threshold. The simulated MC data are also used to estimate the *Energy Threshold* of the analysis defined in eq. (2.2). The MC data are simulated assuming a power law spectral distribution with a given index (usually 2). The distribution of the reconstructed energy of the simulated events surviving the cuts is usually a power law with a low-energy suppression at the energy threshold E_{thr} . The peak of the distribution can be used to estimate E_{thr} . If the target source of the analysis has an expected spectrum different from the one used to simulate the MC events, the estimation of the energy threshold is more complex, as it requires weighting the events by the different expected spectrum. The simulated events must be assigned a *spectral weight* given by the ratio of the requested spectrum and the simulation power law. For instance, if the MC events are simulated with a power law spectrum with index 2, and the target source has a power law spectrum with index γ , each event is assigned a weight $w(E_{\text{reco}})$ that is a function of its reconstructed energy:

$$w(E_{\text{reco}}) = \frac{n_{\gamma} (E_{\text{reco}}/E_0)^{-\gamma}}{n_2 (E_{\text{reco}}/E_0)^{-2}}, \quad (2.4)$$

where n_2 and n_{γ} are the normalisation factors (spectra are normalised to the total number of simulated events) and E_0 is a reference energy. The energy threshold of the analysis with the assumed spectral model is the peak of the weighted energy distribution.

The energy threshold of IACTs also depends on other parameters of the simulations and observations, most notably the zenith angle of the telescopes' pointing direction. Low zenith angles result in lower energy thresholds, but also in a lower effective area. For this reason, astrophysical sources that require the best sensitivity should be observed at *large zenith angle*, while sources with softer spectra, e.g. pulsars or AGNs absorbed by *Extra-galactic Background Light* (EBL), should be observed at *small zenith angle*.

2.4 The Scientific Analysis of Cherenkov Data

The DL3 data obtained after event reconstruction and γ /hadron separation consist in a *photon list* of γ -like events and the IRFs that characterise the IACT response. DL3 are the input data of the *high-level* analysis of Cherenkov data, i.e. the statistical methods used to estimate the significance of a signal and its scientific properties such as the source flux. In the context of CTAO data flow, the high-level analysis elaborates DL3 data into **Data Level 4** (DL4). DL4 are *binned data*, such as 3D counts cubes (two spatial and a spectral dimension), exposure maps, and the statistical significance associated to a signal excess. The significance is usually estimated through the standard *Aperture Photometry* method, described in section 2.4.1, after the evaluation of the γ -like background. We discuss different background estimation methods in section 2.4.2. A useful type of plots used in VHE astronomy to evaluate the quality of the data are the θ^2 plots (see section 2.4.3). DL4 can be further processed into **Data Level 5** (DL5) by model fitting. DL5 are the *science products* associated with an astrophysical source, such as fluxes, light curves, SEDs, flux maps. We describe the estimation of the flux according to the *Maximum Likelihood Estimation* technique in section 2.4.4.

2.4.1 Aperture Photometry

Aperture Photometry (AP) in astronomy is the measurement of light which falls inside a specific region (the aperture) in the sky, usually, a circular aperture of some fixed size. In *High-Energy Astrophysics*, Aperture Photometry consists in counting photons inside the aperture. The ideal aperture should be large enough to include the source under investigation, but little extra photons (and noise) from the background sky. Some typical values for the aperture are about $1.5 \div 2$ of the PSF *Full Width at Half Maximum* (FWHM).

The standard AP method for gamma-ray astronomy was introduced by Li and Ma (1983), who define two types of regions used for AP: the *ON Region*, which we assume containing the source plus the background, and that we use as a *test region* for the hypotheses made on the source; the *OFF Regions*, that are the *background control regions* containing only background events. We assume that the background level of the ON Region is similar to those of the OFF Regions, so that we can use the OFF counts to estimate the background in the ON Region. The counts from the ON region are defined as N_{ON} , the counts from the OFF region as N_{OFF} , the estimated background counts in the ON region are:

$$\hat{N}_B = \alpha N_{OFF}, \quad (2.5)$$

where α is known as the *acceptance ratio*. It describes the relative size of the ON and OFF regions, and it depends on the type of experiment and method we use to select the OFF regions. We discuss the choice of the OFF regions and α in section 2.4.2. The *observed signal counts* or *Excess counts* are defined as the number of counts we attribute to the source in the ON region:

$$N_S = N_{ON} - \hat{N}_B = N_{ON} - \alpha N_{OFF}. \quad (2.6)$$

The Li&Ma Statistical Significance. Li and Ma (1983) provide a method to evaluate the statistical significance of a source with a positive excess based on hypothesis testing. We discuss hypothesis testing in detail in Appendix A.1 and derive the Li&Ma significance in Appendix A.2. The Li&Ma significance σ is the statistic of a likelihood ratio test where each likelihood is the product of two Poisson distributions (Cash 1979). The first one is the distribution of the ON region and the second one is the distribution of the OFF regions, thus the number of counts N_{ON} and N_{OFF} detected in the regions are random Poisson variates. The Li&Ma significance σ is a function of N_{ON} , N_{OFF} and the acceptance ratio α :

$$\sigma = \sqrt{2} \left[N_{ON} \ln \left(\frac{1 + \alpha}{\alpha} \frac{N_{ON}}{N_{ON} + N_{OFF}} \right) + N_{OFF} \ln \left((1 + \alpha) \frac{N_{OFF}}{N_{ON} + N_{OFF}} \right) \right]^{1/2}. \quad (2.7)$$

This computation was first reported in Li and Ma (1983) eq. 17. Under the Null Hypothesis (i.e., not having any astrophysical source, and the excess of the ON region being due to background fluctuations only), σ^2 is distributed according to a χ^2 distribution with 1 degree of freedom, like the square of a standard Gaussian variable (according to Wilks' theorem, Wilks 1938; Cash 1979). For this reason, the statistic is equivalent to the Gaussian significance of the detection. The Li&Ma significance is valid under the hypothesis of Wilks' theorem, which is asymptotically valid for large data sets, as the size of the sample $\rightarrow \infty$. From a practical point of view, eq. (2.7) is valid as long as N_{ON} and N_{OFF} are not too small (usually $\gtrsim 10$ counts each), otherwise the statistic will not follow a χ^2 distribution. For this reason, it cannot be used in a *low-photon-statistics* regime, that may occur when using small integration times, e.g. to detect short transient bursts. To work in such a regime, we developed a *Burst analysis* based on Poisson statistics (see chapter 6).

2.4.2 Background Estimation Techniques

The determination of the OFF regions and the *acceptance ratio* α is a key issue in the Aperture Photometry technique (Berge et al. 2007). Background counts in IACTs are mostly due to residual hadronic events that have not been discarded by the γ /hadron separation cuts, and must be removed when estimating the signal attributed to a source. Errors in the estimation of this “ γ -like background” are the main source of systematic errors in the AP analysis.

To define the OFF regions, IACTs follow two main approaches according to the observation mode adopted: the *ON/OFF* and the *wobble* methods. In the **ON/OFF method**, observations are carried out on-axis, i.e. with the telescope pointing on the coordinates of the target source. These “ON” observations are interspersed with *equallength* observations of a close empty field (“OFF” observations), with similar zenith angle and NSB level. The background is assumed to be equal in the two runs, the difference between them provides a measurement of the γ -ray signal. A major drawback of this approach is that only half of the available dark time is spent ON-source. **Wobble mode** observations keep the target region in the FoV at all times, with a fixed offset with respect to the telescope pointing (usually ≈ 0.4 deg). A background estimate for the source region can then be derived from a region on the opposite side of the FoV and with the same offset, under the assumption that the telescope camera has a symmetric response.

The *acceptance ratio* (α) parameter introduced in eq. (2.5) is a normalisation factor that accounts for differences between the test region and background control region. We can define it as the ratio of the camera acceptance-weighted exposure integrated in time and angular space over the signal (ON) and background (OFF) regions (Berge et al. 2007):

$$\alpha = \frac{\int_{\text{ON}} A_{\text{ON}}^{\gamma}(\boldsymbol{\psi}, \phi_z, E, t) d\boldsymbol{\psi} d\phi_z dE dt}{\int_{\text{OFF}} A_{\text{OFF}}^{\gamma}(\boldsymbol{\psi}, \phi_z, E, t) d\boldsymbol{\psi} d\phi_z dE dt}, \quad (2.8)$$

where A^{γ} is the *detector acceptance* for γ -ray-like events, and it defines the probability of accepting a γ -like event reconstructed at a given position in the camera FoV and with a given energy. It is usually expressed as a number of events and it depends on:

- The position of the region considered in the camera FoV ($\boldsymbol{\psi}$). If the camera has a spherical symmetric response, then A^{γ} depends only on the distance from the pointing direction $|\boldsymbol{\psi}|$.
- The *reconstructed energy* E , due to the different Cherenkov photon density of showers with different energy.
- The exposure time t of observations, and the *epoch of the observations* to account for any change in configuration or mirror ageing.
- The *zenith angle* ϕ_z and the *azimuth* of the observation, due to different rates of Cherenkov images, different NSB levels, and the asymmetry of the Earth’s magnetic field, which may affect the development of EASs.

The acceptance describes the response of the camera and of the reconstruction algorithm, and it is generally extracted from observations without significant γ -ray emission in the FoV. The system acceptance A^{γ} is assumed to be identical for the ON and OFF regions, so differences in the integrals of equation (2.8) are due to the integration time and region size. A choice of background regions such that $\alpha \ll 1$ (achievable, e.g., by choosing much larger OFF than ON

regions) results generally in higher statistical significance, because background fluctuations are reduced, but may also result in increased systematic errors.

Background modelling strategies. The goal of a background modelling strategy is to provide the quantities N_{OFF} and α used to estimate the significance of a detection. An ideal background model must have the following properties (Berge et al. 2007):

- *Contemporaneous.* Background and signal events should be taken in the same observation period.
- *FoV position.* Background events should be computed in a similar position in the FoV to signal events, to have a similar value of the system acceptance function.
- *Sky position.* Background and signal events should be taken from similar regions in the sky to have a similar NSB Levels.
- *Event statistics.* The event statistics of the background should be much larger than the signal statistics, to avoid fluctuations and have $\alpha \ll 1$.
- *Event type.* Signal and background events should come from the same region in an image-parameter phase space to assure a similar system response and reduce the importance of the correct system-acceptance model.

We discuss the main background modelling strategies adopted in High-Energy Astrophysics, and we report in table 2.1 which of the requirements listed above they satisfy. The evaluation of a background model is performed by evaluating the significance of many empty field regions: the distributions of the significance is expected to be Gaussian (Berge et al. 2007).

- **Ring Background.** The background counts are taken from an annular region centred on the ON-region circle. The parameter α is the ratio of the solid angle of the ring (radius ~ 0.5 deg) to the trial source region and is typically chosen to be $\approx 1/7$:

$$\alpha = \frac{\Omega_{ON}}{\Omega_{OFF}} \quad (2.9)$$

However, the acceptance within the ring is not constant as it covers areas with different offsets, therefore we must include a correction of the acceptance A^γ for the different $|\psi|$ of the regions. This method is easy to define and apply, but it is not recommended for spectra as the acceptance curve change with energy, and for the analysis of crowded regions due to the risk of nearby γ -ray contamination of the background regions. For its few biases, it is recommended for source detection. A scheme of the Ring Background can be seen in figure 2.15a.

- **Reflected Regions Background.** This method was originally developed for *Wobble* observations. The off-axis source position defines a ring of n_{off} OFF regions, equal in size and system centre offset to the ON-region, but in different directions: the ON region is reflected with respect to the FoV centre to obtain the OFF regions (see figure 2.15b). The area close to the ON position must be avoided to prevent contamination of the background estimate by mis-reconstructed γ -rays. Due to the equal offset of ON and OFF regions from the pointing direction of the system, under the assumption of a symmetric camera response α is just given by:

$$\alpha = \frac{1}{n_{OFF}}. \quad (2.10)$$

This is particularly helpful for spectral analysis where an energy-dependent radial acceptance function would otherwise be required. This method is not suited for analysis of crowded regions because of nearby γ -ray contamination of the background regions. When we choose $n_{OFF} = 3$ and define the ON and OFF regions at symmetrical positions with respect to the FoV centre, equidistant one from the other, i.e. with a 90° aperture distance from each other, the reflection method is also known as the **Cross Background**.

- **ON/OFF Background.** This method has the disadvantage of requiring twice the time of observations since the ON and OFF regions are observed in different runs and sky positions, but the only assumption needed is that the system acceptance is the same in both exposures, having similar NSB level and zenith angle of the observation. Today, many dark sky regions with no emission are known and they can be used to build an archive of OFF observations that can be used by future observations. The normalisation α is deduced from the total event numbers in the two runs, excluding the nominal γ -ray source region. If the conditions of the ON and OFF observations are not the same, the acceptance ratio is not given just by the exposure ratio, but it must be estimated manually from the distribution of the off-source events. This method can be applied to any source, even if very extended and in crowded fields, but it has less statistics than other methods and is sensitive to differences in the NSB level of the ON/OFF regions.
- **FoV Background.** The acceptance model is derived from a set of OFF runs where the entire FoV (excluding regions of known γ -ray emission) is used to compute α . This model can be readily applied to morphological studies of extended sources and results in the highest possible statistical significance. NSB level variations or unbalanced wobble conditions may introduce systematic errors.

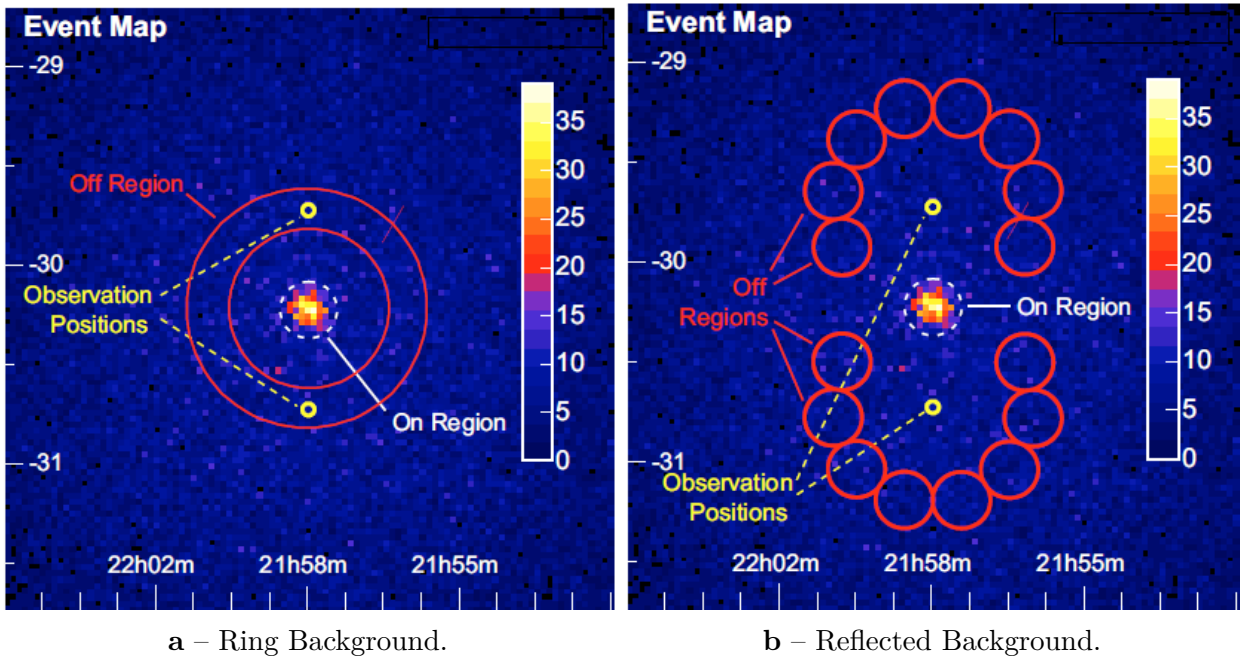


Figure 2.15 – A general scheme of the Ring and Reflected background models to define α and the OFF Regions. Credit: Berge et al. (2007).

- **Template Background.** In this method, events are considered to be part of the ON region or the OFF region not according to their position in the coordinate space, but their position in a parameter phase space. For each event, we can define the *Mean Reduced Scale Width* (MRSW) as the deviation of the measured *Hillas Image Width* from the simulated expectation value averaged over all the telescopes that recorded the event, in units of standard deviations. The MRSW distribution of simulated γ -induced events follows approximately a standard Gaussian distribution, while the distribution for simulated CR-induced events has a high-value tail. Events are classified according to their MRSW value, e.g. events with $\text{MRSW} \in [3.5; 8.0]$ are usually considered as events of the “background regime”. α is defined as the ratio between the number of events in the signal regime and in the background regime. A correction factor in the radial acceptance function for the position in the FoV is also needed since the system responds differently to the cosmic-ray-like than to the γ -ray-like events. This method has the advantage that the background is determined in the same region as the signal and is also suited also for extended sources.

Table 2.1 – Overview of the properties of the different background models described here. For each feature, we quote if a given model fulfils (Y) or fails (N) this condition.

Model	Ring	Reflected reg.	Template	FoV	ON/OFF
Contemp.	Y	Y	Y	Y	N
Fov Pos.	N	Y	Y	N	Y
Sky Pos.	N	N	Y	N	N
Evt Stat.	Y	Y*	Y	Y	N
Evt Type.	Y	Y	N	Y	Y

* if n_{OFF} is large.

2.4.3 Theta Squared Plots

Theta Squared (θ^2) plots are one of the most used plots in VHE gamma-ray data analysis to evaluate the significance of a source and test the response of IACTs. θ^2 plots show the distribution of events as a function of their squared angular distance (the θ^2 quantity) from a reference position. Usually, two distributions are plotted: the *ON* distribution, with reference position being the nominal position of an astrophysical source; the *OFF* distribution, with reference position having no astrophysical source and acting as a control distribution. For instance, in ON/OFF-mode observations, the ON and OFF positions are the same within the FoV of the telescope, but taken from the ON and OFF observations, respectively. In Wobble-mode observations, the OFF position is symmetric to the ON position with respect to the telescope pointing.

We show an example of a θ^2 plot in figure 2.16, computed using one of the simulated observations on a point-like source described in section 5. The OFF distribution is flat as expected, while the ON distribution is given by the sum of a flat background distribution plus an exponential-like distribution at small θ^2 due to the presence of a simulated source. The two distributions are expected to be consistent at large θ^2 , where no source is present,

if the acceptance of the IACT is symmetrical. The telescope acceptance A^γ introduced in section 2.4.2 can be evaluated for the ON (A_{ON}^γ) and OFF (A_{OFF}^γ) regions simply by summing the counts of the distribution within a range of θ^2 not contaminated by the source. For instance, in figure 2.16 we summed the counts in the $0.10 - 0.40 \text{ deg}^2$ range to obtain the acceptances. Their ratio is the parameter $\alpha = \frac{A_{\text{ON}}^\gamma}{A_{\text{OFF}}^\gamma}$. If $\alpha \sim 1$, then the response of the telescope is symmetrical in the ON and OFF positions, as it is usually expected. Instrumental or atmospheric problems, such as humidity patches on the camera, may affect the IACT response creating inhomogeneities in the FoV. In such a case, α would be $\ll 1$ or $\gg 1$. For this reason, θ^2 plots are useful tests for asymmetries in the detector's response and can be used to perform *Data Quality* checks.

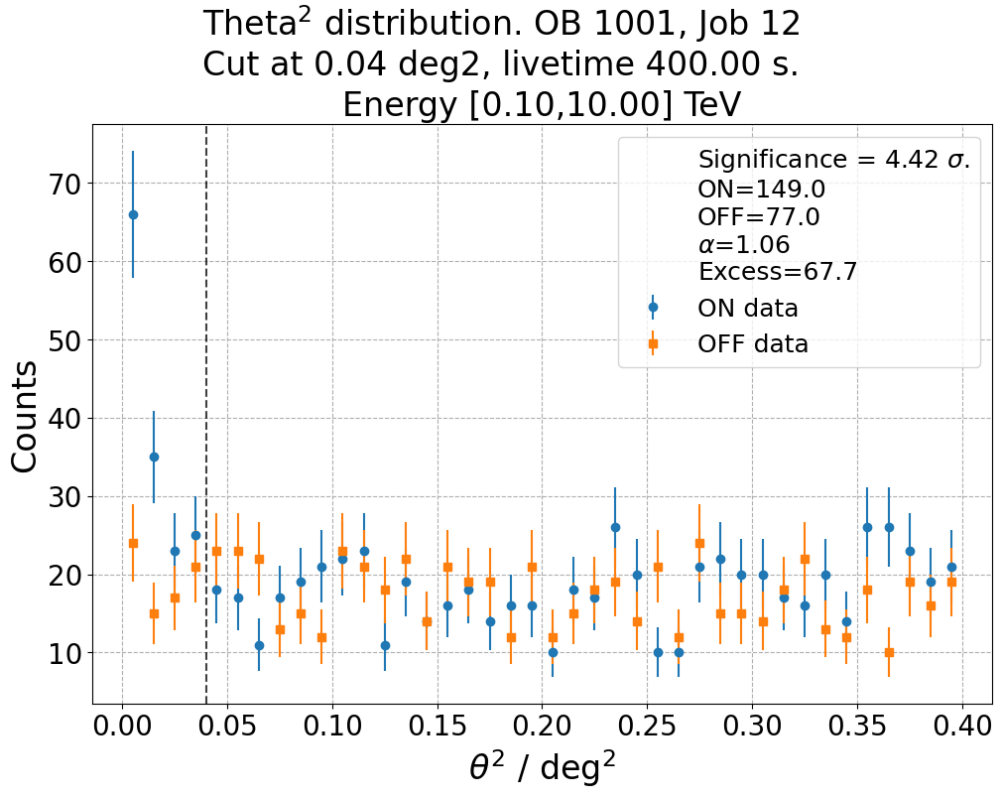


Figure 2.16 – θ^2 plot of a simulated point-like source. The ON and OFF distributions are consistent at large θ^2 , where there is only background signal. The acceptance of the distributions is evaluated $0.10 - 0.40 \text{ deg}^2$ and their ratio is $\alpha \approx 1$, proving the response of the instrument has no asymmetries. The ON and OFF counts are summed for $\theta^2 < 0.04 \text{ deg}^2$ and are used to evaluate the Li&Ma significance of the source $\sigma = 4.42$.

An evaluation of the Li&Ma significance of the source can be performed through the θ^2 plots. The N_{ON} (and N_{OFF}) counts are the sum of the counts of the ON (and OFF) distributions with $\theta^2 < \theta_{\text{cut}}^2$, where θ_{cut} is the size of the aperture region, usually obtained through γ /hadron cuts optimisation (see section 2.3.4) or by evaluating the PSF.

2.4.4 Maximum Likelihood Estimation

The *Maximum Likelihood Estimation* (MLE) is a technique where a 3D spectro-morphological models that describe one or more astrophysical sources and background components is fit

to the observed data. The fit maximise the likelihood of the data and results in a complete spectral and spatial description of the FoV. In the *binned* Maximum Likelihood Analysis, the observed counts n_i in each spatial and spectral bin are compared with the predicted counts $\nu_i(\Theta)$ from a model with parameters Θ through the assumption of Poisson Likelihood and statistical independence of each bin:

$$\mathcal{L}(\{n_i\}_i | \Theta) = \prod_i \mathcal{P}(n_i | \nu_i(\Theta)) = \prod_i \frac{[\nu_i(\Theta)]^{n_i}}{n_i!} e^{-\nu_i(\Theta)}. \quad (2.11)$$

The main difference with the Aperture Photometry approach of section 2.4.1, which also relies on Poisson statistics (see appendix A.2.1), is that the expected counts in an observation are *not* the parameters that need to be estimated or maximised: the real parameters are the ones that describe the spectra and the morphology of the astrophysical sources. The expected counts are thus a function of the physical models. The number of predicted photons in a given spatial and spectral bin i is given by the sum of the predicted counts for every source and background component assumed in the *Sky model* that describes the FoV:

$$\nu_i(\Theta) = N(\mathbf{x}_i, E_i | \Theta) = \sum_j N_{bg,j}(\mathbf{x}_i, E_i | \Theta) + \sum_k N_{src,k}(\mathbf{x}_i, E_i | \Theta). \quad (2.12)$$

The predicted counts for each source/background component are obtained by performing a convolution of the sky model with the IRFs (*forward-folding* technique). We provide a more in-depth description of source models, background components and IRFs in appendix A.3. The MLE technique is used for a *Likelihood Ratio Test* (Cash 1979): the likelihood of eq. (2.11) is evaluated under a Null Hypothesis (e.g. no astrophysical source is present) and an Alternative hypothesis. The test statistic TS is given by the logarithm of their ratio:

$$TS = -2 \ln \frac{\mathcal{L}_0}{\mathcal{L}_1}, \quad (2.13)$$

where $\mathcal{L}_0$ and $\mathcal{L}_1$ are the likelihood optimised under the null and alternative hypothesis respectively. Under Wilks' theorem (Wilks 1938) $TS \sim \chi_r^2$ where r is the difference in number of parameters under null and alternative hypothesis. Wilks' theorem is asymptotically valid for large datasets, as the size of the sample $\rightarrow \infty$. The Null hypothesis must also satisfy two constraints: the model of the null hypothesis must be a simpler model nested within the more complex model of the alternative hypothesis, and the simpler model should not fall on the edge of the parameter space spanned by the more complex model. If these conditions are respected, TS can be used to evaluate the p -value and test the validity of the alternative hypothesis and the maximisation of the likelihood. The MLE technique was originally used by high-energy space satellites such as Fermi and AGILE (Bulgarelli et al. 2012), while IACTs preferred aperture photometry approaches. Today, IACTs are also implementing MLE techniques: the estimation of the flux of a source is usually performed through a simplified 1D-version of the MLE technique where the model has only spectral parameters free, while the spatial model is a fixed point-like model. Another notable difference is that HE satellites adopt complex background emission models that describe the Galactic and extra-galactic emission (Giuliani et al. 2004; Bulgarelli et al. 2019), and then fold them with the satellite response to estimate the predicted background counts. On the other hand, the main source of background for IACTs in the VHE gamma-ray band is the γ -like background produced by mis-reconstructed CR showers that survive the γ -hadron separation cuts. For this reason, background models for IACTs are already provided in terms of expected counts and do not need further convolution (e.g. the CTAO models, Cherenkov Telescope Array Observatory and Cherenkov Telescope Array Consortium 2021).

Chapter 3

The Cherenkov Telescope Array Observatory in the Era of Time Domain Astrophysics

Gamma-ray astronomy is currently undergoing a golden age, thanks to the work of space satellites and ground-based facilities, that increased our knowledge on the most energetic and extreme processes of the Universe. The major discoveries of the last ten years in γ -ray astronomy are connected to *Time-Domain* (TD) Astrophysics and transient events, and have greatly benefited from a *Multi-Wavelength* (MWL) and *Multi-Messenger* (MM) approach. In this chapter, we discuss the role of Time-Domain, Multi-Wavelength and Multi-Messenger Astrophysics on the development of Gamma-ray Astronomy and new γ -ray observatories. This is the main field of my PhD research, so we also discuss my work and results.

In section 3.1, we describe the relevance of the Time-Domain, Multi-Wavelength and Multi-Messenger approaches in High-Energy Astrophysics today, and the major discoveries they produced. In particular, in section 3.1.1 we discuss the role of Real-Time Analysis systems, Burst Advocate activity and Science Alerts in the field. One of the results of my PhD research was publishing several Science Alerts, thanks to the Burst Advocate work I performed for the AGILE Collaboration. I also played an active role in the AGILE detection and analysis of GRB 221009A, an extraordinary case study of the effectiveness of the MWL approach in TD and γ -ray astrophysics, that we describe in section 3.1.2.

The major observatory for VHE γ -ray astrophysics in the next decade and beyond is going to be the *Cherenkov Telescope Array Observatory* (CTAO), that we describe in section 3.2. In particular, we describe its *Key Science Projects* (KSPs) in section 3.2.1. The CTAO is going to be extremely relevant in TD astrophysics, thus in section 3.2.2, we focus on the *Transients* KSP and the CTAO capabilities at short time scales. The first *Large-Sized Telescope Prototype* (LST-1) of the CTAO is already working at the *Observatorio del Roque de los Muchachos*, La Palma island, Canary Islands, Spain. We describe it and its first scientific results in section 3.2.3. I also describe my work in the LST Collaboration as part of my PhD, including being Co-P.I. of several observational proposals on transient sources, taking part in an observation shift at the LST-1 and researching the Galactic magnetar SGR 1935+2154 at VHE. The study of SGR 1935+2154 is the main topic of chapter 6.

In section 3.3, we describe the *Array Control and Data Acquisition* (ACADA) software system of the CTAO. The subsystem of ACADA dedicated to the real-time analysis of CTAO

data is the *Science Alert Generation* (SAG) pipeline, that we describe in section 3.4. I personally contributed to the development of SAG, for instance in section 3.4 we present the strategies I developed for the *Data Quality* checks of DL2 and DL3 CTAO data. Nevertheless, my main contribution to SAG and one of the main topics of my PhD research, is the development of the high-level, real-time analysis pipeline of SAG, called **SAG-SCI**. The development and validation of **SAG-SCI** is the main topic of chapters 4 and 5, respectively.

3.1 Multi-Wavelength, Multi-Messenger and Time Domain Astrophysics

In the last few decades, astronomers started using a **Multi-Wavelength** approach to study astrophysical sources. MWL Astronomy allows to create more complete pictures of the emission processes of astrophysical sources, gathering information across all the spectrum to help identifying sources, localising them, understanding the chemical and physical processes at work, and how they interact with the surrounding medium. An example of this approach can be seen in the MWL image of the Crab Nebula in figure 3.1. The image combines data from five different spectral bands:

- The radio band in red, of the *Very large Array* (VLA), shows the synchrotron emission of a wind of charged particles energised by the Crab pulsar.
- The infrared in yellow, of the *Spitzer Space Telescope*, includes the glow of dust particle absorbing UV and visible light and re-emitting it at lower energies.
- The visible in green, of the *Hubble Space Telescope*, offers a very sharp view of the hot filamentary structures that permeate the nebula.
- The ultraviolet in blue, of the *XMM-Newton Telescope*, shows the lower-energy core cloud of electrons accelerated by the pulsar.
- The soft X-ray in purple, of the *Chandra X-ray Observatory*, shows the higher-energy core cloud of electrons accelerated by the pulsar.

Each observational technique reveals a distinct and complementary perspective into the source. Emission in different energy ranges results from different physical processes, and an integral view of the sources is only possible through a combined, MWL approach.

One of the most relevant MWL events of the last few years was the association of the radio transient FRB 200428D with an X-ray burst of the Galactic magnetar SGR 1935+2154, already introduced in chapter 1.6.3 (CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020; Mereghetti et al. 2020; Ridnaia et al. 2021a; Li et al. 2021; Tavani et al. 2021). We show a superimposed light curve of the X-ray burst and FRB in figure 3.2. This discovery provided the first evidence that magnetars can be one of the progenitors of FRBs, and that magnetar bursts may exhibit broad-band emission, challenging our understanding of these events. We adopt a MWL approach using X-rays and TeV γ -rays to discuss the properties of the persistent and transient emission of SGR 1935+2154 in chapter 6.

In the last decade, the MWL approach started to include information gathered by astrophysical *messengers* that are not photons: Cosmic Rays (CRs), Neutrinos and Gravitational Waves (GWs), evolving into the frontier field of **Multi-Messenger** Astrophysics. MM Astrophysics emerged as a major field in astrophysics thanks to two breakthrough discoveries.

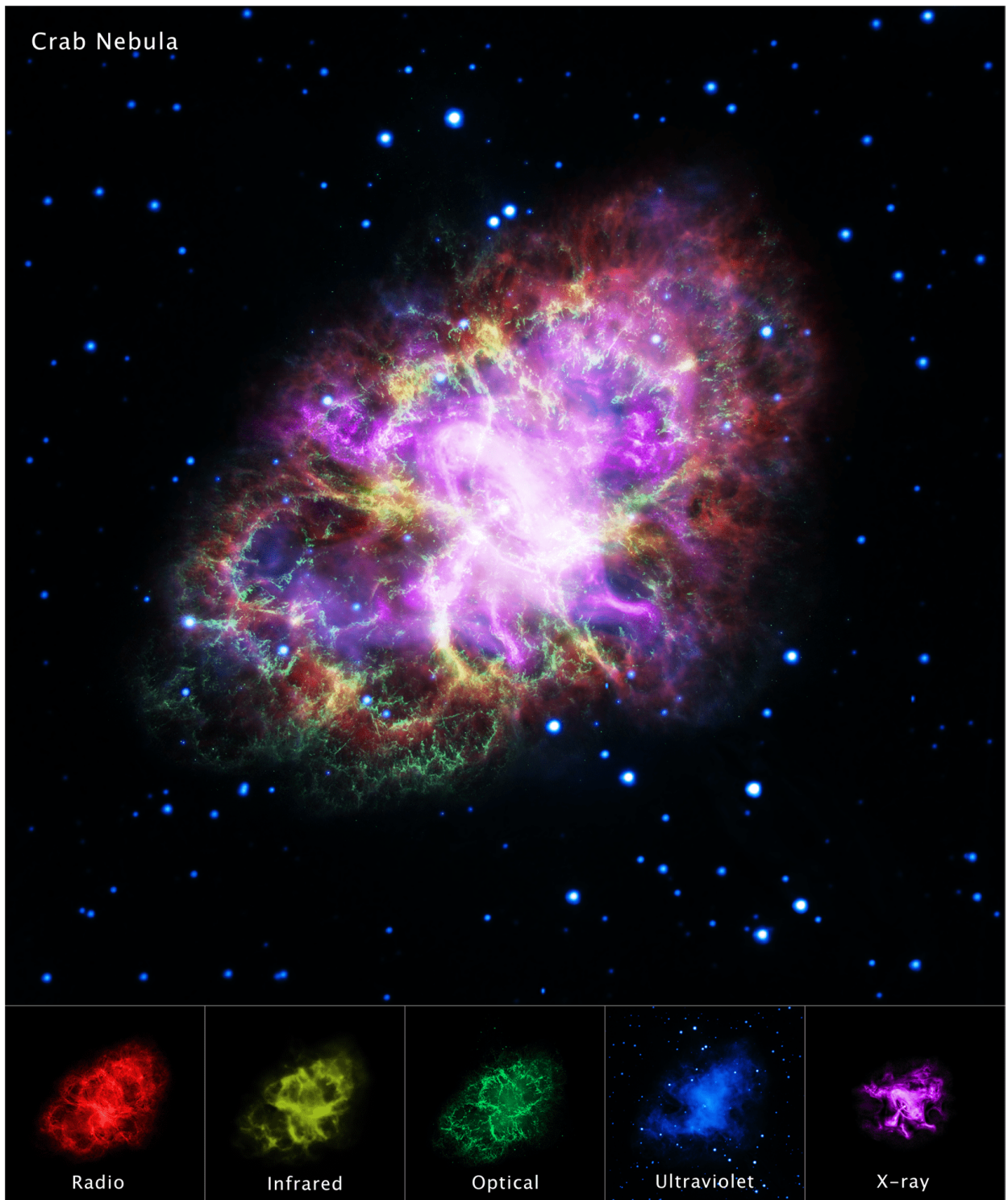


Figure 3.1 – Multi-wavelength view of the Crab Nebula. The image combines data from five different telescopes: VLA (radio) in red; Spitzer Space Telescope (infrared) in yellow; Hubble Space Telescope (visible) in green; XMM-Newton (ultraviolet) in blue; and Chandra X-ray Observatory (X-ray) in purple. Credit: Hubble Space Telescope at <https://hubblesite.org/contents/media/images/2017/21/4027-Image.html>.

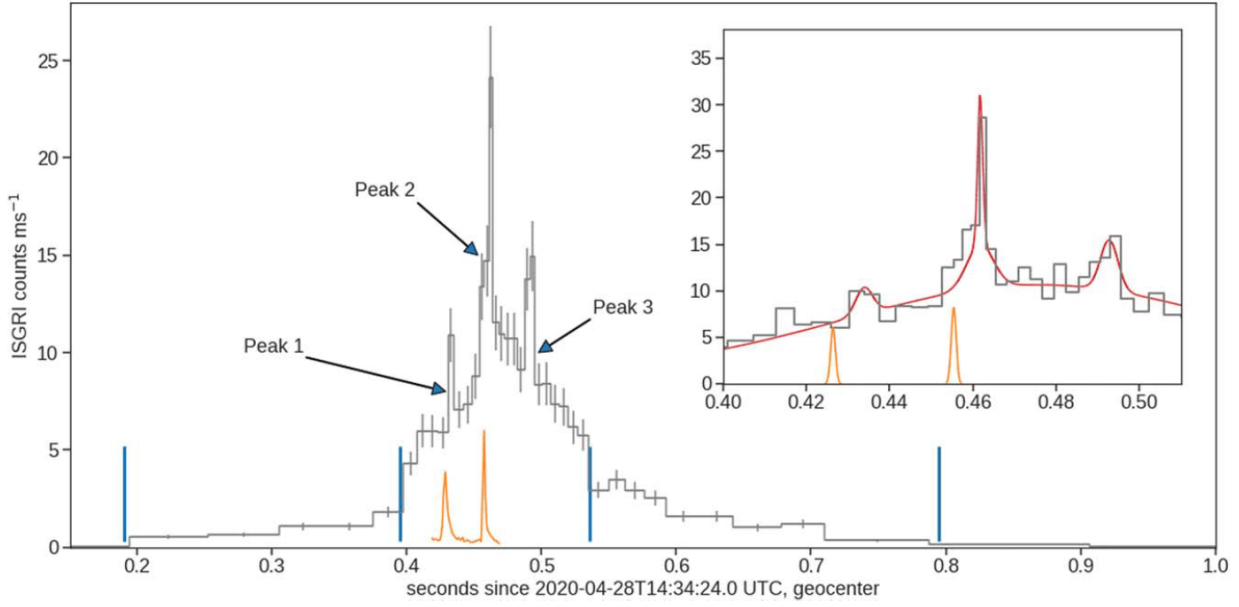


Figure 3.2 – Light curve of the X-ray burst of SGR 1935+2154 in grey. Credit: Mereghetti et al. (2020). The pulses are fitted by the red lines, and blue lines show reference intervals used for the analysis. The yellow curve shows the radio signal of FRB 200428 localised on the magnetar (CHIME/FRB Collaboration et al. 2020). This burst was a major event in MWL astrophysics.

The first one was the discovery of astrophysical high-energy neutrinos by the IceCube experiment in Antarctica (Aartsen et al. 2013; IceCube Collaboration 2013) and the association of blazar TXS 0506+056 with high-energy neutrinos (IceCube Collaboration 2018). As discussed in chapter 1.4, the detection of neutrinos is considered as a signature of *hadronic* acceleration processes, that can also emit γ -rays. The second breakthrough discovery that pushed the field of MM Astrophysics was the detection of the first GW signal by the LIGO and VIRGO Collaborations attributed to the merger of two stellar-mass black holes (Abbott et al. 2016), and the detection of the GW 170817 signal from the coalescence of a binary NS system associated with the short GRB 170817A (Abbott et al. 2017; Goldstein et al. 2017; Savchenko et al. 2017). The identification of a short GRB as electromagnetic counterpart of a GW signal triggered by a binary neutron star merger provided the first solid evidence on the nature of short GRBs’ progenitors. We show the light curve of the GRB versus (vs) the detection time of the GW event in figure 3.3.

The major recent discoveries in MWL and MM Astrophysics here discussed have two aspects in common: they are all transient events (*transients* for short), and γ -ray data played a key role in both the discovery and interpretation of the emission. Indeed, only the most extreme environments and processes in the Universe, such as the sites of CR acceleration and compact objects like NSs and BHs, have the dynamic processes and energy budget needed to produce high-energy photons, neutrinos and GWs, and they are most suited to emit them during violent transient events. **Time-Domain** Astrophysics emerged thus in the last few years as a relevant and interesting field, describing the evolution of transient events and variable sources on a wide range of time scales, from ms to years.

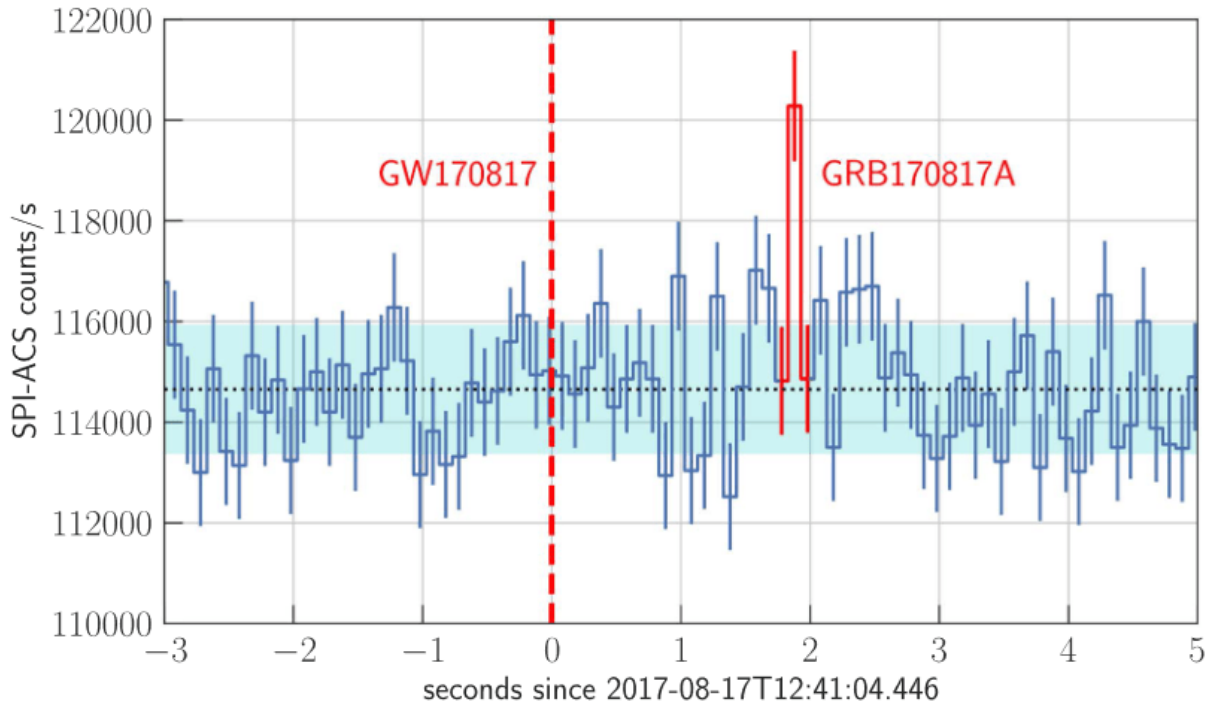


Figure 3.3 – INTEGRAL light curve of GRB 170817A vs the detection time of GW 170817. This burst was a major event in MM astrophysics. Credit: Savchenko et al. (2017).

3.1.1 Science Alerts and Burst Advocate Activity

Gamma-ray Astrophysics sits at the crossroads of MWL, MM and TD Astrophysics, and is uniquely suited to provide insights into the physics of the *variable sky*. Most γ -ray Observatories and Experiments set up strategies to detect transients, analyse them as fast as possible and alert the scientific community when one occurs. These communications are known as **Science Alerts**. They are usually transmitted through the *General Coordinate Network* (GCN, NASA 2024), either as an *automatic notice* or a *manually authored circular*, or by writing *Astronomer’s Telegrams* (ATels, Rutledge 1998; The Astronomer’s Telegram 2024). Observatories and Experiments usually have systems dedicated to receiving Science Alerts, especially automatic GCN notices that are written on public servers in a machine-readable format. As an example, the AGILE Collaboration used to have a **Real-Time Analysis** (RTA) system (Parmiggiani et al. 2023) capable to analyse satellite data as soon as they reached the data centre, and issue a GCN notice if the automatic pipeline detected a transient. When an external facility issued a notice, the RTA system would automatically analyse the archival data in coincidence with the alert. The RTA system worked until January 2024, when the AGILE satellite ceased its operations and re-entered the Earth’s atmosphere¹.

Scientific Collaborations do not rely only on automatic approaches, but require some members to perform **Flare/Burst Advocate** shifts. Burst Advocates check the data acquisition and the RTA pipelines, follow the manual alerts published as GCN circulars and ATels, and perform the necessary analyses to publish a new Science Alert. Burst Advocates can also trigger *Target of Opportunity* (ToO) observations of a telescope, to ensure quasi-simultaneous and MWL follow-up observations of relevant transients.

From September 2022 to January 2024, I worked as a Burst Advocate for the AGILE

¹Sadly.

Collaboration as part of my PhD research, to gain direct experience in the field of TD astrophysics. I performed monthly shifts of 48 h in which I was required to check the correct reception of AGILE data, the automatic analyses of the RTA pipelines and the latest Science Alerts. When a transient event occurred during my shift, I analysed its data and published a Science Alert. This led to the publication of 5 GCNs ([#33113](#), [#33656](#), [#33867](#), [#34237](#), [#35244](#)) and 1 ATel ([#15782](#)) on GRBs and AGN flares as a primary author (Panebianco and AGILE Team [2023](#)), and to being co-author of more than 40 alerts of the AGILE Team.

3.1.2 An Extraordinary Case Study for Multi-Wavelength and Time Domain Astrophysics: GRB 221009A

I was on a Burst Advocate shift on October 9th, 2022 when the AGILE data centre received the first batch of data of GRB 221009A, the **Brightest Of All Times** (BOAT). We issued Science Alerts confirming the detection of the GRB with a preliminary analysis (Ursi et al. [2022](#); Piano et al. [2022](#)), then worked on a refined analysis (Tavani et al. [2023](#)). We show a sky map of the AGILE observations in figure [3.4](#).

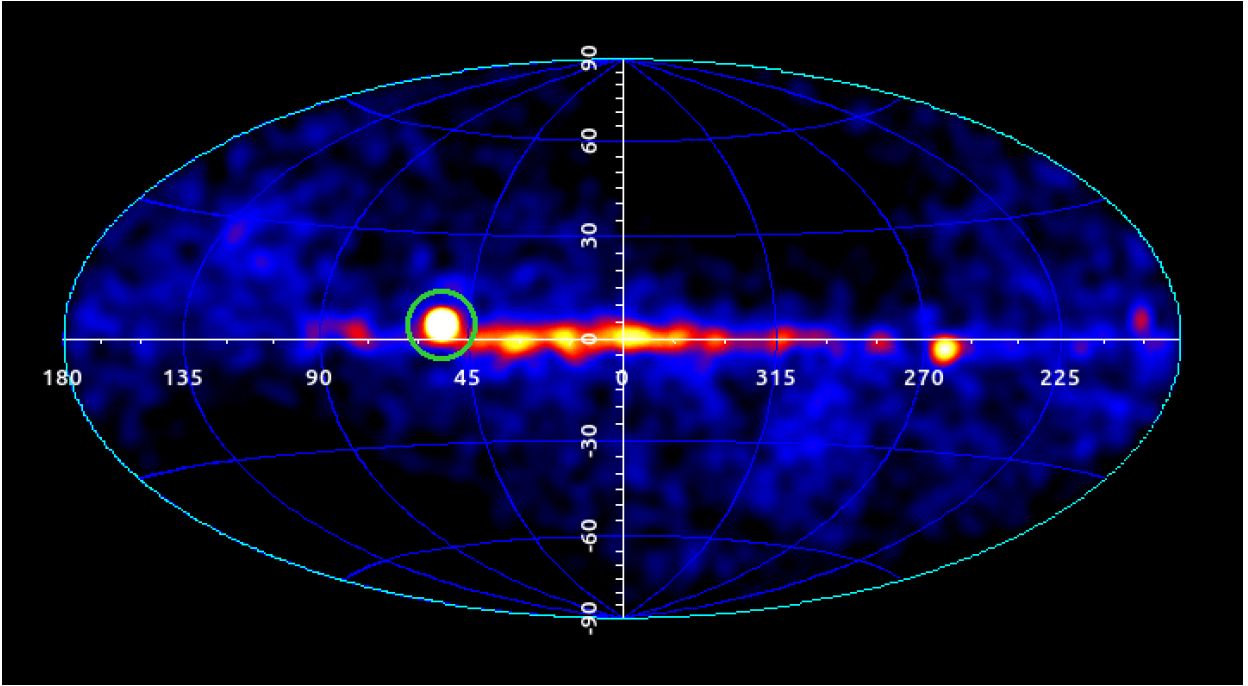


Figure 3.4 – Sky count map of the above 100 MeV in Galactic coordinates of the AGILE-GRID detector, integrated for 48 h after T_0 . GRB 221009A is shown inside the green circle, with a record significance of $\sim 20\sigma$. The darkened sky regions are due to seasonal lack of exposure of the GRID detector, due to solar panel constraints. Credit: (Tavani et al. [2023](#)).

GRB 221009A was a very long GRB, with a prompt emission lasting ~ 500 s after $T_0 = 2022-10-09\ 13:16:59.99$ UT and showing a complex structure composed of several pulses, see figure [3.5](#). The flux of the main peaks of the prompt was so high that saturated several satellites, including AGILE. The estimated fluence of the burst is $\gtrsim 5 \cdot 10^{-2} \text{ erg cm}^{-2}$ in the 20 keV to 10 MeV energy range, 3 order of magnitude above average GRB values. This can be explained by a very high intrinsic energy of the GRB ($E_{\text{iso}} \sim 10^{54} \text{ erg}$) and a low redshift $z \sim 0.15$, corresponding to a distance of $\approx 750 \text{ Mpc}$ (Lesage et al. [2023](#)).

Our analysis provided crucial results in a MWL context, as AGILE observed simultaneous

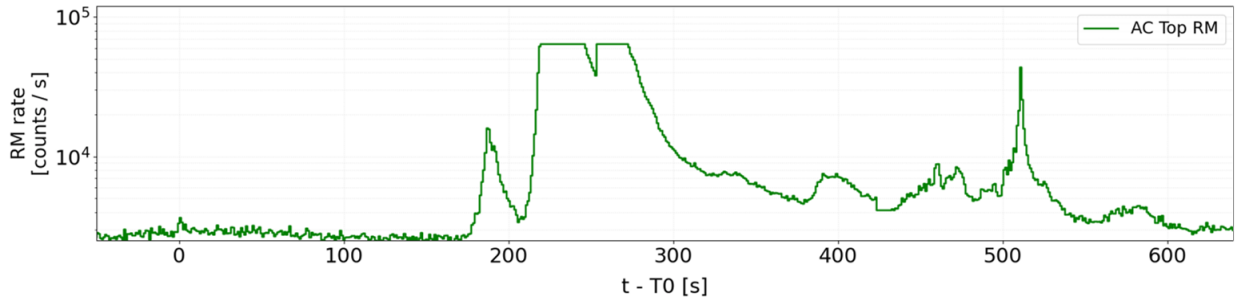


Figure 3.5 – Prompt emission of GRB 221009A as detected by the Anti-Coincidence System (ACS) of the AGILE satellite in the 50 – 200 keV range. We assume $T_0 = 2022-10-09\ 13:16:59.99$ UT. The main pulses of the GRB were so bright that saturated AGILE. Credit: (Tavani et al. 2023).

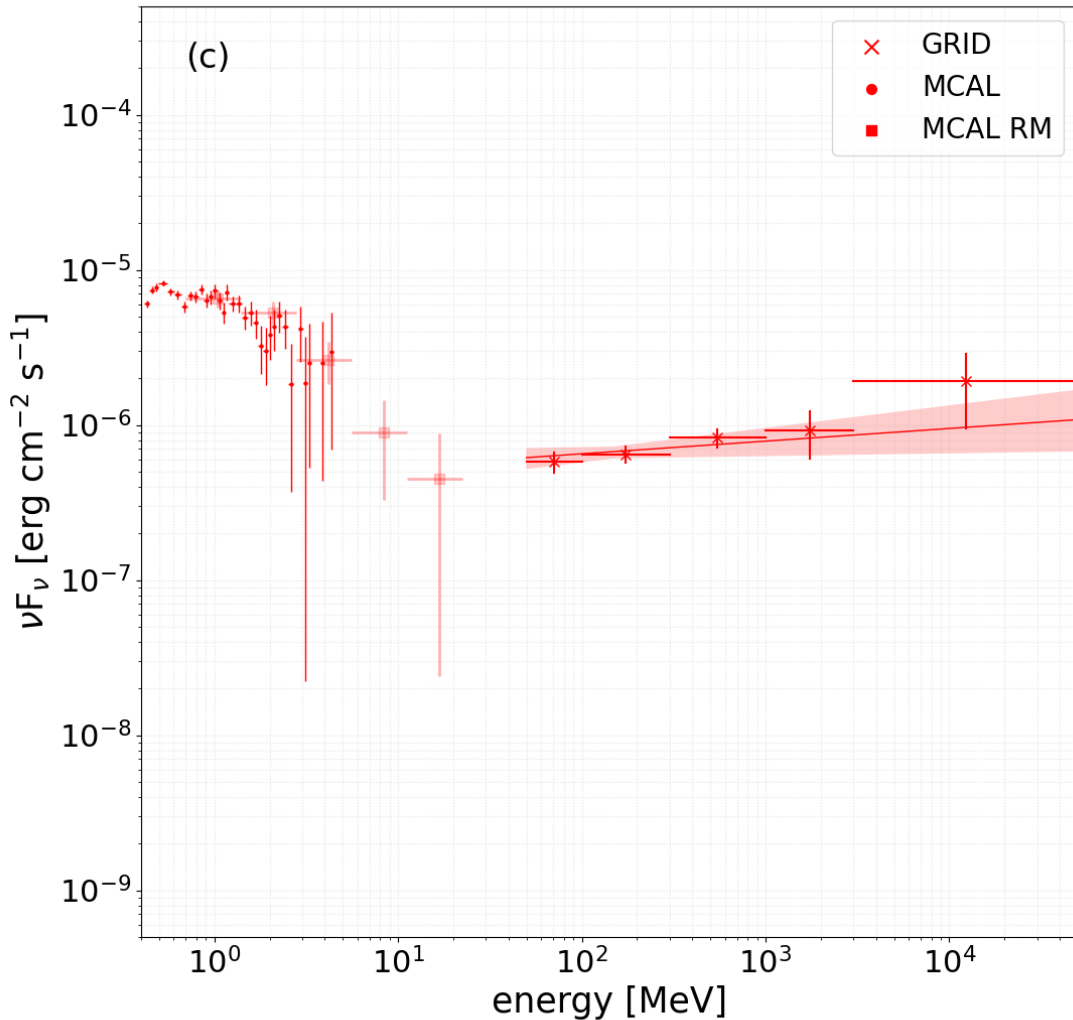


Figure 3.6 – Multi-wavelength emission of GRB 221009A detected by AGILE. The MeV component is interpreted as synchrotron *prompt* emission, while the GeV component is the IC *afterglow*. They were detected simultaneously by the AGILE-MCAL and AGILE-GRID instruments, respectively, and they offer a rare view of the onset of the afterglow of a GRB, when the jets start to interact with the surrounding medium. Credit: (Tavani et al. 2023).

MeV-GeV components of the GRB, see figure 3.6. The MeV component is interpreted as synchrotron *prompt* emission, while the GeV component is the IC *afterglow*, see section 1.6.3 for details. These components were detected simultaneously by the AGILE-MCAL and AGILE-GRID instruments, respectively, presenting a rare view of the *onset* of the afterglow of a GRB, when the jets start to interact with the surrounding medium. The AGILE data were used to compute the MWL light curve of the BOAT GRB (see figure 3.7), that shows a slope of the afterglow emission consistent with the one detected by Swift-XRT (Williams et al. 2023).

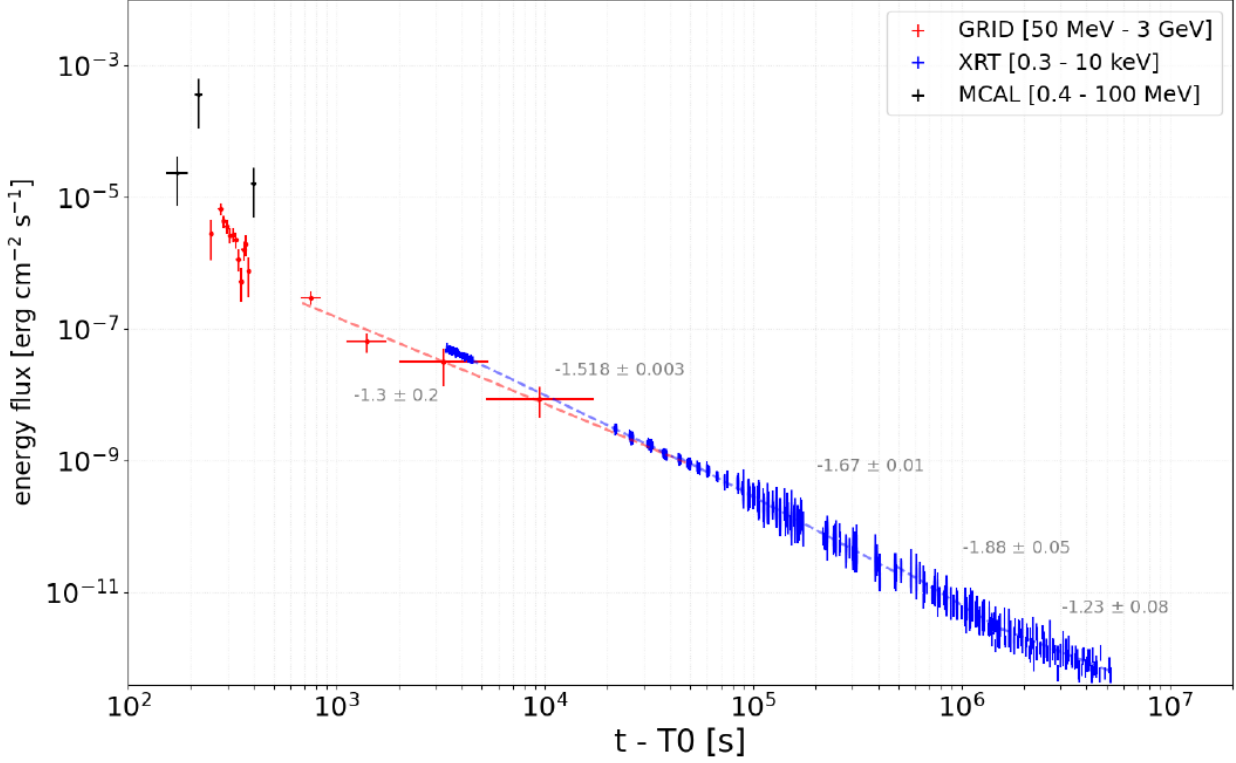


Figure 3.7 – Multi-wavelength light curve of GRB 221009A. The points at $t \lesssim 6 \cdot 10^2$ s from T_0 show the prompt emission, while the points after show the afterglow, compared with Swift-XRT data (Williams et al. 2023). The slopes of the AGILE and Swift afterglow light curves are consistent. Credit: (Tavani et al. 2023).

Remarkably, AGILE detected the afterglow onset simultaneously to LHAASO (Cao et al. 2023), see figure 3.8, that allowed us to perform a preliminary MWL modelling of the afterglow. The afterglow is interpreted as IC emission, a theoretical model supported by the detection of TeV emission from LHAASO. In this scenario, the AGILE GeV data represent the rising part of the IC emission. The AGILE results on this extraordinary GRB presented in Tavani et al. (2023) show the effectiveness of the MWL and TD approaches to astrophysics. The Science Alerts and Burst Advocate systems enabled a swift response of the astronomer community, ensuring a successful MWL coverage of the transient. The MWL data were crucial in the interpretation and modelling of the emission. Foffano et al. (2024) provided a more complex MWL modelling of the afterglow emission of GRB 221009A within the fireball scenario. The afterglow emission is well described by IC emission by a fireball with adiabatic evolution in the slow-cooling regime. The model can describe not only the AGILE-LHAASO data, but can also be extended to later times when also optical and X-ray data are available, resulting in a coherent physical framework that successfully describes all observed properties of the afterglow up to very late times (10^6 s).

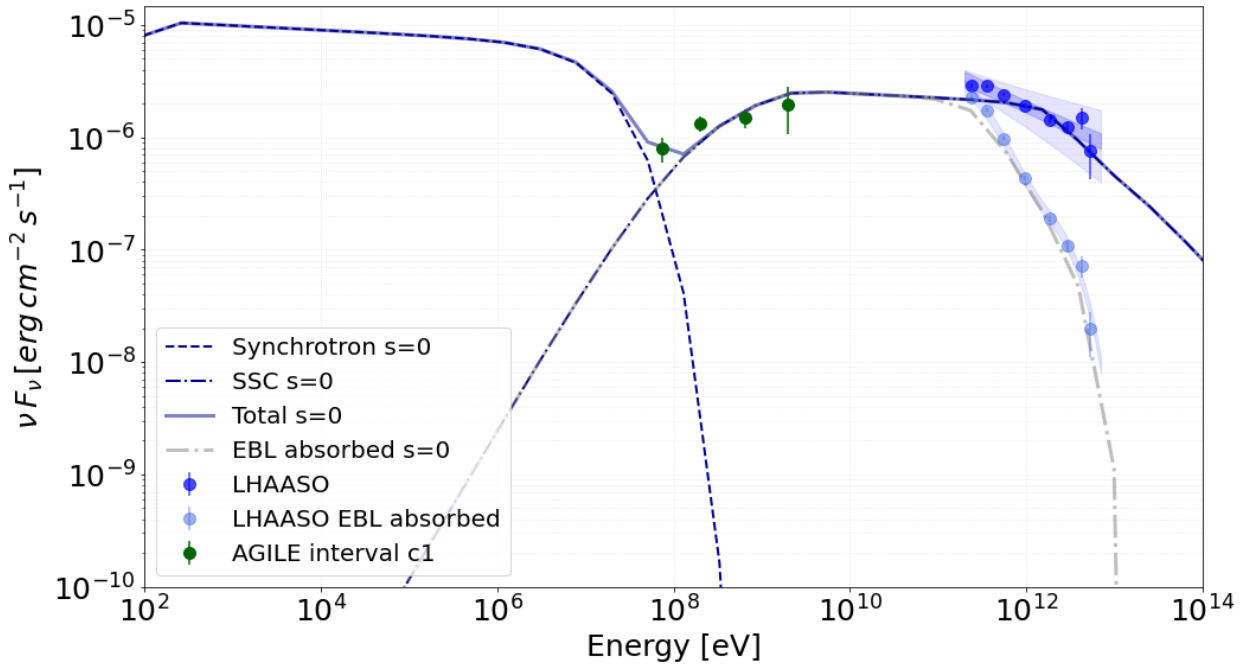


Figure 3.8 – Multi-Wavelength modelling of the afterglow emission of GRB 221009A with AGILE and LHAASO data. The afterglow is interpreted as IC emission, a scenario supported by the detection of TeV emission from LHAASO. In this scenario, the AGILE GeV data represent the rising part of the IC emission. Credit: (Tavani et al. 2023).

3.2 The Cherenkov Telescope Array Observatory

Ground-based γ -ray astrophysics is currently undergoing a golden age, following the scientific and technical developments described in chapters 1 and 2, and the relevance of the VHE γ -ray energy band for MWL, MM and TD Astrophysics. This is the scientific context in which the **Cherenkov Telescope Array Observatory** (CTAO) is being developed. It is going to be the major global observatory for very high energy astrophysics in the next decade and beyond (Cherenkov Telescope Array Consortium et al. 2019; Zanin et al. 2022; McMuldroch et al. 2024), capable to transform our understanding of the high-energy Universe and explore questions in physics of fundamental importance. The CTAO will address a wide range of questions in and beyond astrophysics, such as: understanding the origin, role and acceleration of CRs; probing extreme environments in the Universe like NSs, BHs and transients; exploring frontier topics in physics like the nature of Dark Matter. We will discuss the Key Science Projects of the CTAO in section 3.2.1. These core questions guide the design of the CTAO. The CTAO will be operated as an open, proposal-driven Observatory for the first time in VHE astronomy. This operation mode is expected to significantly boost scientific output by engaging a wider research community than ever before in ground-based γ -ray astronomy.

The CTAO will be composed of more than 60 telescopes distributed in two sites, one in the Northern hemisphere and one in the Southern to achieve a full-sky coverage. The CTAO-North site is located on *La Palma* (Canary Islands, Spain), at the *Observatorio del Roque de los Muchachos*, while the CTAO-South site is located in the Atacama Desert, Chile. These are in the best astronomical sites in the world, thanks to their high-altitude, extremely good weather conditions and low humidity. The CTAO will include three classes of IACTs, capable to cover a wide energy range, from 20 GeV to 300 TeV: the *Large-Sized Telescopes* (LSTs), the *Medium-Sized Telescopes* (MSTs) and the *Small-Sized Telescopes* (SSTs).

Covering a wide energy range is a key feature to maximise the scientific impact of the CTAO: the lowest energies avoid significant γ - γ absorption due to the Extra-galactic Background Light (EBL), thus providing access to high-redshift sources; the highest energies are needed to study the extreme CR accelerators of the Galaxy. Having a wide energy range also maximises the chances of serendipitous detection of new classes of sources with unknown spectral characteristics, for example in the search for Dark Matter. The mirror of the CTAO telescopes follows a design invented by Guido Horn d'Arturo in the 1930s: it is not a single dish, but is composed of many highly reflective hexagonal mirror facets closely connected. The CTAO will use computer-controlled optics systems to actively align the mirror facets to focus light into the telescopes cameras. CTAO cameras will be composed of PMTs or Silicon Photomultipliers (SiPM) and will be able to capture Cherenkov flashes to produce high-quality waveforms for every camera pixel, as the Imaging Atmospheric Cherenkov technique requires (see chapter 2.3.1).

The latest official configuration of CTAO telescopes, called the *Alpha Configuration*, includes 4 LSTs plus 9 MSTs in the Northern site (see figure 3.9), and 14 MSTs plus 37 SSTs in the Southern site (see figure 3.10). CTAO-North specialises in extra-galactic and transient science due to LSTs covering a lower energy range, while CTAO-South specialises in Galactic science due to the higher energy range covered by SSTs and being able to observe the Galactic Centre. We describe in detail the three types of telescopes below. Figure 3.11a shows the performance of the CTAO-North and CTAO-South Full Arrays. CTAO is expected to provide an improvement in sensitivity by about one order of magnitude with respect to existing IACTs, reaching $\sim 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ at a few TeV. Figure 3.11 show other performance indicators of the CTAO: panel 3.11b shows a predicted angular resolution ranging from 0.05 deg to 0.25 deg according to the considered energy range, improving at least by a factor 2 the angular resolution of current facilities. The bump around 5 TeV is connected to the smaller FoV of the LSTs with respect to that of the MSTs: it indicates the transition from events with a large multiplicity (detected by LSTs and MSTs) to events detected only by MSTs. Panel 3.11c shows the expected γ -like background rate of mis-reconstructed hadronic events that survived the γ /hadron separation cuts (see the discussion in chapter 2.3.4). The CTAO will be able not only to observe with full arrays, but also perform simultaneous observations on different targets using parallel sub-arrays of telescopes. Parallel observations of different targets will reduce the sensitivities of individual sub-arrays, but offer a large increase of the FoV covered, effectively multiplying the observation time reserved to scientific proposals.

Large-Sized Telescopes. The LSTs are parabolic telescopes with a diameter of 23 m, a 45 m height and a weight of 100 tonnes. Their camera is so large that requires a metal tower to support it when the telescope is parked. It has an hexagonal grid of 1855 pixels, each connected to a PMT covering 0.1 deg, with a resulting FoV of ~ 4 deg. Despite their size, LSTs are very nimble and can reposition between any two points in the sky within 30 s with a precision of ~ 0.04 deg, crucial features to perform ToO observations of transients. LSTs are sensitive at the lowest energy range of CTAO thanks to the large size of their reflector, capable to detect the faintest Cherenkov flashes from EASs, that are initiated by low-energy particles. These showers are more frequent than high-energy shower, so having a smaller number of telescopes spread over a smaller area does not limit the chances of detection. The sensitivity of LSTs is optimised in the 0.020 TeV to 0.150 TeV energy range when working in stereoscopic mode, but it extends up to 10 TeV. In this energy range, CTAO overlaps

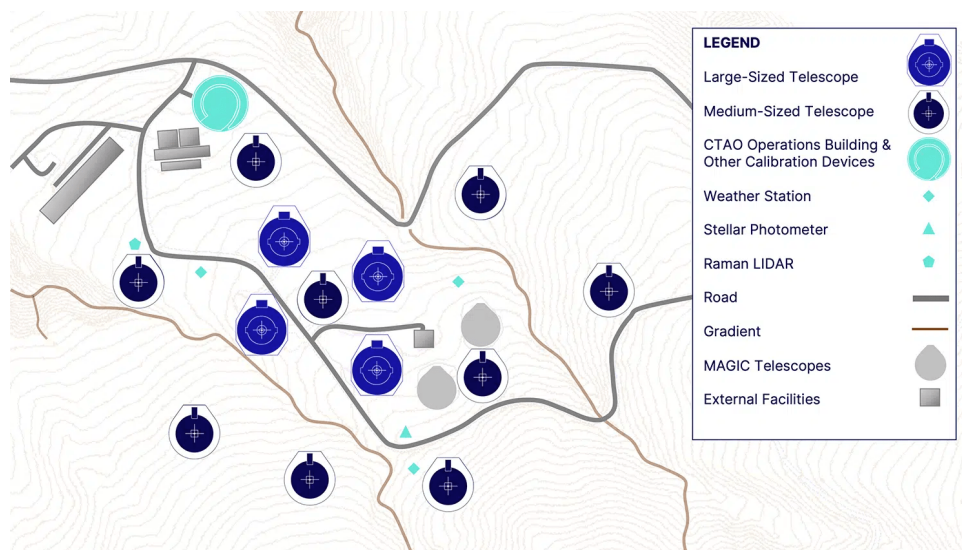


Figure 3.9 – Alpha Configuration for CTAO-North, including 4 LSTs and 9 MSTs. CTAO-North is located on the Spanish island of *La Palma*, in the Canary Islands. Credit: CTAO-North (2024).

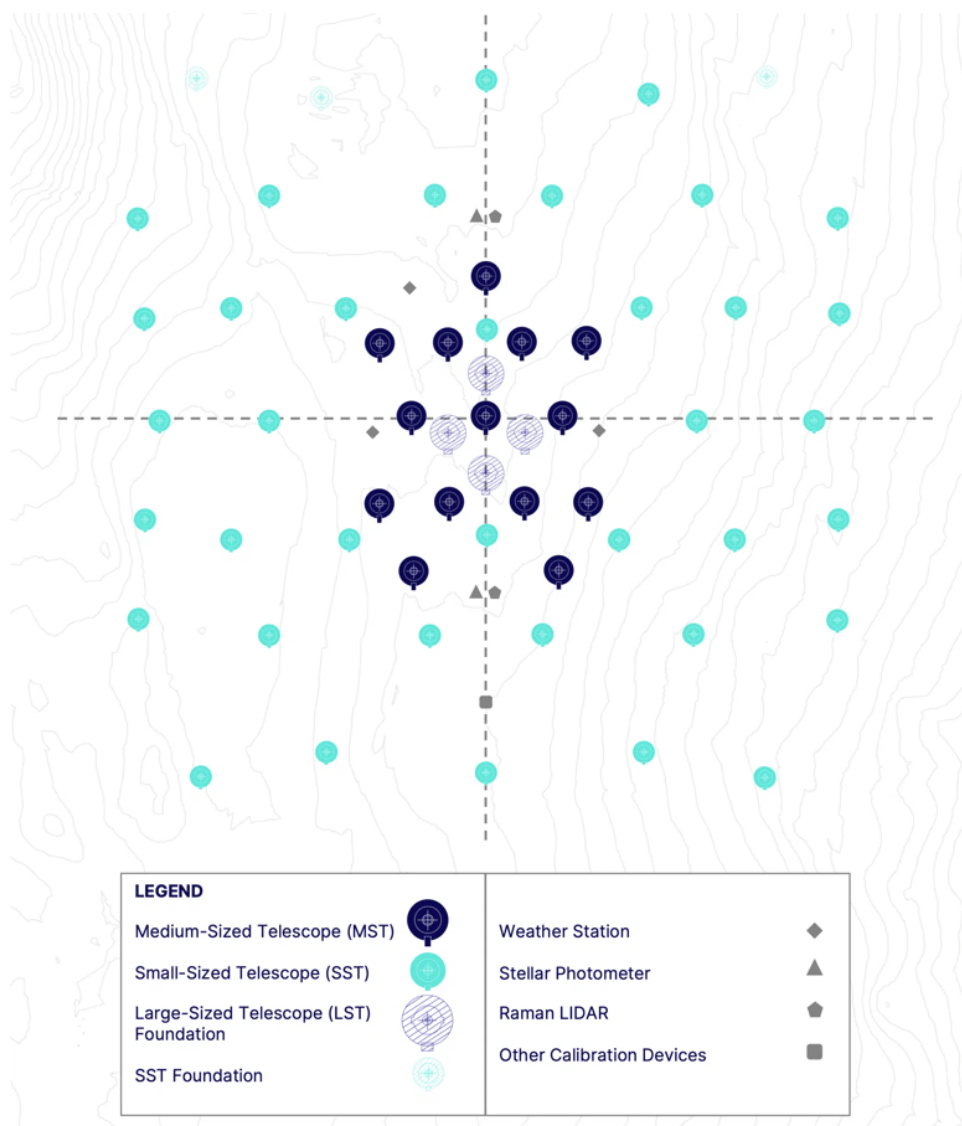
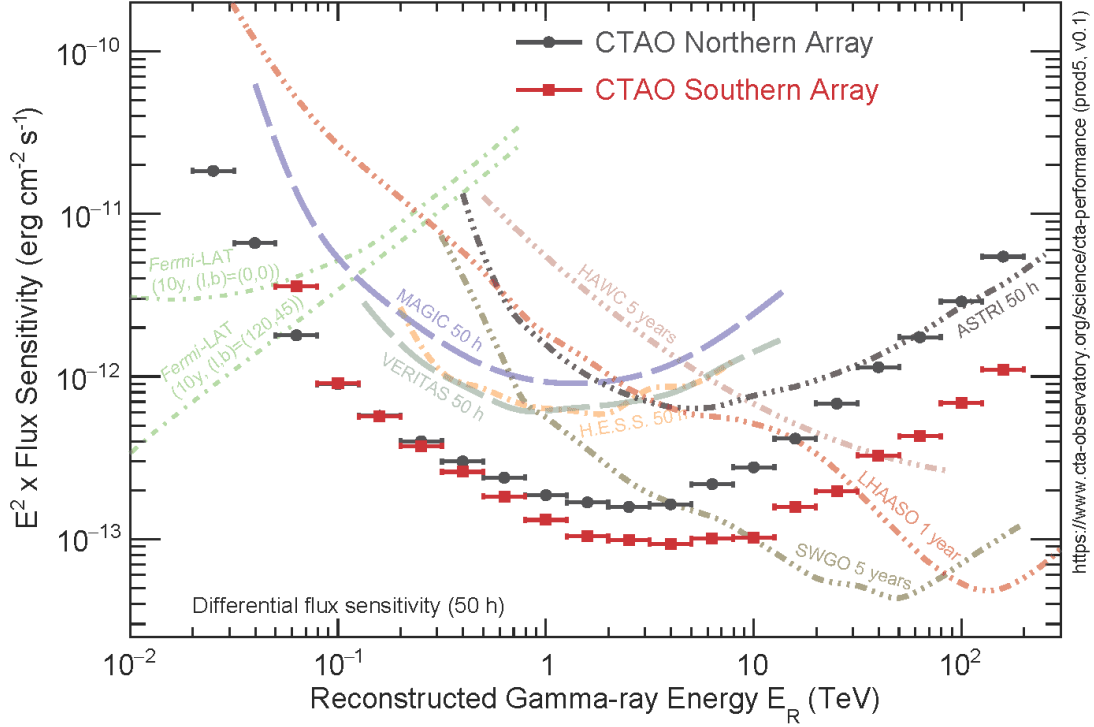
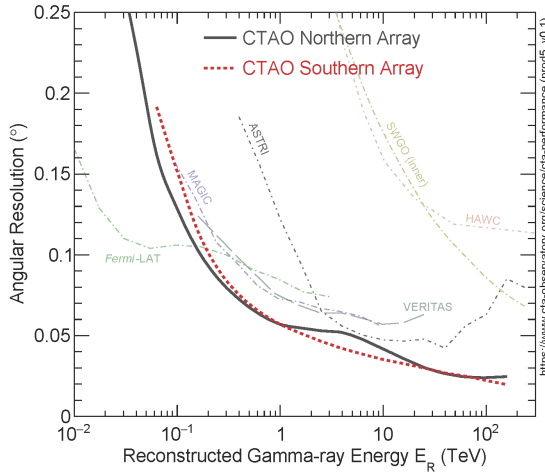


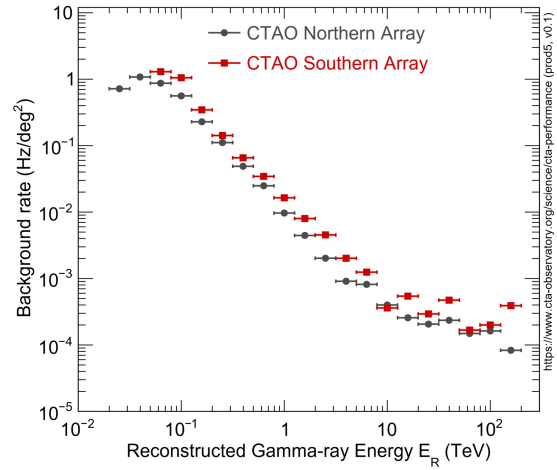
Figure 3.10 – Alpha Configuration for CTAO-South, including 14 MSTs and 37 SSTs. CTAO-South is located in the Atacama Desert, Chile. Credit: CTAO-South (2024).



a – Sensitivity



b – Angular resolution



c – Background rate

Figure 3.11 – Performance of the CTAO. Panel 3.11a shows the 50 h sensitivity of the CTAO Northern and Southern Full Arrays in the Alpha Configuration. It is compared with the typical sensitivities of other IACTs and major γ -ray telescopes. Panel 3.11b shows the angular resolution of the full arrays compared with other γ -ray facilities. Panel 3.11c shows the predicted background rate spectrum due to the γ -like background of shower events surviving the γ /hadron separation cuts. Credit: <https://www.ctao.org/for-scientists/performance/>.

with space satellites, most notably Fermi-LAT. CTAO outperforms Fermi-LAT from 50 GeV for long-term exposures (see figure 3.11a), and it outperforms it on short-term exposures ($\lesssim 10$ h) by several orders of magnitude (see figure 3.13 later in the discussion). The first prototype of LSTs, called LST-1, is already working at the *Observatorio del Roque de los Muchachos*, see section 3.2.3.

The Italian community plays a crucial role into expanding the possibilities of the CTAO. The **CTA+ Project**, financed with the *Next Generation EU* funds, will allow for the construction of at least two LSTs in CTA-South, strongly improving its sensitivity at the lowest energies.

Medium-Sized Telescopes. The MSTs constitute the backbone of the CTAO, covering its core energy range with sensitivity optimised between 0.150 TeV and 5 TeV, and being deployed in both sites (Bradascio and CTAO-MST Project 2023). They have properties intermediate between LSTs and SSTs. MSTs have a modified Davies-Cotton design similar to the one used by HEGRA, H.E.S.S. and VERITAS, and a ~ 12 m diameter. MSTs will use two different types of PMT cameras, *NectarCAM* for the CTAO-North and *FlashCAM* for CTAO-South, both with a FoV of ~ 8 deg. An MST prototype, see figure 3.12a, operated in Berlin between 2012 and 2020 to validate the design of the individual components and their integration.

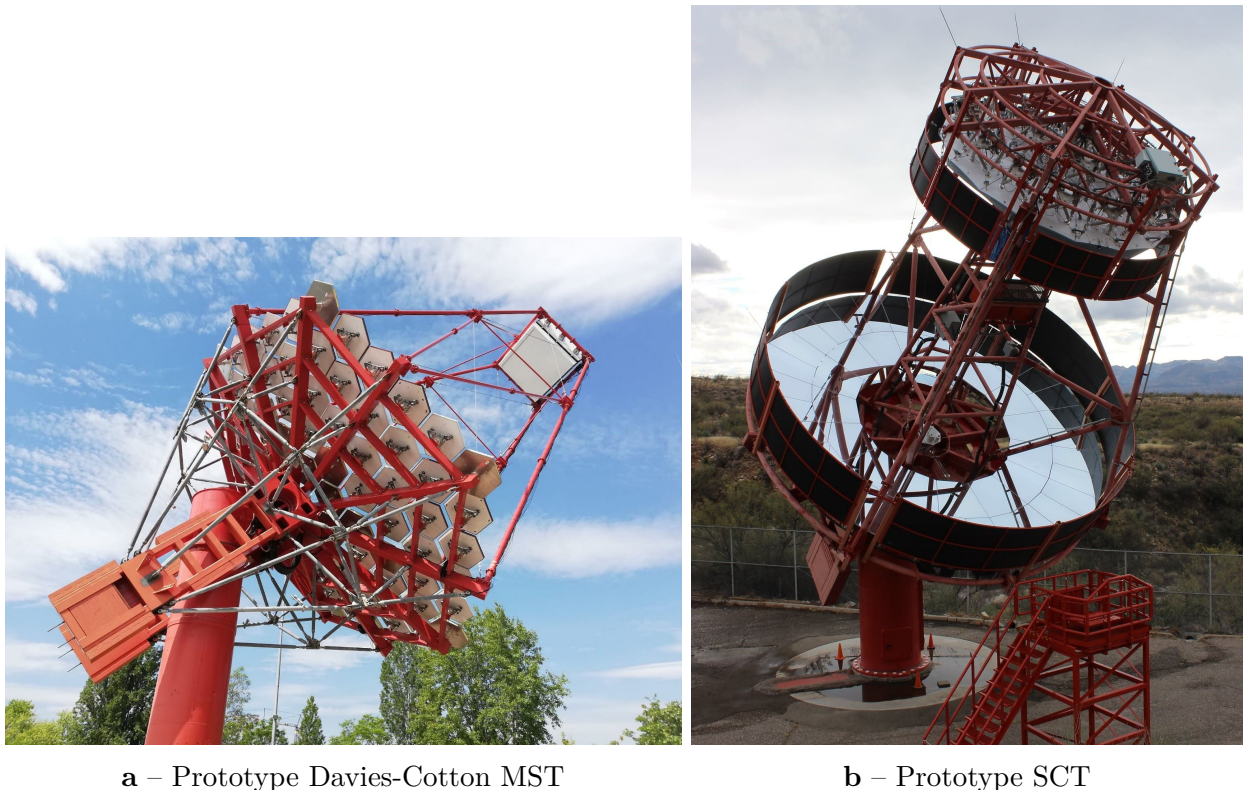


Figure 3.12 – Prototypes of CTAO MSTs. Panel 3.12a shows the Davies-Cotton prototype installed in Berlin, while panel 3.12b shows the pSCT installed in Arizona. Credit: CTAO Flickr.

The CTAO-MST Project aims at installing a prototype in each site before 2026, as part of the *CTAO Pathfinder project*, whose goal is to have intermediate sub-arrays of CTAO working by 2027. The definitive design of MSTs has not been fully approved yet. A dual-mirrored version of the MST, the *Schwarzschild-Couder Telescope* (SCT), is proposed as an

alternative design to the Davies-Cotton. Its two-mirror optical system is designed to better focus the light into a high-resolution SiPM camera. The SCT can improve MST performances up to an order of magnitude with respect to Davies-Cotton MST by having greater imaging detail and better off-axis optical PSF. The prototype SCT (pSCT, see figure 3.12b), has been constructed at the Fred Lawrence Whipple Observatory in Arizona, USA, and detected the Crab Nebula in 2020 (Mode et al. 2022).

Small-Sized Telescopes. The SSTs are designed to cover the higher energy range of CTAO. The Cherenkov flashes from EASs are very bright, so a small reflector can capture them, but they are less frequent in number than lower-energy flashes, which requires spreading many SSTs over a large area to improve detection chances. SSTs achieve the best sensitivity in the 5 TeV to 300 TeV. SSTs rely on a modified Schwarzschild-Couder dual-mirror optical design. The primary reflector has a ~ 4 m diameter, and reflects the light into a monolithic ~ 2 m reflector, which focuses the light into a the camera. The camera uses 32 SiPM tiles, for a total of 2048 pixels, covering a FoV of ~ 9 deg.

INAF is also developing the *ASTRI Mini-Array*, which will be composed of 9 SST-like telescopes at the *Teide Observatory* on Tenerife (Canary Islands, Spain). It will operate as an independent but complementary observatory to CTA-North, that lacks SSTs, to ensure a coverage of the Northern sky at the highest energy range.

3.2.1 Key Science Projects of the CTAO

The CTAO will address a wide range of questions in and beyond astrophysics, regarding three core themes (Cherenkov Telescope Array Consortium et al. 2019):

1. Understanding the origin, role and acceleration processes of relativistic cosmic particles, searching the answer for questions like:
 - What are the sites of high-energy particle acceleration in the universe?
 - What are the mechanisms for CR acceleration?
 - What role do accelerated particles play in feedback on star formation and galaxy evolution?
2. Probing extreme environments in the Universe, such as:
 - Neutron Stars and Black Holes, understanding the physical processes at work in these compact objects.
 - Relativistic Jets, winds, explosions and their characteristics.
 - Radiation and Magnetic fields in cosmic voids, and their evolution.
3. Exploring Frontier topics in Physics, for instance:
 - What is the nature and distribution of Dark Matter?
 - Do axion-like particles exist?
 - Are there quantum gravitational effects on photon propagation?

These core questions guide the design of the CTAO, and the definition of its *Key Science Projects* (KSPs), the core projects of the CTAO. KSPs observations will be reserved at least 40% of the time in the first ten years of operations. CTAO defined 9 KSPs, four of which are *surveys*. Indeed, no sensitive surveys of the VHE sky exist yet, and CTAO measurements are

expected to be revolutionary and have long-lasting value. CTAO will conduct both deep-field surveys of some key regions hosting prominent targets, and wider and shallower surveys to build up unbiased population samples and to search for unexpected emission. We present an overview of the KSPs of the CTAO below, with the exception of the *Transients* KSP, that we discuss in section 3.2.2 along with the capabilities of the CTAO at short time scales.

Galactic Plane Survey. It consists in an entire scan of the Galactic plane up to 5 deg in latitude with a sensitivity of 5 mCrab². This survey will fulfil several science goals, such as:

- Providing a census of Galactic VHE populations of SNRs, PWNe and binary systems, detecting hundreds of new sources. This is particularly important as today there are about 250 VHE sources known in total, as we discussed in chapter 1.6. Detecting a large number of new sources will allow for more advanced population studies.
- Identifying a list of promising targets for follow-up observations, such as new γ -ray binaries and PeVatron candidates.
- Determining the properties of the diffuse emission from the Galactic plane at VHE.
- Producing a multi-purpose, legacy dataset of the Galactic plane at VHE with long-lasting scientific value.
- Discovering new and unexpected phenomena in the Galaxy, such as new source classes and types of transients.

Galactic Centre Survey. It will provide a deep field scan of a 20 deg² region around the Galactic Centre with a 2 mCrab sensitivity, and it will be complemented by even more observations of the inner region around Sgr A*. The region within a few degrees of the Galactic Centre contains a wide variety of possible VHE emitters, including the supermassive BH of the Galaxy, dense molecular clouds, strong star-forming regions, multiple SNRs and PWNe, PeVatrons, the base of what may be large-scale Galactic outflows (the *Fermi Bubbles*). This region is also one of the most suited to search for Dark Matter signals. The CTAO unprecedented angular resolution will allow for high-precision studies of the central region, and it may be able to identify the central source, disentangling the models that have been put forth to explain its extended emission.

Large Magellanic Cloud Survey. It is a deep field survey that can be conducted with CTAO-South. The *Large Magellanic Cloud* (LMC) is a unique galaxy, a satellite of the *Milky Way*, hosting a large number of astrophysical sources with major relevance. They include the most active star-forming region of the Local Group (30 Doradus), the super star cluster R136 with a large concentration of massive O and Wolf-Rayet stars, supernova SN1987A (the closest supernova in modern times), and the puzzling 30 Dor C superbubble with rare non-thermal emission). It is also one of the nearest star-forming galaxies, with more than 60 SNRs, dozens of HII regions and bubbles observed at various wavelengths, all of which promise fruitful gamma-ray observations. It is therefore a unique place to obtain a significantly-resolved global view of a star-forming galaxy at very high energies. The interpretation of VHE γ -ray observations of the LMC will benefit from a large and comprehensive MWL context, and will offer a unique point of view on non-thermal processes. E.g. analyses of CR

²We define 1 mCrab = $5.07 \cdot 10^{-13}$ phs⁻¹cm⁻² above 125 GeV, it is 0.1% of the Crab Nebula flux.

populations in the LMC may be of interest for studies of the Interstellar Medium conducted by radio and infrared observatories.

Cosmic Ray PeVatrons. The study of Galactic PeVatrons and candidate-PeVatron SNRs will be primarily conducted with SSTs. CTAO is expected to help distinguish between acceleration models of SNRs, as a detection at > 10 TeV would favour hadronic emission scenarios. This task is challenging for current IACTs, due to their limited sensitivity in the > 10 TeV energy domain, but it is well within the reach of CTAO. Another advantage of the CTAO is to cover regions of the sky not visible by LHAASO, currently the most sensitive particle detector.

Star Forming Systems. CTAO observations of star-forming systems will help to unveil the relationship between high-energy particles and the star-formation process. The study of individual star-forming regions and star-forming galaxies will furthermore help to disentangle source-specific properties from global ones. The study of targets such as the Carina and Cygnus regions will allow to constrain the fraction of stellar wind energy transferred into γ -rays, study particle acceleration in Galactic stellar clusters and superbubbles, and search for signs of CR propagation and interaction with the ISM.

Extra-galactic Survey. It will provide the first unbiased scan of the VHE sky, with the aim to cover 25% of the sky with a 5 mCrab sensitivity. The current sample of extra-galactic objects at VHE is biased due to the limited sensitivity of current IACTs (see chapter 2.2.3). With the predicted CTAO sensitivity, it will be possible to construct an unbiased sample of VHE AGN in the nearby universe, up to a redshift of $z \approx 0.2$. It will be particularly relevant for sources like BL Lacs, whose luminosity function is not well characterised today. More distant sources will be detectable if in elevated or flaring flux states. A second objective of this KSP is to provide a high-resolution map of the extra-galactic sky between 50 GeV and 10 TeV. A third objective is to search for unexpected and serendipitous VHE phenomena over a large portion of the sky. The area covered by the Extra-galactic Survey will connect to the Galactic Plane Survey so that no Galactic latitude is left un-surveyed.

Active Galactic Nuclei. Currently, 40% of the known VHE sources are AGN. They will remain one of the main targets of the CTAO, as they are extremely “versatile” sources that can be used to test all of the CTAO core themes, such as studying the physics of compact objects like the supermassive BHs at the centre of AGN and the particle acceleration processes. AGN observations can also be used to search for Axion-like particles and signals of Lorentz Invariance Violation, frontier topics in Physics, with repercussions on our understanding of General Relativity, Quantum Physics and Dark Matter. The CTAO has the potential to substantially increase the number of known AGN, especially at high redshifts. In addition, the CTAO will allow us for the first time to study the VHE variability of numerous sources during their quiescent or low-flux states, of which very little is known up to now.

Clusters of Galaxies. Galaxy clusters are expected to be reservoirs of CRs accelerated by structure formation processes, galaxies and AGN. There is currently no direct evidence for proton acceleration in Galaxy clusters, but CTAO could detect it by observing γ -rays emitted

from π^0 decay (see chapter 1.4). Additionally, some of the galaxies hosted in clusters could be detected in gamma rays individually, if harbouring AGN, or via their summed output, e.g. in the case of star-forming galaxies. Finally, about 80% of the mass of clusters is in the form of Dark Matter and therefore they are considered prime targets for indirect Dark Matter searches.

3.2.2 The Transients Program of the CTAO

CTAO is going to be a uniquely powerful instrument for the exploration of the violent and variable universe thanks to its unprecedented sensitivity to short timescale phenomena, wide field of view and broad energy range. For this reason, the study of *Transients* is one of the KSPs of the CTAO. In figure 3.13, we show the sensitivity of the CTAO-North and Fermi-LAT at the same energies as a function of the observation time. The CTAO's sensitivity is going to be 3 to 6 orders of magnitude lower than Fermi-LAT's one. CR detectors such as HAWC also have limited sensitivity at short timescales compared to CTAO, due to a small collection area and a low signal-to-noise ratio. The ability to probe short timescales at the highest energies will allow the CTAO to explore the connection between accretion and ejection phenomena surrounding compact objects, study phenomena occurring in relativistic outflows, and open up significant phase space for serendipitous discovery. For instance, the CTAO is expected to create the first sample of GRBs detected at VHE, probing new spectral components which will shed light on the physical processes at work in these systems. Major improvements are expected on all galactic and extra-galactic transient sources described in section 1.6.3.

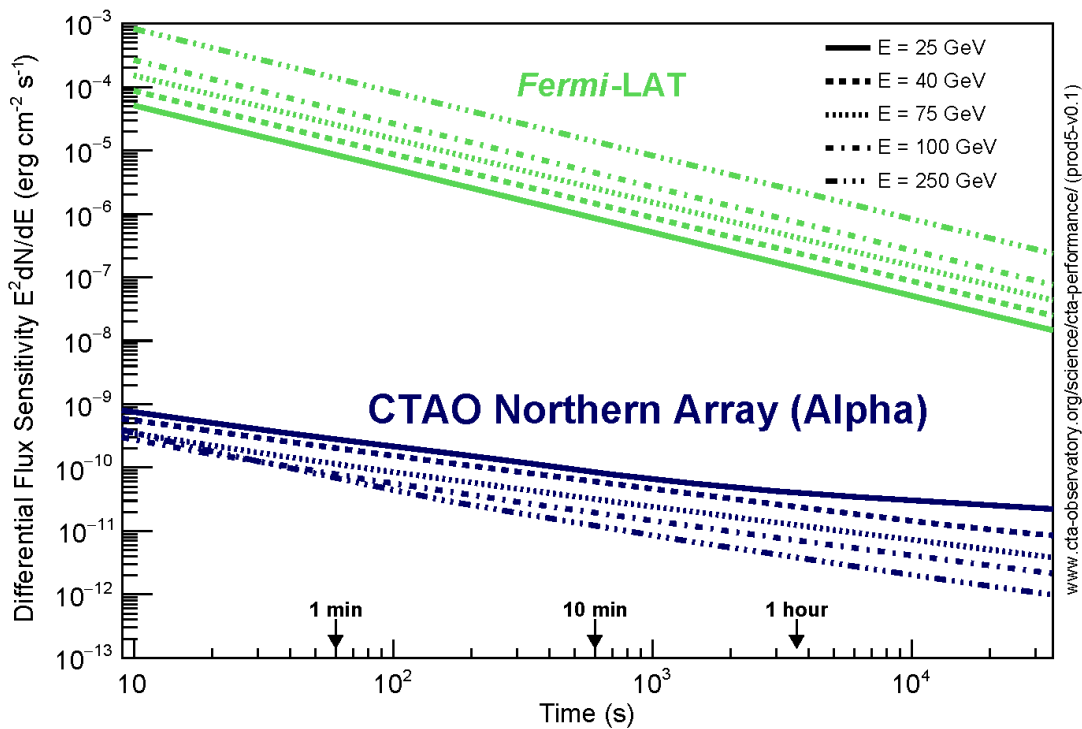


Figure 3.13 – Sensitivity of the CTAO-North at short term timescales and different energies. It is 3 to 6 orders of magnitude lower than Fermi-LAT. Credit: <https://www.ctao.org/for-scientists/performance/>.

As well as having unprecedented sensitivity to emission on short timescales, the CTAO will be able to respond very rapidly both to the reception of external Science Alerts and the issuing of internal Science Alerts to other observatories. CTAO LSTs will be able to re-point anywhere in the sky in $\lesssim 30$ s, while MSTs and SSTs in $\lesssim 90$ s, with the goal of reaching shorter slewing times. This **fast slewing** capability is particularly important for capturing fast transients such as GRB prompt emission. The wide FoV and high sensitivity of the CTAO make the *serendipitous* detection of transient or variable VHE emission likely, especially during surveys.

To maximise its scientific return, the CTAO will be equipped with a low-latency, effectively *Real-Time Analysis* (RTA) pipeline which will monitor the FoV for variability on a wide range of timescales. The detection of a γ -ray flare in the FoV will be able to trigger the issuing of an internal Science Alert within 60 s, informing other observatories to allow rapid and MWL follow-up of the transient. The CTAO will itself respond to both internal and external Science Alerts by repositioning the telescopes and modifying the observing schedule. The RTA pipeline, called the **Science Alert Generation** (SAG) system, will allow CTAO to become a powerful instrument for time-domain astrophysics and enable multi-wavelength and multi-messenger approaches that will lead to a deeper understanding of the broad-band non-thermal properties of target sources. We describe the SAG pipeline in section 3.4. A major part of my work is the development of the **SAG-SCI** software, the scientific, high-level analysis pipeline of SAG that implements the methods described in chapter 2.4. We will describe **SAG-SCI** in detail in chapter 4, and test it on simulated CTAO data in section 5.

3.2.3 The Large-Sized Telescope Prototype: LST-1

The first *Large-Sized Telescope Prototype* (LST-1) is located at the CTAO-North site, at the *Observatorio del Roque de los Muchachos*. The Observatory is located atop the *Caldera Taburiente* volcano, at $\simeq 2400$ m a.s.l., in the island of La Palma, Canary Islands, Spain. LST-1 started performing astronomical observations in November 2019, during its commissioning phase, and it has been taking data since then. Scientific observations are usually alternated with technical test and observations, as the LST-1 is undergoing internal review in order to be formally accepted as a CTAO telescope. Currently, the LST Collaboration, a project within CTAO, is responsible for the telescope, as much as for the construction of the other LSTs. The structure of the other three LSTs of the Northern site has already been built, and they are expected to begin their operations by 2026. A picture of the LST-1 under the evening sky is shown in figure 3.14. The picture clearly shows all the main components of the telescope: the mirror made up by hexagonal tiles, the camera and its support tower (behind the telescope) and the 45 m tall parabolic structure.

The performance of the LST-1 has been tested with observations of the Crab Nebula, the standard candle of VHE γ -ray astronomy. It is described in CTA-LST project et al. (2023). The energy threshold at trigger level is around 20 GeV, rising to $\simeq 30$ GeV after data analysis. Performance parameters depend strongly on energy, and on the strength of the γ /hadron separation cuts adopted. The angular resolution ranges from 0.12 deg to 0.40 deg, and the flux sensitivity is around 1.1% of the Crab Nebula flux above 250 GeV for a 50 h observation (12% for 0.5 h), see figure 3.15. LST-1 sensitivity is lower than MAGIC by a factor 1.5 on average due to not using stereoscopic reconstruction (see chapter 2.3). The Crab Nebula SED was determined in the 0.03 TeV to 30 TeV range and agreed with previous measurements, considering statistical and systematic uncertainties.



Figure 3.14 – A picture of the LST–1 under the evening sky and a shooting star. Credit: CTAO Flickr <https://www.flickr.com/photos/ctao-universe/>.

The positive results of the performance paper (CTA-LST project et al. 2023) allowed the LST Collaboration to publish the first LST–1 results in 2023, a MWL study of the Galactic PeVatron candidate LHAASO J2108+5157 (Abe et al. 2023b). The LST–1 was also used in a stereoscopic system with the two MAGIC telescopes, providing a 30% improvement of the sensitivity (Abe et al. 2023a).

Since 2023, the LST Collaboration increased its scientific activity, implementing a system of **proposal cycles** to request observations, open to members and external collaborators. As part of my PhD activities, I was co-P.I. of the “ToO Observations of Galactic Transient Sources” proposals in 2023 and 2024 (~ 33 h per year), focusing on magnetar bursts, and the “Follow-up Observations of Fast Radio Bursts” 2024 proposal (~ 27 h). These proposals are complementary to my research on SGR 1935+2154 and the Burst Analysis we developed, discussed in Panebianco and CTAO-LST Project (2025, under internal review at the time of writing), and in chapter 6.

As part of my PhD activities, I participated in a three-weeks **nightly observation shift** at LST–1 in February 2023. The shift was a hands-on experience that allowed me to learn how Cherenkov telescopes acquire data, how they are calibrated and elaborated into Cherenkov images. I gained valuable insights into how collaborations manage observations and the impact on γ -ray data quality. A *typical observation night* starts at about 18:00 UTC when the LST–1 is un-parked and the camera freed from its support tower, then brought to its working temperature in about ~ 45 min. LST–1 performs then nightly calibration runs, including: a measurement of the optical PSF of the telescope, evaluated on reference stars; a run with closed camera shutter to measure the electronic noise of the camera: a *pedestal calibration* run on a dark field to measure the NSB and the background telescope rate at the

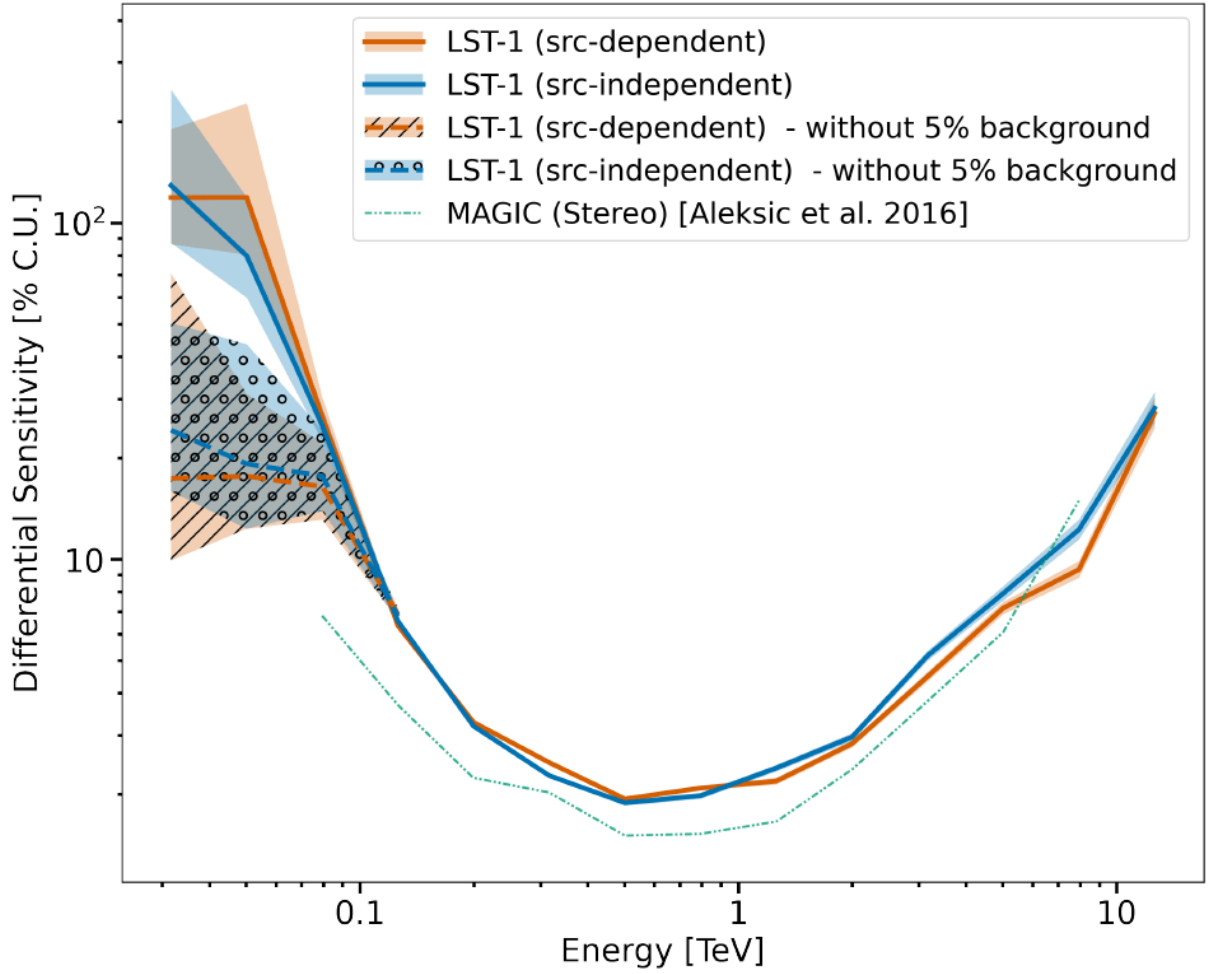


Figure 3.15 – Sensitivity of the LST–1, compared with MAGIC (Aleksic et al. 2016a), in units of Crab Nebula flux. The sensitivity is computed for the source-independent and source-dependent analyses that use different Hillas parameters (see chapter 2.3.2). The sensitivity was computed with and without the additional requirement of achieving a signal-to-background ratio of 5%, which worsen the sensitivity below 100 GeV. MAGIC has a higher sensitivity by a factor 1.5 in average due to using stereoscopic reconstruction (see chapter 2.3). Credit: CTA-LST project et al. (2023).

beginning of the night. After calibrations, operators schedule the nightly observations, that usually include technical tests and scientific observations. The most common configuration for observations is the *wobble-mode* with ~ 20 min runs at 0.4 deg offset (see chapter 2.4). Since April 2023, the RTA system we developed as part of this work is active (see chapter 4), analysing the LST–1 data and reporting it in a *Graphical User Interface* (GUI) that the shifters need to monitor. If the RTA detects a transient, its observations are extended. Weather conditions must be checked in at all times, and operations must be interrupted and the telescope brought in a safe position if bad-weather conditions are reached (such as high humidity, rain or strong winds). The shifters keep track of the observations and technical issues all night, and before dawn they shut down the camera, park and secure the telescope, completing the operations at sunrise³.

³A truly remarkable view from the top of La Palma.

3.3 Array Control And Data Acquisition of the CTAO

Software development is a key component of the CTAO, as it is a *big data* project that will generate a few PB of data in a year to be analysed and stored. There are four main software projects being developed by the CTAO:

- The **Array Control and Data Acquisition** (ACADA) software controls, supervises, and handles the data generated by the telescopes and the auxiliary instruments (such as weather-monitoring instruments).
- The **Data Processing and Preservation System** (DPPS) stores the data and perform next-day processing and long-term processing of the data.
- The **Science User Support System** (SUSS) is dedicated to the creation of the science archive of the CTAO, collecting observations proposals from scientists, and delivering the requested science products once they are available.
- The **Science Operations Support System** (SOSS) interacts with the other systems to coordinate software and hardware operations on-site and off-site.

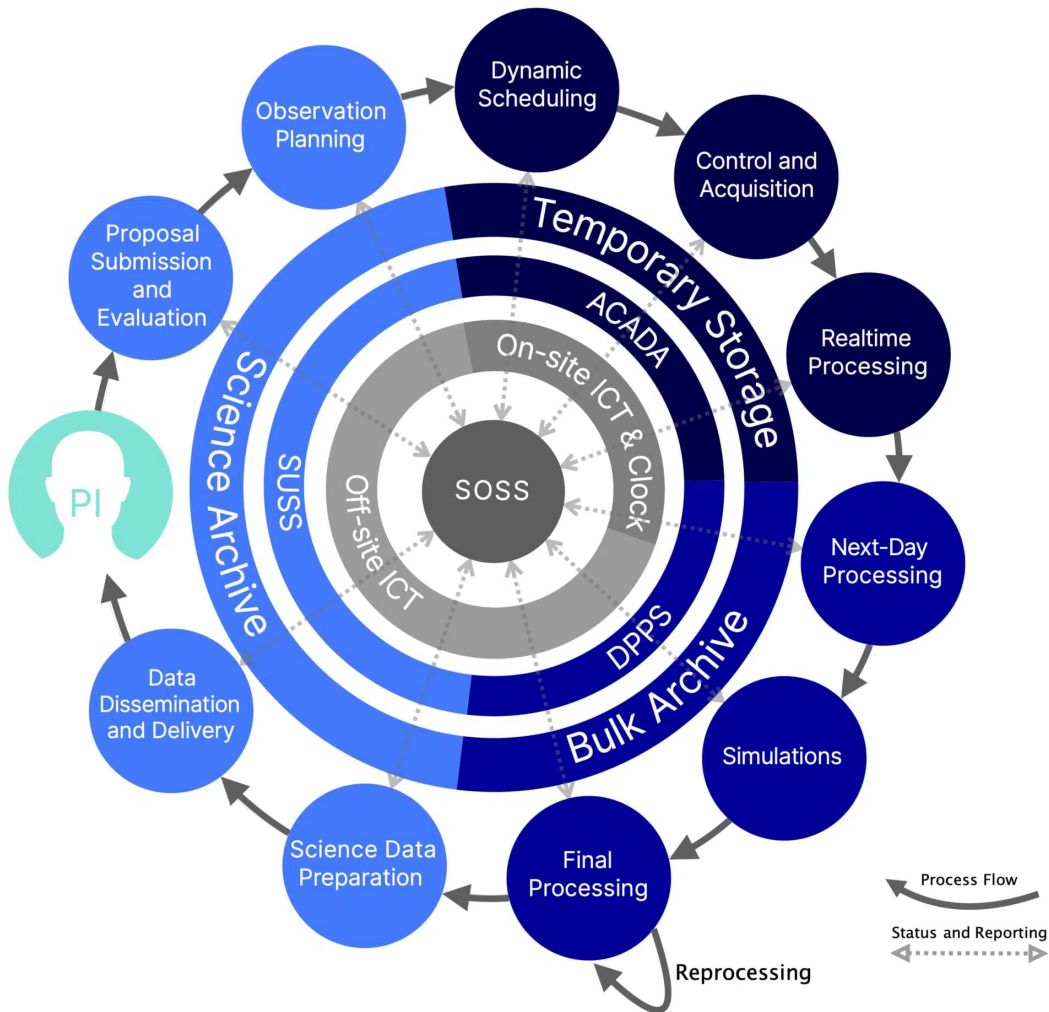


Figure 3.16 – Flow of data through CTAO’s software projects: SOSS, SUSS, ACADA and DPPS. Credit: CTAO at <https://www.ctao.org/emission-to-discovery/data-and-computing/>.

We show a scheme of the data flow through the CTAO software in figure 3.16. SUSS collects the observation proposals and prepare the *long-term schedule*. ACADA executes the schedule and the observations, although it can alter it to perform follow-up observations of transients. The data acquired undergoes the *on-site, on-line* analysis in real-time with the SAG software (see section 3.4). The data is also sent to DPPS, that creates a bulk archive of data, performing two other analyses: a *on-site, off-line* analysis (next-day processing) and a consolidated, final analysis (*off-site, off-line*) that will produce the final results, delivered to SUSS and the scientific community. SOSS coordinates software and hardware operations with the other three systems.

ACADA is responsible for the acquisition of data from the telescopes (Oya et al. 2024). It has to satisfy several requirements to enhance the capabilities of the CTAO. The most relevant to this work are:

- ACADA will be able to operate at least eight independent groups of telescopes (sub-arrays) at the same time. Sub-arrays are dynamically formed from distinct subsets of available telescopes at a given site.
- ACADA will collect data from all CTAO telescope cameras, handling data volumes up to 24 GB s^{-1} for each LST, 12 GB s^{-1} for each MST, 2 GB s^{-1} for each SST.
- ACADA will reduce the data volume of the cameras on the fly, delivering $< 5 \text{ GB s}^{-1}$ to the DPPS at each site while minimising the impact on scientific performance.
- ACADA will acquire data from auxiliary elements such as LIDAR instruments, stellar photometers, all-sky cameras, weather stations, ceilometers, and external light sources for camera calibrations.
- ACADA will handle external and internal Science Alerts with the SAG system, see section 3.4.
- ACADA will be able to revise the observation schedule of the night in case of transients.
- ACADA will be suitable to be operated by two individuals: an operator and a support support astronomer.
- ACADA will be available for 99% of the time in which observations are possible, and will be able to restart within 2 min.

ACADA is composed of 11 subsystems, that we show in figure 3.17. The diagram uses the *Unified Modeling Language* (UML) component notation⁴. The subsystems are represented by pink boxes, while blue squares are *ports* that identify the interfaces of the system, and dashed arrows show the flow of data elements. The subsystems that compose ACADA are:

1. **Resource Manager (RM)**. It supervises the the other subsystems and coordinates the allocation of telescopes to sub-arrays (Melkumyan et al. 2024).
2. **Central Control (CC)**. It executes the observations provided by the short-term scheduler and supervises ongoing operations (Melkumyan et al. 2024).
3. **Human-Machine Interface (HMI)**. It offers a view a comprehensive view of the status of the observations to the operators, providing means to supervise and interact with the array elements.
4. **Array Data Handler (ADH)**. It handles the stream of data from the telescopes and auxiliary instruments into ACADA, also performing data volume reduction. It provides the input DL0 data to SAG.

⁴<https://www.omg.org/spec/UML/2.5.1/PDF>

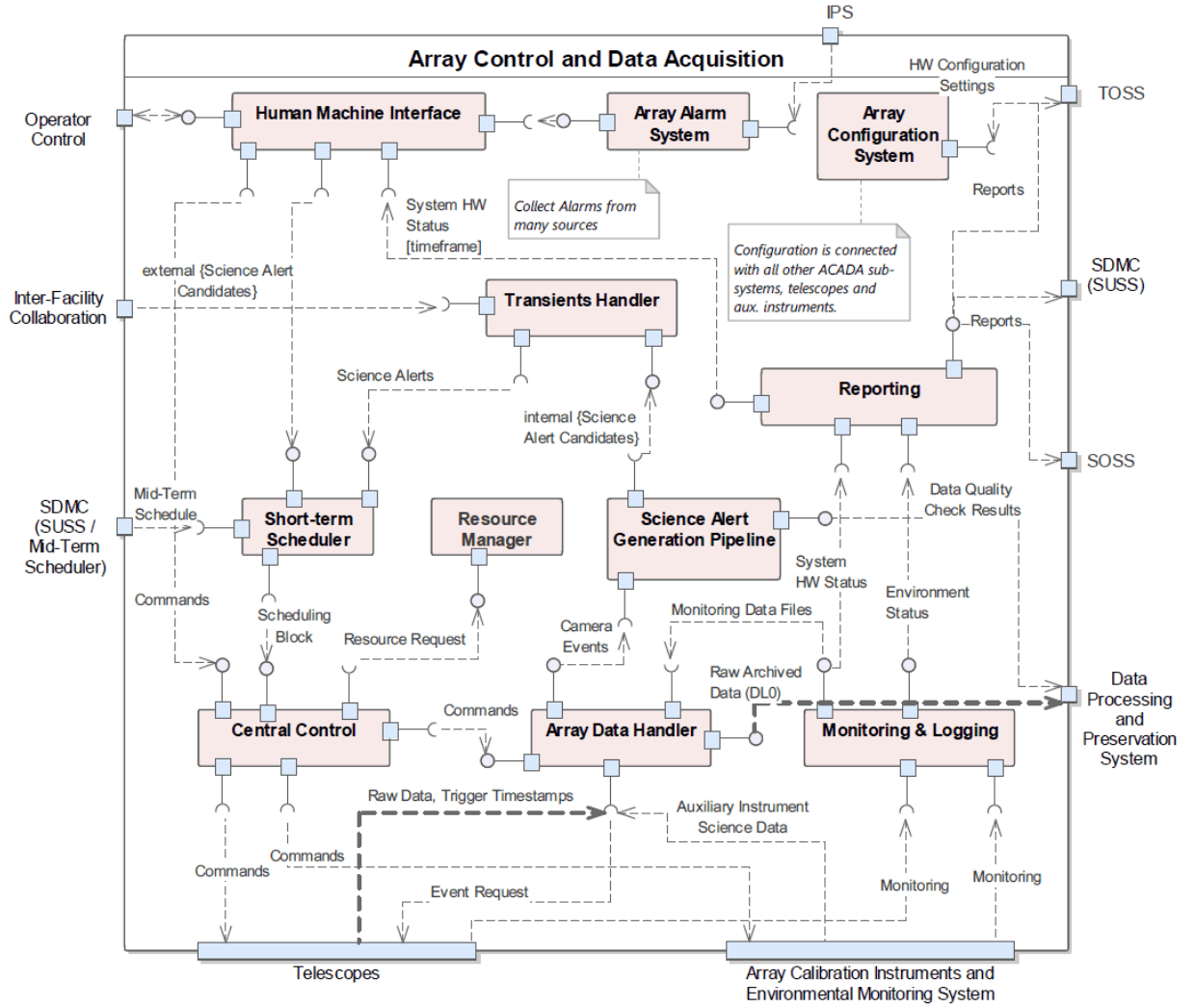


Figure 3.17 – Logical view of ACADA, representing and its main components. Pink boxes are software components, while blue squares are *ports* that identify the interfaces of the system. The dashed arrows show the flow of data elements. Credit: Oya et al. (2024).

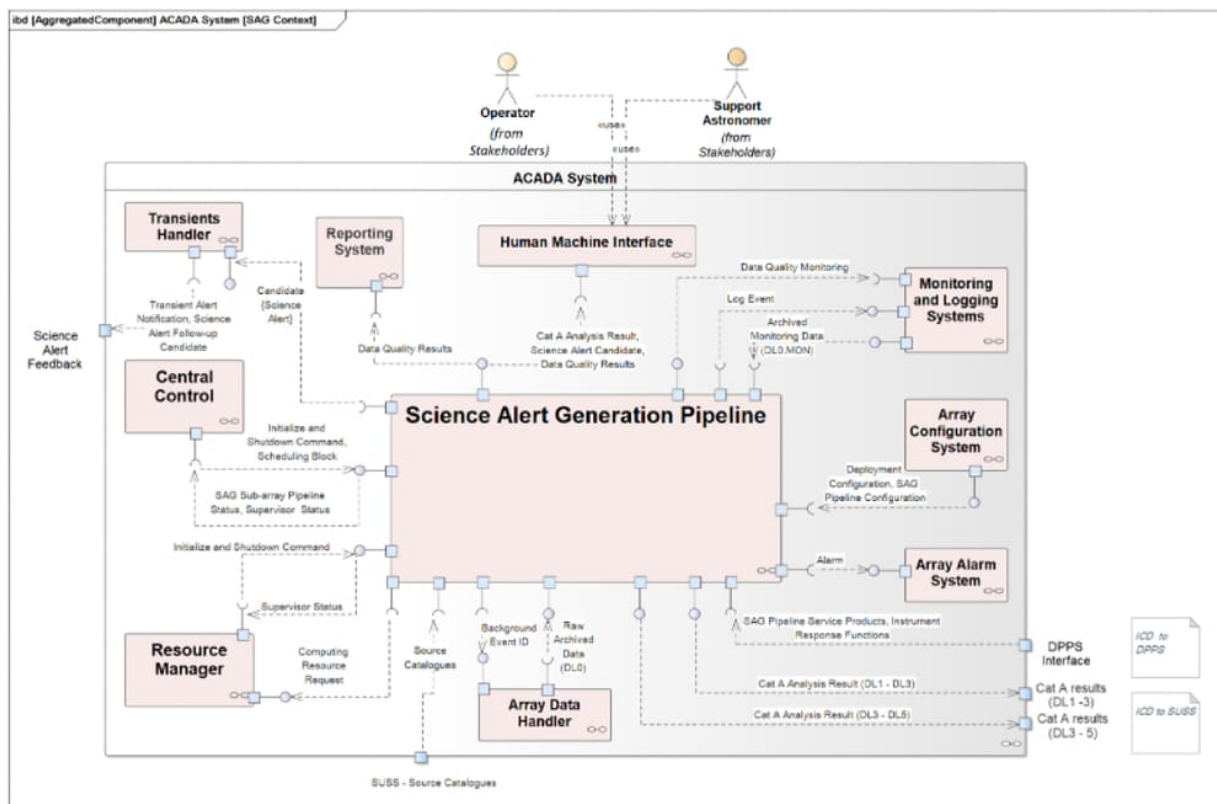
5. **Short-Term Scheduler (STS)**. It decides in real-time how to group and use the telescopes to perform nightly observations, based on a mid-term schedule supplied to it at the beginning of the night. It reacts to changes in environmental conditions and Science Alert observation requested by the Transient Handler by changing the schedule.
6. **Transient Handler (TH)**. It is responsible for managing *internal* and *external* transient Science Alert candidates by filtering, processing, and ranking them, and requesting immediate reaction to the STS if needed (Steppa et al. 2024).
7. **Science Alert Generation Pipeline (SAG)**. It performs quick-look analysis of the acquired data with the purpose of performing science monitoring and generating internal candidates Science Alerts, that are submitted to the TH for a final evaluation. Quick-look analyses include the *Reconstruction* of Cherenkov data, *Data Quality* checks on the reconstructed data, high-level *Scientific* analysis of the reconstructed data. We discuss SAG in section 3.4.
8. **Monitoring and Logging Systems (MON)**. They provide logging services for all ACADA, and elaborate the environmental data, delivering them to HMI and SAG for quality checks (Costa et al. 2024).
9. **Array Alarm System (AAS)**. It identifies alarms based on the logs acquired by MON (Costa et al. 2024).
10. **Array Configuration System**, or *ACADA Configuration Database (CDB)*. It stores deployment configuration and the setting of the instrumentation and the pipelines.
11. **Reporting System (REP)**. It gathers relevant data from other sub-systems and produce quality reports for the HMI and CTAO systems outside ACADA, e.g. SOSS.

The subsystems of ACADA have been integrated and tested together (Lopez et al. 2024; Conforti et al. 2024). The first release of the ACADA software, ACADA REL1, was finalised in July 2023, and integrated after a testing campaign with the LST–1 finalised in October 2023. The testing campaign was successful and lead to the detection of the Crab Nebula using SAG (ACADA and CTAO-LST Project 2023).

3.4 The Science Alert Generation system of the CTAO

The **Science Alert Generation (SAG)** pipeline (Bulgarelli et al. 2024) is a key system of the CTAO and ACADA, that employs RTA pipelines with the goal of performing science monitoring on observation targets and generating candidate Science Alerts that will be sent to the ACADA TH, that will accept or refuse the candidate Science Alert. SAG will allow CTAO to become a powerful instrument for Time-Domain astrophysics and enable Multi-Wavelength and Multi-Messenger approaches that will lead to a deeper understanding of the broad-band non-thermal properties of target sources.

Figure 3.18 shows the logical view of SAG within ACADA and its main interfaces with other sub-systems. The ADH sends DL0 data (see chapter 2.3.1) to SAG for the real-time reconstruction and analysis. The RM allocates SAG resources, the CC provides information to SAG on the setting of the ongoing observations, and the CDB provides the deployment configuration that must be used. The MON and AAS systems send information on the environmental conditions and alarms to SAG, and receive its logging and the alarms it raises. After its analyses, SAG sends the TH the candidate Science Alerts it detected. SAG sends its reports to the REP and its results to the HMI. Being part of ACADA, the SAG interfaces also



The main SAG requirements relevant to this work can be summarised as follows:

shall work with different versions of the Instrument Response Functions (IRFs).

- **Parallel processing.** SAG shall execute parallel analyses for multiple sub-arrays observing simultaneously. All SAG sub-array pipelines shall run in parallel.
- **Analysis priority.** SAG will prioritise the analysis of urgent scientific targets.
- **Sensitivity.** SAG shall have a point-source integral sensitivity on a 0.5 h time scale within a factor two of that required for the full system with fully calibrated data off-line.

We describe below the functional diagram of SAG, shown in figure 3.19, and the data flow during observations across its four sub-systems:

1. **SAG-Reconstruction (RECO).** It is the low-level analysis pipeline, dedicated to the *Reconstruction* of Cherenkov data, from DL0 to DL3, according to the steps described in chapter 2.3.
2. **SAG-Data-Quality (DQ).** Pipeline dedicated to performing online *Data Quality* checks on the data produced by SAG-RECO, to assess the status of the instruments during data acquisition.
3. **SAG-Science (SCI).** It is the high-level analysis pipeline, dedicated to performing the *Scientific* analysis of γ -ray data, from DL3 to DL5, following the methods described in chapter 2.4.
4. **SAG-Supervisor (SUP).** Pipeline dedicated to the *Supervision* of the other three components, and the integration with the rest of ACADA systems.

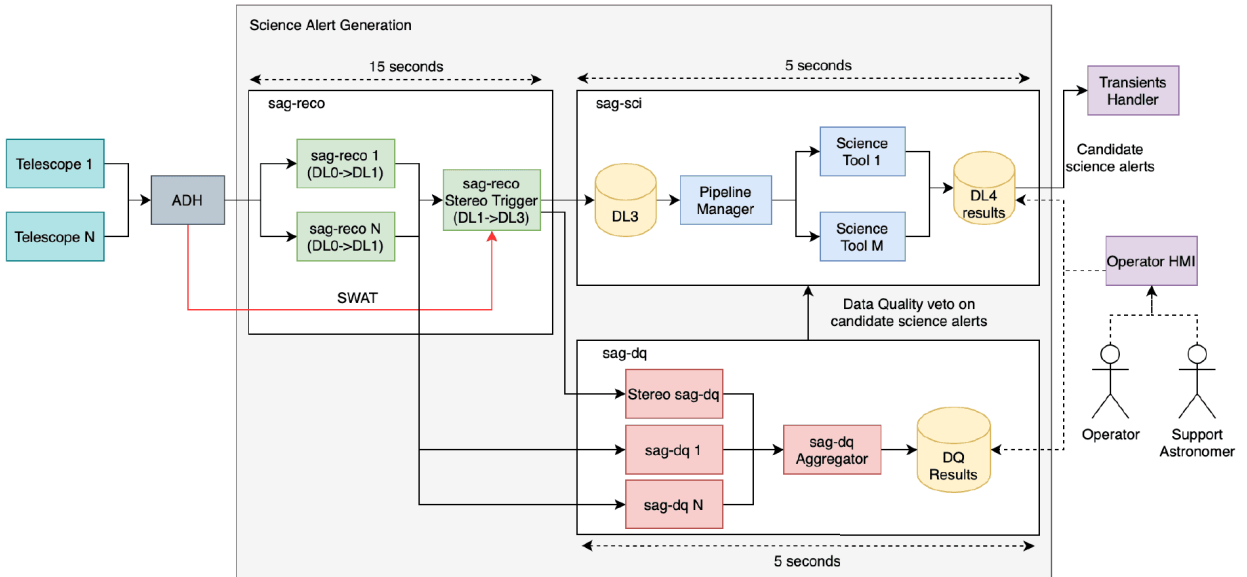


Figure 3.19 – Data flow between SAG subsystems. Credit: Bulgarelli et al. (2024).

SAG-RECO. The ADH acquires DL0 data streams from the telescopes, that SAG-RECO receives as a *stream* of events. SAG-RECO groups the data in *batches* of 10 000 shower events, a file size that can optimise the speed of the reconstruction process, and assign the batch to one of 4 parallel pipelines, that perform the same operations. Parallelisation of the low-level analysis is possible due to the fact that the reconstruction of a shower event is statistically independent from the others. SAG-RECO performs the traditional steps of Cherenkov reconstruction on every event (see section 2.3): it creates charge and time images from DL0 waveforms, performs image cleaning, and compute the Hillas parameters to get DL1 data.

SAG-RECO uses dedicated Random Forests (RFs, see section 2.3) to reconstruct the DL2 data, and applies γ /hadron separation cuts to obtain the DL3 files. The RFs used are trained offline, for different bands of zenith angle and NSB levels, and only the RF closest to the observing conditions is used in real-time. The γ /hadron separation cuts are also optimised off-line. The off-line simulations and optimisation allow the creation of a pre-defined set of IRFs, that will be used in the high-level analysis. **SAG-RECO** is based on the HiPeRTA software (Caroff et al. 2023; Aubert et al. 2024) library for the DL1 production and on `lstchain` (López-Coto et al. 2021) for the DL1 to DL3 steps. **SAG-RECO** currently does not support stereoscopic reconstruction and it uses only one model of RFs optimised for observations at a 20 deg zenith angle. Future versions will include the stereo reconstruction and multiple RFs.

SAG-DQ. The results of **SAG-RECO** (DL1, DL2, DL3) are input for **SAG-DQ**, that is developed using the `rta-dq-lib` library in `python` and `C++` (Baroncelli et al. 2022). The DL1 data quality checks can be performed both on single-telescope data and on array data (after the stereo trigger), and entail computing the distribution of some relevant image parameters and comparing it with the expected results.

Currently, no DL2 and DL3 checks are implemented, but we developed a strategy to implement them as a part of my work. We studied and defined a useful set of DL2 DQ checks on reconstructed event properties, that we applied on a dataset of LST–1 observations on SGR 1935+2154 to characterise the background of the observations. We present our checks in chapter 6.7, that will be included in a future version of **SAG-DQ**. DL3 DQ checks are in part superimposed with **SAG-SCI** analyses. The most useful check that can be done at this level is the θ^2 plot described in section 2.4.3. Currently, θ^2 plots are implemented as part of **SAG-SCI**, but they might be moved to **SAG-DQ** in a future version of the software.

The data quality results of all **SAG-DQ** pipelines are aggregated and stored in a database. These results also verify if the data quality level meets the requirements to generate a candidate science alert: to give an example, candidate Science Alerts cannot be generated if instrumental issues such as humidity patches are found on the camera. The operator and the support astronomer can visualise the results of both the **SAG-DQ** and **SAG-SCI** pipelines using the HMI, but this feature is not available yet. Future releases of **SAG-DQ** will include the checks on DL2, DL3, and the interface with the HMI and MON systems.

SAG-SCI. **SAG-SCI** receives DL3 data from the parallel lines of **SAG-RECO**. It merges the data, as the statistical methods of the high-level analysis require aggregated data (see chapter 2.4). It produces high-level products such as DL4 data cubes, estimation of the DL5 flux, SED and light curve of a source, estimation of the Li&Ma significance, generation of candidate Science Alerts. The development of **SAG-SCI** is one of the key results of this work, and it is described in detail in chapter 4. We test **SAG-SCI** on simulated data in chapter 5.

SAG-SUP. This component manages the execution of the other three. It is the main interface with the rest of ACADA, being notified of any status change of the system, and delivering the final results to the HMI and REP. **SAG-SUP** uses the *Alma Common Software* (ACS, Chiozzi et al. 2002) as a basic middleware. ACS is a framework for distributed systems that supports the development and integration of software *components* and facilitates the operation of ACADA in the on-site data centre. **SAG-SUP** instantiate an ACS component for every sub-array, and runs the *Sub-Array Supervisor* inside it. This component retrieves

all necessary information from ACADA to perform the analyses, instantiate the *SAG Pipe* components that execute the three analysis pipelines (**SAG-RECO**, **SAG-DQ** and **SAG-SCI**), and monitors their execution to collect operational data, such as processing rates.

Chapter 4

SAG-SCI: A Real-Time, High-Level Analysis Software for the CTAO

In chapter 3, we described the CTAO, the next-generation observatory for VHE γ -ray astrophysics (Cherenkov Telescope Array Consortium et al. 2019; Zanin et al. 2022; McMuldroch et al. 2024), and the SAG pipeline (Bulgarelli et al. 2024), its RTA software that has the goal to perform science monitoring of the observed sources and generate candidate Science Alerts. SAG is a key software in the development of the CTAO, that will allow it to become a crucial observatory in the context of Time-domain, Multi-wavelength and Multi-messenger astrophysics. The SAG pipeline dedicated to the High-Level analysis of reconstructed γ -ray data is called **SAG-Science** (**SAG-SCI**). It will perform the statistical analyses described in chapter 2.4, such as the evaluation of the Li&Ma statistical significance (section 2.4.1) and the γ -like background (section 2.4.2), the computation of θ^2 plots (section 2.4.3) and the MLE of the flux of a target source (section 2.4.4). **SAG-SCI** is based on the RTAPipe Framework (Parmiggiani et al. 2022), previously employed for the RTA pipelines of the AGILE satellite (Parmiggiani et al. 2023).

The development of **SAG-SCI**, as well as the other SAG subsystems, is a multi-year project that started before I begun my PhD research, and that will continue after I finish it. The SAG team developed a prototype version of **SAG-SCI**, with limited functionalities, in 2021 before the start of my PhD research (Tampieri 2020; Di Piano et al. 2022). One of the main results of my thesis and PhD research is the development of **SAG-SCI** from a prototype to a fully-integrated software that can be used in ACADA and respects the CTAO requirements. We summarise the the functionalities of the prototype, the current functionalities of **SAG-SCI** and my contribution to the development in section 4.3. Our development allowed us to provide a *first* release of the **SAG-SCI** software in July 2023 as part of ACADA REL1 (Di Piano et al. 2023). The software was tested on the LST-1 in October 2023 and lead to the detection of the Crab Nebula using **SAG-SCI** (ACADA and CTAO-LST Project 2023). After the test, we further developed **SAG-SCI** to the version described in this work. We released it in September 2024 as part of ACADA REL1.5, that will be tested again on the LST-1 in October 2024. The next release planned is for ACADA REL2 in 2025. We also deployed a stand-alone version of **SAG-SCI**, called RTA-SCI, to the LST Collaboration in April 2023. RTA-SCI analyses the LST-1 data every observation night and reports the results in a GUI monitored by the shifters.

In this chapter, we describe **SAG-SCI** in detail. Section 4.2 describes the RTAPipe frame-

work used to develop **SAG-SCI**. In section 4.3, we present an overview of the components, requirements and execution of **SAG-SCI**, while the following sections are dedicated to the description of each component. Section 4.4 describes the **MySQL Database** (DB) used to store information on the status of the pipeline. In particular, section 4.5 describes the strategy I developed during my PhD research to manage the database. In section 4.6, we describe the *Pipeline Manager* component that receives input DL3 data and schedules the analyses; part of my work was updating it with a re-factorisation in classes. In section 4.7, we describe the *Science Tool Wrappers* dedicated to performing scientific analyses. A key result of my work was the development of the **Gammapy wrapper**, described in section 4.7.3. **Gammapy** (Donath et al. 2023; Acero et al. 2022) is a community-developed, open-source Python package for gamma-ray astronomy built on **numpy**, **scipy** and **astropy** (Harris et al. 2020; Virtanen et al. 2020; Astropy Collaboration et al. 2022). It is the core library adopted for the CTAO Science Analysis Tools (CTAO 2021) and can also be used to analyse data from existing IACTs. **SAG-SCI** must satisfy several software development standard requirements, such as having dedicated *Test Suites* that assess its correct behaviour. In section 4.8, we describe the test suites we developed for **SAG-SCI**. A notable result of my work was the development of new **SAG-SCI** tests that increased the *code coverage* from 30% to 60%, complying with the ACADA REL1 code quality requirement of 50%. Finally, section 4.9 describes the integration strategy with higher level software, such as **SAG-SUP** (see section 3.4).

4.1 Software Requirements

SAG-SCI is the sub-module of **SAG** dedicated to the *High-Level* analysis of CTAO data (DL3 to DL5), with the goals of **performing science monitoring** and **generating candidate science alerts**. **SAG-SCI** will analyse every scientific observation run of the CTAO. All software provided to CTAO must satisfy strict requirements which aim to ensure the quality of the product and of the scientific results (Bulgarelli and Caroff 2023). Software requirements are also used as goals to develop the software. The requirements of **SAG-SCI** relevant to this work are:

1. **Main purposes.** **SAG-SCI** shall provide results with two purposes: science monitoring (detection and analysis of signals from astrophysical sources) and generation of candidate science alerts.
2. **Latency.** **SAG-SCI** shall be capable of identifying candidates Science Alerts with a total latency, from a configurable flux threshold being surpassed at source, of less than 5 s since data becomes available to **SAG-SCI**.
3. **Scientific Results.** **SAG-SCI** shall provide high-level analysis for Science Monitoring, to produce science quick look results (DL4 and DL5 data levels) and Science Alert candidates.
 - (a) Quick look results include flux, position, significance, light curves of astrophysical sources and sky maps.
 - (b) **SAG-SCI** shall conduct full-FoV searches to detect known and unknown sources.
 - (c) **SAG-SCI** shall provide to the ACADA HMI, SUSS and TH the results of RTA during the observation of a candidate Science Alert or follow-up of a Science Alert. Results include proposal ID, significance, flux, best fit peak position, exposure, observation time interval. The selection of candidate Science Alerts shall be based on configurable detection thresholds and conditions.

4. **Analysis flexibility.** SAG-SCI pipeline shall allow the integration of different scientific analysis methods, tools and time scales. SAG-SCI shall search for transient and/or time variable phenomena on timescales from 10 s to 180 min.
5. **Prioritisation.** SAG-SCI will perform different scientific analyses with configurable priorities. SAG-SCI pipeline shall manage the priority between different processes, executing first the high-priority tasks and suspending low priority task if all resources are busy. The search for a candidate Science Alert shall have the highest priority for the follow-up of some classes of external science alerts (e.g. gravitational waves, gamma-ray bursts or neutrino alerts).
6. **Parallel processing.** SAG-SCI will perform different scientific analyses in parallel. Analysis at different timescales must be performed in parallel.
7. **Candidate Science Alerts Quality.** It shall be possible to mark candidate Science Alerts or prevent their generation if data quality warning or alarms are present. SAG-SCI shall support optional human intervention prior to issuing a candidate Science Alert. SAG-SCI shall request Support Astronomer via the HMI confirmation to verify marginal or sub-threshold detection of important scientific targets.
8. **Software integration requirements.** SAG-SCI shall be able to work both as a stand-alone software, and as an integrated module of ACADA-SAG.

These software requirements lead the software design and architecture choices, and we chose to adopt RTApipe as a software framework for SAG-SCI as it can satisfy them, see section 4.2.

4.2 The RTApipe Framework

RTApipe (Parmiggiani et al. 2022) is a software framework designed to simplify the development of real-time analysis pipelines that have to achieve two main *Use Cases* (UCs):

1. Performing periodical scientific analyses, searching for transient events, and promptly generating Science Alerts to share the information with the community.
2. Reacting to external Science Alerts and executing scientific analyses on available data, or waiting for the data if not available yet.

RTApipe is a flexible framework capable to adapt to several scientific projects based on different programming languages and tools:

- The framework can be used in different missions, experiments and observatories, both space-based and ground-based, with a single telescope or an array of telescopes.
- It can analyse in parallel data acquired by multiple arrays of telescopes.
- It can be configured to perform different types of analyses, with different science tools, time scales (from seconds to hours) and priorities.
- It can perform analyses on both new data as they arrive and on data already present in the archive.
- It can manage queues and priorities to optimise the available computing resources, and it is scalable on machines with different computing resources.

We show the software architecture of the RTApipe framework in figure 4.1. It is composed of four logical components. The first one is the **Data Model**, that defines the data structure

of the framework, its entities and their relationships. The second one is the **Science Logic**, that implements the rules to execute the analyses described by the Data Model and satisfy the software requirements and the use cases. The third one is the **Pipeline Manager**, that handles the execution of the analyses as processes through a dedicated **Task Manager** (the fourth component). In order to be implemented in a specific project, the RTApipe framework must be integrated using interfaces with additional components, such as the **Data Sources**, i.e. the input data generated by the instruments (e.g. γ -ray data, logs, auxiliaries) or external science alerts. A dedicated software component must store them and notify RTApipe of their arrival, which triggers the execution of the Science Logic rules. Other external components are the **Science Tools**, i.e. the libraries and packages used to perform the analyses, and called by *Wrapper* scripts executed by the Task Manager. Finally, the **Analysis Results** are produced by the Science Tools and saved in a storage system.

The steps performed by the RTApipe framework shown in figure 4.1 can be summed up as it follows:

1. A Data Source software component notifies RTApipe of the arrival of new data
2. Alternatively, a Data Source notifies RTApipe of the arrival of science alerts.
3. The Science Logic rules prepare the new analyses to be executed.
4. The Pipeline Manager periodically queries the Data Model to check if new analyses are ready to be processed, and when a new analysis is available, the Pipeline Manager submits it to the Task Manager.
5. The Task Manager executes the wrappers that interface the required science tools on the available computing resources.
6. The Wrappers use the Science Tools to execute the analysis.
7. The Wrappers read data from the Data source storage, and perform the analysis.
8. The Wrappers save the results in a chosen storage system.

Examples of implementation of the framework are the RTA system of the AGILE mission (Parmiggiani et al. 2023), the SAG-SCI for CTAO (Bulgarelli et al. 2024), the *High-level Real-Time Analysis* software for LST-1 (RTA-SCI).

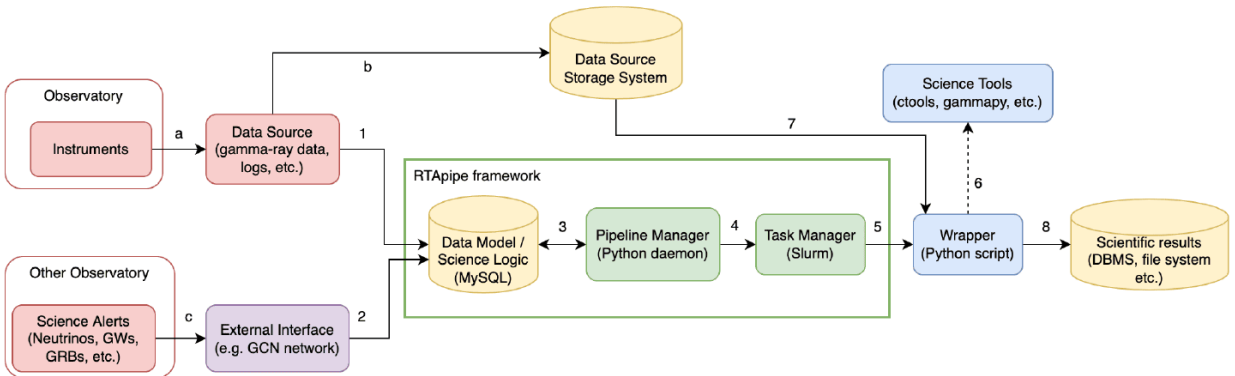


Figure 4.1 – Software Architecture of the RTApipe framework. The schema shows the internal components and the external entities interfaced with the framework. The lines indicate the data flow. The numbers show actions managed by the framework, and the letters show external actions. The dashed line represents the software dependency between the wrappers and the science tools. Credit: Parmiggiani et al. (2022).

When the RTApipe framework is implemented into a specific pipeline, it shows extreme versatility, allowing to (Parmiggiani et al. 2022):

- Execute analyses on compatible data types.
- Perform analyses integrating data for the entire duration of an observation, or in smaller time windows.
- Configure variable analysis time windows starting every new analysis at the end of the previous one.
- Set analyses with fixed time windows, or a large time window divided in time bins.
- Start analyses only when a Science Alert from a specific instrument is received.
- Configure analyses with partial data coverage, that can be interrupted when the entire data arrive and can be replaced by analyses with full data coverage.
- Define analyses with different priority. High-priority analyses can suspend low-priority analyses.
- Enable or disable analyses using a boolean flag.

For these reasons, we chose to adopt RTApipe as the software framework of SAG-SCI.

4.3 SAG-SCI: an Overview

We present here a general overview of the SAG-SCI software, and we use the next sections to present more detailed descriptions of each component. Within the CTAO and ACADA context, an observation run is called **Observing Block** (OB) and defined as an uninterrupted observation of a scientific target with a fixed pointing direction of the telescopes. The CTAO also defines a **Scheduling Block** (SB) as a set of OBs with the same science target. For example, a SB can include 4 *wobble-mode* (see chapter 2.4.2) OBs with different pointing directions that alternate around the same astrophysical source of interest.

4.3.1 Software Dependencies

SAG-SCI is developed as a `python` package with a `MySQL`¹ interface. `MySQL` is a *Relational Database Management System*; a relational database is a set of interconnected tables whose columns can reference entries of other tables. For example, a table “analysis” may be a list of analyses executed by the pipeline, and one of their columns may be the ID of an OB, referencing a pre-existing row of an “Observing Block” table listing all OBs executed and their properties. The definition of the tables and their relationships, without any specific data inserted into them, is commonly known as a *schema*. A useful feature of `MySQL` is the possibility of defining *triggers*, stored procedures automatically executed by the database *before* or *after* a specific event, that can be the *insertion* or *update* or *deletion* of a row in a table. Other relevant features used in SAG-SCI are the `MySQL views`, dynamical selections of the data of a table according to a pre-defined set of filters, capable to show real-time variations of a table. `MySQL` entries of a table are always identified by a unique *primary key*, but multiple secondary *keys* (a set of columns) can be used to identify entries. `MySQL` can also define *constraints* on the columns, ensuring that the values in a column satisfies a specific condition and that they can be modified only under specific conditions, respecting relationships with other tables.

¹<https://www.mysql.com>

SAG-SCI is an implementation of the RTApipe framework. RTApipe can work with multiple Task Managers; for SAG-SCI we adopted the **Simple Linux Utility for Resource Management**, or **slurm** Workload Manager² (Yoo et al. 2003). SAG-SCI components (described in section 4.3.2) request the execution of scientific analyses, but **slurm** is responsible for allocating computing resources, scheduling and performing their execution. The execution of a script with **slurm** is commonly referred to as a **job**. Jobs can be organised in multiple queues, have different priorities, and require a different amount of resources. **slurm** optimises their execution, and can even temporarily suspend low-priority jobs to execute high-priority jobs (e.g., the follow-up of an external Science Alert). We adopted **slurm** for SAG-SCI as it is an open-source, fault-tolerant, highly-scalable job scheduling system for large and small Linux clusters. It can manage thousands of jobs and can easily scale from one to hundreds of servers by modifying a few lines in its configuration. If **slurm** is configured in a cluster of multiple nodes, it can also manage their failure, keeping the pipeline always operational.

We developed SAG-SCI as a **python** package that must be installed and executed in a dedicated **conda** environment (Anaconda Inc. 2020), that can be built with a configuration file we provide. The environment is similar to the one available for **gammapy** (Donath et al. 2023; Acero et al. 2022), with the addition of specific packages: **mysql-connector-python** to use **MySQL** from inside a **python** script; **watchdog** to detect when a DL3 file is written on the file system; **lxml** to read and write XML files; **pytest** and **coverage** for testing purposes. In the context of ACADA, a dedicated *Software Development Environment* (SDE) is available, composed by **docker** containers (Merkel 2014) with **MySQL** and **conda**.

4.3.2 Software Architecture

We show the software architecture of SAG-SCI in figure 4.2. SAG-SCI is developed by implementing the RTApipe framework into three main components:

1. The **Pipeline Manager** (see section 4.6): a set of 5 daemons that manage the operations of the pipeline. A *daemon* is a computer program that runs as a background process and is not under the direct control of an interactive user. SAG-SCI daemons receive input files, insert their information into the database, query the database to assess the status of the ongoing pipelines, execute scientific analyses. They can be classified in:
 - 2 OB-specific daemons (**DL3Merger**, **DataFlowManager**) that act as SAG-SCI's main Data Source by receiving, reading and storing the DL3 files of an OB.
 - 3 SB-specific daemons (**SubmitJob**, **UpdateJobStatus**, **CancelJob**) that implement the Pipeline Manager component of the RTApipe framework by executing analyses through the chosen Task Manager, **slurm**.
2. The **Database**: a set of 4 **MySQL** database schema and 13 **MySQL** triggers that store information on the data received, the analysis performed, the pipeline current status and the scientific results obtained. It implements the Data Model and Science Logic components of RTApipe. We describe the Database in section 4.4.
3. The **Science Tool Wrappers**: a set of scripts and classes that perform scientific analyses using different Science Tools. We implemented 2 wrappers:

²<https://slurm.schedmd.com/>

- (a) The **Real-Time Aperture Photometry** (RTAPH) wrapper (Di Piano et al. 2022), a `python` tool that performs Aperture Photometry on a scientific target. We describe it in section 4.7.2.
- (b) The **Gammapy** wrapper, based on the `gammapy` python package (Donath et al. 2023; Acero et al. 2022), adopted by CTAO as the science analysis tool for the observatory (CTAO 2021). We describe it in section 4.7.3.

The `sagsci` package has a modular structure, and we developed each of the components defined above in a dedicated module (e.g., `sagsci.wrappers.gammapy` for the `gammapy` wrapper). Other modules include the scripts and classes that SAG-SUP uses to configure and execute SAG-SCI (`sagsci.entrypoints`, see section 4.9), the module `sagsci.gammapipecommon` with functions and classes common to the wrappers, and utilities in `sagsci.tools`.

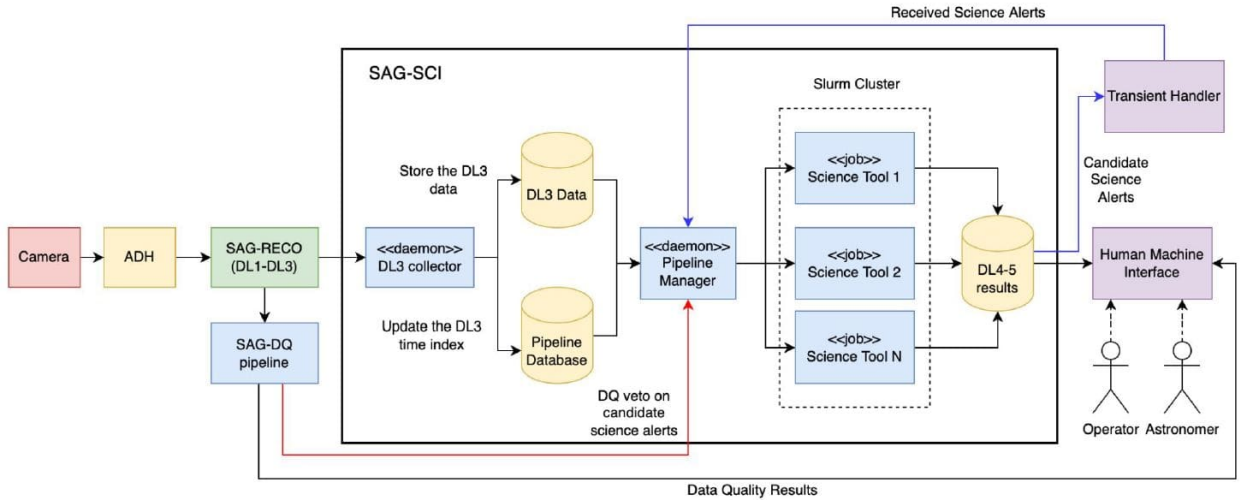


Figure 4.2 – Software Architecture of the SAG-SCI. The schema shows the internal components and the ACADA components interfaced with the pipeline. The interaction with SAG-SUP is not reported here. The lines indicate the data flow. Credit: N. Parmiggiani (e.g., Parmiggiani et al. 2022).

In figure 4.2 we show the steps performed by the SAG-SCI pipeline, that implements those of the RTApipe framework described in section 4.2:

1. SAG-SUP inserts information on a new OB and its Scientific Target in the Database. SAG-RECO writes DL3 files of the OB in a dedicated directory. The `DL3Merger` and the `DataFlowManager` daemons of the SAG-SCI Pipeline Manager insert the DL3 information and the events in the SAG-SCI Database.
2. Alternatively, a Science Alert is received and SAG-SCI waits to receive the data covering the alert.
3. The insertion of new data in the SAG-SCI Database triggers the creation of new analysis jobs according to the logic of the SAG-SCI DB Triggers. A single analysis job covers a specific time window of the OB.
4. The `SubmitJob` daemon of the SAG-SCI Pipeline Manager periodically queries the Data Model to check if new analyses are ready to be processed.
5. When a new analysis is available, the `SubmitJob` submits it to `slurm` as a job, and the `UpdateJobStatus` registers the submission. The `CancelJobStatus` may pause or cancel jobs if analyses with higher priorities have to be executed.

6. `slurm` runs the requested Science Tool Wrapper on the available computing resources.
7. The wrapper execute the analysis.
8. The wrapper saves the results in the file system and in the **SAG-SCI** Database.

We note that the Task Manager `slurm` is used to execute analysis jobs with the wrappers. `slurm` allows to automatically allocate computing resources and perform analyses in parallel, but introduces a small delay in the execution process. We discuss the performance of **SAG-SCI** and possible alternatives to `slurm` and the SB daemons in chapter 5.8.

SAG-SCI development as part of my PhD research. The SAG Team developed a *prototype* version of **SAG-SCI**, with limited functionalities, in 2021 before the start of my PhD research (Tampieri 2020; Di Piano et al. 2022). One of the main results of PhD research is the development of **SAG-SCI** from a prototype to a fully-integrated software that satisfy the CTAO requirements for ACADA REL1 and ACADA REL1.5. I contributed to the development of all **SAG-SCI** components in a major way. The prototype lacked the `DatabaseManager` component, that I developed as an efficient tool to handle multiple versions of the Database (we discuss it in section 4.5). The prototype had Pipeline Manager daemons designed in a *function-oriented* way. Part of my research work was to convert them into an *object-oriented* design, to comply with the CTAO development standards. Having object-oriented daemons that use methods to execute their tasks makes it easier to develop effective tests (see section 4.8 for a description of our test strategies). The prototype used the `RTAPH` wrapper and a `ctools` wrapper (Knödlseider et al. 2016). It lacked the `gammapy` wrapper, that I developed as part of my PhD research after the CTAO adopted `gammapy` as its core library (CTAO 2021). The `ctools` wrapper is deprecated and not included in the current version of **SAG-SCI**. The prototype did not have strategies for the generation of candidate Science Alerts, that we present in section 4.7.1 for the first time. I also contributed to developing tests so that the code quality complies with the CTAO requirements (see section 4.8). Finally, the prototype worked as a stand-alone software, so I worked with the SAG Team at developing and implementing strategies to integrate it with the other components of SAG and ACADA (see section 4.9). As a consequence of this development work, ACADA was able to formally accept **SAG-SCI** for its v1 and v1.5 releases, and **SAG-SCI** could detect the Crab Nebula during the October 2023 test campaign (Di Piano et al. 2023; ACADA and CTAO-LST Project 2023).

4.4 The SAG-SCI Database

The `sagsci.database` module provides the implementation and usage of the MySQL **SAG-SCI** database, i.e. a set of schema and triggers that store information on the data received, the available analysis types, the pipeline status and the scientific results. The **SAG-SCI** database is composed of 4 MySQL databases:

1. The **Pipe Manager** Database: it contains information on the active pipelines, each of them managed by one *Pipeline* DB.
2. The **Pipeline** Database: it contains information on the current pipeline, e.g. the active science tools, active analysis types, the scheduled observations and the analyses performed.

3. The **Events** Database: it contains information on the active reconstruction lines, the files and the events received.
4. The **Results** Database: it contains information on the results of the analyses.

Our databases are composed of three logical components: the schema, the triggers and the specific data content of a DB, that we also refer to as a **population**. All database populations must comply to the same schema and triggers. The `sagsci.database` module manages these components with the `DatabaseManager` (see section 4.5) and the `ConfigureDB` (see section 4.5.1) utilities.

4.4.1 Pipe Manager Database

The **Pipe Manager Database** contains information on the active SAG-SCI pipelines, each of them managed by one *Pipeline* database. The Pipe Manager contains a single `pipe_list` table, where each row represents a SAG-SCI pipeline, identifiable by the name and connection parameters of its Pipeline DB. It is used by the SAG-SCI SB daemons to query all the available pipelines and optimise the resource management and distribution. Currently, SAG-SCI adopts a single Pipeline DB. In the future, when CTAO will have multiple arrays working in parallel, multiple Pipeline DBs may be employed to reduce the amount of data contained in each of them and improve the speed of queries.

4.4.2 Events Database

The **Events Database** contains information on the input DL3 data provided by SAG-RECO.

SAG-RECO (Caroff et al. 2023) uses parallel computation to reconstruct event properties from DL0 to DL3 level. SAG-RECO receives DL0 shower events from the ADH, assigns each event to one of 4 parallel lines and processes the event into DL1 format, then stores it in a buffer until the line reaches 10 000 events. SAG-RECO then groups the 10 000 events in a batch DL1 file that represents a *step* in the reconstruction line. Progressive steps cover progressively increasing time windows with no overlap in the same line, though the same steps of different lines are not synchronised because the files are filled with a fixed number of events. The value of 10 000 is calibrated on the event rate of the LST-1, and usually covers ~ 10 s of data. MSTs and SSTs will have lower rate, and the implementation of the stereoscopic trigger when using multiple IACTs (see section 2.3.2) will also reduce the rate as less (background) shower events will trigger the camera. After creating DL1 files, SAG-RECO reconstructs the events into DL2 and applies γ /hadron separation cuts to turn them into DL3. The DL3 files do not have the same number of events, as a different amount of events in every file survives the cuts.

The reconstruction process results in batches of DL3 events provided to SAG-SCI from several parallel reconstruction lines and incremental steps, where the time windows covered by files of the same step in different lines are similar, but not synchronised, and the file size is also different. SAG-SCI has to merge the data of the events from all the reconstruction lines and store them in a *Data Source* entity before analysing them. The **Events Database** fulfils this purpose using 4 tables:

1. `reco_pipe`. Each row represents one of the SAG-RECO reconstruction parallel lines, that can be identified by their computing core, thread and the OB ID.

2. **evt3_reco_step**. Each row represents one of the reconstruction steps. The table stores the steps' start and stop time, the OB ID and the coverage fraction, i.e. the fraction of reconstruction lines that provided a file for the given step. The start (stop) time of a step is the minimum start (stop) time of the files belonging to the step.
3. **evt3_file**. Each row represents one of the DL3 files provided by SAG-RECO, identified by their line and step IDs. It stores information on the start and stop times of the file (first and last event times) and its creation timestamp.
4. **evt3**. Each row represents a γ -ray reconstructed event. The table stores its file and OB, its arrival UNIX time, the reconstructed position in celestial coordinates (ICRS), reconstructed energy and a status boolean, which is set to 1 when all the events of the file have been inserted in the database. Additionally, we define a *view* **streaming_evt** showing the events with status 1. The wrappers query this view to retrieve the photon list of an analysis job.

We describe how the Pipeline Manager Daemons use these tables later in section 4.6, and we provide a graphical scheme of their interaction in figure 4.6.

4.4.3 Pipeline Database

The **Pipeline Database** contains information on the SAG-SCI pipeline, the available OBs, analyses and their status. It implements the *Data Model* component of the RTApipe framework using 42 tables, and the *Science Logic* using 13 triggers and 8 views. The *Data Model* includes a *static* part configured before the start of the nightly operations (the setup of the static components is described in section 4.5), and a *dynamic* part that the SAG-SCI pipeline updates during operations. We describe here the main entities of the Data Model. The tables of the Pipeline DB that implement them and their relationships are described in table 4.1 and shown in figure 4.3. They are:

1. **Observatory** and **Instruments** (static). They contain the list of observatories and their instruments managed by the system. They can send Science Alerts or produce data to be analysed. They also manage the different observational conditions under which an instrument can be used (e.g. Zenith band, Night Sky Background level, atmospheric conditions).
2. **Data Type** (static). It describes the model and format of the data generated by the observatorys instruments (e.g. DL3 data of CTAO), that can be used for the scientific analyses.
3. **Science Tools** (static). Software packages used for the analyses of scientific data.
4. **Analysis Type** (static). The configuration of the analyses that define the usage of the Science Tools (e.g. performing Aperture Photometry and light curve estimation of a target with a time window of 100 sec). The configuration includes the Science Tool adopted, the commands needed to execute a job on the machine and a template of its configuration file. The template must have some fields with placeholders that will be different for every job of the analysis (e.g. time intervals, pointing and target coordinates, IRFs to be used, output directory and so on...) and some hard-coded fields that identify the type of analysis (e.g. parameters to set the flux computation or the *stack option*, see section 4.7). An analysis can be implemented in multiple time windows and time steps (e.g. 100 s). We can also define the **type of light curve** that can be built:

- **Differential**: consecutive time bins with the same size, e.g. 0 to 100 s, then 100 to 200 s, following the pattern $[\delta t \cdot (n - 1), \delta t \cdot (n)]$.
 - **Integral**: time bins with the same start time and increasing stop time, e.g. 0 to 100 s, then 0 to 200 s, following the pattern $[0, \delta t \cdot (n)]$.
5. **Observation** (dynamic). It describes the OB performed, its pointing and type. SAG-SUP provides this type of information. It also describes the Good Time Intervals (GTIs) of an OB. SAG-DQ can flag time intervals as not-good if there are environmental or instrumental issues, and prevent the generation of candidate Science Alerts. The Observation stop time is updated in real-time by the *Pipeline Manager* using the time of the last reconstruction step closed (see sections 4.4.2 and 4.6). Every time the stop time is updated, a trigger checks if new analysis jobs can be scheduled. E.g., for 100 s analyses, a new job of the analysis is scheduled every time the OB «stop – start time» reaches a multiple of 100 s, i.e. every time we record 100 s of new data.
 6. **Scientific Target** (dynamic). It describes the astrophysical source on which the analysis must be performed, with its names, spectral and spatial models. The information on scientific targets is provided by SAG-SUP.
 7. **Science Alert** (dynamic). It contains information of internal and external Science Alerts. The relevant tables are updated either by SAG-SUP, that receives a Science Alert from the ACADA TH, or by SAG-SCI after generating a candidate Science Alert.
 8. **Analysis** (dynamic). This entity is updated during the operations, as it contains the technical parameters (instruments, IRFs, time windows) on the implementation of the analysis types. An *analysis* instance implements a given *analysis type* using explicitly defined start and stop times. Each analysis instance is created by the *Science Logic Triggers* when the current OB coverage times (recorded in the `observation_to_datarepository` table) allow for the creation of new jobs, according to the time scales of the analysis type (defined in `analysisessiontype`). Each analysis entity defines a job. The Pipeline Manager daemons submit the jobs to `slurm` for execution and monitor their status.

We show the main Pipeline DB tables and their relationship in figure 4.3. The tables are shown as boxes within the black rectangle representing the Pipeline DB. Yellow tables are the *static* components defined typically when the software is deployed, before the nightly operations. Blue tables are the *dynamic components* filled in real-time during the observations. The arrows show the flow of information in the the Database and table constraints: the entries of a table with the arrow head reference pre-existing entries of the table from which the arrow started. Arrows reaching dynamic tables are shown with a full arrow head and thicker lines to represent references being created not at deployment-time, but at run-time. The *Science Logic Triggers* act in two possible scenarios. The first one is when new data are acquired by the instruments and available for the analyses (green arrows in figure 4.3). The second one is when a new Science Alert, either internal or external, is received (orange arrows in figure 4.3). We discuss below the content of the main tables of the database (the *Data Model*) and then the two execution scenarios (the *Science Logic*).

Execution of the Science Logic. SAG-SCI implements the *Science Logic* using MySQL triggers that act before/after the insert/update/delete of rows in specific tables of the *Pipeline Database*. We use MySQL triggers because they can execute algorithms with low latency and consistency, allowing the pipeline to operate in real-time without human intervention. We

Table 4.1 – Description of the main tables of the Pipeline DB, shown in figure 4.3.

ENTITY	TABLE	ROLE DESCRIPTION
Observatory and Instrument	<code>instrument</code>	Define instruments, their observatory and IRFs.
	<code>observing_mode</code>	Manage the observational conditions under which an instrument can be used.
Data Type	<code>datarepository</code>	Define the data type of an instrument.
	<code>analysistrigger</code>	Connect pairs of instrument and data-repository entries, and execute analyses on the compatible instruments and data types.
Science Tools	<code>dataprocessingtool</code>	Define the Science Tools.
Analysis Type	<code>analysistype</code>	Define the types of analyses of an instrument, data type and science tool with a configurable template.
	<code>analysissessiontype</code>	Define the time window of the analysis, the time step and light curve type.
Observation	<code>observationwindowstatus</code>	Define the GTIs of an OB.
	<code>observation</code> <code>observation_to_datarepository</code>	Describe observation parameters. Link an OB with a data-repository; update in real time the OB stop time, used to trigger new analyses.
Scientific Target	<code>target</code>	Define target sources and their models.
Science Alert	<code>receivedsciencealert</code>	Record technical information on a Science Alert (e.g. instrument).
	<code>notice</code>	Record scientific information on a Science Alert (e.g. time, position).
Analysis	<code>analysissession</code>	Implement an <code>analysissessiontype</code> entry using explicitly defined start and stop times.
	<code>job</code>	Describe the submission times and status of the analysis jobs.

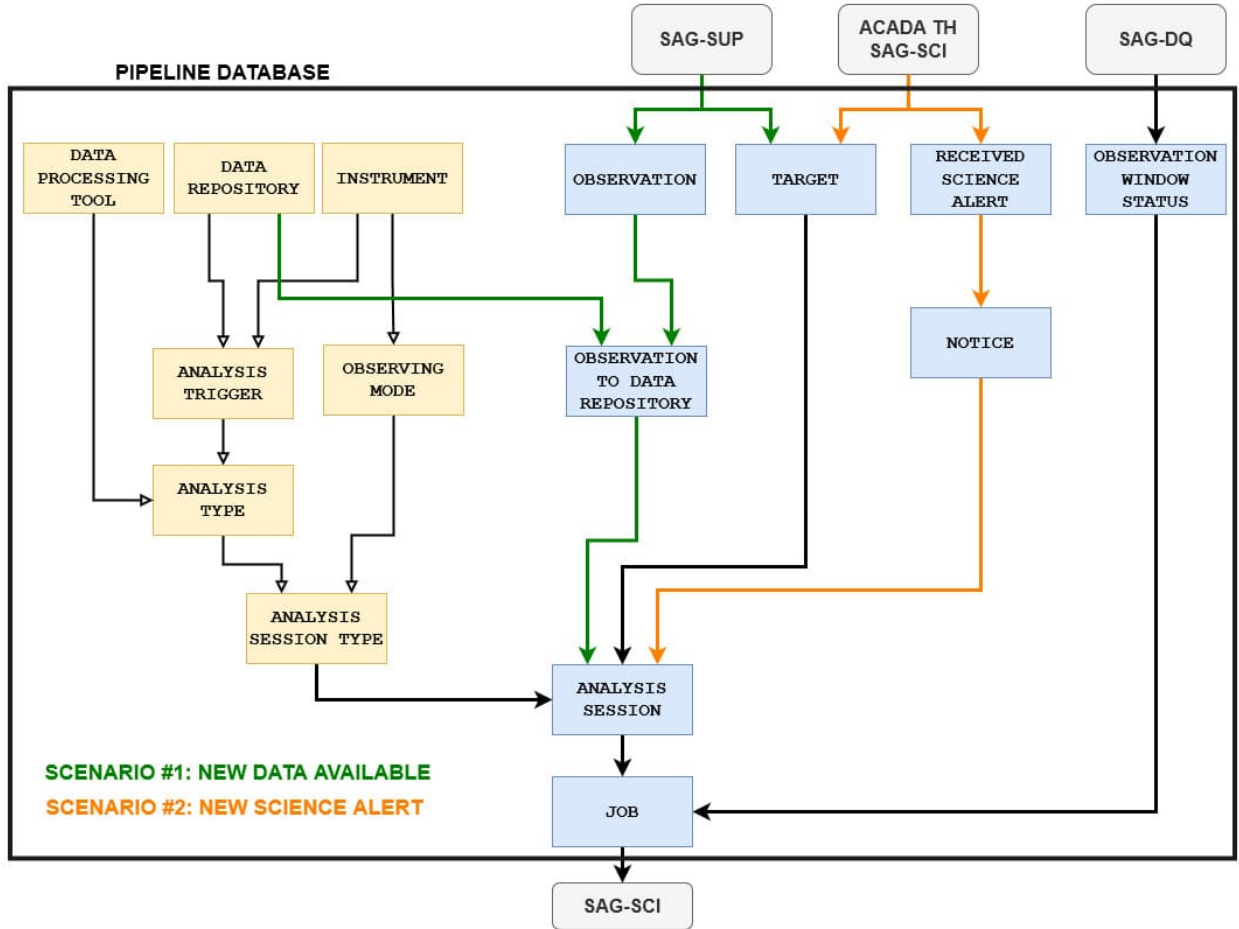


Figure 4.3 – Logical Diagram of the SAG-SCI Pipeline Database (simplified). We show the main tables of the database inside the black rectangle. External entities are grey boxes outside the rectangle. The tables of the database are shown as yellow boxes if they are static tables, defined during the deployment of the software. Blue boxes are the dynamic tables filled during observation with new data in real-time. The arrows show the flow of information in the the Database and table constraints. Green arrows show the data flow when analyses are triggered by the arrival of new data. Orange arrows show the data flow when analyses are triggered by a science alert.

designed the Science logic triggers to act in two scenarios. The first one occurs when the instruments acquire new data for the analyses, the second one when a new Science Alert, either internal or external, is received in the Pipeline Database.

The first scenario, shown with green arrows in figure 4.3, is implemented with triggers on the `observation_to_datarepository` table, that is updated when SAG-SCI **receives new data**. The triggers checks if there are analyses for the instrument and data type received. If there are, the triggers create new analyses in one of two states: *pending for data* when not all required data are available, or *runnable* when all analyses requirements are satisfied. Analysis requirements usually include collecting a minimum amount of data, e.g. 100s; if no time window is configured, the pipeline performs analyses at each update. When new data are available, the triggers also check if analyses in the *pending for data* state can be updated in the *runnable* state. Once in the *runnable* state, the *Pipeline Manager* execute them. Within the CTAO context, this scenario is the most used, as regular observations and follow-up observations of external Science Alerts require to re-point the telescope, start a new OB and acquire new data.

The second scenario, shown with orange arrows in figure 4.3, is implemented with triggers on the `notice` table, updated when a SAG-SCI **receives a new Science Alert**. The triggers checks if there are analyses compatible for the alert and data type received. If there are, the triggers create the analyses in a *pending for data* state, then check if data in the required time window and sky region are available. When data is available, triggers update the analysis state to *runnable*. This scenario was particularly useful in the AGILE RTA system (Parmiggiani et al. 2023) that operated in a spinning mode. Within the CTAO context, this scenario will be used if the blind search algorithms (described in detail later in section 4.7) find a serendipitous transient in the FoV, and the data already acquired by the telescopes need to be re-analysed using the new target.

4.4.4 Results Database

The **Results Database** contains information on the results of the analysis jobs and the candidate Science Alerts. The Wrappers insert their results in the database using a common class called `ImportResults`. The main table of the database is the `detection` table, where each row represents the results of an analysis job. It contains information on the time window of the job, the position of the target analysed, the *single-job* Aperture Photometry results and flux, the *stacked* Aperture Photometry results and flux (see section 4.7). Another relevant table is the `alert` table, that stores the *candidate Science Alerts* and reference the analysis job that produced them. SAG-SCI must produce candidate Science Alerts when it detects a new source (i.e., a source not associated with any entry of available science catalogues), or when it detects a known source in a flaring state, above configurable thresholds of flux and sensitivity. We discuss this topic in further detail in section 4.7.1.

4.5 Database Management

The development of a Database management system is one the key results of this chapter. The *Pipeline Database* described in Section 4.4.3 is composed not only of dynamic components updated during observations, but also of static components that must be defined

during the deployment phase of **SAG-SCI**. Some of these static components depends on the specific characteristics of the system where the pipelines are going to run, e.g. the name of the **slurm** partitions reserved to **SAG-SCI** in a cluster, or the absolute path where the calibration database with IRFs is stored. Other static components must be defined by the user taking into account their scientific goals, e.g. the list of analysis available, the science tools used, the available instruments. We adopt several implementations, or **populations**, of the DB in the context of ACADA, using a version for the **SAG-SCI Unit Test**, one for the *Verification Test*, one for the *SAG Integration Test* and the *ACADA Use Case Test* (see section 4.8 for a description of the test strategies). The analysis presented in Section 5 of this work employs a dedicated DB population. The version of **SAG-SCI** deployed on the LST-1, RTA-SCI, has a database population for the regular observations (the *production* database) and one population for tests and development.

```

185 ### CREATE TABLE: analysistrigger
186 CREATE TABLE `analysistrigger` (
187   `analysistriggerid`          int UNSIGNED      NOT NULL AUTO_INCREMENT,
188   `name`                      char(128)         NOT NULL,
189   `shortname`                 char(15)          NOT NULL,
190   `category`                  int                NOT NULL,
191   `triggersourcedatarepositoryid` int UNSIGNED DEFAULT NULL,
192   `triggersourcedatarepositoryinstrumentid` int UNSIGNED DEFAULT NULL,
193   `triggersourcesciencealertinstrumentid` int UNSIGNED DEFAULT NULL,
194   `basedirresults`            text              NOT NULL,
195   `basedirjob`                text              NOT NULL,
196   `status`                    int                NOT NULL,
197   PRIMARY KEY (`analysistriggerid`),
198   UNIQUE KEY `shortname` (`shortname`),
199   UNIQUE KEY `index6` (`triggersourcedatarepositoryinstrumentid`, `triggersourcedatarepositoryid`),
200   UNIQUE KEY `index7` (`triggersourcesciencealertinstrumentid`),
201   KEY `triggersourcedatarepositoryid` (`triggersourcedatarepositoryid`),
202   KEY `triggersourcedatarepositoryinstrumentid` (`triggersourcedatarepositoryinstrumentid`),
203   KEY `triggersourcesciencealertinstrumentid` (`triggersourcesciencealertinstrumentid`),
204   CONSTRAINT `analysistrigger_ibfk_1` FOREIGN KEY (`triggersourcedatarepositoryinstrumentid`) REFERENCES `instrument` (`instrumentid`) ON UPDATE NO ACTION,
205   CONSTRAINT `analysistrigger_ibfk_2` FOREIGN KEY (`triggersourcesciencealertinstrumentid`) REFERENCES `instrument` (`instrumentid`) ON UPDATE NO ACTION,
206   CONSTRAINT `analysistrigger_ibfk_1` FOREIGN KEY (`triggersourcedatarepositoryid`) REFERENCES `datarepository` (`datarepositoryid`) ON DELETE CASCADE,
207 ) ENGINE=InnoDB DEFAULT CHARSET=utf8mb3;
208

```

a – Schema of the *analysistrigger* table

```

105 ### INSERT INTO TABLE: analysistrigger
106 INSERT INTO `analysistrigger`
107 (`analysistriggerid`, `name`, `shortname`, `category`, `triggersourcedatarepositoryid`, `triggersourcedatarepositoryinstrumentid`, `triggersourcesciencealertinstrumentid`, `basedirresults`, `basedirjob`, `status`)
108 VALUES
109 (1, 'CTA_NORTH_PROD3_EVT3DB', 'CTA_N_PROD3_DB', 0, 1, 1, 1, '$ACSDATA/DLS/', '$ACSDATA/DL4/', 1),
110 (2, 'LST-1_PROD3_EVT3DB', 'LST-1_PROD3_DB', 0, 1, 2, 2, '$ACSDATA/DLS/', '$ACSDATA/DL4/', 1);
111

```

b – Example of a population of the *analysistrigger* table

Figure 4.4 – Example of the separation between schema and population in the SAG-SCI DB, reported for the table *analysistrigger* of the *Pipeline* DB. The schema, shown in panel 4.4a, is used to create the table, define its columns, their type, the keys used to identify entries, and the *foreign key constraints*, i.e. the columns that must reference entries of pre-existing tables. All DB populations use the same schema, but they may differ in the content of the table. Panel 4.4b shows an example of a population for *analysistrigger* with two entries, that differ in the *instrument* they reference. The rows reference a “CTA-North” and a “LST-1” instruments (names are placeholder used for testing purposes).

Different implementations of the **SAG-SCI** DB can differ in the content of their static components and the MySQL connection parameters, but they must comply to the same *Data Model* schema and implement the same *Science Logic* triggers. For this reason, we separated the *creation* of the **SAG-SCI** schema and triggers from the *insertion* of a data population. From the implementation point of view, a database population is identified by a JSON *DB configuration file* that contains the MySQL connection parameters (DB name, host, port, user, password) and by one or more *.sql* scripts with *INSERT* statements that insert the data population in the database. An example of the separation between schema and population

for the `analysistrigger` table, extracted from the relevant `.sql` scripts, can be seen in figure 4.4. The schema is used to `CREATE` the table, while the population to `INSERT` data. A population ready for observations must provide data for the Pipeline and Pipe Manager DBs. Populations for the Events and Results DB may be provided for testing purposes, where a pre-filled DB is needed to run tests quickly.

We developed the `DatabaseManager` script to manage the setup of a DB population. Its arguments are: the *mode* defining the task to execute; the JSON *database configuration file* with MySQL connection parameters (an example is showed in figure 4.5b); the directory containing the *population .sql* scripts (like the one showed in figure 4.4b). The available modes are:

1. **Create.** Create the **SAG-SCI** DB with the schema and triggers, but no data. Databases are created by running 4 `.sql` scripts installed in `sagsci.database.schema` (one for database) and 13 `.sql` SCRIPTS installed in `sagsci.database.triggers` (one for trigger), that define the tables available and the trigger operations. An excerpt of these scripts is shown in figure 4.4a.
2. **Populate.** Insert the data of a population in a pre-existing DB. The `DatabaseManager` reads the `.sql` scripts contained in the input population directory and run their `INSERT` statements. An excerpt of these scripts is shown in figure 4.4b.
3. **Delete.** Permanently deletes the DB and all of its content with `DROP` statements.
4. **Setup.** Shortcut for *Create + Populate*.
5. **Clear.** Shortcut for *Delete + Create*.
6. **Reset.** Shortcut for *Delete + Create + Populate*.
7. **Backup.** Backup the databases by using the `mysqldump` tool. It writes an `.sql` script for each DB with all of its tables, data and trigger. These files contain both `CREATE` and `INSERT` statements, mixing the schema and triggers with the data.
8. **Restore.** Restore a set of backed up databases by running the `.sql` files with their schema, triggers and data.

Before we implemented the schema-data separation and the `DatabaseManager` during my PhD research, the *restore* approach was the only one used for development. It required keeping tracks of multiple large files that may diverge and cause the pipeline to crash if the updates reported in a version of the database were not reported in all of the others. Our current approach allows us to separate the schema of the *Data Model* and the *Science Logic* triggers from the static data inserted during the deployment stage and the dynamic data inserted during the execution of the pipeline. It also provides an easy way to backup our data at any moment and restore the database to a previous state using backed up data.

4.5.1 Database Configuration of New Observations

The first step in the execution of the **SAG-SCI** pipeline is notifying the DB that a new scientific observation, an *Observing Block* for CTAO, has started. For this purpose, we implemented a `ConfigureDB` class inside the `sagsci.database` module. The `ConfigureDB` must receive:

1. A `YAML` file containing the information on the Observing Block, such as the observation ID, start time, planned stop time, pointing coordinates, target coordinates, proposal information, expected **SAG-SCI** output directory. We show a template for this file in figure 4.5a.

2. A XML file containing the Sky Model of the Target Source.
3. A YAML file with the MySQL connection parameters of the DB. We show an example in figure 4.5b.

The `ConfigureDB` inserts the information related to OB and target in the following tables of the Pipeline DB: `observation`, `target`, `observation_to_target` that links their N to N relationship, `observation_to_datarepository` that will trigger the analysis jobs. The configuration files are created by *Data Source* software components external to SAG-SCI, e.g., within ACADA they are provided by SAG-SUP, which retrieves them from other ACADA subsystems. In the context of RTA-SCI on LST-1, they are provided by a external script we developed to retrieve them from the *Telescope Control Unit* database, which registers new telescope runs. Further discussion of the integration of SAG-SCI with external software is provided in section 4.9. The `ConfigureDB` also includes utility functions to: modify the status of analyses in the table `analysissessiontype` of the Pipeline DB, turning them on or off on request; clear the database and remove rows related to specific targets or observations; create the YAML configuration files and the XML target files from a template. Once an OB and target have been configured, the SAG-SCI pipeline can start operating by activating the daemons of the *Pipeline Manager*, see section 4.6.

4.6 The SAG-SCI Pipeline Manager

The **SAG-SCI Pipeline Manager** is a set of 5 `python` daemons that manage the operations of the pipeline: receiving input DL3 files, inserting their information in the database, querying it to assess the status of the analyses and executing them when available. The daemons can be classified in:

1. 2 OB-specific daemons: `DL3Merger` and `DataFlowManager`. They receive and read the DL3 files of an Observing Block.
2. 3 SB-specific daemons: `SubmitJob`, `UpdateJobStatus` and `CancelJob` execute the available analysis jobs of all the OBs of a SB through the `slurm` Workload Manager.

All daemons are implemented through a `python` class and script with dedicated arguments. One argument common to all daemons is the JSON *Database Configuration file*, that we use to connect the daemons to the SAG-SCI databases of the pipeline, see figure 4.5b. All daemons can be stopped by sending them through `slurm` an *interruption signal* (SIGINT) which will automatically stop the daemon after the end of a timeout (default value is 600s). The signal is sent by SAG-SUP at the end of an OB, and the timeout allows to have extra time to complete processing the last SAG-RECO data. The refactoring of the Pipeline manager Daemons into object-oriented classes is one the key results of this chapter.

4.6.1 DL3 Merger

The `DL3Merger` is an OB-specific daemon initialised with the OB ID and the path to the directory where SAG-RECO writes the DL3 files. It uses the `python` library `watchdog` to monitor the DL3 input directory with a *polling* operation, i.e. cyclically sampling the status of the directory. Every time SAG-RECO writes a new DL3 file in the input directory, the

<pre> 1 observation: 2 observationid: "#@observationid@" 3 inputtime : "#@inputtime@" 4 planned_tstart: "#@planned_tstart@" 5 planned_tstop: "#@planned_tstop@" 6 real_tstart: "#@real_tstart@" 7 real_tstop: "#@real_tstop@" 8 inputcoordinate: "#@obs_inputcoordinate@" 9 coord0: "#@obs_coord0@" 10 coord1: "#@obs_coord1@" 11 status: "#@status@" 12 timereftypeid: "#@timereftypeid@" 13 skyreftypeid: "#@skyreftypeid@" 14 name: "#@obs_name@" 15 outputdirectoryjob: "#@outputdirectoryjob@" 16 outputdirectoryres: "#@outputdirectoryres@" 17 18 target: 19 targetid: "#@target_id@" 20 target_code: "#@target_code@" 21 proposal_id: "#@proposal_id@" 22 observingmode_id: "#@observingmode_id@" 23 name: "#@targetname@" 24 inputcoordinate: "#@target_inputcoordinate@" 25 coord0: "#@target_coord0@" 26 coord1: "#@target_coord1@" 27 emin: "#@emin@" 28 emax: "#@emax@" 29 30 observation_to_datarepository: 31 datarepositoryid: "#@datarepositoryid@" </pre>	<pre> 1 { 2 "datarepositoryId": "1", 3 "databases": { 4 "pipe_manager": { 5 "host": "mysql", 6 "port": 3306, 7 "user": "rta", 8 "password": "password", 9 "database": "sag_sci_pipe_manager" 10 }, 11 "pipe_db": { 12 "host": "mysql", 13 "port": 3306, 14 "user": "rta", 15 "password": "password", 16 "database": "sag_sci_pipe_db" 17 }, 18 "sci_results": { 19 "host": "mysql", 20 "port": 3306, 21 "user": "rta", 22 "password": "password", 23 "database": "sag_sci_results" 24 }, 25 "evt_db": { 26 "host": "mysql", 27 "port": 3306, 28 "user": "rta", 29 "password": "password", 30 "database": "sag_sci_evt_db" 31 } 32 } 33 } </pre>
--	--

a – Template for OB Configuration

b – Database Connection Parameters

Figure 4.5 – Example of Configuration files used for the SAG-SCI Database. Panel 4.5a shows the template of the YAML configuration file used to insert new OBs into the SAG-SCI Database. The most important quantities that must be configured are the ID, start time and pointing direction of the OB, and the name and coordinates of the target. Panel 4.5b shows an example of a JSON configuration file with the DB connection parameters.

DL3 Merger is able to detect the file, read it and insert its content in the *Events Database* (see section 4.4.2). We show the operations performed by the daemon and its interaction with the Database in figure 4.6. The DL3 Merger must:

1. Read the file name and creation timestamp. The file name must respect a pattern that allows to identify the reconstruction step and line.
2. Open the DL3 file and read its *photon list*. The photon list is table where every row is a photon and the available columns describe its properties: reconstructed celestial coordinates, arrival time, reconstructed energy and an ID.
3. Compute the real start and stop times of the file as the times of its first and last photon.
4. Get the ID of the reconstruction line of the file. If no line is found, create it (this happens for the first file of the line).
5. Get the ID of the reconstruction step of the file. If no step is found, create it (this happens for the first file of the step) with status 0, which means the step is *open* and waiting to receive more files from different lines. Instead, if a step is found and is still open, update its start and stop times with the information of the new file. The start (stop) time of a step is defined as the *minimum* time of all the start (stop) times of the step files coming from different lines.
6. Once the file has an associated line and step, create its entry in the `evt3_file` table of the *Events Database* recording its start and stop times, the file creation timestamp and status 0 (file information not complete, as we still need to insert the events).
7. Insert the file photons in the `evt3` table of the *Events database*, recording their ID, OB, file id, detection time, reconstructed position and energy, and status 0 (events belonging to a step not closed).
8. If no error occurred, set the file status to 1 as all of its information was inserted in the database.

When a step is found with status 1 it means that the step was already closed (see section 4.6.2). This can happen if one reconstruction line has a strong delay with respect to the others. The `DataFlowManager` will close the step even if the file of a line is missing and submit the analysis. If the line is then recovered and the DL3 file is provided, its events will be uploaded directly with status 1 to be used in later analyses.

4.6.2 Data Flow Manager

The `DataFlowManager` is an OB-specific python daemon with the role of monitoring the status of the steps recorded in the `evt3_reco_step` table of the Events Database. It receives in input the OB ID, the number of SAG-RECO parallel lines processing data and a *maximum delay time*. The `DataFlowManager` will close a step setting its status to 1 either when all the files of the step from different lines are received (100% coverage) or when the maximum delay time has passed since the first file of the step was received. Closing a step implies setting the status of its events to 1 in the `evt3` table, making them available for the analyses, and updating the stop time of the current OB entry of the `observation_to_datarepository` table, triggering the *Science Logic* and creating new analysis jobs if possible. We show the operations performed by the daemon and its interaction with the Database in figure 4.6. The Data Flow Manager implements a loop that performs the following operations:

1. Query the oldest open step (status 0 in the `evt3_reco_step` table).

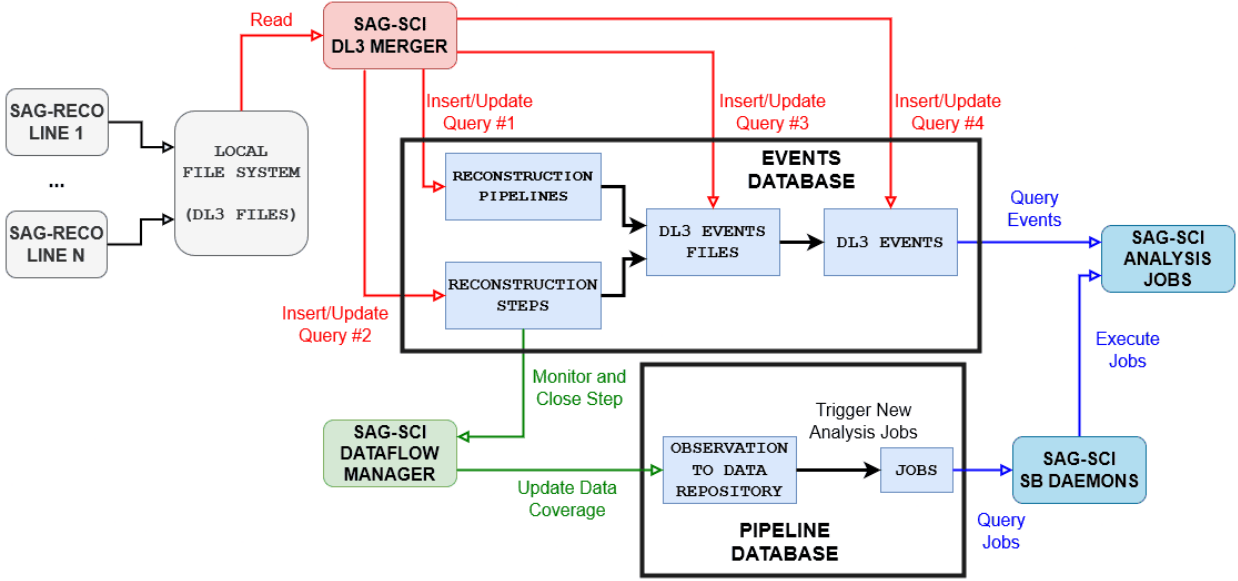


Figure 4.6 – Logical Diagram of the SAG-SCI Events Database and its interactions with the Pipeline Manager OB Daemons (simplified). First, the parallel lines of SAG-RECO write DL3 files in a desired directory. The DL3 Merger watches it with a polling operation and when a new file is written, it reads it. The information of the file is inserted in the Events Database. The Dataflow Manager monitors the Events Database and when a step is complete, it closes the step and update the data coverage in the Pipeline Database. The Science Logic Triggers create new analysis jobs, that the SB daemons, slurm and the Science Tool Wrappers execute. The wrappers query the relevant events from the Events Database.

2. Query the number of files of the step with status 1 (events inserted in the database, from the `evt3_file`).
3. Estimate the step *coverage* as the number of files of the step received over the expected value (number of parallel **SAG-RECO** lines).
4. If the coverage fraction is 100%, call the function to close the step.
5. If it is not, evaluate the *time delay*, i.e. how much time has passed since the creation timestamp of the first file of the step received. If the time delay is higher than the maximum set, call the function to close the step even if it is not complete. If the time delay is less than the maximum value, restart the loop.
6. When the `close_step` function is called, it performs the following operations:
 - (a) Set the step status to 1 (closed step).
 - (b) Set the status of the events of the step to 1 (available for analysis).
 - (c) If the step is the first one of the OB, update its start time³ to be the same of the step, i.e. the time of the first photon detected.
 - (d) Update the stop time of the OB³ to match the one of the step, which is the minimum time of all files belonging to the step. This will ensure that the analyses are performed up to a time where data from all the available lines is recorded.

4.6.3 Submit Job

The `SubmitJob` is a daemon that cyclically queries the *Pipeline DB* to check if there are analysis jobs in *runnable* status, and submits the available ones to `slurm` for their execution.

³In table `observation_to_datarepository`.

When the *Science Logic* triggers create new analysis jobs, they are written in the `job` table of the Pipeline Database and can be visualised through the dedicated `job_runnable` view. The `SubmitJob` daemon queries it, orders the jobs by id, submit them to `slurm` and set their status to *queued*. If there are multiple *Pipeline DB*, the operation is repeated for every DB listed in the *Pipe Manager DB* (see section 4.4.1).

In order to submit a job, the `SubmitJob` executes a `submit_job` function. The function creates the input files for the *Wrappers* using the job information queried, such as start and stop time, IRF, pointing and target coordinates. The function also creates the `slurm` execution script. It specifies the task to execute, namely the setup of the environment and the execution of the Science Tool Wrappers with the correct input files; the script also specifies several `slurm` parameters such as the priority of the job, the name of the partition and reservation assigned to `SAG-SCI`. If the analysis has the *stack* option active, the function also queries from the database the `slurm` ID of the previous job of the same analysis, so that the jobs are forced to be executed in an *ordered* sequence and each job stacks its results with the ones of the previous job.

4.6.4 Update Job Status and Cancel Job

The `UpdateJobStatus` is a daemon that cyclically queries the *Pipeline DB* to check if there are analysis in the *queued* (waiting for computing resources to be executed), *running* or *suspended* status, compare their registered status with their true `slurm` status and update it if necessary. The daemon queries the `job_queued`, `job_running`, `job_suspended` views of every *Pipeline DB* listed in the *Pipe Manager DB*, retrieves their `slurm` ID, then asks `slurm` their metadata with the dedicated `sacct` command. The main information queried is the status of the job, e.g. *pending* (queued), *running*, *suspended*, *completed* (with no errors), *failed* (terminated with errors), *stopped*. Other information queried include the time for submission, start and stop of the execution. The `UpdateJobStatus` updates then the `job` table with the new information if it has changed.

If new analyses with full results have to replace analyses with partial results, Science Logic Triggers will set the status of partial analysis jobs to *to cancel*, and they will appear in the `job_to_cancel` view. The `CancelJob` daemon checks all the `job_to_cancel` views of the *Pipeline DB* listed in the *Pipe Manager DB*, gets their IDs and cancels them by sending the `slurm scancel` command, and updates their DB status to *cancelled*. In future versions of `SAG-SCI`, the `CancelJob` daemon will become a part of the `UpdateJobStatus` daemon.

4.7 The Science Tool Wrappers

The *Science Tool Wrappers* are a set of scripts and classes that perform scientific analyses. We implemented 2 wrappers: `RTAPH`, see section 4.7.2 and the `gammapy` wrapper, see section 4.7.3. Both wrappers use the same interface to interact with the rest of the `SAG-SCI` pipeline.

The wrappers are executed by running a `execute.py` script located in the wrapper's module, which reads the input files and call the classes and functions to perform the analysis. Two `XML` input files define the configuration of the analysis: one provides information on the observation parameters, such as pointing coordinates and IRF, and one on the job-specific parameters, such as start and stop time of the job and the tasks to perform. For

ACADA REL2, we plan to merge them into a single input file in JSON format, to reduce the cognitive complexity. Another input file is the *Target XML* file, which describes the spatial and spectral Sky model used as input. An optional parameter is a DL3 file: if not provided, the wrappers will query the photon list for the analysis from the database (regular operation mode). If it is provided, the photon list will be read from the file (testing mode on local data).

The analysis performed by the wrappers follow this general workflow:

1. The wrappers import their dependencies and read the input files to configure the analysis.
2. Events are queried from the database, the IRFs are read from a pre-determined archive in the file system. Wrappers query only the events of the current OB in the configured time window.
3. The *Science Tools* perform the configured analysis tasks (see chapter 2.4), such as estimation of the significance, MLE of the source flux, θ^2 plot computation, *Blind Search* of astrophysical sources on a sky map. The results are relative to the analysed time window, so they represent one data point in a time series (or a light curve).
4. If configured, a **stacking** step is performed: the wrappers query the results of the previous job of the analysis on the same target, and stack them with the results of the current job. Stacking results means summing the ON counts, the OFF counts, recomputing the significance with the updated values, computing the average flux weighted by the observation time. We implemented the option to stack results within a single OB, restarting from zero when the OB changes (**Run-wise Stack**), or to stack the results of all the OBs on the same target during the night (**Night-wise Stack**).
5. The *job* results and the *stacked* results are stored in a file system in FITS files, PNG images and an XML summary result file. It will be changed in a JSON file for ACADA REL2.
6. The results of the single target analysis are also inserted in the *Results* DB, so that they can be available for the HMI and can be used by the next jobs for stacking.
7. The wrappers also evaluate if issuing a candidate Science Alert on the analysis, see section 4.7.1.

Currently, only *wobble-mode* observations are supported (see section 2.4.2). Future versions of SAG-SCI will include support for *ON/OFF-mode* observations by linking ON OBs with their OFF OBs. SAG-SCI will also support *grid-mode* observations, typically used in follow-up observations of Gravitational Waves alerts. In such observations, a SB will include ON observations centred on different coordinates with the aim of creating a *mosaic* of observations covering the alert region. The background will be estimated from archival observations (*template background*), normalised for the current acceptance of the camera (see section 2.4.2). We are currently evaluating adding other types of stack for future releases of SAG-SCI, e.g. stacking all the results of a SB, or all the results on a target within the observations of a proposal.

4.7.1 On the generation of candidate Science Alerts

The *Science Tool Wrappers* are also responsible for the generation of **Candidate Science Alerts**. We developed the following strategies for the generation of Science Alerts:

1. **Detection of a Flaring State of a known source.** When the Scientific Target of an OB is a known source, its flux is computed and compared with the values provided in a scientific catalogue. If the flux of the source is *significantly higher* than the catalogue's one, the source is defined to be in a *flaring state*, and a candidate Science Alert must be generated and inserted in the *Results* DB, so that it can be available for the ACADA HMI and TH. An example of this scenario is provided in chapter 5.5. If the detected flux is significantly *lower* than the catalogue value, a candidate Science Alert can also be generated, as low states are interesting for targets such as AGNs.
2. **ToO follow-up observation of a target with high-precision localisation.** ToO observations on a flaring target are triggered after receiving external Science Alerts. The vast majority of Science Alerts provide the target coordinates with high precision (localisation error $\lesssim 0.1$ deg), so SAG-SCI can analyse it as it would during regular observations. If the target is detected, a candidate Science Alert must be generated so that the CTAO can issue its response. Comparison with a catalogue, when possible (e.g. for a flaring AGN) is useful but not *strictly* required, as we already assume the source being in a flaring state. For one-time transients, such as GRBs, a catalogue cross-matching can be useful to identify possible counterparts of the source. An example of this scenario is provided in chapter 5.6.
3. **Detection of a Serendipitous Transient.** SAG-SCI cyclically runs *Blind Search* algorithms across its FoV (see section 4.7.3). The Blind Search identifies *hot-spots* of excess counts in the FoV, whose statistical significance must be determined with the Li&Ma method (section 2.4.1). If it is significant *enough*, the flux is evaluated, and the source is cross-correlated with a catalogue to check if it is an unknown source, a known source in a flaring state, or a known source in a regular state and its detection was expected. In the first two cases, SAG-SCI must generate a candidate Science Alert, and insert it not only in the *Results* DB, but also in the `notice` table of the *Pipeline* DB, triggering a new set of high-priority analyses centred on the hot-spot. An example of this scenario is provided in chapter 5.7.
4. **ToO follow-up observation of a target with low-precision localisation.** GW are currently poorly localised, with localisation area covering several deg². All High-Energy observatories are planning observational strategies to optimise the chances of detection. Currently, the favoured approach is having multiple observations, shorter than usual, with a *grid-mode* pointing capable to cover a mosaic in the Sky. SAG-SCI will run *Blind Search* algorithms on the FoV to search for a γ -ray counterpart of the GW signal. If an hot-spot is detected, SAG-SCI will act in a similar way to the case of *serendipitous discovery* discussed above (see chapter 5.7 for an example). The significance and flux of the hot-spot will be evaluated, cross-correlated with available catalogues, and a candidate Science Alert will be generated. It will be inserted in the *Results* DB for the HMI and TH, and in the *Pipeline* DB `notice` table to trigger new dedicated analyses.

The strategy to generate candidate Science Alerts is not implemented in the SAG-SCI software yet and will be included in ACADA REL2. A dedicated `ScienceAlertManager` class is under development to fully implement the scenarios described above. The class will define the thresholds of significance and flux needed to issue Science Alerts according to a general configuration provided by SAG-SUP, as stated in the SAG-SCI requirements (see section 4.1). Typical significance thresholds might be 3σ (sub-threshold Science Alert candidates) and 5σ (fully detected Science Alert candidates). The SAG-SCI requirements state

that the generation of Science Alerts can be prevented from configurable sky regions (e.g. where there are known sources, or where a Blind Search was already performed to limit the number of trials) and during observation times affected by *Data Quality* issues. The **ScienceAlertManager** will manage these exceptions and will prevent the generation of new candidate Science Alerts from the same region in following analyses, updating the existing ones. The **ScienceAlertManager** will also have to use **scientific catalogues** to cross-correlate the hot-spots with the known sources and compare their fluxes. When the CTAO will be operative, it will conduct surveys and create its own catalogues, that SUSS will provide to SAG (see chapter 3). Currently, the *TeVCat* (Wakely and Horan 2008) is the main catalogue available at VHE and will be included in the SAG-SCI workflow. Another possibility is to use catalogues from other γ -ray facilities and energy ranges, such *Fermi-LAT*, X-ray satellites or radio catalogues. They can be used for cross-correlation analyses, to identify VHE counterparts of known sources, but they cannot be used to compare the flux, as emission models cannot always be extended in a different energy range. Finally, the **ScienceAlertManager** will have to account for the number of trials performed to generate the candidate Science Alert, and compute the post-trial significance of the detection (see chapter 6.9). Trials will be computed by retrieving from the database the number of times the same analysis that yielded the detection was performed within the Scheduling Block.

Even if the **ScienceAlertManager** has not been implemented yet, SAG-SCI can still be used to manually evaluate the results of the observation. For instance, the version we deployed on the LST-1, RTA-SCI, shows sky maps of the observation run and reports the significance of the target analysed. These results are evaluated by the operators and used to decide if the observations of a target can be extended and if there are interesting sources. If RTA-SCI detects a significance $> 3\sigma$ during a ToO follow-up observation of a GRB, the observation time is extended.

4.7.2 The RTAPH Wrapper

RTAPH (Di Piano et al. 2022) was developed as the native Science Tool of SAG-SCI, before the CTAO selected **gammapy** as its high-level Science Tool (CTAO 2021). RTAPH's main *use case* is to perform a single-target, single energy bin, wobble analysis to estimate the significance and flux of the target and produce the counts map of the observation. In particular, the wrapper:

1. Performs the setup and event query as described at the start of section 4.7.
2. Compute the Aperture Photometry quantities (Li and Ma 1983): it computes the ON and OFF regions from the pointing and target coordinates; it computes ON and OFF counts by selecting photons in the proper regions and energy range, α assuming symmetric telescope response, the excess counts and the Li&Ma significance (as described in section 2.4).
3. It computes the exposure from the IRFs assuming a spectral index from the configuration files. IRFs can have both a point-like format and a full-enclosure format (see section 2.3.3). It estimates the source flux as the excess counts over the exposure and propagates the errors.
4. It writes and plots the counts map of the observation.
5. It performs the stack as described at the start of section 4.7.

All these tasks can be activated, deactivated and configured from the input files. We show

an example of the execution of RTAPH in chapter 5.3.3.

4.7.3 The Gammapy Wrapper

The development of the `gammapy` wrapper, after CTAO adopted the `gammapy` package (Donath et al. 2023) for its science tools (CTAO 2021), is one of the key results of this work. We show the data flow of `gammapy` from DL3 to DL5, implemented in the wrapper, in figure 4.7. The wrapper can use `gammapy` functionalities to not only perform the *Aperture Photometry* tasks, but it can also use multiple energy bins to perform spectral fitting, MLE of the flux, SED estimation, θ^2 plots, blind search of astrophysical sources on a FoV, estimation of the sensitivity of the analysis. The development of this wrapper is one the key results of this chapter. In particular the wrapper:

1. Performs the setup and event query as described at the start of section 4.7.
2. Reads the IRFs if available, which can be full-enclosure or point-like (see section 2.3.3).
3. It performs, if required, the tasks of a 3D full-FoV analysis, using maps centred on the telescope pointing direction:
 - (a) The events are bundled in a DL4 Counts Dataset⁴, i.e. a 3D cube of counts, centred on the pointing, with two spatial axes and one spectral axis. It is saved as a DL4 counts cube and plotted as a counts map.
 - (b) The IRFs are bundled in a DL4 **Reduced-IRFs** Dataset, i.e. 3D cubes of binned data. The Dataset contains: background expected counts (according to a background model provided in the IRFs), exposure cubes, maps of energy dispersion and PSF. The Reduced-IRFs depend only on the chosen IRFs and the OB pointing, so they are computed only during the first job of the OB and saved in the file system. The following jobs read the *Reduced-IRFs* file, scale the quantities to account for different integration times, and use it for the analysis. This step is required as the reduction of the IRFs is one of the most time consuming tasks of `gammapy`. For this reason, the reduction of the IRFs is performed only when strictly necessary, i.e. when a background map is required for the *blind search* task. Future versions of **SAG-SCI** will include the production of 3D flux maps through MLE, that also require the production of background and exposure maps. When produced, the *Reduced-IRFs* Dataset is appended to the Counts Dataset.
 - (c) A full-FoV *Blind Search* of astrophysical signals is performed if a background model is available. The blind search provides the coordinates of *hot-spots*, candidate point-like sources. We use the `ExcessMapEstimator` class⁵ to carry out the blind search. The class estimates on the pixels of a 2D map the **CSTAT Cash statistics** (we describe it in appendix A.2.1) comparing the observed counts with the background counts given by the assumed model, and computing the likelihood ratio. The evaluation is performed on a smoothed map, so the counts evaluated are not those of the a single pixel, but the value averaged in a circle centred on the selected pixel (using a *Tophat 2D kernel* with a configurable radius).
4. For every target provided (one from the configuration and those of the blind search) the wrapper can execute a 1D spectral analysis:

⁴Dataset is the official `gammapy` name for this class of objects.

⁵<https://docs.gammapy.org/1.0/api/gammapy.estimators.ExcessMapEstimator.html>

- (a) It produces the θ^2 plots.
 - (b) It computes the OFF regions and saves them in the file system. In future versions of SAG-SCI, this computation will be performed only once per OB, as it depends only on the pointing and target coordinates. The following jobs will read the off regions and use them for the analysis, improving the speed of the wrapper.
 - (c) It estimates the Li&Ma statistical significance through the reflected background regions method (see section 2.4).
 - (d) It bundles the events in a DL4 Counts Dataset centred on the target coordinates, that can be used to produce a counts map and stack the target data.
 - (e) If the IRFs are provided, it can perform a MLE of the flux by fitting an input spectral model (currently a power law), and estimate the SED using multiple energy bins if requested.
 - (f) It can evaluate the IRFs differential sensitivity. Integral sensitivity will be provided for ACADA REL2, following an update of environment using `gammapy v>1.2`.
5. Finally, the `gammapy` wrapper can stack the results for a given target (AP counts, flux, θ^2 plot and counts map).

All these tasks can be activated, deactivated and configured from the input files.

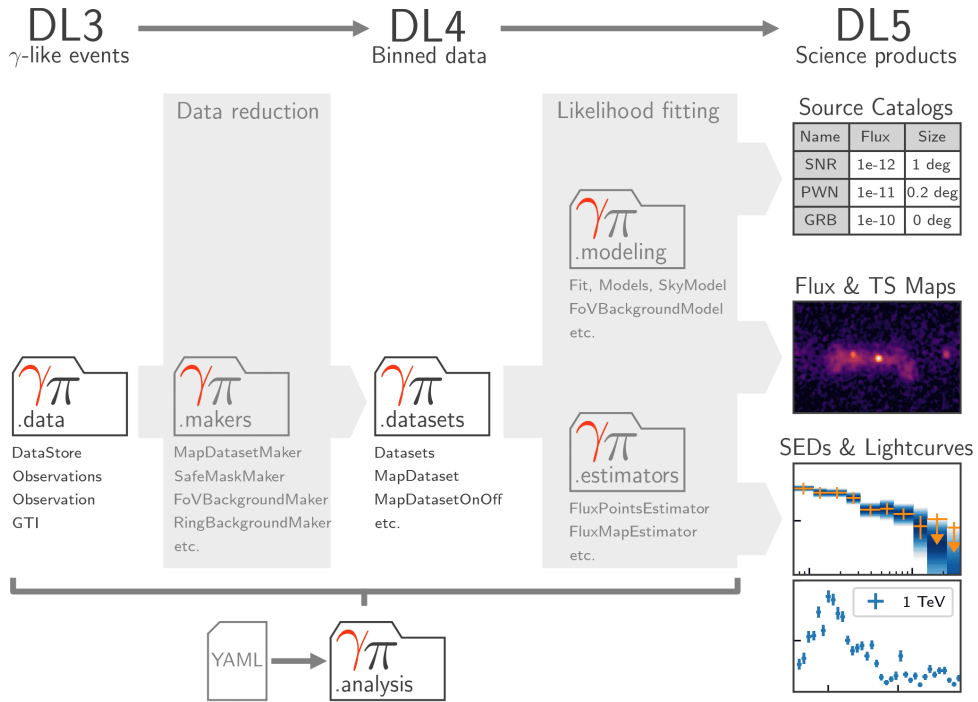


Figure 4.7 – Data flow and sub-package structure of Gammapy. The folder icons represent the corresponding sub-packages. The direction of the data flow is illustrated with shaded arrows. The top section shows the data levels as defined by the CTAO.

4.8 Test Suites and Code Quality

One of the core activities of any software development is **testing**, to ensure that it follows the correct behaviour. We developed two different test suites for SAG-SCI using the `pytest`

framework (Krekel et al. 2004). Within this framework, a test is defined as “a function that executes a section of source code and verify that the results are consistent with the expected behaviour”. The first test suite developed is the **Unit Test**, that executes isolated sections of the source code, e.g. a single function, class or script, and asserts if the expected results were obtained or not. The second suite is the **Requirement Verification Test**, which executes the entire **SAG-SCI** pipeline on simulated data and checks that the results satisfy the ACADA requirements described in section 4.3, e.g. computation of a light curve, detection of a source, identification of a source with a full-FoV blind search, execution of parallel analyses, computation of the sensitivity.

Tests can be performed manually on a local machine, but ACADA also relies on *Continuous Integration* to perform many different tests in an automated way, ranging from unit to software requirements tests. The continuous integration is operated with the open-source, automated **Jenkins**⁶ server, that executes on the CTAO machines the test suites every time the **SAG-SCI** code is updated on the CTAO **GitLab** with new commits⁷. The **Jenkins** automatic pipelines also perform *code quality and security analysis* using the **SonarQube** tools⁸. We show the **SonarQube** quality report in figure 4.8. **SAG-SCI** is composed of over 6000 lines of code, with an *A-score reliability* and *security*, i.e. the code quality analysis does not find any major bug nor security issues. **SonarQube** tracks the *line coverage* of the code, e.g. the fraction of lines executed during Unit Tests that satisfy the expected behaviour. During the development of **SAG-SCI**, I increased the code coverage from $\approx 30\%$ to $\approx 60\%$, surpassing the 50% milestone of ACADA REL1. This value underestimates the real coverage of the code, as it does not take into account the Verification Tests. **SonarQube** also reports a code duplication fraction of 1.1%, under the required 3%.

Additional test suites are the **SAG-SUP** requirement verification tests and the ACADA Use Case tests, that execute **SAG-SCI** not as a standalone software, but as a sub-system of **SAG** and **ACADA**.

4.9 Integration strategies for SAG-SCI

The individual components of **SAG-SCI** need to be integrated by a “pipeline sub-array supervisor” component that configures and executes the **SAG-SCI** pipeline. The supervisor component must:

1. Receive the list of telescopes composing a sub-array and information on the current Scheduling Block and Observing Block, to retrieve the observation’s schedule, pointing direction, Scientific Target, proposal, start time.
2. Configure the **SAG-SCI** database by inserting the Observation, Target and Proposal information in the DB, checking that the relevant analyses are active.
3. Configure the **SAG-SCI** daemons according to the deployment configuration, the Scientific case and the settings of the observation.
4. Start the **SAG-SCI** daemons with the correct configuration.
5. Handle the lifecycle of the **SAG-SCI** daemons, starting (stopping) them at the beginning (end) of the scheduled observation.

⁶<https://www.jenkins.io/>

⁷<https://gitlab.cta-observatory.org/cta-computing/acada/sag-sci>

⁸<https://www.sonarsource.com/products/sonarqube/>

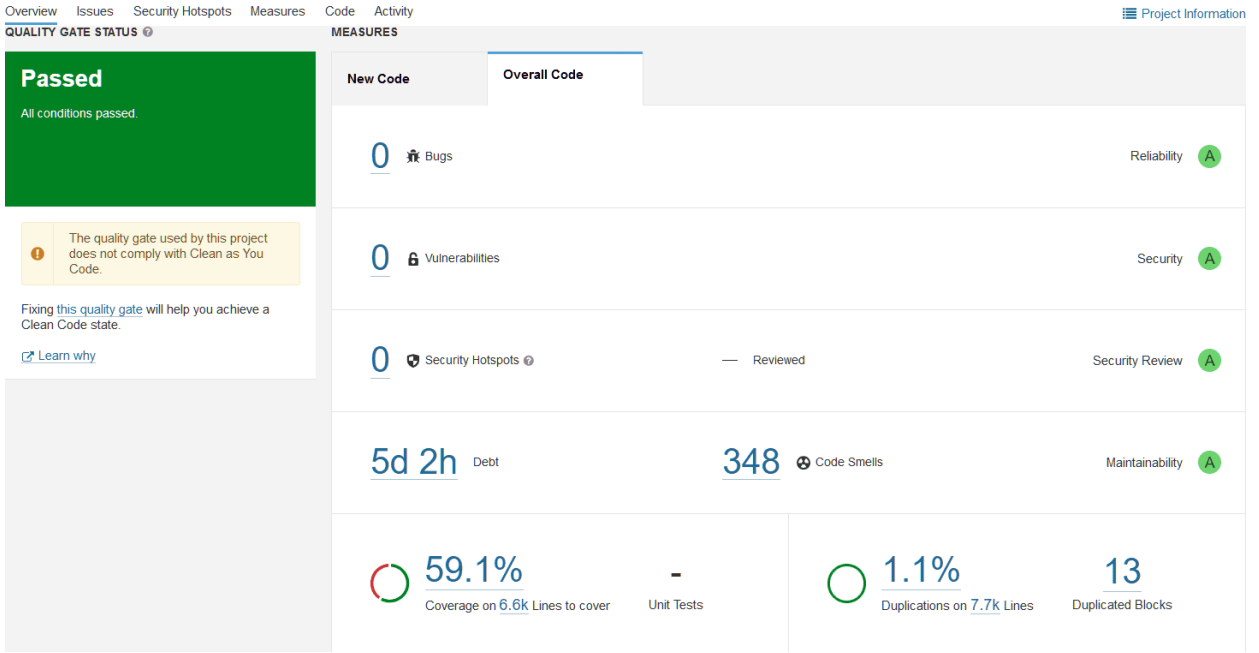


Figure 4.8 – Software quality metrics of SAG-SCI, as measured by the SonarQube service. The code has an A-score in reliability and security, code coverage is $\approx 59\%$, duplication fraction is 1.1%, ensuring all ACADA requirements on software quality are respected. *Code smells* are minor formatting issues, and suggestions to make the code more readable.

Within ACADA, SAG-SUP is the system responsible for the execution of SAG-RECO, SAG-DQ and SAG-SCI pipelines. It retrieves information on the ongoing SB and OB from other ACADA subsystems. It interacts and executes SAG-SCI by calling 2 scripts that we developed in a dedicated `sagsci.entrpoints` module. The first one is called `sci_configuredb`: it wraps `ConfigureDB` (see section 4.5.1) with the goals of activating the required analyses, and inserting observations and targets in the database. The second one is a `SciController` class that starts the SAG-SCI daemons by submitting them as `slurm` jobs, and stops them by sending them an interruption signal (`SIGINT`). The parameters of the daemons, such as OB, JSON file for database connection, expected DL3 input directory, logging directory, are set through a YAML file, for which we show a template in figure 4.9.

For the RTA-SCI version, working on the LST-1, we set up a script that queries the LST *Telescope Control Unit* database to register when a new observation starts, and execute the SAG-SCI pipeline. The SB daemons are activated once per night, the OB daemons every run. We did not deploy SAG-SUP due to being strongly dependent on its interfaces with the rest of ACADA, which is not running on the LST-1. SAG-RECO and SAG-SCI work as standalone software on the LST-1. We plan to deploy SAG-DQ as well in 2025.

For the analyses performed in chapter 5 for this thesis, we developed a `PipelineRunner` script to configure and execute SAG-SCI, see section 5.2.

```
1  daemonsConfigs:
2  - args:
3    - '@maxdelay_sec@'
4    - '@db_json_config_file@'
5    name: cancel_job
6    type: sb
7  - args:
8    - '@maxdelay_sec@'
9    - '@db_json_config_file@'
10   name: submit_job
11   type: sb
12  - args:
13    - '@maxdelay_sec@'
14    - '@db_json_config_file@'
15   name: update_job_status
16   type: sb
17  - args:
18    - '@dl3merger_inputdir@'
19    - '@obs_id_@'
20    - '@datarepository_id@'
21    - '@db_json_config_file@'
22   name: dl3_merger_job
23   type: ob
24  - args:
25    - '@obs_id_@'
26    - '@datarepository_id@'
27    - '@sb_id_@'
28    - '@n_of_processinglines@'
29    - '@maxdelay_sec@'
30    - '@db_json_config_file@'
31   name: data_flow_manager
32   type: ob
```

Figure 4.9 – YAML template for the configuration of the SAG-SCI daemons. The daemon arguments are set by a supervisor component, such as SAG-SUP in ACADA.

Chapter 5

Validation of SAG-SCI Performance in Observational Scenarios Simulated with the CTAO

The scientific and technical performance of **SAG-SCI** is tested using several test suites (see section 4.8) and, most notably, was verified during the ACADA Test campaign on the LST-1 in October 2023 (ACADA and CTAO-LST Project 2023). In this chapter, we crafted 5 observational scenarios relevant for **SAG-SCI**, which provide an overview of its most useful applications and test its scientific performance with simulated CTAO DL3 data.

In section 5.1 we describe the simulation process, the IRFs adopted and the sensitivity of our analyses. In section 5.2 we discuss the strategies developed to perform **SAG-SCI** analyses ensuring that all the relevant scientific results are produced, both in the context of this thesis and of a real-time environment. The first simulated observational scenario, described in section 5.3, is the observation of a **Standard Candle**: a bright, point-like, steady source with a Power Law spectrum. We use it to validate the algorithms employed in **SAG-SCI**. In section 5.4 we estimate the systematic errors on the flux when a wrong spectral model for the analysis is assumed. We use the analysis of the Standard Candle to estimate the systematic errors when incorrect values of the spectral index are assumed. In section 5.4.1 we move a step further estimating the systematic errors when the spectral curvature of a source is disregarded. This estimation is performed by analysing a simulated source with the same curved spectrum of the **Crab Nebula** at VHE (CTA-LST project et al. 2023), which is our second observational scenario. We focus our study of the systematic uncertainties on those introduced by **SAG-SCI**. A comprehensive study of other potential sources of systematic errors in CTAO analyses, such as weather variability, discretization of the MC training grid or assumption of γ -hadron separation cuts, lies beyond the scope of this work.

The following sections are used to describe observational scenarios where transient events occur and **SAG-SCI** has to generate candidate Science Alerts, according to the conditions described in section 4.7.1. In section 5.5 we discuss our third scenario, the observation of a **Flaring Source**, as it may happen to an AGN or a PWN (see section 1.6). Section 5.6 describes the scenario of the **Follow-up ToO observation of a GRB**, with a source decreasing in flux, as expected for the GRB afterglow emission (see chapter 1.6.3). In section 5.7 we discuss the scenario where the *Blind Search* algorithm (described in section 4.7.3) detects a **Serendipitous Transient** during the observation of a different nominal Scientific Target.

This scenario is particularly relevant for CTAO surveys (see chapter 3.2.1) and follow-up observations of Gravitational Waves. Finally, section 5.8 conclude the chapter by describing the software performance of SAG-SCI tasks.

5.1 Simulation of the CTAO Dataset

We adopted `gammapy v1.2` to perform all of our simulations (Donath et al. 2023; Acero et al. 2024). For every observational scenario, we simulated a Scheduling Block composed of one 1200s-long Observing Block¹ with *wobble-mode* pointing (i.e., the Scientific target is observed off-axis). The simulated scientific models are described in the relevant sections later in the chapter, though most sources have a fixed pointing-target *offset* of 0.4 deg. We simulated all data using one of the CTAO Prod5 IRFs (Cherenkov Telescope Array Observatory and Cherenkov Telescope Array Consortium 2021). We assumed observations at the CTAO-North site using a sub-array of 4 LSTs, pointed at a zenith angle of 20° and at an average azimuth angle (neither North- nor South-oriented), and using γ /hadron separation cuts optimised for a $\simeq 0.5$ h observation livetime².

We show the Effective Area of the IRFs in figure 5.1a, and the Background Spectral Model in figure 5.1b for different pointing-target offsets. We always used this model to simulate the background of our observations. The performance of the IACTs worsen off-axis, and the effective area becomes irregular due to *low-photon-statistics* for energies $\gtrsim 10$ TeV. We show the Energy Dispersion in panels 5.1c and 5.1d, evaluated at a 0.4 deg offset. They show that the particle energy is mis-reconstructed for energies $\lesssim 0.1$ TeV, with large dispersion in the Energy Migration Distribution (panel 5.1c). Taking into account these features, we restricted the analysis in the 0.1 TeV to 10 TeV energy range.

In figure 5.2 we show the Point Spread Function of the IRFs, plotted as the 68% (panel 5.2a) and 95% (panel 5.2b) containment radius of a point-like signal. The average value of the 95% containment radius for a target at a 0.4 deg offset in the 0.1 TeV to 10 TeV energy range is ≈ 0.2 deg, that we assume as radius of the ON and OFF regions in the analysis.

Sensitivity We evaluated the *sensitivity* of our analyses. It is defined (see chapter 2.3.4) as the minimum flux detectable with 5σ significance for a given observation time and spectral model. We assumed a point-like source with a Power Law spectral model (see equation (5.1)) with index 2. We estimate the significance through the Li&Ma method, assuming a pointing-target offset of 0.4 deg, 4 off regions ($\alpha = 0.25$), and we evaluate the flux through MLE (see section 2.4). Additionally, we require a minimum of 10 expected signal counts per bin and an amount of excess counts $> 10\%$ of the background counts (*Signal-to-Noise Ratio*, SNR, requirement). In figure 5.3 we show the *differential* sensitivity for a 1 h integration time. The additional requirement on SNR provide a worse sensitivity in the low-energy range with respect to the basic definition, while the *high-photon-statistics* requirement does the same in the high-energy range. In figure 5.4 we show the photon flux sensitivity as a function of the integration time in the 0.1 TeV to 10 TeV energy range; the minimum detectable flux follows a power law, as expected.

¹A Scheduling Block is usually composed by several Observing Blocks, but one is sufficient for the purposes of this thesis.

²Namely, we used the `Prod5-North-20deg-AverageAz-4LSTs.1800s-v0.1.fits` file.

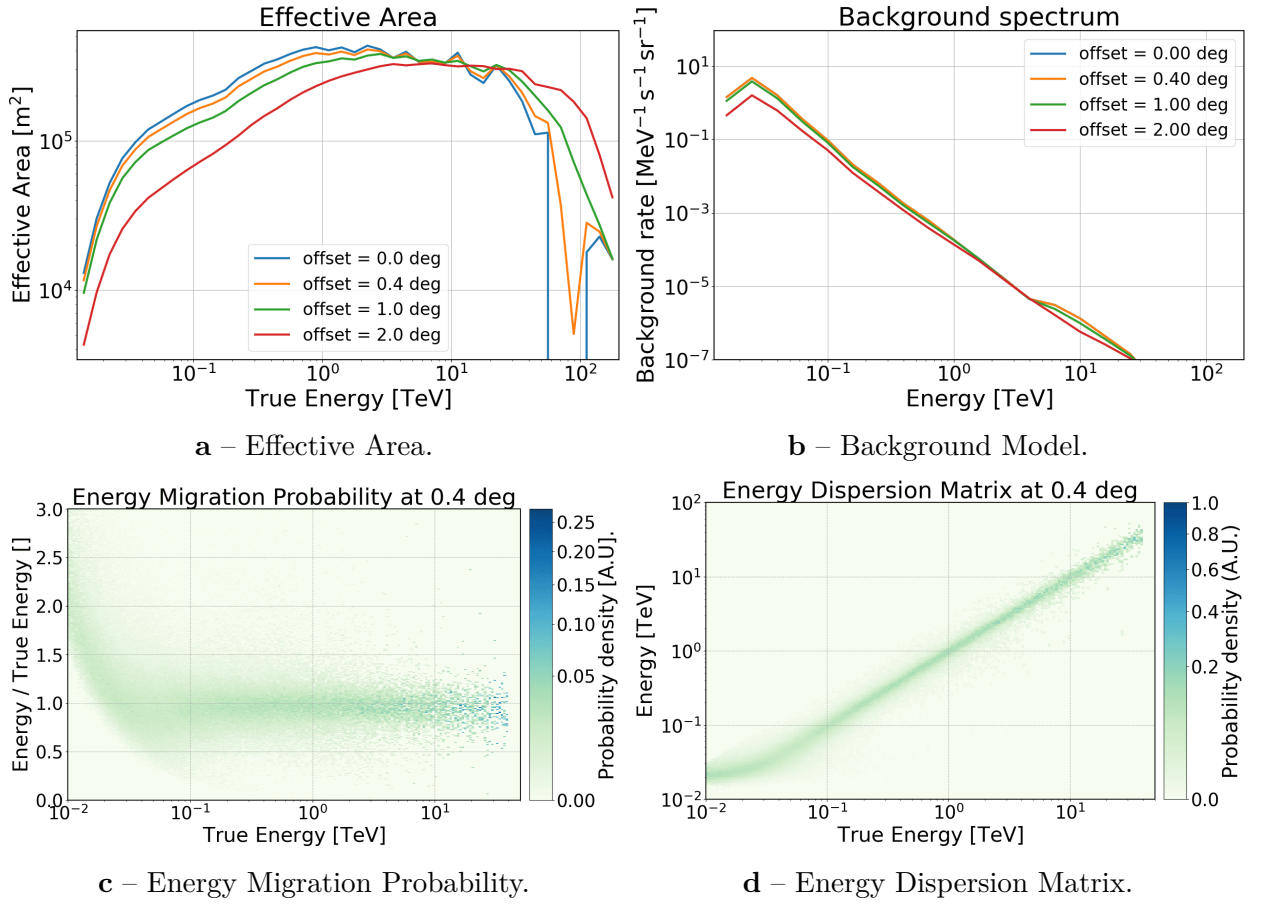


Figure 5.1 – IRFs used for the dataset simulation, evaluated at 4 offset values. Panel 5.1a shows the Effective Area, while panel 5.1b the Background Model. The Effective Area becomes highly irregular above 10 TeV due to *low-photon-statistics*. The lower panels show the Energy Dispersion Probability evaluated for a 0.4deg offset. Panel 5.1c shows the probability distribution of the energy migration (i.e. the ratio between reconstructed and true energy), and panel 5.1d shows the Energy Dispersion Matrix. They highlight a mis-reconstruction of particle energy below 0.1 TeV.

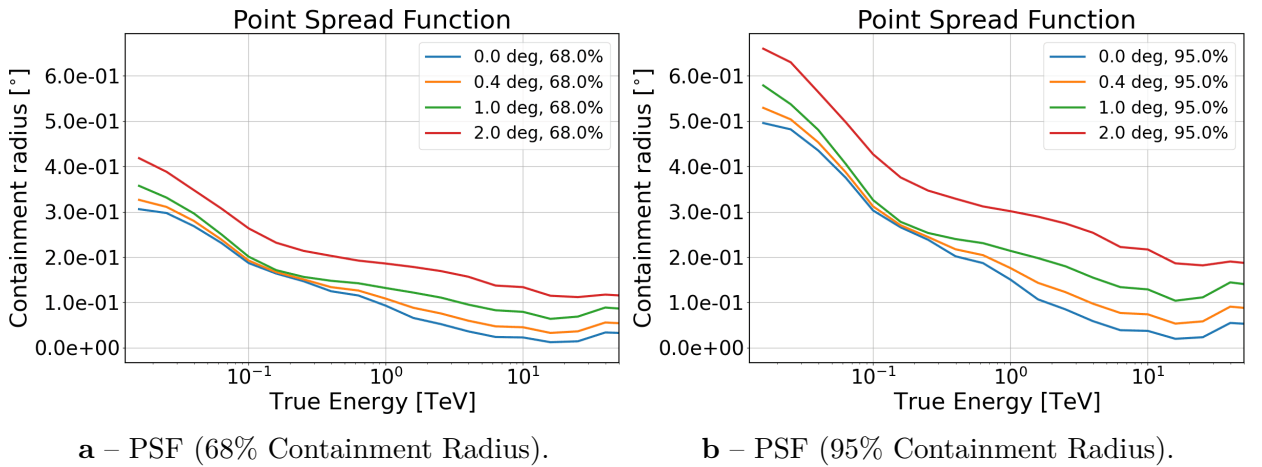


Figure 5.2 – Point Spread Function of the IRFs used for the dataset simulation, evaluated at 4 different pointing-target offsets: 0 deg, 0.4 deg, 1 deg and 2 deg. The panel shows the containment radius of 68% (panel 5.2a) and 95% (panel 5.2b) of the signal. The average value of the 95% containment radius for a 0.4deg offset in the 0.1 TeV to 10 TeV energy range is ≈ 0.2 deg, that we assume as radius of the ON and OFF regions.

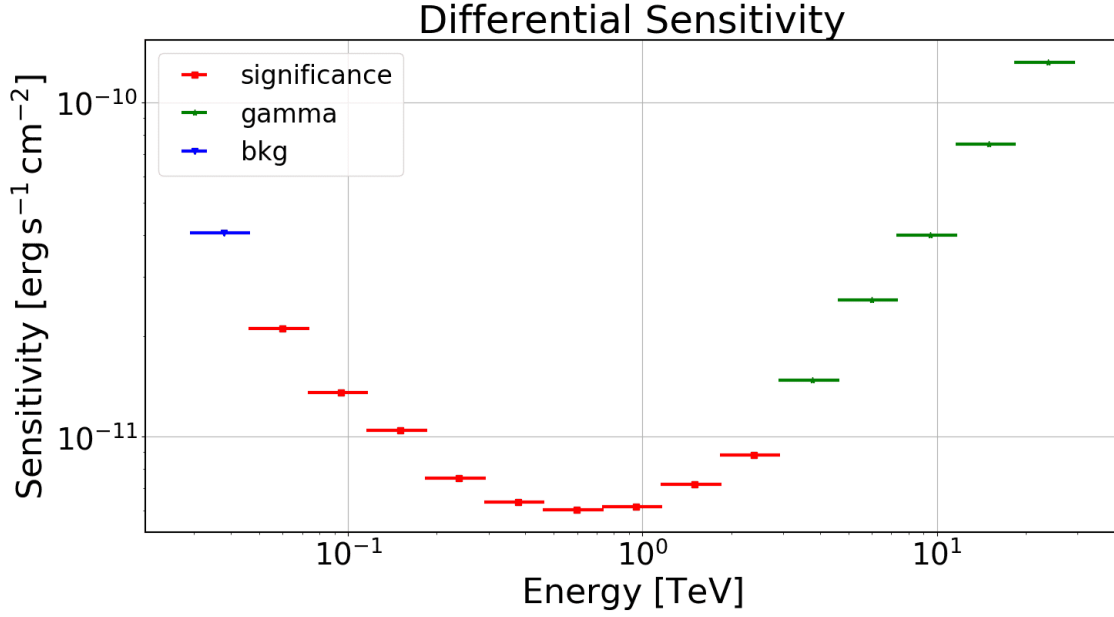


Figure 5.3 – Differential Sensitivity of the analysis. The sensitivity is defined as the minimum flux detectable with 5σ significance for a given observation time and spectral model. We show the sensitivity for 1 h integration time of a point-like source with a Power Law spectrum with index 2. We estimate the significance through the Li&Ma method, assuming $\alpha = 0.25$ (4 off regions), and evaluate the flux through MLE. Additionally, we require a minimum of 10 expected signal counts per energy bin and an amount of excess counts $> 10\%$ of the background counts (see section 2.4). The additional requirement on SNR (*high-photon-statistics*) provide a worse sensitivity in the low-energy (high-energy) range with respect to the basic definition.

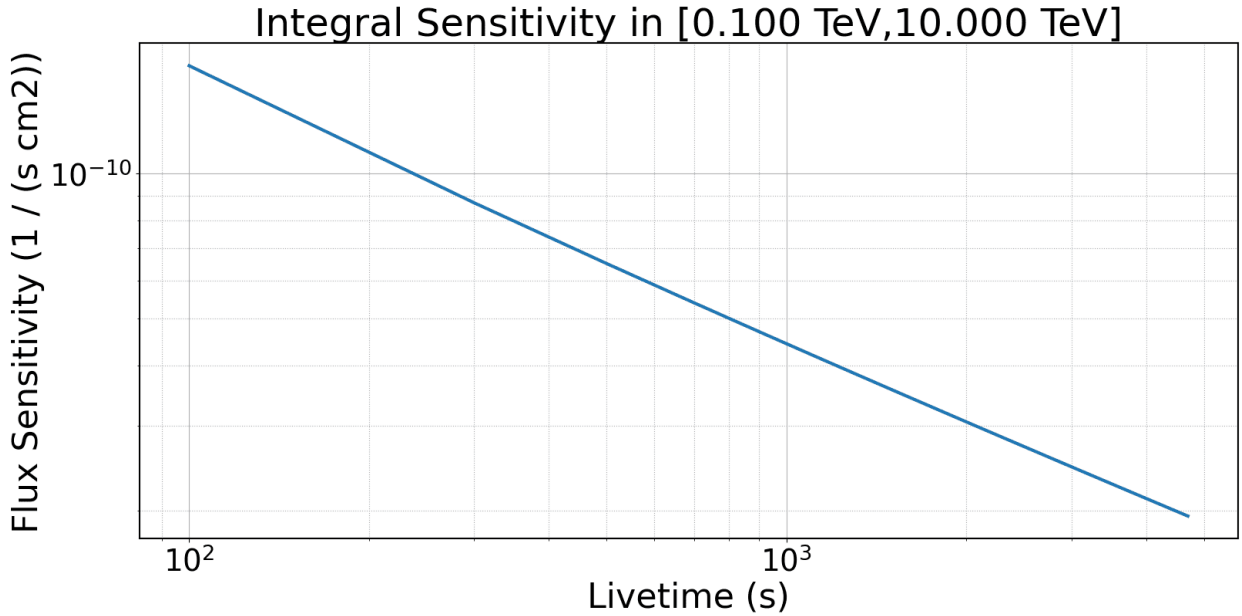


Figure 5.4 – Photon flux sensitivity as a function of the integration time in the $[0.1 - 10]$ TeV energy range. The minimum flux detectable follows a power law, as expected.

5.1.1 Dataset Preparation and Pipeline Execution

The output of one of our `gammapy` simulations is a single DL3 file containing the photon list of an Observing Block. To reproduce the arrival of SAG-RECO data in parallel lines and progressive steps (described in section 4.4.2), we set up a `DL3Splitter` python script to split the simulated DL3 file into many smaller FITS files. We assumed having 4 reconstruction lines that provide files of ≈ 10 s of data (one *step*), a setup similar to the one used for RTA-SCI on the LST-1. Our script computes the number of steps needed to cover the simulated interval with the requested step size, and the time windows covered by each step. Then, it randomly assign every event to a reconstruction line. To reproduce the de-synchronisation of the steps of different lines (see section 4.4.2 for details), the time windows of every line are randomly shifted using a Gaussian distribution with $\sigma = 0.5$ s. According to our setup, the 1200 s-long simulated photon list of an OB is split into 480 DL3 files, covering 4 parallel lines with 120 steps of ≈ 10 s of data.

Pipeline Execution. In order to execute SAG-SCI, we deployed a database dedicated to this thesis only to avoid interactions with the populations used for testing (see section 4.5). We developed a `PipelineRunner` script to run SAG-SCI that:

1. Activates the analyses requested for an Observing Block by setting their flag to 1 in `analysissessiontype` table of Pipeline DB, see section 4.4.3.
2. Reads a YAML configuration file to insert an Observation and its *nominal* Scientific Target in the DB using `sagsci.database.ConfigureDB` (see section 4.5.1).
3. Reads a YAML configuration file to activate the daemons using the `SciController` class (see section 4.9).
4. Simulates the arrival of DL3 data of the OB by copying them into the expected input directory. The script copies all the files of a step together, then waits for 5 s to copy the files of the following step, simulating the reconstruction process typical of SAG-RECO.
5. SAG-SCI automatically performs the analyses, and the script stops the daemons when we reach the expected amount of results by checking the `Results` DB.

In a *real-time analysis* scenario, the Support Astronomer and Operator access the results using a GUI developed by the ACADA HMI (see section 3.3). The LST-1 operators currently check RTA-SCI results through a GUI we developed. For this thesis, I developed a `ResultParser` script that collects the results of an OB by checking the Database, the output files, and is able to plot light curves and time series.

5.2 Strategies for Real-Time Analysis with SAG-SCI

For this thesis, we defined two types of **Parallel Analyses** performed by SAG-SCI:

1. **Light Curve and Stack.** We perform Aperture Photometry and MLE of the flux of a single target source with known position in a wobble observation, using a *sliding-window* approach with 100 s time bins. We refer to this analysis as the **Differential** analysis (see section 4.4.3). It produces *time series* of the ON (N_{ON}) and OFF (N_{OFF}) counts, the Excess counts N_{exc} , the Li&Ma significance σ , the Flux, the counts map and

θ^2 plots. The time series of the flux forms the **Light Curve** of the observed source, a primary result. Progressively *stacking* the results of each bin in the Differential analysis yields the **Stacked Analysis** results (see section 4.7), which show the source’s time-averaged properties. Examples of Differential and Stacked analysis time series are shown in the left and right panels of figure 5.5, respectively.

2. **Blind Search on Integral Analysis.** We perform an **Integral** analysis (as defined in chapter 4.4.3) with bin duration increasing by 100 s per step, yielding time-averaged results. The *high-photon-statistics* allows to perform a **Blind Search** of targets in the FoV with the **gammapy** wrapper. The most significant target found is analysed with a 1D analysis (see section 4.7.3). An example of time series can be seen in figure 5.7.

These analyses test all **SAG-SCI** features relevant for this thesis. In practice, tasks would be split into smaller, faster, parallel analyses, optimised for machine performance, for example:

- Producing θ^2 plots and Sky maps separately, with the **ACADA** HMI displaying the latest maps via GUI.
- A *Blind Search* analysis to detect *hot-spots* inconsistent with the nominal Scientific Target of the OB.
- Multiple analyses for the Scientific Target, including a 10 s Light Curve & Stack analysis to ensure timely updates for the CTAO Operator and Support Astronomer.
- A *Fast* analysis optimised to perform only AP significance computation and MLE of the flux, capable of issuing candidate Science Alerts in < 5 s of DL3 data availability, the main time requirement of **SAG-SCI** (see chapter 4.1).
- A *Slower* analysis collecting *high-photon-statistics* over larger time-scales (from several minutes to one entire OB) for *Science Monitoring* tasks like multi-parameter spectral fittings and estimation of the SED.

The performance and need for parallelisation in **SAG-SCI** are discussed in section 5.8. The 100 s binning used in this work is tailored to the simulated sources. Real-life binning would depend on the target’s properties and expected variability. In general, *Observing Modes* and *Scientific Targets* dictate the type of analysis. For instance, **Surveys** would focus on the *Blind Search*, while observations of **Extended Sources** would require the production of *Sky Maps* such as counts maps, significance maps and Flux maps. Follow-up observations of **Gravitational Waves** in a *Grid* pointing mode would need to associate the maps produced in different OBs in a single *Mosaic* with a complex exposure pattern. **Follow-up** observations of External Science Alerts would focus on the evaluation of the *Light Curve* and the *Stacked* results. Observations of **Fast Transients** (magnetar bursts, short GRBs, FRBs) may benefit from applying the *Burst Analysis* we developed (see chapter 6), although **SAG-SCI** is formally required to perform analyses only with time scales ranging from 10 s to 180 min (see chapter 4.1).

The overview of the potential analyses presented here is preliminary, as the final configuration of **SAG-SCI** will be determined at a later stage in the development of **ACADA** and **CTAO**. It is important to note that the implementation of variability algorithms (e.g., Bayesian Blocks analysis, computation of the doubling time and estimation of variability indices) is not explicitly required for **SAG-SCI**. Such algorithms are typically unnecessary for issuing Science Alerts, and they are used for more detailed analyses than the quick-look monitoring of a source, which are the two goals of **SAG-SCI**. Instead, these algorithms are more suited to off-line analyses. Nonetheless, future implementations of **SAG-SCI** may incorporate the estimation of basic variability indices.

5.3 Validation of SAG-SCI using a Standard Candle

Our first goal in this chapter is to validate the scientific performance of **SAG-SCI**, testing that we are able to detect the simulated sources and their flux is consistent with the simulated value. We also aim at comparing the performance of different wrappers (**RTAPH** vs **gammapy**) and analysis methods to ensure that all of our algorithms are self-consistent and capable to reproduce the expected values.

The *first* observational scenario we simulate is also the most simple: the observation of a **Standard Candle**, defined as a bright, point-like and steady³ source with a Power Law spectrum. The Power Law Spectrum is defined by the function:

$$\frac{dN}{dE}(E) = N_0 \left(\frac{E}{E_0} \right)^{-\Gamma}, \quad (5.1)$$

where N_0 is the amplitude, in units of $\text{ph s}^{-1} \text{cm}^{-1} \text{eV}^{-2}$, evaluated at a reference energy E_0 , and Γ is the spectral index. We simulated a Standard Candle with index $\Gamma = 2$ and amplitude $N_0 = 10^{-11} \text{ s}^{-1} \text{cm}^{-2} \text{TeV}^{-1}$ at a reference energy $E_0 = 1 \text{ TeV}$. Its photon flux in the 0.1 TeV to 10 TeV is constant at value $\phi = 9.9 \cdot 10^{-11} \text{ s}^{-1} \text{cm}^{-2}$ according to equation (1.6). According to our IRFs sensitivity (figure 5.4), the source is detectable in $\approx 100 \text{ s}$ to 200 s .

5.3.1 Validation of the Gammapy Wrapper

In figure 5.5 we report the Aperture Photometry results of the **Differential** (left panels) and **Stacked** (right panels) analyses performed with the **gammapy** wrapper, and defined in section 5.2. Panel 5.5a shows the ON counts (N_{ON}) and the Background counts ($\alpha \cdot N_{\text{OFF}}$); they are approximately constant and subject to statistical fluctuations as expected. Their difference in panel 5.5c is the N_{exc} light curve associated with the source emission; we performed a linear fit to verify that it is consistent with a constant time series, as expected from a steady source. Panel 5.5e shows the Li&Ma significance (σ) of every bin, that fluctuates mainly between 3 and 5; two bins have significance < 3 and one > 5 . The time series of the σ is a set of statistically independent trials used to detect a steady source, thus we need to correct them for the number of trials. For instance, the last bin has pre-trial $\sigma = 5.35$, that corresponds to $\sigma = 4.88$ assuming 12 trials (we discuss the *post-trial* correction later in chapter 6.9). Panel 5.5g shows the photon flux light curve in the 0.1 TeV to 10 TeV energy range, compared with the simulated flux (red line). Flux points are consistent with the simulated value within errors, which include only statistical errors of the **gammapy** flux fit.

The right panels in figure 5.5 show the *Stacked* results. Panel 5.5b shows the stacked N_{ON} and background counts, obtained by summing the data of a bin with the previous results. This makes panel 5.5b the cumulative version of panel 5.5a. Panel 5.5d shows the stacked N_{exc} , that are $\propto$ the integration time as expected. The linear correlation is strongly significant: we performed a linear fit and rejected the null hypothesis of “not correlated values” with a p-value of $1.1 \cdot 10^{-13}$ (7σ significance). The stacked significance of the source shown in panel 5.5f. It is $\propto \sqrt{t}$ as expected and verified by the fit shown in the picture. Our *Standard Candle* is detected in the third bin (300 s integration time), in agreement with the expected detection time of $\sim 200 \text{ s}$. Panel 5.5h shows the stacked flux, which represents the

³I.e., not variable in time.

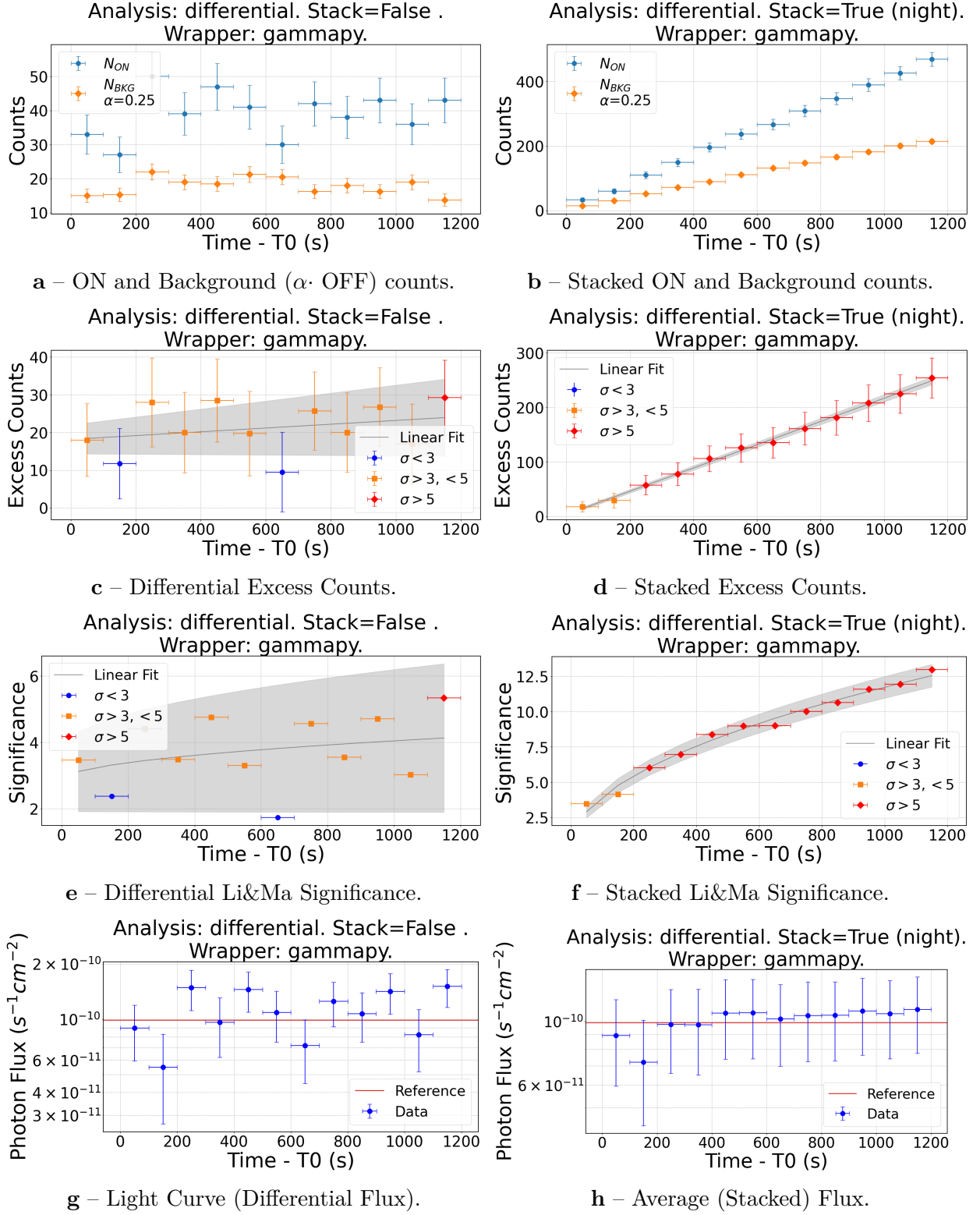


Figure 5.5 – Results of the Differential (left panels) and Stacked (right panels) analyses of a *Standard Candle*. The source is detected in the expected time and its photon flux is consistent with the simulated value, shown as a red line in the flux panels.

average flux from the start of the observation to the current data point. It is consistent with the simulated value within the (propagated) statistical errors.

We computed the Counts Maps and the θ^2 plots in every analysis bin, and we report those of the fourth bin in figure 5.6. We show the counts map (panel 5.6a) and θ^2 plot (panel 5.6c) of the *Differential* analysis, and the corresponding *stacked* counts map (panel 5.6b) and θ^2 plot (panel 5.6d) integrated over 400 s. The significance reported in the θ^2 plots differs from the one reported in figure 5.5 for the same bin due to using only one OFF region and computing α as the acceptance ratio, without the assumption of symmetrical response from the telescope (see chapter 2.4). As $\alpha \approx 1$, we verified that the response of the telescope is radially symmetric.

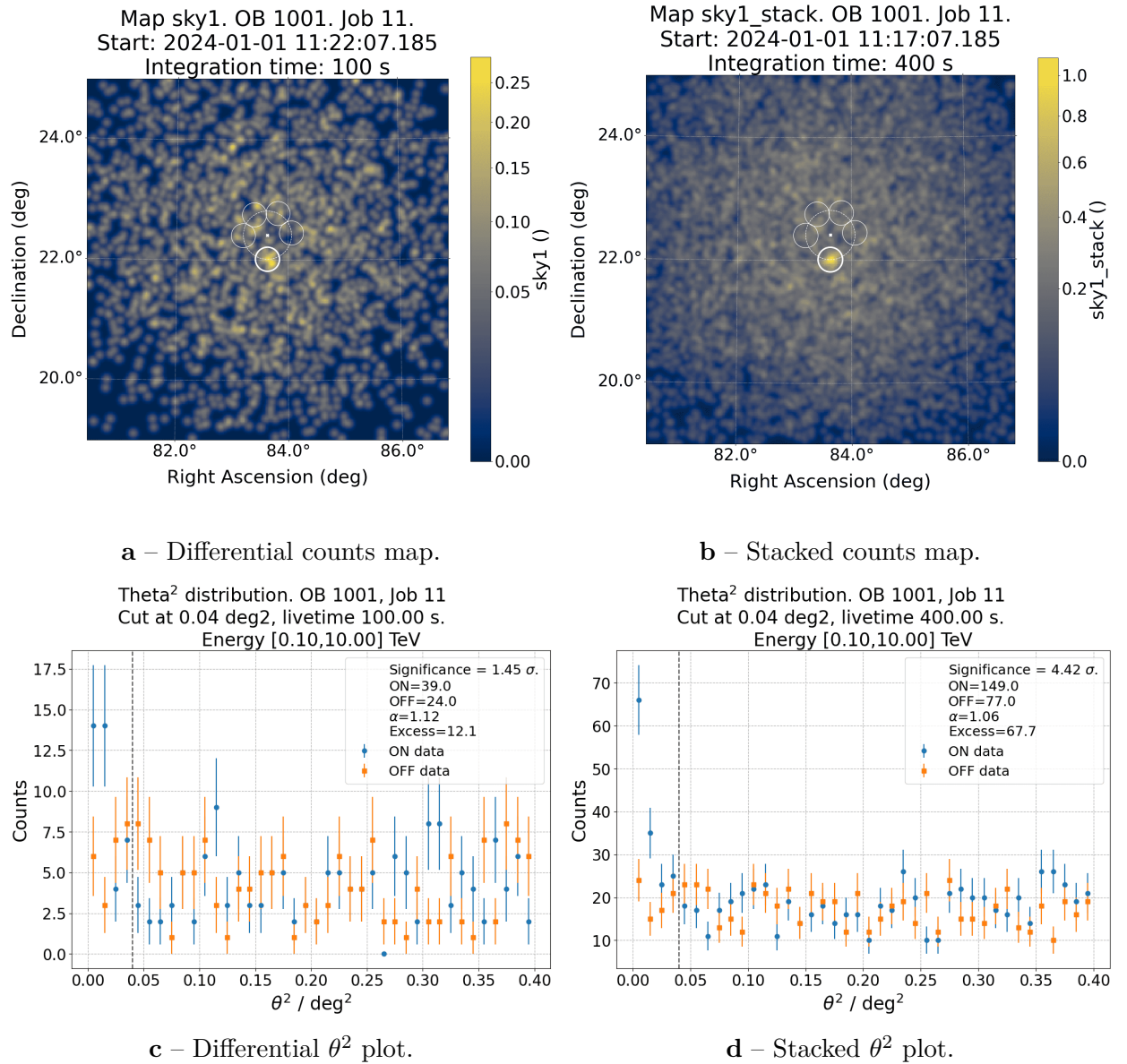


Figure 5.6 – Comparison of counts map and θ^2 plots of the fourth bin of the Differential and Stacked analyses on a Standard Candle. The counts maps highlight the ON region (thick circle) and the OFF regions used to estimate the background (thin circles), that are distributed on a circle with the same offset of the target with respect to the array pointing.

5.3.2 Validation of the Stacking and Blind Search Algorithms

To validate the **Stacking** algorithm, we performed an **Integral** analysis. While in the *Differential + Stacked* analysis we analyse each 100 s time bin independently and then stack the results, in the *Integral* analysis we analyse the same data multiple times, using time bins of increasing size and querying all events from the start of the observation. We thus expect the Integral and Stacked results to be the same, and we compare them in figure 5.7. We verify that N_{ON} , N_{OFF} , N_{exc} , σ and the Flux of the Stacked and Integral analyses are equal. We note that the flux errors of the Integral analysis (statistical errors from the **gammapy** spectral fit) are smaller than those of the Stacked analysis, more reliable as they are obtained from the propagation of uncertainties. In figure 5.8a we plot the counts map obtained from the Integral analysis, which is consistent with the Stacked counts map of figure 5.6b. In figure 5.8b we show the Integral θ^2 plot, consistent with the Stacked one in figure 5.6d. These comparisons validate our stacking algorithm.

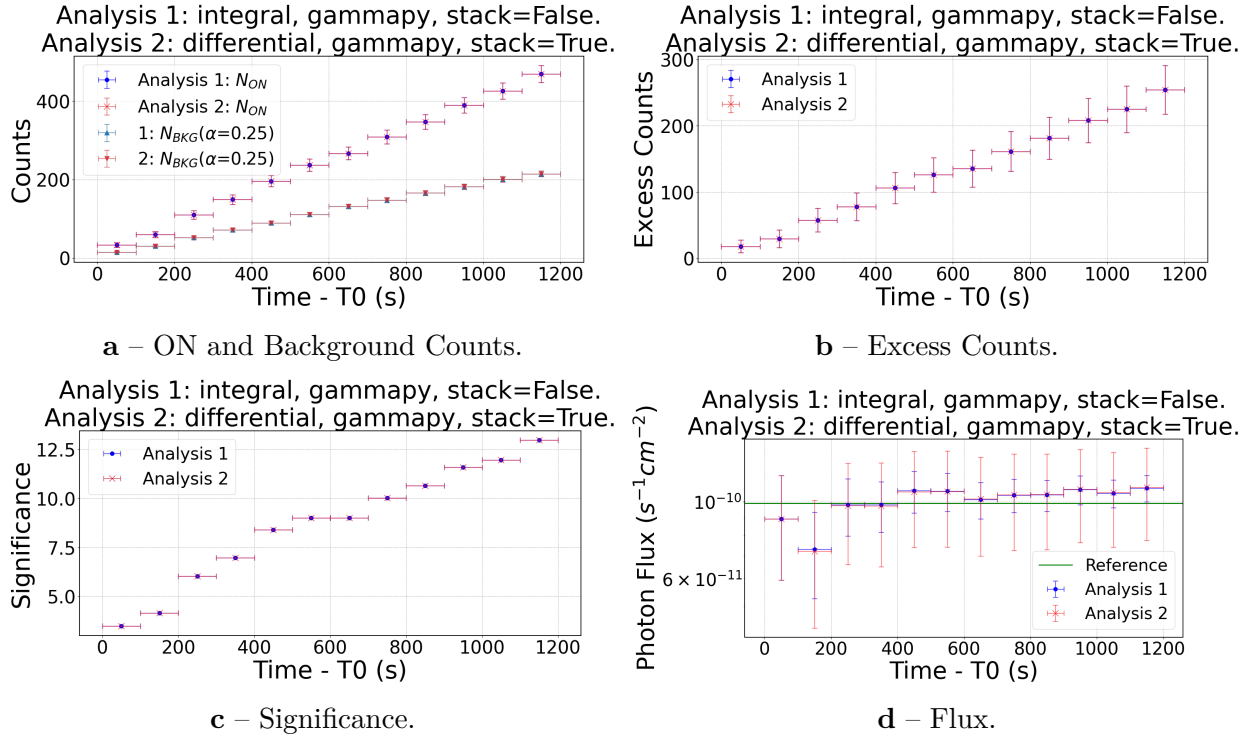


Figure 5.7 – Comparison between Aperture Photometry results of the Stacked and Integral analyses of a Standard Candle. They are consistent and validate the stacking algorithm.

One of the tasks of the *Integral* analysis we performed was the **Blind Search** for hot-spots in the FoV. We report the signed $\sqrt{TS}$ map used to search for hot-spots in figure 5.9. The TS is the CSTAT statistics described in appendix A.2.1 and does *not* correspond to the Li&Ma significance, which must be evaluated with a dedicated 1D analysis centred on the hot-spot's coordinates. The hot-spot with the simulated source is detected with $\sqrt{TS} = 8.2$. Other spots in the map represent fluctuations with $\sqrt{TS} > 3.0$. The hot-spots identified by the Blind Search are listed in order of $\sqrt{TS}$, and the most significant is analysed with the Li&Ma method. In case an hot-spot is spatially consistent with the nominal Scientific Target (i.e., their distance is less than the ON region radius), the Target coordinates can either be *updated*, *kept* equal to the configured values, or the hot-spot can be *discarded* altogether to focus only on new source candidates. For the analysis of the Standard Candle we kept the

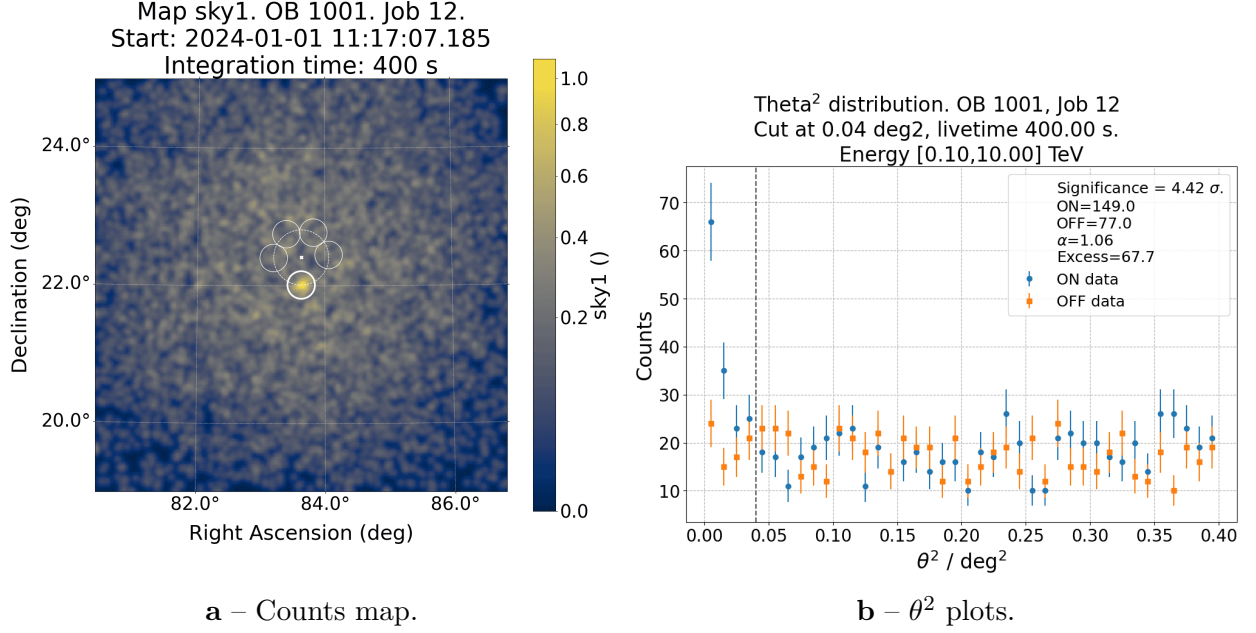


Figure 5.8 – Counts map (panel 5.8a) and θ^2 plot (panel 5.8b) of the fourth bin of the Integral analysis of a Standard Candle. They are consistent with the same plots of the Stacked analysis shown in figures 5.6b and 5.6d, respectively, validating the stacking algorithm.

nominal coordinates to allow for a direct comparison of the *Integral* and *Stacked* results. Analyses which aim at *localising* a target will have to update the results. Analyses dedicated to the searching for *new transients* will discard the Target to focus only on new sources. We show examples of these types of Blind Search later in section 5.7.

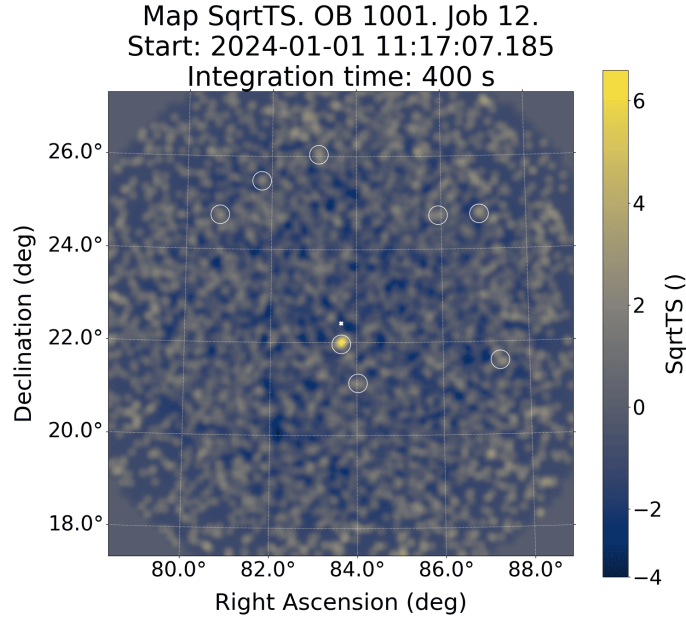


Figure 5.9 – Blind Search on the FoV during the fourth bin of the Integral analysis of a Standard Candle. We show the $\sqrt{TS}$ Map and the hot-spots in the circles. The Standard Candle is visible in the brightest spot with $\sqrt{TS} = 8.2$. Dimmer hot-spots are fluctuation with $\sqrt{TS} > 3.0$ (the minimum TS threshold can be configured).

5.3.3 Validation of the RTAPH Wrapper

We performed a Differential and Stacked analysis with RTAPH to ensure that the wrappers produce compatible results. We compare the Differential Aperture Photometry results of RTAPH and `gammapy` in figure 5.10. We note that N_{ON} are equal as expected (panel 5.10a). The N_{OFF} , N_{exc} and σ are different due to the different OFF regions used, but still compatible (panels 5.10a, 5.10b, 5.10c and 5.10d). The values of the Flux estimated are different due to the different background and algorithm used (MLE fit for `gammapy`, estimation of excess over exposure for RTAPH), but they are consistent within the errors with the simulated value. The RTAPH counts map of the fourth bin is reported in figure 5.11.

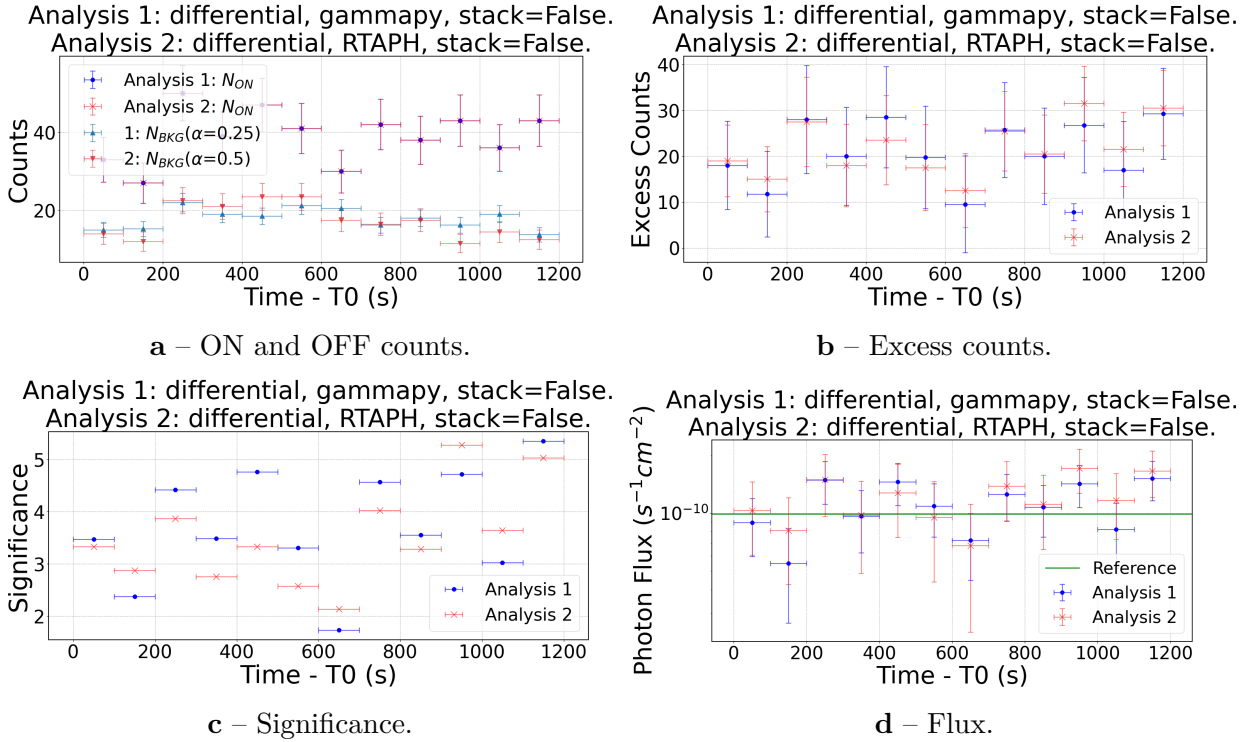


Figure 5.10 – Comparison between the Aperture Photometry results of the Differential analyses of `gammapy` and RTAPH wrappers. Difference in the OFF counts, excess counts, significance and flux can be attributed to a different choice of OFF regions. The OFF regions used by the `gammapy` wrappers are shown in figure 5.6a, those used by the RTAPH wrapper in figure 5.11. The Light Curves are consistent within errors with the simulated values.

5.4 Estimation of Systematic Errors due to Spectral Uncertainty

The estimation of the Exposure, and thus the Flux, always depends on the *assumed* spectral model for the analysis, as its calculation over a given energy range is weighted by the assumed spectrum. This dependence arises because the exposure is influenced by the MC reconstruction efficiency, which varies with the spectral shape (see section 2.3.3). The analyses showed in section 5.3 were able to reproduce the simulated flux because we adopted the same spectrum shape (a Power Law) and the same spectral index ($\Gamma = 2$) used for the simulation.

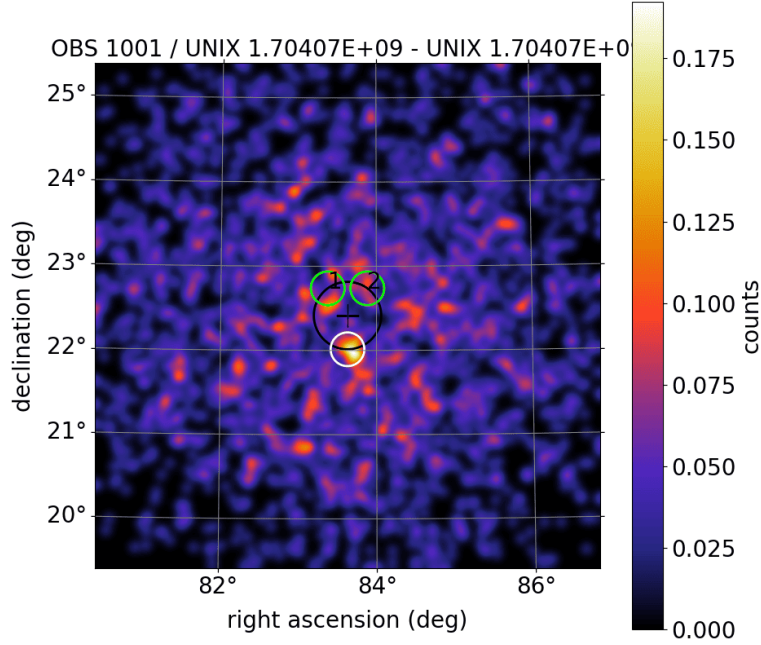


Figure 5.11 – Example of a counts map of the RTAPH wrapper, taken from the fourth bin of the Differential analysis.

In a *real-time analysis* environment, the spectral shape and index of the nominal Scientific Targets are often not known, and assuming the wrong value *will* cause a systematic error.

We performed an estimation of the systematic error caused by assuming a wrong spectral index by running the analyses shown in section 5.3 on the Standard Candle, but assuming *incorrect* indexes by $\pm 20\%$, namely $\Gamma = 1.6$ and $\Gamma = 2.4$. We compare the fluxes estimated with wrong indexes in figure 5.12 and their ratio. Assuming a 20% *harder* index (i.e. $\Gamma = 1.6$) results in an underestimation of the flux by $\approx 35\%$ in average (because we overestimate the exposure), while assuming a 20% *softer* index (i.e. $\Gamma = 2.4$) results in an overestimation of the flux by $\approx 25\%$. To produce reliable results with SAG-SCI, we need to add a (configurable) systematic uncertainty when computing the flux errors. If we introduce a $\approx 30\%$ systematic uncertainty, we can take into account the assumption of a 20% incorrect index.

5.4.1 Observations of a Crab-like Source with a Curved Spectrum

Another source of systematic errors during a spectral analysis is the presence of *curvature* in the spectrum. Currently, SAG-SCI always assumes a Power Law spectrum, which is not curved⁴, but VHE γ -ray sources such as PWNe (like the Crab Nebula, e.g., CTA-LST project et al. 2023) may show curvature. Even if future versions of SAG-SCI will employ more complex models, most Scientific Targets are not described with the same accuracy of the Crab Nebula and their curvature may not be well characterised. In this section, we aim at evaluating the systematic error introduced by disregarding the spectral *curvature* when estimating the flux.

⁴In a log-log representation.

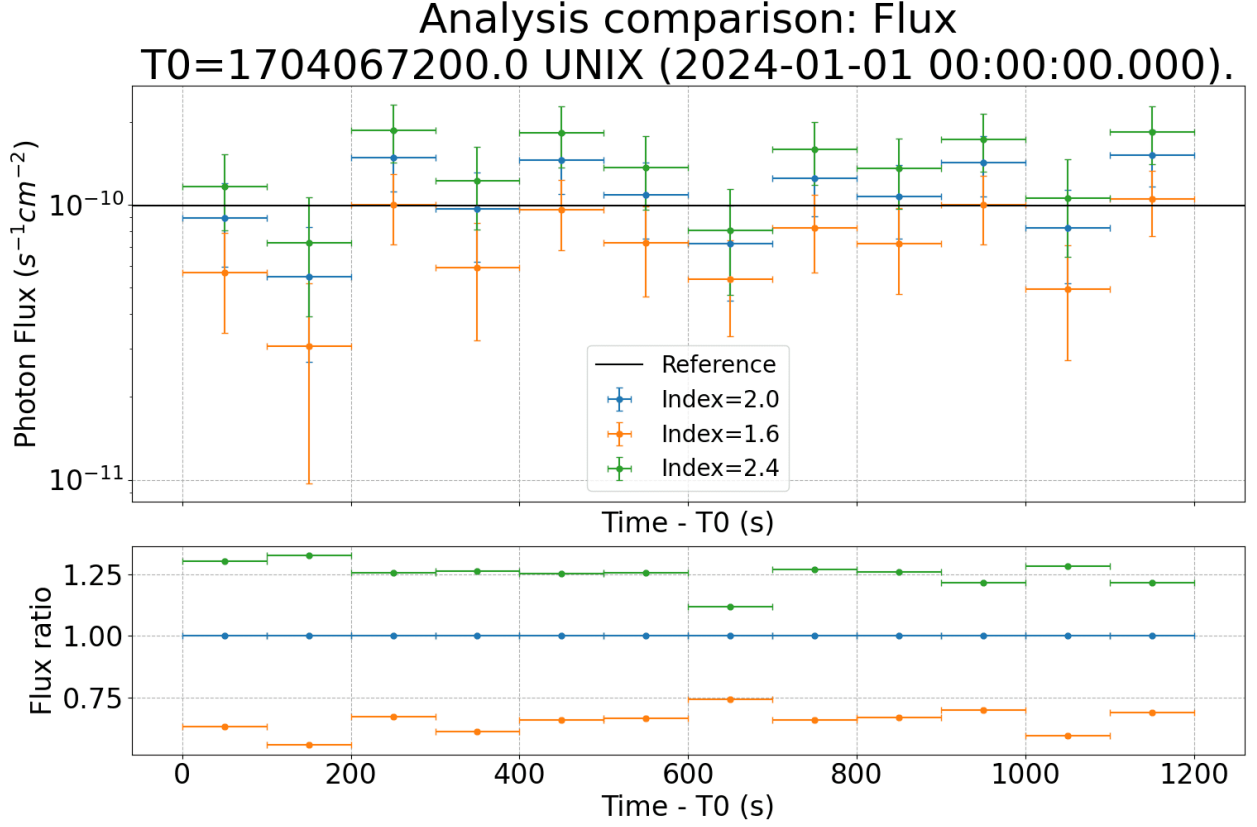


Figure 5.12 – Evaluation of systematic errors when the assumed spectral index is incorrect by $\pm 20\%$. A $\approx 30\%$ systematic uncertainty can be used to take into account the spectral uncertainty.

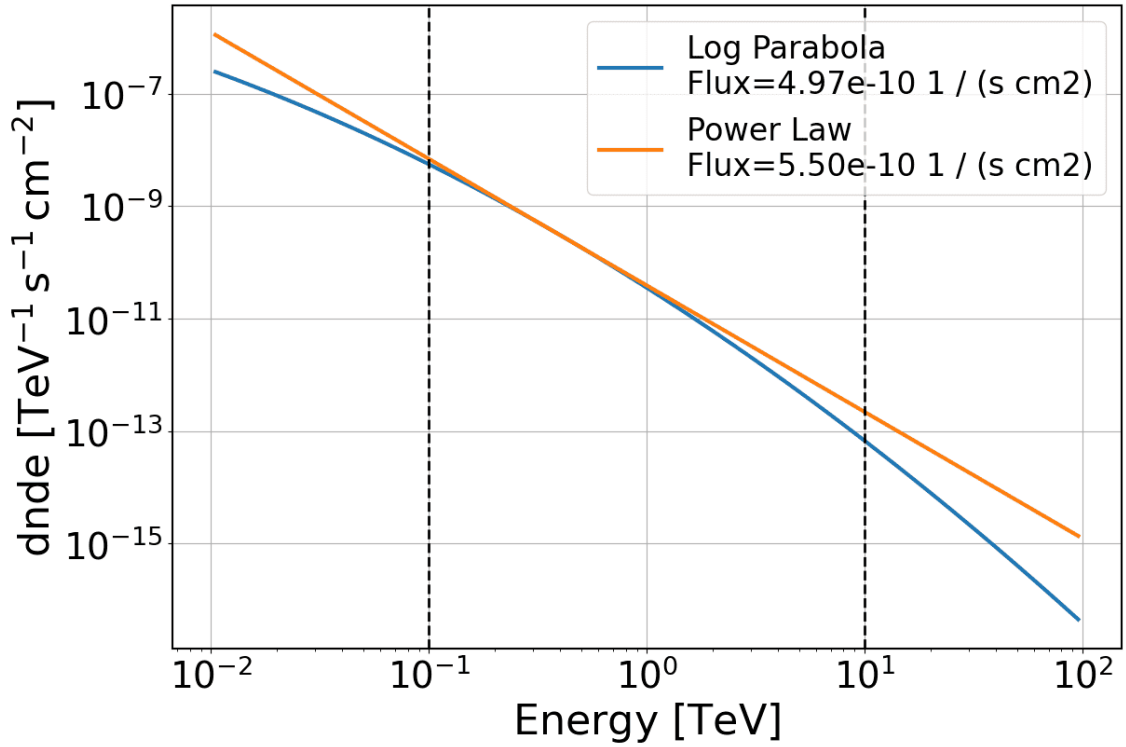


Figure 5.13 – Comparison between Spectral Models of a Crab-like source. In blue we show the *Log-Parabola* model determined in CTA-LST project et al. (2023), that has a photon flux $\phi = 4.97 \cdot 10^{-10} s^{-1}cm^{-2}$ in the 0.1 TeV to 10 TeV range. In orange we show its *Power Law* approximation, with flux $\phi = 5.50 \cdot 10^{-10} s^{-1}cm^{-2}$, that overestimates the true value by $\approx 10\%$.

The *second* scenario we simulate is thus the observation of the **Crab Nebula**, that has a *Log-Parabola* curved spectrum, defined as:

$$\frac{dN}{dE}(E) = N_0 \left(\frac{E}{E_0} \right)^{-\Gamma - \beta \ln\left(\frac{E}{E_0}\right)}. \quad (5.2)$$

The Power Law described in equation 5.1 is a special case of the Log-Parabola with curvature parameter $\beta = 0$. The Log-Parabola spectrum is used to reproduce the Inverse Compton bump observed in this energy range in the Crab Nebula spectrum and other PWNe (see section 1.6). We used the Crab Nebula parameters estimated in CTA-LST project et al. (2023) with the LST-1: amplitude $N_0 = 3.05 \cdot 10^{-10} \text{ s}^{-1} \text{ cm}^{-2} \text{ TeV}^{-1}$ at a reference energy $E_0 = 0.4 \text{ TeV}$, spectral index $\Gamma = 2.25$ and $\beta = 0.114$. For comparison with the other sources described in this chapter, the amplitude at 1 TeV is $3.53 \cdot 10^{-11} \text{ s}^{-1} \text{ cm}^{-2} \text{ TeV}^{-1}$. Its photon flux in the 0.1 TeV to 10 TeV is $\phi = 4.97 \cdot 10^{-10} \text{ s}^{-1} \text{ cm}^{-2}$ and constant. According to the sensitivity curve of our IRFs (see figure 5.4), the source is detectable in $\lesssim 100 \text{ s}$. In figure 5.13 we show the difference between the *Log-Parabola* spectral model and its *Power Law* approximation, i.e. the model obtained by placing $\beta = 0$ and keeping the same N_0 , E_0 and Γ . Its photon flux is $\phi = 5.50 \cdot 10^{-10} \text{ s}^{-1} \text{ cm}^{-2}$ in the 0.1 TeV to 10 TeV range, overestimating the true value by $\approx 10\%$.

We analysed a 1200 s-long OB in wobble-mode of the simulated *Crab-like* source with SAG-SCI assuming a Power Law spectrum with index $\Gamma = 2.25$. In figure 5.14, we show the Aperture Photometry results of the Differential (left panels) and Stacked (right panels) analyses. The source is detected in every bin as expected, and its flux is consistent with the expected value under the Power Law approximation, overestimating the true value by $\approx 10\%$. Introducing an additional 10% systematic uncertainty in the flux error computation can help account for disregarding the *curvature* of the spectrum. We note that our estimation is based on the Crab Nebula spectrum in the 0.1 TeV to 10 TeV energy range, but the Power Law and Log-Parabola models have larger differences above 10 TeV. In general, different spectral models and energy ranges may lead to different systematic errors.

We note that CTAO analyses may include other potential sources of systematic errors, such as weather variability, discretization of the MC training grid, or assumption of γ -hadron separation cuts. A comprehensive study of these effects, which are not specifically dependent on SAG-SCI, lies beyond the scope of this work.

5.5 Science Alert Generation: Detection of a Gamma-ray Flare

We begin now to craft observational scenarios that include transient sources and in which SAG-SCI will have to issue a candidate Science Alert. We discussed the conditions to generate candidate Science Alerts in chapter 4.7.1. One of them is the detection of a **Gamma-ray Flare** of a known source that is being monitored. Usually, the scientific community is alerted of ongoing Flares through external Science Alerts, namely GCN notices, circulars and ATels (see section 3.1.1). When a source undergoes a flare, CTAO receives an external Science Alert, repositions its telescopes and starts observing the source. SAG-SCI will be required to compute the flux of the source, and compare it with a quiescent-state level read from a catalogue. It will issue a candidate Science Alert if detects any variability in the analysed

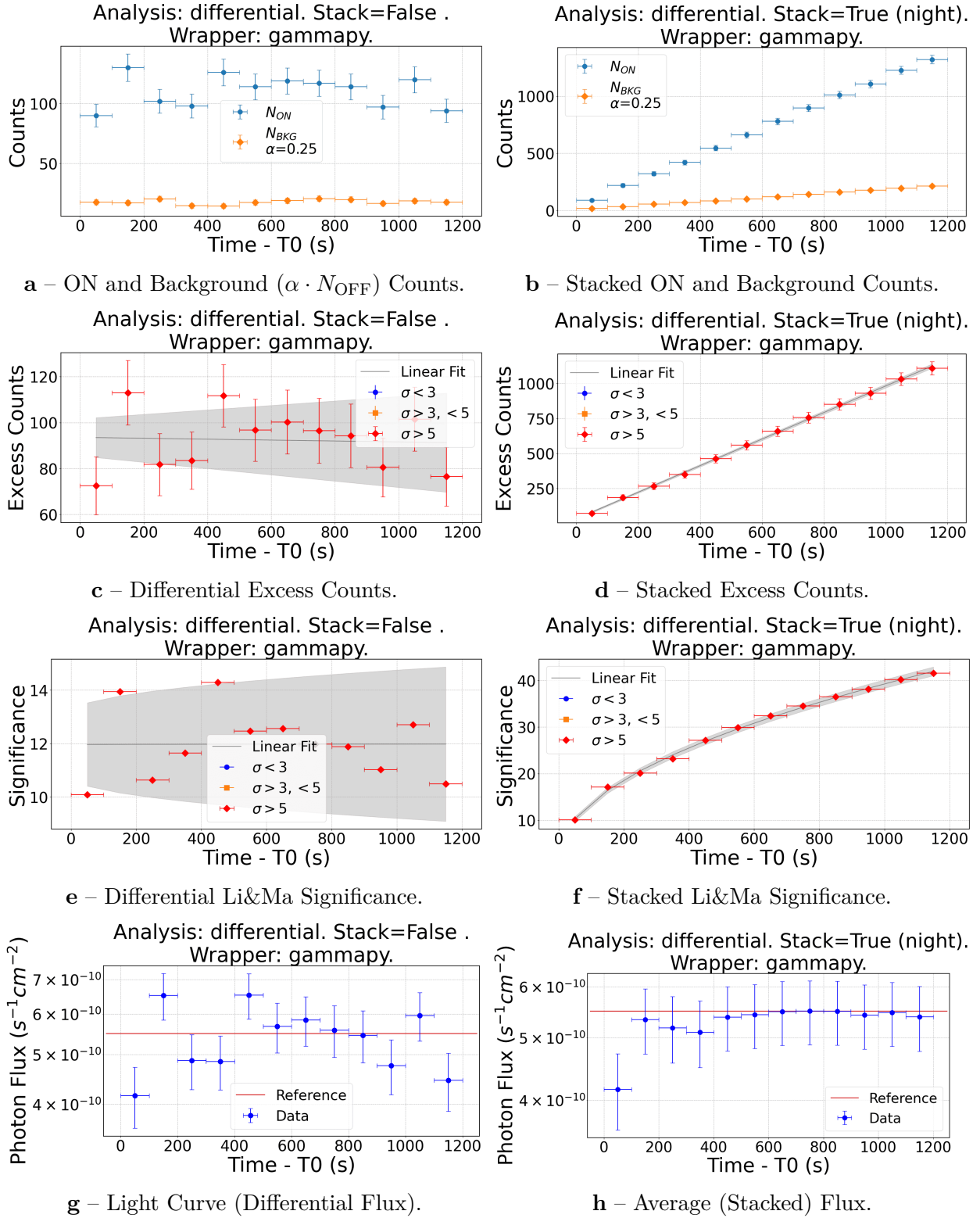


Figure 5.14 – Results of the Differential (left panels) and Stacked (right panels) analyses of a Crab-like source. The source is detected in the expected time and its flux is consistent with the reference value in Power Law approximation.

energy range. From an operational point of view, this scenario is similar to those described in sections 5.3 and 5.4.1. In this section, we discuss a scenario where CTAO would play a more active role: we simulated a source *undergoing* a flare during an observation, and CTAO would be the first observatory to issue a Science Alert.

We simulated a point-like, Power Law source, see equation (5.1), assuming spectral amplitude $N_0 = 7 \cdot 10^{-12} \text{ s}^{-1} \text{ cm}^{-2} \text{ TeV}^{-1}$ at a reference energy $E_0 = 1 \text{ TeV}$ and spectral index $\Gamma = 2$. This model represents the *quiescent* state of the source, with a photon flux $\phi = 6.93 \cdot 10^{-11} \text{ s}^{-1} \text{ cm}^{-2}$ in the 0.1 TeV to 10 TeV range, detectable in $\approx 500 \text{ s}$ according to the sensitivity in figure 5.4. We simulated a *flare* component by defining a piece-wise *Exponential Decay Temporal Model*:

$$f(t) = \begin{cases} 1 & \text{if } t < t_0, \\ \max(f_0 \cdot \exp(-\frac{t-t_0}{\tau}), 1) & \text{if } t > t_0, \end{cases} \quad (5.3)$$

where $f(t)$ is an adimensional temporal modulation factor which multiplies the spectral model. In equation (5.3) t_0 represents the *Burst Onset*, and the source is at its quiescent level before ($f = 1$) before t_0 . We show the temporal model we assumed in figure 5.15. After t_0 , the flux is modulated by the exponential term with temporal amplitude $f_0 = 10$ (which represents the flux increase at the beginning of the flare), decay time scale $\tau = 300 \text{ s}$, and burst starting at $t_0 = 400 \text{ s}$ after the beginning of the Observing Block (which lasts 1200 s). When the exponential function becomes < 1 , we imposed $f(t) = 1$ to avoid going under the pre-flare flux level.

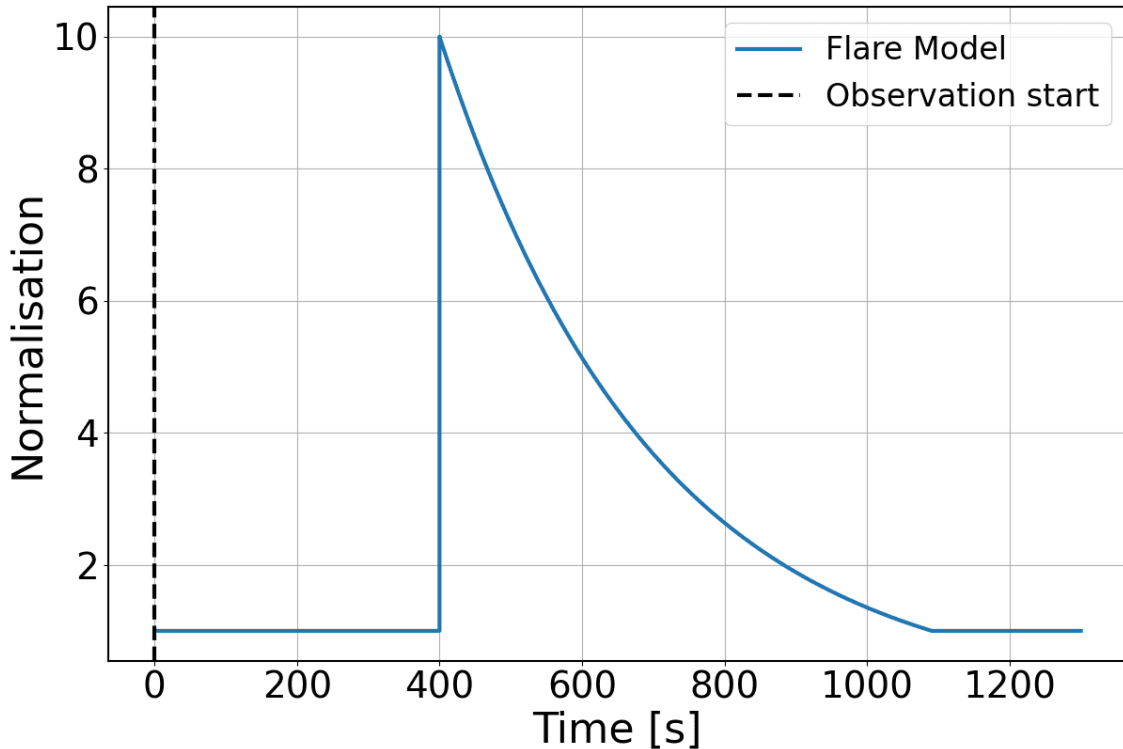


Figure 5.15 – Temporal model used to describe a flare from a γ -ray source. We show the modulation (or normalisation) factor $f(t)$ which multiplies the Spectral Model (a Power Law). The factor is 1 before the burst onset at $t_0 = 400 \text{ s}$ (relative to the OB start), then it follows the Exponential Decay function described in equation (5.3), and it is set equal to 1 at larger times when the exponential function is < 1 (after $\approx 1100 \text{ s}$).

We show the Differential results in figure 5.16. The flare is detected from the fifth bin

as expected, and its flux is consistent with the simulated value. The average flux measured in the fifth bin, at the beginning of the burst, is $\phi = 6.6 \cdot 10^{-10} \text{ s}^{-1} \text{ cm}^{-2}$, which is 10 times larger than the quiescent value. A future implementation of SAG-SCI will include the `ScienceAlertManager` class (see chapter 4.7.1) to compare the measured flux with the quiescent-state value read from a catalogue. As the source is detected in a single 100 s bin with significance $\sigma > 5$ and its flux is “significantly higher” than the quiescent value, the `ScienceAlertManager` would issue a candidate Science Alert. The threshold of flux enhancement needed to consider the Target in a flaring state is not fixed and, according to SAG-SCI requirements (see section 4.1) must be configurable. For this analysis, we detected a flux 10 times higher than the quiescent value, and we consider it sufficient to issue a candidate Science Alert. The ACADA TH and HMI would be notified, and the Operator and the Support Astronomer in the control room would be able to check the results in real-time. They would also check auxiliary results such as the Counts Maps, that we show in figure 5.17a for the fourth bin and in figure 5.17b for the fifth bin.

We also performed an Integral analysis with Blind Search, selecting hot-spots with $\sqrt{TS} > 4$. We show the $\sqrt{TS}$ maps of the fourth and fifth bin in panels 5.17c and 5.17d. The source is identified as a candidate hot-spot even before the flare, but its $\sqrt{TS}$ strongly increases from 6.3 to 13.5 after the flare. Let us note again that the TS of the Blind Search is the CSTAT statistics described in appendix A.2.1 and does not correspond to the Li&Ma statistical significance σ , which must always be evaluated with a dedicated 1D analysis centred on the hot-spots coordinates.

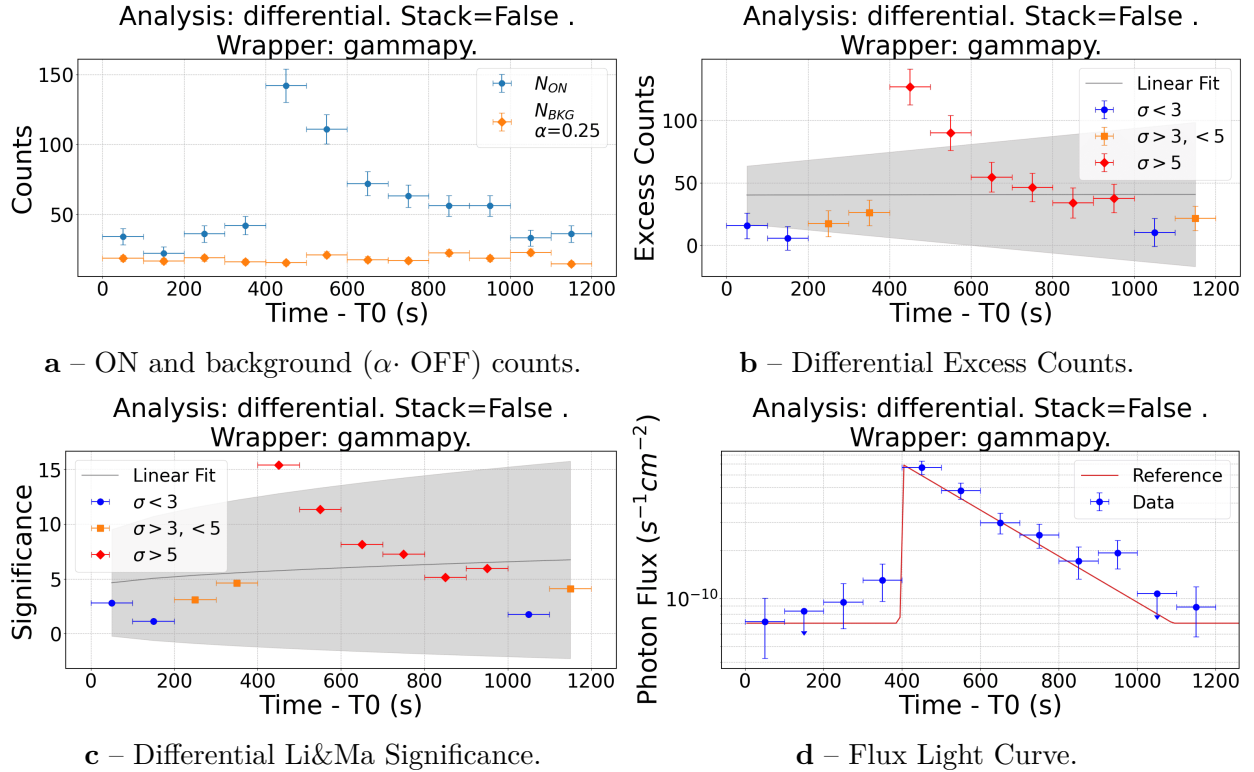


Figure 5.16 – Results of the Differential analysis of a Flaring source. The flare is visible from the fifth bin, as expected. The Light Curve flux is consistent with the simulated values.

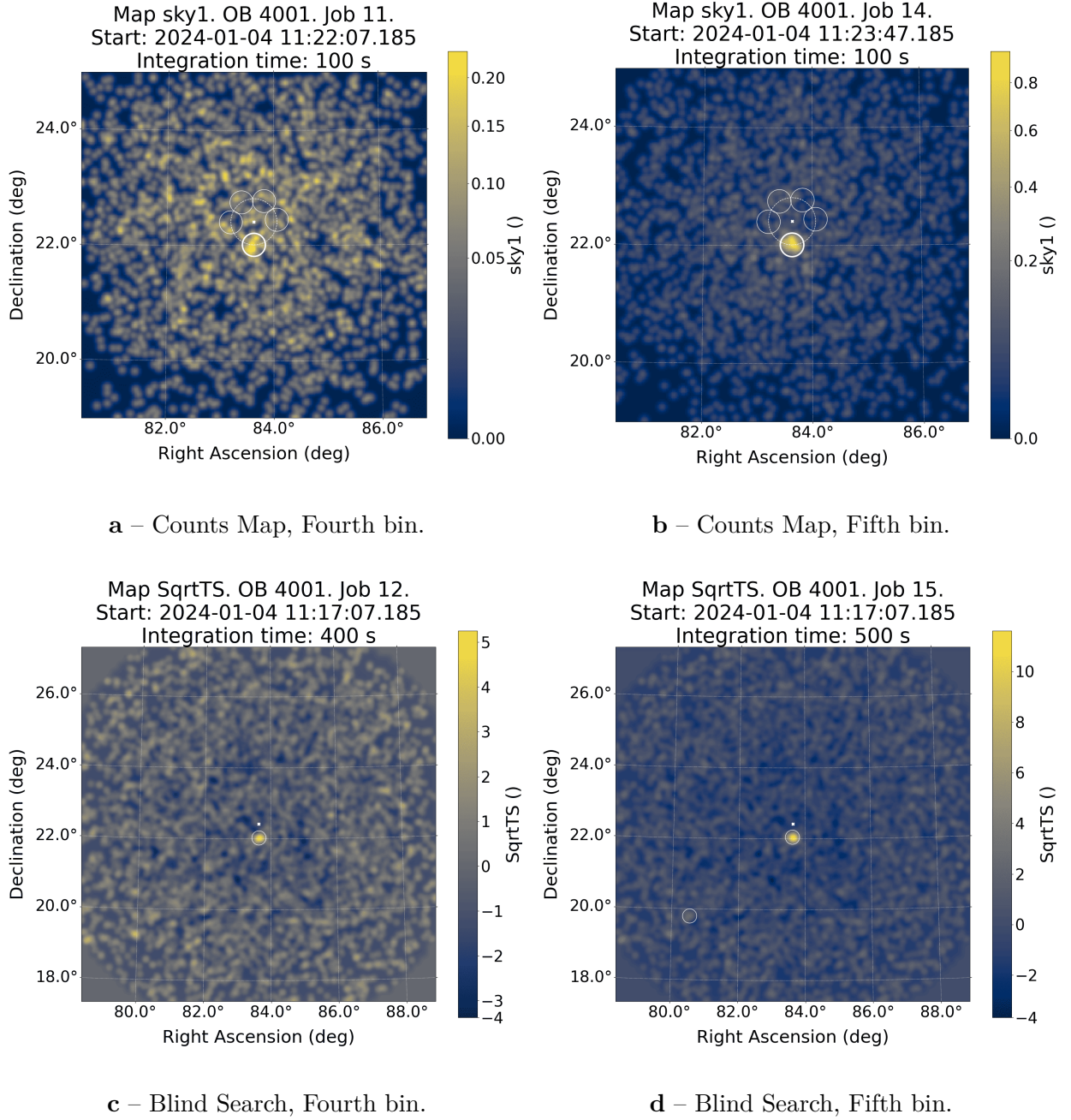


Figure 5.17 – Comparison between Sky Maps of the fourth bin (left panels) and fifth bin (right panels) of the analysis, i.e. before and at the beginning of the flare. Panels 5.17a and 5.17b show the Differential Counts Maps (100s integration). The flaring state of the source in the fifth bin allows it to appear brighter on the background. Panels 5.17c and 5.17d show the Integral $\sqrt{TS}$ Maps with the hot-spots found by the Blind Search. The simulated source is identified in the fourth bin (quiescent state, 400s integration) with $\sqrt{TS} = 6.3$, but it jumps to $\sqrt{TS} = 13.5$ in the fifth bin due to the flaring emission. Another hot-spot with $\sqrt{TS} = 4$ is visible in the map but it is due to fluctuations.

5.6 Science Alert Generation: ToO Follow-up observation of a GRB

The *fourth* scenario we designed is a *follow-up ToO observation* of a **GRB Afterglow**. This is one of the conditions in which **SAG-SCI** will have to issue a candidate Science Alert, as discussed in chapter 4.7.1. We simulated a simplified version of GRB 190114C, one of the four GRBs detected at VHE by IACTs (MAGIC Collaboration et al. 2019; Noda and Parsons 2022). The spectral Model is a Power Law model corrected for the *Extragalactic Background Light* (EBL) absorption. The EBL is the accumulated infrared, optical and ultraviolet radiation in the Universe due to star formation processes and AGN, and is responsible for absorbing extra-galactic TeV γ -rays via photon-photon pair production (Dwek and Krennrich 2013). This absorption effect is relevant at energies $\gtrsim 1$ TeV and is more severe for sources with higher redshift. We assumed to have independent spectral and temporal models, disregarding the *temporal evolution* of the spectral parameters, which may be relevant for real GRBs. We used an Exponential Decay Temporal Model to describe the evolution of the flux. The complete model used for the simulation is thus:

$$\frac{dN}{dE}(E) = N_0 \left(\frac{E}{E_0} \right)^{-\Gamma} e^{-\alpha_0 \cdot \alpha(E,z)} \cdot e^{(t-t_0)/\tau}, \quad (5.4)$$

where $\alpha(E, z)$ is the *Optical Depth* model assumed to describe the EBL, that depends on the redshift z of the source and the photon energy E , and α_0 is the normalisation of the EBL model. t_0 is the reference time and τ the reference scale for the temporal model.

For the spectral model, we assumed parameters similar to those measured by MAGIC for GRB 190114C in MAGIC Collaboration et al. (2019), namely: $N_0 = 1.5 \cdot 10^{-9} \text{ s}^{-1} \text{ cm}^{-2} \text{ TeV}^{-1}$ at a reference energy $E_0 = 1 \text{ TeV}$, $\Gamma = 2.22$, $\alpha_0 = 1$, redshift $z = 0.42$ and the Optical Depth α described by Domínguez et al. (2011). The photon flux of the spectral model at $t = t_0$ in the 0.1 TeV to 10 TeV range is $\phi = 1.02 \cdot 10^{-8} \text{ s}^{-1} \text{ cm}^{-2}$. The EBL absorption strongly modifies the intrinsic spectrum, so that the observed one is *dampened* and *curved*. We show the intrinsic and observed spectrum in figure 5.18a. As **SAG-SCI** currently assumes a Power Law model for the analysis, we fit the predicted observed spectrum with a Power Law in the 0.1 TeV to 5 TeV energy range. Above 5 TeV, the EBL absorption is dominant over the intrinsic emission. The best fit index is 5.16 ± 0.02 , and we assumed the best fit value to perform the **SAG-SCI** analyses.

For the temporal model, we assumed $\tau = 50 \text{ s}$ and $t_0 = 50 \text{ s}$ before the *start* of the observation. t_0 represents the time delay in observations due to the time needed for an external observatory to emit an automatic notice, $\sim 20 \text{ s}$ (see chapter 3.1.1), plus the re-pointing time of the telescopes, that are 30 s at most for an LST (see chapter 3.2). For comparison, MAGIC started the observations of GRB 190114C at $t_0 + 56 \text{ s}$. We show the temporal model in figure 5.18b, compared with t_0 and the start of the observation.

We assumed that a single observation is able to cover the error region of the GRB localisation, which is not always the case and depends on the properties of the instrument which issued the alert. We show the results of the Differential analysis in figure 5.19. The GRB is detected in the first bin of the analysis as expected. In such a scenario, the **ScienceAlertManager** issues a candidate Science Alert, so that the **ACADA TH** could confirm the detection in the VHE band and the CTAO could publish a Science Alert for the external community.

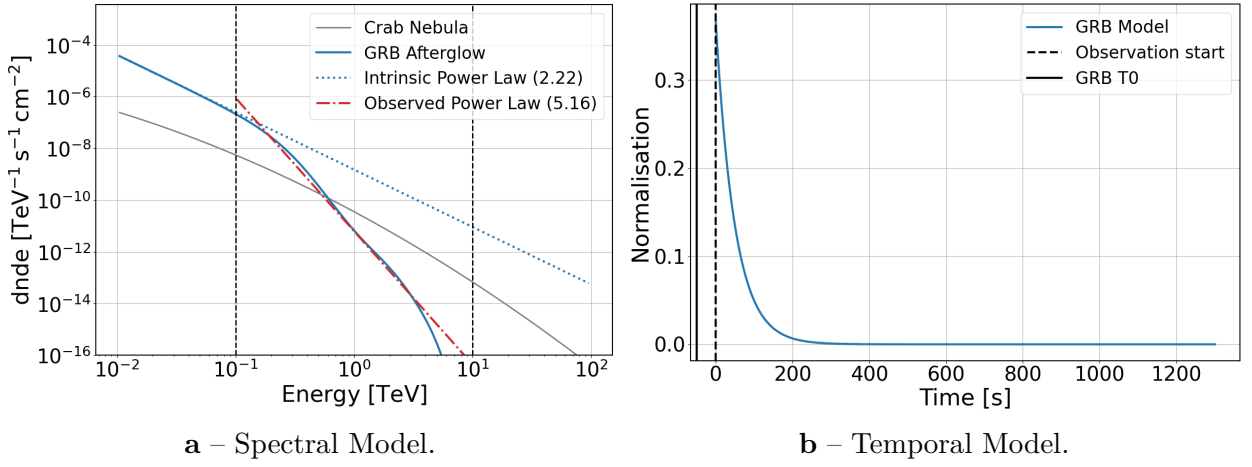


Figure 5.18 – Models adopted to simulate the afterglow emission of a GRB. Panel 5.18a shows the adopted spectral model. The intrinsic GRB emission is a Power Law with index 2.22, that is modified by the EBL absorption (Domínguez et al. 2011) into a curved shape. The observed spectrum is best fit by a Power Law with index 5.16. We also show the Crab Nebula model used in section 5.4.1 for comparison. Panel 5.18b shows the temporal model, an Exponential Decay with $t_0 = 50$ s before the start of the observation, and scale $\tau = 50$ s.

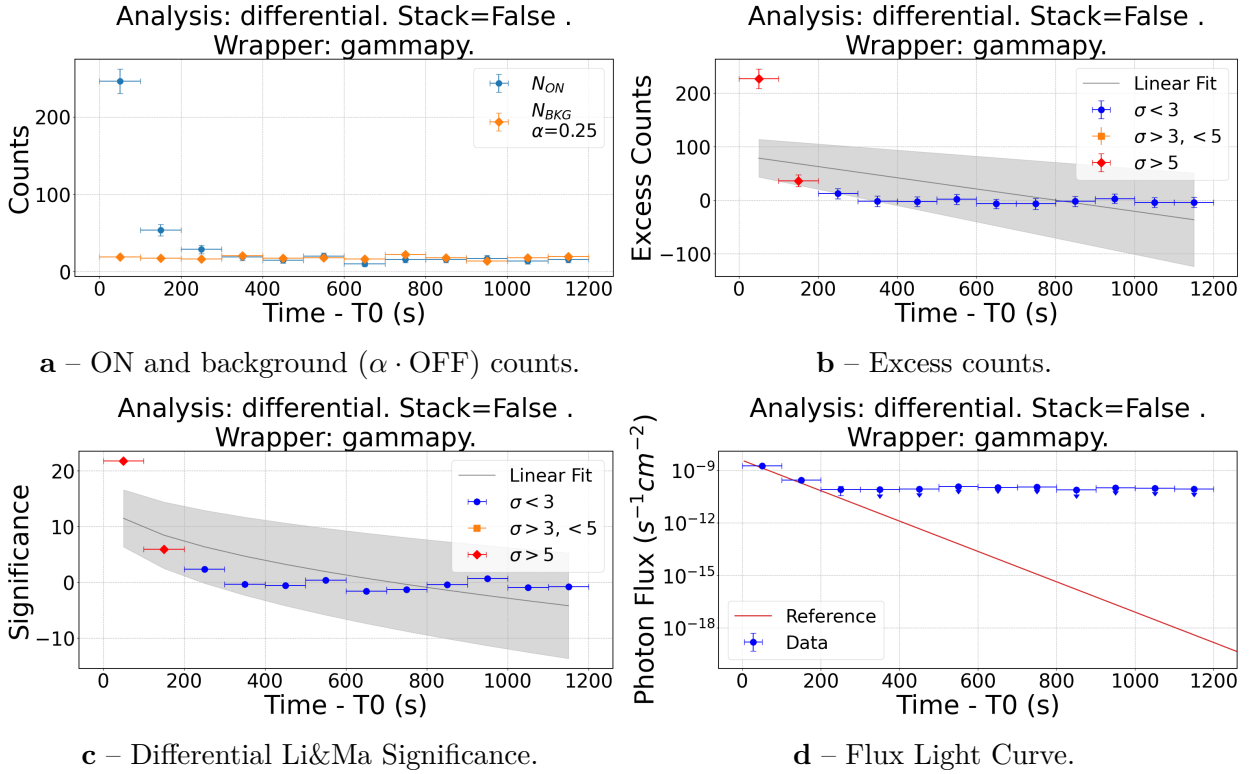


Figure 5.19 – Results of the Differential Analysis on the follow-up observation of a simulated GRB. Panel 5.19a shows the ON and OFF counts, panel 5.19b the excess counts, panel 5.19c the significance of every bin. The source is detected in the first two bins. The flux light curve is presented in panel 5.19d, and it is consistent with the value simulated for the transient emission.

In this scenario, the `ScienceAlertManager` may compare the localisation of the observed GRB with other catalogues to identify possible counterparts of the source. When searching for GRB emission at VHE, the significance is the most important quantity that a *real-time analysis* software like **SAG-SCI** has to provide, to confirm the detection of the transient. The flux we estimate is *strongly* model-dependent due to the presence of EBL absorption, which must be considered when an extra-galactic source is analysed. The analysis of a GRB is particularly tricky in this regard, as the redshift is often unknown and the EBL might not be properly modelled in the sky region of the GRB. **SAG-SCI** must assume a spectral model to perform the analysis, which may be suggested by theoretical predictions (e.g. Bernardini et al. 2019). Alternatively, it may be suggested by the observations, although there are currently only 4 GRBs detected by IACTs with different redshifts. For this reason, future version of **SAG-SCI** will have to implement more complex spectral modelling and perform a preliminary estimation of the observed spectral index, provided there is a high enough photon statistics.

5.7 Science Alert Generation: Serendipitous Discovery of a Transient

The final observational scenario we crafted is the **Serendipitous Discovery of a Transient** thanks to the *Blind Search* algorithm of the `gammapy` wrapper (see section 4.7.3), which may arise during CTAO observations. It is particularly relevant for CTAO *surveys* and during *Follow-up ToO observations of a GW alert*, as discussed in section 4.7.1.

We simulated two sources in the FoV. The first one is a *Steady* source, the nominal Scientific Target of the OB, simulated at a 0.4 deg offset. It has a Power Law Spectrum, see equation (5.1), with spectral amplitude $N_0 = 5 \cdot 10^{-12} \text{ s}^{-1} \text{ cm}^{-2} \text{ TeV}^{-1}$ at a reference energy $E_0 = 1 \text{ TeV}$ and spectral index $\Gamma = 2$. The photon flux of the source in the 0.1 TeV to 10 TeV range is $\phi = 4.95 \cdot 10^{-11} \text{ s}^{-1} \text{ cm}^{-2}$, detectable in $\approx 800 \text{ s}$ according to the sensitivity in figure 5.4. The second source is the *Serendipitous Transient*, that we simulated with an offset of 0.8 deg in a position symmetrical to the steady source with respect to the centre of the FoV. The Transient has a Power Law Spectrum with amplitude $N_0 = 7 \cdot 10^{-12} \text{ s}^{-1} \text{ cm}^{-2} \text{ TeV}^{-1}$ at a reference energy $E_0 = 1 \text{ TeV}$ and spectral index $\Gamma = 2$, resulting in a photon flux $\phi = 6.93 \cdot 10^{-11} \text{ s}^{-1} \text{ cm}^{-2}$. Its amplitude is modulated by an Exponential Decay Temporal Model, described in equation (5.3). We set the Burst Onset at $t_0 = 400 \text{ s}$ after the beginning of the Observing Block (which lasts 1200 s), the temporal amplitude $f_0 = 10$, the decay time scale $\tau = 300 \text{ s}$. We show the temporal model in figure 5.20. It is slightly different from the one we adopted for the Flare in section 5.5, as we did not set $f(t) = 1$ as a lower limit: the flux of the Transient source before t_0 is zero.

We performed two analyses: a Differential + Stacked analysis on the nominal Scientific Target of the OB (the Steady source) and an Integral analysis with Blind Search, as described in section 5.2). We configured the Blind Search to discard hot-spots consistent with the Steady Source, to focus only on new sources in the FoV. We show the results of the analysis of the Steady source in figure 5.21. They represent the main scientific target of the OB before **SAG-SCI** detects the Serendipitous Transient. The stacked Excess counts plot in panel 5.21a shows that **SAG-SCI** detected the Steady source in 800 s. In figure 5.21b we show the Flux Light Curve, which is consistent with the simulated value. In figure 5.21c we show the counts

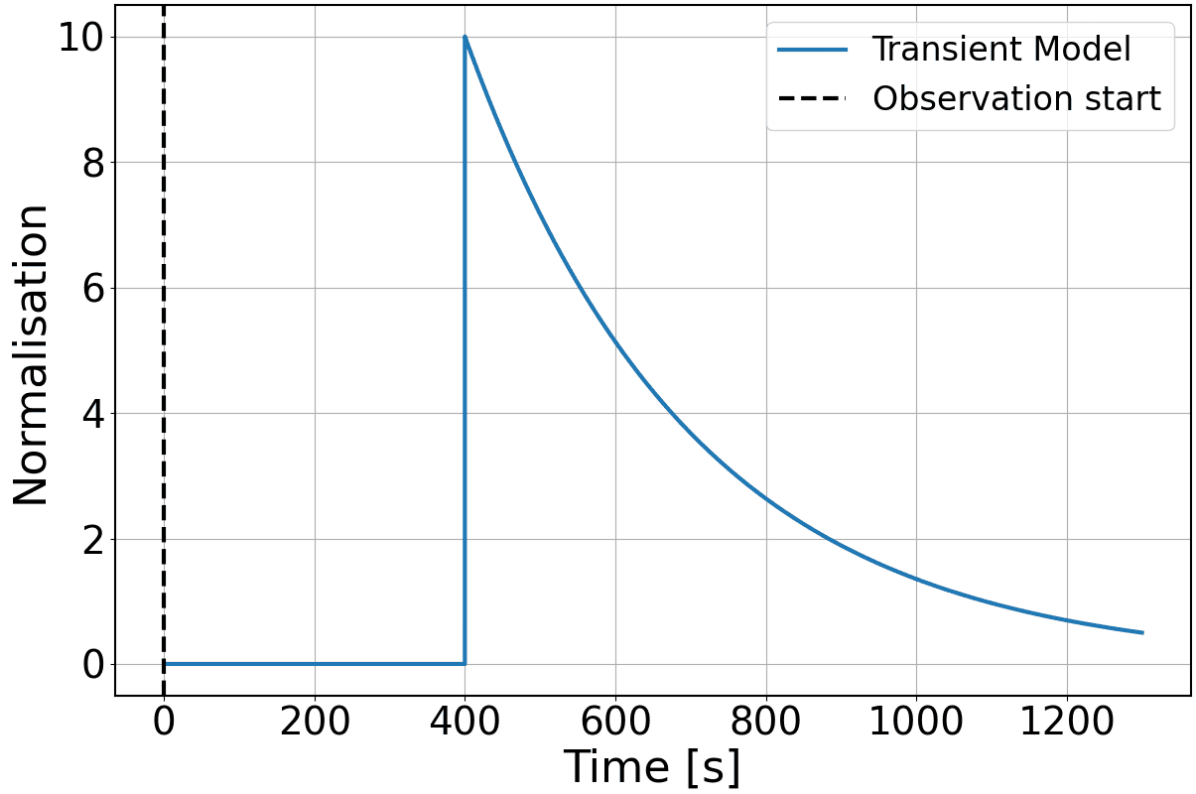


Figure 5.20 – Temporal model used to describe a serendipitous transient in the FoV. We show the modulation (or normalisation) factor $f(t)$ which multiplies the Spectral Model. The factor is 0 before the burst onset at $t_0 = 400$ s after the OB start, then it follows an Exponential Decay.

map of the 8th bin, where the source is first detected with significance $\sigma > 5$. Notably, the map also shows the Serendipitous Transient.

The Blind Search algorithm executed during the Integral analysis is able to detect the Serendipitous transient as expected during the fifth bin of the analysis, at its start. We show the Sky maps of the analysis in figure 5.22. We show the $\sqrt{TS}$ maps of the fourth bin in panel 5.22a; no hot-spot is detected in this bin, which is before the onset of the Transient. Conversely, in panel 5.22b the $\sqrt{TS}$ map of the fifth bin shows the hot-spot of the Serendipitous transient with $\sqrt{TS} = 7.0$. The ICRS coordinates of the hot-spot are R.A. = 83.5743, Dec = 23.2247, consistent with the simulated value: their distance is 0.05 deg. SAG-SCI adopts these coordinates to estimate the excess counts $N_{\text{exc}} = 76 \pm 32$ and the classical Li&Ma significance $\sigma = 6.9$. In panel 5.22c we show the counts map of the fifth bin, with the ON and OFF regions used for the significance estimation.

The detection of the Serendipitous Transient with $\sigma = 6.9$ prompts the **ScienceAlert-Manager** component to issue a candidate Science Alert. The alert is uploaded in the Results Database (see section 4.4.4), but it is also inserted as an *internal notice* in the Pipeline Database (see section 4.4.3) as it represents a *new* Scientific Target that must be properly analysed. The insertion of the internal notice triggers the Science Logic as described in section 4.4.3. SAG-SCI can thus perform a new set of analyses where the Serendipitous Transient is the nominal target. As the **ScienceAlertManager** component is not available in SAG-SCI yet, we triggered the new analyses manually. We performed two analyses on the new target: a Differential analysis with Stacking and an Integral analysis with Blind Search. This time, the Blind Search is used for *localisation* purposes, as we configured it to include hot-spots consistent with the Serendipitous Transient, and to use the hot-spot coordinates

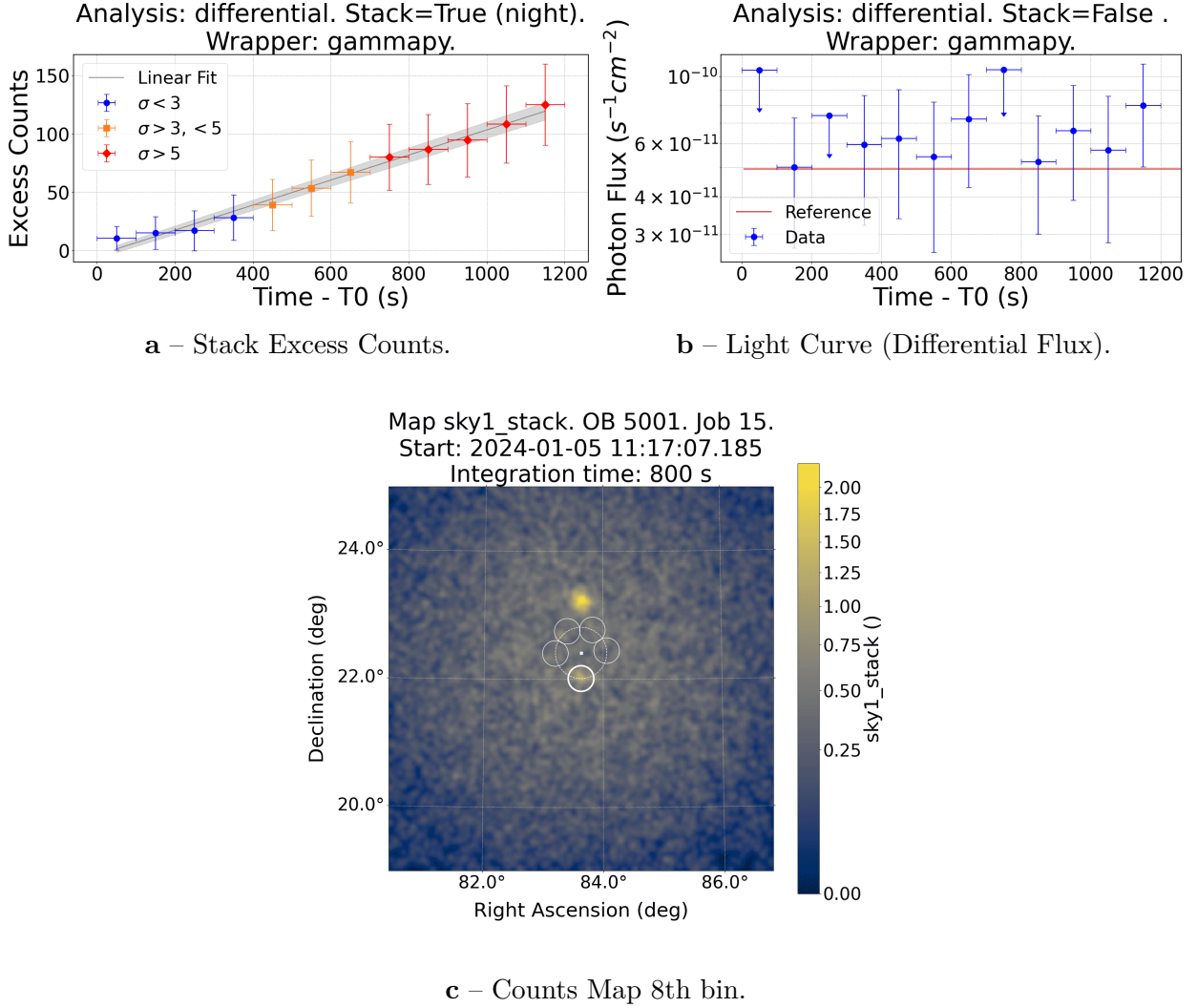


Figure 5.21 – Analysis of the Steady source, the nominal Scientific Target of the OB before the Blind Search detects a serendipitous transient. Panel 5.21a shows the stacked excess counts and panel 5.21b the Light Curve. The source is detected in 800s and the flux is consistent with the simulated value. Panel 5.21c shows the counts map of the 8th bin, when the source is detected with significance $\sigma > 5$. The bright spot in the higher part of the map is the Serendipitous Transient.

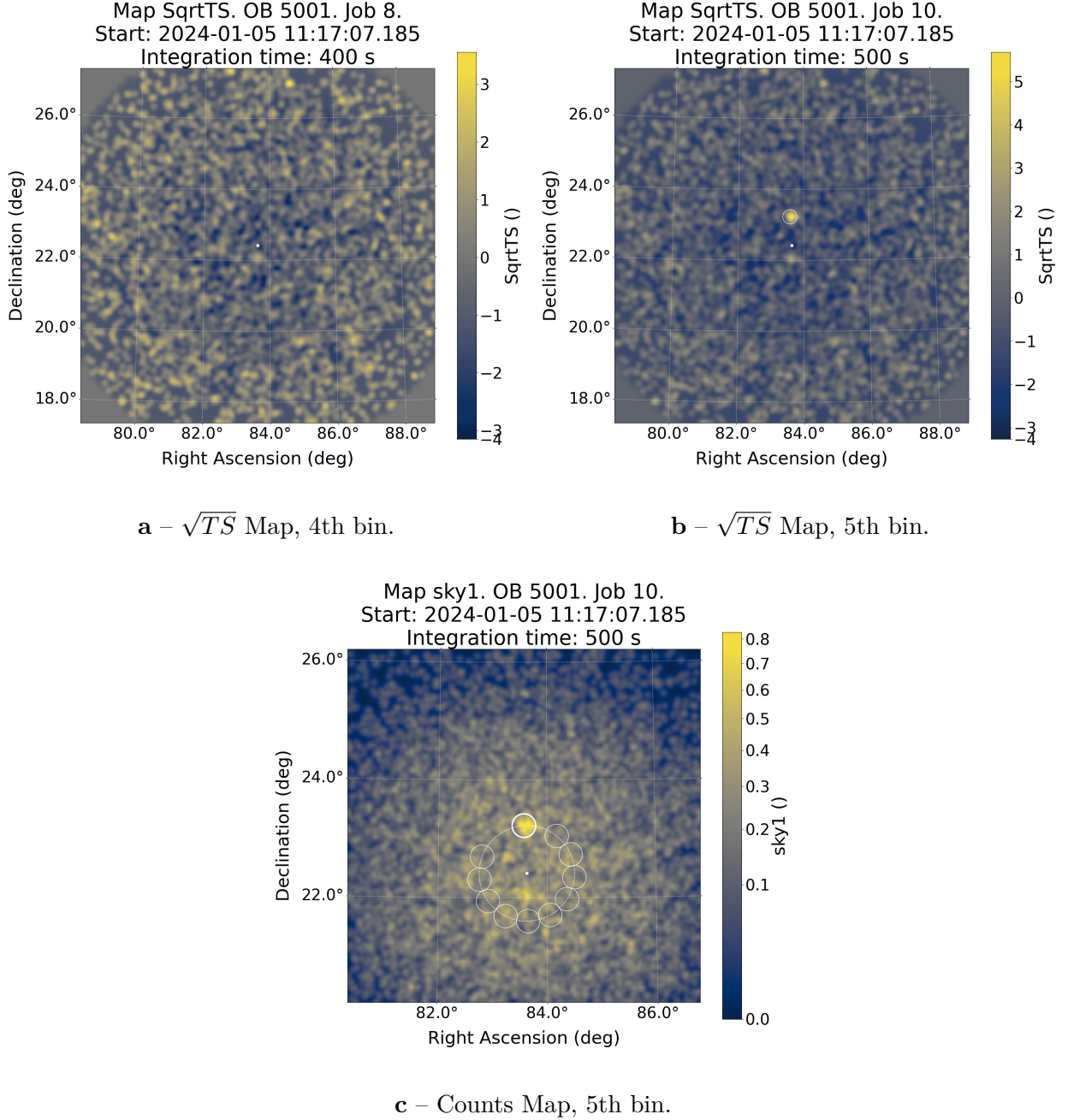


Figure 5.22 – Results of the Blind Search algorithm run of the $\sqrt{TS}$ Maps computed during the fourth (panel 5.22a) and fifth bin (panel 5.22b). The Blind Search detects the Serendipitous transient in the fifth bin as expected, with $\sqrt{TS} = 7.0$. The source is then analysed to determine the significance. Panel 5.22c shows the counts map with the ON and OFF regions, yielding $\sigma = 6.9$.

to update the target coordinates that must be analysed. From the sixth bin onwards, the Blind Search detects the Serendipitous Transient at R.A. = 83.6613, Dec = 23.2247, similar to the coordinates found in the fifth bin, but even closer to the true simulated value (at a distance of 0.03 deg). The Differential analysis is performed on the coordinates found by the original Blind Search that detected the Serendipitous Transient, and we show the Aperture Photometry results in figure 5.23. Panel 5.23a shows the ON and OFF counts, panel 5.23b the excess counts, panel 5.23c the significance of every bin. In the first four bins there is no detection as expected, and the transient emission is detected from the fifth bin onwards. The flux light curve is presented in panel 5.23d and is consistent with the value simulated for the transient emission.

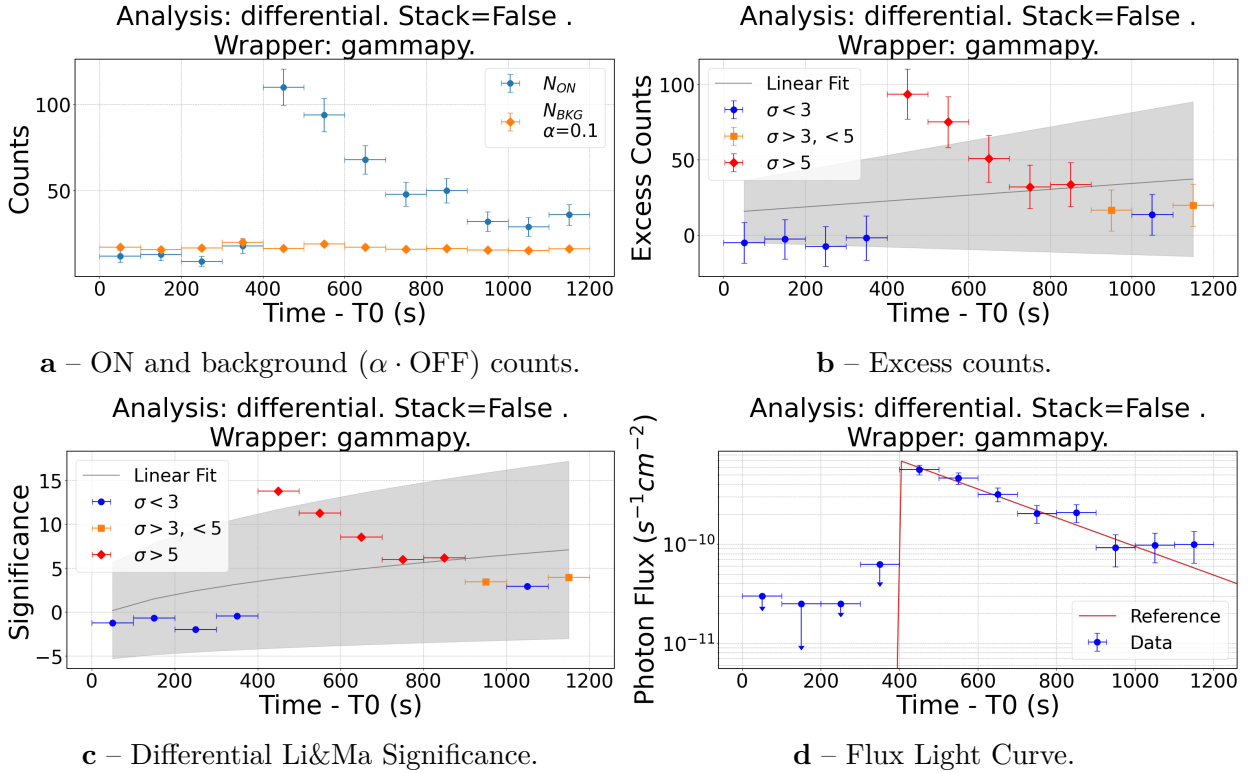


Figure 5.23 – Results of the Differential Analysis on the Serendipitous Transient discovered by the Blind Search algorithm. Panel 5.23a shows the ON and OFF counts, panel 5.23b the excess counts, panel 5.23c the significance of every bin. In the first four bins there is no simulated signal and no detection. The transient emission is detected from the fifth bin onwards. The flux light curve is presented in panel 5.23d, and it is consistent with the value simulated for the transient emission.

We note that, currently, the significance of the detection does not include a post-trial correction (described in chapter 6.9), that will be applied by the **ScienceAlertManager** component by counting the number of times the analysis was performed within the SB.

5.8 Evaluating the Performance of SAG-SCI

One of the main requirements of SAG-SCI (see section 4.1) is the capacity to issue candidate Science Alerts within 5s from the data becoming available. For this reason, in table 5.1 we recorded the speed of every task performed by SAG-SCI. We measured the execution times both in the CTAO server that we use to execute the Verification Test Suite (see chapter 4.8),

and the INAF machine that we used to perform the analyses shown in this chapter. The execution times reported are *not* to be considered as the definitive benchmarks, but they are just meant to provide typical values and help identify the most computationally intensive tasks. This is due to the fact that the execution times of the analyses strongly depend on the machine used (the CTAO server is systematically faster than the INAF one) and the tasks performed. The official performance tests, meant to certify that **SAG-SCI** is able to generate a candidate Science Alert in < 5 s, will be performed by a future version of **ACADA** using the definitive computing environment of CTAO and **SAG-SCI** configuration.

The execution times presented in table 5.1 allow us to discuss some features of the **SAG-SCI** architecture. The first part of the pipeline is relatively quick: the **DL3Merger**, **DataFlowManager** daemons and the *Science Logic Triggers* allow **SAG-SCI** to prepare the analysis jobs in $\lesssim 0.5$ s. After the jobs are prepared in the Database, the pipeline introduces additional time before their execution, because the **SubmitJob** must first select the *runnable* jobs, then prepare and write the configuration files and finally submit them to **slurm**. The Task Manager **slurm** must first find new available resources for the analysis job (a process not under our control), then it must start the job importing every time the dependencies of the Wrapper, which is a relatively slow process in **python**. We are currently studying the feasibility of a different approach: replacing the **SubmitJob** daemon and **slurm** with a set of “Analysis Daemons”. An **AnalysisDaemon** would operate in a loop, querying at each cycle the *runnable* jobs, selecting the most relevant one to execute and calling directly the Wrapper’s classes to perform its analysis. The main advantages of this approach would be to eliminate the **slurm** queue time and the import time of the wrapper’s dependencies. The main disadvantage is renouncing to the extreme flexibility of **slurm**, capable to automatically allocate resources and manage the priorities of the jobs in every computing cluster.

When we look at the performance of the **gammpy** wrapper presented in table 5.1, some tasks appear to be more computationally intensive than others.

- The first intensive task is the *Reduction of the IRFs*, i.e. the production of DL4 maps of exposure and background counts starting from DL3 IRFs with the format shown in figures 5.1 and 5.2. They are obtained by evaluating the IRFs on a 3D grid (one spectral and two spatial axes), as described in chapter 4.7.3. I optimised this task by performing it only once per OB, during the first job of an analysis which require having these maps. Currently, the Reduced IRFs are required only to perform the Blind Search on a $\sqrt{TS}$ map, while future versions of **SAG-SCI** might include the computation of Flux Maps which will also require them.
- The computation of $\sqrt{TS}$ maps to perform the Blind Search is another computationally intensive task. For the analyses of this chapter, we employed a squared grid with a 10 deg-long side and 0.02 deg-long pixels, i.e. a 500×500 grid. The computation of any map can be strongly optimised by using a grid with worse resolution.
- The production of plots is another slow task, that should be completely avoided by fast analyses. The Wrappers should focus only on writing the DL4 and DL5 data products, and let the **ACADA HMI**, or to a set of low-priority jobs, produce the plots from the data products. The grid resolution of the 2D maps has also an impact on the plotting speed.

To improve the wrapper speed even more, the analyses dedicated to the generation of candidate Science Alerts, which are required to take < 5 s, should perform only the necessary tasks, avoiding those that can be performed by dedicated low-priority jobs, such as the production of θ^2 plots and counts maps.

To provide an example, we compute the execution of analysis jobs similar to those described throughout this chapter, using the measurements provided in table 5.1. The execution of a job of a Differential + Stacked Analysis, performing a full 1D wobble analysis on a known target without the production of plots, would take ≈ 2.7 s on one of the CTAO machines currently active, of which 1.2 s are dedicated to importing software dependencies. The execution of a job of an Integral Analysis with Blind Search would take ≈ 5.3 s, of which 1.2 s are dedicated to importing software dependencies, and ~ 2.7 s to the production of $\sqrt{TS}$ maps using a grid of 500×500 pixels, which can be significantly reduced to improve the speed of the task.

Table 5.1 – Performance of the main tasks of SAG-SCI, expressed in seconds required for the execution. The analysis are always performed with the *gammapy* wrapper. The execution times are measured on a CTAO machine and an INAF machine.

COMPONENT	TASK	CTAO s	INAF s
DL3 Merger	Insert Events in DB (~ 1000 events)	0.07	0.30
Pipeline Database	Science Logic Triggers	~ 0.3	~ 0.4
SubmitJob	1 Job Preparation Time	0.07	0.08
Slurm	Queue time*	~ 4	~ 1.2
Wrapper Setup	Imports	1.18	1.70
	Query Events (scaled to $\sim 25\,000$ events)	0.25	0.46
	Event Selection	0.04	0.09
Wrapper Full-FoV Analysis	IRFs Reduction	1.93	4.40
	Reduced IRFs Write/Read	0.11	0.27
	Write Counts Cube	0.01	0.03
	Plot Counts Map	0.48	1.06
	$\sqrt{TS}$ Map and Blind Search	2.69	7.10
	Blind Search Plots	0.49	1.13
Wrapper 1D Analysis	Compute θ^2 distribution	0.09	0.21
	Plot θ^2 distribution	0.17	0.38
	Compute OFF Regions	0.06	0.06
	Aperture Photometry and Significance	0.50	0.85
	Plot Counts Map and Write Counts Cube	0.38	0.77
	Spectral Fit and Flux Estimation	0.28	0.60
Wrapper Stack Analysis	Aperture Photometry	0.03	0.03
	Compute θ^2 stacked distribution	0.07	0.17
	Plot θ^2 stacked distribution	0.14	0.31
	Compute Counts Cube	0.10	0.26
	Plot Counts Cube	0.38	0.88
Wrapper Output	Copy files from Job to Result Directory	0.10	0.13
	Insert Results into Database	0.02	0.06

* It strongly depends on the available resources at the moment of execution.

Chapter 6

Analysis of sub-second bursts from fast transient sources: the case study of the Galactic magnetar SGR 1935+2154

The statistical methods for the analysis of VHE gamma-ray data described in section 2.4, such as Li&Ma significance estimation (Li and Ma 1983) and MLE (Cash 1979) cannot be applied under the hypothesis of *low-photon-statistics* regime, due to Wilks’ theorem not being valid (Wilks 1938). There are several classes of transient sources showing burst emission on very short time scales ($\lesssim 10$ s), such as short Gamma-Ray Bursts (GRBs), Magnetar bursts, Magnetar Giant Flares (MGFs), and Fast Radio Bursts (FRBs), that may fall under this regime.

One of the key results of my work is the development of a **Burst Analysis** that is statistically valid in the *low-photon-statistics* regime, under short time scales. We applied the *Burst Analysis* to the case study of the Soft Gamma Repeater (SGR) 1935+2154, a Galactic magnetar that is known to occasionally emit ~ 0.1 s bursts at keV – MeV energies. We used the CTAO LST–1 to search for a TeV counterpart of the soft gamma-ray bursts of SGR 1935+2154. The LST–1 analysis of both the persistent and transient emission of SGR 1935+2154 is discussed in Panebianco and CTAO-LST Project (2025, under internal review at the time of writing), where we present the first TeV upper limits on the 0.1 s short bursts of the source.

In this chapter, we present a detailed discussion on the topics of the article, delving more into detail. We discuss the emission of magnetars and their connection to FRBs in section 6.1, and we describe SGR 1935+2154 in section 6.2. We report on the LST–1 observations on the source in section 6.3, and present a standard stacked spectral analysis in section 6.4. We describe the statistical methods of the *Burst Analysis* and the `python` pipeline we developed to analyse the LST–1 data from section 6.5. The pipeline is available in a protected GitHub repository (GitHub/BurstAnalysis, Panebianco 2024), and can be accessed on request. The *Burst Analysis* is composed of three main steps. The first one is the optimisation of the *Burst cuts*, that we describe from a theoretical point of view in section 6.6, and its software implementation in section 6.7. The second step is the evaluation of the TeV signal in coincidence with short magnetar bursts detected in the soft gamma-ray

energy range (section 6.8), and the third is searching for non-simultaneous TeV bursts in all the available data (section 6.9). Finally, we discuss our results on the persistent and transient analysis of SGR 1935+2154 within the context of magnetar emission in section 6.10.

6.1 Introduction on Magnetars

Magnetars are a class of slowly rotating ($P \sim 1 - 12$ s), isolated neutron stars (NS) with a strong magnetic field of 10^{14} G to 10^{15} G, about 3 orders of magnitude higher than that of regular NS (Olausen and Kaspi 2014; Kaspi and Beloborodov 2017). The magnetic field acts as the main energy source of the emission, that can be distinguished in two categories: the *persistent* emission from the pulsar (and the surrounding nebula if present), and a *transient* emission made up by outburst episodes with bursts or flares on different timescales, likely caused by crustal fractures and/or rearrangements of the magnetosphere (Beloborodov and Thompson 2007; Mereghetti et al. 2015; Carosi and López-Oramas 2024). There are about 30 known magnetars in the Galaxy and Magellanic Clouds (McGill Pulsar Group 2014). Many of them spend most of the time at low luminosity and only during outbursts, lasting from a few weeks to many months, their luminosity rapidly increases of a few orders of magnitude up to a few 10^{36} erg s $^{-1}$. The X-ray spectrum of the persistent emission typically consists of a soft thermal component plus a hard power-law tail likely originating from multiple cyclotron resonant scattering in the magnetosphere. Persistent emission above 10 keV has been detected in a few magnetars, but the upper limits in the MeV range indicate that this hard component cannot be extrapolated to higher energies (den Hartog et al. 2006). Several space-based and ground-based facilities, such as Fermi, MAGIC and H.E.S.S., performed intensive observation campaigns to monitor and detect HE and VHE emission from magnetars, with negative results (Abdo et al. 2010; Aleksic et al. 2013; Li et al. 2017; H.E.S.S. Collaboration et al. 2021; López-Oramas et al. 2022).

6.1.1 Magnetar flares in Multi-Wavelength Astronomy

Hard X-ray bursts have been detected from nearly all magnetars, often during active periods when tens-hundreds of bursts are emitted within hours, but also sporadically. These bursts, emitted in the keV – MeV bands, are short (≈ 0.1 s), have a total energy release of 10^{38} erg to 10^{40} erg, and peak X-ray luminosities of 10^{36} erg s $^{-1}$ to 10^{43} erg s $^{-1}$ (Israel and Dall’Osso 2011; Kozlova et al. 2016; Kaspi and Beloborodov 2017). Some of the bursts, called *intermediate flares*, may be characterised by a longer duration (few seconds - few tens of seconds) and higher fluences (Olive et al. 2004), while the much rarer *giant flares* (only three observed) reach peak X-ray luminosities of 10^{44} erg s $^{-1}$ to 10^{47} erg s $^{-1}$. The term *outburst* is instead used to describe a sudden but much longer-lived (weeks to months) flux enhancement, which typically involves many of the shorter bursts, and a long (many months) *tail* or *afterglow* (Kaspi and Beloborodov 2017). The diversified phenomenology of burst activity of magnetars led to an historical classification of these objects in *Anomalous X-ray Pulsars* (AXPs) with long spin periods, and *Soft Gamma Repeaters* (SGRs), occasionally bursting objects (Mereghetti 2008; Rea and Esposito 2011; Israel and Dall’Osso 2011). Today, this classification is considered inaccurate, as both classes are expression of the same astrophysical objects, isolated magnetars.

In the magnetar model, the magnetic field is the dominant source of free energy, and

it powers both the persistent and transient emission. The persistent emission is powered through low-level seismic activity and heating of the stellar interior (Israel and Dall’Osso 2011). Transient emission occurs when magnetic stresses build up sufficiently to crack a patch of the neutron star crust, ejecting hot plasma into the magnetosphere (Thompson and Duncan 1995). Other models suggest that short bursts may arise from magnetic reconnection in the magnetosphere (Lyutikov 2002).

Magnetar Giant Flares (MGFs) are a peculiar and very rare class of transient events emitted from magnetars, with peak X-ray luminosities of 10^{44} erg s $^{-1}$ to 10^{47} erg s $^{-1}$. Few MGFs have been detected so far in our Galaxy (Hurley et al. 1999; Palmer et al. 2005; Hurley et al. 2005), in the Large Magellanic Cloud (Mazets et al. 1979), and in the nearby starburst galaxy M82 (Mereghetti et al. 2024). The peak luminosities make MGFs detectable up to a few tens of Mpc, although they are difficult to distinguish from short GRBs. In fact, several candidate MGFs have been proposed in nearby galaxies, with detections up to the GeV energy range (Ajello et al. 2021; Svinkin et al. 2021). MGFs might result from a sudden reconfiguration of the magnetic field of the NS, that propagates outwards through Alfvén waves and leads to the production of large fractures in the crust (Schwartz et al. 2005).

A candidate MGF was detected in the Sculptor galaxy NGC 253 at GeV energies from 19 s to 284 s after the detection of an initial MeV signal (Ajello et al. 2021). The GeV signal was likely generated by the interaction of an ultra-relativistic outflow of electrons (that first emitted the MeV photons) with environmental gas. The shock waves could accelerate the electrons to VHE and emit GeV gamma-rays as optically thin synchrotron radiation.

Magnetar flares are one of the possible explanations for **Fast Radio Bursts** (FRBs), a class of millisecond-duration radio transients that originate from cosmological distances and whose origin is still unknown (Lorimer et al. 2007; Cordes and Chatterjee 2019; Petroff et al. 2019). The first evidence for the FRB-magnetar connection was provided in April 2020, when FRB 20200428D was detected from a direction consistent with SGR 1935+2154 and in coincidence with one of its flaring episodes in the hard X-ray and soft gamma-ray bands (Tavani et al. 2021; Mereghetti et al. 2020; CHIME/FRB Collaboration et al. 2020; Ridnaia et al. 2021a; Li et al. 2021). It represented the first detection of a FRB from a known source and the first FRB of Galactic origin. Even though the majority of high-energy bursts of SGR 1935+2154 are not correlated with FRBs (Lin et al. 2020a; Bailes et al. 2021), this discovery supported the theoretical interpretation of magnetars being one of the possible progenitors of FRBs (Zhang 2020) and boosted the production of models to explain the simultaneous production of FRBs and X-ray bursts (Beloborodov 2017; Lu et al. 2020; Yuan et al. 2020; Yang and Zhang 2021; Chen and Zhang 2023) and multi-wavelength observations of FRBs (Tendulkar et al. 2016; Trudu et al. 2023; Principe et al. 2023; Pellicciari et al. 2023). Several other FRBs were associated with SGR 1935+2154 on 2020-10-08 (Good and Chime/Frb Collaboration 2020), on 2022-10-14 and 2022-10-21 associated with X-ray bursts (Dong and Chime/Frb Collaboration 2022; Wang et al. 2022; Frederiks et al. 2022; Maan et al. 2022; Huang et al. 2022; Li et al. 2022a; Li et al. 2022b) and on 2022-12-01 (Pearlman and Chime/Frb Collaboration 2022). A wide variety of models have been proposed to explain the emission of FRBs, including magnetars, young isolated pulsars, merger of compact objects, stellar-mass black holes and cataclysmic events (Zhang 2023). The discovery of FRB 20200428D, the first one detected within the Galaxy and with a known origin, gave a strong support to the classes of FRB models based on the presence of a magnetar and raised the interest for multi-wavelength observations of SGR 1935+2154. The connection between FRBs and magnetar bursts is not fully understood yet, though the proposed emission

processes may involve coherent radiation mechanisms such as synchrotron maser radiation in magnetar shock models, capable of generating both polarised radio emission and X-rays and gamma-rays via synchrotron emission (Metzger et al. 2019; Beloborodov 2020). Some models also predict the emission of high-energy and very high-energy photons and neutrinos (Lyubarsky 2014; Murase et al. 2016; Murase et al. 2017; Metzger et al. 2020), even though none of them has been detected to the time of writing.

In view of the rich phenomenology and the unique physical conditions found in these objects, the observation of magnetars in the gamma-ray range is of great interest. However, only upper limits have been derived at 0.1 GeV to 10 GeV energies (Li et al. 2017). Gamma-ray emission spatially coincident with some magnetars has been detected, but it is thought to originate from the surrounding SNRs (Li et al. 2017; H.E.S.S. Collaboration et al. 2018b).

6.2 Introduction on SGR 1935+2154

SGR 1935+2154 was discovered in 2014 through the detection of a burst and classified as a magnetar with spin period $P \simeq 3.24$ s and period derivative $\dot{P} = 1.43 \pm 0.01 \cdot 10^{-11} \text{ s s}^{-1}$ (Israel et al. 2016). These values correspond to a dipole field $B_{\text{dipole}} \sim 2.2 \cdot 10^{14} \text{ G}$, a characteristic age ~ 3.6 kyr, and a spin-down power $L_{\text{sd}} \simeq 1.7 \cdot 10^{34} \text{ erg s}^{-1}$. SGR 1935+2154 is located close to the centre of the Galactic supernova remnant G57.2+0.8, which has an estimated distance between 6 kpc to 12 kpc (Kothes et al. 2018; Zhou et al. 2020; Lin et al. 2020b; Lin et al. 2020c). The analysis of expanding X-ray rings caused by dust scattering of bright bursts, allowed Mereghetti et al. (2020) to derive a magnetar distance of $4.4_{-1.3}^{+2.8} \text{ kpc}$, that does not depend on its presumed association with the SNR.

The persistent emission from SGR 1935+2154 was detected at 1 keV to 10 keV by *Chandra* and *XMM-Newton* (Israel et al. 2016) as a pulsed emission. Its X-ray spectrum is described by an *absorbed Black Body* (BB) plus a *power law* (PL) component, with BB temperature $0.47 \pm 0.02 \text{ keV}$ and PL index 1.8 ± 0.5 . The thermal component is thought to arise from the NS surface, while the power-law tail likely arises from a combination of atmospheric and magnetosphere effects, which can distort the the surface thermal emission. The power-law component may not represent a physically distinct process, but it may be needed to correct the simple black body model (Mereghetti et al. 2015; Kaspi and Beloborodov 2017). Israel et al. (2016) also detected steady emission from an extended component around SGR 1935+2154 on spatial scales from about 1 arcsec to 1 arcmin. It is constant in flux and modelled by a power law spectrum steeper than the one of the pulsar. It is probably due to either a scattering halo or a pulsar wind nebula (PWN).

This source has been the most prolific magnetar in the last years, with at least 4 outburst periods characterised by the production of many bursts, including intermediate flares (Kozlova et al. 2016; Lin et al. 2020d; Denissenya et al. 2021; Borghese et al. 2022; Rehan and Ibrahim 2023; Ge et al. 2023). The most notable event was the burst emitted on 28 April 2020, simultaneously detected in the radio (FRB 20200428D, CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020) and X-ray bands (Mereghetti et al. 2020; Ridnaia et al. 2021a; Li et al. 2021; Tavani et al. 2021). The radio properties of this event are very similar to those of the FRBs, an enigmatic class of extra-galactic radio transients whose origin is still unknown (Cordes and Chatterjee 2019; Petroff et al. 2019). This discovery gave a strong support to the classes of FRB models based on the presence of a magnetar and raised the in-

terest for multi-wavelength observations of SGR 1935+2154. Many observations were carried out from the radio band (Bailes et al. 2021) to VHE gamma-rays. IACTs like H.E.S.S. and MAGIC performed observation campaigns at TeV energies without detecting the magnetar (H.E.S.S. Collaboration et al. 2021; López-Oramas et al. 2022). SGR 1935+2154 latest activity was recorded in December 2022 (Ridnaia et al. 2022).

The physical mechanisms that originated the simultaneous radio and X-ray burst emission are not fully understood yet. Several models (Zhang 2020; Lu et al. 2020; Chen and Zhang 2023) were proposed to explain the simultaneous FRBs and X-ray bursts from SGR 1935+2154 and its VHE upper limits, including (but not only) synchrotron maser shock (Margalit et al. 2020), NS crust fractures (Yang and Zhang 2021), NS phase transitions (Shen et al. 2023), expanding fireballs (Wada and Ioka 2023), ultra-relativistic shocks (Yuan et al. 2020; Metzger et al. 2020), hadronic processes (Anjos et al. 2021; Coelho et al. 2022).

6.3 LST-1 Observations of SGR 1935+2154

LST-1 observed SGR 1935+2154 for approximately 37.8 h, performing 118 observation runs over 17 nights during July 2021, September 2021, June 2022 and October 2022. Most of the data (≈ 32.9 h) were taken in *wobble mode* for a simultaneous evaluation of the background (e.g., Fomin et al. 1994; Berge et al. 2007), see chapter 2.4. The offset angle, i.e. the distance between the source position and the centre of the telescope’s field of view (FoV), was ≈ 0.4 deg for each wobble observation. The remaining 4.9 h of data were taken in *ON mode*; this data include the entirety of October 2022 observations and 1 h in July 2021. The observations were taken up to 55 deg zenith angle, and with the Moon both below and above horizon (up to 20 deg), but not every run was used as we applied quality selection criteria (see sections 6.4 and 6.5). We show the distribution of the parameters of the observation conditions in figures 6.1 and 6.2 for every *observation run* of LST-1. A *run* is a continuous observation on a fixed target, that usually lasts ≈ 20 min.

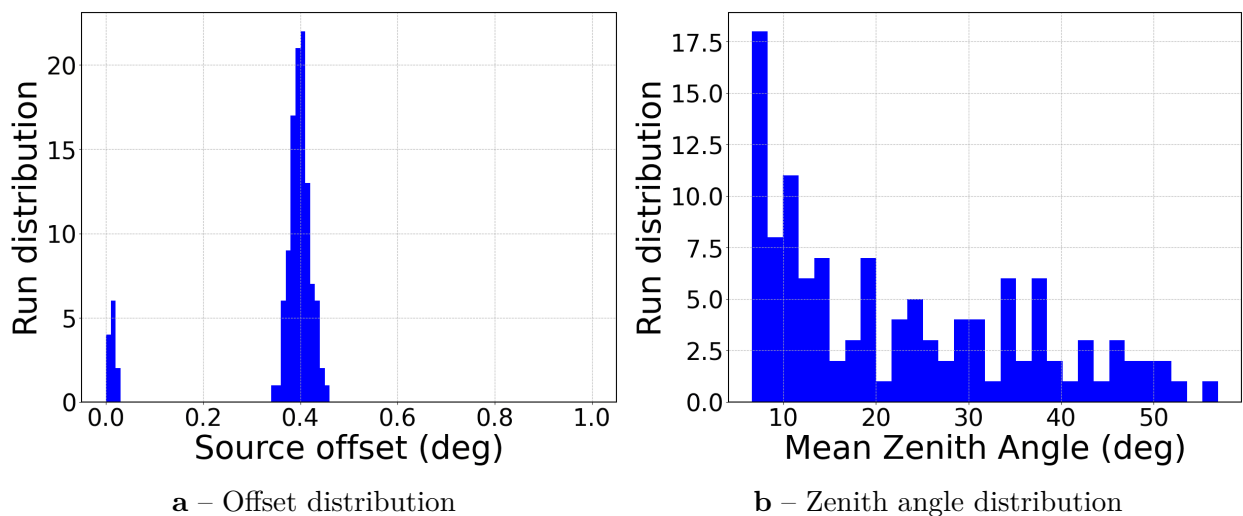


Figure 6.1 – LST-1 configuration during SGR 1935+2154 observation runs. Panel 6.1a shows the distribution of the target-pointing offset, composed by two groups: *ON-mode* runs (at offset ≈ 0 deg) and *wobble-mode* runs (at offset ≈ 0.4 deg) Panel 6.1b shows the distribution of the zenith angle of the pointing direction.

Panel 6.1a shows the distribution of the target-pointing offset, and allows to easily

distinguish ON observations (offset ≈ 0 deg) from wobble observations (offset ≈ 0.4 deg). Panel 6.1b shows the distribution of the zenith angle of the pointing direction, and panel 6.2a the zenith angle as a function of the run date. SGR 1935+2154 observations were taken without constraints on the zenith angle. Panel 6.2b shows the Moon altitude as a function of the *standard deviation of the pedestal charge* (σ_{ped}). Interleaved pedestals are events that contain no Cherenkov flashes and can be used to measure the NSB level and its variations (see chapter 2.3). A value of $\sigma_{\text{ped}} \gtrsim 2$ p.e. in LST-1 is usually due to an elevated level of Moon background light and it is a discriminator for bad quality runs, as can be seen in the figure.

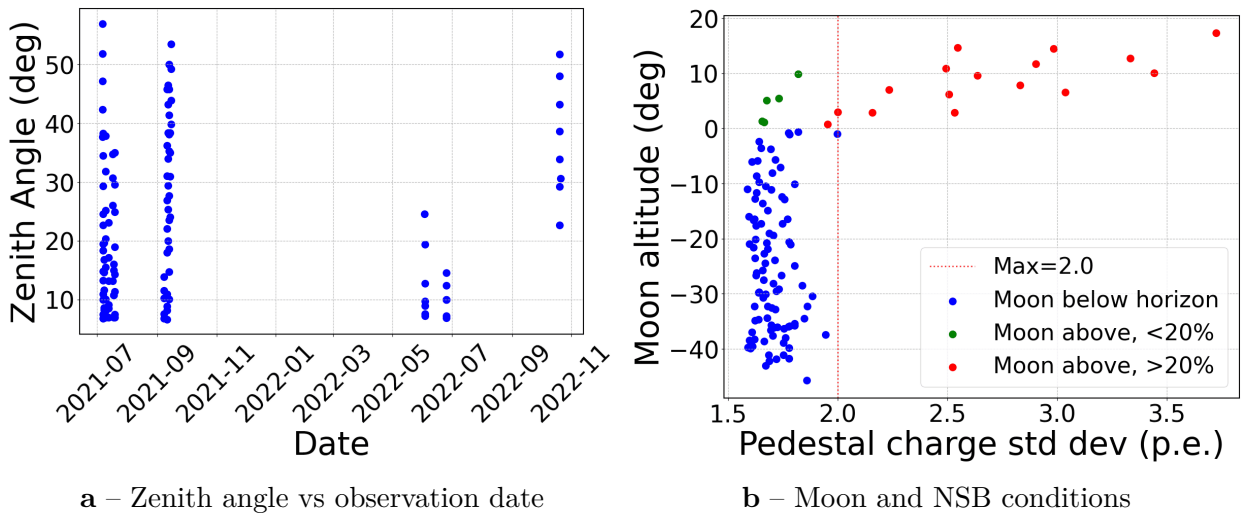


Figure 6.2 – LST-1 configuration during SGR 1935+2154 runs. Panel 6.2a shows the distribution of the zenith as a function of the run date. Panel 6.2b shows the Moon altitude as a function of the *standard deviation of the pedestal charge*, a measure of the NSB fluctuations in calibration events.

LST-1 observations were carried out during periods of known burst activity of the source, but magnetar bursts are random and irregular transient events and there is no guarantee that a burst will happen after a *Target of Opportunity* (ToO) observation starts. Unless a system of real-time analysis detects one or more bursts, scientific collaborations alert the astronomer community of their occurrence with a significant delay, generally using *General Coordinate Network* circulars (GCNs, NASA 2024) and *Astronomer’s Telegrams* (ATels, Rutledge 1998; The Astronomer’s Telegram 2024). We reconstructed the history of known high-energy and radio bursts attributed to SGR1935+2154 by recording all relevant GCNs and ATels from June 2020 to December 2022, and every trigger time reported by HE satellites or radio facilities localised on SGR 1935+2154. We considered these trigger times as the *Time of Alert* (ToA) of the bursts. Looking at more than 150 GCNs and ATels, we recorded over 450 ToAs, 9 of which occurred simultaneously to LST-1 observations, see table 6.1.

Burst #1 was a bright burst that occurred on 2021-07-07 and was detected by several satellites: Fermi-GBM (Hamburg et al. 2021a; Hamburg et al. 2021b), GECAM (Xiao et al. 2021), CALET (Nakahira et al. 2021) and Konus-Wind (Ridnaia et al. 2021b). The other 8 bursts occurred in 3 nights during September 2021. They were significantly dimmer (a 1 – 2 order of magnitude) than burst #1, and for only 3 of them the fluence and spectral analysis is available in literature, as they were detected by Fermi-GBM or NICER (Roberts et al. 2021a; Roberts and Wood 2021; Guver et al. 2021; Roberts et al. 2021b; Rehan and Ibrahim 2023). These bursts are usually described either by a *Two Black Body* model or a *Power Law with exponential cutoff*. These 4 bursts are softer and dimmer than the X-ray burst detected

Table 6.1 – External Science Alerts on SGR 1935+2154 simultaneous to LST–1 observations. We show the ToA of the burst, the instrument that detected it, the LST–1 run simultaneous to the burst and the simulated coordinates of the closest IRF to the pointing of the telescope (θ is the zenith, ϕ the azimuth angle), used to analyse the burst.

#	TIME OF ALERT ISOT UTC	INSTRUMENT	LST–1 RUN	IRF NODE (θ, ϕ) deg
1	2021-07-07 00:33:31.670	See section 6.3	5163	23.630, 100.758
2	2021-09-10 23:40:34.460	Fermi-GBM (Roberts et al. 2021a; Roberts and Wood 2021)	6205	37.814, 270.000
3	2021-09-11 22:51:41.600	GECAM (Xue et al. 2021)	6223	23.630, 259.265
4	2021-09-11 23:55:45.872	NICER (Guver et al. 2021)	6226	37.814, 270.000
5	2021-09-12 00:34:37.450	GECAM (Xue et al. 2021)	6228	47.952, 270.000
6	2021-09-12 00:45:49.400	GECAM (Xue et al. 2021)	6229	47.952, 270.000
7	2021-09-12 22:16:36.200	GECAM (Cai et al. 2021)	6245	10.000, 248.117
8	2021-09-12 23:19:32.080	Fermi-GBM (Roberts et al. 2021b)	6248	23.630, 259.265
9	2021-09-13 00:27:25.200	GECAM (Cai et al. 2021)	6251	37.814, 270.000

on April 2020 simultaneously to FRB 20200428D (Mereghetti et al. 2020). The remaining 5 bursts were detected by GECAM, and do not have data or spectral analysis available (Xue et al. 2021; Cai et al. 2021).

6.3.1 Low-level Analysis and NSB Tuning

The Cherenkov reconstruction technique described in chapter 2.3 was applied to the LST–1 data. The raw data acquired from the camera were processed using **LSTOSA**, the semi-automatic pipeline of the LST Collaboration (Ruiz et al. 2022; Morcuende et al. 2022), which connects the different steps of **lstchain**, the low-level analysis software developed for LST–1 (López-Coto et al. 2021; Lopez-Coto et al. 2023). **LSTOSA** acquires *Raw level 0 data* (R0) from the telescope’s camera, i.e. uncalibrated waveform signal, and performs waveform calibration, charge integration in every pixel to produce Cherenkov images, image cleaning and image parameterisation, providing DL1 data. **lstchain** then process DL1 data by applying dedicated Random Forests (RFs, see chapter 2.3) to obtain the DL2 data.

The RFs were trained on MC simulated images of gamma-rays and hadronic events, tuned to the NSB level of the data. The **NSB tuning** of the RFs is a necessary step because MC events are simulated assuming a NSB level typical of a “dark” sky field (i.e. away from the Galactic disk and the zodiacal plane), resulting in an average p.e. rate of 193 MHz per pixel. LST–1 real observations, on the other hand, are performed in a wide range of NSB conditions. To reach the best analysis performance for the specific SGR 1935+2154 dataset, we *tuned* the NSB levels in the training sample of the MC events to the one of our real data with the “noise padding” method described in section 2.3.3. It consists in adding some random Poisson noise during the analysis of the MC events (before the image cleaning), to match the average NSB level in the data. We implemented it by evaluating the NSB level of our data with **lstchain** using the *interleaved pedestal events* acquired during real

observations. `1stchain` characterises the NSB of a telescope sub-run (≈ 15 s of data) with 3 parameters: the *extra bias* in dim pixels and *extra noise* in *dim* and *bright* pixels that must be added to match the observed data. The transition charge between dim and bright pixels is 8 p.e.. We first evaluated the NSB in a reduced sample of sub-runs, obtaining: *extra noise in dim pixels* 1.309, *extra bias in dim pixels* 0.54, *extra noise in bright pixels* 1.79. We used these values to perform noise padding, and the dedicated `1stMCpipe` (Garcia et al. 2022; Vuillaume et al. 2023) software to obtain a set of MC simulated events and trained RF forests tuned to the NSB of our dataset. In particular, we obtained one set of MC events and RFs for every **MC simulation node**, i.e. the choice of a telescope pointing direction in horizontal coordinates (azimuth and zenith angle), as the reconstruction strongly depends on the direction of the EAS. A subset of simulated events was used as a *test sample* to compute the Instrument Response Functions (IRFs, see chapter 2.3). We processed all data with these MC simulations, using only one NSB tuning because all data were recorded in the same sky region and Moon runs were not used in the high-level analysis. The spectrum of the simulated MC γ -ray events is a power law with index 2.

We evaluated the NSB level on a reduced sample of the dataset due to computational time issues. In a second moment, during periods of low-activity on the IT Cluster of LST–1, we completed the systematic study of the distribution of the NSB parameters in all the sub-runs of the dataset. The median parameters we found in the distributions of Moon-less sub-runs were compatible with the values we already found. We show the distributions of the 3 NSB parameters in all the sub-runs and the Moon-less ones in figure 6.3.

6.4 Persistent Emission Data Analysis

In order to evaluate the level of VHE persistent emission from SGR 1935+2154, we selected a sub-sample of our dataset, considering only *good quality* runs according to three criteria:

1. We selected *wobble* runs with a pointing-target offset between 0.35 deg and 0.45 deg, discarding *on* runs for the lack of suitable *off* observations. The distribution of the offset is shown in figure 6.1a.
2. We selected only *dark time* runs with no Moon contamination by assuming $\sigma_{\text{ped}} < 2$ p.e.. The distribution of σ_{ped} is shown in figure 6.2b.
3. We selected runs with a rate of *cosmic* events $> 2500 \text{ s}^{-1}$, as lower values can be attributed to instrumental or environmental issues such as the *calima*, a meteorological phenomenon typical of the Canary Islands in which fine sand and dust particles from the *Sahara Desert* are lifted into the atmosphere and transported by winds. The distribution of the rate of cosmic events is shown in figure 6.4.
4. We manually removed run 6253 due to the presence of instrumental issues, likely a humidity patch on the camera, see figure 6.5.

This selection provided 25.5 h of good quality data, distributed over 82 runs taken in 13 nights during July 2021, September 2021 and June 2022.

We used the DL2 data obtained with the NSB-tuned RFs described in section 6.3.1 to obtain with `1stchain` the DL3 data: the photon lists and the IRFs (obtained from the test sample of MC simulated data). To produce DL3 data, we adopted the “standard” γ /hadron separation cuts, optimised for a Crab spectral analysis in CTA-LST project et al. (2023),

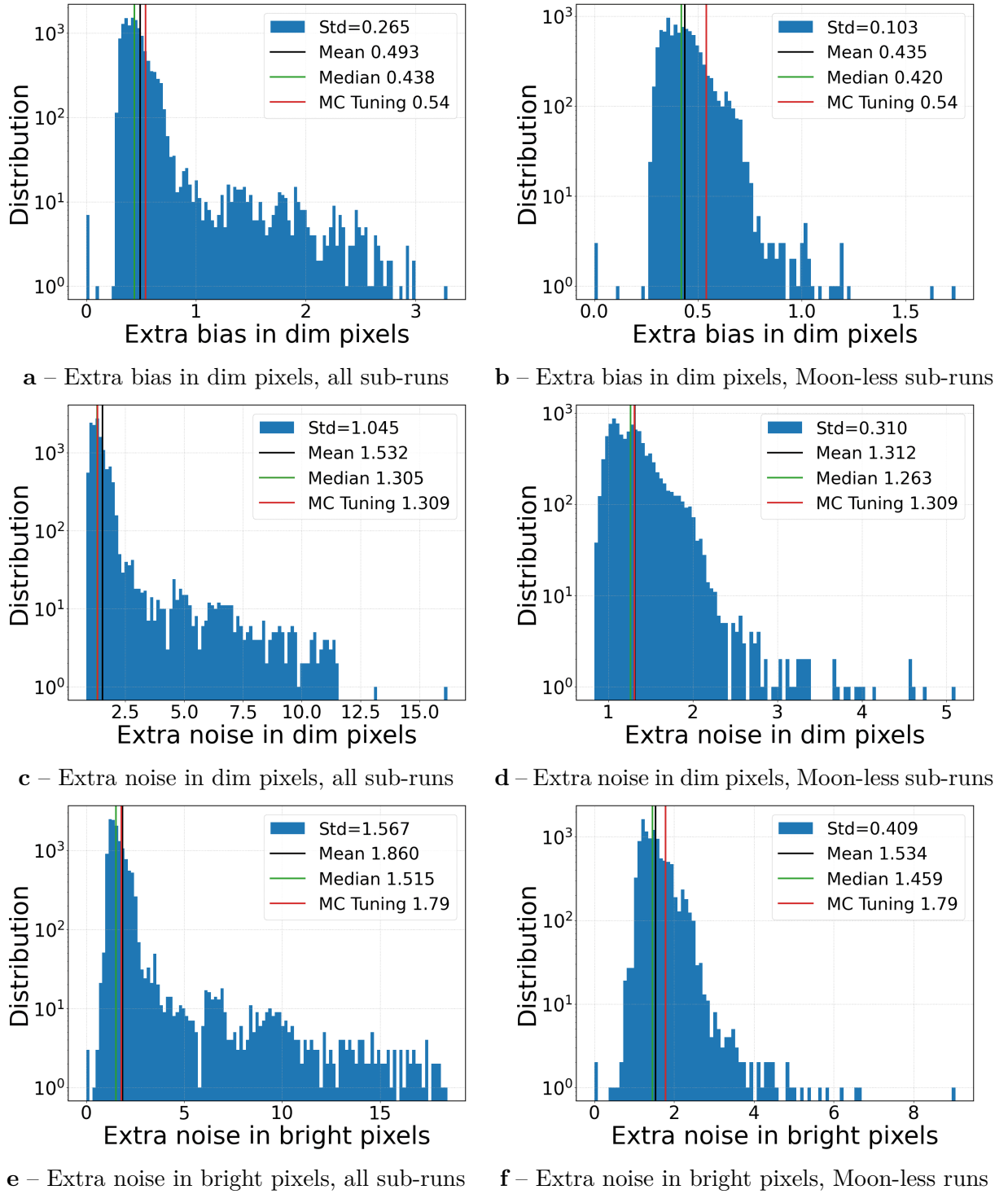
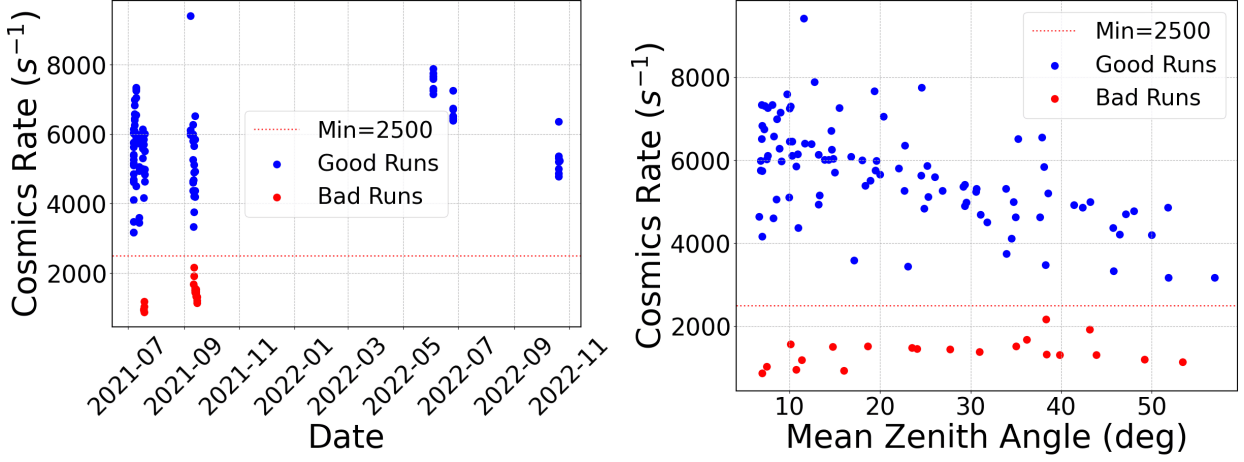


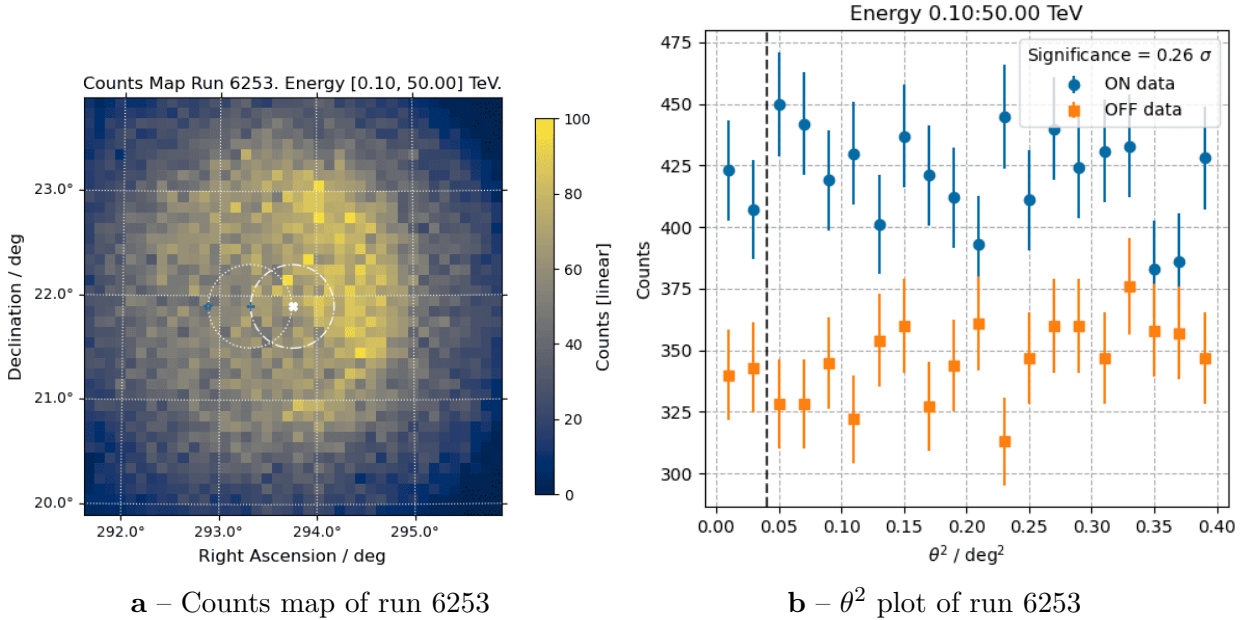
Figure 6.3 – Distribution of the NSB parameters. By comparing left-side and right-side panels we note that Moon runs add a non negligible tail in the distribution of all parameters, and would require a different tuning than Moon-less runs if used in the analysis.

and that can be applied to most standard spectral analyses performed with LST–1 (e.g., Abe et al. 2023b). The cuts are *intensity* > 80 p.e., *θ -containment* 0.68 and an energy-dependent *γ /hadron separation efficiency* (*gh-efficiency*) 0.70. The produced IRFs follow the *Gamma Astro Data Format* (GADF) (Nigro et al. 2021b) for *point-like* IRFs with a fixed offset of 0.4 deg. They include the *effective area*, the *energy dispersion matrix* and the (energy-dependent) *radius of an event selection region*, in the ≈ 0.12 deg to 0.22 deg range.



a – Rate of cosmic events of the runs vs date b – Rate of cosmic events of the runs vs zenith

Figure 6.4 – Distribution of the rate of cosmic events of the LST–1 runs as a function of run date and zenith angle. All the runs with rate $< 2500 s^{-1}$ were taken during a July 2021 night, that likely suffered from calima or other bad-weather conditions.



a – Counts map of run 6253

b – θ^2 plot of run 6253

Figure 6.5 – Counts map and θ^2 plot of run 6253. The white X is the position of SGR 1935+2154, the blue cross the pointing direction and the blue star on the left the OFF position. An asymmetry, likely due to an humidity patch on the camera, is clearly visible on the right side of the plot, and it results on a different normalisation in the ON and OFF distribution. If the asymmetry were not taken into account, the estimation of the Li&Ma significance σ with $\alpha = 1/n_{OFF} = 1$ would yield $\sigma \approx 7$. The correct evaluation of $\alpha \approx 2$ from the ON and OFF acceptance ration (see section 2.4.3) yields $\sigma = 0.26$. Due to the uncertain nature of the issue, we decided to discard this run.

We performed the *high-level analysis* with `gammapy v1.0` (Donath et al. 2023; Acero et al. 2022) by stacking all data of the selected runs. We used a minimum energy of 0.1 TeV to take into account the different energy thresholds of the runs due to their wide zenith angle distribution. We estimated the number of background events in the signal region through the *reflected regions* method (Berge et al. 2007), using one OFF region whose size is equal to the one of the ON region and energy-dependent. The θ^2 plot for the selected data does not show any significant signal, see figure 6.6.

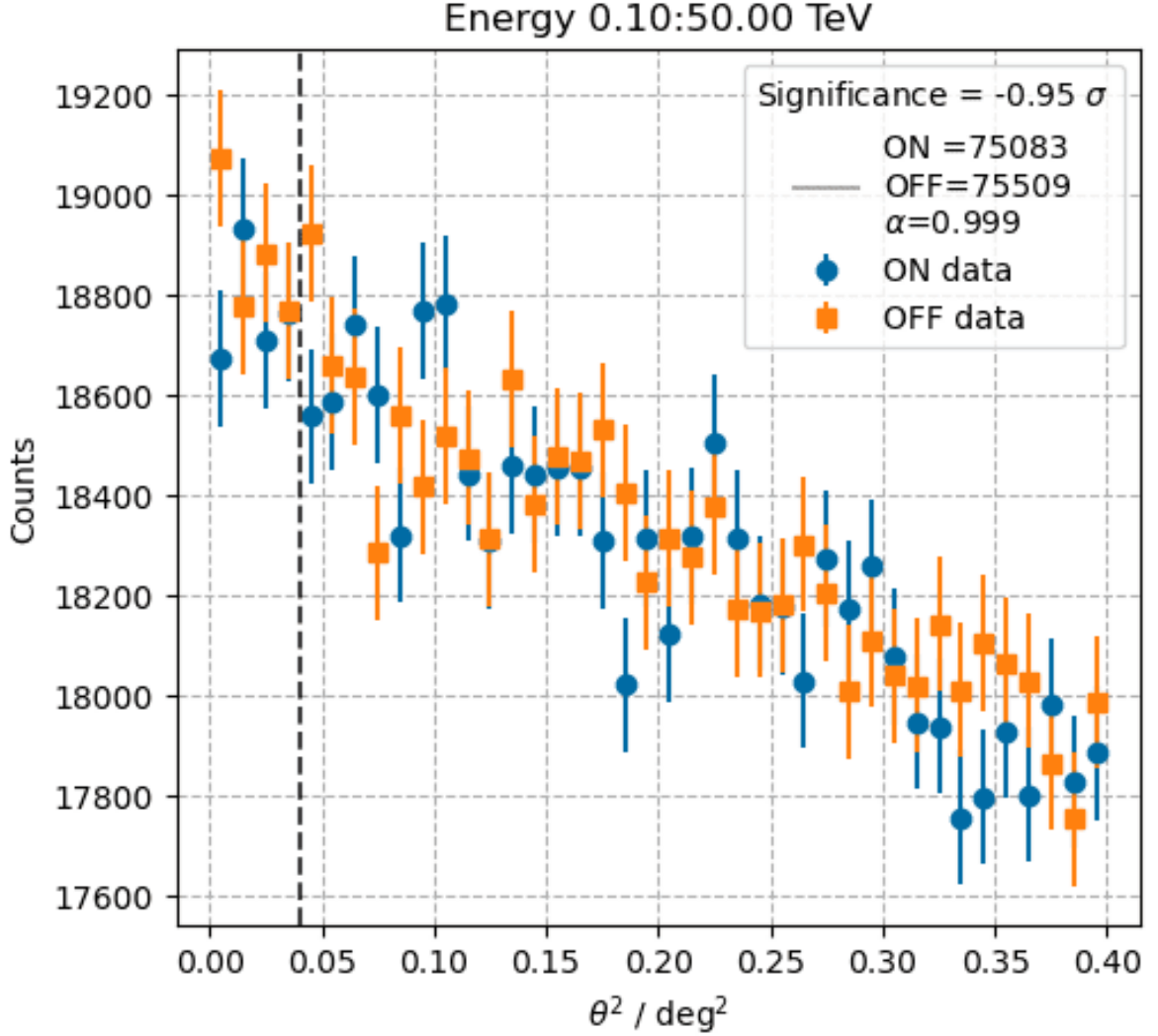


Figure 6.6 – θ^2 distribution of SGR 1935+2154. The acceptance ratio α was computed in the $0.10 - 0.40 \text{ deg}^2$ range as described in section 2.4.3. The ON and OFF counts are estimated with a $\theta_{\text{cut}}^2 = 0.04 \text{ deg}^2$ and yield a negative excess and significance.

As we did not detect the source, we performed a 1D MLE spectral analysis to estimate the 95% confidence level upper limits (ULs). We used ten logarithmically-spaced bins between 0.1 TeV and 10 TeV and assumed a point-like source with a power law spectrum with photon index 2.5, an average value for TeV sources that have not a known emission model in literature, already proposed by H.E.S.S. Collaboration et al. (2021). The resulting upper limits, discussed later in section 6.10.1 and plotted in figure 6.23, are lower than the ones in H.E.S.S. Collaboration et al. (2021). The UL on the integrated flux in the 0.1 TeV to 10 TeV range is $5.0 \cdot 10^{-12} \text{ s}^{-1} \text{ cm}^{-2}$, corresponding to $2.4 \cdot 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$. The flux upper limit above

0.6 TeV, for direct comparison with H.E.S.S., is $3.1 \cdot 10^{-13} \text{ s}^{-1} \text{ cm}^{-2}$ ($7.4 \cdot 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$). The choice of the spectral index 2.5 is to some extent arbitrary and may introduce systematic errors in the computation of the ULs. For this reason, we also computed the ULs by changing the index by 20%, that resulted in a $\lesssim 10\%$ variation of the ULs. A softer spectrum (e.g. index 3) results in systematically lower ULs. The most significant variation (10%) is at the energy threshold (0.1 TeV).

We searched for source variability by computing the nightly light curve and SED of the emission ($\approx 2 \text{ h}$ livetime), but we did not detect the source in any of the observation nights.

6.5 The Burst Analysis: Overture

The stacked spectral analysis performed in section 6.4 follows the traditional statistical methods presented in chapter 2.4. It can be used to evaluate the presence of a persistent signal using long exposure times. As a general principle, it is possible to apply it on shorter time scales, e.g. to compute light curves and detect flux variations, until the regime of *low-photon-statistics* ($\lesssim 10$ photon counts per temporal bin) is reached. The time scale corresponding to such limit depends on the instrument's effective area and its reconstruction algorithm. LST-1 light curves are usually computed down to $\sim 1 \text{ h}$ time scales in off-line analyses, and down to 100 s-long time bins in the RTA-SCI system (see chapter 4), while the *low-photon-statistics* regime is at $\lesssim 10 \text{ s}$. This value can hinder LST-1 capabilities to detect and analyse the emission of fast transients such as the prompt emission of short GRBs, magnetar flares and FRBs (see chapter 1.6.3). There are two possible solutions to the *low-photon-statistics* issue: either by improving the instrument (e.g. by adding more IACTs and adopting the stereoscopic reconstruction), or changing the type of analysis performed.

The **Burst Analysis** we present was first developed in Particle Physics to solve the *Small-N problem* in particle-counting experiments (Cowan 2007), and was once adapted to MAGIC data when searching for VHE counterpart of FRB emission (MAGIC Collaboration et al. 2018). We developed a `python` pipeline to implement the *Burst Analysis* for the CTAO-LST Collaboration, and we applied it on the SGR 1935+2154 case study, searching for TeV magnetar burst emission on a $\delta t = 0.1 \text{ s}$ time scale (typical duration of a magnetar X-ray burst). The pipeline ([GitHub/BurstAnalysis](#), Panebianco 2024), performs 3 tasks:

1. Optimisation of the γ /hadron separation *Burst cuts* to improve the sensitivity of the analysis. We describe it from a theoretical point of view in section 6.6, and from a software point of view section 6.7.
2. Evaluation of the VHE signal in a δt -long time bin simultaneous to a magnetar burst detected by an external facility, see section 6.8.
3. Search for VHE δt -long bursts in all of our dataset, non simultaneous to the known bursts, see section 6.9.

We show in figure 6.7 a schema of the data flow and analysis tasks of the persistent and transient emission. Both analyses perform the same low-level reconstruction process described in section 6.3.1 up to the DL2 level. The persistent analysis continues by applying standard γ /hadron separation cuts and the high-level analysis methods described in section 6.4. The burst analysis executes the 3 tasks described above.

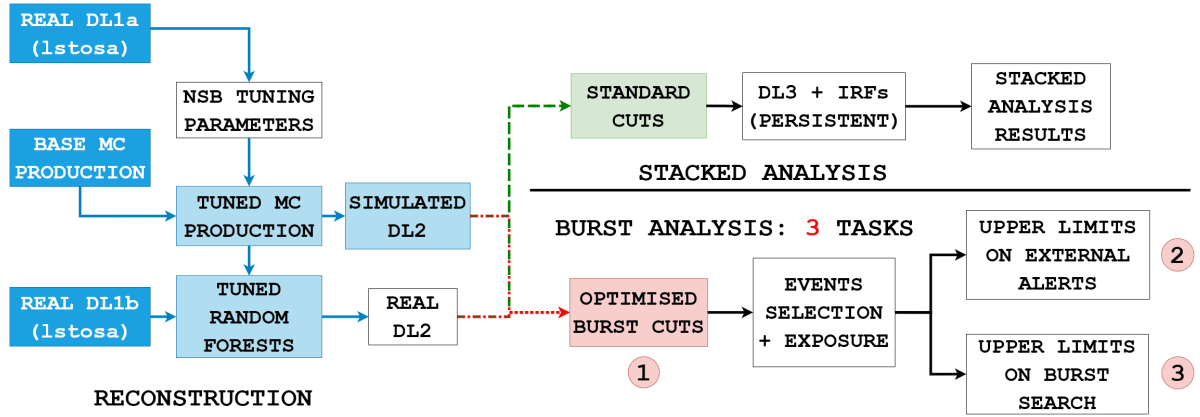


Figure 6.7 – Schema of the data flow of the standard and burst analysis of SGR 1935+2154. Both analyses use the same reconstruction process up to DL2 level, but adopt different γ /hadron separation cuts and high-level analysis methods.

6.6 The Burst Analysis: Theory of Cuts and Sensitivity Optimisation

As discussed in section 2.3.4, the goal of any optimisation procedure of γ /hadron separation cuts is to improve as much as possible the *sensitivity* of the analysis. For this reason, we first need to provide a definition of *Burst Analysis* sensitivity from a theoretical point of view. Then, we need to evaluate the sensitivity scanning a grid of possible cuts values, and choose the optimal set of cuts.

Sensitivity of the Burst Analysis. Let us work under the hypothesis of observing a *non detected point-like source*, as it is the case of SGR 1935+2154 (see section 6.4). Any DL3 photon counts observed inside the ON region centred on the source can either be attributed to the γ -like *background* or to a possible short burst. We can estimate the expected background from an OFF region symmetric to the ON region with the respect to the telescope pointing, assuming a *radial* camera response. The background rate depends on the specific conditions of the observation, e.g. zenith angle, source offset, NSB level, atmospheric conditions. For most IACT observations, without any severe instrumental or weather issues, we can assume the background being *constant* within an observation run (≈ 20 min). Possible changes in the background are due to weather conditions, such as the presence of clouds or variation of the humidity, NSB evolution, and variation of the observed zenith angle due to telescope tracking, which may be particularly relevant for large-zenith angle observations. We can check the background rate being constant by performing a linear fit and an hypothesis test that evaluates if the fit slope is consistent with zero or not (e.g., using [scipy stats linregress](#), Virtanen et al. 2020).

For the SGR 1935+2154 case study, we adopt the hypothesis of *run-wise constant background rate*, tested with a single energy bin starting at 0.03 TeV, the nominal energy threshold of LST–1 in our NSB-tuned MC simulations. We performed a linear fit of the background rate as a function of time to check that, within our runs, background variations were negligible. The background rate $R_{\text{bkg}}(\Theta; k)$ of an observation run k is thus a function *only* of the γ /hadron separation cuts Θ that we need to optimise. We aim to optimise the cuts $\Theta = (g_{\text{cut}}, \theta_{\text{cut}}^2, i_{\text{cut}})$, where i_{cut} is the cut in image intensity (total charge of the Cherenkov

cleaned image), g_{cut} in event *gammaness* and θ_{cut}^2 in the squared radius of the ON and OFF regions (Bock et al. 2004; Berge et al. 2007; CTA-LST project et al. 2023).

Under the hypothesis of *constant* background rate $R_{\text{bkg}}(\Theta; k)$, the number of background events selected with cuts Θ observed in a time bin with duration δt is a random variate distributed according to a **Poisson** distribution with expected value (Feigelson and Babu 2012):

$$\mu_{\text{bkg}}(\Theta; k) = \delta t \cdot R_{\text{bkg}}(\Theta; k). \quad (6.1)$$

We can thus define a frequentist hypothesis test (see section A.1) where the test statistics TS is the number of observed ON counts in a time bin and the *Null Hypothesis* H_0 is: “there is no transient emission and the observed counts can be attributed to the background Poisson distribution”. The *sensitivity of the test* is the number of counts $N_{5\sigma}$ required in a bin to reject the null hypothesis H_0 and claim the detection of transient emission with a 5σ statistical significance in a Gaussian one-sided test, i.e. with **p-value** $p \simeq 2.87 \cdot 10^{-7}$ (Cowan 2007). $N_{5\sigma}$ can be estimated as the inverse of the *Survival Function* (SF) of the background Poisson distribution:

$$N_{5\sigma}(\Theta; k) = SF_{\text{Poisson}}^{-1}(p; \mu_{\text{bkg}}(\Theta; k)), \quad (6.2)$$

where SF is just 1 minus the *Cumulative Mass Function* (CMF) of the distribution, and it is evaluated at p-value $p = 2.87 \cdot 10^{-7}$. An example of these quantities is provided in figure 6.8. Panel 6.8a shows the background rates R_{bkg} as a function of g_{cut} , θ_{cut}^2 and for a fixed $i_{\text{cut}} = 50$ p.e., while panel 6.8b shows the expected number of background counts $\mu_{\text{bkg}} = \delta t \cdot R_{\text{bkg}}$. As expected, they show a continuous distribution of values where *tighter* cuts (i.e. higher g_{cut} , i_{cut} and lower θ_{cut}^2), provide lower rates. Tight cuts risk discarding real γ -rays with poor gammaness score, while *looser* cuts may introduce hadronic events in the analysis. The distribution of $N_{5\sigma}$, see figure 6.8c, follows the same general pattern of R_{bkg} and μ_{bkg} , but it is a *discrete* variable as required by the Poisson distribution.

$N_{5\sigma}$ represents the *sensitivity of the hypothesis test*, but it is *not* the sensitivity of the entire analysis. According to the discussion presented in section 2.3.4, we can define the **Flux Sensitivity of the Burst Analysis** as the minimum *photon flux* detectable from a point-like source in the ON region with a predefined *spectral* model with 5σ statistical significance in a $\delta t = 0.1$ s interval. In order to obtain it, we need to divide $N_{5\sigma}$ for the *Exposure* $\mathcal{E}$ of the observation. As we discuss in appendix A.3, the exposure is the product of the observation livetime δt times the effective area A_{eff} , that is the product of the geometrical collection area A_{geom} (order of $\sim 10^4$ m² for the LST-1) times the **Reconstruction Efficiency** ϵ :

$$\mathcal{E} = \delta t \cdot A_{\text{eff}} = \delta t \cdot A_{\text{geom}} \cdot \epsilon. \quad (6.3)$$

The Reconstruction Efficiency represents the fraction events induced by γ -rays that survive the entire reconstruction process, from the imaging step to the γ /hadron separation. We can evaluate the Efficiency of a set of cuts on the *test sample* of the MC-simulated DL2 data, as they only contain shower events initiated by γ -rays. For a given MC simulation node j of assigned zenith and azimuth angles, the efficiency $\epsilon(\Theta; j)$ is the fraction of events surviving the cuts Θ in a given energy bin. We show an example of this quantity in figure 6.8d. As the geometrical collection area and the observation time define a constant factor $A_{\text{geom}} \cdot \delta t$ which does not depend on the cuts assumed, we can simplify our definition of the **Burst Analysis Sensitivity** ξ as the ratio between the test sensitivity $N_{5\sigma}$ and the Efficiency ϵ :

$$\xi(\Theta; j, k) = \frac{N_{5\sigma}(\Theta; k)}{\epsilon(\Theta; j)}, \quad (6.4)$$

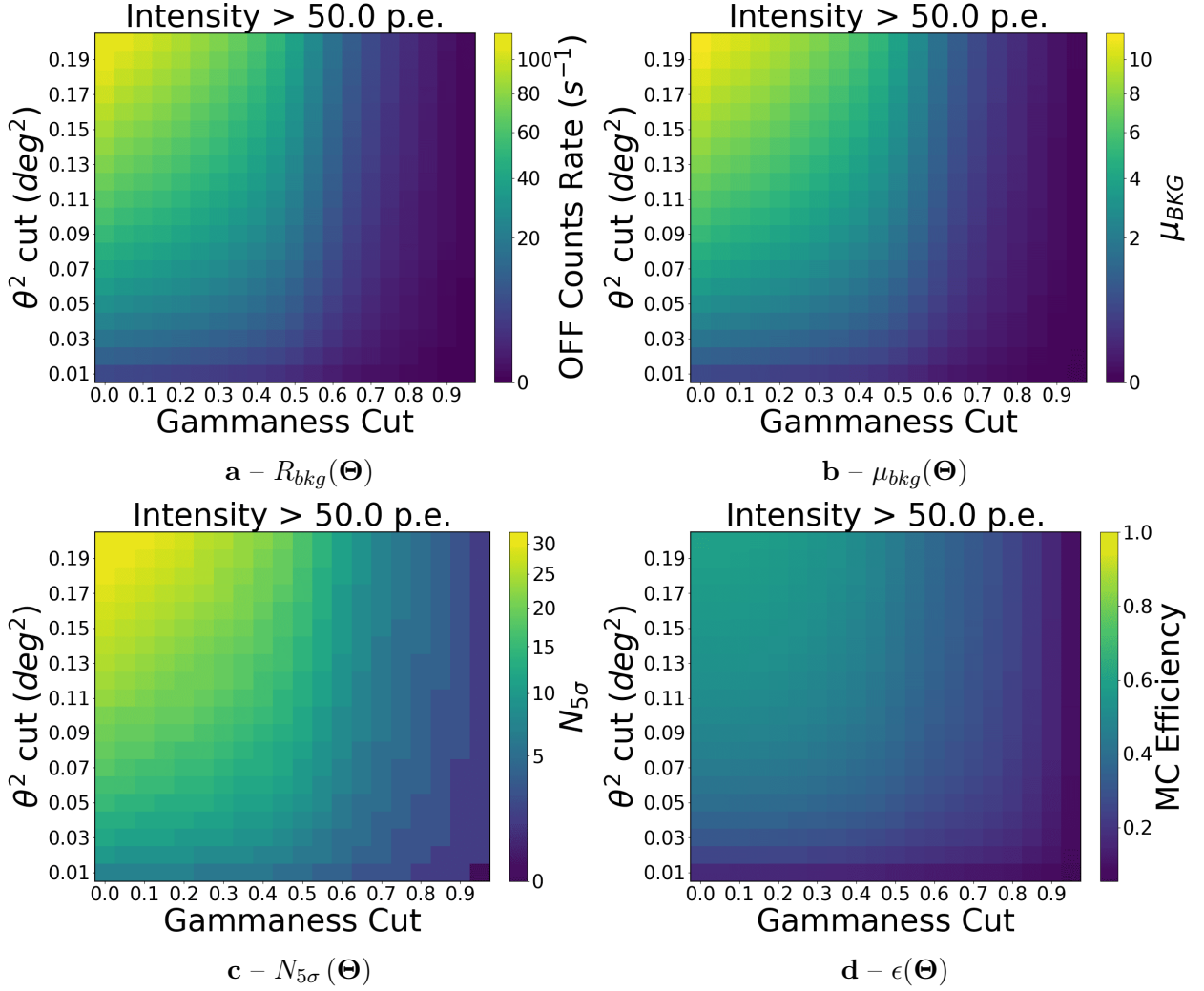


Figure 6.8 – Distribution of the Background rates R_{bkg} (panel 6.8a), Poisson expected background counts μ_{bkg} (panel 6.8b, let us note that $\mu_{bkg} = R_{bkg} \cdot 0.1 \text{ s}$) and test sensitivity $N_{5\sigma}$ (panel 6.8c) as a function of g_{cut} and θ_{cut}^2 , and for a fixed $i_{\text{cut}} = 50 \text{ p.e.}$, evaluated from LST–1 real data. Panel 6.8d shows the distribution of the efficiency ϵ obtained from MC simulated data.

where j refers to the MC simulation node closest in azimuth and zenith angles to the telescope pointing of the observation run k , which has a specific Poisson background. We define the *Optimal Burst Cuts* to detect a short δt -long transient emission as the ones optimising the analysis sensitivity, i.e. with lowest $\xi(\Theta; j, k)$. ξ is an adimensional quantity, the photon flux sensitivity is:

$$\phi = \frac{\xi(\Theta; j, k)}{A_{\text{geom}} \cdot \delta t}. \quad (6.5)$$

Dependency of the Efficiency on a Spectral Model. Let us now address a fine detail of the analysis. The definition of sensitivity is dependent on an assumed spectrum for the target source. This dependency lies within the efficiency ϵ , due to the fact that MC data are simulated with an assumed spectrum, and the same γ /hadron separation cuts $(\Theta; j, k)$ yield different efficiencies on photons simulated with different spectra. It can be explained by considering that a given cut value *always* keeps a higher fraction of higher-energy γ -rays as they are easier to reconstruct. Lower-energy γ -rays are produced by fainter showers, that are more difficult to reconstruct. Thus, steeper (softer) spectra result in a smaller fraction of

survivors and smaller efficiencies. Different spectra can be considered either by producing new MC simulations, or simply by assigning a *spectral weight* $w(E_{\text{true}})$ to the simulated events. The weight is given by the ratio of the requested and the simulation spectra, computed at the *reconstructed* energy of the event E_{true} . For instance, if the MC events are simulated with a power law spectrum with index 2, and we want to analyse the target source with a power law spectrum with index γ , each event is assigned a weight:

$$w(E_{\text{true}}) = \frac{n_\gamma (E_{\text{true}}/E_0)^{-\gamma}}{n_2 (E_{\text{true}}/E_0)^{-2}}, \quad (6.6)$$

where n_2 and n_γ are the normalisation factors (spectra are normalised to the total number of simulated events) and E_0 is a reference energy. This is the same weighting technique described in section 2.3.4 and used to compute the energy threshold of an analysis. The reconstruction efficiency is thus given by:

$$\epsilon(\Theta) = \frac{\text{weighted N events after cuts}(\Theta)}{\text{weighted N events before cuts}(\Theta)}, \quad (6.7)$$

where the *weighted number of events* is equal to the sum of the weights.

Sensitivity of Stacked Data. The definition of $\xi(\Theta; j, k)$ of eq. (6.4) applies to the case of a single observation run and a single MC node. In reality, analyses include several runs and MC nodes. For instance, the LST–1 dataset on SGR 1935+2154 is composed of 118 runs with a wide distribution of background rates and zenith angles, and 84 MC nodes spanning a grid of possible horizontal coordinates of the telescope. We optimised the cuts only on a subset of “average”¹ runs, and we assumed the optimal cuts for the whole dataset. The criterion to select “average” runs is to some extent arbitrary. In our case study, we excluded runs with a total rate of *cosmic* events $< 2500 \text{ s}^{-1}$ (to avoid bias due to environmental conditions) and the *ON* runs (due to not having the OFF region), then we performed a fit of the run’s rate of cosmic events as a function of its zenith angle, and considered for the cuts optimisation process only the runs with rate of cosmic events within 15% of the best fit value. We show these runs in figure 6.9. We stacked the counts of all the selected “average” runs and estimated the background rate $R_{bkg}(\Theta)$ as the rate of events surviving the cuts Θ in the OFF region, and we computed the corresponding $N_{5\sigma}(\Theta)$ with eq. (6.2). To estimate the cut efficiency $\epsilon(\Theta)$, we weighted the cut efficiency of every simulation node with the number of times they were the closest one to a selected runs.

Burst Cuts for LST–1. We present the Burst Analysis sensitivity $\xi(\Theta) = \frac{N_{5\sigma}}{\epsilon}(\Theta)$ in figure 6.10. It shows the existence of a region in the Θ parameter space where $\xi(\Theta)$ has the lowest values, comprised between $i_{\text{cut}} \approx 25 \text{ p.e.}$ to 100 p.e. (not in the figure), $g_{\text{cut}} \approx 0.70$ to 0.90 and $\theta_{\text{cut}}^2 \approx 0.03 \text{ deg}^2$ to 0.10 deg^2 . Assuming γ /hadron separation cuts in this range optimises the analysis for the detection of 0.1 s bursts over a Poisson background. The existence of a broad minimum suggests that the analysis is not strongly sensitive on a precise choice of cuts, which adds to its robustness. We assumed $g_{\text{cut}} = 0.75$, $i_{\text{cut}} = 50 \text{ p.e.}$ and $\theta_{\text{cut}}^2 = 0.08 \text{ deg}^2$ as they are within the optimisation region but on the loose side, to improve

¹We use this term to select runs representative of the whole sample, that are not outliers due to instrumental issues or peculiar observational conditions.

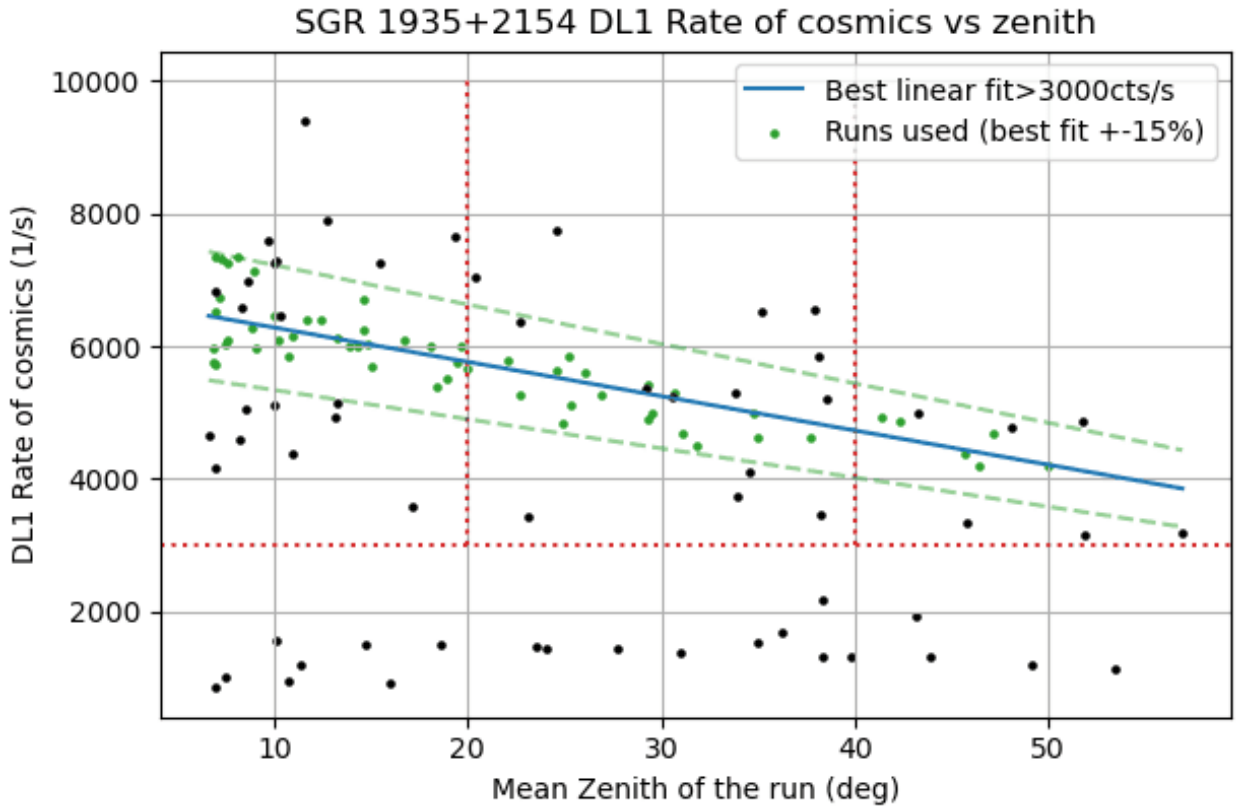


Figure 6.9 – Distribution of the rate of cosms of every observation run on SGR 1935+2154 as a function of the zenith angle. We separated the runs with a bad rate of cosms from the other ones. We performed a linear fit of the wobble-mode runs (blue line), and considered for the cuts optimisation process the runs within 15% of the best fit value (green dots). We performed the cuts optimisation first on all the selected runs, then separately on three bands of zenith angle (red lines) to check for zenith evolution of the cuts.

statistics. These cuts have a stricter g_{cut} , but looser i_{cut} and θ_{cut}^2 compared to the ones adopted in section 6.4. They are also defined on a single energy bin, while the values of the persistent emission cuts changes in the energy bins adopted.

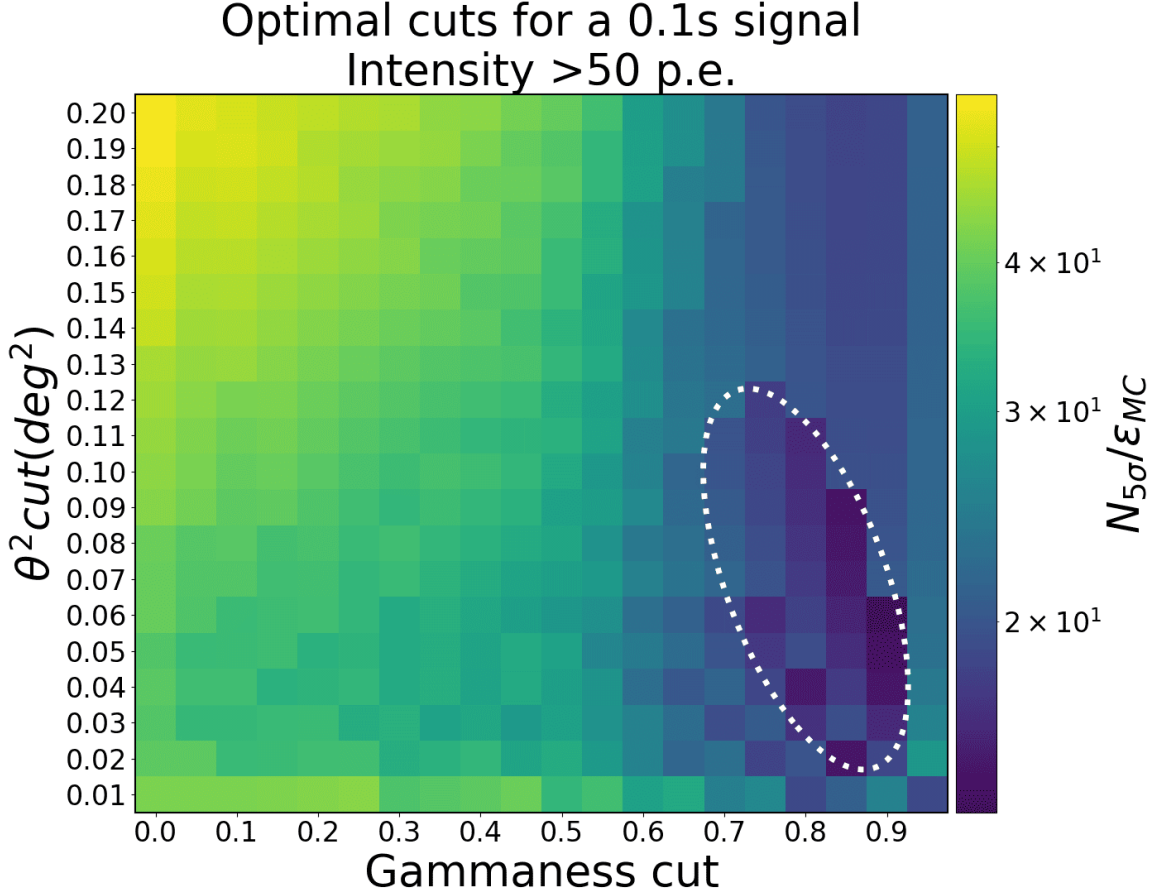


Figure 6.10 – Cuts optimisation for the low zenith band. The $\frac{N_{5\sigma}}{\epsilon}$ ratio is proportional to the flux sensitivity of the analysis and is evaluated for a grid of possible cuts value. An optimisation region with the best analysis sensitivity is highlighted by the ellipse.

We computed the sensitivity ξ under a wide range of conditions to test for **systematic** uncertainties. We performed the optimisation separately for 3 different zenith ranges (below 20 deg, above 40 deg, intermediate), and then for the entire range, obtaining consistent results. We also computed the efficiency assuming different spectral indexes: 2, 2.4, 3, see figure 6.11. Our study does not suggest variations in the optimal range of the i_{cut} , but shows that for index ≈ 3 the analysis becomes less sensitive to the θ_{cut}^2 and the optimal gammaness cut is reduced to $g_{\text{cut}} \approx 0.3$. This can be explained considering that softer spectra introduce more low-energy photons, that are more difficult to reconstruct and may require looser cuts in gammaness to be selected for the analysis. As the efficiency ϵ is systematically lower for softer spectra, the sensitivity also lowers (i.e. higher values of ξ and ϕ). When the index changes by $\approx 20\%$ with respect to a ~ 2.5 value, the resulting ξ changes by $\lesssim 20\%$, worsening for softer spectra.

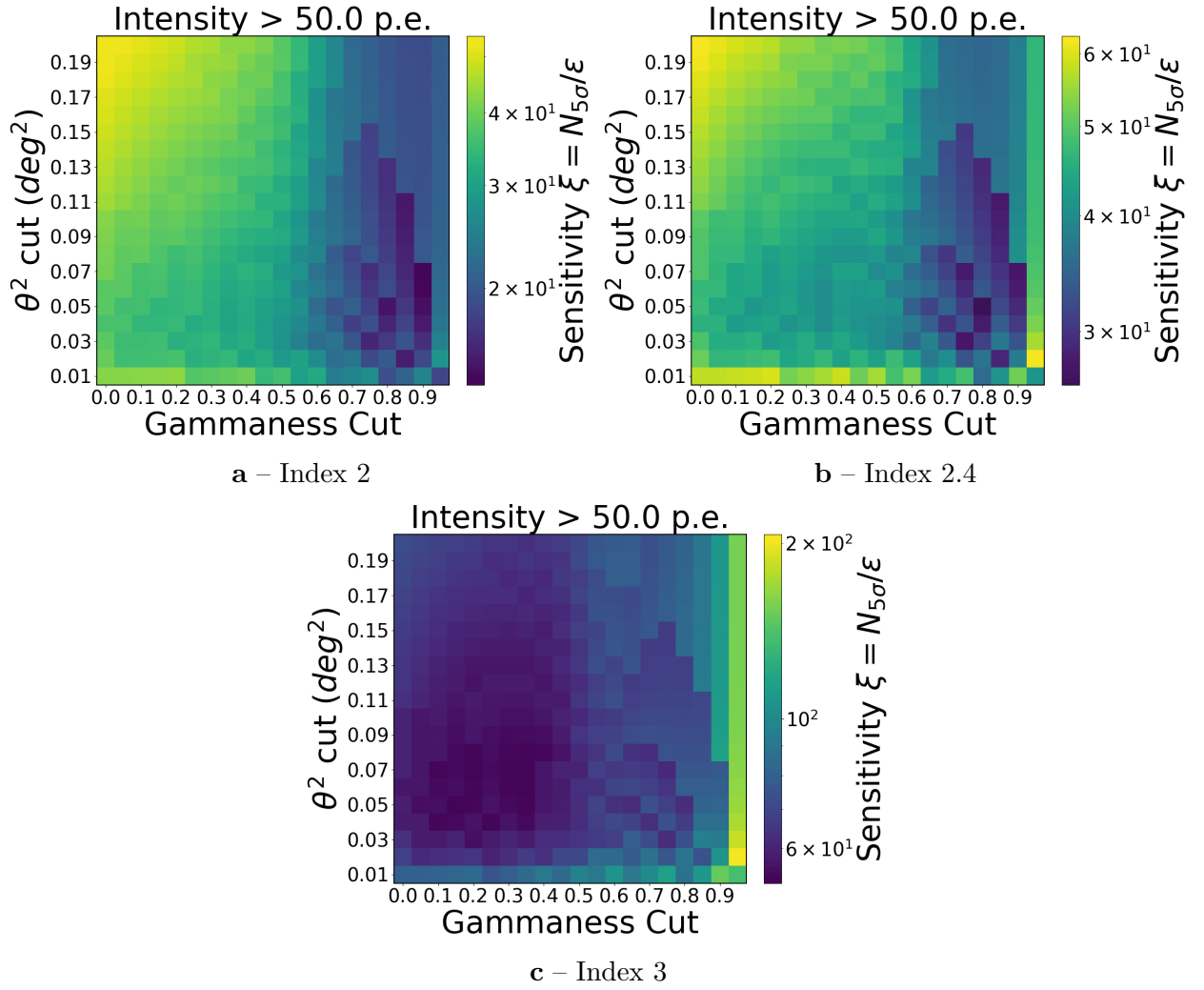


Figure 6.11 – Evaluation of the Burst Analysis Sensitivity $\xi(\Theta)$ when different power law indexes are used to compute the efficiency $\epsilon(\Theta)$.

6.7 The Burst Analysis: Development of the Pipeline

We implemented a python `BurstAnalysis` pipeline to perform the burst cuts optimisation on LST–1 DL2 data, i.e. event lists of reconstructed energy, direction and gammaness of a shower event. We used the same DL2 dataset of the persistent emission analysis obtained with `LSTOSA`, `lstchain` and `lstMCpipe` (see section 6.3.1), composed by 118 real data files (one for every observation run) and 84 simulated data files (one for every MC simulation node). We developed three scripts and one notebook to perform the burst cuts optimisation, that rely on `lstchain` to read data (López-Coto et al. 2021; Lopez-Coto et al. 2023), `astropy` to perform the event selection cuts (Astropy Collaboration et al. 2022) and `scipy` for statistical calculations (Virtanen et al. 2020). Each of the scripts works by reading and operating only on one file per execution. We took advantage of the computational capabilities of the LST–1 IT cluster to submit ~ 100 parallel jobs and process all our files at the same time. The *Burst Analysis* pipeline also performs standard *data quality* checks that in the future will be implemented in `SAG-DQ` (see chapter 3) and performed in real-time on DL2 data.

6.7.1 Computation of the Reconstruction Efficiency

The first script of the pipeline, `CutEfficiencyMC`, reads one MC-simulated DL2 file, and plots the distribution of several event properties. Figure 6.12 shows the distribution of the intensity, gammaness, true energy and reconstructed energy of the events. The intensity ($\propto$ shower energy) shows a peak at ~ 50 p.e., the intensity threshold of the telescope, then a $\sim$ power law distribution with a high-intensity cutoff. The gammaness shows a double-peaked distribution, where the low-gammaness peak are the events badly reconstructed, that appear similar to hadronic events, while the high-gammaness peak includes well-reconstructed events. The true (simulated) energy distribution is a power law with index 2 and a low-energy cutoff below ~ 30 GeV, the telescope threshold for our NSB-tuned simulations. The reconstructed energy distribution shows how the simulated spectrum is distorted, especially near the energy threshold. Figure 6.13 shows the distribution of the true and reconstructed position of the events in the camera frame. Events are simulated in a ring with fixed offset of 0.4 deg, which appears as a blurred ring in reconstructed coordinates due to reconstruction uncertainty. This type of simulations can only be used to produce *point-like* IRFs as discussed in section 2.3.3. Figure 6.14 shows the θ^2 distributions of the events, where θ for a simulated events is the angular distance between true and reconstructed position. The distributions are shown for different bands of intensity and different gammaness cuts, for a direct comparison with the LST–1 performance paper (CTA-LST project et al. 2023).

The `CutEfficiencyMC` script must receive as input a configuration file that specifies the grid of cuts values explored, the energy bins, the power law spectral indexes requested to compute the efficiency $\epsilon(\Theta)$. We provide an example in figure 6.15. The script computes all the possible combinations of cuts values, and for every combination it records the number of *weighted* counts, see eq. (6.6), in the selected energy bin before and after applying the cuts, and compute the efficiency $\epsilon(\Theta)$ as their ratio, according to eq. (6.7). The efficiencies are the main output of the script, saved as a table in *ECSV* format, where every line is a combination of cuts values, their weighted counts and efficiency. We provide an example of the output in figure 6.16. We also save the plots of the table, that are similar to the one we showed in figure 6.8d.

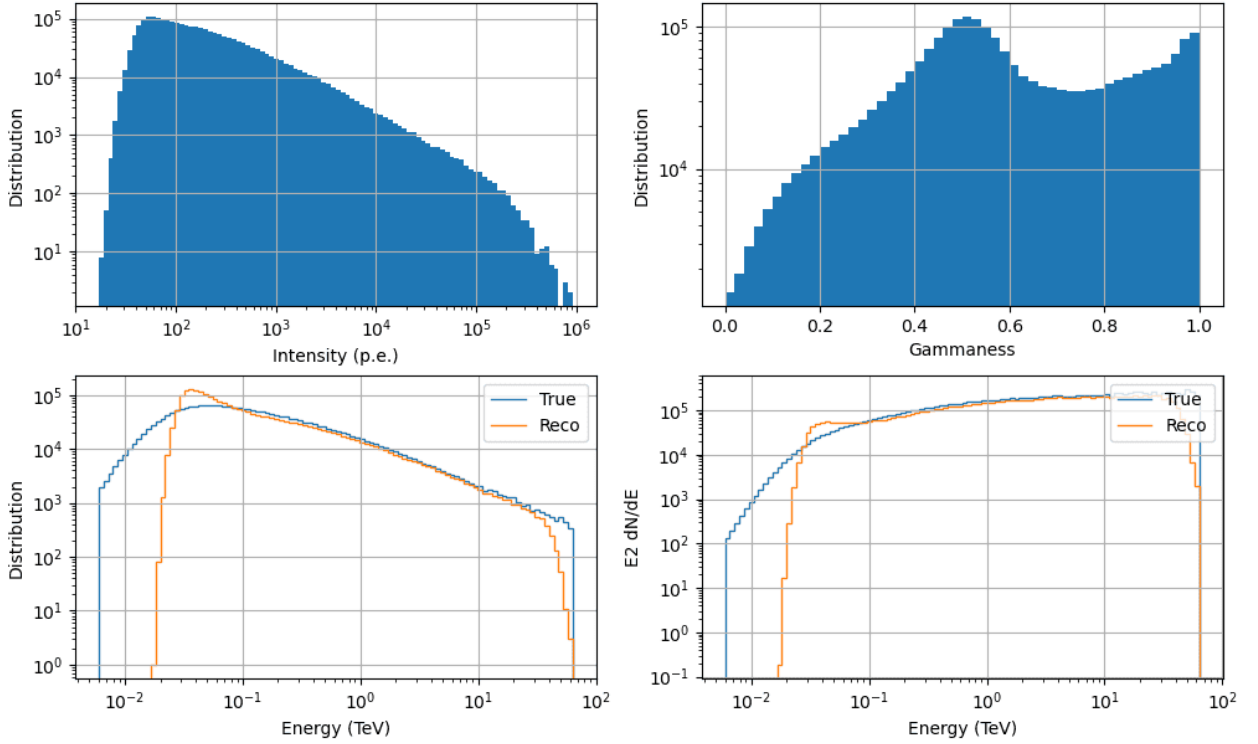


Figure 6.12 – Data quality plots of the MC data, simulation node with zenith and azimuth coordinates $(\theta_z, \phi_z) = (23.630, 100.758)$ deg. Distribution of the gammaness, intensity, true and reconstructed energy. The gammaness shows a double-peaked distribution, where the low-gammaness peak are the events badly reconstructed, that appear similar to hadronic events, while the high-gammaness peak includes well-reconstructed events. The intensity, which is proportional to the simulated energy of the particle, follows a power law distribution with a low-energy and a high-energy cutoff. The reconstructed energy distribution shows how the simulated spectrum is distorted, especially near the energy threshold.

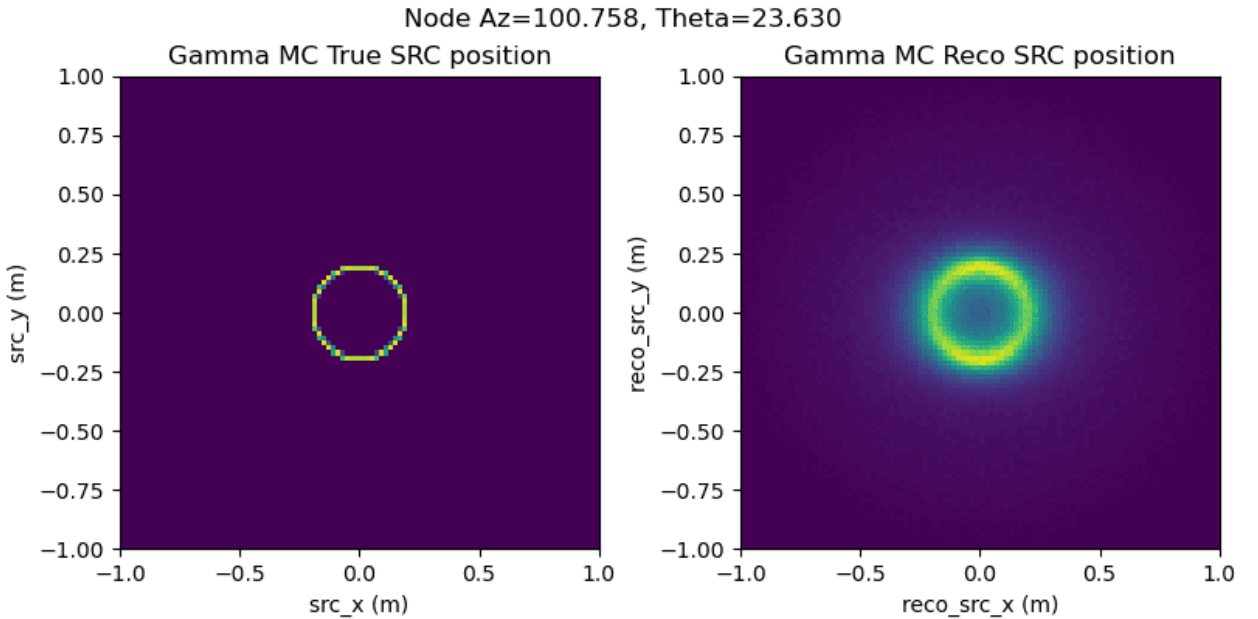


Figure 6.13 – Data quality plots of the MC data, simulation node with zenith and azimuth coordinates $(\theta_z, \phi_z) = (23.630, 100.758)$ deg. Distribution of the true and reconstructed position in camera coordinates ($0.1 \text{ m} = 0.2 \text{ deg}$ for the LST-1 camera).

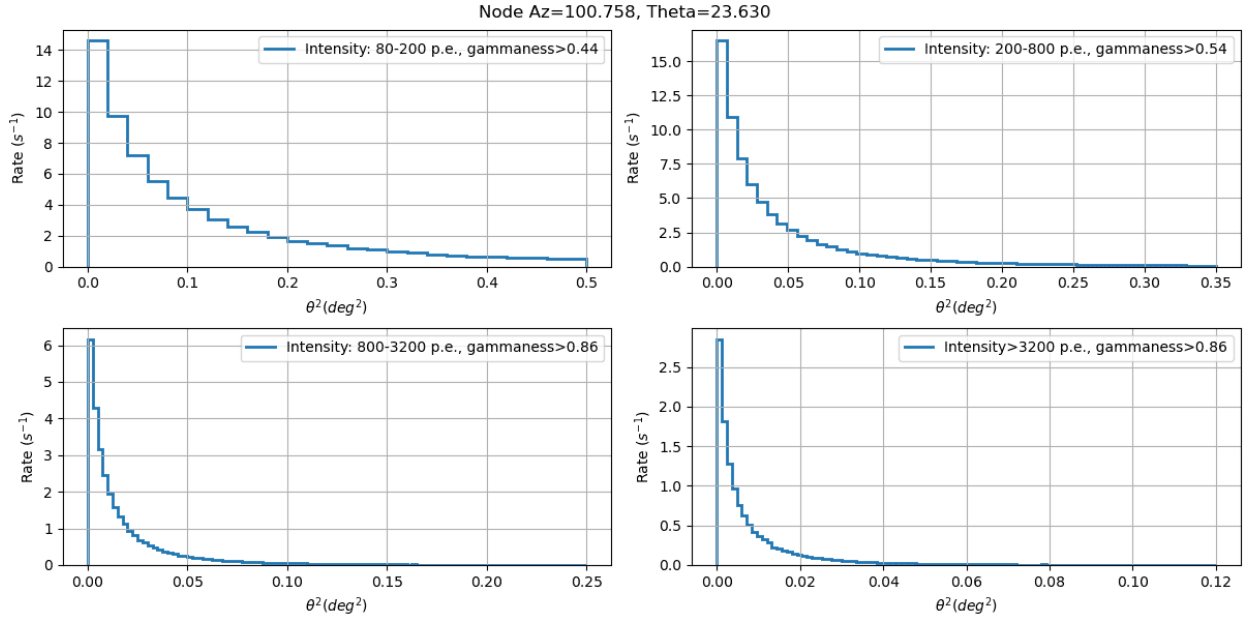


Figure 6.14 – Data quality plots of the MC data, simulation node with zenith and azimuth coordinates $(\theta_z, \phi_z) = (23.630, 100.758)$ deg. Distribution of the θ^2 distribution under different intensity and gammaness cuts.

```

1 cuts:
2   intensity: [25, 50, 80, 100, 150, 200, 800, 3200]
3   gammaness: [0.00, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, 0.60, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90, 0.95]
4   theta2_deg: [0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14, 0.15, 0.16, 0.17, 0.18, 0.19, 0.20]
5 parameters:
6   energy_reco_min_TeV: [0.03]
7   energy_reco_max_TeV: [100]
8   index: [2.0, 2.4, 3.0, 4.0]

```

Figure 6.15 – Input file of the Burst Analysis pipeline with configured grid of cuts, spectral models and energy bin used.

```

30 # value: 0.4001
31 # schema: astropy-2.0
32 energy gammaness intensity theta2 bin_counts selected_counts MCEfficiency CorrectionFactor
33 0.03 0.0 25.0 0.01 2071200.0 348086.0 0.16806006179992275 5.950253672942893
34 0.03 0.0 25.0 0.02 2071200.0 533557.0 0.2576076670529162 3.881872039913261
35 0.03 0.0 25.0 0.03 2071200.0 659812.0 0.31856508304364617 3.139075979218323
36 0.03 0.0 25.0 0.04 2071200.0 755335.0 0.3646847238315952 2.742094567311193
37 0.03 0.0 25.0 0.05 2071200.0 830896.0 0.4011664735419081 2.492730738865032
38 0.03 0.0 25.0 0.06 2071200.0 893583.0 0.4314325028968714 2.3178596728004
39 0.03 0.0 25.0 0.07 2071200.0 946113.0 0.45679461181923525 2.1891676787022267
40 0.03 0.0 25.0 0.08 2071200.0 991470.0 0.47869351100811125 2.0890193349269266

```

Figure 6.16 – Output file of the Burst Analysis pipeline with the cuts efficiencies for every combination of cuts.

6.7.2 Formatting Real Data Files

The second script of the pipeline, `Theta2Calculator`, is used to format the real DL2 files for the rest of the analysis. This step is required because regular DL2 files contains events in Camera coordinates only, while celestial coordinates are usually added only at DL3 level with `lstchain` after cut selection. We use the script to create a lightweight version of a DL2 file with only some relevant fields, such as reconstructed energy, gammaness, time and so on, to speed up file reading in later steps. We call the official `lstchain` functions to compute the celestial coordinates of the events, Right Ascension (R.A.) and Declination (Dec), and we compute the squared angular distance (θ^2) of each event with respect to an ON position (nominal target coordinates), the run pointing and an OFF position symmetric to the ON region with respect to the pointing. The script will compute the OFF θ^2 distribution only if the source-pointing offset is > 0.1 deg. Otherwise, the run will be considered as a ON run without any suitable OFF position.

The output of this script is a lightweight DL2 file in *HDF5* format.

6.7.3 Estimation of the Poisson Background and Sensitivity

The third script, `BurstCutsOptimiser`, evaluates the Poisson background distribution of a real observation run with a DL2 file, and computes the analysis sensitivity $\xi(\Theta)$ according to eq. (6.4). The script:

1. Reads in input a time scale δt , a lightweight DL2 file of a LST-1 run obtained with `Theta2Calculator`, and a file with the efficiencies ϵ computed with `CutEfficiencyMC`. We adopted the efficiencies of the MC simulation node with the closest azimuth and zenith coordinates to the run's ones.
2. It selects the cosmics events, disregarding calibration events present in the DL2 file, and adopts as observation time T_{obs} the *time of the last event minus the first one*.
3. If needed, a further selection with customised filters on parameters is possible (e.g. to exclude run anomalies) providing an appropriate configuration file. We have not used this feature for the SGR 1935+2154 analysis.
4. It produces data quality plots of the DL2 data:
 - Counts map.
 - Differential and cumulative distribution of the intensity of the events in the ON and OFF regions, with the performance paper cuts (CTA-LST project et al. 2023), see figure 6.17.
 - θ^2 distribution with the performance paper cuts, see figure 6.18.
 - Differential (figure 6.19) and cumulative (figure 6.20) distribution of the gammaness of the events with the performance paper cuts and its Crab data for comparison (CTA-LST project et al. 2023).
5. It estimates the ON and OFF counts rate ($R_{\text{ON}}(\Theta)$, $R_{\text{OFF}}(\Theta)$) for a grid of cuts as the number of events surviving the cuts in a given energy bin, inside the ON and OFF (wobble runs only) regions, divided by T_{obs} . It saves a plot similar to the one we show in figure 6.8a.
6. The grid of cuts Θ must be the same used for the efficiency computation and must be provided with an input file like the one showed in figure 6.16.

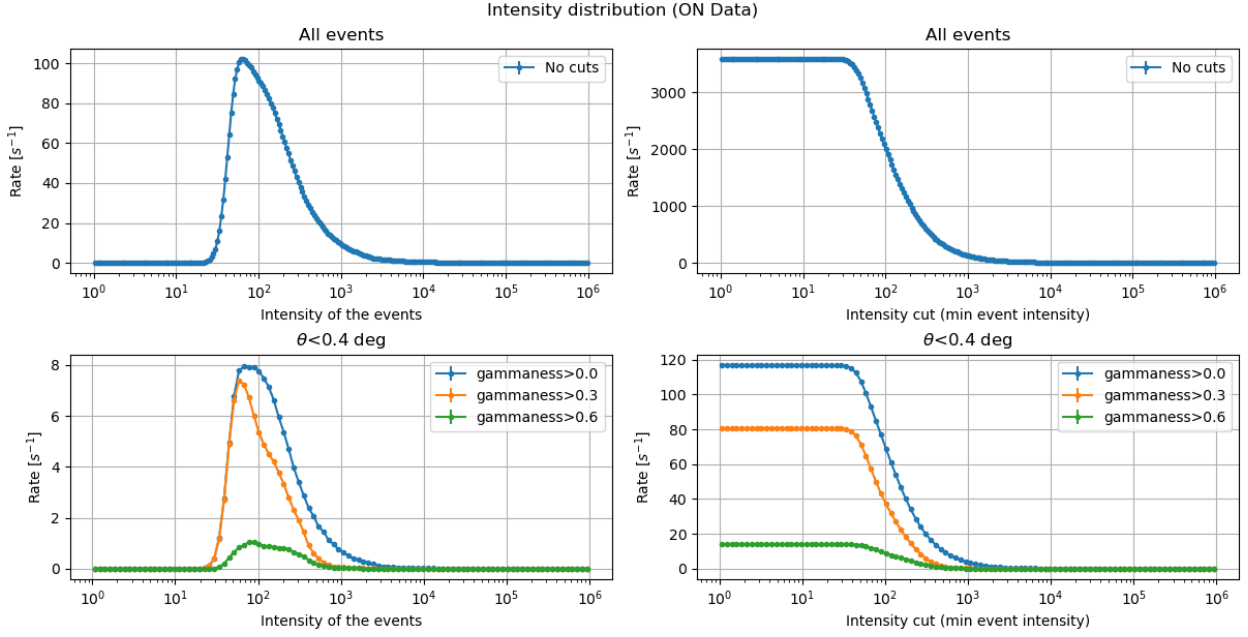


Figure 6.17 – Distribution of the Intensity of the events of a real DL2 file. We show differential distributions on the left panels and the corresponding cumulative distributions on the right panels. The cumulative distributions represent the physical rates of the telescope under different set of cuts. Upper panels show the distribution of all the data, while lower panels adopt a $\theta_{\text{cut}} = 0.4$ deg centred on the ON region with different cuts in gammaness g_{cut} .

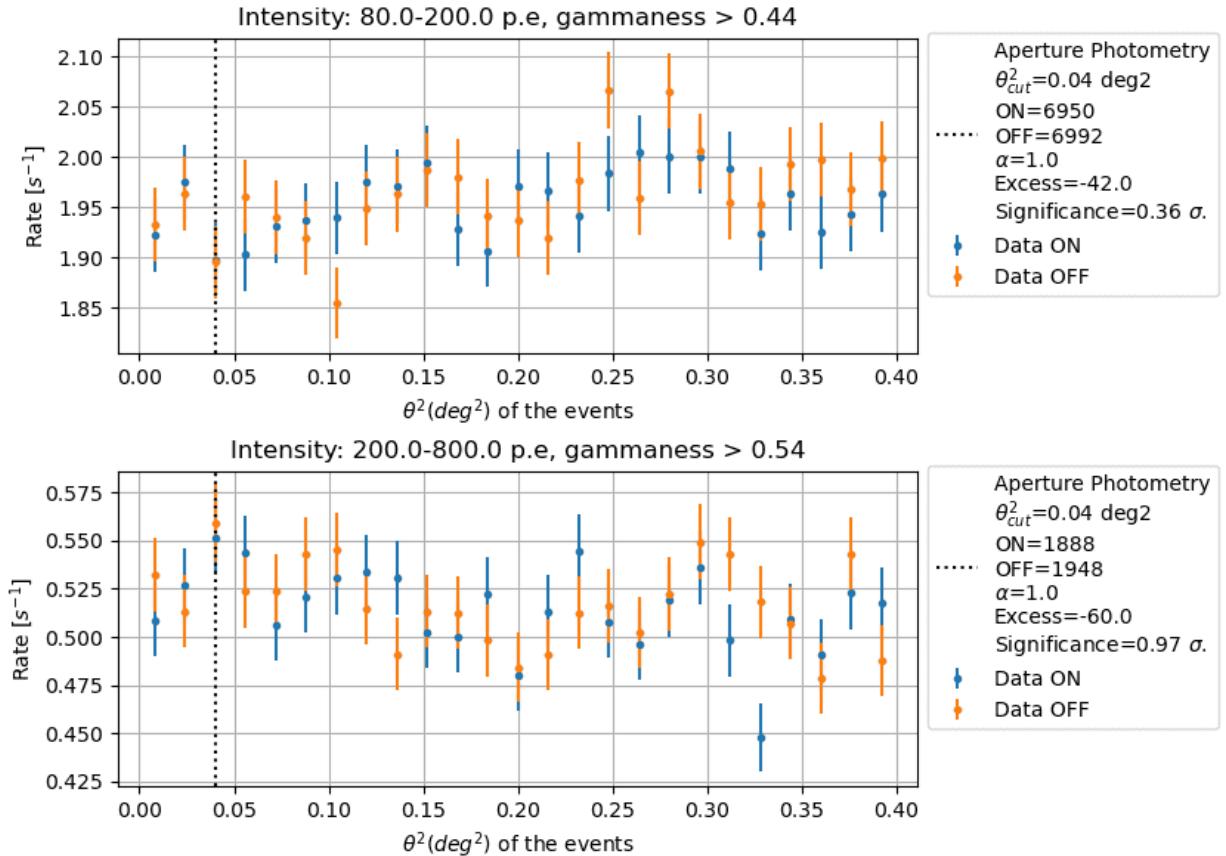


Figure 6.18 – θ^2 distribution and significance estimation computed using different sets of cuts.

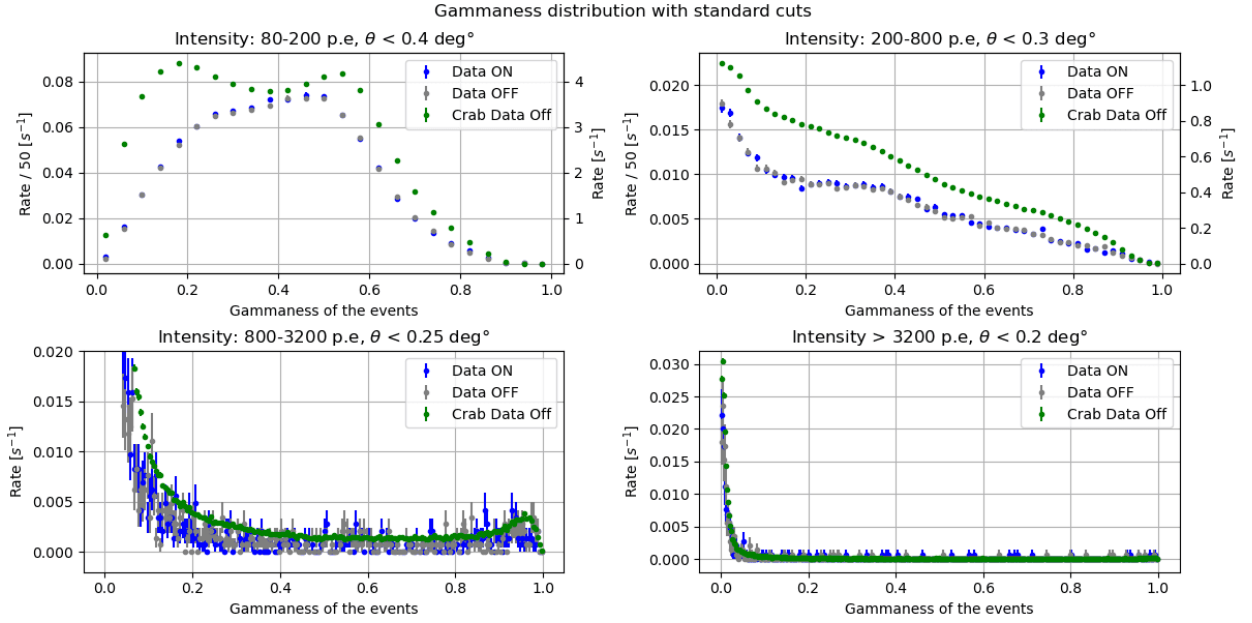


Figure 6.19 – Distribution of the gammaness of the events in the ON and OFF regions using different sets of cuts, compared with Crab data (CTA-LST project et al. 2023).

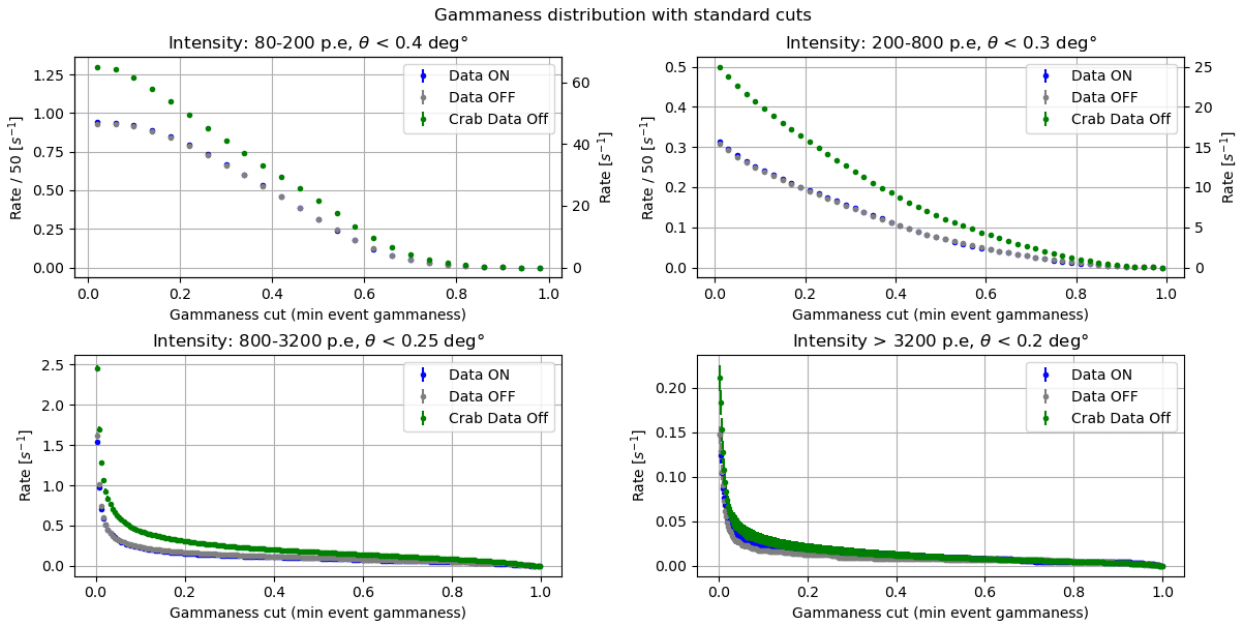


Figure 6.20 – Cumulative distribution of the gammaness of the events in the ON and OFF regions using different sets of cuts, compared with Crab data (CTA-LST project et al. 2023). Cumulative distributions represent the physical rates of the telescope under different set of cuts.

7. It associates in a table the rates computed with a given set of cuts to the efficiency computed with the same cuts, that can be found in one of the input files.
8. It assumes the OFF distribution as background distribution, and from the measured rates $R_{\text{bkg}}(\Theta) = R_{\text{OFF}}(\Theta)$ it estimates $\mu_{\text{bkg}}(\Theta)$, $N_{5\sigma}(\Theta)$ and $\xi(\Theta)$ according to equations (6.1), (6.2) and (6.4) respectively. It saves plots of these quantities, similar to the ones we show in figures 6.8b, 6.8c and 6.10 respectively. The user can look at the plots of $\xi(\Theta)$ to choose the optimised cuts, although results are relative to one run only.
 - Let us note that, in case of having an ON run, the background rate is the ON region rate: $R_{\text{bkg}}(\Theta) = R_{\text{ON}}(\Theta)$. The ON region can be used for the computation of the background rate under specific conditions, such as the assumption of the target source being undetected, and excluding time intervals where known bursts occurred. Under these conditions, the signal of the ON region can be attributed to the γ -like background only, even if a non simultaneous, serendipitous burst may bias the estimation of the background rate. To avoid these biases, we decided not to use ON runs for the optimisation of the cuts. Another possible approach to evaluate the background is to scramble events in time and space in order to smear out potential short lived transients.
9. It makes preliminary quick-look plots for the Burst Search for 3 predefined sets of cuts (loose, strict, optimised) to check if the ON data follow the assumed background or not, and if any burst is already detected above the threshold (with a preliminary correction for trials). See section 6.9 and figure 6.21 for details.

6.7.4 Result Stacking

The `BurstCutsOptimiser` script works by optimising cuts only for one run and the MC simulation node closest to it. We usually work with several runs and MC files. In order to optimise cuts using more statistics, the user should select some runs on which to perform the cuts optimisation with good quality properties. Then, the notebook `StackedCuts` can be used to evaluate the stacked background rates by summing the counts and dividing for the sum of the observation times. The stacked efficiency is obtained by averaging the efficiencies of every node weighted by the number of times they are the closest node to a telescope run. We described the criteria adopted to select “average” runs for the SGR 1935+2154 dataset in section 6.6.

We performed the optimisation separately for three different zenith ranges (below 20 deg, above 40 deg, intermediate) and we obtained consistent results, see figure 6.10. We used this plot to choose as *Optimal Burst Cuts* $g_{\text{cut}} = 0.75$, $i_{\text{cut}} = 50$ p.e. and $\theta_{\text{cut}}^2 = 0.08 \text{ deg}^2$.

6.8 The Burst Analysis: VHE Upper Limits of known Bursts

We adopted the *Burst Cuts* described in section 6.6 to produce a new set of DL3 data for the 9 LST–1 runs comprising the Time of Alerts (ToAs) listed in table 6.1, and the point-like IRFs for the closest simulation node to every run. We used the IRFs to evaluate the energy

threshold of the analysis (0.1 TeV) and to obtain the exposure $\mathcal{E}$ for a 0.1 s time windows in the 0.1 TeV to 10 TeV energy range, assuming a power law spectrum with index 2.

For each of the 9 bursts listed in table 6.1, we selected the number of photons N_{ON} in the ON region centred on SGR 1935+2154 (with size given by θ_{cut}^2), in a $\delta t = 0.1$ s time window centred around the ToA of each of the 9 bursts, and in the 0.1 TeV to 10 TeV energy range. None of the 9 bursts is detected by LST-1, as N_{ON} is always lower than the $N_{5\sigma}$ threshold needed to claim a detection. We report these quantities in table 6.1. Let us note that the ToA given by space satellites needs to be corrected to account for the light travelling from the satellite to the site of the telescope. In our case, the satellites that detected the bursts (Fermi, NICER, GECAM) are in a *Low Earth Orbit* (altitude $\lesssim 500$ km), so the time delay is $\lesssim 0.002$ s and we could neglect it as it is $\ll \delta t$.

For each run, the number of photons expected due to the Poisson background is μ_{bkg} . We assume the presence of a *signal Poisson distribution* with unknown expected value μ_s (MAGIC Collaboration et al. 2018). We can compute the *Bayesian* upper limit for μ_s given N_{ON} observed events:

$$\mu_{s,\text{UL}} = \frac{1}{2} F_{\chi^2}^{-1}(1 - \alpha; 2(N_{\text{ON}} + 1)) - \mu_{\text{bkg}}, \quad (6.8)$$

where $F_{\chi^2}^{-1}$ is the percent point function, i.e. the inverse of the cumulative distribution function F_{χ^2} of a χ^2 distribution with $2(N_{\text{ON}} + 1)$ degrees of freedom, $1 - \alpha$ is the confidence level and μ_{bkg} the expected background counts (Cowan 2007; Patrignani 2016). To provide an example, under the assumption of a 95% confidence level ($\alpha = 0.05$) and negligible background, equation (6.8) yields: $\mu_{s,\text{UL}}(N_{\text{ON}} = 0) = 3$, $\mu_{s,\text{UL}}(N_{\text{ON}} = 1) = 4.74$.

We report the upper limits $\mu_{s,\text{UL}}$ for every burst in table 6.2, and we compute the corresponding upper limits on the integral flux by dividing $\mu_{s,\text{UL}}$ by the *exposure* of the time window. The average photon flux upper limit for a 0.1 s burst is $2.2 \pm 0.5 \cdot 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$, the average energy fluence upper limit is $1.6 \pm 0.4 \cdot 10^{-9} \text{ erg cm}^{-2}$.

We stacked the counts and the exposure of every burst window to compute the upper limits on the total very-high energy burst activity of SGR 1935+2154, reported in table 6.2 under the assumption of average background and effective area. The stacked photon flux upper limit on the transient emission is then $3.0 \cdot 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$.

Let us note that, *if* a burst were detected, the best estimate for μ_s would be:

$$\mu_s = N_{\text{ON}} - \mu_{\text{bkg}}, \quad (6.9)$$

with error given by propagation of the errors on N_{ON} and μ_{bkg} , and we could obtain the corresponding flux by dividing $\mu_{s,\text{UL}}$ for the *exposure* $\mathcal{E}$ of the time window.

We computed the ULs assuming different spectral indexes to test for **systematic errors**. A softer spectrum produced by a 20% higher spectral index, i.e. 2.5, lowers the reconstruction efficiency ϵ and the exposure $\mathcal{E}$ by $\approx 20\%$, resulting in $\approx 20\%$ higher photon flux ULs.

Pipeline Implementation We implemented the estimation of the burst flux or the upper limit with a notebook `FluxAtToA`. The notebook reads a DL2 file, applies the *Burst cuts* and checks with a linear fit that the background distribution has a constant rate, so that it can be described by a Poisson distribution. It then counts the N_{ON} photons in the requested time window, determines if the burst is detected or not, and it computes the flux or upper limit with equations (6.8) and (6.9).

Table 6.2 – Upper limits on bursts simultaneous to LST–1 in the energy range 0.1 TeV to 10 TeV. The exposure $\mathcal{E}$ is given for a $\delta t = 0.1$ s observation time assuming a power law spectrum with index=2. The background rate is estimated in a OFF region, $\mu_{\text{bkg}} = R_{\text{bkg}} \cdot \delta t$ and it is used to estimate $N_{5\sigma}$ according to eq. (6.2). The ON counts are evaluated in a 0.1 s time window centred around the burst ToA and are used to compute $\mu_{s,\text{UL}}$ according to eq. (6.8). The photon flux ULs are given by dividing $\mu_{s,\text{UL}}$ over the exposure. The fluence ULs are obtained converting the photon flux into energy flux and integrating over δt . The stacked entry assumes $\delta t = 0.9$ s, average background rate and average effective area.

#	$\mathcal{E}$ $10^8 \text{ cm}^2\text{s}$	R_{bkg} s^{-1}	μ_{bkg}	$N_{5\sigma}$	N_{ON}	$\mu_{s,\text{UL}}$	FLUX UL $10^{-8} \text{ cm}^{-2}/\text{s}^{-1}$	FLUENCE UL $10^{-9} \text{ erg}/\text{cm}^2$
1	1.448	0.81 ± 0.02	0.081 ± 0.002	4	0	2.92	2.01	1.50
2	1.485	1.05 ± 0.03	0.105 ± 0.003	4	0	2.89	1.95	1.45
3	1.430	0.95 ± 0.03	0.095 ± 0.003	4	0	2.90	2.03	1.51
4	1.485	1.01 ± 0.03	0.101 ± 0.003	4	0	2.89	1.94	1.45
5	1.491	0.61 ± 0.03	0.061 ± 0.003	4	0	3.94	1.97	1.47
6	1.491	0.66 ± 0.03	0.066 ± 0.003	4	0	2.93	1.96	1.46
7	1.296	0.68 ± 0.02	0.068 ± 0.002	4	1	4.68	3.61	2.69
8	1.430	1.04 ± 0.03	0.104 ± 0.003	4	0	2.89	2.02	1.51
9	1.485	1.04 ± 0.03	0.104 ± 0.003	4	0	2.89	1.95	1.45
-	13.041	0.87 ± 0.04	0.783 ± 0.036	8	1	3.96	0.30	0.20

6.9 The Burst Analysis: Searching for Non Simultaneous Bursts

We searched for possible 0.1 s bursts in our dataset by selecting the events in an ON region centred on SGR 1935+2154 according to the short time scale cuts described in section 6.6, in the 0.1 TeV to 10 TeV energy range. We binned these events in 0.1 s time bins starting at the beginning of each observation run. We evaluated if any of the bins contained a number of counts greater than the counts threshold needed for a 5σ detection over a Poisson background corrected for the number of trials $\tilde{N}_{5\sigma}$ (Li and Ma 1983; Bulgarelli et al. 2012) and we did not find any detection.

The p-value p , or *comparison-wise error rate*, represents the probability of making a *false positive error* in a single trial, i.e. rejecting a true null hypothesis and, in our case, wrongly claiming that a bin contains the detection of a burst. The probability of making *at least one* false positive error in N_{trials} trials is:

$$\pi = 1 - (1 - p)^{N_{\text{trials}}} , \quad (6.10)$$

where π is also called *experiment-wide error rate*, or the post-trial probability of making at least one false positive error (Li and Ma 1983; Bulgarelli et al. 2012; Brun et al. 2020). In order to claim that a bin contains the detection of a burst it must have post trial $\pi < 2.87 \cdot 10^{-7}$. The *pre-trial* p-value $\tilde{p}$ required to do so is found by inverting eq. (6.10):

$$\tilde{p} = 1 - (1 - \pi)^{1/N_{\text{trials}}} \quad (6.11)$$

and using $\pi = 2.87 \cdot 10^{-7}$. For the SGR 1935+2154 analysis, we used $N_{\text{trials}} = 1\,355\,170$, that

yields a pre-trial $\tilde{p} = 2.11 \cdot 10^{-13}$ to claim a detection. The post-trial counts threshold for a 5σ detection above a Poisson background $\tilde{N}_{5\sigma}$ can then be found evaluating eq. (6.2) at $\tilde{p}$.

The mean and standard deviation of the background rates across the runs of our dataset are $0.9 \pm 0.3 \text{ s}^{-1}$, which provide pre-trial $N_{5\sigma}$ from 3 to 5. Differences in the runs can be attributed to different zenith angle and atmospheric conditions. We performed the burst search across all our dataset, considering each 0.1 s time bin as a trial, with a total number of trials $N_{\text{trials}} = 1\,355\,170$. The corrected post-trial $\tilde{N}_{5\sigma}$ range from 5 to 8. The flux sensitivity for our non simultaneous burst search can be evaluated by diving the highest $\tilde{N}_{5\sigma}$, i.e. 8, by the lowest 0.1 s exposure of our dataset in the 0.1 TeV to 10 TeV, i.e. $1.296 \cdot 10^8 \text{ cm}^2 \text{ s}$, providing a minimum detectable photon flux of $6.2 \cdot 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$. Its value worsens with respect to the sensitivities of the analysis in section 6.8 due to the large number of trials.

Pipeline Implementation We used `BurstCutsOptimiser` during the preliminary analysis of the data to plot the result of a burst search computed with predefined sets of cuts, see figure 6.21. After selecting the optimal burst cuts, we computed the total number of bins of all the runs ($N_{\text{trials}} = 1\,355\,170$), then used the `BurstCutsOptimiser` notebook to perform and plot the burst search on all the runs with the final cuts and post-trial corrections. We did not find any detection of non-simultaneous bursts across our dataset. We show the burst search on run 5163 as an example in figure 6.22.

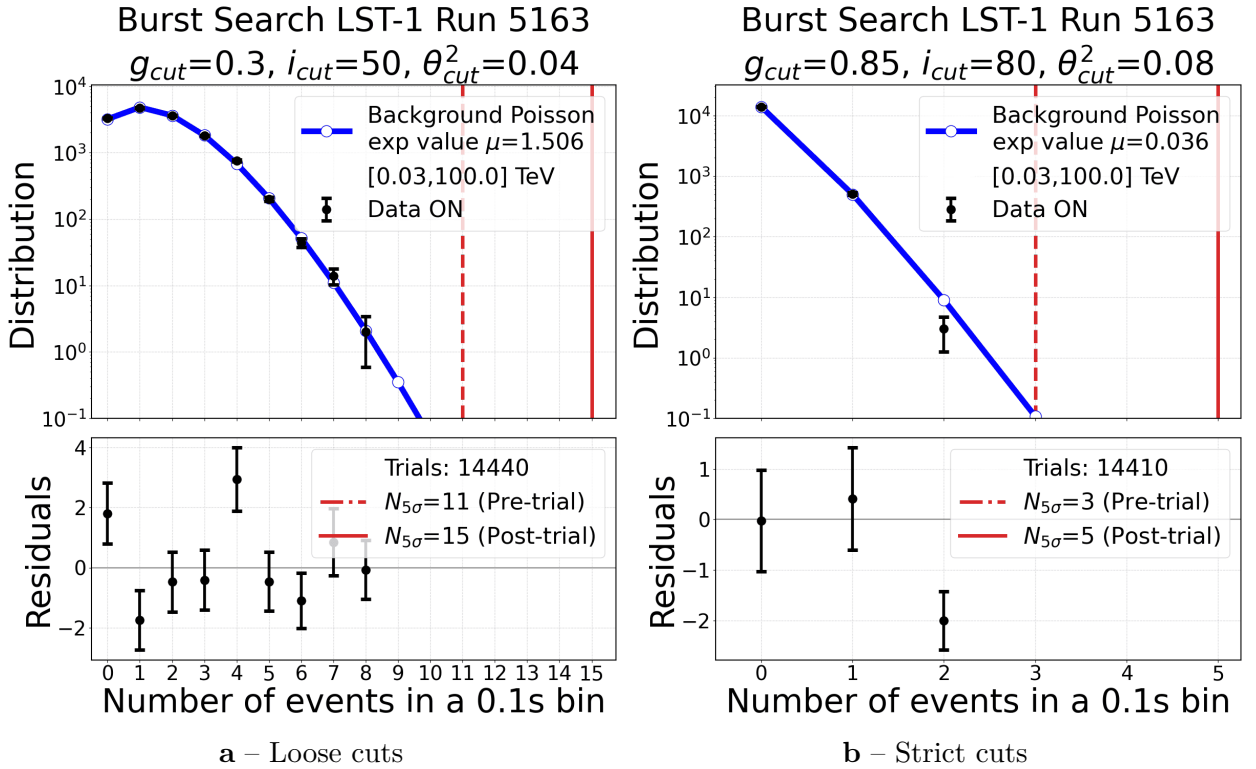


Figure 6.21 – Background characterisation and preliminary burst search using two predefined sets of cuts. The upper panels show the distribution of the number of events in the time bins (black dots), compared with the expected Poisson background. If the ON and background distributions agree, it means that the background was correctly estimated (residuals are shown in the lower panels) and there is no signal detected. If the data showed a tail of bins with a high number of counts, it would identify time bins where a burst occurred. We show the 5σ detection thresholds, both pre-trial and post-trial, assuming N_{trials} equal to the number of time bins of the run.

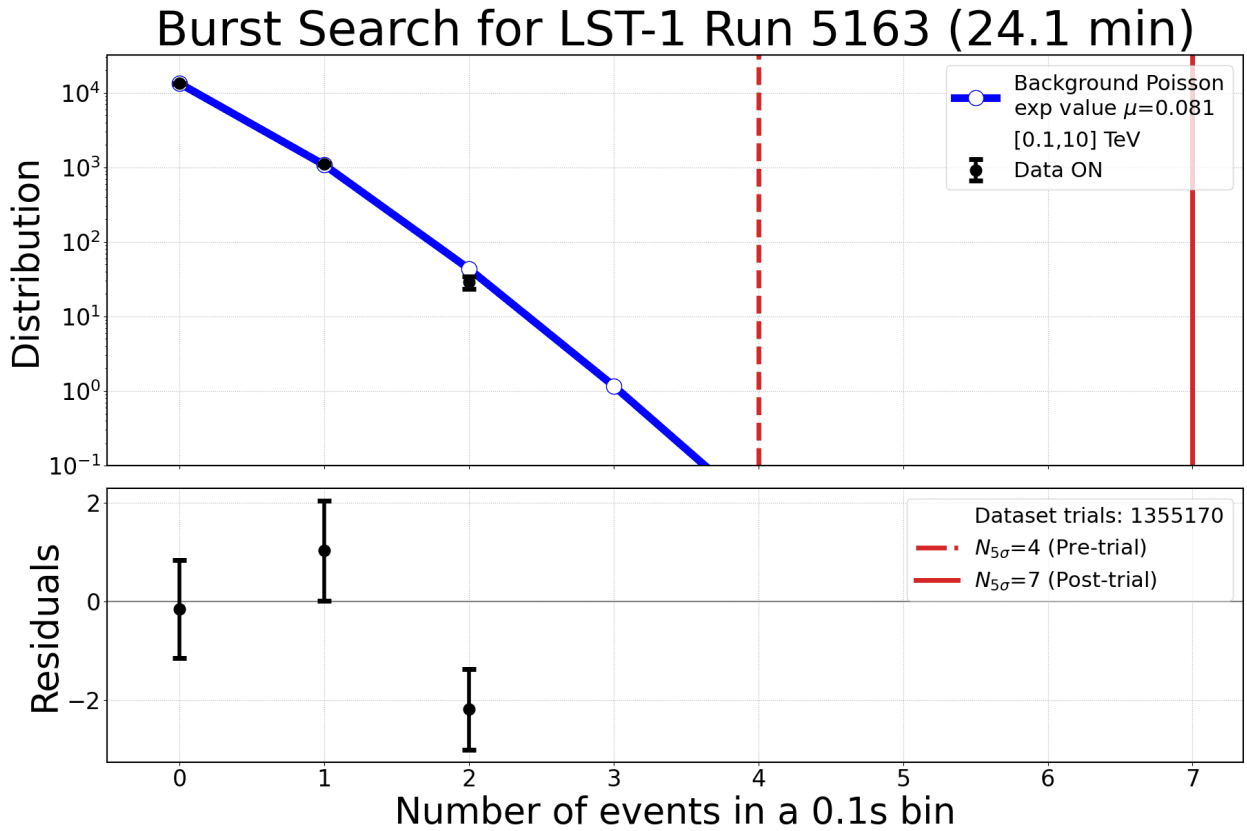


Figure 6.22 – Burst search on LST–1 run 5163. The upper panel shows the distribution of the number of ON events in 0.1 s bins (black dots), compared with the expected Poisson background (blue line). The ON and the background distributions agree, which means that the background was correctly estimated (residuals are shown in the lower panel) and there is no signal detected. We show the 5σ detection thresholds, both pre-trial and post-trial, assuming the total number of trials of the dataset $N_{\text{trials}} = 1\,355\,170$.

6.10 Discussion of SGR 1935+2154 Results

We analysed over 25 h of VHE gamma-ray observations of SGR 1935+2154 with LST–1 during periods of known magnetar activity. We did not detect persistent nor transient emission from the source and constrained it with upper limits. We discuss below our constraints in the context of multi-wavelength observations of SGR 1935+2154 and its emission scenarios.

6.10.1 Persistent Emission

Figure 6.23 shows the multi-band spectral energy distribution (SED) of SGR 1935+2154. Black lines show the best fit emission model in the X-ray and soft gamma-ray bands extracted from June 2020 observations of the source with *Swift* and *NuSTAR*. The model is composed of a black-body spectrum plus a power law component (Borghese et al. 2022). No upper limits are available in literature in the MeV – GeV energy range for SGR 1935+2154, even though they have been computed for several other magnetars. As an example, we report the upper limits on 4U 0142+61, the brightest of the magnetars, measured with COMPTEL (den Hartog et al. 2006) and Fermi-LAT (Li et al. 2017). In the VHE band, our upper limits confirm the non-detection obtained by H.E.S.S. Collaboration et al. (2021), extending the covered energy range down to 0.1 TeV and lowering them by factors 2 to 5. The TeV upper limits are about the same order of magnitude of the X-ray emission of SGR 1935+2154, and confirm previous results, suggesting that the power-law component observed in the SED above > 10 keV must have a break at ~ 1 MeV.

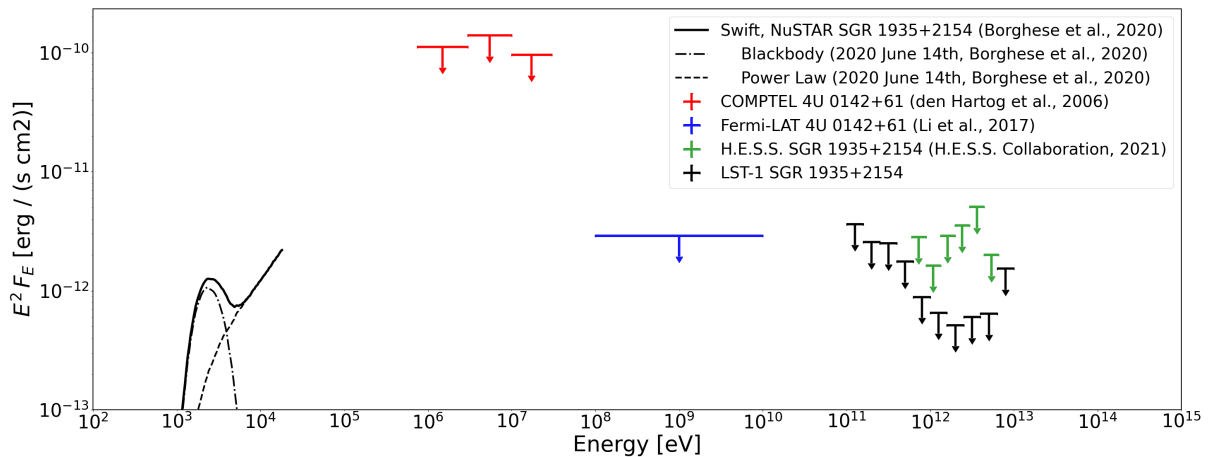


Figure 6.23 – SED of the persistent emission of SGR 1935+2154.

Most models explain the persistent emission of magnetars in the X-ray band using two components. The first one is the thermal emission arising from the neutron star surface and its thin atmosphere (Mereghetti et al. 2015). The second one is due to the presence of accelerated particles in a magnetosphere with a complex geometry, that can modify the emitted spectrum producing hard tails by resonant cyclotron scattering of the thermal photons (Thompson et al. 2002). More complex models include MC simulations to study the motions of charged particles flowing in twisted magnetic loops (e.g. Fernández and Thompson 2007; Beloborodov 2013). Current models can produce power-law emission spectra with a suppression above the MeV range, but the details of the modelling are not fully understood yet.

This is also due to the lack of data in this energy range. Future facilities capable of observing at ~ 1 MeV, e.g. the upcoming COSI satellite mission (Tomsick et al. 2023), may detect the power law cutoff and validate these models. If this were the case, it would confirm the scenario in which magnetars like SGR 1935+2154 are not high-energy and very high-energy gamma-ray emitters.

This may not be the case for other similar sources, such as the progenitors of FRBs (Cordes and Chatterjee 2019; Zhang 2023). For instance, FRB 121102 (Spitler et al. 2014) is associated to a persistent radio source (PRS) (Chatterjee et al. 2017) and an optical counterpart classified as a low-metallicity star-forming dwarf galaxy (Tendulkar et al. 2017; Bassa et al. 2017). The PRS emission is not identified, but is likely due to synchrotron emission of relativistic electrons from a surrounding nebula (e.g., Marcote et al. 2017; Metzger et al. 2017), possibly a SNR, a pulsar wind nebula (PWN), or a hyper-accreting X-ray binary (Sridhar and Metzger 2022). The recent detection of a PRS for FRB 20190520B (Niu et al. 2022), FRB 20201124A (Bruni et al. 2024a) and FRB 20240114A (Bruni et al. 2024b), support nebular models powered by NS as origin of FRBs. Even though no HE counterparts of FRBs or their associated PRS have been detected (Scholz et al. 2017; Zhang 2024), the progenitors proposed may emit HE and VHE gamma-rays with mechanisms similar to known PWNe or SNRs. These observations and models suggest magnetars similar to SGR 1935+2154 can be interesting targets for IACTs such as LST-1 and the upcoming arrays of CTAO (Cherenkov Telescope Array Consortium 2024).

6.10.2 Transient Emission

In section 6.8 and table 6.2, we obtained the VHE upper limits to the transient emission of SGR 1935+2154 on a 0.1 s timescale, centred on the ToAs of simultaneous bursts. Burst fluences and spectral analyses are available in literature for the 4 bursts detected by Fermi-GBM and NICER, and we can compare their X-ray flux with the simultaneous VHE UL.

The brightest is burst #1, detected by Fermi-GBM with $T_0=2021-07-07$ 00:33:31.67 (Hamburg et al. 2021a; Hamburg et al. 2021b). It has a single peak with $T_{90} \approx 0.1$ s, is best fit by a power law function with index 0.54 ± 0.07 and an exponential high-energy cutoff at $E_{\text{peak}} = 36.1 \pm 0.3$ keV, with average photon flux of 289 ± 3 s $^{-1}$ cm $^{-2}$, average energy flux of $1.3 \pm 0.2 \cdot 10^{-5}$ erg s $^{-1}$ cm $^{-2}$ and fluence $2.52 \pm 0.03 \cdot 10^{-6}$ erg cm $^{-2}$ (10 keV to 1000 keV, $T_0 - 0.064$ s to $T_0 + 0.128$ s). The 0.1–10 TeV flux upper limit over 0.1 s is $1.5 \cdot 10^{-8}$ erg s $^{-1}$ cm $^{-2}$ (see table 6.2). We show in figure 6.24 the SED of burst #1 using the Fermi-GBM flux point and the VHE upper limit. It is the first SED of a magnetar burst with a < 1 s time scale and simultaneous X-ray and VHE data, and it constrains the ratio between the VHE and X-ray flux to a factor $\lesssim 10^{-3}$.

Most magnetar models predict transient emission in the X-ray and soft gamma-ray bands, either when magnetic stresses build up sufficiently to crack a patch of the neutron star crust, ejecting hot plasma into the magnetosphere (e.g. Thompson and Duncan 1995), or after magnetic reconnection events in the magnetosphere (Lyutikov 2002). Such models do not predict gamma-ray emission in the GeV – TeV energy ranges, but more complex magnetar models predicts mechanism to emit FRBs accompanied by high-energy GeV – TeV bursts. For instance, (Lyubarsky 2014) predicts that FRBs and strong millisecond bursts in the TeV range can originate from the synchrotron maser emission caused by magnetised shocks that occur when highly magnetised plasma bursting from a magnetar reaches the medium

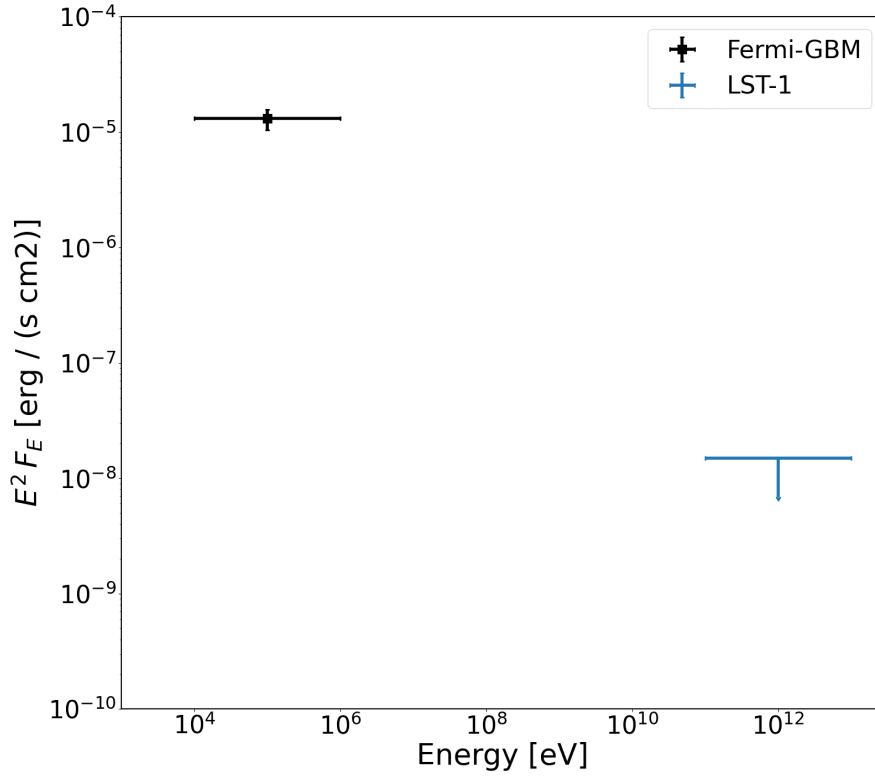


Figure 6.24 – Soft-gamma and very high-energy SED of the transient emission of SGR 1935+2154 during the burst on 2021-07-07 00:33:31.670, measured on a ~ 0.1 s timescale.

surrounding the nebula.

Murase et al. (2016) and Murase et al. (2017) suggested a scenario for the production of FRBs where the spin-down power of a magnetar creates a relativistic wind bubble embedded in baryonic ejecta surrounding the NS, a scenario similar to PWNe. An impulsive energy injection of relativistic flow, which may originate from magnetic dissipation in the magnetosphere, can shock the nebula, causing the emission of a broadband flare observable from the radio band to the high-energy gamma-ray band. The fluence φ predicted for a high-energy gamma-ray flash (HEGF) in the fast cooling scenario (electrons and positrons cool within the dynamical time) at TeV energies is:

$$\varphi \sim 8 \cdot 10^{-7} \text{ erg cm}^{-2} \left(\frac{E_{\text{outflow}}}{10^{48} \text{ erg}} \right) \left(\frac{d}{10^{26} \text{ cm}} \right)^{-2}, \quad (6.12)$$

where E_{outflow} is the total energy of the burst outflow and d is the distance of the magnetar nebula. A TeV fluence upper limit of $1.5 \cdot 10^{-9} \text{ erg cm}^{-2}$ like the one we obtained for the SGR 1935+2154 burst #1 would constrain the total energy of the burst outflow to $E_{\text{outflow}} \lesssim 1.9 \cdot 10^{45} \text{ erg}$ assuming $d = 10^{26} \text{ cm}$. It would yield $E_{\text{outflow}} \lesssim 3.8 \cdot 10^{37} \text{ erg}$ assuming $d = 4.4 \text{ kpc}$ as measured for SGR 1935+2154 (Mereghetti et al. 2020). We stress that the model cannot be directly applied to burst #1 as it is a typical magnetar flare with no radio counterpart, and a softer index and peak energy with respect to the burst on April 28th, 2020 associated with radio bursts (Mereghetti et al. 2020). Furthermore, SGR 1935+2154 lacks the nebular structure that Murase et al. (2016) requires for a FRB-HEGF event. Nevertheless, other sources of FRBs may possess the structures required for HEGFs, and these theoretical models motivate the search for counterparts of FRBs and magnetar flares at VHE with IACTs.

The detection of a candidate MGF in the nearby (3.5 Mpc) Sculptor galaxy at GeV energies (Ajello et al. 2021) also motivates the search for magnetar flares at HE and VHE, as such a flare would have been detectable by LST-1. It was described by a power-law spectrum with index -1.7 ± 0.3 and integral flux above 0.1 GeV $\Phi(> 0.1 \text{ GeV}) = (4.1 \pm 2.2) 10^{-6} \text{ s}^{-1} \text{ cm}^{-2}$ (Ajello et al. 2021). Under the assumption that the spectrum can be extended at TeV energies, we can estimate the flux above 0.1 TeV at the distance of SGR 1935+2154 (i.e., 4.4 kpc): $\Phi(> 0.1 \text{ TeV}) \simeq 2.0 \cdot 10^{-3} \text{ s}^{-1} \text{ cm}^{-2}$, above the sensitivity of LST-1 for a 0.1 s burst of $\simeq 3 \cdot 10^{-8} \text{ s}^{-1} \text{ cm}^{-2}$. According to this sensitivity value, the MGF could have been detected up to a distance of the same order of the Sculptor galaxy, assuming that the spectrum measured by Ajello et al. (2021) could be extended to TeV energies.

Chapter 7

Conclusion and future perspectives

In this work, we developed two powerful tools for the analysis of gamma-ray data in the context of Multi-Wavelength, Multi-Messenger and Time-Domain Astrophysics: the **SAG-SCI** software, validated on CTAO simulated data, and the *Burst Analysis*, applied to the interesting case study of SGR 1935+2154. MWL, MM and TD Astrophysics emerged in the last decade as three approaches capable to significantly deepen our understanding of the Universe, as discussed in chapter 3.1. A notable case study that shows the effectiveness of the MWL, MM and TD Astrophysics is the AGILE observation of GRB 221009A, to which I contributed as part of my research (Tavani et al. 2023, refer to chapter 3.1.2).

SAG-SCI We presented the **SAG-SCI** software for the real-time analysis of CTAO data and the generation of candidate Science Alerts in chapter 4. When I started my PhD research, only a stand-alone prototype was available (Di Piano et al. 2022). I contributed to the development of all **SAG-SCI** components. The most relevant achievements I accomplished in this work are:

- Full development of the **gammapy** wrapper, using the namesake **python** library that the CTAO adopted for its official science analysis tools (CTAO 2021), see section 4.7.3.
- Review and modularisation of the Databases and full development of the **Database Manager** that ensures having a smart deployment system for the software, see section 4.5.
- Refactoring of the Pipeline Manager Deamons into object-oriented classes, to facilitate their usage and testing, see section 4.6.
- Development of Unit tests for the **gammapy** wrapper and Database module, that improved the code coverage from 30% to 60%, passing the 50% requirement of ACADA, see section 4.8.
- Development of the Verification tests to ensure that the scientific requirements of ACADA REL1 are satisfied, see section 4.8.
- Release of two **SAG-SCI** versions, for ACADA REL1 and ACADA REL1.5 (Di Piano et al. 2023).
- Detection of the Crab Nebula during the test campaign of ACADA REL1 on the LST-1 in October 2023 (ACADA and CTAO-LST Project 2023).
- Deployment and monitoring of **RTA-SCI** on the LST-1 since April 2023.

We also present in this work for the first time:

1. The strategies and scenarios for the generation of candidate Science Alerts (see section 4.7.1).
2. The strategies to perform scientific analyses that ensure all the required DL4 and DL5 outputs are produced (see section 5.2), and they are optimised to the Scientific Target observed.
3. Strategies to optimise the analyses from a computational point of view (see section 5.8).

Our development of **SAG-SCI** resulted in a software composed by more than 6000 lines of code that satisfy strict quality requirements, and can be used as a stand-alone installation (like **RTA-SCI**) and as a fully-integrated sub-system of **SAG** and **ACADA**. We validated our software on CTAO simulated data in chapter 5. In particular, the simulation of a *Standard Candle* (see section 5.3) allowed us to validate the algorithms that compute the Li&Ma significance and the MLE of the Flux, our main scientific results, but also the Blind Search algorithm, the production of Counts Maps and θ^2 plots, and the Stacking algorithm. We validated both the **RTAPH** and **gammapy** wrapper. We used the *Standard Candle* and the *Crab-like* source to estimate the systematic errors introduced when assuming an incorrect spectral model for the analysis, see section 5.4. We found that, by introducing a $\approx 30\%$ systematic uncertainty, we can account for the assumption of a 20% incorrect index, and an additional $\approx 10\%$ uncertainty is required to account for analysing a *curved* spectrum with a simple *Power Law*.

We presented three scenarios in which **SAG-SCI** will have to generate candidate Science Alerts, namely the detection of a gamma-ray Flare (section 5.5), the detection of the afterglow of a GRB in a Follow-up ToO observation (section 5.6) and the detection of a Serendipitous Transient in the FoV through the Blind Search algorithm (section 5.7). Finally, we evaluated the performance of the analysis tasks of **SAG-SCI**, identified the most computationally intensive ones, and proposed several possible strategies to make the software faster in section 5.8. These strategies include a smart production of the **gammapy** Reduced IRFs, reducing the resolution of the Sky maps, separating the computation of the DL4 and DL5 outputs from their plots, assigning tasks not relevant to the generation of candidate Science Alerts to low-priority analyses.

SGR 1935+2154 We performed over 25 h of good-quality observations of the Galactic magnetar SGR 1935+2154 with LST-1 to search for a VHE counterpart to its X-ray and soft gamma-ray emission. We did not detect the persistent emission of the source in the 0.1 TeV to 10 TeV energy range, in agreement with previous observations (H.E.S.S. Collaboration et al. 2021), as expected from magnetar emission models which predict a cut-off of its power law component at ~ 1 MeV. Our TeV SED upper limits are about the same order of magnitude of the X-ray emission of SGR 1935+2154.

We conducted our observations during periods of known high-energy activity of the source, and simultaneously to 9 short magnetar flares detected by high-energy space satellites. We searched for a transient VHE emission of SGR 1935+2154 in coincidence with the high-energy bursts on a time scale of 0.1 s, in a *low-photon-statistics* regime and under the hypothesis of a Poisson background, optimising the event selection cuts for the analysis. For the first time, we provided the VHE flux upper limits to the emission of a short magnetar flare ($\sim 2 \cdot 10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2}$) simultaneous to its soft gamma-ray flux. For the brightest burst in our sample, the ratio between the VHE and X-ray flux is $\lesssim 10^{-3}$. We also searched for possible 0.1 s long bursts in our dataset and we did not find any detection.

Future perspectives We discuss here future perspectives of the research projects presented in this thesis.

We employed the *Burst Analysis* to search for a TeV counterpart of the soft gamma-ray emission of SGR 1935+2154. Although no persistent nor flaring emission has been detected at TeV energies yet from SGR 1935 1935+2154 and other magnetars, both the detection of MeV – GeV emission and theoretical predictions for a VHE component in flares make magnetars and FRBs interesting candidate sources for IACTs and CTAO in particular. A flare with the same power-law spectrum as the candidate MGF detected in the Sculptor galaxy (Ajello et al. 2021) could have been detected by LST–1, assuming the power-law could be extended up to TeV energies. A next-generation facility like the CTAO will be particularly suited for fast transient astronomy thanks to its improved VHE sensitivity (more than one order of magnitude better than the current sensitivity of LST–1), that will allow for observations of gamma-ray fluxes comparable with the ones expected from magnetars (Carosi et al. 2021; Cherenkov Telescope Array Consortium et al. 2019; Zanin et al. 2022). The *Burst Analysis* method described in chapter 6 is an alternative to the standard methods of chapter 2, particularly useful for the analysis of fast transients such as FRBs, magnetar flares and short Gamma-ray Bursts, that may belong to a *small-photon-statistics* regime.

Additionally, the **BurstAnalysis** software pipeline (described in section 6.7) performs *Data Quality* evaluation of DL2 data, that we can implement into the **SAG-DQ** pipeline.

The development of **SAG-SCI** is still ongoing and will continue likely for the next 1 – 2 years, together with the development of future releases of **ACADA** and the construction of the next CTAO telescopes. Following the discussion presented in chapters 4 and 5, the next features we plan to implement are:

- Adding the possibility to compare our real-time results with reference values contained in scientific catalogues.
- Implementing the **ScienceAlertManager** which will insert automatically the candidate Science Alerts in the Database.
- Improving the spectral modelling capabilities of **SAG-SCI**, as currently the source flux is estimated only by assuming a Power Law Model with fixed index.
- Preparing a reference table of candidate input models (e.g. a model for GRBs, one for AGN, one for PWNe, a model for Serendipitous Transients and so on) that can be used to configure **SAG-SCI** according to its nominal Scientific Target.

The next release of **SAG-SCI** is planned for **ACADA REL2** in 2025.

In conclusion, our development of the **SAG-SCI** software, complemented by the *Burst Analysis* of fast transients, will ensure CTAO becomes a relevant facility for Time-Domain astrophysics, and enable Multi-Wavelength and Multi-Messenger approaches that will lead to a deeper understanding of the Universe.

Appendix A

Statistics Fundamentals for Gamma-ray astronomy

This section discusses in detail the statistical topics mentioned in the main body of this work.

A.1 Frequentist Hypothesis testing

There are two main approaches to statistics: *Bayesian* and *frequentist* statistics (Feigelson and Babu 2012). The *frequentist* approach assumes that the observed data is just one realisation amongst an ensemble of possible datasets obtainable due to noise (i.e., data is probabilistic), but the ultimate physical quantity that the data are describing is immutable, i.e., there is one true *model* that often includes one or more *parameters*. In frequentist statistics model selection is performed through the **Hypothesis Testing** technique, which asks the question of whether an hypothesis is supported by the data or not. Hypothesis testing seeks to disprove a hypothesis by showing that obtaining the observed data would be unlikely if the hypothesis were true. The basic steps in most applications of hypothesis test are as follows:

1. State the hypothesis as a well posed true or false question. This is called the *Null Hypothesis* H_0 (i.e. “There is no source in the data”).
2. Define a *test statistic* (TS), i.e. a quantity that is a function of the data and is affected by the truth of the hypothesis.
3. Determine by analytic or numerical methods the probability distribution of the TS statistic given that the Null Hypothesis is true. Identify the *critical region*, a subset of the possible values of the TS with a low probability of obtaining values in the region. Critical regions are usually defined for large absolute values of the TS .
4. Calculate the value of the TS statistic with the available data.
5. Calculate the probability of getting worse values of the TS statistic than the one obtained with the data. This probability is called the **p-value** of the data.
6. If the *p-value* of the data is lower than a predefined threshold, then the Null Hypothesis is ruled out, because it is improbable to get the measured dataset when we assume H_0 is true. If the p-value is not sufficiently low, then the dataset is compatible with the Null Hypothesis, that cannot be ruled out.

Gamma-ray astrophysics usually adopts $2.87 \cdot 10^{-7}$ as *p-value* threshold for the detection of a signal. This number corresponds to the probability of getting a sample $> 5\sigma$ from a standard Gaussian distribution. The *p-value* of the data is often converted into a Gaussian significance expressed in terms of standard deviations σ .

A.2 The Li&Ma Statistical Significance

This section delves deeper into the definition of the Li&Ma statistical significance (Li and Ma 1983) with respect to section 2.4.1.

In the AP problem there are two unknown numbers: the expected number of photons from the source $\langle N_S \rangle$ and from the background $\langle N_B \rangle$ in the chosen ON and OFF regions. We define the null hypothesis H_0 as the hypothesis where there is no source and all the photons are due to background, i.e. $\langle N_S \rangle_{H_0} = 0$. The test statistics adopted is the *likelihood ratio* and its properties are described by *Wilks' Theorem* (Wilks 1938).

Theorem 1 (Wilks' theorem). *Let $\mathbf{X} = (x_1, x_N)$ be a dataset, described by a model M with unknown parameters $\Theta = (\mathbf{E}, \mathbf{T}) = (\eta_1, \dots, \varepsilon_r, \varepsilon_1, \dots, \tau_s)$. Let us assume the null hypothesis H_0 as: $\mathbf{E} = \mathbf{E}_0$. Let us assume a likelihood function for the data $\mathcal{L}(\mathbf{X} | \mathbf{E}, \mathbf{T})$. Let $\hat{\mathbf{T}}_C$ be the conditional maximum likelihood estimates of the parameters under the null hypothesis H_0 . Let $(\hat{\mathbf{E}}, \hat{\mathbf{T}})$ be the maximum likelihood estimates of the parameters under the alternative hypothesis where E are not known. Let us define the goodness-of-fit statistic TS of the likelihood ratio λ :*

$$TS = -2 \ln \lambda = -2 \ln \left(\frac{\mathcal{L}(\mathbf{X} | \mathbf{E}_0, \hat{\mathbf{T}}_C)}{\mathcal{L}(\mathbf{X} | \hat{\mathbf{E}}, \hat{\mathbf{T}})} \right). \quad (\text{A.1})$$

On condition of null hypothesis $E = E_0$ being true, the variable TS will asymptotically follow a χ^2 distribution with r degrees of freedom while $N \rightarrow \infty$:

$$TS = -2 \ln \lambda \sim \chi_r^2. \quad (\text{A.2})$$

Wilks' theorem can be applied to the Aperture Photometry problem, where the observed data are $\mathbf{X} = (N_{ON}, N_{OFF})$. We assume that the model distribution is the *Poisson distribution*, hence our unknown parameters are the mean of the Poisson distributions for the source and background: $\Theta = (\nu_S, \nu_B)$. The null hypothesis H_0 is the lack of an astrophysical source, $\nu_S = 0$, while the alternative hypothesis H_1 is the presence of an astrophysical source, $\nu_S > 0$. For Poisson Likelihood the Maximum Likelihood Estimates of mean ν are the measured counts N themselves: $\hat{\nu} = N$ (Feigelson and Babu 2012). For the sake of this demonstration, we consider a *ratemeter* experiment where the ON and OFF regions are the temporal intervals we spend on (t_{ON}) and off (t_{OFF}) source, thus α is the ratio of their observing time: $\alpha = \frac{t_{ON}}{t_{OFF}}$. This assumption is not the only one possible. In a line-detection experiment usually the ON region are the n_s energy channels where we assume there is a spectral line, the OFF regions are the n_b energy channels adjacent to the line where we assume there is only continuum radiation, thus α is the ratio of the numbers of energy channels on and off line: $\alpha = \frac{n_s}{n_b}$. In IACT data analysis the ON and OFF regions are usually spatial regions, and α is the ratio of their total area.

We wish to compute the likelihood ratio defined in equation (A.1).

1. Under H_1 the background and source photons come from two independent Poisson distributions, so the MLE of the parameters are:

$$\hat{\nu}_S = \langle \hat{N}_S \rangle = N_S = N_{ON} - \alpha N_{OFF}, \quad (\text{A.3})$$

$$\hat{\nu}_B = \langle \hat{N}_B \rangle = N_B = \alpha N_{OFF}. \quad (\text{A.4})$$

We have to consider the probability distribution for our (independent) random variables. N_{OFF} is a Poisson variable with the same rate as N_B , hence the best estimate of the mean is $\langle \hat{N}_{OFF} \rangle = N_{OFF}$. N_{ON} is the sum of two random Poisson variables N_S , N_B , hence it follows a Poisson distribution with mean given by the sum of their means, hence $\langle \hat{N}_{ON} \rangle = \langle \hat{N}_S \rangle + \langle \hat{N}_B \rangle = N_S + N_B = N_{ON}$. The Likelihood is the product of the two Poisson distributions:

$$\begin{aligned} \mathcal{L}(\mathbf{X} | \hat{\mathbf{E}}, \hat{\mathbf{T}}) &= \mathcal{L}((N_{ON}, N_{OFF}) | (\hat{\nu}_S, \hat{\nu}_B)) \\ &= \mathcal{P}(N_{ON} | \hat{\nu}_{ON} = N_{ON}) \times \mathcal{P}(N_{OFF} | \hat{\nu}_{OFF} = N_{OFF}) \\ &= \frac{N_{ON}^{N_{ON}}}{N_{ON}!} e^{-N_{ON}} \frac{N_{OFF}^{N_{OFF}}}{N_{OFF}!} e^{-N_{OFF}}. \end{aligned} \quad (\text{A.5})$$

2. Under the H_0 both the photons of the ON and OFF regions come from the background, from the same Poisson distribution. The best estimate of the expected counts over t_{ON} (t_{OFF}) is given by t_{ON} (t_{OFF}) times the best estimate of the background rate $\hat{\lambda}_B$, which is given by the total number of counts we get divided the total observation time:

$$\hat{\nu}_{ON} = t_{ON} \hat{\lambda}_B = t_{ON} \frac{N_{ON} + N_{OFF}}{t_{ON} + t_{OFF}} = \frac{\alpha}{1 + \alpha} (N_{ON} + N_{OFF}). \quad (\text{A.6})$$

$$\hat{\nu}_{OFF} = t_{OFF} \hat{\lambda}_B = t_{OFF} \frac{N_{ON} + N_{OFF}}{t_{ON} + t_{OFF}} = \frac{1}{1 + \alpha} (N_{ON} + N_{OFF}). \quad (\text{A.7})$$

The Likelihood is the product of the two independent probabilities to get N_{ON} from a Poisson with mean $\hat{\nu}_{ON}$ and N_{OFF} from a Poisson with mean $\hat{\nu}_{OFF}$:

$$\begin{aligned} \mathcal{L}(\mathbf{X} | \mathbf{E}_0, \hat{\mathbf{T}}_C) &= \mathcal{L}((N_{ON}, N_{OFF}) | (\nu_S = 0, \hat{\nu}_{B,0})) \\ &= \mathcal{P}(N_{ON} | \hat{\nu}_{ON}) \times \mathcal{P}(N_{OFF} | \hat{\nu}_{OFF}) \\ &= \frac{1}{N_{ON}!} \left[\frac{\alpha (N_{ON} + N_{OFF})}{1 + \alpha} \right]^{N_{ON}} \exp \left[-\frac{\alpha (N_{ON} + N_{OFF})}{1 + \alpha} \right] \times \\ &\quad \times \frac{1}{N_{OFF}!} \left[\frac{(N_{ON} + N_{OFF})}{1 + \alpha} \right]^{N_{OFF}} \exp \left[-\frac{(N_{ON} + N_{OFF})}{1 + \alpha} \right]. \end{aligned} \quad (\text{A.8})$$

3. The Likelihood Ratio is

$$\lambda = \frac{\mathcal{L}(\mathbf{X} | \mathbf{E}_0, \hat{\mathbf{T}}_C)}{\mathcal{L}(\mathbf{X} | \hat{\mathbf{E}}, \hat{\mathbf{T}})} = \left[\frac{\alpha}{1 + \alpha} \frac{N_{ON} + N_{OFF}}{N_{ON}} \right]^{N_{ON}} \left[\frac{1}{1 + \alpha} \frac{N_{ON} + N_{OFF}}{N_{OFF}} \right]^{N_{OFF}}. \quad (\text{A.9})$$

According to theorem 1 as long as N_{ON} and N_{OFF} are not too small (we usually require $N_{ON} \gtrsim 10$, $N_{OFF} \gtrsim 10$), under the null hypothesis H_0 the statistic $TS = -2 \ln \lambda \sim \chi_1^2$, as there is one free parameter.

This result can provide an additional meaning to TS . If $u \sim \mathcal{N}(0, 1)$ (u is a Gaussian standard variable) then $u^2 \sim \chi_1^2$, $|u| \sim \chi_1$. We can thus consider $\sqrt{TS}$ equivalent to the absolute value of a standard normal variable. The counts can be considered as a “ $\sqrt{TS}$ standard deviation”. For this reason the Li&Ma $\sqrt{TS}$ is referred to as the significance σ of the event.

$$\begin{aligned}\sigma &= \sqrt{TS} = \sqrt{-2 \ln \lambda} = \\ &= \sqrt{2} \left[N_{ON} \ln \left(\frac{1 + \alpha}{\alpha} \frac{N_{ON}}{N_{ON} + N_{OFF}} \right) + N_{OFF} \ln \left((1 + \alpha) \frac{N_{OFF}}{N_{ON} + N_{OFF}} \right) \right]^{1/2}.\end{aligned}\quad (\text{A.10})$$

The hypothesis testing technique requires to evaluate the *p-value*. The probability that the observed excess with significance σ is due to background only (H_0 condition) is:

$$p = P(u \geq \sigma \mid H_0) = \int_{\sigma}^{\infty} \mathcal{N}(u \mid 0, 1) du. \quad (\text{A.11})$$

In gamma-ray astronomy the typical threshold is $\sigma_{thr} = 5$, corresponding to $p_{thr} = 2.87 \cdot 10^{-7}$. If our detection has $\sigma \geq 5$ (or, equivalently $p < p_{thr}$) then we can reject the null hypothesis and claim a source detection. Otherwise we cannot reject H_0 and we cannot be sure that the excess has been caused by a source.

The probability that a real source exists is the *confidence level*:

$$\xi = 1 - p. \quad (\text{A.12})$$

This probability is also known as the *pre-trial* probability, it is correct only if a single observation is made. If repeat the experiment M times (for instance by repeating the measurement or scanning an area of the sky or a range of energies) then the confidence level does depend on the total number of analysed samples. The probability, p , that an event with a significance not being less than σ is produced by the background in a single observation can be evaluated by equation (A.12). Then the probability of producing k such events by the background is given by the *Binomial distribution*

$$P(k \mid M, p) = \binom{M}{k} p^k (1 - p)^{M-k}. \quad (\text{A.13})$$

the probability that none of the candidate source events ($k = 0$) is produced by the background in all M observations, i.e. the probability that the event is due to a real source is the *post-trial confidence level*:

$$\xi = P(0 \mid M, p) = (1 - p)^M. \quad (\text{A.14})$$

A.2.1 Cash Statistics

The Li&Ma Significance is one application of the *Cash statistic* when the background is not known but estimated through measurement. In general a Cash Statistic is defined as -2 times the log-likelihood of Poisson measurements (Cash 1979). Let us assume we have N bins with n_i measured counts in each bin, let's assume the measurements are independent and

sampled from an underlying Poisson distribution, where the expected values ν_i are predicted by a model with parameters Θ . We define the Cash Statistic as

$$C = -2 \ln P(\{n_i\}_{i=1}^N | \{\nu_i\}_{i=1}^N) = -2 \sum_{i=1}^N \ln \mathcal{P}(n_i | \nu_i) = -2 \sum_{i=1}^N (n_i \ln \nu_i - \nu_i - \ln n_i!) . \quad (\text{A.15})$$

As we are going to consider only differences in the C statistic we can omit the $\ln n_i!$ term and re-define it as:

$$C = 2 \sum_{i=1}^N [\nu_i(\Theta) - n_i \ln(\nu_i(\Theta))] . \quad (\text{A.16})$$

The difference of two Cash statistics where ν_i have been estimated under different hypothesis (say, H_0 and H_1) is the likelihood ratio described by Wilks' Theorem (1). In order to apply the theorem, we perform the Maximum Likelihood estimation (C minimisation) of the p free parameters under the alternative hypothesis H_1 : $\hat{\Theta}_{H_1}$. Then, we assume the null hypothesis H_0 , fix q parameters and perform Maximum Likelihood Estimation of the remaining parameters: $\hat{\Theta}_{H_0} = (\{\theta_0\}_{i=1}^q, \{\hat{\theta}\}_{i=q+1}^p)$. We can then compute the difference:

$$\Delta C = C(\{n_i\} | \hat{\Theta}_{H_0}) - C(\{n_i\} | \hat{\Theta}_{H_1}) . \quad (\text{A.17})$$

According to Wilks' theorem (1), $\Delta C \sim \chi_q^2$.

It is important to understand the regime of applicability of Wilks' Theorem. It is asymptotically valid for large data sets, as the size of the sample $\rightarrow \infty$. There are two additional conditions that are crucial: first, the simpler model must be nested within the complex model, and second, the simpler model should not fall on the edge of the parameter space spanned by the complex model. The first condition precludes direct comparisons between, e.g., power-law and blackbody spectral models. The second indicates, for instance, that the existence of emission (or absorption) lines cannot be searched for in this manner, because the simpler model (one with no emission line) is identical to the boundary of the complex model where line intensity is zero. In such cases, ΔC is not well described by the χ^2 distribution.

Cash Statistics in Gammapy Cash Statistics are implemented in **Gammapy** (Donath et al. 2023) in two different conditions:

- The *CSTAT* statistic describes Poisson Data with background estimated from a known background model. The expected counts ν in the ON region are distributed according to a Poisson distribution which is the sum of two Poisson variables, the counts from the source (average ν_S) and the background (average ν_B , known). Then $\nu = \nu_S + \nu_B$ and equation (A.16) can be expressed as the *CSTAT*:

$$CSTAT = 2 [(\nu_S + \nu_B) - N_{ON} \log(\nu_S + \nu_B)] . \quad (\text{A.18})$$

Here ν_B is known, fixed parameter, while ν_s is free and used to estimate Maximum Likelihood: it is 0 under the null hypothesis, free under the alternative hypothesis.

- The *WSTAT* statistic describes Poisson Data with unknown background, that is estimated from the data. The Likelihood is thus composed by the product of two Poisson distributions, one representing the background and one representing the the random

variable N_{ON} , sampled from a Poisson distribution with mean $\nu_S + \nu_B$. Equation (A.16) can be expressed as the *WSTAT*:

$$\begin{aligned} WSTAT &= 2 \left[\nu_S + \nu_B - N_{ON} \log(\nu_S + \nu_B) + \frac{\nu_B}{\alpha} - N_{OFF} \log \frac{\nu_B}{\alpha} \right] \\ &= 2 \left[\nu_S + \frac{1+\alpha}{\alpha} \nu_B - N_{ON} \log(\nu_S + \nu_B) - N_{OFF} \log \frac{\nu_B}{\alpha} \right]. \end{aligned} \quad (\text{A.19})$$

Under the null hypothesis $\nu_S = 0$, ν_B is free and its best estimate is given by equation (A.6): $\hat{\nu}_B = \frac{\alpha}{1+\alpha}(N_{ON} + N_{OFF})$. Under the alternative hypothesis they are both free and the best estimates are $\hat{\nu}_B = \alpha N_{OFF}$ and $\hat{\nu}_S = N_{ON} - \alpha N_{OFF}$. The corresponding ΔW is the Li&Ma *TS*, so $\sqrt{\Delta W} = \sigma$ as in equation (A.10).

A.3 Astrophysical models for Maximum Likelihood Estimation

This section describes the models used to characterise astrophysical sources, background components and IRFs in the Maximum Likelihood Estimation analysis introduced in section 2.4.4.

Source Models An astrophysical source is described by a function $\Phi(\mathbf{x}_T, E_T, t | \Theta)$ that describe the number of photons N_T produced by the source per units of time t , area A , solid angle Ω and energy E_T . It is a function of the true position $\mathbf{x}_T$, the true photon energy E_T and the time t and the parameters Θ . The function is usually factorised into a *temporal*, a *spatial*, a *spectral* independent components and a normalisation factor. The normalisation factor usually account for the dimensions of the functions while the other terms are adimensional. The model is a differential photon flux model with dimensions $[T]^{-1}[L]^{-2}[E]^{-1}[\Omega]^{-1}$ and typical units ph/s/m²/eV/sr. The flux of a source is thus described by the model function:

$$\Phi(\mathbf{x}_T, E_T, t | \Theta) = \frac{dN_T}{dA dt d\Omega dE_T} = \Phi_0 \cdot \Phi_E(E_T | \Theta_E) \cdot \Phi_x(\mathbf{x}_T | \Theta_x) \cdot \Phi_t(t | \Theta_t). \quad (\text{A.20})$$

Instrument Response Functions The model Φ of eq. (A.20) must be folded with the IRFs to obtain the predicted counts from the source. The most common IRFs used in VHE astrophysics are:

- **Exposure.** It is the product of the *Observation Livetime* times the *Effective Area* $A_{\text{eff}}(\mathbf{x}_T, E_T)$. The livetime Δt equals the observation time corrected by a *deadtime* factor which takes into account the observation intervals where the telescope cannot record photons due to the response time of the camera. The effective area equals the geometrical collection area A_{geom} of the detector times its efficiency $\varepsilon(\mathbf{x}_T, E_T)$ for a given true position $\mathbf{x}_T$ and true energy E_T .

$$\mathcal{E}(\mathbf{x}_T, E_T | \Delta t) = \Delta t \cdot A_{\text{eff}}(\mathbf{x}_T, E_T) = \Delta t \cdot A_{\text{geom}} \cdot \varepsilon(\mathbf{x}_T, E_T). \quad (\text{A.21})$$

Exposure dimensions are $[L]^2[T]$, typical units m²s. In IACTs the Exposure is usually a radially symmetrical function from the FoV centre, while in satellites such as AGILE

and Fermi the detector FoV changes continuously due to the satellite's orbital motion and it must be computed by using spacecraft files.

- **Energy Dispersion Probability Matrix.** The Energy Dispersion $\mathcal{E}(E | E_T, \mathbf{x}_T)$ is the probability to reconstruct the photon at energy E when the true energy is E_T and the true position $\mathbf{x}_T$. Energy Dispersion dimensions are $[E]^{-1}$, typical units TeV^{-1} .
- **Point Spread Function.** The $PSF(\mathbf{x} | \mathbf{x}_T, E_T)$ gives the probability of measuring a direction $\mathbf{x}$ when the true direction is $\mathbf{x}_T$ and the true energy is E_T . The PSF dimensions are $[\Omega]^{-1}$, units sr^{-1} .

The predicted counts for a source with model Φ are found by a convolution of the model and the IRFs:

$$N(\mathbf{x}, E | \Theta) = \int \int PSF(\mathbf{x} | \mathbf{x}_T, E_T) \cdot \mathcal{E}(E | E_T, \mathbf{x}_T) \cdot A_{\text{eff}}(\mathbf{x}_T, E_T) \cdot \Delta t \cdot \langle \Phi(\mathbf{x}_T, E_T, t | \Theta) \rangle_{\Delta t} d\mathbf{x}_T dE_T, \quad (\text{A.22})$$

where the temporal component of the model is averaged over the observation time.

Background Models Background components can be modelled with the same formalism of astrophysical sources by assuming a 3D flux model $\Phi_{\text{bkg}}(\mathbf{x}_T, E_T)$. In order to get the background counts we need to perform the same IRF convolution described in eq. (A.22) but using a background sky model instead of a source model. In HE space satellites such as Fermi and AGILE, the background model is a function of the position and energy and it is computed from known emission models of the Galactic and extra-galactic medium (Giuliani et al. 2004; Bulgarelli et al. 2019). It is usually composed by two background components: the *galactic* and the *isotropic* diffuse emission, and the complete model is a linear combination of the two:

$$\Phi_{\text{bkg}}(\mathbf{x}_T, E_T) = g_{\text{gal}}(E_T) \cdot \Phi_{\text{gal}}(\mathbf{x}_T) + g_{\text{iso}}(E_T) \cdot \Phi_{\text{iso}}. \quad (\text{A.23})$$

The Galactic diffuse emission is produced by the interaction of CRs with the Galactic interstellar medium, the CMB radiation and the interstellar radiation field (ISRF) through three physical processes: hadron-hadron collision, Bremsstrahlung, and inverse Compton emission. We show in figure A.1 the diffuse γ -ray background galactic emission model used by AGILE (Giuliani et al. 2004). The (quasi) isotropic background includes both a contribution from the cosmic extra-galactic diffuse emission and a component of noise due to residual CR induced backgrounds at the detector level. Typical values are between $(4 - 8) \cdot 10^{-5} \text{ cts/s/cm}^2/\text{sr}$ in the $100 \text{ MeV} \div 10 \text{ GeV}$ energy range.

The Background models for IACTs, for instance the one computed by CTAO (Cherenkov Telescope Array Observatory and Cherenkov Telescope Array Consortium 2021), are already provided *after* IRF convolution, as the main background component is not residual γ -ray emission from the sky, but the γ -like background of mis-reconstructed hadronic events. The background model is usually expressed as a function of offset and reconstructed energy: $B(\mathbf{x}, E)$, with dimensions of $[T]^{-1}[E]^{-1}[\theta]^{-1}$ and typical units cts/s/TeV/sr . In order to obtain the background counts N_{bkg} in a given bin of space and energy it is required to integrate the model over the appropriate energy range, spatial bin, and time interval Δt :

$$N_{\text{bkg}}(\mathbf{x}_k, E_k) = \int_{E_{k, \text{min}}}^{E_{k, \text{max}}} \int_{\text{Area } \mathbf{x}_k} \Delta t \cdot B(\mathbf{x}, E) d\mathbf{x} dE. \quad (\text{A.24})$$

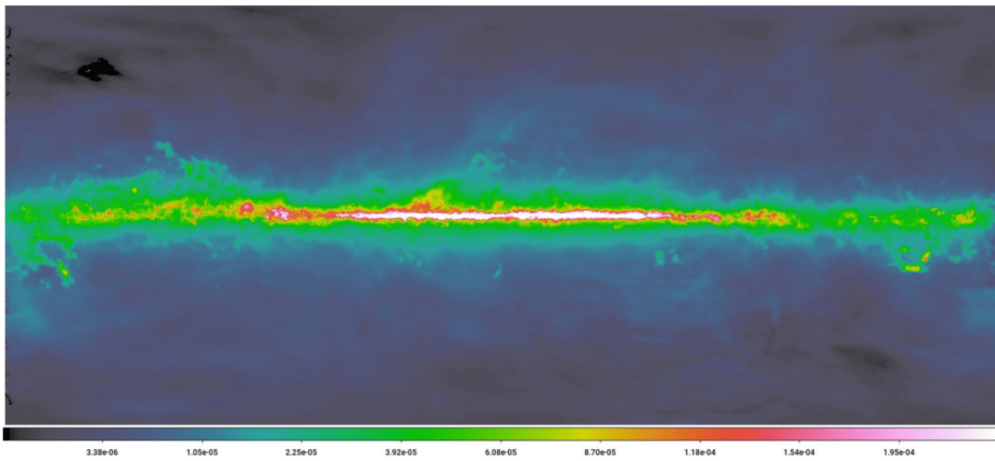


Figure A.1 – AGILE diffuse γ -ray background emission model in the 300 MeV – 1 GeV energy range, in units of $\text{ph/s/cm}^2/\text{sr}$. Credit: Giuliani et al. (2004).

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