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**The Milky Way assembly as traced by its stars and
globular clusters**

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*“Even if you are not ready for the day,
it cannot always be night”*

G. Brooks

Abstract

Over the past decade, the advent of the *Gaia* mission has revolutionized our understanding of the Milky Way, thanks to the extremely precise 6D phase-space information provided for millions of stars. This incredible dataset revealed a complex evolutionary history for the Galaxy, marked by multiple accretions of dwarf galaxies whose stellar relics can be identified as substructures in phase-space in the Halo. While the access to precise stellar 6D phase-space coordinates is crucial to trace such relics, interpretations based only on dynamics are often prone to degeneracies and contamination from unrelated sources.

The study of the chemical makeup of these stellar substructures offers one of the most powerful and direct tools to decode their origin, complementing and deepening the picture provided by dynamics alone. Indeed, while the ‘dynamical imprints’ of past accretion events may partially fade over billions of years due, e.g., to the variation of the Galactic potential, the chemical composition in the atmosphere of low-mass, long-lived stars remains unchanged for most of the metals. In other words, stars may wander through the Galaxy, but their chemical DNA forever ties them to their original family.

However, since progenitor galaxies of Halo substructures shared similar chemical evolutionary histories and were accreted relatively early in cosmic time, the resulting differences between chemical patterns of their stellar remnants are intrinsically subtle. Capturing these faint chemical signatures requires the highest possible level of precision and homogeneity, as even small systematic offsets between different analyses can easily erase the very contrasts that chemical tagging relies on, making cross-study comparisons unreliable. This Thesis fully embraces this idea by using high-resolution spectroscopy to derive *precise and internally homogeneous* chemical abundances of either field stars and globular clusters, which have long served as the principal tracers of the Milky Way evolution. This will provide a robust framework to characterise Halo substructures that dynamics alone is not able to disentangle and interpret appropriately.

Specifically, this Thesis focuses on the retrograde stellar Halo, through the *A Walk on the Retrograde Side* (WRS) project. In this context, I built and analysed the largest homogeneous catalogue of high-resolution abundances for retrograde Halo stars to date (~ 650 stars), allowing for a systematic comparison between the chemistry of *all* different retrograde accreted components previously identified as dynamical substructures for the first time. This work has refined the understanding of the major building blocks of the Halo, by providing the required additional ingredients to untangle the otherwise unsolvable dynamical complexity.

Using WRS data, I confirmed that the debris of the *Gaia*-Sausage-Enceladus (GSE) system dominates the retrograde Halo, showing chemical signatures coherent with formation in a massive satellite accreted at early epochs. Among the newly explored substructures, Antaeus emerged as chemically distinct from GSE, suggesting that it traces the debris of an independent progenitor. By comparing Antaeus with ED-3, I noticed remarkable similarities in their orbits, metallicity, and chemical compositions, supporting the idea that they originate from the same accretion event. I found an exceptionally small spread in $[\text{Fe}/\text{H}]$ in the extremely metal-poor substructure ED-2, strongly suggesting that its progenitor was not a dwarf galaxy but, instead, a stellar cluster. A comparison between GSE and Sequoia revealed clear differences at $[\text{Fe}/\text{H}] < -1.5$ dex in the α -elements, highlighting different enrichment histories for these stellar populations. Finally, a thorough chemical analysis of dynamically-

selected members of the candidate relic Thamnos revealed that this phase-space overdensity is dominated by in-situ stars, yet still preserving the possible imprint of a low-mass accreted progenitor in its most metal-poor tail at $[\text{Fe}/\text{H}] < -2.0$ dex.

Building up on results obtained for field stars, I extended this homogeneous chemical approach to globular clusters. These old stellar systems have been used as key tracers of the Milky Way formation since the dawn of Galactic astronomy. Yet, the detailed comparative analysis of their chemical composition to reveal the origin of individual clusters is still in its infancy. By analysing a set of clusters with well-established progenitors, I demonstrated that their different origin is imprinted in their chemical properties. Specifically, chemical tagging can distinguish between in-situ and accreted globular clusters using elements such as Mg, Zn, and Eu. Furthermore, it can even discriminate clusters born in different accreted progenitors, as I show with the case of Ruprecht 106. On top of this, I further combined dynamics and chemistry with precise age determinations, in the context of the *Cluster Ages to Reconstruct the Milky Way Assembly* (CARMA) project, to solve the most complex cases. This approach proved essential to tackle the long-debated case on the origin of NGC 288, which emerged as the first identified example of a *Splashed* globular cluster – a system formed in-situ, as revealed by its chemical composition and age, but moving on a Halo-like orbit due to dynamical heating induced by the *Gaia*-Sausage-Enceladus merger.

Together, these efforts show that precise stellar chemical abundances from high-resolution spectroscopy, when applied within a homogeneous framework, provides a uniquely powerful lens to put into focus the accurate reconstruction of the Milky Way assembly. The combined study of field stars and globular clusters demonstrates that both tracers encode complementary pieces of the past history of our Galaxy, and that the interplay between chemical, dynamical, and chronological information opens the path toward a truly comprehensive understanding of how the Milky Way came to be.

Contents

1	Introduction	1
1.1	Galactic Archaeology in the <i>Gaia</i> era	2
1.1.1	Dynamics	2
1.1.2	Chemistry	5
1.1.3	Ages	10
1.2	The accretion history of the Milky Way	11
1.2.1	The ongoing accretion of the Sagittarius dwarf spheroidal galaxy . .	11
1.2.2	<i>Gaia</i> -Sausage-Enceladus: the last major merger	13
1.2.3	The Sequoia dwarf: a complex retrograde substructure	15
1.2.4	The Helmi Streams	17
1.2.5	The very early accretion of the small satellite Thamnos	17
1.2.6	Kraken, Heracles, and the proto-Galaxy: a (blurry) picture of the Milky Way earliest epoch	18
1.3	The contribution of this Thesis	21
1.3.1	The <i>A Walk on the Retrograde Side</i> project	21
1.3.2	Chemical tagging of Milky Way globular clusters	22
1.3.3	The <i>Cluster Ages to Reconstruct the Milky Way Assembly</i> project	23
2	Tidying up the retrograde Halo with high-resolution spectroscopy	25
2.1	Selection of the sample and observations	26
2.1.1	High-resolution spectroscopy for selected stars	27
2.2	Orbital parameters	30
2.3	Identification of substructures in the RH	31
2.4	Abundance analysis	35
2.4.1	Stellar parameters	35
2.4.2	Line selection	36
2.4.3	Chemical analysis	37
2.4.4	Abundance uncertainties	40
2.5	Comparison with the literature	40
2.6	Chemical abundances of RH substructures	44
2.6.1	Metallicity distribution functions	44
2.6.2	Light elements	46
2.6.3	α -elements	47
2.6.4	Iron-peak elements	50
2.6.5	Neutron-capture elements	50
2.7	Summary and conclusions	51

3	Chemistry to disentangle in-situ and accreted components in Thamnos	55
3.1	Selection of candidate Thamnos and GSE stars	56
3.2	Orbital parameters	56
3.3	The chemical composition of Thamnos and GSE	58
3.3.1	Metallicity distributions	60
3.3.2	Abundances of light elements	61
3.3.3	Abundances of α -elements	62
3.3.4	Abundances of iron-peak elements	63
3.3.5	Abundances of neutron capture elements	64
3.4	Comparison with galactic chemical evolution models	67
3.4.1	Basic ingredients	68
3.4.2	Models for GSE and Thamnos progenitors	69
3.5	Discussion and conclusion	71
4	A comparative high-resolution spectroscopic analysis of in-situ and accreted GCs	75
4.1	Spectroscopic dataset	76
4.2	Chemical analysis	77
4.2.1	Stellar parameters	77
4.2.2	Deriving the abundances	79
4.2.3	Uncertainties on the abundance ratios	80
4.3	Chemical abundances of target GCs	80
4.3.1	α -elements	81
4.3.2	Iron-peak elements	82
4.3.3	Neutron-capture elements	85
4.3.4	Validation of the abundances	86
4.4	Comparison with field stars from the likely progenitor	88
4.4.1	NGC 6218, NGC 6522, NGC 6626, and the Milky Way	88
4.4.2	NGC 362, NGC 1261, and <i>Gaia</i> -Sausage-Enceladus	88
4.4.3	Ruprecht 106 and the Helmi Streams	91
4.5	Possible origins of Ruprecht 106	91
4.5.1	Comparison with NGC 121	93
4.5.2	Comparison with surviving dwarf galaxies	93
4.6	Conclusion	95
5	NGC 288 as the first Splashed globular cluster	97
5.1	The globular cluster NGC 288	98
5.2	The CARMA method	99
5.2.1	Stellar evolution framework	99
5.2.2	The isochrone-fitting code	100
5.3	Comparison between the age of NGC 288 and in-situ globular clusters	101
5.4	The chemical composition of NGC 288	103
5.5	Discussion and conclusion	108
5.6	The CARMA project at a glance: current status and key results	111
5.6.1	The final word on the origin of NGC 6388 and NGC 6441	111
5.6.2	The age-metallicity relation of <i>Gaia</i> -Sausage-Enceladus globular clusters	112

5.6.3	Chrono-dynamics of seven old star clusters in the Large Magellanic Cloud and the peculiar origin of NGC 1841	114
5.6.4	The Milky Way experienced a significant merger only 1.5 Gyr after the Big Bang	117
6	Conclusions	121
6.1	Summary of the main findings of this Thesis	121
6.1.1	Chemistry of field stars as a tool for Galactic Archaeology	122
6.1.2	Chemistry of GCs as a tool for Galactic Archaeology	123
6.2	Future perspectives	124
6.2.1	The chemical makeup of the disrupted stellar system ED-2	124
6.2.2	Final WRS data release	125
6.2.3	Exploring synergies between <i>Gaia</i> DR4 and next generation large spectroscopic surveys	125
	Bibliography	127

1 | Introduction

The Λ -cold dark matter (Λ -CDM) cosmological paradigm describes galaxy growth as a hierarchical process, where systems gradually assemble their mass through mergers with smaller companions (White & Frenk 1991). Our own Milky Way is no exception, with the latest phases of this process being strikingly exemplified by the ongoing cannibalisation of the Sagittarius dwarf spheroidal galaxy (Ibata et al. 1994). In this framework, galaxies form inside dark matter halos which experienced most of their growth early in cosmic history, when the higher density of the Universe promoted more frequent mergers (White & Rees 1978). Also, Λ -CDM predicts a strong imbalance in the abundance of structures, with low-mass systems far outnumbering massive ones (Moore et al. 1999; Tinker et al. 2008). As a result, a dark matter halo comparable in size to that of the Milky Way is expected to accrete many more small companions than large ones over cosmic time (Fakhouri et al. 2010), with these galaxies ending up in building a sparse stellar halo (Bullock & Johnston 2005; Cooper et al. 2010).

The efficiency of star formation, however, depends strongly on the environment and the mass of the dark halo. Thus, the stellar halo of the surviving galaxy is predominantly built from populations initially hosted in the more massive accreted systems, while smaller and more numerous satellites contribute relatively little (Purcell et al. 2007; Monachesi et al. 2019). This pattern is clearly seen in the Milky Way, where, according to galaxy formation models and simulations, the bulk of the stellar Halo originates from just a few ($\sim 1 - 2$) relatively massive dwarf galaxies (De Lucia & Helmi 2008; Deason et al. 2016; Fattahi et al. 2020).

Owing to the low density in the stellar halo of the Galaxy (which reflects in long dynamical timescales), debris from individual progenitor galaxies maintain a dynamical coherency in the space defined by the integrals of motion (IoM), such as energy (E) and angular momentum (L) in a slowly evolving potential (Helmi & de Zeeuw 2000). As a result, the stellar Halo preserves the long-term imprint of the growth of the Galaxy, acting as an archive of its past accretion events. Because its stars originated in systems that were accreted and disrupted early in time, this diffuse component serves also as a laboratory for investigating the properties of ancient dwarf galaxies that no longer exist in their original form, opening a window onto the high-redshift Universe directly from our home garden. Together, these principles lay at the foundation of Galactic Archaeology.

1.1 Galactic Archaeology in the *Gaia* era

The Milky Way offers a unique powerful setting for exploring the evolution of disc galaxies, as it is the only example where the entire spectrum of its resolved stellar populations can be investigated in exquisite detail (see [Bland-Hawthorn & Gerhard 2016](#), for a review). Yet, our own perspective is inevitably biased: observing the Galaxy from within presents significant challenges, limiting our ability to obtain a complete, unobstructed view of its structure in a whole. Despite these difficulties, it is well-established that, in terms of structure, our Galaxy is a barred spiral, featuring a central box/peanut-shaped bulge, a prominent stellar disc, and an extended, diffuse stellar halo. When considering its global properties (e.g. luminosity, stellar mass, current star formation rate, baryon fraction), the Milky Way fits well within the population of large disc galaxies found in low-density environments ([de Rossi et al. 2009](#); [Kormendy et al. 2010](#)).

While the Milky Way’s present-day structure is relatively well constrained, its formation history remains far less certain. With the term ‘Galactic Archaeology’, we typically refer to the field of research that seeks to reconstruct the Milky Way history by decoding the fossil records preserved in its oldest components, much like archaeologists do to piece together human history. Typically, two cosmic objects have been used to trace back the evolution of the Galaxy:

- *Field stars*. The underlying principle is that low-mass stars bear memory of their origins and can survive from the earliest epochs of the Universe to the present day, carrying within them crucial clues about their birth environments. These stellar ‘records’ manifest in several key ways, such as their motion in the Galaxy, the chemical abundances in their atmospheres, and their age (see [Helmi 2020](#); [Deason & Belokurov 2024](#), for complete reviews).
- *Globular clusters*. In the Λ -CDM hierarchical framework, the most massive among the ingested dwarf galaxies harboured their own system of globular clusters (GCs) that can survive the merging process alongside field stars, contributing to the formation of the present-day Milky Way GC system (e.g. [Brodie & Strader 2006](#); [Forbes & Bridges 2010](#)). Thus, the study and characterization of GCs from a chrono-chemo-dynamical point of view stand out as a powerful probe of the Milky Way assembly processes.

In the following, I will describe in detail the principal tools and methods currently used to define the timeline of events that shaped the past of the Milky Way.

1.1.1 Dynamics

Orbits of stars and GCs can be described in terms of the IoM, that are quantities that remain approximately conserved in a time-independent gravitational potential. These include the orbital energy (E), the total angular momentum (L), some of its components (e.g. L_z and $L_\perp$) depending on the symmetry of the system, and the corresponding actions (J_R , J_ϕ , and J_z). If these quantities remain roughly conserved, as expected during minor mergers (which do not completely reshape the Galactic potential), stars stripped by tidal forces will continue to follow orbits very similar to those of their parent system. Depending on the mass of the

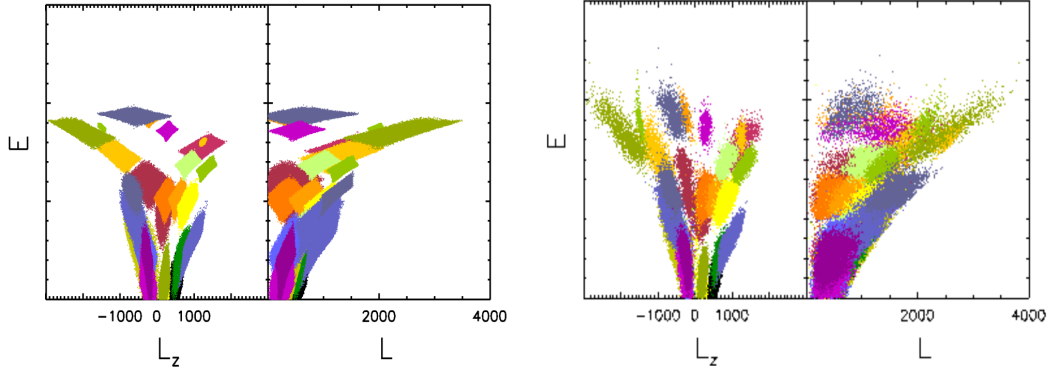


FIGURE 1.1 : Initial (left) and final (right) distributions of particles ($V < 15$ and $D < 6.0$ kpc) in the IoM space after 12 Gyr, after convolution with the errors expected for *Gaia* for the original potential. Figure adapted from [Helmi & de Zeeuw \(2000\)](#).

infalling object, this can result in very different outcomes. Stars coming from a small galaxy will spread out along the orbit of the progenitor, forming a stellar stream with a leading and a trailing tail ([Helmi & White 1999](#); [Bonaca & Price-Whelan 2025](#)). For more massive progenitors, tidal disruption operates in the same way as for smaller systems, but produces a broader distribution of orbits, as accreted stars span a wider range of energies (due to a larger initial velocity dispersion in the parent galaxy and possibly to dynamical friction acting during the progressive disruption of the progenitor). This results in a more diffuse and complex stream, with characteristics depending on the configuration of the merger and the initial orbit of the accreted galaxy ([Helmi & White 1999](#); [Jiang & Binney 2000](#); [Amorisco 2017](#); [Vasiliev et al. 2022](#)).

The characteristics of a stellar stream not only depend on the size of its progenitor, but also on the time elapsed since its stars became unbound, and the orbital timescales. In fact, shortly after disruption, streams remain dense and spatially coherent, producing clear overdensities in the sky where long orbital periods and weaker tides slow their dispersal, which are conditions typical of streams in the outer Halo ([Ibata et al. 1994](#); [Helmi et al. 1999](#); [Belokurov et al. 2006](#); [Mateu 2023](#); [Ibata et al. 2024](#); [Bonaca & Price-Whelan 2025](#)). In higher density regions, shorter orbital times lead to rapid dilution, even for streams originating from small progenitors. Over time, streams stretch and mix spatially, so that a single accretion event can give rise to multiple moving groups within the different region of the Galaxy, until they phase-mix completely in few Gyr, and lose entirely their spatial coherency ([Johnston et al. 2008](#); [Gómez et al. 2010](#); [Gómez & Helmi 2010](#); [Belokurov et al. 2023](#)).

From an observational perspective, the quest to identify satellites that merged with the Milky Way long ago has historically relied on the detection of overdensities in the IoM space, an approach that first led to the discovery of the Helmi Streams ([Helmi et al. 1999](#), see Section 1.2.4). Follow-up theoretical work and simulations have since shown that the debris of tidally disrupted dwarf galaxies can preserve a remarkable degree of coherence in the $E - L_z - L_\perp$ and action spaces even after several Gyr of evolution (as shown in Figure 1.1), provided the Galactic potential evolves only slowly over time ([Johnston et al. 1996](#); [Helmi & de Zeeuw 2000](#); [McMillan & Binney 2008](#); [Gómez & Helmi 2010](#)). However, even when full cosmological evolution is included, this conservation remains valid, at least to a first approximation

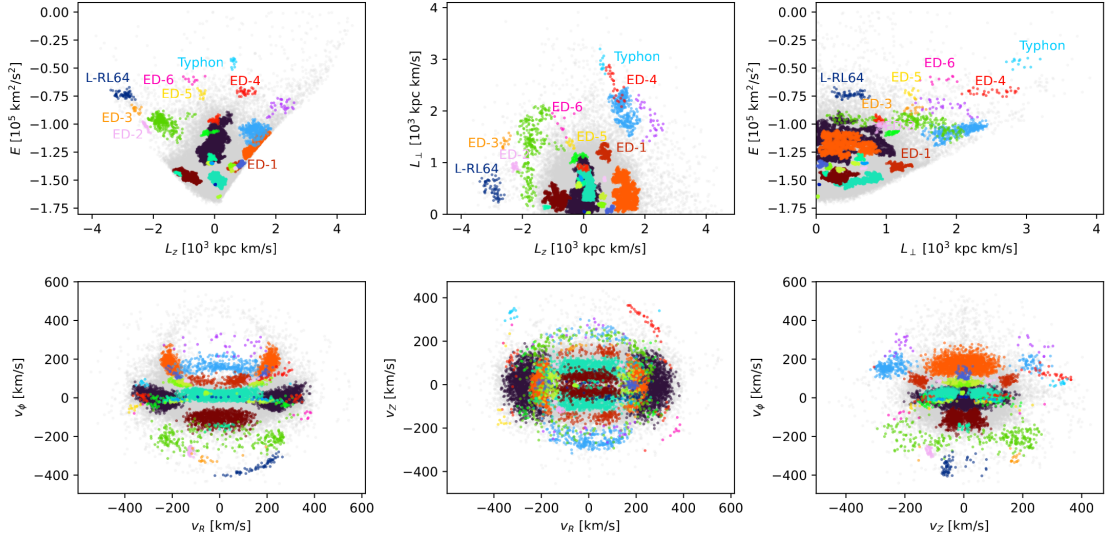


FIGURE 1.2 : Dynamical substructure identified using to *Gaia* DR3 by [Dodd et al. \(2023\)](#) in the local ($D < 2.5$ kpc) stellar Halo in the energy – angular momenta (top) and in the cylindrical velocity spaces.

(e.g. [Gómez et al. 2013](#)).

In recent years, a major breakthrough in this field has been driven by *Gaia* ([Gaia Collaboration et al. 2016, 2018a, 2021, 2023](#)), an ambitious astrometric space mission (providing also photometry) designed to chart the full phase-space distribution of the Milky Way. *Gaia* provides positions, parallaxes, and proper motions for ~ 1.5 billion stars down to a limiting magnitude of $G \sim 21$ (as of the latest data release) complemented by line-of-sight velocities and stellar parameters for a brighter subset (~ 33 million stars down to $G \sim 13.7$), the *Gaia* RVS sample ([Recio-Blanco et al. 2023](#)). As illustrated in Figure 1.2, this unprecedented trove of high-quality 6D phase-space data from *Gaia* has transformed our ability to reconstruct the orbits of stars within the Galaxy with unprecedented precision, leading to the identification of numerous accreted substructures in the Milky Way stellar halo that bear witness to its long and complex assembly history (e.g. [Belokurov et al. 2018](#); [Helmi et al. 2018](#); [Myeong et al. 2018](#); [Koppelman et al. 2019b](#); [Massari et al. 2019](#); [Myeong et al. 2019](#); [Kruijssen et al. 2020](#); [Naidu et al. 2020](#); [Necib et al. 2020](#); [Yuan et al. 2020](#); [Horta et al. 2021](#); [Ibata et al. 2021](#); [Re Fiorentin et al. 2021](#); [Malhan et al. 2022](#); [Mardini et al. 2022](#); [Myeong et al. 2022](#); [Oria et al. 2022](#); [Ruiz-Lara et al. 2022a](#); [Shank et al. 2022](#); [Tenachi et al. 2022](#); [Dodd et al. 2023](#); [Mikkola et al. 2023](#); [Cabrera Garcia et al. 2024](#); [Malhan & Rix 2024](#); [Berni et al. 2025](#)). Also, the orbits of Milky Way GCs have been reconstructed with exceptional precision. Through the analysis of their orbital properties, Milky Way GCs have been classified into distinct groups by several authors ([Massari et al. 2019](#); [Forbes 2020](#); [Callingham et al. 2022](#); [Malhan et al. 2022](#); [Chen & Gnedin 2024](#)), distinguishing those accreted from disrupted dwarf galaxies from those formed in-situ (see Figure 1.3). However, the interpretation of these numerous recent discoveries can be extremely challenging from a pure dynamical point of view. On the one hand, it has become more and more clear that remnants from the same merging event can result in overdensities at various locations in the space defined by the IoM, which could be mistaken for independent substructures (e.g. [Koppelman et al. 2020](#); [Naidu et al. 2021](#);

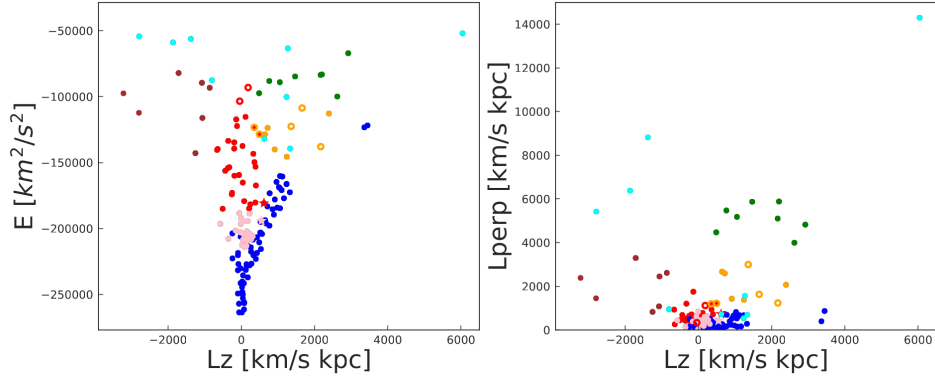


FIGURE 1.3 : Distribution of Milky Way GCs in $E - L_z - L_\perp$ spaces, colour-coded according to their associations with different progenitors. Figure from [Massari et al. \(2019\)](#).

[Amarante et al. 2022](#); [Khoperskov & Gerhard 2022](#); [Belokurov et al. 2023](#); [Davies et al. 2023](#); [Pagnini et al. 2023](#); [Chen & Gnedin 2024](#); [Mori et al. 2024](#)). On the other hand, relics with different origin may significantly overlap in the IoM space ([Myeong et al. 2019](#); [Naidu et al. 2020](#); [Lövdal et al. 2022](#); [Matsuno et al. 2022a](#); [Dodd et al. 2023](#)) and unrelated sources can drastically contaminate samples of candidate members of a given substructure selected kinematically ([Buder et al. 2022](#); [Rey et al. 2023](#); [Dodd et al. 2025a](#); [Thomas et al. 2025](#)). In the end, substructures formation may be triggered by phenomena internal to the host galaxy, as a dynamical reassessing after a merging event ([Jean-Baptiste et al. 2017](#)) or resonances induced by the presence of a rotating bar ([Dillamore & Sanders 2025](#); [Woudenbergh & Helmi 2025](#)). A possible solution to this dynamical degeneracy can be achieved by adding entirely independent dimensions to the analysis, that are, the chemical and chronological information.

1.1.2 Chemistry

The atmosphere of stars preserve a chemical fingerprint of the gas clouds from which they formed, since their present-day elemental abundances still reflect the composition of their natal molecular clouds, acting as a long-lasting record of their birth conditions. The very first stars contained virtually no metals heavier than lithium, but as these massive pioneers ended their lives in supernovae (SNe) explosions, they enriched the surrounding interstellar medium with heavier elements synthesized in their interiors. Each successive stellar generation was therefore born from gas that had been progressively chemically enriched, creating a gradual increase in the overall metallicity. The patterns of abundances of many chemical elements observed today are shaped by key factors such as the efficiency and timescale of star formation within a galaxy, the mixing of enriched material throughout the interstellar medium, the initial mass function (IMF), and the site of production of each element (e.g. [Kobayashi et al. 2006](#); [Romano et al. 2010](#); [Nomoto et al. 2013](#); [Kobayashi et al. 2020b](#), see Figure 1.4).

Chemical elements heavier than lithium can be divided into groups depending on the different nucleosynthetic path. Those that are most commonly used as tracers for Galactic Archaeology are:

- Light-elements Na and Al. In the low metallicity regime, they are primarily synthesized in massive stars that explode as core-collapse supernovae (CC-SNe) whereas at in-

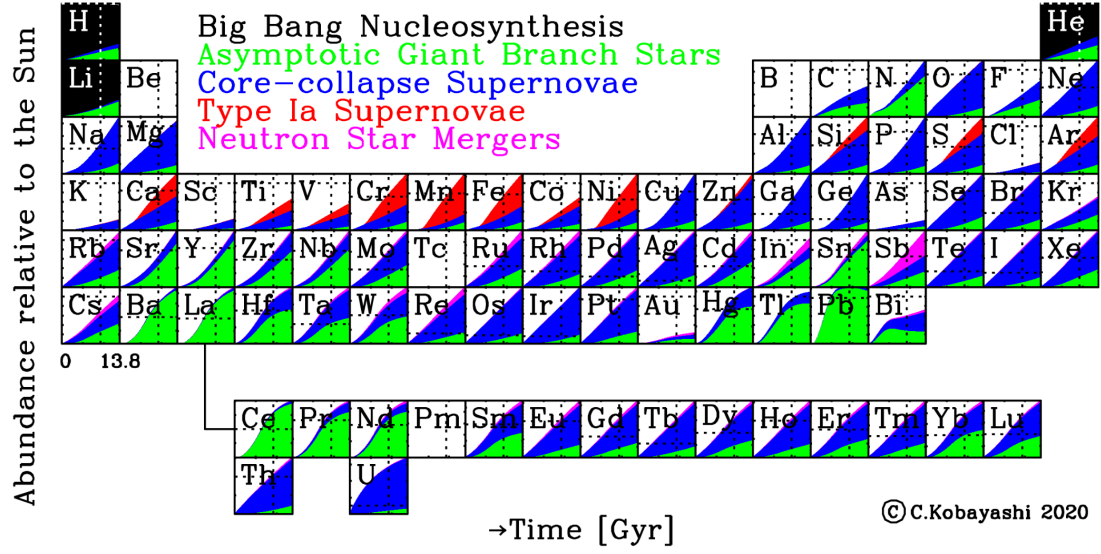


FIGURE 1.4 : The time evolution (in Gyr) of the origin of elements in the periodic table based on the main nucleosynthetic pathways. The dotted lines indicate the observed solar values. Figure from Kobayashi et al. (2020b).

intermediate metallicity they are also produced in non-negligible amount in asymptotic giant branch (AGB) stars. For both the elements, the production depends on the metallicity as it stems from a neutron excess generated during the CNO cycle (Kobayashi & Nomoto 2009; Nomoto et al. 2013).

- α -elements. These elements are mainly synthesized in the core of massive stars and diffused into the interstellar medium through CC-SNe, while a small fraction is also produced in Type Ia supernovae (SNe Ia, see e.g. Kobayashi et al. 2020b). Mg is synthesized through the hydrostatic burning of He, C, and Ne in massive stars ($30 - 35 M_{\odot}$) with a negligible contribution by SNe Ia (Woosley & Weaver 1995; Arnett 1996). The explosive α -elements (Ca and Ti) are mainly produced in less massive stars ($15 - 25 M_{\odot}$), with a considerable fraction formed also in SNe Ia (Kobayashi et al. 2020b).
- Iron-peak elements. The production of iron-peak elements (Sc, Cr, Mn, Fe, Co, Ni, Cu and Zn) is sourced from a variety of nucleosynthesis formation pathways, with SNe Ia, CC-SNe, and hypernovae (HNe)¹ all making a sizeable contribution to the overall production of these chemical elements (Romano et al. 2010; Leung & Nomoto 2018; Kobayashi et al. 2020b; Lach et al. 2020). Sc is mainly produced in CC-SNe in the burning of C and Ne (Woosley et al. 2002), with a small contribution by SNe Ia (Kobayashi et al. 2020b), while for V and Co the contribution of SNe Ia is not negligible. Mn is almost entirely produced by SNe Ia, with a relative contribution by CC-SNe and HNe even lower than Fe (Kobayashi & Nomoto 2009; Kobayashi et al. 2020b). SNe Ia are also the predominant channel of formation of Cr and Ni, although it can be produced in CC-SNe, as for Fe. Cu is predominantly synthesized in massive stars via the

¹These events represent a class of massive ($\geq 20 M_{\odot}$) CC-SNe with 10 times or more higher explosion energies relative to standard ones ($E = 10^{51}$ erg, see e.g. Umeda & Nomoto 2002; Kobayashi et al. 2006).

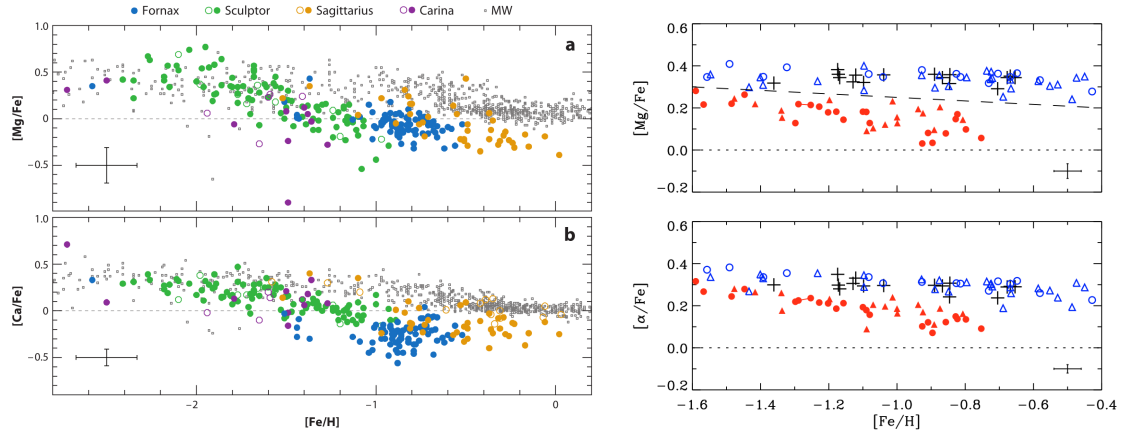


FIGURE 1.5 : Left panel: Mg and Ca abundances in four nearby dwarf spheroidal galaxies and from a compilation of the Milky Way disc and Halo star abundances (in gray), figure from [Tolstoy et al. \(2009\)](#). Right panel: two populations in the Milky Way halo with distinct α -elements, figure from [Nissen & Schuster \(2010\)](#).

weak s -process, with a yield depended on the metallicity ([Romano & Matteucci 2007](#); [Prantzos et al. 2018](#)). In the end, Zn is synthesized in the highest energy HNe.

- Neutron capture elements. This family of elements is divided into two classes depending on the efficiency of neutron capture compared to the timescale of the β -decay. In particular, slow neutron capture (s -process) elements are predominantly synthesized in either massive stars and intermediate mass AGB stars (light/weak s -process elements, e.g. Y) or low mass (heavy/main s -process elements, e.g. Ba and La) AGB stars ([Kobayashi et al. 2020b](#)). In contrast, rapid (r -) neutron capture elements (e.g. Eu) are produced through a variety of astrophysical events, including sources responsible for prompt (e.g. magneto-rotational supernovae and/or collapsars, [Mösta et al. 2018](#); [Siegel et al. 2019](#)), and delayed (neutron star mergers, NSMs, [Lattimer & Schramm 1974](#); [Argast et al. 2004](#)) enrichment.

By measuring the abundances of these elements, we gain direct access to the physical and chemical state of the gas at the time of the birth of a star, allowing us to probe environments that were dramatically different from the present-day Milky Way ([Frebel & Norris 2015](#)). It is reasonable to think that stars that share similar abundance patterns are likely to have originated from the same progenitor system, each one with its own peculiar star formation and chemical enrichment history. Thus, identifying such chemically related stars, an approach known as *chemical tagging* ([Freeman & Bland-Hawthorn 2002](#)), has become a key tool in tracing the the assembly history of our Galaxy.

It is well-established that stars belonging to the stellar Halo are, on average, significantly more metal-poor ($[\text{Fe}/\text{H}]^2 < -1.0$ dex) than those found in the Galactic disc or bulge (see e.g. [Searle & Zinn 1978](#)). This trend is naturally explained if the Halo was primarily assembled from low-mass progenitors, which underwent less efficient chemical enrichment than

²Throughout this Thesis, I will present chemical abundances using the common notation: $[X/W] = \log(N_X/N_W) - \log(N_{X,\odot}/N_{W,\odot})$, where N_X and N_W are the number of particles of the elements X and W in the stellar atmosphere.

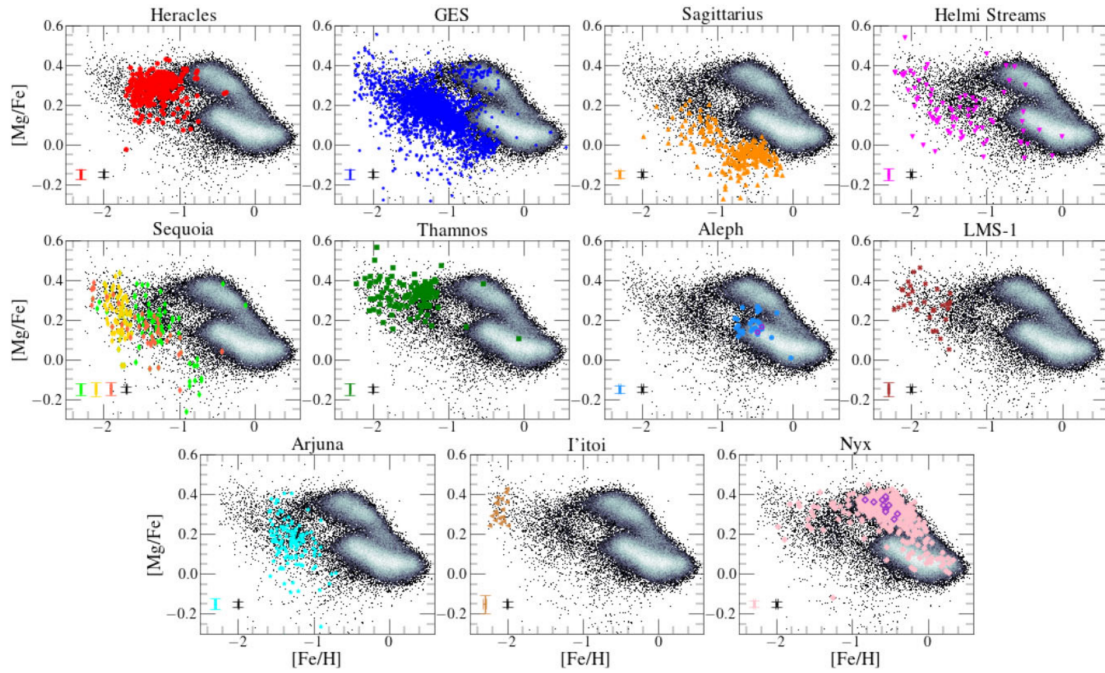


FIGURE 1.6 : Chemical trends of Halo substructures in the $[\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]$ plane as seen by APOGEE DR17. Figure from [Horta et al. \(2023\)](#).

a massive system like the Milky Way (as predicted by the stellar mass-metallicity relation of galaxies, see e.g. [Erb et al. 2006](#); [Mannucci et al. 2010](#); [Kirby et al. 2013](#); [Curti et al. 2020](#)). Whether this metallicity distribution points to the dominance of one particularly massive accreted galaxy, or instead reflects the combined contribution of many smaller systems, remained for long an open question. To disentangle these possibilities, more detailed chemical diagnostics, especially the study of α -element abundances relative to iron, provided a far more sensitive probe of the Halo enrichment history. Indeed, the $[\alpha/\text{Fe}]$ is an effective tracer of the star formation timescales and efficiency of a given environment (see e.g. [Matteucci 2012](#)). The interstellar medium is enriched on short timescales with both α -elements and Fe due to the explosion of CC-SNe. However, Fe is also significantly produced by SNe Ia, which originate from the explosions of white dwarfs after binary interactions in low-mass stellar systems ([Kobayashi et al. 2020b](#)). Thus, the chemical patterns of these elements can be used as a proxy of the different timescales of star formation. A typical indicator of the star formation efficiency of a galaxy is the metallicity of the ‘knee’ in the $[\alpha/\text{Fe}] - [\text{Fe}/\text{H}]$ plane, which denotes the beginning of a sizeable contribution to the chemical enrichment by SNe Ia ([Tinsley 1979](#); [Matteucci & Greggio 1986](#)). Given the delayed onset of SNe Ia, systems with inefficient star formation timescales tend to exhibit lower $[\alpha/\text{Fe}]$ ratios ([Matteucci & Brocato 1990](#)). Different trends in the $[\alpha/\text{Fe}] - [\text{Fe}/\text{H}]$ plane have been indeed observed in Local Group dwarf galaxies with different masses (e.g. [Venn et al. 2004](#); [Tolstoy et al. 2009](#); [Hill et al. 2019](#), see left panel of Figure 1.5). Similarly, also the pure tracer of r -process element Eu has recently started to be used as an effective tagger for the origin of stars ([Aguado et al. 2021](#); [Matsuno et al. 2021](#)). The observed enrichment in Eu in dwarf galaxies (e.g. [Tolstoy et al. 2009](#); [Lemasle et al. 2014](#)) is explained by the interplay of the low star formation efficiency in the progenitor galaxy and the consequent more efficient contribution in the

production of r -process by delayed sources (i.e. NSM, [Cescutti et al. 2015](#); [Siegel et al. 2019](#); [Naidu et al. 2022b](#); [Ou et al. 2024](#)). However, the chemical abundance patterns of Milky Way halo stars differ markedly compared to those of surviving dwarf spheroidal satellites, failing also to match that of massive satellites like the Large Magellanic Cloud (LMC) or the Sagittarius dwarf spheroidal (Sgr dSph, see also Section 1.2.1). Models that combine early accretion histories with chemical evolution show that the Halo was most likely assembled from a few massive dwarfs accreted at early times, whose brief star formation histories naturally differ from those of present-day or late-accreted systems ([Font et al. 2006](#)).

The idea that the Milky Way stellar halo is not a single, homogeneous structure, but instead composed of two distinct components, was first brought to attention by [Carollo et al. \(2007\)](#). They revealed the co-existence of an inner Halo, characterised by a mild prograde rotation and relatively higher metallicity, and an outer Halo, which displays a net retrograde motion and a overall more metal-poor composition. A significant leap came from the seminal work of [Nissen & Schuster \(2010\)](#), who used high-precision abundances to identify two distinct Halo populations in the Solar Neighbourhood (see right panel of Figure 1.5): a high- α sequence (in blue), plausibly linked to an in-situ component, and a low- α sequence (in orange), which bears the chemical signature of an accreted population. The advent of large spectroscopic surveys, such as APOGEE ([Majewski et al. 2017](#); [Abdurro'uf et al. 2022](#)), GALAH ([Buder et al. 2021](#)), and H3 ([Conroy et al. 2019](#)), have made it possible to conduct in-depth studies in this field, providing detailed elemental abundances and line-of-sight velocity for millions of stars. Building up on the breakthrough finding by [Nissen & Schuster \(2010\)](#), and extending to all the other groups of chemical elements, many recent works have taken advantage of these large spectroscopic datasets, to chemically characterise the more prominent Halo substructures (see Figure 1.6) and, through their distinct abundance patterns, to infer the properties of their progenitor galaxies (e.g. [Helmi et al. 2018](#); [Haywood et al. 2018](#); [Mackereth et al. 2019](#); [Myeong et al. 2019](#); [Das et al. 2020](#); [Monty et al. 2020](#); [Naidu et al. 2020](#); [Aguado et al. 2021](#); [Bonifacio et al. 2021](#); [Feuillet et al. 2021](#); [Horta et al. 2021](#); [Matsuno et al. 2021](#); [Naidu et al. 2021](#); [Limberg et al. 2022](#); [Matsuno et al. 2022a,b](#); [Horta et al. 2023](#); [Zhang et al. 2024](#); [Dodd et al. 2025b](#); [Giribaldi et al. 2025](#); [Skúladóttir et al. 2025](#)). Despite the tremendous progress achieved, it is still impossible to identify chemical spaces where the remnant of accreted dwarfs can be cleanly separated among each other or from the in-situ Halo populations in the very metal-poor regime ($[\text{Fe}/\text{H}] < -1.6$ dex, e.g. [Horta & Schiavon 2025](#)). This limitation is in fact a well-known issue: Galactic chemical evolution (GCEs) models show that in such a metal-poor regime, the chemical tracks of different progenitors tend to strongly overlap, which makes it extremely difficult to isolate the contribution of a single system (e.g. [Kobayashi et al. 2020b](#); [Palla et al. 2020a](#)). The absence of clear, distinctive trends may reflect several factors. First, the number of metal-poor stars that can be securely associate with different Halo substructures is relatively small, which naturally reduces the statistical power of the analysis and highlights the importance of upcoming large-scale spectroscopic surveys. Second, the physical processes that govern the chemical enrichment at such low metallicity (i.e. the evolution and explosion of massive stars) are inherently stochastic, which implies that the intrinsic dispersion in the abundances is larger than any underlying chemical pattern. Finally, by assuming that stochasticity is less dominant, it is possible that the spectral resolution of the available data might not be sufficient to probe the subtle chemical differences expected at these low metallicity.

1.1.3 Ages

Determining accurate ages for ancient stars remains one of the biggest hurdles in stellar astrophysics (Soderblom 2010). The challenge arises from both observations and the models used to interpret them: since age determinations rely on comparing observational properties (e.g. luminosity, effective temperature, metallicity) to predictions from stellar evolution theory, any gaps in our understanding of the stellar physics (or simplifications in the models) inevitably introduce systematic uncertainties in the final results (Lebreton et al. 2014).

Traditionally, ages have been estimated by comparing the position of stars in the colour-magnitude diagram (CMD) with theoretical isochrones (e.g. Jørgensen & Lindegren 2005; Haywood et al. 2016). However, for individual field stars, this approach is fundamentally limited by the accuracy and precision of distance estimates: even the most precise photometry cannot yield reliable ages without an equally precise determination of the distance (or, equivalently, the mass). The advent of *Gaia* has therefore marked a turning point, providing accurate parallaxes that, when combined with spectroscopic metallicity from large surveys (such as APOGEE), have enabled the determination of robust stellar ages. Recent works (e.g. Queiroz et al. 2018; Bonaca et al. 2020; Xiang & Rix 2022) have demonstrated that focusing on well-defined evolutionary phases, such as sub-giant branch stars, and exploiting precise astrometric and spectroscopic information, yields significantly improved age estimates, particularly for the oldest stellar populations. A transformative development is expected to arise thanks to asteroseismology, a technique that probes the stellar interior structure through the detection of tiny, periodic brightness variations caused by internal oscillations, which can lead to a $\sim 10\%$ precision estimate of the age (Miglio et al. 2021; Montalbán et al. 2021).

Alternatively, the age distribution of stellar systems can be inferred simultaneously via CMD-fitting. This technique looks for the combination of synthetic populations of different metallicity and ages that better reproduces the observed CMD, allowing to reconstruct the star formation history (SFH) of the system as a whole. CMD-fitting has been extensively applied to nearby dwarf galaxies (e.g. Hernandez et al. 1999; Gallart et al. 2005; Monelli et al. 2010; Ruiz-Lara et al. 2018), which are close enough for individual stars to be resolved but distant enough that their members can be assumed to be at the same distance. It is only with the arrival of *Gaia* extremely precise parallaxes that this approach has begun to be effectively applied to thousands of stars within the Milky Way outside the Solar Neighbourhood (see Figure 1.7), allowing for the reconstruction of their age-metallicity relations (AMRs) and SFHs with a level of precision never achieved before (Gallart et al. 2019; Ruiz-Lara et al. 2020a, 2022b; Gallart et al. 2024; Dodd et al. 2025a; Fernández-Alvar et al. 2025; González-Koda et al. 2025).

In spite of their small number in comparison to field stars, GCs are special tracers since they sample the earliest epochs of galaxy formation, and, above all, their ages can be measured with great precision if excellent photometry is available (~ 500 Myr, VandenBerg et al. 2013) and chemical composition is known, while comparatively precise ages of distant field stars are still out of our reach. Indeed, unlike dwarf galaxies where ages must be inferred on a star by star basis, GCs consist of nearly coeval and chemically homogeneous stellar populations, allowing to fit their entire CMD to constrain a single and well-defined age. Such precise ages enabled the reconstruction of the AMR of Milky Way GCs, which rapidly became a key diagnostic for identifying whether a given cluster formed within the Galaxy itself or was accreted from an external system (see e.g. Forbes et al. 2004). Indeed, the AMR of Milky Way

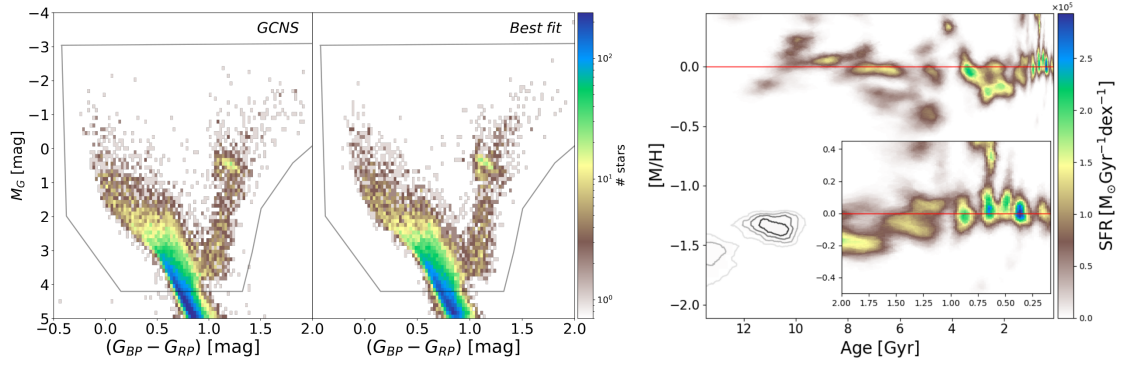


FIGURE 1.7 : Left panel: observed and best-fit CMDs of Galactic disc stars within 100 pc of the Sun, obtained using the BaSTI-IAC stellar evolution library (Hidalgo et al. 2018; Pietrinferni et al. 2021). Right panel: derived age-metallicity distribution of the mass transformed into stars as a function of time and $[M/H]$. Figures adapted from Gallart et al. (2024).

GCs reveals two distinct tracks at $[\text{Fe}/\text{H}] > -1.5$ dex (see Figure 1.8): a population of older and more metal-rich GCs (~ 0.5 dex at fixed age), more likely to be born in a galaxy with a high star formation efficiency, such as the Milky Way in its earliest phases, and another of younger, more metal-poor clusters (Marín-Franch et al. 2009; Dotter et al. 2010; Forbes & Bridges 2010; Leaman et al. 2013; VandenBerg et al. 2013). Leveraging the extremely precise kinematic *Gaia* data, it has been established that the younger sequence in the age-metallicity space is entirely populated by GCs moving on orbits that are consistent with being accreted from smaller galaxies (Kruijssen et al. 2019; Massari et al. 2019; Myeong et al. 2019; Callingham et al. 2022), confirming the dual nature of the Milky Way GC system in this plane already found in the pre-*Gaia* era (see Figure 1.8). Still, as shown by Massari et al. (2019), the level of precision required to fully resolve whether GCs accreted from different progenitors define distinct AMR sequences or not remains just beyond our current capabilities (see Section 1.3.3 for a complete discussion).

1.2 The accretion history of the Milky Way

Building on the discussion about the main tools of Galactic Archaeology, I can now turn to how these techniques have been applied and review the state of the art regarding the assembly history of the Milky Way, proceeding backward in time from the most recent accretion event (Kruijssen et al. 2020, see Figure 1.9).

1.2.1 The ongoing accretion of the Sagittarius dwarf spheroidal galaxy

The Galaxy is currently in the midst of the accretion of a dwarf spheroidal galaxy, Sagittarius (Sgr dSph, Ibata et al. 1994), which stands as one of the most striking examples of a satellite in the final stages of being tidally disrupted. Its ongoing accretion provides a unique real-time laboratory to study a merger event as it unfolds: the system consist of a faint, elongated main body and two extended stellar streams that wraps around the Galaxy along a nearly polar orbit, stretching for tens of kiloparsecs (Majewski et al. 2003; Antoja et al. 2020; Ibata

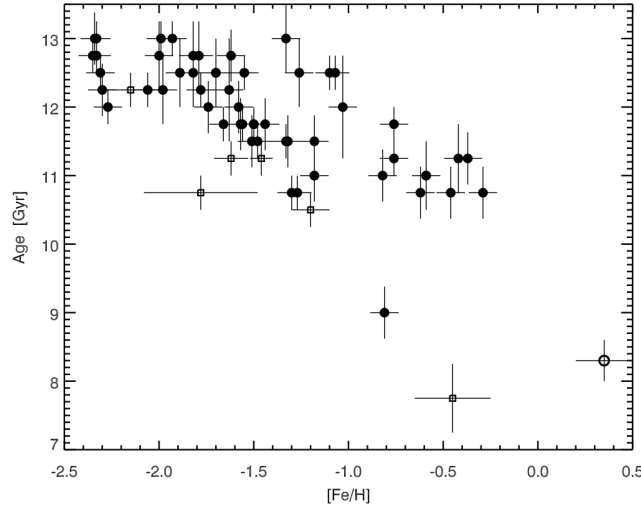


FIGURE 1.8 : Age-metallicity relation for Milky Way GCs obtained from the compilation of ages by [VandenBerg et al. \(2013\)](#). Figure adapted from [Leaman et al. \(2013\)](#).

[et al. 2020](#); [Ramos et al. 2020](#); [Cunningham et al. 2024](#)). Sgr dSph began its gradual infall $\sim 4 - 6$ Gyr ago ([Laporte et al. 2018](#); [Kruijssen et al. 2020](#); [Ruiz-Lara et al. 2020a](#)), making it a relatively recent accretion event in cosmological terms. Over successive close passages, the dwarf has lost stars (as well as $8 - 10$ GCs according to [Massari et al. 2019](#); [Bellazzini et al. 2020](#); [Callingham et al. 2022](#); [Chen & Gnedin 2024](#)) that now trace its orbit, providing a special opportunity to measure the Milky Way gravitational potential and to reconstruct the mass and orbit of the progenitor galaxy (e.g. [Law & Majewski 2010](#); [Niederste-Ostholt et al. 2012](#); [Gibbons et al. 2017](#); [Vasiliev et al. 2021](#)). The progenitor itself is thought to have been a relatively massive satellite ($M_{\star} \sim 10^8 M_{\odot}$, [Peñarrubia et al. 2010](#); [Deason et al. 2019](#)) and its ongoing interaction is believed to have significantly influenced the Milky Way, both by triggering star formation activity ([Laporte et al. 2018](#); [Ruiz-Lara et al. 2020a](#)), and by inducing perturbations in the Galactic disc (e.g. [Gómez et al. 2012](#); [Antoja et al. 2018](#); [Bland-Hawthorn et al. 2019](#); [Laporte et al. 2019](#)).

The metallicity distribution (MDF) of stars in the main body of Sgr dSph has one main peak around $[\text{Fe}/\text{H}] \sim -0.5$ dex, which extends in the more metal-poor regime down to $[\text{Fe}/\text{H}] \sim -2.0$ dex ([Hayes et al. 2020](#); [Minelli et al. 2023](#)). Its chemical patterns differs from those of the Milky Way at $[\text{Fe}/\text{H}] > -1.5$ dex, resembling those of surviving dwarf spheroidal galaxies (e.g. [Tolstoy et al. 2009](#); [Letarte et al. 2010](#); [Van der Swaelmen et al. 2013](#); [Hill et al. 2019](#); [Hasselquist et al. 2021](#); [Horta et al. 2023](#); [Liberatori et al. 2025](#), see Figure 1.5). It also displays a radial metallicity gradient (traced also by its streams), where stars become progressively more metal-poor the farther they are from the central regions (e.g. [Bellazzini et al. 2006](#); [Gibbons et al. 2017](#); [Hayes et al. 2020](#); [Vitali et al. 2022](#)). In stark contrast, there is a central stellar nucleus (hosting the massive cluster M54) that is a complex mix of at least three distinct populations of stars: an ancient (> 10 Gyr) and metal-poor one with $[\text{Fe}/\text{H}] \sim -1.6$ dex, an intermediate one, both in terms of age ($4 - 6$ Gyr) and metallicity ($[\text{Fe}/\text{H}] \sim -0.5$ dex), and a young (< 1 Gyr) population with super-solar metallicity ([Siegel et al. 2007](#); [Bellazzini et al. 2008](#); [Mucciarelli et al. 2017b](#); [Alfaro-Cuello et al. 2019](#)). This may hint that Sgr dSph was initially gas-rich, as star formation continued near its core for

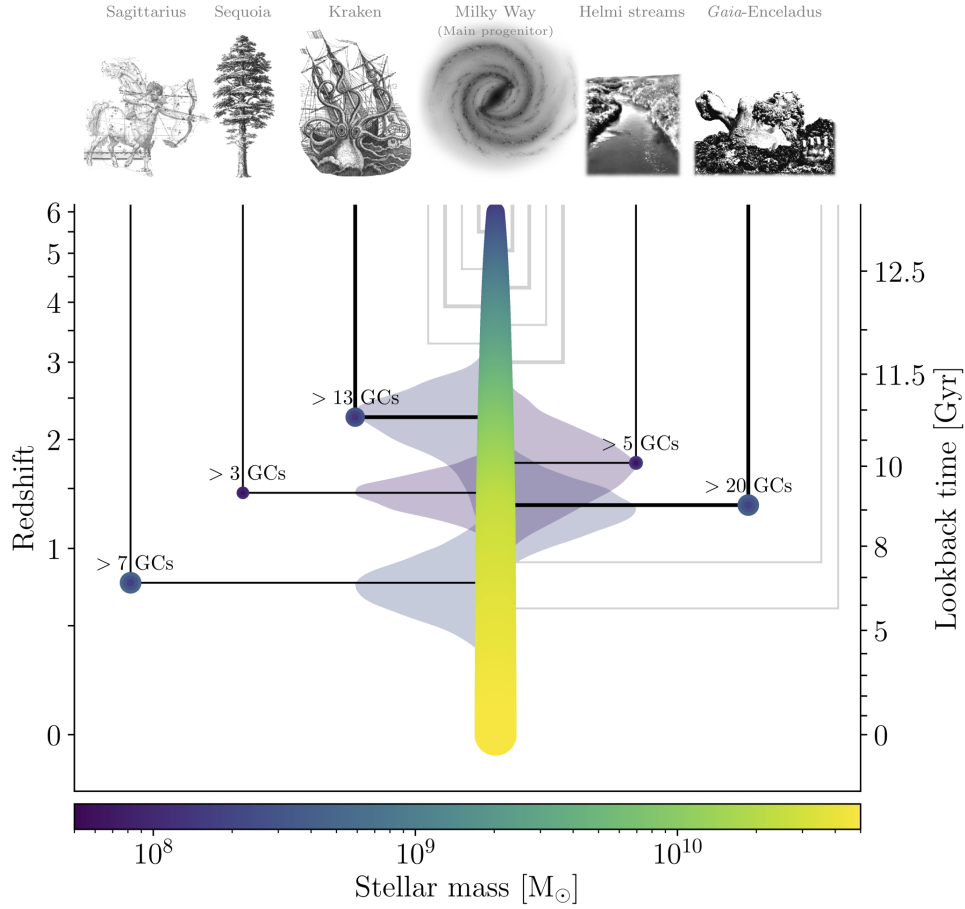


FIGURE 1.9 : Merger tree of the Milky Way, as inferred by [Kruijssen et al. \(2020\)](#). The main progenitor is denoted by the trunk of the tree, coloured by its stellar mass. Only accreted dwarf galaxies hosting a system of GCs are included.

Gyr after its accretion, likely boosted by the repeated pericentric passages around the Milky Way ([Siegel et al. 2007](#)).

1.2.2 Gaia-Sausage-Enceladus: the last major merger

With the advent of the first data release of *Gaia* ([Gaia Collaboration et al. 2016](#)), a population of unexpectedly metal-rich stars ($[\text{Fe}/\text{H}] > -1.0$ dex) was initially identified moving on Halo-like orbits ([Bonaca et al. 2017](#)). By cross-matching SDSS observations with *Gaia* DR1 astrometry, [Belokurov et al. \(2018\)](#) showed that a substantial fraction of Halo stars followed strongly radial orbits. Comparisons with zoom-in cosmological simulations suggested that such orbital anisotropy (which appeared as a ‘sausage’-like kinematic structure, see also [Myeong et al. 2018](#)) could be explained by a major accretion event occurring at redshift $z \sim 1 - 3$. At the time, however, alternative scenarios were still viable to interpret such feature ([Eggen et al. 1962](#)), since the data lacked clear retrograde signatures (due to the low astrometric precision) and did not include chemical abundances. However, early chemical analyses already started to hint at the presence of two distinct α -sequences, suggesting for

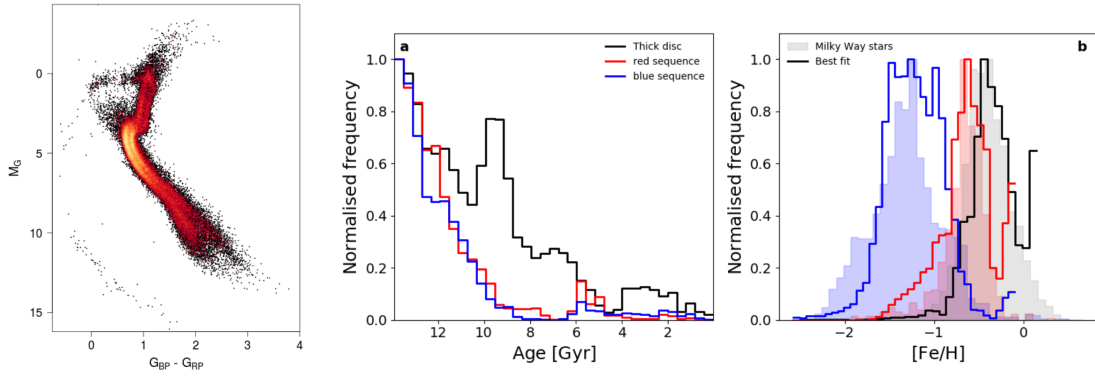


FIGURE 1.10 : Left panel: double sequence in the Halo CMDs as revealed by [Gaia Collaboration et al. \(2018b, left panel\)](#). Right panel: age (a) and metallicity (b) distributions for the two sequences in the Halo and for the Milky Way thick disc, from [Gallart et al. \(2019\)](#).

the coexistence of in-situ and accreted stellar populations in the Halo ([Nissen & Schuster 2010](#); [Hawkins et al. 2015](#); [Fernández-Alvar et al. 2018](#); [Hayes et al. 2018](#)).

The decisive step forward came with *Gaia* DR2 ([Gaia Collaboration et al. 2018a](#)), which allowed the detection of a double sequence in the CMD of Halo stars ([Gaia Collaboration et al. 2018b](#), see left panel of Figure 1.10). This confirmed the existence of two main stellar populations with distinct ages and metallicity in the Halo, consistent with earlier findings ([Carollo et al. 2007](#); [Nissen & Schuster 2010](#); [Bonaca et al. 2017](#)). In particular, the bluer sequence in the CMD was demonstrated to be part of a coherent, large, highly eccentric and slightly retrograde kinematic structure ([Haywood et al. 2018](#); [Koppelman et al. 2018](#)), resembling the remnants of minor mergers observed in simulations ([Villalobos & Helmi 2008](#)). Finally, by selecting stars belonging to this structure, [Helmi et al. \(2018\)](#) discovered that they lay on a well-defined, extended, and α -poor sequence in the $[\alpha/Fe] - [Fe/H]$ plane (see Figure 1.11), putting all the pieces of the puzzle together and demonstrating that they originated in an environment characterised by a less efficient star formation compared to the Milky Way (see e.g. [Fernández-Alvar et al. 2018](#); [Vincenzo et al. 2019](#)). On this basis, they concluded that these stars were accreted from a massive dwarf galaxy, which they named *Gaia-Enceladus*. Taken together, these results established that the local stellar Halo is largely dominated by the remnant of the last major merger experienced by the Milky Way (total mass ratio of 4 : 1), involving an ancient (~ 10 Gyr ago) and relatively massive — from a few $\times 10^8 M_\odot$ ([Helmi et al. 2018](#); [Lane et al. 2023](#)) to some $\times 10^9 M_\odot$ ([Fattahi et al. 2019](#); [Vincenzo et al. 2019](#); [Das et al. 2020](#)) — dwarf galaxy, now commonly referred to as *Gaia-Sausage-Enceladus* (GSE, [Belokurov et al. 2018](#); [Helmi et al. 2018](#)).

When deriving the properties of the progenitor galaxy, it is important to note that the selection of GSE stars has a strong impact on them, as no membership criteria can provide a pure and complete sample of the progenitor galaxy (e.g. [Feuillet et al. 2021](#); [Buder et al. 2022](#); [Lane et al. 2023](#); [Carrillo et al. 2024](#); [Thomas et al. 2025](#)). The metallicity distribution function of GSE peaks from $[Fe/H] \sim -1.5$ to -1.1 dex, with stars as metal-rich as $[Fe/H] \sim -0.5$ dex, depending on the sample selection and the spectroscopic survey ([Naidu et al. 2020](#); [Feuillet et al. 2020](#); [Bonifacio et al. 2021](#); [Bellazzini et al. 2023](#)). It is well-established that GSE stars follow a decreasing trend in $[\alpha/Fe] - [Fe/H]$, with the exact

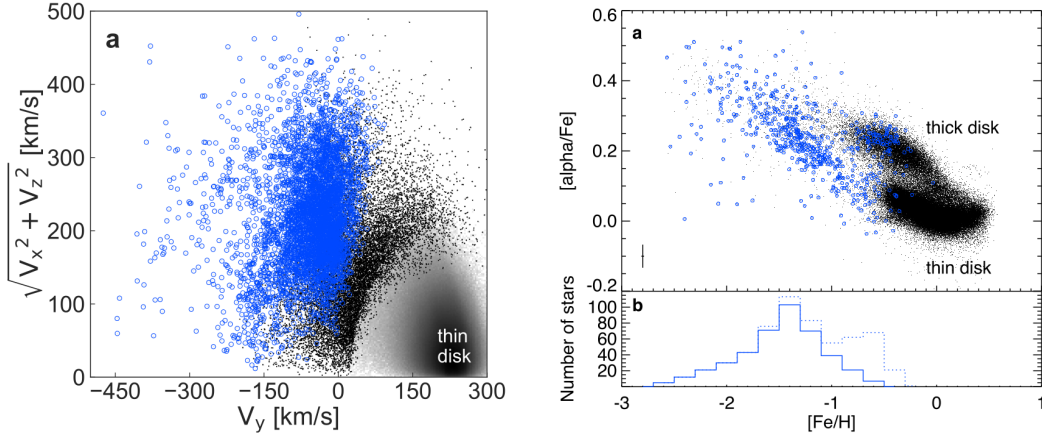


FIGURE 1.11: Left panel: GSE structure in the velocity space, together with disc stars with grey density contours. Right panel: GSE stars and in the $[\alpha/\text{Fe}] - [\text{Fe}/\text{H}]$ from APOGEE compared to the Milky Way disc. Figures adapted from [Helmi et al. \(2018\)](#).

position of the downturn (the so-called ‘ α -knee’) still being a matter of debate, ranging from $[\text{Fe}/\text{H}] \sim -1.5$ dex ([Monty et al. 2020](#); [Matsuno et al. 2022a](#)) to $[\text{Fe}/\text{H}] \sim -1.1$ dex ([Mackereth et al. 2019](#); [Myeong et al. 2019](#); [Horta et al. 2023](#)). Also, GSE stars show the enrichment in the r -process typical of dwarf galaxies ([Aguado et al. 2021](#); [Matsuno et al. 2021](#); [Naidu et al. 2022b](#); [Ou et al. 2024](#)). All these works agree that GSE sustained a more efficient star formation compared to present-day dwarf galaxies (see also [Hasselquist et al. 2021](#)), which was halted after 3 – 4 Gyr due to the stripping of its gas by the Milky Way during the merging process ([Fernández-Alvar et al. 2018](#); [Gallart et al. 2019](#); [Vincenzo et al. 2019](#); [Sanders et al. 2021](#); [González-Koda et al. 2025](#)).

The arrival of GSE had a strong impact on the young Milky Way. There is general consensus that the more metal-rich sequence in the Halo CMD is composed of a population of stars that was populating the pre-existing disc of the Milky Way ([Haywood et al. 2018](#); [Di Matteo et al. 2019](#); [Gallart et al. 2019](#), see right panel of Figure 1.10). The impact with GSE dynamically heated the proto-disc of the Milky Way, causing these stars to move on Halo-like orbits, an event that is generally referred to as the Splash ([Belokurov et al. 2020](#)).

More than 20 GCs were brought in the Milky Way by GSE, which lay in the younger branch of the AMR ([Massari et al. 2019](#); [Myeong et al. 2019](#); [Forbes 2020](#); [Callingham et al. 2022](#); [Chen & Gnedin 2024](#)). Preliminary evidence for distinct chemical composition with respect to in-situ clusters has been observed ([Horta et al. 2020](#)). However, it is still unclear whether these GCs formed in GSE during its evolution in isolation, or their formation was triggered during the merging process ([Valenzuela et al. 2024](#)).

1.2.3 The Sequoia dwarf: a complex retrograde substructure

The first evidence of the presence of the remnant of an accreted dwarf galaxy in the low-eccentricity retrograde Halo came with the identification of a clump of stars moving on highly retrograde orbits, with large orbital energy (green points in Figure 1.2), and forming an arc-like structure in the Toomre diagram, now dubbed Sequoia ([Myeong et al. 2018](#); [Kop-](#)

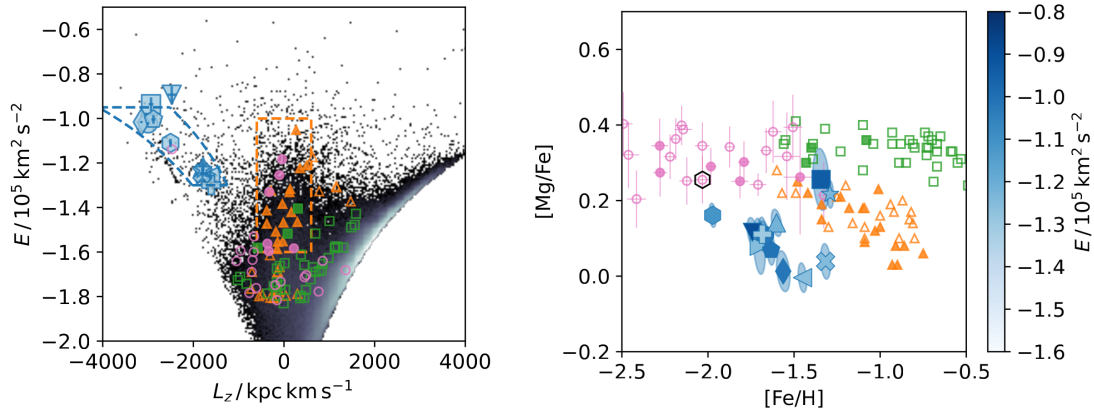


FIGURE 1.12 : Left panel: distribution of Sequoia stars (blue symbols) in the $E - L_z$ space (note the wide selection range). Right panel: $[\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]$ for Sequoia stars compared to GSE (orange symbols) and the Milky Way disc (green symbols). Figures adapted from [Matsuno et al. \(2022a\)](#).

[pelman et al. 2018](#); [Matsuno et al. 2019](#); [Myeong et al. 2019](#)). Sequoia has been proposed to be the remnant of a small dwarf galaxy ($M_\star \sim 10^7 M_\odot$) based on its chemo-dynamical properties, accreted 9 – 11 Gyr ago ([Koppelman et al. 2019b](#); [Myeong et al. 2019](#); [Kruijssen et al. 2020](#)). The chemical composition of Sequoia remains a subject of ongoing debate, as different studies have yielded conflicting results regarding its abundance of α -elements compared to the GSE substructure, reporting either enhancement ([Mackereth et al. 2019](#); [Myeong et al. 2019](#)) or depletion ([Monty et al. 2020](#); [Matsuno et al. 2022a](#)).

However, the actual complexity of this substructure far exceeded initial expectations. A different scenario has been proposed to explain the Sequoia overdensity, possibly making it tightly related to the GSE accretion event. In fact, it has been shown that a GSE-like progenitor, depending on its orbital configuration and morphology, is able to display its debris on orbits that reproduce the same arc-like feature associated with Sequoia ([Koppelman et al. 2020](#); [Amarante et al. 2022](#); [Belokurov et al. 2023](#)). Moreover, [Naidu et al. \(2020\)](#) found a multiple-peaked metallicity distribution for Sequoia, and claimed that two additional sub-components, namely Arjuna and I’toi, occupy the same region in the IoM space (see also [Bellazzini et al. 2023](#)).

To further complicate things out, with the advent of the more precise kinematic measurements of the *Gaia* EDR3 ([Gaia Collaboration et al. 2021](#)), [Lövdal et al. \(2022\)](#) and [Ruiz-Lara et al. \(2022a\)](#) discovered three disconnected clumps with different MDFs (not related to the previous ones) that might trace different progenitors in the region of the IoM space previously associated to Sequoia. Among these newly identified clusters, the one that was initially believed to be the extreme retrograde tail of Sequoia, L-RL64, has been subsequently and independently rediscovered in the action space by [Oria et al. \(2022\)](#), who named it Antaeus. The peculiar kinematics of this clump (which I henceforth refer to as Antaeus) suggest for an independent origin for this substructure with respect to Sequoia. In the end, [Dodd et al. \(2023\)](#) confirmed the highly structured nature of the high-energy retrograde Halo, spotting two new small clumps near Sequoia, namely ED-2 and ED-3, which are extremely tight in the IoM and velocity spaces (see Figure 1.2). To date, however, no detailed chemical abundances are available for Antaeus, ED-2 and ED-3. The literature so far has largely treated these stars

as part of Sequoia (by selecting across a broad retrograde region in IoM space), without accounting for the presence of several distinct substructures (see Figure 1.12). Hence, the nature of their progenitor and their role in the assembly of the Milky Way are still unknown.

1.2.4 The Helmi Streams

First reported by Helmi et al. (1999), the Streams manifest as a two kinematic substructures among Halo stars with anomalously high (both positive and negative) velocity along the z -component in the Solar Neighbourhood (see left panel of Figure 1.13). The progenitor system is thought to be a dwarf galaxy with an estimated stellar mass of $M_{\star} \sim 10^8 M_{\odot}$ (Kepley et al. 2007; Koppelman et al. 2019a). The time of its accretion is still a matter of debate. First estimates based on dynamical N -body modelling revealed that the progenitor of the Helmi Streams merged with the Milky Way approximately 5 – 8 Gyr ago (Kepley et al. 2007; Koppelman et al. 2019a). However, the late arrival of such a relatively low-mass object in the inner Halo is somehow surprising (Helmi 2020). Given that its stars are not trapped by resonances induced by the Milky Way bar that would delay their dispersal (Dillamore & Sanders 2025; Woudenberg & Helmi 2025), a plausible explanation is that this dwarf galaxy may have been accreted as part of a larger group of satellites (Sales et al. 2017; Callingham & Helmi 2025). Hints on properties of the progenitor also comes from its association with 7 – 10 GCs in the Milky Way (Massari et al. 2019; Callingham et al. 2022; Chen & Gnedin 2024), consistent with expectations from the GC specific frequency relation (Zaritsky et al. 2016). Thus, Kruijssen et al. (2020) trained an artificial neural network on cosmological simulations of co-formation of GCs and their host galaxies, to infer that the progenitor of the Helmi Streams should have been accreted ~ 1 Gyr prior to GSE, according to orbital properties, ages and metallicity of its GCs.

The progenitor itself experienced a prolonged yet relatively quiescent star formation activity, until it completely quenched ~ 8 Gyr ago (Naidu et al. 2022a; Ruiz-Lara et al. 2022b). The subsequent chemical enrichment reflects an environment where star formation was overall inefficient, resulting in typically metal-poor stars with $[\text{Fe}/\text{H}] \leq -1.0$ dex, as well as in low and constant $[\alpha/\text{Fe}]$ values, as confirmed by spectroscopic analyses (Matsuno et al. 2022b; Horta et al. 2023, see right panel of Figure 1.13). Also, the Helmi Streams are depleted in Na, Zn, and Y at $[\text{Fe}/\text{H}] \leq -1.5$ dex compared to more massive Halo substructures such as GSE, a feature commonly seen among present-day dwarf galaxies (Frebel & Norris 2015).

1.2.5 The very early accretion of the small satellite Thamnos

As we proceed back in time, reconstructing what happened in the earliest phases of the life of the Milky Way, more than 11 Gyr ago, gets significantly more challenging. One of the first actor playing in this story is Thamnos, identified as a small clump in the IoM space using the HDBSCAN clustering algorithm on the *Gaia* DR2 RVS sample, complemented with line-of-sight velocities and $[\text{Fe}/\text{H}]$ from large spectroscopic surveys (Koppelman et al. 2019b, see left panel of Figure 1.14). Its stars move on low-inclination and mildly eccentric retrograde orbits. Thamnos is a less populated substructure compared to GSE, with generally more bounded and retrograde orbits. Given its limited range in orbital energy and unusual position in the IoM spaces, Thamnos is believed to possibly be the leftover of a very early merger with a low-mass systems ($M_{\star} < 5 \times 10^6 M_{\odot}$, Koppelman et al. 2019b), although, as shown in Figure 1.14,

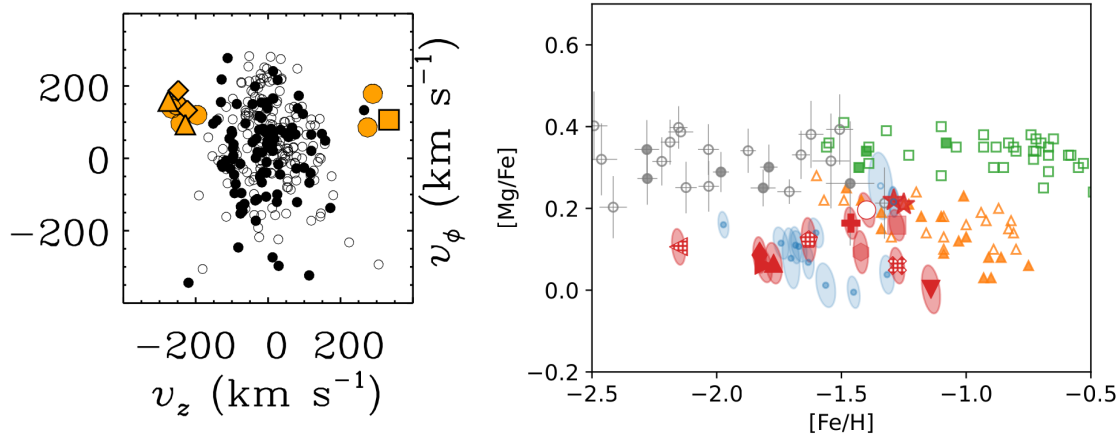


FIGURE 1.13: Left panel: discovery of the Helmi Streams stars (orange symbols) in the velocity spaces. Figure from [Helmi et al. \(1999\)](#). Right panel: $[Mg/Fe] - [Fe/H]$ for Helmi stream stars compared to GSE (orange symbols), Sequoia (blue symbols), and the Milky Way disc (green symbols). Figure from [Matsuno et al. \(2022b\)](#).

it remains uncertain whether the stars linked to this structure originate from a single merger or two separate ones, with the Thamnos 1 sub-population being on average significantly more metal poor ([Koppelman et al. 2019b](#); [Ruiz-Lara et al. 2022a](#); [Bellazzini et al. 2023](#)).

The median metallicity of Thamnos ranges from -1.4 to -1.2 dex depending on the dynamical selection of its stars, which is slightly more metal-rich than other retrograde substructures, such as Sequoia and Antaeus, hinting at some possible contamination by stars with different origin ([Lövdal et al. 2022](#); [Ruiz-Lara et al. 2022a](#); [Bellazzini et al. 2023](#); [Dodd et al. 2023, 2025a](#)). Indeed, the very limited (and inhomogeneous) chemical information available for the Thamnos substructure seems to suggest a significant amount of contamination from the in-situ Milky Way and possibly also GSE (up to 50%), as part of its stars show high $[\alpha/Fe]$ ratios ([Monty et al. 2020](#); [Dodd et al. 2023](#); [Horta et al. 2023](#); [Zhang et al. 2024](#); [Mori et al. 2025](#), see right panel of Figure 1.14). This hypothesis has been further strengthened by the application of substructures identification to cosmological hydrodynamical simulations, which show that the IoM region occupied by Thamnos can be largely populated by in-situ stars and/or by stars from different progenitors ([Thomas et al. 2025](#)). However, [Dodd et al. \(2025a\)](#) find via CMD-fitting technique ([Gallart et al. 2024](#)) that the age-metallicity distribution at low metallicity ($[Fe/H] < -1.5$ dex) for stars dynamically linked to the Thamnos substructure is statistically different to that of these possible contaminants, consistent with the presence of a very old stellar population (half of its stellar mass was already built ~ 12.3 Gyr ago). Still, the nature of this substructure is far from being assessed.

1.2.6 Kraken, Heracles, and the proto-Galaxy: a (blurry) picture of the Milky Way earliest epoch

At very early times ($> 11 - 12$ Gyr ago), the mass of the young Galaxy was still modest and comparable to that of surrounding (and/or accreting) systems. This condition, combined with extremely short dynamical and chemical evolutionary timescales, makes it difficult to-

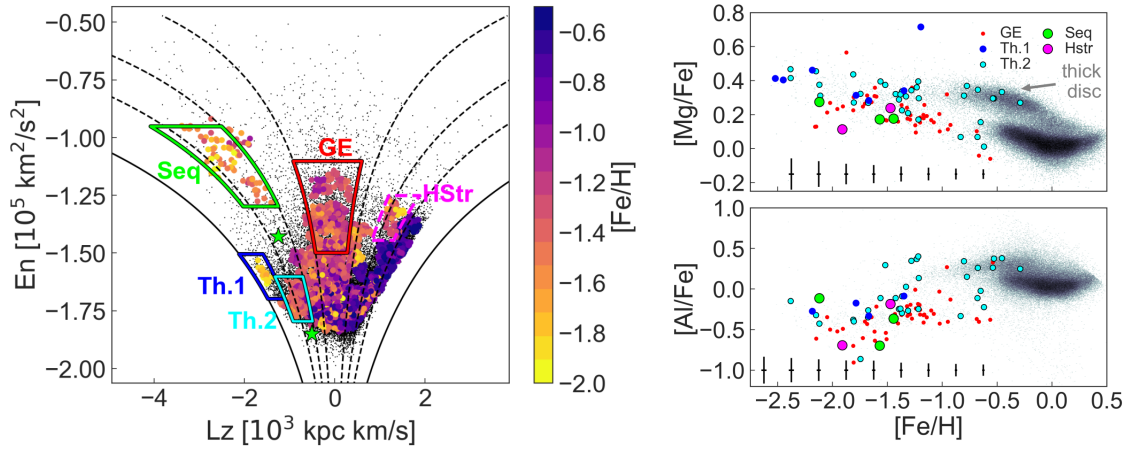


FIGURE 1.14 : Left panel: position of Thamnos (blue and cyan contours) in the IoM space compared to that of other Halo substructures. Note that Thamnos might be divided into two clumps based on the metallicity. Right panel: $[\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]$ (top) and $[\text{Al}/\text{Fe}] - [\text{Fe}/\text{H}]$ (bottom) for Halo substructures obtained from APOGEE. Figures from [Koppelman et al. \(2019b\)](#).

day to disentangle the stars formed within the main progenitor of the Milky Way from those originating in early accreted galaxies ([Santistevan et al. 2020](#); [Orkney et al. 2022](#); [Horta et al. 2024a](#)). Given the extreme complexity in untangling these two populations, it is now common to collectively describe the building-blocks of the early Milky Way as the ‘proto-Galaxy’ ([Conroy et al. 2022](#); [Rix et al. 2024](#); [Horta & Schiavon 2025](#)).

The current view is that the proto-Galaxy is represented by a dynamically hot, chemically-unevolved stellar population, whose more tightly bound component is concentrated in the inner 3 kpc of the present-day Galaxy ([Horta et al. 2021](#); [Belokurov & Kravtsov 2022](#); [Rix et al. 2022](#); [Horta & Schiavon 2025](#)). This population most likely represents a mixture of stars born in-situ and from early accreted systems, even though some works interpret it as purely composed of in-situ stars (e.g. [Belokurov & Kravtsov 2022](#)). On the one hand, the in-situ component, often referred to as Aurora, is a metal-poor ($[\text{Fe}/\text{H}] \leq -1.3$ dex), turbulent stellar population with low overall angular momentum and net prograde rotation, born before the settling of the Milky Way proto-disc ([Belokurov & Kravtsov 2022](#), see upper panel of Figure 1.15). On the other hand, evidence for an early accretion event buried in the inner Halo emerged from the identification of a group of GCs at low orbital energy (the ‘low-energy’ group, [Massari et al. 2019](#)), concentrated within 6 kpc from the Galactic centre. This group was later associated with the Kraken merger, proposed from the excess of GCs of unknown origin along the young branch of the Milky Way GC AMR ([Kruijssen et al. 2019, 2020](#)), though its nature has been questioned since then (see e.g. [Belokurov & Kravtsov 2024](#); [Chen & Gnedin 2024](#)). Searches for stellar debris linked to this episode of accretion revealed the existence of the so-called Heracles population ([Horta et al. 2021](#), see lower panel of Figure 1.15), which is embedded in the inner Halo and shares similar orbital signatures with the ‘low-energy’ group. Heracles has been identified based on its chemical properties, specifically its location in the $[\text{Mg}/\text{Mn}] - [\text{Al}/\text{Fe}]$ plane ([Hawkins et al. 2015](#); [Das et al. 2020](#)). Yet, the separation of accreted stars from in-situ stars within the Heracles population is challenging in the metal-poor regime, especially at $[\text{Fe}/\text{H}] \leq -1.6$ dex ([Vasini](#)

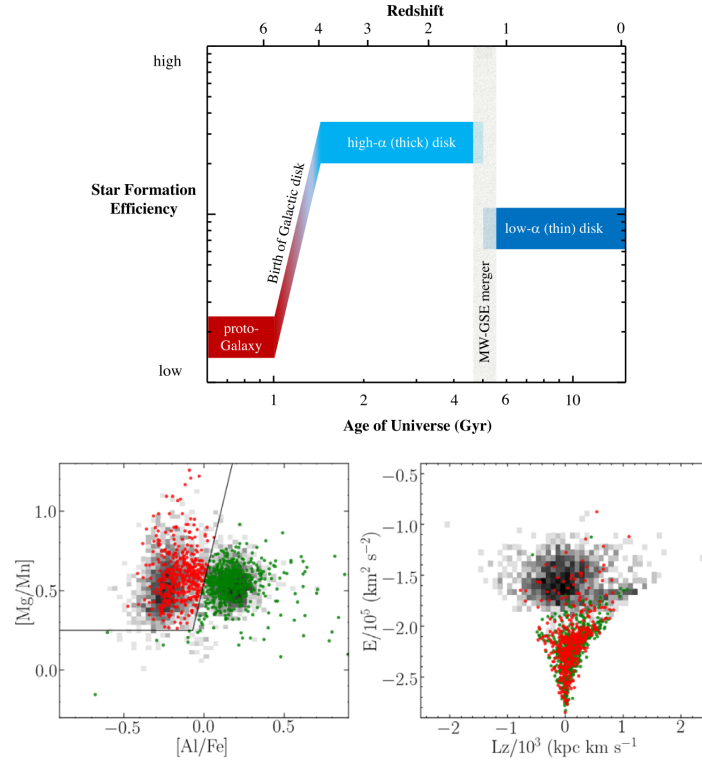


FIGURE 1.15 : Top panel: cartoon overview of the Galactic star formation efficiency from the earliest times to the arrival of GSE. Figure from [Conroy et al. \(2022\)](#). Bottom panel: separation between chemically evolved (green) and unevolved stars (red) in the inner Galaxy (within 4 kpc from the centre) using the the $[\text{Mg}/\text{Mn}] - [\text{Al}/\text{Fe}]$ plane. Note that their distribution is totally overlapping in the IoM space. Figure from [Horta et al. \(2021\)](#).

[et al. 2024](#); [Horta & Schiavon 2025](#)). This is confirmed by cosmological simulations, too, that predict that such mergers are likely to happen in the early histories of Milky Way-like galaxies ([Horta et al. 2024a](#); [Wempe et al. 2024](#); [Callingham & Helmi 2025](#)), when stars did not have the time to chemically evolve enough to separate based on their formation environment. The estimated Kraken/Heracles stellar mass ($\sim 7 \times 10^8 M_{\odot}$), together with its very early accretion, posit it as the most significant merger experienced by our Galaxy ([Horta et al. 2024a](#); [Horta & Schiavon 2025](#)). However, such a claim suffers from the fact that any current mass estimate could be biased by the inclusion of in-situ metal-poor stars in the Heracles sample, as well as by the fact that Heracles is likely the sum of a number of merging event. A better resolution of the intricate sequence of mergers in the early history of the Galaxy is required to properly characterise them.

This early chaotic period of the Milky Way lifetime likely concluded with a rapid ‘spin-up’ transition phase, occurring when the Galaxy reached a metallicity of $[\text{Fe}/\text{H}] \sim -1.3$ dex, which marked the onset of the formation of the proto-disc ([Belokurov & Kravtsov 2022](#); [Conroy et al. 2022](#), see top panel of Figure 1.15).

1.3 The contribution of this Thesis

Given the current open questions on the Milky Way assembly, specifically about the identification and characterisation of the individual merging events that shaped its evolution, *in this Thesis I aim to demonstrate how high-resolution spectroscopy, combined with chronological and dynamical information, can provide the crucial ingredient to disentangle the complex formation history of the Galaxy.*

A central aspect of this project is the establishment of a fully homogeneous analytical framework, for both stars and globular clusters, designed to overcome the inconsistencies and systematics that arise when comparing results obtained through heterogeneous methodologies. Such a framework is essential for uncovering and characterizing subtle chemical signatures within Halo substructures that might be otherwise obscured by such systematics. By applying this methodology to substructures for which abundance data are currently incomplete or entirely missing, this Thesis aims to constrain the properties of their progenitors, such as their star formation efficiency, mass, and chemical evolution pathways, and thereby to reconstruct their role in the broader context of the Milky Way hierarchical build-up.

1.3.1 The *A Walk on the Retrograde Side* project

Chemical tagging offers a powerful way to trace the origin of stellar substructures, helping to separate between accreted galaxies and in-situ formation, and/or to infer the properties of the (now dissolved) progenitor satellites (see Section 1.1.2). Yet, the knowledge we gained from this field is far from complete. In fact, most current efforts focus on the chemical analysis of the most prominent components, such as GSE (Helmi et al. 2018; Aguado et al. 2021; Bonifacio et al. 2021; Hasselquist et al. 2021; Matsuno et al. 2021; Limberg et al. 2022), while other interesting regions of the IoM space remain only sparsely explored. For instance, the highly retrograde Halo, expected to contain a large fraction of accreted stars (Sante et al. 2024), hosts several identified substructures (Dodd et al. 2023) that still lack a thorough chemical characterization (Matsuno et al. 2022a). Also, the merging and comparison between chemical abundances from different sources has been shown to be somehow problematic due to the lack of homogeneity in the chemical analyses (see, e.g., Helmi 2020, for a discussion). Indeed, software and tools used to derive the chemical abundances, methods for estimating the atmospheric parameters (i.e. effective temperature, surface gravity and microturbulent velocity), linelists, model atmospheres, different atomic data and solar reference abundances, non-local thermal equilibrium (NLTE) corrections, spectra obtained with different instruments, signal-to-noise ratio (S/N) and spectral resolution, all introduce systematics in the absolute values of chemical abundances that make the comparison of the results not trivial.

To move past these limitations, I will present in Chapters 2 and 3 the main outcomes of a small spectroscopic survey aimed at delivering detailed and homogeneous chemical tagging of stars in the retrograde Halo with accurate distance and kinematics from *Gaia* DR3, based on the precise measurements of the abundances of several elements (e.g., Fe, Na, Mg, Al, Ca, Sc, Ti, Mn, Ni, Cu, Zn, Y, Ba, La, Eu). The *A Walk on the Retrograde Side* (WRS) project (Ceccarelli et al. 2024a, 2025a) is aimed at obtaining chemical abundances for ~ 650 stars, using high-resolution optical spectrographs mounted at 8-m telescopes (UVES@VLT from the South, and PEPSI@LBT from the North). Spectroscopic observations of relatively bright stars ($G \leq$

15.0) can be an excellent use of nights with sub-optimal seeing and lunar illumination at large telescopes. This is the niche that has been used for WRS observations.

The multi-dimensional dataset I am constructing will provide deep insight on the origin of each target star, by looking at similarities in the orbits and abundance patterns along with those of known relics of merging events in a completely homogeneous fashion. The approach I propose is complementary to that of large-scale spectroscopic surveys such as H3 (e.g. [Naidu et al. 2020](#)) and APOGEE (e.g. [Horta et al. 2023](#)). Indeed, the WRS project is highly focused, targeting only retrograde Halo stars in the Solar Neighbourhood ($D \leq 3.0$ kpc), while large spectroscopic surveys observe stars of any Galactic component (mainly the disc) and only sparsely sample the high-energy retrograde Halo. By adding extremely precise and accurate line-of-sight velocity measurements obtained from high-resolution spectra, WRS will ensure the most reliable determination of orbital parameters for the sample of stars. Finally, the stellar spectra obtained for WRS have higher spectral resolution ($R \sim 40,000$) than those from large spectroscopic surveys. Such high spectral resolution facilitates the precise determination of chemical abundances and offers finer insights into abundance patterns of different substructures.

1.3.2 Chemical tagging of Milky Way globular clusters

Studies of the chemical abundances of GCs have revealed that certain chemical species, such as the α -elements, Cu, and Zn, can display measurable differences between clusters belonging to the Milky Way and those associated with present-day dwarf galaxies, such as the LMC (e.g. [Mucciarelli et al. 2021a](#)). These variations suggest that chemical tagging can, at least in principle, be used to disentangle clusters of external origin from those formed in-situ. Nevertheless, when focusing only on populations of GCs dynamically associated to different progenitors, the observed chemical differences are subtle. This behaviour is likely a consequence of the fact that GC formation might not necessarily follow the same pathways as standard star formation ([Kruijssen et al. 2015](#)). As a result, the gas from which GCs originate may undergo chemical enrichment at a faster rate than that forming field stars, thereby lowering the observable chemical contrasts among clusters born in different environments and complicating the task of interpreting the results. Nonetheless, several works found that the positions of both in-situ and accreted GCs in some chemical spaces align with those of their field-star counterparts ([Recio-Blanco 2018](#); [Horta et al. 2020](#); [Minelli et al. 2021](#); [Belokurov & Kravtsov 2024](#); [Monty et al. 2024](#); [Lin et al. 2025](#)). Still, none of these works were able to effectively identify different behaviours from GCs that were brought in by separate progenitors, possibly because of the higher precision and/or spectral resolution needed. Also, GCs associated with the same progenitor show distinctions in their chemical compositions, which could be interpreted either as stemming from chemical inhomogeneities in the progenitor itself or as a consequence of internal chemical evolution within the GCs ([Monty et al. 2023a,b](#)). In light of all the mentioned complexities, which underline, once again, the challenges associated with interpreting results when comparing diverse studies, it becomes evident that maintaining homogeneity is imperative in chemical analyses aimed at verifying the origin of GCs.

In Chapter 4, I will select a representative sample of six GCs, both in-situ and accreted, that have been consistently associated with different progenitors (based on chronological

and dynamical information) according to all *Gaia*-based investigations (Massari et al. 2019; Forbes 2020; Callingham et al. 2022; Chen & Gnedin 2024). I will derive high-precision abundances through a fully homogeneous analysis to explore whether precise chemical tagging can effectively discriminate between GCs formed within the Milky Way and those accreted from external systems (Ceccarelli et al. 2024b). These GCs lie in the metallicity range ($-1.3 \leq [\text{Fe}/\text{H}] \leq -1.0$ dex) best suited for chemical tagging studies, where abundance trends of in-situ and accreted field stars start to significantly part ways (Nissen & Schuster 2010; Helmi et al. 2018; Matsuno et al. 2022a). Thus, this approach also enables determination of whether or not the progenitor galaxy and the associated GC candidates are chemically compatible. For this to be effective, I require a combination of high precision in abundance derivations, which can only be achieved using high-quality data, and homogeneity in the detailed analysis. This is why I reanalysed archival data for these six clusters, allowing the comparison with each other with the utmost precision.

If successful, this methodology will then be applied to GCs with uncertain origins to test whether their detailed chemistry can resolve existing chrono-dynamical ambiguities regarding their association and finally settle the long-standing question about their true origin.

1.3.3 The Cluster Ages to Reconstruct the Milky Way Assembly project

Another crucial information that can help to unravel the Milky Way assembly history, particularly when chemo-dynamical properties are not enough (e.g., in the metal-poor regime) is age. As discussed in Section 1.1.3, among the tracers of the Milky Way assembly history, those for which age can be measured in the most precise way are GCs. Unfortunately, precise and homogeneous GC age measurements are limited to relatively small samples. Different age indicators, photometric catalogues, assumptions on distance and reddening (absolute and differential), and theoretical models are examples of the many sources of systematic uncertainties that affect different compilations of GC ages. By comparing the results from Forbes & Bridges (2010) and VandenBerg et al. (2013), Massari et al. (2019) demonstrated that these systematic errors can add up to differences of 2 Gyr or more, and that properly taking them into account and correcting for them is not trivial, as they might depend on the GC age itself as well as on the GC metallicity.

The objective of the *Cluster Ages to Reconstruct the Milky Way Assembly* (CARMA) project (Massari et al. 2023) is to overcome this limitation by building up the first complete and homogeneous catalogue of Milky Way GC ages. The strength of CARMA relies on the use of homogeneous photometry, theoretical isochrones, and statistical methods, which will allow to define a systematic uncertainty-free chronological scale for the complete sample of Milky Way GCs. In combination with the dynamical and chemical properties of the GCs, this will enable a complete characterisation of the accreted and in-situ population of Milky Way GCs by solving the cases for which the origin remains ambiguous (see e.g., Minelli et al. 2021; Carretta & Bragaglia 2022). At the same time, this approach will allow to characterise the progenitors of the past merger events in terms of accretion time thanks to analysis of their AMRs, and from analysis of the CMDs of the progenitor systems through CMD-fitting (e.g., Gallart et al. 2019; Ruiz-Lara et al. 2022b; Gallart et al. 2024; Dodd et al. 2025a; González-Koda et al. 2025), whenever possible. The method employed to determine the age of each GC, which is a refined and updated version of the isochrone-fitting code from Saracino et al.

(2019), is presented in details in Section 5.2.

In Chapter 5 I will extend the application of detailed chemical tagging to NGC 288, a peculiar GC whose origin remains debated (Ceccarelli et al. 2025b), building up on the results presented in Chapter 4. On the one hand, analyses of its orbital properties have consistently led to an association with the GSE dwarf (Massari et al. 2019; Callingham et al. 2022; Chen & Gnedin 2024). On the other hand, recent findings from the CARMA project (Aguado-Agelet et al. 2025, see Section 5.6.2) revealed that NGC 288 appears to be about 2 Gyr older than other GSE clusters of comparable metallicity, challenging the hypothesis of a common origin. This makes NGC 288 an ideal test case for assessing whether chemical tagging can provide the decisive evidence needed to clarify its past.

During my PhD project, I significantly contributed to other works of the CARMA collaboration (Massari et al. 2023; Aguado-Agelet et al. 2025; Niederhofer et al. 2025; Massari et al. 2026). These will be briefly described at the end of the CARMA-related Chapter 5.

2 | Tidying up the retrograde Halo with high-resolution spectroscopy

*Based on the published paper by [Ceccarelli et al. \(2024a\)](#), *A&A*, 684, A37*

In this Chapter, I show how the chemical composition of *field stars* in the galactic Halo can be used as a pivotal tool for Galactic Archaeology to get clearer insights on the nature of some poorly explored stellar Halo substructures. To do so, I introduce the *A Walk on the Retrograde Side* (WRS) project (see Section 1.3.1 for an overview of the main goals of the survey) by describing the sample selection process, and presenting the results of the analysis of a first batch of 186 stars. Briefly, I conduct a high-precision and homogeneous abundance analysis on stars in the retrograde halo (RH) of the Milky Way (MW) that are associated with different dynamical substructures according to [Dodd et al. \(2023\)](#), and compare the results obtained for these substructures with the aim of understanding whether they are all independently accreted components or whether some have originated from the same progenitor galaxy. In Section 2.1 I describe the selection criteria used to identify RH stars and I present the high-resolution spectroscopic dataset. In Section 2.2 I present the dynamical properties of the sample of stars, while in Section 2.3 I provide a detailed description of the criteria that were employed to define each individual substructure in the RH. The chemical analysis is described in Section 2.4, with a comparison with literature results in Section 2.5. In Section 2.6 I examine the Halo substructures in different chemical planes, focusing in particular on light elements (Section 2.6.2), α -elements (Section 2.6.3), iron-peak elements (Section 2.6.4), and neutron capture elements (Section 2.6.5), and in Section 2.7 I summarize and discuss the main results.

2.1 Selection of the sample and observations

At the epoch when the WRS project was conceived, I had to face the problem of selecting retrograde stars from catalogues, like the *Gaia* DR2 (Gaia Collaboration et al. 2018a) and EDR3 (Gaia Collaboration et al. 2021) databases¹, where most of the stars were lacking a line-of-sight velocity (V_{los}) measurement in the range of apparent magnitudes of interest ($G < 14.0$, for the time being). I tackled this issue by realizing that a selection in tangential velocity $V_T = \sqrt{V_{\text{R.A.}}^2 + V_{\text{Dec.}}^2}$, that is the linear velocity in the plane of the sky, can be used to effectively select very likely retrograde stars.

This technique is illustrated in Figure 2.1, where the well-measured *Gaia* EDR3 stars within 1.0 kpc from the Sun with the complete 6D phase-space information available are plotted in a Toomre diagram that is colour-coded according to V_T ². It is quite clear that in the vicinity of the Sun, high V_T values are displayed only by stars on retrograde orbits or on slightly prograde orbits but high $\sqrt{V_R^2 + V_Z^2}$, the latter being equally interesting, as they are typically associated with GSE. Hence, I adopted $V_T > 400 \text{ km s}^{-1}$ as a criterion to select likely retrograde stars. The criterion proved to be very effective as only 16 out of the 186 stars considered here and selected in this way are not retrograde, all of them having $L_z < 800 \text{ kpc km s}^{-1}$, while 123 of them have $L_z \leq -500 \text{ kpc km s}^{-1}$. In future observational campaigns, I plan to select retrograde targets directly in V_Φ among stars having V_{los} measurements in the *Gaia* DR3 catalogue or catalogues from future *Gaia* data releases. This will allow to sample also the mildly retrograde stars at relatively low total velocity ($-100 \text{ km s}^{-1} \leq V_\Phi < 0.0 \text{ km s}^{-1}$ and $\sqrt{V_R^2 + V_Z^2} \leq 200 \text{ km s}^{-1}$) that are now excluded by the selection in V_T , as well as to target specific substructures.

The additional selection criteria I adopted were intended to select well-measured stars in the Solar Neighbourhood. In particular, I selected the targets among $V_T > 400 \text{ km s}^{-1}$ stars having $G < 14.0$. This suitable magnitude range was selected in order to get high signal-to-noise ratio (S/N), high-resolution spectra with 8 m class telescopes with relatively short exposures (typically $\leq 3000 \text{ s}$). Then, I imposed an error on the parallax lower than 10%: this implies small errors in the distance and, typically, in the proper motion. I selected stars with a distance from the Sun of $D \leq 1.0 \text{ kpc}$. I adopted the following criteria in order to ensure that the *Gaia* astrometry and photometry of the target stars are of the highest quality: $\text{RUWE} \leq 1.3$ (Gaia Collaboration et al. 2021) and $C^* < 3\sigma$ (Riello et al. 2021). The first criterion is also effective in excluding astrometric binaries (see Andrew et al. 2022, and references therein). Finally, by inspecting the CMD, I excluded by hand a few dwarf stars that may be unresolved binaries, which are located slightly above the main sequence.

The most relevant outcome of the selections above, complemented by uncertainties in the V_{los} measured from high-resolution spectra lower than 0.9 km s^{-1} , is that the typical uncertainty on the IoM is just a few percent (see Section 2.2), hence, the noise in the phase-space is minimal. Basic information on target stars is listed in Table 2.1.

¹That have the information on the V_{los} for $\sim 7.2 \times 10^6$ stars with $G \leq 13.0$, while the most recent release, DR3 (Gaia Collaboration et al. 2023), includes V_{los} for $\sim 33.8 \times 10^6$ stars down to $G \leq 14.0$

²The adopted solar motion is from Schönrich et al. (2010), while the distance between the Sun and the Galactic centre and the rotational velocity of the Sun are the same used in McMillan (2017).

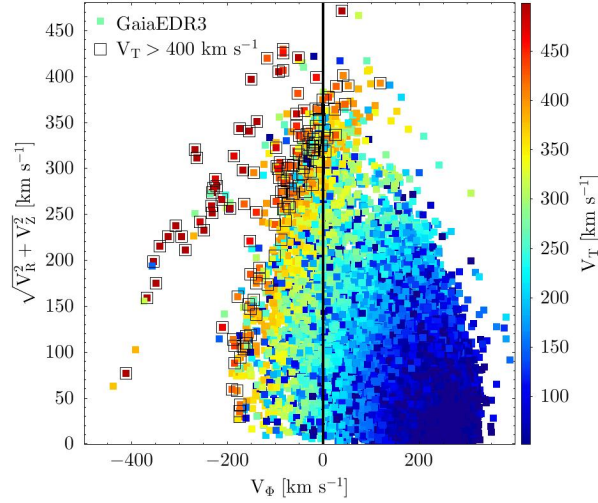


FIGURE 2.1 : Toomre diagram of the ~ 2.4 million stars within 1.0 kpc from the Sun, having V_{los} values measured in *Gaia* EDR3 and passing all the quality criteria I adopted for the WRS sample. Stars are colour-coded according to their tangential velocity and stars with $V_T > 400 \text{ km s}^{-1}$ are highlighted with a black empty square.

TABLE 2.1 : Main target information.

ID <i>Gaia</i> EDR3	R.A. (deg)	Dec. (deg)	G (mag)	$E(B - V)$ (mag)	ϖ (mas)	Spectr.
1156158780372565120	229.2131	4.8164	13.016	0.04	1.5060	U/P
6155896330944952576	194.4547	-35.1402	13.057	0.04	2.3572	U
3028486001397877120	111.2785	-15.5695	12.962	0.08	2.0451	U
2391446689585357568	351.9054	-21.6728	13.016	0.02	1.3880	U
...	...	...	...	...	...	...

NOTES. ID, coordinates, apparent magnitudes and parallax from *Gaia* EDR3, colour excess from the **EXPLORE** tool, and the instrument used to collect the spectrum (U for UVES@VLT, P for PEPSI@LBT). The entire table is available in the electronic version of the paper [Ceccarelli et al. \(2024a\)](#).

2.1.1 High-resolution spectroscopy for selected stars

In this first work, I have collected high-resolution spectra for 98 stars (Program IT-2021B-004 and Program IT-2022B-006, P.I.: M. Bellazzini) with the optical spectrograph PEPSI ([Strassmeier et al. 2015](#)) mounted at the Large Binocular Telescope (LBT) in Arizona. The observations have been performed with the CD3 grating for the Blue Arm, which cover the spectral range between $4800 - 5440 \text{ \AA}$, and the CD6 grating for the Red Arm with a spectral coverage between $7410 - 9140 \text{ \AA}$, both with a spectral resolution of $R \sim 40000$. The choice of this set-up for the two arms was dictated by the trade-off between the access to measurable lines, allowing to derive the abundance of scientifically relevant chemical elements, and the efficiency of the spectrograph with the goal of achieving $S/N > 30$ for a reliable measure of

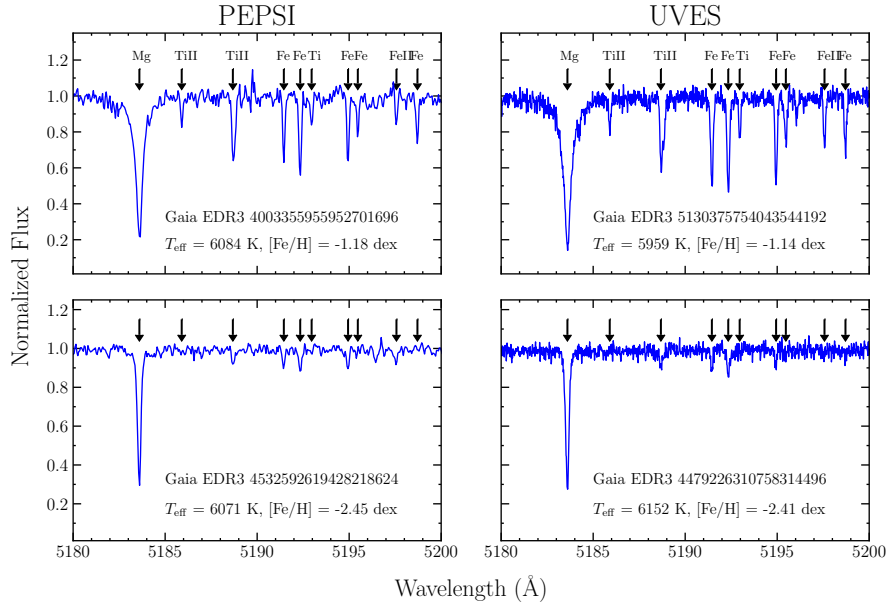


FIGURE 2.2 : Comparison between the spectra of two stars observed with PEPSI at LBT, shown on the left. Right column shows the same comparison, but for two stars observed with UVES at VLT. These stars have very similar T_{eff} and $\log g$ but they differ in the iron content. Black arrows indicate the position of some atomic lines of interest.

TABLE 2.2 : Magnitude, exposure times (t_{exp}), airmass, and S/N s for some of the observed target spectra with the spectrographs UVES and PEPSI.

ID Gaia EDR3	Spectr.	G (mag)	t_{exp} (s)	Airmass	S/N (5200 Å)
5138126933062532352	U	12.289	400	1.48	60
3531611252266342400	U	12.395	600	1.03	62
4479226310758314496	U	12.923	1000	2.39	42
5146060253053394176	U	13.298	1200	2.05	51
3857833427353671808	P	11.455	1200	1.46	85
4479226310758314496	P	12.923	1600	1.14	48
4566011038396861440	P	13.671	2400	1.27	44
2565307863375846912	P	13.816	3000	1.21	63

the chemical abundances I am interested in. In order to maximize the number of observed stars, I aimed for short exposures ($t_{\text{exp}} \leq 3000$ s). This translates into a magnitude limit of $G \leq 14.0$. The CD3 grating is less efficient than CD6, therefore it drives the exposure times. The short exposures allow us to reach typically $S/N \geq 40$ for the CD3 grating and $S/N \geq 60$ for CD6. The spectra have been reduced with the dedicated PEPSI pipeline, which contains bias subtraction, flat-fielding, spectral extraction, wavelength calibration and normalization. The observations of close sky region in the same exposure times of the targets have been executed in order to subtract the sky contribution to the stellar spectra.

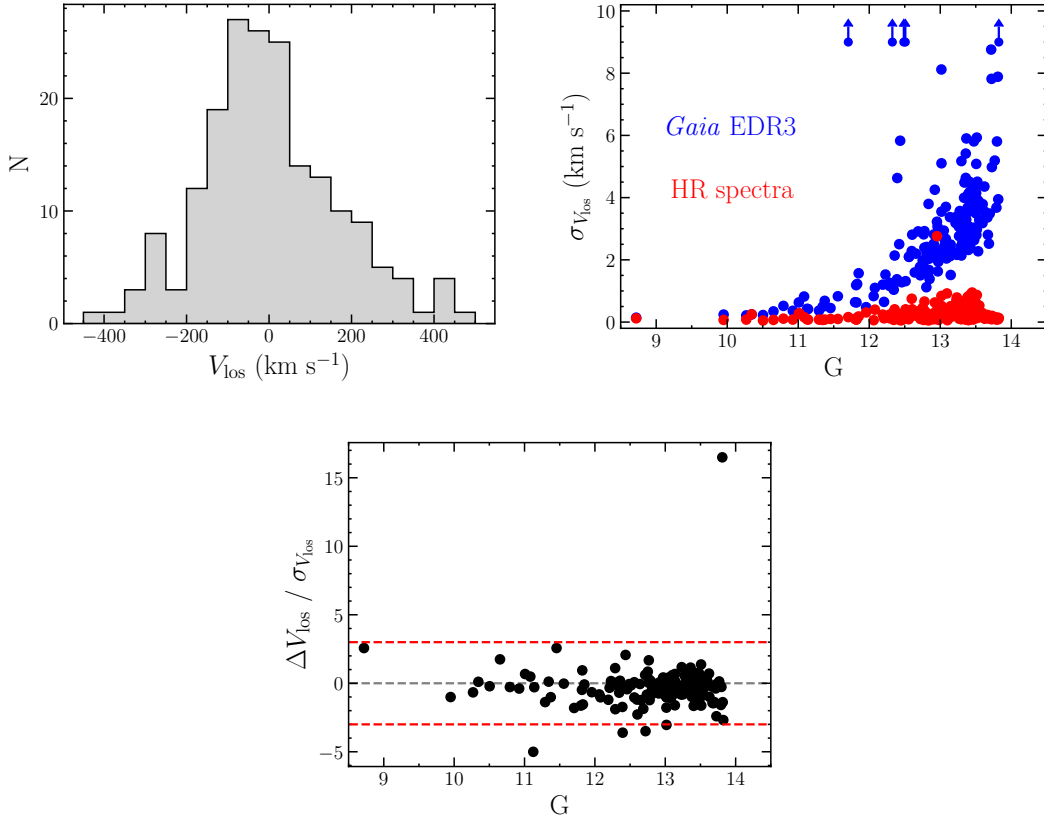


FIGURE 2.3 : Line-of-sight velocity distribution for the entire stellar sample, shown on top left. Top right panel shows comparison between the uncertainty on the line-of-sight velocity provided by *Gaia* (blue filled circles) and the one measured with high-resolution spectroscopy (red filled circles) as a function of observed *G* magnitude. The blue arrows point out the outliers in the distribution, specifically representing target stars with errors in the *Gaia* velocity measurement larger than 10 km s^{-1} . Bottom panel shows the difference between the two measurements of the line-of-sight velocity. The red dashed lines mark the $\pm 3\sigma$ threshold.

I also collected spectra for 100 stars (Program 0109.B-0522, P.I.: A. Mucciarelli) with the optical spectrograph UVES (Dekker et al. 2000) mounted at the Very Large Telescope (VLT) of the European Southern Observatory (ESO). Observations were performed with UVES in Dichroic mode adopting the standard settings Dic 1 Blue Arm CD2 390 ($3600 - 4800 \text{ \AA}$) and Dic 1 Red Arm CD3 564 ($4800 - 6600 \text{ \AA}$) and with the $1'' \times 12''$ slit, thus yielding a resolution of $R \sim 40000$. I am able to obtain, on average, $S/N \geq 20$ for the Blue Arm and $S/N \geq 40$ for the Red Arm. All the observed spectra have been reduced with the ESO pipeline³. The spectra of 12 targets were collected with both instruments as a reference point for the purpose of calibration and direct comparison.

Detailed information on some representative stellar spectra are listed in Table 2.2, bracketing the range of exposure times adopted and reporting the achieved S/N in several spectral region of interest. As an example of the quality of the spectroscopic dataset, I plot in Figure

³<https://www.eso.org/sci/software/pipelines/>

2.2 the spectra of four target stars with very similar atmospheric parameters and a difference in $[\text{Fe}/\text{H}] > 1$ dex.

2.2 Orbital parameters

Position, proper motion, and parallax measurements were taken from *Gaia* EDR3 (Gaia Collaboration et al. 2021). I corrected each star’s parallax for zero-point offsets following the prescriptions described by Lindegren et al. (2021). Also, V_{los} was measured from the high-resolution spectra by cross-correlation with template spectra using the `fxcor` task of IRAF⁴. For each star, I used a synthetic spectrum calculated using the correct atmospheric parameters as template (see Sections 2.4.1 and 2.4.2). The V_{los} is measured at the maximum peak of the cross-correlation function. Uncertainties on the line-of-sight velocity were computed following the method described in Tonry & Davis (1979). As shown in the top right panel of Figure 2.3, they are of the order of $0.1 - 0.9 \text{ km s}^{-1}$, which significantly reduce the uncertainties arising from the *Gaia* measurements, especially for fainter stars. Furthermore, I corrected the measured V_{los} for the gravitational redshift effect following the prescription described by Zwitter et al. (2018). Since most of the stars are dwarfs and the precision of V_{los} measures is so high, this correction (albeit small) is non-negligible, ranging from $0.1 - 0.7 \text{ km s}^{-1}$. The distribution of the final V_{los} is displayed in the top left panel of Figure 2.3 and the values are listed in Table 2.3. The difference between these measurements and those from *Gaia* DR3 (Gaia Collaboration et al. 2023; Katz et al. 2023), defined as $\Delta V_{\text{los}} = V_{\text{los, spectrum}} - V_{\text{los, GaiaDR3}}$, is consistent within 3σ for all except five stars, where σ is calculated as the squared sum of the uncertainties arising from high-resolution spectroscopy and *Gaia* DR3 (see bottom panel of Figure 2.3). The discrepancy observed in these five stars could hint at a binary nature for these objects. This implies the possibility of them following a distinct and unconventional chemical evolution or either having the spectrum contaminated by the companion star. Consequently, I flag these stars with a distinct marking in Table 2.3, and they will be omitted from the chemical analysis. The final V_{los} values have been coupled with the parallax and proper motions provided by the *Gaia* EDR3 to draw the complete 6D phase-space information for each target.

I then transformed the observed kinematic information to the Galactocentric reference frame. To do so, I assume the Sun to be located $R_0 = 8.122 \text{ kpc}$ away from the Galactic centre (GRAVITY Collaboration et al. 2018) and $z_\odot = 20.8 \text{ pc}$ above the midplane (Bennett & Bovy 2019). I obtain the solar velocity by combining the definition of the local standard of rest by Schönrich et al. (2010) with the proper motion of Sgr A* (Reid & Brunthaler 2004). In this frame, the Sun moves with $(U_\odot, V_\odot, W_\odot) = (12.9, 245.6, 7.78) \text{ km s}^{-1}$ (Drimmel & Poggio 2018). I computed stars orbital parameters with the software AGAMA (Vasiliev 2019) using a McMillan (2017) potential for the MW. I ran 100 Monte Carlo simulations of the orbit for each star assuming Gaussian distributions for the uncertainties in distance, proper motion, and line-of-sight velocity. The final values of the dynamical parameters are computed as the median of their derived distributions, with associated uncertainties at the 16th and 84th percentiles. The typical error in E , L_z and $L_\perp$ are $\leq 0.8\%$, $\leq 2.6\%$, and $\leq 1.8\%$,

⁴ IRAF was distributed by the National Optical Astronomy Observatory, which was managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

TABLE 2.3 : Kinematic information for the stars.

ID <i>Gaia</i> EDR3	E ($\times 10^5 \text{ km}^2 \text{ s}^{-2}$)	L_z (kpc km s^{-1})	L_{perp} (kpc km s^{-1})	V_{los} (km s^{-1})
1156158780372565120	-1.307 ± 0.010	-923 ± 20	1726 ± 18	-89.6 ± 0.4
6155896330944952576	-1.323 ± 0.009	-86 ± 19	738 ± 10	-10.2 ± 0.4
3028486001397877120	-1.236 ± 0.008	-65 ± 24	626 ± 4	-18.2 ± 0.5
2391446689585357568	-1.254 ± 0.011	-60 ± 17	843 ± 18	-6.4 ± 0.8
...	...	...	...	...

NOTES. ID from *Gaia* EDR3, orbital energy (E), angular momentum along the z -axis (L_z), perpendicular angular momentum (L_{perp}), and line-of-sight velocity (V_{los}), with uncertainties. The entire table is available in the electronic version of the paper [Ceccarelli et al. \(2024a\)](#).

respectively. The distribution of the sample in these dynamical spaces is shown in Section 2.3.

2.3 Identification of substructures in the RH

Recent studies have revealed that the RH exhibits plenty of substructures that significantly contribute to the total mass budget of the stellar Halo ([Naidu et al. 2020](#)). In most cases, they have been identified as overdensities in the space of IoM, such as their actions, the orbital energy (E), the angular momentum along the z -direction (L_z), and the angular momentum perpendicular to L_z ($L_{\perp}$). I note that $L_{\perp}$ has been extensively used to identify stars formed in the same progenitor, even if it is not completely conserved in an axisymmetric potential such as the one assumed for the Galaxy ([Helmi et al. 1999](#); [Helmi & de Zeeuw 2000](#); [Bonaca et al. 2021](#)).

As a first application of this first bunch of WRS data, I attempted to carry out a chemical characterization of some of the substructures recently listed and discussed by [Dodd et al. \(2023, D23 hereafter\)](#), who built on the findings by [Lövdal et al. \(2022\)](#) and [Ruiz-Lara et al. \(2022a\)](#). These authors used a specifically designed clustering algorithm based on the IoM computed using *Gaia* DR3 data to identify groups of stars sharing similar properties in the phase-space.

In the region of the E , L_z , and $L_{\perp}$ space covered by the sample, the most widely represented among the D23 groups is GSE, for which I sample the most retrograde and high energy slice, based on the selection window (see Section 2.1). In addition, there are two mid-sized slightly retrograde substructures associated to Sequoia ([Myeong et al. 2019](#)) and Thamnos ([Koppelman et al. 2019b](#)), as well as three newly found, small, high-energy, and extremely retrograde clumps, namely L-RL64, also known as Antaeus ([Oria et al. 2022](#)), ED-2, and ED-3, plus other minor groups that do not appear to have significant overlap with the sample (see more details below). Indeed, I find that 179 of the 186 stars are included in the D23 sample, and 55 of them are associated with one of the D23 groups. However, there are five groups that have just one member star included in the sample, namely Thamnos, ED-5, ED-6, Group 13, and Group 14. Since no meaningful conclusion can be drawn from the chemistry of an indi-

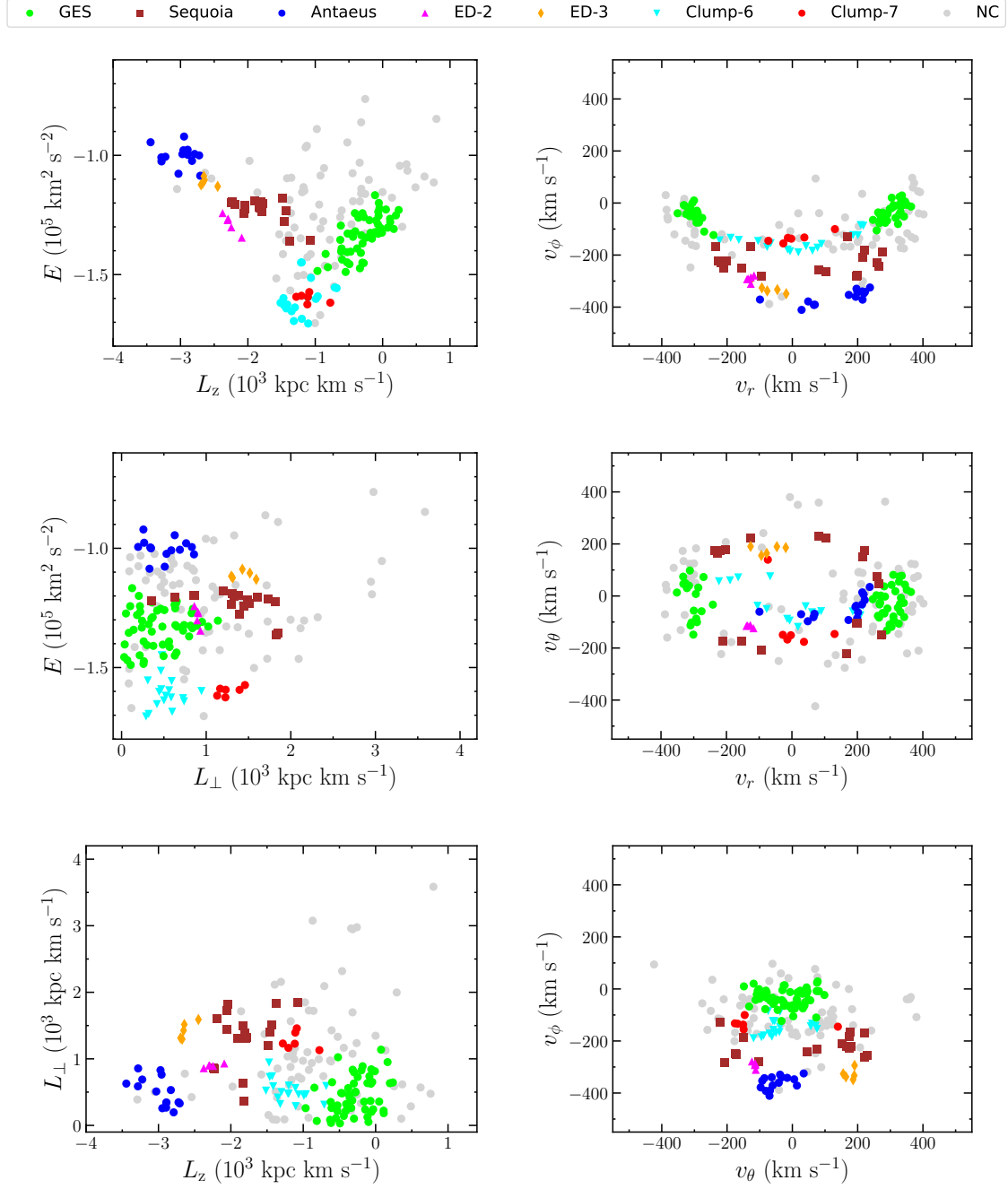


FIGURE 2.4 : Distribution of the observed stars in IoM and velocity space (top and bottom panels, respectively). I highlight stars associated with various substructures with different colours (green for GSE, brown for Sequoia, blue for Antaeus, magenta for ED-2, orange for ED-3, cyan for Clump-6 and red for Clump-7).

vidual star, I do not consider these substructures in the following. Still, I make the chemical abundances available (see Table 2.6) since they might be of interest for upcoming investigations. Of the remaining 50 stars, 12 are associated to GSE, 18 to Sequoia, 11 to Antaeus, 4 to ED-2, and 5 to ED-3.

Starting from these 50 ‘core members’, and with the aim to increase the number of stars associated to a substructure, I performed a clustering analysis in the IoM space. I tested several clustering algorithms (e.g. DBSCAN, HDBSCAN, OPTICS), and empirically assessed their performance by comparing the resulting memberships with those reported in D23. Among those that have been tested, DBSCAN (Ester et al. 1996) provided the closest match to the D23 selection while allowing for the identification of additional members. For this reason, I adopted DBSCAN as reference algorithm for the final membership reclassification. Specifically, I used E , L_z , and $L_\perp$ as the input parameters for the clustering algorithm, for the purpose of having a fair comparison with D23. I scaled the space of these parameters with the RobustScaler tool in scikit-learn (Pedregosa et al. 2011). Due to the significant overlap between Halo substructures in the IoM spaces, it is difficult for any clustering algorithm to identify each individual overdensity. Furthermore, some of the newly discovered substructures include a low number of stars. For these reasons, the algorithm used in this study was fine-tuned to detect all the small-scale clumps identified by D23. I find the best matching results with D23 by using DBSCAN default hyperparameters and by setting $\epsilon_{\text{ps}} = 0.34$ and $\text{min_samples} = 5$. Figure 2.4 shows the position of the final candidate members of each substructure in the IoM space. With this final selection, I am able to relate 119 stars in the parent sample to a known retrograde substructure.

Before starting the discussion of the various substructures, it is important to note that the identification and classification of completely disrupted relics of ancient merging events is still in its infancy and, as made clear in the following, it is subject to considerable uncertainty. On the one hand, there is no consensus on the best selection criteria to isolate the purest samples of a given substructure and any criterion will imply some degree of contamination from unrelated sources (see, e.g., Buder et al. 2022, for references and discussion). On the other hand, as stated above, there are substructures that may be erroneously considered as an individual entity when they may, in fact, be the sum of independent ones or the unrecognized part of a larger one (Koppelman et al. 2020; Naidu et al. 2020; Belokurov et al. 2023; Dodd et al. 2023). Here, I aim to get a clearer insight into the nature of some of the retrograde substructures by adding the chemical dimensions, as done by other authors (e.g., Feuillet et al. 2020, 2021; Buder et al. 2022; Horta et al. 2023). Overall, this is not an easy task in the present phase and it is worthwhile to proceed cautiously, taking care of every step along our exploratory path. In the following, I describe in details the samples from different retrograde substructures that will be later analysed:

- *Gaia-Sausage-Enceladus*. Due to the criterion employed to select retrograde stars (see Section 2.1), which significantly cuts the IoM region typically populated by GSE stars, I am able to retain only 12 stars in common with D23 belonging to GSE. By using the clustering algorithm, all of the original members of this cluster were retained as GSE members and an additional 41 stars were added to it, making the total number of stars in this cluster equal to 53 (see the green-coloured symbols in Figure 2.4 and thereafter).
- *Sequoia*. The cross-match provides 18 common members between the targets and the

Sequoia sample of stars identified by D23. When using the DBSCAN algorithm, only 8 stars were found to belong to this clump; additionally, 2 stars from the original sample were associated with ED-2 (see below). This association was primarily based on the alignment of these two stars with the ED-2 clump in the $L_z - L_\perp$ space. However, they were found to move on higher energy orbits with respect to ED-2. Consequently, this distinctive orbital behaviour points towards the association with the Sequoia substructure. In the end, since all the 8 stars are part of the 18 original members, I decided to stick with the D23 classification for Sequoia. Thus, the final Sequoia sample contains 18 stars (brown-coloured symbols in Figure 2.4).

- *Antaeus/L-RL64*. The comparison with D23 data shows that 11 stars in the WRS sample are associated with Antaeus. Moreover, the clustering algorithm identifies two separate clumps composed of 15 stars moving on extremely retrograde orbits. Here, I treat them as one single substructure (blue-coloured symbols in Figure 2.4), since their position in the IoM spaces is totally consistent with the one of Antaeus and 13 out of these 15 stars are labelled by *Oria et al. (2022)* as members of this group. Thus, with this final selection I define a fair sample of this newly discovered substructure and I will be able to provide its detailed chemical characterization for the first time.
- *ED-2 and ED-3*. D23 spotted two new small highly retrograde clusters near Sequoia, namely ED-2 and ED-3, which are extremely tight in the IoM and velocity spaces (see their Fig. 3). I have a total of 4 and 5 stars in common with the ED-2 and ED-3 clusters, respectively. The results provided by DBSCAN show that I am able to retain all the 5 stars in the ED-3 clump and also add 1 star to the ED-2 substructure (orange- and magenta-coloured symbols in Figure 2.4, respectively). Notably, as remarked above, the clustering algorithm spotted 2 additional stars that were previously associated with Sequoia as members of ED-2.
- *Thamnos, Clump-6, and Clump-7*. In the entire sample, only 1 star is linked to Thamnos according to D23. As is in the case with GSE, the selection method used does not allow us to include stars with orbital energy as low as Thamnos, which means I am unable to sample this particular substructure. Interestingly, DBSCAN spots two clusters composed of 17 and 6 stars in the low energy regime of the sample at slightly higher orbital energy with respect to Thamnos. These two groups have very similar E and L_z , but they differ in $L_\perp$. It is worth noting that these clumps may be artificial overdensities identified by the algorithm and produced by the selection cut. In the following, I refer to them as Clump-6 and Clump-7 (cyan- and red-coloured symbols in Figure 2.4).
- *Unassociated stars*. A significant fraction of the initial sample, 67 out of 186 stars, does not appear to be associated with any known structure according to neither D23 nor the clustering algorithm. In the rest of the Chapter, I will not focus on the chemical features of these unassociated stars, as they will be part of future contributions to the WRS project, looking at their chemistry to determine whether they are accreted.

2.4 Abundance analysis

In this Section, I describe in detail the steps of the chemical analysis. It is important to note that absolute values of chemical abundances derived with different methodologies may be affected by systematic zero-point offsets, due to differences in the adopted model atmospheres, stellar parameters, linelists, atomic data (e.g., $\log gf$), and used tools. Thus, the same methodology described here will be applied consistently in the following Chapters dedicated to the WRS project, as maintaining homogeneity is essential for comparing the results and avoiding the introduction of systematic uncertainties arising from the analysis itself. Given that the differences in chemical patterns of Halo substructures are already subtle due to the similar natures and chemical enrichment histories of their progenitors – particularly in the metal-poor regime – it is crucial to prevent the addition of any spurious signal or noise stemming from variations in the analysis.

2.4.1 Stellar parameters

Establishing precise atmospheric parameters (i.e., effective temperature, T_{eff} , surface gravity, $\log g$, and microturbulent velocity, v_t) is a crucial step to obtaining reliable chemical abundances.

I derived both T_{eff} and $\log g$ relying on the extremely accurate and precise *Gaia* EDR3 photometry (see Table 2.1). I adopted a photometric approach instead of a spectroscopic one, as the latter is known to yield biased stellar parameters for metal-poor stars ($[\text{Fe}/\text{H}] < -1.5$ dex), typically resulting in underestimated T_{eff} and $\log g$, likely due to limitations in the adopted physical assumptions, such as departures from LTE and simplifications in the model atmospheres (Mucciarelli & Bonifacio 2020).

In particular, T_{eff} has been calculated with the $(BP - RP)_0 - T_{\text{eff}}$ relation provided by Mucciarelli et al. (2021b). The colour $(BP - RP)$ has been corrected for extinction following the iterative procedure described in Gaia Collaboration et al. (2018b). The colour excess $E(B - V)$ adopted for each star is provided by the online tool EXPLORÉ⁵. Since the adopted colour – T_{eff} relation depends on the metallicity, which is not known a priori, I calculated T_{eff} while assuming a fixed value of $[\text{Fe}/\text{H}] = -1.5$ dex for any star. The uncertainty on T_{eff} is due to the errors in photometric data, parallax, colour excess, and $(BP - RP)_0 - T_{\text{eff}}$ relation. Given that the observed targets are bright, very nearby and affected by minimal extinction, the main source of error in the effective temperature arises from the colour and T_{eff} relation. Thus, I assumed the dispersion of the $(BP - RP)_0 - T_{\text{eff}}$ relation, which is 61 K (Mucciarelli et al. 2021b), as the typical internal error on T_{eff} . Surface gravities have been estimated assuming the photometric T_{eff} , a stellar mass derived from a BaSTI isochrone (Pietrinferni et al. 2021) with 12 Gyr, $[\text{Fe}/\text{H}] = -1.5$ dex and $[\alpha/\text{Fe}] = +0.4$ dex (according to the typical values for the accreted component of the stellar Halo derived in previous studies, see e.g. Nissen & Schuster 2010, Kruijssen et al. 2020, Montalbán et al. 2021, Horta et al. 2023) and the G -band bolometric corrections described by Andrae et al. (2018). I note that using an alternative isochrone varying the parameters has a minimal impact on the resulting surface gravity of the star. For instance, when using an isochrone with 10 Gyr age, $[\text{Fe}/\text{H}] = -1.1$ dex and $[\alpha/\text{Fe}] = +0.4$ dex, the discrepancy with the first results remains consistently below

⁵<https://explore-platform.eu/>

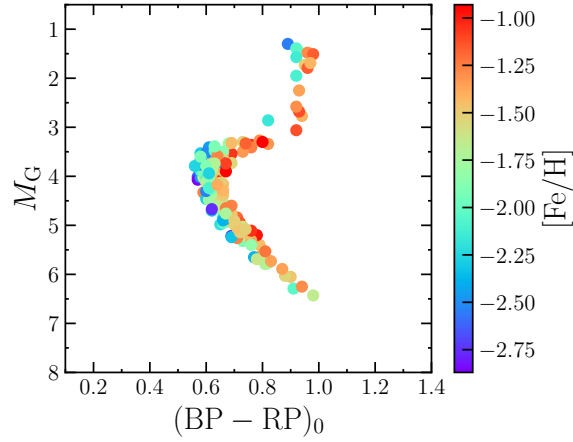


FIGURE 2.5 : *Gaia* EDR3 distance-corrected CMD of the 175 analysed stars. Targets are colour-coded based on the metallicity.

0.04 dex. The uncertainties on $\log g$ are derived through the propagation of the errors on the effective temperature, photometry, and distance. The obtained values are systematically lower than 0.1 dex. Finally, microturbulent velocities were calculated by requiring no trend between iron abundances and reduced equivalent widths, defined as $\log_{10}(\text{EW}/\lambda)$. The uncertainties on v_t are estimated as described in Mucciarelli et al. (2013) and they are of the order of 0.2 km s^{-1} .

Subsequently, I improved the estimate of the stellar parameters by using the correct $[\text{Fe}/\text{H}]$ value derived from the chemical analysis. The final effective temperature value deviates from the initial estimate by less than 60 K. I excluded from the chemical analysis the three hottest stars of the sample ($T_{\text{eff}} > 6650 \text{ K}$): the combination of their atmospheric parameters leads to the formation of extremely weak absorption lines, making the measurement of abundances unreliable. In Figure 2.5, I show the CMD for all the analysed stars, colour-coded based on the metallicity. The final values of the atmospheric parameters are listed in Table 2.4.

2.4.2 Line selection

To obtain the chemical abundances of each star, I made a list of unblended lines to analyse, automatically pre-selected with the proprietary code **AUTOKUR** and consequently refined with a visual comparison between the observed and the synthetic spectra. The latter were calculated with the code **SYNTHE** (Kurucz 2005), adopting the stellar parameters of the observed targets (see Section 2.4.1), assuming **ATLAS9** (Kurucz 2005) model atmospheres, and using the linelists containing atomic and molecular data from the Kurucz/Castelli⁶ database, updating the oscillator strengths for some transitions of interest (see Mucciarelli et al. 2017a, and references therein). Synthetic spectra have been convolved with a Gaussian profile to reproduce the observed resolution.

To address the fact that the degree of blending for a particular transition is dependent

⁶<http://wwwuser.oats.inaf.it/castelli/linelists.html>

TABLE 2.4 : Stellar parameters for the targets.

ID <i>Gaia</i> EDR3	T_{eff} (K)	$\log g$ (dex)	v_t (km s ⁻¹)	[Fe/H] (dex)
1156158780372565120	6426	4.20	1.0	-2.06 ± 0.05
6155896330944952576	6137	4.47	0.9	-2.21 ± 0.05
3028486001397877120	6412	4.36	1.3	-1.26 ± 0.04
2391446689585357568	6140	4.07	0.1	-2.54 ± 0.05
...	...	...	...	...

NOTES. ID from *Gaia* EDR3, derived effective temperature (T_{eff}), surface gravity ($\log g$), microturbulent velocity (v_t), and iron abundance ratio. The complete table is available in the electronic version of the paper [Ceccarelli et al. \(2024a\)](#).

on the metallicity, which is not known a priori in this case, I used an iterative approach to establish the list of spectral lines to analyse for each star. The synthetic spectra have been calculated adopting an α -enhanced mixture ($[\alpha/\text{Fe}] = +0.4$ dex) with an initial metallicity of $[\text{Fe}/\text{H}] = -1.5$ dex. Following the initial chemical analysis, a revised set of unblended spectral lines has been identified for each star using a synthetic spectrum that was computed using the appropriate chemical composition. It is worth noting that I prioritized the use of spectral lines whose atomic data have been determined from laboratory measurements.

During the visual inspection, I noticed that the spectra of three low-main sequence stars ($T_{\text{eff}} < 5250$ K and $\log g > 4.60$) were highly contaminated by molecular transitions from MgH. Thus, I opted to exclude them from the abundance analysis. In the end, when considering also the exclusion of the 5 binary stars, a total of 11 stars were removed from the initial sample. I chose to exclude them from further consideration in this study. Among these 11 excluded stars, four were associated with GSE, one with ED-2, one with Sequoia, one with Clump-6 and four stars remained unassociated with any specific substructure.

2.4.3 Chemical analysis

The chemical abundances of Na, Ca, Ti, Fe, Ni, and Zn were derived through a comparison between the observed equivalent widths (EWs) and the theoretical line strengths using the code **GALA** ([Mucciarelli et al. 2013](#)). The EWs were measured with the code **DAOSPEC** ([Stetson & Pancino 2008](#)) via the automatic tool **4DAO** ([Mucciarelli 2013](#)).

The chemical abundances of elements which show saturated core lines, but with wings that are still sensitive to the abundance or hyperfine/isotopic splitting transitions (Mg, Al, Sc, Mn, and Y) were derived through spectral synthesis with the proprietary code **SALVADOR**. This program runs a χ^2 -minimization between the observed line and a grid of synthetic spectra computed on-the-fly by the code **SYNTHE**, keeping the stellar parameters fixed and varying only the abundance of the matching element.

All the abundances were scaled to the solar composition, taking as reference the values from [Grevesse & Sauval \(1998\)](#). I adopted these solar abundances since the **ATLAS9** model atmospheres used in this study are computed based on a chemical mixture consistent with the one outlined in [Grevesse & Sauval \(1998\)](#), as described in [Castelli & Kurucz \(2003\)](#). For all

TABLE 2.5 : Differences in chemical abundances obtained from the UVES and PEPsi samples.

Element	Δ_{abu}	σ	$N_{\star}$
Fe	0.02	0.05	12
Mg	−0.01	0.06	12
Ca	0.09	0.06	9
Sc	−0.18	0.22	10
Ti I	0.00	0.06	12
Ti II	0.00	0.10	11
Mn	−0.05	0.14	8
Ni	0.05	0.08	8
Zn	0.11	0.07	5
Y	0.12	0.11	4

NOTES. I list the calculated offsets (Δ_{abu}), the corresponding standard deviations, and the number of stars used for each element. These values were employed to ensure a consistent scale alignment between the two sets of measurements.

the elements that were examined, in cases where the spectral lines were not clearly detectable, I determined upper limits by comparing the observed spectra to the synthetic spectra.

To put the chemical abundances measured for the stars in the UVES and PEPsi samples onto the same scale, I made a direct comparison between the final abundances ratios of the 12 stars that have been observed with both instruments. For each element, I determined a median abundance difference ($\Delta_{\text{abu}} = [\text{X}/\text{Fe}]_{\text{PEPSI}} - [\text{X}/\text{Fe}]_{\text{UVES}}$) and I applied an offset correction by adopting UVES as the reference scale (due to the largest number of available lines) in the cases where:

$$\Delta_{\text{abu}} > \frac{\sigma}{\sqrt{N_{\star} - 1}} \quad (2.1)$$

and where σ is the standard deviation of the abundance differences for a given element and $N_{\star}$ is the number of stars with a measured abundance with both instruments for that specific element. For Fe, Ca, Sc, Ni, Zn, and Y, I corrected the abundances for the PEPsi sample by subtracting the offsets listed in Table 2.5, thus bringing them onto the UVES scale. The observed offset is mostly systematic, reflecting differences in data reduction pipelines, spectral resolution and coverage of the two instruments. Also, variations in the S/N may play a role. In the following, I focus on the methodology I employed specifically to derive chemical abundances for problematic species:

- *Sodium.* The two lines of Na available in the spectral range of PEPsi are centred at 8183.3 and 8194.8 Å. I highlight that these atomic lines are situated within a spectral region significantly affected by telluric absorption lines. As a precautionary measure to ensure the robustness of the analysis, I visually inspected the possible telluric contamination of the Na lines using appropriate synthetic spectra of the Earth atmosphere calculated with **TAPAS** (Bertaux et al. 2014). Subsequently, I excluded any Na line exhibiting signs of contamination attributable to telluric features. I applied NLTE

TABLE 2.6 : Chemical abundances for the stars associated to known substructures.

ID <i>Gaia</i> EDR3	[Na/Fe]	[Mg/Fe]	[Al/Fe]
6155896330944952576	—	0.23 ± 0.03	-0.15 ± 0.11
3028486001397877120	—	0.25 ± 0.03	-0.37 ± 0.09
2391446689585357568	—	0.24 ± 0.03	-0.44 ± 0.11
6378884813840372864	—	-0.02 ± 0.04	—
...	...	...	...
[Ca/Fe]	[TiI/Fe]	[TiII/Fe]	[ScII/Fe]
0.26 ± 0.04	0.29 ± 0.02	0.58 ± 0.32	0.07 ± 0.07
0.35 ± 0.04	0.29 ± 0.02	0.28 ± 0.02	0.12 ± 0.06
0.43 ± 0.03	0.43 ± 0.02	0.50 ± 0.10	0.22 ± 0.07
0.26 ± 0.03	0.26 ± 0.03	0.23 ± 0.03	0.02 ± 0.08
...	...	...	...
[Mn/Fe]	[Ni/Fe]	[Zn/Fe]	[YII/Fe]
-0.46 ± 0.10	-0.06 ± 0.02	—	-0.04 ± 0.08
-0.41 ± 0.11	-0.07 ± 0.03	-0.01 ± 0.02	-0.18 ± 0.09
-0.51 ± 0.10	0.17 ± 0.02	—	-0.01 ± 0.08
-0.48 ± 0.10	-0.08 ± 0.04	—	0.09 ± 0.08
...	...	...	...
ID <i>Gaia</i> EDR3	Substructure (D23)		
6155896330944952576	GSE (GSE)		
3028486001397877120	GSE (N/A)		
2391446689585357568	GSE (Group 14)		
6378884813840372864	GSE (N/A)		
...	...		

NOTES. In the last column I report our association with the former progenitor and the result provided by D23 (inside the brackets). The entire table is available in the electronic version of the paper Ceccarelli et al. (2024a).

correction from Lind et al. (2011). All the corrections for Na are available through the INSPECT database⁷. The values listed in Table 2.6 are corrected for NLTE.

- *Aluminum.* Within the UVES spectral range, the presence of Al is characterised by solely two strong lines located at 3944.0 and 3961.5 Å. However, these lines become saturated at $[\text{Fe}/\text{H}] > -1.3$ dex. In contrast, the PEPSI sample features only three weak Al lines suitable for the chemical analysis: one line at 7836.1 Å and the doublet at 8772 – 73 Å. Unfortunately, these weak lines are not detected at metallicity lower than ~ -1.5 dex. The corrections for NLTE effects for each line are taken from Lind et al. (2022).

⁷<http://www.inspect-stars.com/>

2.4.4 Abundance uncertainties

When inferring the uncertainties on the abundance ratios, it is essential to consider two primary sources of error: internal errors related to EW measurements and errors arising from the adopted atmospheric parameters.

Uncertainties due to EW measurements have been estimated as the dispersion around the mean of the individual line measurements, divided by the root mean square of the number of used lines. For elements whose abundances have been measured using spectral synthesis, I performed Monte Carlo simulations to estimate the internal error. Specifically, I generated a sample of 500 synthetic spectra with Poissonian noise to reproduce the S/N of the observed spectra and then I repeated the analysis to derive the abundance. The internal error is estimated as the standard deviation of the abundance distribution of the 500 noisy synthetic spectra.

To determine the uncertainties arising from atmospheric parameters, I replicated the chemical analysis by varying only one stellar parameter at a time and keeping the others fixed (see Section 2.4.1 for the details about the derivation of the uncertainties on the atmospheric parameters). Since I refer to chemical abundances with abundance ratios ($[X/Fe]$), the uncertainties on the iron abundance $[Fe/H]$ have been considered as well.

The intrinsic and systematic components have been summed in quadrature to compute the total uncertainty. Therefore, the final errors have been estimated as:

$$\sigma_{[Fe/H]} = \sqrt{\frac{\sigma_{Fe}^2}{N_{Fe}} + (\delta_{Fe}^{T_{\text{eff}}})^2 + (\delta_{Fe}^{\log g})^2 + (\delta_{Fe}^{v_t})^2}$$

$$\sigma_{[X/Fe]} = \sqrt{\frac{\sigma_X^2}{N_X} + \frac{\sigma_{Fe}^2}{N_{Fe}} + (\delta_X^{T_{\text{eff}}} - \delta_{Fe}^{T_{\text{eff}}})^2 + (\delta_X^{\log g} - \delta_{Fe}^{\log g})^2 + (\delta_X^{v_t} - \delta_{Fe}^{v_t})^2}$$

where $\sigma_{X,Fe}$ is the dispersion around the mean of chemical abundances, $N_{X,Fe}$ is the number of used lines and $\delta_{X,Fe}^i$ are the abundance differences obtained by varying the parameter i . All the abundance ratios for individual stars are listed in Table 2.6, together with the corresponding uncertainties.

2.5 Comparison with the literature

To put the results in a more general context, in this Section I compare WRS chemical abundances with external datasets, starting with the sample of metal-poor dwarf and subgiant stars associated with the Halo population analysed by [Nissen & Schuster \(2010, NS10 hereafter\)](#). This choice was guided by the extremely high-quality stellar spectra used by [NS10](#) (S/N ranging from 250 to 500) that guarantees accurate measurements of chemical abundances. By using a sample of stars observed with UVES@VLT and FIES@NOT, these authors revealed for the first time the existence of two distinct populations within the nearby MW stellar halo, composed of stars having different kinematics and chemical patterns. [NS10](#) proposed that the Galactic halo population ($[Fe/H] \leq -0.8$ dex) following the low- α sequence

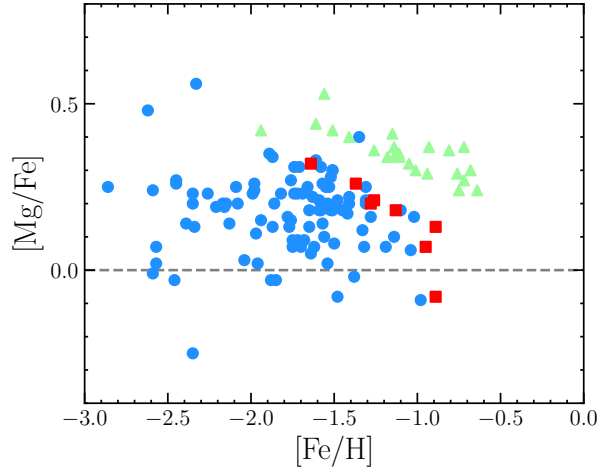


FIGURE 2.6 : Comparison of Mg abundance ratios of target stars observed with UVES (blue filled circles) and the NS10 reference sub-sample (red filled squares and green filled triangles for low- α and high- α sequences, respectively). The errorbar in the top-right corner indicates the typical uncertainties.

in the classical $[\alpha/\text{Fe}] - [\text{Fe}/\text{H}]$ plane (red squares in Figure 2.6) is composed of stars accreted from disrupted dwarf galaxies, whereas the high- α population (green triangles in Figure 2.6) is made up of stars that have formed in-situ, a view that finds general confirmation nowadays (see, e.g., Bonaca et al. 2017; Hayes et al. 2018; Haywood et al. 2018; Helmi et al. 2018; Mackereth et al. 2019; Helmi 2020). To avoid the introduction of systematic errors due to the different chemical analysis and ensure a fair comparison between homogeneous results, I defined the reference targets based on a sub-sample of 41 NS10 stars that have been observed with UVES using the same instrument setup as WRS targets and covering a similar range of atmospheric parameters. I re-analysed the NS10 spectra following the same procedure described in Section 2.4 and using the same linelist. I found a median discrepancy of $[\text{Fe}/\text{H}] = -0.05$ dex and $\sigma_{[\text{Fe}/\text{H}]} = 0.08$ dex. Given that these values adhere to the criteria described in Equation 2.1, I adjusted the abundances to ensure congruence within the NS10 reference frame. The estimates of $[\text{Mg}/\text{Fe}]$ display a median difference of 0.01 dex and $\sigma_{[\text{Mg}/\text{Fe}]} = 0.08$ dex.

I show the final comparison in Figure 2.6: as expected from the selection imposed (which should predominantly include retrograde accreted objects), stars from the WRS sample (blue symbols) are located in the same region of the α -elements chemical planes as the low- α population from NS10, with abundances that are systematically lower (~ 0.2 dex on average) than the high- α population composed of in-situ stars. It is also interesting to note that the low- α sequence of NS10 targets basically defines the upper limit of the distribution of WRS targets, which are mostly at lower $[\alpha/\text{Fe}]$ abundances. This might reflect the fact that I am sampling regions of the RH populated also by several different low-mass mergers, for which theoretical models predict low (and different) $[\alpha/\text{Fe}]$ levels already at fairly low metallicity (Matsuno et al. 2022a). On the other hand, the accreted population of NS10 likely belongs to the most-massive merger, GSE.

As a further and independent check, I also made a comparison with chemical abun-

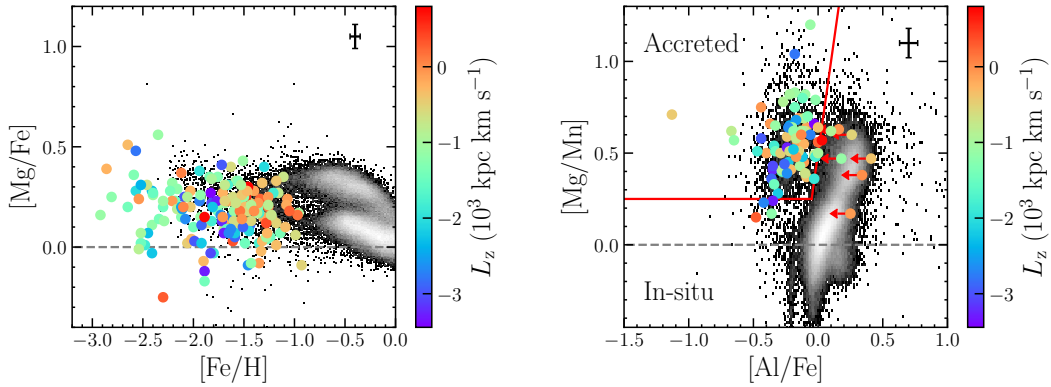


FIGURE 2.7 : $[\text{Mg}/\text{Fe}]$ abundance ratios as a function of $[\text{Fe}/\text{H}]$ for the WRS sample (colour-coded by the angular momentum along the z -direction, L_z) and for the APOGEE control sample (greyscale 2D histogram) shown on the left. The errorbar in the top-right corner displays the typical uncertainties. $[\text{Mg}/\text{Mn}]$ abundance ratios as a function of $[\text{Al}/\text{Fe}]$ for the same samples, with the same arrangement shown on the right. Red arrows indicate upper limits.

dances from the large and widely used APOGEE DR17 (Abdurro'uf et al. 2022) dataset. I limited the comparison to well-measured APOGEE abundances by selecting only stars having `ASPCAPFLAG` = 0, `STARFLAG` = 0, `EXTRATARG` = 0, `SNR` > 70, `FE_H_ERR` < 0.1, and `ALPHA_M_ERR` < 0.2⁸. The final APOGEE sample (APOGEE control sample hereafter), which I use as a reference throughout the paper, is composed of 122262 stars. The left panel of Figure 2.7 reveals that, in the $[\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]$ plane, WRS targets show a good agreement in the common metallicity range of $-2.4 \leq [\text{Fe}/\text{H}] \leq -0.8$ dex with the low- α population stars from the APOGEE control sample. Interestingly, the stars from WRS sample that move on more extreme retrograde orbits ($L_z < -2500$ kpc km s⁻¹) appear to lay on a different pattern with respect to the low- α population at $[\text{Fe}/\text{H}] < -1.5$ dex, with lower $[\text{Mg}/\text{Fe}]$ at fixed metallicity. In the right panel of Figure 2.7, I show the $[\text{Mg}/\text{Mn}] - [\text{Al}/\text{Fe}]$ chemical space, which serves as a diagnostic to distinguish between accreted and in-situ populations (Hawkins et al. 2015; Das et al. 2020). Contrary to the APOGEE control sample, nearly all of WRS targets are located in the area of the plot where it is expected to find accreted stars (Horta et al. 2021; Horta & Schiavon 2025), emphasizing the fact that I am observing a poorly explored area of the Solar Neighbourhood. Indeed, only less than 1% of the stars within the APOGEE control sample are located at $D < 1$ kpc and move on retrograde orbits. It is worth noting that only 11 stars in the WRS sample are listed in the entire APOGEE DR17 catalogue, with only one of them aligning with the selection criteria expounded above. Moreover, through the entire WRS program, I have the capability to provide detailed chemical abundance data for elements that are notably absent in APOGEE (e.g., Sc, Zn, and Y) and for elements whose chemical trends in APOGEE may diverge from theoretical expectations (Na and Ti).

The comparisons presented above show that the selection I adopted was very effective in selecting stars that very likely originated in ancient and now-dissolved MW satellites. In

⁸See https://data.sdss.org/datamodel/files/APOGEE_ASPCAP/APRED_VERS/ASPCAP_VERS/allStarLite.html for definitions.

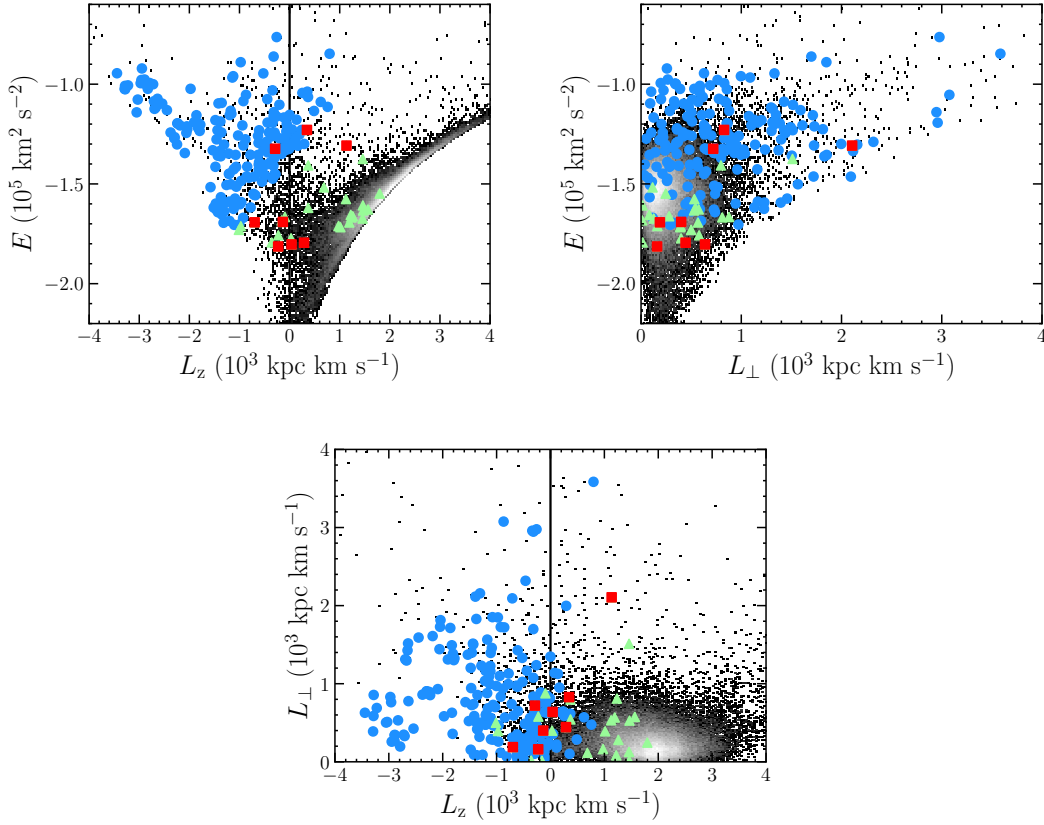


FIGURE 2.8 : Distribution of the targets stars in the IoM space compared with the **NS10** stars and the APOGEE sample. The colour coding is the same as in Figure 2.6.

addition to the location of WRS stars in the $[\text{Mg}/\text{Mn}] - [\text{Al}/\text{Fe}]$ plane, it is worth noting that: (a) the kinematic selection picked up only metal-poor stars ($[\text{Fe}/\text{H}] \leq -0.8$ dex), the majority of which (65%) have $[\text{Fe}/\text{H}] \leq -1.5$ dex, with a significant very metal-poor tail (47 stars with $-2.0 \leq [\text{Fe}/\text{H}] < -3.0$ dex, 26% of the sample), a component that is poorly probed by the APOGEE control sample; and (b) despite the higher resolution, WRS stars show a larger scatter in $[\text{Mg}/\text{Fe}]$ with respect to APOGEE (increasing with decreasing metallicity), suggesting again that I have been more effective in sampling stars from a variety of disrupted satellites, with different chemical evolutionary paths. In summary, the results of the adopted selection are fully compliant with the main rationale of WRS.

In Figure 2.8, I compare the IoM of WRS targets with those of the **NS10** sample and APOGEE. I computed the IoM for the **NS10** stars using the 6D phase-space information provided by the *Gaia* EDR3. Instead, for the APOGEE control sample I used the phase-space values from *Gaia* listed in the APOGEE DR17 catalogue. First, Figure 2.8 provides a direct view of the efficiency of the adopted selection criterion in picking up Halo stars in retrograde motion, as discussed in Section 2.1. However, this criterion does introduce a clear bias, since it prevents from picking stars with low orbital energy ($E \leq 1.5 \times 10^5 \text{ km}^2 \text{ s}^{-2}$) moving on slightly retrograde orbits ($L_z \geq -0.5 \times 10^3 \text{ kpc km s}^{-1}$). At the same time, it is clear that high-quality APOGEE measures primarily targets disc stars with a quite sparse sampling of the retrograde component of the halo. For what it concerns the **NS10** sample, although

some high- α stars are interestingly located in the retrograde region (they might be part of the dynamically heated disc, sometimes referred to as the Splash, [Belokurov et al. 2020](#)), the bulk of this population moves on disc-like orbits, whereas the low- α moves on high eccentricity orbits, as expected for GSE stars.

2.6 Chemical abundances of RH substructures

Here, I present the chemical abundances of the substructures in the RH of the MW. Having inspected the $[X/Fe] - [Fe/H]$ diagrams for all the elements, I discuss only those that appear to provide the clearest view of the substructures I consider here. In particular, I focus on the abundances of Na, Mg, Al, Ca, Sc, TiI, TiII, Mn, Ni, Zn, and Y. It is important to note that, owing to the combined effects of the atmospheric parameters on the shapes of absorption lines, it is not possible to reliably measure the abundances of all chemical elements for every WRS target. As a result, some stars are not included in specific figures.

2.6.1 Metallicity distribution functions

I go on to examine the metallicity distribution functions (MDFs) of the six substructures that were built based only on the IoM. In Figure 2.9 I display the results, which suggest that the global MDF of this sample is bimodal, with a primary peak at $[Fe/H] \sim -1.4$ dex and a secondary peak at $[Fe/H] \sim -2.4$ dex. The high-metallicity end of the RH stars distribution is dominated by GSE, with a median metallicity of $[Fe/H] = -1.47$ dex and $\sigma_{[Fe/H]} = 0.32$ dex. This result is consistent with [Bonifacio et al. \(2021\)](#) and 0.2 – 0.3 dex more metal-poor than indicated by typical literature values ([Vincenzo et al. 2019](#); [Naidu et al. 2020](#); [Feuillet et al. 2021](#); [Buder et al. 2022](#); [Bellazzini et al. 2023](#)). Once again, I wish to emphasize the importance of the adopted selection criterion for GSE stars. This criterion is structured in such a way that prevents us from including stars from the Solar Neighbourhood with $[Fe/H] > -0.80$ dex, while exclusively observing the higher energy populations of GSE. As shown in [Koppelman et al. \(2020\)](#), the high-energy debris of a merger event typically consists of the first stars lost by the progenitor, meaning those in its peripheries. As commonly observed in dwarf spheroidal galaxies orbiting the MW (see, e.g., [Tolstoy et al. 2023](#)), it is reasonable to expect a negative metallicity gradient that would explain why WRS targets are slightly more metal-poor than lower-energy GSE samples. Stars assigned to Sequoia are, on average, slightly more metal-poor with respect to GSE and display a broad MDF, with a median metallicity of $[Fe/H] = -1.66$ dex and $\sigma_{[Fe/H]} = 0.37$ dex, which is consistent with the result by [D23](#). The two most metal-poor stars in Sequoia have a metallicity that overlaps with that of ED-2. However, these two stars occupy a place in the IoM space that is significantly different with respect to the ED-2 clump. Moreover, they do not exhibit the distinctive high $[Ti/Fe]$ ratios observed in the stars of ED-2 at a comparable metallicity (see Figure 2.13). As a result, I exclude a possible association of these stars with the ED-2 substructure based on their chemical features. Antaeus displays a coherent MDF with a median metallicity of $[Fe/H] = -1.83$ dex and $\sigma_{[Fe/H]} = 0.27$ dex, which is consistent with the value of $[Fe/H] = -1.74$ dex provided by [Oria et al. \(2022\)](#). The MDF of ED-3 resembles the one of Antaeus with very small dispersion, having a median metallicity of $[Fe/H] = -1.73$ dex and $\sigma_{[Fe/H]} = 0.21$ dex, thus hinting that the two substructures might be related. ED-2 is the

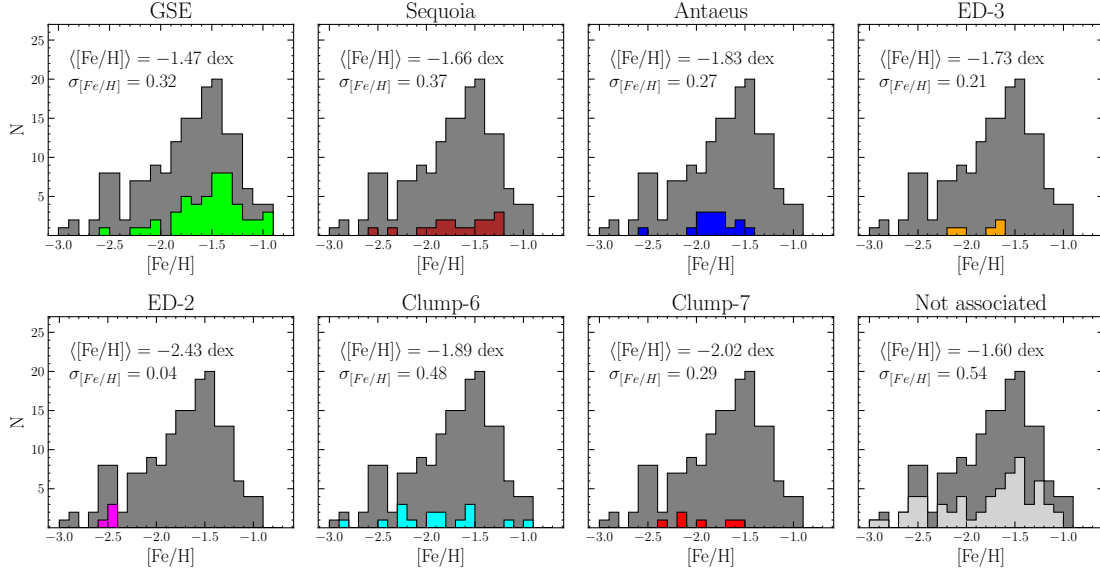


FIGURE 2.9 : Metallicity distribution functions for the RH substructures labeled at the top of each panel compared to the MDF of the entire sample of stars. The median metallicity value and the standard deviation of the distribution are also reported. The colour coding is the same as in Figure 2.4.

most metal-poor substructure and has an extremely tight MDF with a median metallicity of $[\text{Fe}/\text{H}] = -2.43$ dex and $\sigma_{[\text{Fe}/\text{H}]} = 0.04$ dex, which is consistent with the metallicity range reported by [Balbinot et al. \(2023\)](#) for the stars associated to this substructure. In the end, Clump-6 and Clump-7 show rather flat, unpeaked and broad MDFs, with median metallicity of $[\text{Fe}/\text{H}] = -1.89$ and -2.02 dex and $\sigma_{[\text{Fe}/\text{H}]} = 0.48$ and 0.29 dex, respectively.

To obtain a clearer view, I explored also the space defined by the orbital eccentricity, defined as $ecc = (apo - peri)/(apo + peri)$, where *apo* and *peri* are the orbital apocenter and pericenter, respectively. This dynamical parameter can help to efficiently differentiate the various substructures. Each substructure comprises stars that predominantly follow orbits characterised by very similar eccentricity (see Figure 2.10). The exceptions are Clump-6 and Clump-7, whose stars are spread across the range of $ecc \sim 0.1 - 0.8$.

In the left panel of Figure 2.11 I plot the behaviour of *ecc* as a function of the metallicity, finding that only stars with $[\text{Fe}/\text{H}] < -1.5$ dex are moving on low eccentricity orbits ($ecc < 0.4$). As made evident in the right-hand panel of Figure 2.11, RH substructures are well separated in the $ecc - Z_{\text{max}}$ space as well, where Z_{max} indicates the maximum absolute height over the Galactic plane reached by a star during its orbit. Once again, the exceptions are Clump-6 and Clump-7. The broad spread in the eccentricity values for the stars in these substructures, coupled with the shape of their MDFs, compels us to attribute the existence of these cluster to a combination of the selection criterion and the choice of hyperparameters in the clustering algorithm. As a result, I do not consider Clump-6 and Clump-7 to be genuine substructures or independent accretion events. Thus, I excluded stars associated to these two clusters from the rest of the analysis.

Based on the MDF and the eccentricity parameter, three substructures emerge as notably more coherent. GSE distinguishes itself as the most metal-rich component, characterised by

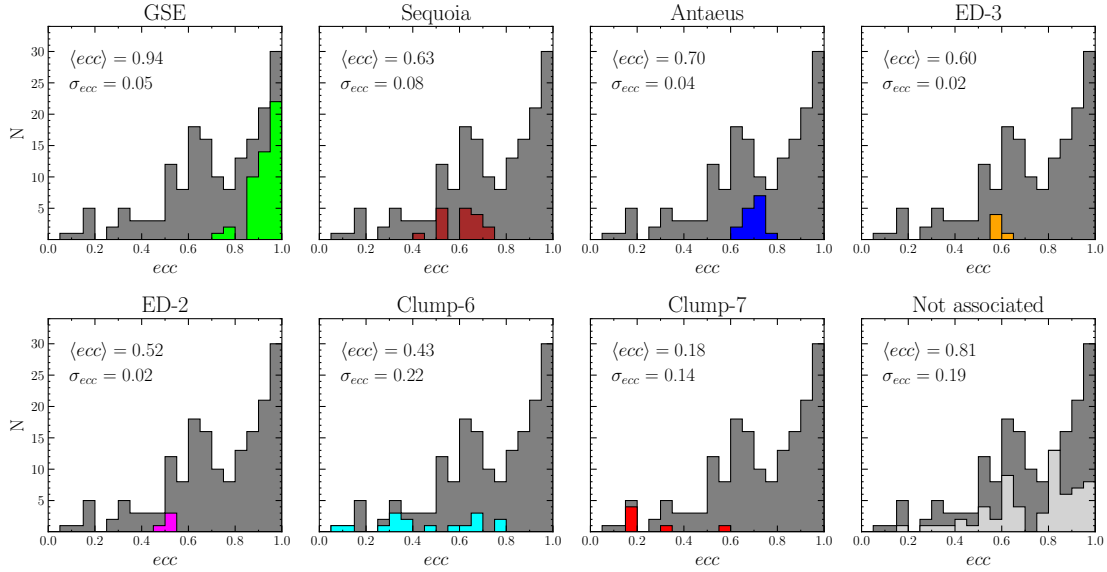


FIGURE 2.10 : Eccentricity distribution functions for the RH substructures labeled at the top of each panel compared to the distribution of the entire sample of stars. The median eccentricity value and the standard deviation of the distribution are also reported. The colour coding is the same as in Figure 2.4.

a peak in the MDF that closely mirrors the primary peak observed in the overall sample. Furthermore, GSE comprises stars that exhibit the highest eccentricities in their orbital motion. Then, Antaeus is identified as another well-defined substructure, with its stars primarily having orbits characterised by a relatively high eccentricity ($ecc \sim 0.7$). Finally, ED-2 exhibits distinctive features in its MDF and ecc , both being characterised by a remarkably narrow distribution. It is interesting to note that the two stars that were incorporated into the ED-2 clump by the clustering algorithm have $[\text{Fe}/\text{H}] \sim -1.90$ dex and also showcase a behaviour that is more akin to that of Sequoia in terms of eccentricity ($ecc > 0.6$) and $[\text{Ti}/\text{Fe}]$. These values support the choice to incorporate them as part of Sequoia.

2.6.2 Light elements

Recent studies have demonstrated that stars that have formed in-situ are enhanced in light elements abundances with respect to accreted populations and stars in dwarf satellite galaxies of the MW (Tolstoy et al. 2009; Feuillet et al. 2021; Hasselquist et al. 2021; Belokurov & Kravtsov 2022).

I show in Figure 2.12 that the stars from this sample display sub-solar values of $[\text{Na}/\text{Fe}]$, in agreement with the findings by Nissen & Schuster (2010). Moreover, it is evident that Antaeus displays a depletion in Na relative to GSE, consistently registering values ~ 0.2 dex lower. The sequence defined by Antaeus closely resembles the pattern found by Matsuno et al. (2022a) for the stars belonging to Sequoia, whereas WRS stars associated with Sequoia exhibit a behaviour that is more akin to that of GSE. However, Matsuno et al. (2022a) employed a relatively wide retrograde region within the IoM space to identify members of Sequoia (with L_z values ranging from -1600 to -3100 kpc km s $^{-1}$), making very likely that some Antaeus

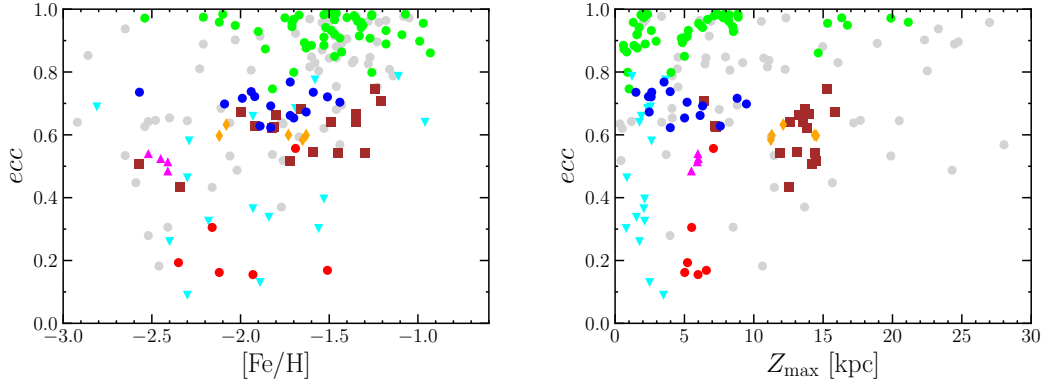


FIGURE 2.11: Distribution of the RH substructures in the $ecc - [\text{Fe}/\text{H}]$ space (left panel) and in the $ecc - Z_{\text{max}}$ (right panel). The colour coding is the same as in Figure 2.4.

stars inadvertently contaminate their Sequoia sample, thus potentially contributing to the observed similarities. Figure 2.12 also shows that the $[\text{Al}/\text{Fe}]$ trend of the targets is almost flat at $[\text{Al}/\text{Fe}] \sim -0.3$ dex up to $[\text{Fe}/\text{H}] < -1.0$ dex. The Al abundances observed in the majority of the target stars show a distinctively lower level compared to the typical values observed in the MW disc, thereby indicating a consistency with the position occupied by accreted systems. Interestingly, I find a spread of about 0.5 dex in the values of $[\text{Na}/\text{Fe}]$ and $[\text{Al}/\text{Fe}]$ for the associated stars, which might hint at a different fraction of massive stars exploding as hypernovae in the progenitors (Smiljanic et al. 2016).

2.6.3 α -elements

As shown in Figure 2.13, the interpretation of the findings is rather challenging. The spread of the measured $[\alpha/\text{Fe}]$ is significantly larger than the uncertainties. The fact that the WRS sample is systematically more metal-poor than typical disc stars makes the comparison with the APOGEE control sample not trivial (see Mg and Ca in Figure 2.13). Indeed, the $[\text{Mg}/\text{Fe}]$ of the sample seems systematically lower at $[\text{Fe}/\text{H}] > -1.5$ dex, when the patterns expected for a dwarf galaxy start to part ways from that expected for the MW (Tolstoy et al. 2009; Nissen & Schuster 2010; Hayes et al. 2018; Horta et al. 2023). In the most metal-poor regime, the two populations mix, but this is not surprising given that SNe Ia still have to start exploding. Conversely, for elements like Ti, where the reliability of APOGEE derived abundances is uncertain, I have opted to juxtapose the abundances with established high-resolution spectroscopy literature data. As demonstrated in Figure 2.13, the abundances are in agreement with those obtained for the MW halo. With a knowledge of this general behaviour, I can now focus in detail on the α -elements trends of the six substructures and discuss the possible origin of the distinct chemical patterns, described below:

- *Gaia-Sausage-Enceladus*. The Mg abundance ratios of the GSE stars overlap the metal-poor tail of the distribution of the low- α MW population, as already observed in previous works (Helmi et al. 2018; Mackereth et al. 2019). The reason for the difference in abundance between GSE and high- α stars is commonly believed to be the result of chemical enrichment by SNe Ia. In fact, in-situ stars have not undergone significant

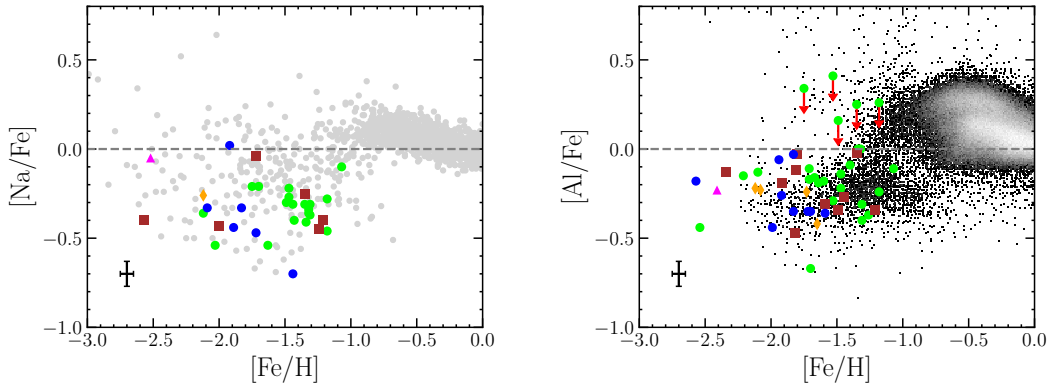


FIGURE 2.12 : behaviour of the light elements $[\text{Na}/\text{Fe}]$ and $[\text{Al}/\text{Fe}]$ abundance ratios as a function of $[\text{Fe}/\text{H}]$ for GSE, Sequoia, Antaeus, ED-2, and ED-3 stars (green, brown, blue, magenta, and orange, respectively). Red arrows indicate the upper limits. The errorbars in the lower-left corner indicate the typical uncertainties. The MW literature data for Na abundances are taken from [Edvardsson et al. \(1993\)](#); [Fulbright \(2000\)](#); [Stephens & Boesgaard \(2002\)](#); [Gratton et al. \(2003\)](#); [Reddy et al. \(2003, 2006\)](#); [Bensby et al. \(2005, 2014\)](#); [Roederer et al. \(2014\)](#) and [Reggiani et al. \(2017\)](#). The APOGEE control sample, as defined in Section 2.5, is plotted as a 2D histogram for Al, where black and white colours stand for low and high density regions, respectively.

enrichment by SNe Ia at $[\text{Fe}/\text{H}] \sim -1.0$ dex, whereas a dwarf galaxy like GSE has already experienced such enrichment due to a less efficient star formation history.

- *Sequoia*. The stars associated to Sequoia exhibit flat $[\alpha/\text{Fe}]$ patterns across the entire metallicity range. In particular, Sequoia occupies the same region of GSE at $[\text{Fe}/\text{H}] > -1.5$ dex, especially in the chemical plane of TiII. At lower metallicity, however, the behaviour shown by the Sequoia substructure more closely resembles that of the smaller retrograde substructures. At the same time, Sequoia seems to display $[\text{Mg}/\text{Fe}]$ and $[\text{Ca}/\text{Fe}]$ ratios that are $0.1 - 0.2$ dex lower than GSE, in agreement with the results by [Matsuno et al. \(2022a\)](#). Based on these findings, I favour the interpretation of Sequoia as an independent merger event with respect to GSE. Lower $[\alpha/\text{Fe}]$ values at fixed metallicity cannot be explained by the scenario that considers Sequoia as the outskirts of GSE that were first lost during the tidal disruption of the galaxy, as this would mean that the outer regions were polluted by SNe Ia ejecta before the inner ones, which is a feature yet not observed in existing dwarf MW satellites.
- *Antaeus*. The abundances of the α -elements suggest that Antaeus follows a distinctive chemical sequence in all the $[\alpha/\text{Fe}]$ planes at lower values at fixed metallicity with respect to the dominant components in the RH (GSE and Sequoia). At $[\text{Fe}/\text{H}] \sim -1.5$ dex, the $[\alpha/\text{Fe}]$ of Antaeus is consistently $0.1 - 0.2$ dex lower than those observed in GSE. I interpret this feature as evidence for the existence of Antaeus as an independent merging event, characterised by a progenitor with lower SFR compared to GSE and Sequoia.
- *ED-3*. This substructure is located in a region of the $[\alpha/\text{Fe}]$ chemical plane that is consistent with that of Antaeus. Constituted of only five stars, ED-3 overlaps with the

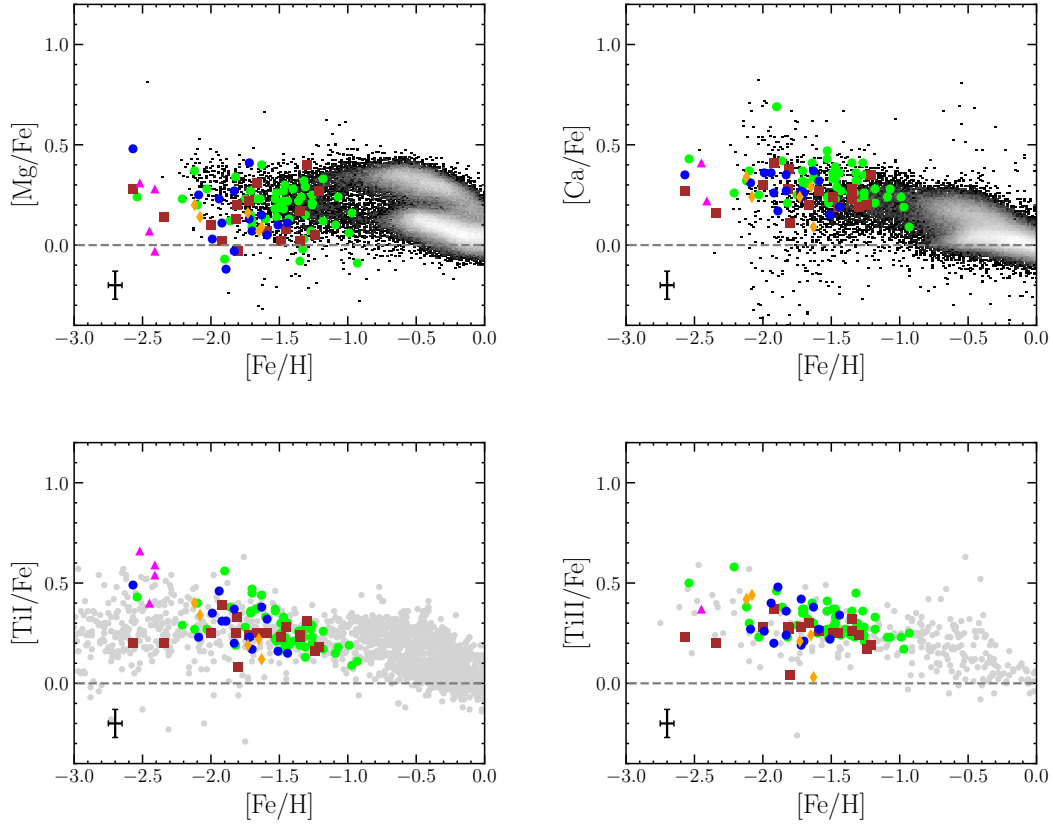


FIGURE 2.13 : Same illustration as Figure 2.12 for the α -elements $[\text{Mg}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, $[\text{TiI}/\text{Fe}]$, and $[\text{TiII}/\text{Fe}]$ abundance ratios. The MW literature data for TiI and TiII abundances are taken from Edvardsson et al. (1993); Fulbright (2000); Stephens & Boesgaard (2002); Gratton et al. (2003); Reddy et al. (2003, 2006); Barklem et al. (2005); Bensby et al. (2005, 2014); Roederer et al. (2014) and Reggiani et al. (2017).

Antaeus clump across its entire metallicity range. The two systems display a high degree of proximity in terms of their E and L_z , resulting in significant overlap within this parameter space. Based on this new chemo-dynamical evidence, I conclude that Antaeus / L-RL64 and ED-3 are actually part of the same relic. This evidence is confirmed in all of the chemical planes, as I will show in the next paragraphs.

- *ED-2*. The four stars associated with ED-2 occupy the very metal-poor end of the chemical planes, being all located at $-2.6 < [\text{Fe}/\text{H}] < -2.4$ dex. This system exhibits a markedly narrow metallicity distribution and its chemical composition is generally consistent with that of the other RH substructures, with the exception of Ti, where it seems to be enhanced. Its position in the $[\alpha/\text{Fe}]$ plane seems to recall the one of I'toi (Naidu et al. 2022a). Given the small sample, any conclusions inferred about the chemical pattern of this system would be premature and require further investigation on a much extended sample of stars (see Section 6.2.1).

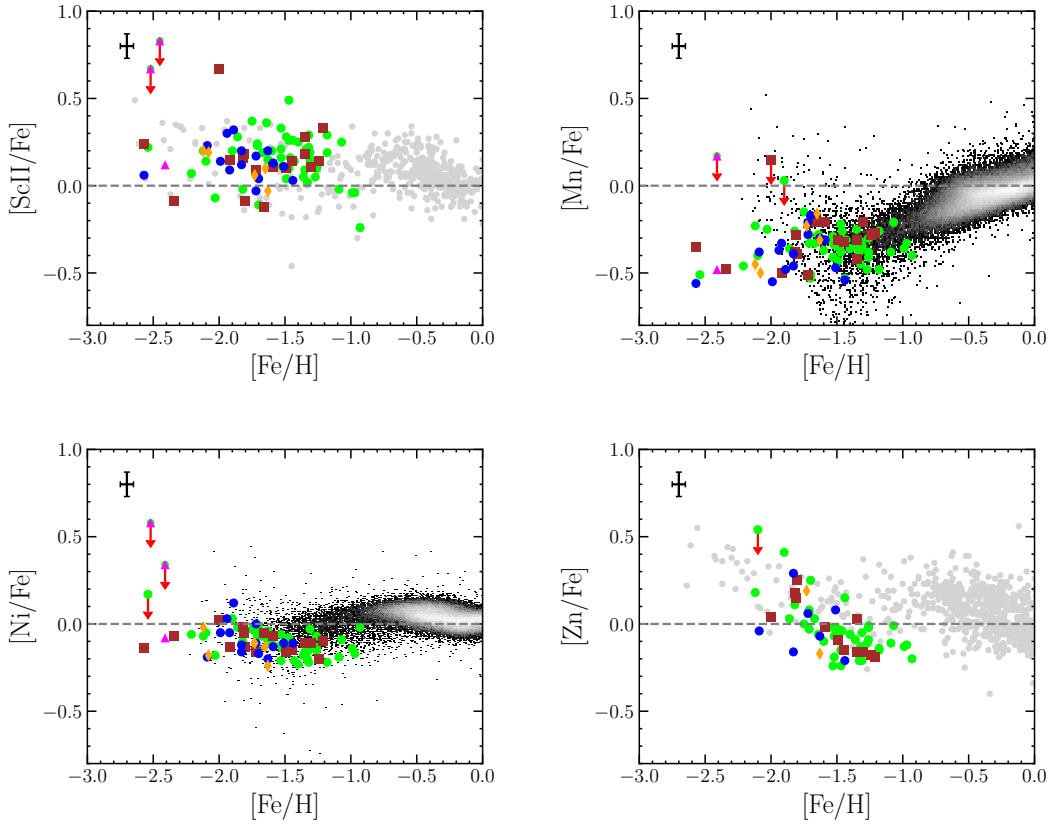


FIGURE 2.14: Same illustration as Figure 2.12 for the iron-peak elements $[\text{ScII}/\text{Fe}]$, $[\text{Mn}/\text{Fe}]$, $[\text{Ni}/\text{Fe}]$ and $[\text{Zn}/\text{Fe}]$ abundance ratios. The MW literature data for Sc and Zn abundances are taken from Stephens & Boesgaard (2002); Gratton et al. (2003); Reddy et al. (2003, 2006); Bensby et al. (2005, 2014); Roederer et al. (2014) and Reggiani et al. (2017).

2.6.4 Iron-peak elements

As shown in Figure 2.14, all the RH substructures exhibit abundances that are remarkably similar to those observed in accreted populations and low-mass satellite galaxies of the MW (Nissen & Schuster 1997; Tolstoy et al. 2009). The interpretation of these results is complex, as the small differences between the various substructures can be explained by both the diverse production sites of these elements and the metallicity dependencies of their yields at low metallicity (Weinberg et al. 2022). The chemical patterns of the iron-peak elements for the different substructures seem to reveal that GSE and Sequoia display a similar distribution. Moreover, Antaeus and ED-3 exhibit, once again, an overlap in their respective loci within these chemical plane, providing additional support for the hypothesis that they are associated with the same accretion event.

2.6.5 Neutron-capture elements

Of all neutron-capture elements, I focus only on yttrium (Y) in this Chapter. This element is predominantly formed by the slow neutron capture process (*s*-process, i.e., neutron capture

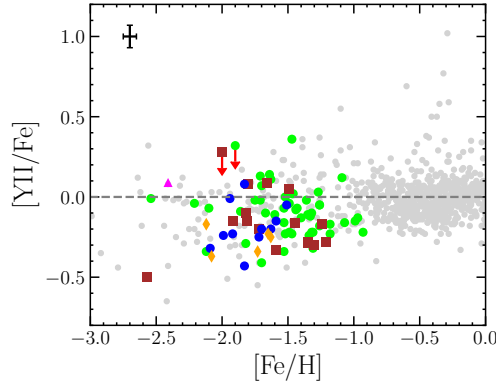


FIGURE 2.15 : Same illustration as Figure 2.12 for the neutron capture element $[YII/Fe]$ abundance ratios. The MW literature data for Y abundances are taken from [Edvardsson et al. \(1993\)](#); [Fulbright \(2000\)](#); [Stephens & Boesgaard \(2002\)](#); [Reddy et al. \(2003, 2006\)](#); [Bensby et al. \(2005\)](#) and [Reggiani et al. \(2017\)](#).

that is slower than the β -decay).

Y is mainly synthesized by s -processes in the envelope of low-mass ($1 - 4 M_{\odot}$) AGB stars and, to a lesser extent, in massive stars ([Busso et al. 1999](#); [Pignatari et al. 2010](#); [Cristallo et al. 2015](#)). At low metallicity, magneto-rotational SNe and mergers of neutron stars contribute significantly to the production of these neutron-capture elements via r -processes, thus explaining the observed scatter ([Kasen et al. 2017](#); [Molero et al. 2023](#)).

Despite the huge scatter between abundances of stars born in the same progenitor, the results in Figure 2.15 show that the average abundances for the Sequoia substructure is comparable to the one of GSE, as previously hinted also by [Aguado et al. \(2021\)](#). Within the common metallicity range, Antaeus and ED-3 exhibit a pronounced degree of overlapping, consistently displaying average abundances that are lower ($\sim 0.1 - 0.2$ dex) than those observed in GSE.

2.7 Summary and conclusions

In this first Chapter dedicated to the WRS series, I introduce the project, describing the methodology and highlighting the scientific goals it aims to pursue. To demonstrate the potential of this project, I have narrowed the focus to the subset composed of 90 stars associated by the DBSCAN clustering algorithm with various RH substructures within the IoM space (see [Dodd et al. 2023](#)) and I have analysed their chemical properties. The interpretation of the chemical patterns of unassociated stars will be left to future contributions to the series (see Section 6.2.2). I present a concise summary of the principal findings of this Chapter below:

1. A selection criterion based on tangential velocity only (thus not requiring the V_{los} information) is able to select stars that move on retrograde motions with a 91.4% efficiency (by requiring $V_T > 400 \text{ km s}^{-1}$). All of the stars included in the sample consistently exhibit chemical pattern across all chemical element planes that aligns

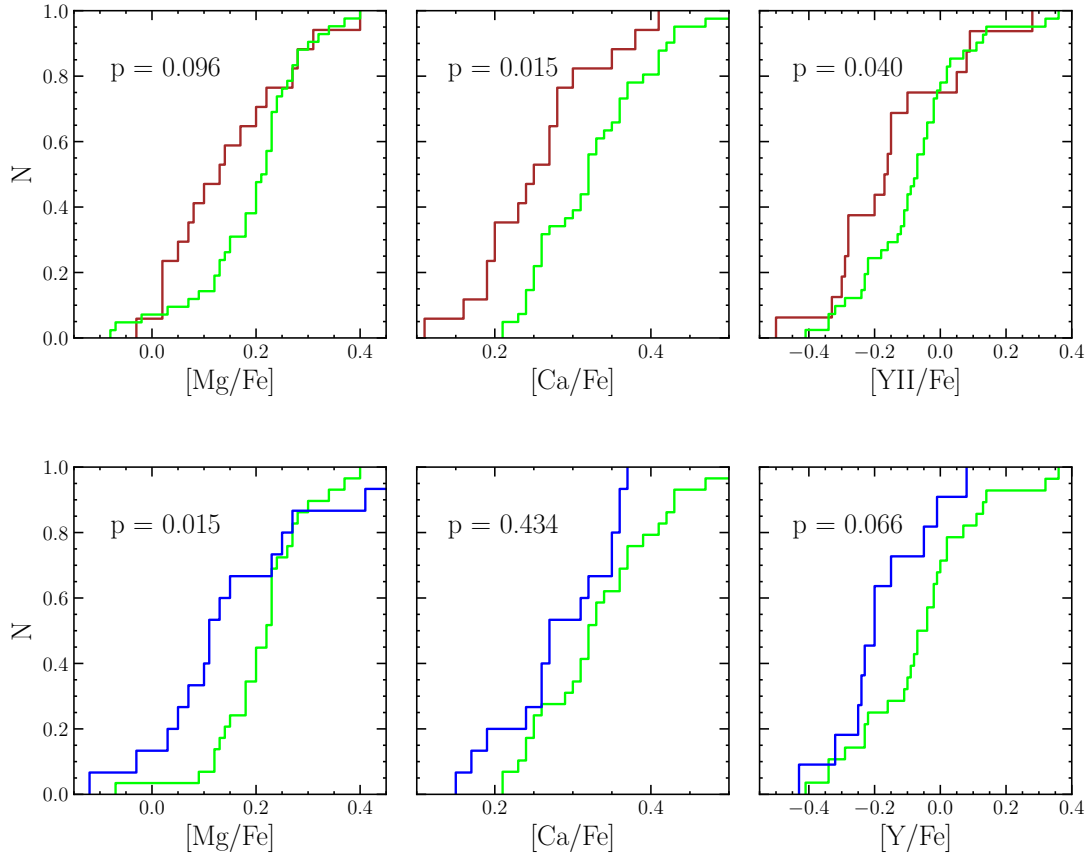


FIGURE 2.16 : Comparison of the cumulative distribution functions of $[\text{Mg}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$ and $[\text{YII}/\text{Fe}]$ for Sequoia and GSE stars (brown and green lines, respectively) in the common metallicity range $(-2.60 < [\text{Fe}/\text{H}] < -1.20 \text{ dex})$ shown at the top. I report the probability that the two distributions are drawn from the same parent sample according to a Kolmogorov-Smirnov test. Bottom panel is the same as the top, but for for Antaeus and GSE stars (blue and green lines, respectively) in the common metallicity range $(-2.60 < [\text{Fe}/\text{H}] < -1.45 \text{ dex})$.

with the characteristic abundance patterns displayed by accreted systems and dwarf galaxies.

2. In spite of the selection criteria leaving out the bulk of GSE stars at higher L_z and lower energy from our sample, GSE stands out as the largest and most metal-rich component within the RH. This supports the hypothesis that it represents the remnant of the most massive galaxy that was accreted by the MW.
3. The chemical patterns of GSE and Sequoia display similar trends at $[\text{Fe}/\text{H}] > -1.5 \text{ dex}$. However, significant distinctions become evident at lower metallicity, specifically characterised by a discernible difference in the α -elements. In particular (as shown in the top panel of Figure 2.16), Sequoia exhibit a pronounced excess of stars with lower $[\text{Mg}/\text{Fe}]$ and $[\text{Ca}/\text{Fe}]$ ratios with respect to GSE. Consequently, this discrepancy leads to interpret Sequoia as an independent accretion event distinct from GSE.

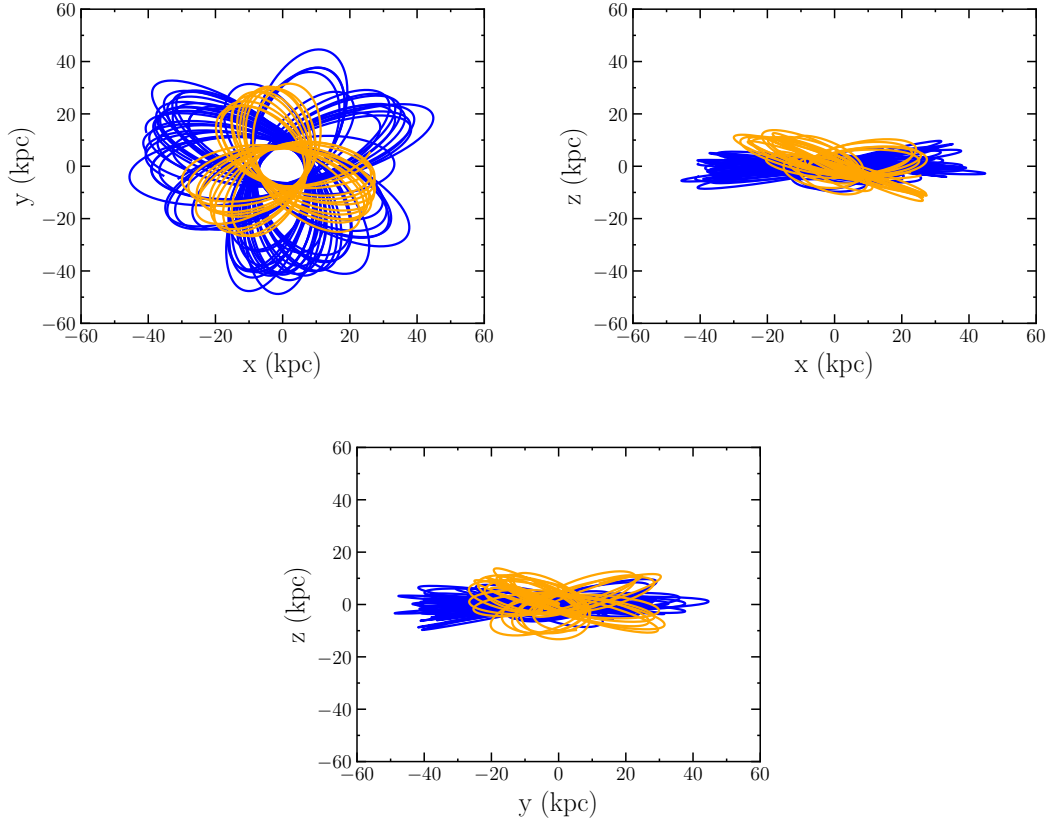


FIGURE 2.17 : Orbits of Antaeus (blue lines) and ED-3 (orange lines) stars in the Galactocentric reference frame integrated backwards in time for 2.5 Gyr in a [McMillan \(2017\)](#) potential for the MW.

4. For the first time, I have achieved a comprehensive chemical characterization of Antaeus, encompassing detailed chemical abundances for numerous elements. The analysis reveals distinct behaviour in the chemical space compared to GSE within the same metallicity range (see bottom panel of Figure 2.16), reinforcing the idea that it constitutes the remnant of an accretion event independent of GSE.
5. Antaeus and ED-3 exhibit analogous positions in the IoM spaces, albeit with some distinctions in $L_{\perp}$. Additionally, they share similarities in terms of their metallicity distribution function and orbital eccentricity. Furthermore, the chemical patterns observed in Antaeus and ED-3 are consistent across all chemical elements. In the end, I integrated backwards in time (for 2.5 Gyr) the orbits of the stars associated to these two substructures in a [McMillan \(2017\)](#) potential for the MW. As depicted in Figure 2.17, stars from the two substructures appear to move on very similar orbits. Collectively, these lines of evidence lead to interpret them as components of the same merging event. Henceforth, I refer to this merging event as Antaeus.
6. ED-2 is the most metal-poor component, with a remarkably narrow MDF peaked at $[\text{Fe}/\text{H}] = -2.43$ dex, in agreement with the findings of [Balbinot et al. \(2023\)](#). The limited number of stars within the ED-2 substructure, coupled with the specific combination of their stellar parameters ($T_{\text{eff}} > 6000$ K and $[\text{Fe}/\text{H}] < -2.4$ dex) which

leads to the manifestation of weak spectral lines, restricts the capacity to attain detailed chemical abundances across all elements. As a consequence, I am unable to definitively assert whether ED-2 constitutes the remnant of a globular cluster or a dwarf galaxy. In this regard, a search for the characteristic anti-correlations commonly associated with globular clusters will serve to dispel this doubt (Section 6.2.1).

In light of the aforementioned complexities in identifying and interpreting MW halo substructures based on orbital information alone, the significance of these results lies in the fact that they are based on a pre-established classification, adding clarity amidst the ongoing confusion surrounding the newly identified substructures. While this study represents a crucial first step towards unravelling their true nature, it is crucial to acknowledge the need for more extensive investigations. Indeed, detailed chemical abundance measurements for a broader range of stars in the Galactic halo remain lacking. Future investigations by WRS will target RH stars that have already been associated to different disrupted progenitors (see Chapter 3), in order to disentangle ambiguous associations and shed lights on the chemical features of the retrograde substructures.

As we continue to expand our knowledge, the pursuit of larger datasets of high-resolution spectroscopy, alongside future large spectroscopic surveys of MW halo stars and dwarf galaxies, such as WEAVE (Dalton et al. 2020) and 4MOST (de Jong et al. 2019), will undoubtedly propel us towards a more comprehensive understanding of the Galactic halo's diverse substructures. Thus, we will be able to better constrain the evolutionary history of the Milky Way.

3 | Chemistry to disentangle in-situ and accreted components in Thamnos

Based on the published paper by Ceccarelli et al. (2025a), A&A, 704, A180

In this Chapter, I present the results of the second paper dedicated to the WRS project (Ceccarelli et al. 2024a), focused on the first systematic high-resolution chemical analysis of the Thamnos substructure, a candidate relic of the process of hierarchical merging of the MW. Despite its relevance, the true nature of Thamnos remains uncertain, as described in Section 1.2.5. Previous studies have raised doubts about its identity as an independent merging event, suggesting possible contamination from other Halo components (i.e. GSE and the in-situ Halo). However, these works were often based on limited samples and/or lower resolution spectroscopic data (e.g. from APOGEE), preventing a definitive characterization of its properties. With this study, I aim to address this open question by establishing, once and for all, the detailed chemical fingerprint of Thamnos through high-resolution spectroscopy. In particular, I seek to clarify its intrinsic chemical properties and, if possible, define criteria to identify stars accreted from Thamnos via comparison with galactic chemical evolution models, thereby constraining its origin and role in the early evolution of the MW. The study and interpretation of the results are performed in comparison with the GSE remnant, within the fully self-consistent and homogeneous framework established by the WRS project. The observational strategy and the dataset used in this work are explained in Section 3.1. In Section 3.2 and Section 3.3 I briefly describe the methods employed to carry the chemodynamical analysis, and present the results. In Section 3.4 I compare the abundances with predictions from galactic chemical evolution models. Section 3.5 concludes.

In what follows, I refer to Thamnos and the Thamnos substructure indistinctly. As I progress in the analysis and especially in later sections, I refer to the ‘true Thamnos’ as a putative accreted component distinct from GSE and the in-situ population.

3.1 Selection of candidate Thamnos and GSE stars

I used the catalogue of accreted stars based on the third data release of *Gaia* (DR3, [Gaia Collaboration et al. 2023](#)) provided in [Dodd et al. \(2023\)](#), focusing on bright ($G < 15$) RGB stars linked to Thamnos and GSE (see their Section 2 for all the quality cuts applied to *Gaia* data). The final sample comprises 142 stars associated to Thamnos and 78 to GSE. In the left panel of Figure 3.1 I show the CMD of selected targets superimposed to a sample of the full Halo within 2 kpc. Magnitudes have been corrected taking $E(B - V)$ values from the [EXPLORE¹](#) webpage.

The high-resolution spectra of the targets were collected with the optical spectrograph UVES ([Dekker et al. 2000](#)) at the VLT@ESO under the programs 0112.B-0236 (P.I.: E. Ceccarelli) and 0113.B-0196 (P.I.: E. Ceccarelli). Observations were taken with UVES in Dichroic mode using the Dic 1 Blue Arm CD2 390 (3300 – 4500 Å) and the Dic 1 Red Arm CD3 580 (4800 – 6800 Å) and adopting the $1 \times 12''$ slit ($R \sim 40000$). The average S/N is typically higher than 25 for the Blue Arm and 50 for the Red Arm. The obtained target spectra have been reduced with the dedicated ESO pipeline². I provide in the right panel of Figure 3.1 the spectra of several targets with similar atmospheric parameters (i.e. effective temperature and surface gravity) but different $[\text{Fe}/\text{H}]$. Information on representative target stars can be found in Table 3.1.

3.2 Orbital parameters

A detailed description of the methods used to study the orbits of target stars is presented in Section 2.2. Briefly, I combined the 5D phase-space information from *Gaia* DR3 with the V_{los} obtained from high-resolution spectra via cross-correlation with template spectra with the same atmospheric parameters through `fxcor` from `IRAF`. Typical uncertainties on the V_{los} for each spectrum are computed as described in [Tonry & Davis \(1979\)](#), and they are typically $< 0.4 \text{ km s}^{-1}$. I corrected both parallax and V_{los} for the effects of the *Gaia* zero-point offset ([Lindgren et al. 2021](#)) and the gravitational redshift ([Zwitter et al. 2018](#)), respectively. Within the sample, I find 9 stars with a difference with the *Gaia* V_{los} measurement larger than 3σ , and I flag them as potential binaries in the final catalogue. The median orbital parameters for each target, together with the line-of-sight velocity, are listed in Table 3.2.

In Figure 3.2 I show the position of the targets superimposed with stars from [Ceccarelli et al. \(2024a, Paper I hereafter\)](#). I remind that in [Paper I](#) I selected retrograde stars in the Halo by imposing a cut in the linear velocity in the sky plane ($V_{\text{T}} > 400 \text{ km s}^{-1}$, see Section 2.1 for a complete discussion). This criterion prevented to select either stars with low orbital energy ($E \leq -1.7 \times 10^5 \text{ km}^2 \text{ s}^{-2}$) moving on retrograde orbits ($L_z \sim -1000 \text{ kpc km s}^{-1}$) and stars with slightly higher orbital energy ($E \leq -1.5 \times 10^5 \text{ km}^2 \text{ s}^{-2}$) and almost null net rotation, that is where Thamnos and the bulk population of GSE are located, respectively. As evident from Figure 3.2, in this work I am able to sample these two substructures appropriately.

¹<https://explore-platform.eu/>

²<https://www.eso.org/sci/software/pipelines/>

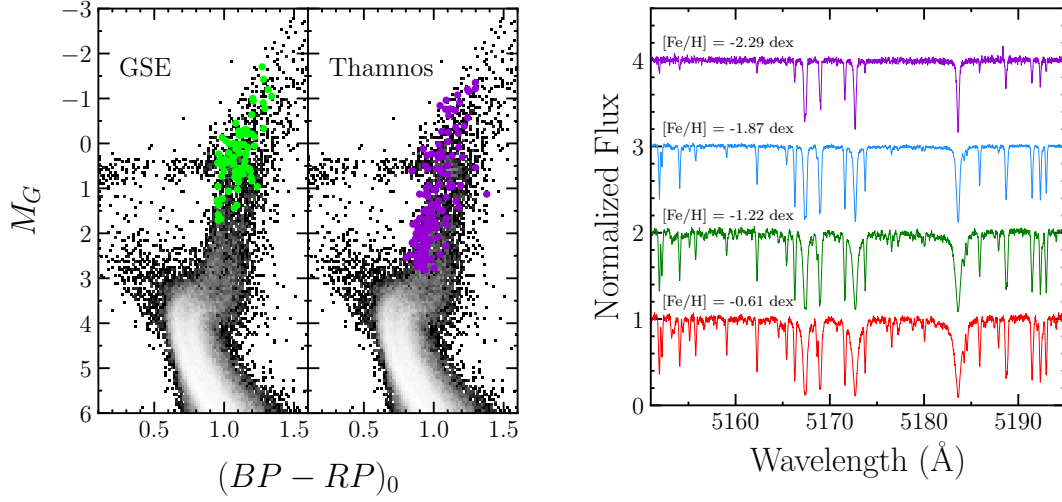


FIGURE 3.1 : Left panel: CMD of stars associated to GSE and Thamnos (green and purple filled symbols, respectively). In the background a density map of nearby Halo stars ($d < 2$ kpc) is plotted. Right panel: UVES spectra of four target stars with similar atmospheric parameters and different metallicity. The spectra have been arbitrarily shifted vertically for plotting purposes.

TABLE 3.1 : Information for some representative targets.

ID <i>Gaia</i> DR3	RA (deg)	Dec (deg)	$E(B - V)$ (mag)	G (mag)
5138126933062532352	30.8293700	-18.833342	0.02	10.5038
3541053961204824832	172.587726	-22.548268	0.04	11.2243
5828822717270400128	243.864451	-64.377047	0.15	12.4347
6435410912786146816	288.023829	-65.008052	0.06	13.4251
6794113593364452608	312.424452	-31.081279	0.06	13.8453
ID <i>Gaia</i> DR3	t_{exp} (s)	Airmass	S/N (3900 Å)	S/N (5800 Å)
5138126933062532352	200	1.727	27	71
3541053961204824832	400	1.298	20	48
5828822717270400128	1000	1.302	22	62
6435410912786146816	1600	1.195	29	75
6794113593364452608	3000	1.260	32	78

NOTES. ID and coordinates from *Gaia* DR3, colour excess, apparent G magnitude, exposure time (t_{exp}), airmass, and S/N at the centre of the Blue and Red Arms of UVES for some of the observed target spectra.

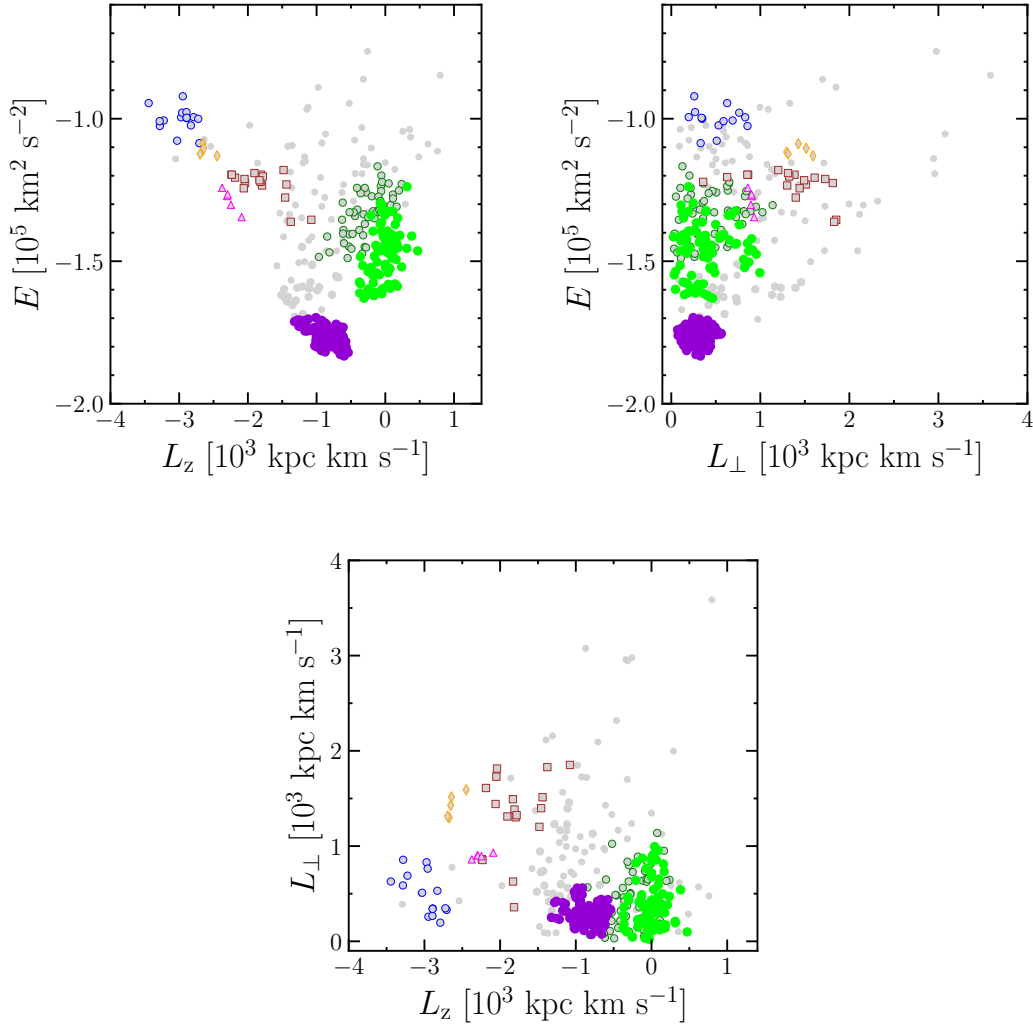


FIGURE 3.2 : Distribution of the observed stars in $E - L_z - L_\perp$ spaces. Stars associated to Thamnos and GSE by [Dodd et al. \(2023\)](#) are plotted in purple and green, respectively. Stars from [Paper I](#) are reported in background as gray points. The colour coding of the border of these points reflect the association provided in [Paper I](#) (see also [Figure 2.4](#)): dark green for GSE, brown for Sequoia, blue for Antaeus, magenta for ED-2, orange for ED-3, and gray for stars that are not associated to any substructure.

3.3 The chemical composition of Thamnos and GSE

To erase the chance that some offset is introduced in the final results due to differences in the assumptions in the chemical analysis, I stick to the procedure followed in [Section 2.4](#).

In particular, first input effective temperatures (T_{eff}) have been estimated following the colour – temperature relation by [Mucciarelli et al. \(2021b\)](#) using the $(BP - RP)$ colour, assuming $E(B - V)$ from the **EXPLORE** tool and $[\text{Fe}/\text{H}] = -1.5$ dex. Surface gravities ($\log g$) have been derived through the Stefan-Boltzmann relation (see [Section 2.4.1](#)) and microturbulent velocities (v_t) have been obtained by imposing no the trend between iron abundances

TABLE 3.2 : Dynamical information for selected targets (extract).

ID <i>Gaia</i> DR3	E ($\times 10^5 \text{ km}^2 \text{ s}^{-2}$)	L_z (kpc km s^{-1})
5138126933062532352	-1.599 ± 0.010	-203 ± 53
3541053961204824832	-1.323 ± 0.047	-46 ± 83
5828822717270400128	-1.790 ± 0.009	-728 ± 37
...	...	...
L_{perp} (kpc km s^{-1})	V_{los} (kpc km s^{-1})	Binary (km s^{-1})
46 ± 22	-52.5 ± 0.5	no
391 ± 36	133.3 ± 0.4	no
185 ± 10	315.7 ± 0.4	no
...	...	...

NOTES. ID from *Gaia* DR3, orbital energy, angular momentum along the z -axis, perpendicular angular momentum, and line-of-sight velocity with uncertainties. The complete table is available in the electronic form of the paper [Ceccarelli et al. \(2025a\)](#).

and reduced equivalent widths. As the colour-temperature depends on metallicity, first estimates for the stellar parameters were subsequently refined adopting the correct $[\text{Fe}/\text{H}]$ values. Derived atmospheric parameters for target stars are listed in Table 3.3.

Chemical abundances are derived using **ATLAS9** ([Kurucz 2005](#)) model atmospheres and the linelists with atomic and molecular data from the Kurucz/Castelli³ database. The abundance analysis for Na, Mg, Ca, Ti, Cr, Fe, Ni, and Zn is based on the equivalent width (EW) method, using the code **GALA** ([Mucciarelli et al. 2013](#)). EWs are measured with **DAOSPEC** ([Stetson & Pancino 2008](#)). For the elements with hyperfine/isotopic splitting transitions and/or blended lines (Al, Mn, Co, Cu, Y, Ba, La and Eu), the abundances were derived via spectral synthesis using the proprietary code **SALVADOR**. All the abundance ratios refer to the solar composition by [Grevesse & Sauval \(1998\)](#). The procedure for error estimates is described in detail in Section 2.4.4.

Among the stars analysed in this work, I find 4 showing significant C enhancement, resulting in spectra that are heavily contaminated by molecular absorption features. Additionally, 4 stars show high Li abundances. Of these 8 chemically peculiar stars, 5 are associated with Thamnos and 3 with GSE. Since the primary objective of this work is to interpret abundance patterns as tracers of the distinct chemical enrichment histories of the progenitors, I neglect stars that behave in a peculiar way compared to the bulk of the populations under study. Carbon and lithium enrichment are commonly linked to binary evolution, implying that the observed abundances may no longer reflect the original chemical signature of the formation environment but rather the influence of the co-evolution with the companion star. For this reason, I exclude these stars from the subsequent analysis. Their properties will be explored in detail in a forthcoming, dedicated study.

In the end, I derive abundances for 137 and 75 stars associated to Thamnos and GSE,

³<http://wwwuser.oats.inaf.it/castelli/linelists.html>

TABLE 3.3: Stellar parameters for the selected targets (extract).

ID <i>Gaia</i> DR3	T_{eff} (K)	$\log g$ (dex)	v_t (km s ⁻¹)
5138126933062532352	5157	2.44	1.5
3541053961204824832	4864	2.03	1.4
5828822717270400128	5183	2.35	1.9
...	...	...	...

NOTES. ID from *Gaia* DR3, effective temperature (T_{eff}), surface gravity ($\log g$), and microturbulent velocity (v_t). Typical uncertainties on T_{eff} , $\log g$, and v_t are of the order of 100 K, 0.1 dex and 0.2 km s⁻¹. The complete table is available in the electronic form of the paper [Ceccarelli et al. \(2025a\)](#).

respectively. Values of the abundance ratios of light, α -, iron-peak and neutron capture elements are reported in Table 3.4. In the following I discuss results obtained from the analysis.

3.3.1 Metallicity distributions

I use the Fe abundance derived from approximately 100 neutral lines per star as a proxy for metallicity. In Figure 3.3 I show the MDFs of GSE and Thamnos (left and right panels, respectively). The median and standard deviation are reported in each panel. I also display for GSE the stacked histogram obtained adding the sample from [Paper I](#) (dark green line). I note that the two GSE samples analysed in [Paper I](#) and in the present work are entirely independent, with no overlap between the stars. I find that the MDF of the GSE stars analysed in this work is, on average, 0.3 dex more metal-rich than that reported in [Paper I](#). This is somehow expected, as the selection criteria adopted in [Paper I](#) preferentially target GSE stars moving on higher-energy and more retrograde orbits (see top left panel of Figure 3.2), which are likely to represent the earliest stars stripped during the merging event and to originate from the outer regions of the progenitor ([Koppelman et al. 2020](#); [Amarante et al. 2022](#); [Skúladóttir et al. 2025](#)). Thus, if a negative metallicity gradient was in place in GSE, as observed for surviving dwarf galaxies (see e.g. [Tolstoy et al. 2009](#)), stars from [Paper I](#) should be on average more metal-poor than the bulk population of GSE. Taken together, these considerations suggest that the most representative picture of the GSE progenitor is obtained by combining the two samples, with the present work tracing the bulk of the system (due to the dynamical selection of [Dodd et al. \(2023\)](#), which prefers purity over completeness), and [Paper I](#) preferentially probing stars presumably stripped from the outskirts of the progenitor galaxy. The peak and shape of the overall GSE MDF are consistent with previous literature investigations (e.g. [Helmi et al. 2018](#); [Vincenzo et al. 2019](#); [Naidu et al. 2020](#); [Myeong et al. 2022](#); [Dodd et al. 2025a](#)). For Thamnos candidate members, I find that the MDF is slightly more metal-poor than that of GSE, with a peak at $[\text{Fe}/\text{H}] \sim -1.5$ dex, and a slightly more pronounced tail at low metallicity, similar to that presented in [Dodd et al. \(2025a\)](#).

Given that stars in Thamnos display low orbital energy and retrograde motion, a region of the IoM space typically dominated by in-situ stars (i.e. the Aurora population, [Belokurov & Kravtsov 2022](#)), some level of contamination from such stellar population is expected (see also [Dodd et al. 2025a](#)). Also, if the Aurora population is indeed the dominant source of

TABLE 3.4: Chemical abundances for the light, α -, iron-peak and neutron capture elements (extract).

ID <i>Gaia</i> DR3	[Fe/H]	[Na/Fe]	[Al/Fe]	[Mg/Fe]
5138126933062532352	-0.78 ± 0.10	-0.23 ± 0.05	0.00 ± 0.12	0.14 ± 0.02
3541053961204824832	-1.34 ± 0.11	-0.36 ± 0.08	-0.02 ± 0.13	0.35 ± 0.03
5828822717270400128	-2.31 ± 0.10	—	-0.36 ± 0.12	0.35 ± 0.04
...	...	...	...	...
[Ca/Fe]	[Ti/Fe]	[ScII/Fe]	[Cr/Fe]	[Mn/Fe]
0.09 ± 0.03	-0.06 ± 0.05	0.10 ± 0.07	-0.13 ± 0.03	-0.31 ± 0.14
0.31 ± 0.04	0.18 ± 0.06	0.11 ± 0.08	-0.09 ± 0.03	-0.39 ± 0.15
0.35 ± 0.04	0.31 ± 0.04	0.11 ± 0.07	-0.12 ± 0.03	—
...	...	...	...	...
[Ni/Fe]	[Cu/Fe]	[Zn/Fe]	[YII/Fe]	[BaII/Fe]
-0.17 ± 0.04	-0.20 ± 0.16	-0.04 ± 0.12	-0.12 ± 0.10	0.46 ± 0.17
-0.15 ± 0.04	-0.54 ± 0.16	-0.02 ± 0.13	-0.16 ± 0.10	0.26 ± 0.17
0.05 ± 0.05	—	0.13 ± 0.06	-0.28 ± 0.10	-0.10 ± 0.17
...	...	...	...	...
	[LaII/Fe]	[EuII/Fe]	Progenitor (D23)	
	0.36 ± 0.06	0.36 ± 0.05	GSE	
	0.42 ± 0.06	0.69 ± 0.05	GSE	
	0.35 ± 0.06	0.59 ± 0.05	Thamnos	
	...	...	...	

NOTES. In the last column I report the dynamical association with the former progenitor by [Dodd et al. \(2023\)](#). The entire table is available in the electronic form of the paper [Ceccarelli et al. \(2025a\)](#).

contamination, it could also explain the sharp decline in the MDF observed at $[\text{Fe}/\text{H}] \sim -1.3$ dex. The earlier mentioned excess of stars with $[\text{Fe}/\text{H}] < -2.0$ dex relative to GSE, is consistent with findings by [Dodd et al. \(2025a\)](#), and may signal the presence of the residual stellar debris from the ‘true Thamnos’ progenitor. In the following, I discuss the detailed chemical abundances of several elements that will help in disentangling the contribution of in-situ contamination from the real accreted population in the Thamnos substructure.

3.3.2 Abundances of light elements

In Figure 3.4 I present the abundance ratios of light elements Na and Al as a function with $[\text{Fe}/\text{H}]$ for Thamnos and GSE (purple and green points, respectively). Specifically, Na has been measured through EW using the doublet at ~ 5680 Å while abundances for Al have been measured via spectral synthesis of the doublets at $3944 - 3962$ Å and $6696 - 6698$ Å. Abundances of Na and Al have been corrected for NLTE effects interpolating the grids provided by [Lind et al. \(2022\)](#).

As evident from the top panel of Fig. 3.4, both Thamnos and GSE show tight patterns in $[\text{Na}/\text{Fe}]$, yet they differ on average by 0.2 dex at fixed metallicity. In particular, Thamnos shows a flat trend at $[\text{Na}/\text{Fe}] \sim -0.3$ dex up to $[\text{Fe}/\text{H}] \sim -0.5$ dex while GSE is depleted,

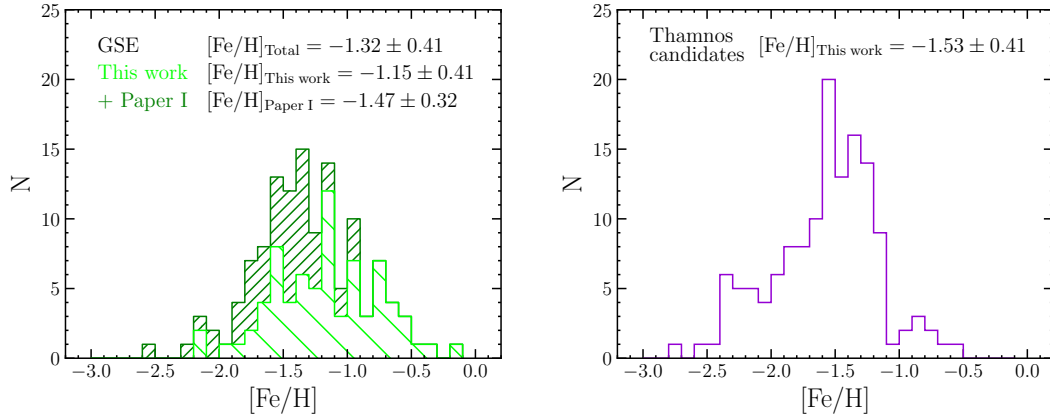


FIGURE 3.3 : Metallicity distributions of the GSE (left panel) and Thamnos (right panel) coming from neutral Fe lines. The median metallicity of the distributions and the standard deviation are also reported in each panel. For GSE I report the MDF derived in this work (green) alongside the stacked MDF using also stars from [Paper I](#) (dark green). I note that the shift in metallicity I find between the two samples in GSE might be due to a gradient in the progenitor reflected by the position of its stars in the $E - L_z$ plane (see discussion in the text).

with $[\text{Na}/\text{Fe}] \sim -0.5$ dex.

A different behaviour between the two substructures can be seen in Al abundances, too. Indeed, GSE stars follow a flat trend with $[\text{Al}/\text{Fe}] \sim -0.2$ dex across the entire metallicity range, in agreement with results from [Paper I](#) (gray points with dark green borders). In contrast, Thamnos stars show a clear increase in $[\text{Al}/\text{Fe}]$ with metallicity: their values are comparable to those of GSE up to $[\text{Fe}/\text{H}] \sim -1.7$ dex, beyond which they rise steadily, reaching enhancements of ~ 0.4 dex at $[\text{Fe}/\text{H}] \sim -1.0$ dex and overlapping with the trend described by the in-situ population. This behaviour is typical of an environment that efficiently undergoes rapid chemical self-enrichment, allowing the $[\text{Al}/\text{Fe}]$ to grow before the onset of SNe Ia, as the yield of Al strongly depends on the metallicity of the progenitor star ([Hawkins et al. 2015](#); [Hayes et al. 2018](#); [Kobayashi et al. 2020b](#)). On the contrary, the star formation in GSE-like systems is not efficient enough to produce such a trend.

3.3.3 Abundances of α -elements

In this work, Mg abundances are derived from the 5528 Å and 5711 Å lines. To ensure consistency with the results presented in [Paper I](#), where only the Mg b triplet lines were available, I additionally derived Mg abundances using this feature for the current dataset. I find a systematic offset of 0.12 dex ($\sigma = 0.04$ dex) between the two sets of measurements, with the Mg b triplet yielding lower abundances. Therefore, to enable a homogeneous comparison, the Mg abundances from [Paper I](#) presented in top panel of Figure 3.5 (gray points with dark green borders) have been rescaled by this offset. I note that the GSE stars analysed in this work follow a well-defined $[\text{Mg}/\text{Fe}]$ trend that closely aligns with the main distribution reported by [Paper I](#). However, I also identify a few stars from the [Paper I](#) sample exhibiting $[\text{Mg}/\text{Fe}] < 0.2$ dex at $[\text{Fe}/\text{H}] < -1.3$ dex. These outliers may originate from lower-mass accreted systems and could have been inadvertently included in the GSE sample due to the

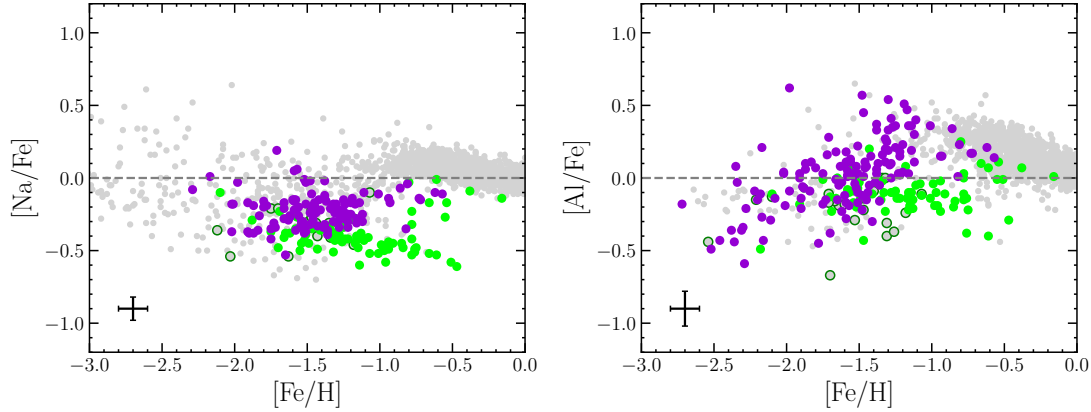


FIGURE 3.4 : Abundance ratios of the light elements Na and Al for the selected stars corrected for NLTE effects. The colour coding is the same as in Figure 3.2. In the lower left corner of each panel I report typical uncertainties for the abundance ratios. Literature abundances for MW stars are taken from [Edvardsson et al. \(1993\)](#); [Fulbright \(2000\)](#); [Stephens & Boesgaard \(2002\)](#); [Gratton et al. \(2003\)](#); [Reddy et al. \(2003, 2006\)](#); [Barklem et al. \(2005\)](#); [Bensby et al. \(2005, 2014\)](#); [Roederer et al. \(2014\)](#), [Reggiani et al. \(2017\)](#), and [Paper I](#). Gray points with dark green borders are GSE stars from [Paper I](#).

specific selection criteria adopted in that study (see discussion above).

At $[\text{Fe}/\text{H}] > -1.5$ dex, Thamnos and GSE appear to follow distinct trends, whereas at lower metallicity their distributions increasingly overlap. As observed also in the light elements (see Figure 3.4), Thamnos exhibits enhanced abundances in all α -elements (Mg, Ca, and Ti) compared to GSE by up to 0.2 dex at $[\text{Fe}/\text{H}] > -1.5$ dex. Indeed, the α -element abundances in Thamnos are consistent with those observed in the MW high- α sequence ([Nissen & Schuster 2010](#)), showing a flat trend up to $[\text{Fe}/\text{H}] \sim -0.5$ dex and hinting at a strong in-situ contamination in the higher metallicity regime. On the contrary, GSE $[\alpha/\text{Fe}]$ ratios start to drop at $[\text{Fe}/\text{H}] \sim -1.2$ dex, reflecting a non-negligible contribution by SNe Ia to the chemical enrichment of the gas already in place at this metallicity, likely due to a less efficient star formation compared to the MW ([Vincenzo et al. 2019](#); [Gallart et al. 2019](#); [González-Koda et al. 2025](#)).

3.3.4 Abundances of iron-peak elements

Results for the iron-peak elements are shown in Figure 3.6. The chemical trends of GSE match those reported in [Paper I](#), and the relative abundances to Thamnos resemble the differences observed between low- and high- α population in the MW ([Nissen & Schuster 2010, 2011](#)). In particular, Thamnos is on average enhanced in Cr, Co, Ni, and Zn compared to GSE at fixed metallicity, especially at $[\text{Fe}/\text{H}] > -1.5$ dex. Among the elements I analysed, the largest difference (~ 0.3 dex) arise in the light/weak s -process Cu. Indeed, $[\text{Cu}/\text{Fe}]$ abundances are significantly sub-solar (≤ -0.5 dex) in both structures at $[\text{Fe}/\text{H}] \sim -2$ dex, but increase with metallicity, with a steeper rise in Thamnos candidate stars compared to GSE. From a theoretical perspective, Cu is mainly produced in massive stars via the weak s -process, and its yield is expected to grow with metallicity due to the higher availability of metal seed nuclei ([Romano & Matteucci 2007](#); [Prantzos et al. 2018](#)). The shallower $[\text{Cu}/\text{Fe}]$

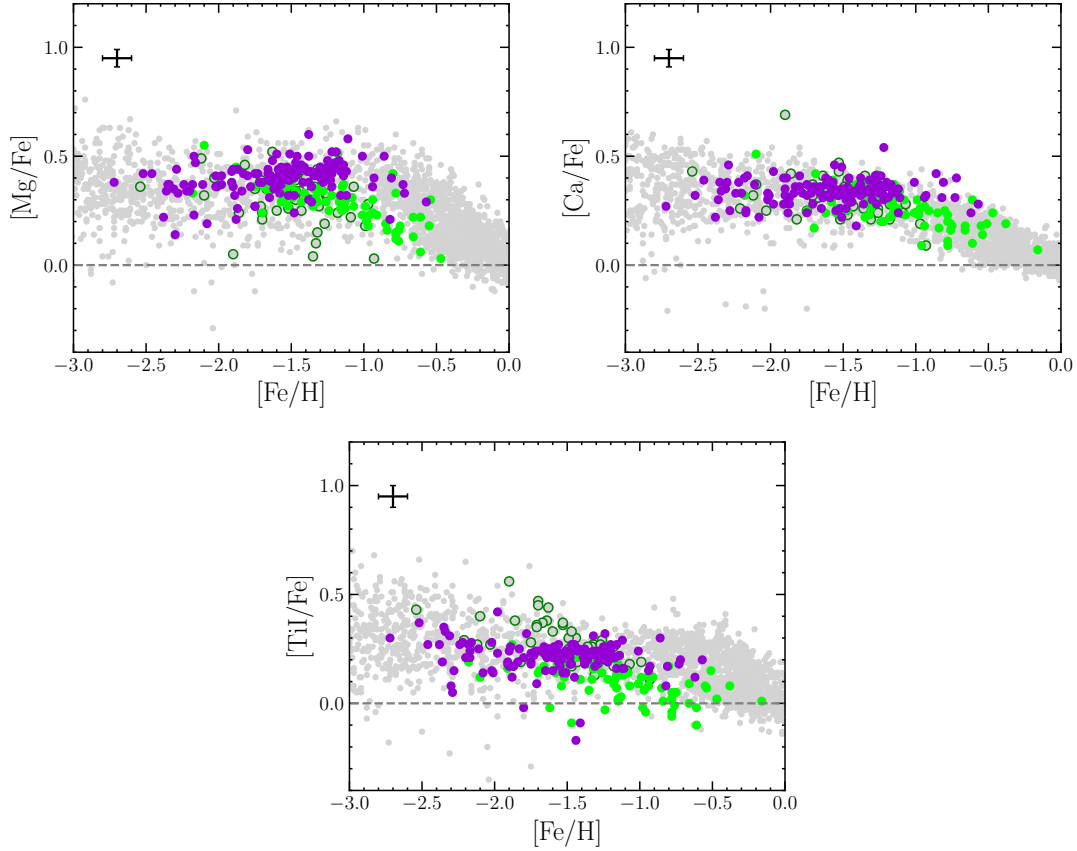


FIGURE 3.5 : Same as Figure 3.4 but for Mg, Ca, and Ti.

increase in GSE suggests a reduced contribution from massive stars, consistent with theoretical predictions and observations in other dwarf galaxies, such as the Magellanic Clouds (Van der Swaelmen et al. 2013; Mucciarelli et al. 2023). However, I caution that NLTE effects can be significant, especially at low metallicity, limiting the reliability of Cu as a precise chemical tagger (e.g. Andrievsky et al. 2018). I see no difference in the trends of Thamnos and GSE in Mn. All of this evidence combined suggests that the chemical enrichment of the interstellar medium where dynamically selected Thamnos stars with $[\text{Fe}/\text{H}] > -1.5$ dex formed, was more strongly influenced by massive stars or did not receive significant contribution by SNe Ia. This in turn highlights an origin from a stronger star forming environment than that of GSE.

3.3.5 Abundances of neutron capture elements

Figure 3.7 presents the abundance trends for neutron capture elements. I observe a significantly larger scatter in the $[\text{YII}/\text{Fe}]$, $[\text{LaII}/\text{Fe}]$, and $[\text{BaII}/\text{Fe}]$ ratios for both Thamnos and GSE, relative to the tighter trends seen in the α - and iron-peak elements (see Figures 3.4 – 3.6), consistent with previous findings by Matsuno et al. (2022a). This increased dispersion is likely attributable to the combined contributions from the light, heavy s - and r - process formation channels involved in the synthesis of these elements (Kasen et al. 2017). I identify an excess of stars enhanced in all s -process elements (i.e., $[\text{YII}/\text{Fe}] > 0.2$ dex, $[\text{LaII}/\text{Fe}] > 0.5$

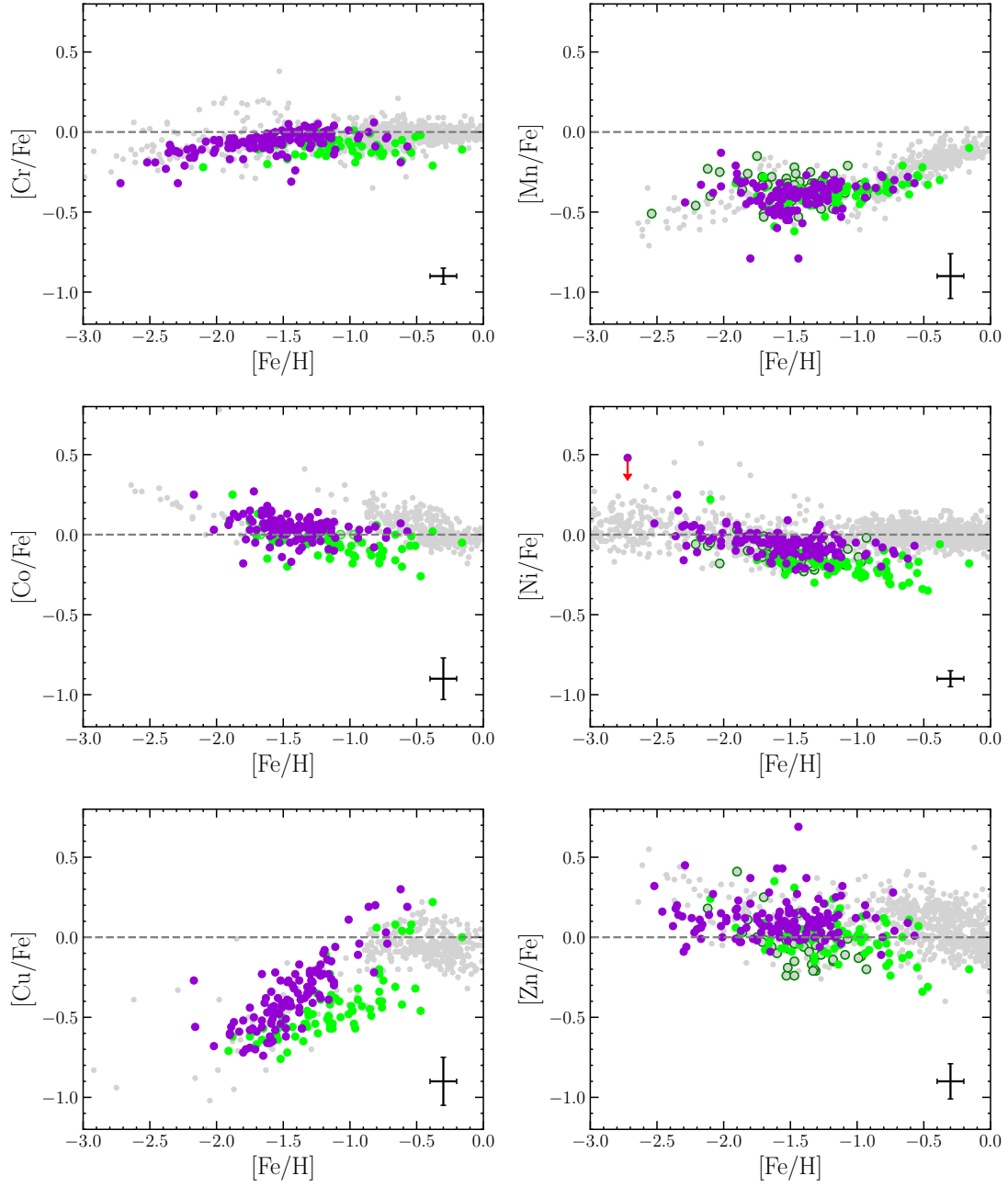


FIGURE 3.6 : Same as Figure 3.4 but for Cr, Mn, Co, Ni, Cu, and Zn. Upper limits are plotted as red arrows.

dex, and $[\text{BaII}/\text{Fe}] > 0.5$ dex) within the metallicity range $-2.0 < [\text{Fe}/\text{H}] < -1.0$ dex, which may indicate a binary origin. Nevertheless, all of these stars exhibit reliable astrometric solutions from *Gaia* ($\text{RUWE} < 1.4$, [El-Badry 2024](#), and references therein), while only two have a spectroscopic V_{los} that differs from the *Gaia* values at the 3σ level. To probe the relative efficiency of these processes, I examine the $[\text{YII}/\text{BaII}]$ and the $[\text{EuII}/\text{BaII}]$ ratios (see top panels of Figure 3.8). The $[\text{YII}/\text{BaII}]$ ratio shows, on average, lower values in GSE stars at $[\text{Fe}/\text{H}] > -1.5$ dex, as also observed by various authors when comparing to in-situ stars ([Nissen & Schuster 2011](#); [Matsuno et al. 2021](#)). This trend may reflect a reduced efficiency in the production of light s -process elements in GSE, which is corroborated by the depletion observed in other weak s -process tracers such as Cu (see Figure 3.6). Also, I can attribute the lower $[\text{YII}/\text{BaII}]$ to more prominent contribution of strong s -process production by low-mass stars at equivalent metallicity, as the slower pace at which chemical enrichment proceeded in GSE allowed a more efficient enrichment by delayed stellar populations. Indeed, this rise is not observable in the $[\text{BaII}/\text{Fe}]$ plot due to more prominent contribution by SNe Ia, which have similar timescale of enrichment than that of low-mass stars, preventing a rise in the $[\text{BaII}/\text{Fe}]$. Therefore, the lower light-to-heavy s -ratios at $[\text{Fe}/\text{H}] > -1.5$ dex can be explained by a combination of smaller production from the weak s -process and larger production in strong s -process. Concerning the r -process contribution, GSE population show an enhanced production through this channel, which is also mirrored by its enhancement in Eu, a pure tracer of r -process (see Figure 3.7). Indeed, among the neutron capture species, Eu exhibits the clearest distinction between Thamnos and GSE: stars with $[\text{Fe}/\text{H}] > -1.5$ dex in the Thamnos substructure are on average depleted in $[\text{EuII}/\text{Fe}]$ by ~ 0.3 dex compared to GSE candidates. This appears to be a common feature when comparing the abundance patterns of MW satellites with that of MW in-situ stars (e.g. [Palla et al. 2025](#)). Indeed, the Eu abundances in our sample, derived from the EuII lines at 4129 Å and 6645 Å, reach $[\text{EuII}/\text{Fe}] \geq 0.4$ dex in GSE stars, consistent with prior determination in literature for samples of either GSE stars ([Aguado et al. 2021](#); [Matsuno et al. 2021](#); [Naidu et al. 2022b](#)) and globular clusters ([Ceccarelli et al. 2024b](#); [Monty et al. 2024](#)), and resembles the enhancement observed in surviving dwarf galaxies ([Letarte et al. 2010](#); [Lemasle et al. 2014](#); [Liberatori et al. 2025](#)). The different $[\text{EuII}/\text{Fe}]$ patterns can explain the different behaviour in $[\text{EuII}/\text{BaII}]$ shown by Thamnos candidates and GSE, with the latter enhanced relative to the former at $[\text{Fe}/\text{H}] > -1.5$ dex. This means that the enhancement in r -process (traced by Eu) is in proportion more efficient than the one from the strong s -process (traced by Ba). Moreover, the distinct trends exhibited by Thamnos and GSE stars in the $[\text{EuII}/\text{Mg}]$ abundance plane at $[\text{Fe}/\text{H}] > -1.5$ dex (see bottom panel of Figure 3.8) provide compelling evidence for the differing star formation timescales and efficiencies that characterised their respective progenitor environments at these high metallicity. In fact, despite Eu being a mixture of CC-SNe-like and delayed events (see [Côté et al. 2019](#); [Molero et al. 2023](#)), recent evidence highlight that the main source of r -process at $[\text{Fe}/\text{H}] \leq -1$ dex are NSM ([Palla et al. 2025](#)). Therefore, given that in the observed regime Mg and Eu trace nucleosynthetic sources operating on markedly different timescales (i.e. CC-SNe and delayed r -process events, respectively), the observed depletion further supports the conclusion that stars in the Thamnos substructure with $[\text{Fe}/\text{H}] > -1.5$ dex experienced a star formation history more consistent with that of in-situ populations. On the other hand, for $[\text{Fe}/\text{H}] < -2$ dex, the abundances are more consistent with those of GSE, with possibly slightly larger scatter (in e.g. $[\text{Mg}/\text{Fe}]$, $[\text{TiI}/\text{Fe}]$,

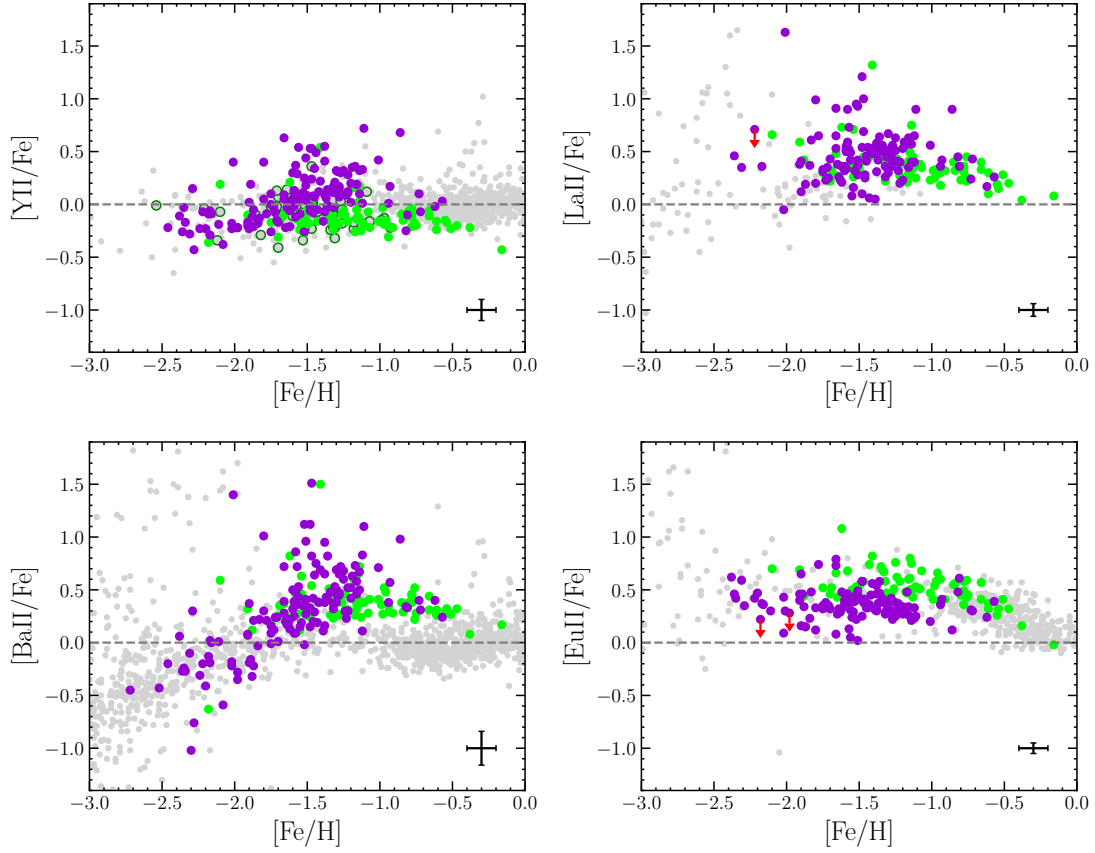


FIGURE 3.7 : Same as Figure 3.4 but for Y, La, Ba, and Eu. Upper limits are plotted as red arrows.

[LaII/BaII] and [EuII/Mg].)

3.4 Comparison with galactic chemical evolution models

The chemical patterns observed in many chemical elements (e.g. α -elements, Na, Al, Cu, Zn, and Eu) for the dynamically selected Thamnos stars with $[\text{Fe}/\text{H}] > -1.5$ dex are reminiscent of those typically measured for in-situ stars, and stand in contrast to the abundances generally found in stars associated with accreted substructures or surviving dwarf galaxies at this metallicity (Venn et al. 2004; Tolstoy et al. 2009; Nissen & Schuster 2010; Aguado et al. 2021; Belokurov & Kravtsov 2022; Matsuno et al. 2022a; Horta et al. 2023, Paper I). In light of these results, it is likely that the Thamnos sample is significantly contaminated by in-situ stars, especially in the higher metallicity regime. To further investigate this hypothesis on a more quantitative basis, I developed galactic chemical evolution (GCE) models to reproduce and interpret the chemical trends observed in these substructures.

In the following, I briefly recap the main ingredients of GCE models. For more details on the general model structure and equations, I address the reader to Palla et al. (2020b); Matteucci (2021).

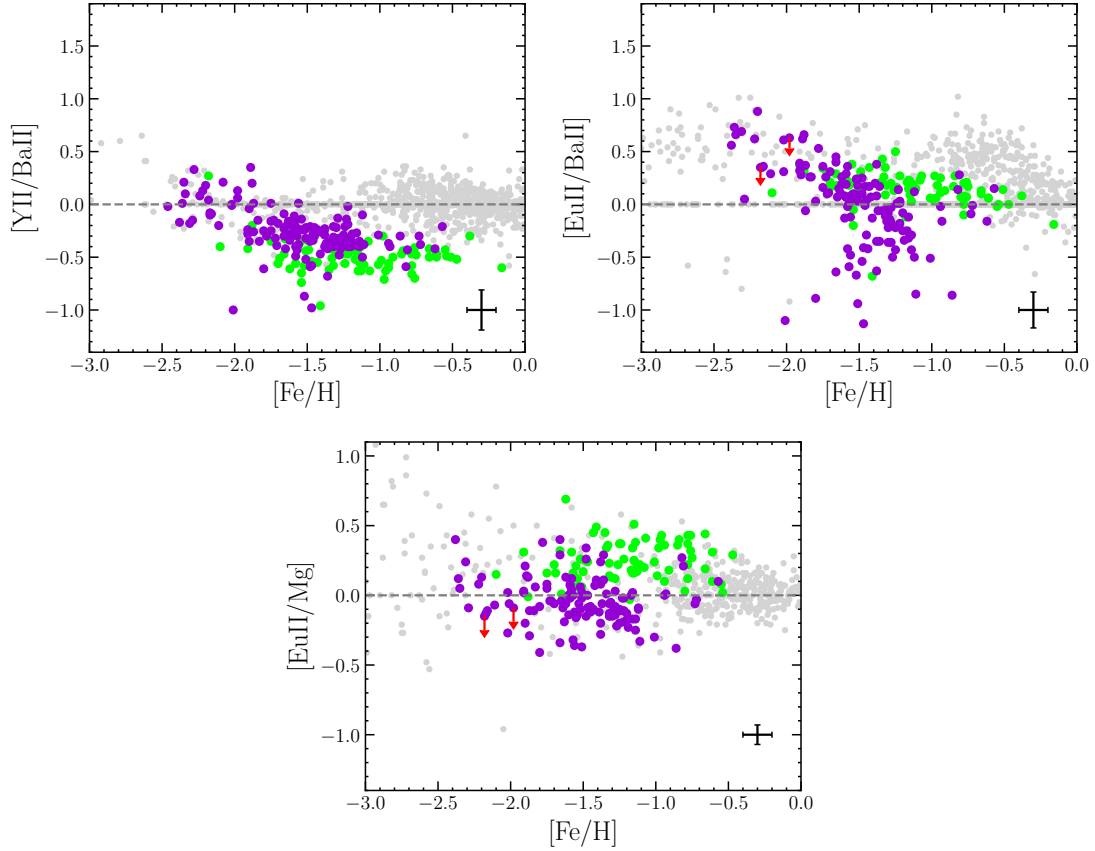


FIGURE 3.8 : Same as Figure 3.4 but for the $[YII/BaII]$, $[EuII/BaII]$, and $[EuII/Mg]$ ratios. Upper limits are plotted as red arrows.

3.4.1 Basic ingredients

As commonly assumed in the galactic chemical evolution literature (Romano & Starkenburg 2013; Vincenzo et al. 2019; Kobayashi et al. 2020a), to fuel star formation cold gas of primordial chemical composition is accreted to the galaxy at an exponentially decreasing rate:

$$\dot{M}_{inf}(t) \propto e^{-t/\tau_{inf}}, \quad (3.1)$$

where $M_{inf}(t)$ is the mass accreted at time t and τ_{inf} the e-folding time for gas accretion. The star formation rate (SFR) is implemented according to the Kennicutt-Schmidt law (Kennicutt 1998):

$$\psi(t) = \nu M_{gas}(t)^k, \quad (3.2)$$

with $k = 1$ and the star formation efficiency (SFE) ν as the control parameter that represents the SFR per unit mass of gas, $M_{gas}(t)$.

As I am dealing with systems with shallower potential wells due to their fairly low masses, the models also allow for gas loss through outflows. Here, I assume them to be proportional to the SFR (e.g. Vincenzo et al. 2015; Molero et al. 2021; Palla et al. 2024):

$$\dot{M}_{out}(t) = \omega \psi(t), \quad (3.3)$$

where ω is the mass loading factor parameter.

For what concerns the stellar nucleosynthesis, all the models adopted in this work relax the instantaneous recycling approximation, therefore allowing the different elements to be restored to the interstellar medium according to the lifetimes of their stellar progenitors. These are weighted according to the stellar initial mass function, for which I use the one by [Kroupa et al. \(1993\)](#), extensively used to model the evolution of the MW components and its satellites (e.g. [Romano et al. 2005](#); [Vincenzo et al. 2019](#); [Palla et al. 2020a](#); [Nieuwmunster et al. 2023](#)).

I adopt well-tested yield sets by [Karakas \(2010\)](#) for low- and intermediate-mass stars, [Nomoto et al. \(2013\)](#) for massive stars/CC-SNe and [Iwamoto et al. \(1999\)](#) for SNe Ia. For the latter, the delay-time-distribution by [Matteucci & Recchi \(2001\)](#), see also [Palla 2021](#) for details) is assumed. For [Nomoto et al. \(2013\)](#) massive star yields instead, I assume a decreasing HNe fraction with metallicity as in [Mucciarelli et al. \(2021a\)](#).

3.4.2 Models for GSE and Thamnos progenitors

Below, I summarize the main model assumptions for the adopted GCE models tailored reproduce the available observables for the GSE and Thamnos progenitors. It is worth noting that, when possible, the adopted assumptions anchor on previously tested GCE modelling for the specific objects.

- *GSE progenitor.* The GCE model adopted for the GSE galaxy progenitor is analogue to the one proposed by [Vincenzo et al. \(2019\)](#). This model is characterised by a mild star formation efficiency ($\nu \simeq 0.4 \text{ Gyr}^{-1}$, i.e. $\sim \times 5$ smaller than the one adopted for modelling the MW halo and thick disk, see e.g. [Spitoni et al. 2019](#)), very fast infall timescale ($\tau_{inf} \sim 0.25 \text{ Gyr}$) and a mild outflow efficiency ($\omega = 0.5$). For more details, I refer to the original paper of [Vincenzo et al. \(2019\)](#);
- *Thamnos progenitor.* I build a model for a Thamnos progenitor based on the information from the MDF provided in this work. To avoid contamination from likely the Aurora population and catch the signature of the ‘true Thamnos’ (see Section 3.3.1), I fix the GCE model parameters in order to reproduce the peak at $[\text{Fe}/\text{H}] < -2.0$ dex in the MDF of the Thamnos substructure. To isolate such a component, I assume the MDF shown in Figure 3.3 lower panel as composed by the sum of two Gaussian distributions and consider the low-metallicity component (‘distr1’ in the left panel of Figure 3.9) as the putative ‘true Thamnos’ MDF.

I am able to reproduce ‘distr1’ with a model with small gas accretion timescales ($\sim 0.5 \text{ Gyr}$) and large wind mass loading factor (~ 10), combined by a modest star formation efficiency ($\sim 0.1 \text{ Gyr}^{-1}$). These ingredients lead to a very short star forming episode (see right panel of Figure 3.9), with most of the stellar mass ($\sim 85\%$) built during the first Gyr of evolution. This is comparable to the estimate that the ‘true Thamnos’ already built half of its mass $12.3 \pm 0.3 \text{ Gyr}$ ago ([Dodd et al. 2025a](#)). Such a star formation history (SFH) allows to keep a MDF peaking at low metallicity ($[\text{Fe}/\text{H}] \sim -2.15$ dex) with a relatively narrow distribution ($\pm 1\sigma \sim 0.45$ dex), as shown in the central panel of Figure 3.9.

Figure 3.10 shows the predicted abundance tracks by the models described above for GSE (in green curve) and for the ‘true Thamnos’ (in purple) compared with the observations for

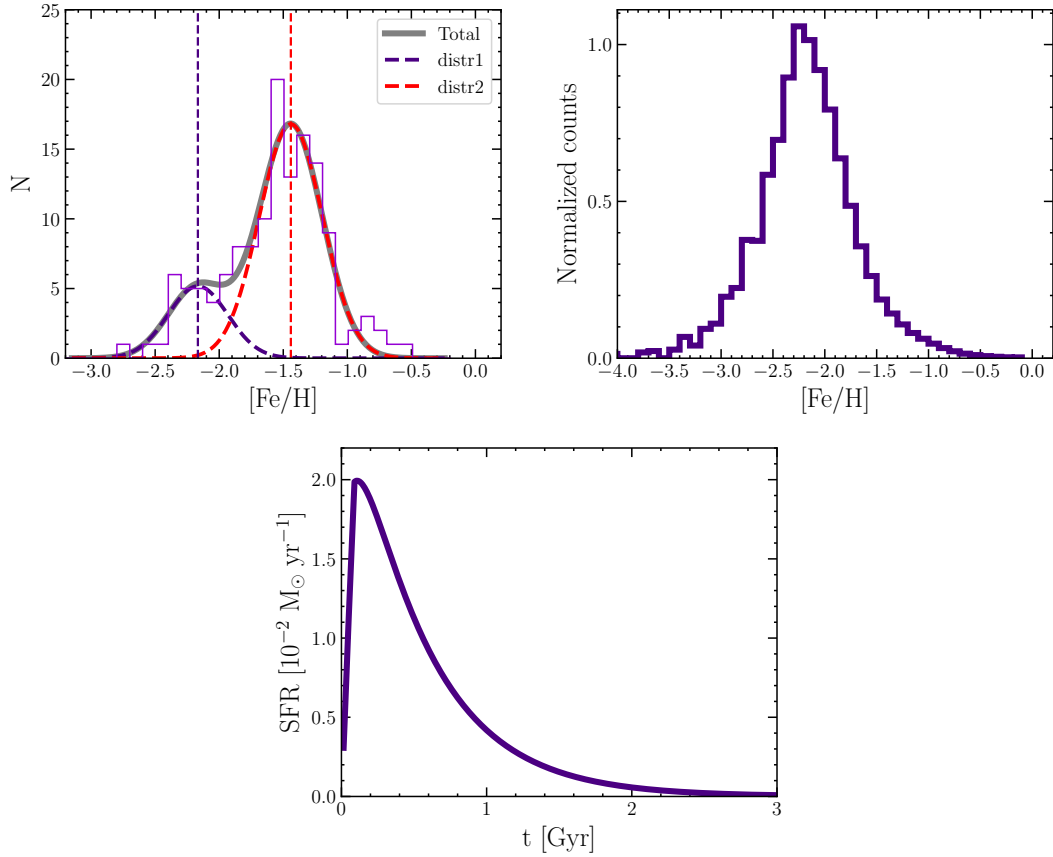


FIGURE 3.9 : Division of the MDF of the Thamnos substructure (see Figure 3.3 left panel) into two distributions to identify the ‘true’ Thamnos component and the contamination from in-situ stars (left panel) and MDF, SFH as predicted by the model built for Thamnos progenitor presented in Section 3.4.2 (top left and bottom panels, respectively). In the top left panel, the ‘true’ Thamnos distribution traced by observation is labelled with ‘distr1’ (dashed blue line), while MW in-situ contamination would be represented by ‘distr2’ (dashed red line).

$[\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]$ (left panel) and $[\text{Mg}/\text{Mn}] - [\text{Al}/\text{Fe}]$ (right panel). These chemical diagnostic diagrams can be used as a powerful probe for the SFH of galaxies as due to the time-delay model (Matteucci 2012; Hawkins et al. 2015; Das et al. 2020; Matteucci 2021). As shown in the left panel of Figure 3.10, the predicted chemical track for the GSE progenitor aligns well with the observed trend, following tightly the $[\text{Mg}/\text{Fe}]$ evolution up to the metal-rich end of GSE stars. The latter fall below the general trend for MW stars (grey points), highlighting an environment with less efficient star formation. On the other hand, the predicted $[\text{Mg}/\text{Fe}]$ evolution for the Thamnos progenitor (purple line) allows us to identify the trend for putative ‘true Thamnos’ stars. Indeed, the model follows closely the metal-poor end of the observed stars, whose $[\text{Mg}/\text{Fe}]$ level is depleted relative to the bulk of the dynamically selected Thamnos sample, which shows instead a $[\text{Mg}/\text{Fe}]$ plateau similar to what seen in the MW in-situ halo. A possible, qualitative indication emerging from the model is that Thamnos stars might exhibit nearly solar $[\text{Mg}/\text{Fe}]$ at metallicity around $[\text{Fe}/\text{H}] \sim -2$ dex. However, only with larger and more statistically significant samples will it be possible to spectroscopically confirm this prediction.

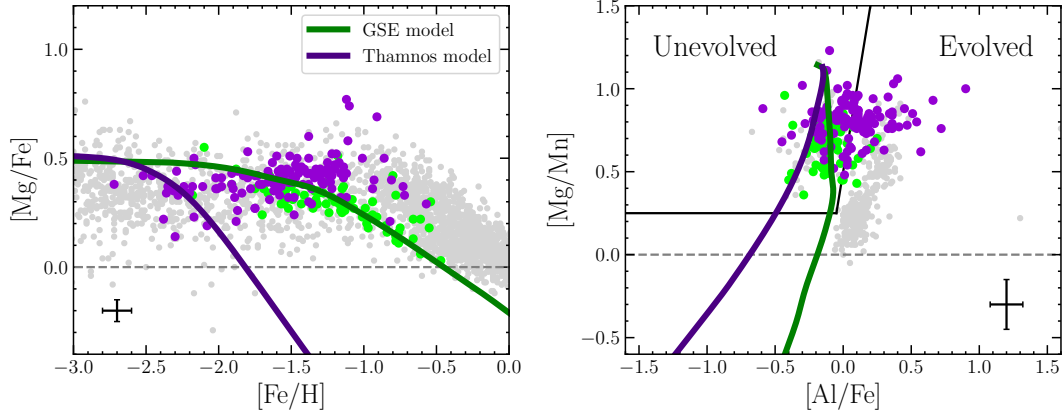


FIGURE 3.10 : $[Mg/Fe]$ – $[Fe/H]$ (left panel) and $[Mg/Mn]$ – $[Al/Fe]$ (right panel) as predicted by the GCE models presented in Section 3.4 compared with the abundances measured in Thamnos and GSE candidates (purple and green points, respectively). Solid lines identify model tracks for GSE (green) and Thamnos (purple). In the right panel, the thin black line represents the division between chemically ‘unevolved’ (top left) and ‘evolved’ regions (top right) presented in [Horta et al. \(2021\)](#).

The likely heavy contamination of MW in-situ stars in the Thamnos substructure can be also noted in the right panel of Figure 3.10, where I plot the $[Mg/Mn]$ – $[Al/Fe]$ space. This diagnostic diagram is divided into regions corresponding to chemically distinct stellar populations, as defined by ([Horta et al. 2021](#)). Particularly, chemically ‘unevolved’ stars are those that formed in environments that did not experience substantial chemical enrichment, thus they are typically interpreted as either stars accreted from low-mass dwarf galaxies or those born in-situ in the early proto-Galaxy. Conversely, the chemically ‘evolved’ population shows abundances typical of stars formed in an environment that underwent efficient star formation, indicative of in-situ formation ([Horta & Schiavon 2025](#)). Indeed, a large fraction ($\sim 50\%$) of dynamically selected Thamnos stars fall in the ‘evolved’ region, whereas model predictions (and the rest of the Thamnos stars) remain in the region of chemically ‘unevolved’ stars, in agreement with the low SFE and therefore SFRs as for the Thamnos model. Less contamination from in-situ stars is instead seen for GSE stars (only $\sim 10\%$ of stars in the ‘evolved’ region), with observations following closely the model predictions. The GSE model favours a system with stronger star formation than the putative ‘true Thamnos’ progenitor, with $[Mg/Fe]$ knee at larger metallicity and greater $[Al/Fe]$ ratios, but still lower than the MW in-situ population.

3.5 Discussion and conclusion

In this work, I am able to fully characterise for the first time the chemical composition of a large sample of stars dynamically selected to be tentative members of Thamnos using high-resolution spectroscopy, comparing its abundance patterns with those of GSE and evaluating the observed trends against predictions from GCE models. In the following, I summarize and discuss the main findings:

- The dynamical region identified to have stars from Thamnos (see [Dodd et al. 2023](#)) has

an overlap of populations with different chemistry. Indeed, on average, this dynamically identified Thamnos substructure is more metal-poor than GSE, yet exhibits systematically enhancement in the $[\alpha/\text{Fe}]$ ratios in the more-metal rich regime ($[\text{Fe}/\text{H}] > -1.7$ dex). This peculiar behaviour in the α -elements has been previously tentatively noted based on limited samples from spectroscopic surveys with lower spectral resolution, such as APOGEE and LAMOST (Koppelman et al. 2019b; Dodd et al. 2023; Horta et al. 2023). As this work represents the first dedicated high-resolution spectroscopic study of a large sample of stars in the Thamnos substructure, I firmly establish the peculiarity of their chemical composition relative to other retrograde substructures.

- The enrichment in the $[\alpha/\text{Fe}]$ ratios in the Thamnos substructure (see Figure 3.5) is atypical for stars with similar $[\text{Fe}/\text{H}]$ formed in low-mass dwarf galaxies, as shown by the α -element depletion commonly observed in remnants of minor merger, such as Sequoia or the Helmi streams (Matsuno et al. 2022a,b; Horta et al. 2023, Paper I), and in surviving dwarf galaxies (see e.g. Tolstoy et al. 2009; Venn et al. 2012; Hill et al. 2019). As shown in Figure 3.5, a large fraction of the stars in the Thamnos substructure lies along the high- α sequence, suggesting these have in-situ origin. This interpretation is further supported by the observed sharp rise in $[\text{Al}/\text{Fe}]$ between $-1.7 < [\text{Fe}/\text{H}] < -1.0$ dex (see Figure 3.4), a behaviour expected and observed in massive galaxies like the MW (Hawkins et al. 2015; Das et al. 2020; Horta et al. 2021; Belokurov & Kravtsov 2022). Additional support for in-situ contamination comes from the enhancement of other elements produced by massive stars, such as Na, Co, Cu, and Zn. This is particularly apparent at $[\text{Fe}/\text{H}] > -1.5$ dex, where stars in the Thamnos substructure overlap in metallicity with GSE, yet consistently follow in-situ chemical trends.
- In contrast, GSE stars are either at the lower end of these distributions (e.g., Cr, Mn, Y) or appear to be depleted (e.g., Co, Ni, Cu, Zn). A notable case is that of Eu, a pure tracer of r -process nucleosynthesis. I find that stars dynamically selected to be in the Thamnos substructure are, on average, depleted in $[\text{EuII}/\text{Fe}]$ by ~ 0.3 dex compared to GSE at $[\text{Fe}/\text{H}] > -1.5$ dex. If this clump is indeed contaminated by in-situ stars, then this trend is consistent with expectations: the high star formation efficiency in a massive galaxy like the MW reduces the impact in Eu production by delayed r -process sources (NSMs, e.g. Cescutti et al. 2015; Matsuno et al. 2021; Ou et al. 2024), thus lowering the final $[\text{EuII}/\text{Fe}]$ and $[\text{EuII}/\text{Mg}]$ ratios, as observed in Thamnos (see Figure 3.8).
- The metallicity distribution of stars in the dynamically selected Thamnos sample reveals a small bump at metallicity $[\text{Fe}/\text{H}] < -2.0$ dex (see Figure 3.3), which I interpret as the potential signature of the accreted Thamnos dwarf galaxy. This is supported by the predictions of a GCE model tailored to fit this peak, which overlap with the observed abundances at these low metallicity (see Figure 3.10), for a system with a very low star formation efficiency, large wind mass loading and which built most of its mass in the first Gyr of evolution, as expected for an accreted dwarf galaxy. This model also highlights how such a system could not have the anomalously high $[\alpha/\text{Fe}]$ values observed (see Figure 3.10), and supports the evidence of a significant amount of contamination in the Thamnos overdensity.

- I estimate the level of contamination from in-situ stars in the dynamically selected Thamnos sample using the MDF, as the ratio between the area under the more metal-rich Gaussian component ('distr2') and the total area under the best-fit curve, obtained by summing the two Gaussian components (see Figure 3.9). In this way I infer a contamination fraction of $\sim 78\%$ across the entire metallicity range. This value is slightly higher than that estimated by Dodd et al. (2025a), who reconstructed the star formation history of Thamnos using CMD fitting. By comparing their results with mock samples with different levels of contamination by in-situ stars on similarly bound orbits, they find an excess of metal-poor stars at $[\text{Fe}/\text{H}] \sim -2.0$ dex and infer a contamination lower than 50%, arguing that higher values would result in a too young and metal-rich population compared to the observed one. It is worth noting, however, that the contamination inferred in this work is not necessarily attributable exclusively to in-situ stars, as there is room for a contribution from GSE. This interpretation is in line with predictions from cosmological hydrodynamical simulations. Specifically, Thomas et al. (2025) report that contamination by in-situ stars in substructures on bound and retrograde orbits like Thamnos can range from $\sim 30\%$ up to $\sim 80\%$ for MW analogues in the Auriga suite of cosmological simulations (Grand et al. 2017). Furthermore, they find that most of these substructures are comprised of stars accreted from two progenitor galaxies, with a typical population ratio of $\sim 30\%$, although this assertion might be a reflection of the limited resolution of their simulations, as they are unable to resolve dwarf galaxies with stellar mass $\leq 10^8 M_\odot$ (most being above $5 \times 10^8 M_\odot$). If such a scenario also applies to the MW, GSE would be the primary accreted contaminant within the Thamnos region of the IoM space. This is due to either the large range in energy and L_z covered by debris of such a massive dwarf galaxy (Koppelman et al. 2020; Amarante et al. 2022; Mori et al. 2024) and the presence of a rotating bar in the MW, which might push the low energy tail of GSE to more bound and more retrograde orbits, close to Thamnos (Dillamore & Sanders 2025; Woudenberg & Helmi 2025). The possibility that Thamnos consists of two overlapping substructures (i.e. Thamnos 1 and 2) has been theorized since its discovery (Koppelman et al. 2019b; Lövdal et al. 2022; Ruiz-Lara et al. 2022a; Bellazzini et al. 2023). The two distinct peaks in the MDFs (see Figure 3.3) may offer observational evidence that these components trace two separate populations, with Thamnos 1 representing the more metal-poor, accreted dwarf galaxy and Thamnos 2 reflecting a population largely composed of contaminants. In summary, the contamination fraction inferred through this chemical analysis is in excellent agreement with previous estimates derived from fully independent methodologies, including dynamics and photometry. This concordance reinforces the idea that the majority of stars currently associated with the Thamnos substructure are likely of in-situ origin or GSE contamination. Nevertheless, this work also suggests that the imprint of the original accreted dwarf galaxy may remain detectable within the metal-poor tail of the distribution, preserving valuable information on early accretion history of the MW.
- GSE stars selected based on their dynamical properties exhibit coherent and well-defined chemical abundance trends across all the analysed chemical planes (see Figures 3.4 – 3.7). As shown in Figure 3.10, the derived abundances well match predictions from a GCE model for a GSE-like galaxy (Vincenzo et al. 2019). Thus, this work

remarks once again the effectiveness of high-resolution spectroscopy in disentangling chemical patterns of different Halo substructures and characterising their progenitor galaxies. Also, this result highlights that the dynamical classification provided by [Dodd et al. \(2023\)](#) yields a remarkably pure GSE sample, with minimal contamination from non-accreted components. Indeed, within this sample, only 9 stars at $[\text{Fe}/\text{H}] \geq -0.8$ dex deviate significantly from the mean GSE distributions, showing enhancement in several elements (Na, Al, Mg, Ti, Mn, Co, Ni, Cu, and Zn) and falling in the ‘evolved’ regime in the $[\text{Mg}/\text{Mn}] - [\text{Al}/\text{Fe}]$ space (see right panel of Figure 3.10). The abundances derived for these few stars align with the chemical trends observed in the metal-rich regime of Thamnos, and therefore I interpret them as likely contaminants from the in-situ stellar population.

To conclude, the results of this study emphasize once again the complex and heterogeneous nature of stellar Halo substructures and the essential role of chemical abundances in disentangling their origins. While dynamics offers a strong starting point, it is only adding independent analysis, like high-resolution spectroscopy, that the nature of these systems can be robustly assessed. The forthcoming *Gaia* DR4, combined with next-generation spectroscopic surveys, such as 4MOST ([de Jong et al. 2019](#)) and WEAVE ([Dalton et al. 2020](#)), will be pivotal in extending such analyses to more distant and fainter stars. These efforts will dramatically improve our ability to resolve the evolutionary history of the MW by enabling a more complete and detailed chemodynamical mapping of its accreted and in-situ Halo components.

4 | A comparative high-resolution spectroscopic analysis of in-situ and accreted globular clusters

*Based on the published paper by [Ceccarelli et al. \(2024b\)](#), *A&A*, 691, A226*

In previous Chapters, I demonstrate the effectiveness of chemical tagging of field stars in disentangling the origin of Halo substructures and characterizing the properties of their progenitor galaxies. In this Chapter, I will shift the paradigm and extend the approach to *globular clusters*, as they represent equally powerful tracers of the Galaxy formation history, especially at larger distances and through more extinct regions, and provide a complementary perspective on the assembly of the Milky Way where observations for field stars get too challenging. Despite their potential, the chemical properties of GCs have so far been only marginally used as indicators of their origin. The use of their detailed abundances as tracers of accreted versus in-situ formation remains largely unexplored, often due to the scarcity of homogeneous and/or high-precision data. In this Chapter, I therefore present a systematic comparison of six GCs with similar metallicity ($-1.3 \leq [\text{Fe}/\text{H}] \leq -1.0$ dex) that are expected to have formed in different environments, to decipher which abundance ratios are most sensitive to their different origin. In Sections 4.1 and 4.2 I list the observations that were collected to compile the spectroscopic dataset, and describe the methodology employed to carry out the chemical analysis. The output of the analysis is shown in Section 4.3, together with a description of the chemical composition of target GCs and a comparison of the results with the literature in Section 4.4. In the final two Sections (4.5 – 4.6) I discuss possible scenarios that could explain the origin of Ruprecht 106 and summarise the main results.

4.1 Spectroscopic dataset

I retrieved the entire spectroscopic dataset from the ESO archive. The spectra of these stars were all acquired using the multi-object spectrograph UVES-FLAMES (Pasquini et al. 2002) or UVES (Dekker et al. 2000) mounted at the VLT of the ESO. Stars were observed using the Red Arm 580 CD3 grating with a spectral coverage between 4800 and 6800 Å and a spectral resolution of $R \sim 40000$. Typical signal-to-noise ratios for these spectra are in the range of $40 \leq S/N \leq 65$ at 5000 Å and $60 \leq S/N \leq 90$ at 6000 Å. The spectra were reduced using the dedicated ESO pipeline¹, which includes bias subtraction, flat-fielding, wavelength calibration, spectral extraction, and order merging. For stars observed with UVES@VLT, the contribution of the sky was properly removed from each stellar spectrum during the pipeline reduction. For the stars observed with UVES-FLAMES@VLT, the sky contribution was taken into account by acquiring the spectra of some nearby sky regions at the same time as the science targets and subtracting it from each individual exposure. In the end, single exposures of the same star were merged to obtain the final spectrum for each target. Figure 4.1 shows the spectra of six stars, one per target cluster, to showcase the quality of the dataset.

The sample of GCs studied here was selected based on their similar metallicity and chrono-dynamical association (which is consistent among the different studies; e.g. Massari et al. 2019; Forbes 2020; Callingham et al. 2022, see below). The individual spectroscopic targets were selected as follows:

- *NGC 362*. This cluster has been categorised as accreted during the merger with GSE. The mean metallicity of NGC 362 is $[\text{Fe}/\text{H}] = -1.17 \pm 0.05$ dex (Carretta et al. 2013). I collected the spectra of 14 RGB stars observed under the ESO-VLT Programme 083.D-0208 (PI: E. Carretta).
- *NGC 1261*. This GC has also been associated with the GSE accretion event. The mean metallicity of this cluster is $[\text{Fe}/\text{H}] = -1.28 \pm 0.02$ dex (Marino et al. 2021). The dataset includes the spectra of 12 RGB stars. Among them, six were observed under the ESO-VLT Programme 0101.D-0109 (PI: A. Marino), four under the ESO-VLT Programme 197.B-1074 (PI: G. F. Gilmore), and two under the ESO-VLT Programme 193.D-0232 (PI: F. R. Ferraro).
- *NGC 6218*. This system is an in-situ GC located in the MW disc. NGC 6218 has a mean metallicity of $[\text{Fe}/\text{H}] = -1.33 \pm 0.08$ dex (Carretta et al. 2009). I include in the analysis 11 RGB stars observed under the ESO-VLT Programme 073.D-0211 (PI: E. Carretta).
- *NGC 6522*. This is an in-situ cluster placed in the MW bulge. Its mean metallicity is $[\text{Fe}/\text{H}] = -1.16 \pm 0.05$ dex (Barbuy et al. 2021). The sample is composed of four RGB stars observed under the ESO-VLT Programme 097.D-0175 (PI: B. Barbuy).
- *NGC 6626*. This is also an in-situ MW bulge GC with a mean metallicity of $[\text{Fe}/\text{H}] = -1.29 \pm 0.01$ dex (Villanova et al. 2017). I collected the spectra of 16 RGB stars observed under the ESO-VLT Programme 091.D-0535 (PI: C. Moni Bidin).

¹<https://www.eso.org/sci/software/pipelines/>

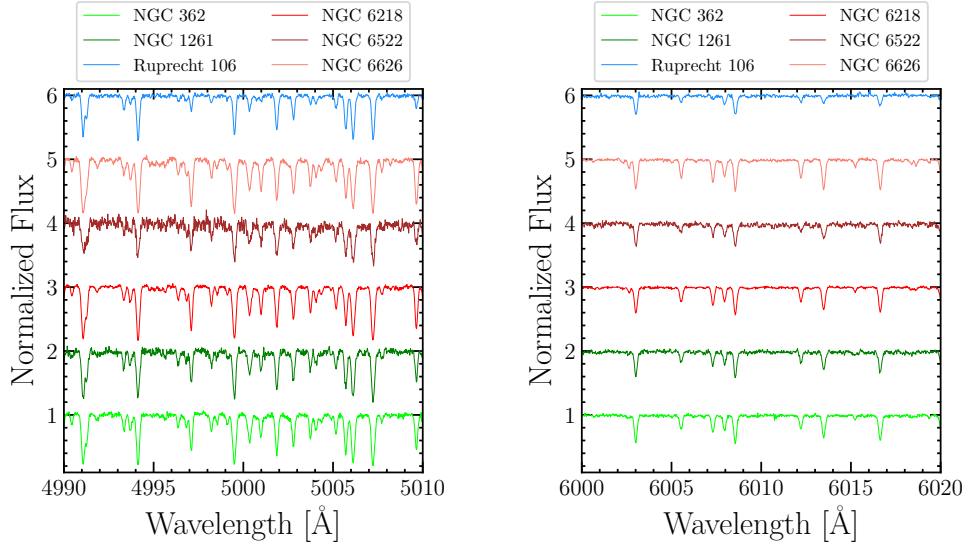


FIGURE 4.1 : Spectra of stars from the six target clusters observed with UVES and UVES-FLAMES at the VLT at different wavelengths. The spectra have been vertically shifted for the sake of clarity.

- *Ruprecht 106*. Among the population of accreted GCs, one that has always attracted significant attention within the community is Ruprecht 106 (Rup106 hereafter). Its orbit is typical of the Galactic halo (Freijj et al. 2021) and due to its positioning in the spaces defined by the integrals of motion, this GC has been tentatively linked with the progenitor of the Helmi Streams. The chemical peculiarity of Rup106 has been revealed by several spectroscopic analyses (e.g. Brown et al. 1997; Villanova et al. 2013, V13 hereafter), which find that all Rup106 stars are depleted in $[\alpha/\text{Fe}]$ compared to GCs and field stars of the same metallicity, that is $[\text{Fe}/\text{H}] = -1.37 \pm 0.11$ dex (Lucertini et al. 2023). I collected the spectra of nine RGB stars that have been observed under the ESO-VLT Programme 069.D-0642 (PI: P. François).

4.2 Chemical analysis

4.2.1 Stellar parameters

I derived both the effective temperature (T_{eff}) and the surface gravity ($\log g$) relying on the *Gaia* DR3 (Gaia Collaboration et al. 2023) photometric dataset. It is important to note that stars in GCs are located at significant distances and within crowded environments, which may result in a slight degradation of the quality of *Gaia* photometry. Stars with $\text{ruwe} > 1.4$ were flagged because their photometry might be of lower quality (Gaia Collaboration et al. 2021).

I determined the T_{eff} for all the targets of the sample using the empirically calibrated $(BP - RP)_0 - T_{\text{eff}}$ relation provided by Mucciarelli et al. (2021b). The choice of using the $(BP - RP)$ colour is guided by the fact that it is the most extended in wavelength among

TABLE 4.1: Selected target information (extract).

Cluster	Star ID	ID <i>Gaia</i> DR3	T_{eff} (K)	$\log g$ (dex)	v_t (km s ⁻¹)	flag_ruwe
NGC 362	1037	4690839791797266688	4549	1.35	1.4	0
NGC 362	1840	4690841273563721728	4485	1.28	1.5	0
NGC 362	2683	4690886834576765952	4142	0.69	1.6	0
NGC 362	3392	4690888105887037184	4522	1.33	1.5	0
...	...	...	...	...	...	...

NOTES. I list star ID from previous literature works, ID from *Gaia* DR3, effective temperature, surface gravity, microturbulent velocity, and a flag to check the quality of the *Gaia* photometry of the star (flag_ruwe = 0 stands for ruwe < 1.4). The complete table is available in the electronic form of the paper [Ceccarelli et al. \(2024b\)](#).

Gaia colours, thus ensuring an optimal sampling of the spectral energy distribution of the star. This approach also eliminates the need to rely on measurements from other photometric systems, which may have lower precision than *Gaia*. I verified that using other *Gaia* colours results in T_{eff} differences that are consistently smaller than 50 K, which is below the current uncertainties. The colour excess $E(B - V)$ adopted for each GC is taken from [Harris \(2010\)](#). Given the high extinction in the direction of the Galactic bulge, I corrected the *Gaia* photometry of NGC 6522 and NGC 6626 for effects of differential reddening following the prescription described in [Milone et al. \(2012\)](#), and using the [Cardelli et al. \(1989\)](#) extinction law. This analysis was performed on the catalogues provided by [Vasiliev & Baumgardt \(2021\)](#), focusing on stars with a probability membership of > 90%. The effects of the extinction on the observed colour ($BP - RP$) have been taken into account following the iterative prescription described in [Gaia Collaboration et al. \(2018b\)](#). As the colour – T_{eff} relation I employed is sensitive to the metallicity of the star, I assumed the [Fe/H] value listed in the [Harris \(2010\)](#) catalogue as representative of the GC under investigation to get an initial estimate of T_{eff} . I note that estimating the T_{eff} using the derived [Fe/H] values leads to differences from the initial values consistently lower than 20 K. Internal errors in T_{eff} due to the uncertainties in photometric data, reddening, and the assumed colour – T_{eff} relation are in the range of 80 – 110 K. I estimated surface gravities from the Stefan-Boltzmann relation using the photometric T_{eff} and a representative stellar mass of $0.8 M_{\odot}$, typical for RGB stars in old isochrones at this metallicity, the G-band bolometric corrections described by [Andrae et al. \(2018\)](#), and the distance provided by [Baumgardt & Vasiliev \(2021\)](#). The uncertainties on the $\log g$ were derived through the propagation of the errors on T_{eff} , photometry, and distance, and they are always under 0.1 dex. In the end, I calculated microturbulent velocities (v_t) by minimising the trend between iron abundances and reduced equivalent widths, defined as $\log_{10}(\text{EW}/\lambda)$. To do so, I used ≥ 100 iron lines per star on average. I assumed a conservative uncertainty of 0.2 km s^{-1} . All the atmospheric parameters are listed in Table 4.1.

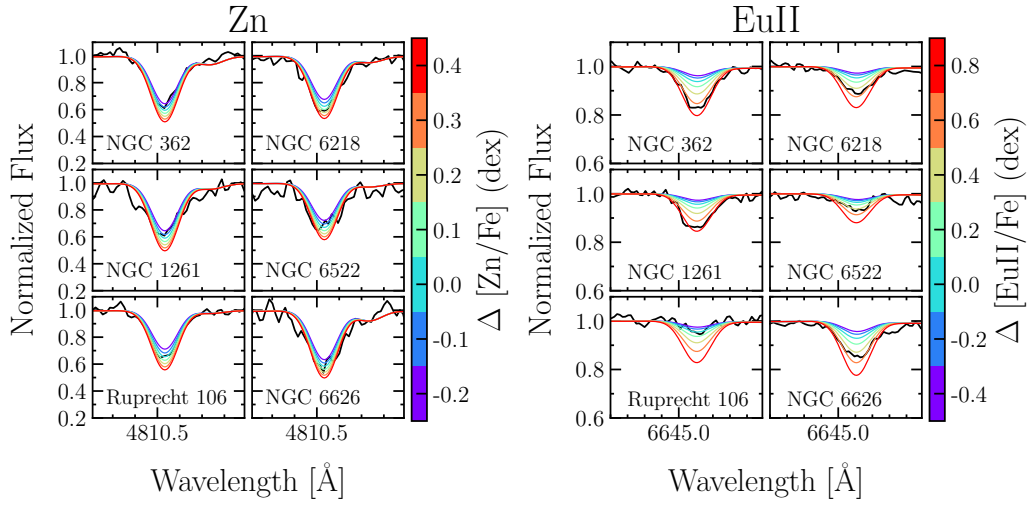


FIGURE 4.2: Comparison around the 4810.5 Å Zn (left panel) and the 6645.1 Å EuII (right panel) lines between the observed spectra and seven synthetic spectra computed assuming the derived atmospheric parameters for each star and varying the level of $[Zn/Fe]$ and $[EuII/Fe]$. The variations are computed with respect to the abundances measured in Rup106.

4.2.2 Deriving the abundances

The determination of chemical abundances of Mg, Si, Ca, TiI, TiII, Cr, Fe, Ni, and Zn was conducted by means of a comparative analysis between the observed equivalent widths (EWs) – measured with the code **DAOSPEC** (Stetson & Pancino 2008) and using the automatic tool **4DAO** (Mucciarelli 2013) – and theoretical line strengths. This analysis was executed using the code **GALA** (Mucciarelli et al. 2013).

I employed the spectral synthesis using the proprietary code **SALVADOR** to derive the chemical abundances for the species that have hyperfine or isotopic splitting transitions (ScII, V, Mn, Co, Cu, YII, BaII, LaII, and EuII). **SALVADOR** runs a χ^2 -minimisation between the observed line and a grid of suitable synthetic spectra computed on the fly by the code **SYNTHE** (Kurucz 2005) varying only the abundance of the matching element and keeping the stellar parameters fixed. Synthetic spectra were computed using all the atomic and molecular transitions available in the Kurucz/Castelli² database.

I used **ATLAS9** (Kurucz 2005) model atmospheres computed assuming plane-parallel geometry, hydrostatic and radiative equilibrium, and local thermodynamic equilibrium for all the chemical elements. I started from an α -enhanced model atmosphere ($[\alpha/Fe] = +0.4$ dex) for all the target GCs except for Rup106, for which I used a solar-scaled chemical mixture according to the values of $[\alpha/Fe]$ I derived. Examples of fits around absorption lines of elements of interest (i.e. Zn and EuII; see Sections 4.3.2 and 4.3.3) are displayed in Figure 4.2. Different synthetic spectra are computed for each star by assuming the atmospheric parameters derived as described in Section 4.2.1, and varying the abundances of Zn and EuII. Finally, I scale the abundance ratios to the solar values using the chemical composition described in Grevesse & Sauval (1998), as **ATLAS9** model atmospheres are computed based on this solar mixture (Castelli & Kurucz 2003).

²<http://wwwuser.oats.inaf.it/castelli/linelists.html>

4.2.3 Uncertainties on the abundance ratios

During the determination of the uncertainties associated with abundance ratios, it is imperative to account for two principal sources of error: first, internal errors stemming from the measurement of the EW, and second, errors originating from the selection of atmospheric parameters.

I estimated the uncertainties attributed to EW measurements as the dispersion observed around the mean of individual line measurements divided by the root mean square of the number of lines employed in the analysis. The internal error on chemical abundances derived with spectral synthesis were quantified using Monte Carlo simulations. To do so, I repeated the analysis on 1000 noisy synthetic spectra obtained adding Poissonian noise in order to mimic the S/N of the real spectra. The uncertainty is estimated as the standard deviation of the abundance distribution of the 1000 noisy synthetic spectra.

Finally, I performed new calculations of the chemical abundances, considering also the uncertainties associated with the atmospheric parameters. This involved varying one stellar parameter at a time while keeping the others fixed. In the end, all the sources of error are added in quadrature. Given that chemical abundances are expressed as abundance ratios ($[X/Fe]$), the uncertainties on the iron abundance $[Fe/H]$ have been taken into account. I estimated the total uncertainty as the squared sum of these two components. Therefore, the final errors were calculated as:

$$\sigma_{[Fe/H]} = \sqrt{\frac{\sigma_{Fe}^2}{N_{Fe}} + (\delta_{Fe}^{T_{\text{eff}}})^2 + (\delta_{Fe}^{\log g})^2 + (\delta_{Fe}^{v_t})^2}$$

$$\sigma_{[X/Fe]} = \sqrt{\frac{\sigma_X^2}{N_X} + \frac{\sigma_{Fe}^2}{N_{Fe}} + (\delta_X^{T_{\text{eff}}} - \delta_{Fe}^{T_{\text{eff}}})^2 + (\delta_X^{\log g} - \delta_{Fe}^{\log g})^2 + (\delta_X^{v_t} - \delta_{Fe}^{v_t})^2}$$

where $\sigma_{X,Fe}$ is the dispersion around the mean of chemical abundances, $N_{X,Fe}$ is the number of used lines, and $\delta_{X,Fe}^i$ are the abundance differences obtained by varying the parameter i .

4.3 Chemical abundances of target GCs

In this section, I discuss the abundances of α -, iron-peak, and neutron-capture elements of target GCs. I exercise caution when interpreting the abundances of certain chemical elements that may be influenced by the presence of multiple populations within GCs (e.g. O, Na, Mg, and Al; see [Bastian & Lardo 2018](#)). Among these species, I focus only on Mg, which exhibits minimal dispersion within five out of the six GCs in the sample. This is expected, particularly considering that most of the targeted systems are not massive nor metal-poor enough to efficiently activate the MgAl burning channel ([Ventura et al. 2013](#); [Dell'Agli et al. 2018](#); [Alvarez Garay et al. 2024](#)). Indeed, I find spread in the distribution of $[Mg/Fe]$ only in the most massive among target clusters, NGC 6626. As I am only concerned with the pristine chemical composition of the gas that formed the cluster, I derived the mean value of $[Mg/Fe]$ using only first-generation stars. The results obtained from the homogeneous

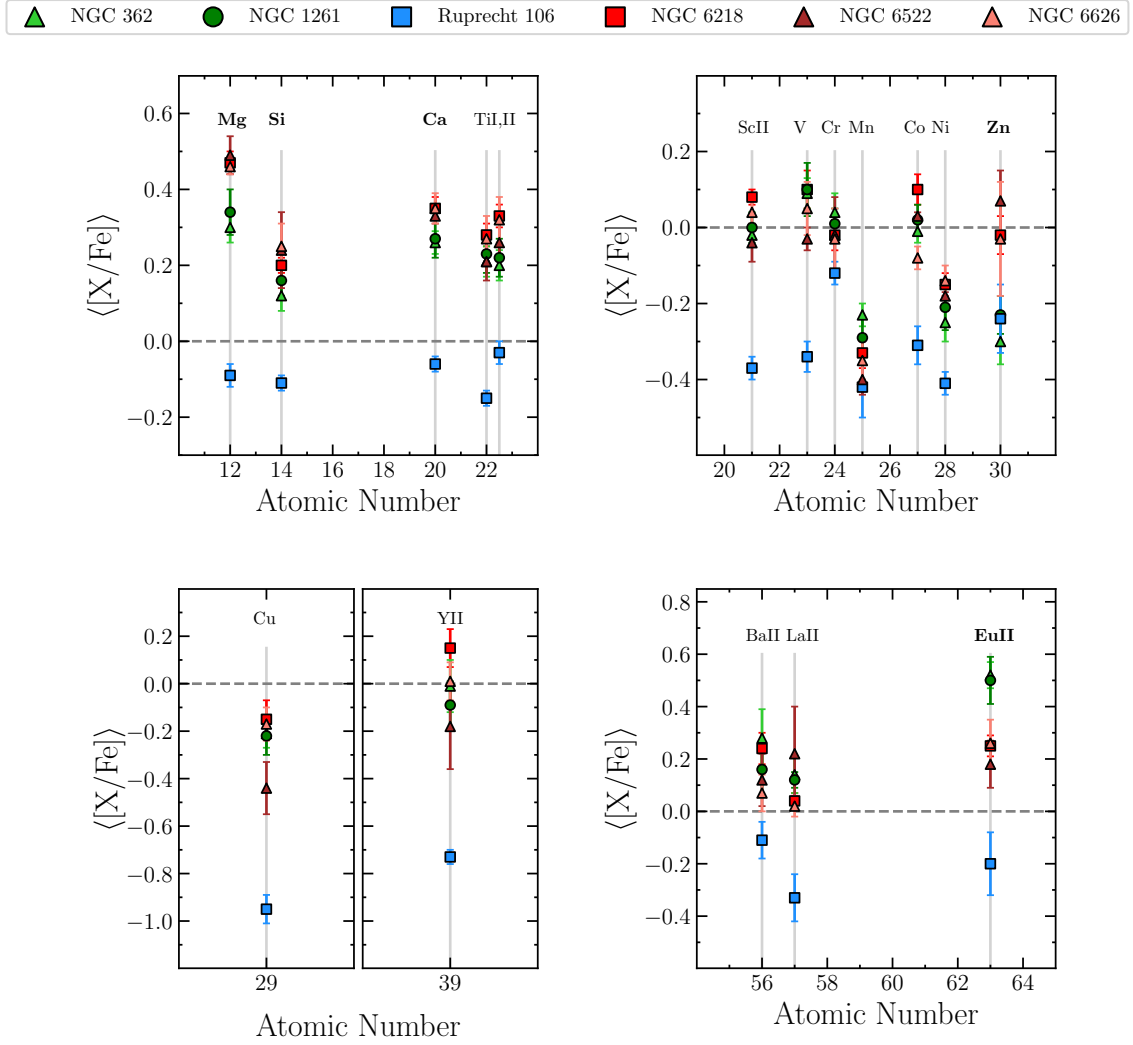


FIGURE 4.3 : Comparison of mean $[X/Fe]$ ratios of the α - (Mg, Si, Ca, TiI, and TiII), iron-peak (ScII, V, Cr, Mn, Co, Ni, Cu and Zn), and neutron capture (YII, BaII, LaII, and EuII) elements for target GCs NGC 362 (green triangles), NGC 1261 (dark green circles), NGC 6218 (red squares), NGC 6522 (brown triangles), NGC 6626 (pink triangles), and Rup106 (blue squares). Error bars indicate the standard deviation.

chemical analysis of 66 RGB stars of the sample of six GCs are listed in Table 4.2. The mean abundances for each GC are available in Table 4.3. The average abundance ratios of the target GCs are illustrated in Figure 4.3.

4.3.1 α -elements

The top left panel of Figure 4.3 shows the mean values of the α -elements abundances. First of all, I find that the two GCs associated to GSE (green filled symbols) show identical abundances, within the uncertainties, in all the analysed α -elements. Second, I show that the mean abundances of Mg, Si, and Ca of the three in-situ GCs, namely NGC 6218, NGC 6522, and NGC 6626 (red, brown and pink filled symbols, respectively), are fully compatible among

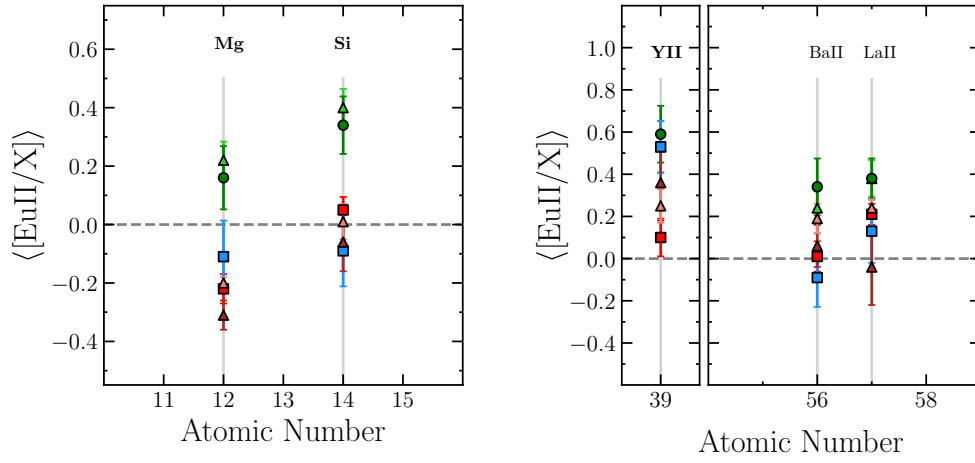


FIGURE 4.4 : Comparison of mean abundance ratios of EuII relative to other chemical elements for target GCs. The colour coding is the same as in Fig. 4.3. Error bars indicate the standard deviation.

each other. For Ti, this consistency is less evident. Third, I find that NGC 362 and NGC 1261 are α -depleted compared to the in-situ GCs. They display differences in the α -element at the 1σ level in Mg and Ca when comparing the average abundances and the respective standard deviations (see Section 4.3.4 for a comparison with literature). Finally, I derive subsolar abundances in the α -elements of Rup106 (blue filled squares), specifically with $[\alpha/\text{Fe}] \sim -0.1$ dex, which is in good agreement with the literature (Brown et al. 1997, V13, see Section 4.3.4 for a comparison with the results of V13). This is, on average, 0.3 – 0.4 dex lower than the other five target clusters.

These results show that α -elements can be used to distinguish the origin of GCs. The observed trend is a good match to expectations based on the cluster chrono-dynamical associations. Indeed, GSE clusters NGC 1261 and NGC 362 share the same α -element abundances, as expected for clusters accreted from the same progenitor, with lower $[\alpha/\text{Fe}]$ values compared to NGC 6218, NGC 6522, and NGC 6626. Indeed, the in-situ GCs consistently show higher $[\alpha/\text{Fe}]$ abundances, as predicted for systems born in the MW at this metallicity, where the contribution of SNIa to the gas chemical enrichment was not yet significant. Finally, Rup106 has an even lower $[\alpha/\text{Fe}]$ than the GSE GCs, and can be distinguished from them in this respect; this indicates an even more different birth environment, probably characterised by very low star formation efficiency.

4.3.2 Iron-peak elements

The results shown in the top right panel of Figure 4.3 indicate that most of the iron-peak elements do not provide a means to effectively and clearly discriminate between in-situ and GSE clusters. Indeed, target GCs display coherent values in all the chemical spaces with the exception, once again, of Rup106, which is underabundant in ScII, V, Mn, Co, and Ni. In the bottom left panel of Figure 4.3, I highlight the two elements where Rup106 is most depleted compared to the other systems. Specifically, Cu is the most underabundant among the chemical elements derived in this work ($[\text{Cu}/\text{Fe}] = -0.95$ dex for Rup106). Such low values of

TABLE 4.2 : Chemical abundances for target stars (extract).

Cluster	Star ID	[Fe/H] (dex)	[Mg/Fe] (dex)	[Si/Fe] (dex)
NGC 362	1037	-1.04 ± 0.09	0.28 ± 0.04	0.10 ± 0.10
NGC 362	1840	-1.04 ± 0.09	0.25 ± 0.04	0.08 ± 0.10
NGC 362	2683	-1.12 ± 0.06	0.36 ± 0.05	0.20 ± 0.11
NGC 362	3392	-1.07 ± 0.09	0.28 ± 0.03	0.11 ± 0.10
...	...	...	...	...
[Ca/Fe] (dex)	[TiI/Fe] (dex)	[TiII/Fe] (dex)	[ScII/Fe] (dex)	[V/Fe] (dex)
0.27 ± 0.05	0.20 ± 0.09	0.21 ± 0.12	-0.03 ± 0.08	0.09 ± 0.18
0.22 ± 0.06	0.18 ± 0.10	0.17 ± 0.11	-0.04 ± 0.07	0.08 ± 0.18
0.30 ± 0.08	0.24 ± 0.15	0.21 ± 0.11	0.01 ± 0.07	0.13 ± 0.18
0.24 ± 0.05	0.17 ± 0.09	0.22 ± 0.12	-0.07 ± 0.08	0.06 ± 0.18
...	...	...	...	...
[Cr/Fe] (dex)	[Mn/Fe] (dex)	[Co/Fe] (dex)	[Ni/Fe] (dex)	[Cu/Fe] (dex)
-0.01 ± 0.09	-0.26 ± 0.15	0.01 ± 0.13	-0.21 ± 0.04	-0.26 ± 0.18
-0.04 ± 0.09	-0.22 ± 0.15	0.03 ± 0.13	-0.22 ± 0.04	-0.27 ± 0.18
0.12 ± 0.12	-0.20 ± 0.15	-0.02 ± 0.13	-0.31 ± 0.04	-0.15 ± 0.18
-0.01 ± 0.08	-0.27 ± 0.15	0.00 ± 0.13	-0.14 ± 0.04	-0.31 ± 0.18
...	...	...	...	...
[Zn/Fe] (dex)	[YII/Fe] (dex)	[BaII/Fe] (dex)	[LaII/Fe] (dex)	[EuII/Fe] (dex)
-0.20 ± 0.15	-0.01 ± 0.15	0.27 ± 0.17	0.15 ± 0.05	0.51 ± 0.05
-0.27 ± 0.14	-0.05 ± 0.15	0.24 ± 0.17	0.13 ± 0.05	0.50 ± 0.04
-0.39 ± 0.13	0.05 ± 0.15	0.28 ± 0.17	0.16 ± 0.05	0.52 ± 0.04
-0.24 ± 0.14	-0.10 ± 0.15	0.19 ± 0.17	0.12 ± 0.05	0.44 ± 0.05
...	...	...	...	...

NOTES. The complete table is available in the electronic form of the paper [Ceccarelli et al. \(2024b\)](#).

[Cu/Fe] can be reproduced in stellar systems with a chemical evolutionary model assuming very inefficient star formation (star formation rate $< 5 \times 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1}$, [Mucciarelli et al. 2021a](#)). Thus, the pronounced depletion in all of these elements might indicate that Rup106 was born in an environment where the contribution of massive stars was extremely low.

Among the iron-peak elements, the only one to demonstrate a statistically significant difference between accreted and in-situ GCs is Zn: all the in-situ GCs are overabundant with respect to GSE GCs and Rup106 at the 1σ level. In passing, I note that NGC 6626 shows a significant spread in [Zn/Fe], as already found in [Villanova et al. \(2017\)](#). Therefore, Zn appears to be a good tracer of the in-situ or accreted origin of GCs, but it is not sensitive enough to help distinguish among different accreted progenitors. Such a conclusion was also drawn by [Minelli et al. \(2021\)](#), even though these authors used a sample of GCs at higher metallicity. Indeed, high [Zn/Fe] ratios are expected for in-situ GCs, and the rationale be-

TABLE 4.3: Mean abundances ratios for the six GCs analysed in this work.

Element	NGC 362	NGC 1261	NGC 6218
$\langle[\text{Fe}/\text{H}]\rangle$	-1.06 ± 0.01 (0.03)	-1.14 ± 0.02 (0.06)	-1.24 ± 0.01 (0.02)
$\langle[\text{Mg}/\text{Fe}]\rangle$	0.30 ± 0.01 (0.04)	0.34 ± 0.02 (0.06)	0.47 ± 0.01 (0.03)
$\langle[\text{Si}/\text{Fe}]\rangle$	0.12 ± 0.01 (0.04)	0.16 ± 0.01 (0.04)	0.20 ± 0.01 (0.02)
$\langle[\text{Ca}/\text{Fe}]\rangle$	0.26 ± 0.01 (0.03)	0.27 ± 0.01 (0.05)	0.35 ± 0.01 (0.03)
$\langle[\text{ScII}/\text{Fe}]\rangle$	-0.02 ± 0.01 (0.03)	0.00 ± 0.01 (0.04)	0.08 ± 0.01 (0.02)
$\langle[\text{Ti}/\text{Fe}]\rangle$	0.21 ± 0.01 (0.04)	0.23 ± 0.01 (0.05)	0.28 ± 0.01 (0.03)
$\langle[\text{TiII}/\text{Fe}]\rangle$	0.20 ± 0.01 (0.04)	0.22 ± 0.01 (0.05)	0.33 ± 0.01 (0.03)
$\langle[\text{V}/\text{Fe}]\rangle$	0.09 ± 0.01 (0.04)	0.10 ± 0.02 (0.07)	0.10 ± 0.02 (0.05)
$\langle[\text{Cr}/\text{Fe}]\rangle$	0.04 ± 0.01 (0.05)	0.01 ± 0.01 (0.04)	-0.02 ± 0.01 (0.04)
$\langle[\text{Mn}/\text{Fe}]\rangle$	-0.23 ± 0.01 (0.03)	-0.29 ± 0.01 (0.05)	-0.33 ± 0.01 (0.04)
$\langle[\text{Co}/\text{Fe}]\rangle$	-0.01 ± 0.01 (0.03)	0.02 ± 0.01 (0.04)	0.10 ± 0.01 (0.04)
$\langle[\text{Ni}/\text{Fe}]\rangle$	-0.25 ± 0.01 (0.05)	-0.21 ± 0.02 (0.06)	-0.15 ± 0.01 (0.03)
$\langle[\text{Cu}/\text{Fe}]\rangle$	-0.21 ± 0.02 (0.06)	-0.22 ± 0.02 (0.08)	-0.15 ± 0.02 (0.08)
$\langle[\text{Zn}/\text{Fe}]\rangle$	-0.30 ± 0.02 (0.06)	-0.23 ± 0.01 (0.05)	-0.02 ± 0.02 (0.05)
$\langle[\text{YII}/\text{Fe}]\rangle$	-0.01 ± 0.03 (0.11)	-0.09 ± 0.03 (0.10)	0.15 ± 0.02 (0.08)
$\langle[\text{BaII}/\text{Fe}]\rangle$	0.28 ± 0.03 (0.11)	0.16 ± 0.03 (0.10)	0.24 ± 0.02 (0.06)
$\langle[\text{LaII}/\text{Fe}]\rangle$	0.14 ± 0.02 (0.07)	0.12 ± 0.01 (0.03)	0.04 ± 0.01 (0.03)
$\langle[\text{EuII}/\text{Fe}]\rangle$	0.52 ± 0.01 (0.05)	0.50 ± 0.02 (0.09)	0.25 ± 0.01 (0.04)
Element	NGC 6522	NGC 6626	Ruprecht 106
$\langle[\text{Fe}/\text{H}]\rangle$	-1.07 ± 0.01 (0.05)	-1.11 ± 0.01 (0.06)	-1.30 ± 0.01 (0.05)
$\langle[\text{Mg}/\text{Fe}]\rangle$	0.49 ± 0.03 (0.05)	0.46 ± 0.01 (0.02)	-0.09 ± 0.01 (0.03)
$\langle[\text{Si}/\text{Fe}]\rangle$	0.24 ± 0.05 (0.10)	0.25 ± 0.02 (0.06)	-0.11 ± 0.01 (0.02)
$\langle[\text{Ca}/\text{Fe}]\rangle$	0.33 ± 0.01 (0.02)	0.35 ± 0.01 (0.04)	-0.06 ± 0.01 (0.02)
$\langle[\text{ScII}/\text{Fe}]\rangle$	-0.04 ± 0.02 (0.05)	0.04 ± 0.01 (0.04)	-0.37 ± 0.01 (0.03)
$\langle[\text{Ti}/\text{Fe}]\rangle$	0.21 ± 0.03 (0.05)	0.27 ± 0.01 (0.06)	-0.15 ± 0.01 (0.02)
$\langle[\text{TiII}/\text{Fe}]\rangle$	0.26 ± 0.03 (0.07)	0.32 ± 0.01 (0.06)	-0.03 ± 0.01 (0.03)
$\langle[\text{V}/\text{Fe}]\rangle$	-0.03 ± 0.01 (0.03)	0.05 ± 0.02 (0.07)	-0.34 ± 0.01 (0.04)
$\langle[\text{Cr}/\text{Fe}]\rangle$	-0.02 ± 0.05 (0.10)	-0.03 ± 0.02 (0.08)	-0.12 ± 0.01 (0.03)
$\langle[\text{Mn}/\text{Fe}]\rangle$	-0.40 ± 0.02 (0.04)	-0.35 ± 0.01 (0.05)	-0.42 ± 0.03 (0.08)
$\langle[\text{Co}/\text{Fe}]\rangle$	0.03 ± 0.01 (0.01)	-0.08 ± 0.01 (0.03)	-0.31 ± 0.02 (0.05)
$\langle[\text{Ni}/\text{Fe}]\rangle$	-0.18 ± 0.01 (0.01)	-0.14 ± 0.01 (0.04)	-0.41 ± 0.01 (0.03)
$\langle[\text{Cu}/\text{Fe}]\rangle$	-0.44 ± 0.05 (0.11)	-0.17 ± 0.02 (0.07)	-0.95 ± 0.02 (0.06)
$\langle[\text{Zn}/\text{Fe}]\rangle$	0.07 ± 0.04 (0.08)	-0.03 ± 0.04 (0.15)	-0.24 ± 0.03 (0.09)
$\langle[\text{YII}/\text{Fe}]\rangle$	-0.18 ± 0.09 (0.18)	0.01 ± 0.02 (0.08)	-0.73 ± 0.01 (0.03)
$\langle[\text{BaII}/\text{Fe}]\rangle$	0.12 ± 0.05 (0.10)	0.07 ± 0.02 (0.07)	-0.11 ± 0.02 (0.07)
$\langle[\text{LaII}/\text{Fe}]\rangle$	0.22 ± 0.10 (0.18)	0.02 ± 0.01 (0.04)	-0.33 ± 0.03 (0.09)
$\langle[\text{EuII}/\text{Fe}]\rangle$	0.18 ± 0.06 (0.09)	0.26 ± 0.02 (0.09)	-0.20 ± 0.04 (0.12)

NOTES. The standard deviation is reported in parenthesis.

hind this expectation lies in the fact that the primary contributors to Zn production are HNe, which are linked to stars with masses of around $25 - 30 M_{\odot}$ (Romano et al. 2010; Kobayashi et al. 2020b). Consequently, galaxies with lower star formation rates should manifest lower $[\text{Zn}/\text{Fe}]$ ratios due to the reduced impact of massive stars (Yan et al. 2020).

4.3.3 Neutron-capture elements

First of all, I observe that the in-situ NGC 6218 is enhanced (≥ 0.2 dex) in $[\text{YII}/\text{Fe}]$ compared to the other two in-situ GCs and two GSE GCs. Additionally, among the neutron-capture elements, this is the chemical space in which Rup106 is the most depleted (see bottom left panel of Figure 4.3). This finding is particularly intriguing, as Cu, the other element where Rup106 is notably depleted, is also produced by massive stars through weak s -processes, with a small contribution also by AGB stars (Kobayashi & Nomoto 2009; Kobayashi et al. 2020b). Thus, if the lack of weak s -process products is responsible for the low derived Cu abundance, light neutron-capture elements are also expected to be similarly depleted, as is observed for Y.

When examining the abundances of the other neutron-capture elements (see bottom right panel of Figure 4.3), the most notable distinctions between various GCs arise in the r -process element Eu. The two GSE GCs exhibit values that are ~ 0.3 dex higher compared to in-situ GCs. The enhancement in r -process of NGC 362 and NGC 1261 was also highlighted by Monty et al. (2023b) and by Koch-Hansen et al. (2021), respectively, and resembles a behaviour seen in both GSE field stars at this metallicity (Nissen & Schuster 2011; Fishlock et al. 2017; Aguado et al. 2021; Matsuno et al. 2021; Naidu et al. 2022c) and surviving dwarf galaxies, such as the Large Magellanic Cloud, Sculptor, and Fornax (Tolstoy et al. 2009; Letarte et al. 2010; Van der Swaelmen et al. 2013; Lemasle et al. 2014). This might be explained by a joint effect of the different star formation efficiency in the progenitor galaxy and the impact of delayed r -process sources (i.e. NSMs), with minimum delay times of the order of $10 - 1000$ Myr in producing Eu (Cescutti et al. 2015; Siegel et al. 2019; Naidu et al. 2022c; Ou et al. 2024). Once again, Rup106 is $0.3 - 0.6$ dex underabundant in all neutron-capture elements, indicating a different birth environment.

Recently, the $[\text{EuII}/\alpha]$ ratio has been proposed as a strong discriminant between accreted and in-situ GCs due to its effectiveness in tracing different timescales of star formation (Monty et al. 2024; Ou et al. 2024). As shown in the left panel of Figure 4.4, the observed differences between the two GSE GCs and the in-situ GCs are consistent with literature results, while I do not find signs of a consistent enhancement in $[\text{EuII}/\alpha]$ for Rup106. Thus, I recommend caution when using this diagnostic, as it might be effective for individual progenitors like GSE, but not in general for birth environments spanning a wide range of formation and evolutionary properties. Moreover, as demonstrated by the $[\text{EuII}/\text{BaII}]$ and the $[\text{EuII}/\text{LaII}]$ ratios (see the right panel of Figure 4.4), the in-situ GCs and Rup106 show signs of higher efficiency in the production of heavy s -process elements with respect to the r -process elements when compared to the GSE GCs. I highlight that the accreted systems considered here can be either r -process dominated (GSE) or s -process dominated (Rup106). Moreover, I find a difference of ≥ 0.2 dex in $[\text{EuII}/\text{YII}]$ between the three accreted clusters and the three in-situ systems. Interestingly, the $[\text{EuII}/\text{YII}]$ ratio is similar in all accreted systems, regardless of the r -/ s - process dominance. This comparison may suggest that the

applicability of [EuII/YII] as a tracer of the accreted or in-situ origin is more general than [EuII/BaII] and [EuII/LaII]. Thus, this abundance ratio can play an important role in discriminating between in-situ and accreted GCs at this metallicity, but, as for Zn, I point out that this diagnostic might lack the required sensitivity to discriminate between independent accreted progenitors.

4.3.4 Validation of the abundances

4.3.4.1 GSE globular clusters

To validate these findings, I undertake a comparative analysis with two distinct independent studies conducted on two of the six target GCs. Specifically, I compare the results to those obtained by the seminal works by Carretta et al. (2009, 2010, 2013) and to those provided by the latest data release of the APOGEE survey (Abdurro'uf et al. 2022). In particular, I use the APOGEE value-added catalogue of Galactic GC stars (Schiavon et al. 2024), limiting the comparison only to well-measured stars. To do so, I remove all the stars with the following flags³ in the quality parameters:

- ASPCAPFLAG = 16, 17, 23;
- STARFLAG = 3, 4, 9, 12, 13, 16;
- EXTRATARG = 4;
- VB_PROB > 0.99.

The choice of using these two dataset was guided by their execution of identical chemical analyses on two out of the four target GCs, thereby ensuring consistency in their outcomes. I limit the comparison with Carretta et al. (2009, 2010, 2013) and APOGEE only to the chemical elements identified as sensitive to the origin of GCs available in these dataset, that are Mg, Si and Ca. As shown in Figure 4.5, the results from this work are in agreement within the uncertainties with those provided by Carretta et al. (2009, 2010, 2013) and APOGEE, consistently yielding an enhancement of 0.1 – 0.2 dex in the α -elements (Mg, Si, and Ca) of NGC 6218 with respect to NGC 362.

4.3.4.2 Comparison with V13

A comparison with the results of V13, who analysed the same Rup106 dataset, further confirms the peculiarity of this system. Indeed, their findings indicate that, within this cluster, the observed spread in all chemical elements is consistent with the uncertainty on the measurement, suggesting Rup106 to be a single population GC, as also confirmed photometrically in more recent works (Dotter et al. 2018; Lagioia et al. 2025). Moreover, their analysis reveals solar-like abundances in the α -elements, alongside a notable underabundance in the iron peak elements relative to iron, ranging from 0.1 up to 0.8 dex. Firstly, when comparing the atmospheric parameters of Rup106 targets, I find a significant difference in the adopted T_{eff} scales, with an average discrepancy (this work – V13) of +169 K ($\sigma = 55$ K). The average

³Flags definition available at <https://www.sdss4.org/dr17/irspec/apogee-bitmasks/>

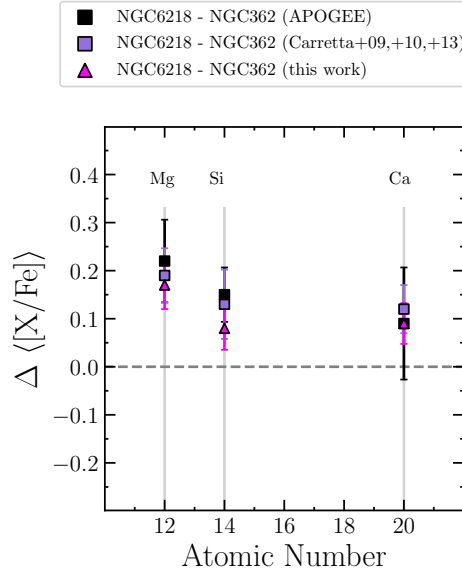


FIGURE 4.5 : Difference of mean abundance ratios of the α -elements $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, and $[\text{Ca}/\text{Fe}]$ between NGC 6218 and NGC 362 from this work (pink triangles), Carretta et al. (2009, 2010, 2013) (purple squares), and APOGEE (black squares). Error bars indicate the standard deviation.

difference for the surface gravity is $+0.65$ dex ($\sigma = 0.14$ dex) and that for v_t is -0.07 km/s ($\sigma = 0.05$ km/s). These discrepancies arise from the fact that V13 constrained T_{eff} and $\log g$ with a similar methodology, deriving them from the photometry, but based on a different colour – T_{eff} relation. On the other hand, V13 assumed a v_t derived from the relation by Marino et al. (2008), while I constrained it spectroscopically (see Section 4.2.1). To ensure a fair comparison between the results, I rescaled the abundance ratios reported in V13 on the Grevesse & Sauval (1998) solar composition. Firstly, I note an average offset of $+0.17$ dex ($\sigma = 0.07$ dex) in the star-to-star metallicity estimate of Rup106, which can be explained by the difference in the derived effective temperatures. By comparing these two independent results performed on the same dataset, I find agreement with V13 at the 1σ level for Mg, Ti, ScII, Cr, Mn, Zn, YII, LaII, and EuII, while I note differences up to ~ 0.2 dex for Si, Ca, V, Co, Ni, Cu, and BaII. I attribute these inconsistencies to the different scale adopted for surface gravities and, most importantly, effective temperatures. This comparison proves that diverse assumptions in the procedure to derive chemical abundances make the results of two independent approaches not directly comparable and that the only reliable chemical analysis is within an homogeneous procedure. In general, notwithstanding differences stemming from varied assumptions in the chemical analysis, I reaffirm the distinct chemical characteristics of Rup106 within the MW GC system, alongside the minimal dispersion in chemical abundances among its stars.

4.4 Comparison with field stars from the likely progenitor

In this Section I investigate the compatibility of the abundances derived for accreted GCs with those derived for the field stars associated with their respective progenitors, and in passing I note once again that homogeneity in this kind of comparison is crucial. Indeed, several factors may contribute to a zero-point offset in abundance between results presented here and those from the literature (e.g. assumptions on atmospheric parameters, model atmosphere, solar mixture, line list, and atomic data).

4.4.1 NGC 6218, NGC 6522, NGC 6626, and the Milky Way

I use the results obtained from high-resolution spectroscopy of MW field stars as a comparison, focusing on the chemical elements that show significant differences between accreted and in-situ GCs. To do so, given the extremely high quality of their stellar spectra, I selected the catalogue of [Nissen & Schuster \(2010, 2011\)](#) as benchmark comparison dataset, and in particular I focus on stars in the high- α sequence that have been observed with UVES@VLT. To maintain homogeneity in the chemical analysis, I re-derived abundances from the spectra of these stars (see the detailed method in Sect. 4.2). The only exception in this homogeneous comparison is the element EuII, as (i) the number of available spectra in the literature is limited (and many of them were obtained with different instruments and S/N), and (ii) abundances are derived from different spectral lines due to the different evolutionary stages of the observed stars. I chose to compare these results with EuII abundances from the high- α sequence of [Fishlock et al. \(2017\)](#).

Figure 4.6 shows that the abundances of NGC 6218, NGC 6522, and NGC 6626 match those of the field stars (grey filled points) in all chemical spaces of interest (i.e. Ca, TiI, Zn, YII, and EuII) except for Mg, where the three in-situ target GCs show enhancement in $[Mg/Fe]$ compared to MW high- α sequence stars, which is found to be outside the 2σ of their distribution in the metallicity range of $-1.3 \leq [Fe/H] \leq -1.0$ dex.

4.4.2 NGC 362, NGC 1261, and Gaia-Sausage-Enceladus

The reference catalogue used for this comparison is that of Chapter 2, which was produced with the same methods as those described here. Additionally, I re-derived the abundances for the stars in the low- α sequence of [Nissen & Schuster \(2010\)](#). Finally, I compared these abundances with the results from the low- α stars in [Fishlock et al. \(2017\)](#); [Aguado et al. \(2021\)](#); [Carrillo et al. \(2022\)](#); [Giribaldi & Smiljanic \(2023\)](#), and [François et al. \(2024\)](#) for EuII. As displayed in Figure 4.7, there is excellent agreement between the chemical composition of NGC 362 and NGC 1261 and the patterns shown by GSE stars (grey filled points) in the α -elements Ca and TiI, while, as for in-situ GCs, NGC 362 and NGC 1261 lay in the upper boundaries (at the 1.3σ and 1.6σ levels for NGC 362 and NGC 1261, respectively) of the distribution of GSE field stars in $[Mg/Fe]$ in the metallicity range of interest. The value of $[Zn/Fe]$ derived in NGC 1261 is consistent with those observed in the most Zn-poor stars in GSE, while NGC 362 seems to be slightly depleted (~ 0.1 dex) compared to them. Particularly, they deviate from the average of the field stars (at $-1.2 < [Fe/H] < -1.0$ dex) at the 2.1σ and 2.7σ levels, respectively. Finally, the slightly subsolar values of $[YII/Fe]$ found

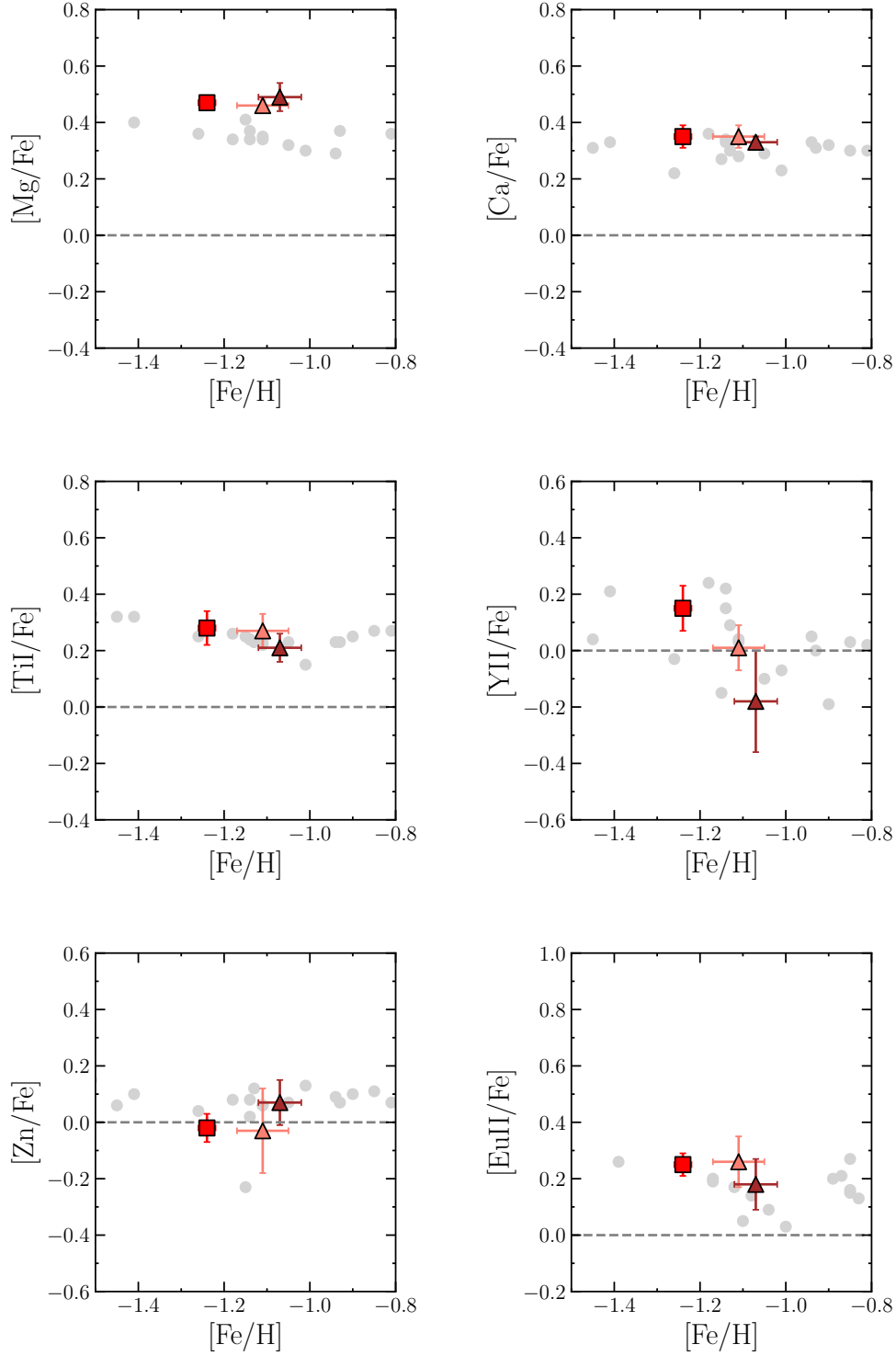


FIGURE 4.6 : Mean abundances of NGC 6218, NGC 6522, and NGC 6626 derived in this work (the colour coding is the same as in Fig. 4.3) compared with those derived for MW stars (grey filled points). $[EuII/Fe]$ literature abundances are taken from [Fishlock et al. \(2017\)](#). Error bars show the standard deviation.

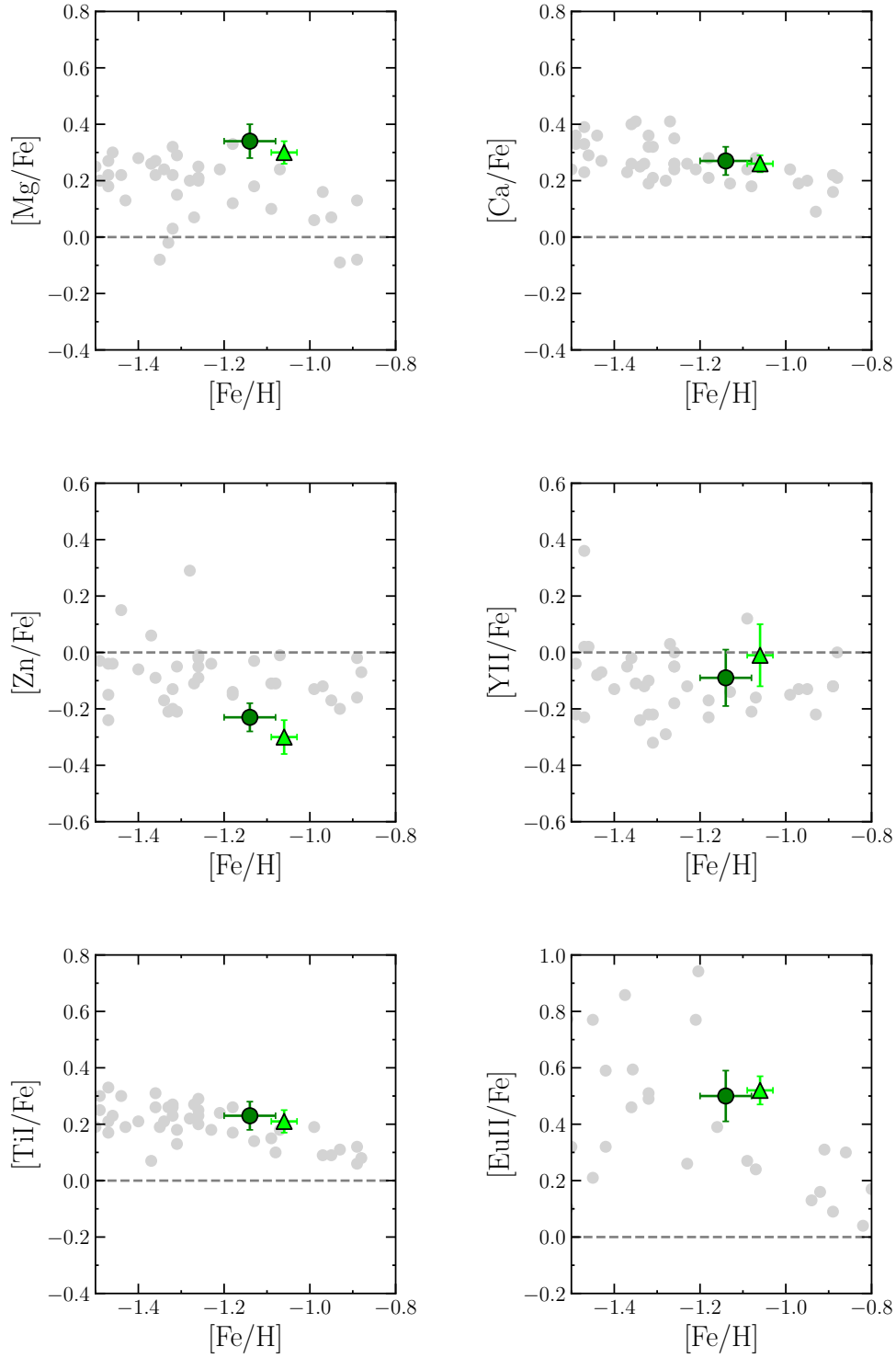


FIGURE 4.7 : Mean abundances of NGC 362 and NGC 1261 derived in this work (the colour coding is the same as in Figure 4.3) compared with those of GSE stars (grey filled points, either derived in this work or by [Ceccarelli et al. \(2024a\)](#) for Mg, Ca, TiI, Zn, and YII). Literature abundances for $[EuII/Fe]$ are taken from [Fishlock et al. \(2017\)](#); [Aguado et al. \(2021\)](#); [Carrillo et al. \(2022\)](#); [Giribaldi & Smiljanic \(2023\)](#); [François et al. \(2024\)](#). Error bars stand for the standard deviation.

for NGC 362 and NGC 1261 are consistent with those observed in the literature (Aguado et al. 2021; Ceccarelli et al. 2024a; François et al. 2024), as are the high $[\text{EuII}/\text{Fe}]$ ratios (see also, Aguado et al. 2021; Matsuno et al. 2021; François et al. 2024; Ou et al. 2024).

This comparison represents strong additional evidence that the two selected GCs were indeed born in the GSE dwarf galaxy, and provides important confirmation that GCs and stars trace the same chemical evolution when sharing the birth environment (see also Monty et al. 2024).

4.4.3 Ruprecht 106 and the Helmi Streams

In this Section, I investigate the compatibility of the chemical composition of Rup106 and that of stars formed in the galaxy that originated the Helmi Streams (Helmi et al. 1999), as a tentative dynamical connection between the two has been pointed out by several works (Mas-sari et al. 2019; Forbes 2020; Callingham et al. 2022). In Figure 4.8 I present the mean abundances of Rup106 derived in this work (blue filled squares) compared to the high-resolution abundances of 11 stars linked to the Helmi Streams (grey filled points; Matsuno et al. 2022b, M22 hereafter). I note that I cannot compare EuII abundances as they were not published in M22, and I therefore show Ni as an additional comparison, representative of the iron-peak group. To ensure homogeneity in the comparison, I reanalysed the spectra of the Helmi Streams stars following the procedure described in Section 4.2. The results are shown in Figure 4.8 (black filled points). The average offset between abundances in this work and those of M22 is consistent with zero for all the elements I show in Figure 4.8, except for TiI, Ni, and YII, for which I find mild offsets of $+0.08$ dex ($\sigma = 0.04$), -0.08 dex ($\sigma = 0.05$), and $+0.09$ dex ($\sigma = 0.07$), respectively. Regardless of the adopted data set (even though the most homogeneous comparison is the one with re-analysed abundances), when comparing the mean abundance ratios of Rup106 to the trend observed in the Helmi Streams, a noticeable difference emerges, particularly in the α -elements. These findings consistently indicate $[\alpha/\text{Fe}]$ values approximately 0.2 dex lower in comparison to the Helmi Streams, hinting at a lower star formation efficiency in the environment where Rup106 formed. Among the other elements studied, the most significant differences arise in Ni and YII with Rup106 being depleted by ~ 0.2 dex and by ~ 0.4 dex, respectively. Therefore, in order to account for the observed differences shown in Figure 4.8, the progenitor of the Helmi Streams would need to have been massive enough to be chemically inhomogeneous. Otherwise, this chemical incongruity is strong evidence in support of the interpretation that Rup106 was born in a different environment from the progenitor of the Helmi Streams.

4.5 Possible origins of Ruprecht 106

In light of the chemical difference between Rup106 and the Helmi Streams stars, and given its peculiar chemical composition compared to many other GCs (e.g. Brown et al. 1997; Carretta et al. 2009, 2013; Villanova et al. 2013; Monaco et al. 2018; Puls et al. 2018; Crestani et al. 2019; Masseron et al. 2019; Horta et al. 2020; Mucciarelli et al. 2021a), the birth environment of Rup106 likely underwent a unique chemical evolution. In the following, I discuss some possible interpretations.

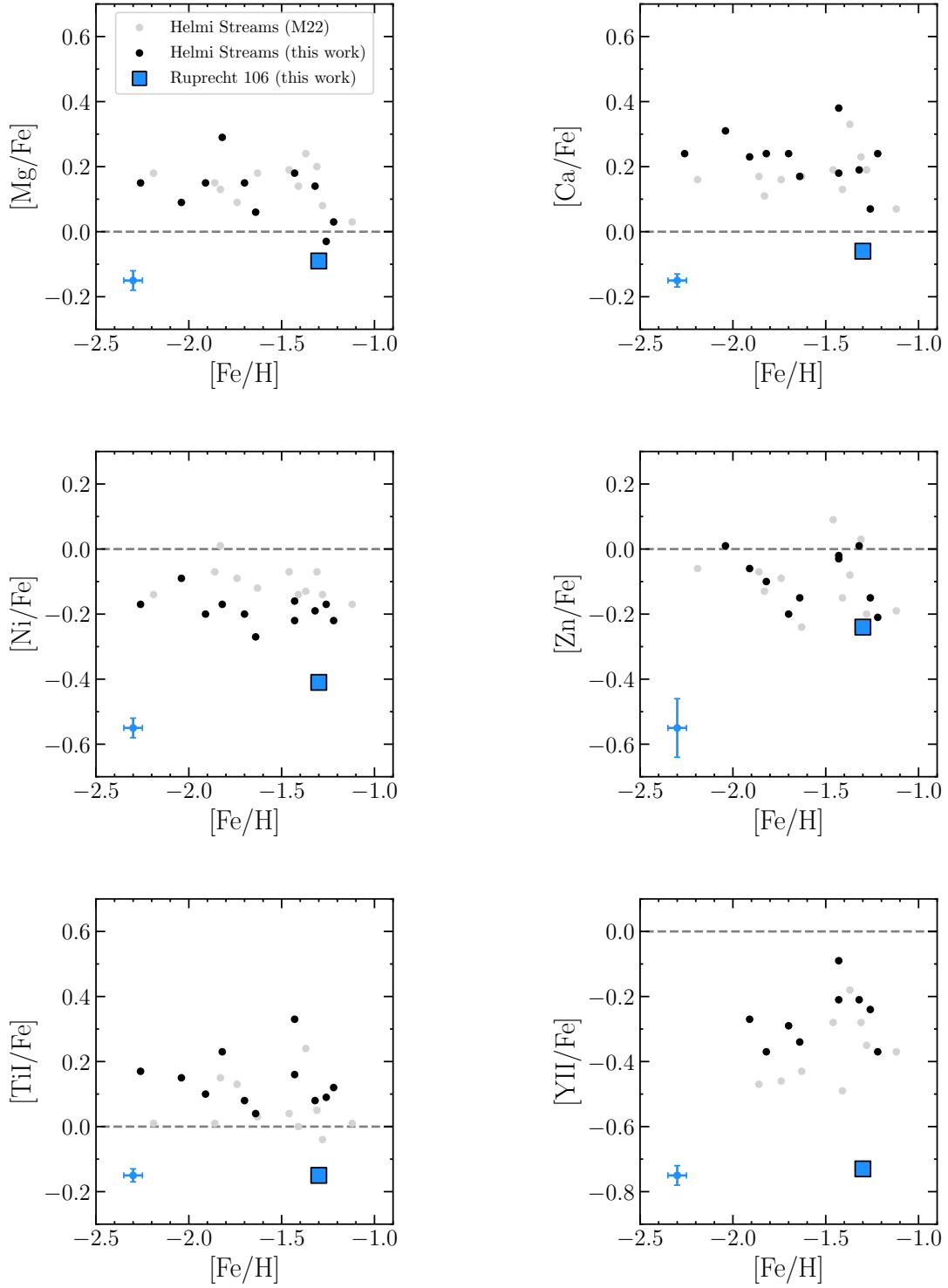


FIGURE 4.8 : Mean abundances of Rup106 derived in this work (blue filled squares) compared with those derived for field stars associated with the Helmi Streams. Results from this work and from M22 are shown in black and grey, respectively. The standard deviation is plotted in the bottom left corner.

4.5.1 Comparison with NGC 121

Given its extremely peculiar chemical makeup, Rup106 has long been regarded as originating in an extragalactic environment. Initially, several works proposed that it was likely to have been accreted from the Magellanic Clouds (Lin & Richer 1992; Fusi Pecci et al. 1995), and particularly from the Small Magellanic Cloud (SMC). Although recent post-*Gaia* kinematics studies of the orbit in the MW of Rup106 (see Section 4.1) have excluded such possibility, it is interesting to note that Rup106 is coeval with NGC 121, the oldest known SMC GC (~ 10.5 Gyr, Glatt et al. 2008; Forbes & Bridges 2010; Dotter et al. 2011) and shows very similar metallicity (Dalessandro et al. 2016; Mucciarelli et al. 2023). Therefore, this presents an excellent opportunity to explore the possibility that an SMC-like galaxy is the progenitor of Rup106. I directly compared results from Mucciarelli et al. (2023), given the congruent analytical approaches. As shown in Figure 4.9, NGC 121 (yellow filled squares) has solar-scaled $[\alpha/\text{Fe}]$, hinting at an enrichment due to SNe Ia already in place in the SMC ~ 10.5 Gyr ago. These values are, on average, $0.1 - 0.2$ dex α -enriched relative to what I find for Rup106, suggesting that Rup106 likely formed in an environment with even less efficient star formation than that of the SMC. Regarding the iron-peak elements, I find comparable values in the abundance ratios of Cu. The very low values of $[\text{Cu}/\text{Fe}]$ found in both Rup106 and NGC 121 are consistent with those of the SMC field stars (Mucciarelli et al. 2023) and are 0.5 dex underabundant compared to MW GCs and stars, favouring a chemical-enrichment scenario in which the contribution by massive stars is extremely reduced, as also discussed in Section 4.3.2. Additionally, Rup106 shows lower abundances (~ 0.2 dex) of other elements produced in massive stars (i.e. Sc, V, and Co) relative to NGC 121 and also in Ni. Interestingly, the only elements in which enhancement is detected in Rup106 are Cr and Mn. These elements are predominantly synthesised by SNe Ia, with yields depending on the metallicity of the progenitor SNe Ia. Unfortunately, Mucciarelli et al. (2023) do not provide an estimate of $[\text{Zn}/\text{Fe}]$ for NGC 121. When assessing *s*-process elements, I note similar Ba abundances between the two clusters, yet they discern distinct values in Y and La, with Rup106 being, once again, depleted in these elements. Given that NGC 121 demonstrates pronounced deficiencies in these elements relative to the only other SMC GC of similar age, this discrepancy highlights the unique conditions under which Rup106 formed. Also, the efficiency of the production of *r*-process elements is extremely low, with Rup106 being ~ 0.7 dex underabundant in Eu relative to NGC 121, which conversely aligns with observations of GSE GCs and SMC stars. This comparison further supports the idea that Rup106 originated in an environment that was significantly different from the SMC of 10.5 Gyr ago and was probably characterised by an exceptionally low star formation efficiency and likely featured a truncated initial mass function (IMF) with a minimal contribution from massive stars.

4.5.2 Comparison with surviving dwarf galaxies

A similar chemical composition to that of Rup106 has been observed in stars belonging to dwarf galaxies in the Local Group (Venn et al. 2004; Tolstoy et al. 2009). Indeed, subsolar $[\alpha/\text{Fe}]$ values at $[\text{Fe}/\text{H}] \leq -1.5$ dex are observed in surviving dwarf galaxies such as Carina, Fornax, Sculptor, Sextans, and Ursa Minor (Venn et al. 2012; Hendricks et al. 2014; Hill et al. 2019; Theler et al. 2020; Fernandes et al. 2023; Sestito et al. 2023). The low values of Zn ($[\text{Zn}/\text{Fe}] \sim -0.3$ dex) derived for Rup106 compared to those found in MW stars are

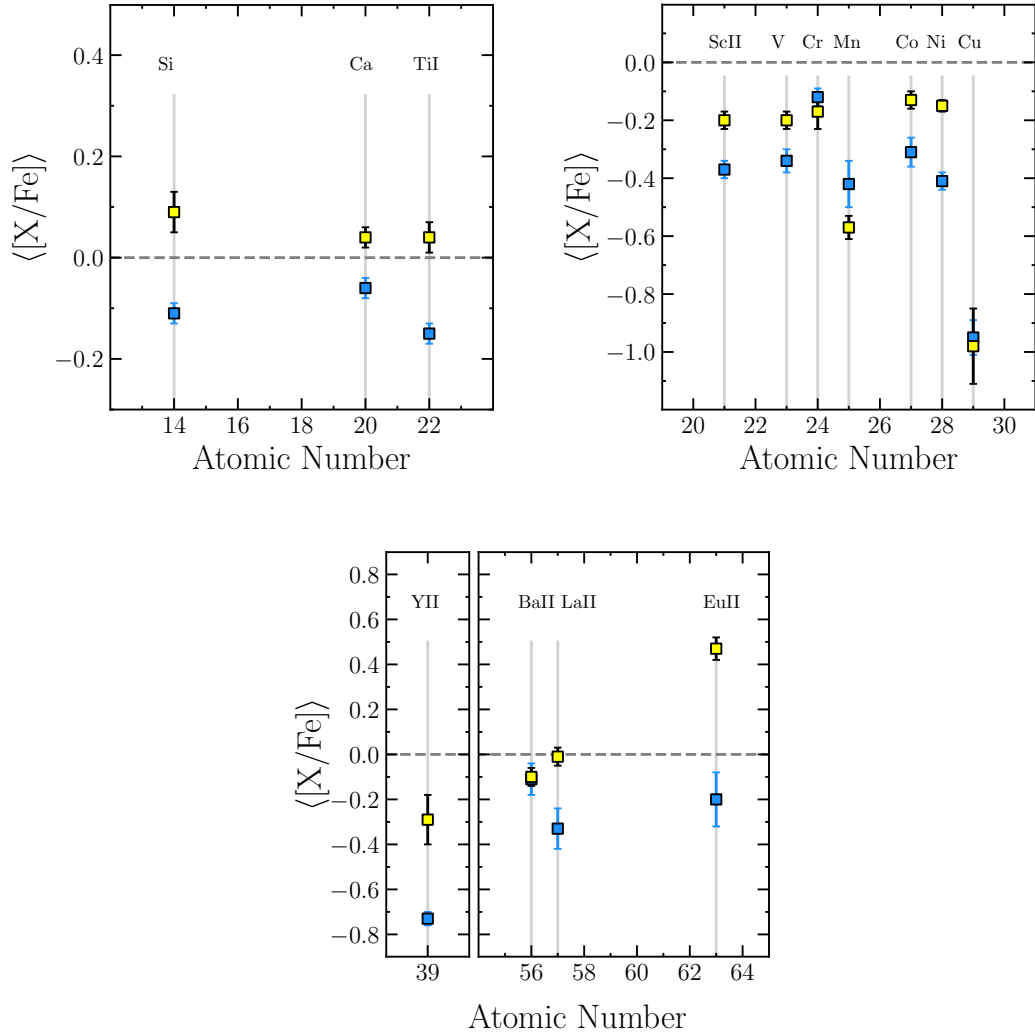


FIGURE 4.9 : Mean abundances of the α - (left panel), iron-peak (middle panel), and neutron-capture (right panel) elements in Rup106 (blue filled squares) and NGC 121 (yellow filled triangles). Error bars indicate the standard deviation.

also typical of these systems (see Figure 16 of [Skúladóttir et al. 2017](#), and reference therein). Finally, most of the dwarf galaxies show enhancement in $[EuII/Fe]$ compared to MW stars due to either the very low star formation efficiency or the delayed contribution to the production of Eu by NSMs ([Letarte et al. 2010](#); [Venn et al. 2012](#); [Lemasle et al. 2014](#)). However, even the extremely low $[EuII/Fe]$ of Rup106 can be reproduced in some of these systems, such as Sculptor ([Hill et al. 2019](#)). Indeed, these latter authors find several stars in Sculptor with subsolar values (~ -0.1 dex) of $[EuII/BaII]$ at $[Fe/H] \sim -1.3$ dex, suggesting that the onset of s -process enrichment was already in place at this metallicity. It is interesting to note that the chemical composition of Rup106 resembles that found in iron-rich metal-poor stars (IRMP), despite these latter being unlikely to form in GCs, thus indicating a birth environment enriched by the (double) detonation of sub-Chandrasekhar-mass CO white dwarfs ([Reggiani et al. 2023](#)). This further supports the idea that Rup106 formed in a dwarf galaxy,

as these authors demonstrated that IRMP stars are easier to find in surviving dwarf galaxies and the Magellanic Clouds, rather than in the halo of the MW.

It is important to note that the majority of the existing systems that reproduce the peculiar chemistry of Rup106 have a stellar mass ($\sim 10^6 M_\odot$, [McConnachie 2012](#)) that is not compatible with that estimated for the progenitor of the Helmi Streams, with the latter being roughly 100 times more massive ([Koppelman et al. 2019b](#)). Therefore, if the dynamical association of Rup106 is accurate, the possibility that it did not form directly in the progenitor of the Helmi Streams cannot be ruled out. I speculate that Rup106 could have formed in a dwarf galaxy with a mass comparable to that of Sculptor; the dynamical properties of Rup106 suggest that this could have been a satellite of the progenitor of the Helmi Streams or the Sagittarius dwarf ([Davies et al. 2024](#)), similarly to the case of the GC NGC 2005 in the Large Magellanic Cloud ([Mucciarelli et al. 2021a](#)).

4.6 Conclusion

The primary aim of this work is to investigate the potential differences in elemental abundances between six GCs of very similar metallicity ($-1.3 \leq [\text{Fe}/\text{H}] \leq -1.0$ dex) that are expected to have formed in different environments, and to decipher which abundance ratios are most sensitive to their different origin.

The outcome of this homogeneous chemical analysis reveals striking similarities in the chemical abundances of NGC 362 and NGC 1261, two GCs that were accreted during the merger event of the *Gaia*-Sausage-Enceladus dwarf galaxy. When comparing the chemical abundances of these GCs with those of the in-situ GCs NGC 6218, NGC 6522, and NGC 6626, a coherent and distinct overall pattern emerges in the α -elements, especially in Mg, Si, and Ca, where I identify a depletion of ~ 0.1 dex in the GSE GCs with respect to in-situ GCs. This finding agrees with observations of field stars of the Galactic halo in this metallicity range, where distinctions between chemical patterns of in-situ and accreted stars are discernible, especially in the α -elements, whereas trends become indistinguishable at lower metallicity ([Horta et al. 2023](#); [Ceccarelli et al. 2024a](#)). This is consistent with the fact that it took 2 Gyr less for NGC 6218, NGC 6522, and NGC 6626 to reach the same metallicity as the GSE GCs ([Dotter et al. 2010, 2011](#); [VandenBerg et al. 2013](#); [Villanova et al. 2017](#); [Kerber et al. 2018](#)), indicating that the contribution of SNe Ia to the chemical enrichment of the gas was not in place at the time when these systems formed. Moreover, statistically significant variations are observed in specific elements such as Zn and Eu, whose production sites are directly associated with massive stars (HNe for Zn and rCC-SNe+NSMs for Eu). It is worth noting that these events are inherently rare, and might exert a profound influence on the abundances within a given environment. These results reinforce the idea that chemical tagging is an effective tool for investigating the origin of GCs, even when comparing the chemical compositions of GCs formed in different progenitors, but at the same time demonstrate that not every element is equally sensitive in this sense.

In this coherent picture, Rup106 stands out as a distinct system. Indeed, Rup106 follows the AMR of accreted GCs ([Forbes & Bridges 2010](#); [Dotter et al. 2010, 2011](#); [VandenBerg et al. 2013](#)), whereas MW in-situ clusters of similar age clearly experienced a different chemical enrichment path, exhibiting significantly higher metallicity (0.5 – 0.8 dex more metal rich; [Massari et al. 2023](#)). Despite the congruence between Rup106 and the GSE GCs in the

age–metallicity space, differences emerge when examining all their chemical elements. Particularly, Rup106 exhibits subsolar $[\alpha/\text{Fe}]$ values typical of an environment already enriched by SNe Ia, in contrast to GSE clusters ($[\alpha/\text{Fe}] > 0.3$ dex), where SNe Ia have only just started contributing to the enrichment of the gas. This comparison underlines distinct chemical evolution histories between GSE and the environment in which Rup106 formed, with the latter experiencing slower and less efficient star formation and likely an IMF truncated of most of the massive stars, indicating a lower mass for the host of Rup106 at ~ 10.5 Gyr ago compared to GSE. I interpret the extreme peculiarity of the chemistry of Rup106 as due to the particular evolution of its progenitor, which could be the galaxy that gave rise to the Helmi Streams. However, the remarkably low values of the $[\alpha/\text{Fe}]$ abundance ratios, as well as of some other heavier elements, compared to Helmi Streams stars lend weight to the possibility that Rup106 originated from an even smaller galaxy, with a stellar mass comparable to that of some surviving dwarf galaxies (e.g. Sculptor).

In light of these results, this work demonstrates that the exceptionally high precision offered by a strictly homogeneous chemical analysis allows chemical tagging to play a crucial role in uncovering the true origin of GCs. Particularly, this method enables not only to clearly discriminate between GCs formed within the MW and those formed in other accreted galaxies, but also to distinguish the chemical signatures of GCs originating from independent accreted progenitors.

The results presented in Chapters 2, 3, and 4 underscore the strength of chemical tagging as a powerful and reliable tool for Galactic Archaeology. Through the homogeneous and systematic approach developed in this Thesis, I have shown that *both field stars and globular clusters* can serve as complementary and equally insightful tracers of the Milky Way assembly. Together, they offer a coherent and nuanced picture of how our Galaxy was built, revealing the intricate interplay between its accreted and in-situ components.

5 | NGC 288 as the first Splashed globular cluster

*Based on the published paper by [Ceccarelli et al. \(2025b\)](#), *A&A*, 704, A256*

NGC 288 occupies a distinctive place among the globular clusters in the Milky Way, as its orbital properties, chronological information, and detailed chemical composition have long challenged a straightforward interpretation of its origin. In this Chapter, I provide a full chrono-chemo-dynamical screening of this globular cluster within the completely homogeneous and self-consistent framework established in Chapter 4, with the objective of shedding light on its puzzling origin and clarifying the ambiguities surrounding its associations, as reported in the literature. This work is the third contribution to the *Cluster Ages to Reconstruct the Milky Way Assembly* (CARMA) collaboration ([Massari et al. 2023](#)). In Section 5.1 I introduce the scientific case. In Section 5.3 I derive the age of in-situ GCs at the same global metallicity as NGC 288. In Section 5.4 I derive the abundances of NGC 288 and compare its chemical makeup with that of in-situ GCs. In Section 5.5 I discuss the chrono-chemical comparison and draw firm conclusions about the origin of NGC 288.

Finally, in Section 5.6 I will summarize the current progress of the CARMA project, emphasizing the key results obtained in the four papers published to date, and to which I have actively contributed throughout my PhD ([Massari et al. 2023](#); [Aguado-Agelet et al. 2025](#); [Niederhofer et al. 2025](#); [Massari et al. 2026](#)).

5.1 The globular cluster NGC 288

As extensively discussed in Sections 1.1.3 and 1.3.3, GCs that formed in accreted dwarf galaxies exhibit distinct AMRs, which distinguish them from the trajectory followed by GCs formed in-situ (Marín-Franch et al. 2009; Forbes & Bridges 2010; Dotter et al. 2010; Leaman et al. 2013; Massari et al. 2019; Kruijssen et al. 2020), at least in the metal-intermediate and metal-rich regimes ($[M/H] > -1.3$ dex).

In this context, one peculiar case is that related to the globular cluster NGC 288. In fact, the orbital properties of this system, which is located in the Halo at a distance of 9.0 kpc from us (Vasiliev & Baumgardt 2021), suggest for an accreted origin during the GSE merger event (Massari et al. 2019; Forbes 2020; Callingham et al. 2022; Chen & Gnedin 2024). However, contrasting evidence has been found in the literature regarding its age. For example, several works found NGC 288 to be about 2 Gyr older than NGC 362 (i.e. a GSE GC with similar metallicity, Green & Norris 1990; Sarajedini & Demarque 1990; Bellazzini et al. 2001; Gontcharov et al. 2021, see also Section 5.6.2 for a discussion on the AMR of GSE derived within the CARMA project by Aguado-Agelet et al. 2025), whereas other works have reported an age difference between the two GCs always smaller than 1 Gyr (Stetson et al. 1996; Dotter et al. 2010; VandenBerg et al. 2013). These inconsistencies might be caused by systematic effects due to different photometric systems, methods, and adopted theoretical models, that can easily add up to ~ 2 Gyr (Massari et al. 2019). Further, several studies hint at differences in the chemical composition of NGC 288 compared to accreted GCs, especially when looking at the α - (Horta et al. 2020) and the light elements (Belokurov & Kravtsov 2024), pointing towards a potential in-situ formation. On top of this, Monty et al. (2023b) highlighted a poor agreement between NGC 288 and GSE field stars in the s - and r - process elements, showing that a chemical evolutionary model of a GSE-like galaxy fails to reproduce the abundances measured in NGC 288. However, also in these cases, the chemical evidence comes from spectra covering different spectral ranges analysed with different methods, and from the adoption of different models, which might result in significant systematic errors.

In this Chapter, I examine the chrono-chemo-dynamical profile of the globular cluster NGC 288, aiming to resolve the apparent contradictions arising from its peculiar properties. To do so, I compare age and chemical composition of NGC 288 with those of two in-situ MW GCs in the same metallicity range ($[M/H] \sim -1.0$ dex). The novelty of this study is that it is conducted within a completely homogeneous framework. On the one hand, homogeneous GC ages are estimated by means of the tools developed within the *Cluster Ages to Reconstruct the Milky Way Assembly* (CARMA) collaboration (Massari et al. 2023; Aguado-Agelet et al. 2025). On the other hand, the chemical analysis follows the same prescriptions and uses optical spectra obtained with the same instrument and with the same quality as in Chapter 4 (Ceccarelli et al. 2024b, C24b hereafter). This kind of analysis erases any potential offset introduced by the use of different approaches, leading to an interpretation of the observational evidence with the utmost precision.

5.2 The CARMA method

In this Section, I present the method employed by the CARMA project to determine the age of each GC, which is based on the isochrone fitting code presented in [Saracino et al. \(2019\)](#).

5.2.1 Stellar evolution framework

CARMA relies on the adoption of the stellar theoretical models provided within the latest release of the *Bag of Stellar Tracks and Isochrones* (BaSTI) database ([Hidalgo et al. 2018](#); [Pietrinferni et al. 2021](#)). More specifically, for the present analysis, I adopt the model sets accounting for the occurrence of diffusive processes (I refer to [Hidalgo et al. 2018](#), for a detailed discussion on the adopted input physics and physical assumptions). For the sake of the aim of this project, which is to ensure the highest possible degree of precision in terms of age determination, only solar-scaled models have been used. This prescription and use of the global metallicity $[M/H]$ rather than the iron content $[Fe/H]$ as input for the code allows to avoid making any assumption on the α -element abundance of each GC, which would otherwise be based on heterogeneous measurements coming from many different sources. Indeed, [Salaris et al. \(1993\)](#) demonstrated that the impact of different $[\alpha/Fe]$ mixtures on theoretical models for population II stars can simply be treated as an additional term on the global metallicity $[M/H]$, according to the relation¹:

$$[M/H] = [Fe/H] + \log(0.694 \times 10^{[\alpha/Fe]} + 0.301), \quad (5.1)$$

this is especially true when working in the optical–infrared colour combinations adopted in this work, as in these bands the effect of the specific α -elements distribution on the bolometric corrections becomes negligible ([Cassisi et al. 2004](#)). Estimates of $[\alpha/Fe]$ for the target GCs are only used a posteriori to perform a direct comparison of our best-fit metallicity with existing (possibly high-resolution) spectroscopic measurements. The whole sets of isochrones adopted in the present work were transferred from the theoretical Hertzsprung–Russell diagram to the various relevant photometric planes by adopting self-consistent colour – temperature (T_{eff}) relations and bolometric corrections ([Hidalgo et al. 2018](#)). The ratio between the extinction in a given photometric band A_λ and A_V depends on the flux distribution of the stellar source, and is in principle dependent on parameters such as T_{eff} , surface gravity ($\log g$), and the chemical composition (see e.g. [Bedin et al. 2005](#), for a discussion on this issue). When A_V is small, this effect is also small and a single value of A_λ/A_V can be safely applied along the whole isochrone. However, for those clusters affected by large extinction (typically for values larger than $E(B - V) = 0.10$ mag), it is necessary to consider the variation of A_λ/A_V along the isochrones in the fit to the observed CMD. Such an effect is increasingly significant towards bluer photometric passbands. To properly take into account this effect in the procedure of isochrone fitting to the CMD of those clusters affected by large extinction, T_{eff} -dependent reddening corrections have been applied to the magnitudes of the theoretical isochrones. The T_{eff} -dependent corrections were evaluated by adopting the web

¹The coefficients of this relation are slightly different from the ones provided by [Salaris et al. \(1993\)](#) in order to take into account the use of a different reference solar mixture between the BaSTI models, which are based on the heavy-element distribution provided by [Caffau et al. \(2011\)](#), whereas the models by [Salaris et al. \(1993\)](#) were based on the [Ross & Aller \(1976\)](#) mixture.

interface² that implements the prescriptions by Girardi et al. (2008) in order to determine the extinctions in the various photometric passbands, covering a wide range of T_{eff} and values of interstellar extinction.

5.2.2 The isochrone-fitting code

The isochrone-fitting algorithm developed within CARMA is a series of procedures that provide age, metallicity, distance, and reddening best-fit values within a Markov Chain Monte Carlo (MCMC) statistical framework, thus further associating robust uncertainty estimates to all of the output parameters. The steps followed by the algorithm are described in detail, as follows:

1. The first step of the algorithm consists in the construction of the best CMD to be fit. This includes the application of photometric quality cuts; the selection of GC member stars via kinematic information (whenever available) or via a selection based on the distance from the cluster centre; the correction of differential reddening effects; and the exclusion of obvious photometric binaries along the CMD main sequence. The details of this step applied to the case under study are described in Section 5.3.
2. A grid of BaSTI (Hidalgo et al. 2018) theoretical isochrones in the appropriate photometric bands is created with a very fine sampling of the age–metallicity space. The adopted step in $[M/H]$ is of 0.01 dex, whereas the step in age is of 100 Myr, but the parameter space could be more finely sampled through a linear interpolation³. The adopted models have a solar-scaled $[\alpha/Fe]$ mixture (see discussion about this assumption in Section 5.2.1), including diffusion effects as well as mass loss, and are corrected for T_{eff} -dependent reddening effects. Finally, the models are converted to the observational plane by applying the cluster distance modulus and extinction, by assuming the reddening law by Cardelli et al. (1989).
3. At this point a fitting function is defined, which measures the goodness-of-fit between the isochrones and the observed CMD. The portion of the isochrones that is fit to the CMD goes from the bottom of the main sequence to the tip of the red giant branch. Building upon the method presented in Saracino et al. (2019), the proposed function is the sum of two terms. The first term ($\mathcal{L}_{\text{priors}}$) is the likelihood that evaluates the consistency of the inferred parameters with the initial priors on $[M/H]$, distance, and $E(B - V)$; it has a Gaussian form and, when expressed in natural logarithm, can be written as:

$$\mathcal{L}_{\text{priors}} = \mathcal{L}_{E(B-V)} + \mathcal{L}_{\text{DM}} + \mathcal{L}_{[M/H]}, \quad (5.2)$$

where each individual term is in turn expressed as the natural logarithm of a Gaussian function:

$$\mathcal{L}_x = -0.5 \times (x - x_{\text{prior}})^2 / x_{\text{std}}^2, \quad (5.3)$$

²<http://stev.oapd.inaf.it/cgi-bin/cmd>

³The interpolation is performed by means of the Python library `scipy.interpolate.1d` (Virtanen et al. 2020). Different choices of interpolation algorithms might introduce further small systematic errors on the age estimates, but CARMA avoids this source of inhomogeneity as well.

with $x = [E(B - V), \text{DM}, [\text{M}/\text{H}]]$, and x_{prior} and x_{std} being the adopted values of the priors and their associated uncertainties, respectively. The second term ($\mathcal{L}_{\text{fit}}$) is the likelihood associated to the fit of the i individual points of the CMD, and is computed as:

$$\mathcal{L}_{\text{fit}} = \sum_{i=1}^N [\min(\text{dist}_i)]^2 / \sigma_i^2, \quad (5.4)$$

where N is the total number of stars in the CMD, $\min(\text{dist})$ is the minimum distance between data and model, and σ is the photometric error. After some testing, it has been realised that in few cases the fitting algorithm prefers local solutions that are significantly different (by more than 0.5 dex) from the spectroscopic measurements of $[\text{M}/\text{H}]$ used as prior. Given that the spectroscopic metallicity is an independent and very robust prior, the algorithm has been helped to avoid these local solutions — which are clearly offset even by visual inspection — by assigning greater importance to the first term, with a weight of 1. Conversely, the second term, which measures the disparity between the CMD and the isochrone, is assigned a lower weight, but not so low as to force the solution on the priors. Rather, the MCMC chains must still sample a wide range of parameters that can deviate from the values of the priors while still providing visually good fits. After some tests, the best weight to assign to the second term in this sense is found to be 0.3, so that:

$$\mathcal{L}_{\text{tot}} = \mathcal{L}_{\text{priors}} + 0.3 \times \mathcal{L}_{\text{fit}}. \quad (5.5)$$

4. The algorithm then looks for the best-fitting isochrone — meaning the model that minimizes $\mathcal{L}_{\text{tot}}$ — by exploring the parameter space (age, $[\text{M}/\text{H}]$, distance, and reddening) by means of the **emcee** (Foreman-Mackey et al. 2019) Python package that provides an efficient implementation of the affine-invariant MCMC ensemble planner.
5. Finally, the algorithm provides the best solution in terms of age, $[\text{M}/\text{H}]$, distance, and $E(B - V)$, together with the associated uncertainties (corresponding to the 16th and the 84th percentiles of the posterior distributions) and their correlation parameter. The results coming from the application of this algorithm to the GCs under study are shown in Figures 5.2 and 5.3.

5.3 Comparison between the age of NGC 288 and in-situ globular clusters

The first objective of this work is to compare the age of NGC 288 as found in Aguado-Agelet et al. (2025) with that of GCs at similar metallicity whose origin is clearly in-situ. This type of relative comparison is, in fact, the best way to assess whether the hypothesis that NGC 288 is too old compared to GSE GCs to have been accreted is correct. According to the classifications by Massari et al. (2019) and Callingham et al. (2022), the only in-situ disc GCs at $[\text{M}/\text{H}] \sim -1.0$ dex for which public *Hubble Space Telescope* (HST) photometry is available are NGC 6218 and NGC 6362. For both GCs, an in-situ origin is supported by chemistry as well as by dynamics (Belokurov & Kravtsov 2024, C24b).

To estimate the age of NGC 6218 and NGC 6362, I used photometry in the HST F606W and F814W filters from the HUGS survey (Piotto et al. 2015; Nardiello et al. 2018). In accordance with the typical prescriptions adopted by CARMA, and to ensure the highest quality data for the fitting process, I applied a differential reddening correction to the HST photometry of NGC 6218 and NGC 6362 following the approach described by Milone et al. (2012), after selecting for proper-motion based membership ($p > 90\%$). I used RGB stars to define the reference sample, as their lower photometric errors make them preferable over main sequence stars, despite their smaller number. The differential reddening value ($\Delta E(B - V)$) associated with each star was derived as the median offset from the RGB mean ridge line, defined in a CMD oriented along the reddening vector, based on the 30 nearest reference stars. I employed the Cardelli et al. (1989) extinction law, adopting $R_V = 3.1$. This iterative process was repeated for each star until the residual $\Delta E(B - V)$ matched the typical photometric error, reaching convergence after two iterations. The effect of the differential reddening corrections on the CMD of NGC 6362 is illustrated in top left and central panels of Figure 5.1, while the corresponding reddening map is displayed in the bottom panel.

The isochrone fitting method used to derive the age of NGC 6218 and NGC 6362 is presented in Section 5.2. The results of the isochrone fitting in both optical CMDs for these GCs are shown in Figures 5.2 and 5.3 and summarised in Table 5.1. In the top panels of each figure, I show the best-fit isochrone superimposed on the two CMDs. Grey points represent the stars selected according to the methods described above (see also Section 1.3.3), while green points indicate stars specifically used for the fit. The posterior distributions of the parameters of the models are presented in bottom panels alongside the corner plot with the best fit values for $[M/H]$, colour excess, distance modulus, and age. To compare the global metallicity with literature results, I transformed $[M/H]$ into the iron abundance following the prescriptions described in Aguado-Agelet et al. (2025). Thus, the photometric solution derived in this work translates to $[Fe/H] = -1.38$ dex for NGC 6218 and $[Fe/H] = -1.08$ dex for NGC 6362, which is consistent within 0.1 dex with spectroscopic measurements (Carretta et al. 2009; Massari et al. 2017). The median colour excess values are $E(B - V) = 0.20 \pm 0.01$ and $E(B - V) = 0.07 \pm 0.01$ for NGC 6218 and NGC 6362, respectively. This is also in agreement with previous literature estimates reported in Harris (2010). Also, the distance modulus is well recovered, with differences with values listed in the Harris (2010) catalogue up to 0.15 mag, but fully consistent with results from Baumgardt & Vasiliev (2021).

In Figure 5.4, I present the AMR for the two GCs under study in this work (red filled squares) together with the results obtained for the metal-rich in-situ GCs (red filled circles) in Massari et al. (2023), the in-situ cluster ESO452-11 (red filled triangle) from Massari et al. (2025), and the dynamically selected GSE GCs (green filled circles) in Aguado-Agelet et al. (2025). As made evident by the figure, the age of NGC 288 is fully consistent within the uncertainties with that of the two in-situ GCs analysed here. The mean age of the three GCs is 13.68 Gyr, with a very small dispersion of 0.19 Gyr. This in turn means that the three GCs are ~ 2.5 Gyr older than the sample of GSE GCs at the same metallicity, as expected for clusters that formed in an environment characterised by a higher star formation efficiency, compared to a dwarf galaxy such as GSE (Kruijssen et al. 2019; Souza et al. 2024; González-Koda et al. 2025). All the collected evidence therefore supports the interpretation of NGC 288 as born in-situ in the MW, in contrast to its orbital properties (Massari et al. 2019; Callingham et al. 2022). Finally, I note that one additional GSE system (i.e. NGC 6205,

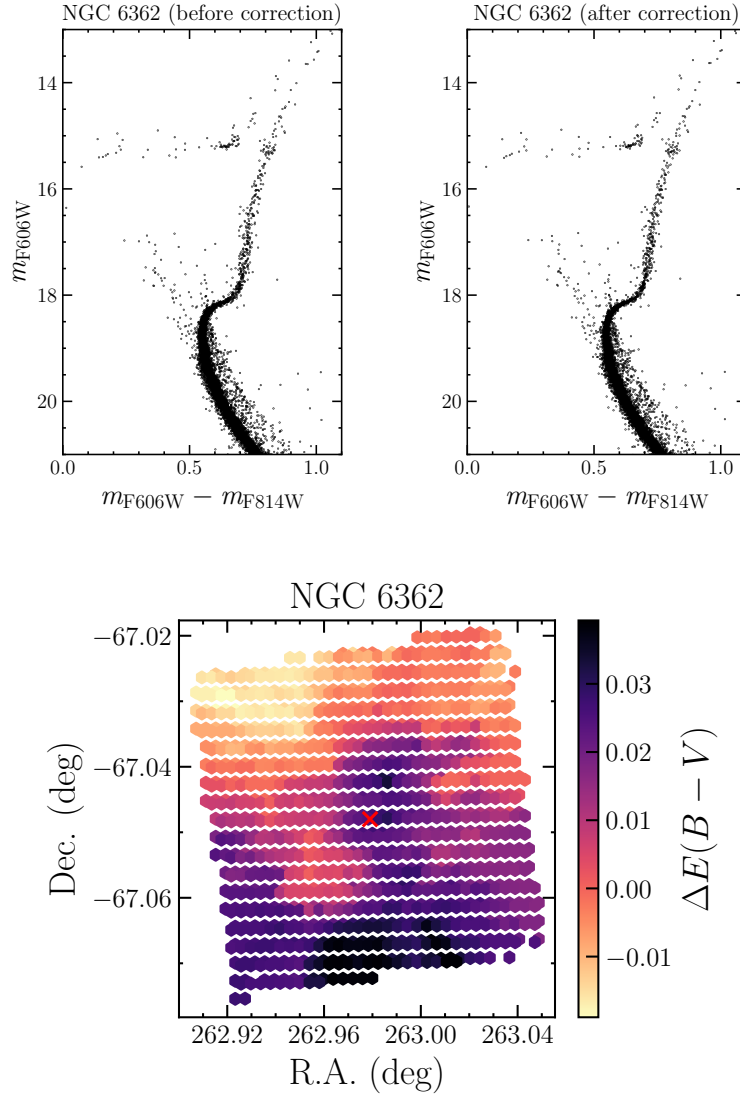


FIGURE 5.1 : Comparison of the CMDs of NGC 6362 before (top left panel) and after (top right panel) correcting for the effect of differential reddening, and differential reddening map for the GC NGC 6362 (bottom panel). The red cross indicates the centre of the cluster (Vasiliev & Baumgardt 2021).

red empty circle) follows the same AMR as the three GCs described above, reinforcing the idea presented in Aguado-Agelet et al. (2025), namely, that it is a contaminant in the fully dynamical selected GSE sample with a likely in-situ origin. As this GC is more metal-poor than those analysed here, a comprehensive analysis of NGC 6205 is left to a future dedicated work.

5.4 The chemical composition of NGC 288

The combination of the chrono-dynamical information leads to contrasting results about the origin of NGC 288. In this context, the chemical composition of this system can play

TABLE 5.1 : Results of the isochrone fitting for NGC 6218, NGC 6362 (from this work) and NGC 288 (from [Aguado-Agelet et al. 2025](#)).

Name	[M/H] (dex)	$E(B - V)$ (mag)	$(m - M)_0$ (mag)	Age (Gyr)
NGC 6218	$-1.17^{+0.05}_{-0.02}$	$0.20^{+0.01}_{-0.01}$	$13.57^{+0.01}_{-0.02}$	$13.42^{+0.38}_{-0.40}$
NGC 6362	$-0.92^{+0.02}_{-0.02}$	$0.07^{+0.01}_{-0.01}$	$14.43^{+0.01}_{-0.01}$	$13.86^{+0.33}_{-0.36}$
NGC 288	$-1.12^{+0.08}_{-0.08}$	$0.02^{+0.01}_{-0.01}$	$14.77^{+0.01}_{-0.01}$	$13.75^{+0.28}_{-0.22}$

NOTES. The CMD fits and corner plots are shown in Figures 5.2 and 5.3. All results obtained from the CARMA project can be found at: <https://www.oas.inaf.it/en/research/m2-en/carma-en/>

a crucial role, since the abundances of stars reflect the chemical enrichment history of the environment where they formed. Thus, a detailed study of the chemical makeup of this GC can favour one of the two scenarios described above, offering clues to finally solving the puzzle regarding its origins. To do so, I followed the same approach used for the chronological information: a relative, systematic-free comparison between the abundances of NGC 288 and that of in-situ and accreted GCs (see the full description in Section 4.2).

To perform the chemical analysis, I collected archival data of ten red giant branch (RGB) stars in NGC 288 that have been observed under the ESO-VLT Programme 073.D-0211 (PI: E. Carretta) using the multi-object spectrograph UVES-FLAMES ([Pasquini et al. 2002](#)) mounted at the VLT. The spectra were acquired using the Red Arm 580 CD3 grating with a spectral coverage between 4800 and 6800 Å, along with a spectral resolution of $R \sim 40000$. The typical signal-to-noise ratio is $S/N \geq 55$ at 6000 Å. The spectra were reduced using the dedicated ESO pipeline⁴. The sky background emission was measured by observing empty sky regions and subsequently subtracted from each single stellar spectrum. To ensure homogeneity in the spectroscopic analysis, I followed the same approach used in [C24b](#) (Section 4.2.1) to derive the atmospheric parameters and elemental abundances of target stars. For details of the procedure, I refer to [C24b](#) (Section 4.2) and references therein. The values for the stellar parameters are tabulated in Table 5.2. The mean abundances for NGC 288 for key chemical elements that have proven their efficiency in disentangling accreted and in-situ formation (i.e. α -elements, Zn, Eu, [C24b](#)) are listed in Table 5.4. The abundances of single stars can be found in Table 5.3. The average iron content derived from neutral iron lines is $[\text{Fe}/\text{H}] = -1.21 \pm 0.01$ dex, in good agreement with either spectroscopic ([Carretta et al. 2009](#); [Horta et al. 2020](#)) and photometric solutions (see [Aguado-Agelet et al. 2025](#)).

In Figure 5.5, I compare the average abundance of NGC 288 (blue symbol) and several MW GCs from [C24b](#), distinguishing between in-situ (NGC 6218, NGC 6522 and NGC 6626, red symbols) and accreted from GSE (NGC 362 and NGC 1261, green symbols). As illustrated in the left panel, NGC 288 consistently shows enhancement (≥ 0.1 dex) in α -elements Si and

⁴<https://www.eso.org/sci/software/pipelines/>

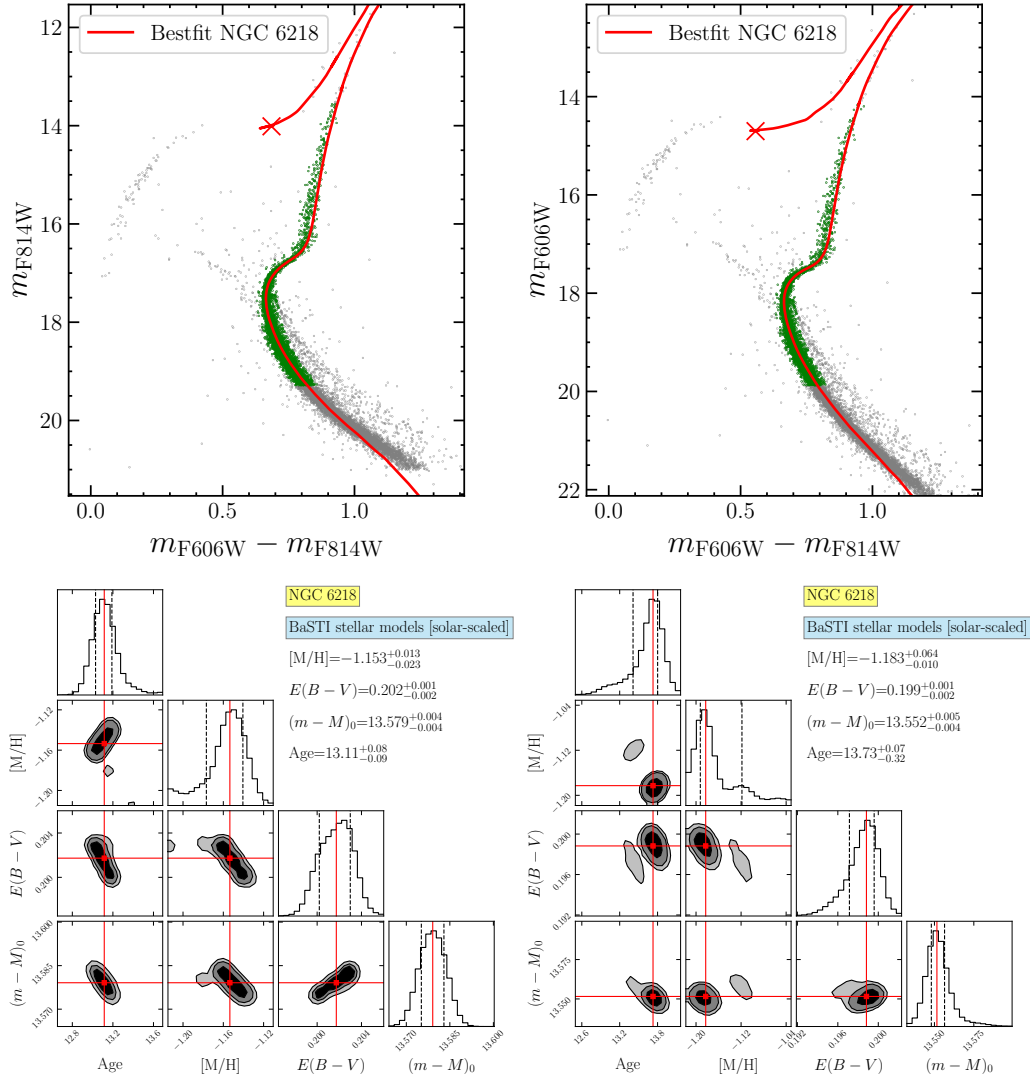


FIGURE 5.2 : Results for NGC 6218. Top-left: Best-fit model in the $(m_{F814W}, m_{F606W} - m_{F814W})$ CMD. Top-right: Best-fit model in the $(m_{F606W}, m_{F606W} - m_{F814W})$ CMD. Bottom-left: Posterior distributions for the output parameters and the best-fit solution, quoted in the labels, in the $(m_{F814W}, m_{F606W} - m_{F814W})$ CMD. Bottom-right: Posterior distributions for the output parameters and the best-fit solution, quoted in the labels, in the $(m_{F606W}, m_{F606W} - m_{F814W})$ CMD.

Ti, compared to GSE GCs, with values comparable to those found in in-situ GCs. A similar enhancement is also observed in Mg. Moreover, the average $[Zn/Fe]$ ratio in NGC 288 is consistent (within the uncertainties) with that of in-situ GCs. Given that absolute values of abundance ratios across different inhomogeneous studies may be subject to systematic zero-point offsets, the comparisons with literature are based on relative abundance differences derived within homogeneous analyses. The α -element enhancements I find for NGC 288 relative to the GSE GC NGC 362 are consistent with results from previous studies (Shetrone & Keane 2000; Carretta et al. 2009, 2010, 2013; Horta et al. 2020; Monty et al. 2023a,b, see also the discussion in Section 4.3.4). Additionally, Monty et al. (2023a,b) also found a

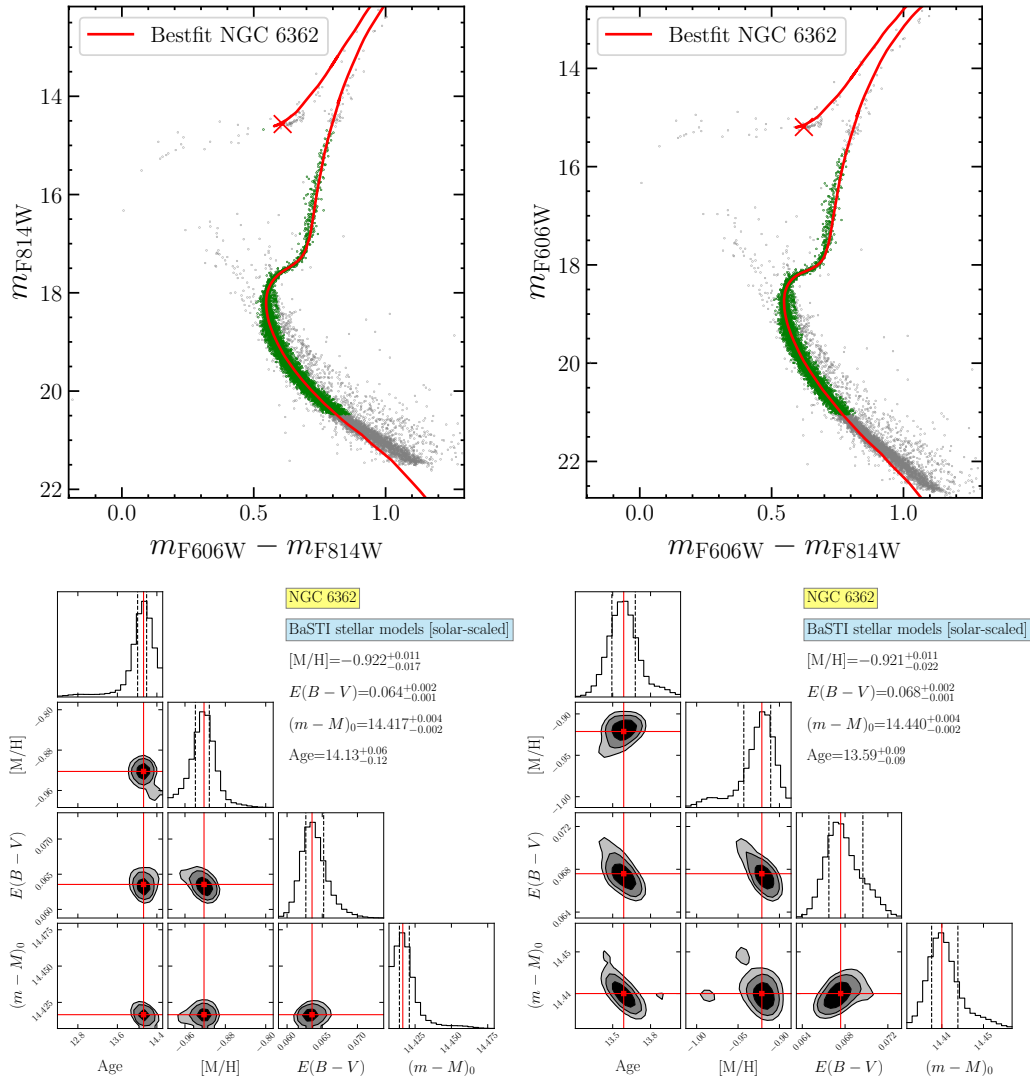


FIGURE 5.3 : Same as Figure 5.2, but for NGC 6362.

mild (~ 0.1 dex) $[\text{Zn}/\text{Fe}]$ enhancement in NGC 288 relative to NGC 362. Furthermore, the differences detected in the α - and neutron capture elements in NGC 288 and the in-situ GC NGC 6218 are in agreement with those reported by Carretta et al. (2009, 2010); Horta et al. (2020); Schiappacasse-Ulloa et al. (2024).

Finally, I find that the $[\text{EuII}/\text{Fe}]$ of NGC 288 falls in between the GSE and in-situ groups, in agreement with literature results (Shetrone & Keane 2000; Monty et al. 2024; Schiappacasse-Ulloa et al. 2025). However, since Eu is synthesized in various rare stellar events (e.g., magneto-rotational supernovae, collapsars, neutron star mergers, see Cescutti et al. 2015; Mösta et al. 2018; Siegel et al. 2019), its abundance is known to show significant intrinsic scatter, even among populations formed in the same environment (see e.g. Venn et al. 2012; Hill et al. 2019; Matsuno et al. 2021; Ou et al. 2024). As shown in the right panel of Figure 5.5, the chemical spaces where the consistency between NGC 288 and in-situ GCs

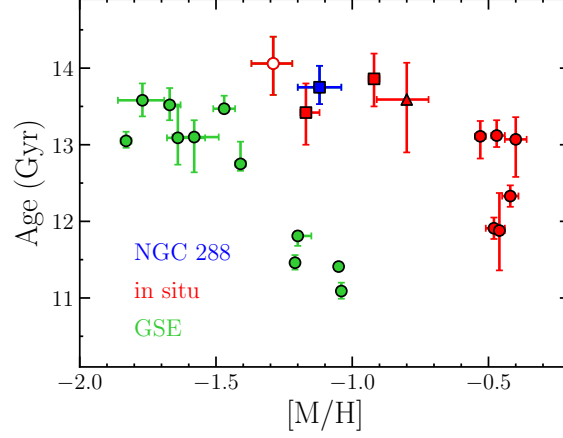


FIGURE 5.4 : Age-metallicity plane for all the GCs studied so far in the CARMA project. I plot the results for NGC 6218 and 6362 from this work as red filled squares. The position of NGC 288 from [Aguado-Agelet et al. \(2025\)](#) is highlighted as a blue filled square. Red and green filled circles represent in-situ and GSE GCs from [Massari et al. \(2023\)](#) and [Aguado-Agelet et al. \(2025\)](#), respectively, while the red empty circle is NGC 6205. The red filled triangle is ESO452-11 from [Massari et al. \(2025\)](#).

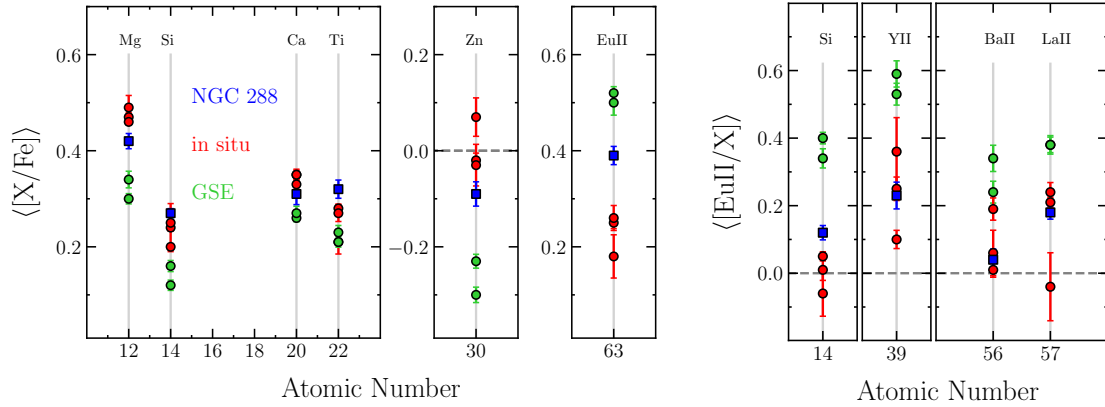


FIGURE 5.5 : Left panel: Difference of mean abundance ratios of the α -elements Mg, Si, Ca, Ti, as well as Zn and EuII between NGC 288 and GCs analysed in [C24b](#). GCs are colour coded according to their progenitors as in Figure 5.4. Right panel: Comparison of mean abundance ratios of EuII relative to other chemical elements (i.e. Si, YII, BaII, and LaII). Standard errors associated with the mean abundances are also reported.

TABLE 5.2 : Information on the targets.

Star ID	ID <i>Gaia</i> DR3	T_{eff} (K)	$\log g$ (dex)	v_t (km s ⁻¹)
200011	2342906141734490880	4486	1.32	1.4
200055	2342907825361664128	4844	2.00	1.5
200050	2342903083717827200	4823	1.96	1.4
200004	2342903118077555840	4242	0.87	1.5
200002	2342903045061492224	4093	0.65	1.5
200009	2342907580546992128	4458	1.24	1.5
200038	2342903045061492224	4745	1.78	1.4
200021	2342904698625661824	4616	1.53	1.4
200061	2342908340757896704	4908	2.08	1.4
200020	2342904423747772416	4597	1.49	1.4

NOTES. I list the star ID from previous literature works (e.g. Carretta et al. 2009), ID from *Gaia* DR3, effective temperature, surface gravity, and microturbulent velocity. Typical uncertainties are of the order of 100 K, 0.01 dex, and 0.2 km s⁻¹ for T_{eff} , $\log g$, and v_t respectively.

is more remarkable are those relative to Eu. It has been well-established that the [EuII/X] ratios are a powerful tool to discriminate between in-situ and accreted GCs due to the different sites and timescales of production of this species compared to the α -elements and to the light and heavy *s*-process elements (Kobayashi et al. 2020b; Molero et al. 2023; Ou et al. 2024). Indeed, chemical evolutionary models predict that a more massive galaxy, such as the MW compared to GSE, would be expected to have lower values of Eu compared to these chemical elements that are due to either a higher star formation efficiency or the reduced impact of delayed *r*-process sources, such as neutron star mergers (Côté et al. 2019; Palla et al. 2025). I find that NGC 288 is depleted in all [EuII/X] ratios compared to GSE GCs and always shows compatible values with in-situ GCs from C24b. The relative differences between these two groups are consistent with those observed for either GCs and field stars (Fishlock et al. 2017; Aguado et al. 2021; Monty et al. 2024; Ou et al. 2024; Schiappacasse-Ulloa et al. 2025). This comparison demonstrates that the conditions of the gas where these clusters formed were extremely similar and coherent with the expectations for a galaxy like the MW in its earliest phases.

5.5 Discussion and conclusion

The picture that arises after combining all of these properties clearly suggests an in-situ formation for NGC 288, which is at odds with its dynamical properties. Yet, just because these contradictory features have been determined in an extremely precise way, I can put forward a scenario that can accommodate all the observational evidences in a coherent picture. In fact, I suggest that NGC 288 originally formed in-situ within the MW, likely on a near-circular orbit with a low vertical height (Pfeffer et al. 2020), until the merger with GSE took place. It is well established that this interaction likely dynamically heated up the pre-existing MW

TABLE 5.3 : Chemical abundance ratios for targets in NGC 288.

Star ID	[Fe/H] (dex)	[Mg/Fe] (dex)	[Si/Fe] (dex)	[Ca/Fe] (dex)	[Ti/Fe] (dex)
200011	-1.19 ± 0.09	0.49 ± 0.04	0.29 ± 0.10	0.34 ± 0.05	0.33 ± 0.09
200055	-1.15 ± 0.11	0.38 ± 0.03	0.25 ± 0.10	0.19 ± 0.04	0.24 ± 0.05
200050	-1.21 ± 0.10	0.44 ± 0.02	0.28 ± 0.09	0.40 ± 0.06	0.28 ± 0.06
200004	-1.26 ± 0.07	—	0.27 ± 0.11	0.41 ± 0.07	0.42 ± 0.13
200002	-1.26 ± 0.06	—	0.32 ± 0.12	0.40 ± 0.10	0.43 ± 0.15
200009	-1.22 ± 0.10	0.45 ± 0.04	0.22 ± 0.12	0.29 ± 0.05	0.33 ± 0.09
200038	-1.17 ± 0.11	0.40 ± 0.04	0.26 ± 0.10	0.27 ± 0.04	0.28 ± 0.06
200021	-1.21 ± 0.10	0.43 ± 0.03	0.25 ± 0.10	0.30 ± 0.05	0.32 ± 0.07
200061	-1.22 ± 0.10	0.33 ± 0.03	0.28 ± 0.08	0.23 ± 0.05	0.26 ± 0.05
200020	-1.21 ± 0.10	0.43 ± 0.03	0.27 ± 0.10	0.26 ± 0.04	0.29 ± 0.08
Star ID	[Zn/Fe] (dex)	[YII/Fe] (dex)	[BaII/Fe] (dex)	[LaII/Fe] (dex)	[EuII/Fe] (dex)
200011	-0.09 ± 0.16	0.38 ± 0.15	0.49 ± 0.17	0.20 ± 0.05	0.43 ± 0.05
200055	-0.03 ± 0.14	-0.01 ± 0.15	0.17 ± 0.17	0.21 ± 0.05	0.35 ± 0.06
200050	-0.06 ± 0.13	0.15 ± 0.14	0.39 ± 0.16	0.17 ± 0.05	0.37 ± 0.06
200004	-0.21 ± 0.15	0.19 ± 0.15	0.32 ± 0.15	0.20 ± 0.05	0.40 ± 0.05
200002	-0.24 ± 0.14	0.31 ± 0.15	0.37 ± 0.16	0.22 ± 0.05	0.47 ± 0.05
200009	-0.06 ± 0.16	0.10 ± 0.15	0.27 ± 0.16	0.20 ± 0.05	0.36 ± 0.05
200038	0.02 ± 0.14	0.04 ± 0.13	0.31 ± 0.15	0.22 ± 0.05	0.40 ± 0.06
200021	-0.08 ± 0.15	0.10 ± 0.15	0.35 ± 0.16	0.21 ± 0.04	0.46 ± 0.05
200061	-0.01 ± 0.14	0.15 ± 0.14	0.39 ± 0.15	0.26 ± 0.06	0.28 ± 0.06
200020	-0.13 ± 0.15	0.22 ± 0.15	0.39 ± 0.16	0.18 ± 0.05	0.34 ± 0.05

TABLE 5.4 : Average chemical abundance ratios for NGC 288.

Element	NGC 288 (dex)
$\langle[\text{Fe}/\text{H}]\rangle$	-1.21 ± 0.01 (0.03)
$\langle[\text{Mg}/\text{Fe}]\rangle$	0.42 ± 0.02 (0.05)
$\langle[\text{Si}/\text{Fe}]\rangle$	0.27 ± 0.01 (0.03)
$\langle[\text{Ca}/\text{Fe}]\rangle$	0.31 ± 0.02 (0.07)
$\langle[\text{Ti}/\text{Fe}]\rangle$	0.32 ± 0.02 (0.06)
$\langle[\text{Zn}/\text{Fe}]\rangle$	-0.09 ± 0.02 (0.08)
$\langle[\text{YII}/\text{Fe}]\rangle$	0.16 ± 0.04 (0.11)
$\langle[\text{BaII}/\text{Fe}]\rangle$	0.35 ± 0.03 (0.08)
$\langle[\text{LaII}/\text{Fe}]\rangle$	0.21 ± 0.01 (0.02)
$\langle[\text{EuII}/\text{Fe}]\rangle$	0.39 ± 0.02 (0.06)

NOTES. The standard deviation is reported in parenthesis.

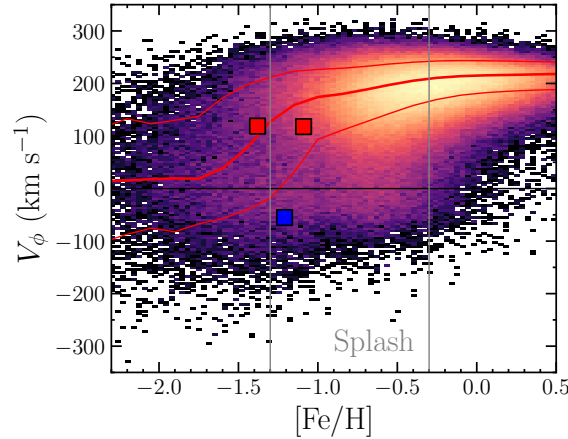


FIGURE 5.6 : Position of the NGC 288 (blue filled square) and the two in-situ GCs (red filled squares) in the $V_\phi - [\text{Fe}/\text{H}]$ plane. In background I show the distribution of likely in-situ stars from [Bellazzini et al. \(2024\)](#). The central red line highlights the median of the V_ϕ distribution, while the upper and lower lines trace the 16th and 84th percentiles, respectively. The grey vertical lines represent the upper and lower limits of the metallicity distribution function of Splash stars.

disc, driving stars onto more eccentric orbits ([Helmi et al. 2018](#); [Di Matteo et al. 2019](#)), a process commonly depicted as the Splash event ([Belokurov et al. 2020](#)). In Figure 5.6, I compare the position of NGC 288 (blue filled square) with that of NGC 6218 and NGC 6362 (red filled squares) in the $V_\phi - [\text{Fe}/\text{H}]$ diagram, together with that of in-situ stars⁵ selected by [Bellazzini et al. \(2024\)](#). As depicted in this figure, NGC 6218 and NGC 6362 follow the distribution of in-situ MW stars and GCs ([Belokurov & Kravtsov 2024](#)), likely forming during the rapid spin-up of the MW disc ([Belokurov & Kravtsov 2022](#)). On the contrary, NGC 288 display a V_ϕ value that is consistent with that of stars in the metal-poor tail of the Splash at $[\text{Fe}/\text{H}] \sim -1.2$ dex. This interpretation is further reinforced by the chemical properties of Splash stars, whose abundances of the α -element are enhanced at about $[\alpha/\text{Fe}] = 0.3$ dex ([Belokurov et al. 2020](#)), consistent with values measured for NGC 288. The fact that not all in-situ GCs experienced similar dynamical perturbations from the GSE merger suggests that their initial spatial distribution within the Galaxy played a role in determining their response to this event. For example, the current larger apocentre in the orbit of NGC 288 suggests the possibility that this cluster could have already been located at a greater Galactocentric radius, compared to NGC 6218 and NGC 6362, making it more susceptible to the dynamical perturbations induced by the GSE merger. The idea that a major merger can similarly perturb the orbit of a GC has been supported also by cosmological simulations, which show that such events partially modify the kinematic distributions of in-situ GCs ([Keller et al. 2020](#); [Chen & Gnedin 2022](#)). In particular, mergers can displace a non-negligible fraction of these clusters from the Galactic disc to the halo by increasing their orbital eccentricity and energy ([Li & Gnedin 2019](#); [Trujillo-Gomez et al. 2021](#)). Indeed, some old and metal-poor in-situ GCs are expected to be found in the high energy and retrograde end of the $E - L_z$ plane ([Pfeffer et al. 2020](#); [Pagnini et al. 2023](#)). Thus, this study may provide the first observational evidence

⁵I note that NGC 288, NGC 6218, and NGC 6362 meet the selection criteria defined by these authors.

of such a dynamical effect on an in-situ MW GC, making NGC 288 the first example of a Splashed GC. In conclusion, these results mark NGC 288 as the first GC found to be dynamically consistent with an accreted progenitor, but yet not formed within it, demonstrating the effectiveness of combining homogeneous ages and chemical abundances and opening new avenues for understanding how GCs formed and evolved within our Galaxy.

5.6 The CARMA project at a glance: current status and key results

In the following, I provide a summary of the main findings from four papers belonging to this series (Massari et al. 2023; Aguado-Agelet et al. 2025; Niederhofer et al. 2025; Massari et al. 2026), to which I have directly contributed. This overview aims to highlight the scientific goals of the CARMA project and to demonstrate its potential to advance our understanding on the formation and evolution of the system of GCs within the Milky Way.

5.6.1 The final word on the origin of NGC 6388 and NGC 6441

The goal of the first, proof-of-concept study of the CARMA project (Massari et al. 2023) was the unequivocal determination of the origin of two GCs, namely NGC 6388 and NGC 6441, whose in-situ or accreted nature cannot be unambiguously determined using neither dynamical information nor their chemical properties. Indeed, the pair NGC 6388 – NGC 6441 have attracted particular attention in the literature lately. According to Massari et al. (2019), NGC 6388 is an in-situ GC associated with the bulge of our Galaxy, while NGC 6441 was accreted from the progenitor of the ‘low-energy’ group (Massari et al. 2019, see Section 1.2.6). The proposed origin of these clusters is grounded primarily on their orbital properties. Yet, even this criterion is subject to non-negligible uncertainties: adopting distances from different catalogues (Harris 2010; Baumgardt & Vasiliev 2021) can lead to variations in the derived orbital parameters, with the result that the association of NGC 6388 and NGC 6441 can shift dramatically. For example, according to Forbes (2020) and Callingham et al. (2022), both clusters are in-situ.

A solution was not found for this dynamical ambiguity when including information on the chemistry of the cluster. By performing a direct relative comparison among the abundances of [Sc/Fe], [V/Fe], and [Zn/Fe] of these two GCs and a sample of undoubtedly in-situ GCs, Minelli et al. (2021) found that NGC 6388 and NGC 6441 show systematically lower abundances, and therefore recognised both clusters as accreted. By investigating the same chemical elements for NGC 6388, Carretta & Bragaglia (2022) instead reached the opposite conclusion, associating the cluster to the MW. Finally, by analysing abundances from APOGEE, Horta et al. (2020) suggested a possible accreted origin for NGC 6388. These two clusters are therefore perfect test cases for CARMA, allowing to demonstrate the importance of accurate and precise age measurements in unravelling the origin of the entire system of MW GCs, and in turn to contribute to the reconstruction of our Galaxy assembly history. In particular, the idea of this work is to determine accurate relative ages for a sample that includes these two GCs as well as four clusters in the same metallicity range whose origin is unambiguously in-situ according to all the indicators (dynamics and chemistry) and to the

different studies in the literature (Massari et al. 2019; Bajkova et al. 2020; Forbes 2020; Callingham et al. 2022). These four clusters are NGC 5927, NGC 6304, NGC 6352, and NGC 6496. If NGC 6388 and NGC 6441 were of accreted origin, according to the behaviour of the AMR observed in dwarf galaxies they should be about 2 Gyr younger than the sample of in-situ clusters (Kruijssen et al. 2020).

Figure 5.7 shows the location of the six GCs analysed here in the age–metallicity plane, overplotted on the AMR derived from the Halo field population following the method presented in Gallart et al. (2024). The first immediate feature that stands out is that all of the six GCs have rather similar ages. The youngest is NGC 6388, but its age is perfectly consistent within a 1σ uncertainty with the age of at least two of the in-situ GCs, namely NGC 5927 and NGC 6352. The other cluster with debated origin is NGC 6441, which is even older, and has an age that is consistent with those of NGC 6304 and NGC 6496. By looking at the nominal uncertainties, which take into account the interplay of all of the parameters involved in the fit, it might be tempting to distinguish the six GCs in two groups with strikingly similar age, one group (NGC 6441, NGC 6304 and NGC 6496) with a mean $\langle t \rangle = 13.10$ Gyr (and a tiny dispersion of $\sigma_t = 0.03$ Gyr), and a second group (NGC 6388, NGC 5927 and NGC 6352) with $\langle t \rangle = 12.05$ Gyr and $\sigma_t = 0.25$ Gyr. If this second group consists of the youngest among the in-situ GCs, as CARMA will determine when the sample of GC ages becomes increasingly complete, they might precisely pin-point an important event in the MW merger history that halted the in-situ GC formation. Moreover, the quoted numbers are not dissimilar from the estimated accretion time the GSE merger event (Helmi et al. 2018; Gallart et al. 2019; Montalbán et al. 2021; Xiang & Rix 2022; Ciucă et al. 2024). For the moment though, given the focus here on age differences, it is preferable not to make strong claims, and to leave this possible evidence as an interesting feature to be more thoroughly investigated in the future.

In order to come to an unequivocal conclusion as to the origin of the two GCs NGC 6388 and NGC 6441, in Figure 5.7 their position on the age–metallicity plane is compared with the AMR for the Halo field population, which clearly shows the signature of GSE at low metallicity ($[M/H] < -0.75$ dex, black dashed line) and that of the in-situ disc population at the highest metallicity end (black ellipse), that remains ~ 13 Gyr old up to $[M/H] \sim -0.7$ dex and then becomes younger at higher metallicity. Very clearly, the six GCs studied here are all entirely consistent with the pattern expected for an in-situ formation. In particular, to be located on the AMR of an accreted system like GSE, NGC 6388 and NGC 6441 should be about 2 Gyr younger (or more) than the in-situ GCs, which is excluded at levels of 2.5σ and 7σ , respectively. Therefore, both clusters can be interpreted as born in the MW with a high statistical significance.

5.6.2 The age-metallicity relation of *Gaia*-Sausage-Enceladus globular clusters

In this work (Aguado-Agelet et al. 2025), the focus is shifted to the GC population of the GSE dwarf galaxy (Helmi et al. 2018; Belokurov et al. 2018), the latest significant accretion event experienced by the MW about ~ 10 Gyr ago (see Section 1.2.2). Due to its high mass, GSE likely hosted a large system of GCs, with the current number of candidate members varying between 20 and 26 (Massari et al. 2019; Forbes 2020; Callingham et al. 2022; Chen

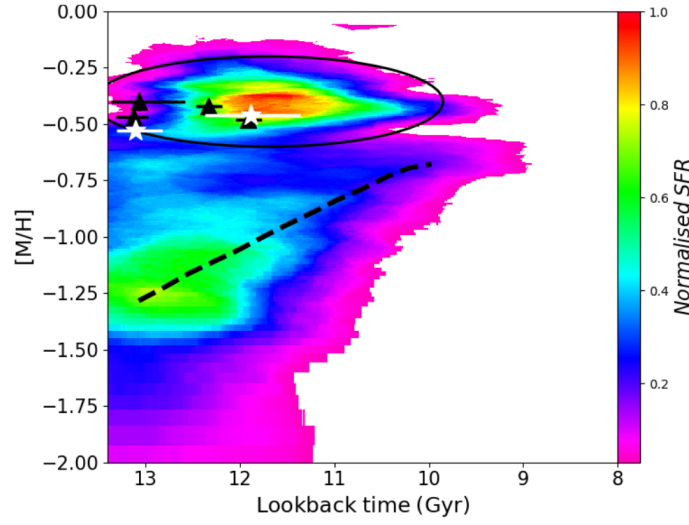


FIGURE 5.7 : Location of the six GCs under study in the age–metallicity plane, overplotted on the AMR derived from the Halo CMD. GCs with undoubted in-situ origin are shown as black symbols, while NGC 6388 and NGC 6441 are marked in white. The location of GSE (black dashed line) and of the MW thick disc (black ellipse) are shown for comparison. Figure adapted from [Massari et al. \(2023\)](#).

& [Gnedin 2024](#)). Starting from a sub-sample of likely GSE members with publicly available HST photometry, the goal is to improve the uncertainty on the individual GC associations, and to assess some of the properties of the GSE dwarf galaxy from the findings on the AMR of its GC system. The sample includes 13 out of the 17 GCs associated with GSE according to both [Massari et al. \(2019\)](#) and [Callingham et al. \(2022\)](#).

The AMR of the GSE GCs resulting from the analysis performed in this study, shown in Figure 5.8 (black points), spans a 3 Gyr-wide range of ages across ~ 1 dex in metallicity. The unprecedented precision in the age determination allows to clearly identify a few GCs that, despite their dynamical properties, are probably not members of the GSE GC system. The most obvious ones are NGC 288 and NGC 6205, which are found to be significantly older (by 2 Gyr or more) than the other GSE GCs at a similar metallicity. This is a clear indication that these two systems might have been born in the MW, rather than in an accreted dwarf galaxy (see Chapter 5 for a complete analysis). Moreover, out of the remaining eleven accreted GCs, nine describe a very tight AMR, whereas two, namely NGC 7099 and NGC 5286, appear as outliers. While the location in the AMR plane, the retrograde orbit, and the $[\text{Eu}/\text{Si}]$ abundance ([Monty et al. 2024](#)) of NGC 7099 still indicate a likely accreted origin, the properties of NGC 5286 leave its association quite uncertain, with its possible progenitors being GSE itself, Kraken, or the MW. The remaining nine genuine members of GSE describe a well-defined AMR that shows a remarkably clear bimodal distribution. The two peaks of GC formation are separated by ~ 2 Gyr, have a duration (computed as the 1σ age dispersion) of 0.3 Gyr, and their mean age is similar to that of the two groups of in-situ GCs studied in [Massari et al. \(2023\)](#). The same slope and possible bursty features have been detected in the AMR of GSE field stars by [González-Koda et al. \(2025\)](#) using CMD fitting, see Figure 5.9. Thus, these two bursts of star formation might be linked to the orbital properties of GSE,

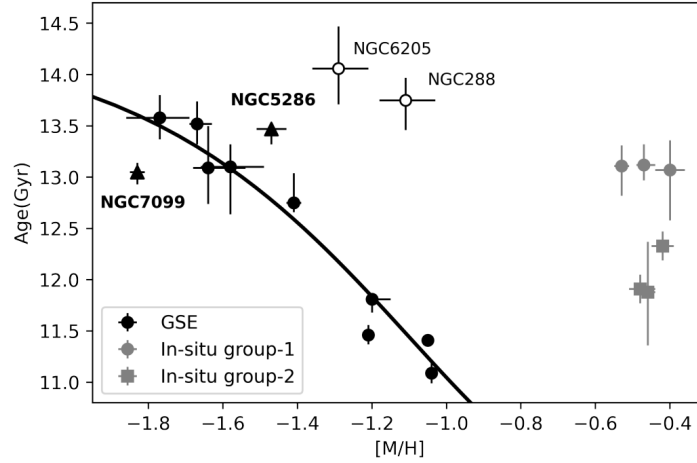


FIGURE 5.8 : AMR of the sample of dynamically selected GSE GCs. Candidate in-situ clusters (namely NGC 288 and NGC 6205) are shown as open circles. GCs with uncertain membership to GSE (namely NGC 5286 and NGC 7099) are shown as filled black triangles. The metal-rich, in-situ GCs analysed in [Massari et al. \(2023\)](#) are shown in grey for the sake of comparison, with the younger and older groups marked with different symbols. A representative AMR model for the GSE genuine members is also shown as a solid black line. Figure from [Aguado-Agelet et al. \(2025\)](#).

with the first pericentric passage and/or its final phase of coalescence with the MW being primary candidates responsible for the star-formation triggers ([Di Matteo et al. 2008](#)). The earliest epoch of GC formation, whose location in the AMR matches remarkably well that of GSE stars ([Horta et al. 2024b](#)) as measured by [Xiang & Rix \(2022\)](#), might even correspond to the initial phase during which GSE evolved in isolation. In any case, these age estimates would provide a robust and independent measurement of the dynamical timescales of the GSE merger event.

5.6.3 Chrono-dynamics of seven old star clusters in the Large Magellanic Cloud and the peculiar origin of NGC 1841

The hierarchical assembly predicted by the Λ -CMD occurs on all mass scales ([White & Frenk 1991](#)), and the Local Group offers a unique laboratory to study the fingerprints of past dynamical interactions between galaxies, allowing us to investigate a plethora of systems, from large ones, like the MW or M31, to their low-mass dwarf satellites. These interactions leave observable imprints in the structure, dynamics, and SFHs of the surviving galaxies. Even low-mass systems carry the scars of such encounters and the Large Magellanic Cloud (LMC), the most massive satellite orbiting the MW with a total mass of $\sim 1 - 2 \times 10^{11} M_{\odot}$ ([Erkal et al. 2019](#); [Vasiliev et al. 2021](#)), is a prime example. Its own history has been shaped both by mergers with smaller dwarfs ([Mucciarelli et al. 2021a](#)) and by interactions with existing companions, such as the Small Magellanic Cloud (SMC). While a handful of ultra-faint dwarfs remain gravitationally bound to the LMC ([Battaglia et al. 2022](#)), much of the evidence for past interactions may now reside in more subtle features like dynamically distinct stellar populations ([Olsen et al. 2011](#)), accreted GCs ([Mucciarelli et al. 2021a](#)), or bursts in the SFH induced by close encounters with the SMC ([Ruiz-Lara et al. 2020b](#); [Mazzi et al. 2021](#); [Massana et al. 2022](#)).

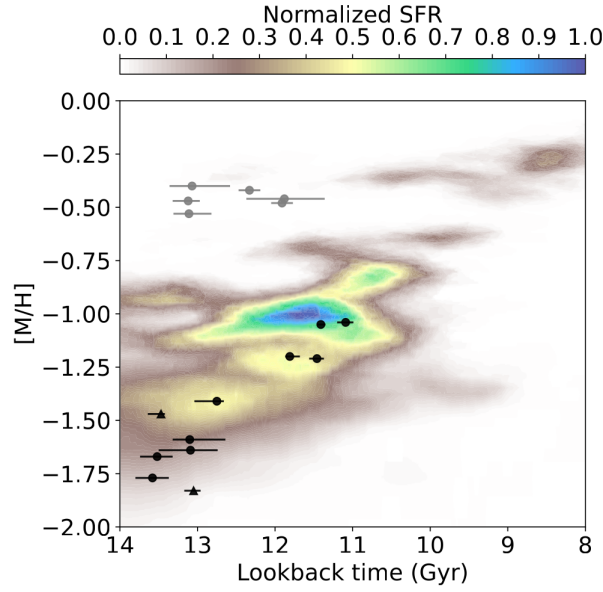


FIGURE 5.9 : Comparison between the AMRs of the most likely GSE GCs (black symbols) and stars (density map from [González-Koda et al. 2025](#)). The location of the six in-situ GCs studied in [Massari et al. \(2023\)](#) is also shown with gray symbols for reference. Figure from [Aguado-Agelet et al. \(2025\)](#).

Studying these fingerprints opens a window into the complex dance between the LMC and its satellites across cosmic time. With the availability of precise proper motion measurements even at the distance of the Clouds ([Massari et al. 2021](#); [Niederhofer et al. 2024](#)), we are now at the advent of studying in detail the chemo-dynamics of their star cluster systems, providing us with additional clues about the formation, assembly and evolution of the galaxies, as well as the origins of their cluster population.

In this paper of the CARMA project ([Niederhofer et al. 2025](#)), proper motions, ages, metallicity and distances of a sample of seven old LMC star clusters with available multi-epoch HST data have been derived in a robust and self-consistent way, employing the recently published HST astro-photometric catalogues by [Niederhofer et al. \(2024\)](#). This work represents the first successful attempt to combine dynamical information with accurate determinations of the cluster properties to investigate the formation of the LMC cluster system.

Figure 5.10 shows the positions of the seven LMC clusters (blue symbols) in the age-metallicity space, compared to that of the nine MW GCs selected as genuine members of the GSE merger event (red symbols) by [Aguado-Agelet et al. \(2025\)](#). GSE has been chosen for the comparison, since its estimated total mass ($6 - 9 \times 10^{10} M_{\odot}$, [Helmi et al. 2018](#); [Kruijssen et al. 2020](#)) is comparable to the one of the LMC. The first feature that is immediately evident is that this sample of LMC clusters can be divided into two age groups. NGC 2005 and Hodge 11 with ages of 14.0 Gyr and 13.8 Gyr, respectively, are the two oldest clusters. The remaining five clusters (NGC 1841, NGC 1898, NGC 2210, NGC 2257 and Reticulum) are significantly younger with similar ages. Their mean age is 12.4 Gyr with a small dispersion of $\sigma_t = 0.2$ Gyr. GSE clusters describe two epochs of formation as well, but at clearly different times. The second remarkable feature is that the general trend of the AMR of the LMC clusters closely follows that shown by the GSE GCs. This is also evident when comparing the location of the LMC clusters with the parametric AMR model derived by

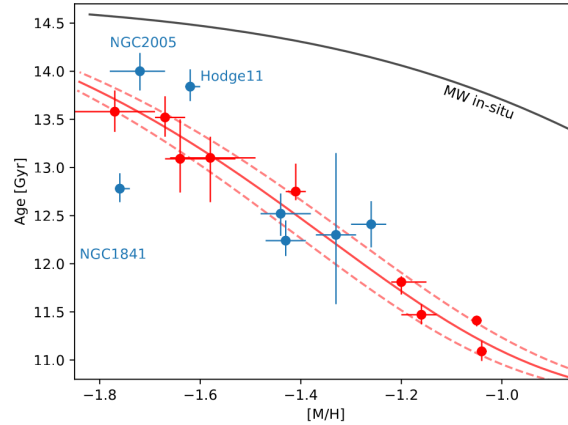


FIGURE 5.10 : Resulting AMR of the seven old LMC clusters studied in this work (blue symbols). For a comparison, nine MW GCs selected as genuine members of GSE (red symbols) are also shown. The red and black solid lines follow the parametric age-metallicity models derived by [Massari et al. \(2019\)](#) for GSE and the MW, respectively. The red dashed lines illustrate the associated uncertainties of the GSE model. Figure adapted from [Niederhofer et al. \(2025\)](#).

[Massari et al. \(2019\)](#) for the GSE GCs (red solid line). The shape of this model ultimately depends on the mass of the progenitor and on its star-formation rate, assumed to be constant ([Prantzos 2008](#)). The similarity of the two observed AMRs points towards a similar early evolution of the two dwarf galaxies, as possibly indicated by the chemistry of their metal-poor populations, too (e.g. [Matsuno et al. 2021](#)). One small difference is given by the location of the two oldest LMC clusters, which seem to be located systematically above the theoretical model, even when considering the associated uncertainty (red dashed lines). Given the shape of the AMR (as described by [Prantzos 2008](#)) this might indicate that the mass, or the star-formation efficiency, of the LMC at the time of the formation of these clusters was slightly lower than that of GSE. The final striking feature is the unique position of NGC 1841 in the age-metallicity space. While the other clusters broadly follow the theoretical AMR model (suggesting they formed within the LMC), NGC 1841 has a significantly lower metallicity than the other clusters in the younger age group. Instead, its $[M/H]$ value is consistent with the one of NGC 2005, the oldest cluster in our sample. This anomalous position of NGC 1841 with respect to the other studied clusters hints that NGC 1841 might not have formed within the LMC, but rather originates from an environment with a lower star-formation efficiency, and thus slower chemical enrichment rate.

To build on the hypothesis regarding the origin of NGC 1841 and to reach an unequivocal conclusion, the dynamics of the clusters within the LMC have been taken into account as well. Combining the observed positions on the sky with literature line-of-sight velocities and distances derived from the isochrone fitting, the full 6D phase-space information for the clusters is available, allowing to examine in detail the velocities, positions and their orbits within the potential of the LMC ([Kacharov et al. 2024](#)). Figure 5.11 presents the resulting orbits of the clusters, together with 50 random realisations, with each panel showing a different projection of the 3D orbits. The current positions of the clusters are indicated by coloured circles. It is immediately evident from the plots that NGC 1841 (orange coloured lines) is

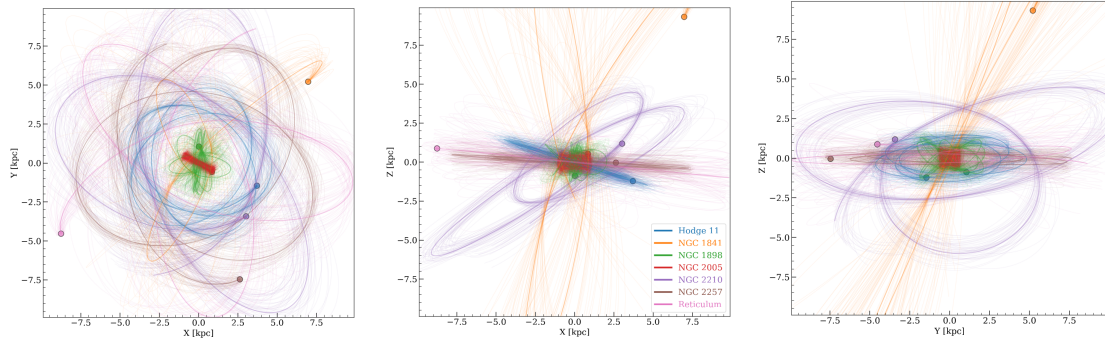


FIGURE 5.11 : Orbits of the seven clusters within the LMC, integrated forward for 1 Gyr. The three panels show projections in the x-y (left), x-z (middle) and y-z (right) planes. The current positions of the clusters are indicated with a circle. Figure adapted from [Niederhofer et al. \(2025\)](#).

on a peculiar orbit that is very different from the ones of the other clusters: it moves on a highly eccentric (0.90 ± 0.04) orbit, highly inclined ($69 \pm 6^\circ$) with respect to the LMC disc plane. Thereby, the cluster can reach a maximum vertical height $Z_{\max} = 14.85 \pm 1.29$ kpc above the disc. It is worth noting that also the MW hosts several GCs with orbital properties similar to the ones of NGC 1841, and all of those clusters have an accreted origin. The combined properties of NGC 1841 (its unique position in the age-metallicity space and its peculiar kinematics) that have been gathered in this work form the consistent picture that NGC 1841 is most likely not a genuine LMC cluster. Since the LMC is massive enough to be accompanied by its own system of dwarf satellite galaxies, including the SMC, of which low-mass ones have been identified within the last years (see, e.g. [Erkal & Belokurov 2020](#); [Patel et al. 2020](#); [Vasiliev 2024](#)), NGC 1841 might have been accreted by the LMC from a smaller companion during a minor merger event.

5.6.4 The Milky Way experienced a significant merger only 1.5 Gyr after the Big Bang

As discussed in Section 1.2.6, disentangling the sequence of events that took place in the proto-Galaxy is extremely challenging. Attempts to isolate the in-situ population from the accreted building blocks using either GCs ([Massari et al. 2019](#)) and field stars ([Horta et al. 2021](#)) have yielded contrasting results so far. In fact, in parallel to the aforementioned works, other analyses have challenged the existence of accreted tracers in the inner galaxy, casting doubts on their extragalactic origin ([Belokurov & Kravtsov 2024](#); [Chen & Gnedin 2024](#)). Thus, since the chemo-dynamical information is not enough to clearly separate accreted tracers from the in-situ ones in the inner Galaxy ([Horta & Schiavon 2025](#)), where the relic of the early mergers should be located ([Pfeffer et al. 2020](#)), the crucial ingredient becomes the chronological dimension.

To solve this long-standing debate, the homogeneous CARMA method has been applied to a sample of 15 GCs in the inner Galaxy ([Massari et al. 2026](#)). These clusters have been dynamically associated with the accreted ‘low-energy’ group in previous works ([Massari et al. 2019](#), see also Section 1.2.6). This fully self-consistent approach delivers highly precise relative ages and metallicity, allowing for a direct, bias-free comparison between the AMR of the

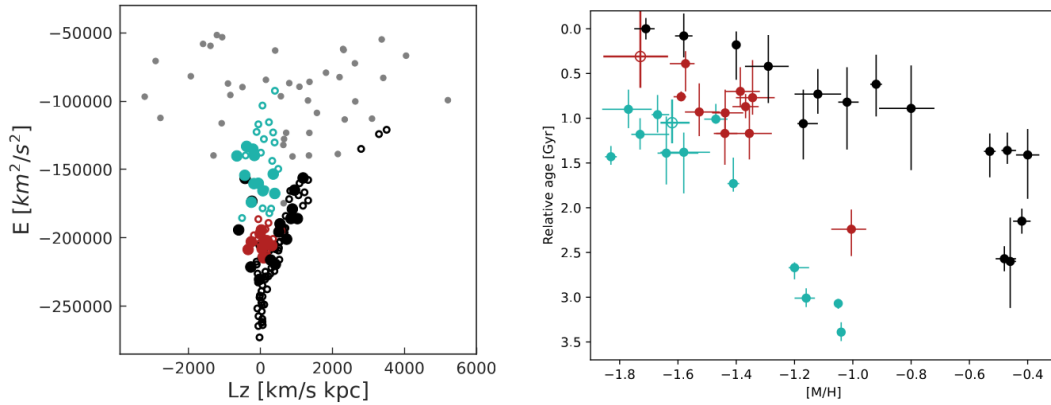


FIGURE 5.12 : Left panel: distribution in the $E - L_z$ space of the selected GCs from [Massari et al. \(2019, eDR3 edition\)](#). Red, cyan and black symbols for the ‘low energy’ group, GSE and in-situ GCs, respectively. Right panel: AMR for the three groups of GCs. The scale on the y -axis is obtained by setting as zero the age obtained from the isochrone fit of the oldest GC in the sample. Figure adapted from [Massari et al. \(2026\)](#).

‘low-energy’ group GCs and those of the two dynamically adjacent progenitors, namely GSE and the in-situ populations (see left panel of Figure 5.12). From the right panel of Figure 5.12 it is immediately evident that most of the ‘low-energy’ GCs describe a population (red symbols) that follows an intermediate AMR that is well separated from that traced by GSE GCs ([Aguado-Agelet et al. 2025](#), cyan symbols) and the in-situ GCs ([Massari et al. 2023](#); [Aguado-Agelet et al. 2025](#); [Ceccarelli et al. 2025b](#); [Massari et al. 2025](#), black symbols). These 11 GCs (out of the 15 in our sample initially associated to the ‘low-energy’ group) are confined within the inner 6 kpc from the Galactic centre, as can be inferred from the upper limit in their energy. This is a clear indication that a high fraction of the ‘low-energy’ GCs formed in an environment that is neither GSE, nor the MW. Given the dynamical properties of the analysed systems, this population of ‘low-energy’ GCs cannot be associated with any of the other known merger events, whose debris is characterised by much higher energies, angular momentum, and is distributed in outer regions of the Galaxy. It follows that this population of GCs is necessarily part of an independent merger event. To characterise it, the AMRs of the three groups have been fitted (see Figure 5.13) with a leaky-box chemical evolution model ([Prantzos 2008](#)), which depends on the stellar mass of a galaxy ([Dekel & Woo 2003](#)) the time at which star formation started, and the time at which it ended, that can be taken as a representation of the galaxy accretion time. Given that the ages estimated by CARMA have to be interpreted in a relative sense, the interpretation of the fit relies on the relative comparison with respect to the model best fitting the GSE GCs. In particular, from the comparison between GSE and the ‘low-energy’ group, it is clear that the stellar masses of their progenitors are well consistent within the uncertainties. Moreover, the accretion time of the ‘low-energy’ group is ~ 1.7 Gyr earlier than GSE. By taking as a reference for GSE a stellar mass of $5 \times 10^8 M_\odot$ ([Helmi et al. 2018](#)) and an accretion time of ~ 10.5 Gyr ([Fernández-Alvar et al. 2025](#); [González-Koda et al. 2025](#)) it follows that the progenitor of the ‘low-energy’ group was a significant merger event that took place ~ 12.2 Gyr ago (at redshift $z > 4$). The estimated stellar mass for these two progenitors is in agreement with the host stellar mass – GC metallicity relation ([Brodie & Strader 2006](#)) according to which

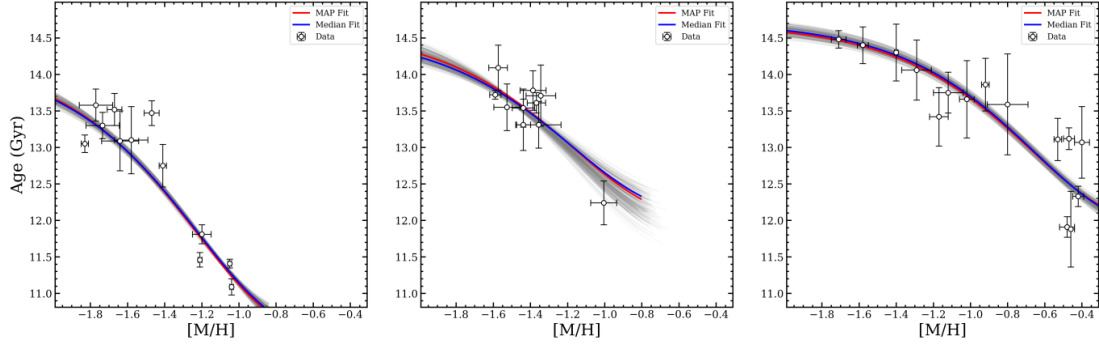


FIGURE 5.13 : Fit to the AMR of the three individual groups, GSE (left), ‘low-energy’ (middle), and in-situ GCs (right). Figure adapted from [Massari et al. \(2026\)](#).

a galaxy this massive should host a GC system of mean metallicity $[M/H] \sim -1.4$ dex. In comparison, the AMR relation of the in-situ GCs follows the trend expected for a system that formed stars and GCs at a much higher rate. According to the fit, the MW formed a factor of ~ 20 more stellar mass than both GSE and the ‘low-energy’ group over a similar time span.

As mentioned in Section 1.2.6, the presence of an accreted population of stars and/or GCs in the inner galaxy has been previously proposed in the literature ([Massari et al. 2019](#); [Kruijsen et al. 2020](#); [Horta et al. 2021](#)). Yet its existence has been highly debated until now, and even the works that support it have yet failed to unequivocally identify individual accretion events, as well as their stellar members, especially in the metal-poor regime $[M/H] < -1.6$ dex ([Horta & Schiavon 2025](#)).

This is therefore the first time that a significant event occurred during the early evolution of the proto-Galaxy has been unambiguously identified from the intricate sequence of mergers and in-situ star formation. We are thus resolving in the local Universe what observations with the James Webb Space Telescope are now unveiling at high-redshift: the early phases of galaxy and of proto-GCs formation ([Adamo et al. 2024](#); [Mowla et al. 2024](#)). Moreover, this study establishes the AMR as the only tracer able to distinguish in the metal-poor regime ($[Fe/H] < -1.6$ dex) the main progenitor of our Galaxy as the building block that evolved with the highest rate. These conclusions are strongly supported by cosmological simulations, which predict the existence of such major mergers in the early life of Milky Way-like galaxies ([Fattahi et al. 2019](#); [Horta et al. 2024a](#); [Wempe et al. 2024](#)), and show a clear separation among the AMR of the three progenitors by ~ 0.5 Gyr at any metallicity, that matches well the separation observed with the GCs analysed in this work ([Callingham & Helmi 2025](#)).

6 | Conclusions

The *Gaia* mission (Gaia Collaboration et al. 2016) had a transformative impact on the way we explore and understand our Galaxy. By delivering precise astrometric data for millions of stars, *Gaia* has opened a new era in Galactic Archaeology, enabling us to map the Milky Way structure with unparalleled precision (Helmi 2020; Deason & Belokurov 2024). The study of stellar dynamics across vast regions of the Galaxy has revealed an intricate history of mergers and dynamical interactions, allowing us to reconstruct a first fuzzy timeline of how the Milky Way assembled over cosmic time (Kruijssen et al. 2020). The relics of these past accretion events manifest today as stellar substructures in the Galactic halo, each carrying the ‘dynamical imprint’ of its progenitor. However, relying only on their dynamics can often lead to degeneracies in the interpretation. It is here that chemistry comes to rescue: by uncovering the unique elemental fingerprints imprinted in stars at birth, it allows to disentangle this dynamical complexity and reveal the true nature of the systems that once contributed to the building of our Galaxy.

Yet, the chemical characterization of the progenitors involved in past interactions remains, in many aspects, incomplete. For several of them, our knowledge of their detailed chemical composition is still fragmentary or entirely absent. High-resolution spectroscopic data are often scarce or derived from heterogeneous analyses based on different assumptions (e.g. atmospheric models, atomic data, stellar parameters). Medium- and low-resolution surveys, though powerful for large-scale statistical analyses, are often not enough to uncover the fine chemical details that distinguish one progenitor from another. To unveil these subtle, yet crucial distinctions, one must turn to the exquisite level of precision that only high-resolution spectroscopy can deliver.

6.1 Summary of the main findings of this Thesis

The main goal of this Thesis has been to use high-resolution spectroscopy to gain new insights into the formation and early assembly history of the Milky Way, and to clarify several open questions regarding the origin and nature of specific Galactic objects. To this end, I have employed the two primary tracers traditionally used in Galactic Archaeology, namely field stars and globular clusters (having dynamical associations to specific substructures for all of them), to explore if and how the properties of the environment they formed in are imprinted in their chemistry. Through this dual approach, in this Thesis I demonstrate that both tracers, when analysed within a fully homogeneous framework, provide powerful and complementary perspectives on the Milky Way origin and growth.

6.1.1 Chemistry of field stars as a tool for Galactic Archaeology

Over the course of this three year PhD project, I started an effort to build the largest catalogue of high-resolution detailed chemical abundances of retrograde Halo stars available in the literature, within the *A Walk on the Retrograde Side* (WRS) project (Ceccarelli et al. 2024a, 2025a). The final catalogue comprises ~ 650 stars observed with UVES@VLT and PEPSI@LBT. WRS was designed to provide a homogeneous and statistically robust foundation for exploring the chemical diversity of the Halo retrograde components. In particular, in Chapters 2 and 3, I have demonstrated the power of homogeneous chemical tagging when applied to Halo stars as:

- I confirmed that GSE represents the dominant and most metal-rich component of the retrograde Halo. Overall, dynamically selected GSE stars exhibit coherent and well-defined chemical abundance trends across all the analysed chemical planes, as expected for stars born in a massive satellite accreted by the Milky Way. I found that GSE stars are, on average, enriched in $[\text{EuII}/\text{Fe}]$ by ~ 0.3 dex compared to the in-situ population at $[\text{Fe}/\text{H}] > -1.5$ dex. Moreover, I showed that the derived abundances are in excellent agreement with a galactic chemical evolution model predictions for a GSE-like galaxy. Finally, I demonstrated that the dynamical selection criteria introduced by Dodd et al. (2023) isolate an exceptionally clean GSE sample, with contamination from non-accreted stars limited to less than $\sim 10\%$.
- I derived the first detailed chemical makeup for the most retrograde and high-energy Halo substructure, Antaeus, demonstrating that its chemical signature does not match that of GSE at the same metallicity in many chemical spaces (e.g. depletion in Na, α -elements, and Y). This provides clear evidence that *Antaeus represents the debris of an independent progenitor*, with an overall less efficient chemical enrichment.
- Stars from Antaeus and ED-3 follow very similar orbits. In this Thesis, I revealed that they also have comparable metallicity distributions, and their chemical compositions are consistent across all measured elements. Taken together, these findings support the idea that *Antaeus and ED-3 are remnants of the same accretion event*.
- I derived the first high-resolution chemical abundances for ED-2, the most metal-poor among the identified components in the retrograde Halo. Its metallicity distribution is extremely narrow ($\sigma = 0.04$ dex), centred at $[\text{Fe}/\text{H}] = -2.43$ dex, with an intrinsic spread that is consistent with zero. Such homogeneity in iron suggests that *ED-2 might be the remnant of a disrupted stellar cluster rather than a dwarf galaxy*.
- I showed that at $[\text{Fe}/\text{H}] > -1.5$ dex, the chemical patterns of GSE and Sequoia appear broadly similar, while at lower metallicity clear differences emerge, particularly a depletion in Mg and Ca, hinting at *formation in different progenitors*.
- I demonstrated that the region of the IoM space generally associated with the Thamnos substructure hosts a mixture of stellar populations with distinct chemical properties. On average, stars within this region are more metal-poor than those of GSE, yet systematically enhanced in $[\alpha/\text{Fe}]$. I also detected a marked increase in $[\text{Al}/\text{Fe}]$, alongside enhancements in Na, Co, Cu, and Zn, and depletion in $[\text{EuII}/\text{Fe}]$ by about

~ 0.3 dex. These trends become especially evident at $[\text{Fe}/\text{H}] > -1.5$ dex, where Thamnos stars overlap in metallicity with GSE but clearly follow the chemical patterns typical of in-situ populations. Such behaviour is consistent with the chemical evolution of massive galaxies like the Milky Way, where the star formation and the production of elements synthesized in massive stars are more efficient. This suggests that *the Thamnos overdensity is heavily contaminated by in-situ stars*, potentially up to $\sim 78\%$. Furthermore, the MDF of the dynamically selected Thamnos sample reveals a secondary peak at $[\text{Fe}/\text{H}] < -2.0$ dex, which I interpreted as *the possible signature of the true accreted Thamnos progenitor*. Predictions from a galactic chemical evolution model specifically tuned to reproduce this metal-poor peak overlap with the observed abundances, as expected for stars from an accreted low-mass dwarf galaxy.

6.1.2 Chemistry of GCs as a tool for Galactic Archaeology

Prior to this Thesis, GCs were already acknowledged as powerful tracers of the Milky Way formation history, primarily through studies of their dynamical and chronological properties. Yet, their chemical compositions have not been fully explored as a means to reveal their origin. By looking at the chemical makeup of six GCs with well-established origin at $-1.3 \leq [\text{Fe}/\text{H}] \leq -1.0$ dex (Ceccarelli et al. 2024b), I demonstrated in Chapter 4 that:

- Clusters sharing the same origin, either in-situ or accreted during the GSE event, display *consistent chemical abundances across all analysed elements*, reinforcing the idea that they were born within similar environments.
- *The elements that best distinguish clusters of different origins are the α -elements, Zn, and Eu*, showing that chemical tagging is sensitive to the in-situ/accreted dichotomy, though not all elements carry the same diagnostic power.
- The globular cluster Ruprecht 106, associated with the Helmi Streams in the literature, is significantly depleted (up to 0.8 dex) in nearly all elements compared to the GCs accreted from GSE. This demonstrate that, when high precision is achieved, *chemical tagging can even discriminate between clusters that formed in distinct progenitor systems*.
- The chemical composition of Ruprecht 106 also differs from that of counterpart field stars from its proposed progenitor (i.e. the Helmi Streams), *suggesting that it formed in a different environment*, characterised by a slower and less efficient chemical enrichment, akin to that observed in some present-day dwarf galaxies.

Since this analysis was based on a sample of clusters with unambiguous origin, the results presented above validated the reliability and strength of chemical tagging as a tool for tracing the origin of GCs in the aforementioned metallicity range. Building on this success, in the third paper dedicated to the CARMA project (Ceccarelli et al. 2025b) I extended this approach to the long-debated case regarding the origin of NGC 288 (see Chapter 5), a cluster dynamically associated to GSE, but with chronological properties typical of in-situ systems (Aguado-Agelet et al. 2025). By combining homogeneous chemical and chronological information, I was able to shed new light on its true nature:

- I showed that the age of NGC 288 is consistent with that of two in-situ GCs at the same metallicity, namely NGC 6218 and NGC 6362, supporting the findings by [Aguado-Agelet et al. \(2025\)](#) that NGC 288 deviates from the AMR of GSE clusters.
- By comparing the homogeneous and detailed abundances of NGC 288 with those of the reference sample of GCs presented in Chapter 4, I found that NGC 288 shares a similar chemical composition with in-situ GCs, especially in the α -elements, and the elemental ratios relative to Eu, further confirming its in-situ formation.
- To bring these results into a coherent picture, I proposed that NGC 288 was born in-situ in the early Milky Way, and that its initial orbit was later reshaped by the violent dynamical heating triggered by the accretion of GSE. This process likely propelled the cluster onto a more eccentric, Halo-like orbit, in analogy with the so-called Splash stellar population. Supported by cosmological simulations, this scenario reveals NGC 288 as the first known example of a *Splashed* globular cluster.

6.2 Future perspectives

The body of work developed in this Thesis opens new windows onto the history of our Galaxy, not only strengthening our current picture of the Milky Way evolution but also pointing toward new and exciting paths for future exploration, bringing us closer to a deeper and more complete understanding of its assembly history. In this last Section, I will provide a short overview of ongoing and future projects related to this Thesis, that will be pursued thanks to already available data and upcoming facilities.

6.2.1 The chemical makeup of the disrupted stellar system ED-2

Among the several dynamical substructures recently identified in the Halo, ED-2 stands out as one of the most intriguing and enigmatic ([Balbinot et al. 2023](#); [Dodd et al. 2023](#)). Its remarkable compactness in velocity space suggests that it has not yet undergone full phase mixing. In other words, its stars still move coherently through the Solar Neighbourhood. Early chemical investigations, based either on low-medium resolution ([Balbinot et al. 2023](#)) or limited samples of high-resolution spectra (less than five stars, see [Ceccarelli et al. 2024a](#); [Dodd et al. 2025b](#)) revealed an exceptionally narrow metallicity distribution centred around $[\text{Fe}/\text{H}] \sim -2.4$ dex. This finding, while intriguing, left open the fundamental question about the origin of ED-2: does it represent the fossil record of a disrupted GC or a low-mass dwarf galaxy? Answering this question requires a complete and homogeneous chemical characterization, with a particular focus on the possible detection of the light-element anticorrelations, that are the hallmark of GCs (see e.g. [Carretta et al. 2009](#)). To this end, within the framework of the WRS project, I have assembled the largest high-resolution spectroscopic dataset of ED-2 to date, composed of 21 stars observed with UVES@VLT and PEPSI@LBT. The analysis of this dataset will provide, for the first time, a definitive chemical portrait of ED-2 and help unveil the true nature of this elusive Halo substructure.

6.2.2 Final WRS data release

The next milestone of my work will be the final data release of the WRS project, which is in its final stages of analysis. I am currently working on deriving homogeneous high-resolution chemical abundances for all the stars observed within the survey. Once complete, this effort will culminate in the publication of a comprehensive catalogue of detailed abundances for up to 15 chemical species in ~ 650 retrograde Halo stars, the largest and most homogeneous high-resolution dataset of its kind available in the literature.

This catalogue will represent a cornerstone for Galactic Archaeology. It will provide, for the first time, a chemically consistent view of all known retrograde substructures of the Milky Way, based on a homogeneous chemical analysis, offering the first-ever high-resolution ($R \sim 40000$) abundance measurements for some of them, and the most detailed and complete characterization for others. Through this, I will be able to dissect the chemical fingerprints of distinct progenitors with unprecedented precision, allowing a systematic exploration of the building blocks that contributed to shaping the Galactic Halo.

Beyond its immediate scientific output, the WRS catalogue will carry substantial legacy value. In the coming years, the field will be transformed by the arrival of next-generation large scale spectroscopic surveys (see Section 6.2.3), many of which will target the Halo as one of their key science drivers. The WRS dataset, with its higher resolution and homogeneous chemical abundances, will serve as a crucial benchmark and reference sample for these future efforts, enabling calibration, validation, and deeper interpretation of the massive spectroscopic datasets that will soon become available.

6.2.3 Exploring synergies between *Gaia* DR4 and next generation large spectroscopic surveys

A key objective for the next years is to investigate stellar streams and dynamical substructures outside the Solar Neighbourhood ($d > 3$ kpc), capitalizing on the upcoming fourth data release of *Gaia* (by the end of 2026). Indeed, *Gaia* DR4 will provide reliable V_{los} measurements for stars as faint as $G \sim 15$, with typical uncertainties ≤ 20 km/s at this magnitude for RGB stars, thereby tripling the number of Halo stars with full 6D phase-space information within $d \leq 10$ kpc. Furthermore, the astrometric precision in DR4 is expected to improve significantly, with proper motion and parallax uncertainties reduced by factors of ~ 2 and $\sim \sqrt{2}$, respectively, thereby enabling the study of Halo substructures at even greater distances. Studying those features in the outer Halo is especially valuable, since these yet poorly explored regions are expected to host the most recent/least massive accretion events. Finally, the substantial increase in the number of Halo stars with complete kinematic data will improve the completeness and statistical robustness of identified substructures in the Solar Neighbourhood. This will allow a far more detailed reconstruction of the SFH and properties of their progenitors, following the path opened by recent works (Ruiz-Lara et al. 2022b; Dodd et al. 2025a; González-Koda et al. 2025).

In the future, I aim to explore possible synergies between *Gaia* DR4 and the upcoming spectroscopic surveys, like, e.g. 4MOST (de Jong et al. 2019) and WEAVE (Dalton et al. 2020). The low- and high-resolution spectra ($R \sim 4000 - 20000$) will provide precise V_{los} for faint stars (down to $G \sim 20$ with uncertainties of ~ 10 km/s). This wealth of new data

will open the door to mapping the Milky Way up to distances of $d \sim 100$ kpc, far beyond the reach of current datasets.

The combination of *Gaia* DR4 astrometry with spectroscopic data from these next generation surveys will yield crucial insights not only into the dynamics, but also into the chemical properties of outer Halo substructures. Current large spectroscopic surveys, such as APOGEE and GALAH, primarily target the Galactic disc, limiting current chemical studies mainly to the most massive accretion events in the Halo. On the contrary, upcoming surveys will provide spectroscopic data for millions of stars in the very far Halo (with metallicity and $[\alpha/\text{Fe}]$ estimates precise to the 0.2 dex level for RGB stars at $d \sim 50$ kpc). This wealth of new data will enable a detailed chemical characterization of lower-mass Halo substructures that have so far remained largely unexplored, and for which I set the first foundations with this Thesis. With elemental abundances for over 20 chemical species, it will finally become possible to trace the chemical enrichment, SFHs, and masses of the faintest and least explored progenitors of the Halo substructures. This will represent a major step forward in completing the merger tree of the Milky Way, a quest that future facilities, like the *Wide-field Spectroscopic Telescope* (Mainieri et al. 2024), will help bring within reach.

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