



UNIVERSITÀ
DEGLI STUDI
FIRENZE

PhD in
Physics and Astronomy

CYCLE XXXVIII

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Bright and dark: the accretion history
of the Milky Way across scales

Academic Discipline (SSD) PHYS-05/A

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Introduction

The standard cosmological scenario (i.e., Λ Cold Dark Matter) predicts a hierarchical formation for galaxies (e.g., [White & Rees, 1978](#)), which are then the result of the mergers of smaller progenitors. On this premise, the accretion history of the Milky Way is key to deciphering its evolution over cosmic time. The stellar halo is the optimal locus where to seek for accreted stellar populations, as it serves as a fossil record of past gravitational interactions owing to its long dynamical timescales (e.g., [Johnston et al., 1996](#)).

The advent of the ESA astrometric mission *Gaia* ([Gaia Collaboration et al., 2016a](#)) offers an unprecedented opportunity to pursue this research providing parallaxes and proper motions for over a billion stars in the Milky Way, empowered by synergy with spectroscopic surveys, such as APOGEE ([Majewski et al., 2017](#)), which supplies radial velocities and the complementary chemical abundances for hundreds of thousands of stars.

Taking advantage of this unparalleled data flow, several substructures have been discovered in the Galactic stellar halo (see [Horta et al., 2023](#), for a recent review). The stars accreted from a single progenitor are identified as overdensities featuring similar integrals of motion, such as energy (E) and angular momentum (L_z) (e.g., [Helmi & de Zeeuw, 2000](#)), along with matching chemical abundances, in particular metallicity distribution functions (MDFs) (e.g., [Myeong et al., 2019](#)). The mean metallicities of these putative accreted substructures are finally used to retrieve the mass of the progenitor galaxy by means of mass-metallicity relations (see [Naidu et al., 2020](#)). In such a way, the “merger tree” of our Galaxy has been reconstructed.

The main purpose of this Thesis is to thoroughly explore the integrals of motion spaces, complemented by chemical abundances, under the light of novel and diverse techniques that combine theory with observations to investigate the accretion history of our Galaxy across different mass scales, studying its baryonic – as well

as dark matter – assembly.

To this aim, we combine state-of-the-art numerical methods (i.e., high-resolution N-body and cosmological simulations) with the latest data releases of large-scale Milky Way surveys (such as *Gaia* and APOGEE), to develop robust methods to trace back its merger history.

The thesis is based on the following publications in peer-reviewed journals:

Mori A., Di Matteo P., Salvadori S., Khoperskov S., Pagnini G., Haywood M.; “*Metallicity distributions of halo stars: do they trace the galactic accretion history?*”. A&A, 690, A136 (2024); doi: [10.1051/0004-6361/202449291](https://doi.org/10.1051/0004-6361/202449291).

Skúladóttir Á., Ernandes H., Feuillet D. K., **Mori A.**, Feltzing S., Lucchesi R., Di Matteo P.; “*Evidence of Gaia Enceladus experiencing several passages around the Milky Way*”. ApJL, 986, L21 (2025); doi: [10.3847/2041-8213/adde66](https://doi.org/10.3847/2041-8213/adde66).

Mori A., Di Matteo P., Salvadori S., Mondelin M., Khoperskov S., Haywood M., Mastrobuono-Battisti A.; “*Chemical decoding of kinematic substructures in the Galactic halo*”. A&A, subm. (2025); arxiv: [2509.13408](https://arxiv.org/abs/2509.13408).

Mori A., Salvadori S., Mastrobuono-Battisti A., Di Matteo P., et al.; “*Characterising the accretion of dark matter satellites hosting (ultra-faint) dwarf galaxies in the Milky Way*”. In prep.

and conference proceedings:

Mori A., Di Matteo P., Salvadori S.; “*Tracing the accretion history of the Galaxy with halo stars*”. Proceedings of the IAU Symposium No. 395 (2025), “Stellar populations in the Milky Way and beyond”; J. Meléndez, C. Chiappini, R. Schiavon & M. Trevisan, eds. In press.

The Milky Way in a cosmological context

This thesis aims to trace the formation and evolution of galaxies, which – according to the standard cosmological model – are thought to grow hierarchically from small subunits that subsequently merge to form the galaxies observed nowadays (e.g., [White & Rees, 1978](#)). In particular, this work seeks to reconstruct the hierarchical build-up of galaxies by focussing on our own Milky Way (MW), with the objective of shedding light on the properties of the building blocks that assembled our Galaxy.

In this chapter, we will begin by introducing the cosmological background in Sec. 1.1. Then we will describe the present-day structure of the Milky Way: the Galactic components in Sec. 1.2, the populations of satellite dwarf galaxies (DGs) and globular clusters (GCs) hosted by our Galaxy in Sec. 1.3, and finally the ongoing accretions of dwarf galaxies and their associated stellar streams in Sec. 1.4. The reconstruction of the past evolution of the Milky Way enabled by Galactic Archaeology will then be described in the following Ch. 2.

1.1 The cosmological hierarchical scenario

The Lambda Cold Dark Matter (Λ CDM) model ([Peebles, 1982](#); [Blumenthal et al., 1984](#)) is the prevailing theory in cosmology. Within this framework, the mass-energy content of the Universe is dominated by the cosmological constant (Λ ; [Carroll et al., 1992](#)), which accounts for $\sim 70\%$ of the total and represents the so-called dark energy that explains the accelerated expansion of the Universe. The cold (non-relativistic) dark matter (CDM), composed of weakly-interacting massive particles (WIMPs; e.g., [Bertone et al., 2005](#)), contributes $\sim 25\%$ and drives the

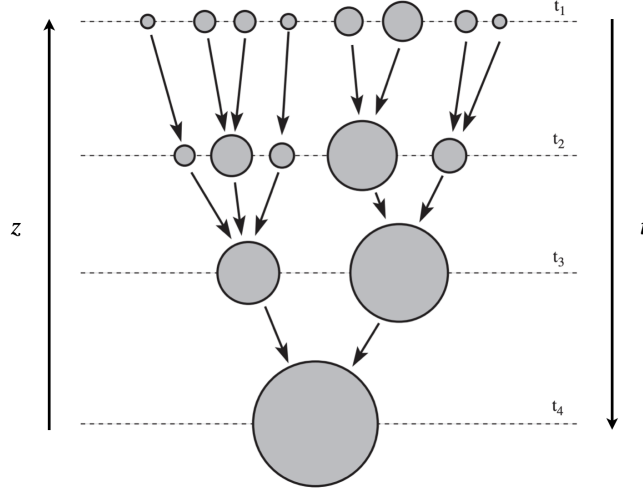


Figura 1.1: The hierarchical galaxy formation: a schematic merger tree, illustrating the merger history of a dark matter halo. It shows, at three different epochs, the progenitor haloes that at time t_4 have merged to form a single halo. The size of each circle represents the mass of the halo. *Adapted from: Mo et al. (2010).*

structure formation. Only a small fraction of the total (the remaining 5%) consists of ordinary baryonic matter, which makes up the cosmic objects we can observe as luminous sources.

In this model, the primordial density fluctuations seed the growth of structure: small dark matter overdensities gravitationally collapse first, forming low-mass haloes (“mini-haloes”; $M \leq 10^7 M_\odot$) at high redshift ($z > 10$). These small haloes then merge over time to build larger haloes in a “bottom-up” or hierarchical fashion, as shown by the merger tree in Fig. 1.1 adapted from Mo et al. (2010). Consequently, the number density of massive haloes grows with time, while low-mass haloes are the most abundant at all cosmic epochs (Press & Schechter, 1974).

Small dwarf galaxies ($M_* \leq 10^9 M_\odot$) originate as baryons fall into these low-mass early dark matter haloes, cool, and form stars. Then they may grow their baryonic mass by gas accretion from cosmic filaments or by merging with other galaxies in a hierarchical way (e.g., White & Rees, 1978).

However, not all dark matter haloes are able to form stars and host galaxies, since the least massive ones will not be able to cool down the gas and collapse (Tegmark et al., 1997). Furthermore, the total stellar mass formed in a DM halo is a function of the halo mass: it is lower at very low and high masses, due to feedback from supernovae and active galactic nuclei, respectively (Moster et al., 2010; Silk & Mamon, 2012). Indeed, feedback effects eject part of the gas outside of the galaxies

and into the intergalactic medium, thus lowering the total gas reservoir.

Combining the above considerations, [Deason et al. \(2016\)](#) showed that the stellar haloes of Milky Way-like haloes ($M \sim 10^{12} M_\odot$) are mainly composed of a small number (1-2) of relatively massive dwarf galaxies ($M \sim 10^{11} M_\odot$, $M_* \sim 10^{8-9} M_\odot$); while low-mass dwarfs' contribution to the total stellar mass is negligible, yet being relevant for the total mass of dark matter (see also [Purcell et al., 2007](#)).

1.2 Anatomy of our Galaxy

The Milky Way is a barred spiral galaxy typical in morphology, mass, size, and star formation ([Bland-Hawthorn & Gerhard, 2016](#)). It is embedded in a dark matter halo, which also comprises a population of satellite dwarf galaxies and globular clusters.

The total mass of the MW is dominated by the dark matter component and is equal to $M = (1.2 \pm 0.5) \times 10^{12} M_\odot$ (see [Strigari, 2025](#), for a review of the methods to estimate the virial mass of the MW); while the total stellar mass is $M_* = (5 \pm 1) \times 10^{10} M_\odot$ ([Licquia & Newman, 2015](#); [Bland-Hawthorn & Gerhard, 2016](#); [McMillan, 2017](#)). As long as its baryonic content is concerned, it is composed of a rotating disc, a central bulge, and an extended stellar halo (Figure 1.2), which we will review in the following. We will describe these stellar populations as they are observed today, while the impact of the reconstructed merger history of our Galaxy on these components will be reported in Chapter 2. Furthermore, will mainly focus on the stellar halo, since – as we will see in the relevant paragraph – it is the optimal region in which to study the merger history of our Galaxy.

Our interest in the study of the assembly history of our Galaxy resides in several reasons. The total stellar mass of the Milky Way places it at the peak of the distribution of galaxy masses in the Local Universe ([Papovich et al., 2015](#)). Thus, the study of the merging history of the Milky Way is crucial not only to understand how the Milky Way formed and evolved, but also in general to understand how a large fraction of galaxies did. Moreover, the Milky Way is the only massive galaxy for which we are able to resolve single stars of different masses, ages and compositions, and to study their distances, motions, chemical abundances and ages. Therefore, it is the benchmark for the study of galaxy formation and evolution: any galactic model should reproduce the features observed in detail in the Milky Way.

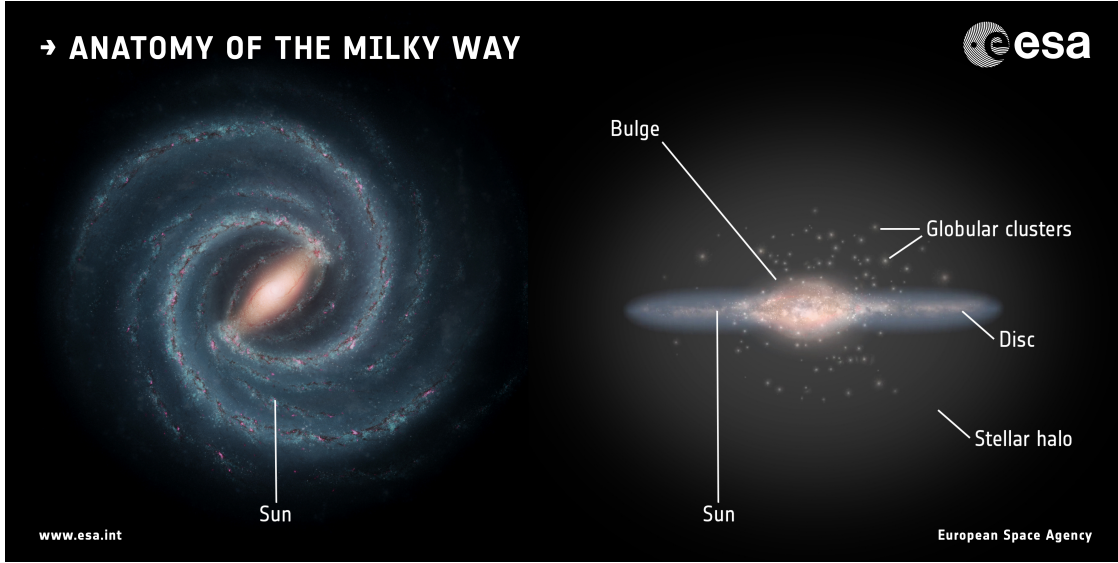


Figura 1.2: The Milky Way broken down in its Galactic components: the bulge, the disc, and the stellar halo. The figure also shows the population of Galactic globular cluster (see Sec. 1.3) and the position of the Sun. *Credit:* ESA/ATG medialab.

1.2.1 The bulge and the bar

In the inner regions of the Galaxy, there is a structure called “bulge” ($M_* \sim (1 - 2) \times 10^{10} M_\odot$; [Bland-Hawthorn & Gerhard, 2016](#)), which extends for about 2 kpc in a boxy/peanut shape (e.g., [Wegg & Gerhard, 2013](#)). Its stars are mainly old (≥ 8 Gyr) ([Hasselquist et al., 2020](#)), and they feature a negative vertical metallicity gradient ([Zoccali et al., 2008](#)).

The bulk of this component is in fact the inner thickened part of the Galactic bar ([Bland-Hawthorn & Gerhard, 2016](#)). The bar is estimated to be ~ 5 kpc long with a $28^\circ - 33^\circ$ angle with respect to the line-of-sight ([Wegg et al., 2015](#)).

1.2.2 The thin and the thick discs

The disc is the most massive Galactic component ($M_* \sim (4 \pm 1) \times 10^{10} M_\odot$; [Bland-Hawthorn & Gerhard, 2016](#)) and is divided into two stellar populations: a thin disc and a thick disc with different properties.

The former has a scale height of ~ 0.3 kpc, while its scale length is around ~ 3.5 kpc ([Bovy et al., 2012b](#)). It is mainly made of stars, but there is also a thinner disc of gas and dust, which forms a central bar and a number of spiral arms, where most of the star formation takes place inside the Galaxy. Therefore, young (ages < 8

Gyr) and metal-rich (typically solar, i.e. $[\text{Fe}/\text{H}] \sim 0$) stars are found mainly in the thin disc, while old metal-poor and α -enhanced ones on average are redistributed in a thicker disc (Fuhrmann, 1998; Bovy et al., 2012a; Haywood et al., 2013; Bensby et al., 2014; Recio-Blanco et al., 2014; Hayden et al., 2015), with a variable scale height $\sim 0.3 - 1$ kpc and a smaller scale length ~ 2 kpc (Bovy et al., 2012b).

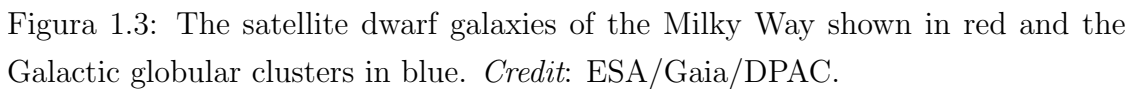
Thin disc stars are characterised by a high azimuthal velocity ($v_\phi \sim 220$ km/s), while thick disc ones feature lower rotation and a higher velocity dispersion ($\sigma \sim 50$ km/s), being more kinematically hot (Soubiran et al., 2003; Kordopatis et al., 2017; Gaia Collaboration et al., 2023).

Furthermore, the thin disc displays a negative metallicity gradient (-0.056 ± 0.007 dex/kpc; Gaia Collaboration et al., 2023). This gradient actually flattens at large radii at 11-12 kpc (Haywood et al., 2024), possibly due to radial migration in the disc (e.g., Minchev & Famaey, 2010), that is, stars move from their birth radii to different ones in the disc, caused by corotation resonances with spiral arms or the bar.

1.2.3 The stellar halo

The last stellar Galactic component that we will describe is a diffuse and light stellar halo ($M_* \sim (4-7) \times 10^8$; Bland-Hawthorn & Gerhard, 2016). It is a spherical structure that extends hundreds of kpc from the Galactic centre. Its stars exhibit negligible net rotation (e.g., Helmi 2008; but see Zhang et al. 2024; González Rivera de La Vernhe et al. 2024, for a rotating component - especially in the inner halo - with a total net rotation of $v_\phi \simeq 40 - 80$ km/s). The halo also contains the Galaxy's oldest (ages ≥ 10 Gyr) and the most metal-poor ($[\text{Fe}/\text{H}] \leq -1$) stars (e.g., Chiba & Beers, 2000; Freeman & Bland-Hawthorn, 2002), designating the halo as the key component for studying the Galaxy's earliest formation phases.

Owing to its low density and thus long dynamical timescale, the stellar halo is rich in substructures and serves as a fossil record of the past evolution – and in particular of the accretion history – of the Galaxy. Stars recently stripped off from accreted dwarf galaxies are observed as stellar streams in the stellar halo, the most famous example of which is the Sagittarius dSph and Stream (Ibata et al., 1994), along with the population of globular clusters and their associated streams (Bellazzini et al., 2020; Malhan et al., 2022; Mateu, 2023). Moreover, it contains a population of surviving satellite dwarf galaxies. Both these populations will be further described in Sec. 1.4.



Indeed, while historically modelled with a simple power-law (< 20 kpc), the stellar halo density profile is better characterised by a broken power-law beyond ~ 25 kpc (Deason et al., 2011; Sesar et al., 2011). Deason et al. (2013) then showed that debris from individual stellar halo progenitors follow broken power-laws and the break radius highlights the last apocentre, suggesting that the Galactic stellar halo is actually dominated by one progenitor only (see Chapter 2).

Our Galaxy is part of the Local Group (LG), which consists of two main massive spiral galaxies: Andromeda (M31) and the Milky Way itself (e.g., [Strigari, 2025](#)). The third largest spiral galaxy in the LG is Triangulum (M33), which is usually considered as a satellite of M31 (e.g., [van der Marel et al., 2019](#)). Moreover, several

other dwarf galaxies embedded in their own dark matter haloes have been detected as stellar overdensities thanks to the Sloan Digital Sky Survey (SDSS; e.g., [Belokurov et al., 2007](#)). More than 70 of these satellites are located within 300 kpc from the MW (e.g., [McConnachie, 2012](#)). The most massive and studied ones are shown by the red empty circles in Figure 1.3. Furthermore, the MW hosts a population of more than 160 globular clusters, as shown by the blue empty circles in Figure 1.3. They are dense old only-stellar systems orbiting the MW (mainly in the halo) as well (e.g., [Baumgardt & Vasiliev, 2021](#)).

1.3.1 Satellite dwarf galaxies

Many local dwarf galaxies orbit inside the dark matter halo of the MW and within its virial radius (~ 300 kpc) and are then satellites of the MW (e.g., [McConnachie & Venn, 2020](#); [Battaglia & Nipoti, 2022](#), for recent reviews). Their stellar masses range between $10^2 \leq M_*/M_\odot \leq 10^9$ (while the total masses $10^7 \leq M/M_\odot \leq 10^{11}$), with half-light radii $10 \leq r/pc \leq 1000$ (e.g., [McConnachie, 2012](#)). They feature a great variety of different properties (e.g., [Tolstoy et al., 2009](#)) and are categorised in the following classes on the basis of their decreasing luminosities (masses):

“Irregular” (dIrr). The dIrr are typically gas-rich and star-forming dwarf galaxies. There are two dIrr orbiting the MW, i.e. the Large and Small Magellanic Clouds (LMC and SMC), which are the most massive MW satellites ($10^7 \leq M_*/M_\odot \leq 10^9$, $10^9 \leq M/M_\odot \leq 10^{11}$; e.g., [McConnachie, 2012](#)). They can be easily identified in the southern hemisphere (Fig. 1.3), as they are even visible to the naked eye. They are thought to be at the first stages of being accreted by the MW (see Sec. 1.4.1).

“Spheroidal” (dSph). The dSph are instead passive galaxies, with no gas and ongoing star-formation, and mainly dominated by old stellar populations. Among the dSph in the MW, we can see the massive Sagittarius (Sgr) dSph close to the Galactic plane in Fig. 1.3. It is in the process of being accreted as traced by its stellar stream and as further detailed in Sec. 1.4.2. Moreover, other well-studied “classical” dSph shown in Fig. 1.3 are Fornax, Sculptor, Sextans, Carina, Draco, Ursa Minor, Leo I, and II, featuring luminosities $10^5 \leq L_*/L_\odot \leq 10^7$, stellar masses $10^5 \leq M_*/M_\odot \leq 10^7$, and total masses $10^8 \leq M/M_\odot \leq 10^9$ (e.g., [Tolstoy et al., 2009](#); [McConnachie, 2012](#); [McConnachie & Venn, 2020](#); [Battaglia & Nipoti, 2022](#)).

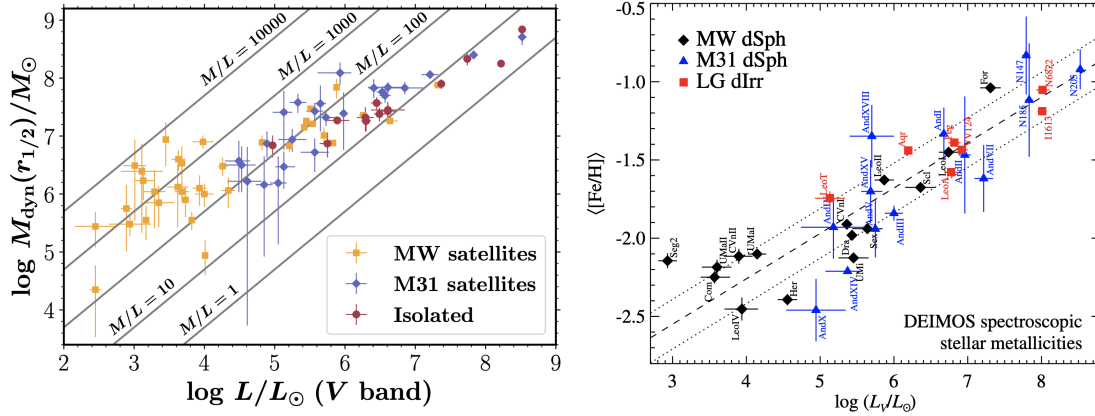


Figure 1.4: Properties of local dwarf galaxies. *Left panel:* dynamical masses as a function of luminosity. *From:* Battaglia & Nipoti (2022). *Right panel:* mean stellar metallicity as a function of luminosity. *From:* Kirby et al. (2013).

“Ultra-Faint” (UFD). UFDs are the most common type of dwarf galaxies in the LG. They are the oldest, the most metal-poor, and the least chemically evolved dSph galaxies. UFDs are the faintest and the most dark matter-dominated stellar systems known (see Simon, 2019; Battaglia & Nipoti, 2022, for recent reviews). Indeed, their luminosities are $L \leq 10^5 L_{\odot}$, their stellar masses $M_* \leq 10^5 M_{\odot}$, and their total masses $10^7 \leq M/M_{\odot} \leq 10^8$. As a consequence, they feature mass-to-light ratios of $10^2 M_{\odot}/L_{\odot} \leq M/L \leq 10^4 M_{\odot}/L_{\odot}$ (see left panel of Fig. 1.4 in Battaglia & Nipoti, 2022). We note that Fig. 1.4 shows the dynamical masses of these systems, that is, the dark matter mass comprised within their half-light radii ($r_{1/2}$), computed as $M_{\text{dyn}}(< r_{1/2}) \approx \sigma_{\text{los}}^2 r_{1/2} / G$, where σ_{los}^2 is the line-of-sight velocity dispersion (e.g., Battaglia & Nipoti, 2022). Thus, dynamical masses represent lower limits for the total dark matter mass of these galaxies. Since they have the smallest dark matter halos they are more sensitive to feedback processes, representing an extreme limit of galaxy formation. UFDs likely are the fossil relics of the first galaxies that formed before cosmic reionization (e.g., Salvadori & Ferrara, 2009). Indeed, their star formation histories reveal that more than 80% of their stars have ages $\gtrsim 13$ Gyr and that they experienced simple assembly histories without major merger events (Brown et al., 2014; Gallart et al., 2021). We will further discuss these findings in Chapter 7 in light of the analysis of cosmological simulations. The first UFD galaxy discovered is Boötes I, which was found thanks to the SDSS by Belokurov et al. (2006b), as it is one of the most luminous ($L \sim 10^{4.5} L_{\odot}$).

Mass-metallicity relation. Satellite galaxies of the LG follow a (stellar) mass–(stellar) metallicity relation, as shown by the right panel of Fig. 1.4 (Kirby et al., 2013). This result is an extension at lower masses of the stellar mass – metallicity relation for SDSS galaxies found by Gallazzi et al. (2005), hinting at a universal galactic law. According to this relation, the less massive, the more metal-poor galaxies are, reflecting the increasing inefficiency of metal retention as gravitational potential wells become shallower.

1.3.2 Galactic globular clusters

Globular clusters are dense, roughly spherical, gravitationally bound stellar systems. Their masses range between $10^4 \leq M_*/M_\odot \leq 10^6$, typically featuring $M_* \sim 10^5 M_\odot$; while their half-light radii span $\sim 1 - 10$ pc (Baumgardt & Hilker, 2018). They are among the oldest stellar systems known, with ages up to ~ 13 Gyr. Unlike dwarf galaxies, globular clusters lack dark matter component (VandenBerg et al., 2013).

We will only briefly mention these objects, as their origin is still disputed in the literature, and they will not be the subject of study in this work. However, we will introduce the most massive Galactic GC which is ω Centauri. It can be identified as the brightest blue circle above the Galactic disc in Fig. 1.3, denoted as NGC5139. Its total stellar mass is $3.55 \pm 0.03 \times 10^6 M_\odot$, half-mass radius of 10.04 pc (Baumgardt & Hilker, 2018).

Our interest in this object is motivated by the fact that it is claimed to be the nuclear star cluster (NSC) of an accreted dwarf galaxy (Norris & Da Costa, 1995; Bekki & Freeman, 2003). A possible central black hole has indeed been found within ω Centauri (Häberle et al., 2024), supporting the hypothesis that it is a NSC. It has often been related to overdense substructures in the Galactic halo thought to be the debris of merger events. For instance, it is associated with the last massive accretion experienced by the Galaxy with *Gaia*-Sausage/Enceladus (see Sec. 2.4; e.g., Massari et al., 2019) or with a smaller accreted galaxy (namely Sequoia, see 2.6; e.g., Myeong et al., 2019). More recently, it has been claimed to be the remnant of an accreted galaxy dubbed “Nephele” by Pagnini et al. (2025).

1.4 Ongoing accretions and stellar streams

So far, we have described our Galaxy in terms of its various components and companions, treating them as if they were independent one of each other given their distinct properties. However, the Milky Way is in reality a dynamically evolving, out-of-equilibrium system: the events it experiences affect the Galaxy as a whole. In particular, merger events can trigger the bulge formation (e.g., [Barnes, 1992](#)), kinematically heat the disc (e.g., [Quinn et al., 1993](#)), along with build up the halo through heated disc and accreted stars (e.g., [Zolotov et al., 2009](#); [Purcell et al., 2007](#), see also Sec. 2.5), possibly even triggering the formation of the bar (e.g., [Gerin et al., 1990](#)). If we want to understand thoroughly how our Galaxy came to be as we observe it today, we have therefore to uncover the connections between its components and the ongoing interactions that continue to shape its evolution.

Firstly, the MW is thought to be on a collision course with M31, due to the negative radial velocity of M31 towards the MW (e.g., [Peebles et al., 2001](#); [van der Marel & Guhathakurta, 2008](#)). The two galaxies are predicted to merge in 5 Gyr to create a giant elliptical galaxy (e.g., [Cox & Loeb, 2008](#); [van der Marel et al., 2012b](#)). However, more recent works showed that the LMC – moving perpendicularly with respect to the MW-M31 orbital plane – is lowering the probability of the major merger to only $\sim 50\%$ ([Sawala et al., 2025](#)).

Other current accretions of the MW are the ones with the Magellanic Clouds and with the Sagittarius dSph, which are indeed subject to tidal stripping (see Sec. 3.1), creating stellar streams and driving dynamical responses in our Galaxy.

1.4.1 Magellanic Clouds and the wake

At a distance of around 50 kpc, we find the Large and Small Magellanic Cloud (LMC and SMC) satellite galaxies, the most massive MW satellites (e.g., [McConnachie, 2012](#)). The initial stellar mass of the SMC was supposed to be of the order of $M_* \sim 5 \times 10^8 M_\odot$, while the total mass equal to $M \sim 6.5 \times 10^9 M_\odot$ ([Bekki & Stanimirović, 2009](#); [Rubele et al., 2018](#)). The stellar mass of the LMC is $M_* \sim (1 - 3) \times 10^9 M_\odot$ ([van der Marel et al., 2002](#); [McConnachie, 2012](#)), while its total mass $M \sim 10^{11} M_\odot$ ([Moster et al., 2013](#); [Peñarrubia et al., 2016](#); [Erkal et al., 2019](#); [Erkal & Belokurov, 2020](#); [Vasiliev et al., 2021](#); [Shipp et al., 2021](#); [Koposov et al., 2023](#)), thus approximately one tenth that of the Galaxy.

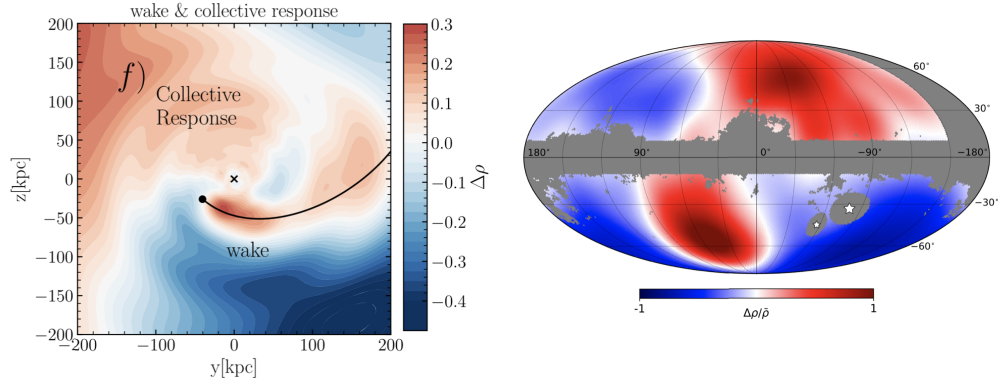


Figura 1.5: The LMC wake and collective response. *Left panel:* wake model. *From:* Garavito-Camargo et al. (2021). *Right panel:* *Gaia* DR3 and WISE data for MW outer halo stars. *From:* Conroy et al. (2021).

The LMC is probably at its first passage around the Milky Way, since it is still rich in gas, and is predicted to merge with the Galaxy in approximately 2.4 Gyr (e.g., Cautun et al., 2019). Indeed, it created the Magellanic Stream, which is a narrow band of neutral hydrogen, trailing the MCs along their orbit around the Milky Way (e.g., Putman et al., 2003).

Such a massive satellite galaxy at this proximity can significantly displace the centre of mass of the MW, as shown by Gómez et al. (2015). As a consequence, we expect a collective response within the MW, even though different depending on the distance (the outer parts of the Galaxy will respond more slowly). The global result is a dipole-like signature in the density (and velocity) space, due to a transient “wake” of field stars along the past LMC orbit (see the model predictions in the left panel of Fig. 1.5; Garavito-Camargo et al., 2019, 2021). This configuration has been observed in the density map of the outer halo ($R_{gal} > 60$ kpc) with *Gaia* DR3 and WISE data (Conroy et al., 2021), as shown by the right panel of Fig. 1.5

1.4.2 Sagittarius stream and the disc snail

As far as ongoing advanced merger events are concerned, direct evidence of stars belonging to the different satellite galaxies in the process of being accreted are still observable in the Galactic halo, since these satellites are not totally disrupted yet, but rather form stellar streams that are still identifiable in the plane of the sky due to tidal stripping. Some examples are shown in “the field of streams” from SDSS (left panel of Figure 1.6) by Belokurov et al. (2006a).

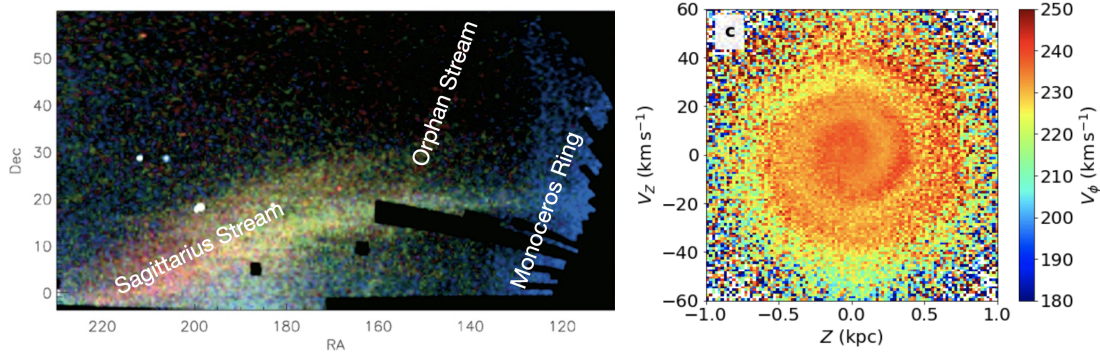


Figure 1.6: *Left panel:* The field of streams. *Adapted from:* Belokurov et al. (2006a). *Right panel:* Vertical position and velocity space $z - v_z$ colour-coded by azimuthal velocity v_ϕ of Milky Way disc stars. *From:* Antoja et al. (2018).

The most remarkable example is the destruction in progress of the Sagittarius (Sgr) dSph galaxy (discovered by Ibata et al., 1994) at only 26 kpc from the Sun (e.g. McConnachie, 2012), as manifested by its associated stellar stream on a polar-like orbit (Newberg et al., 2002; Majewski et al., 2003; Antoja et al., 2020). Moreover, the fact that the progenitor galaxy still exists suggests that the accretion began recently ($z < 1$). The stellar stream crucially enabled the measurements of the orbit and mass of the Sgr progenitor galaxy, along with the estimates of the Galactic potential (Law et al., 2009; Law & Majewski, 2010; Vasiliev et al., 2021).

Furthermore, *Gaia* DR2 (Gaia Collaboration et al., 2018a) provided evidence of the perturbation of the Galactic disc as induced by the interaction with Sgr dSph. Indeed, as can be seen in the right panel of Figure 1.6, Antoja et al. (2018) unambiguously showed that disc stars feature spirals in the phase-space (called “Snail”), characteristic of phase-mixing following gravitational instabilities (see also Laporte et al., 2018, for model predictions).

Canis Major dIrr and Monoceros ring. A disputed case is represented by the Canis Major dwarf galaxy and its associated Monoceros ring stream (see left panel of Fig. 1.6; Martin et al., 2004). It is located at only 7.7 kpc from the Sun in the anticentre direction, thus thought to be the debris of a dwarf galaxy accreted on a co-planar orbit (Helmi et al., 2003; Peñarrubia et al., 2005). However, its existence is debated, since the kinematics of the ring stars clearly exhibit remnant disc rotation (de Boer et al., 2018). Currently, rather than an accretion remnant, this overdensity is associated with a warped, strongly perturbed Galactic disc population (Momany et al., 2006; Sheffield et al., 2018), possibly even by the first

pericentre passage of Sgr ([Laporte et al., 2020](#)).

Once described the various components that constitute the Milky Way as we observe them today, along with the satellites currently orbiting and interacting within its halo, we can now move on to illustrating the state-of-the-art of the knowledge of its accretion history, as traced back by Galactic Archaeology and presented in the next Chapter.

Galactic archaeology in the Gaia era

As described in the previous Chapter 1, our Galaxy is not only a complex structure consisting of multiple components, but also a nested system comprising satellite dwarf galaxies (and globular clusters). Furthermore, we have seen that – although perceived as a static environment – the Milky Way is actually out of equilibrium and is currently undergoing several dynamical interactions that are continuing to shape the entire Galaxy. As far as ongoing mergers are concerned, they can be identified owing to the spatial coherence that they still feature as creating tidally-stripped stellar streams in the stellar halo given its low density and mixing.

Unluckily, this is no longer true when dealing with past merger events, since the stars accreted from those events are now completely mixed with each other and with the ones formed in situ (i.e., within the Galaxy). In particular, given the mixing timescales in the inner galaxy ($\sim$ a few dynamical timescale, which at solar radius is $t_{dyn} \sim 2\pi r/v \sim 2\pi \times 8 \text{ kpc}/220 \text{ km s}^{-1} \sim 225 \text{ Myr}$), after a few Gyr accreted stars cannot be detected any longer as spatial overdensities in specific regions of the plane of the sky (e.g., Bullock & Johnston, 2005; Johnston et al., 2008). Thus, tracing the past accretions experienced by the Galaxy is not trivial, and we need alternative methods to identify their stars and their impact. These methods include the analysis of the stellar properties, such as kinematics and chemical abundances, along with ages. This is, indeed, the aim of *Galactic Archaeology*, i.e. the reconstruction of the past evolution of the Milky Way (and that of many similar galaxies; see Sec. 1.2) through the properties of the stellar populations that we observe today (for recent reviews, see Belokurov, 2013; Bland-Hawthorn & Gerhard, 2016; Helmi, 2020; Deason & Belokurov, 2024; Bonaca & Price-Whelan, 2025).

The search for accreted stars is currently an active field of research, since they can provide information on the number and mass of the satellites accreted by the Milky Way, and thus on its accretion and evolution history, which in turn could probe the hierarchical cosmological predictions. Galactic Archaeology can rely today on an unprecedented amount of data thanks to the ESA astrometric mission *Gaia* (Gaia Collaboration et al., 2016a), which is delivering parallaxes and proper motions for over a billion stars of the Milky Way, and complementary spectroscopic surveys, such as APOGEE (Majewski et al., 2017), which provide chemical abundances and radial velocities for several hundred thousand stars.

In this chapter, we will describe the tools and findings of Galactic Archaeology so far. In particular, we will describe in further detail the observational datasets currently available in Sec 2.1 and focus on the two most used methods to interpret them, that are, the integrals of motion in Sec. 2.2 and the chemical abundances in Sec. 2.3. We will then introduce in Sec 2.4 the most relevant result in this field, which is the discovery of the last massive merger event of the Milky Way, followed in Sec 2.6 by the characterisation of the minor accretions. Finally, we will summarise our knowledge on the accretion history of the Galaxy in Sec 2.7, and conclude with the aim of this thesis in Sec 2.8.

2.1 A golden age of discovery

In the pre-*Gaia* era, the most comprehensive astrometric data came from the Hipparcos and Tycho catalogues (ESA, 1997; Høg et al., 2000; van Leeuwen, 2007), which together measured positions and motions for only a few million stars, with parallaxes accurate to ~ 1 mas. This framework was dramatically transformed thanks to the ESA astrometric mission *Gaia* (Gaia Collaboration et al., 2016a) and its complementary spectroscopic surveys. Indeed, the early and third *Gaia* data releases (Gaia Collaboration et al., 2021, 2023) delivered precise parallaxes and proper motions for over a billion MW stars, along with full 6D phase-space information for 33 million stars (Katz et al., 2023), that is, a factor of $\times 1000$ in parallaxes and $\times 300$ in 6D data. *Gaia* is revolutionising our ability to map the Milky Way in three dimensions and to study its structure, dynamics, and stellar populations in unprecedented detail. On the other hand, spectroscopic surveys like APOGEE (Majewski et al., 2017), GALAH (De Silva et al., 2015; Buder et al., 2021), *Gaia*-ESO Survey (Gilmore et al., 2012; Randich et al., 2013), *Gaia* RVS (Cropper et al., 2018; Katz et al., 2023; Recio-Blanco et al., 2023), H3 (Conroy

et al., 2019), LAMOST (Zhao et al., 2012) and soon 4MOST (de Jong et al., 2019), WEAVE (Jin et al., 2023), and MOONS (Cirasuolo et al., 2020) are providing chemical abundances and radial velocities for several million stars in the Galaxy up to several kiloparsecs from the Sun. Understanding how to correctly interpret these new data is key to shedding light on the properties of the building blocks that made up our Galaxy.

2.2 Kinematic spaces: integrals of motion

The orbit of a satellite galaxy may be characterised by integrals of motion (IoM), such as energy (E), total angular momentum (L) in the case of a spherical system or one of its components (L_z) for an axisymmetric one, or by associated actions (J_R , J_ϕ , and J_z) (Binney & Tremaine, 2008). To first order, a dwarf galaxy comprises stars with similar positions and velocities, and thus integrals of motion. As a consequence, since these quantities are conserved during gravitational interactions of collisionless systems such as galaxies, the stellar debris of the tidally disrupted satellite is expected to share common dynamical properties, even if the merger event happened several Gyr ago. In particular, stars stripped off from the dwarf follow closely the trajectory of their progenitor, which results in the formation of a narrow stream in the kinematic spaces.

The “Helmi Stream” was the first halo accreted substructure identified in the Milky Way by applying this method (Helmi et al., 1999). It was found as a dynamically coherent structure in the angular momenta space of Galactic halo stars, as shown by the orange points in the upper panel of Figure 2.1, which they associated with an accreted dSph galaxy (see Sec. 2.6 for the characterisation of the stream).

The most used kinematic space is the energy-angular momentum space ($E - L_z$), where E is the total orbital energy and L_z is the z -component of the angular momentum, in a reference system with the origin set at the centre of the Milky Way, the $x - y$ plane set on the plane of the Galactic disc and the z -axis oriented as the spin of the Galaxy¹. An other example of kinematics-related spaces is the $L_\perp - L_z$ space, where $L_\perp$ is the angular momentum component in the x - y plane, assuming that $L_\perp$, though not strictly conserved, varies only marginally during a merging process. Furthermore, spaces related to the orbital parameters are analysed in the same spirit, such as the APL space (apocentre-pericentre-angular momentum space) and its projections, since accreted stars should clump with a similar value

¹For an axis-symmetric potential where z is the symmetry axis.

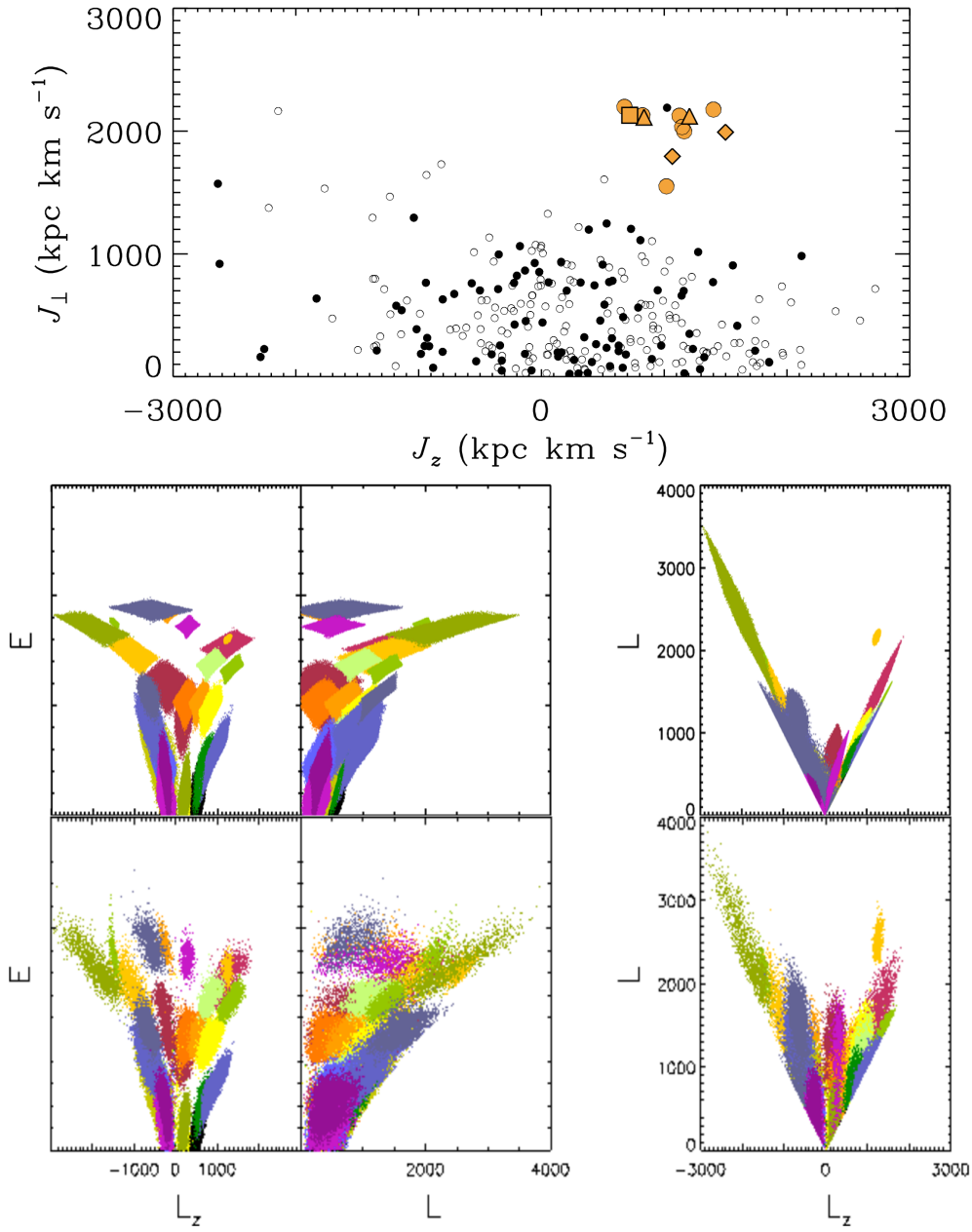


Figure 2.1: *Upper panel:* the distribution of nearby halo stars in the $L_{\perp} - L_z$ plane. The Helmi Stream stars are shown in orange. Note that they use a different notation for the angular momentum components: J_z and $J_{\perp}$. *From:* [Helmi et al. \(1999\)](#). *Lower panel:* numerical simulation of the disruption of satellite galaxies in a Galactic potential. The upper row shows the initial distribution in the $E - L_z$, $E - L$, and $L - L_z$ spaces of stellar particles, where different colours represent different satellites. The lower row shows instead the final distribution after 12 Gyr of evolution. *From:* [Helmi & de Zeeuw \(2000\)](#).

of eccentricity, even if they could have a large range of values for apocentre and pericentre distances (Helmi et al., 2006).

Helmi & de Zeeuw (2000) demonstrated that the stellar overdensity clumps in these kinematics-related spaces are crucial to reconstruct the accretion history of the Galaxy. Indeed, from their number and stellar mass it should be possible to set a lower limit to the number and mass of past accretion events undergone by the Galaxy. In order to achieve these findings, Helmi & de Zeeuw (2000) ran numerical simulations of the disruption of satellite galaxies in a Galactic potential to build up the entire stellar halo. They obtained that the initial clumps in the integral of motion spaces ($E - L_z$, $E - L$ and $L - L_z$) are still present after 12 Gyr of evolution, when the system has phase-mixed completely. The main findings are shown in the lower panel of Figure 2.1: in the upper panel they show the clumps in the kinematics-related spaces at the beginning of the simulation, where different colours correspond to different satellites; in the lower panel the stellar distributions at the end of the simulation are shown and it is possible to see that the clumps corresponding to the different satellites are preserved.

Thus, the space of motion integrals seems to be the natural space where to look for the substructures produced by accreted satellites, with the advantage that the number of clumps will represent the total number of accretion events. Ever since, a wealth of studies have shown that stars accreted long ago, which are by now mixed in the position space, could still be detected as overdense coherent structures in kinematics-related spaces (e.g., Helmi et al., 1999; Helmi & de Zeeuw, 2000; Knebe et al., 2005; Brown et al., 2005; Helmi et al., 2006; Font et al., 2006; Gómez et al., 2010; Re Fiorentin et al., 2015; Koppelman et al., 2018, 2019a,b; Lövdal et al., 2022; Ruiz-Lara et al., 2022; Malhan et al., 2022; Dodd et al., 2023).

2.3 Chemical abundance spaces

The chemical abundances of the stellar photospheres are fossil records of the interstellar medium out of which they have formed. The composition of a star reflects then that of the gas which had already been polluted by previous generations of stars exploded as supernovae or by stellar winds from AGB stars. Accordingly, different abundances may trace distinct environmental chemical enrichment, due to diverse star formation histories, pointing towards distinct origins.

“Chemical labelling” is based on the assumption that stars with similar chemical abundance patterns likely share a common origin (Freeman & Bland-Hawthorn,

2002). This common composition would then allow for the identification of stars with similar histories.

2.3.1 Metallicity Distribution Functions

Iron and the other iron-peak elements (Cr, Mn, Co, and Ni) are mainly produced by supernovae type Ia (SNIa), which are the result of a thermonuclear explosion of a white dwarf in a binary system (Maoz et al., 2014). Since white dwarfs are the late evolutionary stages of low-mass stars, these explosions can take up to $\sim 0.1 - 1$ Gyr to happen (Matteucci & Recchi, 2001; Greggio, 2005).

We are interested in the iron abundance of the stars (throughout this work, $[\text{Fe}/\text{H}]$ is used as a proxy of the total metallicity of the star, i.e. elements heavier than H and He), because it traces the enrichment of the interstellar medium tightly. For instance, as already seen in Sec 1.3, more massive dwarf galaxies feature on average higher mean stellar metallicities, as shown by the upper panel of Figure 2.2 (Salvadori et al., 2015). Satellite dwarf galaxies with different luminosities (and masses) are indeed expected to feature different star formation histories and metallicity distribution functions (MDFs), as predicted by data-calibrated semi-analytic models, and shown by the lower panel of Figure 2.2 adapted from Salvadori et al. (2015) (see also Fig.1 in Kirby et al., 2011, for Keck/DEIMOS data). In particular, the higher the luminosity of the dwarf (downwards direction in the Figure), the more extended the star formation history (SFH) and the more metal-enriched (MDF peaking at higher values of $[\text{Fe}/\text{H}]$) the galaxy is.

This is the reason why stellar populations with different MDFs, that is, different shape, mean, and peak values, are associated with different formation histories.

2.3.2 The evolution of α elements with metallicity

The α elements (e.g., O, Mg, Si, S, Ca, and Ti) are mainly produced by massive stars ($8 \leq M_*/M_\odot \leq 40$) and disperse in the ISM at the end of their life as supernovae type II (SNII) explosions of high-mass stars. SNII events occur after $\sim 3 - 30$ Myr since the star's birth, that is, on shorter timescales with respect to SNIa (e.g., McWilliam, 1997; Maeder & Meynet, 2000). Hence, the $[\alpha/\text{Fe}]$ abundance ratio is very informative on the star formation history of the stellar population considered. In particular, the $[\alpha/\text{Fe}]-[\text{Fe}/\text{H}]$ space, where α can refer to the average abundance of the α -elements mentioned above, or simply the $[\text{Mg}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ is expected to feature a high plateau at first during the

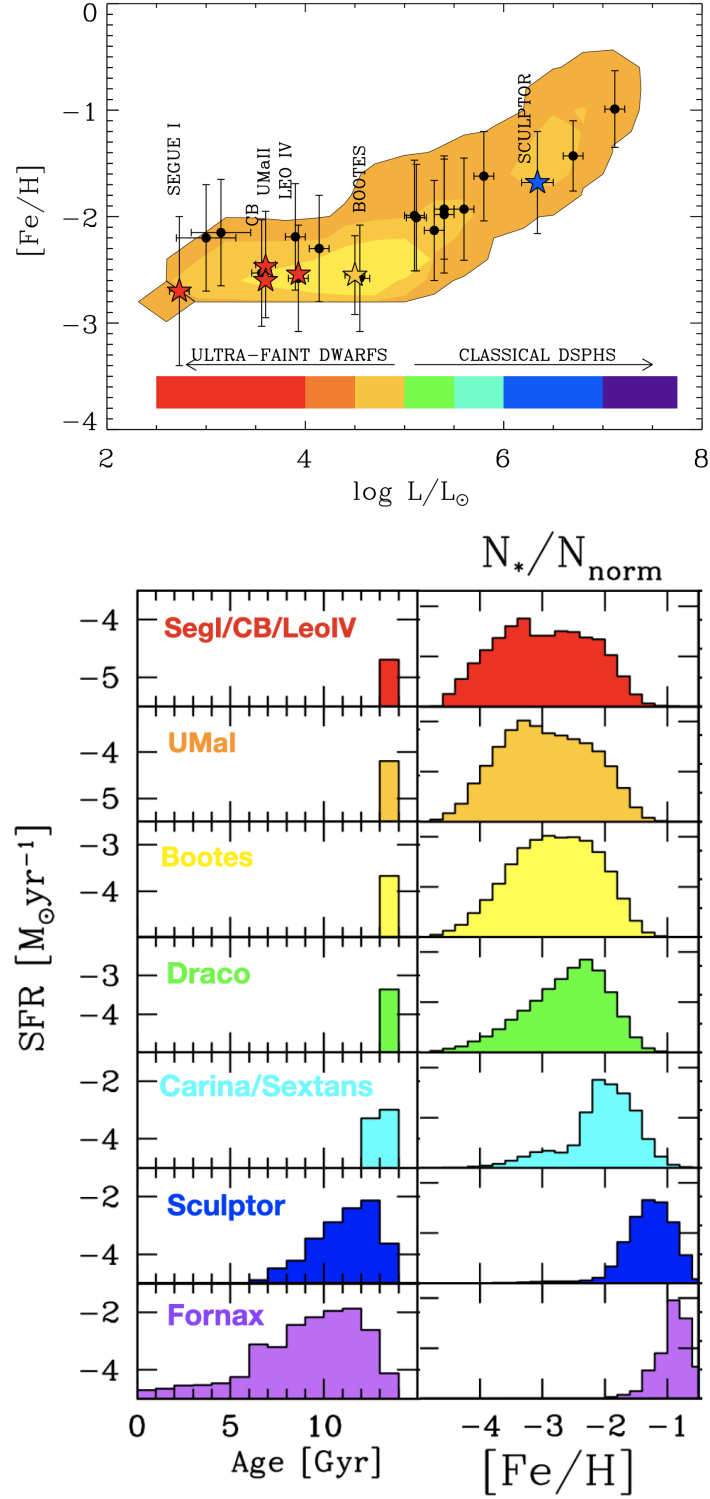


Figura 2.2: *Upper panel:* modelled mass-metallicity relation for local UFDs and dSph. *Lower panel:* modelled SFR and MDF of MW satellite dwarf galaxies in bins of increasing luminosity from top to bottom. *Adapted from:* [Salvadori et al. \(2015\)](#).

explosion of massive stars, and to decrease over time when SNIa start to contribute in iron abundance, which drives the formation of the so-called “knee” (Tinsley, 1979).

This has indeed been observed in local dwarf galaxies, as shown by the $[\text{Mg}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ in the right panel of Figure 2.3, in different colours for different satellites from Tolstoy et al. (2009) (see also, Hasselquist et al., 2021). Interestingly, the position of the knee is related to the mass of the system: for a given $[\text{Fe}/\text{H}]$, the less massive the galaxy is, the lower its $[\alpha/\text{Fe}]$ abundance. This is due to the fact that massive galaxies are more efficient in forming stars and retaining metals, so - by the time of the onset of SNIa - they are more metal-rich.

Therefore, stars born in different galaxies crucially follow different chemical sequences as each system had its own peculiar star formation and chemical enrichment history. In the same spirit, $[\alpha/\text{Fe}]$ can be used as a chemical “clock” to probe the star formation history of a Galactic component.

Applying this method, Nissen & Schuster (2010) found a bimodal distribution of $[\alpha/\text{Fe}]$ for Galactic halo stars in the solar neighbourhood (distances less than 335 pc) in the metallicity range $-1.4 < [\text{Fe}/\text{H}] < -0.4$. They associated the two sequences shown in the lower panel of Figure 2.3 with two different stellar populations, one made up by in situ stars while the other one associated with accreted stars. The “high- α ” population (marked by blue open symbols) features a nearly constant $[\alpha/\text{Fe}]$, similarly to thick disc stars, fact which suggests that these stars formed in regions with such high star formation rate that only SNII contributed to their chemical enrichment (that is, likely, in situ). On the other hand, the “low- α ” population shows a declining $[\alpha/\text{Fe}]$ as a function of increasing metallicity, which then should have originated in regions with a relatively slow chemical evolution so that SNIa have started to contribute iron at $[\text{Fe}/\text{H}] \sim -1.5$ causing $[\alpha/\text{Fe}]$ to decrease toward higher metallicities (i.e., similar to local dwarf galaxies, than possibly accreted). Finally at lower metallicity ($-1.6 < [\text{Fe}/\text{H}] < -1.4$) the two populations tend to merge. Furthermore, we emphasise that the accreted stars feature a narrow sequence, typical of a stellar population coming from the same progenitor galaxy, rather than a mixture of different satellites, even though Nissen & Schuster (2010) suggested the possibility that the low- α sequence comprised more than one accreted galaxy. This will be further developed in Skúladóttir et al. (2025), see Chapter 5.

They also studied the kinematic properties of the stars in the solar neighbourhood in the Toomre diagram, which shows the Galactocentric rotational compo-

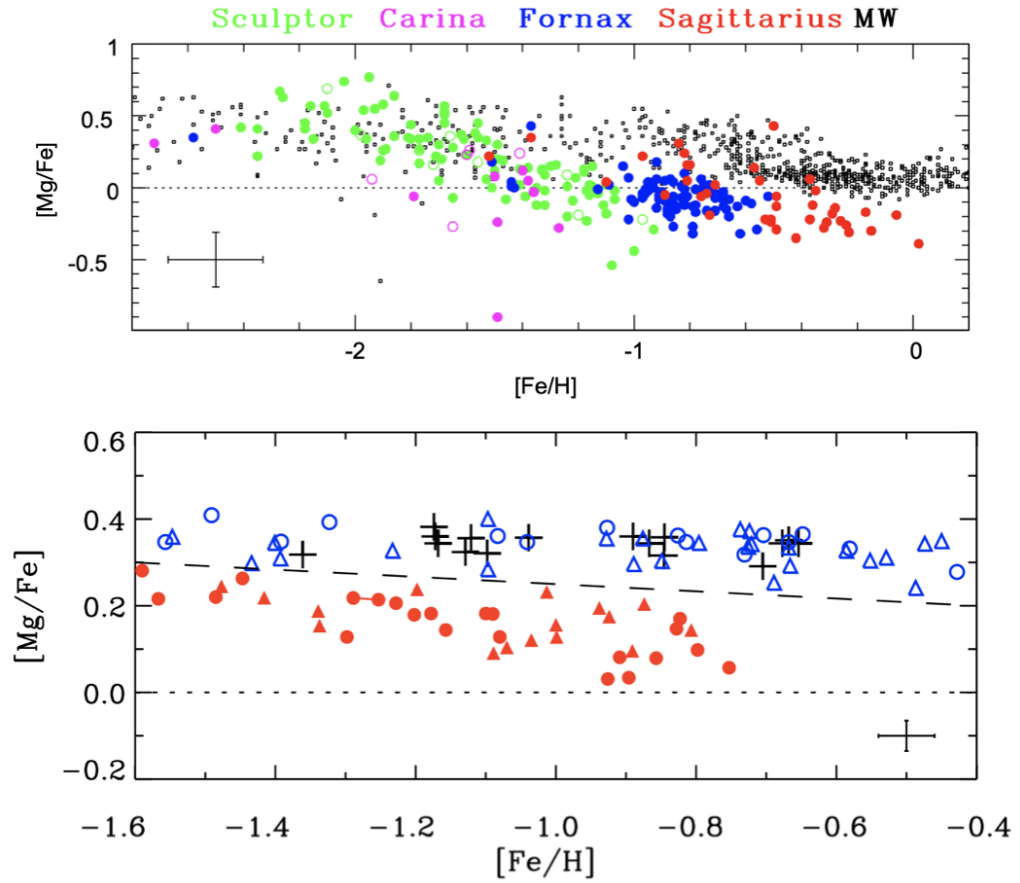


Figura 2.3: *Upper panel:* $[Mg/Fe]$ – $[Fe/H]$ for MW satellites. *From:* Tolstoy et al. (2009). *Lower panel:* $[Mg/Fe]$ – $[Fe/H]$ for MW halo stars. *From:* Nissen & Schuster (2010).

ment of the velocity in the Local Standard Rest (LSR), V_{LSR} , on the x -axis, and the perpendicular component $\sqrt{U_{LSR}^2 + W_{LSR}^2}$, on the y -axis. This space has been widely used to identify major components of the Galaxy: for example, halo stars were defined as having $V_{total} \geq 180$ km/s (e.g., [Venn et al., 2004](#)). In the Toomre diagram, shown bottom left panel of Fig. 2.5, the high- α sequence shows evidence of being more bound to the Galaxy and favouring prograde orbits, while the low- α sequence stars are less bound and the majority of them are on retrograde orbits.

This suggests that the high- α population is connected to a dissipative component of the Galaxy that experienced rapid chemical evolution similar to that of the thick disc ([Gilmore & Wyse, 1998](#)), so its stars could be ancient disc stars heated to halo kinematics by merging satellites. Conversely, low- α population stars were accreted from dwarf galaxies, which had lower SFRs ([Tolstoy et al., 2009](#)).

2.4 The massive *Gaia*-Sausage/Enceladus

A major discovery of the very first *Gaia* data release ([Gaia Collaboration et al., 2016b](#)) – plus SDSS data (see [Deason et al., 2017](#), for tests of the SDSS-*Gaia* DR1 catalogue) – is the last massive merger experienced by the Galaxy. [Belokurov et al. \(2018\)](#) found an elongated distribution in the velocity space of the local halo (azimuthal vs. radial velocity), that is, with high positive and negative V_r , see the left panel of Figure 2.4, which they dubbed *Gaia-Sausage*.

This structure can be appreciated in the relatively metal-rich ($-1.33 < [\text{Fe}/\text{H}] < -1$) distribution of stars near the Galactic plane ($1 < |z| < 3$), which displays two distinct populations: a cold rotating one ($V_\theta \sim 200$ km/s), associated with the thick disc, and a barely rotating, highly radial, and anisotropic one, that is, the Sausage. The orbits of satellites radialise during the gravitational interaction with the Milky Way due to dynamical friction (e.g., [Amorisco, 2017](#)). Since orbital anisotropy is a function of the progenitor’s mass ([Deason et al., 2013](#)), this radially-anisotropic² ($\beta > 0.8$) halo component could only be explained as being the remnant of a massive dwarf galaxy ($M \sim 10^{11} M_\odot$) accreted between $1 < z < 2$.

Additional evidence of these metal-rich ($[\text{Fe}/\text{H}] \lesssim -1$) local halo stars coming from the same relatively massive accreted dwarf galaxy came from [Deason et al. \(2018\)](#). In particular, they computed their orbits and showed that their apocentres pile up around Galactocentric distance ~ 20 kpc. This can be observed in the

²The anistropy parameter is defined as: $\beta = 1 - [(\sigma_\theta^2 + \sigma_\phi^2)/2\sigma_r^2]$, where σ_r , σ_θ , and σ_ϕ are the components of the velocity dispersion in spherical coordinates ([Binney & Tremaine, 2008](#)).

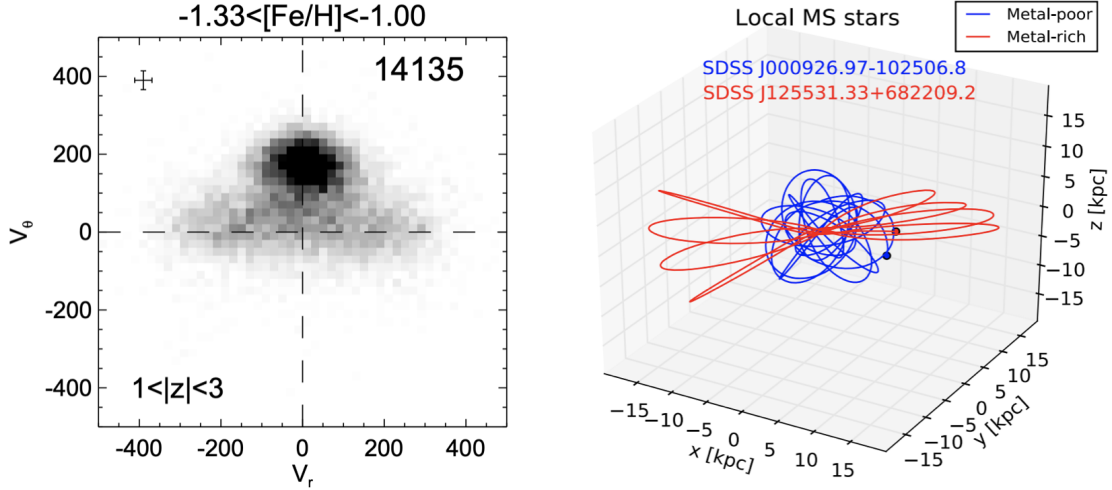


Figure 2.4: *Left panel:* $V_\theta - V_r$ space of local stars at $1 < |z| < 3$ and with $-1.33 < [\text{Fe}/\text{H}] < -1$ in the SDSS-*Gaia* DR1 catalogue. *From:* Belokurov et al. (2018). *Right panel:* Orbits of two local halo main sequence populations, where the metal-rich (poor) one is coloured in blue (red). *From:* Deason et al. (2018).

left panel of Figure 2.4, where the metal-rich local main sequence halo population features highly eccentric orbits, reaching low distances from the centre of the Milky Way, and with apocentres at ~ 20 kpc. Interestingly enough, this value matches the radius at which the stellar halo density breaks (as shown in Sec 1.2.3), which was interpreted as a sign of accretion from one single massive progenitor.

Gaia Data Release 2 (Gaia Collaboration et al., 2018a) represented a major leap forward in the reconstruction of the assembly history of the Galaxy, dramatically increasing the number of precise measurements of parallaxes and proper motions of stars and – together with the complementary spectroscopic surveys – taking the chemo-dynamics analysis of the stellar halo to the next level.

The most relevant result was the dichotomy in the Hertzsprung-Russel (HR) diagram of high tangential-velocity stars ($V > 200 \text{ km/s}$), that is, typical halo kinematics, shown in the top left panel of Figure 2.5 (Gaia Collaboration et al., 2018b). The main sequence is found to be split into two, which they interpreted to be produced by two populations with distinct mean metallicities, $[\text{Fe}/\text{H}] \sim -1.3$ and $[\text{Fe}/\text{H}] \sim -0.5$, highlighting two major components in the Galactic halo.

Further inspection of the two parallel colour sequences in the *Gaia* DR2 HR diagram of stars with high tangential velocities was performed by Haywood et al. (2018b). They studied the kinematic properties of the blue and red-sequences

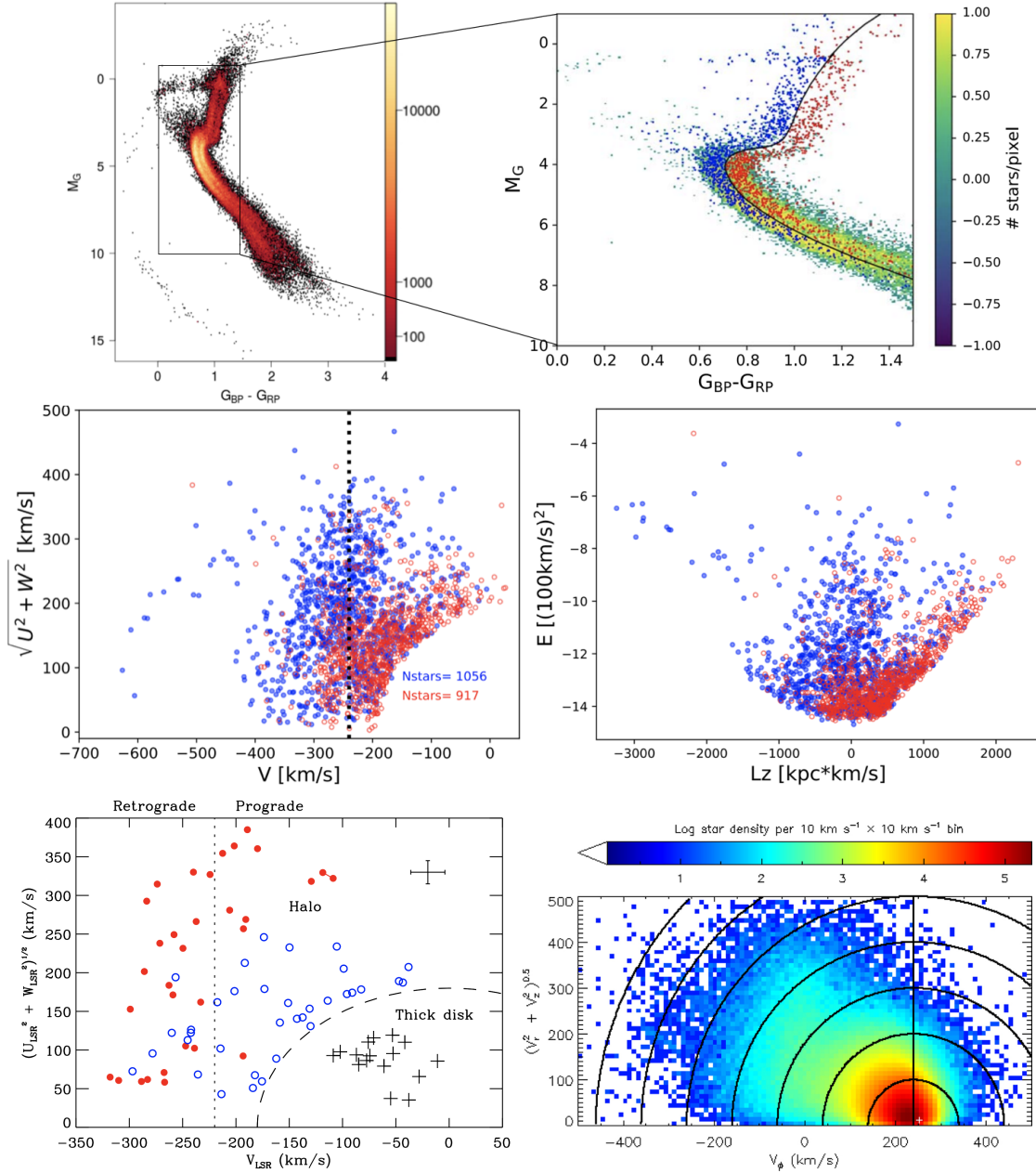


Figure 2.5: *Top left panel:* Gaia DR2 HR diagram of high tangential velocity stars ($V > 200$ km/s). *From:* Gaia Collaboration et al. (2018b). *Top right panel:* The two, well-separated, blue- and red-sequences. *From:* Haywood et al. (2018b). *Middle panels:* Toomre diagram (left) and $E - L_z$ space (right) of stars on the blue sequence (filled blue dots) and on the red sequence (empty red circles). *From:* Haywood et al. (2018b). *Bottom left panel:* Toomre diagram. *From:* Nissen & Schuster (2010). *Bottom right panel:* Toomre diagram of Gaia DR2. *From:* Gaia Collaboration et al. (2018c). Note the different reference frame (here retrograde velocities correspond to $v_\phi < 0$).

(according to their $G_{BP} - G_{RP}$ colour, as highlighted in the top right panel of Fig. 2.5). In particular, they analysed the Toomre diagram (middle left panel of Fig. 2.5) and the $E - L_z$ space (middle right panel of Fig. 2.5), which showed two overlapping structures. The first is a vertical “plume”, which dominates regions with null or retrograde rotation ($V \lesssim -220$ km/s, $L_z \lesssim 0$), high eccentricities and high total orbital energy, composed of blue-sequence stars and the high-energy disc tail with higher rotation. The other structure is composed of the majority of red-sequence stars, which are instead mainly on prograde rotation ($V \gtrsim -220$ km/s, $L_z \gtrsim 0$) and belong to the slow rotating disc tail, even if some of them are around $L_z \sim 0$ but on very bound orbits (low E). The two sequences correspond to the low and high- α populations found by Nissen & Schuster (2010), as can be seen in the bottom left plot of Fig. 2.5. Therefore, *Gaia* DR2 allowed us to extend the low- α identified by Nissen & Schuster (2010) in the solar neighbourhood to a larger scale, as unequivocally represented by the blue-sequence in the HR diagram analysed by Haywood et al. (2018b). Furthermore, the plume at $v_\phi \sim 0$ is also evident in the Toomre diagram of *Gaia* DR2 (see the bottom right panel of Fig. 2.5; Gaia Collaboration et al., 2018c).

Haywood et al. (2018b) concluded that the stars in the reddest-colour sequence, mostly high- α metal-rich ($[\text{Fe}/\text{H}] > -0.8$ dex), are likely dominated by the dynamically hot tail of the thick disc population; while the blue-colour sequence, dominated by metal-poor stars ($[\text{Fe}/\text{H}] < -1.1$ dex) both high and low α , has elemental abundance patterns that can be explained by this population having a relatively low star formation efficiency during its formation, so by being accreted. Thus, the halo consists of two populations: one made of in situ disc stars kinematically heated to halo-orbits (red-colour sequence), the other one being accreted in the stellar halo. The main result of Haywood et al. (2018b) is that the inner halo is probably mainly composed of accreted material left by a single massive merger in our Galaxy, given the tightness of the blue sequence. They argue that stars which are typically assigned to the halo in the solar vicinity are actually both accreted stars lying along the blue sequence in the HR diagram, and the low rotational velocity tail of the old Galactic disc, possibly dynamically heated by past accretion events. These results imply that a halo population formed in situ and responsible for the early chemical enrichment prior to the formation of the thick disc is yet to be robustly identified, and that what has been defined as the stars of the in situ stellar halo of the Galaxy may be in fact fossil records of its last significant merger.

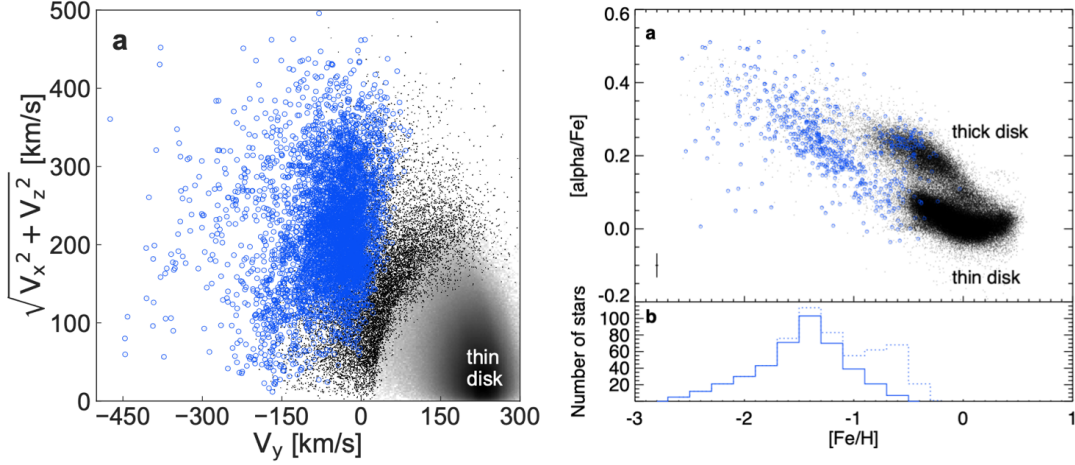


Figure 2.6: *Left panel:* Velocity distribution of stars in the solar vicinity. *Right panel:* α -metallicity space and the projected metallicity distribution function. *From:* Helmi et al. (2018).

Helmi et al. (2018) have indeed found that a simulation of the formation of a thick disc via a 20% mass-ratio merger on a retrograde orbit inclined by $\sim 30^\circ$ to 60° can well reproduce the velocity distribution of halo stars in the solar vicinity inside a volume of 2.5 kpc radius from *Gaia* DR2 (the data are shown in the left panel of Figure 2.6). The blue slightly retrograde structure in the left panel, selected as halo stars ($|v - v_{LSR}| > 210$ km/s) having -1500 kpc km/s $< L_z < 150$ kpc km/s and $E > -1.8 \times 10^5$ km²/s² (see Koppelman et al., 2018), could be thus largely made up of stars originating in an external galaxy that merged with the Milky Way in the past.

This hypothesis is supported by the chemical abundances of stars provided by the APOGEE survey. The $[\alpha/\text{Fe}]-[\text{Fe}/\text{H}]$ space in the right panel of Figure 2.6 shows the well-known sequences defined by the thin and the thick discs (in black), while most of the retrograde structure's stars (in blue) follow a well-defined separate sequence that extends from much lower to relatively high $[\text{Fe}/\text{H}]$. The large metallicity spread ($-3 < [\text{Fe}/\text{H}] < -0.5$) of the retrograde structure (lower right panel of Figure 2.6) implies that they did not form in a single burst in a low-mass system, but rather in a dwarf not much smaller than the LMC. Moreover, they must have been born in a system with a lower star formation rate than the thick disc one, since the most metal-rich stars have lower $[\alpha/\text{Fe}]$ at the characteristic metallicity of the thick disc ($[\text{Fe}/\text{H}] \sim -0.6$). Using a chemical evolution model (Fernández-Alvar et al., 2018), the star formation rate has been computed to be $0.3 M_\odot/\text{yr}$,

lasting for about 2 Gyr, which implies a total stellar mass for the progenitor system of $\sim 6 \times 10^8 M_\odot$. Since [Helmi et al. \(2018\)](#) dubbed the debris *Gaia-Enceladus*, this massive merger is commonly referred to as *Gaia-Sausage/Enceladus* (GSE).

The simulation of [Helmi et al. \(2018\)](#) also suggests that the *Gaia-Enceladus* galaxy could have been responsible for the formation of the thick disc, so that a pre-existing disc must have been in place at the time of the merger. The HR diagram for halo stars shows that the *Gaia-Enceladus* stars populate *Gaia*’s blue sequence, the thinness of which is compatible with an age range from ~ 10 to ~ 13 Gyr given the stars’ abundance sequence. At $-1 < [\text{Fe}/\text{H}] < -0.5$ the stars on the α -poor sequence are younger than those on the α -rich sequence, fact which implies that the progenitor of the Galactic disc was in place when *Gaia-Enceladus* fell in (see also [Gallart et al. 2019](#) for a more thorough discussion of the age distribution of the GSE and in situ components, and simulations of the disc heating; and [Montalbán et al. 2021](#) for more precise asteroseismic ages). Given the ages of its youngest stars, the merger should have thus taken place around 10 Gyr ago ($z \sim 1.8$).

2.5 The kinematic heating of the Galactic disc

As will be further discussed in Sec 3.1, merger events heavily perturb Galactic discs, leading to the redistribution of the satellite orbital energy into internal energy of disc stars, driving the formation of kinematically hot thick discs ([Hernquist & Quinn, 1989](#); [Quinn et al., 1993](#); [Walker et al., 1996](#); [Velazquez & White, 1999](#); [Benson et al., 2004](#); [Kazantzidis et al., 2008](#); [Villalobos & Helmi, 2008, 2009](#); [Qu et al., 2011](#)), and – if massive enough (i.e., mass ratios $\gtrsim 1 : 10$) – they can heat disc stars up onto halo orbits ([Zolotov et al., 2009](#); [Purcell et al., 2007](#); [Qu et al., 2011](#); [Font et al., 2011](#); [McCarthy et al., 2012](#); [Cooper et al., 2015](#); [Jean-Baptiste et al., 2017](#); [Grand et al., 2020](#)). [Jean-Baptiste et al. \(2017\)](#) showed that the in situ component of the halo made up of heated disc stars is a dominant component within ~ 15 kpc, along with the fact that the most intense epoch of accretion and kinematic heating – along with the slowing of the rotation – are tightly related.

[Di Matteo et al. \(2019\)](#) coupled *Gaia* DR2 and APOGEE DR14 data to characterise the kinematics and chemistry of stars in the Galactic halo, to look for signatures of the kinematic heating of the Milky Way disc that must have been

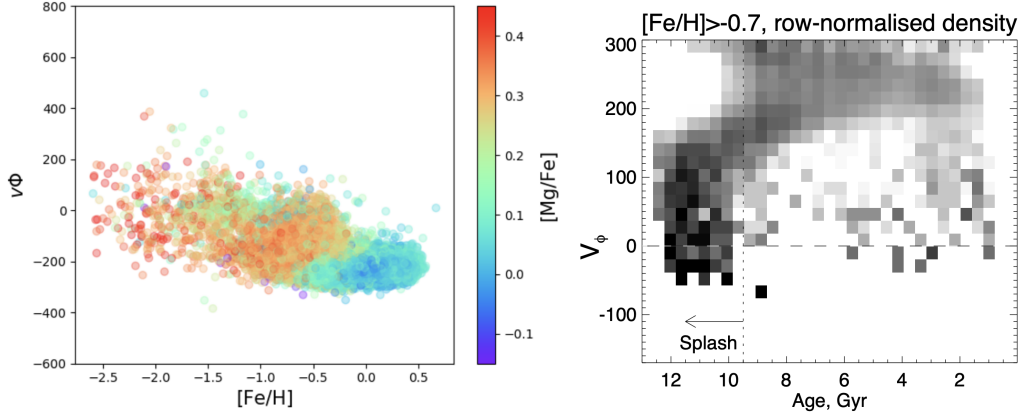


Figure 2.7: *Left panel:* $[\text{Fe}/\text{H}] - v_\phi$ space of stars in *Gaia* DR2+APOGEE DR14, colour-coded by $[\text{Mg}/\text{Fe}]$. *From:* Di Matteo et al. (2019). *Right panel:* $V_\phi - \text{age}$ space for local metal-rich ($[\text{Fe}/\text{H}] > -0.7$) halo stars in *Gaia* DR2. *From:* Belokurov et al. (2020).

generated at the time of the accretion of GSE. In Fig. 2.7, they show the distribution of stars in the $v_\phi - [\text{Fe}/\text{H}]$ plane, colour-coded by $[\text{Mg}/\text{Fe}]$. v_ϕ is the azimuthal velocity of stars, with the convention that prograde (retrograde) motions, in the sense (opposite) of Galactic rotation, correspond to negative (positive) v_ϕ . Halo stars redistribute in a “shoe”-like shape in this space, with the tip of the shoe at high metallicities, $[\text{Fe}/\text{H}] \geq -0.2$, and the instep of the shoe at $[\text{Fe}/\text{H}] \leq -0.3$. The steep rise of v_ϕ with decreasing $[\text{Fe}/\text{H}]$, for $[\text{Fe}/\text{H}] \leq -0.3$, marks a rapid transition from a cold rotating disc (i.e., $v_\phi \sim -200$ km/s, visible at $[\text{Fe}/\text{H}] \geq -0.3$ and with $[\text{Mg}/\text{Fe}] \lesssim 0.2$) to a superposition of disc and halo-like (non rotating, $v_\phi \sim 0$ km/s) kinematics at lower metallicities. This steep rise creates a “plume” at $[\text{Fe}/\text{H}] \lesssim -0.3$, characterised by $[\text{Mg}/\text{Fe}] \gtrsim 0.2$, thus composed of stars with (thick)-disc chemistry, but halo-like kinematics, pinpointing the heating of the disc due to the GSE merger event.

Identifying the value of $[\text{Mg}/\text{Fe}]$ of the rotation decline is crucial, as $[\text{Mg}/\text{Fe}]$ ratio is strongly correlated with the stellar age (Haywood et al., 2013), allowing for the timing of the heating. The $[\text{Mg}/\text{Fe}]$ interval of $[0.2, 0.25]$ corresponds to an age interval of 9 – 11 Gyr, dating the last massive merger event experienced by the Galaxy. Furthermore, by kinematically selecting halo stars in the Toomre diagram ($\sqrt{(v_\phi - v_{\text{LSR}})^2 + v_r^2 + v_z^2} \geq 180$ km/s), they found that $> 50\%$ of them feature $[\text{Fe}/\text{H}] \geq -1$ and $[\text{Mg}/\text{Fe}] \geq 0.2$, that is, thick disc-like chemistry. The MDF of the kinematically-defined halo indeed showed a dominant peak at metallicities of the

thick-disc (see also [Gallart et al., 2019](#)).

Hence, they quantified the heated disc to be a significant component of the halo, which, together with the accreted component, leaves very little room – if any – for an “in situ halo” component in the historical sense, that is, formed by direct gas collapse ([Eggen et al., 1962](#)).

[Belokurov et al. \(2020\)](#) confirmed the presence of a metal-rich halo component (see also [Bonaca et al., 2017](#), for hints on this result, with the limited DR1 data). Analysing the ages of these stars, they found them to be predominantly old, still slightly younger than GSE (by ~ 1 Gyr), and overlapping with the old age tail of the thick disc, as shown by the right panel of Fig. 2.7. In the Figure, the tail of the disc is also connected to the metal-rich halo component in azimuthal velocity V_ϕ . These two arguments together led to the conclusion that this population – dubbed “Splash” – is composed of stars born in the disc and subsequently heated to halo-like orbits around 9.5 Gyr ago (dashed line in the figure) by the GSE merger.

2.6 Minor mergers: the halo substructures

The results presented in the previous sections highlight how powerful the coupling of kinematics and chemistry can be to disentangle the different halo populations. After the discovery of GSE (and the heated disc), this method was then used to identify and characterise many other accretion relics in the Galactic stellar halo.

These studies were generally based on the selection of a clump of stars (and globular clusters) in regions of kinematic spaces (usually $E - L_z$) and on the subsequent study of their chemical characteristics: the eventual difference in their MDFs and/or average chemical abundances would then be the confirmation of the different origin of these stars, i.e. formed in different satellites. Amongst the plethora of recently discovered halo substructures claimed to be independent merger events, we report the most significant ones (in a non-exhaustive way) and show their location in the $E - L_z$ in the upper panels of Figure 2.8 ([Horta et al., 2023](#)): beyond GSE ([Belokurov et al., 2018](#); [Haywood et al., 2018b](#); [Helmi et al., 2018](#); [Vincenzo et al., 2019](#); [Mackereth et al., 2019](#); [Gallart et al., 2019](#); [Feuillet et al., 2020](#)), there are retrograde debris such as Sequoia ([Barbá et al., 2019](#); [Matsuno et al., 2019](#); [Myeong et al., 2019](#); [Naidu et al., 2020](#); [Matsuno et al., 2022a](#)), Thamnos ([Koppelman et al., 2019b](#); [Ruiz-Lara et al., 2022](#)), Arjuna, and I’itoi ([Naidu et al., 2020](#)), prograde ones such as the Helmi Stream ([Helmi et al., 1999](#); [Koppelman et al., 2019a](#)),

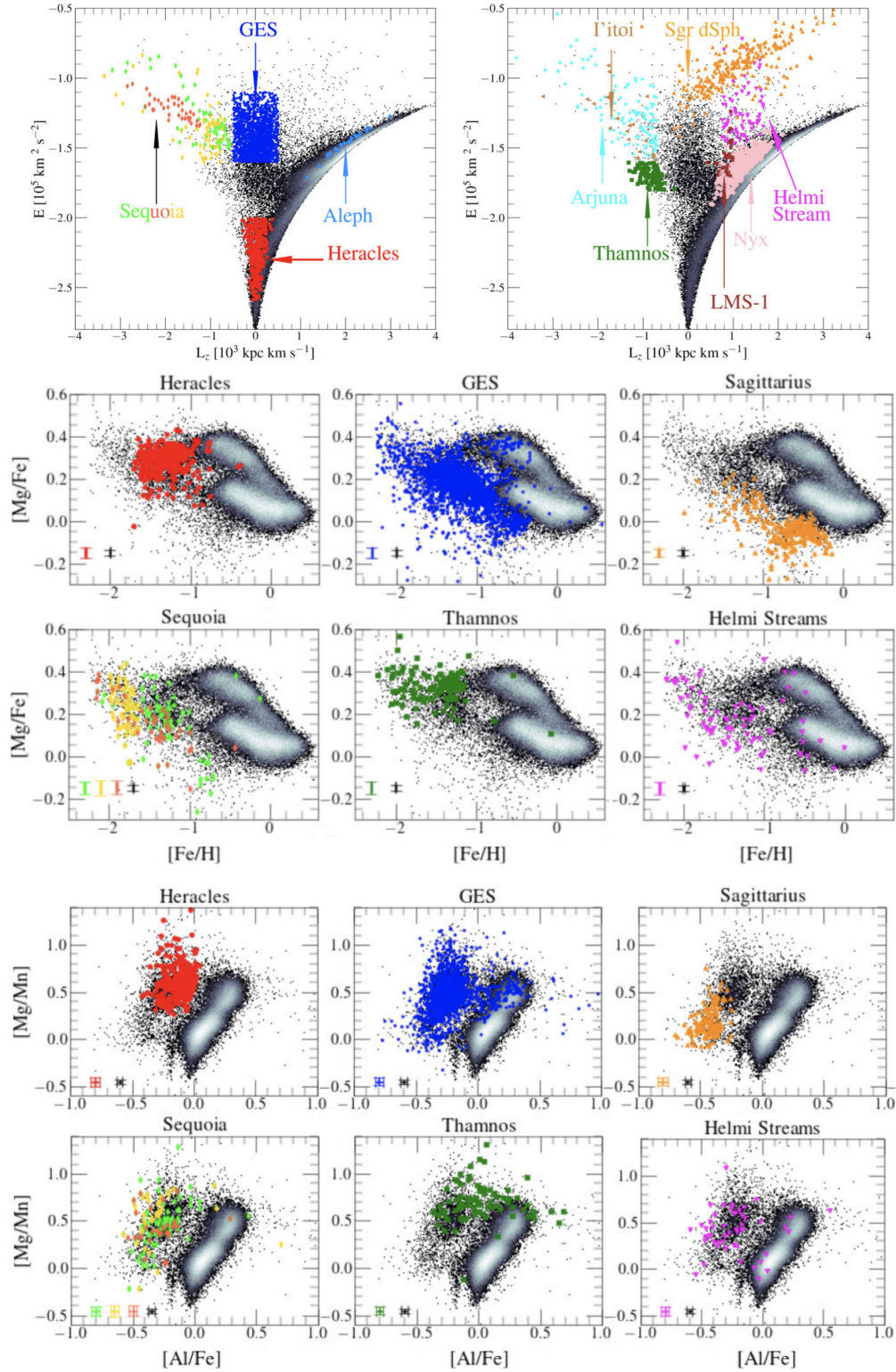


Figure 2.8: Kinematic-defined halo substructures and their chemical properties. *Upper panels:* $E - L_z$ space. *Middle panels:* $[\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]$ spaces. *Lower panels:* $[\text{Mg}/\text{Mn}] - [\text{Al}/\text{Fe}]$ spaces. *Adapted from:* [Horta et al. \(2023\)](#).

Aleph (Naidu et al., 2020), Nyx (Necib et al., 2020), LMS-1/Wukong (Yuan et al., 2020; Naidu et al., 2020), and finally the most bound one which is Kraken/Koala/-Heracles (Kruijssen et al., 2019, 2020; Forbes, 2020; Horta et al., 2021). Moreover, we can appreciate the ongoing merger with the Sagittarius dwarf spheroidal galaxy (Ibata et al., 1994; Majewski et al., 2003).

Several studies have attempted to characterise the halo substructures through their chemical properties by coupling astrometric data from *Gaia* and the complementary large spectroscopic surveys (Monty et al., 2020; Hasselquist et al., 2021; Feuillet et al., 2021; Naidu et al., 2022; Matsuno et al., 2022a,b; Buder et al., 2022; Horta et al., 2023; Ceccarelli et al., 2024, 2025). We show in the middle and lower panels of Figure 2.8 the distribution in the $[\text{Mg}/\text{Fe}]$ – $[\text{Fe}/\text{H}]$ and in the $[\text{Mg}/\text{Mn}]$ – $[\text{Al}/\text{Fe}]$ spaces obtained by the coupling of *Gaia* EDR3 and APOGEE DR17 by Horta et al. (2023). We only include the substructures that will be described in further detail in the following and will be analysed in Chapter 6. The $[\text{Mg}/\text{Mn}]$ – $[\text{Al}/\text{Fe}]$ space was proposed by Hawkins et al. (2015) to disentangle merger debris from in situ populations, as the accreted stars are mainly found at high $[\text{Mg}/\text{Mn}]$ (≥ 0.2) and low $[\text{Al}/\text{Fe}]$ (≤ 0), given the different timescales of ejection of these elements by different types of supernovae: Mn and Fe are mainly produced by SNIa, while Mg and Al by SNII (see also Das et al., 2020). At first glance at these chemical spaces, the halo accreted substructures feature properties similar to those of the surviving local dwarf galaxies. Finally, the chemical information, and in particular the mean stellar metallicities of these systems, allows also for the reconstruction of the stellar mass of the progenitors of the accreted substructures through the use of mass-metallicity relations (e.g., Naidu et al., 2020).

Sequoia. The first halo substructure identified as having kinematic and chemical properties (i.e., MDFs) distinct from GSE was the Sequoia dwarf Galaxy debris (with a progenitor stellar mass $M_* \sim 0.5 - 7 \times 10^7 M_\odot$). This merger event was proposed to have provided the bulk of the high-energy retrograde stars in the stellar halo, while only the null angular momentum component would be related to the GSE event (Myeong et al., 2019), as shown by the bimodality of the distribution function of the azimuthal action (J_ϕ , analogue of L_z for an axis-symmetric potential) for the stars with high energy ($E > -1.1 \times 10^5 \text{ km}^2 \text{ s}^{-2}$) in the left panel of Figure 2.9 (see also Koppelman et al., 2019b). In Fig. 2.8, Sequoia can be found in the left panel in three different colours for three different definitions based on actions/angular momentum/circularity of its stars (Myeong et al., 2019; Koppel-

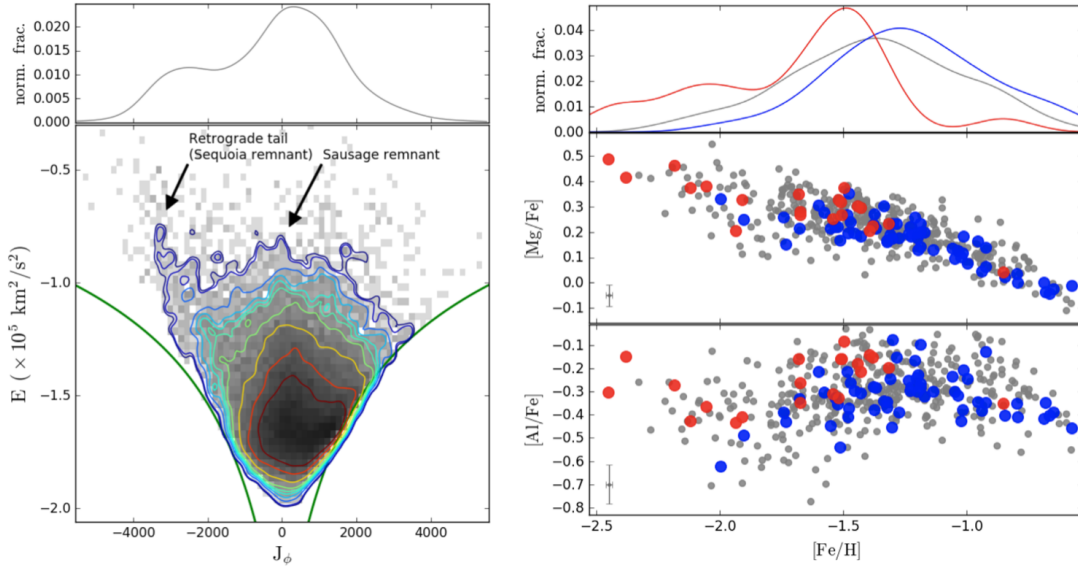


Figure 2.9: *Left panel:* $E - J_\phi$ space for halo stars. *Right panel:* MDF, $[\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]$, and $[\text{Al}/\text{Fe}] - [\text{Fe}/\text{H}]$ distributions of GSE (blue), Sequoia (red) and halo stars (grey). *Adapted from:* Myeong et al. (2019).

man et al., 2019b; Naidu et al., 2020). This distinction was also supported by the fact that these two structures have different MDFs, as shown in the top right panel of Figure 2.9: while the GSE MDF (in blue) peaks at $[\text{Fe}/\text{H}] = -1.3$, the Sequoia MDF peaks at $[\text{Fe}/\text{H}] = -1.6$, being more metal-poor. The lower panels also show different average patterns in the abundance of $[\text{Mg}/\text{Fe}]$ and $[\text{Al}/\text{Fe}]$ as functions of $[\text{Fe}/\text{H}]$ for the two structures.

Thamnos, Arjuna, I'toi. The repartition of the retrograde halo did not end with the high-energy Sequoia identification. The substructure in the lower energy part of the retrograde $E - L_z$ space was proposed to be linked to an independent accretion event, dubbed Thamnos by Koppelman et al. (2019b). Furthermore, Naidu et al. (2020), analysing the H3 spectroscopic survey (Conroy et al., 2019), claimed the existence of two additional substructures, Arjuna and I'toi, which overlap with Sequoia in the retrograde part of the $E - L_z$ space, but differ in their MDFs' peaks, with the latter being more metal-poor than Sequoia ($[\text{Fe}/\text{H}] \leq -2$), while the former is more metal-rich ($[\text{Fe}/\text{H}] \geq -1.6$). The location of these three substructures in the $E - L_z$ space can be found in the right panel of Fig. 2.8.

Helmi Stream. As discussed in Sec. 2.2, the Helmi Stream was the first substructure found in the MW by selecting kinematic clumps. Helmi et al. (1999) showed that $\sim 10\%$ of the metal-poor stars ($[\text{Fe}/\text{H}] \leq -1.6$ dex) in the Galactic halo outside the radius of the Sun orbit come from a single coherent structure, which was at a maximum distance of ~ 16 kpc on a highly inclined orbit and was probably a dSph galaxy. They focused on the $L_\perp - L_z$ plane and found a clump for $500 \text{ kpc km s}^{-1} < L_z < 1500 \text{ kpc km s}^{-1}$ and $L_\perp \sim 2000 \text{ kpc km s}^{-1}$ (see Fig. 2.1), so on a prograde high inclination orbit, represented by orange symbols in Fig. 2.6, in which L_z and $L_\perp$ are denoted as J_z and $J_\perp$. It can be found in the right panel of Fig. 2.8, connecting the disc sequence to Sagittarius. Follow-up work by Koppelman et al. (2019a) with *Gaia* DR2, further characterised the stream, and suggested a progenitor stellar mass of $\sim 10^8 M_\odot$ and an accretion 5-8 Gyr ago.

Heracles. Horta et al. (2021) recently identified a metal-poor eccentric substructure with very low energies (see the left panel of Fig. 2.8). The progenitor was dubbed Heracles and it is supposed to be accreted at high redshift, due to its bound orbits. It is defined in the $[\text{Mg}/\text{Mn}]$ – $[\text{Al}/\text{Fe}]$ space to distinguish it from the more abundant metal-rich (in situ) co-spatial counterpart populations, as shown by the lower panels of Fig. 2.8. Moreover, given its relatively high $[\alpha/\text{Fe}]$ plateau, the progenitor mass was estimated to be $\sim 5 \times 10^8 M_\odot$.

Previous studies proposed the existence of early accretions spatially overlapping with Heracles based on Galactic globular clusters’ properties, named Kraken (Kruijssen et al., 2020) and Koala (Forbes, 2020).

2.7 Overview of the Milky Way assembly

The vast amount of data provided by *Gaia* (Gaia Collaboration et al., 2016a) unveiled the richness in substructures of the Galactic stellar halo. To summarise the current common knowledge on the accretion history of the Galaxy, in Figure 2.10, we show the merger tree as reconstructed by Kruijssen et al. (2020). The main accreted dwarf galaxies are represented on top at the sides of the Milky Way: Sagittarius, Sequoia, Kraken, the progenitor of the Helmi Streams and *Gaia*-Enceladus. The black lines connect these dwarf galaxies to the “major branch” of the MW in the middle, at the lookback time and redshift at which they were accreted, also showing the lower limit for the number of globular clusters they brought into the Galaxy. The “trunk” of the tree represents the evolution of the

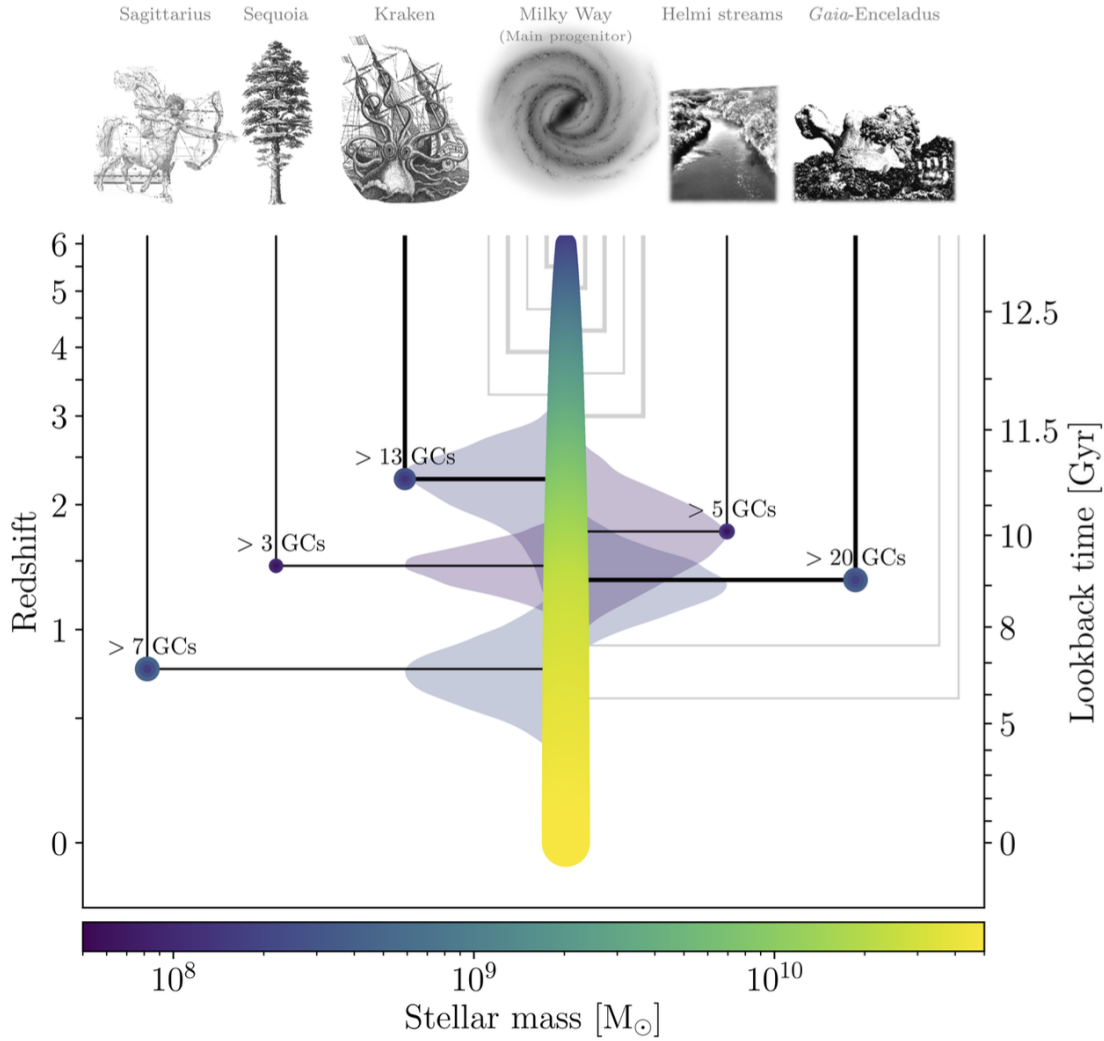


Figura 2.10: The merger tree of the Milky Way. The main progenitor is denoted by the trunk, coloured by stellar mass. Black lines indicate the five identified (and likely most massive) satellites, with the shaded areas visualizing the PDFs of the accretion redshifts. The coloured circles indicate the stellar masses at the time of accretion (both with their colours and sizes) and the subtly different colours of the outer rings and central dots visualize the uncertainties on the stellar masses. From left to right, the six images along the top of the figure indicate the identified progenitors, i.e. Sagittarius, Sequoia, Kraken, the progenitor of the Helmi streams, and Gaia-Enceladus. The annotations list the minimum number of GCs brought in by each satellite. Thin lines mark tiny mergers (with a mass ratio $< 1 : 100$) and thick lines denote minor (or possibly major) mergers (with a mass ratio $> 1 : 100$).
From: Kruijssen et al. (2020).

main progenitor of the MW as it grows over time through the above-mentioned merger events, colour-coded by the stellar mass, which is also shown for the accreted satellites in the corresponding circles. After the very early massive merger with Kraken (or Heracles), the GSE was the last significant accretion event, very close in time to the Sequoia and Helmi Stream accretions, while the merger with the Sagittarius galaxy is still ongoing.

2.8 Aim and outline of the thesis

The merger tree of the Milky Way may seem reconstructed. However, the halo substructures associated with distinct mergers display a significant overlap across chemo-dynamical spaces (see the panels of Figure 2.8). As we will thoroughly discuss in the following Chapter 3, this is due to the fact that if the accretion event is sufficiently massive, the coherence in the $E-L_z$ space is not strictly preserved. In particular, E and L_z are lost because of dynamical friction, as shown by numerical simulations (e.g., [Jean-Baptiste et al., 2017](#)). The latter results shook the very roots of this tree, challenging our understanding of the Milky Way’s assembly history. Several fundamental questions arose that needed robust answers, such as: what do the kinematic clumps really represent? Are they independent of one another? Can chemical abundances – and the MDFs in particular – help determining their putative distinct origin? Can the very low-mass accretions even be detected?

The overall goal of this thesis is to shed light onto the hierarchical assembly of our Galaxy, thoroughly investigating the chemo-dynamical spaces commonly used to identify accreted relics. In particular, we aim at probing whether the putative halo substructures associated with various progenitors on the basis of their distinct chemo-dynamical properties are really the debris of independent accretions. Furthermore, we seek to assess the real extent of the GSE debris in the kinematic spaces, that is, finding methods to associate halo stars with the GSE merger event that do not rely on integral of motions. Finally, we propose to explore the least massive end of accretions of our Galaxy, i.e., analysing the interaction with UFDs, as these extreme systems are predicted to be the main building blocks of the most metal-poor tail of the Galactic halo MDF, preserving the chemical signatures of the first supernovae.

To address the questions above, we will combine theory with observations, also exploiting a variety of different techniques. First of all, we will analyse high-resolution, self-consistent N-body simulations of galaxy mergers to provide the

theoretical framework for interpreting the chemo-dynamical substructures. We will analyse a large stellar sample ($N_* \sim 180000$) coupling the latest data release *Gaia* EDR3 with APOGEE DR17, to verify our predictions for the halo substructures known in the literature. We will also analyse a suite of state-of-the-art cosmological simulations with the highest mass resolution to provide the statistics to set realistic initial conditions for novel direct N-body simulations of UFDs accreting and evolving into the Milky Way.

The body of thesis is organised as reported below. In Chapter 3, we will introduce numerical methods we rely on in this thesis work, namely N-body simulations of a satellite accreting onto a MW-like galaxy with a mass ratio 1:10, described in Mori et al. (2024). Then we will report the results in the chemo-dynamical spaces in Chapter 4, checking whether different MDFs across the kinematic spaces can actually be used to support distinct satellite origin of the stars, as reported in Mori et al. (2024) and in the IAU Symposium 395 proceedings (Mori et al., *in press*). In Chapter 5, we illustrate how the results of the previous chapter were instrumental to find observational evidence for the multiple passages of GSE before merging with the Milky Way, as traced by its chemo-dynamics (Skúladóttir et al., 2025, including Mori). In Chapter 6, we will then perform a revision of the kinematic-defined halo substructures associated with independent merger events in light of the results above, by comparing them in chemical spaces through Gaussian Mixture Models to verify their eventual links to GSE and/or the heated disc (Mori et al., 2025). Chapter 7 then will introduce a statistical analysis of the dark matter assembly history of our Galaxy, focussing on the very-low end of the mass spectrum of accreted galaxy, that is with UFD-hosting haloes (Mori et al., *in prep.*). Finally, the key results and implication of this thesis, along with the future perspectives of this work will be summarised in Chapter 8.

Modelling massive mergers: numerical methods

Reference article

(Mori et al., 2024) **Mori A.**, Di Matteo P., Salvadori S., Khoperskov S., Pagnini G., Haywood M.; “Metallicity distributions of halo stars: do they trace the galactic accretion history?”. A&A, 690, A136; arXiv: [2401.13737](#) (astro-ph.GA); doi: [10.1051/0004-6361/202449291](#).

In the previous chapter, we introduced the widely-used tools of Galactic Archaeology, and in particular the use of integrals of motion (IoM) spaces (see [Klement, 2010](#); [Smith, 2016](#), for reviews). However, this approach has been challenged in these last years (e.g., [Jean-Baptiste et al., 2017](#)), because based on assumptions which are not generally valid. We will detail this point in this chapter as it sets the basis for the results presented in the entire thesis. The chapter is organised as follows. We will begin by recalling the fundamentals merger dynamics in Sec. [3.1](#). We will then delve into the interpretation of IoM spaces of accreted satellites, discussing the caveats of predictions by test particle models in Sec. [3.2](#). Then we will describe the state-of-the-art N-body models that we used in this thesis in Sec. [3.3](#). Finally, we will report the assignment of the chemical abundances that we performed *a posteriori* in Sec. [3.4](#), as described in [Mori et al. \(2024\)](#).

3.1 Merger events and galactic dynamics

The evolution of galaxies is driven by several dynamical processes taking place on different timescales. They can be divided into internal ones, such as protogalactic

collapse and internal secular evolution, and external ones, such as environmental secular evolution and galaxy mergers (see Fig 1.1 in [Kormendy, 2013](#)). In this Section, we will describe the physics of a merger between a main galaxy and a satellite. There are two key physical processes that take place: dynamical friction, which causes the satellite to lose its orbital energy and angular momentum, and tidal stripping, which drives the satellite's mass loss.

Let us consider a satellite travelling through a collection of lighter particles within the main galaxy, which can be both stellar and dark matter particles. The satellite, which for now we consider as a point particle of mass M moving at $\vec{v}_M$, exerts a gravitational attraction onto the field stars of mass $m \ll M$ and velocity distribution $f(\vec{v}_m)$. Some of these stars then accumulate around the satellite, thus creating a matter overdensity behind it. At a certain point, this collection of particles which follows the satellite becomes sufficiently massive to begin to attract back the satellite itself in an opposite direction with respect to its motion, causing an effect of friction. This phenomenon is called *dynamical friction* and – in the case of an isotropic velocity distribution of the field stars – can be expressed by the Chandrasekhar formula ([Binney & Tremaine, 2008](#)):

$$\frac{d\vec{v}_M}{dt} \approx -16\pi^2 G^2 M m \ln \Lambda \left[\int_0^{v_M} dv_m v_m^2 f(v_m) \right] \frac{\vec{v}_M}{v_M^3} \quad (3.1)$$

thus, only stars moving slower than the satellite contribute to the friction. Like an ordinary frictional drag, the force described always opposes the motion ($\frac{d\vec{v}_M}{dt}$ is anti-parallel to $\vec{v}_M$). If $\vec{v}_M$ is sufficiently small, $f(v_m)$ can be replaced by $f(0)$ to find:

$$\frac{d\vec{v}_M}{dt} \approx -\frac{16}{3}\pi^2 G^2 M m \ln \Lambda f(0) \vec{v}_M \quad (3.2)$$

proportional to $\vec{v}_M$, as frictional forces are; otherwise we are dealing with a high-speed encounter, which does not result in a merger. The effect of this friction is that the orbital energy of the satellite decreases and transforms into the internal energy of the field stars, which consequently become kinematically heated and populate regions further from the galactic centre. Analogously, the satellite gets radialised as it loses its angular momentum that is gained by field stars, which then tend to move slightly more in the same general rotational sense as the satellite's orbit.

Moreover, the satellite is not a point mass, but an extended body. Consequently, the gravitational attraction exerted by the main galaxy (of mass M_{host}) provokes tidal effects, as satellite regions closer to the galactic centre experience stronger gravitational force. Let us consider two extreme positions P1 and P2 in the satellite

along the radial direction to the main galaxy. In the reference frame of the satellite, the distance between P1 and P2 is Δr , i.e., the size of the satellite; while the distance between the satellite and the main galaxy is R . We can then compute the difference of the gravitational attraction (i.e., $a(\vec{x}) = -GM_{\text{host}}\vec{x}/|\vec{x}|^3$) experienced by P1 and P2:

$$a_T = a(R + \Delta r) - a(R) \quad (3.3)$$

If $\Delta r \ll R$, we can expand to first order to obtain the tidal differential acceleration:

$$a_T \approx \frac{GM_{\text{host}}\Delta r}{R^3} \quad (3.4)$$

When this tidal force becomes sufficiently strong, satellite stars begin to escape the satellite potential and get lost in the main galaxy potential well along the orbit. This effect is called *tidal stripping* and produces stellar streams before the satellite is completely disrupted.

3.2 Test particle models and limitations

The search for accreted debris in the Galactic stellar halo in the last decades has intensely relied on the IoM spaces, and on the $E - L_z$ space in particular, where to look for overdense stellar clumps in the footsteps of the pioneering works by [Helmi et al. \(1999\)](#) and [Helmi & de Zeeuw \(2000\)](#). As described in Sec. 2.2, the latter indeed modelled the accretion of several satellites onto a MW-like potential and showed that the initial well-separated distributions of the satellites in the $E - L_z$ space were preserved after several Gyr of evolution, that is, after the end of the mergers. As a consequence, it would have been possible to identify the stars accreted from those satellites from their clumpy (final) distribution in the $E - L_z$ space even when they were already completely disrupted. As shown in Ch. 2, this method has been extensively applied to current data, particularly since the second data release of *Gaia* ([Gaia Collaboration et al., 2018a](#)), leading to several putative reconstructed merger events.

However, these results were obtained on the basis of a number of assumptions for the merger model. In particular, [Helmi & de Zeeuw \(2000\)](#) used test particle models, such that the Milky Way was represented by a fixed analytic potential, while only the satellites were modelled as a collection of test particles gravitationally interacting with the external potential. As a consequence, the Galactic potential did not evolve and respond to the interaction with the satellite. Yet, we know that

the field stars of the main galaxy react to the satellite’s passage, producing the net effect of dynamical friction – a drag force that causes the satellite to lose energy and angular momentum (which is gained by the field stars themselves), as we thoroughly discussed in Sec. 3.1. Since these models assume an analytic Galactic potential and no dynamical friction, not even in an analytical way using the Chandrasekhar formula (Binney & Tremaine, 2008), energies and angular momenta of the accreted satellites are conserved by definition¹. Thus, the clumps they create in the integrals of motion spaces and the fact that each one of them corresponds to a single accreted satellite is actually a direct consequence of the model assumptions and not necessarily an intrinsic feature of the accretion event. Even with a time-varying Galactic potential modelled by analytically increasing the masses and scale radii of each component – the results of Gómez & Helmi (2010); Gómez et al. (2010) remained unchanged, again as a direct consequence of neglecting dynamical friction.

Moreover, in these models the in situ stellar population was never taken into account, which actually reacts to the merging event getting kinematically heated and reducing the overdensity contrast, overlapping with the accreted component and smearing out its overdensities. Brown et al. (2005) also modelled an in situ population and found indeed that the background it creates for the accreted clumps severely challenges the search for accreted debris with *Gaia* data. However, they added the in situ population a posteriori, in such a way that it could not self-consistently react to the merger.

N-body simulations, which relax the assumption of a static potential and model both the satellite and the main galaxy as collections of gravitationally interacting particles to get a fully-consistent model, show that the resulting kinematic spaces are very difficult to interpret (Jean-Baptiste et al., 2017).

This is due to the fact that dynamical friction and the reaction of the in situ population are naturally modelled during the interaction, causing several consequences, among which the loss of E and L_z of the satellite(s).

First of all, given the non-conservation of E and L_z , each satellite redistributes in a broad region of the space and gives rise to several independent overdensities, as shown by the top right panel in Fig. 3.1 (Jean-Baptiste et al., 2017), where the red/orange overdensity clumps of the accreted distribution are created by the

¹for the angular momenta, this is true if the potential is spherical, otherwise for an axisymmetric potential only the z -component is strictly conserved.

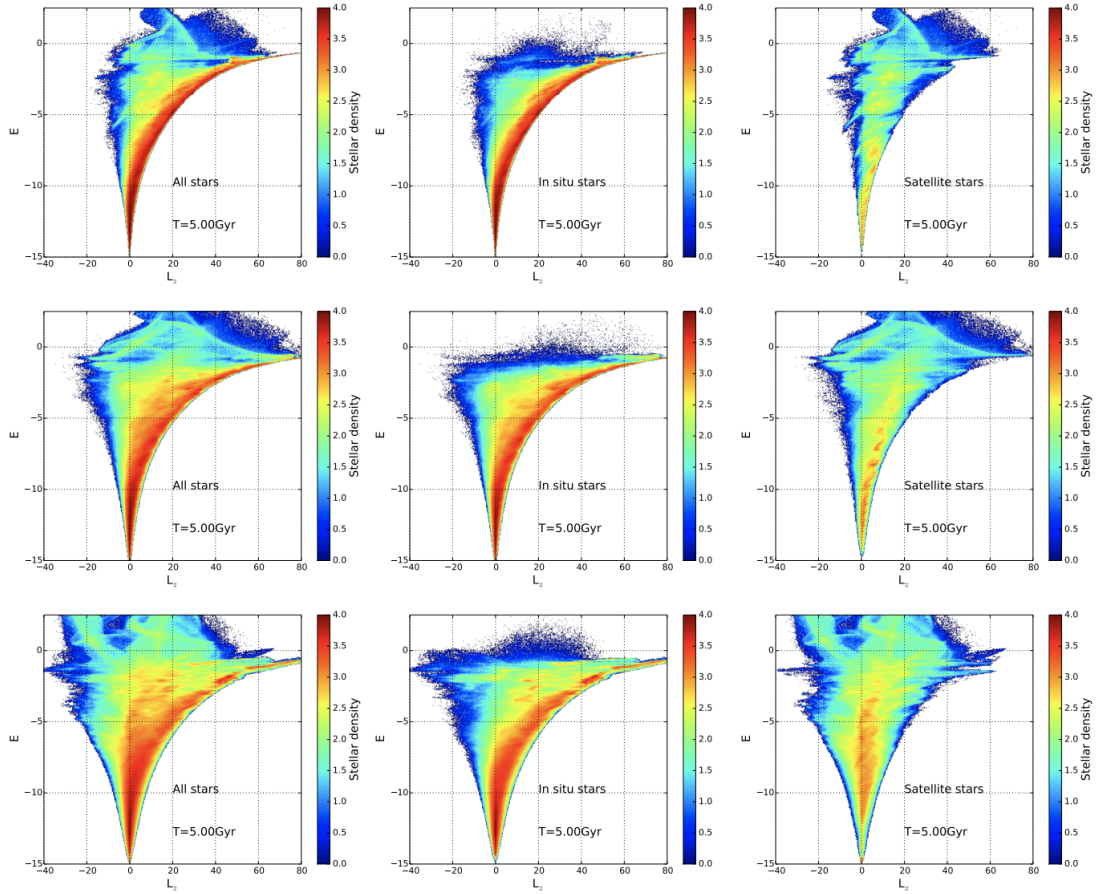


Figure 3.1: Final distribution (after 5 Gyr) in the $E - L_z$ space of all stars (left panel), in situ stars (middle panel) and accreted stars (right panel). Different rows corresponds to the merging event of a Milky Way-type galaxy with one, two and four satellites, each one with a mass ratio of 1:10. *From: Jean-Baptiste et al. (2017).*

same satellite. When more than one satellite with similar masses are modelled, their debris can then overlap with one another (see middle and bottom right panels of Fig. 3.1).

Furthermore, the in situ population gets kinematically heated by the merger, acquiring halo-like orbits and redistributing over the $E - L_z$ space in regions similar to those populated by accreted stars, forming more substructures, as can be seen in the middle columns of Fig. 3.1 (Jean-Baptiste et al., 2017).

The results of Jean-Baptiste et al. (2017) have been confirmed by a number of numerical works (see Koppelman et al. (2020); Amarante et al. (2022) for controlled simulations and Grand et al. (2019); Khoperskov et al. (2023b,c) for simulations in a cosmological context). For these reasons, overdensities in kinematic spaces should be interpreted with caution, as they do not necessarily represent *per se* relics of accreted satellites. To obtain robust results, we will therefore analyse self-consistent N-body models. These simulations were developed at the *Observatoire de Paris* and are similar to those presented in Jean-Baptiste et al. (2017), as will be described in the next section. They have also been analysed by Pagnini et al. (2023) to study the distribution of accreted and in-situ globular clusters in kinematic spaces.

3.3 Self-consistent N-body models

In this work, we analyse seven dissipationless, high-resolution N-body simulations of the accretion of a satellite onto a MW-type galaxy with different orbital parameters. The mass ratio is 1:10 since MW-type galaxies have likely experienced such accretions during their evolution (see Deason et al., 2016; Fattahi et al., 2018; Fragkoudi et al., 2020), while also being the mass ratio that GSE was supposed to have at the time of accretion (e.g., Helmi et al., 2018). These simulations are fully self-consistent, since both the satellites and the main galaxy are modelled as a collection of particles that react to the interaction, experiencing tidal effects and dynamical friction. The interaction is simulated for 5 Gyr, i.e. until the merger completion and after an additional dynamical relaxation time, at least considering the inner regions.

We focus on single accretion events since we show that they already generate complex patterns that are not easily interpretable.

	a	h	M	N	m
MW: thin disc	4.80	0.25	16.21	1×10^7	1.6×10^{-6}
MW: intermediate disc	2.00	0.60	11.69	6×10^6	1.9×10^{-6}
MW: thick disc	2.00	0.80	8.43	4×10^6	2.1×10^{-6}
MW: GC system	2.00	0.80	6.5×10^{-2}	100	6.5×10^{-4}
MW: dark halo	20.00	-	160.00	5×10^6	3.2×10^{-5}
Satellite: thin disc	1.52	0.08	1.69	1×10^6	1.6×10^{-6}
Satellite: intermediate disc	0.63	0.19	1.17	6×10^5	1.9×10^{-6}
Satellite: thick disc	0.63	0.25	0.84	4×10^5	2.1×10^{-6}
Satellite: GC system	0.63	0.25	6.5×10^{-3}	10	6.5×10^{-4}
Satellite: dark halo	6.32	-	16.00	5×10^5	3.2×10^{-5}

Tabella 3.1: Scale lengths (a) and heights (h), mass (M), number of particles (N), and particle mass (m) for the disc components of the MW and the satellite, considering a cut-off in radius at ten times the scale length. Masses are in units of $2.3 \times 10^9 M_\odot$ and distances are in kiloparsecs.

3.3.1 Galactic parameters

All parameters are reported in Table 3.1. The total number of particles (MW and satellite) is $N_{TOT} = 27500110$, of which $N_{MW} = 25000100$ represent MW-type (stellar and dark matter) particles. Both galaxies consist of a thin, an intermediate, and a thick disc, mimicking the galactic thin disc, the young thick disc, and the old thick disc (Haywood et al., 2013; Di Matteo, 2016). The thin disc is as massive as the sum of the thick and intermediate ones (Snaith et al., 2014). The discs have different scale heights (a) and lengths (h). The galaxies also host a hundred globular clusters and are embedded in a dark matter halo. The discs were modelled with Miyamoto-Nagai density distributions (Miyamoto & Nagai, 1975):

$$\rho_*(R, z) = \left(\frac{h_*^2 M_*}{4\pi} \right) \frac{a_* R^2 + (a_* + 3\sqrt{z^2 + h_*^2})(a_* + \sqrt{z^2 + h_*^2})^2}{\left[a^2 + \left(a_* + \sqrt{z^2 + h_*^2} \right)^2 \right]^{5/2} (z^2 + h_*^2)^{3/2}}, \quad (3.5)$$

with M_* , a_* , and h_* masses and characteristic lengths and heights. The dark halo was modelled as a Plummer sphere:

$$\rho_{halo}(r) = \left(\frac{3M_{halo}}{4\pi a_{halo}^3} \right) \left(1 + \frac{r^2}{a_{halo}^2} \right)^{-5/2}, \quad (3.6)$$

with M_{halo} and a_{halo} , a characteristic mass and radius, respectively.

	x_{sat}	y_{sat}	z_{sat}	$v_{x,sat}$	$v_{y,sat}$	$v_{z,sat}$	ϕ_{orb}
$MW_{sat_n1_}\Phi 0$	100.00	0.00	0.00	-2.06	0.42	0.00	0
$MW_{sat_n1_}\Phi 30$	86.60	0.00	-50.00	-1.78	0.42	1.03	30
$MW_{sat_n1_}\Phi 60$	50.00	0.00	-86.60	-1.03	0.42	1.78	60
$MW_{sat_n1_}\Phi 90$	0.00	0.00	-100.00	0.00	0.42	2.06	90
$MW_{sat_n1_}\Phi 120$	-50.00	0.00	-86.60	1.03	0.42	1.78	120
$MW_{sat_n1_}\Phi 150$	-86.60	0.00	-50.00	1.78	0.42	1.03	150
$MW_{sat_n1_}\Phi 180$	-100	0.00	0.00	2.06	0.42	0.00	180

Tabella 3.2: Initial positions and velocities of the satellite. The angle, ϕ_{orb} , is the inclination of the satellite orbital plane with respect to the MW disc (in degrees). Distances are in kiloparsecs and velocities are in units of 100 km/s.

The number of stellar particles in the MW-like galaxy is 20×10^6 with a total mass of $M_* \sim 9 \times 10^{10} M_\odot$; this leads to an average particle mass of $m_* \sim 4 \times 10^3 M_\odot$. The number of dark matter particles is 5×10^6 and the total mass is $M_{DM} \sim 3.7 \times 10^{11} M_\odot$; hence, the dark matter component has a particle mass of $m_{DM} \sim 7 \times 10^4$.

The mass and total number of particles of each disc component of the satellite is ten times smaller, while their sizes are reduced by a factor of $\sqrt{10}$ (see [Fernández Lorenzo et al., 2013](#), for the galaxy mass–size relation), which is reported in Table 3.1. The total mass of the satellite has been assumed to be $M_{halo} = 4.6 \times 10^{10} M_\odot$ and the visible mass $M_* = 9 \times 10^9 M_\odot$, which is compatible with the typical dwarf galaxies in the Local Group. The total mass is smaller than the one estimated for GSE ($\sim 10^{11} M_\odot$); thus, our results would be amplified when modelling the accretion of GSE-tailored satellites. The choice to use a core dark matter halo as supported by observational evidence ([Flores & Primack, 1994](#); [de Blok et al., 2001b,a](#); [Marchesini et al., 2002](#); [Gentile et al., 2005](#); [Kuzio de Naray et al., 2006, 2008](#)).

3.3.2 Kinematic parameters

In a reference frame with the $x - y$ plane initially set on the MW disc and the z axis oriented as its spin, initial satellite positions and 3D velocities relative to the main galaxy are reported in Table 3.2. Their orbital planes are inclined of ϕ_{orb} with respect to the MW-type galaxy disc. The satellite begins at a distan-

ce of 100 kpc from the Milky Way centre. Its initial orbital velocity is set for a parabolic orbit, assuming a 1:10 mass ratio between the satellite and the MW-type galaxy, where the total mass of the system is 200 (in units of this mass). The choice of exploring parabolic orbits is in agreement with cosmological predictions (Khochfar & Burkert, 2006). The seven simulations differ in the initial orientation of the satellite orbital plane, which could have the following values: $\phi_{orb} = 0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ, 180^\circ$, $\phi_{orb} = 0^\circ, 30^\circ, 60^\circ$ corresponding to direct orbits, $\phi_{orb} = 90^\circ$ to a polar orbit, and $\phi_{orb} = 120^\circ, 150^\circ, 180^\circ$ to retrograde orbits.

The initial conditions were generated by adopting the iterative method described in Rodionov et al. (2009). All simulations were run by making use of the TreeSPH code described in Semelin & Combes (2002). Gravitational forces were calculated using a tolerance parameter of $\theta = 0.7$ and include terms up to the quadrupole order in the multiple expansion. A Plummer potential was used to soften gravitational forces, with constant softening lengths for different particle species. In all of the simulations described here, a softening length $\epsilon = 50$ pc was adopted. The equations of motion were integrated using a leapfrog algorithm with a fixed time step of $\Delta t = 2.5 \times 10^5$ yr. In this Chapter and in Chapter 4, the following set of units is used: distances are given in kiloparsecs, angular momenta in 10^2 kpc km/s, energies in 10^4 km²/s², and time in 10^7 yr.

3.4 Chemical abundances assignment

As was stated in the previous section, the simulations analysed in this chapter do not model star formation or chemical enrichment. However, following an approach already used in a number of works (see, for example, Di Matteo et al., 2013; Martinez-Valpuesta & Gerhard, 2013; Fragkoudi et al., 2017, 2018; Khoperskov et al., 2018), we have assigned – a posteriori – chemical abundances to the stellar particles of the MW-type galaxy and the satellite based on their kinematic properties and the current observational constraints, as detailed below.

3.4.1 The case of initial vertical abundance gradients

In this first case, we considered an initial vertical abundance gradient to the disc components of both galaxies. Thus, the mean metallicity of disc particles is independent of the radius; that is, no radial metallicity gradient is initially present in either the disc of the MW-type galaxy or in the satellite. However, a vertical abun-

	μ	σ
$[\text{Fe}/\text{H}]_{\text{MW,thin}}$	0.0	0.25
$[\text{Fe}/\text{H}]_{\text{MW,inter}}$	-0.26	0.2
$[\text{Fe}/\text{H}]_{\text{MW,thick}}$	-0.62	0.26
$[\text{Mg}/\text{Fe}]_{\text{MW,thin}}$	0.0	0.04
$[\text{Mg}/\text{Fe}]_{\text{MW,inter}}$	0.15	0.05
$[\text{Mg}/\text{Fe}]_{\text{MW,thick}}$	0.22	0.04

Tabella 3.3: Mean and standard deviation values of the normal distributions that define the $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{Fe}]$ values for the particles of the thin, intermediate, and thick discs of the MW-type galaxy.

	min	max
$[\text{Fe}/\text{H}]_{\text{sat,thin}}$	-1.1	-0.7
$[\text{Fe}/\text{H}]_{\text{sat,inter}}$	-1.3	-1.1
$[\text{Fe}/\text{H}]_{\text{sat,thick}}$	-1.6	-1.3

Tabella 3.4: Minimum and maximum values of the uniform distributions used to assign a metallicity value to the satellite particles.

dance gradient has been taken into account on the basis of observational evidence in the MW. In our Galaxy, indeed, the thick disc is on average more metal-poor and more α -enhanced with respect to the thin disc, as shown in Sec. 1.2 (Fuhrmann, 1998; Haywood et al., 2013; Bensby et al., 2014; Bovy et al., 2012a). In particular, in the inner regions of the Galaxy, where all the disc components are present, the metallicity and the α abundance can be described by different Gaussian distributions (Hayden et al., 2015).

For the MW-type galaxy, then, the $[\text{Fe}/\text{H}]$ and the $[\text{Mg}/\text{Fe}]$ values were assigned to the particles with normal distributions, with three different mean (μ) and standard deviation (σ) values for the thin, intermediate, and thick discs, with decreasing mean values for the mean metallicity and increasing ones for the α abundances (see Table 3.3).

For the satellite galaxy, metallicities for the thin, intermediate, and thick discs (Table 3.4) were assigned using uniform distributions between specified minimum and maximum values, with an additional dispersion of 0.05 dex applied. In the first place, we assumed a uniform distribution for the sake of simplicity. This simple hypothesis, indeed, already generates a great complexity in the final metallicity

patterns in the $E - L_z$ space, and thus is enough for the point we wanted to make out. The choice to assign different metallicity intervals to the satellite disc components simply mimics the case in which satellite stars with hotter kinematics also have lower mean metallicities. On average, the mean metallicity of the satellite is lower than that of the MW-type galaxy, as was found in observational studies (Kirby et al., 2013). As for the $[\text{Mg}/\text{Fe}]$ abundances of the satellite galaxy, we assigned them in such a way to reproduce qualitatively the behaviour of α -elements with $[\text{Fe}/\text{H}]$, as was observed in a number of dwarf galaxies of the Local group (see, for example, Matteucci, 2007; Tolstoy et al., 2009). These low-mass systems tend to show a nearly flat dependence of α elements with $[\text{Fe}/\text{H}]$ until a characteristic value of $[\text{Fe}/\text{H}]$ (the so-called ‘knee’) at which the $[\alpha/\text{Fe}]$ ratio shows an inflection. For metallicities larger than the value at the knee (hereafter $[\text{Fe}/\text{H}]_{\text{knee}}$), the $[\alpha/\text{Fe}]$ ratios show a decrease with increasing $[\text{Fe}/\text{H}]$. The value of $[\text{Fe}/\text{H}]$ at the knee of the $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$ relation is in general not the same for all dwarf galaxies (see, for example, Fig. 11 in Tolstoy et al., 2009) but changes from galaxy to galaxy, reflecting their different star formation histories. To mimic this behaviour, we assigned $[\text{Mg}/\text{Fe}]$ ratios to the satellite stellar particles in the following way:

$$[\text{Mg}/\text{Fe}]_{\text{sat}} = \begin{cases} [\text{Mg}/\text{Fe}]_{\text{knee}} & \text{if } [\text{Fe}/\text{H}]_{\text{sat}} < [\text{Fe}/\text{H}]_{\text{knee}}, \\ [\text{Fe}/\text{H}]_{\text{sat}} * m + q & \text{if } [\text{Fe}/\text{H}]_{\text{sat}} \geq [\text{Fe}/\text{H}]_{\text{knee}} \end{cases} \quad (3.7)$$

with $[\text{Mg}/\text{Fe}]_{\text{knee}} = 0.22$, $[\text{Fe}/\text{H}]_{\text{knee}} = -1.3$, $m = -0.4$, and $q = -0.3$. With such a choice of values, the distribution of in situ and accreted stars in the $[\text{Mg}/\text{Fe}]$ – $[\text{Fe}/\text{H}]$ plane is qualitatively similar² to that found for stars in the solar vicinity (Nissen & Schuster, 2010) or in a volume a few kiloparsecs from the Sun (Hayes et al., 2018), as shown by the left panel of Fig. 3.2. In particular, the choice of $[\text{Fe}/\text{H}]_{\text{knee}} = -1.3$ was made to be in agreement with the value of metallicity at which Nissen & Schuster (2010) have reported the appearance of the low- α , accreted, halo sequence.

3.4.2 Adding an initial radial metallicity gradient

In this second case, we have explored the possibility that both the thin discs of the MW-type galaxy and the satellite initially show a negative radial metallicity gradient that co-exists with the vertical gradients discussed before.

²We emphasise that the chemical abundances sequence generated with our approach are not a fit to any data, but are simply intended to capture the main trends found in observational $[\text{Mg}/\text{Fe}]$ – $[\text{Fe}/\text{H}]$ planes.

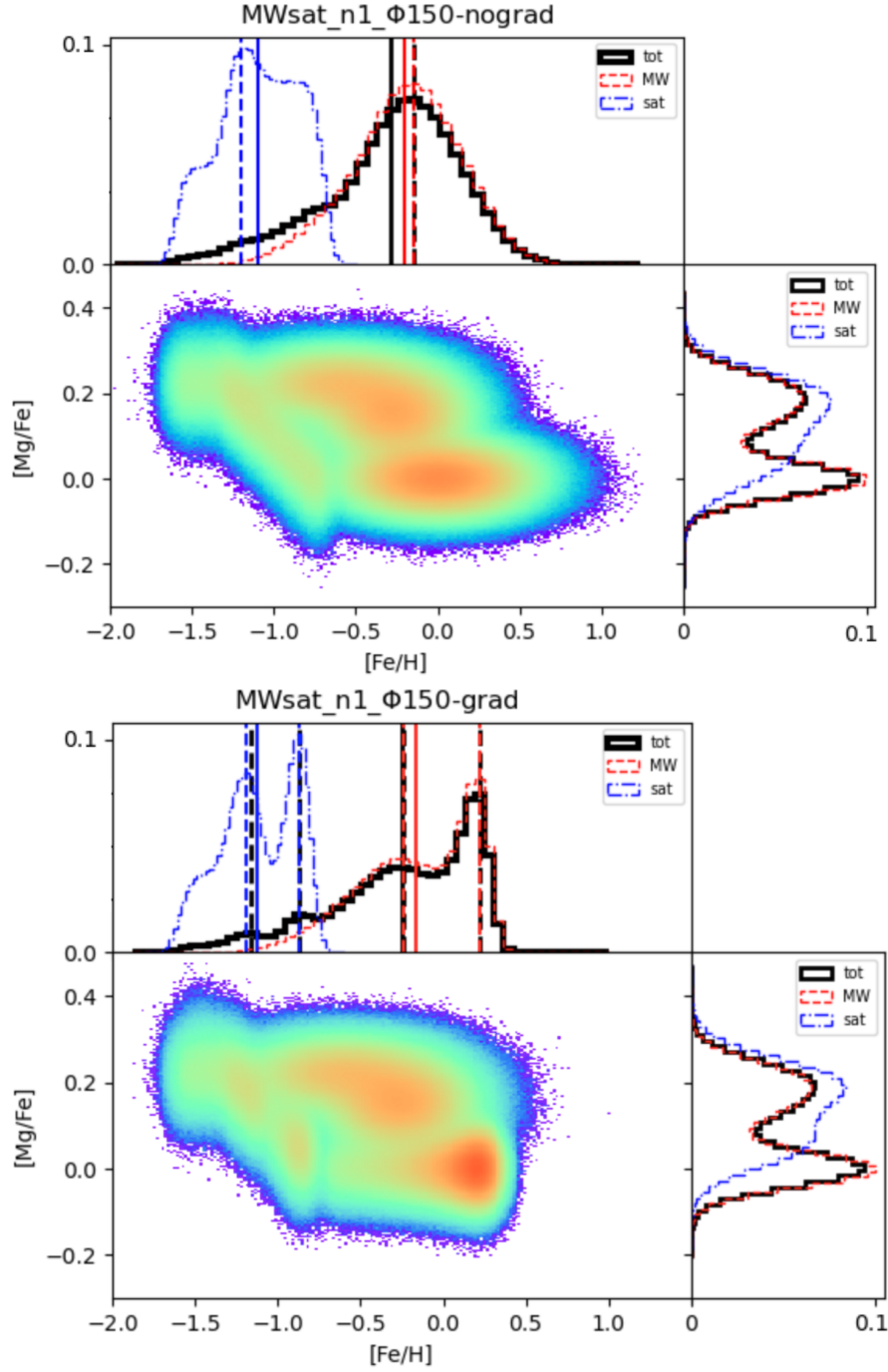


Figura 3.2: The $[\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]$ space and its normalised marginal distributions, in the case of a vertical metallicity gradient only (top panel) and in the case of an additional radial metallicity gradient (bottom panel). *From: Mori et al. (2024).*

In the thin disc of the MW, indeed, it is known that the inner regions have $[\text{Fe}/\text{H}] \sim 0.3$, while the outer regions (beyond 10 kpc) have $[\text{Fe}/\text{H}] \sim -0.7$ (e.g. [Hayden et al., 2015](#)). A metallicity gradient is currently absent in the thick disc ([Cheng et al., 2012; Hayden et al., 2015](#)), a fact that could be due to its formation during a more turbulent phase, which would have led to an efficient mixing of metals ([Haywood et al., 2013, 2015; Lehnert et al., 2014](#)). The assignment of the radial metallicity gradient to the stellar particles was done on the basis of their initial ($t = 0$) positions.

In particular, the metallicity of the thin disc particles of the MW-type galaxy was assigned as follows:

$$[\text{Fe}/\text{H}]_{\text{MW,thin}} = [\text{Fe}/\text{H}]_{\text{MW,thin}}^{\text{max}} - \frac{R}{R_{\text{max,MWthin}}}, \quad (3.8)$$

where R is the distance of the particle from the MW-type galaxy centre, projected in the disc plane, $[\text{Fe}/\text{H}]_{\text{MW,thin}}^{\text{max}}$ is the maximum metallicity at the centre of the thin disc ($R = 0$), which we assigned to be equal to 0.3 dex, and $R_{\text{max,MWthin}}$ is the maximum distance from the galaxy centre at which stellar particles of the thin disc of the MW-type galaxy are found. With $R_{\text{max,MWthin}}$ being equal to 50 kpc, this implies that Eqn. 3.8 can be rewritten as

$$[\text{Fe}/\text{H}]_{\text{MW,thin}} = [\text{Fe}/\text{H}]_{\text{MW,thin}}^{\text{max}} - f_{\text{MWthin}} * R, \quad (3.9)$$

with $f_{\text{MWthin}} = 0.02$ dex/kpc. We caution the reader that the metallicity gradient of the MW disc is known to be more complex than what we have used, with a steeper slope a few kiloparsecs from the Sun (see [Haywood et al., 2024](#), for a recent study). While the adopted values of the gradient can change the mean metallicities of stellar populations and the shapes of the MDFs, the bottom line of the results that we present below does not change.

Similarly, for the thin disc of the satellite galaxy,

$$[\text{Fe}/\text{H}]_{\text{satthin}} = [\text{Fe}/\text{H}]_{\text{satthin}}^{\text{max}} - f_{\text{satthin}} * R, \quad (3.10)$$

where R is now the distance of a stellar particle of the satellite from the satellite centre, $[\text{Fe}/\text{H}]_{\text{sat,thin}}^{\text{max}}$ is the maximum metallicity at the centre of the satellite thin disc (which we assigned to be equal to -0.8 dex), and $f_{\text{satthin}} = 0.05$ dex/kpc, in such a way that the satellite thin disc has a metallicity of -1.5 dex at its edge. This gradient is consistent with the ones observed in Local Group dwarf galaxies (e.g., see [Taibi et al., 2022](#)). In cosmological simulations, similar gradients are also observed (e.g., [Khoperskov et al., 2023d](#)).

The top panel of Figure 3.2 shows the distribution of stars (accreted and in situ) in the $[\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]$ space when an initial radial metallicity gradient is added. The main trends are those observed already in the case of a vertical gradient only: the flatness of the $[\text{Mg}/\text{Fe}]$ ratio for $[\text{Fe}/\text{H}] \lesssim -1.3$ dex, the appearance of a low- α sequence at higher metallicities, and the redistribution of stars into an α -enhanced thick disc and a low- α thin disc counterpart. To these general features, the inclusion of a radial metallicity gradient has the effect of introducing a certain amount of complexity: the low- α thin disc sequence and the low- α accreted sequence are no longer uniformly populated, but show prominent metal-rich peaks that clearly appear in the total MDF, as well as in the MDFs of the satellite and of the MW-type galaxy, taken separately. The α -DFs, instead, stay the same, since in this second scenario no hypothesis about an α -gradient with radius was taken into account. In particular, in both cases (with or without a radial metallicity gradient) the α -DF of the MW-type galaxies is bimodal, as has been found for stars in the MW disc (Haywood et al., 2018a).

In the following of the thesis, we refer to the two different initial conditions for the metallicity gradients with the suffix ‘*nograd*’, to indicate the case in which no radial metallicity gradient is initially present in the main and satellite discs, and with the suffix ‘*grad*’, to indicate the case in which radial metallicity gradients are initially present. This suffix was added to the identifier of the simulation. For example, the simulation named MWsat_n1_Φ0_grad refers to a single 1 : 10 merger, in which the satellite is initially on a planar prograde orbit and in which the thin discs of both the MW-type galaxy and the satellite are initially characterised by a radial metallicity gradient.

In the next Chapter, we will illustrate the results obtained by analysing these simulations. In particular, we will highlight how modelling the merging galaxies self-consistently can impact the final distribution in the chemo-dynamical spaces.

On the MDFs of massive mergers across kinematic spaces

Reference article

(Mori et al., 2024) **Mori A.**, Di Matteo P., Salvadori S., Khoperskov S., Pagnini G., Haywood M.; “Metallicity distributions of halo stars: do they trace the galactic accretion history?”. A&A, 690, A136; arXiv: [2401.13737](#) (astro-ph.GA); doi: [10.1051/0004-6361/202449291](#).

In Chapter 3, we discussed the caveats in using integrals of motion spaces to identify accreted galaxies. In particular, we showed that a self-consistent modelling of one or several accretions naturally leads to the non-conservation of energies and angular momenta of the accreted stars. This finding naturally complicates the interpretation of $E - L_z$ space and questions all reconstructions of the merger history of our Galaxy based on this approach.

A potential way to overcome the problem and still use kinematic information to reconstruct the accretion history of the Galaxy may consist into making use of the metallicity distribution function (MDF) of stars located in different regions of kinematic spaces: groups of stars that are characterised by different kinematic properties and that also have different MDFs can be indicative of independent accretion events (see Sec. 2.3). The discovery of the Sequoia merger event ($M_* \sim 5 \times 10^7 M_\odot$) is an example of this procedure. Sequoia (Myeong et al., 2019) was proposed to have provided the bulk of the high-energy retrograde stars in the stellar halo, while only the null component ($L_z \sim 0$) would be related to the *Gaia*-Sausage/Enceladus (GSE, $M_* \sim 6 \times 10^8 M_\odot$) event (Nissen & Schuster, 2010; Belokurov et al., 2018; Haywood et al., 2018b; Helmi et al., 2018). This distinction

was motivated by the fact that these two structures have different MDFs: while the GSE MDF peaks at $[\text{Fe}/\text{H}] = -1.3$, the Sequoia MDF peaks at $[\text{Fe}/\text{H}] = -1.6$, being more metal-poor (Myeong et al., 2019). A difference in $[\text{Na}/\text{Fe}]$, $[\text{Mg}/\text{Fe}]$ and $[\text{Ca}/\text{Fe}]$ has also been pointed out by Matsuno et al. (2019), but these abundances differ even within the various definitions of Sequoia (see Horta et al., 2023). The general difficulty of reconstructing clean samples for GSE and Sequoia has been rigorously addressed by Feuillet et al. (2020, 2021). The latter study, in particular, recognises how the abundance properties of Sequoia change with its kinematic definition. This kind of study has been applied to other regions of kinematic spaces (see, for example, Naidu et al., 2020; Ruiz-Lara et al., 2022), making use of the same overall approach: once different MDFs have been identified, the average metallicity value for each identified region of the kinematic spaces is calculated and these different average metallicities are associated with different stellar masses of the progenitor satellites by making use of mass-metallicity relations.

Finding different average metallicities for different regions of kinematic spaces may at first glance seem proof that the general approach is correct; if different regions of kinematic spaces also have different average metallicities, the straightforward explanation is that they are populated by stellar populations of different origins. But the question is whether this approach is globally valid or whether we are using a somewhat circular argument, by making use of the results (different MDFs) to support the hypothesis (different kinematic properties identify different progenitors). It is therefore necessary to reverse the problem and ask ourselves how the fact that kinematic quantities, such as energy, angular momentum, and actions, are not generally conserved during a merger (if it is sufficiently massive) is reflected in the MDFs of stars located in different regions of kinematic spaces. It is also necessary to ask how this depends on the initial (pre-accretion) metallicity gradients of the satellite galaxies.

These questions constitute the motivations of the present chapter, the aim of which is to explore to what extent we can couple kinematic characteristics and metallicities of stars in the Galactic halo to reconstruct the accretion history of the Milky Way (MW). In particular, we want to understand whether different regions in the $E - L_z$ space with different MDFs should be associated with distinct merger debris. To do so, we analysed the high-resolution self-consistent N-body simulations presented in Chapter 3. They model a MW-type galaxy accreting a satellite with a mass ratio of 1:10, with different orbital parameters and different chemical abundance gradients, which were assigned a posteriori, as described in

Chapter 3.

This chapter presents the results from [Mori et al. \(2024\)](#) in the kinematic spaces complemented by chemical information, which were assigned as described in Ch. 3. The chapter is organised as follows. In the first place, we report the results obtained in the kinematic spaces in Section 4.1. In Section 4.2, we study the metallicity patterns in these spaces, also focussing on simulated local volumes (Section 4.2.1) and exploring different orbital configurations for the merger (Section 4.2.2). Then we analyse MDFs in different regions of the kinematic spaces and report the results in Section 4.3, varying both the volume of the simulations considered (Section 4.3.1) and the orbital parameters (Section 4.3.2). Furthermore, we make a tentative reconstruction of the accretion history of the Galaxy by means of these MDFs in Section 4.4 and analyse the relation between the pre-merger metallicity gradient in the satellite and the one in the kinematic space as a function of energy in Section 4.5. Finally, the discussion and all the conclusions of the analysis are summarised in Section 4.6.

4.1 Resulting kinematic distributions

As far as the kinematic spaces are concerned, we confirm earlier results ([Jean-Baptiste et al., 2017](#); [Grand et al., 2019](#); [Simpson et al., 2019](#); [Koppelman et al., 2020](#); [Panithanpaisal et al., 2021](#); [Amarante et al., 2022](#); [Khoperskov et al., 2023c](#)); that is, energy and angular momentum are not generally conserved quantities for such a significantly massive satellite due to dynamical friction. Moreover, this is independent of the specific orbital inclination of the satellite galaxy relative to the main galaxy disc.

Therefore, a single accretion event can redistribute stars over a large extent of the $E - L_z$ space and these stars are not smoothly redistributed in this space. They form clumps whose number and density depend on the number of passages the satellite has experienced around the MW-type galaxy before complete coalescence and on the mass loss it has experienced at each passage. Hence, one accreted satellite gives rise to several overdensities in the $E - L_z$ space. The stars lost by the satellite in the early phases of its accretion onto the Galaxy tend to redistribute in the upper part of the $E - L_z$ space; that is, at high energies, as shown by Figure 4.1. This is because – to first order – stars are lost with the value of energy of the satellite baricentre, which is the highest at beginning of the interaction, and then diminishes over time as the satellite is dragged through dynamical friction.

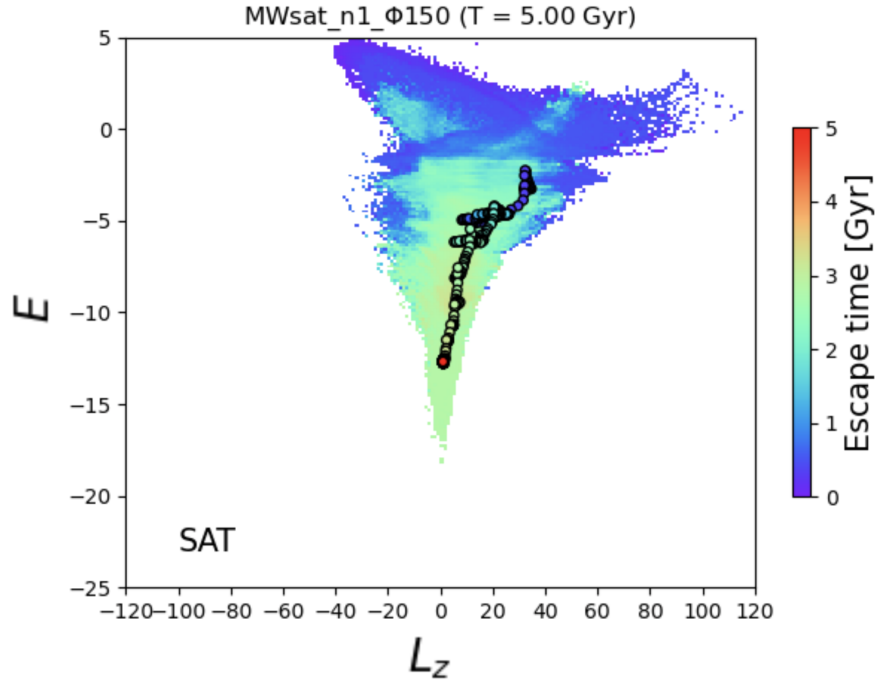


Figure 4.1: Final distribution of the satellite stars in the $E - L_z$ space, colour-coded by their escape time from the satellite potential. The dots represent the mean values of energy and z component of the angular momentum of bound satellite stars, defined by being less than 15 kpc from its barycentre. There are five hundred dots (one for each snapshot of the simulation) and they are colour-coded with the same colour-bar scale but for the time of the simulation (every 10 Myr to cover the 5 Gyr time interval). In this case the initial inclination of the satellite orbital plane was $\phi_{orb} = 150^\circ$. *From: Mori et al. (2024).*

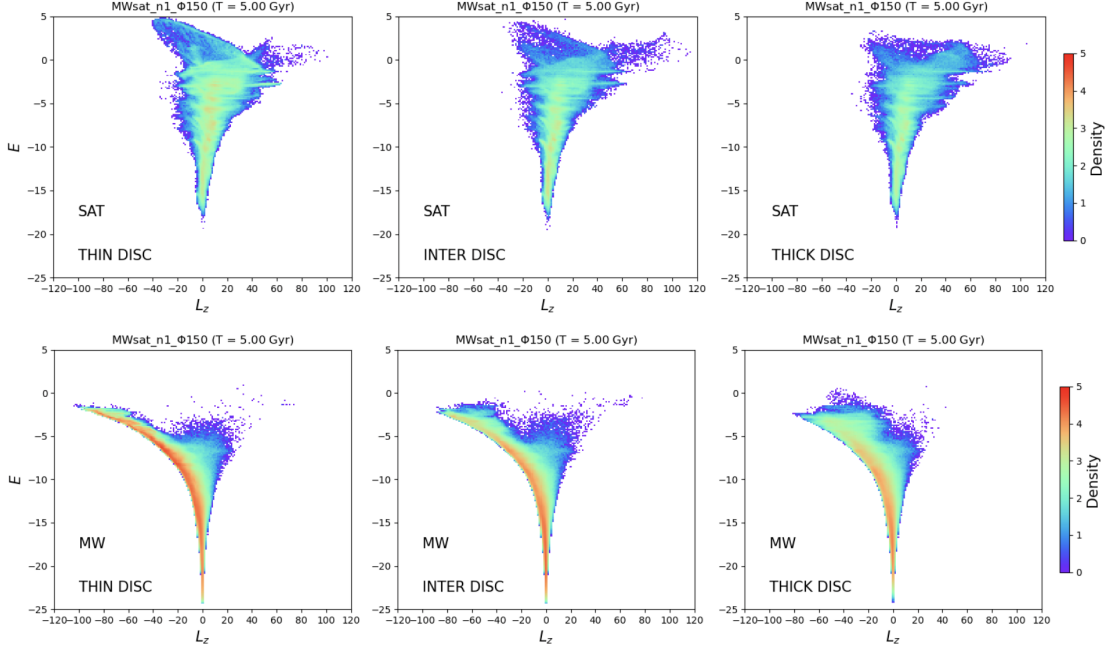


Figure 4.2: Final distributions in the $E - L_z$ space for different disc components (thin, intermediate, and disc components in the first, second, and third columns, respectively), for satellite stars in the first row and in situ stars in the second one. In this case the initial inclination of the satellite orbital plane was $\phi_{orb} = 150^\circ$. From: [Mori et al. \(2024\)](#).

On the other hand, stars that were in the disc of the main galaxy before the accretion are kinematically heated during the interaction, acquiring halo-like kinematics, and thus contributing to the formation of a stellar halo together with accreted stars ([Zolotov et al., 2009](#); [Purcell et al., 2010](#); [Di Matteo et al., 2019](#), and references therein). As a consequence, they redistribute in $E - L_z$ space in a region that partially overlaps with that of accreted stars, as shown by the bottom row of Figure 4.2. In Fig. 4.2, we report the final distribution in the $E - L_z$ space of the satellite (top row) and in situ (bottom row) stars, divided into their disc components: thin, intermediate, and thick disc stars in the first, second, and third columns, respectively.

Since the different disc components have been assigned different metallicity values, these distributions are crucial to interpreting the metallicity patterns and gradients that we will observe at the end in the $E - L_z$ space and which will be described in the next sections.

4.2 Metallicity patterns in kinematic spaces

After assigning the metallicity to the star particles of our simulations (see previous chapter), the first step we took was to study the kinematics-related spaces with this additional information, in order to see where stars with different metallicities would redistribute and to check for a dependence on differences in the initial conditions of the metallicity gradients. We started by analysing the simulation with $\phi_{orb} = 150^\circ$ to show the general trends in the kinematics-related spaces, then we considered different volumes of the simulation to verify the feasibility of this kind of analysis with local observational data (Sec.4.2.1). Finally, we compared it with the outcomes of the other simulations with different orbital parameters (Sec.4.2.2).

In Figure 4.3, we show the distributions in the $E - L_z$ space, since among the different kinematics-related spaces it is the most used one in the literature. They are colour-coded at each point by the mean metallicity of all the overlapping star particles. The different columns of Figure 4.3 correspond to MW-type galaxy (first column), satellite (second one), and total (third one) stellar particles of the simulation. The first row shows the distributions in the $E - L_z$ space of all the star particles of the simulation in the *nograd*¹ case, resulting in both thin discs being more metal-rich than the thick ones on average. The second row shows the $E - L_z$ of the stars in the case of an additional initial radial metallicity gradient. The scales of the colour bars are different depending on which galaxy is considered, in order to make their specific metallicity patterns emerge in a more evident way. For the same purpose, the metallicity colour bar does not cover the whole metallicity range of the metallicity distribution of the star particles of the galaxies of the simulation, but we have considered the percentiles of the distribution and restricted the range of the colour bar to 98% of the metallicity distribution, as done in the rest of this analysis.

As far as the in situ star distribution in the $E - L_z$ space is concerned (top left plot), we can observe where the different disc components of the MW-type galaxy, characterised by different mean metallicities, dominate in the $E - L_z$ space. We can see that the most metal-rich stars (in orange-red) redistribute in the region of pro-grade circular orbits of the thin disc, while the most metal-poor stars (violet-blue) are mainly found in the $E - L_z$ region dominated by the thick disc (see Section 4.1

¹‘*nograd*’ indicates the case in which no radial metallicity gradient is initially present in the main and satellite discs, while ‘*grad*’ denotes the opposite, see Sec. 3.4.

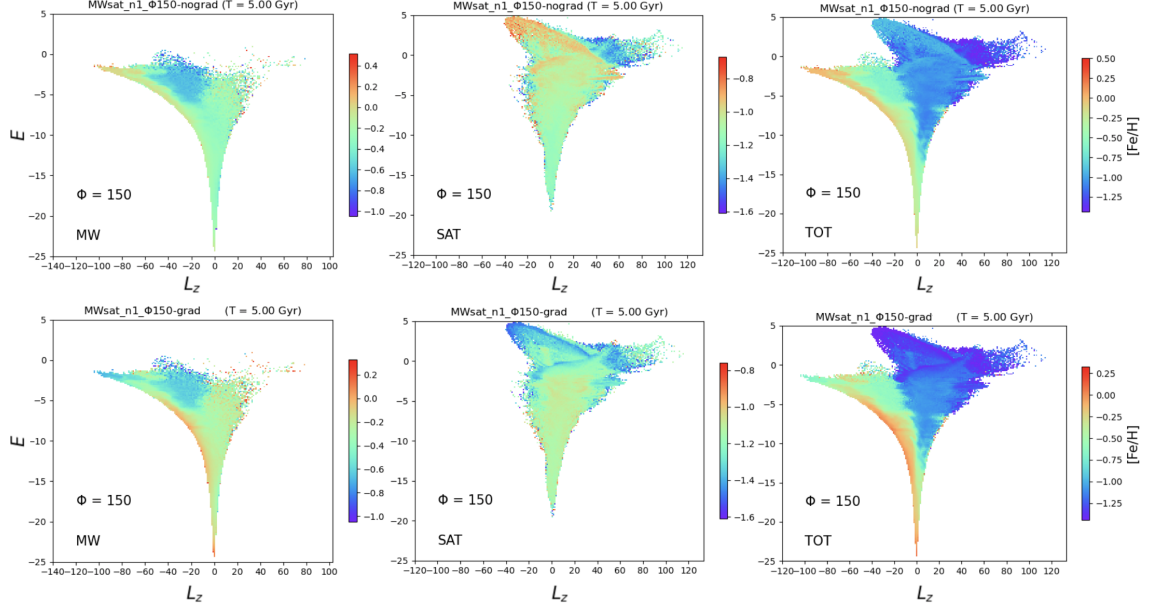


Figure 4.3: $E - L_z$ space of in situ (first column), satellite (second column), and total (third column) star particles in the simulation, colour-coded at each point with the mean metallicity. The first and second rows show the $E - L_z$ space in the case of an initial vertical gradient only and in the case of an additional initial radial metallicity gradient, respectively. The scales of the colour bars are different depending on which galaxy is considered, in order to make their specific metallicity patterns more evident. We also recall that in these plots stars on prograde orbits (which rotate as the disc) have negative L_z , while stars on retrograde orbits have positive L_z . *From: Mori et al. (2024).*

for the distributions of the thin, intermediate, and thick disc stars in the $E - L_z$ space separately).

Regarding the satellite stars' distribution (top middle plot), instead we can notice that there is a region in the upper part of the $E - L_z$ space where the mean metallicity is higher on average. This region is characterised by very high values of energy, and thus is the region populated by the first stars that escape from the satellite during its interaction with the main galaxy, getting bound to the MW-type galaxy potential (Figure 4.1). These stars are those on the outskirts of the satellite thin disc; indeed, since they are at larger (radial) distances from the satellite baricentre, they are less bound by its potential, and thus more inclined to leave it. In the case we are considering now of no radial gradient in the thin disc, but only a negative vertical metallicity gradient, the thin disc stars are the most

metal-rich, which explains the mean metallicity pattern of the satellite distribution in the $E - L_z$ space.

Thus, the existence of an initial metallicity gradient inside the satellite has a consequence in the $E - L_z$ space: different regions show different mean metallicities. We check in the following Section 4.3 how this fact is reflected in the MDFs of the different regions, too, in order to see if in addition to a change in the mean value of the distribution, its shape also changes. Finally, as far as the total stellar distribution is concerned (top right plot), we can observe a strong metallicity gradient in the $E - L_z$ space: metal-rich in-situ stars dominate the low-energy and prograde region of this space, while metal-poor stars mostly lie on the retrograde and high-energy region. In addition to the fact that on average in situ stars are more metal-rich than satellite ones, we can still observe that inside the distribution of these two galaxies there are metallicity gradients, as was described above.

In order to verify whether these results are dependent on differences in the initial metallicity gradient, we have also studied the case of an *additional radial negative gradient in the thin discs of both the satellite and the MW-type galaxy*, with the outskirts of the discs thus being more metal-poor than the inner parts. We report the corresponding results in the second row of Figure 4.3: the MW-type galaxy distribution (left plot) overall resembles the one seen previously in the case of the vertical metallicity gradient only. However, we can notice the effect of having introduced a negative radial gradient too: the region of the $E - L_z$ space populated by the thin disc (towards the edge of the $E - L_z$ distribution, for negative values of L_z) is no longer homogeneously coloured, as it was in the case of the vertical metallicity gradient only, but exhibits a gradient. We can see that the upper regions are more metal-poor than in the previous case. These regions at high energies are indeed populated by stars that initially are less gravitationally bound (i.e. high energies and large distances from the main galaxy centre). On the other hand, the low-energy regions are more metal-rich than before, because the populations that are initially more gravitationally bound (and more metal-rich) are also closer to the galaxy centres. As far as the satellite distribution is concerned (middle plot), we can again observe the signatures of the choice made for the initial metallicity gradient: the upper region that in the previous case was populated by the most metal-rich stars is now conversely populated by the most metal-poor ones. This is clearly a direct consequence of assigning a radial metallicity gradient to satellite disc stars. Finally, regarding the total distribution (right plot), we can again observe

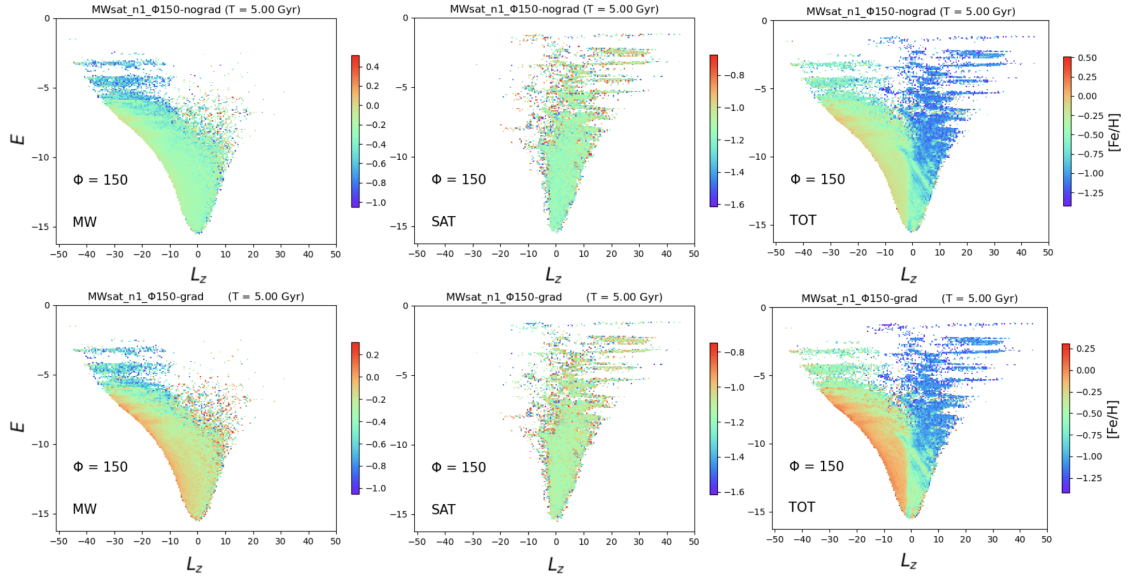


Figure 4.4: $E - L_z$ space of in situ (first column), satellite (second column), and total (third column) star particles in the simulation, colour-coded at each point with the mean metallicity, when the analysis is restricted to a solar-like volume. The first row shows the $E - L_z$ space in the case of an initial vertical metallicity gradient only. Likewise, the second row shows it, but in the case of an additional initial radial metallicity gradient. The scales of the colour bars are different depending on which galaxy is considered, in order to make their specific metallicity patterns emerge in a more evident way. We recall that in these plots stars on prograde orbits (which rotate as the disc) have negative L_z , while stars on retrograde orbits have positive L_z . *From: Mori et al. (2024).*

an overall metallicity gradient. This gradient is even stronger than in the previous case (see Section 4.5), and sub-gradients are still visible in the stars previously belonging to the two accreted galaxies.

4.2.1 Solar-like volume

To check for the feasibility of detecting accreted structures in the $E - L_z$ space with local data, we restricted our analysis to a ‘solar-vicinity’ or a ‘solar-like volume’. This volume was located at 8 kpc from the MW-type galaxy centre and defined as a sphere with a radius of 5 kpc. This is the size around the Sun for which we currently have accurate-enough parallaxes, proper motions, and line-of-sight velocities. In order to take into account the fact that accreted stars do not necessarily redistribute

uniformly, we considered several different volumes homogeneously distributed in the azimuth position of the centre: $\phi_{\odot} = 0^{\circ}, 90^{\circ}, 180^{\circ}, 270^{\circ}$ (in cylindrical coordinates). In the following analysis, we show the results for the $\phi_{\odot} = 0^{\circ}$ case, which are valid for all the other volumes examined. Figure 4.4 shows the final distributions in the $E - L_z$ space when the solar-like volume is considered, colour-coded at each point with the mean metallicity.

The right-most panels of Figure 4.4 shows that the solar vicinity volume exhibits the same overall trends found for the entire galactic volume. We find a metal-poor population on retrograde or null L_z orbits, and a more metal-rich populations on prograde orbits (negative L_z). This trend holds for both metallicity gradient cases. Furthermore, it is interesting to notice how a retrograde single-merger event can produce a Sequoia-like debris, which corresponds to the outer parts of its GSE-like progenitor. However, when the analysis is restricted to 5 kpc around the Sun, we can no longer capture the very metal-rich (metal-poor) satellite stars found at very high energies (see, for example, the orange (blue) colour in the middle panel of the top (bottom) row of Figure 4.3).

This implies that the MDF of the GSE may still exhibit biases, particularly in the absence of observations for the most metal-rich (metal-poor) stars (consistently with the results of Carrillo et al., 2024). This limitation could potentially be addressed more comprehensively with upcoming surveys such as SDSSV, 4MOST, WEAVE or, more promisingly, with MOONS. The former surveys will allow us to get a more complete sample of the accreted stars now bound to the MW, but outside the solar-like volume that we defined. On the other hand, MOONS will survey the bulge of the Galaxy (Gonzalez et al., 2020), allowing us to explore the eventual accreted populations in the innermost regions of the MW and check for differences in the metallicity distributions with respect to those in the solar neighbourhood.

4.2.2 Exploring different orbital inclinations

In order to check the dependence of our results on the satellite orbital parameters, we analysed the star distributions in all the previous spaces (colour-coded at each point with the mean metallicity) for all the other simulations with a different initial inclination of the satellite orbital plane with respect to the MW-type galaxy, $\phi_{orb} = 0^{\circ}, 30^{\circ}, 60^{\circ}, 90^{\circ}, 120^{\circ}, 150^{\circ}, 180^{\circ}$. To seek a synthesis, in the following we only report the results for the $E - L_z$ space for the extreme configurations $\phi_{orb} = 0^{\circ}, 90^{\circ}, 180^{\circ}$. In Figure 4.5, we show the final distributions in the $E - L_z$ space colour-coded at each point with the mean metallicity for the total volume of the simulations, with

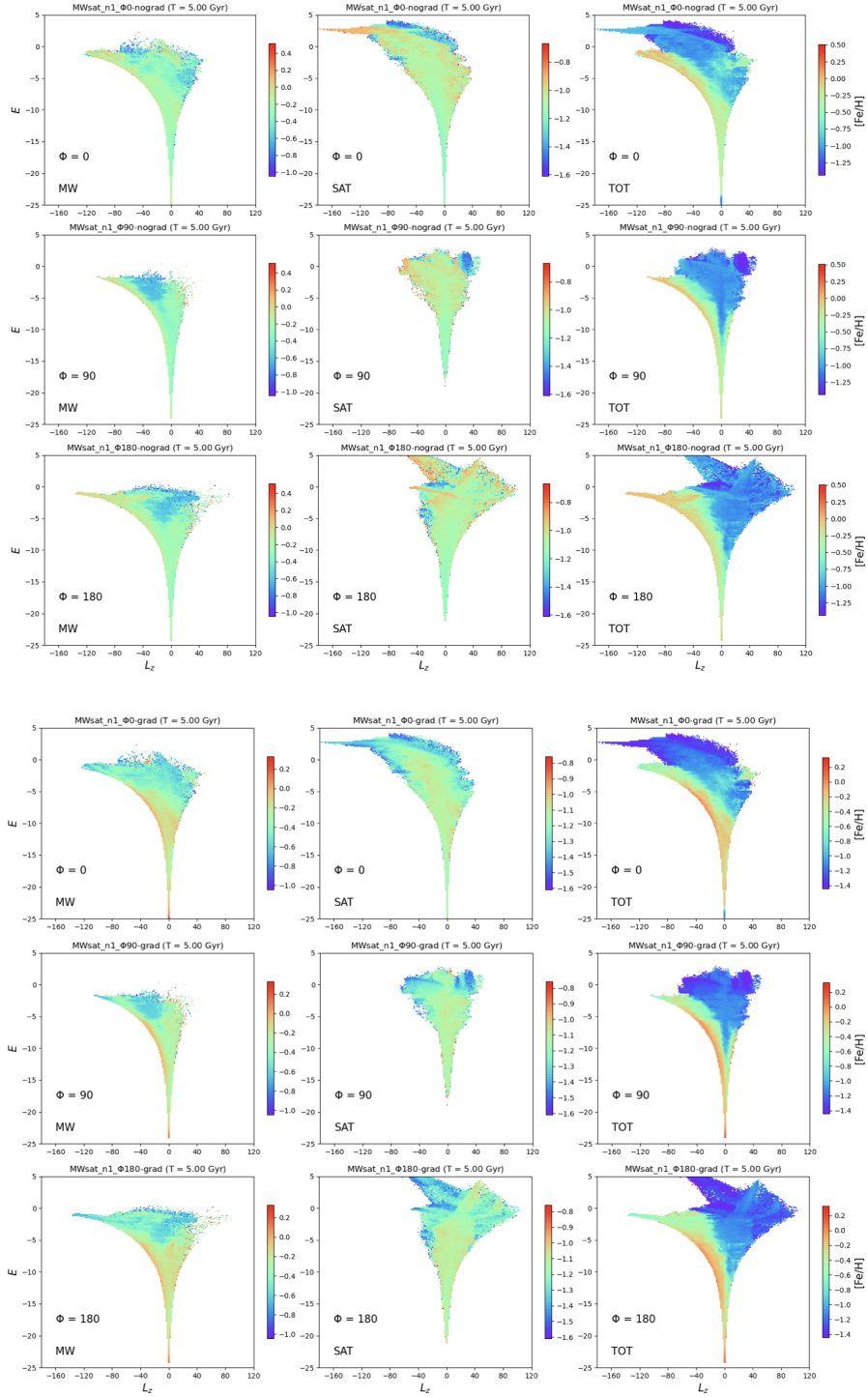


Figure 4.5: $E - L_z$ spaces of the in situ (first column), satellite (second column), and total (third column) star particles in the simulation, colour-coded at each point with the mean metallicity. Each row shows a simulation with a different value of the initial inclination of the satellite orbital plane: $\phi_{orb} = 0^\circ, 90^\circ, 180^\circ$. The upper (lower) panel is for *nograd* (*grad*) case. From: [Mori et al. \(2024\)](#).

$\phi_{orb} = 0^\circ, 90^\circ, 180^\circ$ in different rows, for the in situ (first column), satellite (second column), and total (third column) star particles.

The top panel of Figure 4.5 shows the distributions in the case of an initial vertical metallicity gradient only. The in situ distributions are all very similar. The satellite distributions, instead, show a dependence on the orbital parameter, ϕ_{orb} , with: (i) more metal-poor stars on prograde orbits (negative values of L_z) at high energies for initial prograde orbits of the satellite, and (ii) more on retrograde orbits at high energies for initial retrograde orbits of the satellite. In any case, the most metal-rich stars are those of the thin disc, lost early and at high values of energy. These two features can be observed in the total distribution, which shows different regions dominated by metal-poor stars, depending on the initial satellite orbital properties.

In the bottom panel of Figure 4.5, we show the same distributions in the case of an additional initial radial metallicity gradient. The in situ distributions are all very similar, this time showing the radial metallicity gradient in the region of the circular prograde orbits (thin disc). As far as the satellite distributions are concerned, unlike before, the most metal-poor stars are the ones of the thin disc, lost at low values of time and high values of energy. The distributions of satellite stars still show a dependence on the orbital parameter, ϕ_{orb} , with more metal-poor stars on prograde orbits (negative values of L_z) at high energies for initial prograde orbits of the satellite and more on retrograde orbits at high energies for initial retrograde orbits of the satellite. Again, this can be appreciated in the total distribution, which shows different regions dominated by metal-poor stars, depending on the initial satellite orbital properties.

This dependence could be useful to characterise the orbital parameters of the accretion events experienced by the MW. However, this can be challenging if the analysis is restricted to a volume of a few kiloparsecs in radius around the Sun (as the case with many spectroscopic surveys). When we restrict the analysis to the solar-like volume, indeed, the final distributions in the $E - L_z$ space all become very similar to one another, losing the dependence of the metallicity pattern on the ϕ_{orb} parameter, since the differences in the final distribution considering the whole volume are due to satellite stars deposited at high energy values, which do not reach the solar vicinity.

As was mentioned above, the mean metallicity throughout the $E - L_z$ space for bound regions does not depend strongly on the orbital parameters of the accretion

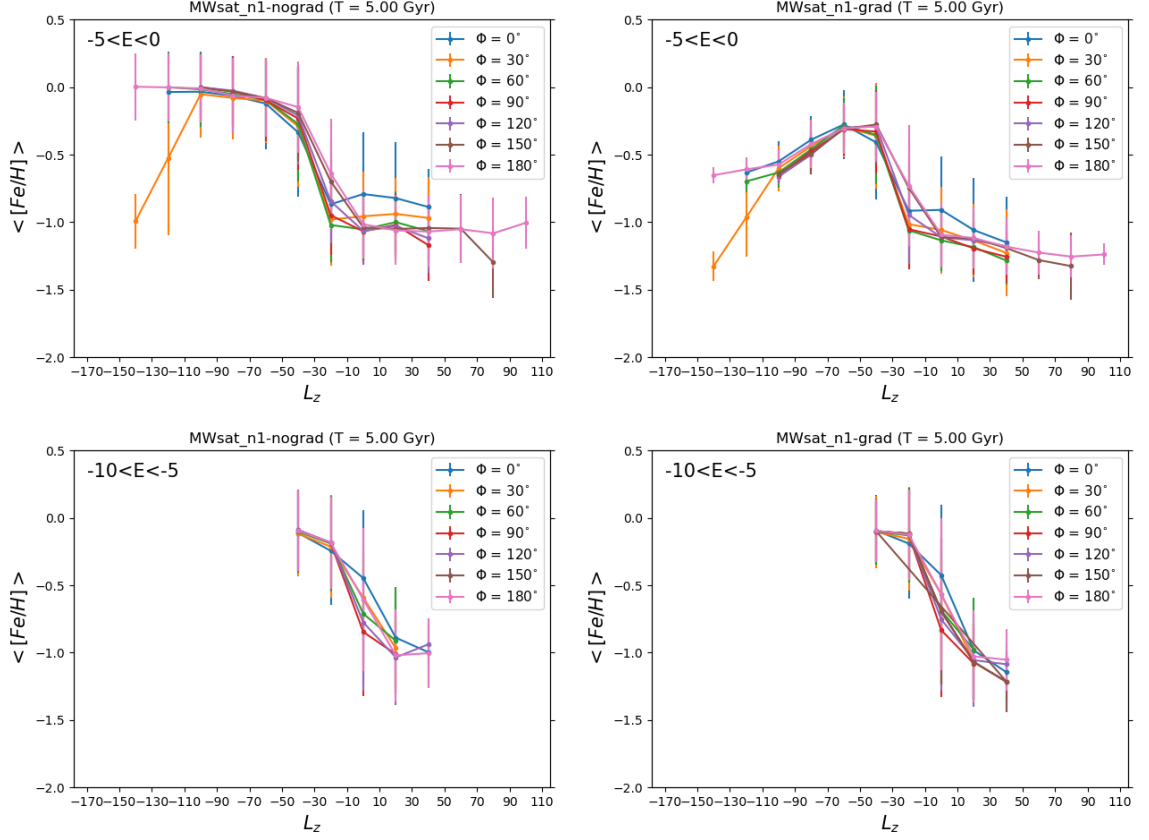


Figure 4.6: Mean metallicity and standard deviation as a function of the angular momentum interval of the $E - L_z$ space (in every column of Figures 4.7, 4.10) for all the simulations with $\Phi = 0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ, 180^\circ$, in the energy range $-5 < E < 0$. The left panel shows the case with the initial vertical metallicity gradient only, while the right panel shows the one with the additional radial metallicity gradient. *From: Mori et al. (2024).*

event. More quantitatively, we show in the upper row of Figure 4.6 the mean metallicity (and standard deviation) in the energy interval $-5 < E < 0$ as a function of the angular momentum for all the possible initial values of the inclination of the satellite orbital plane (different colours) and for both the *nograd* case (left panels) and the *grad* case (right).

We can see a dependence on the initial conditions assumed for the metallicity distribution of the satellite. In fact, both the left and right panels show a knee at approximately null angular momentum and then a plateau at low metallicity at more retrograde L_z values (more positive). However, the *nograd* case also features a plateau at high metallicity and at prograde angular momentum values (negative L_z), whereas the *grad* case shows a decreasing mean metallicity value the more prograde the orbit. In the lower row of Figure 4.6, we also show the same plots in the energy interval $-10 < E < -5$ for a comparison.

4.3 MDFs in different regions of the $E - L_z$ space

After discussing the variation in the mean metallicity across the $E - L_z$ space, the next step was to analyse the variation in the MDFs. The interest in looking at the MDF is due to the fact that all of the previous plots show the average metallicity in a given region of the $E - L_z$ plane, while the MDF can provide more insight into the population(s) which contribute(s) to a given average value. As before, to start off, we show the results for the simulation with an initial inclination of the satellite orbital plane with respect to the MW-type galaxy disc, ϕ_{orb} , equal to 150° . The results concerning the simulations with direct, polar, and retrograde orbits ($\phi_{orb} = 0^\circ, 90^\circ, 180^\circ$) are reported in the Section 4.3.2.

$\downarrow E; L_z \rightarrow$	$(-50, -30)$	$(-30, -10)$	$(-10, 10)$	$(10, 30)$	$(30, 50)$	$(50, 70)$
(0,5)	0.99	1.00	1.00	1.00	1.00	1.00
(-5,0)	-	0.21	0.99	1.00	1.00	1.00
(-10,-5)	-	0.00	0.53	0.96	0.99	-
(-15,-10)	-	-	0.08	0.8	-	-
(-20,-15)	-	-	0.02	-	-	-

Tabella 4.1: Fraction of satellite stars with respect to total in red cells of Fig. 4.7.

In order to analyse the MDFs in different regions of the $E - L_z$ space, we divided this space into rectangles 20×10^2 kpc km/s wide in angular momentum and 5×10^4 km² s⁻² high in energy, so as to reproduce the average dimensions

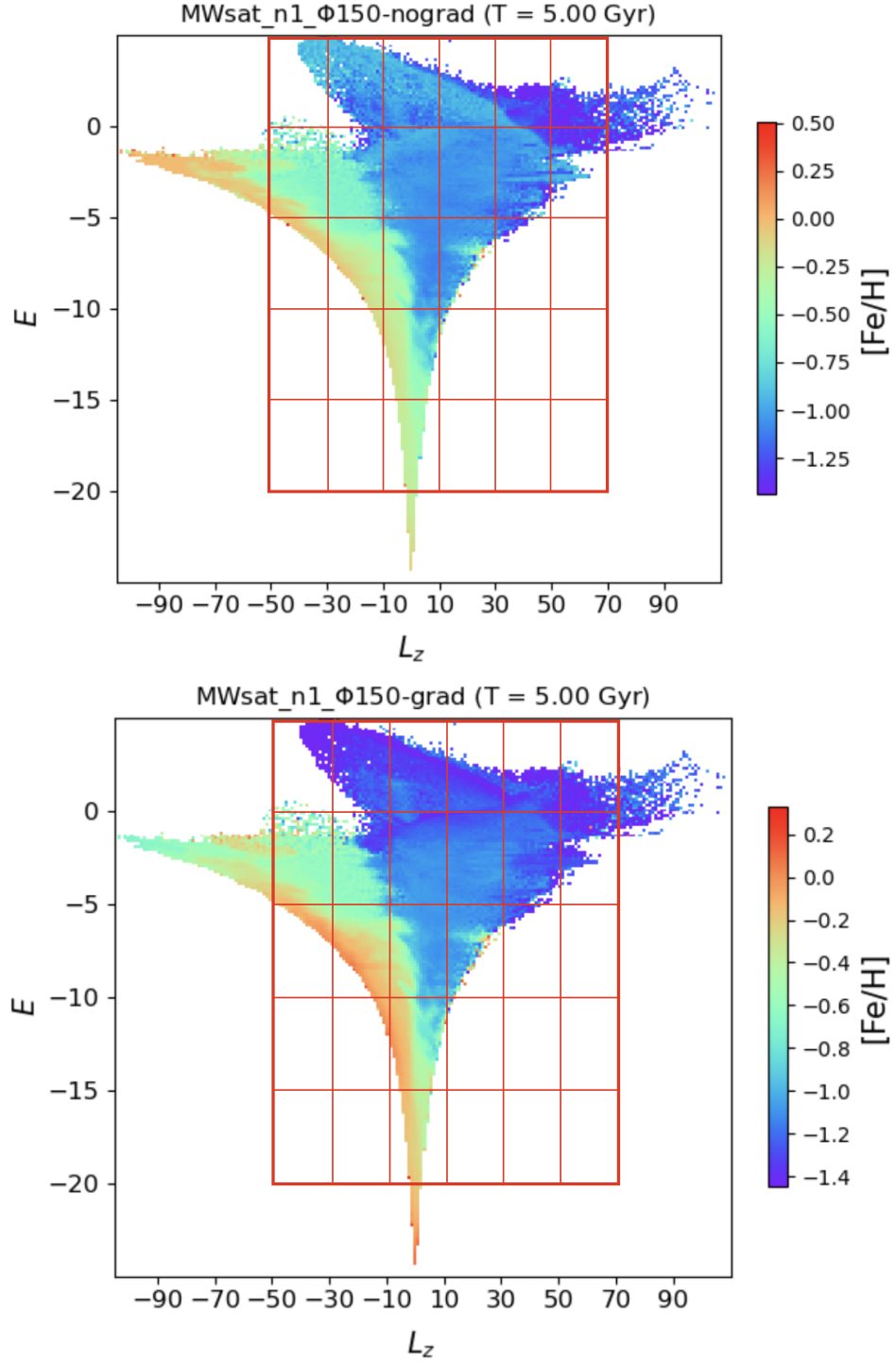


Figure 4.7: Total star distribution in the $E - L_z$ space in the case of an initial vertical metallicity gradient only (upper panel) and an additional initial radial metallicity gradient (lower panel), colour-coded at each point with the mean metallicity. The superimposed grid shows the splitting of the space used to analyse the MDFs in different regions. *From: Mori et al. (2024).*

of the substructures found so far in the $E - L_z$ space. The splitting is shown in Figure 4.7. In Figure 4.8, we show the resulting MDFs for different regions of the $E - L_z$ space contained in the large red rectangle of Figure 4.7. In this way, different rows show the MDFs for a fixed value of energy (increasing in the bottom-up direction), while different columns show the MDFs for a fixed value of angular momentum (increasing in the left-right direction). The angular momentum and energy intervals are reported in every cell, together with the number of in situ and accreted stars, in red and blue, respectively. Every plot then shows the MDF considering all the stars in the region (in black), the MDF of the MW-type stars only (in red), and the MDF of the satellite stars only (in blue), all normalised in order to compare means, peaks, and shapes. The solid lines show the mean of the distribution, while the dotted ones show its peak(s). The fractions of satellite stars in the different $E - L_z$ regions, as well as the mean values of the total MDFs, in the two cases (*nograd* and *grad*) explored in this paper, are reported in Tables 4.1, 4.2 and 4.3, respectively.

We start with the case of the vertical metallicity gradient only. The $E - L_z$ space has been divided, as described above and as shown in the top panel of Figure 4.7. Starting from the bottom row of Figure 4.8, the lowest energy interval considered ($-10 \leq L_z \leq 10, -20 \leq E \leq -15$), the global MDF in black of both accreted and in situ stars almost coincides with that of in situ stars only, since they dominate this region (see Figure 3.2). The central rectangle of the following row ($-15 \leq E \leq -10$) is still dominated by in situ stars, but now the total MDF shows a bump at low metallicity ($[\text{Fe}/\text{H}] \sim -1.2$) due to satellite stars. So far, satellite MDFs are all very similar one to each other, resembling the total satellite MDF (see Figure 3.2): there is a single-peaked distribution (at $[\text{Fe}/\text{H}] \sim -1.2$), with a bump at higher metallicities. The following row ($-10 \leq E \leq -5$) instead shows some differences. The satellite MDF starts to peak at higher metallicities (at $[\text{Fe}/\text{H}] \sim -1$) in the central region with $L_z \sim 0$, due to the fact that a larger fraction of satellite metal-rich stars are found at higher energies as they escape the satellite at earlier times. Moreover, we observe a broader distribution in the region with $-10 \leq L_z \leq 10$ and a region in which the MDF is double-peaked ($10 \leq L_z \leq 30$), even if the initial total MDF of the satellite was not. We also see that the total MDF in regions with stars on more retrograde orbits has significant contributions from the satellite stars at low metallicities. As a consequence, its mean is shifted towards lower metallicities while moving towards more retrograde orbits (more positive values of L_z), but also towards higher energies, where satellite stars represent a higher fraction of

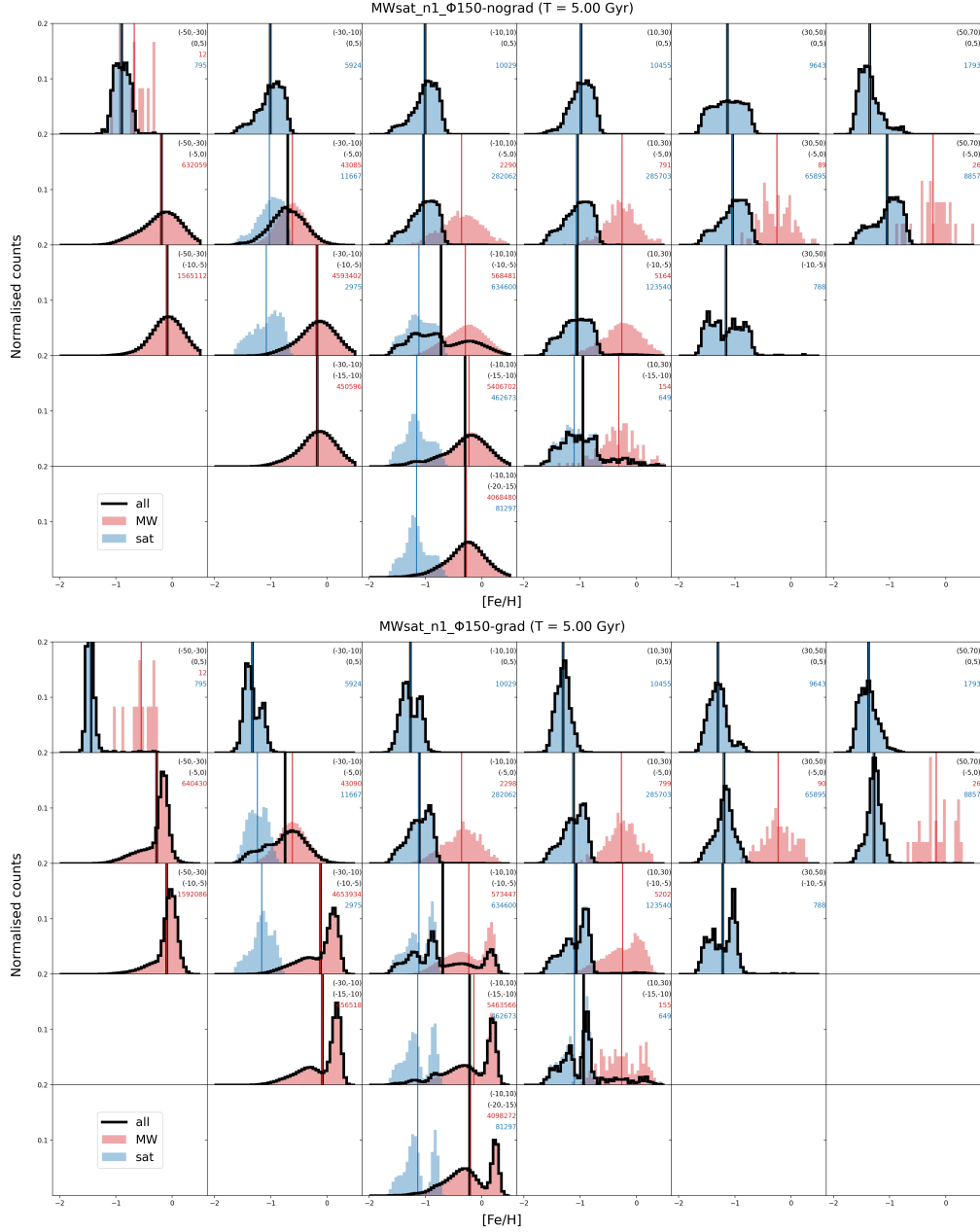


Figure 4.8: MDFs of different regions of the $E - L_z$, in the *nograd* case (top panel) and in the *grad* one (bottom panel). The red, blue, and black histograms show the MW-type galaxy, satellite, and total MDF, respectively, all normalised. The solid lines show the mean of the distribution. Energy intervals row by row (top to bottom): i) $0 < E < 5$, ii) $-5 < E < 0$, iii) $-10 < E < -5$, iv) $-15 < E < -10$, v) $-20 < E < -15$. Angular momentum intervals column by column (left to right): i) $-50 < L_z < -30$, ii) $-30 < L_z < -10$, iii) $-10 < L_z < 10$, iv) $10 < L_z < 30$, v) $30 < L_z < 50$, vi) $50 < L_z < 70$. The red (blue) number shows the amount of in situ (accreted) stars in every cell. *From: Mori et al. (2024).*

the total (see Table 4.1). We can observe all these features in the least bound row ($-5 \leq E \leq 0$), where the distributions are broader and peaked at lower metallicities as we move towards more retrograde star orbits (positive L_z). In particular, the right-most plot of the figure, which contains the stars with the highest energies and most retrograde orbits, is the one where the MDF peaks at the lowest metallicities; that is, at $[\text{Fe}/\text{H}] \sim -1.5$. For completeness, we also report the unbound energy interval $0 < E < 5$, even if these stars end up several hundreds kiloparsecs away from the main galaxy centre. This region exhibits the same trend: the mean total MDF decreases with increasing orbital retrograde motion (see Tables 4.2 and 4.3).

We now discuss the results in the case of an additional initial radial metallicity gradient, both in the satellite and in the MW-type galaxy. We recall that the introduction of the radial gradient makes the MDFs of both the MW-type galaxy and the satellite double-peaked (see Figure 3.2). The highest peak is due to the thin disc component and the second to the intermediate and thick disc components together (see the top panel of Figure 4.9, where we show the MDFs of the various disc components in different colours.) The in situ MDF peaks are at $[\text{Fe}/\text{H}] \sim 0.2$ and at $[\text{Fe}/\text{H}] \sim -0.2$, while the satellite MDFs are at $[\text{Fe}/\text{H}] \sim -0.9$ and $[\text{Fe}/\text{H}] \sim -1.2$. We were interested, then, in checking if we recover these features in the MDF restricted to different regions of the $E - L_z$ space. We proceeded in the same way as the previous case, so the $E - L_z$ space was divided as before and as shown in the lower panel of Figure 4.7. In the bottom row of Figure 4.8, we illustrate the MDFs in the $E - L_z$ space with $E \leq -15$. We can see that the MDF of the single galaxies, the MW-type galaxy (in red) and the satellite (in blue), are usually quite representative of the total initial ones, being bimodal and peaked at the initial positions in metallicities. Nevertheless, considering higher energy intervals ($-15 \leq E \leq -10$ and $-10 \leq E \leq -5$), the total MDF (in black) already starts to change, reflecting the increasing relative importance of the satellite contribution, and thus beginning to show bumps at lower metallicities and means more shifted towards lower metallicities too. This trend is hence independent of the choice of initial conditions for the metallicity gradient, but is mostly due to the fact that regions of higher energies and more retrograde angular momentum are more dominated by satellite stars (see Table 4.1), which are on average more metal-poor. In the regions with the highest energies (bound and not, $-5 \leq E \leq 0$ and $0 \leq E \leq 5$), we can see that the satellite MDFs change a lot in shape and mean, becoming broader, losing bimodality, and being on average at lower metallicities. Once again, the total MDF always coincides more with the satellite one, moving

$\downarrow E; L_z \rightarrow$	$(-50, -30)$	$(-30, -10)$	$(-10, 10)$	$(10, 30)$	$(30, 50)$	$(50, 70)$
$(0, 5)$	-0.90	-1.01	-1.01	-0.99	-1.13	-1.36
$(-5, 0)$	-0.19	-0.69	-1.04	-1.05	-1.04	-1.05
$(-10, -5)$	-0.09	-0.18	-0.72	-1.06	-1.16	-
$(-15, -10)$	-	-0.17	-0.29	-0.96	-	-
$(-20, -15)$	-	-	-0.29	-	-	-

Tabella 4.2: Mean value of the metallicity distribution of all the stars for every cell of the top panel of Figure 4.7 (*nograd* case).

$\downarrow E; L_z \rightarrow$	$(-50, -30)$	$(-30, -10)$	$(-10, 10)$	$(10, 30)$	$(30, 50)$	$(50, 70)$
$(0, 5)$	-1.45	-1.33	-1.27	-1.31	-1.31	-1.38
$(-5, 0)$	-0.28	-0.74	-1.11	-1.12	-1.19	-1.28
$(-10, -5)$	-0.09	-0.12	-0.69	-1.07	-1.22	-
$(-15, -10)$	-	-0.08	-0.22	-0.95	-	-
$(-20, -15)$	-	-	-0.21	-	-	-

Tabella 4.3: Mean value of the metallicity distribution of all the stars for every cell of the bottom panel of Figure 4.7 (*grad* case).

towards higher energies and more retrograde orbits, and thus changing a lot in mean towards lower metallicities.

We can conclude that, independently of the initial choice of metallicity gradient, the MDFs of satellite stars can vary significantly across the $E - L_z$ space, both in shape, as well as in mean, and peak values, even if these MDFs all result from the same accretion event. Therefore, different regions of the $E - L_z$ space showing different kinematic and MDFs can actually be associated with the same single original accreted satellite, making the $E - L_z$ very hard to interpret. Nevertheless, we have found trends in the MDFs' varying E and L_z values. In particular, we have shown that the mean and the peak(s) of the global MDF of both accreted and in situ stars move towards lower metallicities for higher values of E and L_z (i.e. for more retrograde orbits). This is a consequence of the increasing importance of the more metal-poor satellite contribution in stellar density.

4.3.1 Global versus local MDFs

So far, we have shown MDFs estimated over the full galactic extent, in the ideal case – as in a simulation – in which all stars (or stellar particles) in the galaxy can be observed. In reality, spectroscopic surveys provide chemical abundances over

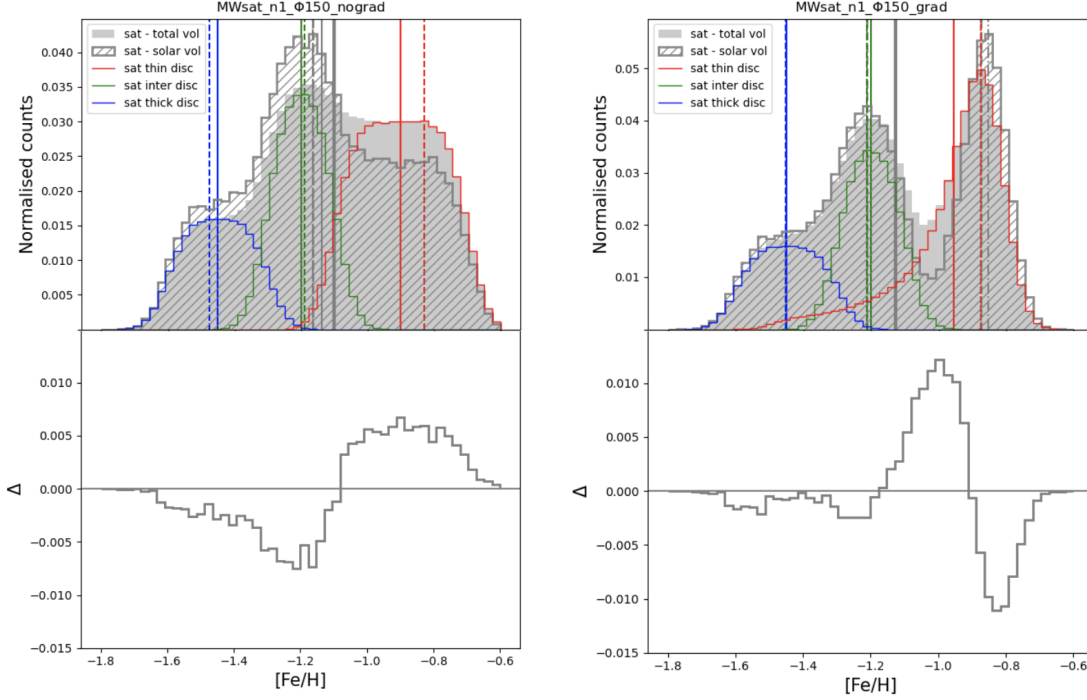


Figure 4.9: Top panels: MDF of the satellite stars (in filled blue) and the same MDF restricted to the satellite stars that reach a solar-like volume by the end of the simulation (in patterned blue). The solid lines are the means of the distributions (broader for the total distribution, thinner for the solar one). The dashed (dash-dotted) lines are the peak(s) of the total (solar) distribution. The satellite MDF divided into disc components is shown by the red, green, and blue curves for the thin, intermediate, and thick discs, respectively. Bottom panel: Difference between the two normalised distributions in the top panel (Δ), i.e. the total distribution minus the solar-like restricted one. The left column shows the case with the vertical metallicity gradient only, and the right column the one with the additional radial metallicity gradient. *From: Mori et al. (2024).*

a limited volume around the Sun. It is thus interesting to understand to what extent ‘local’ MDFs can be representative of the global one. A key consideration is whether we can select a pure, accreted stellar sample within a few kiloparsecs of the Sun whose MDF is representative of the entire accreted system.

We recall that we defined the ‘solar-vicinity’ as a spherical volume centred at 8 kpc from the MW-type galaxy centre and with a radius of 5 kpc. The top panels of Figure 4.9 show the MDF for all stars in the satellite (filled gray). For comparison,

the patterned gray distribution shows the MDF for only those stars located within a solar-like volume at the end of the simulation. Both the cases with and without an initial radial metallicity gradient in the satellite are shown (right and left panels, respectively). In both cases, the global shape of the MDF is conserved, and the metallicity range is also preserved.

The bottom panels of Figure 4.9 show Δ , the difference between the two normalised distributions. We can see that in the *nograd* case there is an under-representation of high-metallicity stars (i.e. stars with $[\text{Fe}/\text{H}] \geq -1.1$), while in the *grad* case there is a deeper drop at $[\text{Fe}/\text{H}] \sim -1.0$.

By way of a comparison with the MDFs of the single disc components (thick, intermediate, and thin ones in red, green, and blue, respectively, in the top panel), we can associate the under-representation with missing thin disc stars; that is, with stars initially on the outskirts of the satellite that are lost in the early phases of the accretion, and that are deposited at energies too high to be sampled in the solar vicinity. Depending on the metallicity that these stars initially have, this will give rise to an under-representation of these metallicities in local MDFs.

4.3.2 MDFs across the $E - L_z$ space for different ϕ_{orb}

We then wanted to check the dependence of the results concerning the MDF analysis on the orbital parameter, ϕ_{orb} ; that is, the initial inclination of the satellite orbital plane. We considered three more cases for a planar, polar, and retrograde orbit, $\phi_{orb} = 0^\circ, 90^\circ, 180^\circ$, and we performed the same analysis made in the $\phi_{orb} = 150^\circ$ case (described in Section 4.3).

In Figure 4.10, we show the final total distribution in the $E - L_z$ plane coloured by the mean metallicity at each point (described in Section 4.2), in which the different columns correspond to $\phi_{orb} = 0^\circ, 90^\circ, 180^\circ$ and the two different rows correspond to the *nograd* and *grad* cases, respectively. The grid shows the splitting of the $E - L_z$ regions in which we analysed the MDFs, and the red rectangles indicate the ones reported in the following Figures, 4.11, 4.12, and 4.13.

Every panel of Figures, 4.11, 4.12, and 4.13 then shows the MDF, considering all the stars in the region (in black), the MDF of the MW-type stars only (in red), and the MDF for the satellite stars only (in blue), all normalised in order to compare means, peaks, and shapes. The solid lines show the mean of the distribution.

In all these figures, different rows show the MDFs for a fixed interval of energy, which from top to bottom are: i) $0 < E < 5$, ii) $-5 < E < 0$, iii) $-10 < E < -5$, iv) $-15 < E < -10$, and v) $-20 < E < -15$.

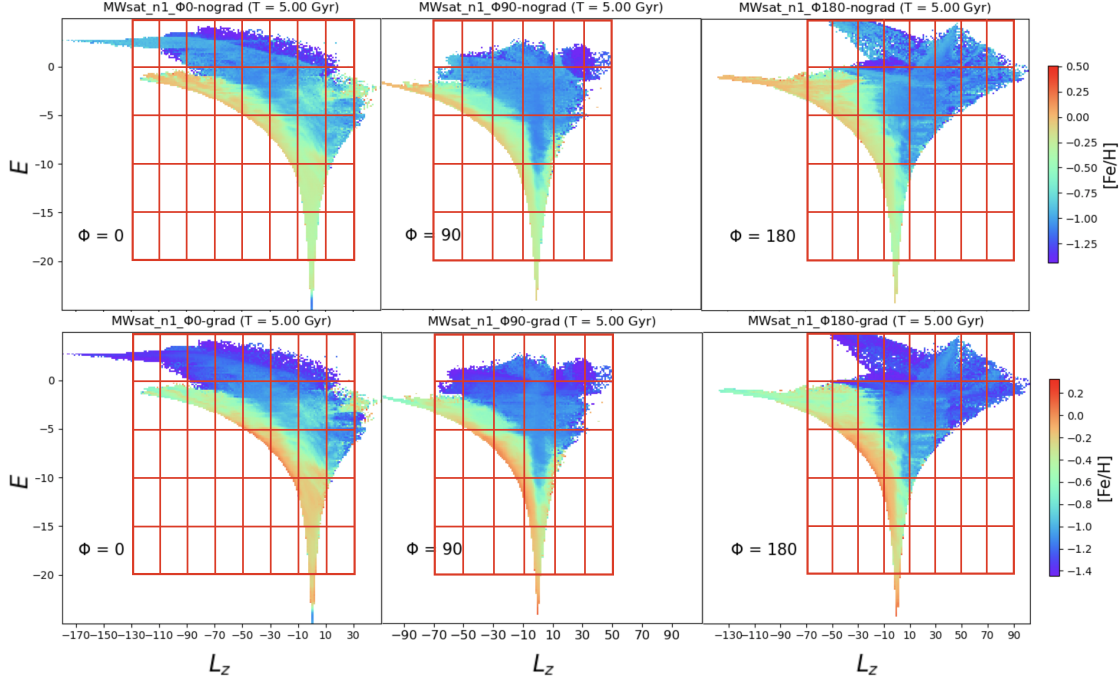


Figure 4.10: Same as Figure 4.7, but for the case of $\phi_{orb} = 0^\circ, 90^\circ, 180^\circ$ in the first, second, and third columns, respectively. The first row shows the case of an initial vertical metallicity gradient only and the second row that with an additional initial radial metallicity gradient. *From: Mori et al. (2024).*

The different columns, on the other hand, show the MDFs for a fixed interval of angular momentum (increasing from left to right).

The angular momentum intervals, column by column, are, from left to right: for Figure 4.11, i) $-130 < L_z < -110$, ii) $-110 < L_z < -90$, iii) $-90 < L_z < -70$, iv) $-70 < L_z < -50$, v) $-50 < L_z < -30$, vi) $-30 < L_z < -10$, vii) $-10 < L_z < 10$, and viii) $10 < L_z < 30$; for Figure 4.12, i) $-70 < L_z < -50$, ii) $-50 < L_z < -30$, iii) $-30 < L_z < -10$, iv) $-10 < L_z < 10$, and v) $10 < L_z < 30$, vi) $30 < L_z < 50$; and for Figure 4.13, i) $-70 < L_z < -50$, ii) $-50 < L_z < -30$, iii) $-30 < L_z < -10$, iv) $-10 < L_z < 10$, v) $10 < L_z < 30$, vi) $30 < L_z < 50$, vii) $50 < L_z < 70$, and viii) $70 < L_z < 90$.

The aim is to analyse the MDF in different regions of the $E - L_z$ space, in order to find any trend in their means, peaks, and overall shape as a function of the region considered; for instance, fixing the value of the energy and varying the one of the angular momentum, and vice versa. All the simulations show a lower value of mean metallicity the higher the energy.

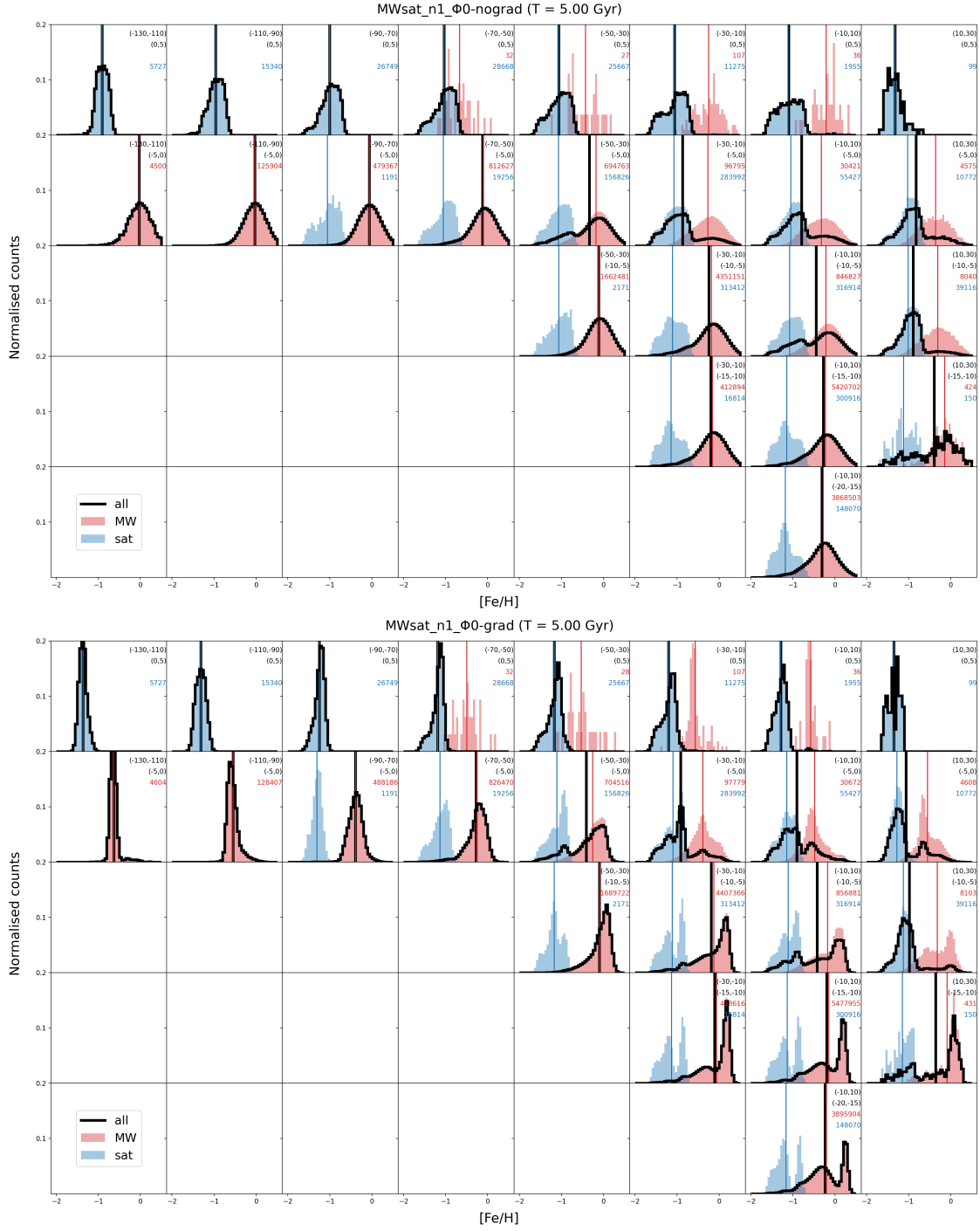


Figure 4.11: Same as Figure 4.8, but for the case of $\phi_{orb} = 0^\circ$. The upper panel shows the case of an initial vertical metallicity gradient only and the lower panel the one with an additional initial radial metallicity gradient. *From: Mori et al. (2024).*

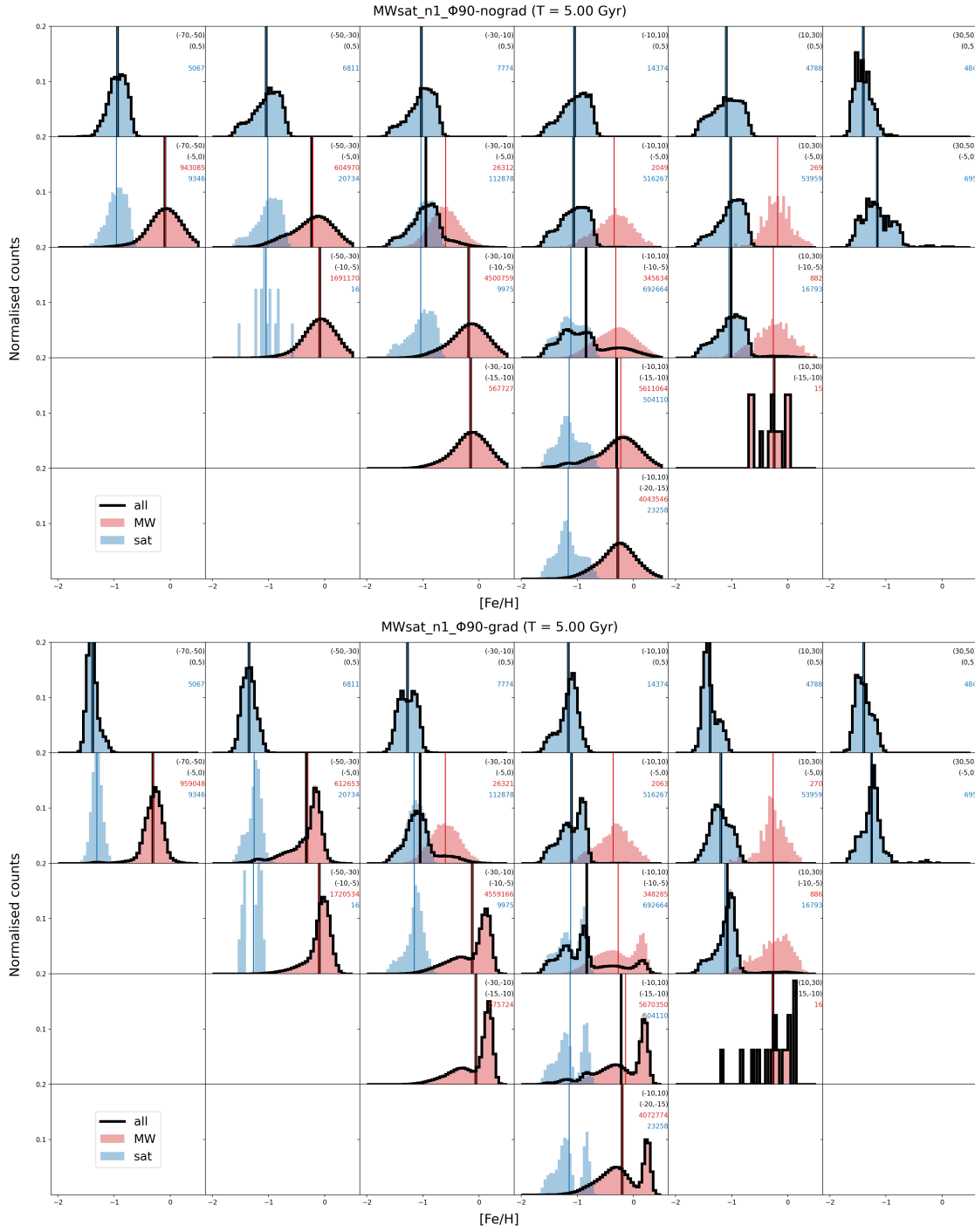


Figure 4.12: Same as Figure 4.8, but for the case of $\phi_{orb} = 90^\circ$. The upper panel shows the case of an initial vertical metallicity gradient only and the lower panel the one with an additional initial radial metallicity gradient. *From: Mori et al. (2024).*

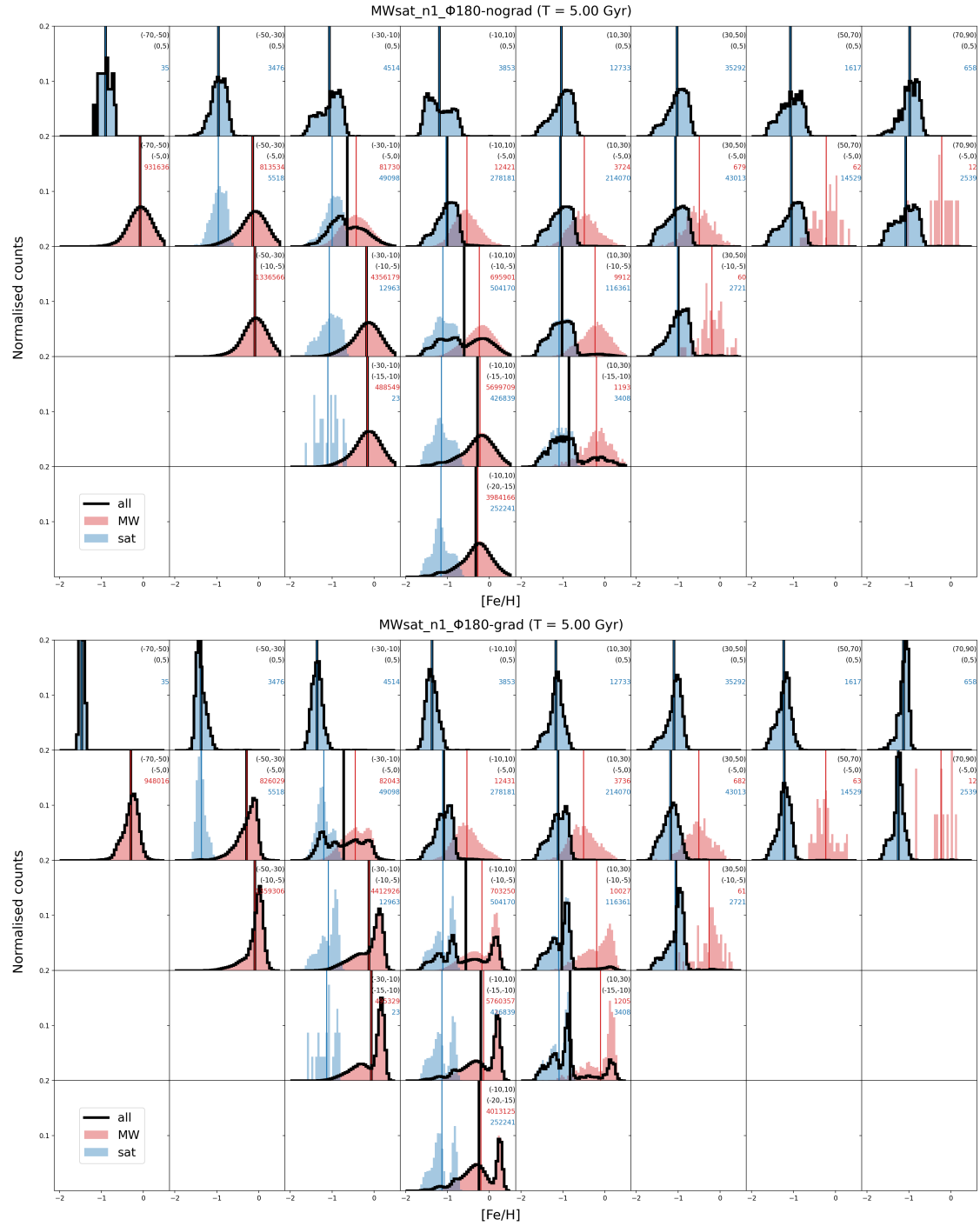


Figure 4.13: Same as Figure 4.8, but for the case of $\phi_{orb} = 180^\circ$. The upper panel shows the case of an initial vertical metallicity gradient only and the lower panel the one with an additional initial radial metallicity gradient. *From: Mori et al. (2024).*

4.4 Do the MDFs trace the accretion history?

The results discussed in the previous section can lead to reconstruct accretion histories that may look realistic, but that are in fact very far from true. An example of the difficulty of using these spaces to reconstruct the merger tree of a MW-type galaxy is given below.

Suppose we have a dataset of halo stars, distributed over an extended range of energies and angular momenta. We might be led to interpret different regions of this space as being dominated by stars of different origins, and to infer the properties of the galaxies in which these stars formed by studying the characteristics of their MDFs.

For example, by making use of a mass-metallicity relation given by (Kirby et al., 2013),

$$\langle [\text{Fe}/\text{H}] \rangle = (-1.69 \pm 0.04) + (0.30 \pm 0.02) \log \left(\frac{M_*}{10^6 M_\odot} \right), \quad (4.1)$$

we may in principle reconstruct the stellar mass of the progenitor galaxies, given the mean metallicity of stars in a given $E - L_z$ region (Tables 4.2 and 4.3). If we apply this reasoning to our simulations, we would get the following:

- Unbound stars ($0 < E < 5$) found in the *nograd* simulation (upper panel of Figure 4.7) are dominated at null angular momentum ($-10 < L_z < 10$) by stars of a galaxy whose stellar mass was $\sim 10^{8.4} M_\odot$, since the mean metallicity of stars in this region is $\langle [\text{Fe}/\text{H}] \rangle \sim -1.0$, while stars of the same energy but more retrograde angular momenta ($50 < L_z < 70$) would be associated with a satellite galaxy with a stellar mass equal to $10^7 M_\odot$, given that the mean stellar metallicity in this region is $\langle [\text{Fe}/\text{H}] \rangle \sim -1.4$.
- At lower energies ($-10 < E < -5$), the problem would persist. In particular, in the region around null angular momentum ($-10 < L_z < 10$), the mean metallicity being $\langle [\text{Fe}/\text{H}] \rangle \sim -0.7$, this may be interpreted as a signature of a massive accretion, $M_* \sim 10^{9.4} M_\odot$.
- Similar conclusions would hold for the *grad* case, in which, depending on the region we look at, we may end up finding traces of low-mass accretions ($M_* \sim 10^{7.4} M_\odot$ at $-5 < E < 0$ and $50 < L_z < 70$, corresponding to a mean of $\langle [\text{Fe}/\text{H}] \rangle \sim -1.3$) and also more massive ones ($M_* \sim 10^{8.4} M_\odot$ at $-10 < E < -5$ and $10 < L_z < 30$, corresponding to a mean of $\langle [\text{Fe}/\text{H}] \rangle \sim -1.0$).

An even more complex situation would arise if we tried to interpret the multiple peaks present in the MDFs of some specific regions of the $E - L_z$ space as being due to distinct accretion events.

Regardless of the details of the average metallicity values, and thus the masses of the progenitors, the common feature of this type of analysis is to overestimate the number of accretions and underestimate the associated masses.

4.5 Imprints of pre-merger metallicity gradients

While in the previous sections we have demonstrated that analysing separately the metallicity distribution of limited regions inside the kinematic spaces is not necessarily informative about the initial conditions of the original satellite, we now move to consider the global picture in order to characterise the accretion event. To this end, we set the initial conditions for both the galaxies to the *grad* case, but while for the MW-type galaxy the gradient slope was fixed as described in Section 3.4, for the satellite we let the steepness of the radial metallicity gradient vary in the range: $f_{satthin} \in [-0.06, 0.02]$. In this way, we could evaluate the dependence on this parameter of the metallicity patterns in the $E - L_z$ space, without pre-selecting a certain group of accreted stars on the basis of kinematic arguments.

For every $f_{satthin}$ value, we considered the final distribution of both satellite and MW-type thin disc stars in the $E - L_z$ space and we computed the mean metallicity as a function of the energy. We generally found a monotonic decreasing function as the energy increases, and thus we fit it with a line (see next paragraph for more details about the method, while see the following for the results) and analysed the relation between the slope of this linear fitting ($d < [\text{Fe}/\text{H}] > /dE$) and $f_{satthin}$ itself.

Fitting the metallicity gradient in the $E - L_z$ space as a function of energy.

In Figure 4.14, we report an example of the analysis we performed for every value of the slope of the radial metallicity gradient in the satellite thin disc before the interaction ($f_{satthin} \in [-0.06, 0.02]$ dex/kpc), in the case of $f_{satthin} = 0.05$ dex/kpc and $f_{MWthin} = 0.02$ dex/kpc, which is also analysed in the rest of the paper. The first column shows the distribution in the $[\text{Mg}/\text{Fe}]$ - $[\text{Fe}/\text{H}]$ space and the MDF for every satellite disc component, with their means (peaks) in solid (dashed) lines. The second column shows instead the final distributions in the $E - L_z$ space of

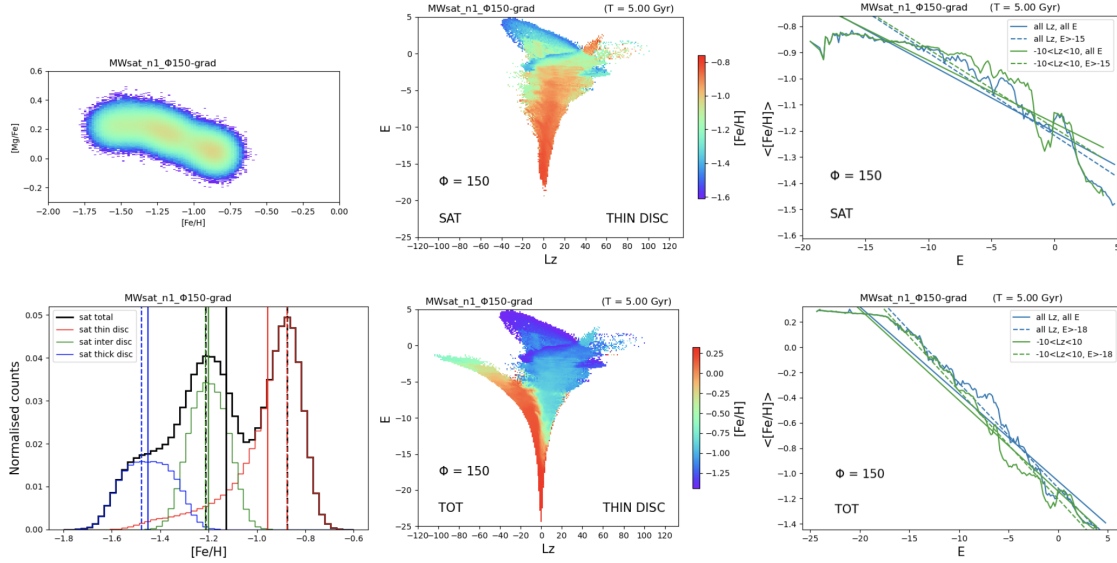


Figure 4.14: Description of the method for fitting the metallicity gradient in the $E - L_z$ space as a function of energy. The first column shows the distribution in the $[Mg/Fe]$ - $[Fe/H]$ space and the MDF for every satellite disc component, with their means (peaks) in solid (dashed) lines. The second column shows instead the final distributions in the $E - L_z$ space of the satellite (and in situ) thin disc stars in the top (bottom) panel, colour-coded at each point with the mean metallicity. Finally, the third column shows the mean metallicity ($\langle [Fe/H] \rangle$) as a function of energy (E) of the satellite (and in situ) thin disc stars in the top (bottom) panel. *From: Mori et al. (2024).*

	all E	$E \geq -15$
all L_z	-0.026	-0.032
$-10 \leq L_z \leq 10$	-0.024	-0.30

Tabella 4.4: Slopes ($d\langle [\text{Fe}/\text{H}] \rangle/dE$) of the linear fit of the mean metallicity of satellite thin disc stars as a function of energy, in the four cases described in the previous paragraph.

	all E	$E \geq -18$
all L_z	-0.069	-0.083
$-10 \leq L_z \leq 10$	-0.072	-0.086

Tabella 4.5: Same as Table 4.4, but for the cases of satellite and in situ thin disc stars.

the satellite (and in situ) thin disc stars in the top (bottom) panel, in the case of the initial inclination of the satellite orbital plane of $\phi_{orb} = 150^\circ$ also analysed in previous sections.

As far as the relation mentioned in Section 4.5 between the metallicity gradient in the satellite and in the $E - L_z$ space is concerned, we proceeded in the following way. We computed the mean metallicity ($\langle [\text{Fe}/\text{H}] \rangle$) as a function of energy (E), reported in the third column of Figure 4.14 for only satellite thin disc stars in the top panel and for satellite and in situ thin disc stars in the bottom one. We then performed a linear fit considering four different cases. The cases we considered differ in the first place in taking into account stars either with all values of angular momentum (L_z) or only in the interval $-10 \leq L_z \leq 10$ ($L_z \sim 0$), and secondly in taking into account stars either with all values of energy (E) or performing a cut at low energy values ($E \geq -15$ for satellite stars only, $E \geq -18$ for satellite stars together with in situ ones), in order to avoid a plateau of the bulk of very bound stars having almost the same iron abundance. From the fits, we derived the slopes ($d\langle [\text{Fe}/\text{H}] \rangle/dE$) that we report in Tables 4.4 and 4.5.

We then selected the case of all L_z values, together with the cut in energy, in order to restrict the analysis to the monotonic behaviour, and related its slope to $f_{satthin}$ in Section 4.5.

The resulting relation. The relation is shown by the solid lines in Figure 4.15, in different colours for the different orbital parameter values (see captions). We can see that it is a linear relation, which is independent of the initial inclination of

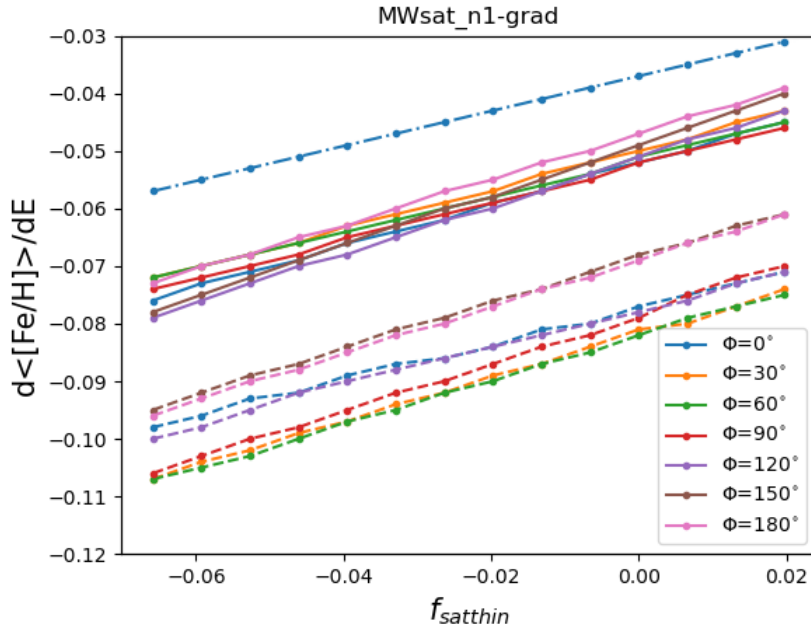


Figure 4.15: Relation between the slope of the initial radial metallicity gradient in the satellite thin disc (f_{satthin}) and the slope of the metallicity gradient in the final distribution of all the thin disc stars in the $E - L_z$ space as a function of energy ($d<[\text{Fe}/\text{H}]>/dE$), in the total volume of the simulation (solid lines), and in the restricted solar-like volume (dashed line). The case of $\phi_{\text{orb}} = 0^\circ$ also features the dash-dotted curve described in Section 4.5. From: [Mori et al. \(2024\)](#).

the satellite orbital plane, and thus from the metallicity gradient in the kinematic space as a function of energy one can obtain information about the initial conditions of the metallicity gradient in the original satellite.

There is only one exception, which is the case of $\phi_{orb} = 0^\circ$ and which is shown by the dash-dotted line in Figure 4.15. This is due to the fact that for this planar orbit satellite stars reach very bound orbits, and thus are redistributed at very low energy values in the $E - L_z$ space. As a consequence, they dump the mean metallicity at low energy, which then becomes an increasing function of energy in the lowest interval, $-25 < E < -22$, and starts to decrease as before after this value. If we then fit the relation with a cut in energy to include only the decreasing range, we obtain the solid blue line that is consistent with all the other curves for the different inclinations.

As a final step, we performed the same analysis considering the final distribution in the $E - L_z$ space of the thin disc stars that reach the solar vicinity. The relations for every ϕ_{orb} value are shown by the dashed lines in Figure 4.15. We obtain the same relation, yet shifted to more negative values of the slope of the metallicity gradient in the final distribution in the $E - L_z$ space as a function of energy ($d < [\text{Fe}/\text{H}] > /dE$).

We have shown that merger debris is not clustered, making it challenging to derive merger parameters due to variations in the MDF across different regions of $E - L_z$. This limitation may seem to render the IOM space less useful. However, there is a positive aspect to consider. Thanks to the energy differentiation of the debris, we gain insights into the structure of the galaxy-progenitors, as demonstrated through the gradient relation in this analysis (see also Khoperskov et al., 2023a). Moreover, this would not be achievable if mergers were viewed as $E - L_z$ clumps.

4.6 Discussion and conclusions

In this chapter, we have presented the analysis of N-body simulations of the accretion of a satellite galaxy onto a MW-type galaxy (an accretion with a mass ratio of 1 : 10), to explore the extent to which we can couple kinematic characteristics and

metallicities of stars in the halo to reconstruct the accretion history of our Galaxy. The main conclusions of our work are the following:

- We confirm earlier results that accreted stars from $\sim 1 : 10$ mass ratio satellites are redistributed in a wide range of energies and angular momenta (Jean-Baptiste et al., 2017; Grand et al., 2019; Simpson et al., 2019; Koppelman et al., 2020; Panithanpaisal et al., 2021; Amarante et al., 2022; Khoperskov et al., 2023c) and that in particular stars deposited at higher energies have on average different metallicities than those of stars that at the end of the accretion process end up being more gravitationally bound to the MW (Amarante et al., 2022; Khoperskov et al., 2023d,a).
- Because satellite stars with different metallicities can be deposited in different regions of the $E - L_z$ space, this implies that a single accretion of $\sim 1 : 10$ can manifest with different MDFs, in different regions of the $E - L_z$ space.
- Groups of stars with different E , L_z , and metallicities may be interpreted as originating from different satellite galaxies, but our analysis shows that these interpretations are not physically motivated.
- When the analysis is restricted to a solar-like volume, we can no longer capture the very metal-rich (or metal-poor, depending on the initial conditions in the satellite) accreted stars found at very high energies. This implies that the MDF of the GSE may still exhibit biases.
- Reconstructing the Galactic accretion history through mass-metallicity relations using the MDF mean values of single clumps can be very misleading. For example, a single merger of a galaxy with a mass of 5×10^{10} can be erroneously interpreted as three with masses of $\sim 10^7$, $\sim 10^{8.4}$, and $\sim 10^{9.4}$. As we show, coupling kinematic information with the MDFs to reconstruct the accretion history of the MW can bias the reconstructed merger tree towards increasing the number of past accretions and decreasing the masses of the progenitor galaxies. See Figure 4.16 for a summary of these points.
- From the metallicity gradient in the $E - L_z$ space as a function of energy, one can retrieve information about the initial conditions of the radial metallicity gradient in the original satellite.

A number of possible accretion events have been proposed in the literature by making use of this approach, and our analysis reinforces previous suggestions that

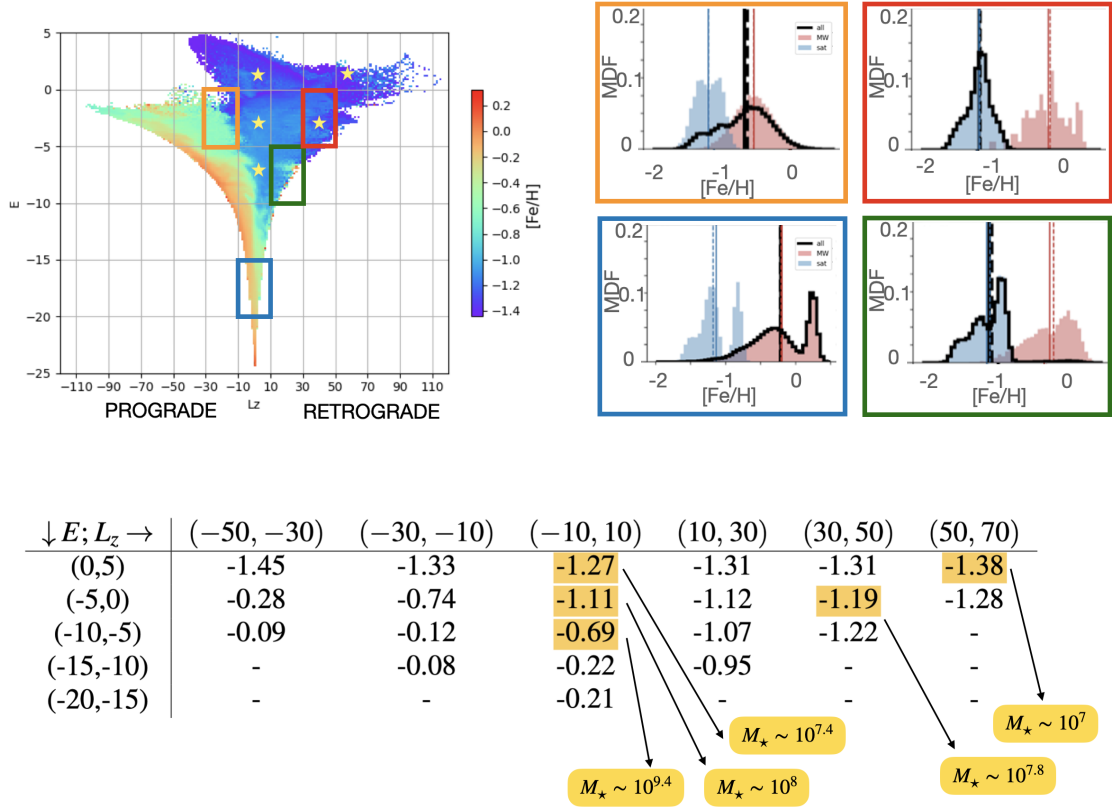


Figura 4.16: *Upper panel:* MDFs of different regions of the $E-L_z$ space, highlighted by the coloured rectangles. The red, blue, and black histograms show the MW-type galaxy, satellite, and total MDF, respectively. They are all normalised. The solid lines show the mean values. *Lower panel:* Mean values of the stellar MDFs in the regions of the $E-L_z$ space (upper panel) and corresponding stellar masses using the mass-metallicity relation from Kirby et al. (2013) for the regions denoted with yellow stars. From: Mori et al., in press; proceedings of the IAU Symposium 395 “Stellar populations in the Milky Way and beyond”, J. Meléndez, C. Chiappini, R. Schiavon, M. Trevisan, eds.

at least some of these accretion events are disputable. Indeed, we have shown how a single massive accretion can produce MDFs whose characteristics change across the $E - L_z$ plane. In a scenario in which the MW may have experienced more than a single significant accretion in its past, it is clear that the interpretation of these spaces, and related MDFs, becomes even more challenging. In this respect, we recall that even the GSE merger initially discovered in a solar vicinity volume (Nissen & Schuster, 2010) was already suspected to have been made by more than one galaxy at the time of its local discovery (see discussion in Nissen & Schuster, 2010). New evidence has recently been published on the possibility that this accretion event indeed hides multiple ones (Donlon & Newberg, 2023; Nissen et al., 2023); see next Chapter 5 for further discussion on this (Skúladóttir et al., 2025, including Mori).

Ultimately, overall the merger tree of the MW is still far from being robustly established, and - even more importantly - we still need to establish sound methods of discriminating between accretion scenarios. Although various abundance ratios have already been used to characterise different accretion events (e.g., Matsuno et al., 2019; Monty et al., 2020; Matsuno et al., 2022a,b; Horta et al., 2023; Ceccarelli et al., 2024), our study emphasises the importance of going not only beyond $[\text{Fe}/\text{H}]$ but also the need for a revision of the kinematic identification of merger debris (which will be developed in Chapter 6; Mori et al., 2025). This will be vital for a more realistic reconstruction of the MW merger history in light of coming data from WEAVE, 4MOST, SDSSV, MOONS, and other spectroscopic surveys.

The multiple passages of GSE around the Milky Way

Reference article

([Skúladóttir et al., 2025](#)) Skúladóttir Á., Ernandes H., Feuillet D. K., **Mori A.**, Feltzing S., Lucchesi R., Di Matteo P., “Evidence of Gaia Enceladus experiencing several passages around the Milky Way”. *ApJL*, 986, L21; arXiv: [2506.00409](#) (astro-ph.GA); doi: [10.3847/2041-8213/addc66](#).

The results of the previous chapter ([Mori et al., 2024](#)) highlighted how a single merger event with a mass ratio $\sim 1 : 10$ can be broadly distributed in kinematic spaces and manifest with different MDFs in different regions of the $E - L_z$ space. These findings provided the interpretative framework for the following work ([Skúladóttir et al., 2025](#), including [Mori](#)). In this work, we traced the multiple passages of the GSE progenitor galaxy around the Milky Way before completing the merger through the analysis of its kinematic and chemical properties.

As detailed in Sec. 2.3, the last massive merger of the Galaxy was first identified over a decade ago through a detailed study of chemical abundances and kinematics of stars in the solar neighbourhood ($d < 350$ pc; [Nissen & Schuster \(1997, 2010, 2011\)](#); hereafter the NS sample). The stars with halo kinematics separated into two populations, with clear differences in the $[\alpha/\text{Fe}]$ abundance ratios (e.g. $[\text{Mg}/\text{Fe}]$). This pioneering study interpreted the high- α population to be stars formed in situ in the Milky Way, and the low- α population as stars accreted from a dwarf galaxy. Recently, this discovery was undeniably confirmed by the *Gaia* space mission and the accreted galaxy was given the name *Gaia*-Sausage/Enceladus ([Belokurov et al.,](#)

2018; Haywood et al., 2018b; Helmi et al., 2018).

Last year, the NS halo sample was reanalysed with improved stellar atmospheric parameters, revealing that the accreted low- α stars above $[\text{Fe}/\text{H}] > -1$ split into two subgroups based on their $[\text{Mg}/\text{Fe}]$ ratios and kinematics (Nissen et al., 2024). The authors suggested that the accreted stars might come from two separate merger events, GSE and Thamnos (Koppelman et al., 2019b). However, Matsuno et al. (2024) found that the kinematics of the second group was not in good agreement with Thamnos and instead suggested that these stars belonged to Eos. The Eos structure was first identified by Myeong et al. (2022), and was proposed to have formed in situ (from gas polluted by GSE), as evident by the observed high $[\text{Al}/\text{Fe}]$ abundance ratios. However, no Al abundances were available for the NS sample to verify this suggestion. Clearly, the origin of this separation in $[\text{Mg}/\text{Fe}]$ is still debated. Therefore, we investigated for the first time the hypothesis that this separation is not showing two separate mergers but instead providing evidence of two groups of stars that have been stripped from GSE at different passages through the Milky Way potential. With a combination of statistical, chemical and kinematical arguments we aimed to identify the stars that were accreted in the early passages of the GSE, versus those that were accreted later. In particular, the kinematic- and MDF-related tracers were adopted from the results presented in the previous chapter.

In this chapter, we present the results of Skúladóttir et al. (2025), including Mori. The observational data and methods are reported in Section 5.1, the splitting of the sample into one accreted earlier and one later on the basis of their kinematic properties (i.e., energies) is described in 5.2, while their relative chemical abundances are analysed in 5.3. Finally, the discussion and the conclusions are drawn in 5.4.

5.1 Observational data and methods

This study analysed the historical local Galactic halo sample (NS sample). In particular, the $[\text{Mg}/\text{Fe}]$ and $[\text{Mg}/\text{Ba}]$ in Sec. 5.3, were adopted from Nissen & Schuster (2011) and Nissen et al. (2024). We also adopted their classification of the halo sample into high- and low- α stars, and included as well their thick disc stars, i.e. with velocities $V_{\text{tot}} < 180 \text{ km s}^{-1}$ (Nissen & Schuster, 2010, see their Fig. 3). The interpretation of the low- α population in the NS sample being formed in a smaller galaxy was originally based on observations which consistently show dwarf

galaxies to have lower $[\alpha/\text{Fe}]$ ratios at a given $[\text{Fe}/\text{H}]$, compared to the Milky Way (e.g., Tolstoy et al., 2009, see Section 2.3). Abundance ratios such as $[\text{Mg}/\text{Fe}]$ and $[\text{Mg}/\text{Ba}]$ are powerful tracers of star formation in different systems, since they are very sensitive to timescales (e.g. Ernandes et al., 2024). The element Mg is created by core-collapse supernovae (ccSN) on short timescales ($\sim 10^7$ Gyr), while Fe is also formed in Type Ia supernovae (SNIa, $\sim 10^9$ Gyr) and Ba is primarily formed in asymptotic giant branch (AGB) stars ($\gtrsim 10^8$ Gyr). Therefore, both $[\text{Mg}/\text{Fe}]$ and $[\text{Mg}/\text{Ba}]$ are typically lower in stars formed in an environment that experienced less efficient star formation and chemical enrichment (e.g. Tolstoy et al., 2009; Skúladóttir et al., 2020; Skúladóttir & Salvadori, 2020).

Furthermore, our work included new measurements of aluminum (the full analysis of the spectra is presented in Ernandes et al., 2025) for a subsample of NS. Similarly, the $[\text{Al}/\text{Fe}]$ abundance ratio can be used to distinguish between stars formed in situ and those formed in a smaller galaxy, which later merged with the Milky Way (Hawkins et al., 2015; Das et al., 2020; Horta et al., 2021; Feuillet et al., 2021; Feltzing & Feuillet, 2023, see Section 2.6). In general, a smaller galaxy will have experienced a slower star formation which results in lower $[\text{Al}/\text{Fe}]$. Differences in elemental abundance ratios are thus found between different galaxies (e.g. Tolstoy et al., 2009), but also between different regions of galaxies which have experienced a variation in their chemical enrichment histories (e.g., Hayden et al. 2015; Lucchesi et al. in prep.).

The new observations in this study come from two ESO VLT/UVES programs (PI: Skúladóttir, ESO Programme IDs: 109.22VP and 110.240W). The spectra are of high-resolution ($R \geq 40\,000$) and have high signal-to-noise ratios, $\text{SNR} \geq 150 \text{ pix}^{-1}$. Since the new observations do not include the entire NS sample, the ESO archive was searched for spectra of comparable quality for the missing stars. This led to spectra for 8 additional low- α stars to be added to the Al analysis. In total, we presented Al measurements for 49 stars from the original NS sample. All results of the data analysis are given in an online table and we refer to Skúladóttir et al. (2025) for further details on the derivation of chemical abundances.

Energies and angular momenta of the stars were calculated using `galpy` (Bovy, 2015) with distances (`distance_gspphot`) and proper motions taken from *Gaia* DR3 (Gaia Collaboration et al., 2016a, 2023) and radial velocities taken from Nissen & Schuster (2010) and Nissen & Schuster (2011). We assumed `MWPotential2014` (Bovy, 2015) as the Milky Way potential model and used the `actionAngleStaeckel` approximation (Bovy & Rix, 2013; Binney, 2012) with a delta value of 0.4. The

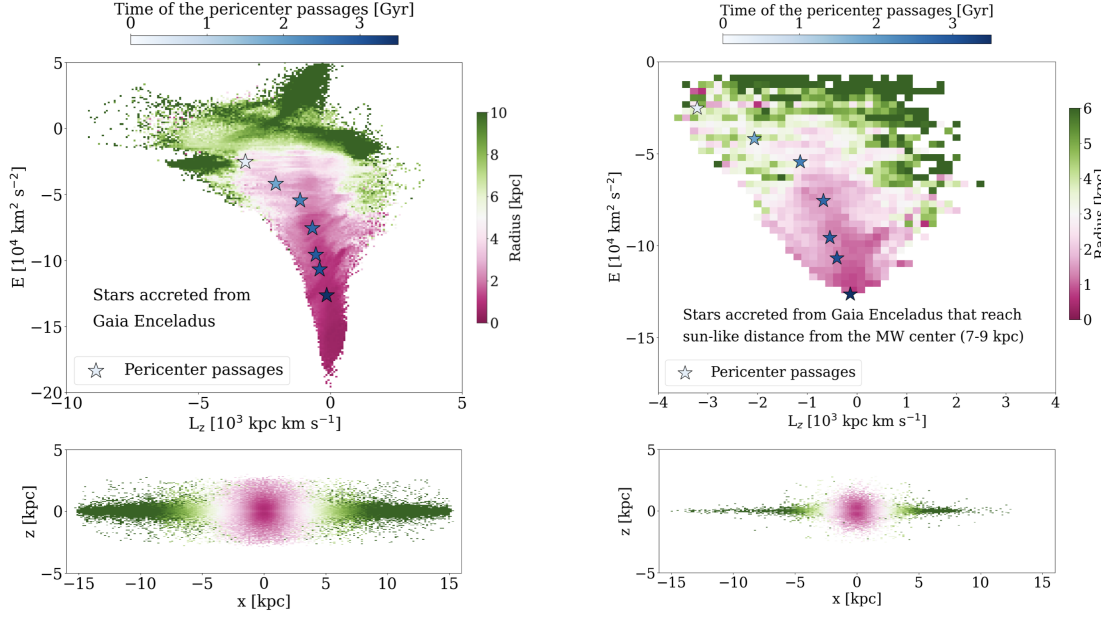


Figure 5.1: Simulation of a GSE-like progenitor galaxy falling into the MW (presented in Ch.3 and 4; Mori et al., 2024). Top panels show the energy and angular momentum ($E - L_z$) relation for the accreted stars (small points) which are now residing in the MW. Left panel shows all stars, and the right panel those at a sun-like distance from the Galactic centre (7-9 kpc). Colour-coding at a given point in ($E - L_z$) shows the average position of stars in GSE before the merger - the outskirts in green, and the inner regions in pink, as shown by the bottom panels. Star symbols (white to blue) show how the barycentre of GSE loses energy and angular momentum with time and more passages through the MW. From: Skúladóttir et al. (2025).

mean uncertainties of our input parameters were 0.7 pc in distance, $0.03 \text{ mas year}^{-1}$ in both RA and Dec proper motion, and 0.3 km s^{-1} in radial velocity. The resulting uncertainties in kinematics are expected to be approximately $0.12 \times 10^3 \text{ kpc km s}^{-1}$ in angular momentum and $0.28 \times 10^4 \text{ km}^2 \text{ s}^{-2}$ in energy based on the Monte Carlo analysis of Gaia parameter uncertainties done by Feuillet et al. (2020).

The simulations we rely on in this work are the ones presented in Chapter 3 and 4.

5.2 High and low energy stars

Simulations show clearly that stars from a massive merger can cover a large range of dynamics (e.g., [Jean-Baptiste et al., 2017](#); [Amarante et al., 2022](#); [Khoperskov et al., 2023c](#); [Mori et al., 2024](#)), with discrete over-densities in the energy-angular momentum ($E - L_z$) plane corresponding to stars stripped during different passages of the merging galaxy through the Milky Way potential, see Fig. 5.1 (left). A possible signature of this has been reported in the Gaia data ([Belokurov et al., 2023](#)). Intuitively, the stars that are more loosely bound to the merging galaxy, i.e. furthest from its centre, are expected to be stripped during the first passages, and this is confirmed in simulations (e.g., [Mori et al., 2024](#)). As the merging galaxy passes through the Milky Way’s potential well for the first time, it has high energy relative to the Milky Way, but with each passage it loses kinetic energy (Fig. 5.1, star symbols). Focussing only on the stars which now reside at Sun-like distances from the Galactic centre (7-9 kpc) shows qualitatively the same trend, see Fig. 5.1 (right). However, the most ($E > 0 \text{ km}^2 \text{ s}^{-2}$) and least ($E < -13 \text{ km}^2 \text{ s}^{-2}$) energetic stars are missing, as they now typically reside at larger and smaller distances from the Galactic centre, respectively. From Fig. 5.1 we conclude that the stars that were accreted first resided in the outer regions of GSE and will typically have higher orbital energy after joining the Milky Way.

Fig. 5.2 shows the energy and angular momentum of the NS sample. The energy range, is in generally good agreement with simulations, see Fig. 5.1 (right). By limiting ourselves to observations in the solar neighbourhood, we do expect lesser range in both radius and energy. This qualitative result is robust, however, we caution that the quantitative scale might be affected by details in the scaling of the simulations (e.g., [Mori et al., 2024](#)).

To test the possibility of multiple passages of GSE, we wanted to explore the chemical signatures of stars potentially stripped at different passages, i.e. stars with different energies. We separated the accreted stars into high- and low- energy subpopulations based on whether their orbital energies lie above or below the limit $E_{\text{cut}} = -4.5 \cdot 10^4 \text{ km}^2 \text{ s}^{-1}$. This is consistent with simulations, which show that stars with $E > -4.5 \cdot 10^4 \text{ km}^2 \text{ s}^{-1}$ are primarily expected to come from the outer regions of GSE, see Fig. 5.1. However, we do note that the quantitative scale of the kinetic energies is dependent on the adopted model for the Milky Way potential. Changing E_{cut} within the refinements of our sample size (to $E_{\text{cut}} = -3.5 \times 10^4 \text{ km}^2 \text{ s}^{-2}$ and $E_{\text{cut}} = -5.5 \times 10^4 \text{ km}^2 \text{ s}^{-2}$) does not affect our final conclusions.

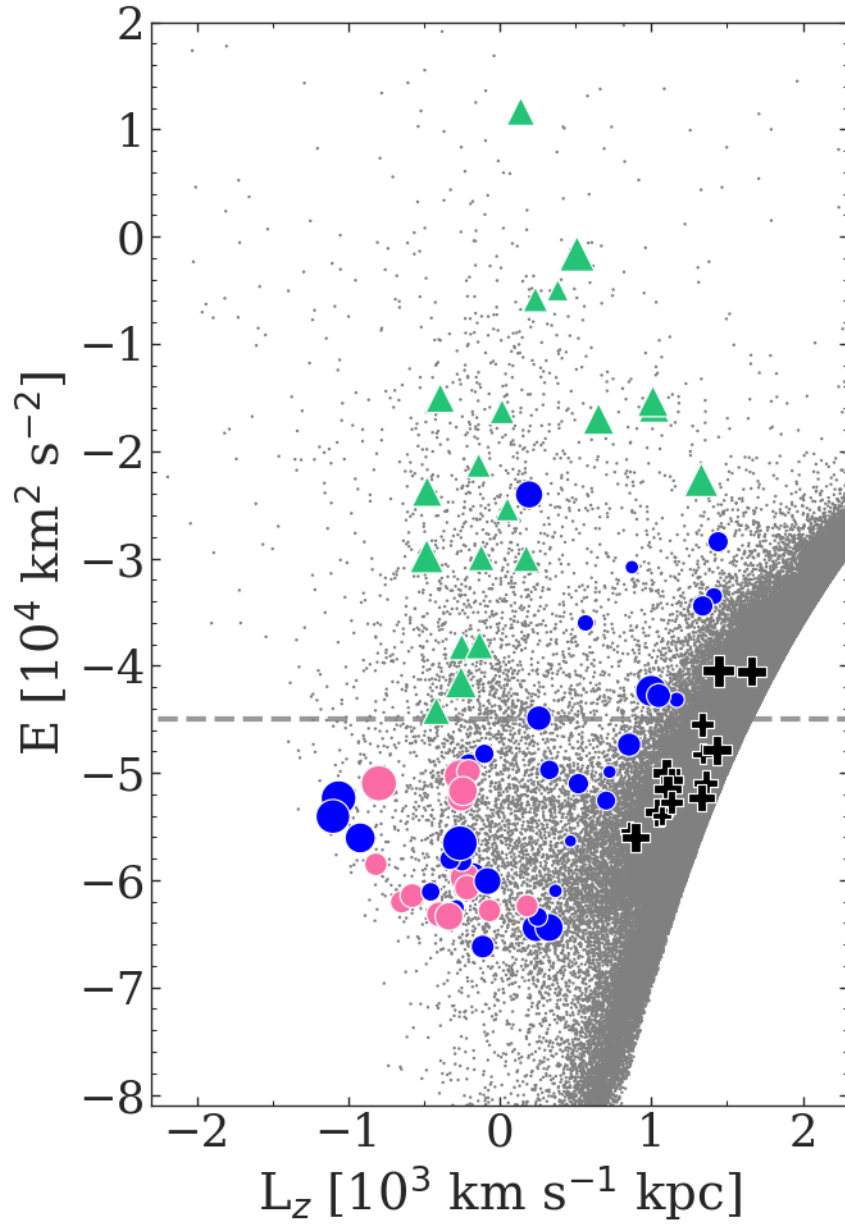


Figure 5.2: Energy and angular momentum ($E - L_z$) space of observed stars. Accreted stars (low- α) are separated into high and low energies, shown with green triangles and pink circles, respectively. Thick disc stars are shown with black crosses, high- α stars with blue circles. The point size increases with decreasing $[\text{Fe}/\text{H}]$. For comparison, Milky Way field stars from APOGEE Data Release 17 are shown with small gray dots (Majewski et al., 2017; Abdurro’uf et al., 2022), selected as described in Feltzing & Feuillet (2023). From: Skúladóttir et al. (2025).

5.3 Elemental abundance trends

Using the definition from Fig. 5.2, we separated the accreted low- α stars into high and low energy, with the aim of investigating the chemical abundance trends of the two samples. It is well established that star formation and chemical enrichment is more efficient in the centres of galaxies compared to their outskirts, as seen by their ubiquitously observed metallicity gradients (e.g. Berg et al., 2013; Tolstoy et al., 2009; Fu et al., 2024). Therefore, if the stars with high energy truly come from the outer regions of GSE, they are expected to have experienced slower chemical enrichment compared to the inner regions traced by the low-energy stars, and this should be reflected in their chemical abundances.

First, we used our new Al measurements to refine the categorisation of stars into the in-situ (high- α) and accreted (low- α) populations, which become hard to separate with α -elements at low $[\text{Fe}/\text{H}] < -1.2$, where the difference in $[\alpha/\text{Fe}]$ is very small ($\lesssim 0.1$ dex), see Fig. 5.3 (middle panel). Based on our new data, we defined a cut between the high- and low- α populations at $[\text{Al}/\text{Fe}] = -0.5$, resulting in 9 stars with Al measurements in the low-energy sample and 13 with high energy. Our results show that the separation between the accreted and in-situ populations in $[\text{Al}/\text{Fe}]$ is very clear ($\gtrsim 0.3$ dex), even at the lowest $[\text{Fe}/\text{H}]$, see Fig. 5.3 (top panel). The new aluminum abundances reveal that one star at $[\text{Fe}/\text{H}] = -1.4$ (named BD+07-4841, pink circle in Fig. 5.3), which was previously categorised as a high- α star, actually belongs to the accreted population (see also Ernandes et al., 2025).

We then compared the measured $[\text{Al}/\text{Fe}]$ ratios in the high- and low-energy samples. The average aluminum for the accreted stars with high energy (as defined in Fig. 5.2), is $\langle [\text{Al}/\text{Fe}] \rangle_{\text{HE}} = -0.67 \pm 0.01$ and for the accreted stars with low energy is $\langle [\text{Al}/\text{Fe}] \rangle_{\text{LE}} = -0.63 \pm 0.03$, using the error of the mean shown with shaded areas around the mean values in Fig. 5.3. Performing a Kolmogorov–Smirnov (KS) test, the hypothesis that these two samples come from the same distribution is rejected, with $p < 0.05$. The two samples therefore show a statistically meaningful difference, with the high-energy stars having lower $[\text{Al}/\text{Fe}]$ as expected for stars coming from regions of less efficient chemical enrichment. However, the difference of the average value is within 2σ , and we do note that aluminum is challenging to measure precisely, and the blue spectra needed for Al measurements were only available for a subset of the original NS sample (Sec. 5.1).

More precise measurements can be made for Mg, and those exist for the entire

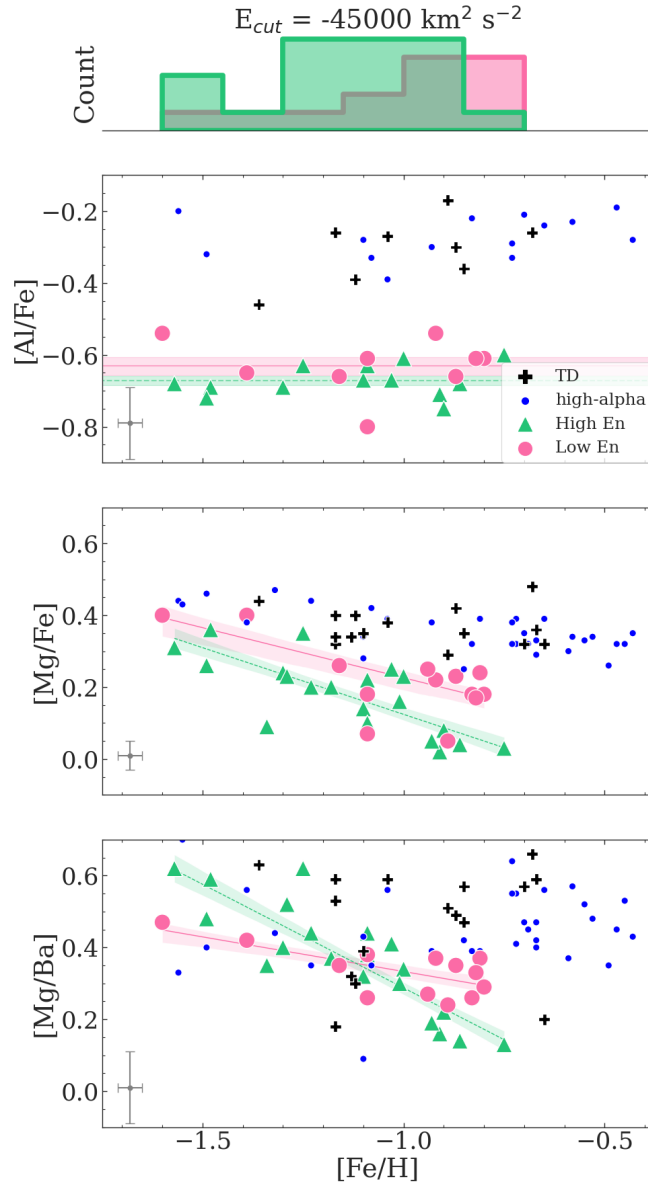


Figure 5.3: Chemical abundances for the accreted stellar sample with low (pink circles) and high (green triangles) energies, as defined in Fig. 5.2. The average values for $[\text{Al}/\text{Fe}]$ are shown with a line, while shaded area shows the error of the mean. For $[\text{Mg}/\text{Fe}]$ and $[\text{Mg}/\text{Ba}]$, trend lines are shown with 68% confidence interval. Top marginal plot shows the metallicity distribution of the accreted samples. For reference, the thick disc and high- α Milky Way populations created in situ are shown with small black crosses and blue circles, respectively. Representative error bar for individual measurements is shown in the bottom left corners. *From: Skúladóttir et al. (2025).*

NS sample of 33 accreted stars with known orbital energies (thereof 20 with high energy, and 13 low-energy stars). In Fig. 5.3 (middle panel) we see two evolutionary tracks of $[\text{Mg}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$. The fits to these tracks were created by a linear regression and limited over the range where the data is available. The shaded areas represent the confidence interval of the linear regression estimates from bootstrap of 68%. Again, the abundance ratios of stars with high energy reflect a birth environment experiencing a slightly less efficient chemical enrichment compared to the low-energy sample. As anticipated, the difference in $[\text{Mg}/\text{Fe}]$ between the two samples is clearest at high $[\text{Fe}/\text{H}] > -1$, where SNIa dominate the production of Fe. The statistical significance of the $[\text{Mg}/\text{Fe}]$ separation in the two subpopulations at high metallicity is corroborated with a KS test which gives $p < 0.01$ for the samples at $[\text{Fe}/\text{H}] > -1$, confirming that they have distinct distributions. We emphasise that this separation is not only seen in Mg, but also in other α -elements, such as Si and Ca (see Figure 5.4).

Finally, we show the $[\text{Mg}/\text{Ba}]$ ratios in Fig. 5.3 (bottom panel). Yet again, we see that the abundance trend of the high-energy stars indicates that they come from a region with less efficient chemical enrichment compared to the low-energy sample. All stellar populations of different galactic origins are expected to have a similar value of $[\text{Mg}/\text{Fe}] \approx +0.4$ at low $[\text{Fe}/\text{H}] \lesssim -1.5$, since at early times Mg and Fe are co-produced in ccSN before the onset of SNIa. This is not the case for $[\text{Mg}/\text{Ba}]$, because Mg and Ba have distinctly different production sites. The $[\text{Mg}/\text{Ba}]$ ratio at low $[\text{Fe}/\text{H}]$ can therefore vary between galaxies and different regions within galaxies (e.g. Skúladóttir & Salvadori, 2020). In Fig. 5.3, we notice that the $[\text{Mg}/\text{Ba}]$ slope of the high-energy sample is significantly steeper than for low-energy stars. This is expected in a region of less efficient star formation, as more intermediate-mass stars reach their AGB phase in the time taken for the region to enrich to the same $[\text{Fe}/\text{H}]$. Performing a two-dimensional KS test is beyond the scope of this work, but comparing $[\text{Mg}/\text{Ba}]$ in the full samples is misleading as there is clearly a trend with $[\text{Fe}/\text{H}]$, which is not fully captured with a one-dimensional test. If we instead perform a focused KS test at high $[\text{Fe}/\text{H}] > -1$ we get $p < 0.01$, confirming that $[\text{Mg}/\text{Ba}]$ separates in the two subpopulations in a statistically meaningful way at high $[\text{Fe}/\text{H}]$. We note that in the bottom panel of Fig. 5.3 we have excluded one Ba-rich star ($[\text{Mg}/\text{Ba}] < 0$) with low kinetic energy. High Ba abundances are typically obtained through binary transfer from an AGB stellar companion (e.g. Karakas & Lattanzio, 2014), and such stars are therefore not representative of the chemical evolution history of their host galaxy.

In summary, the chemical abundance ratios in Fig. 5.3 consistently indicate that the high-energy accreted sample was formed in a region of less efficient chemical enrichment compared to the low-energy accreted stars. This is further supported by the metallicity distribution of the sample (Fig. 5.3, top marginal plot), where the low energy stars are on average more metal-rich, $\langle[\text{Fe}/\text{H}]\rangle_{\text{LE}} = -1.03 \pm 0.06$, compared to the high energy sample $\langle[\text{Fe}/\text{H}]\rangle_{\text{HE}} = -1.16 \pm 0.05$. A one-dimensional KS test of $[\text{Fe}/\text{H}]$ for the entire low- and high-energy samples gives a p-value of $p = 0.19$. Together the metallicity and abundance ratios therefore show that the sample with high energy comes from a region of less efficient star formation, compared to the low-energy stars.

5.4 Discussion and conclusions

In this chapter, as in (Skúladóttir et al., 2025, including Mori), we investigated the hypothesis that evidence of multiple passages of the GSE progenitor galaxy can be seen in the high-quality kinematics and chemical abundances of accreted stars in the Galactic halo. Guided by simulations, we divided the accreted stars from the historical sample of Nissen & Schuster (2010), into two groups, with high and low kinetic energies, as separated by the limit $E_{\text{cut}} = -4.5 \cdot 10^4 \text{ km}^2 \text{ s}^{-1}$. Accreted stars with high energy are predicted to be stripped from the outskirts of GSE during the early passages, while stars which currently have low kinematic energy should come from the more inner regions during later passages (e.g., Mori et al., 2024).

For the first time we provided aluminum measurements for this sample, showing that $[\text{Al}/\text{Fe}]$ ratios are the best tracers of accreted stars with $[\text{Fe}/\text{H}] < -1.2$ (see also Ernandes et al., 2025). We investigated the abundance ratios of $[\text{Al}/\text{Fe}]$, $[\text{Mg}/\text{Fe}]$, and $[\text{Mg}/\text{Ba}]$, which are known to separate in systems with different star formation histories (e.g., Tolstoy et al., 2009; Hawkins et al., 2015; Skúladóttir & Salvadori, 2020). In all observed abundance ratios the stars with high energy show clear evidence of coming from an environment which experienced less efficient chemical enrichment compared to those with low energy. This was confirmed with the low energy sample having on average higher metallicity, $\langle[\text{Fe}/\text{H}]\rangle_{\text{LE}} > \langle[\text{Fe}/\text{H}]\rangle_{\text{HE}}$.

Both kinematically and chemically, the high-energy accreted sample is consistent with what the community has defined as GSE (e.g. Feuillet et al., 2020; Ernandes et al., 2024; Davies et al., 2025). But what is the origin of the low-energy subpopulation? Previously, these stars have been proposed to belong to Thamnos (Nissen et al., 2024) or Eos (Matsuno et al., 2024). However, the Thamnos merger

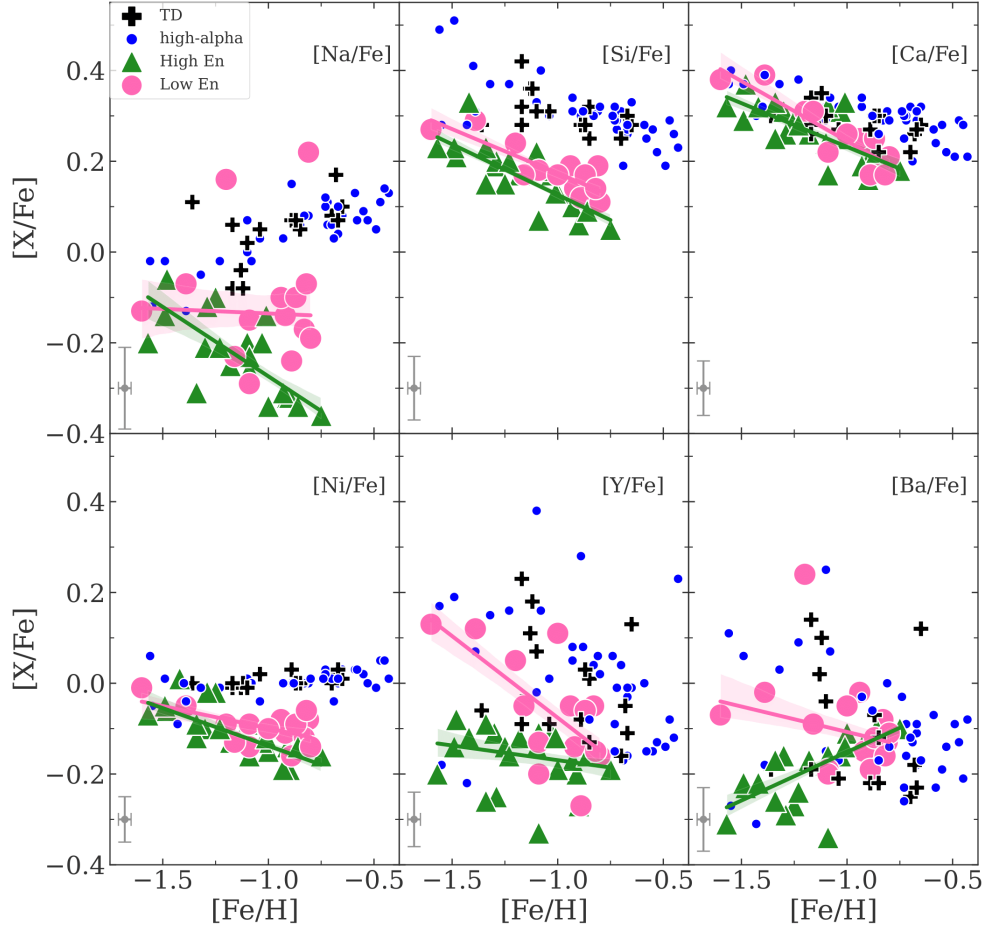


Figure 5.4: Chemical abundances for the NS accreted stellar sample with low (pink circles) and high (green triangles) energies, as defined in Fig. 5.2. For reference, the thick disk and high- α Milky Way populations created in situ are shown with small black crosses and blue circles, respectively. Representative error bars are shown in the bottom left corner of each panel. *From: Skúladóttir et al. (2025).*

event is incompatible with the kinematics of the low-energy population as pointed out by Matsuno et al. (2024). Based on the low $[\text{Al}/\text{Fe}] < -0.5$ values measured here in this sample, the in-situ formed Eos can now also be excluded, since one of its main characteristics are high $[\text{Al}/\text{Fe}]$ abundance ratios (Myeong et al., 2022).

More generally, the hypothesis of the high- and low-energy populations belonging to two separate merger events can be rejected for several reasons: 1) For a second merger to appear unambiguously in such a small sample (≈ 35 accreted stars), would require it to be of comparable mass to GSE, and the higher metallicity of the low-energy population suggests an even larger merger. No evidence of such a merger has been found. 2) It is unphysical to expect that a massive merger of this size would not experience several passages (resulting in a higher-energy counterpart, whose extent may depend on the time of accretion). This goes against theoretical predictions (e.g. Khoperskov et al., 2023c; Mori et al., 2024), and is contrary to what is seen observationally, e.g. in the case of the Sagittarius dwarf spheroidal galaxy currently being disrupted by the Milky Way (Johnston et al., 1995). 3) It is highly improbable that two separate galaxies independently experienced chemical enrichment that was so extremely similar to each other, as seen by the very close abundance trends of accreted stars with high and low energy in Fig. 5.3. Such close similarities are not seen in observations of the different satellite galaxies of the Milky Way, where the typical abundance differences in $[\text{Mg}/\text{Fe}]$ at the highest $[\text{Fe}/\text{H}]$ reach $\gtrsim 0.3$ dex (e.g. Tolstoy et al., 2009). Furthermore, no two satellite galaxies are known to have indistinguishable $[\text{Ca}/\text{Fe}]$ as is the case for the high- and low-energy populations (see Figure 5.4). However, comparable differences (as shown in Fig. 5.3) are seen in the inner and outer regions of the Sculptor dwarf spheroidal galaxy (Lucchesi et al. in prep.).

Therefore, we concluded that these two subpopulations of low and high energy both belong to GSE, and that they correspond to different accretion epochs (see Fig. 5.5, for a schematic representation). In agreement both with simulations and observations, the stars with high energy were accreted earlier, during an initial passage, and stripped from the outer regions of GSE. All the available abundance information (Fig. 5.3) points to a very similar chemical enrichment history between the two groups, where the stars with high energy formed in a region experiencing less efficient star formation, as expected when comparing the outer region of a galaxy to its inner parts. Furthermore, the accreted stars with the highest observed $L_z > 0.5 \times 10^3 \text{ km s}^{-1} \text{ kpc}$, which are predicted to be stars initially residing at large distances from the centre of GSE (see Fig. 5.1), all have low $[\text{Fe}/\text{H}] < -1$, consistent

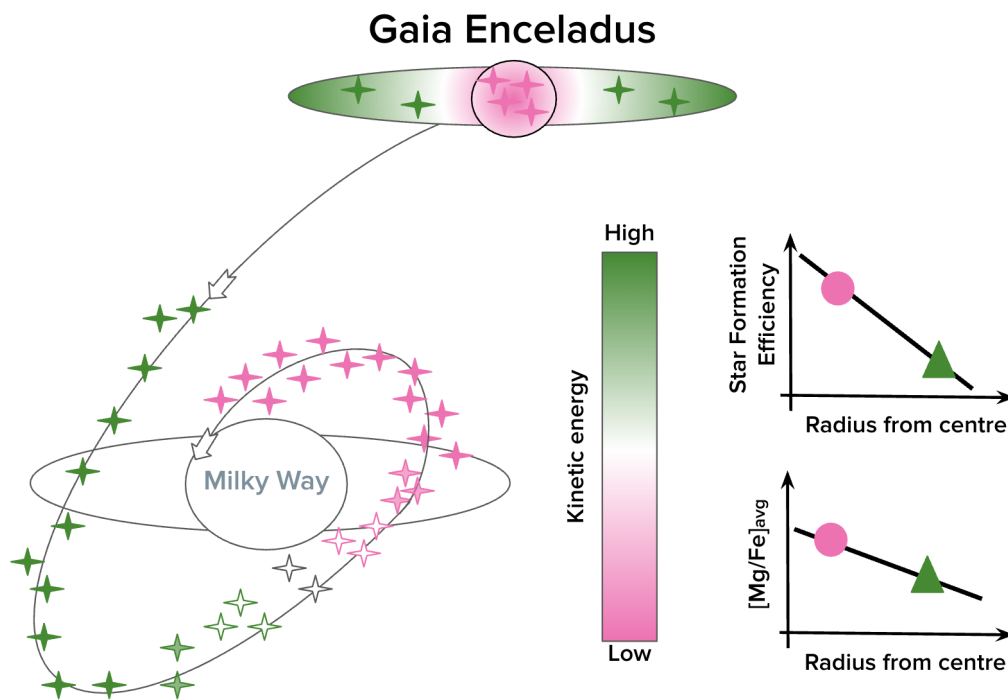


Figura 5.5: Schematic figure showing how GSE fell into the potential of the MW. First to be accreted with high kinetic energies are the outermost stars of GSE (green), from regions with less efficient star formation. These stars can subsequently be recognised by their lower $[\text{Mg}/\text{Fe}]$ ratios at a given $[\text{Fe}/\text{H}]$. Conversely, the stars that originally resided closer to the centre of GSE (pink) are accreted in later passages, thus having lower orbital energies, and the chemical signatures of more efficient star formation (e.g. higher $[\text{Mg}/\text{Fe}]$ at high $[\text{Fe}/\text{H}]$). From: [Skúladóttir et al. \(2025\)](#).

with coming from the outermost least gravitationally bound and least chemically evolved regions of the galaxy.

Unfortunately, our small sample size limited us from further exploring whether the abundance trends change gradually with increasing energy. Furthermore, we were not able to assign stars to specific passages, e.g. we could not determine whether the high-energy sample is dominated by the first passage, or if it is a combination of the first and second passages (see Fig. 5.1). Simulations predict over-densities in the $E - L_z$ plane corresponding to specific passages (Mori et al., 2024), which should be observable with larger sample sizes, making the specific stripping passage of stars easier to identify. We emphasise that for the chemical abundance analysis of such a sample, very high quality spectrum is preferred ($SNR > 100$, $R \gtrsim 40\,000$) as is having a small range in stellar parameters, since a large range in $\log g$ and/or T_{eff} can result in very different non-LTE effects (see e.g. Koutsouridou et al. 2025), causing a measurement scatter that could hide or distort intrinsic trends. Furthermore, having more tailored simulations of the GSE merger would help to establish the robustness of the theoretical predictions.

For the first time, we have presented observational evidence for GSE experiencing at least two passages before being dispersed into the Milky Way. This discovery represents a new phase in the investigation of the hierarchical galaxy formation history of our Milky Way. Instead of looking at a merger as a singular event, we are able to identify several passages, characterised by individual stars. Our results indicate that the general properties of GSE (and perhaps other merger events) need to be revisited: by defining the galaxy only by its outskirts (high-energy stars) while neglecting the inner parts (low-energy stars), both the metallicity and stellar mass could be underestimated, as could the timescale of how long this merger event lasted. With the next generation of data and theoretical models, this discovery gives us the unique opportunity to study in extraordinary detail the spatially resolved star formation history and spatially resolved chemical enrichment history of a galaxy that died ~ 10 Gyr ago. Such high-precision studies can drastically improve our knowledge of galaxy mergers in general, creating invaluable synergies with the more numerous observations of extra-Galactic mergers at higher redshifts, bringing us significantly closer to understanding the complexities of hierarchical galaxy formation throughout the history of our Universe.

Chemical decoding the Galactic merger tree

Reference article

([Mori et al., 2025](#)) **Mori A.**, Di Matteo P., Salvadori S., Mondelin M., Khoperskov S., Haywood M., Mastrobuono-Battisti A.; “Chemical decoding of kinematic substructures in the Galactic halo”. *A&A *subm.**; arXiv: [2509.13408](#) (astro-ph.GA).

The results presented in Chapter 4 and by [Mori et al. \(2024\)](#) indicate that the merger history of the Milky Way remains uncertain and not yet robustly constrained. This conclusion arises primarily from the non-conservation of energy (E) and angular momentum (L_z) in the case of a massive merger (with a mass ratio of approximately 1:10, as for *Gaia*–Sausage/Enceladus, GSE). Consequently, such an event could exhibit different chemical properties across the $E - L_z$ plane, provided it featured abundance gradients prior to the merger (see also [Amarante et al., 2022](#); [Khoperskov et al., 2023d,a](#)). Furthermore, we also showed that a significant part of the early Galactic disc could have been heated to halo orbits due to such accretion (Sec. 4.1, see also [Di Matteo et al. 2019](#); [Belokurov et al. 2020](#)). Therefore, both populations — those associated with the GSE accretion and those originating from the Galactic disc — are expected to overlap across several regions of kinematic space, thereby contaminating other halo substructures as well. However, the extent and significance of this contamination have not yet been quantified.

Thus, the plethora of kinematically-defined halo substructures that have so far been attributed to accretion events independent of GSE and in situ components (see Sec. 2.6 for a review of the most relevant cases) requires re-evaluation — a

task that constitutes the main objective of this Chapter, which is based on the results of [Mori et al. \(2025\)](#). In particular, since the halo substructures are defined by kinematic selections, we aim at cleaning those samples analysing only their chemical properties. Once both types of contamination have been quantified, we will be able to identify real halo substructures – if any – and uncover their specific abundance patterns.

This chapter is organised as follows. The observational data (*Gaia* EDR3 and APOGEE DR17) and the adopted selection criteria are detailed in Sec. 6.1. The kinematic definition of the halo substructures - as assumed in the literature - are recalled in Sec. 6.2, while their main chemical abundance properties are described in Sec. 6.3. The method that we use to chemically characterise and compare the samples is presented in Sec. 6.4. The comparison in chemical spaces of the different halo substructures with the GSE and disc populations is given in Sec. 6.5.1 and Sec. 6.5.2, respectively. The substructures' samples cleaned from both sources of contamination are finally described in Sec. 6.5.3. We then discuss the results in Sec. 6.6, and summarise the conclusions in Sec. 6.7.

6.1 Observational data

The observational data analysed in this work are cross-matched from the early third data release of the ESA astrometric mission *Gaia* (EDR3; [Gaia Collaboration et al., 2021](#)) and the latest data release of the SDSS spectroscopic survey APOGEE (DR17; [Abdurro'uf et al., 2022](#)). Moreover, we combined the APOGEE Value Added Catalogue (VAC) *astroNN* ([Leung & Bovy, 2019](#)), that provides distances from applying the *astroNN* deep-learning code to the APOGEE DR17 spectra retrained with *Gaia* EDR3. This combination allows for full 6D phase-space information for over 700000 Milky Way stars, as it accounts for coordinates, distances (d), proper motions (PM), and radial velocities (RV); along with chemical abundances for over 20 elements. We then make use of the APOGEE VAC of Galactic globular cluster (GC) stars ([Schiavon et al., 2024](#)), in order to remove 7737 GC candidates, identified with the membership probability (*VB_prob*), determined via a Gaussian mixture model of the *Gaia* EDR3 positions and PMs of GC stars ([Vasiliev & Baumgardt, 2021](#); [Baumgardt & Vasiliev, 2021](#)). Stars with *VB_prob* > 0.8 were excluded. Eventually, we took advantage of the APOGEE samples of Massive Milky Way Satellites ([Hasselquist et al., 2021](#)), which enabled us to also remove

stars belonging to the Small and Large Magellanic clouds (5055 in total, 1146 from the SMC and 3909 from the LMC). After having collected our sample, we applied the following selection criteria (as in [Horta et al., 2023](#)): APOGEE atmospheric parameters: $3500 < T_{eff}/K < 5500$ and $\log g < 3.6$ to select giants, spectral S/N > 70 , STARFLAG = 0, astroNN distance accuracy of $d_{\odot, err}/d_{\odot} < 0.2$ ($d_{\odot} \geq 0$), APOGEE X.FE.FLAG = 0 and no nan values. The final sample then comprises 168859 stars of the Milky Way.

As thoroughly detailed in Sec. 2.3, to unravel whether stars of different halo substructures were born in distinct environments, thus possibly in different galaxies, we can study their star formation and chemical evolution histories by analysing their chemical abundances. The abundances of the stellar atmospheres are fossil records of the interstellar medium out of which they formed, that had already been polluted by previous generations of stars exploded as supernovae or by stellar winds from AGB stars. Accordingly, different abundances may trace distinct environmental chemical enrichment, due to diverse star formation histories, pointing towards an independent origin. Given this global picture, we would aim at analysing the highest possible number of chemical elements, as they trace different nucleosynthetic channels. In this sense, the more information we have for the abundances, the better we can discriminate between different star formation histories in principle. For this scope, APOGEE is an excellent tool, providing chemical abundances for more than 20 elements. However, not all of their measurements are given with the same precision and free of quality flags. As to fulfil the selection criteria reported above, but at the same time preserve a statistically relevant number of stars in each analysed substructure, we decided to consider the following abundance ratios: [Fe/H], [Mg/Fe], [Si/Fe], [Ca/Fe], [C/Fe], [Al/Fe], and [Mn/Fe]. In this way, we considered the most reliable elements in APOGEE for the various nucleosynthetic categories: Mg for α , Al for odd- z and Mn for the iron-peak, driven by the APOGEE’s recommendations for giant stars. Thus we obtained high-precision samples (median uncertainties ≤ 0.02) that still allowed us to probe several nucleosynthetic channels. Beyond analysing iron, mainly produced by type Ia supernovae, we study then α -elements (like Mg, Si and Ca), mainly produced instead by type II core-collapse supernovae, a light element like carbon, as to evaluate ancient high-mass star pollution versus later AGB enrichment, an odd- Z element like aluminum to assess the massive star contribution and an iron-peak one that is manganese, to consider the relative impact of type Ia supernovae.

Name	Dynamical (and chemical) selection criteria				N_*	Ref
	E	L_z	$L_\perp$	e	Abu	
GSE (K)	$-1.6 < E < -1.1$	$-0.5 < L_z < 0.5$	-	-	n	954 K19a
GSE (M)	$-1.86 < E < -0.9$	$-0.8 < L_z < 0.62$	$L_\perp < 3.5$	-	n	3341 M19
Sequoia (K)	$-1.35 < E < -1$	$L_z < 0$	-	$0.4 < \sqrt{1-e^2} < 0.65$	n	144 K19b
Sequoia (M)	$-1.5 < E < -0.7$	$-3.7 < L_z < -0.85$	-	-	n	111 M19
Helmi Stream (K)	-	$0.75 < L_z < 1.7$	$1.6 < L_\perp < 3.2$	-	n	54 K19a
Helmi Stream (M)	$E < -1$	$0.35 < L_z < 3$	$1 < L_\perp < 3.2$	-	n	426 M19
Thamnos	$-1.8 < E < -1.6$	$L_z < 0$	-	$e < 0.7$	n	124 K19b
Heracles	$-2.6 < E < -2$	-	-	$e > 0.6$	y	225 Ho21

Tabella 6.1: Selection criteria for the halo substructures. L_z and $L_\perp$ are in units of 10^3 kpc km s $^{-1}$, E of 10^5 km 2 s $^{-2}$. The dynamical criteria are based on total orbital energy (E), angular momentum with respect to the Galactic disc (L_z), perpendicular angular momentum ($L_\perp$) and eccentricity (e). The column “Abu” states whether the selection comprises chemical abundance criteria: Heracles (Ho21) is the only case, described in the text. In addition, we analysed the Sgr dSph and ω Cen GC, whose stars were selected directly from Ha21 and S24 catalogues. The references are the following. K19a: [Koppelman et al. \(2019b\)](#), K19b: [Koppelman et al. \(2019a\)](#), M19: [Massari et al. \(2019\)](#), Ho21: [Horta et al. \(2021\)](#), Ha21: [Hasselquist et al. \(2021\)](#), S24: [Schiavon et al. \(2024\)](#).

6.2 Kinematic definitions

The samples of kinematic substructures in the Galactic halo that we want to compare in chemical abundance spaces are defined as in [Horta et al. \(2023\)](#). To this aim, we transformed the phase-space data from the ICRS frame into Galactocentric coordinates by means of the `astropy` Python library, assuming for the Sun a distance from the Galactic centre of $R_0 = 8.178$ kpc, a vertical height from the midplane of $z_0 = 0.02$ kpc, and a velocity $[U_\odot, V_\odot, W_\odot] = [-11.1, 248.0, 8.5]$ km s $^{-1}$. We then obtained the orbital parameters through the `galpy` code ([Bovy, 2015](#); [Mackereth & Bovy, 2018](#)), assuming the [McMillan \(2017\)](#) Galactic potential.

The selection criteria defining the halo substructures are adopted from the literature (also summarised in [Horta et al., 2023](#)) and are based on purely kinematic assumptions, where possible. In particular, we analysed the accreted debris of the following merger events: GSE, Sequoia, Thamnos, Helmi Stream, Heracles, and Sagittarius (see also Sec 2.6). We included ω Cen in the analyses (see Sec. 1.3), as a candidate remnant of an accretion event and possibly the nuclear star cluster of GSE/Sequoia ([Massari et al., 2019](#); [Myeong et al., 2019](#); [Callingham et al., 2022](#); [Limberg et al., 2022](#)), but see also [Pagnini et al. \(2025\)](#) for a possible diffe-

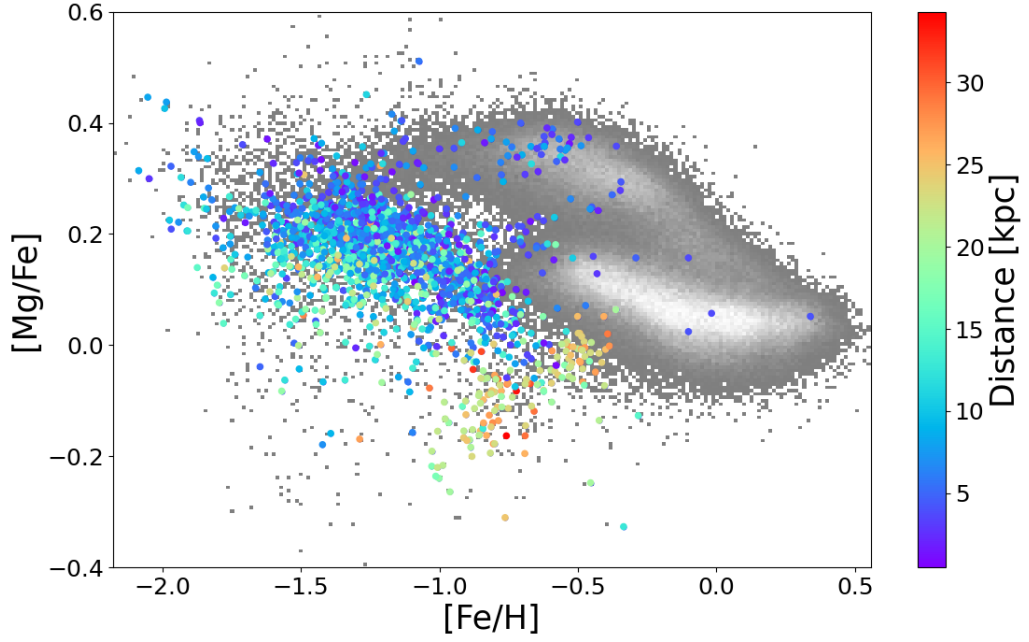


Figura 6.1: GSE (K) distribution in the $[Mg/Fe]$ vs. $[Fe/H]$ space, colour-coded by distance from the Sun. *From: Mori et al. (2025).*

rent origin of ω Cen, independent of GSE or Sequoia. The criteria, the references and the number of stars for each sample are reported in Table 6.2. Sgr and ω Cen are not described in Tab. 6.2, as their stars have been selected directly from the following catalogues: [Hasselquist et al. \(2021\)](#) and [Schiavon et al. \(2024\)](#), respectively. Note that the definition of the Heracles sample provided by [Horta et al. \(2021\)](#) and used in this work is not only based on kinematic cuts, but also on the following chemical selection criteria: $[Al/Fe] < -0.07$ & $[Mg/Mn] \geq 0.25$; $[Al/Fe] \geq -0.07$ & $[Mg/Mn] \geq 4.25 \times [Al/Fe] + 0.5475$; $[Fe/H] > -1.7$. Moreover, we defined the in situ disc by circularity¹ $\eta > 0.8$, and the metal-poor disc when considering an additional cut in metallicity $[Fe/H] \leq -0.6$.

In Fig. 6.1 we show the distribution of GSE stars in the $[Mg/Fe]$ vs. $[Fe/H]$ space obtained by using the aforementioned criteria and coloured according to their distance from the Sun. We can notice that beyond the main bulk of GSE stars drawing the typical low- α sequence of accreted dwarf galaxies, there is an orthogonal sequence due to distant stars (red-orange-green points). As the aim of this work is to evaluate the chemical compatibility of the halo substructure with GSE, we need a clean GSE sample, focussing on the chemical properties characteristic of

¹The circularity is defined as $\eta = \sqrt{1 - e^2}$.

the bulk of its stars. For this reason, we further selected GSE stars by imposing a cut in distance ($d \leq 10$ kpc). We verified that these distant putative GSE stars ($d \sim 20$ kpc) are in fact chemically compatible with Sagittarius and its stream, with some of them (24 out of 1603) are indeed part of the [Hasselquist et al. \(2021\)](#) sample. We will further comment on the chemical compatibility between GSE and Sagittarius in Section 6.5.1.

For a visualisation of these kinematic cuts, in Figure 6.2 we show the orbital energy (E) versus the angular momentum with respect to the Galactic disc (L_z). The different halo substructures are reported in various colours and we can identify them starting from the top (highest energies) to the bottom (lowest energies). At $E \geq -1.7$ we see the bulks of four substructures: the Sagittarius stream and dSph (orange) with mainly prograde orbits $L_z \geq 0.4$ and $E \geq -1.1$; below it ($-1.5 \leq E \leq -1.1$) and with the same L_z we find the Helmi stream (magenta/pink); then we have the GSE remnant (blue/cyan) with zero angular momentum (radial orbits); on the other hand, the Sequoia debris (dark/light green) with retrograde orbits ($L_z \leq -0.4$). In the intermediate energy range, $-2 \leq E \leq -1.6$, and with retrograde orbits, we see both Thamnos (brown) and ω Centauri (turquoise). Finally, at very low energy $E \leq -2$, there is the Heracles debris (red) with zero angular momentum.

Thus, by inspecting Figure 6.2, it is clear that the substructures defined by the dynamical criteria overlap partially, although they generally occupy different regions in the $E - L_z$ space. In particular, the Sequoia debris overlaps with GSE. The fact that the substructures reside in different regions, that is they feature different dynamical properties, is not necessarily a sign of a different origin. Indeed, a massive merger, as the GSE one was, might have left debris on both radial and retrograde orbits, even within the solar neighbourhood ([Mori et al., 2024](#)). On the other hand, the overlap of different substructures is not necessarily due to a common origin, as minor mergers of different accreted satellite galaxies might give rise to remnants that overlap with each other and with the one of the massive merger ([Jean-Baptiste et al., 2017](#)). Since we cannot constrain the merger history of the Milky Way from the halo stars' dynamical properties only, we need additional information, that in this study is provided by the chemical abundances of these stars.

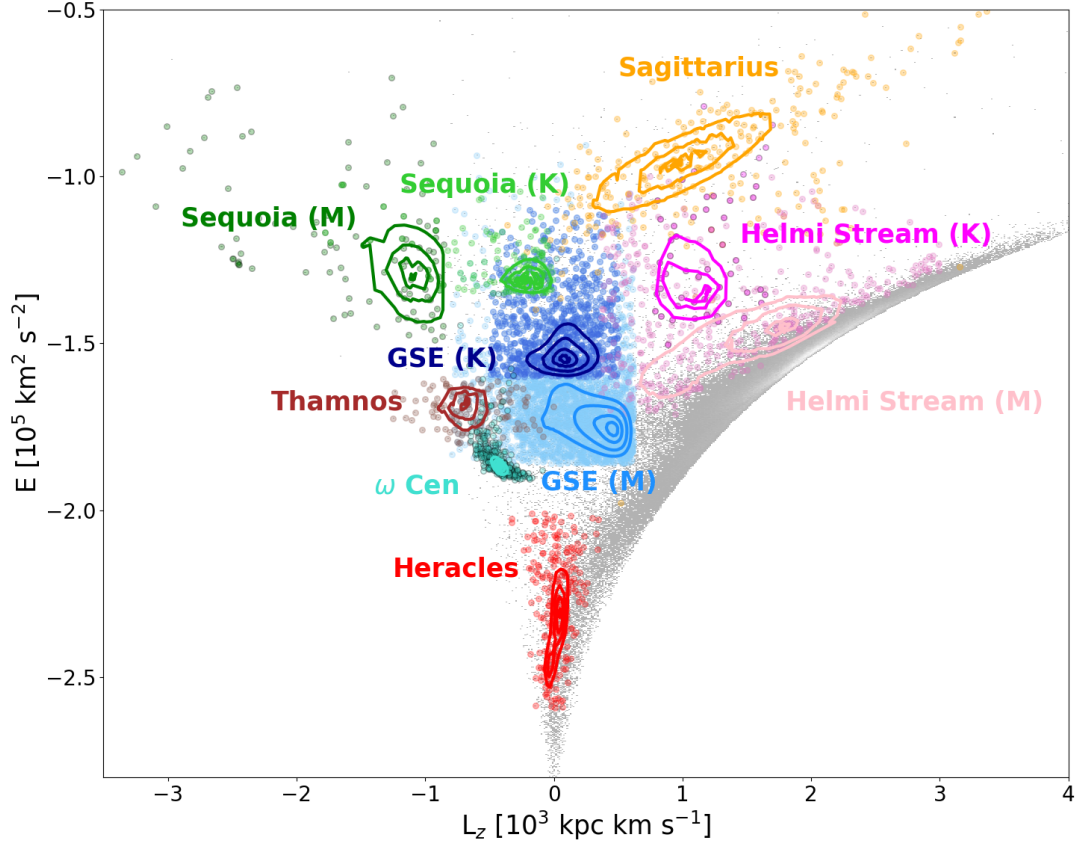


Figura 6.2: Distribution of the halo substructures in the orbital energy (E) versus angular momentum with respect to the Galactic disc (L_z) space. Beyond the dynamical definitions in Table 6.2, we report the Sgr dSph and ω Cen distributions for comparison. The contours represent probability density levels corresponding to 68%, 85%, 95%, 99.7% of the enclosed data for each substructure, based on Gaussian kernel density estimate. *From: Mori et al. (2025).*

6.3 Chemical properties

We begin describing the chemical properties of the halo substructures by showing their metallicity distribution functions (MDFs) in Figure 6.3. The colour legend is the same as in Figure 6.2 and in each panel we also report the GSE MDF for comparison in blue (they are all normalised). The solid lines show the mean of the distributions, while the dashed ones show their peak. In the top left panel, we show the GSE MDF (in blue for the K19 selection and in cyan for the M19 one): its stars are on average metal-poor ($\langle [\text{Fe}/\text{H}] \rangle = -1.15$). Through a comparison with the following panels, we can see that the MDFs of Sequoia (in green for the K19 selection and in light green for the M19 one), Heracles (in red) and Thamnos (in brown) have all similar peak values, being on average slightly more metal-poor than GSE (e.g., see also Myeong et al., 2019; Naidu et al., 2020). Then we show the MDFs of the Helmi Stream (in magenta for the K19b selection and in light pink for the M19 one), and of Sagittarius (in orange), which are on average more metal-rich than GSE and multiple-peaked. Moreover, we show the ω Cen MDF which is the most-metal poor substructure (mean value: -1.53) and peaks at even lower values metallicity. We finally show the MDF of the disc (in purple), and of the metal-poor disc sample (in pink), defined by the additional $[\text{Fe}/\text{H}] \leq -0.6$, which will be used in the following analyses. Similar MDFs could hint at common origin, especially those that show very similar peak values along with similar shapes (e.g, GSE, Sequoia, Heracles, Thamnos). However, different MDFs do not necessarily trace different accretion events, as a single massive satellite galaxy featuring a metallicity gradient can give rise to different MDFs in different regions of the $E - L_z$ space as we have discussed in Chapter 4 (see also Mori et al., 2024). As a consequence, we are not able to discriminate between independent mergers yet.

Beyond $[\text{Fe}/\text{H}]$, APOGEE DR17 provides a number of additional abundance ratios that it is important to explore to compare these halo substructures and quantify their similarities and/or differences. In the bottom panel of Figure 6.3 we show the $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, $[\text{C}/\text{Fe}]$, $[\text{Al}/\text{Fe}]$, and $[\text{Mn}/\text{Fe}]$ abundance ratios as a function of $[\text{Fe}/\text{H}]$. The solid lines show the trend of the medians of the distributions of the various halo substructures, computed with a threshold of minimum 3 stars per bin. The colour legend is the same as in previous figures. The grey 2D-histogram shows the distribution of the whole sample for reference. We can notice that the abundances of Sagittarius (in orange) are generally lower than in all the other substructures, with the exception of manganese. In the $[\text{Mn}/\text{Fe}]$

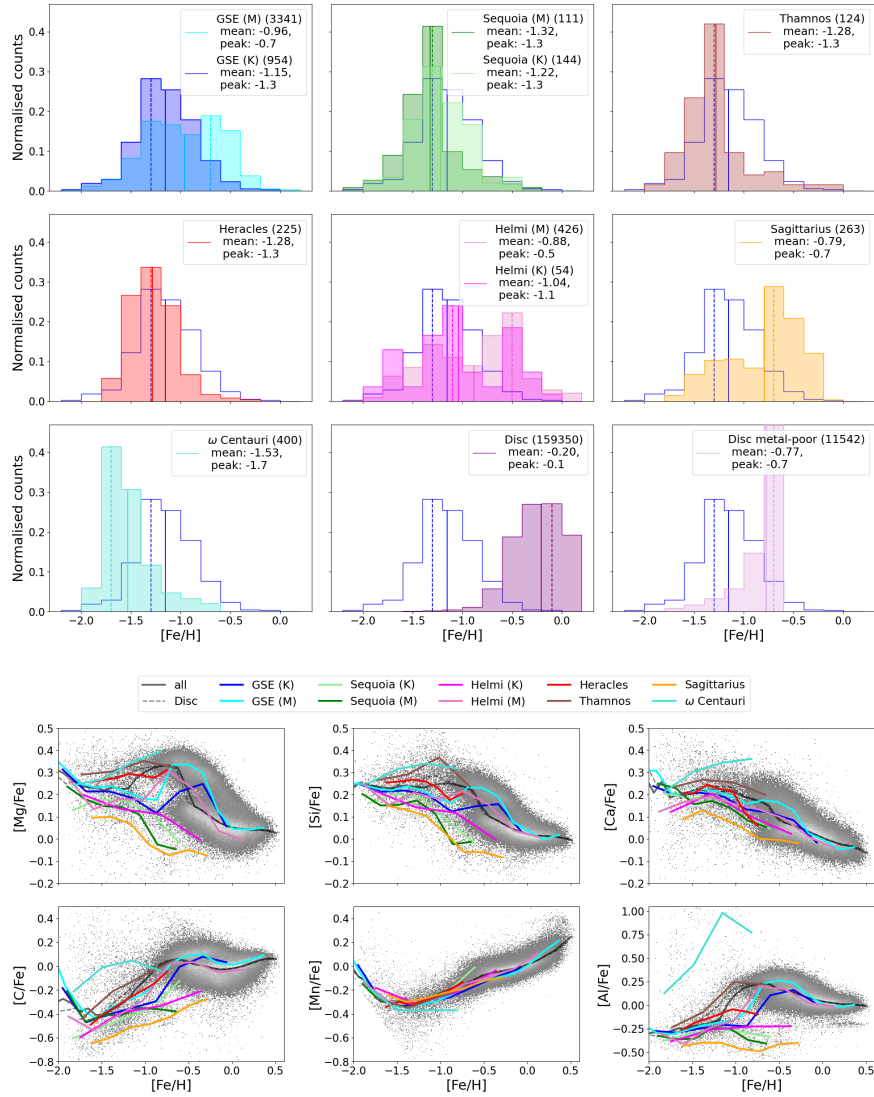


Figura 6.3: Upper panel: MDFs of the halo substructures in different colours with the same colour legend as in Figure 6.2. In the top left panel the GSE MDF (in blue/cyan) is shown for the two definitions considered (K19 and M19). In the following panels the blue GSE (K) MDF is compared to the ones of the other halo substructures, to the one of the disc, and finally to the metal-poor disc ($[Fe/H] < -0.6$) in the bottom right. The solid lines show the means, while the dashed ones the peaks (the values are reported in the legend). Bottom panel: median distribution in the $[Mg/Fe]$, $[Si/Fe]$, $[Ca/Fe]$, $[C/Fe]$, $[Mn/Fe]$ and $[Al/Fe]$ vs. $[Fe/H]$ spaces of the halo substructures, computed with a threshold of minimum 3 stars per bin. The grey distribution shows the whole sample for reference. *From: Mori et al. (2025).*

vs. $[\text{Fe}/\text{H}]$ the lowest median abundance is the one of ω Cen (in turquoise), which conversely is on average higher in all the other chemical spaces, in particular tracing a completely separate high- $[\text{Al}/\text{Fe}]$ sequence. Among the other halo substructures, we can see that GSE (in blue/cyan), Sequoia (in green/light green) and the Helmi Stream (in magenta/pink) usually trace similar sequences, occupying the regions of lower α , C, Al and Mn compared to in situ components, typical of accreted populations and dwarf galaxies satellites of the Milky Way. Heracles and Thamnos feature instead on average higher abundances of α elements, carbon and aluminum, generally connecting with the high- α thick disc sequence. We notice that the definitions of GSE, Sequoia and Helmi Stream from M19 are also closer to the high- α disc sequences with respect to the samples defined by K19, and in general reach higher values of metallicities.

The analysis of the median trends of the halo substructures highlights some differences in their chemical characterisation (see the bottom panel of Figure 6.3). However, computing the median of the abundances in iron bins, although allowing for a quick manifest comparison, on the other hand smooths out the specific patterns of the possible different populations comprised within the sample. In particular, given the broad redistribution in dynamical spaces of the massive merger debris and the consequential kinematic heating of the in situ component, the halo substructures defined by kinematic cuts are likely to feature a non-negligible amount of contamination from the GSE merger and the heated disc stars of the MW that got afterwards on halo-like orbits. However, in the computation of the median, the high- α abundances characteristic of the in situ component might get lost, averaged with the low- α ones typical of GSE and, in general, of the accreted stars, possibly providing as the final result an intermediate α trend, depending on the percentage of contamination from GSE and the heated disc. Our aim is thus quantifying this amount of contamination, in order to verify whether these substructures are actually chemically distinct (on statistical level) from the GSE debris and from disc stellar populations, and in that case unravel their specific chemical patterns, ultimately constraining properties of their galaxy-progenitors and evolutionary history.

6.4 Gaussian Mixture Models

The unravelling of the (possible) intrinsic chemical patterns of the halo substructures requires to quantify (and clean out) the contamination from GSE and from

the kinematically heated in situ disc stars, described in the previous Section 6.3. As the halo substructures are defined by pure kinematic cuts (with the exception of Heracles), we exploit their abundances to investigate their connection with the other halo components. We tackle the chemical comparison of the halo substructures with respect to GSE and the heated disc by means of Gaussian Mixture Models (GMM).

GMM is a probabilistic modelling technique that assumes that the distribution of the dataset is a combination of a finite number of Gaussian components. GMM is particularly well-suited for identifying substructures in multidimensional data, where single-Gaussian assumptions may not accurately capture the complexity of the distribution. The number of Gaussians and their parameters are not known a priori; the optimal model is selected on the basis of the Bayesian Information Criterion (BIC). The minimum of the BIC value indicates the best model while penalising excessive components. This method balances model complexity (number of Gaussians) with goodness-of-fit to prevent overfitting. Compared to alternative clustering techniques such as k-means, which assigns each data point to one cluster, GMM provides a soft clustering approach, assigning probabilities of belonging to different clusters, thus allowing for overlapping distributions and incorporating uncertainties.

The choice of using GMMs is driven by the fact that to perform the analysis we first of all want to take into account several different chemical abundances at the same time, to probe different nucleosynthetic channels, and discriminate between different star formation and chemical evolution histories. We considered the following abundances: $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, $[\text{C}/\text{Fe}]$, $[\text{Al}/\text{Fe}]$ and $[\text{Mn}/\text{Fe}]$, as motivated in Section 6.3. In the second place, we also want to compare the whole distributions of a given element with respect to iron rather than average values, because - knowing that these kinematic-defined samples imply a certain level of contamination - we do not want to lose the information of the different populations comprised that may be traced by the elements' patterns but not by the average. The use of GMMs allows us in this way to encompass the global chemical evolution of the halo substructures, imprinted in the distributions of the abundances, at the same time enabling us to account for all the chosen elements at once, not having to project in 2-dimensional spaces for the analysis.

Our aim is to evaluate the chemical compatibility of the various halo substructures with the main accreted component (GSE) and with the main in situ component (the disc). In order to do so, we considered the GSE distribution in the

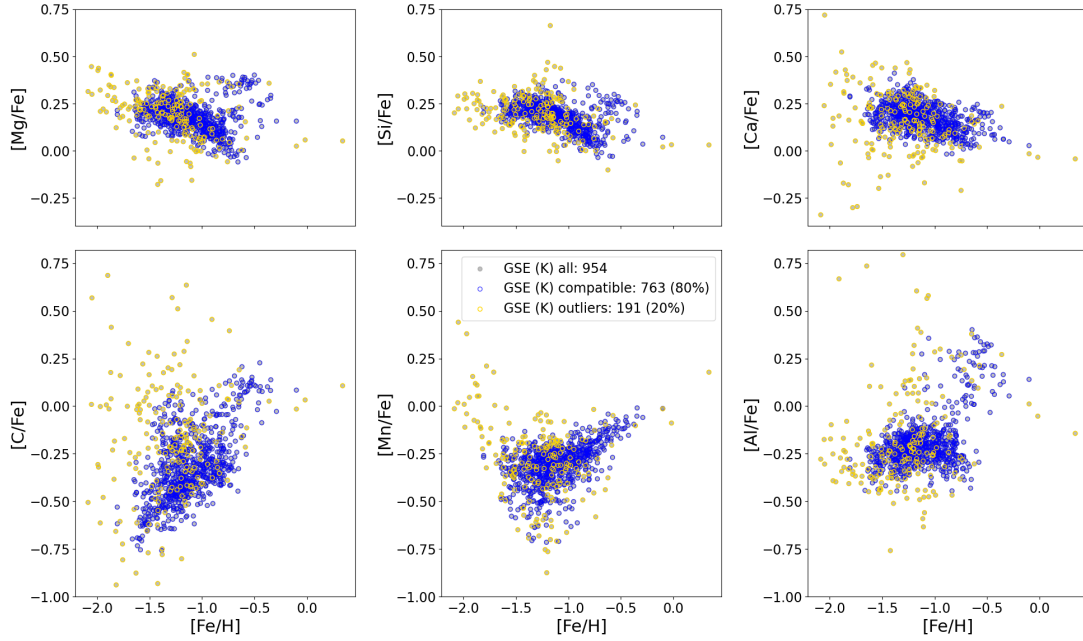


Figure 6.4: GSE distribution in the $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, $[\text{C}/\text{Fe}]$, $[\text{Al}/\text{Fe}]$, and $[\text{Mn}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ spaces. The blue circles highlight the bulk of the distribution, while the yellow ones are the outliers of the GSE distribution with respect to itself when a threshold of 20% is considered. *From: Mori et al. (2025).*

7-dimensional chemical space as our training sample, and we compared all the other substructures' samples with it. We performed the analysis with two definitions of GSE, that is (K) and (M), as to verify whether the results were depending on the kinematic selection assumed, and we tested different thresholds for the GMM.

In Figure 6.4 we show the GSE (K) distribution in the $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, $[\text{C}/\text{Fe}]$, $[\text{Al}/\text{Fe}]$, and $[\text{Mn}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ spaces. The optimal number of Gaussian components for GSE given by the minimisation of the BIC is 4. The blue circles in the figure highlight the bulk of the distribution (combining the four components), defining our GSE reference sample. The yellow circles are the outliers of the GSE distribution with respect to itself, that is the fraction of stars with the lowest probability density of belonging to GSE (in the figure we set the threshold to 20th percentile). We can see that most of the outliers are low-metallicity stars ($[\text{Fe}/\text{H}] \leq -1$), that are very scattered and feature in general higher abundances of carbon, manganese, and aluminium over iron (bottom row), while being still consistent with the bulk of GSE in the α elements (upper row).

We then compared the other halo substructure samples with the GSE reference

one, evaluating the probability density that any of their stars belonged to the GMM of GSE. The ones with a probability higher than the threshold were considered GSE-compatible stars; conversely, they were considered outliers. In this way, we obtain a percentage of chemical compatibility of the various halo substructures with respect to GSE. We associated an uncertainty with these fractions by bootstrap resampling the data a thousand times, considering the uncertainties of the chemical abundances given by APOGEE with a Monte Carlo approach. We finally computed the means and standard deviations of the realisations.

The same approach has been used to quantify the chemical compatibility of the different halo substructures with the kinematically heated disc. Because it is expected that the heated disc has the same chemical abundances of the disc (see, e.g. [Di Matteo et al., 2019](#); [Belokurov et al., 2020](#)), to quantify this compatibility, we made use of the chemical abundances of the disc itself, as defined in Sect. 6.3.

6.5 Chemical compatibility

In this Section, we present the results of the chemical comparison analysis of the various halo substructures with respect to GSE (Sec. 6.5.1) and the heated disc (Sec. 6.5.2), performed by means of GMMs considering the following elements: [Fe/H], [Mg/Fe], [Si/Fe], [Ca/Fe], [C/Fe], [Al/Fe], and [Mn/Fe]. We finally show in Sec. 6.5.3 the pattern of the cleaned halo substructures, that is the stars that are not chemically compatible neither with GSE nor with the heated disc, and that thus could hint new meaningful details about the evolution of the Milky Way.

6.5.1 Comparison with the accreted component: GSE

The fractions of chemically compatible stars within each halo substructure with respect to GSE are reported in the different columns of Table 6.5.1, along with the total number of stars and the associated uncertainty, computed by bootstrap resampling the data ($n_{boot} = 1000$) as described in Section 6.4. Furthermore, we list the results obtained considering different threshold values for the accepted probability density, which are 5, 10, 15 and 20 percentiles. The fractions vary accordingly, but the ranking of the most chemically-compatible substructures is not affected. Finally, we show the chemical comparison with respect to the two different definitions of GSE considered in this work (K and M), the results of which are generally consistent with each other within the uncertainties.

	Heracles	Sequoia (K)	Sequoia (M)	Thamnos	Helmi (K)	Helmi (M)	Sgr	ω Cen
N_*	225	144	111	124	54	426	263	400
GSE (K)								
$f_{comp}(th = 5)$ (%)	90 ± 3	85 ± 4	78 ± 5	80 ± 5	75 ± 8	80 ± 4	68 ± 10	21 ± 4
$f_{comp}(th = 10)$ (%)	82 ± 4	77 ± 4	67 ± 5	68 ± 6	60 ± 8	69 ± 4	51 ± 10	10 ± 3
$f_{comp}(th = 15)$ (%)	74 ± 4	71 ± 4	60 ± 6	58 ± 6	49 ± 8	60 ± 4	40 ± 8	5 ± 2
$f_{comp}(th = 20)$ (%)	66 ± 4	65 ± 4	54 ± 6	48 ± 5	41 ± 7	52 ± 4	32 ± 7	2 ± 1
GSE (M)								
$f_{comp}(th = 5)$ (%)	90 ± 2	82 ± 4	76 ± 5	89 ± 3	75 ± 7	84 ± 2	68 ± 6	23 ± 3
$f_{comp}(th = 10)$ (%)	82 ± 3	74 ± 4	64 ± 5	80 ± 4	58 ± 8	75 ± 3	51 ± 7	11 ± 2
$f_{comp}(th = 15)$ (%)	74 ± 4	67 ± 4	56 ± 5	69 ± 5	47 ± 7	67 ± 3	39 ± 7	5 ± 2
$f_{comp}(th = 20)$ (%)	66 ± 4	61 ± 4	49 ± 5	59 ± 4	39 ± 7	60 ± 3	29 ± 6	2 ± 1

Tabella 6.2: Fraction of chemically compatible stars with GSE. Total number of stars and fraction of chemically compatible stars (with relative uncertainties) for MW halo substructure (different columns) with respect to the different GSE definitions (from top to bottom, GSE (K) and GSE (M)), assuming different thresholds (different rows). We remind that the fractions are relative to the threshold assumed and must be renormalised with the maximum possible (95, 90, 85, 80 when assuming thresholds=5, 10, 15, 20) for absolute values.

The extensive abundance distributions of stars of each halo substructure chemically compatible with GSE, and their outliers, are reported in the upper panels of the figures in the Sec. 6.8, when a threshold of 20 is considered.

In Figure 6.5 we show for each of the halo substructures considered in this study (reported on the x-axis) the relative percentage (and uncertainty) of chemical compatibility with respect to GSE, in blue when considering the GSE (K) definition and in cyan for the GSE (M) case. These percentages were obtained when a threshold of 20% was considered, so in this case the upper limit for the compatibility is 80%. For this reason, we report on the right y-axis the percentages normalised to 80%, to highlight the absolute chemical compatibility. The choice to assume a threshold of 20% to quantify the possible contamination by GSE for the various substructures was driven by the objective of being as conservative as possible, of selecting the very bulk of the GSE's distribution and of finding results independent from its outskirts.

From the fractions of chemically compatible stars, we can draw the following outcomes:

- Heracles and Sequoia (K) feature the highest fraction of chemically compatible stars with GSE (K), 66% and 65% respectively (out of the 80% maximum possible), with comparable values when considering the GSE (M) definition.

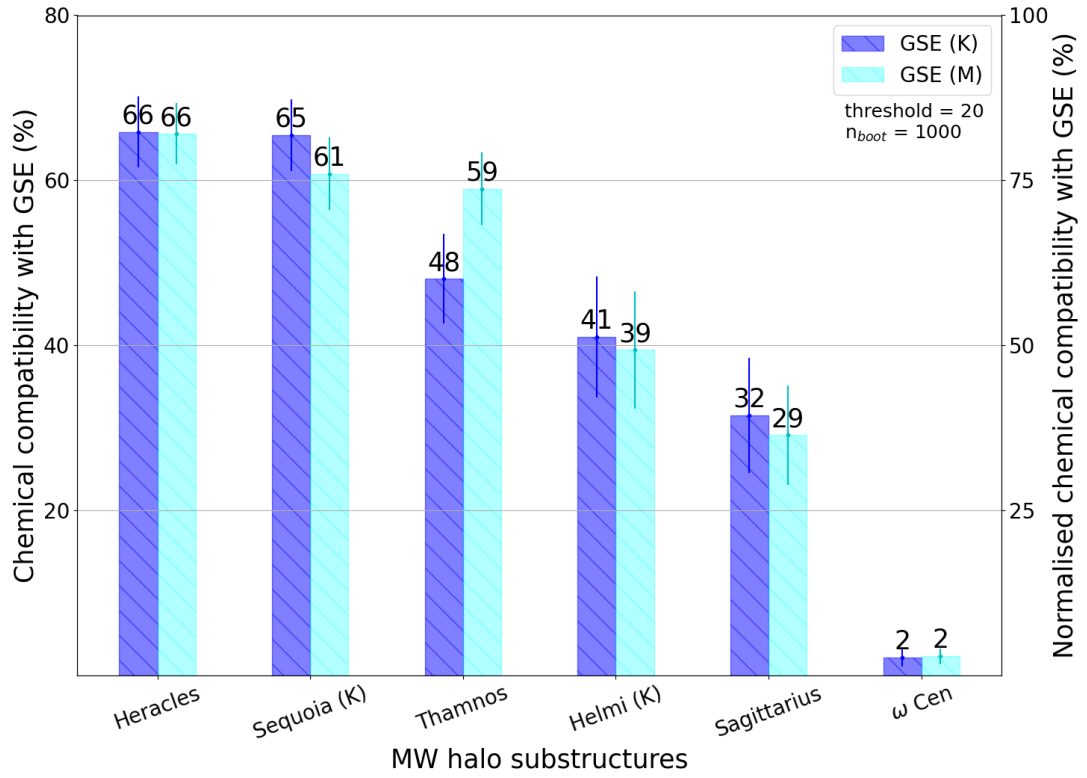


Figure 6.5: Fractions (%) of chemically compatible stars of the Milky Way halo substructures with respect to GSE (K) in blue and GSE (M) in cyan. The relative uncertainties are obtained by bootstrapping the data a thousand times, accounting for the observational uncertainties. The fractions are computed assuming a threshold equal to the 20th percentile of the probability density, thus the chemical compatibility normalised to 80 percent is reported on the right y-axis. *From: Mori et al. (2025).*

In particular, for Sequoia, stars compatible with GSE redistribute quite uniformly over the whole extent of GSE abundances (see the upper panel of Fig. 6.14). These two facts suggest that the bulk of its stars (a fraction higher than 80% in absolute terms) might have had a common origin with GSE. It is unlikely that completely independent systems had such similar chemical patterns, a fortiori given that they are supposed to have been accreted at different redshifts and with different mass ratios (Kruijssen et al., 2020). In any case, it is very hard with current data to distinguish between the nowadays chemical distributions of Sequoia from that of GSE. The Heracles distribution, instead, although featuring the same chemical compatibility with GSE as Sequoia, does not cover completely that of GSE, being generally shifted at higher α abundances (see the upper panel of Fig. 6.13). However, we remind that the Heracles definition is based on abundance criteria as well, artificially removing Al-rich and low [Mg/Mn] stars.

- Thamnos showcases a high percentage of compatibility as well ($\sim 50\%$), meaning that one every two stars in Thamnos is chemically compatible with the restricted bulk of GSE (K). However, in this case, there is a higher discrepancy when considering different GSE definitions, with an even higher compatibility fraction when considering the GSE (M) definition ($\sim 60\%$). This discrepancy will be clearer when putting it in context with the comparison with the heated disc; yet again in both cases the scenario of a shared formation with GSE is plausible, this time possibly comprising at least another population with a different origin.
- The Helmi Stream exhibits a lower percentage of GSE (K) compatible stars, but still equal to 2 every 5 ($\sim 40\%$), consistently with the GSE (M) values. In this case, even though there might be a substantial presence of GSE stars within this sample, we expect a significant contribution from at least another stellar population as well.
- Sagittarius presents approximately one third of stars chemically compatible with GSE, consistently in both definitions. This is interesting because in this case we know already that these must be different systems as we can still observe the elongated spheroid remnant of the dwarf spheroidal galaxy of Sgr and its tidal stream with leading and trailing branches for tens of kpc along their quasi-polar orbit. As a consequence, the non-negligible fraction of chemical compatibility that we find between Sgr and GSE could actually

	GSE (K)	GSE (M)	Heracles	Seq (K)	Seq (M)	Helmi (K)	Helmi (M)	Thamnos	Sgr	ω Cen
N_*	1603	4258	225	144	111	54	426	124	263	400
Metal poor disc										
$f_{comp}(th = 5)$ (%)	63 ± 3	68 ± 2	74 ± 3	58 ± 5	54 ± 5	43 ± 7	63 ± 3	66 ± 5	65 ± 7	4 ± 1
$f_{comp}(th = 10)$ (%)	33 ± 4	45 ± 3	51 ± 4	26 ± 5	26 ± 5	21 ± 6	47 ± 3	41 ± 5	33 ± 10	1 ± 1
$f_{comp}(th = 15)$ (%)	13 ± 3	29 ± 2	33 ± 4	6 ± 3	8 ± 4	10 ± 4	34 ± 3	28 ± 4	9 ± 6	0 ± 0
$f_{comp}(th = 20)$ (%)	5 ± 1	22 ± 1	19 ± 3	1 ± 1	1 ± 1	8 ± 4	26 ± 2	19 ± 4	1 ± 1	0 ± 0

Tabella 6.3: Fraction of chemically compatible stars with the disc. Total number of stars and fraction of chemically compatible stars (with relative uncertainties) for every MW halo substructure (different columns) with respect to the metal-poor disc ($[\text{Fe}/\text{H}] \leq -0.6$), assuming different thresholds (different rows). We remind that the fractions are relative to the threshold assumed and must be renormalised with the maximum possible (95, 90, 85, 80 for thresholds=5, 10, 15, 20) for absolute values.

hint that the GSE sample may comprise stars coming from the Sagittarius Stream itself. This would be also consistent with the fact that we can find Sgr stripped stars at comparable distances from the Sun and that the galaxy is predicted to have passed within the solar neighbourhood contributing to the formation of the stellar halo from both test-particle orbits and N-body simulations (Law et al., 2009; Laporte et al., 2019). On top of that, if we take a look at the $E - L_z$ space (Fig. 6.2), we can also notice that the distribution of Sgr partly overlaps with that of GSE in the high energy region ($1.4 \leq E \leq 1.1$), corroborating the contamination of Sgr stars within the kinematically defined GSE sample.

- ω Cen is the sample that shows the lowest compatibility with GSE in our study (2%). This is a surprising result, because it is commonly considered the nuclear star cluster of GSE (see Massari et al., 2019; Callingham et al., 2022; Limberg et al., 2022). Infact, the two nuclear star clusters for which we have detailed chemical abundances, namely M54 and the Galactic nuclear star cluster, show a remarkably similarity with their host galaxies Sagittarius (see Pagnini et al., 2025) and the Galactic bulge/inner disc itself (Ryde et al., 2025; Nandakumar et al., 2025), respectively.

6.5.2 Comparison with the in situ component: the disc

In a complementary way with respect to the comparison with the main accreted component (i.e., GSE), we want to chemically compare the halo substructures to

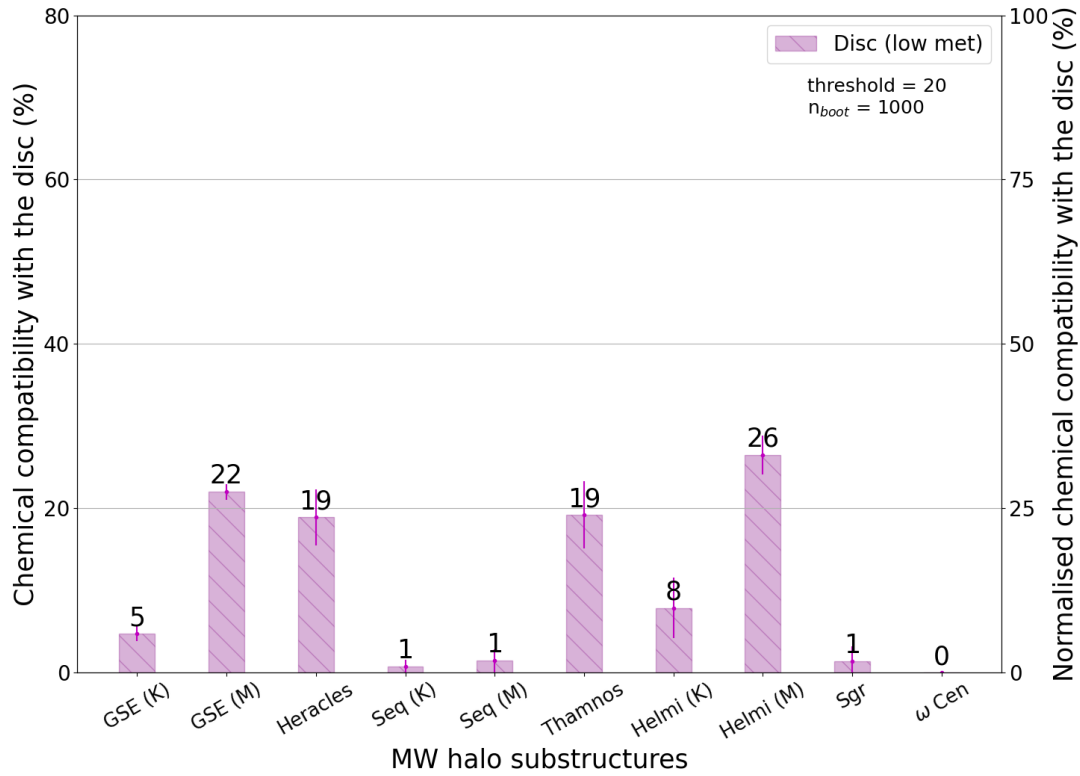


Figura 6.6: Fractions (%) of chemically compatible stars of the Milky Way halo substructures with respect to the metal-poor disc ($[\text{Fe}/\text{H}] \leq -0.6$). The relative uncertainties are obtained by bootstrapping the data a thousand times, accounting for the observational uncertainties. The fractions are computed assuming a threshold equal to the 20th percentile of the probability density, thus the chemical compatibility normalised to 80 percent is reported on the right y-axis. *From: Mori et al. (2025).*

the main in situ component, that is the disc, to quantify the fraction of these substructures which may be contaminated by heated disc stars – that is stars originally born in the disc of the MW, and subsequently heated by one or several merger events to halo kinematics (e.g., [Di Matteo et al., 2019](#); [Belokurov et al., 2020](#)). Because this heated disc is expected to be made of stars with the same chemical abundances of disc stars it originated from, to estimate its contribution to the halo substructures, we quantify the chemical compatibility with the disc itself.

As Figure 6.3 shows, many substructures have chemical tracks which tend to converge to those of the disc at low metallicities. To ensure that we had sufficient statistics to construct a robust GMM model for low-metallicity disc stars, we therefore defined a disc sample, selecting stars with $[\text{Fe}/\text{H}] \leq -0.6$ and circularity $\eta \geq 0.8$.

For each halo substructure, in the different columns of Table 6.5.2 we report the fractions of stars chemically compatible with the metal-poor disc along with the total number of stars and their associated uncertainty ($n_{boot} = 1000$). As for the case of the comparison with GSE (Table 6.5.1), we list the results obtained considering different threshold values for the accepted probability density, that are 5, 10, 15 and 20 percentiles. The fractions vary accordingly, but the following results hold true.

In Figure 6.6 we summarise the relative percentages (and uncertainties) of chemically compatible stars with respect to the metal-poor disc for each of the halo substructures considered in this study (reported on the x-axis). These percentages were also obtained assuming a threshold of 20%, so the upper limit for the compatibility is 80%. For this reason, we report on the right y-axis the percentages normalised to 80%, to highlight the absolute chemical compatibility. As for the corresponding abundance distributions of chemically compatible and outlier stars of each halo substructure with respect to the metal-poor disc, we refer the reader to Sec. 6.8 (bottom panels of the figures).

From the chemical comparison with the metal-poor disc, we might divide the MW halo substructures into two groups:

- one made up of substructures that have little in common with the disc (chemical compatibility $\leq 5\text{-}10\%$). The halo debris with the lowest chemical compatibility with the metal-poor disc are: GSE (K) (5%), Sequoia (1% both in the K and M definitions), ω Cen (0%), the Sagittarius Stream (1%), and the Helmi Stream (K) (with a higher compatibility of 8%). Therefore,

these samples can be fairly considered clean from the presence of metal-poor heated disc stars, with the only exception of the Helmi Stream (K), which shows a low but non-negligible disc contamination.

- the other one comprises the systems that feature instead considerable chemical compatibility with the disc in the low-metallicity regime (on the order of 20-30%). This group includes Heracles (19%) and Thamnos (19%), but also the M19 definitions of GSE (22%) and Helmi Stream (26%). We notice a correlation between the high chemical compatibility with the metal-poor disc and the high α -elements' abundances: the "high- α " halo substructures are generally found to be similar also in the other chemical abundances to the low metallicity tail of the disc by the GMM analysis.

6.5.3 Outliers: the cleaned substructures

Once contamination from the massive merger of GSE and from the heated disc has been identified and quantified in each halo substructure, the contaminant stars can be removed from each substructure to highlight eventual intrinsic chemical patterns in the remaining *outliers*. The conclusions drawn from the analysis of the cleaned substructures are the following.

- In the Heracles sample, the abundances of the vast majority (at least 80%²) of the stars can be explained as a combination of two different stellar populations: the GSE debris and metal-poor disc stars. Thus, very little room is left for interpretation of the outliers with respect to these two components.
- As long as Sequoia is concerned, instead, beyond the high chemical compatibility with GSE, we still have a small but significant group of stars (about 35% of the sample) that result as being compatible neither with GSE nor with the disc. In Figure 6.7 we show the distribution in the chemical spaces for the outliers of Sequoia (K) with respect to GSE (K), with the same colour code as in the previous figures. For reference, we show the 68% (1σ), 80% (bulk considered for the comparison) and 95% (2σ) contours of the GSE probability density distribution (in black), when a threshold of 20 is taken into account. If we take a closer look at these outliers (in green) and we

²This percentage has been derived by adding the percentage of Heracles stars which are compatible either with GSE (K) or with the metal-poor disc, and subtracting to this sum the disc contamination of GSE (K), which is of the order of 5% (see Tab. 6.5.2 and Fig. 6.6).

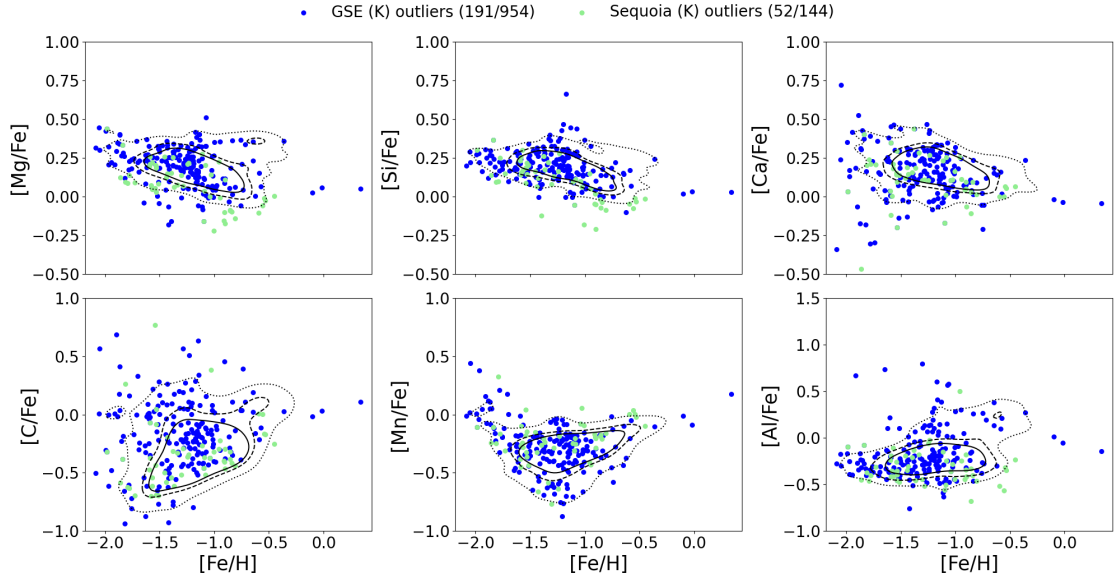


Figure 6.7: Abundance distribution in the $[Mg/Fe]$, $[Si/Fe]$, $[Ca/Fe]$, $[C/Fe]$, $[Al/Fe]$, and $[Mn/Fe]$ vs. $[Fe/H]$ spaces for the outliers of the Sequoia (K) (in green) and GSE (K) (in blue) samples with respect to GSE itself. The black contours show the 68%, 80% and 95% of the GSE probability density distribution for reference, when a threshold of 20% is considered. *From:* [Mori et al. \(2025\)](#).

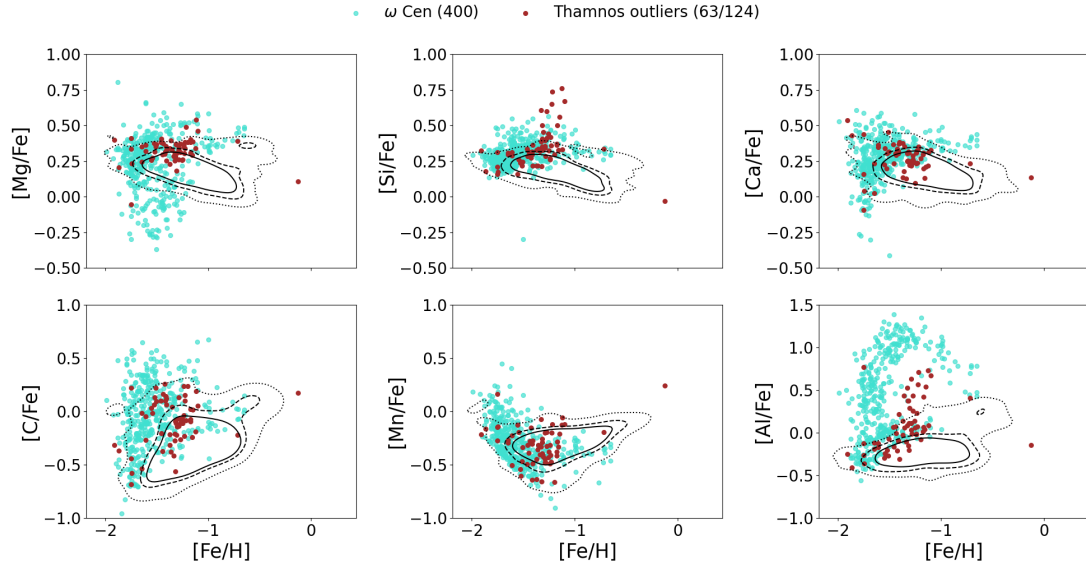


Figure 6.8: Abundance distribution in the $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, $[\text{C}/\text{Fe}]$, $[\text{Al}/\text{Fe}]$, and $[\text{Mn}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ spaces for the outliers of the Thamnos (in brown) and ω Cen (in turquoise). The black contours show the 68%, 80% and 95% of the GSE distribution for reference, when a threshold of 20% is considered. *From: Mori et al. (2025).*

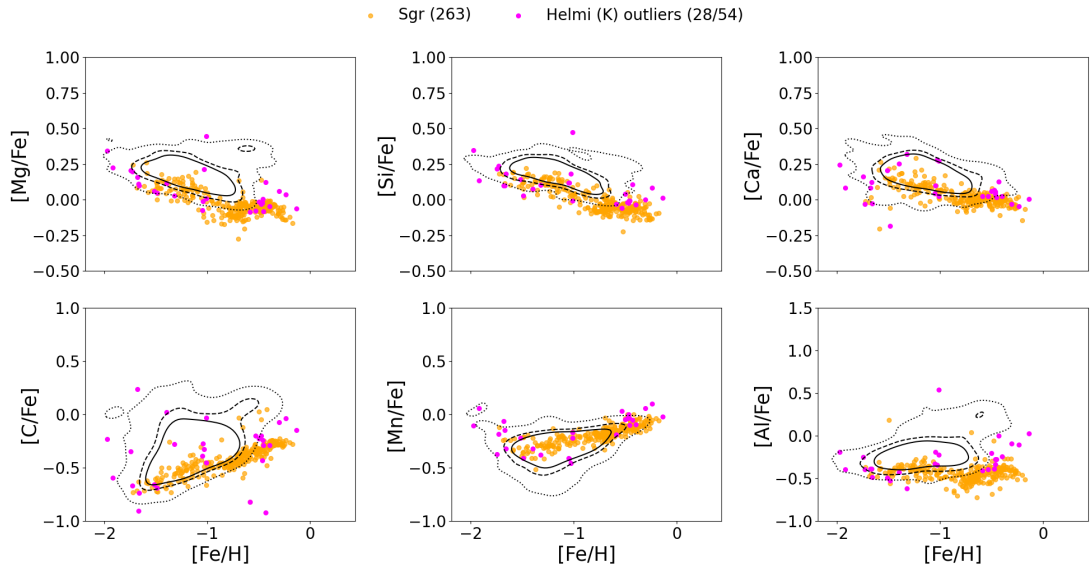


Figure 6.9: Abundance distribution in the $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, $[\text{C}/\text{Fe}]$, $[\text{Al}/\text{Fe}]$, and $[\text{Mn}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ spaces for the outliers of the Helmi Stream (in magenta) and Sagittarius Stream (in orange). The black contours show the 68%, 80% and 95% of the GSE distribution for reference, when a threshold of 20% is considered. *From: Mori et al. (2025).*

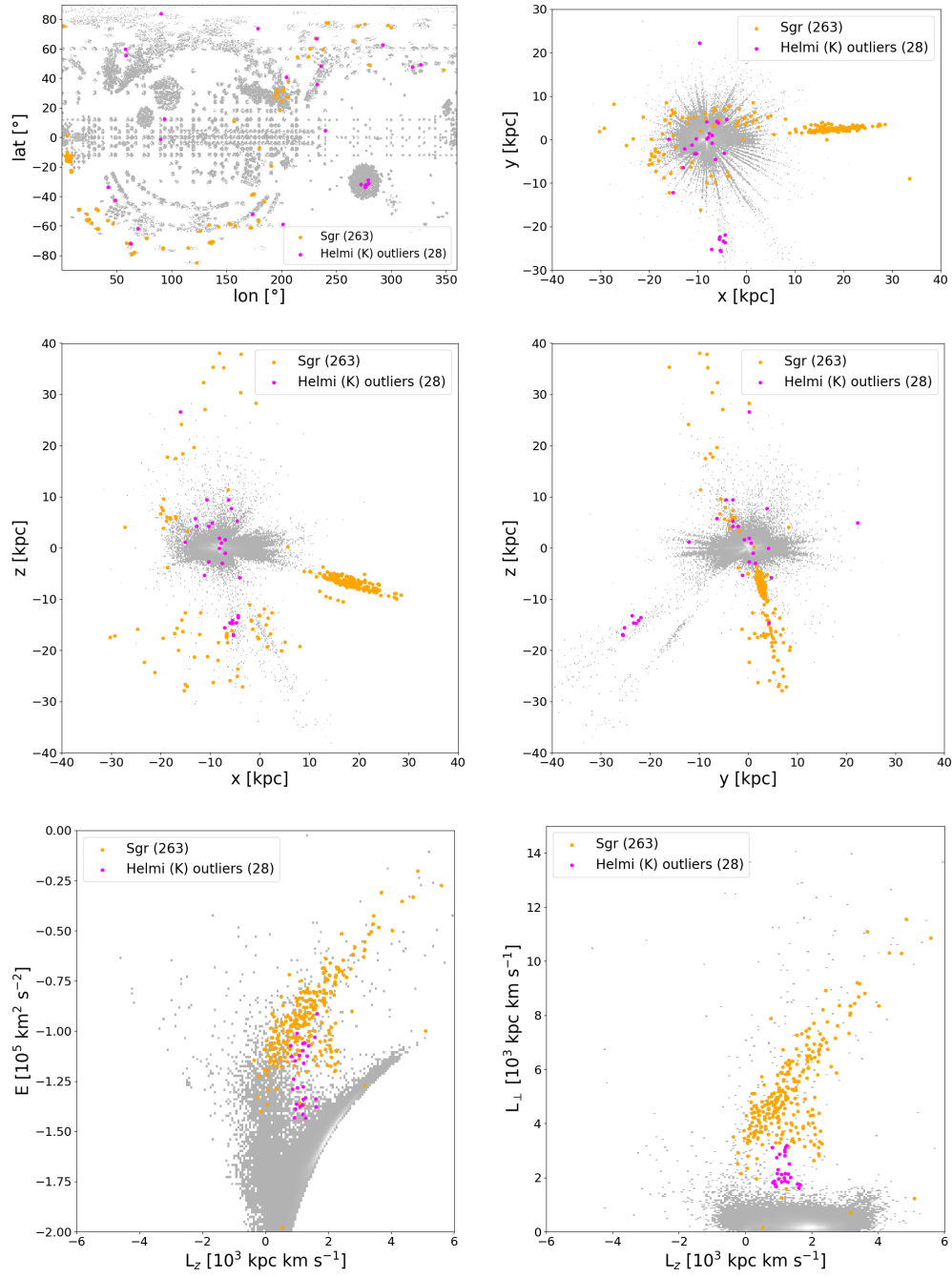


Figure 6.10: Spatial and dynamical distributions in the $lon-lat$, $x-y$, $x-z$, $y-z$, $E-L_z$, $L_{\perp}-L_z$ spaces of the cleaned Helmi Stream (in magenta), Sagittarius' stars (in orange) and the whole sample (in grey). *From: Mori et al. (2025).*

visually compare them to the GSE’s outliers (in blue) with respect to its bulk (black contours), we can actually notice that many of the green points are still distributed within the regions of the chemical spaces where also the blue points lie. This suggests that the threshold assumed for the modelling cut out the same kind of populations from both samples, meaning that the a significant part of the Sequoia’s outliers could actually be compatible with those of GSE. As a consequence, we argue that the chemical compatibility between the Sequoia and the GSE samples is at least as high as 65%, strongly hinting at a common origin for GSE and Sequoia.

In this interpretation, Sequoia would be made of metal-poor³ stars once part of the GSE progenitor, and which were subsequently lost on retrograde orbits, during the early phases of its accretion into the Galaxy. Note that this interpretation is valid if the GSE progenitor had initially a metallicity gradient, as predicted by simulations (e.g., [Koppelman et al., 2020](#); [Amarante et al., 2022](#); [Khoperskov et al., 2023c,a](#); [Mori et al., 2024](#)).

We emphasise, however, that among the stars in Sequoia which have low probability to be chemically compatible with GSE, some have chemical abundances systematically different from that of the GSE outliers. This is mainly visible in Fig. 6.7 at $[\text{Fe}/\text{H}] \gtrsim -1$, where some (5-10) stars (in green) have $[\text{Mg}/\text{Fe}]$ and $[\text{Si}/\text{Fe}]$ lower than those of GSE outliers in the same $[\text{Fe}/\text{H}]$ interval. This could be explained again by abundance gradients within GSE, due to the fact that star formation and chemical enrichment are more efficient in the centres of galaxies compared to their outskirts. Consistently with coming from GSE outskirts, Sequoia stars are not only on average on higher energies and more retrograde orbits (see Fig. 6.2) and are more metal-poor, being the first stars to be lost, but also its outliers feature on average lower $[\text{Mg}/\text{Fe}]$ and $[\text{Al}/\text{Fe}]$ abundances as expected for stars coming from regions of less efficient chemical enrichment (see upper and middle panels in Figure 3 of [Skúladóttir et al., 2025](#), that is, Fig. 5.3 in this thesis). Given the limited statistics, it is difficult to draw definitive conclusions. Nevertheless, we point out that at most 10% of the stars in the Sequoia sample may have an origin other than GSE.

- Regarding Thamnos, despite being significantly compatible with both GSE

³As shown in Fig. 6.3 and by others (e.g., [Myeong et al., 2018](#)), Sequoia has a mean metallicity which is lower than that of GSE.

and the disc, its outliers feature some peculiar trends in their abundances, different from GSE/disc and the other substructures. In particular, we can observe a prominent branch in high $[\text{Al}/\text{Fe}]$ that is unusual in common satellite dwarf galaxies of the MW, but rather typical of globular clusters. We then decided to compare its outliers with ω Cen, as they are also very close (partly overlapping) in the $E - L_z$ space (see Fig. 6.2). In Figure 6.8, we show the distribution in the chemical spaces of the Thamnos' outliers (in brown) and of ω Cen (in turquoise). We can indeed see that Thamnos' outliers overlap with the ω Cen distribution in all the chemical spaces, following quite tightly its trends. However, on average, these outliers are shifted at higher metallicities than the bulk of ω Cen stars. If there is indeed a link between these two systems, it suggests that the progenitor of ω Cen must have also originally had a metallicity gradient. Furthermore, we can observe a metal-rich star of Thamnos ($[\text{Fe}/\text{H}] \sim -0.1$) isolated from both distribution, but we recall that the comparison with the disc is done only for $[\text{Fe}/\text{H}] \leq -0.6$, so that the Thamnos' metal-rich outlier could likely be a heated disc star (see bottom panel of figure 6.15).

- Finally, as for the Helmi Stream, we already mentioned its chemical compatibility with GSE and the disc: both are likely present in the Helmi Stream, but they do not make up the whole sample. We then considered its outliers and compared them this time with the Sagittarius dSph and stream chemical distribution. This choice was driven by the fact that they are very close in the $E - L_z$ space, but also in the $L_\perp - L_z$ space, by which the Helmi Stream is defined (see Figure 6.2 and bottom panels of Figure 6.10), partly overlapping in both spaces, especially in the high- E and high- $L_\perp$ regions. In Figure 6.9, we show the distribution in the chemical spaces of the Helmi Stream's outliers compared to the Sagittarius distribution. We can see that the outliers (in magenta) overlap quite nicely with the Sgr distribution among the chemical spaces. Moreover, we explored the spatial distribution of the Helmi Stream outliers with respect to that of the Sagittarius (see $lon - lat$, $x - y$, $x - z$, and $y - z$ spaces in the upper two rows of Figure 6.10). Especially in the $y - z$ space, it is possible to appreciate how the cleaned Helmi Stream is actually sitting in the middle of the Sagittarius Stream. However, we note that in the $x - z$ space they are not associated with the bulk of the Sagittarius stream at $x > 0$. The combination of these spatial, dynamical and chemical arguments hint in the direction of a significant contamination

from Sagittarius within the Helmi Stream. Finally, we point out that the three Helmi Stream’s outliers that are the most metal-rich and high- α are probably disc stars, as they overlap in all chemical spaces with the in situ distribution, but the GMM-based comparison with the disc had been done only for $[\text{Fe}/\text{H}] \leq -0.6$. These stars would have likely been recognised by the GMM model as disc contaminants if we had used a higher threshold in metallicity for building the GMM model of the disc than what we have chosen.

6.6 Discussion

In the previous Section, we have chemically compared the kinematic substructures in the Milky Way stellar halo with the GSE (K) and the metal-poor disc with GMMs, in order to quantify the contamination from these two components within the system’s samples. We have been able to identify the stars within each substructure that might be related to GSE and/or to the disc, and once we have considered the cleaned substructures’ samples we indeed observed peculiar hidden chemical patterns that might have outshone different formation scenarios for the systems analysed. What about the GSE/disc-compatible stars then? What are their dynamical properties?

To shed light on the potential dynamical distribution of GSE within the $E - L_z$ space, we show all GSE chemically compatible stars of the halo substructures that we discovered from the analyses with GMMs in the left panel of Figure 6.11. For reference, in blue/cyan rectangles we report the GSE dynamical cut definitions from the literature (K and M, respectively), while in the different coloured rectangles the other halo substructures are reported with the same legend as in previous figures. The coloured points are the stars within each halo substructure sample that are chemically compatible with GSE (K), according to the GMM with threshold equal to 20, again with the same colour legend. We can appreciate the very broad distribution of GSE in both angular momentum and energy, as expected from a massive merger (mass ratio $\geq 1:10$) by simulations (e.g., [Koppelman et al., 2020](#); [Amarante et al., 2022](#); [Khoperskov et al., 2023c,a](#); [Mori et al., 2024](#)). We can then see that the compatible stars are actually sparsely distributed within each rectangle, not just concentrated in the closest regions to GSE. This fact means that the issue of associating the accreted stars to different merger debris is not simply due to an imprecise chosen value for the dynamical borders assumed to define the halo

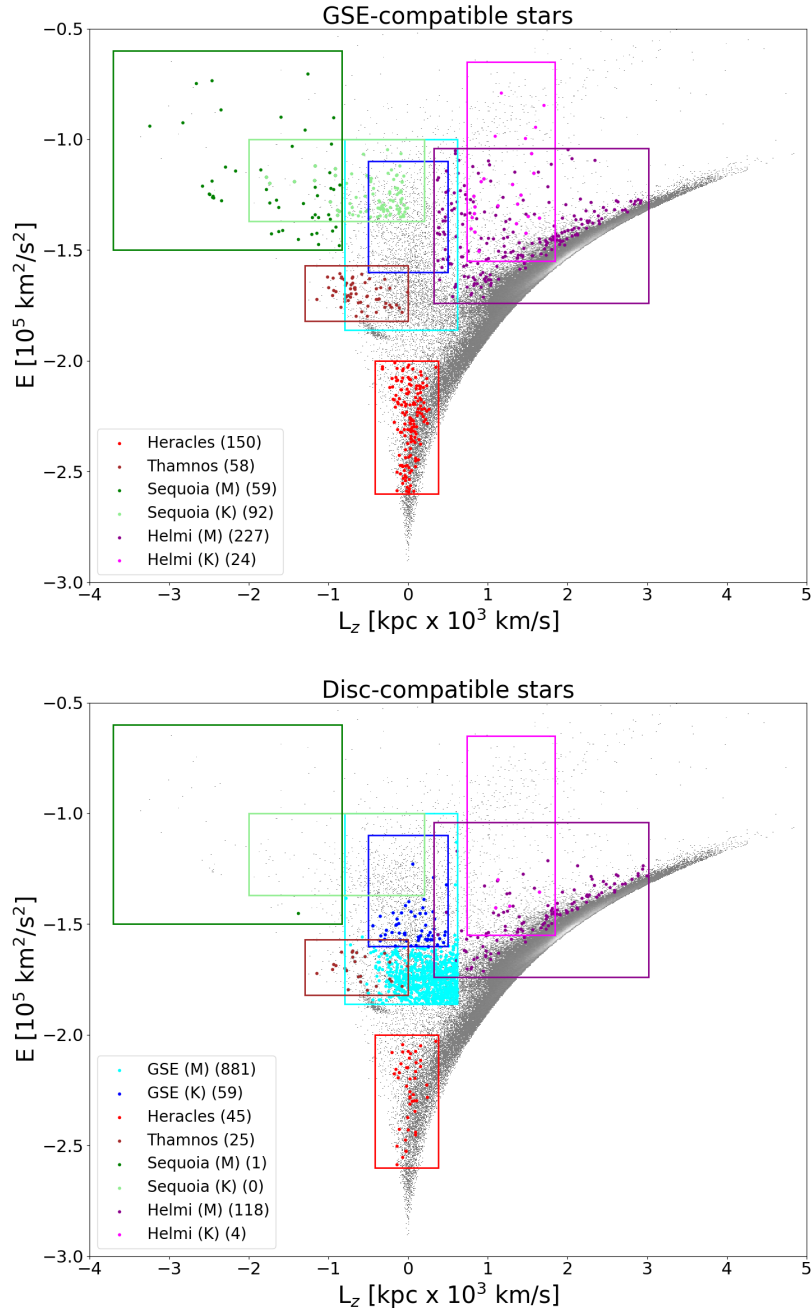


Figura 6.11: Distribution in the $E - L_z$ space of all the stars that are chemically compatible to GSE (K) (left panel) and the metal-poor disc (right panel), within each halo substructure (the number of the compatible stars are reported in the legend). For reference we show the kinematic definitions of these substructures as rectangles with the same colour legend as the points, along with the GSE (K) and (M) definitions in blue and cyan respectively. *From: Mori et al. (2025).*

substructures. It rather hints that we need to reconsider the approach of defining new independent accretion events on the basis of kinematic cuts and chemical averages only.

On the other hand, in the right panel of Figure 6.11, we show the stars of each halo substructure that are chemically compatible with the metal-poor disc, again with the same colour legend for the data points and the defining rectangles. Unlike in the previous case, this time the distributions of chemically compatible stars are not spread out in a wide range of E and L_z within the dynamical definitions. We can see that the highest densities of disc-compatible stars are found in the most prograde and lowest energy regions of the rectangles, that is, the closest $E - L_z$ region to the disc's one, even though the compatibility was established on dynamically unbiased quantities (i.e., chemical abundances). However, this could be due to the intrinsic bias of the sample that features the highest density of data close to the dynamical distribution of the disc. Anyway, we can see that the substructures containing the highest percentages of stars chemically compatible with the metal-poor disc are either those on prograde orbits, such as the Helmi Stream (K) and (M), or those on low-energy retrograde or radial orbits, such as Thamnos, ad GSE (M), and Heracles. Substructures on retrograde and high-energy orbits, such as Sequoia, have a fraction of stars compatible with the disc which is null. This result is compatible with the prediction of numerical simulations, which show that the retrograde heated disc in the $E - L_z$ plane is usually confined to low-energy orbits, unless the early Milky Way had accreted a significant amount of mass through mergers (i.e. about 50% of its total mass at the time of accretion(s), see for example [Jean-Baptiste et al., 2017](#)).

In Table 6.4, we then summarise the fractions (in %) of chemically compatible stars with respect to GSE (K) (first column) and the metal-poor disc (second column) for each of the halo substructures (different rows) when a threshold of 20 is assumed for the GMM analysis. In the third column, we also report the upper limits for their outliers, computed taking into account that the GSE (K) itself features a 5% chemical compatibility with the disc, that is subtracting this 5% from the sum of GSE- and disc-compatible stars.

Moreover, in Figure 6.12, we summarise the fractions (in %, for threshold=20) of chemically compatible stars with respect to GSE (K) (in blue) and the metal-poor disc (in lilac) for each of the halo substructures (listed to the left) for which we further analysed the chemical distributions of the outliers, that is their cleaned

	GSE (K)	Disc	Outliers
Heracles	66 ± 4	19 ± 3	≤ 20
Sequoia (K)	65 ± 4	1 ± 1	≤ 39
Sequoia (M)	54 ± 6	1 ± 1	≤ 50
Thamnos	48 ± 5	19 ± 4	≤ 38
Helmi Stream (K)	41 ± 7	8 ± 4	≤ 56
Helmi Stream (M)	52 ± 4	26 ± 2	≤ 27
Sagittarius	32 ± 7	1 ± 1	≤ 72
ω Centauri	2 ± 1	0 ± 0	≤ 100

Tabella 6.4: Compatibility of halo substructures with GSE and the disc. The fractions (expressed in %) of GSE/disc chemically compatible stars are computed assuming for the GMM a threshold of 20. The GSE definition is the K19 one, while for the disc it is the metal-poor sample. We remind that the fractions are relative to the threshold assumed (20) and must be renormalised with the maximum possible (80) for absolute values. The outliers fractions are upper limits, taking into account that the GSE (K) itself features a 5% chemical compatibility with the disc.

samples. We recall the overlap in the chemical spaces of the outliers (in grey) of Sequoia with those of GSE (K) (in blue), of the outliers of Thamnos with the distribution of ω Cen (in turquoise), and of the outliers of the Helmi Stream (K) with that of Sgr (in orange). The similarity in their chemical distributions may hint at additional contamination from these systems.

We would like to emphasise that the chemical compatibility measured in the previous sections for the different halo substructures cannot be directly interpreted as a common origin between different substructures. If we consider Heracles and Sequoia, for example, they both have a large fraction of stars compatible with GSE, however the bulk of Heracles stars compatible with GSE has $[\text{Fe}/\text{H}]$ values below -1 , while GSE extends well above this threshold. If this chemical compatibility points to a common origin, this behaviour may be explained by a repartition of accreted GSE stars in the $E - Lz$ plane which depends on metallicity, which would be a natural outcome if the GSE progenitor had an initial metallicity gradient. However, this shift in the mean metallicity of GSE and GSE-compatible stars in Heracles may also point out an intrinsically different origin of these two samples of stars.

As for Sequoia, the high level of compatibility that this substructure shows with

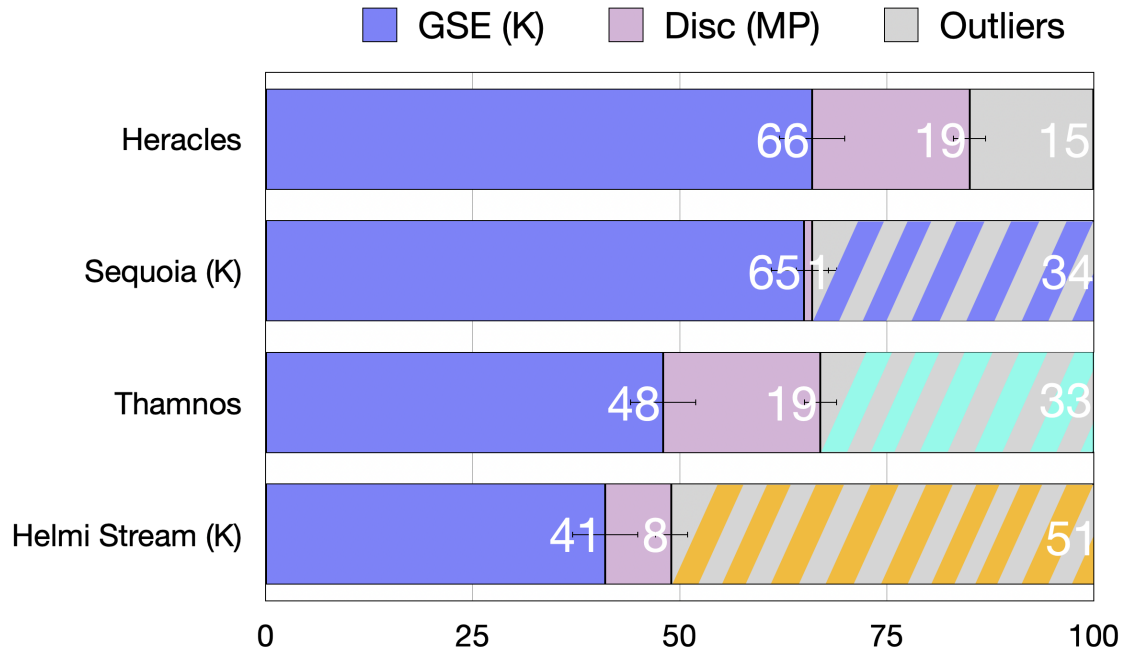


Figura 6.12: For each of the halo substructures listed to the left, we show the fractions (%) of chemically compatible stars with respect to GSE (K) (in blue) and the metal-poor disc (in lilac), along with the lower limit for the outliers (in grey), computed through the GMM analysis assuming a threshold of 20. The patterned grey highlights the similar chemical distribution of the outliers of Sequoia (K) to those of GSE (K) (blue), of the outliers of Thamnos to the distribution of ω Cen (turquoise), and of the outliers of the Helmi Stream (K) to that of Sgr (orange). From: [Mori et al. \(2025\)](#).

GSE is also accompanied by a more homogeneous distribution of its stars over the whole range of chemical abundances spanned by GSE – making the genetic link between these two samples more sound than for the Heracles-GSE case. Also for Sequoia, however, we have found that there may be some contamination – at a few percent level – of relatively metal-rich stars (i.e. with $[\text{Fe}/\text{H}] \gtrsim -1$) which have lower α -abundances than GSE stars at similar metallicities.

While Heracles possibly shares a common origin both with the GSE and with the disc populations, and Sequoia is plausibly associated to GSE, the Helmi Stream is even a more complex mixture of stars. Once cleaned of the possible GSE and heated disc contaminants, the remaining stars show a striking overlap in chemical abundances with the Sagittarius dwarf. This is interesting, given also its proximity in energy and angular momentum. However, this result opens the question about the real nature of this system, whether there is an intrinsic and specific signature of an accretion event (visible in chemical abundances) or whether this structure is the overlap of stars having different origins. It also invites to reconsider the extension in the $E - L_z$ space of stars lost by the Sagittarius dwarf, part of which seems to fall in the Helmi stream selection, part in the GSE selection itself.

Finally, this work used the same dataset and the same selections (for most substructures) as those used by [Horta et al. \(2023\)](#), hereafter H23. Also in H23, the objective was to compare substructures defined on the basis of mainly kinematic criteria in order to quantify their similarity in chemical spaces. There are some methodological differences between the two works, however. The way of quantifying the chemical similarities or differences between substructures is not the same. We take into account all the stars that make up a substructure and quantify the fraction of stars compatible with another substructure, through a GMM approach. H23, on the other hand, use a restricted subset of stars from a given substructure, all with the same specific metallicity – which may vary depending on the substructure considered. For these stars, they estimate the average abundances (relative to iron), which they then compare with those of a comparison substructure. H23’s approach, by its very nature, does not allow to determine whether a structure could be a mixture of several others.

These different approaches, and the impossibility to capture contamination by using mean values, lead H23 to conclude, for example, that GSE and the Helmi stream have a null probability to be chemically compatible, while – as discussed in the previous section – we can assess that in fact 40% of stars in the Helmi stream are

chemically compatible with GSE, concluding that this stream of stars contains also about 10% of stars chemically compatible with the disc and the remaining compatible with the chemical abundances of Sagittarius dwarf stars. Another example is given by Heracles, for which a chemical compatibility with both GSE and the disc is excluded by H23. As we have seen in the previous sections, our analysis leads to a different result, suggesting that about 65% of Heracles stars are chemically compatible with GSE and 20% with the metal-poor disc. These few examples demonstrate how subtle the analysis of these structures can be, and also the complexity that can be hidden in these “systems”, which — it is worth remembering — are often defined on the basis of kinematic criteria alone, the limitations of which have been demonstrated in recent years (see introduction).

Once it has been clarified that regions in the $E - L_z$ space cannot be studied as single populations, making use of their chemical abundances to disentangle their origin becomes much more complex.

6.7 Conclusions

In this chapter and in (Mori et al., 2025), we took advantage of the *Gaia* EDR3 and APOGEE DR17 catalogues to compare from a chemical point of view the halo substructures of the Milky Way that are (quasi-only) defined with dynamical cuts. The objective of the study was to compare the minor accretions of the MW to the last massive merger event of the MW (i.e., GSE) and to the in situ component (that is, the heated disc), in order to clean their samples from these two sources of contamination and study their intrinsic chemical patterns. To this aim, we firstly built a Gaussian Mixture Model assuming a threshold of the 20th percentile of the GSE distribution in a 7-dimensional chemical space given by the following abundances: $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, $[\text{C}/\text{Fe}]$, $[\text{Mn}/\text{Fe}]$, and $[\text{Al}/\text{Fe}]$. These elements allow a thorough analysis of different nucleosynthetic channels (α , iron peak, odd- Z light elements) to probe different chemical enrichment histories on a star-by-star basis, while preserving a very high-precision sample (median uncertainties ≤ 0.02). Given the assumed threshold, we found that:

- A number of halo substructures (e.g., Heracles, Sequoia, and Thamnos) contain a significant ($\gtrsim 50\%$) percentage of stars chemically compatible with GSE. Among them, Sequoia is the one for which the chemical compatibility with GSE seems to robustly indicate a common origin, that is both a high compatibility fraction (66%) and overall overlap of chemical distributions.

- Other systems, such as the Helmi stream and Sagittarius, show an intermediate level (between 30% and 40%) of compatibility with GSE.
- ω Cen features a negligible (2%) chemical compatibility with GSE, although commonly claimed to be its nuclear star cluster in the literature.
- Around half of the samples analysed also feature non-negligible contamination from the metal-poor disc ($\sim 20\%$). In particular, substructures on prograde orbits, as the Helmi Stream, but also on retrograde/radial orbits with low energy, as Thamnos and Heracles, are found to be more contaminated by the metal-poor disc. The latter are also α -enhanced, highlighting a correlation between the "high- α " substructures and the disc contamination.
- The GSE compatible stars are spread throughout the $E - L_z$ space, but also within the whole substructures' kinematic definitions, suggesting that they are not simply imprecisely defined, but rather that these kinematic definitions are poorly meaningful.

Once the contamination by GSE and the heated disc have been removed, the cleaned substructures still reveal a number of interesting features, which lead us to suggest the following:

- Sequoia, while heavily dominated by GSE stars, contains a small fraction of stars (between 5 and 10%) which seem to deviate from the GSE chemical abundance trends, these stars being less α -enhanced (in Mg and Si) than GSE stars at the same metallicities ($[\text{Fe}/\text{H}] \gtrsim -1$). They could represent the less efficiently chemically enriched outskirts of the GSE original galaxy.
- Thamnos cleaned sample ($\sim 35\%$) is mostly made of stars whose chemical patterns overlap with those of ω Cen. This similarity is interesting, given also the proximity of Thamnos and ω Cen in the $E - L_z$ space, possibly suggesting an interconnection between the two systems.
- While half of the Helmi stream appears to be chemically compatible either with GSE ($\sim 40\%$ of its stars) or with the metal-poor disc ($\sim 10\%$ of its stars), the remaining half shows, for the large majority, an impressive similarity to the chemical patterns of the Sagittarius dSph and its stream. Once more, this fact together both with the proximity in the $E - L_z$ and $L_\perp - L_z$ spaces and in their spatial distribution, hints a non-negligible contamination from Sgr within the Helmi Stream.

- The significant compatibility of the chemical patterns of Sagittarius with those of GSE ($\sim 30\%$) seems to suggest that stars from the Sagittarius stream do contaminate the GSE sample as well, a fortiori given the overlap between the two substructures in the $E - L_z$ space at high energies.

In summary, none of these substructures appears as a unique population of stars with its own origin, all show some chemical overlap with GSE, the metal-poor disc, Sagittarius and even ω Cen. The GSE region itself possibly contains part of the Sagittarius stream.

6.8 Appendix

In this appendix, we show the detailed chemical comparison of each of the halo substructures with respect to GSE (K) and the metal-poor disc, in the upper and lower panels of Figures 6.13-6.18, respectively. The extensive abundance distributions of the stars are reported in the following chemical spaces: $[\text{Mg}/\text{Fe}]$, $[\text{Si}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, $[\text{C}/\text{Fe}]$, $[\text{Al}/\text{Fe}]$, and $[\text{Mn}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ spaces.

In particular, in each figure we show in grey the stars of the bulk (80%) of GSE (K) in the upper panel and the ones of the bulk of the metal-poor disc in the lower panel, which are the samples to which we compare the other halo substructures. Then, for example, in the upper panel of Figure 6.13, we highlight in red the stars of Heracles that are identified as chemically compatible with GSE (K) by the GMM analysis with a threshold of 20, while in yellow the ones that are not. The total number of stars of the samples, the fraction of the ones shown (compatible or not), and the relative percentages are reported in the legend above the plot. We remind that these percentages are relative to the threshold assumed (20), so in this case the upper limit for the compatibility is 80% (that is, they should be normalised to 80% for absolute values). This threshold, however, allowed us to be very conservative and select the inner bulk of the GSE/disc distributions. The same is done for the comparison with the metal-poor disc ($[\text{Fe}/\text{H}] \leq -0.6$) in the lower panel.

Analogously, with the colour-coding of the main body of the article, in the following figures 6.14, 6.15, 6.16, 6.17, and 6.18, we show in green, brown, magenta, orange, and turquoise the stars of Sequoia (K), Thamnos, Helmi Stream (K), Sagittarius, and ω Centauri that are chemically compatible with GSE (K) and the metal-poor disc, respectively.

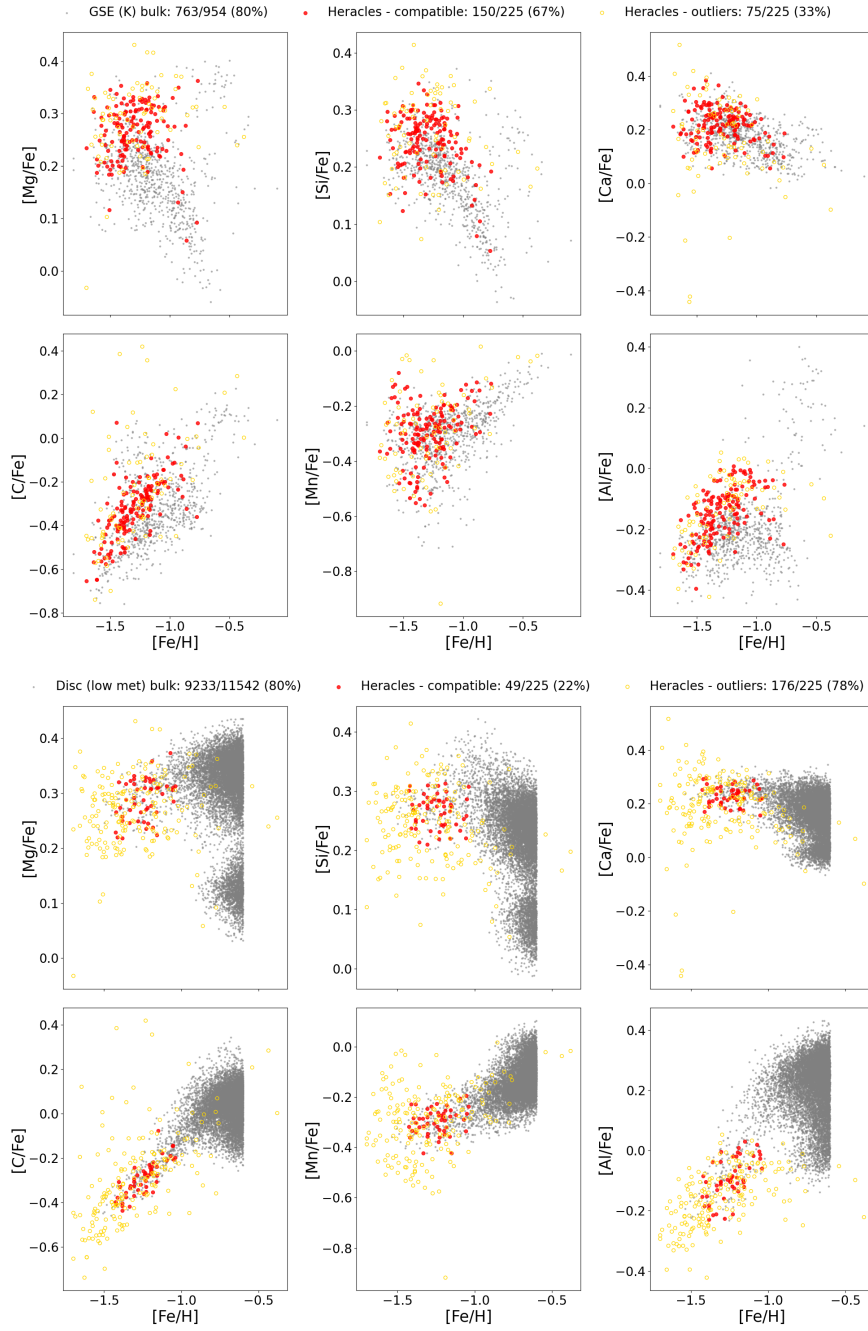


Figura 6.13: Heracles' stars that are chemically compatible (threshold=20) with GSE (K) (upper panel) and with the metal-poor disc (lower panel) are shown in red, while the ones that are not compatible in yellow. The relative percentages are reported in the legend (and have to be normalised to 80% for absolute values). In grey we show the bulk (80%) of GSE and of the metal-poor disc, in the upper and lower panels, respectively. *From: Mori et al. (2025).*

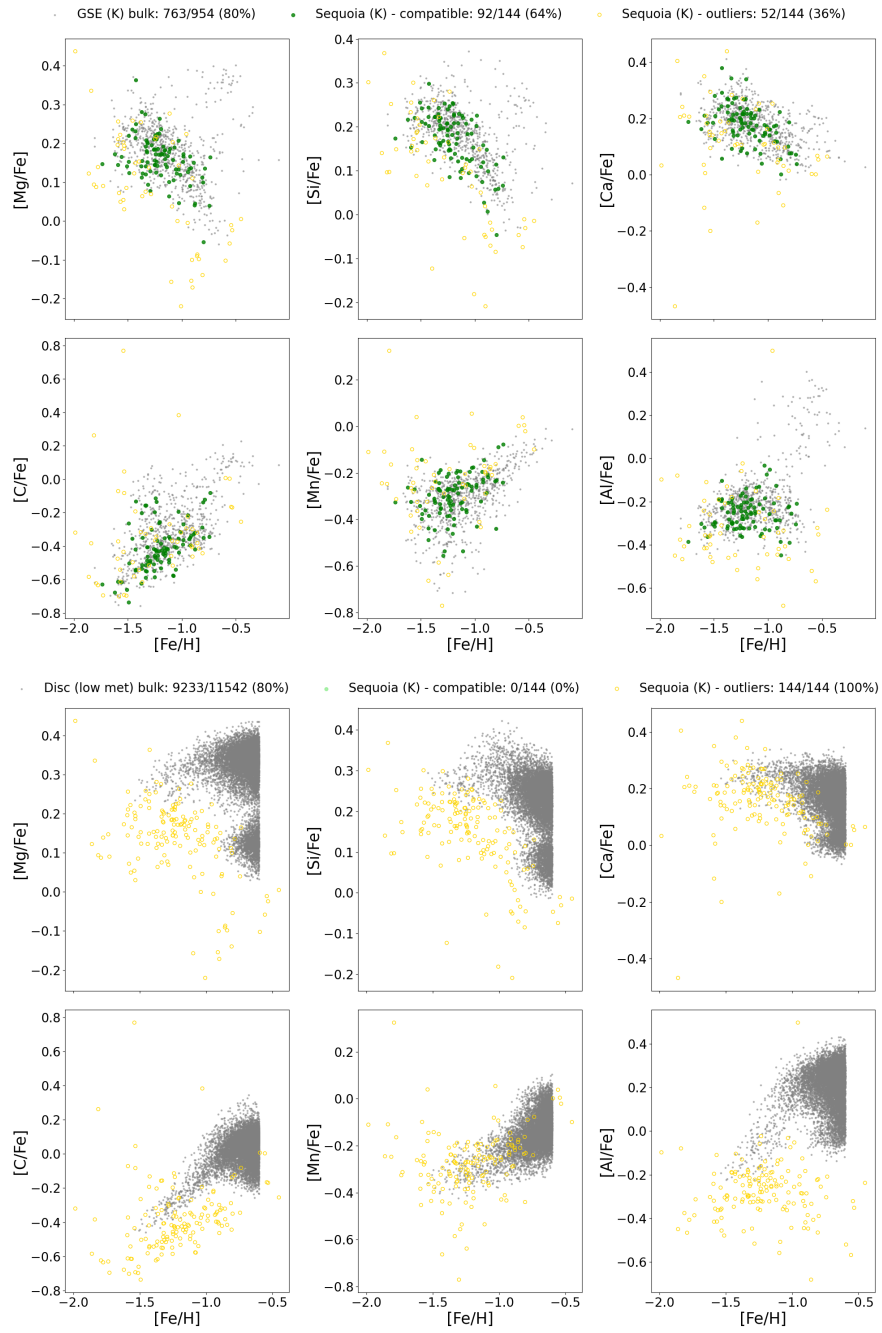


Figura 6.14: Sequoia (K)’s stars that are chemically compatible (threshold=20) with GSE (K) (upper panel) and with the metal-poor disc (lower panel) are shown in green, while the ones that are not compatible in yellow. The relative percentages are reported in the legend (and have to be normalised to 80% for absolute values). In grey we show the bulk (80%) of GSE and of the metal-poor disc, in the upper and lower panels, respectively. *From: Mori et al. (2025).*

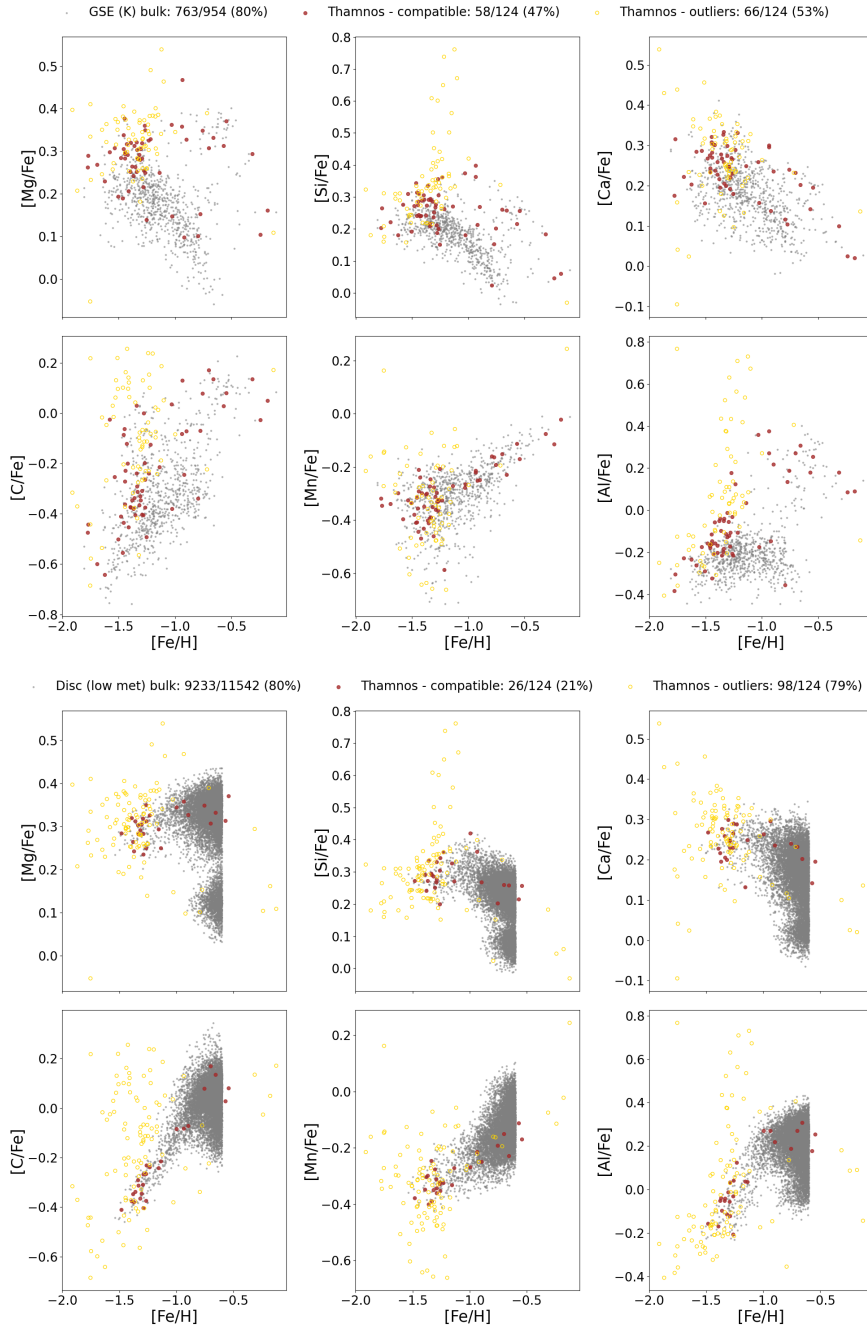


Figura 6.15: Thamnos' stars that are chemically compatible (threshold=20) with GSE (K) (upper panel) and with the metal-poor disc (lower panel) are shown in brown, while the ones that are not compatible in yellow. The relative percentages are reported in the legend (and have to be normalised to 80% for absolute values). In grey we show the bulk (80%) of GSE and of the metal-poor disc, in the upper and lower panels, respectively. *From: Mori et al. (2025).*

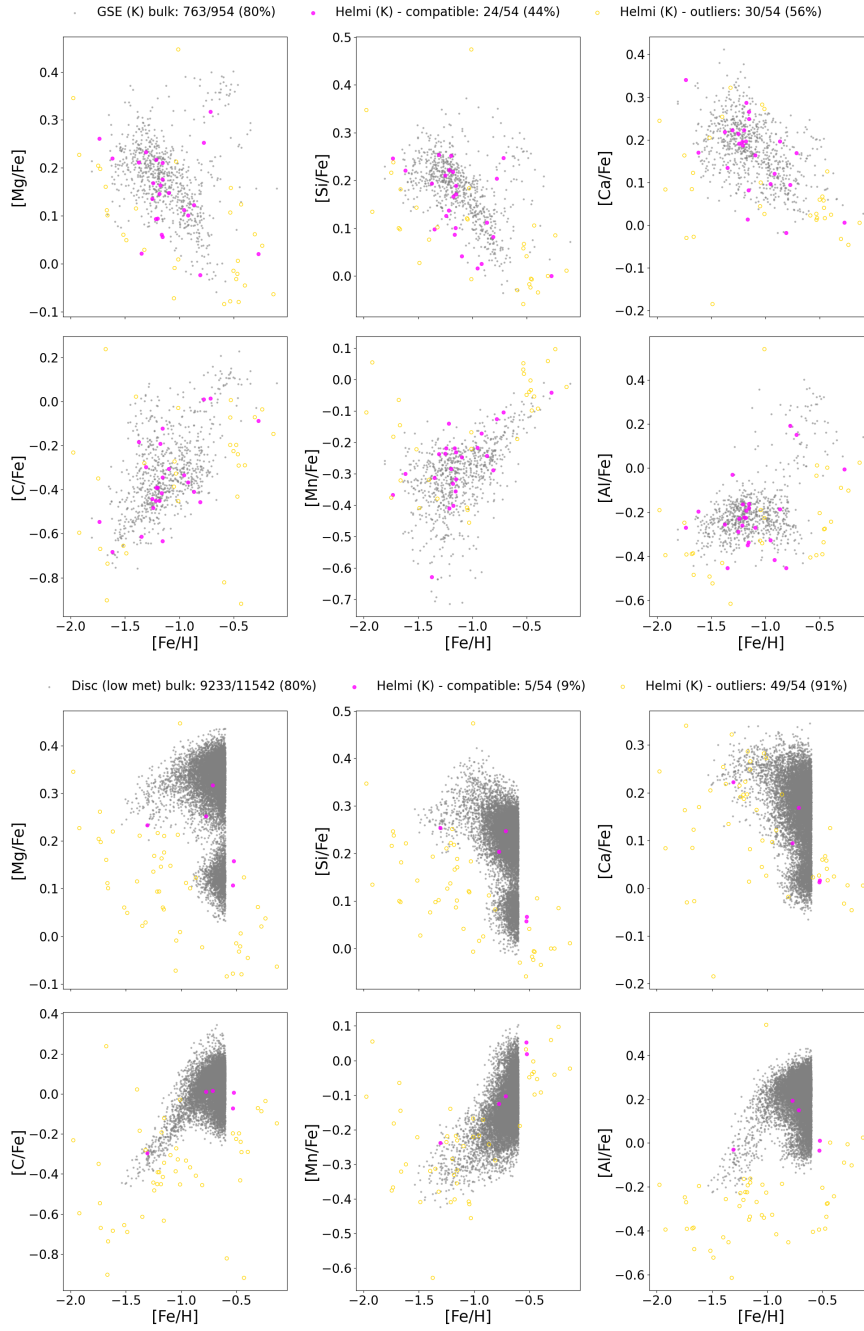


Figura 6.16: Helmi Stream (K)'s stars that are chemically compatible (threshold=20) with GSE (K) (upper panel) and with the metal-poor disc (lower panel) are shown in magenta, while the ones that are not in yellow. The relative percentages are reported in the legend (and have to be normalised to 80% for absolute values). In grey we show the bulk (80%) of GSE and of the metal-poor disc, in the upper and lower panels, respectively. *From: Mori et al. (2025).*

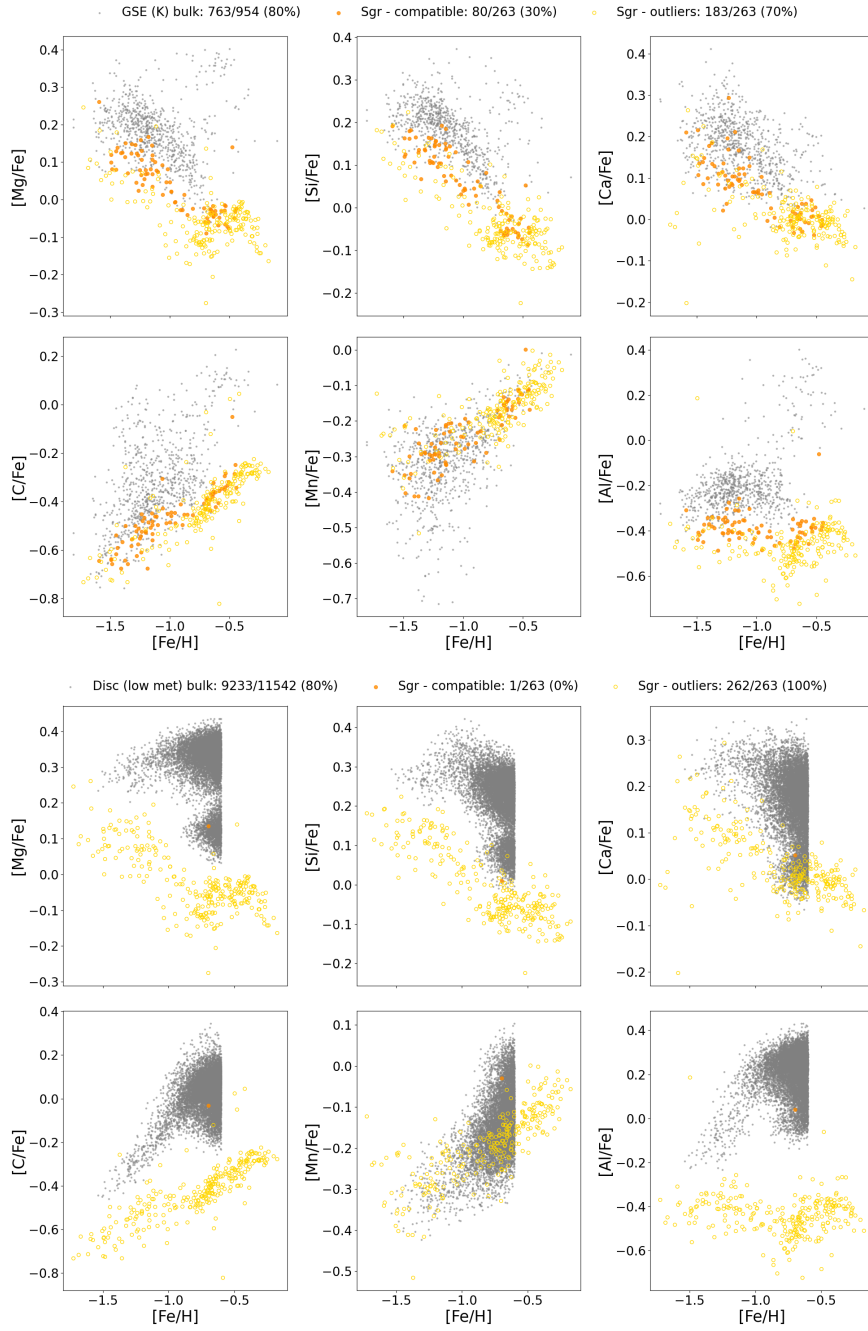


Figura 6.17: Sagittarius' stars that are chemically compatible (threshold=20) with GSE (K) (upper panel) and with the metal-poor disc (lower panel) are shown in orange, while the ones that are not compatible in yellow. The relative percentages are reported in the legend (and have to be normalised to 80% for absolute values). In grey we show the bulk (80%) of GSE and of the metal-poor disc, in the upper and lower panels, respectively. *From: Mori et al. (2025).*

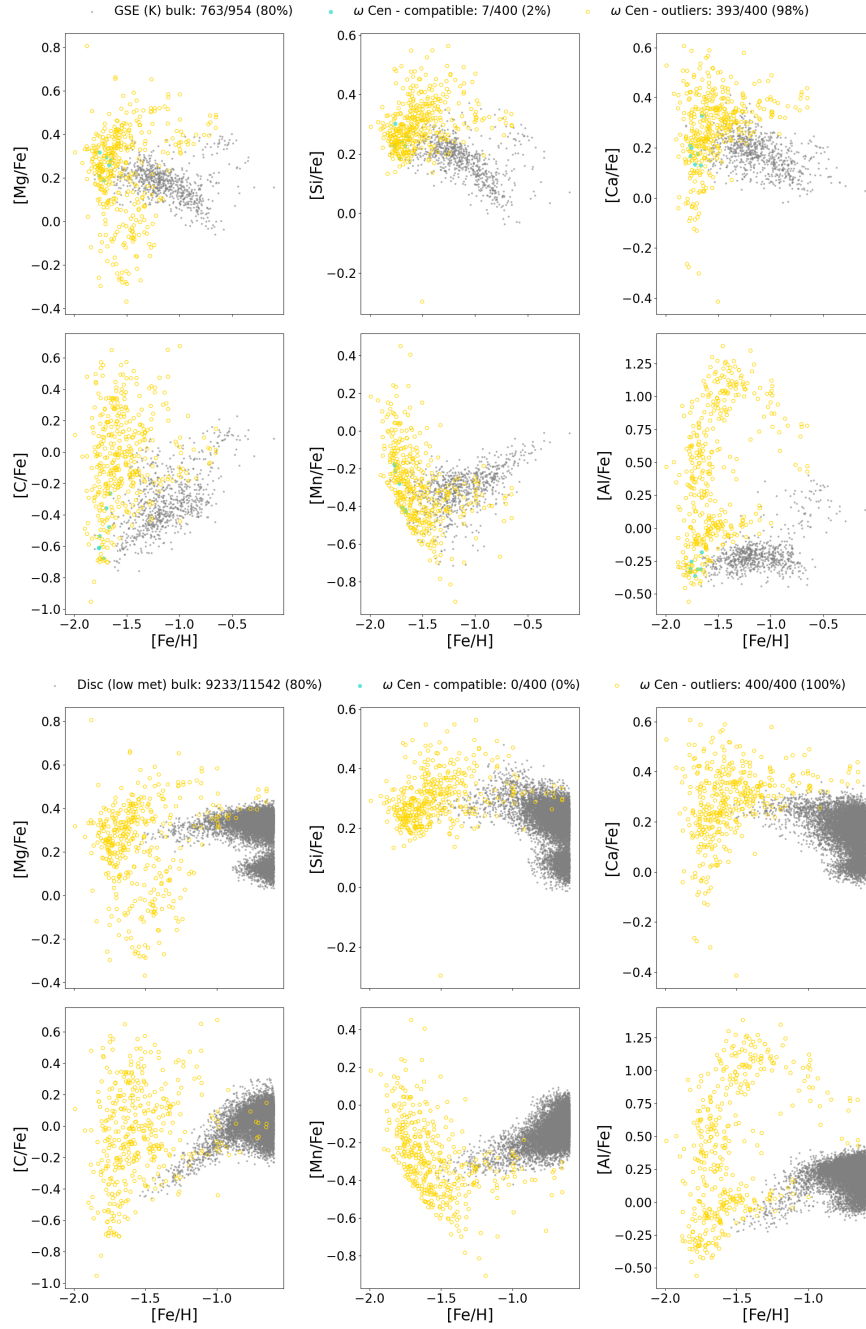


Figura 6.18: ω Cen's stars that are chemically compatible (threshold=20) with GSE (K) (upper panel) and with the metal-poor disc (lower panel) are shown in turquoise, while the ones that are not compatible in yellow. The relative percentages are reported in the legend (and have to be normalised to 80% for absolute values). In grey we show the bulk (80%) of GSE and of the metal-poor disc, in the upper and lower panels, respectively. *From: Mori et al. (2025).*

The dark side of minor accretions

Reference article

([Mori et al., in prep](#)) **Mori A.**, Salvadori S., Mastrobuono-Battisti A., Di Matteo P., et al.; “Characterising the accretion of dark matter satellites hosting (ultra-faint) dwarf galaxies in the Milky Way”, *in prep*.

Hitherto, in the effort to piece together the assembly history of our Galaxy, this thesis has extensively examined the last massive merger as well as several of the numerous minor accretion events. Nevertheless, the latter still spanned a relatively high mass range ($M_* = 10^7 - 10^9 M_\odot$; see [Kruijssen et al., 2020](#)), i.e., that of classical dwarf spheroidal galaxies (see Sec. 1.3). Extending this work to include the lowest-mass accretion events is crucial, as ultra-faint dwarf galaxies (UFDs, $M_* \leq 10^5 M_\odot$; see Sec. 1.3) probe the smallest scales of hierarchical galaxy formation and provide a unique window into the onset of the earliest stages of chemical enrichment from the first generation of stars. Indeed, despite their negligible contribution to the total stellar mass of the Milky Way, they are expected to be the main building blocks of the most metal-poor tail of the Galactic halo MDF (e.g., [Salvadori et al., 2015](#); [Bonifacio et al., 2021](#); [Lucchesi et al., 2024](#)). UFDs host stars that preserve the chemical signatures of the first (Population III) supernovae (e.g., [Salvadori & Ferrara, 2009](#); [Bovill & Ricotti, 2009](#); [Rossi et al., 2025](#)), which are also found among the most metal-poor Galactic halo stars (e.g., [Bonifacio et al., 2015](#); [Koutsouridou et al., 2023](#); [Vanni et al., 2023](#); [Bonifacio et al., 2025](#)). Although the total mass of UFDs is still uncertain, several cosmological models following the formation of the first stars (e.g., [Salvadori & Ferrara, 2009](#); [Bovill & Ricotti, 2009](#); [Jeon et al., 2017](#)) predict it to be of the order of $M \simeq 10^7 M_\odot$. This result is also supported by observations (e.g., [Battaglia & Nipoti, 2022](#)).

These small systems – given their low stellar and dark matter mass compared to the MW – are supposed to experience little dynamical friction when interacting with the Galaxy, thus they should preserve the desirable dynamical coherence in integrals of motion spaces. However, the virial mass of the MW is expected to vary over cosmic time, i.e. the mass ratio between UFDs and the MW could have been significantly higher depending on the epoch of accretion. Furthermore, the orbital decay of UFDs within the MW is affected by their distance (R) from the Galactic centre (tidal acceleration $a_T \propto R^{-3}$, see Sec. 3.1). In particular, the eccentricities of their orbits determine how strongly they are tidally stripped by the interaction with the MW, as higher eccentricities imply closer pericentres.

In light of the foregoing, we are interested in modelling the accretion of UFDs onto the Galactic halo, which will be explored through N-body models that will be described at the end of the next chapter (Sec. 8.2). However, we need to know the evolution of the virial mass of the MW over cosmic time, as well as the typical infall time and orbital eccentricity of UFDs. Therefore, to set realistic initial conditions, we need to explore cosmological simulations to provide guidance. We will then perform a statistical analysis of a large suite of high-resolution, MW halo-sized zoom-in cosmological simulations, specifically the Caterpillar Project (see Sec. 7.1). The results of this thorough analysis will be presented in a dedicated publication currently in preparation (Mori et al., *in prep*).

In this chapter, we will describe the analysis of the accretion of low-mass dark matter satellites which is part of Mori et al., *in prep*. In Sec. 7.1 we will introduce the cosmological simulations we rely on for this work. In Sec. 7.2, we will show the dark matter assembly of a Milky Way-like halo over cosmic time. Then we will focus on the dark matter satellites, in particular in those that will likely host ultra-faint dwarf galaxies. We will discuss their typical infall time into the MW potential in Sec. 7.3.1 and orbits in Sec. 7.3.3, that is, the parameters we need for the initial conditions. Finally, the discussion and conclusions of the statistical analysis will be reported in Sec. 7.4.

7.1 The Caterpillar Project

The Caterpillar Project is a suite of dark matter-only zoom-in cosmological simulations (Griffen et al., 2016). It stands out as providing the largest number (32) of Milky Way-sized haloes ($M \sim 10^{12} M_\odot$) simulated at very high mass

($\sim 10^4 M_\odot$ /particle) and temporal (5 Myr/snapshot) resolution, quadrupling what was currently available in the literature.

Therefore, the Caterpillar suite allows us to explore the dark matter assembly history of MW-sized haloes with statistical significance, along with that of galaxies with similar masses. Indeed, it assumes an extremely weak constraint on the merger history, i.e. no major merger (1 : 3 mass ratio) since $z = 0.05$, corresponding to discarding less than 5% of the candidate haloes to re-simulate. This choice is driven by the aim of building up a representative sample of $10^{12} M_\odot$ DM haloes, which are not necessarily Milky Way analogues. We will then apply additional selection criteria to focus on systems with a Milky Way-like assembly history (see Sec. 7.2).

Furthermore, the exceptional mass resolution enables us to capture the mini-halo formation (with $M \lesssim 10^7 M_\odot$ at $z \geq 10$; see Sec. 1.1) and to study the accretion of dark matter haloes known to host the least massive galaxies (UFDs), that is, with masses of $M \approx 10^7 M_\odot$, both in a cosmological context and in a statistically meaningful way.

The underlying model of the Caterpillar simulations is the Λ CDM with Planck cosmological parameters (Planck Collaboration et al., 2014): $\Omega_m = 0.32$, $\Omega_\Lambda = 0.68$, $\Omega_b = 0.05$, $n_s = 0.96$, $\sigma_8 = 0.83$ and $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1} = 67.11 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The initial conditions are set using MUSIC (Hahn & Abel, 2011). The suite was run with P-GADGET3 and P-GADGET4, tree-based N-body codes based on GADGET2 (Springel, 2005). The haloes are identified through the friends-of-friends algorithm ROCKSTAR (Behroozi et al., 2013a) and the merger trees are constructed via CONSISTENT-TREES (Behroozi et al., 2013b).

The parent simulation boxes (width = $100 h^{-1} \text{ Mpc}$) were run at lower resolution ($N_p = 1024^3$, $m_p = 8.72 \times 10^7 h^{-1} M_\odot$) for the selection of MW-like candidate DM haloes to be re-simulated at high resolution, on the basis of the following criteria on mass and isolation:

- Halo virial masses: $M_{vir} = (0.7 - 3) \times 10^{12} M_\odot$ (estimated virial mass of the MW; see Wang et al., 2015, for a review);
- No haloes with $M_{vir} \geq 7 \times 10^{13} M_\odot$ within 7Mpc (avoiding proximity to large clusters; van der Marel et al., 2012a);
- No haloes with $M_{vir} \geq 0.5 \times M_{host}$ within 2.8 Mpc (avoiding pairs; Tikhonov & Klypin, 2009);

where the last two criteria contain the computational cost for the desired resolution.

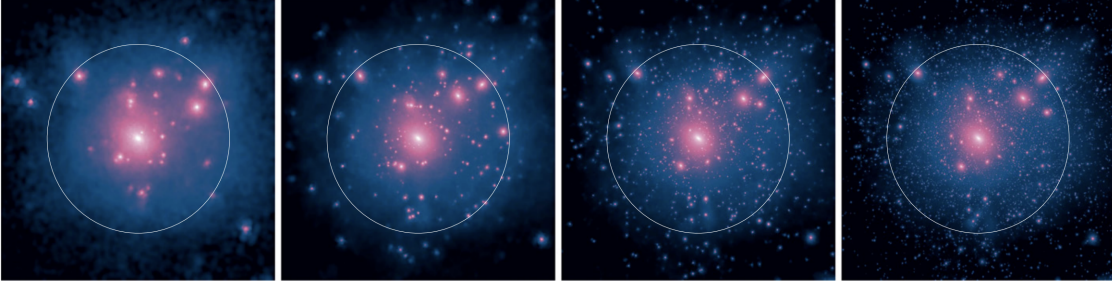


Figura 7.1: $z = 0$ dark matter density of Cat-1 at increasingly higher resolutions from left to right (from $m_p = 1.53 \times 10^8 M_\odot$ to $m_p = 2.99 \times 10^4 M_\odot$). The white circle shows the virial radius. *From: Griffen et al. (2016).*

Each selected halo was then re-simulated at iteratively higher resolution, increasing the particle number by a factor of $\times 8$ each time. In this study, we will make use of the highest resolution simulations (LX14, which adopts a number of particle $N_p = (2^{14})^3 = 16384^3$ and mass resolution $m_p = 2.99 \times 10^4 M_\odot$), an example of which is shown in the rightmost panel of Figure 7.1 where it is compared to lower resolution runs. The impact of increasing mass resolution on the dark matter density at $z = 0$ can be appreciated by inspecting the panels of Figure 7.1 from left to right, where we notice that the number of DM satellites (pink circles) identified within the virial radius of the MW (white circles) increases significantly with resolution.

In each Caterpillar simulation there are 320 snapshots available, but they are spaced differently before/after reionisation ($z = 6$). In particular, the spacing is in the logarithm of the scale factor for $z \geq 6$ (~ 5 Myr/snapshot), while linearly spaced down to $z = 0$ (~ 50 Myr/snapshot). This is motivated by the fact that, when coupled with semi-analytical models for the MW formation (e.g., A-SLOTH, Hartwig et al., 2022; NEFERTITI, Koutsouridou et al., 2023) a high temporal resolution (≤ 10 Myr/snapshot) is required to follow the formation of first stars and their subsequent feedback processes, which include the production and transport of Lyman-Werner (LW) photons (e.g., Agarwal et al., 2012) but also the injection of newly produced chemical elements via SN explosions (e.g., Salvadori et al., 2008). On the other hand, simulating for 13 Gyr (i.e., from reionisation down to $z = 0$) the build-up of a MW-like DM halo with very high mass- and time-resolution is very computationally demanding, yet not required, as for instance disruption timescales of ultra-faint dwarf galaxies are of the order of ~ 50 Myr.

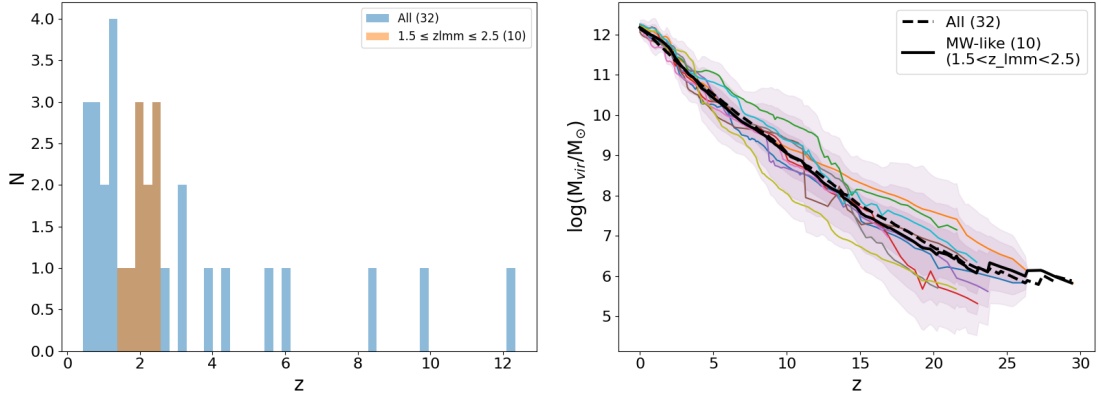


Figure 7.2: *Left panel:* histogram of the redshift of the last major merger (z_{lmm}) in blue, while the haloes such that $1.5 \leq z \leq 2.5$ are highlighted in orange (for 10/32 selected cases). *Right panel:* the coloured curves show the virial mass assembly of the major branch of MW-like haloes ($z_{lmm} \sim 2$) as a function of redshift, the black solid (dashed) line shows the mean (of all 32 simulations) with 1σ , 2σ and 3σ in shaded purple. *From:* Mori et al., in prep.

7.2 The DM assembly history of a MW-like halo

First of all, before delving into the characterisation of the dark matter satellites, we wanted to exploit the Caterpillar suite to analyse the dark matter assembly history of our Galaxy and to understand how much and rapidly the Milky Way potential varies through cosmic time. We have described in Sec. 7.1 the criteria for the selection of the haloes that were re-simulated at higher resolution, which were based only – beyond the isolation constraints computationally driven – on the total virial mass at $z = 0$.

To analyse more tailored MW-like haloes within the accretion history framework, we decided to apply a more restrictive criterium on the merger history, that is, we selected the haloes such that they had their last major merger (i.e., with GSE) in the redshift range of $1.5 \leq z \leq 2.5$, which corresponds to $9.5 \leq t_{lmm} \leq 11$ Gyr in lookback time. This additional constrain led to the analysis of the dark matter assembly history of 10 MW-like haloes ($z_{lmm} \sim 2$), as shown by Figure 7.2. In particular, in the left panel we show the histogram of the last major merger redshifts for all the 32 simulations in blue, while in orange the selected 10 haloes for which $z_{lmm} \sim 2$. In the right panel of Figure 7.2, we then show the evolution of the virial mass of the most massive progenitor of the MW-like ($z_{lmm} \sim 2$) DM halo at each redshift, i.e., “the major branch”, as a function of z (coloured curves). The

black solid line shows the mean of the coloured curves with 1σ , 2σ and 3σ in shaded purple. This is compared to the mean of all 32 simulations of the suite (black dashed line). The mean of the MW-like haloes (solid line) lies below the total mean at high redshift, up $z \sim 2$. After that, they become more massive than the mean down to $z = 0$, as a result of their last major merger. However, there is not a significant difference in the average mass growth of MW-like haloes with respect to the generic $10^{12}M_{\odot}$ ones, as the two mean curves are consistent within 1σ . Notice that the least massive MW progenitor can appear as early as $z_{form} \sim 30$ (that is, ≈ 100 Myr after the Big Bang) having a DM of only $M \sim 10^6 M_{\odot}$, i.e., 1 million times less massive than the present-day MW dark matter halo. We can notice that the scatter among our sub-sample of 10 MW-like assembly histories is quite large at $z \gtrsim 5$, when $M \leq 10^{11} M_{\odot}$. This reflects the unknown assembly history of our Galaxy during the first ~ 1.5 Gyr of cosmic evolution. Indeed, the growth curves of individual MW halos are very different from each others, for example, we can see steep spikes (which mark the major mergers) at very different redshifts, further highlighting the large variety of possible merger histories at $z > 2$, i.e., before the last major merger.

Tracing the evolution of the DM mass of the MW-like haloes over cosmic time is fundamental, since the mass of the major branch dramatically evolves with redshift, thus strongly modifying the gravitational potential to which low-mass satellites (hosting UFDs) are subject as they accrete at different cosmic times. Indeed, in the direct N-body code (that is, NBSymple; [Capuzzo-Dolcetta et al., 2011](#)) that we will use to model UFDs evolving in the Galactic halo (see Sec. 8.2), we will introduce a variable Galactic potential, which is computed using the findings for the MW major branch illustrated in Fig. 7.2.

7.3 Cosmological accretion of DM satellites

To simulate the accretion of an UFD in the Galactic halo, we have to set several parameters, which will represent the initial conditions of our model (see Sec. 8.2). For instance, we have to establish the stellar mass and the half-light radius of the UFD, which can be inferred from observations (e.g., [Simon, 2019](#)), we need to set the total mass and the virial radius which can be taken from cosmological models (e.g., [Salvadori & Ferrara, 2009](#)). Furthermore, we have to establish the initial orbit of the accreting UFD and the time of accretion, which we will infer from the Caterpillar suite of high-resolution cosmological simulations of MW-like

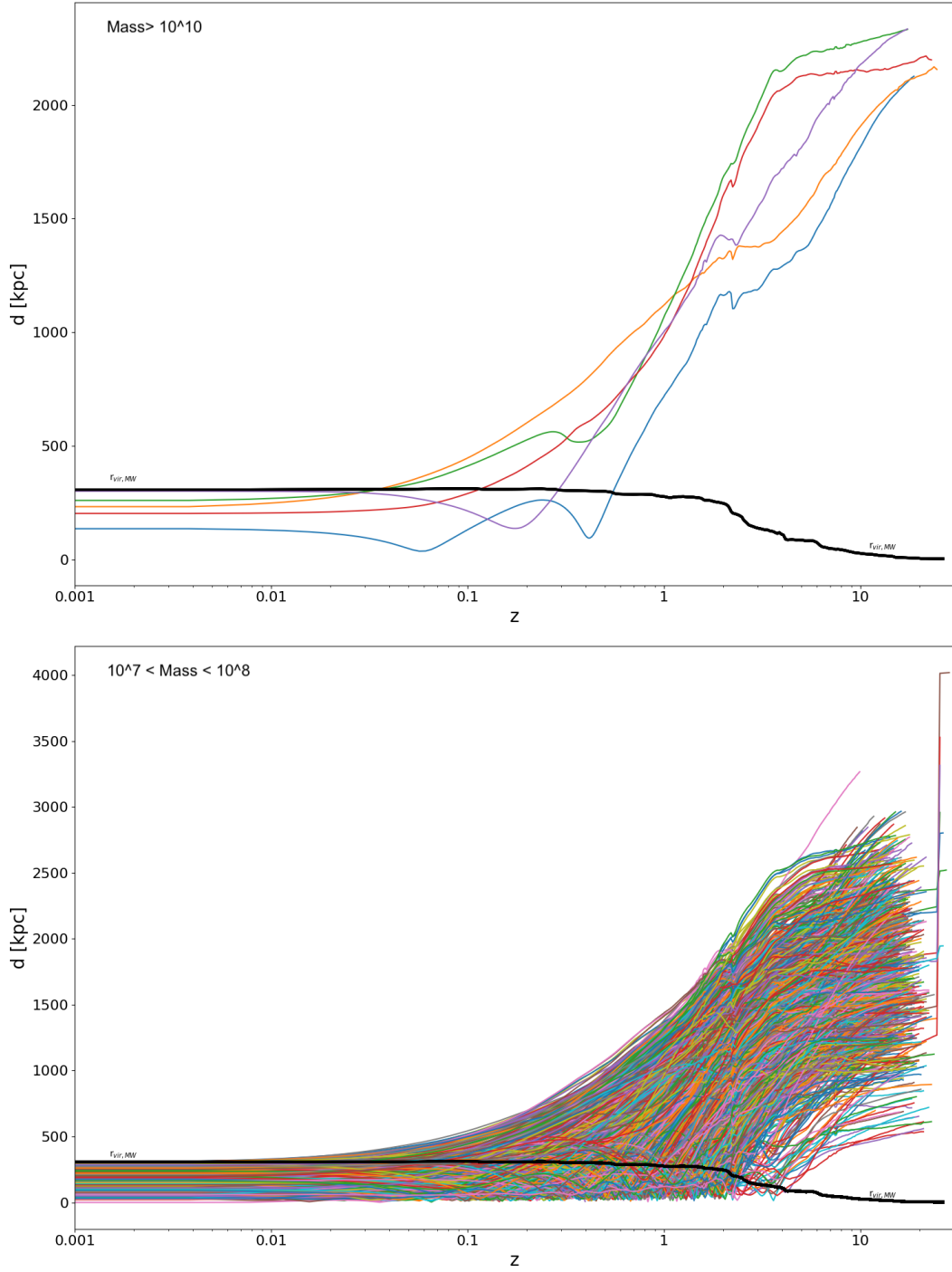


Figura 7.3: Satellite distance from the MW (in kpc) as a function of redshift (in logarithmic scale), divided in mass bins. *Top panel:* $M \geq 10^{10} M_{\odot}$ haloes; *bottom panel:* $10^7 \leq M < 10^8 M_{\odot}$ haloes (likely hosting UFDs). The black solid lines show the evolution of the virial radius of the MW as a function of redshift. From: [Mori et al.](#), *in prep.*

haloes. Note that our interest in modelling UFDs infalling and evolving into the Galactic potential is actually twofold (as will be further detailed in Sec. 8.2): we want to analyse both the accreted UFDs that are now destroyed and those that survive until today.

To model the latter ones, we then have to simulate the evolution of UFDs for as long as they have been orbiting within the halo of the MW, that is, we need to know the typical redshift at which $\approx 10^7 M_\odot$ haloes enter the virial radius of the MW (i.e., infall time) in cosmological simulations. This will be discussed in next Sec. 7.3.1. Moreover, we also have to explore their orbital parameters, in particular their eccentricities, which will be described in Sec. 7.3.3. These properties can be studied by analysing the orbits of the $\approx 10^7 M_\odot$ haloes (likely hosting UFDs) in the Caterpillar suite.

In Figure 7.3, we show the distance of the DM haloes surviving until today as satellites from the central MW-like halo (in kpc) as a function of redshift (in logarithmic scale). The different panels display the evolution of the distance for different mass bins. In particular, we show the most massive DM satellites ($M \geq 10^{10} M_\odot$) in the top panel and those hosting UFDs ($10^7 \leq M < 10^8 M_\odot$) in the lower one. Note that we are showing the results for only one simulation (Cat-1), for clarity. Indeed, we notice that the low mass haloes are so numerous ($\approx 10^3$) that the curves overlap significantly. However, from the different colours we can notice that the redshift of infall (z_{acc}) spans a broad range. The solid black line shows indeed the evolution of the virial radius of the MW and we can see that $\approx 10^7 M_\odot$ haloes cross this line since $z \sim 4$ down to $z = 0$. They also feature various differences in their apocentre and pericentre positions, thus leading to different eccentricities. This can be more easily observed in the upper panel, where there are just 5 curves. Note that for the high-mass DM satellites $z_{acc} \leq 0.5$. Both the infall time and the eccentricity of the orbits for DM satellites will be statistically analysed in the following sections.

7.3.1 The typical infall time

Sales et al. (2007) studied the distribution of the infall time of surviving satellites of MW-like haloes (see their Figure 10), using the N-body simulations Aquarius (Springel et al., 2008). However, the Aquarius simulations only resolve dark matter satellites with masses $\gtrsim$ a few $10^8 M_\odot$, thus they are not informative on the accretion of the low-mass ($\approx 10^7 M_\odot$) DM haloes that will host UFDs. Dooley et al. (2017) analysed the Caterpillar suite with the aim of studying the satellites of local

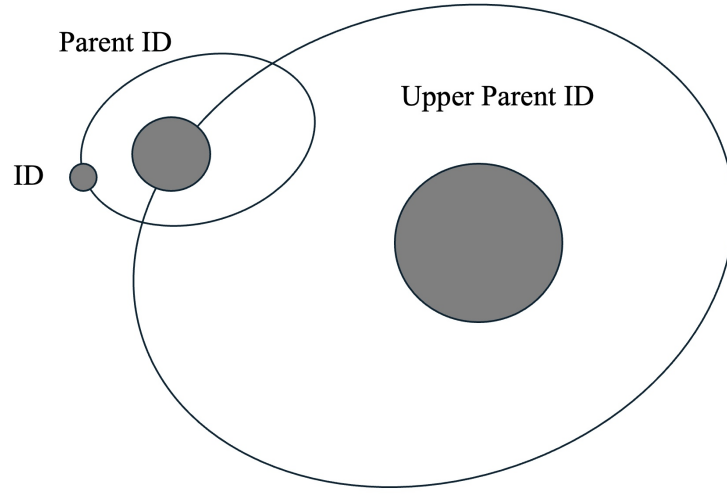


Figure 7.4: Schematic representation of a DM halo, identified with its own ID, orbiting around a *Parent halo*, identified with PID, in turn gravitationally bound to another DM halo called *Upper Parent halo*, identified with UPID. From: [Mori et al.](#), *in prep.*

satellites. Thus, they did not attempt to quantify the infall time of DM satellites onto the major branch of the MW, but they more generically investigated when DM haloes in the simulations become satellite of a more massive system.

In the publicly available outputs from the Caterpillar project, each halo is associated with an ID, which uniquely identifies it at every redshift. Moreover, for every halo there are two additional IDs, one for the “Parent” halo (“PID”) and one for the “Upper Parent” halo (“UPID”). These are, respectively, the closest halo it is orbiting around and the more massive halo they are both possibly orbiting around (analogously to the moon-earth-sun orbital system, as shown in the schematic Figure 7.4). If the halo is not a satellite, both its PID will be equal to -1 .

We can identify the infall times of DM satellites (or subhaloes) by finding the highest lookback time (redshift) for which their UPID $\neq -1$. This is the procedure that we adopted to obtain the distribution of the infall time of DM satellites with different masses reported in the left panel of Fig. 7.5. According to this result, which is in line with the findings of [Dooley et al. \(2017\)](#) (see the blue curve in their Fig.2), the DM haloes will most likely become satellites at lookback times of about $\sim 10 - 12$ Gyr ($z \sim 1.5 - 3.5$), with a secondary minor peak at $0 - 2$ Gyr ago ($z \sim 0 - 0.2$). As noted by [Dooley et al. \(2017\)](#), we can see that the infall time

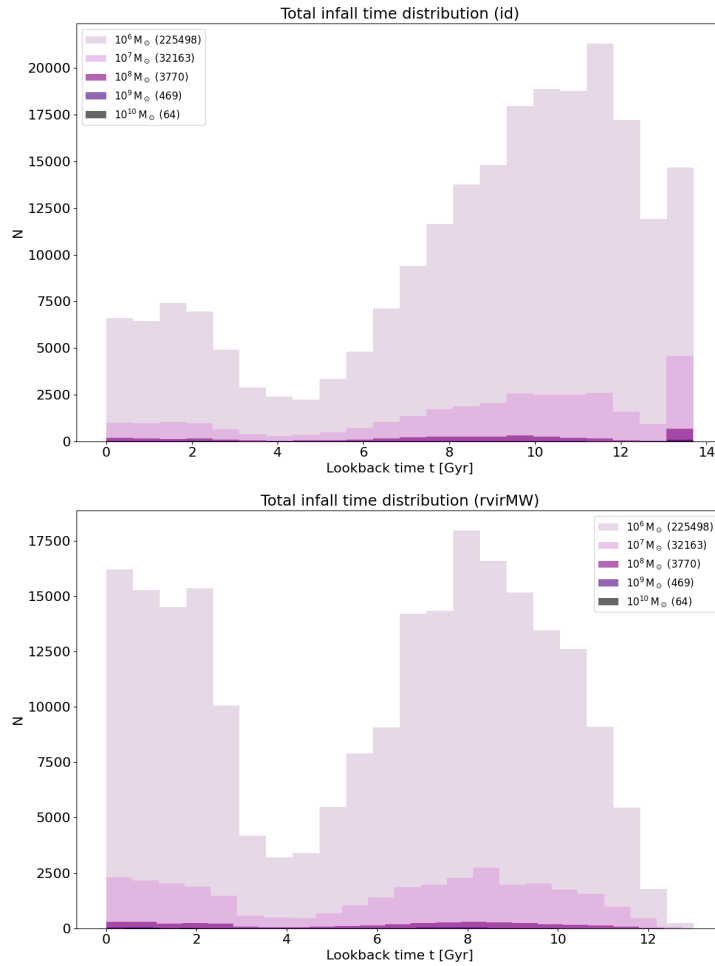


Figura 7.5: Distribution of the infall times of satellite haloes with different masses (see legend). *Left panel:* infall times onto a generic halo host, as provided by the Caterpillar output IDs. *Right panel:* infall times into the MW major branch, as computed identifying the time of crossing of the MW virial radius. *From:* [Mori et al.](#), *in prep.*

distribution does not vary significantly across different halo mass ranges, that is, they feature similar shapes and peak values.

For a sanity check, we also computed the infall time of each satellite by verifying when the distance of the subhalo from the Galactic centre was lower than the virial radius of the MW (hereafter, referred to as the “MW virial radius criterium”). The distribution of the infall times obtained on the basis of the MW virial radius criterium is shown in the right panel of Figure 7.5. We can see that the peak which was secondary in the previous case is now comparable to the main one. This is due to the fact that many of the DM haloes populating the main peak do not become satellites of the MW - i.e., of the major branch in the simulation - but rather of other (less massive) halos. This can be better understood by looking at Figure 7.6, where we show the orbits of DM haloes for which we derive two different infall times (respectively equal to $z_{acc} = 2.24$ and $z_{acc, upid} = 10.90$) by using the two different methods. In the two panels of Fig. 7.6, we can compare the evolution of the distance of the DM satellites from the centre of the MW major branch (black solid lines) with the evolution of the virial radius of the MW (black dashed lines). We can see that the accretion redshift (z_{acc}) obtained with the MW virial radius criterium (vertical blue dashed line) correctly identifies the redshift at which the satellites infall into the MW. On the other hand, the vertical red dashed lines mark all the redshifts such that $UPID \neq -1$. In the upper panel of Fig. 7.6, then, the considered halo became a satellite of another halo at $z \sim 10$ to then leave its virial radius soon after. In other words, the Caterpillar algorithm recognises the given halo as a satellite of a more massive one because of its proximity during a single snapshot. Thus, this halo is not really a bound DM satellite at very high redshift, but it actually becomes a satellite (of the MW) at $z = 2.24$. In the lower panel of Fig. 7.6, showing another DM halo with $M \sim 10^6 M_\odot$, we see the same feature for $z_{acc, upid} = 9.47$. However, after a phase of evolution in isolation, the DM halo becomes a satellite of another one (not the MW major branch), which is marked by a continuum of vertical red dashed lines. We emphasise that these lines appear both before and after the infall into the MW virial radius (blue dashed line), suggesting that the parent halo became a satellite of the MW itself at $z_{acc} = 0.04$.

We repeated the procedure just described to identify real z_{acc} for all the $\approx 10^4$ DM haloes in the Cat-1 simulation. With the aim of providing the initial conditions to model the evolution of DM haloes hosting UFDs, we will now focus on the DM satellites with masses of $\approx 10^7 M_\odot$ which are roughly 1150.

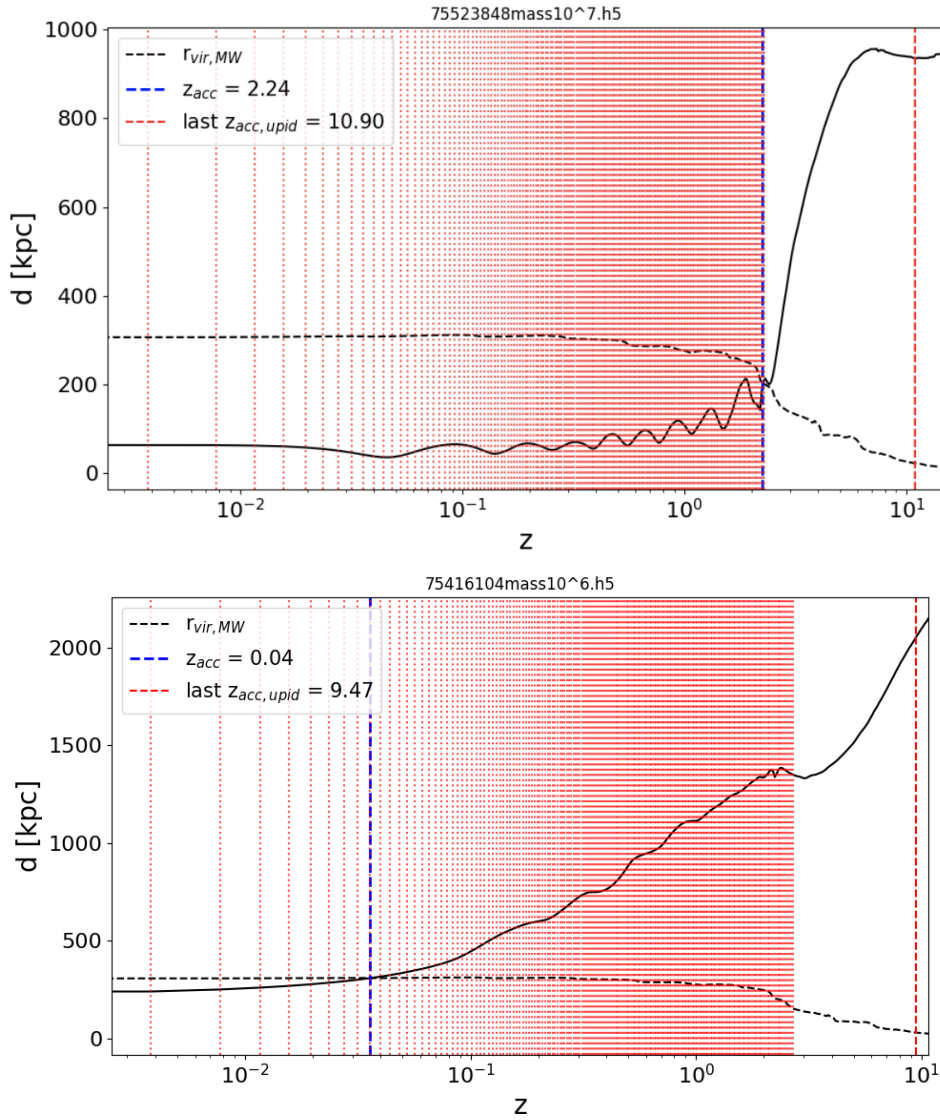


Figura 7.6: Orbits of $\sim 10^7 M_\odot$ haloes. The evolution of the distance of the DM satellites from the MW is shown by the black solid line and compared with the evolution of the virial radius of the MW (black dashed line), both displayed as a function of redshift (in logarithmic scale). The redshift at which the satellites cross the MW virial radius determine their redshift of accretion in the Galactic potential (z_{acc}) and are marked by the vertical blue dashed line (see labels). The vertical red dashed lines show instead the redshift at which the considered DM haloes are orbiting around another one, which is not necessarily the major branch of the MW. The redshift at which the considered haloes become for the first time a satellite of another one determines the infall time in Caterpillar ($z_{acc, upid}$, see labels). *From: Mori et al., in prep.*

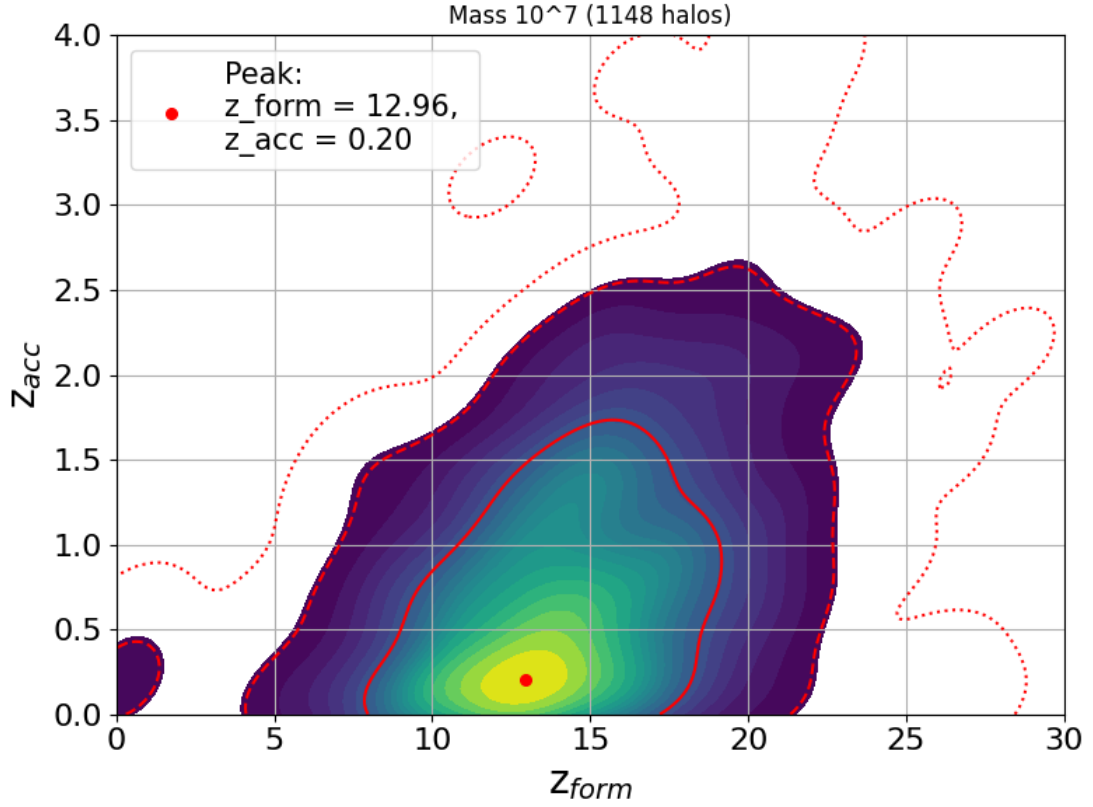


Figure 7.7: Redshift of accretion (z_{acc}) vs. redshift of formation (z_{form}) for $10^7 \leq M < 10^8 M_\odot$ DM satellites. The red solid, dashed, and dotted lines show the 1σ , 2σ , and 3σ of the distribution, respectively. The red dot marks the highest probability which is equal to $(z_{form}, z_{acc}) = (12.96, 0.20)$. From: [Mori et al., in prep.](#)

7.3.2 The typical formation time

To understand for how long DM haloes hosting UFDs evolve in isolation before entering the MW virial radius we need to identify their typical redshift (or time) of formation (z_{form}). This information can be easily obtained from the outputs of the Caterpillar simulations, which provide the highest redshift at which a DM halo is identified as a bound system.

In Figure 7.7, we show the redshift of formation (z_{form}) with respect to the redshift of accretion (z_{acc}) for DM haloes hosting UFDs ($M \approx 10^7 M_\odot$). The colours show the highest probability of being formed at z_{form} and accreted onto the MW at z_{acc} . We can notice that there is a correlation between the redshift of formation and accretion, the higher z_{form} , the higher z_{acc} . The distribution shows a peak at $z_{form} \approx 13$ and $z_{acc} = 0.2$ (see labels). We also notice that the bulk of

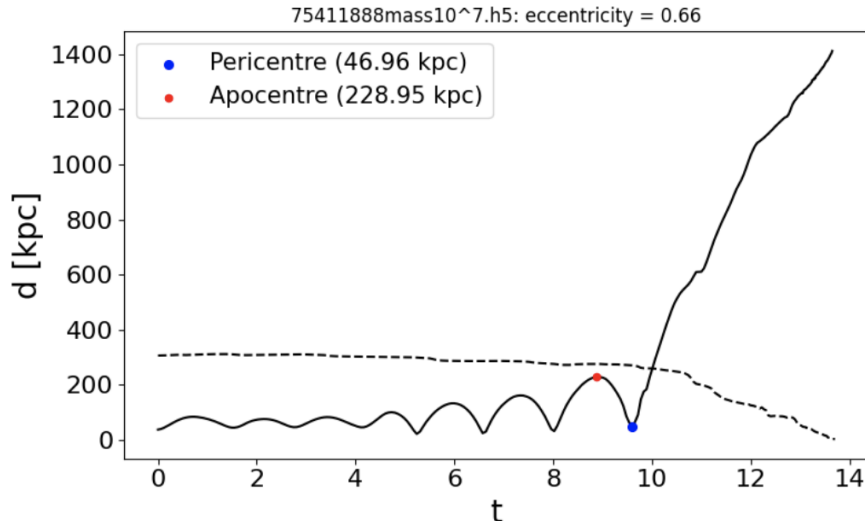


Figure 7.8: Distance of a DM satellite with $M \sim 10^7 M_\odot$ from the Galactic centre as a function of lookback time (solid black line). The evolution of the MW virial radius is shown by the dashed black line. The first pericentre (first minimum after infall into the MW) is marked by the blue dot, while the first apocentre (first maximum) by the red one (see labels for the values). *From: Mori et al., in prep.*

UFD-hosting DM haloes that survived as satellites of the MW until the present day formed between redshift $\sim 18 - 8$ and are accreted between $\sim 1.7 - 0$.

These results are perfectly in line with the predictions of detailed chemical evolution models finding that UFD form at $z > 8$ and host the first stars (e.g., [Salvadori et al., 2015](#); [Rossi et al., 2025](#)). These models predict that the stellar populations in UFDs form in a few hundreds of millions years, being quenched at $z = 6$ (1 Gyr after the Big Bang) for a combination of internal (supernovae) and external (reionisation) feedback processes. These findings are in agreement with the star formation histories of UFDs obtained with deep colour-magnitude diagrams (e.g., [Brown et al., 2014](#)), showing that their stellar population is $\gtrsim 13$ Gyr old. Furthermore, they imply that at the time of accretion into the MW potential these are only made by stellar and dark matter.

7.3.3 The typical eccentricity

The last step to set the initial conditions for UFD-hosting haloes evolving into the Galactic potential is to understand whether they feature a typical eccentricity at the time of accretion. To this end, we further analysed the orbits of $\approx 10^7 M_\odot$ DM haloes in the Cat-1 simulation. We used the first pericentres and apocentres

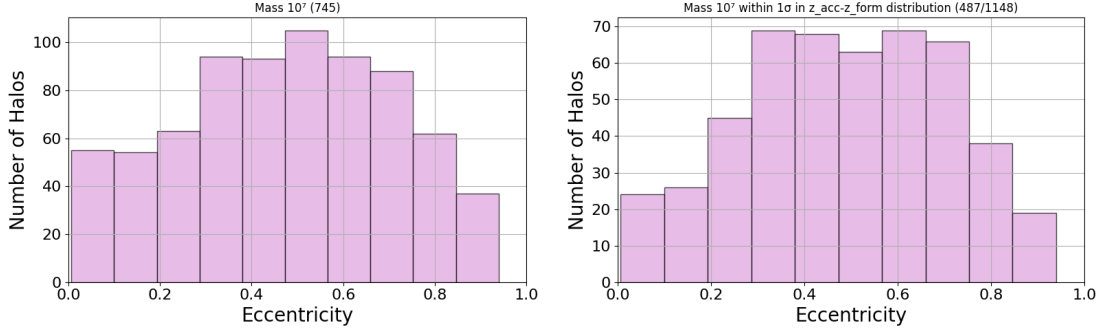


Figure 7.9: *Left panel:* Distribution of eccentricity at the accretion time for $10^7 \leq M/M_\odot \leq 10^8$ haloes with defined first apocentre and pericentre. *Right panel:* Same as left panel, but for the haloes within 1σ of the distribution of Fig. 7.7. From: Mori et al., in prep.

after they crossed the virial radius of the MW to define their eccentricity, which we computed as $(r_{apo} - r_{peri})/(r_{apo} + r_{peri})$. We show an example of this procedure in Figure 7.8, where we obtained an eccentricity of $e = 0.66$ for the considered DM satellite.

The results of the whole analysis for all the $\approx 10^7 M_\odot$ DM haloes in the Cat-1 simulation are reported then in the left panel of Figure 7.9, where we show the distribution of the eccentricities. We can see that the distribution does not show a sharp peak. Rather, it shows a maximum around $e \sim 0.5 - 0.6$ with high tails both towards lower eccentricities (more circular orbits) and towards higher values (more radial ones). Interestingly, if we restrict our analysis to the bulk of the UFD-hosting haloes identified by the red curve in Fig. 7.7, we can see in the right panel of Fig. 7.9 that the peak is even less evident and that the distribution shows roughly equal frequencies in the range $e \approx 0.3 - 0.7$.

7.4 Discussion and conclusions

The Caterpillar suite of cosmological simulations is an invaluable tool for exploring the accretion of very low-mass haloes because of its high mass resolution. Having a mass resolution of a few $10^4 M_\odot$, indeed, implies that we can well resolve haloes with total DM masses of $10^6 M_\odot$ (made up of 100 particles), which are the most common at all redshifts. These low-mass systems are the key to understanding the accretion into our Milky Way of UFD satellites, which are hosted by $\sim 10^7 M_\odot$ DM

haloes (e.g., [Salvadori & Ferrara, 2009](#); [Bovill & Ricotti, 2009](#); [Jeon et al., 2017](#)).

Our final aim is indeed modelling the very low-mass end of the mass spectrum of accretions of the Milky Way with UFD galaxies. They are an extreme population of galaxies, being the faintest, oldest, most metal-poor, and least chemically evolved, therefore the most pristine (still the most common) satellites of our Galaxy. They populate the very metal-poor tail of the Galactic halo MDF. Moreover, they could conserve integrals of motion at a higher degree with respect to their massive counterparts, given the negligible dynamical friction they are supposed to experience.

The analysis revealed a great variety of properties for the UFD-hosting DM haloes both in infall time and in orbital eccentricity. In particular, we found a double-peaked infall time distribution (across all mass ranges of DM halo masses), comprising a peak at $8 - 10$ Gyr in lookback time and one at $0 - 2$ Gyr ago. Furthermore, for the $\sim 10^7 M_\odot$ DM satellites likely hosting UFDs, we observed a roughly flat eccentricity distribution in the range $e \sim 0.3 - 0.7$, but with significant tails both at higher and lower values. Consequently, we would need to probe a wide parameter space to comprehensively simulate the accretion of UFDs onto the Galactic halo.

By inspecting the redshift of formation of the UFD-hosting DM haloes, we found that the bulk of these systems have formed between redshift $\sim 18 - 8$, to be accreted at $z \sim 1.7 - 0$. Indeed, chemical evolution models find that UFDs form at $z > 8$, host the first stars, and are then quenched at $z = 6$ (e.g., [Salvadori et al., 2015](#); [Rossi et al., 2025](#)). Thus, at the time they accrete onto the MW they do not contain gas, fact that will crucially allow us to simulate UFDs with only a stellar and a dark matter component in a realistic way.

Finally, we further selected the 32 simulations of MW-sized haloes, with an additional constraint on the merger history (i.e., redshift of the last major merger $z_{lmm} \sim 2$), obtaining 10 out of 32 cases with a similar assembly to that of the MW. This allowed us to study the typical mass growth of a MW-like halo over cosmic time, which in turn will enable us to implement a variable Galactic potential in the code that we will use for the simulations.

UFD accretion models would then be crucial, as we will soon be able to study their accretions in ever greater detail, by combining precise *Gaia* observations ([Gaia Collaboration et al., 2016a](#)), which has more data releases yet to come, with novel and complementary spectroscopic surveys, such as 4MOST ([de Jong et al.,](#)

2019), which just saw the first light, with its dwarf dedicated survey 4DWARFS (Skúladóttir et al., 2023), but also WEAVE (Jin et al., 2023), which is finally operating. These spectroscopic surveys, combined with those already existing (e.g., Pristine, Starkenburg et al. 2017) will probe the lower metallicity regime, both in dwarf galaxies and in the Galactic halo, potentially allowing to uncover even the assembling of massive dwarf spheroidal galaxies (e.g., Sculptor) via smaller progenitor halos as predicted by cosmological models (e.g., Salvadori et al., 2015).

Conclusions and perspectives

Scattered across the stellar halo lie the fossils of the past (and ongoing) accretions of our Galaxy – stars whose motions and compositions may preserve memory of their birthplaces. Piecing together the assembly history of the Milky Way through the study of its stellar properties is the aim of Galactic Archaeology. Within the hierarchical cosmological paradigm for galaxy formation, indeed the Galactic merger history is key to unravelling its evolution over cosmic time.

The advent of the ESA astrometric mission *Gaia* ([Gaia Collaboration et al., 2016a](#)), complemented by wide-field spectroscopic surveys such as APOGEE ([Majewski et al., 2017](#)), dramatically revolutionised this field of research, providing the community with precise 6D phase-space information and chemical abundance measurements for an unparalleled amount of data.

This thesis fits into this framework and seeks to establish robust methods to trace the accretion history of our Galaxy, probing different mass scales of hierarchical formation in both baryonic and dark components. This objective was pursued exploiting a variety of techniques. We analysed state-of-the-art, high-resolution N-body simulations of galaxy mergers (see [Pagnini et al., 2023](#); [Mori et al., 2024](#)), as well as the latest data releases from *Gaia* (EDR3; [Gaia Collaboration et al., 2021](#)) and APOGEE (DR17; [Abdurro'uf et al., 2022](#)), high-quality spectra from ESO VLT/UVES (PI: Skúladóttir), and high-resolution, dark matter-only cosmological simulations, i.e. the Caterpillar Project ([Griffen et al., 2016](#)).

The combination of these methods enabled us to uncover controversial aspects of how the accretion history of our Galaxy has been reconstructed so far, resulting in novel interpretative frameworks, which we will review in the next section, along with their most relevant implications.

8.1 Key results and implications

In the following, we will summarise the main findings of this thesis work, beginning with the study of the last massive merger event (with *Gaia*-Sausage/Enceladus, GSE; Belokurov et al., 2020; Haywood et al., 2018a; Helmi et al., 2018), analysing then lower-mass accretion events, to end up with the least massive tail of the mass spectrum of accretions onto the Galaxy, that is, with ultra-faint dwarfs, including their dark matter component.

The broad debris of massive mergers in chemo-dynamical spaces

(Mori et al., 2024, A&A)

Stars accreted from dwarf galaxies are identified as overdensities in kinematic spaces, that is, as featuring similar integrals of motion (Helmi & de Zeeuw, 2000) – such as energy (E) and angular momentum (L_z), along with matching chemical abundances – typically, metallicity distribution functions (MDF) or sequences in the α -metallicity plane (e.g., Nissen & Schuster, 2010).

To test these methods, we analysed high-resolution, self-consistent N-body simulations of satellite accreting onto a Milky Way-like galaxy with a mass ratio of 1 : 10 and different orbital inclinations, to which we assigned observationally-driven chemical abundances *a posteriori*, considering different abundance gradients.

We confirmed that accreted stars span a broad range of E and L_z , due to dynamical friction, thus they are not associated with a single region in the $E - L_z$ space, as conventionally assumed (Fig. 4.2). As a result of the merger, the in situ component gets kinematically heated to halo-like orbits, thus getting to overlap with the accreted component and contributing to the formation of the stellar halo (Fig. 4.2).

We found that satellite stars with different metallicities can be deposited in different regions of the $E - L_z$ space, in particular that on average the more metal-rich ones end up more gravitationally bound to the Milky Way (Fig. 4.3). Ultimately, this implies that a single accretion event with a mass ratio $\sim 1 : 10$ can manifest with different MDFs in distinct regions of the $E - L_z$ space, contrary to prevailing paradigms (Fig. 4.8 and Fig. 4.16).

As a consequence, interpreting groups of stars with different E , L_z , and metallicities as originating from different satellite galaxies can bias the reconstructed merger tree of the Milky Way towards increasing the number of past accretions and decreasing the masses of the progenitor galaxies.

The multiple passages of massive mergers traced by chemo-dynamics
(Skúladóttir et al., 2025, including Mori, ApJL).

We presented for the first time observational evidence of the results above, according to which a massive merger can deposit stars with on average different chemo-dynamical properties based on the phase of the accretion they were lost at.

To obtain this result, we analysed the historical sample of Nissen & Schuster (2010) through which the GSE debris were identified for the first time, crucially including new aluminum measurements collected at ESO VLT/UVES (PI: Skúladóttir). We then divided the sample into a high- and a low-energy components, corresponding to stars that were lost earlier during the merger from the outskirts of the GSE progenitor and to the inner parts lost towards the end, as guided by the predictions of Mori et al. (2024), which were therefore key to correctly interpret these novel findings (see Fig. 4.1).

We finally showed that in all observed abundance ratios ($[\text{Fe}/\text{H}]$, $[\text{Al}/\text{Fe}]$, $[\text{Mg}/\text{Fe}]$, and $[\text{Mg}/\text{Ba}]$), stars with high energy show evidence of coming from a less chemically evolved region of the GSE progenitor, that is, its outskirts, compared to the stars with low energy. We therefore concluded that GSE experienced at least two passages before merging with the Milky Way.

The findings of our work bring to light the potential of the synergy of kinematic and chemical information in tracing the different phases of past merger events in remarkable detail; along with the need of self-consistent simulations to interpret observational findings.

The interconnection of halo substructures revealed by their chemistry
(Mori et al., 2025, A&A *subm.*)

The current wealth of observational data led to the identification of several substructures in the Galactic halo defined by different kinematic properties. However, as a consequence of the results discussed above, these substructures are expected to be contaminated by both massive merger(s) and heated disc stars (e.g., Mori et al., 2024).

Aiming at quantifying the contamination of these samples, we analysed *Gaia* EDR3 and APOGEE DR17 data, to compare the kinematically-defined substructures only through their chemical abundances (C, Mg, Al, Si, Ca, Mn, Fe).

To do so, we employed Gaussian Mixture Models as this method allows to incorporate the analysis of various elements that probe different nucleosynthetic channels, providing a percentage of global chemical compatibility.

The results of this analysis revealed that most of the halo substructures studied feature large fractions of stars ($\geq 50\text{--}60\%$, Fig. 6.5) that are chemically compatible with GSE, as well as some of them displaying significant chemical compatibility with the heated disc ($\geq 20\text{--}30\%$, Fig. 6.6). Finally, we showed that a number of these substructures may also be contaminated by the debris of other accretion events, such as that with Sagittarius and the progenitor of ω Centauri (Fig. 6.7, 6.8, 6.9).

This implies that stars with chemical abundances similar to those of GSE are spread throughout the kinematic spaces, that is, we might be severely underestimating its relics in the Galaxy, yet highlighting the power of the chemical abundances to identify them.

The variety of accretion properties of the least massive satellites

(Mori et al., in prep)

With the final aim of modelling the accretion of the lowest massive galaxies (i.e., UFDs, see next Sec. 8.2), we analysed high mass resolution cosmological simulations which provided us with the statistics to set realistic initial conditions.

In particular, we made use of the Caterpillar Project suite of dark matter-only, Milky Way-sized, zoom-in cosmological simulations, which have a mass resolution of a few $10^4 M_\odot$, thus resolving the evolution of $\sim 10^7 M_\odot$ dark matter satellites likely hosting UFDs.

The statistical analysis of the $\sim 10^3$ dark matter satellites with $M \sim 10^7 M_\odot$ unveiled a large heterogeneity in the properties of their accretion. In particular, their infall time into the Milky Way potential span the whole range of lookback time of $0\text{--}12$ Gyr, with two comparable peaks at very recent ($0\text{--}2$ Gyr) or more distant ($8\text{--}10$ Gyr) epochs (Fig. 7.5). Furthermore, their orbital properties feature typical eccentricities of $0.3\text{--}0.7$, still displaying significant tails in the distribution at more circular/radial orbits (Fig. 7.9).

These results predict a wide spectrum of configurations for the accretion of low-mass systems onto our Galaxy, which would then need to be thoroughly probed, implying that to simulate the accretion of UFDs into the Milky Way we need to explore them all, since they can potentially lead to different conclusions.

8.2 Future perspectives

A natural continuation of the aforementioned results of the bulk of my Thesis work led us to explore the least massive end of the hierarchical build-up of our Galaxy, i.e., to model the accretion of UFDs within the Galactic potential. Although they contribute negligibly to the total stellar mass of the Milky Way, in fact, they are expected to represent the principal contributors to the most metal-poor tail of the Galactic halo MDF (e.g., [Salvadori et al., 2015](#)), probing the earliest phases of chemical enrichment and the nature of the first stars ([Rossi et al., 2025](#)).

Furthermore, UFDs ($M_* \leq 10^5 M_\odot$) have mass-to-light ratios $10^2 M_\odot/L_\odot < M/L < 10^4 M_\odot/L_\odot$ ([Battaglia & Nipoti, 2022](#)), thus being the most dark matter-dominated stellar systems known and the best laboratories to explore the nature of dark matter. However, the estimate of UFDs' (dynamical) masses is computed through the stellar velocity dispersion σ , which can be inflated by the presence of binary stars ([Pianta et al., 2022](#)) and can lead to an overestimation of the dark matter fraction in UFDs. Therefore, it is essential to separate the effects of dark matter from those of binary stellar populations on the observed dynamics. It is thus crucial to model UFDs with varying fractions of binary stars to determine their influence on σ , ultimately providing more accurate constraints on the dark matter content in these galaxies.

Solid constraints on their dark matter mass are necessary to model their accretion onto the MW with realistic initial conditions, and thus to study their final configuration reliably. Indeed, by simulating the evolution of a UFD within a Milky Way-like galaxy, we would also be able to discover where the stars accreted from UFDs, which are chemically polluted by the first supernovae, would end up once the interaction is over and whether they preserve or not some sort of phase-space/chemical coherence, unlike more massive mergers (e.g., [Mori et al., 2024](#)). This would be crucial for Galactic Archaeology, since the low-mass regime of the accretion history of our Galaxy is indeed still poorly explored by simulations.

An ongoing project which I lead consists in modelling a Boötes I-like UFD ($M_* \sim 10^5 M_\odot$) - which is one of the most massive and best studied UFDs - accreting and evolving into a Milky Way-like potential. The simulations make use of the NBSymple code ([Capuzzo-Dolcetta, Mastrobuono-Battisti & Maschietti, 2011](#)), which is a parallel, direct and symplectic N-body code running on GPUs. This code has been used in multiple projects involving the modelling of stellar cluster evolution (e.g., [Mastrobuono-Battisti et al., 2012](#); [Sollima et al., 2012](#); [Sollima &](#)

Mastrobuono Battisti, 2014; Lacchin et al., 2024), and it has been optimised to model dark matter components and merger events. Furthermore, we will implement into the code a Milky Way-like potential evolving over time (modelled through the findings reported in Sec. 7.2), so that accretion events at different evolutionary stages of the Milky Way would be simulated.

Based on the results illustrated in Ch. 7 (Mori et al., *in prep*), I am preparing a set of simulations that will span the wide parameter space covered by UFDs evolving into a Galactic potential. In particular, the statistical analysis of the Caterpillar Project suite of cosmological simulations highlighted the necessity of considering a variety of configurations for the orbits of the UFDs (circular, elliptical, and radial; see Sec. 7.3.3), as to check whether they influence the final distribution of the accreted stars in the phase-space. Moreover, these simulations will take into account recent as well as ancient infall times of the UFD into the Milky Way potential, as guided by the cosmological predictions that we obtained (see Sec. 7.3.1).

As we need a statistical sample needed for robust results while exploring different configurations of the model, to run this suite of simulations for accreting UFDs in the Milky Way, we applied to get computational time at the supercomputer Leonardo Booster @ Cineca (PI: Mori). Our HPC project entitled “DNA of Ultra-Faint Dwarf galaxies: uncovering Dark matter and Accretion events” (UFD-sDNA) was allocated 80k GPU hours, which we are already using to set up the simulations.

Through this project, allowed by the collaboration between the University of Florence, University of Padua and Observatoire de Paris, we aim to strengthen our understanding of the dark matter role in the lowest-luminosity stellar systems, leading to more accurate dark matter content estimates in UFDs, along with the evaluation of the UFD contribution in the formation of our Galaxy, by finding methods to identify accreted UFD stars in the Milky Way and uncover the living relics of the first supernovae, i.e., second-generation stars.

Indeed, the future of Galactic Archaeology is bright given the *Gaia* mission (Gaia Collaboration et al., 2016a) and its future releases in December 2026 (DR4) and not before the end of 2030 (DR5), along with the large number of stellar surveys that will probe the stellar halo and the satellite dwarf galaxies, such as WEAVE (Jin et al., 2023) and 4MOST/4DWARFS (Skúladóttir et al., 2023). Only by performing a tight synergy between theory and observations, and by carefully and critically interpreting these novel findings, will we be able to fully exploit the wealth

of observational data that will soon become available and probe the hierarchical build-up of the Milky Way in its entirety.

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