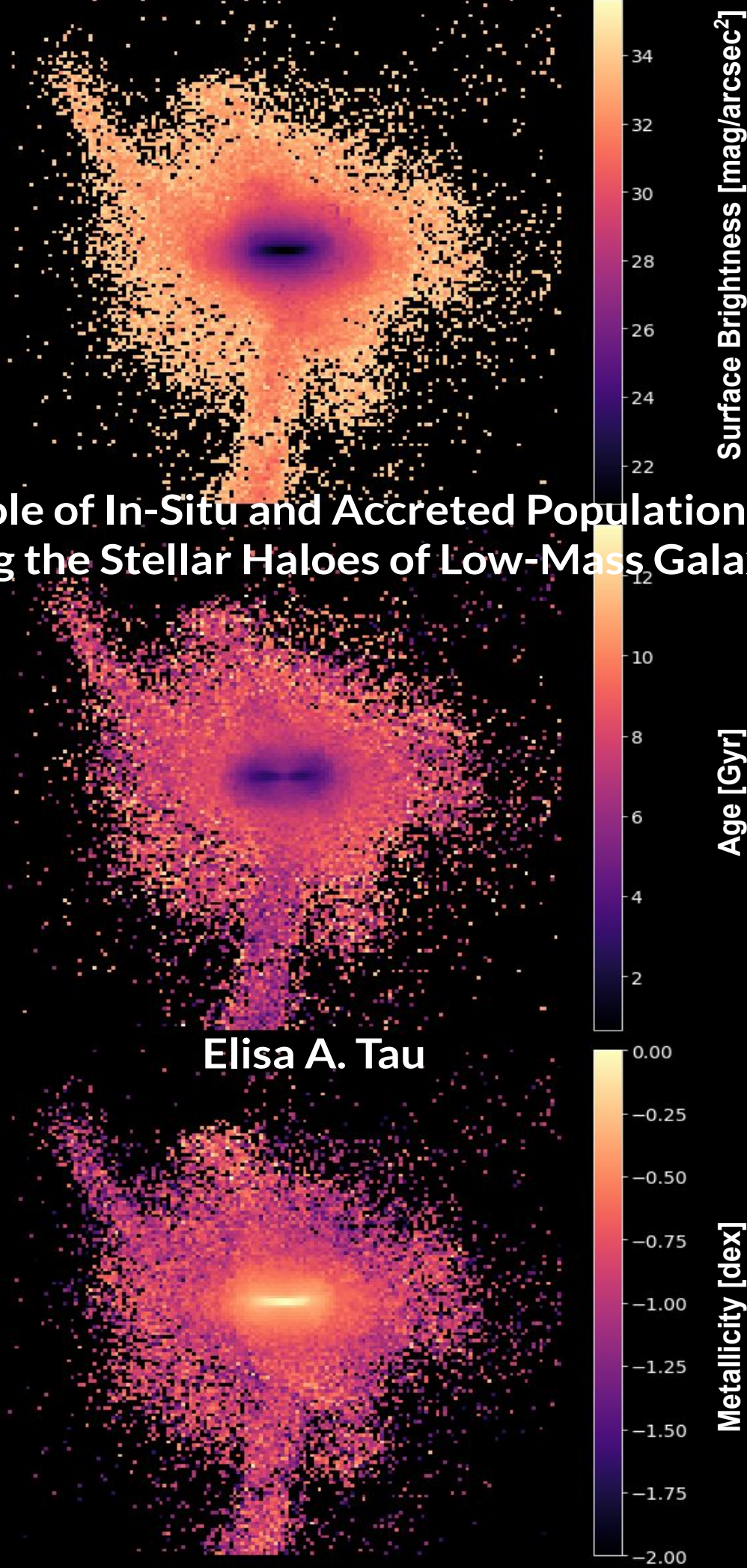


The Role of In-Situ and Accreted Populations in Shaping the Stellar Haloes of Low-Mass Galaxies

Elisa A. Tau



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Cover image: density maps of the surface brightness, the age and the metallicity of Auriga 5, one of the galaxies of the sample analysed in this thesis. The outskirts of this galaxy are populated by stellar material, and features such as stellar streams can be easily identified.

Credit: this image was made by myself, Elisa A. Tau, using data available from the Auriga simulations for this galaxy, which was plotted using Python libraries.

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Abstract

Low-mass galaxies ($M_* \leq 10^{10} M_\odot$) play a fundamental role in our understanding of galaxy formation and evolution, as they are the most numerous galaxies in the Universe and are widely considered the building blocks of more massive systems within the hierarchical Λ Cold Dark Matter paradigm. However, studying their properties observationally in this low-mass regime is particularly challenging due to the faint nature of dwarf galaxies, which have very low surface brightness values. This difficulty extends to their stellar haloes, which are extended, diffuse components that can retain long-term imprints of both accretion and in-situ processes. These structures have only recently begun to be observationally detected in the low-mass regime, making their study a promising but still largely unexplored avenue for understanding dwarf galaxy evolution. For this reason, cosmological simulations provide an indispensable complementary approach, as they allow us to model the structure and evolution of dwarf galaxies and their stellar haloes in detail, and to make predictions that will hopefully be put to the test with the upcoming data from future facilities.

In this thesis, we use the zoom-in hydrodynamical simulations available in the Auriga Project to analyse and characterise 17 isolated dwarf galaxies with stellar masses ranging from $3.28 \times 10^8 M_\odot$ to $2.08 \times 10^{10} M_\odot$. The resolution of these simulated galaxies is of $5 \times 10^4 M_\odot$ in dark matter particles and $\sim 6 \times 10^3 M_\odot$ in baryonic particles, which allows to reliably study low-mass systems. We set a definition for their stellar haloes based on the spatial distribution of the stellar material, considering all stellar particles located at larger distances than $4R_h$ as part of these structures, being R_h the galaxies' half-light radius. We characterise the stellar haloes of these galaxies by studying their metallicity, age, accreted mass fraction, formation time and number of significant progenitors.

We find that the stellar haloes of these galaxies are comprised mainly of in-situ stellar material, and that this component dominates at all radii in those galaxies with stellar masses lower than $4.54 \times 10^8 M_\odot$. Focusing on the formation mechanism of this in-situ component of the stellar halo, we find that it is mostly formed in the inner regions of the galaxies and subsequently kicked out into the outskirts as a consequence of interactions with satellite galaxies. Concerning the accreted component of these stellar haloes, we find that more massive dwarf galaxies have a greater amount of accreted stellar material contained in this region. Furthermore, as more massive galaxies in our sample keep on accreting stellar material until later times than less massive ones, the formation time of their accreted stellar haloes is also later than for less massive galaxies. We find that, for more massive galaxies, their stellar haloes formed about 4 Gyr ago, while for less massive galaxies this was about 7 Gyr ago. Additionally, when analysing the whole galaxy, we find that the majority of them exhibit U-shaped radial age profiles, a feature rarely observed in Milky Way-mass systems, and we show that this behaviour is primarily driven by the redistribution of old in-situ stellar populations to large radii, combined with a lack of recent star formation in their outskirts. We also find a wide variety of metallicity gradients, in agreement with observational results for Local Group dwarfs. Moreover, we demonstrate that while global gradients show no clear dependence on stellar or halo mass, the median metallicity of the accreted stellar haloes strongly correlates with both their mass and the infall time of their dominant progenitor. This extends the stellar halo mass–metallicity relation, well established for Milky Way-mass galaxies, into the low-mass regime.

This thesis therefore provides theoretical predictions for the structure and diversity of dwarf galaxies and their stellar haloes, offering key insights into these structures' formation pathways and valuable

guidance for upcoming observational efforts.

Chapter 1

Introduction

1.1 Hierarchical structure formation: low-mass halos

How many type of galaxies are there in the Universe? The answer to this question has been subject to many studies in the past decades and has also changed through time as new types of galaxies were discovered, or new classifications of them came to exist. As a first step towards the classification of galaxies, Edwin Hubble developed a scheme in 1926 consisting roughly in two categories: elliptical galaxies and spiral galaxies (Hubble, 1926). This diagram also included a transition zone between elliptical and spiral galaxies in which lenticular galaxies were placed. Nowadays, this original classification scheme has been modified to include more types of galaxies, such as irregular galaxies. In addition, the different ranges of masses of the galaxies have become an important characteristic to further discriminate these systems. In Fig. 1.1.1, examples of different low-mass galaxies of the Local Group (LG) are shown, spanning a wide range of sizes and stellar masses, reflecting the diversity of these systems.

Given the wide variety of galaxies found in the Universe, understanding how they form and evolve, as well as what drives these differences, is of great interest. According to the hierarchical formation of structures predicted by the Λ Cold Dark Matter (Λ CDM) paradigm, haloes grow and form from the accretion of less massive systems (White & Rees, 1978; Searle & Zinn, 1978; Frenk et al., 1988; Navarro et al., 1997). The Λ CDM cosmological model involves three main components comprising the Universe: dark energy, cold dark matter and baryonic matter. The dark energy is responsible for the accelerated expansion of the Universe, the dark matter can only be observed via its gravitational interaction with the matter in the Universe, and the baryonic matter can be observed and detected directly. This latter component is made up of protons and neutrons, and accounts for the gas and stars we observe in the Universe, making up $\sim 5\%$ of it (Vogelsberger et al., 2020). The vast majority of the Universe ($\sim 95\%$) consists of the other two components, dark energy and dark matter (Planck Collaboration et al., 2020). In the Λ CDM model, small density fluctuations arose in the distribution of matter after the Universe underwent a rapid expansion, a period known as “inflation” and that happened 10^{-32} seconds after the Big Bang (Guth, 1981). These fluctuations set the initial conditions for dark matter to start to collapse after interacting gravitationally with its surroundings, and due to its collapse it formed haloes (Frenk et al., 1988). Because dark matter haloes can gravitationally attract other haloes, these structures began to merge over time, gradually growing in mass. This process of successive mergers and accretion is known as hierarchical structure formation, a central prediction of the Λ CDM paradigm (e.g., White &

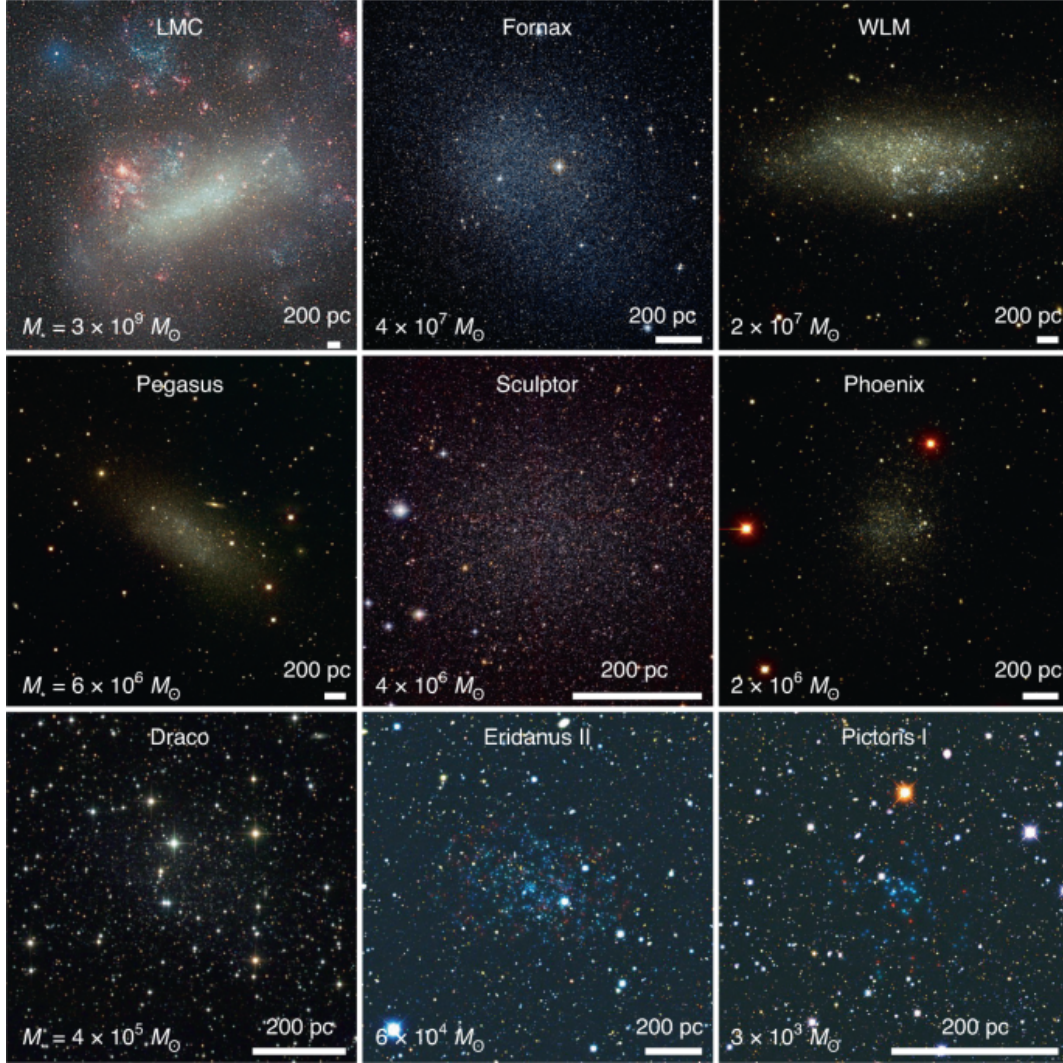


Figure 1.1.1: Images of a representative sample of Local Group dwarf galaxies, spanning a range of stellar masses and sizes. This figure was extracted from [Crnojević & Mutlu-Pakdil \(2021\)](#).

[Rees, 1978](#); [Springel et al., 2006](#)). As a consequence of the gravitational perturbations generated by overdense and underdense regions of matter, gas falls toward the centre of these halos. The accumulated gas can begin to cool via radiative processes ([White & Frenk, 1991](#); [Katz et al., 1992](#)), such as atomic line emission (e.g., Lyman-alpha cooling, [Rees & Ostriker, 1977](#)), and when this cooling occurred, it allowed the gas to lose thermal energy, condense further, and eventually fragment into smaller and denser clumps that are capable of forming stars. These stars mark the birth of the first galaxies, as they assemble within the gravitational potential wells of dark matter haloes, transforming these structures into luminous systems. This hierarchical scheme in which large galaxies arise as a consequence of the merging of less massive structures directly implies the existence of low-mass galaxies, also known as dwarf galaxies, which are the building blocks of more massive systems. An illustration of this model is shown in Fig. 1.1.2, with small galaxies at the top merging to form a more massive one.

However, it is important to note that not all dark matter haloes host galaxies. Many low-mass haloes

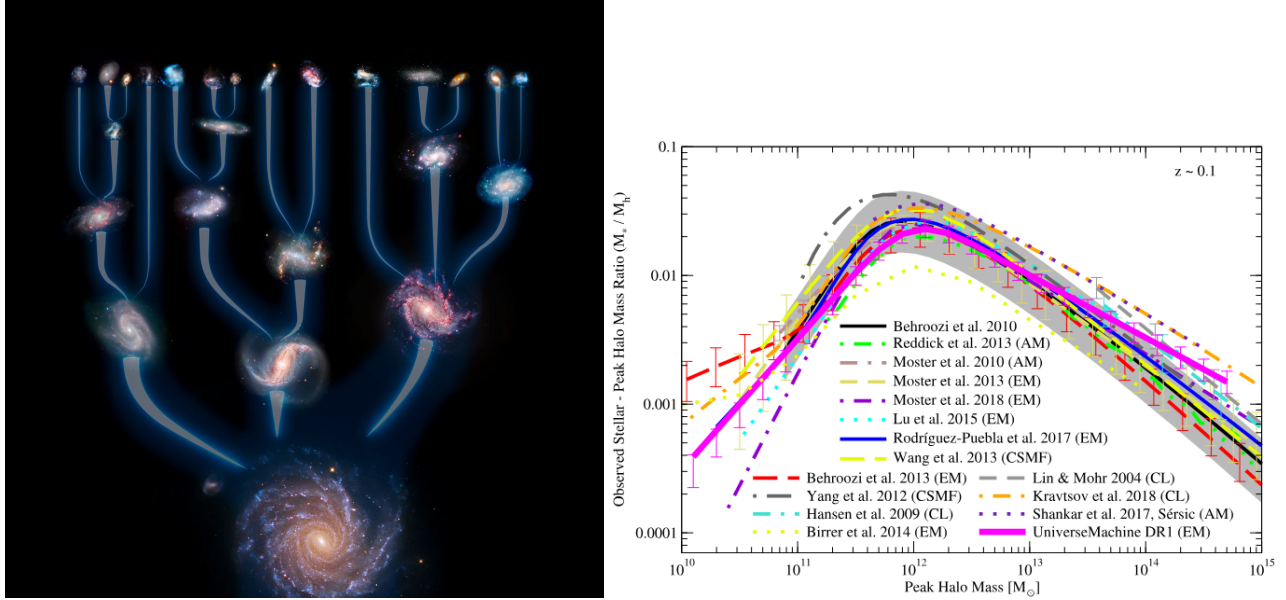


Figure 1.1.2: Left panel: Illustration of the hierarchical model for structure formation: lower-mass galaxies merge and form a more massive galaxy as a result. This image was taken from the European Southern Observatory webpage. Right panel: Median observed stellar mass–halo mass relation for Behroozi et al. (2019) best-fitting model, compared to the results obtained from other models at $z = 0.1$. This figure was extracted from Behroozi et al. (2019).

are unable to retain or cool gas efficiently, preventing star formation. Processes such as cosmic reionization can heat the intergalactic medium, suppressing gas accretion onto small haloes (e.g., Efstathiou, 1992; Bullock et al., 2000). As a result, the galaxy–halo connection is highly dependent on halo mass, with a significant fraction of low-mass haloes remaining dark. This relation is shown in the right panel of Fig. 1.1.2.

In the scenario of hierarchical structure formation, mergers of haloes play a fundamental role in shaping galaxies and influencing their evolution. According to the mass ratio of the merger (i.e., the ratio between the masses of the merging haloes), it can be considered as major or minor. Major mergers, where the mass ratio between interacting haloes is usually 1 : 3 or higher, are significant drivers of stellar mass growth and can drastically alter a galaxy’s structure. In Milky Way (MW)-mass haloes ($M_{DM} > 10^{11} M_{\odot}$), major mergers are known to trigger pronounced disturbances in galactic centres (e.g., disc thickening and warps Grand et al., 2016; Gómez et al., 2017). In contrast, minor mergers, which are much more frequent, involve low-mass satellites and mainly result in the gradual accretion and tidal disruption of dwarf galaxies (Bullock & Johnston, 2005), although they can also induce star formation and produce disc disturbances. As these smaller systems are pulled into the gravitational field of a more massive host, tidal forces strip away their stars and redistribute them. The debris from these disrupted satellites contributes diffuse stellar material to the outskirts of the host, named the stellar halo, often forming recognisable features such as streams, shells, and tidal tails.

When considering the low-mass regime ($M_{Halo} \leq 10^{11} M_{\odot}$) in this context, dwarf galaxies should also grow from the accretion of galaxies of lower mass (Diemand et al., 2007). The stellar material from these accreted systems should contribute to the overall evolution of the host dwarf galaxy, potentially affecting

its chemical enrichment history, stellar halo properties, and structural evolution. However, the extent of this impact depends on the relative mass and frequency of the accreted satellites. Numerical studies show that while some low-mass galaxies may experience only minor accretion with limited influence on their chemical and dynamical properties, others can undergo more significant mergers that leave observable imprints on their stellar populations and metallicity gradients (e.g., [Benítez-Llambay et al., 2016](#)). Although in MW-mass systems such accretion events can contribute to the build-up of diffuse stellar haloes ([Bell et al., 2008](#); [Martínez-Delgado et al., 2010](#); [Ibata et al., 2014](#)), in the low-mass regime it remains uncertain whether dwarf galaxies develop accreted stellar haloes in the same way, as observational evidence is limited and numerical studies, that require high resolution to be able to explore and study this faint component, are only beginning to be developed.

1.2 Properties of low-mass galaxies: clues to their growth and accretion history

Among the observed systems, dwarf galaxies ($M_* \leq 10^{10} M_\odot$) are of particular relevance, and are the subject of study of this thesis. They are known to be the oldest and most metal-poor galaxies in the Universe, as well as systems dominated by dark matter ([Tolstoy et al., 2009](#); [Simon, 2019](#)). There are currently many classifications for dwarf galaxies, depending on their different properties. For example, some subcategories of dwarf galaxies are early-type dwarf spheroidals (dSphs), late-type star-forming dwarf irregulars (dIrr), ultra-faint dwarfs (UFDs), and centrally concentrated actively star-forming blue compact dwarfs (BCDs). Due to their shallow gravitational potential, dwarf galaxies are extremely susceptible to internal and external processes. Internal processes can include star formation and the subsequent stellar feedback (e.g., [El-Badry et al., 2018](#)), while external ones include mergers (e.g., [Deason et al., 2014](#)), ram pressure stripping (e.g., [Grebel et al., 2003](#)), and tidal interaction (e.g., [Fattahi et al., 2018](#)), among others. All of these processes may influence the morphologies of low-mass galaxies (e.g., [Higgs et al., 2021](#)), and have a more drastic impact than in galaxies with larger masses, which have deeper gravitational potentials.

Understanding the intrinsic properties of dwarf galaxies is crucial for several reasons. As the most numerous type of galaxy in the Universe and the presumed building blocks of larger systems in hierarchical cosmology, they offer key insight into galaxy formation and evolution on small scales. Studying their star formation histories (SFH), chemical enrichment, and kinematics helps us reconstruct their individual evolutionary paths and interaction histories, while also providing stringent tests of cosmological models and structure formation in the Λ CDM framework. For example, their diverse SFHs allow us to evaluate how well Λ CDM-based models capture the effects of reionization and environmental quenching at low masses. Moreover, the relatively simple structures of dwarf galaxies compared to massive galaxies make them valuable laboratories for isolating and understanding the fundamental physical processes that shape galaxies, such as chemical enrichment and outflows (e.g., [Kirby et al., 2011b](#)), and tidal and ram-pressure stripping (e.g., [Mayer et al., 2006](#)), among others. Some galaxies are easier to study than others, mainly due to their distance, location in the sky and surface brightness. Low-mass galaxies in the LG are the ones analysed in greatest detail because their proximity allows us to resolve their individual stars, which provides accurate and precise information regarding the properties of the galaxy they belong to, such as their age, SFH, chemical abundances, kinematics, and spatial distributions of different stellar populations.

For instance, studies regarding these systems have revealed that some show extended SFH while others are dominated by older populations with truncated formation early on (e.g., [Weisz et al., 2014](#)). These differences can be seen in Fig. 1.2.1 for dwarf galaxies in the LG. Furthermore, kinematic studies show a range from rotationally supported systems to pressure-supported spheroidal galaxies, illustrating the complex evolutionary paths these low-mass galaxies can follow (e.g., [McConnachie, 2012](#)). Altogether, these findings highlight both the diversity of dwarf galaxy properties and their critical role as benchmarks for testing galaxy formation models.

In addition, many of these dwarf galaxies display significant metallicity gradients and evidence of chemical enrichment over time (e.g., [Kirby et al., 2011a](#)). In this context, metallicity gradients have long been studied as a diagnostic tool to understand galaxy formation and evolution (e.g. [Kudritzki et al., 2012, 2014](#); [Tissera et al., 2012, 2022](#); [Sextl et al., 2024](#)). These gradients can provide insight into star formation histories, internal feedback, and external influences such as mergers (e.g. [Benítez-Llambay et al., 2016](#)) or environmental effects (e.g. [Leaman et al., 2013](#)). Among studies of metallicity gradients, [Battaglia et al. \(2006\)](#) studied the Fornax dwarf spheroidal (dSph) galaxy using Very Large Telescope (VLT)/Fibre Large Array Multi Element Spectrograph (FLAMES) spectra and images from the Dwarf Abundances and Radial velocities Team (DART) large programme at ESO, and distinguished two main components based on metallicity: a metal-poor component with a mean metallicity of $[\text{Fe}/\text{H}] \approx -1.7$, which is found throughout the galaxy, and a more metal-rich component with a mean of $[\text{Fe}/\text{H}] \approx -1$, which is concentrated mainly within 0.7 degrees (~ 1.68 kpc) from its centre. This spatial concentration of the metal-rich stars generates a metallicity gradient. [Battaglia et al. \(2011\)](#) extended this type of analysis to the Sextans dSph galaxy, confirming it is a metal-poor low-mass system, with an average metallicity of $[\text{Fe}/\text{H}] = -1.9$, and that its stars exhibit a wide range of metallicities, indicating a complex chemical enrichment history. The authors also note that the central regions of Sextans are more metal-rich compared to the outer regions, indicating the existence of a metallicity gradient. More recently, [Muñoz et al. \(2023\)](#) reported that both the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) exhibit negative metallicity gradients, with the SMC showing a steeper decline in metallicity with radius compared to the LMC. Additionally, [Taibi et al. \(2022\)](#) analysed the metallicity profiles of 30 dwarf galaxies of the LG and found a wide variety of them, most of them decreasing with radius. This can be seen in Fig. 1.2.2. The authors searched for a correlation between the metallicity gradients of these profiles and the galaxies' properties, such as stellar mass, luminosity, star formation timescales and morphology, but did not find any, not even when analysing their distances to the MW or Andromeda (M31). However, their work shows that the strongest metallicity gradients were found in galaxies that likely experienced past merger events based on their observed structural and kinematic characteristics. This is also found in a numerical work by [Benítez-Llambay et al. \(2016\)](#), where the authors study dwarf galaxies from the Constrained Local Universe Simulations (CLUES) and identify two necessary conditions for establishing strong metallicity gradients: (i) the occurrence of a merger that disperses the older, typically metal-poor stars, and (ii) the subsequent formation of a more centrally concentrated in situ stellar population. Nevertheless, the time at which dwarf galaxies accrete the satellites involved in their assembly has not yet been explored, and this could have an effect on the resulting metallicity of the host galaxy.

Stellar age distributions in dwarf galaxies offer an additional powerful diagnostic of their formation and evolutionary histories. By examining age gradients and the spread of stellar ages across different galactic regions, it is possible to trace episodes of star formation and the imprint of past interactions. In

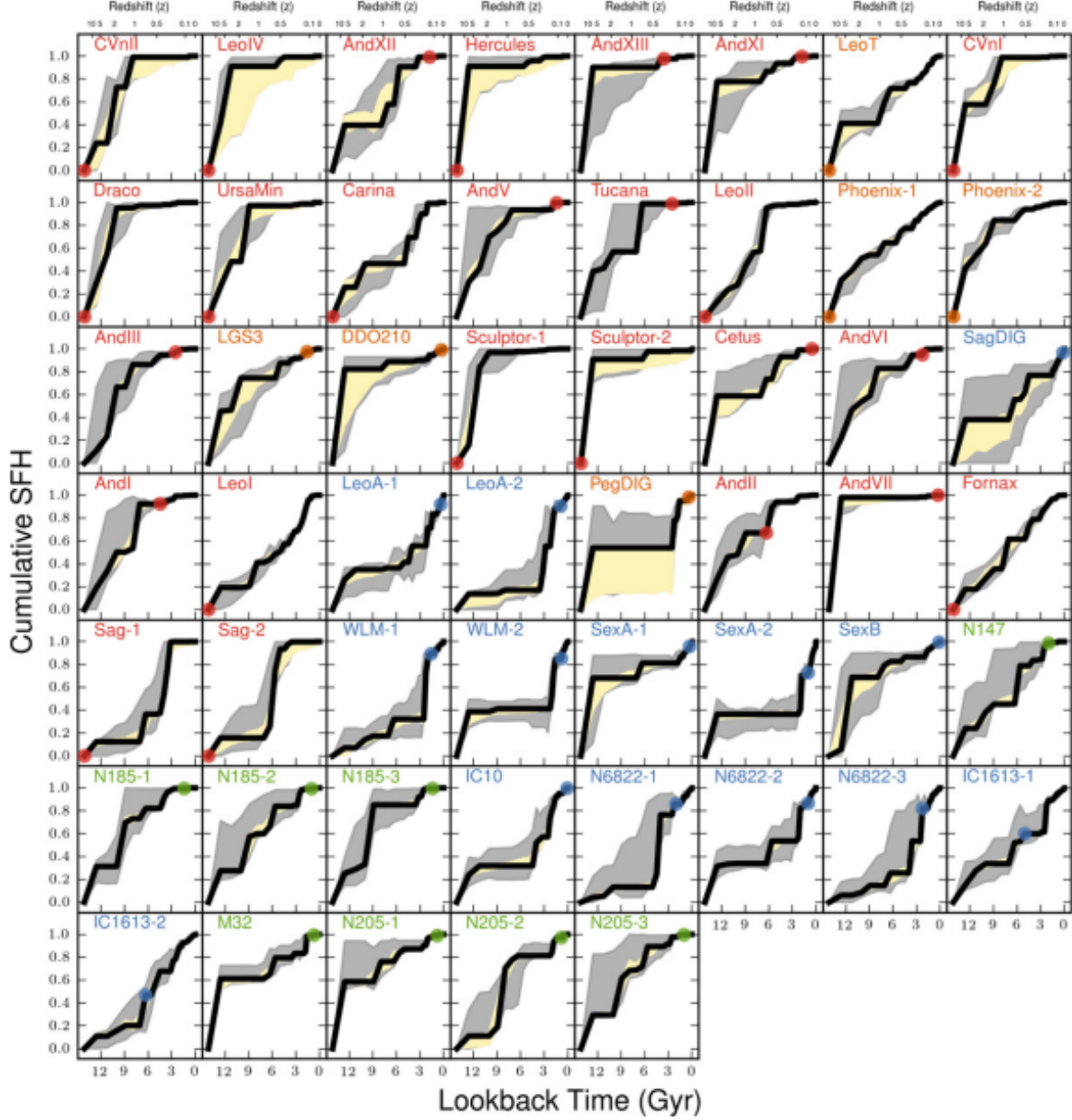


Figure 1.2.1: Cumulative SFHs of the galaxies analysed in [Weisz et al. \(2014\)](#), sorted by increasing absolute V-band luminosity. The fields are colour-coded according to present day morphological type: dSph (red); dIrr (blue); dTrans (orange); dE (green). The solid black line represents the best fit SFH, while shaded envelopes represent the 68% confidence interval due to random uncertainties (yellow) and total uncertainties (random and systematic; gray). Each plot has been normalised such that its total stellar mass formed is unity at the present day. The coloured dots in each panel indicate the approximate age of the oldest main sequence turn-off on each colour-magnitude diagram. This figure was extracted from [Weisz et al. \(2014\)](#).

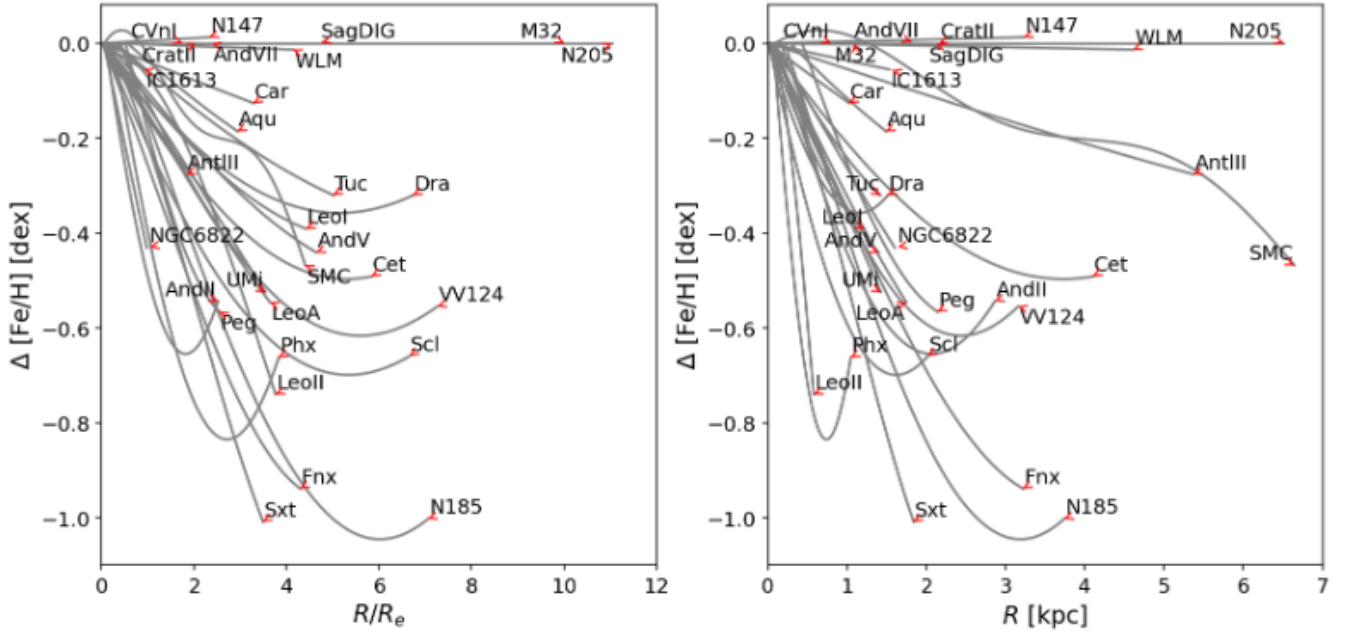


Figure 1.2.2: Radial metallicity profiles calculated for a sample of LG dwarf galaxies. They are smoothed $[\text{Fe}/\text{H}]$ profiles as a function of semi-major axis radius as obtained from the Gaussian process regression fitting method in units of the 2D R_h (left panel) and as a function of physical radius (right panel). This figure was extracted from [Taibi et al. \(2022\)](#).

low-mass galaxies there seems to be an “outside-in” star formation because older stars are observed in their outskirts while younger stellar populations are more centrally concentrated, which is in contrast to the “inside-out” stellar formation reported for MW-mass galaxies, where old and red stars tend to populate the innermost regions, while younger and bluer stars populate larger distances along the discs (e.g. [Kepner, 1999](#); [Chiappini et al., 2001](#)). This outside-in scenario has been reported in many observational works of both isolated and non-isolated dwarfs, such as [Tully et al. \(1996\)](#); [Gallart et al. \(2008\)](#); [del Pino et al. \(2015\)](#); [Weisz et al. \(2015\)](#); [Bettinelli et al. \(2019\)](#); [Martínez-Vázquez et al. \(2021\)](#); [Zhuang et al. \(2021\)](#); [Ferré-Mateu et al. \(2021\)](#); [Liao & Cooper \(2023\)](#); [Cohen et al. \(2024b\)](#), among others.

One explanation for this outside-in trend in low-mass galaxies suggests that old stars indeed formed in the outer regions and younger stars formed at smaller galactocentric radii. For this scenario to happen, star formation in the outskirts must be suppressed while continuing in central regions. This suppression likely results from gas depletion or reduced gas density in the outer parts. Simulations suggest that environmental effects during infall into a larger halo, such as ram-pressure stripping (e.g. [Mayer et al., 2006](#)), can facilitate this process. However, this cannot explain the outside-in star formation found in some isolated dwarfs (e.g., [Martínez-Vázquez et al., 2021](#)). Hence, another way of explaining this trend could be with an inside-out formation scenario and a later redistribution or reshuffling of the stellar material. [Riggs et al. \(2024\)](#) used a sample of 73 simulated dwarf galaxies from the Marvel and DCJL simulations and found that they generally form their stars inside-out, similar to more massive galaxies. However, the oldest stars are often reshuffled to larger radii due to fluctuations in the gravitational potential well caused by stellar feedback, leading to an apparent outside-in age gradient at $z = 0$.

Interestingly, some low-mass galaxies show a reversal in their age profiles, forming stars inside-out

in the central regions but transitioning to an outside-in pattern in the outskirts (e.g. [Williams et al., 2009](#); [Mostoghiu et al., 2018](#); [Pessa et al., 2023](#); [Cohen et al., 2024a](#)). This highlights the complexity of star formation and redistribution processes in low-mass systems, and also raises the question of how stellar ages behave specifically in the stellar halos, which represent the outermost regions of these galaxies. Studying the age distributions in stellar halos is particularly important because these extended components could retain the long-term imprints of both in-situ star formation and past accretion events, offering unique constraints on the evolutionary histories of dwarf galaxies and their connection to hierarchical galaxy formation.

Yet, disentangling the role of past accretions in shaping stellar haloes is especially challenging when the main galaxy itself is a satellite of a more massive host, since the additional perturbations from the environment can strongly influence its morphology and stellar populations. For instance, low-mass galaxies present in the LG are constantly being perturbed by more massive galaxies. Therefore, LG dwarf galaxies that are satellites of larger hosts are not ideal candidates for studying the intrinsic properties of low-mass systems. In contrast, isolated dwarf galaxies offer a more pristine laboratory to investigate their formation and evolution histories free from external influences, although they are usually harder to observe due to instrumental limitations when considering their generally much larger distances. Thus, studying the stellar haloes of dwarf galaxies is essential for building a complete picture of their formation and evolution, and studying these structures in isolated dwarf galaxies is especially valuable, as it allows to investigate their intrinsic formation and evolution histories without the confounding effects of environmental interactions, providing an unbiased view of their development.

1.3 Stellar haloes

Stellar haloes are extended low-surface brightness structures surrounding galaxies, and are widely regarded as a direct evidence of the hierarchical formation of structures because, on the one hand, the interacting satellite galaxies can deposit a significant fraction of this material in the outer regions of their host galaxies during the merging process ([Bullock & Johnston, 2005](#); [Monachesi et al., 2019](#)), and on the other hand, during the interactions between galaxies, stars that were originally located in their inner regions can be heated up, and end up reaching more distant orbits ([Purcell et al., 2010](#); [Tissera et al., 2013](#)). Detecting and analysing these stellar haloes is challenging due to their faint nature, typically with surface brightnesses fainter than $\mu \sim 30 \text{ mag arcsec}^{-2}$. When considering the low-mass regime, these tasks become harder because these structures will be even fainter, as stellar halo mass and stellar halo fractions have been shown to decrease with decreasing host galaxy mass ([Cooper et al., 2013](#)).

Stellar halos of galaxies hold valuable information regarding the formation history of the galaxies they surround, which can be retrieved by studying their composition. In particular, the metallicities and ages of the stellar populations in these substructures offer key insights into the timing and nature of accretion events, as well as the chemical evolution of the progenitor satellites that contributed to the stellar halo.

Until recently, only stellar haloes of MW-mass galaxies had been studied in detail both observationally and numerically (e.g., [Zolotov et al., 2009](#); [Peacock et al., 2015](#); [Monachesi et al., 2016a,b](#); [Fattahi et al., 2020](#); [Rey & Starkenburg, 2022](#)). However, stellar haloes of low-mass galaxies have become an object of study in the last years (e.g., [Qi et al., 2022](#); [Sestito et al., 2023a,b](#); [Waller et al., 2023](#); [Jensen et al., 2024](#)), and new numerical simulations with high resolution have encouraged their modelling.

1.3.1 Stellar haloes in MW-mass galaxies

In the MW, it is easier to observationally study the stellar halo because our location allows us to analyse in detail the stars that comprise it, and it has been a subject of study in the last decades. For example, [Jurić et al. \(2008\)](#) used data from the Sloan Digital Sky Survey (SDSS) and found evidence for a MW oblate stellar halo. [Bell et al. \(2008\)](#) also used SDSS data and proved that the MW stellar halo is highly structured, which can be explained with accretions from satellite galaxies. More recently, Gaia data were released ([Gaia Collaboration et al., 2016](#)) and it was useful to study the stellar halo of the MW in more detail, allowing the discovery of many substructures of which it is comprised (e.g., the Gaia-Enceladus debris, [Helmi et al., 2018](#); [Belokurov et al., 2018](#)). In terms of stellar populations, the MW stellar halo has been found to be mostly old (~ 10 Gyr, e.g. [Helmi, 2020](#)) and to contain both metal-poor and metal-rich substructures. Furthermore, [Conroy et al. \(2019\)](#) used data from the H3 Survey and found that the stellar halo of the MW is overall relatively metal-rich, with no discernible metallicity gradient observed over the range of 6 to 100 kpc, supporting the notion of a diverse accretion history where various dwarf galaxies contributed to a relatively uniform metallicity in the stellar halo.

In contrast, the stellar halo of M31, which has also been detected (e.g., [Guhathakurta et al., 2005](#); [McConnachie et al., 2009](#); [Gilbert et al., 2012, 2014](#); [Ibata et al., 2014](#)), shows clear evidence of a more active and recent accretion history, highlighting the diversity in these structures among MW-mass galaxies. Observations reveal that its halo is, on average, much more metal-rich than that of the MW (e.g. [Gilbert et al., 2014](#)), and resolved stellar population studies have detected intermediate-age stars (< 10 Gyr) in its outer halo ([Brown et al., 2008](#)), pointing to more recent accretion events compared to the MW (e.g. [D’Souza & Bell, 2018a](#)).

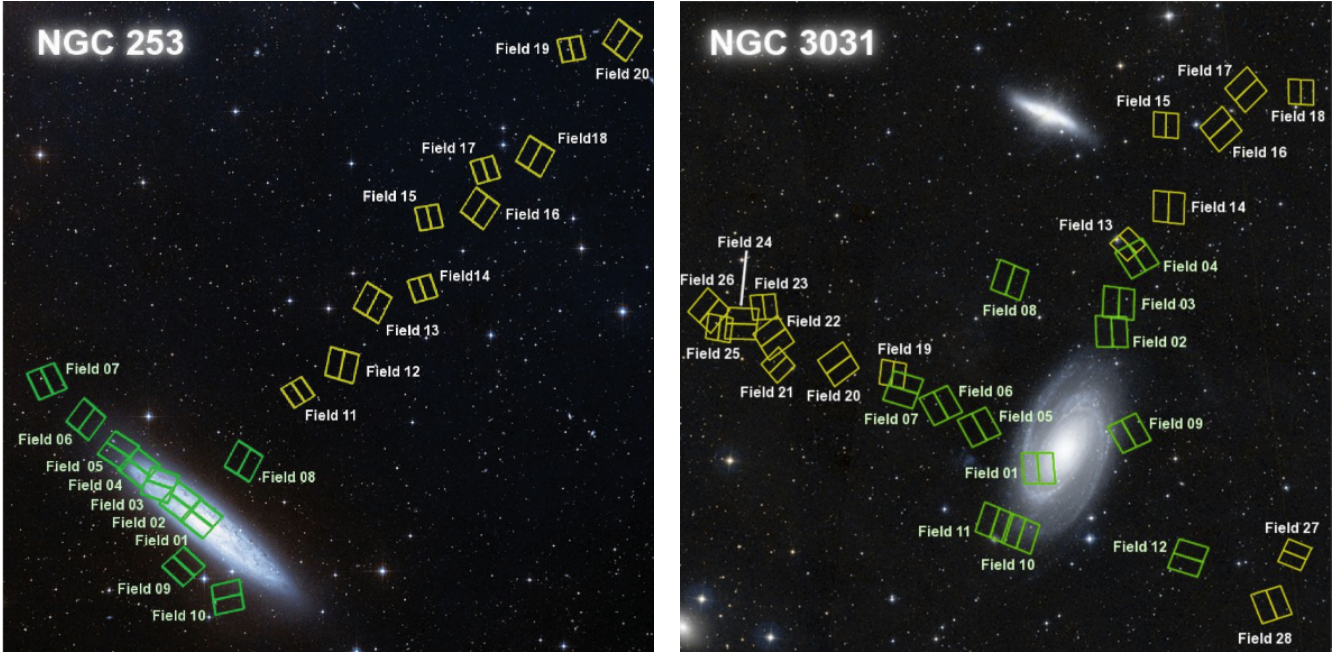


Figure 1.3.1: Examples of two galaxies from the GHOSTS survey (NGC 253 and NGC 3031 in the left and right panel, respectively). This survey provides data of the regions where the fields are shown. Both figures were extracted from [Monachesi et al. \(2016a\)](#).

Besides our own galaxy and M31, several other MW-mass galaxies beyond the LG have been found to have stellar haloes and have been subject of many studies. Such is the case of NGC 253, NGC 891, NGC 3031, NGC 4565, NGC 4945, NGC 7814, M101 and CenA (e.g., [Monachesi et al., 2016a](#); [Crnojević et al., 2016](#); [Harmsen et al., 2017](#); [Jang et al., 2020](#); [Harmsen et al., 2023](#); [Beltrand et al., 2024](#)), among others. Most of these galaxies were studied as part of the Galaxy Halos, Outer disks, Substructure, Thick disks and Star clusters (GHOSTS) survey ([Radburn-Smith et al., 2011](#)). Fig. 1.3.1 shows two galaxies, NGC 253 and NGC 3031, as an example of the galaxies available in said data. In this MW stellar mass range, [Monachesi et al. \(2016a\)](#) found that the outskirts of the six galaxies from GHOSTS were built from smaller accreted objects and present a diversity in their metallicity profiles, and [Harmsen et al. \(2017\)](#) discovered a strong correlation between the stellar halo metallicities and the stellar halo masses of those same galaxies. In addition, the authors found a diversity in the stellar halo properties (such as their stellar masses and their profile density's power-law slope) of galaxies that are alike in terms of mass and morphology. The mass-metallicity relation of the stellar haloes found in said work indicates that the properties of stellar haloes in MW-like galaxies are dominated by the most massive accretion event (see also [Bell et al., 2017](#); [Smercina et al., 2020](#)).

From the theoretical side, numerical approaches have also been undertaken in the past years to model and further comprehend the formation of the stellar halo in MW-mass galaxies (e.g., [Bullock & Johnston, 2005](#); [Cooper et al., 2010](#); [Tumlinson, 2010](#); [Gómez et al., 2012](#); [Tissera et al., 2013, 2014](#); [Monachesi et al., 2016b, 2019](#); [Vera-Casanova et al., 2022](#); [Rey & Starkenburg, 2022](#); [Orkney et al., 2023](#); [Mori et al., 2024](#)) using N-body and hydrodynamical simulations. For example, [Amorisco \(2017\)](#) analysed the contributions of satellite galaxies to the accreted component of stellar haloes and concluded that more massive and concentrated satellites deposit their stars deeper into the host's gravitational potential (i.e., they sink deeper due to increased dynamical friction) while dynamical friction is too slow and therefore not effective to drag the low-mass satellites towards the centre of the host galaxy, meaning that they are more likely to contribute to the outer parts of the stellar haloes. Additionally, using hydrodynamical simulations, [Monachesi et al. \(2019\)](#) studied the stellar haloes in MW-mass galaxies, focusing on the differences present when analysing the stellar haloes' properties along the semi-minor and semi-major axes of the galaxies (e.g., differences in the metallicity), as well as comparing these numerical results with the GHOSTS galaxies, the MW and M31. Among these comparisons, the authors find that the observed correlation between the stellar haloes' metallicities and their stellar masses ([Harmsen et al., 2017](#)) is also predicted by the numerical models (see left panel of Fig. 1.3.2). In addition, they do not find a strong correlation between the fraction of stellar halo mass to total stellar mass and the total stellar mass of the galaxies in this mass range (see right panel of Fig. 1.3.2). Furthermore, [Fattahi et al. \(2020\)](#) also used hydrodynamical simulations to show that only a minority of the accreted satellites survive to $z = 0$, with survival strongly depending on their infall time and mass. The authors demonstrated that a few massive progenitors dominate the inner stellar halo, while the outer regions of MW-mass galaxies are built up from the disrupted debris of numerous low-mass systems, highlighting the key role of progenitor properties and accretion timing in shaping stellar haloes.

In a much smaller percentage, the outskirts of MW-mass galaxies have been found to also be comprised by in-situ stellar material, which includes stars that were originally located in the inner regions of these galaxies and that, due to interactions with other galaxies, got kicked out and reached farther orbits where they are found today ([Zolotov et al., 2009](#); [Purcell et al., 2010](#); [Tissera et al., 2014](#)). [Cooper et al. \(2015\)](#) also consider these heated stars as a formation mechanism for the in-situ stellar halo, and

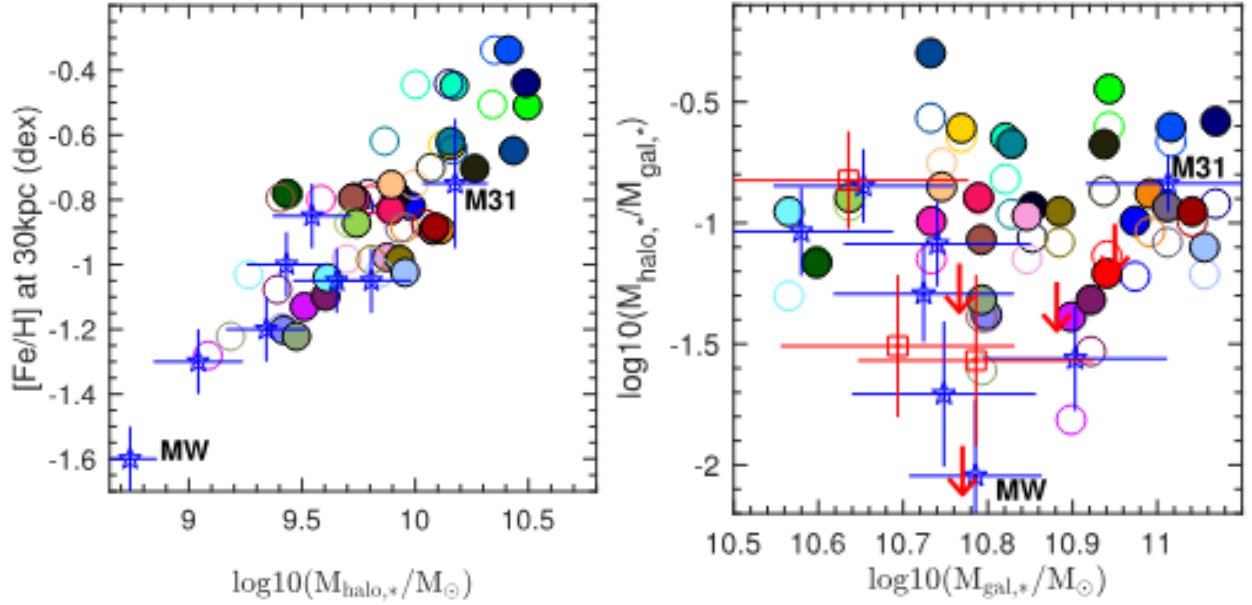


Figure 1.3.2: *Left panel:* Correlation between the stellar haloes’ metallicities and their masses when considering a MW stellar mass range. *Right panel:* Fraction of stellar halo mass to total stellar mass as a function of total stellar mass. Circles represent simulated galaxies and blue stars represent data from the GHOSTS galaxies, the MW and M31. Both figures were extracted from Figure 17 of [Monachesi et al. \(2019\)](#).

they contemplate two other possible scenarios: stars that formed from gas from the intergalactic medium that was smoothly accreted on to the stellar halo and stars that formed in streams of gas stripped from infalling satellites.

However, disentangling between the in-situ and the accreted stellar material from an observational point of view is rather difficult, as it requires high-precision measurements of chemical and kinematical properties that are used to make the classification. As mentioned before, the easiest disentanglement of this type is that of the MW stellar halo due to our location. A number of recent studies have successfully distinguished between in-situ and accreted stellar halo components in the MW using a combination of precise astrometric and spectroscopic data. For instance, [Helmi et al. \(2018\)](#) and [Belokurov et al. \(2020\)](#) identified the Gaia-Enceladus/Sausage structure as an accreted component of the halo based on its distinct kinematics and metallicity distribution, using data from Gaia. Beyond the Milky Way, M31 has served as an important external reference for studying the origin of stellar halo populations. Using the Spectroscopic and Panchromatic Landscape of Andromeda’s Stellar Halo (SPLASH) survey, [Dorman et al. \(2013\)](#) performed a kinematic decomposition of M31’s inner halo, finding evidence for a metal-rich, rotating in-situ component that formed in the disc and was afterwards dynamically heated. [Gilbert et al. \(2014\)](#) further analysed M31’s halo using spectroscopy of individual red giant branch (RGB) stars and detected significant substructure consistent with multiple accretion events. More recently, [Beltrand et al. \(2024\)](#) analysed the kinematics of a stellar halo beyond the LG for the first time. They studied the velocity of the stellar halo of NGC 4945, using spectroscopic data of individual RGB stars and found a slight counter-rotation of the stellar halo, a clear evidence of an accreted component in the galaxy’s outskirts. These external galaxy studies, although more observationally challenging, continue to refine

our understanding of the formation of stellar haloes and their in-situ and/or accreted origins.

1.3.2 Stellar haloes in low-mass galaxies

As previously mentioned in Sect. 1.1, in principle the hierarchical formation of structures should work at all scales. Therefore, it is also possible that low-mass galaxies have stellar haloes composed of accreted stellar material that came from even less massive galaxies, as well as a fraction of in-situ stellar material contributing to it. Nonetheless, the mechanisms by which low-mass galaxies form their stellar haloes is not completely understood and, until recently, there were not many observations available of these substructures. Some pioneering studies investigating this stellar mass regime include the works of [Minniti et al. \(1999\)](#) and [Aparicio et al. \(2000\)](#), where the authors detected extended stellar populations in the isolated dwarfs NGC 3109 and DDO 187, respectively. In the past decades, efforts have been made to observationally detect stellar haloes of low-mass galaxies using currently available instrumentation. Due to their proximity to the MW, the Magellanic Clouds are the most detailed studied low-mass systems, and their stellar haloes have been identified. [Borissova et al. \(2004\)](#) measured the velocity dispersion of 43 RR Lyrae stars belonging to the Large Magellanic Cloud (LMC) and found that this galaxy has a kinematically hot population forming a stellar halo. Later on, [Belokurov & Koposov \(2016\)](#) detected an extended and lumpy stellar distribution surrounding the Magellanic Clouds that reaches a distance of at least $\sim 30^\circ$ from the LMC, and concluded that the stellar halo around the LMC is traceable to between 25 and 50 kpc. Moreover, [Nidever et al. \(2019\)](#) detected an extended low surface brightness stellar component around the LMC which, according to [Muñoz et al. \(2023\)](#), is likely a mix of LMC stars and tidally stripped stars from the Small Magellanic Cloud (SMC).

More recently, the Smallest Scale of Hierarchy (SSH) survey ([Annibali et al., 2020](#)) became available, which aimed to detect faint stellar streams and satellites around 45 late-type dwarf galaxies within 10 Mpc in the Local Universe using the Large Binocular Telescope. This survey successfully reaches a surface brightness limit as faint as $\mu(r) \sim 31 \text{ mag arcsec}^{-2}$ for both resolved individual stars and diffuse light in the targeted galaxies. This is suitable to observe stellar haloes and they do in fact detect extended low surface brightness stellar envelopes around the dwarf galaxies. Making use of data from this survey, [Annibali et al. \(2022\)](#) studied NGC 3741 and reported signatures of accretion events, and they also found that the spherical old stellar population present in NGC 3741 is less extended than a young stellar population that reaches farther distances from the centre of the galaxy, hinting at the existence of a stellar halo.

Another survey related to the stellar halo of a dwarf galaxy that is being carried on is the TRIangulum EXtended Survey (TRES, [Quirk et al., 2022](#)). This survey targets M33 and provides spectroscopic data of different regions of this galaxy (see Fig. 1.3.3). [Gilbert et al. \(2022\)](#) used data from TRES to model the kinematics of ~ 1700 RGB stars belonging to M33 and concluded that there are at least two distinct populations in its inner region. One of the components they found is rotating in the plane of M33's HI disc, while the other component has a significantly higher velocity dispersion and rotates very slowly in the plane of the disc, suggesting that it is a stellar halo rather than a thick disc population. [Cullinane et al. \(2023\)](#) characterised the two distinct kinematic components in both the old and intermediate-age populations and found that the fraction of stars associated with the halo component differs between the two populations: the intermediate-age population has around 10% halo stars, while the old population shows a decrease in the fraction of halo stars from around 34% to 10% with increasing radius. That study

also suggests that in-situ formation mechanisms and potential tidal interactions have strongly contributed to M33's stellar halo formation rather than accretion events, mainly due to the intermediate-age population found in it. Moreover, using the Panchromatic Hubble Andromeda Treasury Triangulum Extended Region (PHATTER) survey (Williams et al., 2021), Smercina et al. (2023) estimated the total stellar halo mass of this galaxy to be approximately $5 \times 10^8 M_\odot$, most of it residing within 2.5 kpc of the centre. However, these studies concentrated on the inner stellar halo of M33. Lately, Ogami et al. (2024) presented another survey of this galaxy using Subaru/Hyper Suprime-Cam (HSC) to focus on its western outer region (5 – 30 kpc), which is perpendicular to the major-axis of its disc (and hence not significantly contaminated by it). The authors found that M33 has a shallow stellar halo in the outer region (which would extend beyond 15 kpc) with a surface brightness of $\mu_V = 35.72 \pm 0.08 \text{ mag arcsec}^{-2}$.

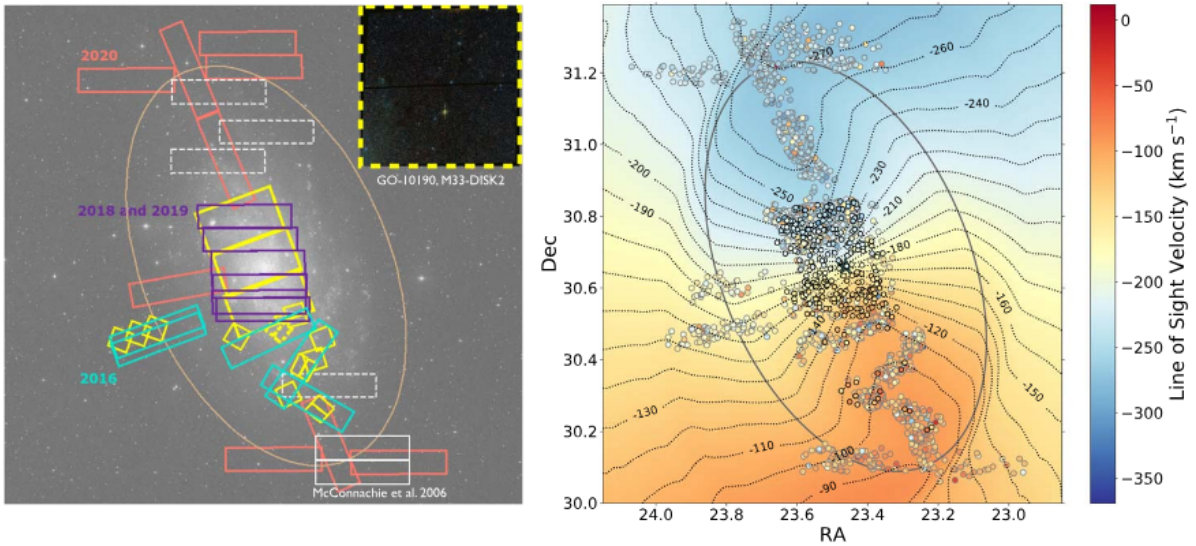


Figure 1.3.3: *Left panel*: footprints of the 36 spectroscopic slitmasks obtained in the TREX survey for M33. The inset shows the stellar density at the edge of the PHATTER survey. *Right panel*: location on the sky of the RGB star sample (gray outlined points) and young star comparison sample (black outlined points). The stellar points are colour coded by their measured line-of-sight velocity. In both panels, the ellipse denotes the approximate location of the break in the surface density profile of M33's disc. This figure was extracted from Gilbert et al. (2022).

The existence and formation mechanism of stellar haloes in low-mass galaxies are also only recently being investigated from a theoretical point of view. In the past years some N-body and hydrodynamical cosmological simulations have increased their resolution and hence become more suitable to carry out this type of analysis. Fitts et al. (2018) used the Feedback in Realistic Environments (FIRE) simulations to study the stellar mass assembly history of isolated dwarf galaxies and found that their stellar populations are formed mainly in situ, with over 90% of the stellar mass formed in the main progenitor. The authors also concluded that these galaxies went through merging processes (if any) at $z \gtrsim 3$ and that the small contribution of accreted stellar material makes it difficult to detect the effects of mergers in the majority of the dwarf galaxies in their sample. Moreover, focusing specifically on stellar haloes, Kado-Fong et al. (2022) analysed the stellar haloes of 9 simulated dwarf galaxies ($10^{8.5} M_\odot < M_* < 10^{9.6} M_\odot$) using the FIRE simulations, and concluded that they are primarily formed through the migration of in-situ

stars due to internal feedback-driven mechanisms, thus proposing the heating of disc stars as a suitable formation mechanism. In addition, [Deason et al. \(2022\)](#) used the Copernicus Complexio (COCO) suite of N-body simulations to study the merger history of low-mass galaxies with DM haloes of $\sim 10^{10} M_{\odot}$ and concluded that the number of major and minor mergers depends on the type of dark matter implemented, with minor mergers being greatly suppressed when using warm dark matter models. Their work claimed that dwarf-dwarf mergers with intermediate dark matter merger ratios maximize the growth of distant stellar haloes, and that gas-rich mergers can have a considerable effect on the star formation and stellar distribution of the merger remnant. In contrast to the early mergers scenario, [Goater et al. \(2024\)](#) proposed that the existence of anisotropic and extended stellar outskirts found in isolated ultra-faint dwarf galaxies (UFDs) in the Engineering Dwarfs at Galaxy Formation’s Edge (EDGE) simulations originate from late-time accretions of lower-mass companions.

As mentioned in Sect. 1.2, most of these studied low-mass galaxies are satellite systems that are constantly being perturbed by more massive galaxies. In contrast, isolated systems are excellent targets to study the consequences of the hierarchical mass assembly at a low-mass scale since they are not being disturbed nor stripped by a more massive galaxy. This is hard to do with observations because isolated galaxies are very far away, which impedes us from resolving the stars located in their outskirts. Therefore, numerical simulations become invaluable tools for investigating the formation and evolution of these systems in detail, providing an alternative approach to explore their structure, stellar populations, and assembly histories when direct observations are limited.

To interpret the observational data already available and that of the upcoming facilities and instrumentation such as the Vera Rubin Observatory and the Nancy Grace Roman Space Telescope, we need to be able to rely on strong theoretical models that provide accurate predictions. Understanding the formation and evolution of galaxies is very challenging because it involves different physical processes happening altogether and taking place at different scales. Thus, cosmological numerical simulations come in handy for modelling and studying the properties, formation, growth and evolution of galaxies and their interactions and merger events with other galaxies. These numerical tools allow us to discriminate between different components of the galaxies, distinguish between accreted and in-situ material, follow the evolution of galaxies through time, and track merger events, among other things that cannot be studied with such certainty and precision from observations. Additionally, they are crucial for studying dark matter (DM), as they allow us to model its distribution within and around galaxies, and to make predictions or place constraints on observational signatures that can be used to test its nature. Hence, simulations bridge the gap between theory and observations.

1.4 This thesis

As discussed above, the existence of stellar haloes in low-mass galaxies has been recently confirmed due to new surveys that allowed their detection, such as the PHATTER, TREX and SSH ones mentioned in Sect. 1.3.2. Until recently, it was not even clear whether dwarf galaxies hosted such extended structures, and only after their observational discovery did the systematic study of their properties begin in earnest (e.g. [Longeard et al., 2023](#); [Jensen et al., 2024](#); [Tau et al., 2024](#); [Wheeler et al., 2025](#)). Understanding the structure and origin of these stellar haloes in the low-mass regime is essential for testing the predictions of hierarchical structure formation and for gaining insight into the assembly histories of the smallest galaxies. In this context, the formation mechanism(s) of stellar haloes in low-mass galaxies is(are) not

yet completely understood and there are many open questions regarding this topic. For instance, is there a threshold in mass below which dwarf galaxies do not have stellar haloes? Are these haloes primarily composed of accreted material, or do they contain a significant in-situ component? If the latter, was this material formed predominantly at early epochs or at later times?

Additionally, exploring the metallicity and age distributions in this mass regime provides a powerful pathway to assess whether similar evolutionary trends hold for dwarf galaxies as in more massive systems, and to evaluate the extent to which the hierarchical formation model predicted by the Λ CDM for the MW-mass regime applies at lower mass scales.

Moreover, by comparing the properties and formation mechanisms of stellar haloes in dwarf galaxies with those in more massive systems, such as MW-like galaxies, we can explore how galaxy evolution varies across different mass scales and whether the processes that shape their outskirts are universal or mass-dependent.

1.4.1 Objectives of this thesis

The main goal of this thesis is to provide a characterisation of the stellar haloes of dwarf galaxies from a theoretical point of view, as well as a better understanding of their formation and evolution history.

The specific scientific objectives of this thesis include: *i)* the study of the stellar halo mass fraction in low-mass galaxies, *ii)* the characterisation of their surface brightness, metallicity and age profiles, *iii)* tracing and studying the evolution of these stellar haloes through time in order to characterise their assembly history, *iv)* quantifying their significant progenitors, *v)* the characterisation of the accreted and in-situ stellar mass fraction of the low-mass galaxies' stellar haloes, *vi)* comparing these results from numerical simulations with the available observations of low-mass systems, *vii)* comparing the stellar haloes' properties of dwarf galaxies with those of MW-mass galaxies present in the literature, and *viii)* the analysis and interpretation of how these characteristics of the stellar haloes behave as a function of their host galaxies' mass.

1.4.2 Outline of this thesis

In Chapter 2 we introduce the numerical simulations and methodology used in this work, and we describe the sample of analysed low-mass galaxies. We also give important definitions that are considered throughout this thesis. In Chapter 3 we present our analysis and characterisation of the galaxies of our sample and their stellar haloes, as well as compare our results with observational data of low-mass galaxies. One of the main results in this chapter is that we find that the stellar haloes of all galaxies are dominated by in-situ stellar material in their inner regions (between ~ 4 and ~ 6 half-light radii), and that this dominance extends to all radii when considering dwarf galaxies with $M_* < 4.5 \times 10^8 M_\odot$. Regarding the accreted component, we found that more massive dwarf galaxies ($M_* \geq 6.30 \times 10^9 M_\odot$) keep on accreting stellar material until later times than less massive ones, which has an impact on the formation time of their accreted stellar halos, being also later for these galaxies than for the less massive ones. Moreover, we find that galaxies that accreted more stellar material have obtained it by accreting more massive satellites, and that the satellite galaxy that contributed the most to the accreted component of the stellar halo also contributed the most to the overall accreted material. In this Chapter we also analyse the metallicity, stellar mass, accreted mass fraction, surface brightness and number of progenitors of

the galaxies in our sample. In addition, we place our results in a broader context, comparing them to observations and theoretical predictions for MW-mass galaxies. For example, we find that the correlation previously found in MW-mass galaxies where more massive stellar haloes are also more metal rich than less massive ones is also present in this low-mass range, but only when considering the accreted component of the stellar halo.

In Chapter 4 we explore the age and metallicity of the dwarf galaxies of our sample in detail, analysing their radial age and metallicity profiles. Regarding the metallicity analysis, we find that the link between the evolution of the galaxies and their resulting metallicity gradients is not so straightforward to measure in the low-mass regime, given that we find no correlation between the metallicity gradients of the galaxies and their stellar mass, their accreted stellar mass, their accreted mass fraction or the number of significant progenitors they have. However, we find that more massive accreted stellar halos ($M_{acchalo} \geq 10^8 M_{\odot}$) are also more metal-rich (median $[Fe/H]$ values ≥ -1.22), and that, at a given accreted stellar halo mass, the dwarf galaxies that accreted satellites at later times have a more metal-rich accreted stellar halo. Concerning the age analysis, we find that the mean ages of the main body of the galaxies are generally lower than the mean ages of their total stellar halos. We also find that the majority of the galaxies present a prominent U-shape in their radial age profiles, and this feature is mainly driven by the in-situ stellar population.

Chapter 5 focuses on the formation mechanism of these stellar haloes of low-mass galaxies, considering both the in-situ and the accreted component of these structures. We find that the in-situ component of the stellar haloes is formed in the inner regions of the galaxies and subsequently ejected into the outskirts as a consequence of interactions and merger events. Additionally, the accreted satellite galaxies provide the main galaxy with gas in some cases, which can end up being used to form in-situ stellar material that is later found in the outskirts at $z = 0$. In Chapter 6 we summarise our main results and highlight our conclusions. Finally, in Chapter 7 we discuss some follow-up studies based on the results obtained throughout this thesis.

Chapter 2

Numerical Models and Methodology

In this thesis we use numerical simulations to study low-mass galaxies. This Chapter contains a brief description of the different types of simulations, and focuses on the Auriga Project, which we use in this work. We also present the sample of galaxies we selected for the analysis, and their global properties, as well as the definition of in-situ and accreted components that we use throughout this thesis.

2.1 Numerical Simulations

Simulations can be classified according to whether or not they contain baryons: if they do not contain baryons, they are called dark matter-only simulations, also known as N-body simulations; if they do contain baryons in addition to DM, they are called hydrodynamical simulations. In this thesis, we focus on hydrodynamical cosmological simulations for the formation and evolution of low-mass galaxies. Unlike pure N-body simulations, which model only the gravitational interactions of DM particles, hydrodynamical simulations incorporate baryonic physics, such as gas dynamics, star formation, and feedback processes. This allows for a more realistic representation of galaxy formation and evolution, capturing the complex interplay between DM and baryons that shapes observable properties like stellar populations, metallicity distributions, and structural features (e.g., [Vogelsberger et al., 2014](#); [Schaye et al., 2015](#)). Numerical models have significantly evolved over the past decades. Early simulations were limited to gravity-only N-body calculations, capable of tracing large-scale structure formation but unable to model the internal physics of galaxies. The next generation introduced semi-analytic models (SAMs) to approximate baryonic processes on top of DM halo merger trees ([White & Frenk, 1991](#); [Cole et al., 2000](#)). More recently, full hydrodynamical simulations have become increasingly sophisticated, solving the equations of fluid dynamics and incorporating detailed subgrid models for cooling, star formation, chemical enrichment, and stellar and AGN feedback.

Cosmological simulations of galaxy formation are performed within a cosmological model, and specific initial conditions need to be set at the beginning in order to start running them. The initial conditions specify the perturbations imposed on top of a homogeneous expanding background. These initial conditions typically include the density and velocity fields derived from the primordial power spectrum of fluctuations (e.g., consistent with measurements from the cosmic microwave background), the cosmological parameters, and the distribution of DM and baryonic particles in a large simulated volume. Two common approaches for setting initial conditions in simulations are: using large, uniformly sampled

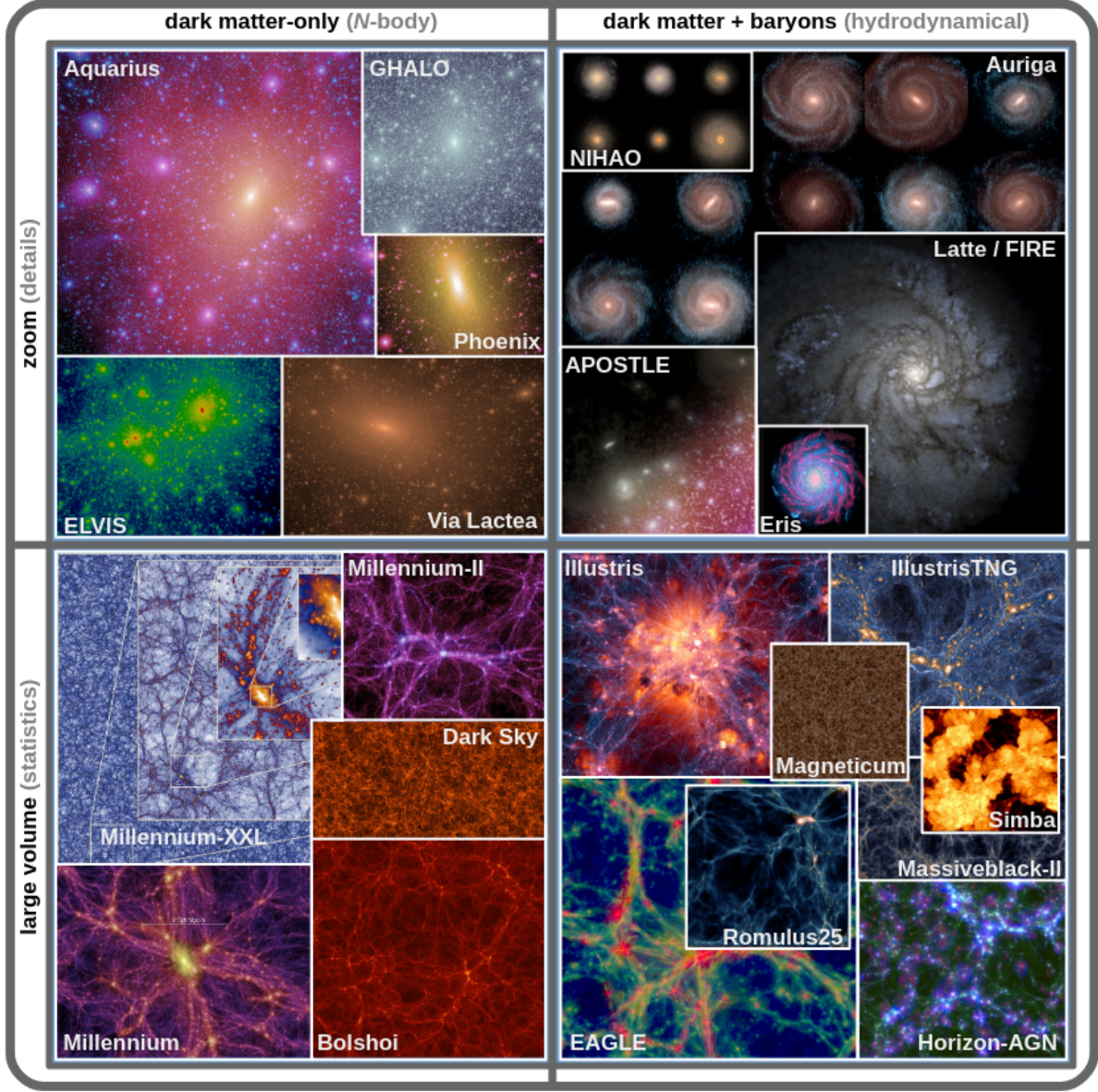


Figure 2.1.1: Visual representations of some structure and galaxy formation simulations. They are divided in large volume simulations that provide statistical samples of galaxies (bottom panels), and zoom simulations resolving smaller scales in more detail (top panels). They are also divided in dark matter-only (i.e. N -body) and dark matter plus baryons (i.e. hydrodynamical simulations). On the top right panel we can see the Auriga simulations used in this thesis. This image was taken from [Vogelsberger et al. \(2020\)](#).

periodic volumes, or employing zoom-in techniques. The latter involves a low resolution background realisation of the density fields surrounding a high resolution target region ([Vogelsberger et al., 2020](#)). In addition, depending on the specific cosmology that is being modelled, the corresponding fundamental cosmological parameters (taken from observational measurements) are set. In particular, for a Λ CDM cosmology, these include the matter density Ω_m , the baryon density Ω_b , the Dark Energy density Ω_Λ and

the Hubble constant H_0 . In Fig. 2.1.1, a sample of modern large volume simulations (bottom panels) and zoom-in simulations (top panels) is shown.

N-body simulations are often employed to follow the collisionless dynamics of DM, using identical particles interacting gravitationally in three dimensions. They typically solve Newton’s equations of motion using efficient algorithms such as the tree method (Barnes & Hut, 1986; Hernquist, 1987) or particle mesh schemes (Klypin & Shandarin, 1983; White et al., 1983) to reduce computational costs, not including baryonic physics like gas dynamics, star formation, or feedback processes. These type of simulations, as already mentioned, have been extremely successful in reproducing the large-scale structure of the Universe, including the cosmic web of filaments, voids, and clusters (e.g., Springel 2005; Vogelsberger et al. 2014). Nevertheless, without baryonic physics, these models cannot predict internal galaxy properties (e.g., stellar masses, morphologies), and they struggle with well-known small-scale challenges in Λ CDM, such as the “missing satellites” problem and the “cusp–core” problem (e.g., Klypin et al., 1999; Moore et al., 1999; Bullock & Boylan-Kolchin, 2017). These limitations highlighted the need to incorporate the complex physics of baryons, and thus hydrodynamical models became an essential tool to address these issues. Hydrodynamical simulations solve the equations of hydrodynamics (usually the Euler equations) coupled with gravity, often using methods such as smoothed particle hydrodynamics (SPH) (e.g., Gingold & Monaghan 1977) or adaptive mesh refinement (AMR) (e.g., Teyssier 2002). More recently, moving mesh schemes have become popular for combining the strengths of both Lagrangian and Eulerian methods to solve the equations of hydrodynamics. The moving mesh approach is based on a moving and adaptive grid, as opposed to the static grids used in AMR. This mesh changes as the simulation evolves. An example of this is the AREPO code (Springel, 2010). AREPO employs a moving, unstructured Voronoi mesh that naturally adapts to the motion of the fluid, providing Lagrangian-like adaptability and resolution. This approach offers significant advantages: while SPH suffers from difficulties in resolving fluid instabilities and capturing shocks accurately, and Eulerian methods lack Galilean invariance, AREPO overcomes both limitations. Unlike SPH, which struggles with instabilities like Kelvin-Helmholtz and Rayleigh-Taylor (Gingold & Monaghan, 1977; Lucy, 1977; Tasker et al., 2008), AREPO dynamically concentrates resolution in dense regions, such as galaxies, while conserving computational resources in low-density areas. Moreover, its second-order Godunov scheme with an exact Riemann solver allows for precise treatment of shocks and discontinuities, making it especially suitable for modelling energetic astrophysical events like supernovae and galaxy mergers. Additionally, AREPO is highly parallelised, enabling the efficient execution of large, high-resolution simulations of galaxy formation and cosmic structure. The AREPO code was used to run the Auriga simulations used in this thesis, as explained next in Sec. 2.2.

2.2 The Auriga Project

The Auriga project (Grand et al., 2017) is a state-of-the-art suite of cosmological magneto-hydrodynamical zoom-in simulations of very high resolution of the formation of galaxies. The haloes to be resimulated were chosen from the EAGLE project (Schaye et al., 2015) and are isolated enough at $z = 0$ so as to be the most massive one in their environment. This isolation was quantified with an isolation parameter, which involves the virial mass and radius of the main halo and those from which the distance is computed at $z = 0$. Briefly, to be considered as isolated, the centre of a target halo must be located at least 9 times the virial radius from any other halo (i.e., $9R_{200,i}$, where i accounts for each halo) whose

virial mass exceeds 3% of that of the target halo. We refer the reader to [Grand et al. \(2017\)](#) for further details. The resimulated galaxies were then randomly selected from the most isolated quartile at $z = 0$. They were run considering a Λ CDM cosmology, being $\Omega_m = 0.307$, $\Omega_b = 0.048$ and $\Omega_\Lambda = 0.693$ the cosmological parameters used. The Hubble constant was taken from [Planck Collaboration et al. \(2014\)](#), where its value is $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $h = 0.6777$. The simulations were run using the magnetohydrodynamic code AREPO ([Springel, 2010; Pakmor et al., 2014](#)) with a detailed model for galaxy formation (see [Grand et al., 2017](#), for further details). This model includes relevant baryonic processes for the physics involved in galaxy formation, such as a uniform ultraviolet background ([Vogelsberger et al., 2013](#)), cooling processes from primordial and metal lines, a subgrid approach for star formation ([Springel & Hernquist, 2003](#)), stellar evolution, and supernova feedback mechanisms, metal enrichment from Type II and Ia supernovae (SNII and SNIa), and asymptotic giant branch (AGB) stars, black hole formation and active galactic nucleus feedback.

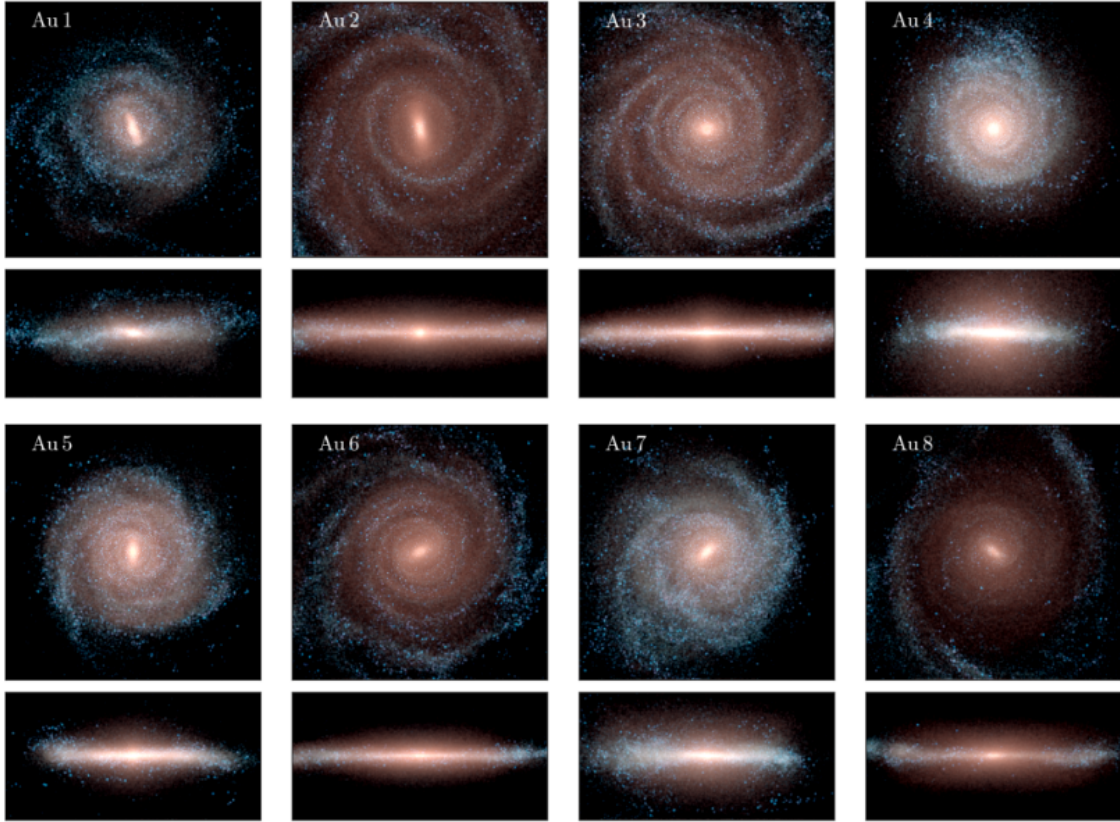


Figure 2.2.1: Face-on and edge-on projected stellar density at $z = 0$ for 8 of the 30 MW-mass fiducial simulations of the Auriga Project. This figure was extracted from Figure 1 of [Grand et al. \(2017\)](#).

The galaxies present in these simulations span a wide range in DM and stellar mass. The fiducial suite of 30 Auriga simulations, with a resolution of $10^5 M_\odot$ in dark matter particles and of $\sim 5 \times 10^4 M_\odot$ in baryonic particles, has been used to represent MW-mass galaxies in diverse studies (e.g., [Marinacci et al., 2017](#); [Gómez et al., 2017](#); [Monachesi et al., 2019](#); [Gargiulo et al., 2019](#); [Vera-Casanova et al., 2022, 2025](#); [Fragkoudi et al., 2025](#); [López et al., 2025](#); [Kunder et al., 2025](#)). The face-on and edge-on projected stellar density at $z = 0$ for some of these MW-mass simulated galaxies are shown in Fig. 2.2.1.

Recently, a new set of lower mass galaxies has been made available in [Grand et al. \(2024\)](#). This new set of 26 low-mass galaxies with higher resolution have become available, and these available galaxies are composed of particles with a resolution of $5 \times 10^4 M_\odot$ in DM mass and $\sim 6 \times 10^3 M_\odot$ in baryonic mass. The mass range spanned by these low-mass galaxies goes from $5 \times 10^9 M_\odot$ to $5 \times 10^{11} M_\odot$ for the DM haloes and from $1.23 \times 10^5 M_\odot$ to $2.08 \times 10^{10} M_\odot$ for their stellar mass. [Grand et al. \(2024\)](#) showed that these galaxies reliably reproduce many observed galaxy properties and scaling relations, such as the stellar mass - halo mass relation and also the scalings of, for example, rotation velocity and star formation rate fractions as a function of stellar mass.

2.2.1 Galaxy sample selection and characterisation

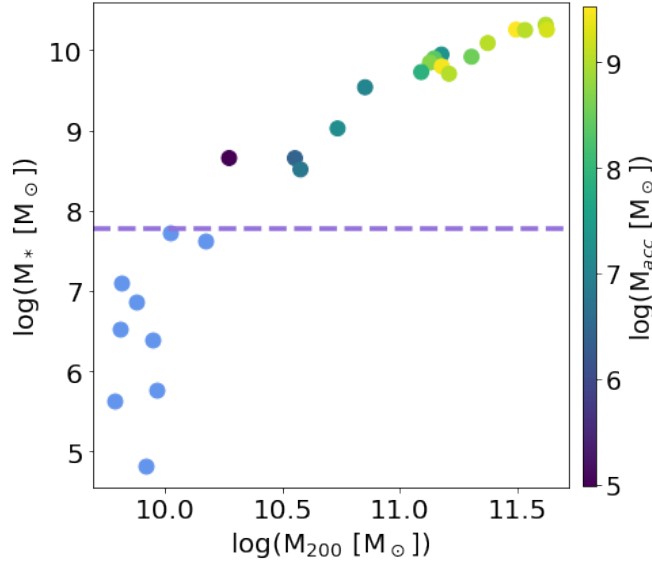


Figure 2.2.2: Stellar mass of the complete sample of low-mass galaxies available in the Auriga Project as a function of their M_{200} mass at $z = 0$. In this work we only analyse those galaxies that have more than 10000 stellar particles, which translates into $M_* \geq 6 \times 10^7 M_\odot$. The horizontal dashed line represents this threshold in stellar mass in logarithmic scale. The galaxies used in this work are colour-coded by their amount of accreted stellar mass.

In this thesis we use a sub-sample of the total sample of 26 central low-mass galaxies described previously. We select only those low-mass galaxies that have more than 10000 stellar particles, so that each galaxy in our sample is reasonably resolved. We require that the galaxies have this minimum number of stellar particles because we are interested in studying their outskirts, which already have fewer particles than the central regions. By defining the above threshold in stellar particles we ensure that all galaxies analysed in this work have a considerable number of stellar particles (more than 2000) at large distances so as to be able to rely on the obtained results. Fig. 2.2.2 shows the stellar mass of the galaxies as a function of their M_{200} mass, which represents the total mass enclosed in a sphere with a mean density that equals 200 times the critical density of the Universe. The horizontal dashed line represents the threshold in stellar mass considered in this work. Consequently, the sample of low-mass galaxies

analysed in this work consists of 17 galaxies that meet this criterion, with DM masses ranging from $3.06 \times 10^{10} M_{\odot}$ to $3.73 \times 10^{11} M_{\odot}$ and stellar masses ranging from $3.28 \times 10^8 M_{\odot}$ to $2.08 \times 10^{10} M_{\odot}$. Dwarf galaxies considered in this thesis are colour-coded by their accreted stellar mass (see Sec. 2.4 for the accreted definition). The main characteristics of these selected galaxies are presented in Table 2.2.1 and the galaxies are listed by decreasing stellar mass values. The denominator in columns 8 and 9 (i.e., M_{halo}) refers to the total stellar mass of the stellar halo, and we use this denotation to refer to this quantity throughout this work.

Table 2.2.1: Characteristics of the galaxies of our sample. The galaxies are listed in order of decreasing stellar mass. The columns indicate: (1): label used in this work, (2): Auriga ID in [Grand et al. \(2024\)](#), (3): stellar mass, (4): DM mass, (5): R_{200} , (6): half-light radius, (7): accreted stellar mass, (8): accreted mass fraction of the stellar halo (inner limit of $4R_h$, see Sec. 3.1), and (9) accreted mass fraction of the stellar halo but considering an inner limit of $5R_h$. An ‘L’ or ‘LL’ is added to the Auriga ID to distinguish DM halo masses of $10^{11} M_{\odot}$ and $10^{10} M_{\odot}$, respectively.

Label	Auriga	Stellar mass [$M_{\odot}$]	DM mass [$M_{\odot}$]	R_{200} [kpc]	R_h [kpc]	M_{acc} [$M_{\odot}$]	$M_{acc}^{halo} / M_{halo}$ > $4R_h$	$M_{acc}^{halo} / M_{halo}$ > $5R_h$
1	L5	2.08×10^{10}	3.73×10^{11}	138.179	7.736	1.08×10^9	0.24	0.37
2	L1	1.81×10^{10}	2.76×10^{11}	125.475	5.394	3.45×10^9	0.61	0.67
3	L4	1.80×10^{10}	3.44×10^{11}	138.676	6.793	1.77×10^9	0.39	0.49
4	L3	1.78×10^{10}	3.15×10^{11}	129.183	5.554	1.10×10^9	0.34	0.50
5	L7	1.23×10^{10}	1.98×10^{11}	114.386	5.032	1.19×10^9	0.45	0.54
6	L0	8.83×10^9	1.36×10^{11}	98.366	1.180	2.14×10^7	0.01	0.01
7	L2	8.29×10^9	1.76×10^{11}	108.487	7.050	3.44×10^8	0.53	0.69
8	L6	7.89×10^9	1.15×10^{11}	96.061	4.802	2.37×10^8	0.32	0.47
9	L11	7.02×10^9	1.16×10^{11}	94.728	4.544	5.11×10^8	0.31	0.38
10	L9	6.30×10^9	1.24×10^{11}	98.478	3.938	2.93×10^9	0.18	0.17
11	L10	5.34×10^9	1.02×10^{11}	92.078	3.314	7.71×10^7	0.07	0.11
12	L8	5.09×10^9	1.37×10^{11}	100.823	5.540	1.09×10^9	0.43	0.50
13	LL2	3.46×10^9	6.10×10^{10}	76.679	3.063	1.12×10^7	0.02	0.03
14	LL9	1.06×10^9	4.44×10^{10}	70.103	3.500	1.66×10^7	0.04	0.10
15	LL8	4.54×10^8	1.55×10^{10}	49.224	1.034	9.74×10^4	0.00	0.00
16	LL6	4.53×10^8	3.66×10^{10}	61.001	1.923	2.70×10^6	0.01	0.01
17	LL11	3.28×10^8	3.06×10^{10}	62.116	3.161	6.40×10^6	0.04	0.06

Since the low-mass galaxies available in the Auriga project are separated in two simulation sets according to their DM halo mass, the Auriga identification numbers (*run numbers* in [Grand et al., 2024](#)) are repeated for different galaxies in different simulation sets. For clarity, we assign our own ID number to refer to each simulated galaxy (column 1 of Table 2.2.1). To refer to their original run numbers and not repeat them, for the galaxies in the simulation set that contains DM haloes of $\sim 10^{11} M_{\odot}$ we added an L

to their Auriga number and for those galaxies in the simulation set containing DM haloes of $\sim 10^{10} M_\odot$ we added two L (e.g., the Auriga 2 of the most massive simulation set is renamed as "L2", while the Auriga 2 of the least massive simulation set is renamed as "LL2"). Throughout this thesis, we refer to galaxies with $M_* \geq 6.3 \times 10^9 M_\odot$ as *more massive* galaxies, while dwarfs with lower stellar masses are referred to as *less massive* galaxies.

The galaxies were rotated from their originally random configuration such that the XY plane corresponds to the disc plane and, thus, the Z-axis is aligned with the disc's angular momentum vector for all particles.

2.3 Global properties of the Auriga low-mass galaxies used in this thesis

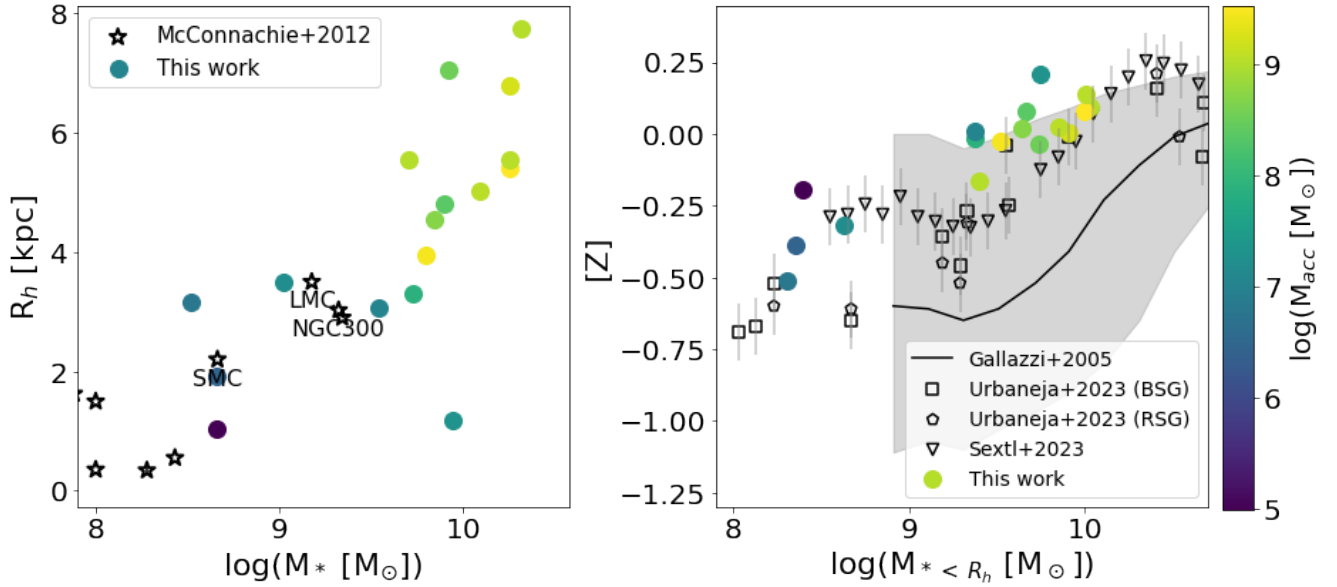


Figure 2.3.1: *Left panel:* computed R_h for the galaxies of our sample as a function of their total stellar mass. The star symbols represent observational data of some relatively isolated dwarf galaxies taken from [McConnachie \(2012\)](#) that fit our mass range and the LMC and SMC. *Right panel:* computed mean metallicities for each galaxy of our sample as a function of their stellar mass within R_h . Observational data of some galaxies taken from [Urbaneja et al. \(2023\)](#) and [Sextl et al. \(2023\)](#) are represented with pentagons and squares, and upside-down triangles respectively. The solid line represents data taken from [Gallazzi et al. \(2005\)](#). In both panels, the simulated galaxies are colour-coded by their amount of total accreted stellar mass.

In Fig. 2.3.1 we show the half-light radius (R_h) for each galaxy in our sample as a function of their stellar mass. The stellar mass of each galaxy, listed in the third column of Table 2.2.1, was computed considering all the stellar particles within its R_{200} that are bound to it. Here, R_{200} refers to the radius inside which the enclosed mass volume density equals 200 times the critical density of the Universe, and

it is listed in the fifth column of Table 2.2.1. We measure the R_h by first computing the total luminosity of the galaxy in the r band, summing the flux contribution of every stellar particle that is located within a radius of $0.2R_{200}$. The R_h is then obtained by identifying the minimum radius at which the cumulative flux distribution accounts for half of the galaxy’s total luminosity. Its value for each galaxy of our sample is shown in the sixth column of Table 2.2.1. Comparing to the R_h values presented in [McConnachie \(2012\)](#) for some relatively isolated galaxies, we find that the values we obtained for this parameter are in good agreement in our lower stellar mass range. Because of the resolution of the Auriga simulations, we do not compare our results with the dwarf galaxies with $M_* \lesssim 10^8 M_\odot$ presented in [McConnachie \(2012\)](#). The simulated galaxies are also colour-coded by their accreted stellar mass. We note that there is a trend such that more massive dwarfs accrete a higher amount of stellar material than the least massive ones.

The right panel of Fig. 2.3.1 shows the median of the total metallicity $[Z]$ for each galaxy, as a function of their stellar mass within R_h . The Auriga low-mass galaxies follow a mass-metallicity relation as expected, where higher mass galaxies are more metal rich (see also [Grand et al., 2024](#)). Since this is the first time this simulation set is analysed, we compare these values with observations to assess how well it reproduces the data. Using observational results from [Urbaneja et al. \(2023\)](#) and [Sextl et al. \(2023\)](#) for a sample of isolated galaxies, we find that the obtained metallicities are generally consistent with the observed values, as they mostly fall within the observational scatter (especially the less massive simulated galaxies). Despite the good agreement, we note that the Auriga galaxies seem to be a bit over-enriched for a given stellar mass when comparing with the observed $[Z]$ from [Gallazzi et al. \(2005\)](#) computed for a sample of 44254 galaxies taken from SDSS. The $[Z]$ offset between [Sextl et al. \(2023\)](#) and [Gallazzi et al. \(2005\)](#) studies may be due to the different spectral libraries used in those works to analyse their data. [Gallazzi et al. \(2005\)](#) used synthesis models based on the STELIB library, while [Sextl et al. \(2023\)](#) adopted the MILES stellar spectral library.

In Fig. 2.3.2, we show the r band surface brightness radial profiles of all galaxies, colour-coded by their total amount of accreted stellar mass. We computed these profiles considering the surface brightness of the stellar particles contained in different concentric 2D annuli and as a function of radius, considering an edge-on projection. To make a fair comparison, distances in all profiles were normalised by the corresponding R_h . At approximately $4R_h$, most of these galaxies (all but two) have already reached a surface brightness fainter than $\sim 28 \text{ mag arcsec}^{-2}$, reflecting the very dim nature of these galaxies outskirts. There is also a large diversity in these profiles as we consider farther regions from the centre of each galaxies, spanning a wide range of surface brightness values, especially in their stellar haloes. The spread between different galaxies is about $0.5 \text{ mag arcsec}^{-2}$ for the values of the inner regions of these profiles, whereas it is about $7 \text{ mag arcsec}^{-2}$ in the outer regions. We also find that there is no clear relation between the amount of accreted stellar mass these galaxies have and the surface brightness values they reach along their profiles. We note that the two brightest profiles correspond to Auriga 6 and Auriga 15. These galaxies have a very small R_h (see Table 2.2.1), so these are very compact galaxies that have their stellar mass more concentrated. This translates into higher values of surface brightness in the outer regions in Fig. 2.3.2.

2.4 Definition of in-situ and accreted stellar component

The aim of this thesis, as mentioned previously, is to analyse and characterise the stellar haloes of low-mass galaxies. This structure will be comprised of in-situ and accreted stellar material, as well as the rest

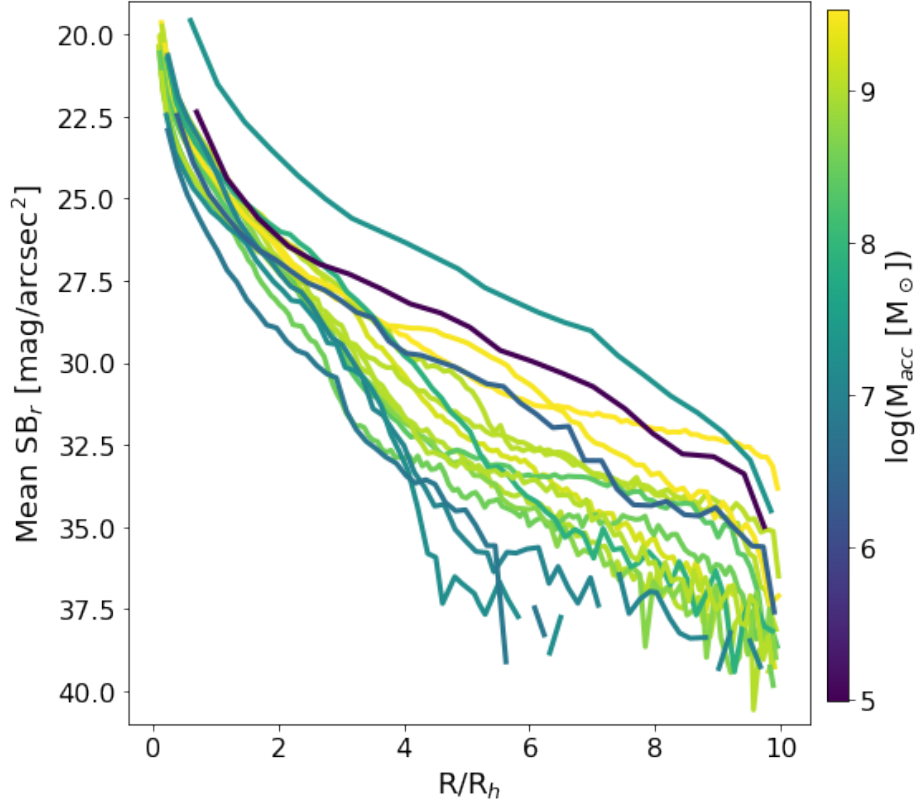


Figure 2.3.2: Surface brightness profiles in the r band for all galaxies in our sample, normalized by their respective R_h and colour-coded by their total amount of accreted stellar mass. These profiles were computed in the XZ projection using an annular aperture.

of the galaxy. Hence, it is important to define what we consider as in-situ or accreted stellar material and how we distinguish one from another.

Throughout their evolution, galaxies interact with satellite galaxies and can undergo a series of merger events. In these processes, the stellar material of the interacting galaxies can get mixed and end up belonging to a different galaxy than the one they originally belonged to. In this sense, it becomes necessary to distinguish the stellar particles that were originally formed in the main galaxy from the ones born in satellites and later accreted onto the main galaxy to be able to study the evolution of the main galaxy and its accretion history.

In this work, we classify the stellar particles of the main galaxy as either in-situ or accreted. We define in-situ particles as those stellar particles that were born from gas that was bound to the main galaxy, regardless of the origin of the gas (i.e., regardless of whether the gas was formed in the host galaxy or was provided by a gas-rich satellite). In contrast, we define accreted particles as those stellar particles originated from gas that was bound to a different galaxy than the main one (i.e., a satellite galaxy), regardless of the location of the satellite galaxy. Hence, even if the satellite galaxy had already entered the virial radius of the host galaxy at the moment the stellar particle was born, this stellar particle is considered as accreted if it was bound to it. We emphasise that there are some authors that consider these particles as endo-debris (e.g., see [Gonzalez-Jara et al., 2025](#)).

We make use of the accreted catalogues available in the Auriga simulations. These catalogues contain a list with some properties of the accreted stellar particles that can be found at $z = 0$, such as their unique identification number (ID), their peak mass index and the lookback time at which the star particle first became bound to the main galaxy (for further details see [Grand et al., 2024](#), and for the complete list of available properties). The catalogues were designed to help understand the origin and accretion history of star particles that were born in satellite galaxies and accreted into the main galaxy later on, where we can find them at $z = 0$.

In addition, given that the particles' IDs are unique and that they do not change over time, it is also possible to classify the stellar particles at higher z using these same catalogues. However, we take caution when considering high z (i.e., $z > 3$), because at such early epochs there will be a large amount of mergers involved in the growth of these low-mass systems and it will become hard to distinguish between the main galaxy and satellite galaxies. This will cause uncertainty in the classification of stellar particles, given that it is difficult to determine with precision whether the particles were born bounded to the main galaxy or to a satellite.

Chapter 3

Characterisation of stellar haloes in low-mass galaxies¹

As mentioned in Sec. 1.4.1, in this thesis we want to characterise the stellar haloes of the dwarf galaxies of our simulated sample. In this Chapter, we elucidate our definition for the stellar halo. We also present some properties of these structures, the distribution of their in-situ and accreted material at $z = 0$, and the accretion histories of these galaxies, showing how they impact the formation time of the stellar haloes.

3.1 Definition of stellar haloes in Auriga low-mass galaxies

There are different approaches to define the stellar halos of dwarf galaxies. Some recent observational studies define this component based on the spatial distribution of the stellar material, using the R_h of the galaxy and/or the detection of low-density outer profiles (e.g., [Sestito et al., 2023a,b](#); [Jensen et al., 2024](#); [Waller et al., 2023](#); [Tau et al., 2024](#)). Other theoretical studies base this definition on kinematic properties using the circularity parameter (ϵ , [Abadi et al., 2003](#)) of the stellar particles. In this thesis, we consider a definition based on a spatial selection criterion: stellar particles located outside an oblate region are considered as part of the stellar halo. We define this region such that the semi-major and intermediate axes are $a = b = 4R_h$. The semi-minor axis (c) was computed using the eigenvalues of the inertia tensor considering the stellar component of each galaxy, and the definition of the inertia tensor used in this work is $M_{ij} = \sum_{k=1}^{N_{200}} m_k r_{k,i} r_{k,j}$ ([Barnes et al., 2021](#)), where m_k is the mass of the k th particle, $r_{k,i}$ is the i th component of the position vector r_k in galactocentric coordinates and the sum is over the number of particles (N_{200}) within R_{200} . The surface of this ellipsoid, determined by the equation $(\frac{x}{4R_h})^2 + (\frac{y}{4R_h})^2 + (\frac{z}{c})^2 = 1$, was used as the inner limit of the stellar halo and all stellar particles that are located up to a distance of $10R_h$ in all directions are considered as part of the stellar halo. The amount of particles found at distances greater than $10R_h$ is not significant and does not have a meaningful impact on our results. We preferred an ellipsoidal-based definition for the beginning of the stellar halo's structure rather than a completely spherical one (such as the one used in [Tau et al., 2024](#)) because this way we better delimit a possible disc structure that the galaxies of our sample could have and we lose fewer particles that would belong to the stellar halo. We bear in mind that there are some other works that consider the stellar halo to

¹Based on Tau, Monachesi, Gómez, et al. 2025, A&A, Volume 699, id.A93

begin at either shorter or longer distances from the centre of the galaxies. To explore whether our stellar halo inner limit has a significant effect on our results, we also computed the stellar halo mass considering an oblate region with semi-major axes of $5R_h$, as some observational works (e.g., Gilhuly et al., 2022) use this threshold to define the stellar halo. However, we did not find any significant differences between our proposed inner limit and a slightly larger one.

As mentioned before, another way to determine the stellar halo is through the circularity parameter of the stellar particles. This parameter is defined as $\epsilon = J_z/J(E)$ (Abadi et al., 2003), where J_z is the angular momentum around the disc symmetry axis and $J(E)$ the maximum specific angular momentum possible at the same specific binding energy (E). If the value of ϵ satisfies that $|\epsilon| > 0.7$ for a given particle, we can assume that it belongs to the disc because it has an orbit close to circular and thus the angular momentum of the particle's orbit aligns with the angular momentum of the galaxy; otherwise, if $|\epsilon| < 0.7$, the particle belongs to a spheroidal component, either to the bulge or to the stellar halo. We bear in mind that this threshold in ϵ is quite arbitrary, so there might be some stellar particles with $|\epsilon|$ below 0.7 that could belong to some kind of disc-like component. We show the ϵ values of the stellar particles of the galaxies analysed in this thesis in Fig. 3.1.1. This parameter is useful to discriminate between disc particles from the stellar halo ones when working with MW-like galaxies, but it is not practical in this work since our sample of low-mass galaxies does not always present very well-defined discs. Nonetheless, we did compute ϵ to check if our definition of the stellar halo based on a spatial cut made a similar selection of particles to the one that would be made with this parameter in the cases where we have a disc. We found no significant differences in the results obtained with both selection methods. The percentage of particles with $|\epsilon| > 0.7$ belonging to our spatially selected stellar halo is less than 10% for the majority of the galaxies in our sample, with only 5 of them having a percentage higher than 10%, but all of these were lower than $\sim 20\%$. Thus, we conclude that our spatial definition for the stellar halo is robust and does not differ much from the one based on the particles' circularity when the galaxy has a well-defined disc. Moreover, a spatially selected region allows for a more straightforward comparison with observational results.

In Fig. 3.1.2 we show the surface brightness maps in the r band obtained for our sample of dwarf galaxies. The inner limit of the stellar halo according to our definition is represented by a white ellipse. We note that the galaxies have different extents and that their outer parts reach very low surface brightness values ($\mu > 32 \text{ mag arcsec}^{-2}$), as expected. Some galaxies, such as Auriga 2, Auriga 5 and Auriga 8, show clear stellar streams and shell features in their stellar haloes.

3.2 In-situ and accreted stellar material distribution

We computed the accreted mass fractions of our previously defined stellar haloes (see Sec. 3.1) for each galaxy of our sample. These values are shown in the eighth column of Table 2.2.1. Interestingly, we see that almost all of the galaxies (save for 2 of them - Auriga 2 and 7) have less than half of their total stellar halo mass composed of accreted material. This leads us to analyse the radial distribution of the accreted stellar mass fraction at $z = 0$, in order to further understand the contribution of this component as a function of radius. To do so, we obtained the in-situ and accreted stellar mass ratios at $z = 0$ considering the total stellar mass of each galaxy (i.e., M_{ins}/M_* and M_{acc}/M_*). In Fig. 3.2.1 we show the radial distribution of these latter ratios up to $10R_h$, and colour-coded by each galaxy's DM mass. The in-situ mass ratio profiles can be inferred from the ones shown in this figure. For visualisation

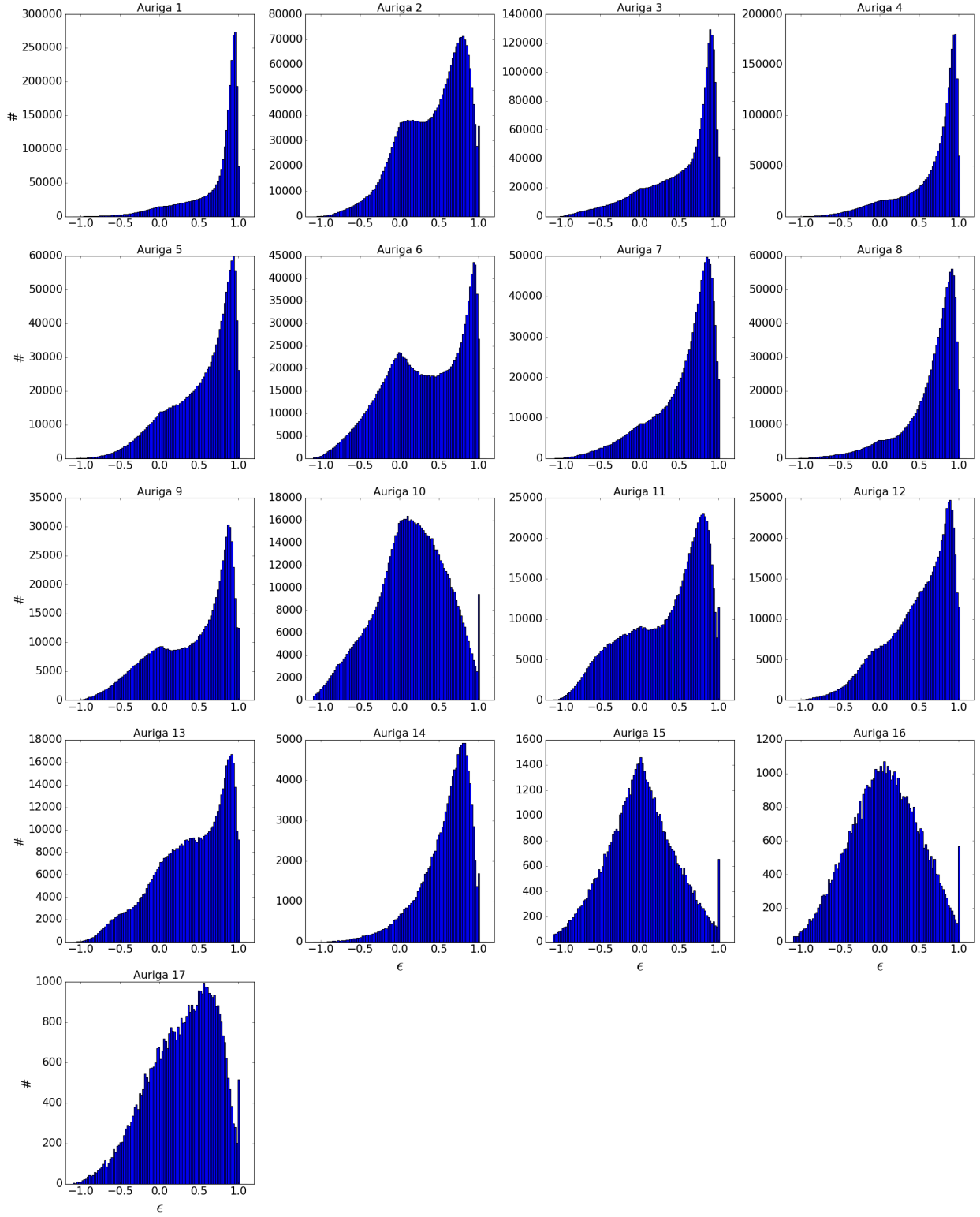


Figure 3.1.1: Distribution of the ϵ values of the stellar particles of the galaxies in our sample.

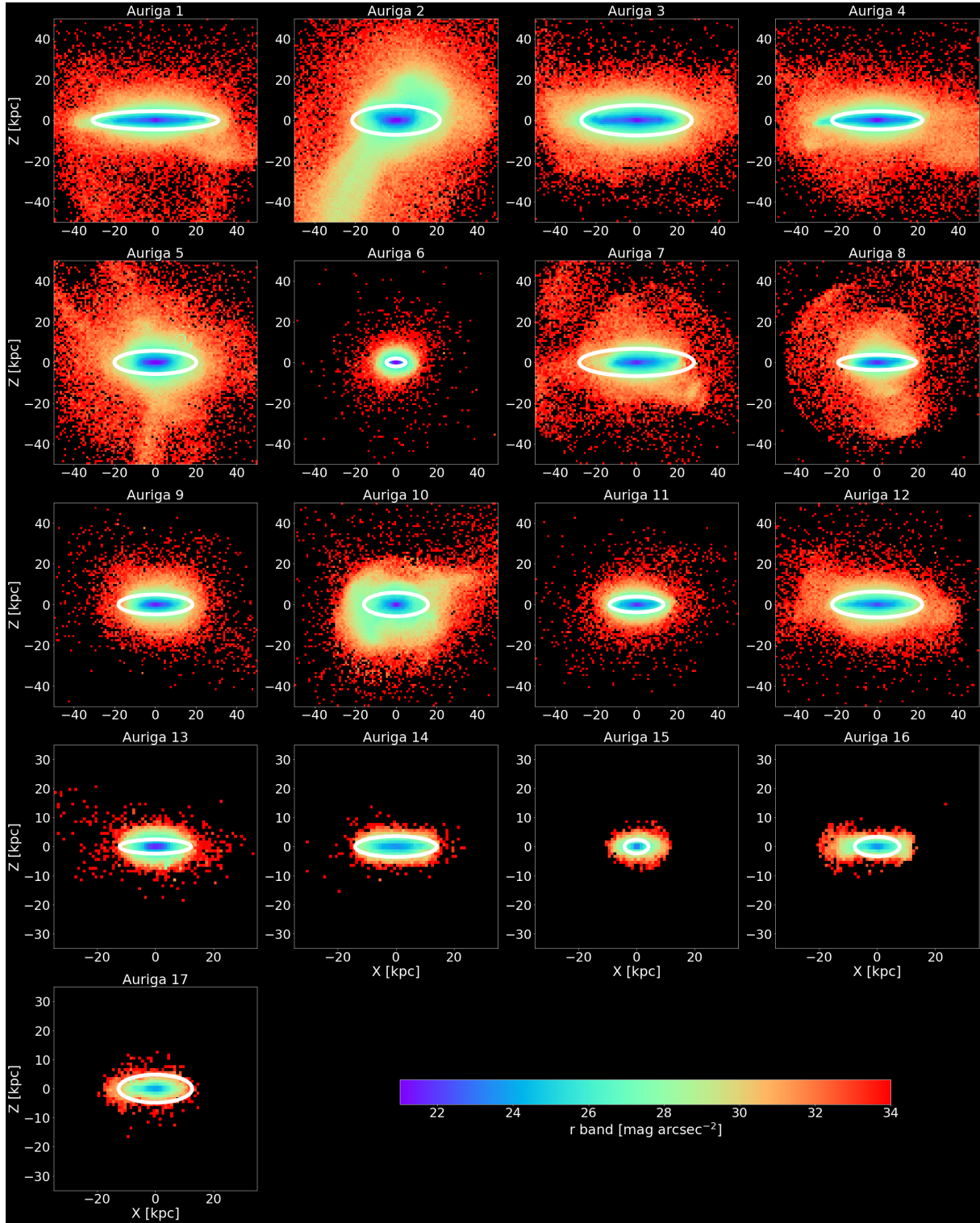


Figure 3.1.2: Surface brightness maps in the XZ projection. The solid white ellipse, with a semi-major axis equal to $4R_h$, represents the beginning of the stellar halo. The colour bar is colour-coded according to the r band surface brightness.

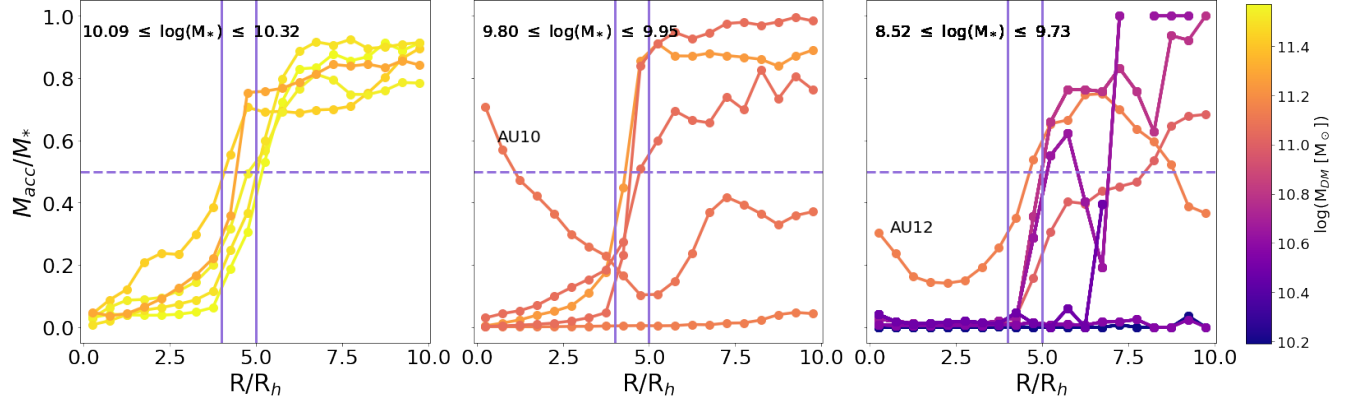


Figure 3.2.1: Ratio between the accreted mass and the total stellar mass of each galaxy as a function of radius. The colour bar shows the DM mass values of the galaxies. The solid vertical lines mark $4R_h$ (i.e., the beginning of the stellar halo) and $5R_h$, and the horizontal dashed line marks 50% of the mass fraction. The inner stellar haloes (from 4 to $\sim 6R_h$) are dominated by in-situ material. Galaxies with $M_* \leq 4.54 \times 10^8 M_\odot$ are dominated by in-situ material at all radii.

purposes, we divided the sample in three groups, with galaxies ordered by decreasing total stellar mass. The solid vertical lines mark $4R_h$ (i.e., the beginning of the stellar halo according to our definition) and $5R_h$. Between $4R_h$ and $\sim 6R_h$ we see that all of these analysed galaxies have a considerable amount of in-situ stellar material, which accounts for the dominance of the in-situ material to the total mass of the stellar halo for almost every dwarf (see column 8 of Table 2.2.1), even when they are not dominated by in-situ material at all radii. Indeed, the outskirts of most galaxies of our sample are dominated by accreted stellar material. However, for galaxies with lower stellar mass ($\log(M_*) \leq 9.95$, middle and right panels of Fig. 3.2.1), we observe a greater spread in the amount of accreted material present in their outer regions. Additionally, 3 galaxies (Auriga 15, 16 and 17) are never dominated by accreted material at any radius (right panel).²

The case of Auriga 10 (middle panel) is particularly interesting because this galaxy is dominated by accreted material in its innermost region. This is due to the fact that it accreted a satellite comparable in mass to its own at very late times (~ 0.58 Gyr ago). The maximum amount of total mass reached by this satellite is $\log(M_{\text{peak}} [M_\odot]) = 10.97$, and the ratio between the satellite’s total mass and the host’s M_{200} at the moment they merged was $\frac{M_{\text{tot, sat}}}{M_{200}} = 0.62$, i.e., a major merger. As a result of the merging process, we found that the satellite deposited the vast majority of its stellar material in the innermost region of this host galaxy, leaving it with an accreted-mass-dominated core. This can be seen in Fig. 3.2.2, where we show the stellar mass density of the accreted particles that belonged to the satellite in green and the rest of the Auriga 10 particles (i.e., in-situ and accreted particles that belonged to other satellites) in blue.

Another interesting case is that of Auriga 12 (right panel), where we find that a massive satellite contributes a substantial amount of accreted material within the central $\sim 0.5R_h$ due to dynamical friction dragging the satellite’s stellar material deep into the galaxy’s potential well (Amorisco, 2017). Between ~ 1 and $\sim 5R_h$, the amount of accreted material decreases, until it starts to be significant again due to the

²We note that this result is not currently statistically significant. This should be tested using higher-resolution simulations and/or a larger sample set of simulated galaxies at the current resolution.

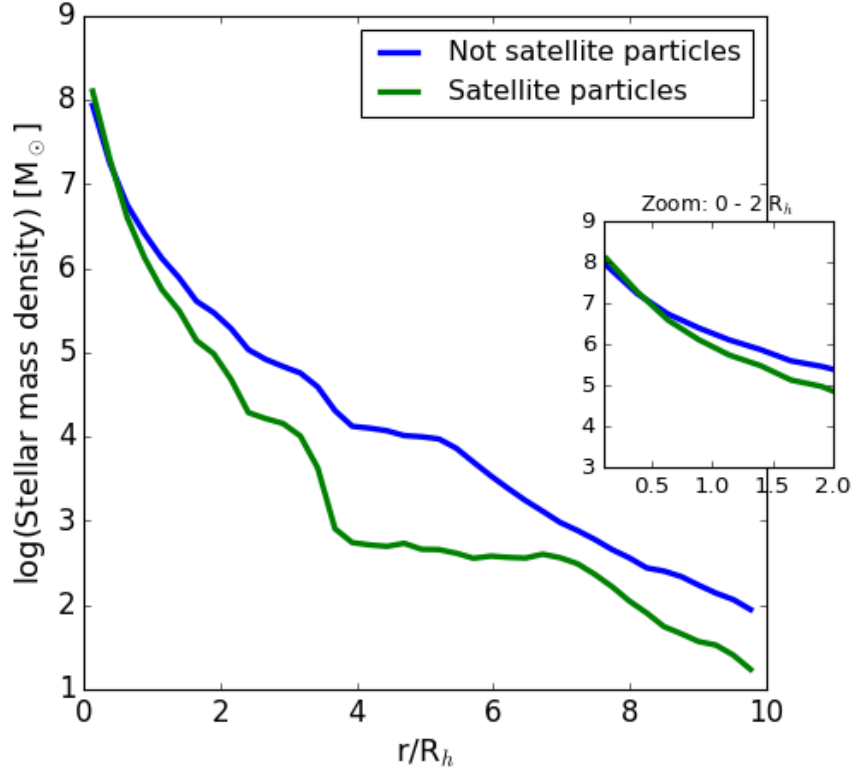


Figure 3.2.2: Stellar mass density of the massive satellite accreted by the Auriga 10 (green) and the rest of the Auriga 10 particles (i.e., in-situ and accreted particles that belonged to other satellites, blue). We show a zoomed-in region between 0 and $2R_h$, where it is clear that the accreted particles that came from the massive satellite alone dominate the stellar material up to $\sim 0.5R_h$.

contribution made by an earlier accretion event involving the near-simultaneous merger of three smaller satellites. Finally, we see a dominance of accreted material from $\sim 5.5R_h$, where the contribution of these accreted satellites plays a major role.

In Fig. 3.2.3 we show the accreted stellar halo mass fraction of the galaxies as a function of their total stellar mass, colour-coded by their total accreted mass fraction. We find a strong relation between these two quantities. For comparison, we also include results from MW-mass simulated Auriga galaxies (triangles), similarly colour-coded, as well as observed MW-like galaxies from the GHOSTS (stars, [Harmsen et al., 2017](#); [Gozman et al., 2023](#)) and Dragonfly (squares, [Gilhuly et al., 2022](#)) surveys. We highlight that the values of the observed data take into account the total stellar material instead of being limited to the accreted material, because isolating the accreted component is not feasible. However, since these quantities were estimated from observations along the galaxies' semi-minor axis, beyond 10 kpc, they are predicted by models to be dominated by accreted material ([Pillepich et al., 2015](#); [Monachesi et al., 2016b](#)). This dominance is also inferred from the comparison between the total and accreted mass quantities of haloes with these observations (e.g., [Harmsen et al., 2017](#); [D'Souza & Bell, 2018b](#); [Monachesi et al., 2019](#)). Our results are in good agreement with those of [Gilhuly et al. \(2022\)](#), based on observations in a similar stellar mass range. We note however that in general the galaxies of our sample have a higher accreted stellar halo mass fraction than the observed ones. We notice that the stellar halo fraction of the

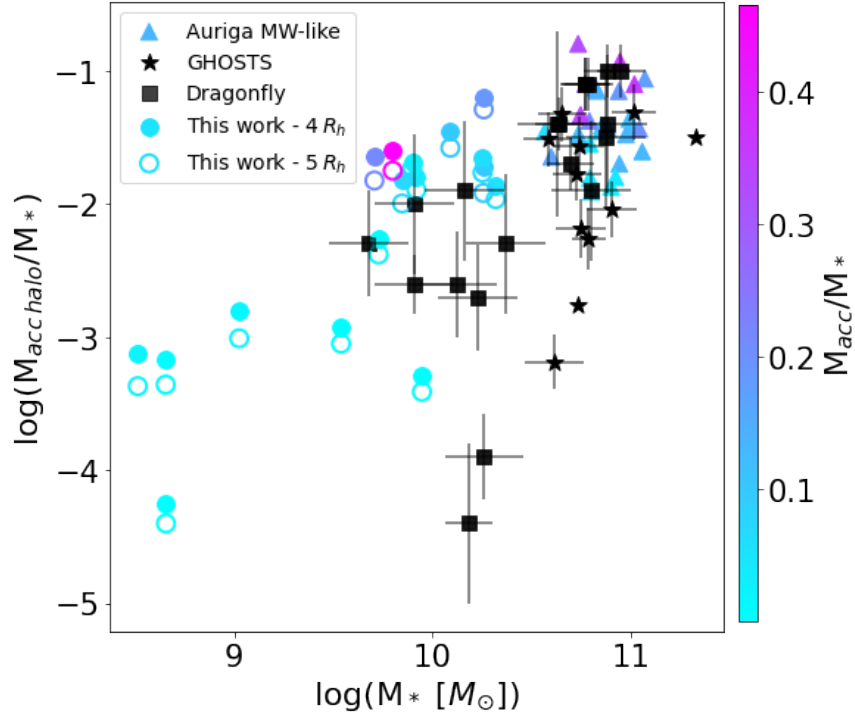


Figure 3.2.3: Accreted stellar halo mass fraction as a function of the galaxies’ total stellar mass. Filled circles represent computed mass fraction considering $4R_h$ as the inner limit of the stellar haloes, while empty circles consider this limit as $5R_h$. the Auriga MW-like galaxies are also shown, represented with triangles (Monachesi et al., 2019). All simulated galaxies are colour-coded with their accreted mass fraction. Observed galaxies taken from the GHOSTS (Harmsen et al., 2017; Gozman et al., 2023) and Dragonfly (Gilhuly et al., 2022) surveys are symbolised with stars and squares respectively. The stellar halo fraction of the Dragonfly sample that was considered in this plot is the one computed outside $5R_h$ of each galaxy.

Dragonfly sample that was considered in this plot is the one computed outside $5R_h$ of each galaxy. When computing this value for the galaxies of our sample, we consider the stellar halo to start at $4R_h$ from the dwarfs’ centres, which translates into a larger amount of stellar material in the outskirts and therefore will cause a slight increase of our values over those of Gilhuly et al. (2022). However, to illustrate that there is no significant difference, we show with empty circles the accreted stellar halo mass fraction of our simulated sample computed beyond $5R_h$.

It can be derived from the colour bar in Fig. 3.2.3 that low-mass galaxies have a wide range of accreted mass fraction, from 0.0002 to 0.47. Thus, they can have larger accreted mass fractions than MW-mass galaxies (Pillepich et al., 2015; Monachesi et al., 2019).

3.3 Metallicity of the stellar haloes

A correlation between the mass and the metallicity of the galaxies is expected because more massive galaxies are able to better retain metals due to a deeper gravitational potential well than less massive

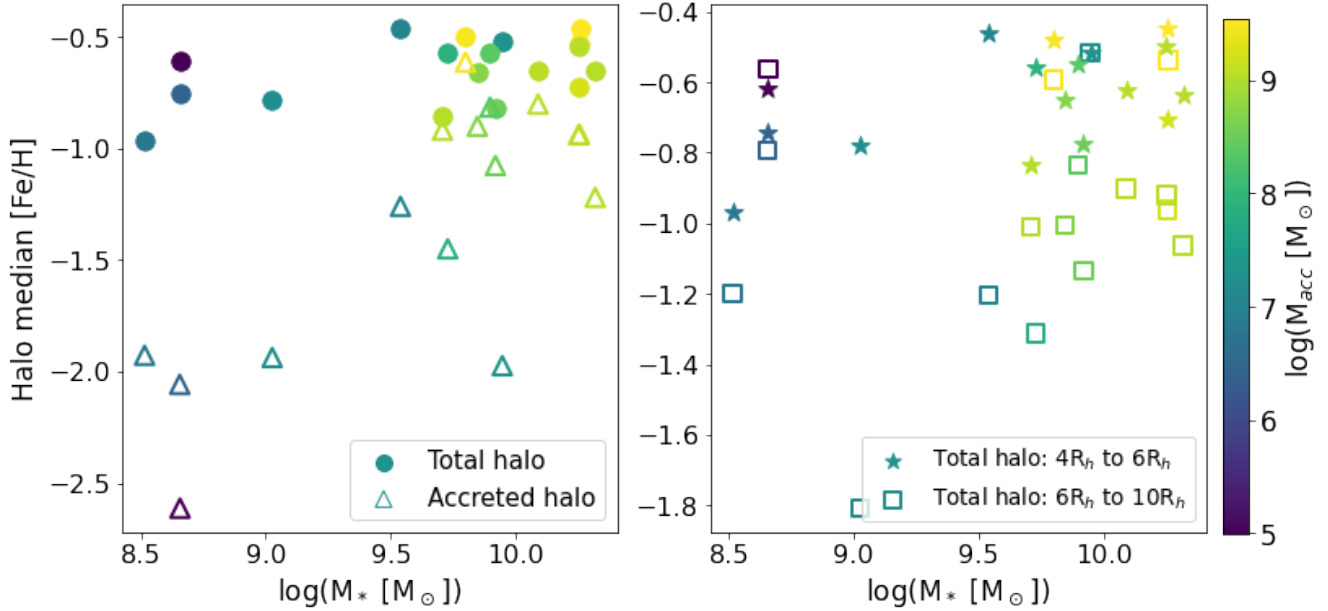


Figure 3.3.1: *Left panel:* median [Fe/H] of the stellar halo (circles) and the accreted stellar halo (triangles) as a function of the galaxies’ total stellar mass. *Right panel:* median [Fe/H] of the inner stellar halo between $4R_h$ and $6R_h$ (stars), and of the outer stellar halo between $6R_h$ and $10R_h$ (squares) as a function of the galaxies’ total stellar mass. The colour bar represents the total amount of accreted stellar material of the galaxies.

ones (Tremonti et al., 2004), and can better survive and grow through accretion events, which gradually increases their metallicity due to the accreted stars they gain (Fattahi et al., 2020). Additionally, a correlation between the mass of the stellar haloes and their metallicity was observationally found for MW-like galaxies (Harmsen et al., 2017). Monachesi et al. (2019) confirmed that the numerical models also predict this stellar halo mass-metallicity correlation for this stellar mass range, which is driven by the fact that more massive stellar haloes primarily form through the accretion of few more massive progenitor galaxies, which were more metal-rich at the time of their accretion due to the well-established mass-metallicity relation for dwarf galaxies (Kirby et al., 2013). Given this expectation for MW-mass galaxies, another interesting property to study in this work is the metallicity of the stellar haloes to see if a similar correlation with stellar halo mass holds in the low-mass regime as well.

We computed their median [Fe/H] considering their total stellar component and also just the accreted one. This is shown as a function of each galaxy’s total stellar mass in Fig. 3.3.1 (left panel) and represented with circles and triangles, respectively. The colour bar represents the total amount of accreted mass the galaxies have. We find a clear relation in the accreted stellar haloes such that more massive dwarf galaxies have more metal rich accreted stellar haloes than less massive dwarf galaxies. However, when considering the total stellar halo mass, this relation is flattened and there is virtually no such relation with stellar mass. For the accreted stellar halo we obtain lower values of [Fe/H] than the ones corresponding to the whole stellar halo. This is expected because it formed as a result of the accretion of typically less massive satellite galaxies, which should be more metal poor assuming the mass-metallicity relation of dwarf galaxies obtained at $z = 0$ (Kirby et al., 2013). When considering different regions of the stellar

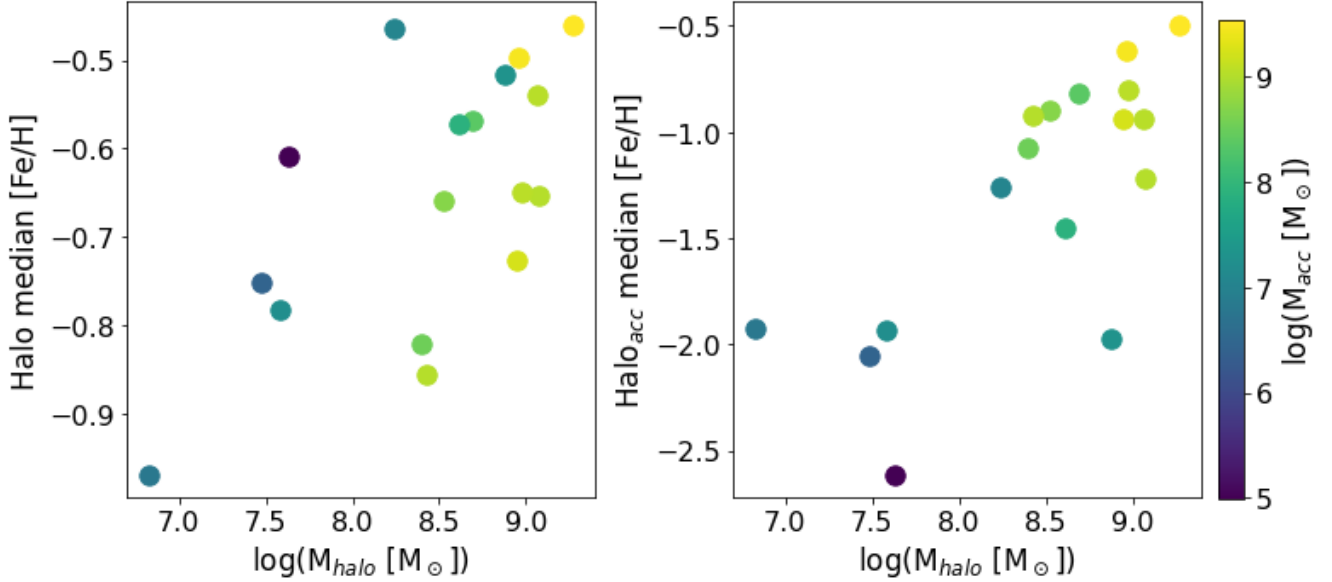


Figure 3.3.2: *Left panel:* median $[\text{Fe}/\text{H}]$ of the stellar halo as a function of its total stellar mass. *Right panel:* median $[\text{Fe}/\text{H}]$ of the accreted part of the stellar halo as a function of its total stellar mass. The colour bar represents the total amount of accreted mass of the galaxies.

halo (right panel) we note a variation between its median metallicity in the inner stellar halo (between $4R_h$ and $6R_h$, star symbols) and in the outer stellar halo (between $6R_h$ and $10R_h$, square symbols). The outer stellar halo tends to be more metal poor than the inner stellar halo, which can be explained by a greater presence of accreted material in this region, as shown in Fig. 3.2.1.

As mentioned before, a correlation between the total mass of stellar haloes and their $[\text{Fe}/\text{H}]$ at 30 kpc along the minor axis was observationally discovered by [Harmsen et al. \(2017\)](#) using data of MW-like galaxies taken from the GHOSTS survey. Later on, [Monachesi et al. \(2019\)](#) were able to numerically reproduce this result using the MW-like simulated galaxies available in the Auriga project (see also [Bell et al., 2017](#); [D’Souza & Bell, 2018b](#)). According to these works, more massive stellar haloes tend to be more metal rich, which reflects the fact that the properties of the stellar halos at those distances are dominated by the most massive accretion events (one to three) that a galaxy has had. It is thus interesting to investigate if this correlation also persists when considering low-mass galaxies. We computed the median $[\text{Fe}/\text{H}]$ of the stellar halo and of the accreted stellar halo and analysed these values as a function of the total stellar halo mass, as shown in the left and right panel, respectively, of Fig. 3.3.2. The colour bar represents the total amount of accreted stellar material of the galaxies. We find that, overall, more massive stellar haloes are more metal rich than the less massive ones, though with a large scatter when considering the total (in-situ + accreted) stellar halo (left panel). The median $[\text{Fe}/\text{H}]$ values range from -0.46 to -0.97 . This relation becomes tighter when computing the metallicity of the accreted stellar halo (right panel), in addition to getting a larger spread of median $[\text{Fe}/\text{H}]$ values, going from -0.49 to -2.61 . Hence, it is worth exploring if this correlation remains when considering only the accreted stellar halo mass.

The left panel of Fig. 3.3.3 shows the median $[\text{Fe}/\text{H}]$ of the accreted stellar halo that was computed considering all the accreted stellar particles of the stellar halo located in the direction of the semi-minor

axis of each galaxy up to a distance of $10R_h$. This was done to then compare with data of some observed MW-mass galaxies taken from the GHOSTS survey (triangular symbols) and also with the Auriga MW-mass results obtained in Monachesi et al. (2019) (square symbols). These values are shown as a function of each galaxy’s accreted stellar halo mass. Indeed, we find a very strong correlation between accreted stellar halo mass and the median metallicity of this component. All simulated galaxies are colour-coded according to their total DM mass. We also find that the more massive the accreted stellar halo is, the more metal rich it is. Moreover, for a given halo metallicity value, galaxies with a larger dark matter halo have a more massive accreted stellar halo. We note that at a given accreted stellar halo mass dwarf galaxies are more metal rich than the observed and simulated MW-mass galaxies.

The right panel of Fig. 3.3.3 shows the accreted stellar halo median $[\text{Fe}/\text{H}]$ of each galaxy as a function of the total stellar mass of the satellite galaxy that contributed the most to the stellar halo (i.e., the most dominant satellite of the stellar halo). We find a relation such that galaxies with a more metal-rich accreted stellar halo have a larger most dominant satellite. Additionally, we find that, for all galaxies in our sample, the most dominant satellite of the accreted stellar halo is also the most dominant satellite when considering the whole galaxy. In other words, the satellite galaxy that contributed the most to the accreted component of the stellar halo is also the one that contributed the most to the overall accreted stellar material of the galaxy.

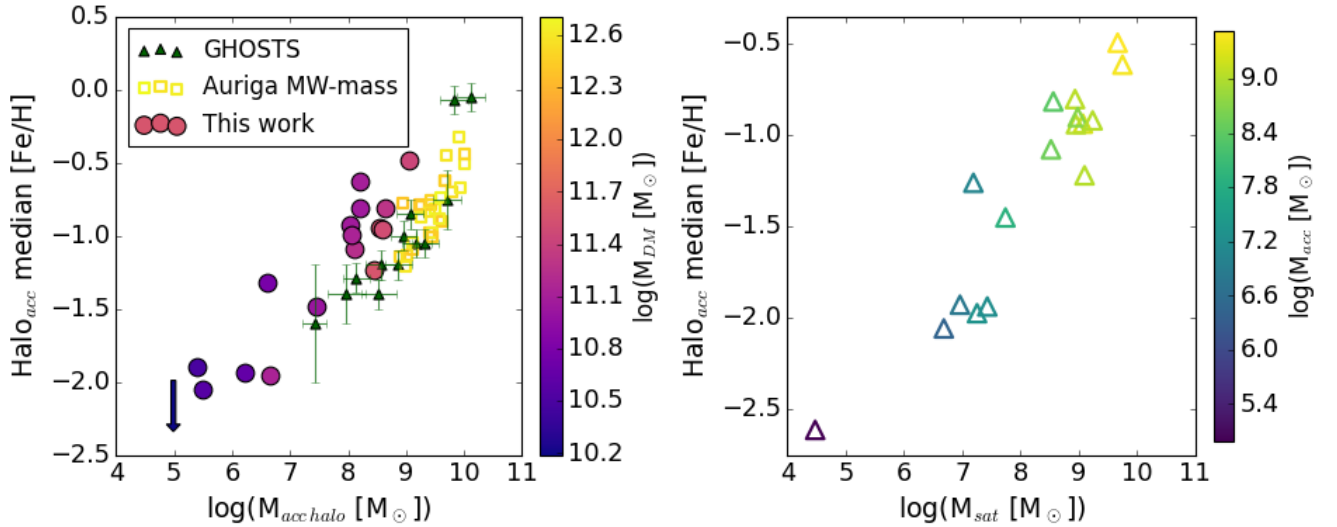


Figure 3.3.3: *Left panel*: median $[\text{Fe}/\text{H}]$ of the accreted part of the stellar halo along the semi-minor axis as a function of the accreted stellar halo mass of each galaxy. Some observed MW-mass galaxies taken from GHOSTS data are also shown as green triangles, as well as the MW-mass set of Auriga simulations represented with squares. All simulated galaxies are colour-coded according to their total DM mass. We find a strong correlation between the $[\text{Fe}/\text{H}]$ and the stellar mass of accreted stellar halo. The arrow represents the Auriga 15 that does not have accreted material in the direction of the semi-minor axis of its stellar halo. *Right panel*: median $[\text{Fe}/\text{H}]$ of the accreted stellar halo as a function of the stellar mass provided to the whole galaxy by the most dominant satellite of the accreted stellar halo. All galaxies are colour-coded by their total accreted stellar mass.

3.4 Accretion history of low-mass galaxies and its connection to their stellar haloes

The accretion history of the analysed galaxies can help explain the results found in Secs. 3.2 and 3.3 regarding the distribution of the accreted stellar component and its metallicity in the stellar haloes. In Fig. 3.4.1 we show the evolution of the accreted stellar mass component of each dwarf galaxy of our sample through time. This was computed as the ratio of the accreted stellar mass at a given time to the total amount of accreted stellar mass that each galaxy has at $z = 0$ ($M_{\text{acc}}(z)/M_{\text{acc},z=0}$). Each galaxy is colour-coded according to their total stellar mass at $z = 0$. For a clearer visualisation, we split the sample panels based on their stellar mass. We note that, in general, the more massive galaxies ($M_* \geq 6.30 \times 10^9 M_\odot$, left panel of Fig. 3.4.1) keep on accreting material until later times than the less massive ones. To quantify this, we computed the formation time of the accreted component, i.e. the mean time of each subsample by which galaxies have obtained 90% of their accreted material (t_{90}), as well as the mean time by which they had obtained 50% of their accreted material. Both of these times are represented with vertical lines. The more massive galaxies (left panel) had accreted 50% of their accreted component 6.35 Gyr ago, and 90% of it 4.44 Gyr ago, whereas the less massive ones (right panel) had already obtained these amounts of accreted material 9.77 Gyr and 8.17 Gyr ago respectively. Thus, the more massive galaxies have formed their accreted component at later times, about 4 Gyr later than the less massive ones.

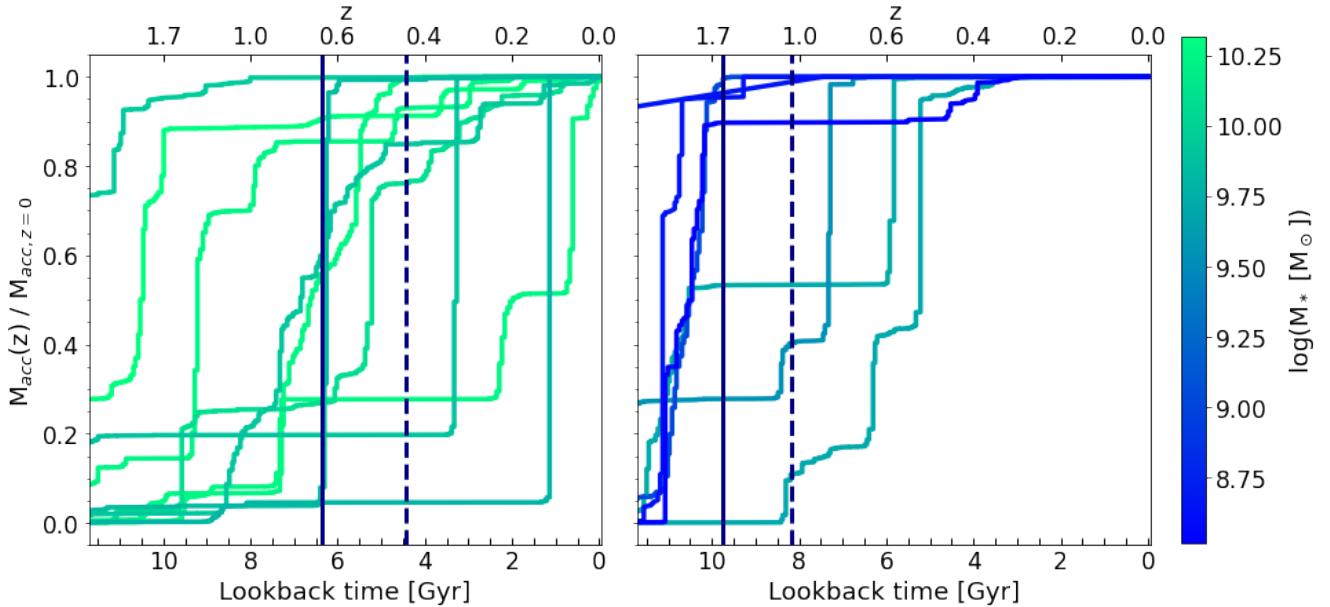


Figure 3.4.1: Evolution through time of the ratio between the accreted mass at a given z and the total amount of accreted stellar mass at $z = 0$. *Left panel*: galaxies with stellar mass ranging from $6.30 \times 10^9 M_\odot$ to $2.08 \times 10^{10} M_\odot$; *right panel*: galaxies with stellar masses ranging from $3.28 \times 10^8 M_\odot$ to $5.34 \times 10^9 M_\odot$. The solid and dashed vertical lines represent the mean look-back time by which the galaxies in those panels had already accreted 50% and 90% of their accreted material respectively.

From Fig. 3.4.1 we can also infer that the fact that the in-situ component dominates at all radii

for the three least massive galaxies (as seen in the right panel of Fig. 3.2.1) is more related to these galaxies' stellar mass rather than the quietness of their accretion history. Some more massive galaxies ($M_* \geq 6.30 \times 10^9 M_\odot$, left panel of Fig. 3.4.1) with quiet accretion histories (i.e., no evidence of accretion later than $z \sim 0.4$) still show accretion-dominated outskirts. This is consistent with findings for MW-mass galaxies, whose outskirts are accretion-dominated regardless of whether accretion occurred early or late (e.g., [Deason et al., 2013, 2016](#)).

As a means to better understand the accretion events that these galaxies have undergone, we analysed the progenitors that contributed to the accreted material present at $z = 0$ in each of them. The left panel of Fig. 3.4.2 shows the cumulative accreted stellar mass of each galaxy as a function of the number of progenitors (i.e. accreted satellites), colour-coded by the galaxies' total stellar mass. The x-axis is limited to the 10 progenitors that contributed the most. We consider a progenitor to be significant if it is within the number of satellites that contributed to 90% of the accreted material of the galaxy; i.e., the significant progenitors are those satellites that account for 90% of the accreted stellar mass. The horizontal dashed line in Fig. 3.4.2 marks this 90% threshold. The galaxies in our sample have between 1 and 7 significant progenitors (but see below for further discussion). We do not find any clear relation between the number of significant progenitors and the stellar mass of the main galaxies. This can be inferred from the colour bar, which shows that galaxies with stellar masses of about $10^{10} M_\odot$ can have as many significant progenitors as galaxies with stellar masses of about $10^9 M_\odot$. For example, in the cases of Auriga 2 and Auriga 14, they both have 3 significant progenitors, but they have stellar masses of $M_* = 1.81 \times 10^{10} M_\odot$ and $M_* = 1.06 \times 10^9 M_\odot$, respectively.

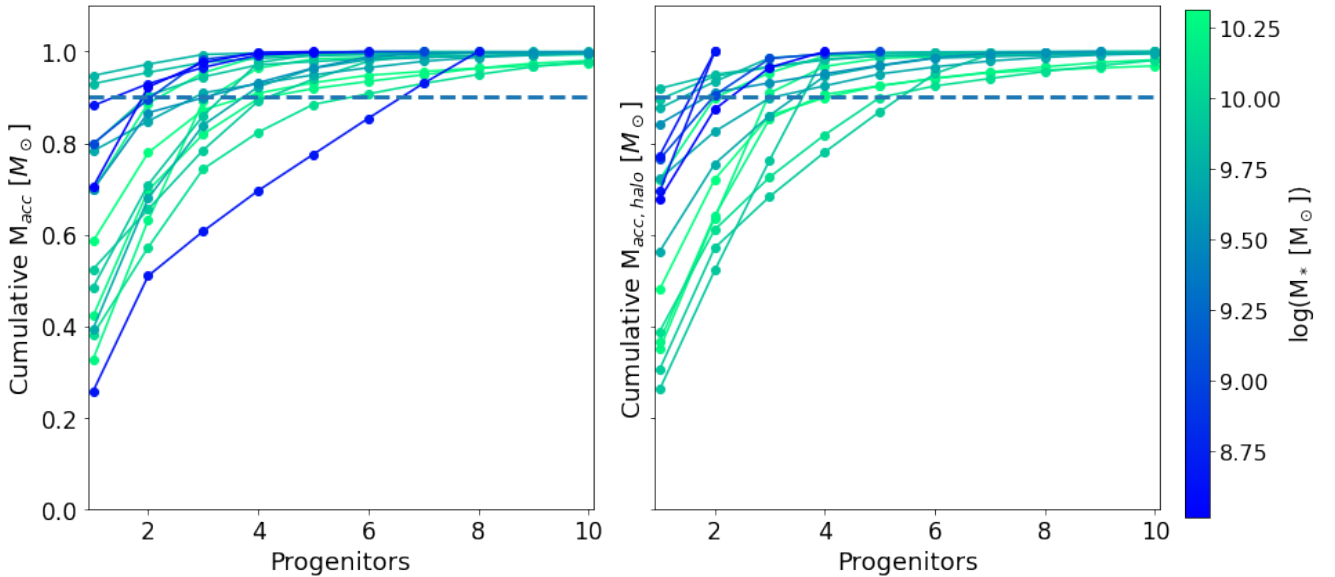


Figure 3.4.2: *Left panel*: cumulative accreted stellar mass as a function of the progenitors of each galaxy. *Right panel*: cumulative sum of the accreted stellar mass located in the stellar halo as a function of the progenitors. We only show up to 10 progenitors for the most massive dwarf galaxies, but some of them have even more. The threshold that marks 90% of the accreted mass is represented with a horizontal dashed line. We do not find a correlation between the number of significant progenitors and the stellar mass of the galaxies.

On the right-hand panel of Fig. 3.4.2 we show the progenitors' contribution to the accreted part of the stellar halo. The galaxies in our sample have between 1 and 6 significant progenitors in their stellar haloes. Similar to when considering the whole galaxy, there is no clear correlation between the number of significant progenitors that contributed to the stellar halo and the stellar mass of the galaxies. For 12 galaxies in our sample (70.6%), we find that all of the significant progenitors of the stellar halo are also significant progenitors when considering the total amount of accreted material in the whole galaxy. The remaining 5 galaxies (29.4%) have at least 1 significant progenitor of the stellar halo that is also a significant progenitor when considering the whole galaxy.

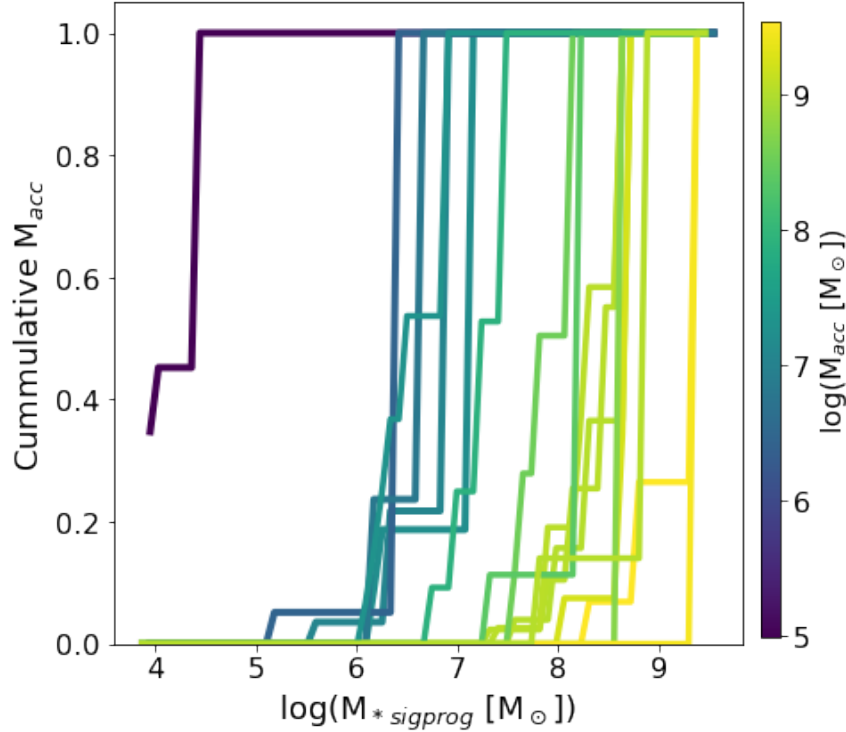


Figure 3.4.3: Cumulative sum of the accreted component provided by each galaxy's significant progenitors as a function of their significant progenitors' mass. Galaxies with more accreted material have accreted more massive significant progenitors.

In Fig. 3.4.3 we show the cumulative accreted stellar mass for each galaxy as a function of their significant progenitors' stellar mass, colour-coded by the amount of total accreted stellar mass of the host. We note that the galaxies with more accreted material have accreted more massive significant progenitors. Furthermore, in Fig. 3.4.4 we show the number of significant progenitors the galaxies have against their total accreted mass to analyse whether there is a relation. However, we do not find any clear correlation between these quantities, as opposed to what it is found in MW-mass galaxies in which the higher the amount of accreted material is, the fewer significant progenitors the galaxy had (Monachesi et al., 2019). If any, there seems to be an opposite trend for this stellar mass range: the higher the accreted component, the larger the number of significant progenitors. This is consistent with the results from Gonzalez-Jara et al. (2025). We note that this lack of correlation between total M_{acc} and the number of significant progenitors would persist regardless of the orbital parameters of the satellite galaxies. If

anything, the orbital parameters may influence the distribution of the accreted stellar mass, potentially affecting the relation between the number of significant progenitors and the accreted mass in our defined stellar halo region. The open circle represents Auriga 15, which is a galaxy with an accreted stellar mass of $M_{acc} = 9.74 \times 10^4 M_{\odot}$. Given that the stellar particle resolution of the Auriga simulations is $6 \times 10^3 M_{\odot}$, the amount of accreted stellar material in this galaxy is at the resolution's limit. Analysing this galaxy in detail, we find that it has a very low number of accreted particles and that not all of them belonged to the same satellite galaxy before being accreted. This is the reason why Auriga 15 has 7 significant progenitors, and we highlight that this number must be taken with caution. If we discard Auriga 15 when analysing Fig. 3.4.4, we still find no correlation between the number of significant progenitors of the galaxies and their accreted stellar mass. This was also quantified with the Spearman correlation coefficient, for which we obtained a value of $\rho = 0.177$ implying that there is no meaningful correlation between these quantities. The colour bar shown in Fig. 3.4.4 represents the total stellar halo mass of the galaxies, but once again we see a huge spread and we do not find any correlation between the mass of the stellar haloes and the amount of significant progenitors of the galaxies.

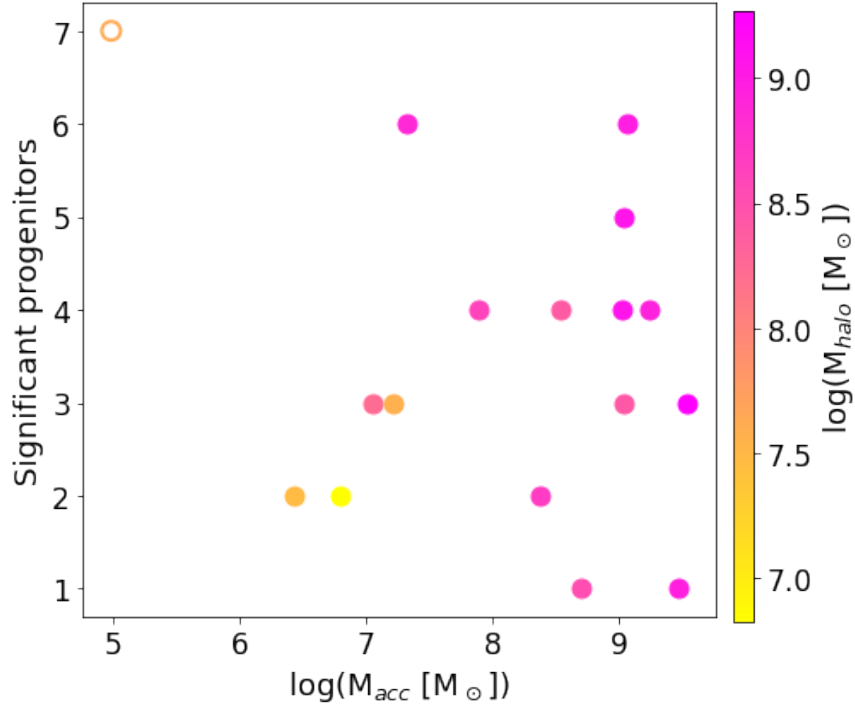


Figure 3.4.4: Number of significant progenitors as a function of each galaxies' accreted mass, colour-coded by their stellar halo mass. We do not find any clear correlation between these quantities. The open circle represents Auriga 15 with $M_{acc} = 9.74 \times 10^4 M_{\odot}$, which means that it has a low amount of accreted particles due to the simulation's resolution and hence the number of these particles is insufficient for a robust result.

3.5 Discussion and contextualisation

In this section we compare our results with observational works, aiming to explain properties present in some observed dwarf galaxies. We also place our results in context with the results of stellar haloes of MW-mass galaxies.

3.5.1 Stellar halo characterisation

In this Chapter we find that the stellar haloes of the Auriga low-mass galaxies are mostly composed of in-situ stellar material in the inner regions ($4 - 6R_h$) for all galaxies, and that the in-situ material even dominates at all regions in the less massive galaxies. Placing this result in a broader context, this is different to what is found in MW-mass stellar haloes (Helmi, 2008; Pillepich et al., 2015; Bland-Hawthorn & Gerhard, 2016; Harmsen et al., 2017; Helmi et al., 2018; Monachesi et al., 2016b, 2019), where the outskirts of these structures are always dominated by accreted material. The contribution of the accreted stellar component in the stellar haloes of the low-mass galaxies analysed here dominates always in the higher-mass range ($M_* \geq 1 \times 10^9 M_\odot$) of our sample beyond $\sim 5R_h$ (see Fig. 3.2.1), resembling the behaviour observed in MW-mass galaxies (Zolotov et al., 2009; Font et al., 2011; Tissera et al., 2012; Monachesi et al., 2016b, 2019), except for two galaxies (see below). Interestingly, we find that the Auriga galaxies with a stellar mass lower than $4.54 \times 10^8 M_\odot$ have their stellar haloes dominated by in-situ material at all radii. We note, however, that for stellar masses between $1.06 \times 10^9 M_\odot$ and $8.83 \times 10^9 M_\odot$ it could also happen that their outskirts are dominated by in-situ stars. This is the case of Auriga 6 and Auriga 10, which are both dominated by in-situ material at large radii (see middle panel of Fig. 3.2.1). Auriga 6 is a very compact dwarf galaxy (see Fig. 3.1.2) and Auriga 10 has accreted a satellite galaxy comparable in mass to its own, which sunk into its centre (see Sec. 3.2). Therefore, we find that the outer regions of high-mass dwarf galaxies of our sample are dominated by accreted material, but that the in-situ component dominates in those of less massive dwarfs, indicating that its in-situ material is more prone to migrate into the outskirts. It can also imply that the satellites they accrete contain very little stellar material because they are very small and mostly comprised by dark matter, and thus they are unable to contribute to the accreted stellar halo.

Concerning the metallicity of these stellar haloes, the correlation between the mass of these structures and their metallicities found by Harmsen et al. (2017) in MW-mass galaxies extends to the lower mass range analysed in this work, when considering only the accreted stellar halo. We see in Fig. 3.3.3 that galaxies with a more massive accreted stellar halo are more metal rich than those with a less massive accreted stellar halo. However, when considering the MW-mass regime, this relation implied that their outskirts are dominated by one to three major accretion events, and hence we can use the stellar halo mass or its metallicity to estimate the most massive accretion event that a galaxy has had. In the low-mass regime we do not observe a correlation between the number of significant progenitors and the accreted mass of the galaxies (see Sec. 3.5.2 for further discussion). In addition, as the stellar haloes of low-mass galaxies are dominated by in-situ material in their inner regions ($4 - 6R_h$), analysing their metallicities does not provide such a straightforward link with the satellite galaxies they accreted. This can only be considered beyond $\sim 6R_h$ for more massive dwarf galaxies, where the accreted stellar material dominates.

3.5.2 Accreted component of the stellar halo

As we analysed the accretion history of these dwarf galaxies, we found that the most massive ones keep on accreting material until later times, while the least massive ones typically stop undergoing merger events earlier on (see Fig. 3.4.1). The mean formation time of the accreted component (τ_{90}) of the more massive galaxies in our sample is $\tau_{90} = 4.44$ Gyr ago, while in the case of the less massive galaxies of our sample it is $\tau_{90} = 8.17$ Gyr ago. We also computed τ_{90} considering only the accreted stellar particles that belong to the stellar halo (as opposed to the overall accreted component), to see if this trend is also reflected in this structure. We found that $\tau_{90} = 3.93$ Gyr ago for the accreted stellar haloes of the more massive galaxies in our sample, while $\tau_{90} = 7.03$ Gyr ago for those in less massive galaxies. Thus, accreted stellar haloes of more massive dwarf galaxies keep on forming until later times than those of less massive dwarfs.

This scenario could apply to the case of the observed isolated dSph galaxy KKs 3 studied by [Karachentsev et al. \(2015\)](#) and [Sharina et al. \(2018\)](#). This galaxy has a stellar mass $M_* = 2.3 \times 10^7 M_\odot$ and these authors stated that it has not been perturbed in the last 10 Gyr. This conclusion is supported by the lack of star formation in the last Gyr, the galaxy’s isolated position (located approximately 2 Mpc from the nearest large galaxy and 1 Mpc from any known dwarf galaxy), and the absence of any significant star formation events after the one it experienced over 12 Gyr ago. Even though the galaxies in our sample do not reach such a low stellar mass, one could assume that the correlation between τ_{90} and the stellar mass extends to a less massive regime. If this were the case, our results suggest that KKs 3 did not interact with satellite galaxies in the last ~ 10 Gyr indeed. A detailed analysis using high-resolution simulations of less massive galaxies is needed to corroborate this.

We also found that, regardless of the total stellar mass of the dwarf galaxy, the number of significant progenitors of the galaxies in our sample are rather few and ranges from 1 to 7 (see Fig. 3.4.2). Our analysis shows no meaningful correlation between the stellar mass of the dwarfs and the number of significant progenitors. We also do not find any clear relation between the accreted mass of the galaxies and the number of significant progenitors they have, as shown in Fig. 3.4.4. This means that the correlation found in the MW-mass range between the number of significant progenitors and the accreted mass of those galaxies ([Monachesi et al., 2019](#)) does not extend to the low-mass regime. However, when studying the stellar mass that the significant progenitors deposited in the galaxies of our sample, we found that the galaxies that have a greater amount of accreted material have obtained it by accreting more massive satellites (see Fig. 3.4.3). This also happens in the mass range of MW-mass galaxies, for which it has also been found that galaxies with more massive stellar haloes and with a higher amount of ex-situ stellar material have gained it during merger events with larger progenitors, and that there is normally one massive satellite that dominates the accreted mass (e.g., [Bell et al., 2017](#); [D’Souza & Bell, 2018b](#); [Monachesi et al., 2019](#)).

Our results can also help shed light on the recently discovered stellar halo around Ark 227, an isolated dwarf galaxy with a stellar mass of $M_* = 5 \times 10^9 M_\odot$, and the accretion history of this galaxy. [Conroy et al. \(2024\)](#) found accreted shells that were likely formed after at least two minor mergers, one with a galaxy of $M_* \sim 10^8 M_\odot$ and another one with a galaxy of $M_* \sim 10^7 M_\odot$. According to our results for Auriga 12, which is the galaxy of our sample closest in stellar mass to Ark 227, it is probable that the observed galaxy accreted this material over ~ 5 Gyr ago, and that the τ_{90} of its stellar halo was around 4.36 Gyr ago. [Conroy et al. \(2024\)](#) also estimated Ark 227 to have a stellar mass of $2 \times 10^8 M_\odot$ within 10 and 50 kpc from its centre and of $10^7 M_\odot$ at distances larger than 50 kpc. Thus, if we consider these

values as a lower limit of the galaxy’s stellar halo mass, we can infer from Fig. 3.4.4 that Ark 227 has likely had between 2 and 4 significant progenitors.

3.6 Summary

In this Chapter, we characterised the stellar haloes of Auriga low-mass galaxies and analysed their main structural and chemical properties, as well as their connection with the galaxies’ accretion histories. Our analysis shows that the stellar haloes of these dwarfs are generally dominated by in-situ material in their inner regions ($4 - 6R_h$), while accreted material becomes increasingly important at larger radii, particularly in more massive galaxies. In contrast, the 3 least massive dwarfs of our sample are dominated by in-situ material at all radii. We also studied the metallicities of the stellar haloes and found that the stellar halo mass–metallicity relation observed in MW-mass galaxies extends to the low-mass regime when considering only the accreted component.

By linking these results to the accretion histories of the dwarfs, we showed that more massive galaxies tend to accrete material until later times than the less massive ones, and that their accreted stellar haloes form correspondingly later. While the total number of significant progenitors ranges from 1 to 7, we find no clear correlation between the number of significant progenitors and the stellar mass or total accreted mass of the dwarfs. Moreover, galaxies with larger accreted components are those that merged with more massive satellites, in agreement with findings for MW-mass galaxies.

Overall, these results indicate that the build-up of stellar haloes in the low-mass regime differs substantially from that in MW-mass systems: in-situ stars play a much more prominent role in shaping the haloes of dwarfs, while accreted stars only dominate their outskirts usually beyond $\sim 6R_h$ or, in the lowest-mass cases ($M_* \leq 4.54 \times 10^8 M_\odot$), remain negligible altogether. This highlights the importance of considering both in-situ and accreted processes when interpreting the observable properties of dwarf galaxy stellar haloes.

Chapter 4

Bridging the outskirts and the central regions of low-mass galaxies¹

In the previous Chapter we mainly focused on the stellar halo’s properties. However, it is important to study how different processes happening in the central regions of the galaxies affect the outskirts. To do so, we must characterise the internal regions as well. In this Chapter, we study the metallicity and age distributions along all radii of the galaxies. We mainly focus on their metallicity and age distributions and profiles, as well as on their stellar haloes’ age and metallicity trends. We also explore whether the accretion time of satellites influences the present-day gradients observed in stellar haloes, and whether the age of the halo itself correlates with its properties.

4.1 Metallicity distributions

In this section, we analyse the metallicity distribution of the overall galaxies, as well as their corresponding stellar haloes. We characterise the metallicity profiles of the different dwarf galaxies of our sample, comparing the metallicity gradients of their central regions to those of their outskirts. We then analyse the metallicity of the accreted stellar haloes and how they are affected by their most dominant progenitor.

4.1.1 Metallicity gradients

In Fig. 4.1.1, we show with a black dotted line the median of the median [Fe/H] profiles of the galaxies in our sample, computed within concentric 3D ellipsoids along the R_h at $z = 0$. The radial axis is normalised by the galaxies’ respective R_h . The pink dash-dotted line represents the median of the [Fe/H] profiles when considering only the accreted stellar material of the galaxies. We note that this accreted profile is remarkably flat. We also show the individual [Fe/H] profiles for 6 galaxies of our sample, colour-coded by their total stellar mass. We note that the values of [Fe/H] decrease from the central regions to the outskirts of the galaxies, indicating that the latter are more metal poor. This can be quantified with the slope of a linear fit within $10 R_h$ weighted by the number of particles made to these profiles, which we will refer to as “metallicity gradient” and accounts for the steepness of the profiles. The values of the

¹Based on Tau, Monachesi, Gómez, et al., to be submitted to A&A

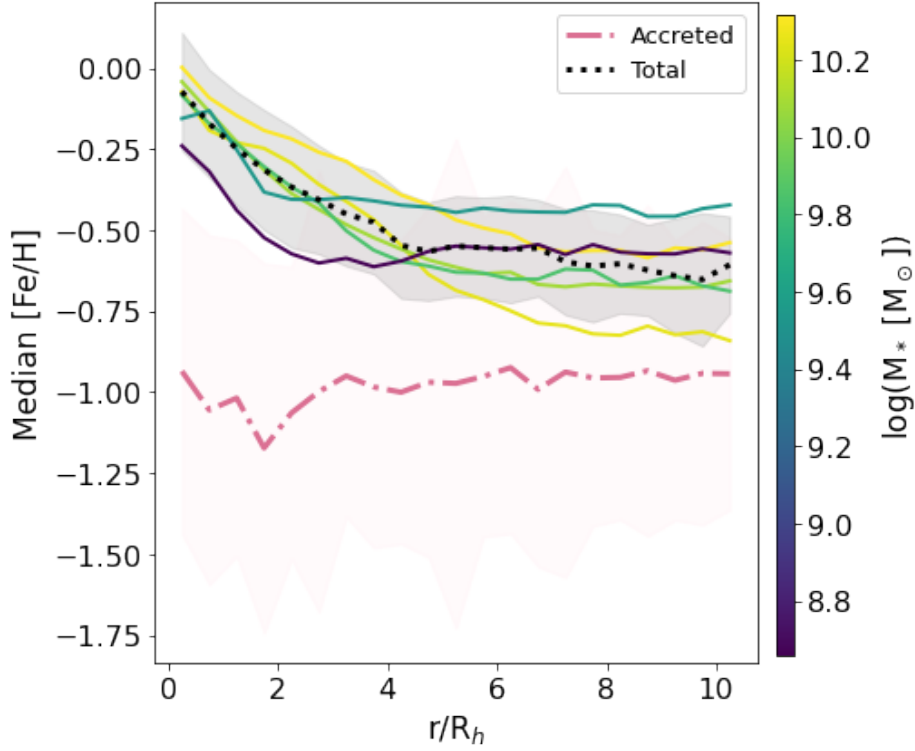


Figure 4.1.1: Total median of the median $[\text{Fe}/\text{H}]$ (black dotted line) and accreted median $[\text{Fe}/\text{H}]$ (pink dash-dotted line) profiles of the galaxies in our sample. Individual median $[\text{Fe}/\text{H}]$ profiles for 6 galaxies of our sample are also shown, normalised by their respective R_h and colour-coded by their stellar masses. The x-axis shows distances along the semi-major axis.

metallicity gradients of the galaxies in our sample range from -0.18 (Auriga 5) to -0.07 (Auriga 13). Higher negative values of metallicity gradients indicate that the metallicity profile is steeper, while lower values imply that the metallicity profile is flatter. Since the $[\text{Fe}/\text{H}]$ profiles do not decrease strictly linearly from the centres to the outskirts, we also computed the metallicity gradients for the galaxy (i.e. particles within $4R_h$) and the stellar halo separately. We bear in mind that these length scales are not the same, one considers a scale of $4R_h$ and the other a scale of $6R_h$ (between 4 and $10R_h$). Hence, it is not so straightforward to compare the values of the gradients obtained at these two scales, but they serve rather as an estimation for the behaviour in the different regions. The metallicity gradients of these galaxies within $4R_h$ range from -0.18 (Auriga 5) to -0.07 (Auriga 17), while in their stellar haloes they range from -0.1 (Auriga 4) to 0.01 (Auriga 15) when considering both the in situ and accreted components, and from -0.29 (Auriga 17) to 0.09 (Auriga 1) when considering only the accreted component. In Fig. 4.1.2, we show the distribution of the gradients within $4R_h$ in blue, and those of the stellar halo and its accreted material in pink and green, respectively. We see that, indeed, the $[\text{Fe}/\text{H}]$ profile radially decreases more steeply within $4R_h$ than it does in the stellar halo. This reflects the fact that the main bodies of the galaxies undergo significant chemical enrichment, producing strong central–outer metallicity differences within $4R_h$, while the stellar haloes are expected to consist mainly of older material, partly associated with old accretion events. Notice however that, as shown in Fig. 4.1.1, the accreted component is typically more

metal poor than the overall stellar halo population. This indicates a significant contribution of in situ material to the outermost regions of these low mass galaxies, as presented in Chapter 3.

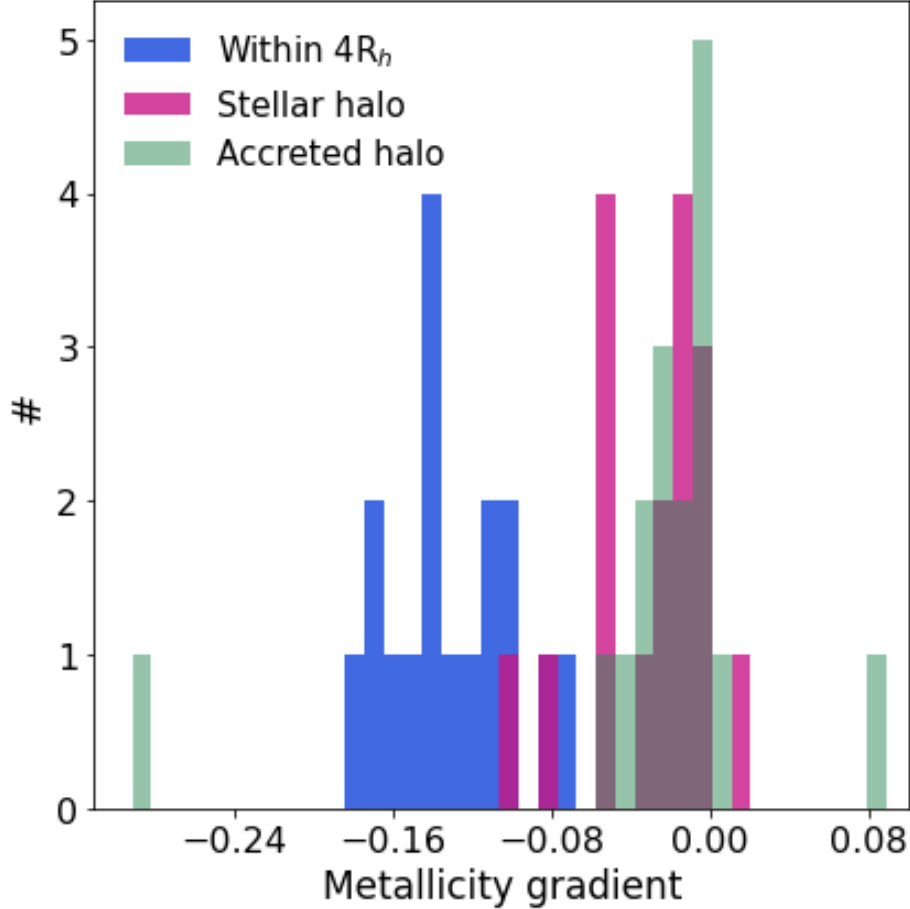


Figure 4.1.2: Metallicity gradients of the galaxies of our sample computed when considering the metallicity profile of the galaxy within $4R_h$ (blue), and the metallicity profile of the total stellar halo (pink) and the accreted stellar halo (green).

Given the variety of metallicity gradient values, it is interesting to see if there is any relation between them and the galaxies' properties. We analyse these values as a function of the galaxies' stellar mass, and we show these results in Fig. 4.1.3. Symbols are colour-coded by the galaxies' accreted mass fraction. The left panel of Fig. 4.1.3 shows the metallicity gradient of the whole galaxy (i.e. $< 10R_h$, filled circles) and within $4R_h$ (empty circles) considering its in situ and accreted components, while the right panel shows the metallicity gradient of the total stellar halo (in situ + accreted, circles) and the accreted stellar halo (triangles) separately. We find no correlation between these gradients and the stellar mass or the accreted mass fraction of the galaxies. We also analysed these metallicity gradient values as a function of the total amount of accreted mass and the number of significant progenitors as well, but again we found no correlation between these quantities. Thus, the metallicity gradients of these galaxies do not seem to be a direct consequence of their evolution pathways. This is opposite to what is found in MW-like models, where a strong correlation is obtained between the metallicity gradient of the accreted component and

the number of significant progenitors (Monachesi et al., 2019). We further explore this distribution in the following section.

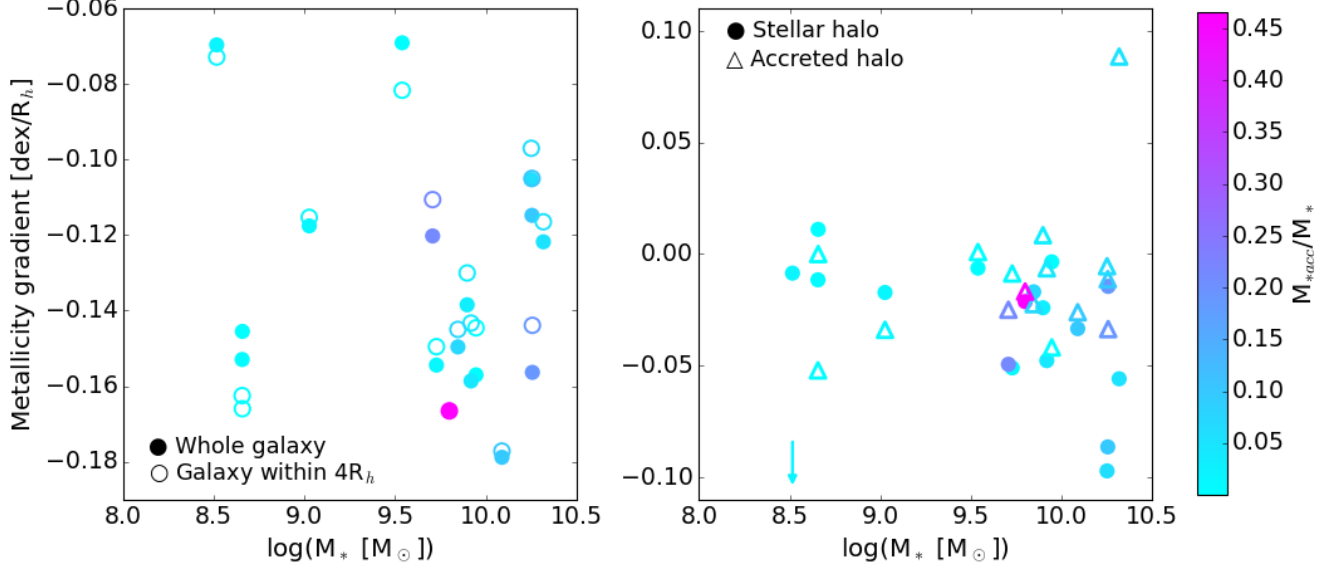


Figure 4.1.3: Left panel: Metallicity gradient of the galaxies of our sample computed within $4R_h$ (empty circles) and $10R_h$ (filled circles), as a function of their stellar mass. Right panel: Metallicity gradients of the total stellar halo (in situ + accreted) and the accreted stellar halo as a function of the galaxies’ stellar mass, represented with filled circles and empty triangles respectively. The arrow represents the value corresponding to the accreted stellar halo of Auriga 17, which is ~ -0.3 . Both panels are colour-coded by the galaxies accreted mass fraction.

4.1.2 The metallicity of the accreted stellar halo

We now explore the correlation between the most dominant contributor’s infall time and the median metallicity of the stellar halo. This allows us to explore whether the infall time of these satellites influences their metallicities. The infall time is defined as the time at which the satellites crossed the R_{200} of the main galaxy. In Fig. 4.1.4, we show the median $[\text{Fe}/\text{H}]$ of the accreted stellar haloes of the galaxies as a function of the infall time of their most dominant satellite, which is the accreted satellite that contributed the most to the stellar halo’s accreted component. We note a correlation between these two quantities such that the more metal-rich accreted stellar haloes accreted their most dominant satellite at later times. Symbols are colour-coded by the stellar mass of these most dominant satellites, and we can see that the more metal-rich accreted stellar haloes have a more massive dominant satellite, as expected. We note that Auriga 2 is an exception to this trend given that it suffered a major merger at early times and accreted a very massive most dominant satellite contributing with a high metallicity. We now examine how the median metallicity of these stellar haloes connects with their total and accreted stellar halo masses, while also considering the infall time of their most dominant satellite.

In Fig. 4.1.5, we show the median $[\text{Fe}/\text{H}]$ computed for the total stellar halo (left panel) and the accreted stellar halo (right panel) as a function of the total stellar halo’s mass and the accreted stellar

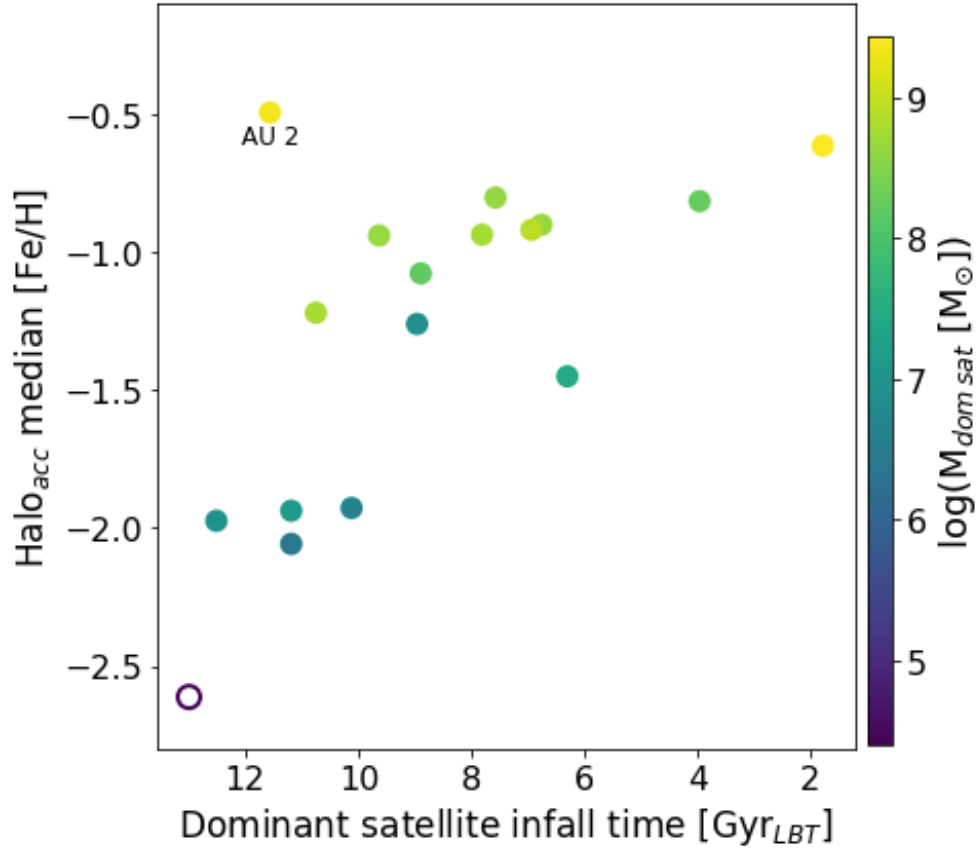


Figure 4.1.4: Median [Fe/H] of the accreted stellar halo of the galaxies as a function of their most dominant satellite’s infall time, colour-coded by these satellites’ stellar mass.

halo’s mass, respectively. Both panels are colour-coded by the infall time of the most dominant satellite. We note a wider range of median [Fe/H] of the accreted halo (right) with respect to the overall population (left), evidencing once more the significant contribution of in-situ material in the stellar haloes of these simulated galaxies. As already presented Chapter 3, there is a tight correlation between the median [Fe/H] values and the stellar haloes’ masses when considering the accreted component: more massive accreted stellar haloes are also more metal rich. As explained, this is due to the fact that more massive stellar haloes mainly form through the accretion of more massive progenitor galaxies which, due to the mass-metallicity relation for dwarf galaxies (Kirby et al., 2013), were more metal-rich at the time they were accreted. Interestingly, we also find a correlation between the metallicities and masses of the accreted stellar haloes, and the infall time of their most dominant satellites, as we can see in the right panel of Fig. 4.1.5: at a given accreted stellar halo mass, the galaxies that accreted their dominant satellites at later times have a more metal-rich accreted stellar halo. This can be explained by the fact that satellites accreted at later times had more time to chemically evolve and enrich their stellar populations prior to disruption, which will then contribute to the accreted stellar halo [Fe/H]. This trend is not found in the left panel, since the mass and metallicity of the total stellar halo is also influenced by the in-situ component.

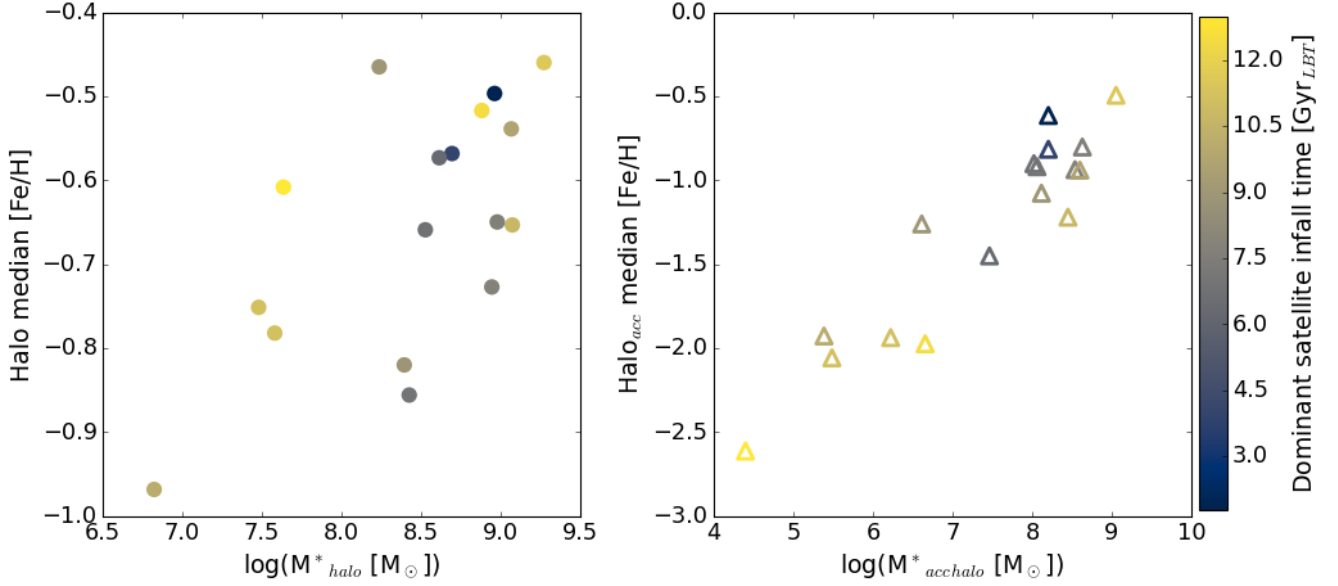


Figure 4.1.5: *Left panel:* median $[\text{Fe}/\text{H}]$ of the stellar haloes of the galaxies as a function of their masses. *Right panel:* median $[\text{Fe}/\text{H}]$ of the accreted stellar haloes of the galaxies as a function of their masses. Both panels are colour-coded by the infall time of the most dominant satellite of the stellar haloes. We note a correlation between the metallicity of the accreted stellar halo and the infall time of its most dominant satellite: more metal rich accreted haloes have accreted this satellite at later times.

4.2 Age analysis

Studying the ages of the galaxies' stellar populations can help shed light on their formation history, provide further insight into their chemical enrichment histories, and help determine whether a relation exists between the age and metallicity of the stellar haloes. This is an observationally challenging task since deriving stellar ages from their stellar populations is difficult. Fortunately, this can be done with simulations, as every stellar particle provides information about their age. Here, we characterise the radial age profiles of the galaxies of our sample, specifically focusing on their internal regions. We then shift to the outskirts and analyse the mean age of both the total and the accreted stellar halo.

4.2.1 Radial age profiles

In Fig. 4.2.1, we present the total (in situ + accreted) mean and the accreted mean of the mean radial age profiles of the low-mass galaxies of our sample, shown as black dotted and pink dash-dotted lines, respectively. The shaded regions represent the standard deviation of these computed means. To compute the individual profiles, we used a set of concentric 3D ellipsoids defined at $z = 0$, where the semi-major axis of each ellipsoid was scaled by the galaxy's R_h . Within each region, we calculated the mean stellar age by averaging over all stellar particles enclosed in it, or only over the accreted ones for the accreted mean age profile. As expected, we find that the age distribution of the accreted component is significantly older than the overall stellar population distribution. The difference can be as large as 5 Gyr within the inner regions, but becomes smaller (~ 3 Gyr) in the outskirts ($r > 7R_h$). We also show the individual

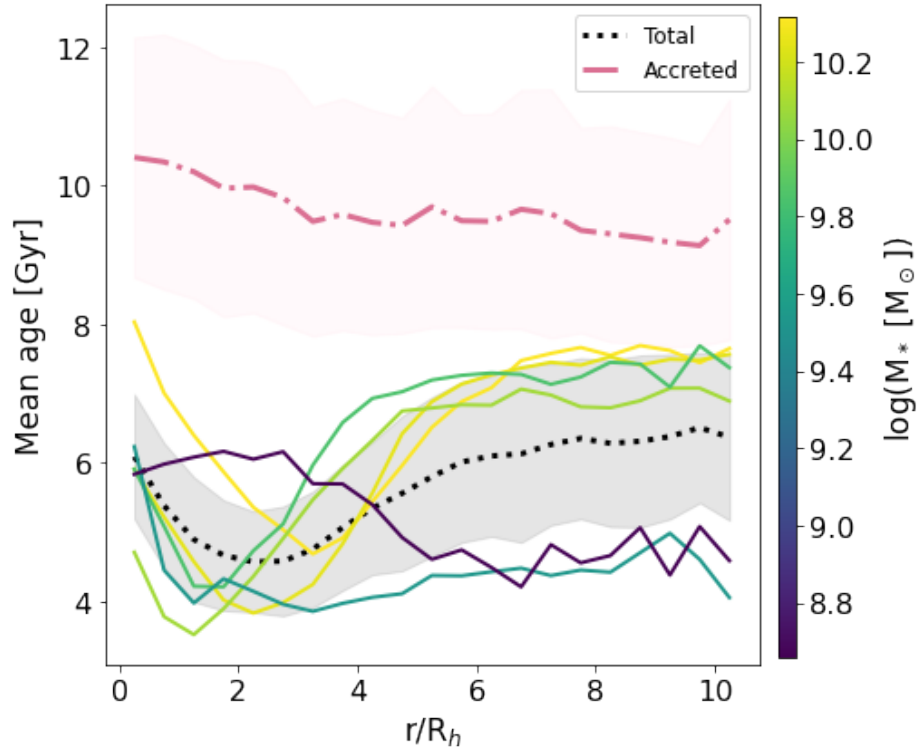


Figure 4.2.1: Total mean age profile (black dotted line) and accreted mean age profile (pink dash-dotted line) of all of the galaxies of our sample. Individual age profiles for 6 galaxies of our sample are also shown, normalised by their respective R_h and colour-coded by the galaxies’ stellar masses. The x-axis shows distances along the semi-major axis. We note a prominent U-shape in the total mean of the age profile of our galaxies, driven by the in situ stellar population.

total age profiles for 6 galaxies of our sample (the same ones shown in Fig. 4.1.1), colour-coded by their stellar masses. Analysing these individual profiles, we find no correlation between the ages found at different radii and the stellar mass of the galaxies. Nonetheless, the innermost regions of the lower-mass objects in our sample tend to be younger than their more massive counterparts. This can be seen in Fig. 4.2.2, where we show the overall individual radial age profiles for all the galaxies in our sample, as well as their in-situ (blue solid line) and accreted (orange solid line) radial age profiles separately.

Interestingly, we find a prominent U-shape in the mean of the total radial age profile of all galaxies (Fig. 4.2.1). This reflects the behaviour of the individual radial age profiles, where 12 of the 17 galaxies in our sample present prominent U-shaped profiles. An inspection of the individual age profiles reveals a general trend: U-shaped profiles tend to appear in the more massive dwarf galaxies, while the less massive ones generally do not exhibit this feature (see Fig. 4.2.2). The age profiles for the in situ and accreted stellar particles, computed separately, show that this U-shaped behaviour is associated with the in-situ component. This can also be inferred from the lack of this feature in the mean of the accreted age profiles shown in Fig. 4.2.1.

As seen in Chapter 3, the outskirts of these galaxies are mostly comprised by in-situ stellar material. Hence, this upturn in the radial age profiles naturally leads us to examine the ages of the stellar haloes

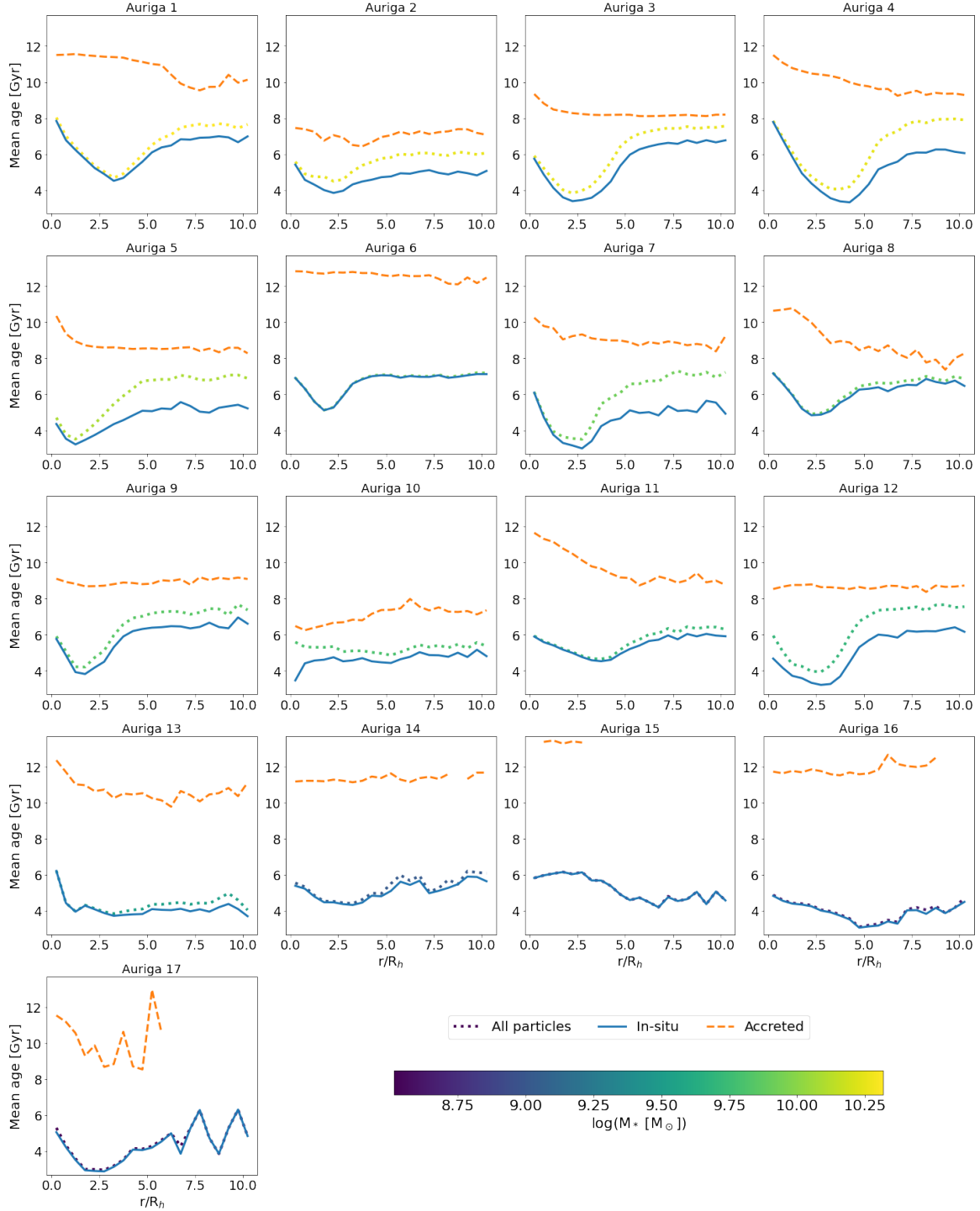


Figure 4.2.2: In situ (blue solid line), accreted (dashed orange line) and total (dotted line) mean age profiles of all galaxies in our sample. The total mean age profiles are coloured according to the galaxies' stellar mass. We note a prominent U-shape in the profile of 12 galaxies, driven by the in situ stellar material.

themselves.

4.2.2 Stellar haloes ages

Building on the results from the radial age profiles, we now turn our focus to the stellar haloes as distinct components of the galaxies. To obtain a more complete picture of these galaxies' evolution (particularly in their outer regions) it is also important to explore how the age of the stellar halo relates to its metallicity and its stellar mass. We note in Fig. 4.2.1 that the mean of the total age profiles tends to increase from $\sim 4R_h$, indicating that the stellar halo is comprised by old stellar material. This can be quantified by computing the mean stellar age of the stellar halo. We obtained this value for the total stellar halo (in situ + accreted stellar material) and for the accreted stellar halo, which are shown in Fig. 4.2.3 as a function of the total stellar halo mass (left panel) and the accreted stellar halo mass (right panel), respectively. Both panels are colour-coded by the galaxies' total stellar mass. We note that the mean ages spanned by the total stellar halo, ranging from ~ 4 to ~ 8 Gyr, are narrower than those spanned by the accreted stellar haloes, which range from ~ 6 to ~ 13 Gyr. Additionally, we find a clear correlation in both cases, although inverted: on one hand, when considering the total stellar halo, we see that more massive stellar haloes are older than less massive ones; on the other hand, when considering only the accreted component of the stellar halo, we see that more massive accreted stellar haloes are younger than less massive ones.

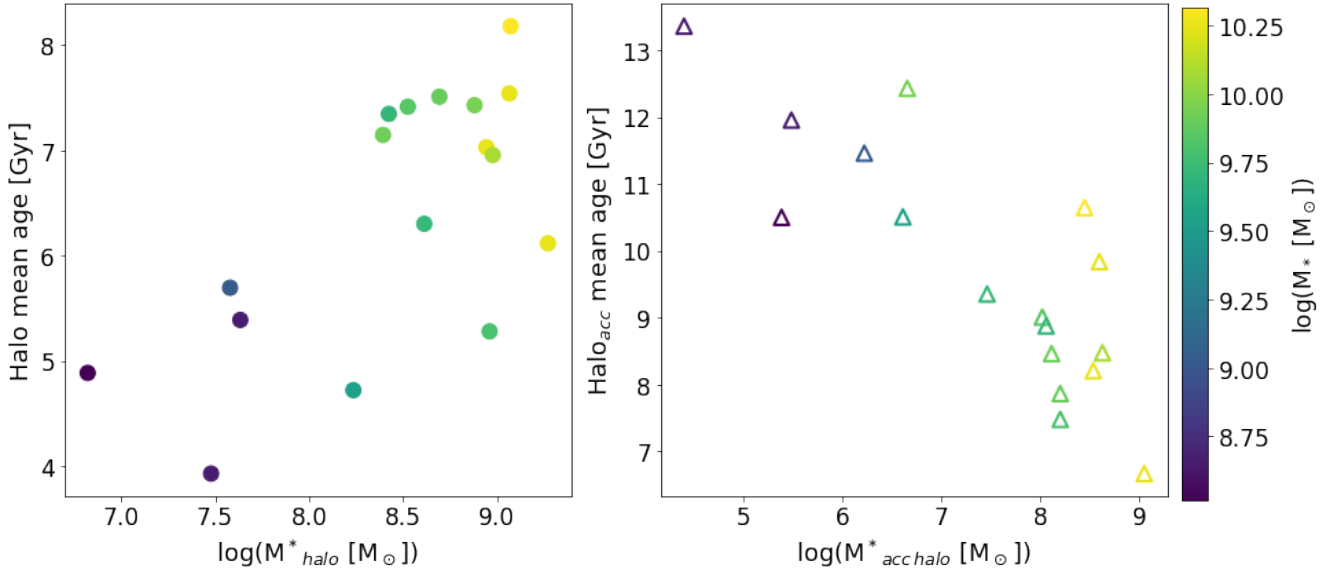


Figure 4.2.3: Left panel: Mean age of the total stellar halo (in situ + accreted) as a function of the total stellar halo mass. Right panel: Mean age of the accreted stellar halo as a function of its mass. Both panels are colour-coded by the total stellar mass of the galaxies. We note a correlation in both panels, although they are inverted: more massive stellar haloes are older than less massive ones, while more massive accreted stellar haloes are younger than the less massive ones.

The correlation seen in the left panel of Fig. 4.2.3 between the age and mass of the total stellar halo suggests that less massive galaxies keep on forming stellar material until later times, which can then end up comprising their stellar haloes. Regarding the correlation in the right panel of Fig. 4.2.3, we can infer

that the less massive galaxies accreted their bulk of stellar material earlier than the more massive ones, leaving them with an older accreted component in their stellar haloes. This is a clear consequence of the results presented in Chapter 3, where it was found that more massive galaxies keep on accreting stellar material until later times, which allows the accreted satellite galaxies to keep on forming stellar material prior to accretion for longer periods so as to then provide the host galaxies with younger stars that end up comprising their accreted stellar halo.

This difference in the accretion time of the satellites also allows them to keep on enriching their stellar populations, which has an impact on their metallicity and the resulting metallicity of the stellar haloes, as seen in the right panel of Fig. 4.1.5. Thus, this could hint at a possible correlation between the age and the metallicity of the stellar haloes. We explore this in the following section.

4.3 Age-metallicity relation of the stellar haloes

The chemical enrichment of stellar populations is closely linked to their age: younger stars tend to be more metal-rich because they form from interstellar material that has been progressively enriched by previous generations of stars (e.g. [Tinsley, 1980](#); [Matteucci, 2003](#)). Consequently, if more massive galaxies accrete satellites at later times, when these satellites are more chemically evolved, they may end up with younger, more metal-rich accreted stellar haloes (e.g. [Font et al., 2006](#); [Cooper et al., 2010](#)). This naturally suggests a possible correlation between the age and metallicity of stellar haloes, which has been studied in MW-mass galaxies (e.g. [Das et al., 2020](#); [Ortega-Martinez et al., 2022](#)).

The youngest total stellar halo of our sample is that of Auriga 16, with a mean age of 3.93 Gyr, while the oldest one is that of Auriga 1, with a mean age of 8.18 Gyr. The mean ages for the total stellar haloes of all galaxies are listed between parenthesis in the fourth column of Table 4.3.1. We find that these structures are, on average, older than the main body of the galaxy (i.e. within $4R_h$), with ages ranging from 4.11 Gyr to 6.77 Gyr (see Table 4.3.1). When analysing the median $[\text{Fe}/\text{H}]$ of the galaxy’s main body and that of the total stellar haloes, we find that the main body is more metal-rich than the total stellar haloes, with median $[\text{Fe}/\text{H}]$ values ranging from -0.70 to 0.00 (see Table 4.3.1). In Fig. 4.3.1, we show the median $[\text{Fe}/\text{H}]$ of the total stellar halo as a function of its mean age (left panel) and the median $[\text{Fe}/\text{H}]$ of the accreted stellar halo as a function of its mean age (right panel). Both panels are colour-coded by the galaxies’ total accreted stellar mass. We note a clear correlation when it comes to the accreted stellar haloes: those that are more metal-rich are also younger, whereas the accreted stellar haloes that are more metal-poor are older. This correlation is not present when considering all of the stellar haloes’ stellar material (i.e. the in situ and accreted components together). This is likely due to the fact that in-situ stars dominate the stellar haloes of dwarf galaxies in terms of mass (as seen in Chapter 3), and their metallicities are primarily governed by the galaxy’s internal chemical enrichment history. As a result, the in situ contribution erases the clear age–metallicity trend observed when considering the accreted halo alone, where the age of the accreted stellar component is affected by the time the satellites stop evolving and are disrupted.

Table 4.3.1: Ages and metallicities of the galaxies of our sample and of their stellar haloes. The galaxies are listed in order of decreasing stellar mass. The columns indicate: (1): label used in this work (original Auriga run number), (2): stellar mass, (3): half-light radius, (4): mean age within $4R_h$ (total stellar halo), (5): median [Fe/H] within $4R_h$ (total stellar halo).

Auriga	Stellar mass [$M_\odot$]	R_h [kpc]	Mean age [Gyr]	Median [Fe/H] dex
1 (L5)	2.08×10^{10}	7.736	6.77 (8.18)	-0.13 (-0.65)
2 (L1)	1.81×10^{10}	5.394	5.07 (6.12)	-0.13 (-0.46)
3 (L4)	1.80×10^{10}	6.793	4.88 (7.03)	-0.22 (-0.73)
4 (L3)	1.78×10^{10}	5.554	6.61 (7.54)	-0.08 (-0.54)
5 (L7)	1.23×10^{10}	5.032	4.11 (6.96)	-0.19 (-0.65)
6 (L0)	8.83×10^9	1.180	6.36 (7.43)	0.00 (-0.52)
7 (L2)	8.29×10^9	7.050	5.03 (7.15)	-0.27 (-0.82)
8 (L6)	7.89×10^9	4.802	6.39 (7.51)	-0.14 (-0.57)
9 (L11)	7.02×10^9	4.544	5.15 (7.41)	-0.21 (-0.66)
10 (L9)	6.30×10^9	3.938	5.41 (5.28)	-0.21 (-0.50)
11 (L10)	5.34×10^9	3.314	5.47 (6.30)	-0.23 (-0.57)
12 (L8)	5.09×10^9	5.540	4.92 (7.35)	-0.37 (-0.86)
13 (LL2)	3.46×10^9	3.063	4.93 (4.72)	-0.22 (-0.46)
14 (LL9)	1.06×10^9	3.500	4.98 (5.70)	-0.52 (-0.78)
15 (LL8)	4.54×10^8	1.034	5.95 (5.39)	-0.37 (-0.61)
16 (LL6)	4.53×10^8	1.923	4.55 (3.93)	-0.57 (-0.75)
17 (LL11)	3.28×10^8	3.161	4.27 (4.87)	-0.70 (-0.97)

4.4 Mechanisms affecting the age and metallicity

In this section, we explore the mechanisms that affect the redistribution of these dwarf galaxies' stellar material throughout all radii. We address internal processes of the galaxies, such as their star formation rate and stellar migration, and external processes such as merger events.

4.4.1 Star formation rate and physical internal processes

Internal processes that are intrinsic to galaxies influence the distribution of their stellar material over time. Such redistribution has a direct impact in the radial [Fe/H] and age profiles we presented in Sects. 4.1.1 and 4.2.1, respectively. The specific star formation rate (sSFR), defined as $\text{sSFR} = \frac{\text{SFR}}{M_*}$, is a key diagnostic of how efficiently galaxies are forming stars relative to their stellar mass, and its evolution provides valuable insight into their growth and star formation histories. Variations in the sSFR, both globally and radially, can directly influence the age and metallicity distributions of galaxies. Therefore,

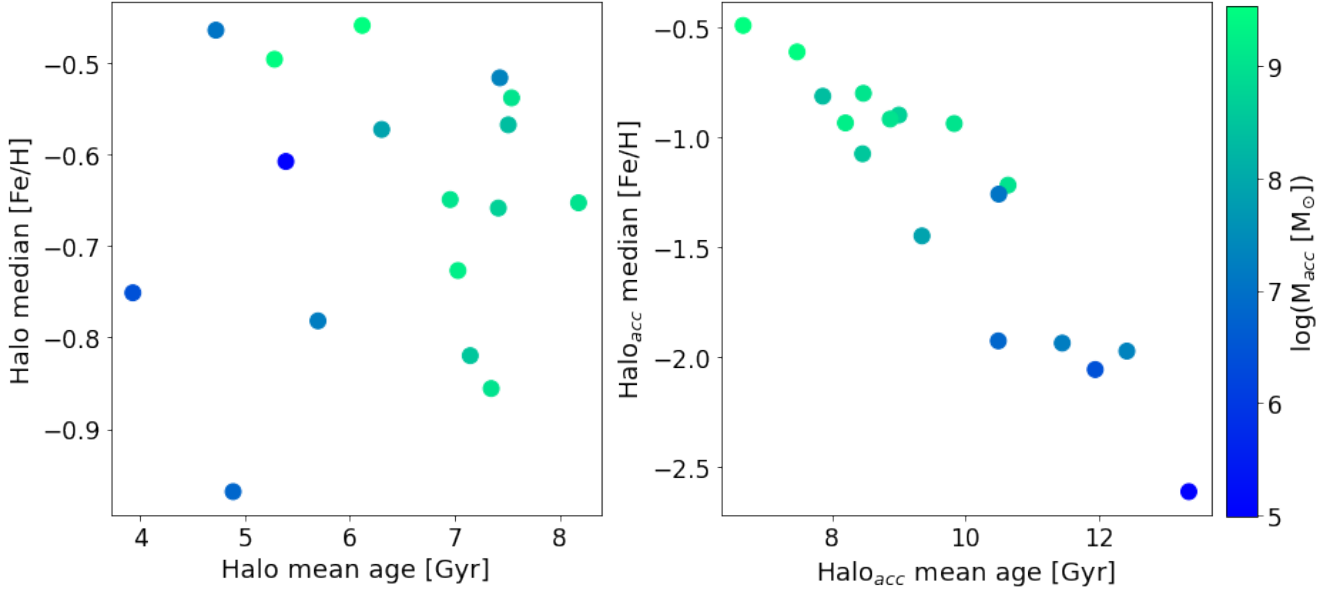


Figure 4.3.1: Age-metallicity relation of the galaxies in our sample, colour-coded by their accreted stellar mass. Left panel: Median $[\text{Fe}/\text{H}]$ of the total stellar halo (in situ + accreted) as a function of its mean age. Right panel: Median $[\text{Fe}/\text{H}]$ of the accreted stellar halo as a function of its mean age. We note a strong correlation between the median $[\text{Fe}/\text{H}]$ and the mean age of the accreted stellar halo, such that the more metal rich accreted stellar haloes are also the younger ones.

studying the sSFR allows us to connect present-day radial profiles with the past star formation activity of galaxies. With this in mind, we investigate the sSFR of our sample to determine whether systematic differences exist between galaxies with and without U-shaped radial age profiles, and how could this affect the metallicity distribution.

One possible explanation for the U-shape behaviour of the age profiles shown in Fig. 4.2.1 is that the star formation of the galaxies presenting this feature is substantially different from that of the galaxies without it. Analysing the overall sSFR of these galaxies, which are shown in Fig. 4.4.1, we find no significant differences between those with a U-shape in their radial age profile and those without it, although galaxies without this feature show a continuous sSFR through the years that increases monotonically until $z = 0$ while galaxies with a U-shaped age profile present more bursty sSFR. We now explore the present-day star formation rate (SFR) radial profiles. To compute these profiles, we considered the in situ stellar particles of young stellar material (≤ 2 Gyr) divided by the total mass enclosed at a given radius. This provides a proxy of the recent SFR. To explore this, we select a subsample of 6 galaxies: the Auriga 1, 3, 5 and 9, all with U-shaped profiles. Conversely, we select Auriga 13 and 15 as cases without U-shaped age profiles. These 6 galaxies are the same ones for which individual profiles are shown in Figs. 4.1.1 and 4.2.1. The black dotted line in of Fig. 4.4.2 represents the mean of all of the $\text{SFR}/M_*(r)$ profiles of our sample, and the coloured solid lines represent the individual profiles of our subsample of 6 galaxies.

We can clearly see that the peak of the mean of all of the $\text{SFR}/M_*(r)$ profiles occurs at the same radial distance at which the minimum of the mean of the age profiles is found, which is shown by the vertical black dotted line. We also show that the same happens for the 4 individual galaxies we present in that

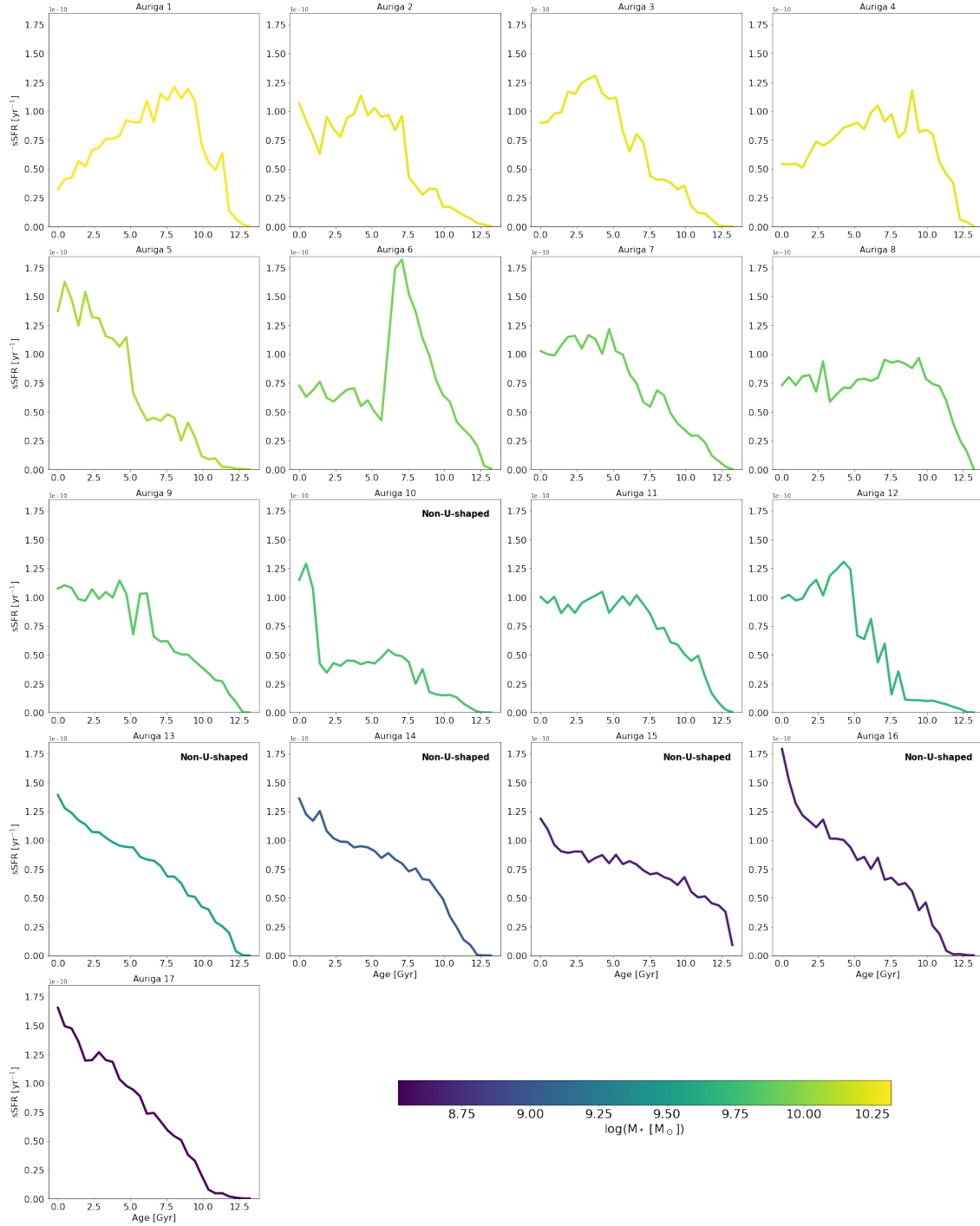


Figure 4.4.1: Overall sSFR of the galaxies analysed in this thesis, colour-coded by the galaxies' stellar mass.

figure as examples of galaxies with U-shaped age profiles, for which radii at which their age profiles reach the youngest age is also shown with vertical dashed lines. Thus, we find that the radial age profiles show an upturn beyond the radii at which these galaxies have a sharp drop in their recent star formation.

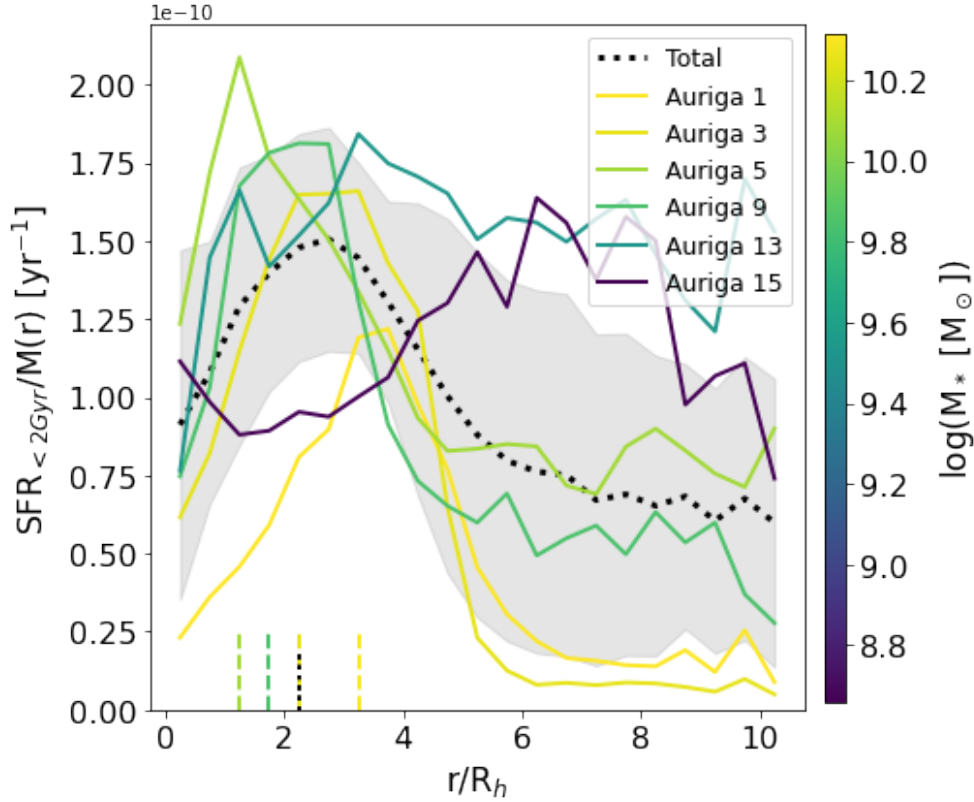


Figure 4.4.2: Mean of the $\text{SFR}/M_*(r)$ profile (black dotted line) of all the galaxies in our sample. The individual $\text{SFR}/M_*(r)$ profiles the subsample of 6 galaxies are also shown, colour-coded by their stellar mass. The x-axis shows distances along the semi-major axis. The vertical dashed lines represent the radius at which the minimum age of the U-shaped age profiles in Fig. 4.2.1 is located. We note that the radius at which the peak of the $\text{SFR}/M_*(r)$ profile occurs matches the radial location of the minimum age of the U-shaped age profiles.

This agrees with previous findings in MW-mass galaxies, such as the work of [Varela-Lavin et al. \(2022\)](#) who used a sample of simulated late-type galaxies from the EAGLE simulations and found U-shaped age profiles to be the most common. They show that the radius at which the minimum of the U-shape occurs matches the drop of young stellar populations. [Debattista et al. \(2017\)](#) and [Sánchez-Blázquez et al. \(2009\)](#) also explained this behaviour in the age profiles of simulated MW-mass galaxies in the same way (see Sect. 4.5.2 for further discussion). As we also show in Fig. 4.4.2, this behaviour is not present in the $\text{SFR}/M_*(r)$ profiles of those galaxies without a U-shaped age profile. In those cases, there is recent star formation ongoing at large distances.

However, it remains to be explained why the age of the galaxies of our sample with U-shape profiles rise at large radii, rather than simply flattening.

A possible mechanism that plays an important role in the redistribution of stellar material, and thus could be behind these U-shaped age profiles, is known as radial migration. This process allows stars to move through the disc plane to different galactocentric radii without significantly increasing their orbital eccentricities. One of the key drivers of radial migration is the interaction of stars with transient spiral



Figure 4.4.3: Fourier modes ($m = 1$ to $m = 4$) of all galaxies of our sample at $z = 0$, computed in the innermost regions (between 0.5 and $2R_h$). We note that the $m = 2$ mode is typically small, indicating there is no presence of spiral arms. The only two cases in which the value of $m = 2$ is large are Auriga 15 and 16. However, this is due to the elongated morphology of these galaxies, rather than the presence of such features.

arms. In this scenario, stars can exchange angular momentum with the spiral pattern, leading them to migrate inward or outward while remaining on nearly circular orbits (Sellwood & Binney, 2002; Roškar et al., 2008b,a). To explore if this mechanism is playing a role in our galaxy sample, we computed the $m = 2$ Fourier mode, which corresponds to a two-armed spiral structure (Grand et al., 2016). These analyses revealed that our galaxies have typically small amplitude of the A2 mode ($\lesssim 0.1$ at $z = 0$), which is shown in Fig. 4.4.3 for all galaxies. Additionally, we show the evolution through time of the A2 mode in Fig. 4.4.4. We note that it has been generally very low within the last ~ 8 Gyr. This implies that spiral arms were not an important driver of stellar population radial mixing in the past either. We thus rule out the influence of spiral arms and radial migration in the rising of the U-shape of the galaxies' radial age profiles.

4.4.2 The impact of merger events in the radial age profiles

An important external mechanism by which stars can be redistributed over time consists of interactions and mergers with satellite galaxies. If the galaxies with U-shaped age profiles underwent merger events at earlier times, these events could have redistributed the older stellar material, making it reach the outskirts of the galaxies. Thus, we analysed the merger events undergone by each galaxy involving satellite galaxies that reached a maximum mass ($M_{peak\,sat}$) of at least $\frac{1}{10} M_{200}$, where the M_{200} of the main galaxy represents the total mass enclosed in a sphere with a mean density of 200 times the critical density of the Universe. In this analysis, we consider the M_{200} at the time at which the satellite galaxy crossed the galaxy's R_{200} for the first time. In Fig. 4.4.5 we show the time evolution of the sSFR of the in situ stellar populations, at different radial ranges, for the subsample of 6 galaxies that we chose as examples. This same plot is shown for all galaxies in Fig. 4.4.6. The colour-coded vertical dashed lines represent the mean age of the stellar particles within radial bins up to $6R_h$. On each panel of Figs. 4.4.5 and 4.4.6, we highlight the significant merger experienced by each galaxy with colour-coded arrows, based on the ratio $M_{peak\,sat}/M_{200}$. Most galaxies (all but Auriga 15) have suffered important merger events, i.e. with merger ratios between 0.1 and ~ 1 . We find that galaxies with U-shaped age profiles undergo merger events both at early and late times. However, most galaxies which do not show U-shaped age profiles, also accrete satellites as massive as some of the satellites accreted by the other galaxies with this feature in their profiles, besides undergoing merger events at similar times (see, for instance, Auriga 13 in Fig. 4.4.5). Hence, merger events alone are not enough to explain this behaviour in the age profiles, but instead this information must be combined with that of the sSFR of the galaxies.

When a galaxy has already formed a considerable amount of stellar material at early times, this old in situ population can be redistributed outward during early mergers. The subsequent inside-out star formation gives rise to the U-shape found at $z = 0$ in its radial age profile, where the inner regions present a negative age gradient until it reaches the location where there is no more recent star formation (see Fig. 4.4.2), and thus the old stellar material that was ejected prevails. From that radius onward, the radial age profile presents an upturn that reflects the older ages found at those large radii. The galaxies with a U-shaped age profile, exemplified in Fig. 4.4.5 with Auriga 1, 3, 5 and 9, had formed sufficient stellar material at early epochs (or by the merger time of the accreted satellites) in order to be redistributed during interactions with satellite galaxies. Additionally, the accreted stellar material that merger events bring is typically old (see Fig. 4.2.1 and Fig. 4.2.2). When this material is deposited in the outer regions of the galaxy, it contributes to increasing the average stellar age at large galactocentric distances. This

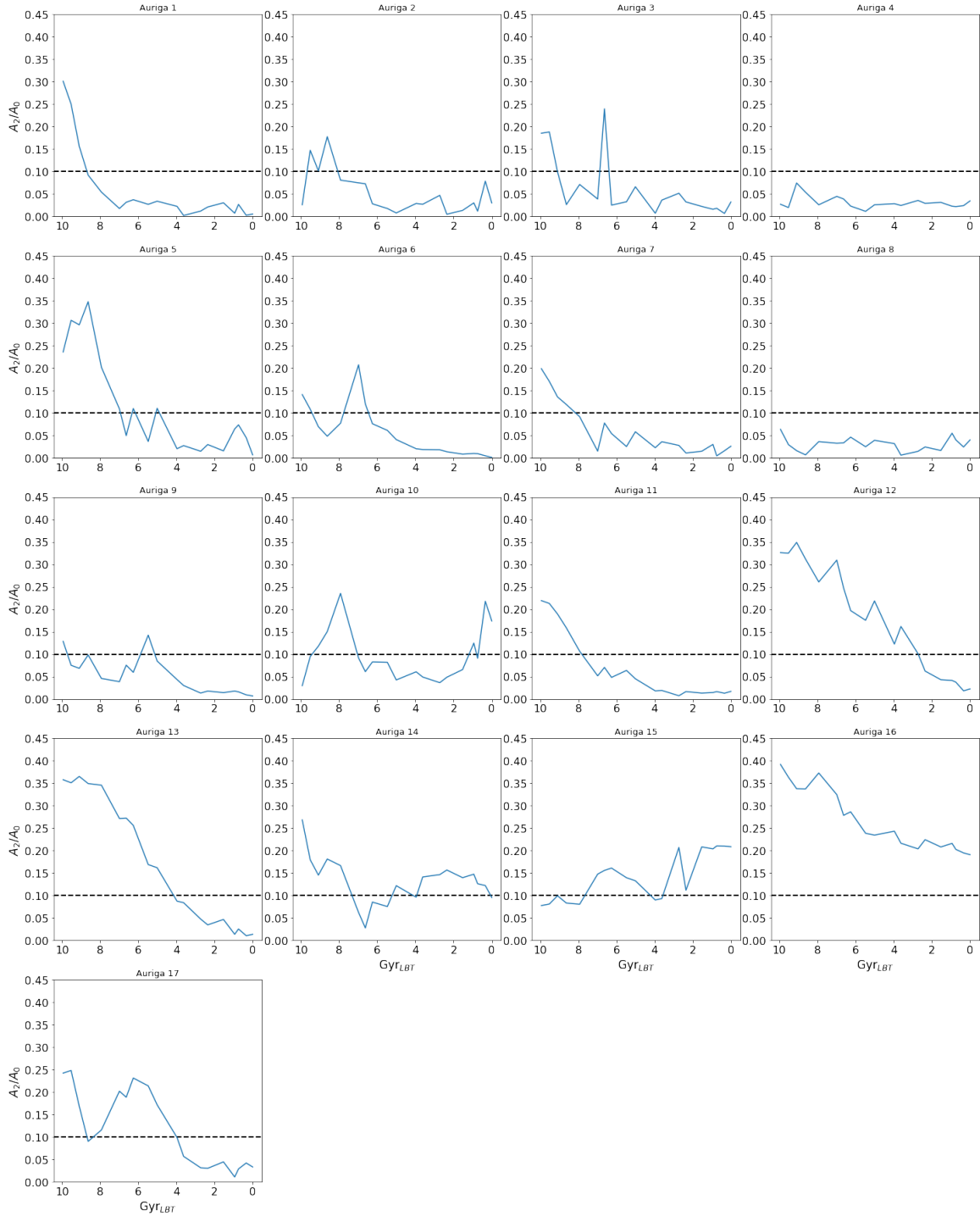


Figure 4.4.4: Evolution of the amplitude of the A2 Fourier mode through time. We see that the values are generally low through time, indicating there is no presence of spiral arms.

additional population of old accreted stars can therefore enhance the upward trend observed in the outer parts of the age profiles, reinforcing the U-shaped behaviour.

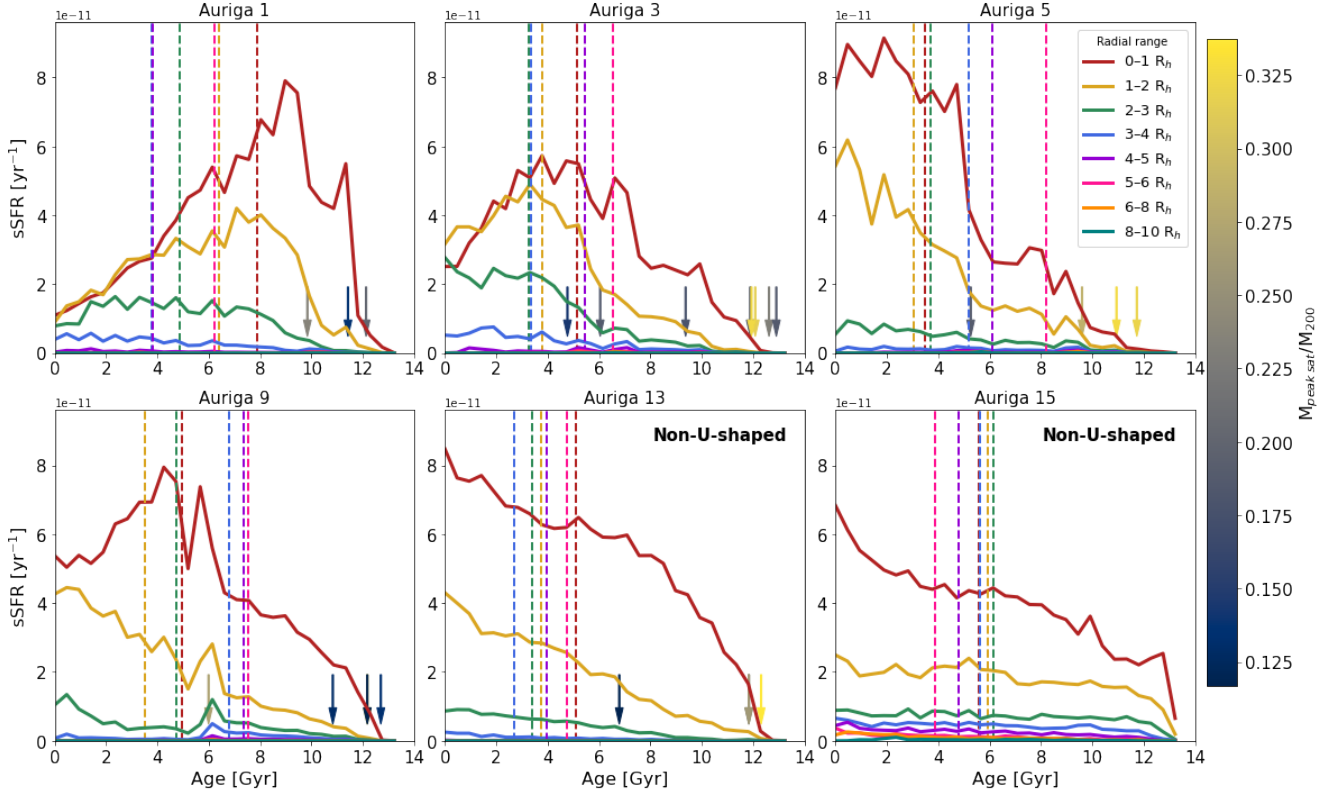


Figure 4.4.5: sSFR of the in situ stellar populations at different radial ranges, as a function of the age of the particles. The arrows represent the merger events that satisfy that the total peak mass of the satellite galaxy was at least $\frac{1}{10}M_{200}$, considering the M_{200} of the host galaxy at the time at which the satellite crossed its R_{200} for the first time. They are colour-coded by the ratio between the $M_{peak,sat}$ and the M_{200} . The vertical dashed lines represent the mean age at the different radii (from $0-1R_h$ to $5-6R_h$), and their colours match those of their corresponding sSFR.

In the case of the galaxies without a U-shaped age profile, we note a clear difference in these galaxies sSFR with respect to those that have this feature. For instance, Auriga 13 and Auriga 15 in Fig. 4.4.5 show a continuous sSFR through the years that increases monotonically until $z = 0$ (i.e., ages ~ 0 Gyr). This means that these galaxies are continuously forming stellar material. Moreover, in some cases these galaxies also sustain star formation at larger radii than those with U-shaped profiles, as seen for example in Auriga 15. The presence of ongoing star formation across all radii, combined with their steadily increasing sSFR, results in either flat or decreasing radial age profiles due to the presence of young stellar populations throughout the galaxy. We also note that Auriga 15 does not suffer any merger as massive as those galaxies with a U-shaped radial age profile that can significantly impact its distribution of stellar material.

We therefore conclude that the cessation of star formation beyond certain radius and the interactions with satellite galaxies are the most dominant mechanisms responsible for the U-shape in the central parts of the radial age profiles, while radial stellar migration has no impact on the matter. The merger events redistribute stars outward, reversing the negative age gradient within the inner disc and contributing to a positive gradient in its outer regions. This trend continues throughout the outskirts of the galaxies

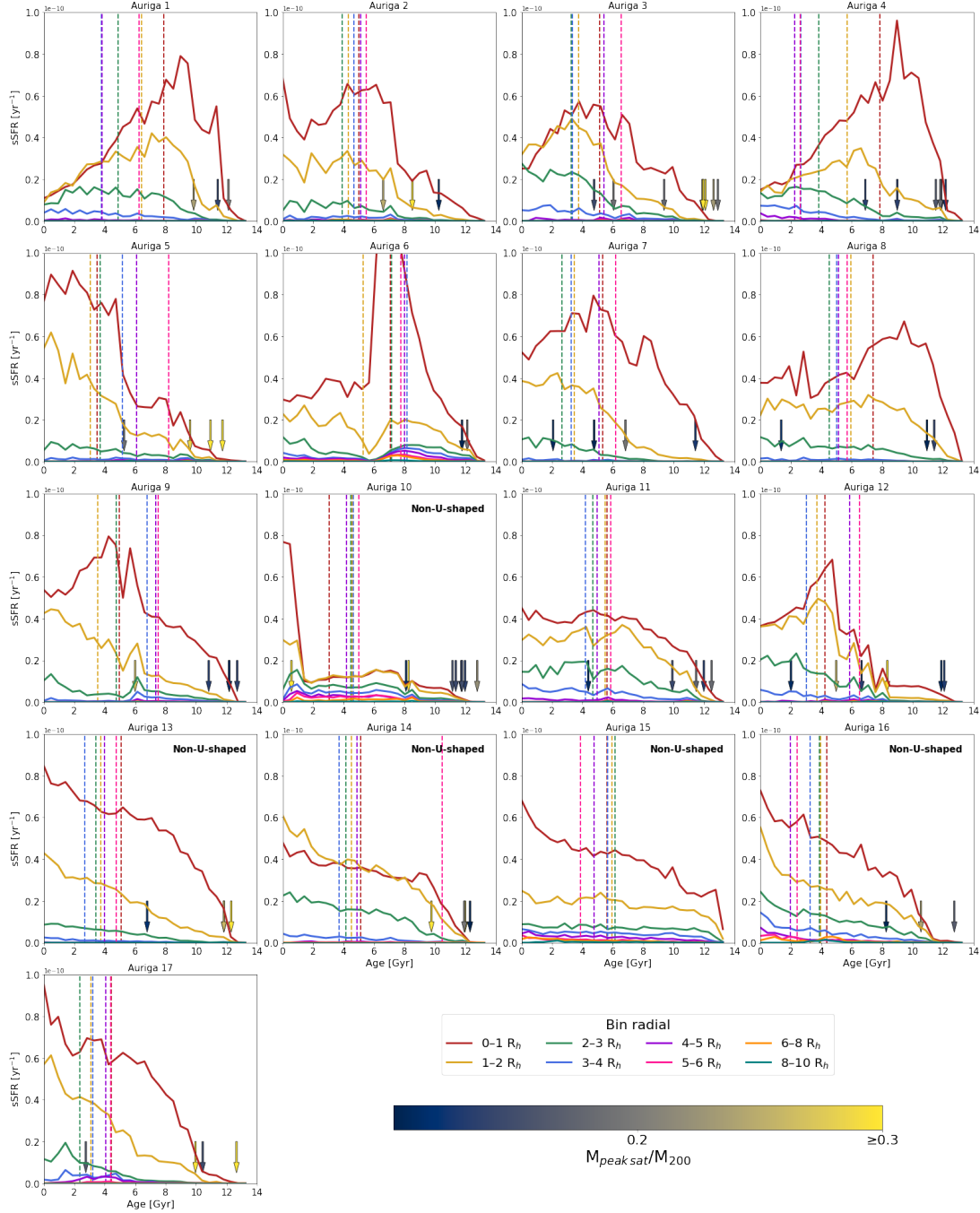


Figure 4.4.6: sSFR of the in situ stellar populations at different radial ranges for all the galaxies of our sample, as a function of the age of the particles. The arrows represent the merger events that satisfy that the total peak mass of the satellite galaxy was at least $\frac{1}{10} M_{200}$, considering the M_{200} of the host galaxy at the time at which the satellite crossed its R_{200} for the first time. They are colour-coded by the ratio between the $M_{peak\ sat}$ and the M_{200} . The vertical dashed lines represent the mean age at the different innermost radii (from $0 - 1 R_h$ to $5 - 6 R_h$), and their colours match those of their corresponding sSFR.

(i.e. beyond $4R_h$), where they are dominated by old stellar populations that also include accreted stellar material, thereby preserving the overall age increase at large radii.

Regarding the effect on the galaxies' metallicity, this redistribution of stellar material also has an impact in their radial $[\text{Fe}/\text{H}]$ profiles given that the outskirts become dominated by older, more metal-poor stellar populations compared to the younger, more enriched centres, and generates the negative metallicity gradients shown in Sect. 4.1. Moreover, as in situ populations of different ages are redistributed to large radii, the resulting mixture of stellar ages enhances the flattening of the metallicity profiles in the outer regions of the galaxies that is already influenced by the different metallicities of the accreted satellites that deposited their material in the outskirts.

4.5 Discussion and observational context

In this section, we place our results in an observational context, and we also compare them to those found in the MW-mass regime.

4.5.1 Metallicity of low-mass galaxies

A wide variety of observed metallicity gradients have been reported when considering the low-mass regime of galaxies (e.g. [Leaman et al., 2013](#); [Taibi et al., 2018](#); [Fu et al., 2024b](#); [Cano-Díaz et al., 2025](#); [Sato et al., 2025](#)), even including galaxies with no metallicity gradients at all (e.g. [Aparicio et al., 2001](#); [Taibi et al., 2024](#)). The metallicity gradients for low-mass galaxies obtained in this work fall well within the observed values for isolated dwarfs (e.g. [Taibi et al., 2020, 2022](#); [Fu et al., 2024a](#)). We do not find any significant correlation between the metallicity gradients of the galaxies in our sample and either their total stellar mass or their accreted stellar mass (see Fig. 4.1.3). This is in agreement with the findings of [Taibi et al. \(2022\)](#), where no correlation is found between the metallicity gradient and the stellar mass of the isolated dwarf galaxies of their sample. This implies that the link between the evolution of the galaxies and their resulting metallicity gradients may not be so straightforward to measure in the low-mass regime. Similarly, when considering only the metallicity gradients of the stellar haloes' both total and accreted components, we also find no clear correlation with their respective stellar halo masses.

As previously shown in Chapter 3, our results demonstrate a clear correlation between the mass and the metallicity of the accreted stellar haloes in low-mass galaxies, in which more massive accreted stellar haloes are also more metal rich (Fig. 4.1.5). This extends the stellar halo mass–metallicity relation found for MW-mass galaxies ([Harmsen et al., 2017](#); [Monachesi et al., 2019](#)) to the low-mass regime. In this work, we analysed the spread in metallicity that accreted stellar haloes with a similar mass have, and we found that it can be attributed to the infall time of the most dominant satellite they accreted. This is due to the fact that a later infall time at similar satellite mass implies that the satellites had more time to enrich their stellar content before disruption. Therefore, the accreted component of the stellar haloes with a later infall time of their dominant satellites will be more metal-rich than those with the same amount of accreted stellar mass that accreted theirs earlier. This interpretation aligns with observational results that point to late massive accretion events being responsible for the relatively metal-rich haloes of MW-mass galaxies like M31 (e.g., [Gilbert et al., 2014](#); [D'Souza & Bell, 2018b](#)). Our results therefore suggest that similar mechanisms operate at lower masses, and highlight that the metallicities of the accreted haloes of dwarf galaxies do retain information of the timing of their most significant accretion events.

4.5.2 U-shaped age profiles in dwarf galaxies

We have found that the majority of the low-mass galaxies of our sample present a U-shaped age profile (Fig. 4.2.1), suggesting intricate star formation and evolution. In MW-mass galaxies it is not common to observe this behaviour in their age profiles. They usually present a negative gradient indicating an inside-out star formation (e.g. [Sánchez-Blázquez et al., 2014](#); [González Delgado et al., 2015](#)), although a U-shape has been observed in a few cases (e.g. [Yoachim et al., 2012](#)). Some theoretical studies have predicted that this U-shape behaviour is possible in such systems. For example, [Roškar et al. \(2008a\)](#) simulate a disc galaxy where the initial system consists of a virialised spherical Navarro-Frenk-White DM halo ([Navarro et al., 1997](#)) and has a mass within the virial radius of $10^{12} M_{\odot}$. The simulated galaxy does not present a bar nor strong spiral arms at $z = 0$. Their model predicts an abrupt change in the radial mean stellar age profile, showing a clear U-shape, and the authors attribute this behaviour to the effect the transient spiral arms have on radial migration, i.e. reshuffling the stellar material. Moreover, [Sánchez-Blázquez et al. \(2009\)](#) use N-body simulations to analyse a disc galaxy of dynamical mass $7.6 \times 10^{11} M_{\odot}$ and find that its age profile also has a U-shape. The authors argue that, apart from radial migration, this U-shape is a direct consequence of a break in the star formation density: beyond the break radius, a sudden decline in star formation leads to older average stellar ages in the outskirts of the disc, preventing the age gradient to decrease or remain constant. They also claim that accretion events have little impact on this gradient. Additionally, [Varela-Lavin et al. \(2022\)](#) studied 1012 disc galaxies from the EAGLE simulations with stellar masses ranging from 10^{10} to $10^{11.5} M_{\odot}$ and found that U-shaped age profiles are frequent in their sample.

In the case of low-mass galaxies, this U-shape trend seems to have been observationally found more often in their age profiles. For example, [Williams et al. \(2009\)](#) used data from the Hubble Space Telescope (HST)/Advanced Camera for Surveys (ACS) to study the age distribution of the stellar populations of the disc of M33 as a function of galactocentric radius. They found an inversion in the radial dependence of stellar age: in the inner disc, the age of the stars decreases with increasing distance from the centre, contrasting with the outer disc where older stars are found. Furthermore, [Pessa et al. \(2023\)](#) observed a U-shaped radial age profile in two of the 19 star-forming galaxies analysed in their work, NGC 1087 and NGC 1385, which are also within the stellar mass range analysed in our work ($\log(M_*/M_{\odot}) = 9.9$ and $\log(M_*/M_{\odot}) = 10$, respectively). More recently, a U-shaped age profile has also been reported in the Large Magellanic Cloud (LMC). [Cohen et al. \(2024a\)](#) argued that the inversion they found in its radial age profile cannot be explained solely by the interaction between the LMC and the Small Magellanic Cloud (SMC) due to the fact that the radial location of this inversion remains constant over a wide range of look-back times, suggesting that the mechanisms influencing star formation in the LMC potentially predate recent interactions with the SMC.

The results obtained in this work regarding the radial mean age profiles of low-mass galaxies can help shed light on these aforementioned observations of such systems. First of all, according to the predictions made by our simulations, it is likely that the U-shaped age profiles observed in the central parts of M33, NGC 1087, NGC 1385 and the LMC is caused by in-situ material redistributed to the outer regions. However, regarding M33, our results do not seem to agree with those of [Mostoghiu et al. \(2018\)](#), where the authors analysed an analogue of M33 from the CLUES simulation and found that the main driver of the mean age profile's U-shape is the accreted component of said galaxy, brought in by minor mergers. While we show here that the accreted material is indeed old and contributes to the older ages in the outer regions, this accreted material is not responsible for the U-shape in the age profiles, which

is generated by in situ material (see Fig. 4.2.2). They also found that the stellar migration of old in situ stellar populations from the central regions towards the outskirts of M33 help shape the radial mean age profile, although to a much lesser extent compared to the contribution of the accreted stellar material.

Secondly, based on our results, we suggest that the U-shape in the radial age profiles of these observed galaxies arises from the absence of recent star formation beyond the radius where the stellar populations are youngest, together with the redistribution due to mergers and interactions of their old stellar populations in those cases in which these are significant given their SFH. In the case of the LMC, [Cohen et al. \(2024a\)](#) demonstrated that the inversion in the galaxy’s age profile approximately matches the drop-off in the HI column density, which agrees with the results of [Meschin et al. \(2014\)](#) that argue that the HI disc of the LMC able to form stars has indeed shrunk at these distances, thus likely limiting star formation in the outer regions. Similarly, recent work by [Corbelli et al. \(2025\)](#) on M33 shows that while the galaxy continues to form stars across its entire star-forming disc, the star formation rate declines significantly with radius, particularly beyond the inner disc, due to variations in gas density, stability, and disc dynamics. Together, these observational findings support the plausibility of our proposed explanation for the formation of U-shaped age profiles in low-mass galaxies. We bear in mind that our numerical predictions are based on isolated galaxies, but similar processes can also operate in satellite low-mass systems. On one hand, denser environments foster frequent interactions and tidal perturbations that can redistribute stellar material. On the other hand, the intrinsic evolution of each galaxy, governed by its star formation history, will happen in galaxies regardless of their environment. Thus, the mechanisms we propose remain relevant for shaping radial age profiles even in dense environments.

Another galaxy that could have a U-shaped age profile is NGC 7793, a relatively isolated low-mass ($M_* \approx 3.32 \times 10^9 M_\odot$, [Dale et al., 2009](#)) spiral galaxy. [Sacchi et al. \(2019\)](#) found an inside-out growth in the inner region of its disc. However, it is not possible to confirm from their data whether this inside-out trend persists across the entire disc, particularly in the outermost regions, where older stellar populations than those found closer to the centre were reported. This inner inside-out growth is also confirmed by [Kang et al. \(2023\)](#), and their reported age profile appears to exhibit either a flattening or a reversal at large radii along the disc. Unfortunately, their analysis, similarly to that of [Sacchi et al. \(2019\)](#), does not cover farther distances. Therefore, more observational data covering large distances from the centre of NGC 7793 could help determine whether this galaxy has a U-shaped radial age profile as well.

Our findings can also be compared with other numerical predictions. [Graus et al. \(2019\)](#) used the Feedback In Realistic Environments (FIRE) to study 26 dwarf galaxies with stellar masses ranging from $\sim 10^5 M_\odot$ to $\sim 10^9 M_\odot$, and found a prevalence of outside-in growth, with the galaxies showing younger stellar populations in their centres than in their outskirts. They attribute these positive age gradients to a combination of mergers and stellar heating, noting that while mergers alone are not particularly effective at shaping the gradients, they can still contribute to some redistribution of stars, which is a result consistent with our own findings. Regarding the redistribution of stars, they explain this with heating by stellar feedback, which strongly affects the galaxies in the FIRE simulations (e.g. [Oñorbe et al., 2015](#); [Fitts et al., 2017](#)). Stellar feedback generates potential fluctuations that dynamically heat stars and drive molecular outflows which subsequently form new (and thus younger) stars ([El-Badry et al., 2016](#)). These feedback episodes promote the outward migration of older stellar populations to larger radii, although the authors do not report the U-shaped feature found in this thesis. Thus, even though [Graus et al. \(2019\)](#) primarily attribute the reshuffling of old stellar material to stellar feedback-driven migration rather than the mechanisms we propose with the Auriga simulations, both works highlight the important role of

mergers in contributing to stellar redistribution.

4.5.3 Stellar haloes age and metallicity

While the correlation between age and metallicity in stellar haloes has been explored in detail for the MW (e.g. Jofré & Weiss, 2011; Schuster et al., 2012), it remains uninvestigated in the low-mass regime because these substructures have just recently started to be detected around low-mass systems. Observational work on dwarf galaxies has primarily focused on characterising metallicity gradients within their main bodies and overall chemical abundance patterns, as discussed in Sect. 4.5.1, often without simultaneously resolving detailed age distributions in their stellar haloes. This is due to the faintness of these structures that makes them difficult to observe at large distances.

Thus, our numerical analysis offers insights into the unexplored age–metallicity relationship in the stellar haloes of dwarf galaxies, revealing a clear correlation between these properties in their accreted component. Confirming such a trend observationally remains challenging at present, which underscores the predictive value of our results. These suggest that, once observations can robustly recover age distributions in dwarf galaxy stellar haloes, a trend should emerge in which more metal-rich accreted stellar haloes are systematically younger. In the meantime, our results provide a framework for inferring a likely age range for the stellar halo of low-mass galaxies based on its measured metallicity or mass, offering a practical tool to interpret existing observational data and to guide future targeted studies. However, observations provide data of the total stellar halo, and as seen in Chapter 3, the inner regions of these structures are dominated by in situ stellar material. Therefore, developing robust methods to disentangle the accreted and in situ components in observed stellar haloes is essential to fully exploit these predictions. One way of doing so could be with a cut in $[\text{Fe}/\text{H}]$ values, considering that those lower than -1 will correspond to the accreted component, given that the total stellar haloes median $[\text{Fe}/\text{H}]$ values range from ~ -1 to ~ -0.4 (see Fig. 4.1.5).

4.6 Summary

In this Chapter, we analysed the metallicity and age distributions of the Auriga low-mass galaxies, focusing on their radial profiles, stellar haloes, and the interplay between in-situ and accreted components. We showed that metallicity profiles systematically decline with radius, generating negative gradients within $4R_h$ that flatten in the outskirts, where stellar haloes are dominated by old populations and mixed accreted material.

We found no significant correlation between metallicity gradients and global galaxy properties such as stellar mass, accreted mass fraction, or number of progenitors. This contrasts with MW-mass systems, where accreted metallicity gradients correlate with merger histories. However, concerning the mass–metallicity relation of accreted stellar haloes according to which more massive accreted haloes are more metal rich, well established for MW-mass galaxies and also held in the low-mass regime (see Chapter 3), we identified a secondary dependence on the infall time of the most dominant progenitor: later-accreted satellites produce more enriched accreted stellar haloes.

Turning to ages, we showed that the mean of the total radial age profiles presents a prominent U-shape in most galaxies, driven by in situ material. This feature is more common in the more massive dwarfs in our sample. We demonstrated that the upturn in these profiles is linked to a sharp decline in recent

star formation at the radii where the U-shape minimum occurs. Internal processes such as bursty star formation, and external ones such as mergers, combine to redistribute stellar populations and enhance this feature.

Finally, we explored the ages of the stellar haloes and their relation to their metallicity. We found that the stellar haloes are systematically older than the main body of the galaxy, and that their mean ages correlate with the stellar halo mass in opposite ways depending on the component: more massive total stellar haloes are older, while more massive accreted haloes are younger, reflecting later accretion. Importantly, we discovered a clear age-metallicity relation in the accreted component of the stellar haloes: younger accreted stellar haloes are also more metal-rich, consistent with the later accretion of chemically enriched satellites. Overall, this Chapter demonstrates that the metallicity and age distributions of dwarf galaxy stellar haloes' encode information about their accretion timescales and star formation histories.

Chapter 5

Formation mechanism of the in-situ stellar haloes in low-mass galaxies¹

The inner regions of the stellar haloes of the low-mass galaxies studied in this work are composed mostly of in-situ stellar material, as seen in Sec. 3.2. It is therefore interesting to understand how this in-situ component of the stellar halo was formed. In this Chapter, we explore the formation mechanism by which this in-situ material reached the outskirts of the dwarf galaxies and ended up comprising their stellar halos.

5.1 In-situ component of the stellar halo

We first select the in-situ stellar particles that are part of the stellar haloes at $z = 0$, and compute their birth positions (R_{birth}). These positions correspond to the location the stellar particles had when they first appeared in the simulation. In Fig. 5.1.1 we show the density maps of their ages (which serves as a star formation history) as a function of their R_{birth} , normalised by each galaxy's R_h . The most dense regions are coloured in yellow while the least dense ones are in blue. There is a wide variety of stellar ages in all stellar haloes, ranging from ~ 12 Gyr to ~ 0.5 Gyr. We also plotted the age distribution of these particles on the right side of each panel. The arrows in these figures correspond to the time when a merger occurred that satisfied that the maximum total mass reached (M_{peak}) by the accreted satellite throughout its evolution was at least $\frac{1}{100}$ times the M_{200} of the main galaxy at $z = 0$. These arrows are colour-coded according to the M_{peak} of the satellite. The vertical dashed lines represent the $4R_h$ values at $z = 0$ and are only shown in the cases where the R_{birth} values reach or exceed that distance.

We find that stellar particles in the in-situ halo at $z = 0$ were formed in the inner regions of the galaxies and were then ejected to the stellar haloes for all cases but one (Auriga 6). Additionally, the most massive merger events shown in Fig. 5.1.1 triggered star formation in the main galaxies. We find that the birth of $\sim 8\%$ (Auriga 13) to $\sim 43\%$ (Auriga 4) of the in-situ stellar particles located in the stellar haloes at $z = 0$ can be associated with a merger event. If the satellite was gas-rich, these stellar particles formed during the interactions are born out of the gas provided by the satellite that mixes with the gas already present in the main galaxy. Then they are subsequently ejected to greater distances than their R_{birth} where

¹Based on Tau, Monachesi, Gómez, et al. 2025, A&A, Volume 699, id.A93

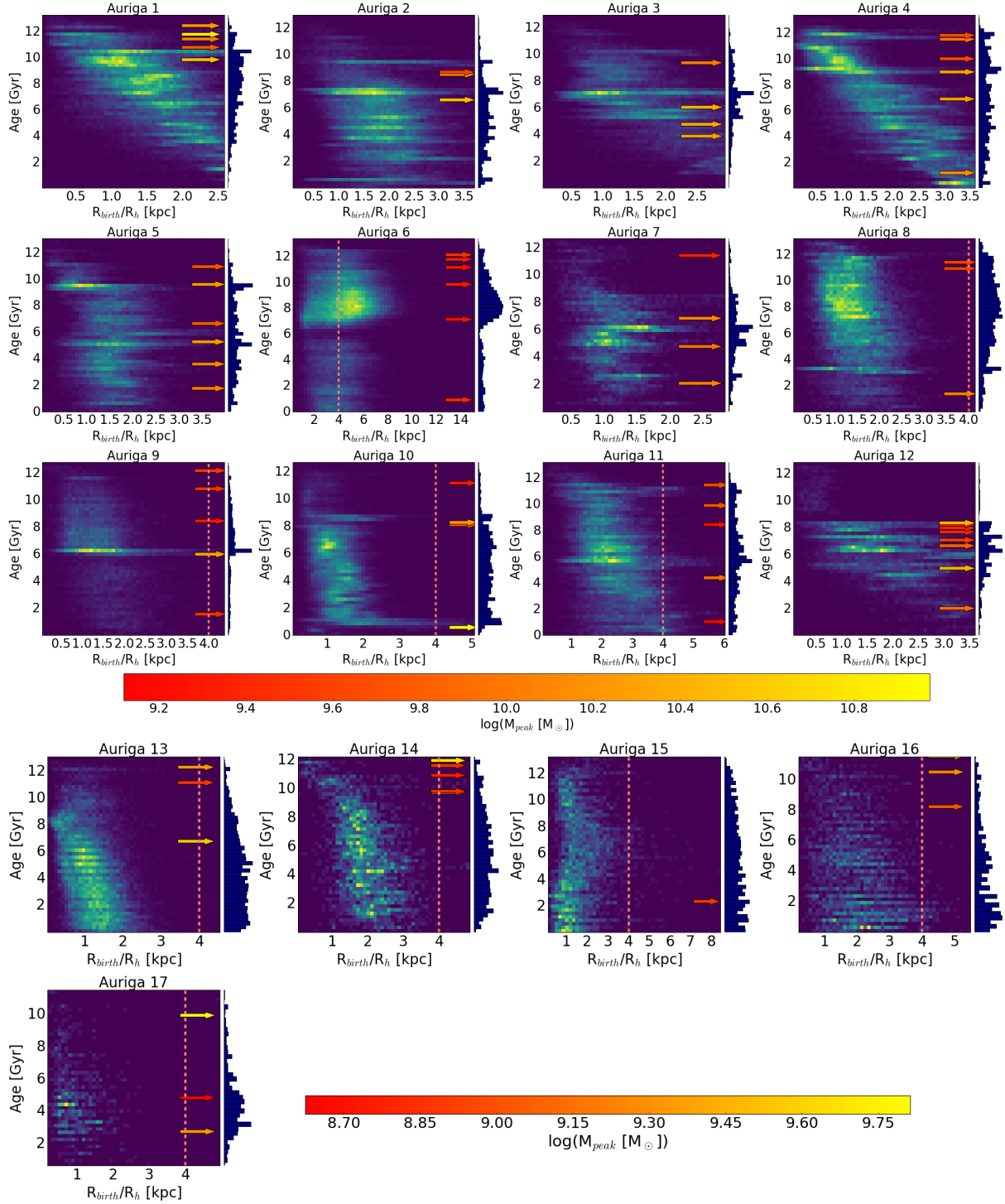


Figure 5.1.1: Age density maps as a function of the R_{birth} for the in-situ stellar particles that comprise the stellar halo at $z = 0$. The arrows represent the time at which the galaxies underwent merger events. Only merger events that satisfy that the maximum total mass reached by the satellite was $\frac{1}{100}$ times the M_{200} of the main galaxy are shown, and they are colour-coded according to their reached maximum total mass. The galaxies are plotted in order of decreasing stellar mass. The vertical dashed lines indicate $4R_h$.

they can be found at $z = 0$ by either the same merger event that provided the gas that contributed to their formation or by a later one. For instance, this is the case of Auriga 9, where we can see that the galaxy has a considerable amount of in-situ stellar particles with ages of ~ 6 Gyr in its stellar halo and that, at the same time that these particles formed, the galaxy was interacting with a satellite of $M_{\text{peak}} \approx 10^{10.2} M_{\odot}$ that ended up merging with it. Fig. 5.1.2 shows the gas and stellar mass fraction (symbolised with circles and stars respectively) of each satellite for 3 galaxies of our sample, computed at the time when these satellites reached their M_{peak} . As presented in the right panel of this figure, the satellite involved in the merger that took place ~ 6 Gyr ago in Auriga 9 had a considerable amount of gas that contributed to the burst of star formation this galaxy underwent at approximately that same time. Merger events happening at different times to a same galaxy help contribute to the variety of stellar ages found at $z = 0$ in their in-situ stellar halo.

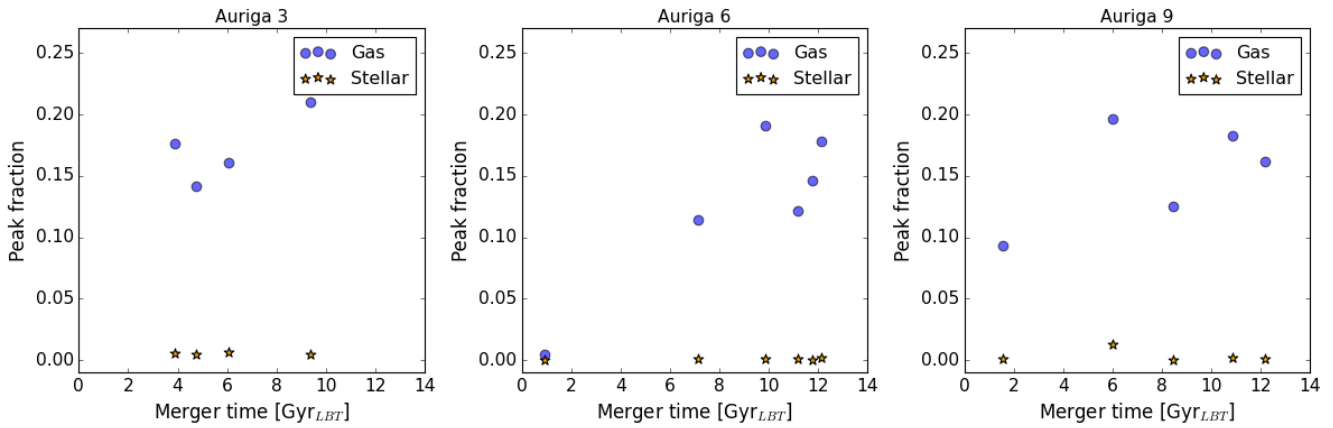


Figure 5.1.2: Gas and stellar mass fraction (circles and star symbols respectively) with which the satellites contribute to the main galaxy during their merger events, shown for 3 galaxies of our sample. The x-axis corresponds to the time of the mergers of these satellites with the main galaxy. These fractions are computed with the amount of gas and stellar mass reached by the satellites at the M_{peak} .

We studied the star formation history (SFH) of the in-situ stellar halo of each galaxy to see if it follows the same SFH as the in-situ material within $4R_h$ (i.e., the in-situ particles that do not belong to the stellar halo). We show these results in Fig. 5.1.3. The light-blue histograms represent the SFH of the in-situ stellar particles that are not part of the stellar halo at $z = 0$, while the violet histograms represent that of the in-situ stellar haloes. Interestingly, we find a difference in the SFH between the in-situ stellar material in the stellar haloes and that within $4R_h$. The SFH of the in-situ halo particles at $z = 0$ shows bursts of star formation coinciding with merger events, indicating that these interactions influenced their formation. In contrast, the SFH of in-situ particles within $4R_h$ at $z = 0$ does not exhibit such pronounced starbursts during merger events. In the few cases in which the SFH are similar, the starbursts are less pronounced when considering the inner region of the galaxy. This fact corroborates that the formation of the particles belonging to the in-situ stellar halo was influenced by an external process, rather than solely resulting from the galaxy's intrinsic star formation. The arrows shown in each panel represent the time at which the galaxies underwent merger events, and they are colour-coded according to the maximum total mass reached by the satellites they interacted with. Only merger events that satisfy that the maximum total mass reached by the satellite was $\frac{1}{100}$ times the M_{200} of the main galaxy are shown. We see that

the times at which the galaxies underwent a merger event correlates with a burst of star formation of the stellar halo material, indicating that the interaction and the merger event played a role in triggering the star formation of the in-situ particles found at $z = 0$ in the stellar haloes.

This scenario regarding the triggering of star formation during interactions is further corroborated when comparing the median $[\text{Fe}/\text{H}]$ of the in-situ stars generated during the interaction or as a consequence of the merger event, and the one of all of the in-situ stellar material of that same age located within $4R_h$ of the galaxy at $z = 0$. We computed these values for all galaxies in our sample and we get that the median $[\text{Fe}/\text{H}]$ value of the stellar particles that are part of a same burst of star formation (i.e., green and yellow over-densities in Fig. 5.1.1) is always lower than the median $[\text{Fe}/\text{H}]$ value of the in-situ population with the same age inside $4R_h$ in each galaxy. The median of the difference between these metallicity values is of 0.3 dex. Therefore, this indicates that the gas brought in by the satellite galaxy played a role in forming stellar material.

We note that the over-density peaks representing bursts of star formation in the lower mass range of our galaxies are less pronounced than those of the higher mass end. Nevertheless, we analysed the median $[\text{Fe}/\text{H}]$ of the stellar particles born in the star formation bursts of the particles that now belong to the in-situ halo and this trend regarding the difference in metallicity is still obtained in these dwarf galaxies.

However, the contribution of stripped gas, provided by gas-rich satellites, to the formation of the in-situ halo stars may not be the same in every main dwarf galaxy. To test this, we analysed the $[\text{Fe}/\text{H}]$ distribution of both the in-situ (blue) and accreted (orange) components of the stellar halo, as shown in Fig. 5.1.4. The in-situ stellar material born as a result of interactions should have a similar metallicity to that of the accreted component if it formed with the gas accreted by the dwarf galaxy. We find a bimodal distribution in 8 out of 17 galaxies ($\sim 50\%$), indicating that in those galaxies the contribution to the stellar halo of in-situ particles born out of accreted gas is not significant. The remaining galaxies do not present a bimodality in their $[\text{Fe}/\text{H}]$ distribution, which means that the in-situ material born out of accreted gas significantly contributes to their in-situ stellar halo. We also show the overall $[\text{Fe}/\text{H}]$ distribution of the stellar halo in Fig. 5.1.4, colour-coded by the accreted stellar halo mass. This overall distribution closely resembles that of the in-situ population in all galaxies, indicating that the in-situ component dominates over the accreted component, as discussed in Sec. 3.2. We also find that it would be suitable to make a cut in $[\text{Fe}/\text{H}] \approx -1.5$ to observationally detect the accreted component of the stellar haloes in low-mass galaxies. Stars with $[\text{Fe}/\text{H}] < -1.5$ can be assumed to be primarily accreted material, although we bear in mind that the accreted component is less abundant than the in-situ one and this classification might therefore not be so straightforward.

The case of Auriga 6 is quite interesting because, as shown in Fig. 5.1.1, this galaxy formed a lot of the in-situ stellar material that belongs to the stellar halo at $z = 0$ already in its outskirts. The satellites that merged with this galaxy between ~ 12 and ~ 7 Gyr ago provided it with a lot of gas (see middle panel of Fig. 5.1.2), but it was not used to form this in-situ component because the $[\text{Fe}/\text{H}]$ distribution of this material does not match the one of the accreted component in the stellar halo (see Fig. 5.1.4). Given the fact that Auriga 6 is a very compact galaxy (see Fig. 3.1.2), even though the majority of the stars formed during these mergers were born at $R_{\text{birth}} \approx 5 - 7$ kpc, their birth locations are considered as part of the stellar halo according to our definition. Hence, it is also possible for a dwarf galaxy to have an in-situ stellar halo comprised of stellar material that was formed already in the galaxy's outskirts if the galaxy is very compact.

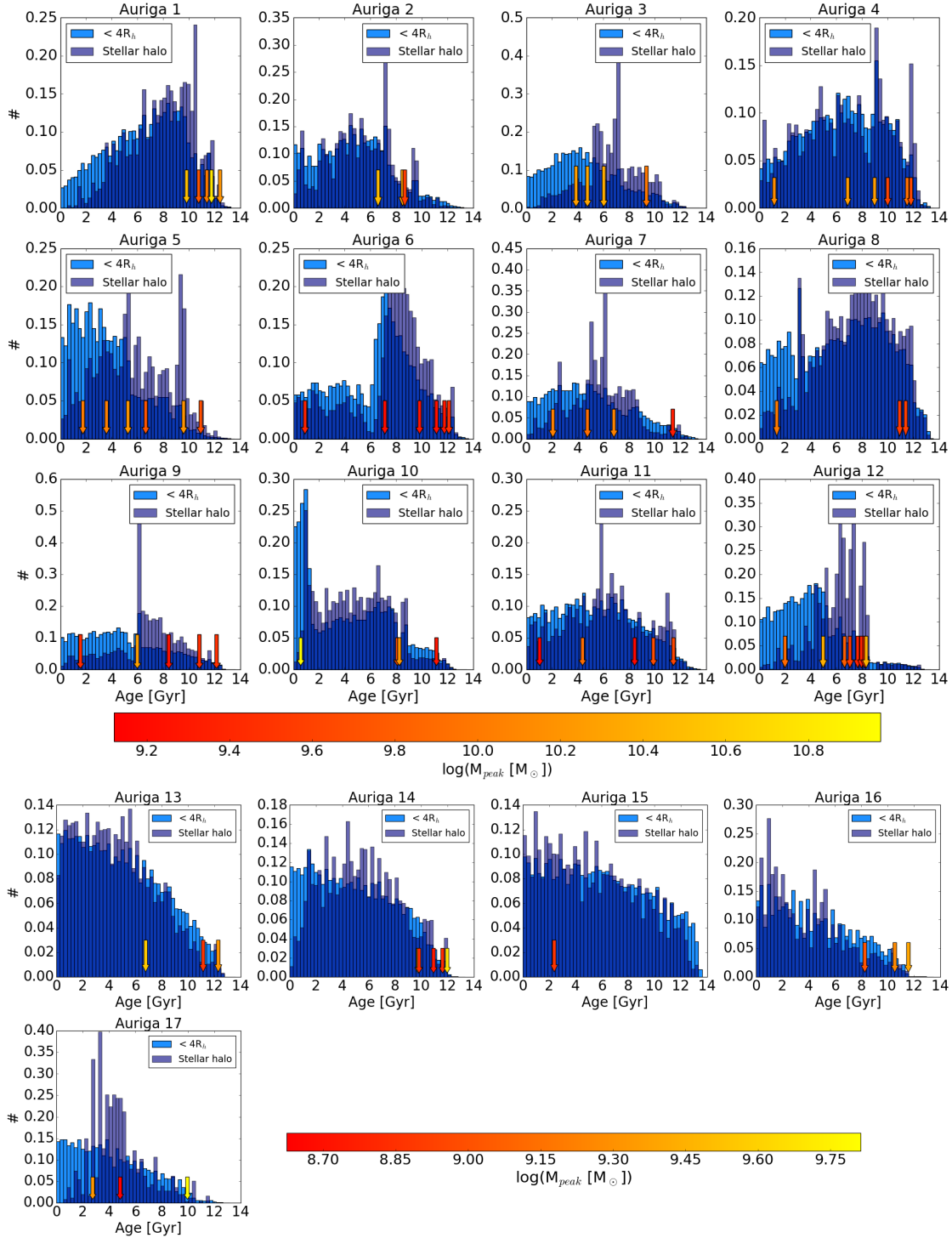


Figure 5.1.3: SFH of the in-situ stellar populations of each galaxy in our sample. Light-blue histograms represent the SFH of the in-situ stellar particles located within $4R_h$, while violet histograms represent that of the in-situ stellar halo. Arrows represent the time at which the galaxies underwent merger events that satisfy that the maximum total mass reached by the satellite was $\frac{1}{100}$ times the M_{200} of the main galaxy. The arrows are colour-coded according to the maximum total mass reached by the satellites.

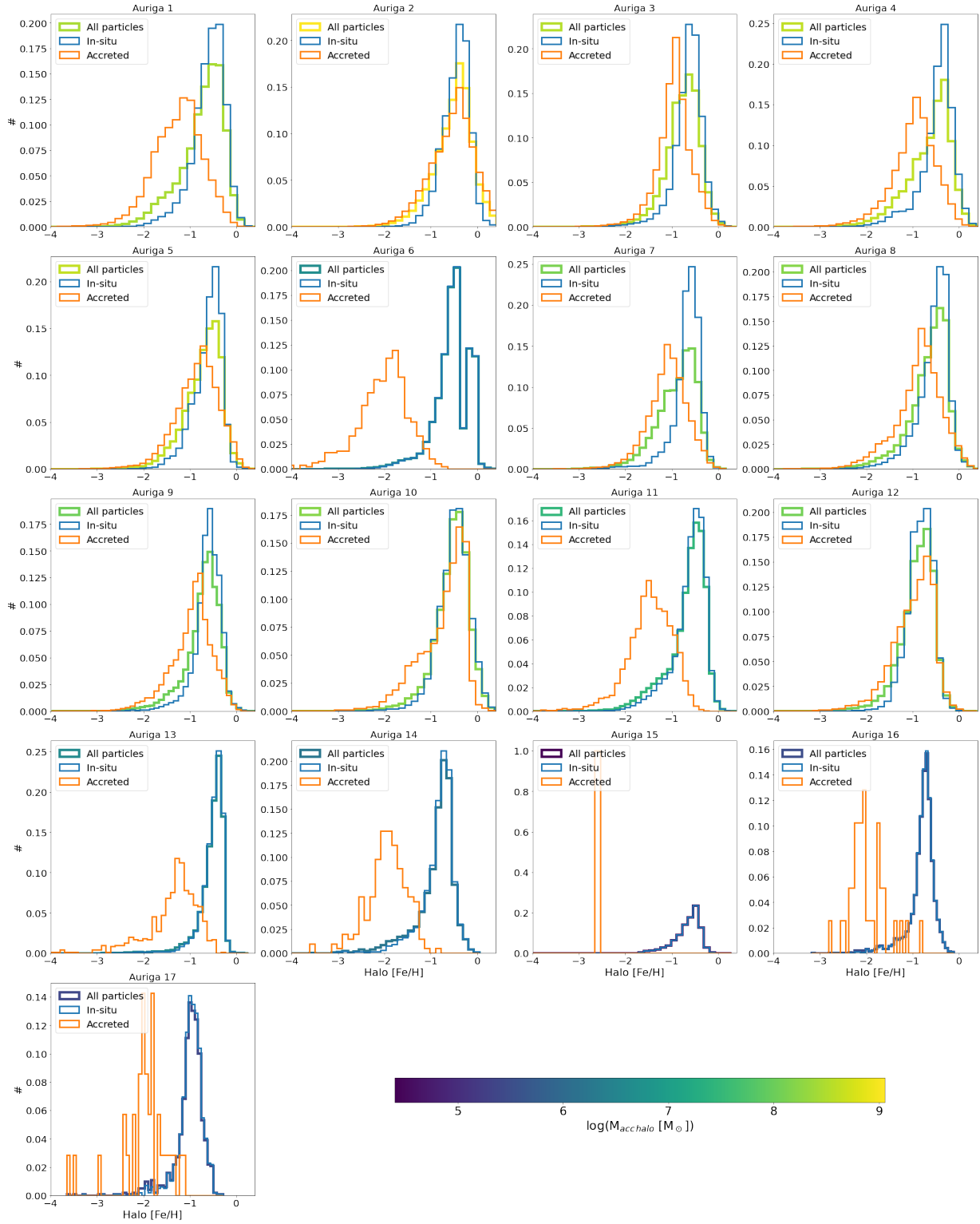


Figure 5.1.4: $[\text{Fe}/\text{H}]$ distributions of the in-situ (blue) and accreted (orange) components of the stellar halo, normalised by the number of particles of each population. We also show the overall $[\text{Fe}/\text{H}]$ distribution of the stellar halo colour-coded by the accreted mass of the stellar halo.

We note that, in this Chapter, we have focused on external processes (i.e., merger events and interactions) that drag in-situ stellar material into the stellar halo, but there can also be internal processes that eject this material into the outskirts (e.g., radial migration, vertical buckling, secular evolution and stellar feedback), as discussed in Chapter 4. However, these processes are not effective in kicking out in-situ stellar particles to such large radii as are found here, in addition to mostly moving these particles radially instead of vertically. If any, the contribution to the in-situ stellar halo due to internal processes is not expected to be dominant, as also presented in Chapter 4 where we find that the contribution of these processes to the redistribution of the in-situ material is dismissible. Moreover, they mostly involve bar-induced instabilities or strong spiral arms, which are not present in our sample.

5.2 Discussion in an observational context

In this Chapter, we explored the formation mechanism of the in-situ component of the stellar haloes and found that it consists mostly of stellar material originally generated in the inner regions of the main galaxy but is then likely expelled to its outskirts during interactions with satellite galaxies. Additionally, some of this in-situ stellar material originated as a direct consequence of merger events, born out of the gas that gas-rich satellites provide the main galaxy with. This supports the results found in [Stierwalt et al. \(2015\)](#), who analysed observational data of 60 isolated dwarf pairs and suggested that, in the stellar mass range $10^7 - 10^9 M_\odot$, the interactions between two dwarf galaxies in this environment can lead to an enhancement in their star formation rate, and that starbursts can be triggered throughout these mergers even in early stages in the interaction. As mentioned before, along with the gas, satellite galaxies can also provide stellar material to the main galaxy and constitute the accreted part of stellar halo seen together with the in-situ one. In the context of relative isolation in which the galaxies of our sample evolve, the interactions between dwarfs lead to their inevitable merger that has this impact in the formation of the main dwarf’s stellar halo. This idea is also supported by [Paudel et al. \(2018\)](#) who found that the probability of having dwarf-dwarf interactions and mergers increases in low-density environments, because in the case that the dwarf galaxies are close to a giant galaxy, the interaction between them will most likely not take place, and instead they will both become satellites of the giant galaxy.

It is important to remark that the R_h we took into consideration when analysing R_{birth} to see if the stellar particles were born in the stellar halo is the one that the galaxies have at $z = 0$. The size of the galaxies will be changing from snapshot to snapshot as the galaxy grows and evolves, so the R_h should be smaller at earlier times. As we base our definition of the stellar halo on R_h , this means that the beginning of this structure would be closer to the galaxy’s centre at earlier times than at the present day. Therefore, some of the stellar particles shown in Fig. 5.1.1 may have been born in the inner stellar haloes of the galaxies.

The outskirts of NGC 5238, a relatively isolated low-mass galaxy of $M_* \sim 10^8 M_\odot$, can also be explained by this scenario where in-situ stars are expelled to the outer regions, matching the claim of [Pascale et al. \(2024\)](#). The authors analysed data of this galaxy taken from the SSH survey and identified low surface brightness tidal features around it, such as a northern “umbrella” and a southern plume. Using N-body simulations, [Pascale et al. \(2024\)](#) tried to reproduce the interaction with a satellite of significantly lower mass than this galaxy had, which could be responsible for the overdensities of old stars present at large distances from the centre of NGC 5238 towards its northern and southern regions. They found that the disc of NGC 5238 was distorted after the interaction and stellar material that belonged to it ended up

located at these farther distances where they are observed today. We suggest, according to our proposed formation mechanism for stellar haloes acting in dwarf galaxies with slightly higher stellar mass than NGC 5238, that some of the stellar material that was dragged to the outskirts of this galaxy should have also been born during this interaction. In addition, following our results for this stellar mass range, we can also suggest that the outskirts of NGC 5238 are dominated by in-situ stellar material at all radii.

Our results also consider the case of the observed isolated dwarf IC 1613 [Pucha et al. \(2019\)](#), with a stellar mass of $M_* = 10^8 M_\odot$ ([McConnachie, 2012](#)). The surface brightness of this galaxy at $\sim 5 R_h$ reaches as low values as $\sim 33.7 \text{ mag arcsec}^{-2}$. According to our analysis presented in Sec. 3.2 and discussed in Sec. 3.5.1, it is probable its stellar halo has a considerable amount of in-situ stellar material that dominates even at its farthest distances. This structure could have also been built up due to interactions and mergers that the galaxies underwent during its evolution and caused a redistribution of stars that were formed in the inner regions. [Pucha et al. \(2019\)](#) claimed that IC 1613 does not present clear evidence of accretion events (such as stellar streams or obvious tidal material), although they do think that some outermost intermediate-age and old stars have structural properties more consistent with accretion than in-situ formation scenarios. In most of the least massive galaxies in our sample, with stellar masses of the order of IC 1613, stellar streams, pronounced shells or any other trace of accretion events are indistinguishable (see Fig. 3.1.2), but these dwarfs do interact with satellite galaxies during their evolution history nonetheless. Thus, our results imply that IC 1613 should have interacted and accreted low-mass satellite galaxies even though the observational evidence is not easily perceived in its outskirts.

Our simulations are also in agreement with results in the Magellanic Clouds' outskirts, although in this case they are not isolated dwarfs. These galaxies are interacting with each other, besides being affected by the MW, which can produce a redistribution of the stellar material of their inner parts. For instance, [Muñoz et al. \(2023\)](#) studied 6 outer regions of the Magellanic Clouds and found that there is stellar material that used to belong to the LMC disc present in the Magellanic Clouds outskirts. Moreover, substructures in the southern periphery displayed a mix of LMC-like and SMC-like populations based on their chemical and kinematic signatures.

It could be natural to consider that the relation discussed in Sec. 3.5.1 between the stellar mass of the galaxy and the dominance of the in-situ component in the stellar halo can be extrapolated to low-mass galaxies with $M_* < 10^8 M_\odot$. Lower-mass galaxies accrete less massive satellites, many of which may not have been able to form stars, leading to a lower amount of accreted stellar mass (see Fig. 2.2.2). In addition to this, the lower the galaxy's mass, the more likely it is to be perturbed by subhalo interactions, which can further promote the formation of stellar haloes from heated in-situ material. Consequently, if this correlation between the stellar mass and the dominance of the in-situ component in the outskirts extends to a lower-mass regime, the stellar haloes found in dwarf galaxies with stellar masses lower than that of our considered mass range, such as Sagittarius DIG ($M_* = 1.14 \times 10^6 M_\odot$, [Higgs et al., 2016](#)), DDO 187 ($M_* = 7.8 \times 10^6 M_\odot$, [McConnachie, 2012](#)) and NGC 3109 ($M_* = 7.6 \times 10^7 M_\odot$, [McConnachie, 2012](#)), should also be dominated by in-situ stellar material at all galactocentric distances. Furthermore, our results suggest that even lower-mass galaxies may form their in-situ stellar halo component through interactions with smaller objects. These encounters could trigger star formation while also heating and kicking out in-situ material. Indeed, [Subramanian et al. \(2024\)](#) performed a UV study of a sample containing 22 interacting and 36 single gas-rich dwarf galaxies and found that, for the $10^7 - 10^8 M_\odot$ stellar mass range, dwarf-dwarf interactions lead to an enhancement in their star formation rate. The authors claim that the interacting systems' star formation rate is enhanced by a factor of 3.4 ± 1.2 compared to

single dwarf galaxies.

5.3 Summary

In this Chapter, we investigated the origin and formation mechanisms of the in-situ component of the stellar haloes of low-mass galaxies. By tracing the birth positions and ages of the in-situ halo stars, we showed that, in nearly all cases, these stars formed in the inner regions of their host galaxies and were subsequently kicked out to larger radii. This redistribution is primarily driven by merger events with satellite galaxies. We find that between $\sim 8\%$ and $\sim 43\%$ of the in-situ halo stars can be directly linked to such merger-induced episodes. In about half of the galaxies, bimodal metallicity distributions suggest limited contribution from accreted gas during interactions, while in the others, in-situ stars formed from accreted gas significantly shape the stellar halo populations. Importantly, the star formation histories of the in-situ haloes differ from those of the in-situ populations within $4R_h$, with the haloes exhibiting clear starbursts coincident with merger times.

This Chapter demonstrates that the in-situ haloes of low-mass galaxies are primarily built through external interactions with satellites, which trigger starbursts and redistribute stars formed in the inner regions. This mechanism provides a framework for interpreting observed stellar haloes in dwarfs across a wide mass range. We also suggest that this scenario should hold for even lower-mass galaxies, although this remains to be tested.

Chapter 6

Summary and Conclusions

The formation and evolution of galaxies at all scales still remain as several of the most intriguing topics in astrophysics. In particular, studying the outskirts or stellar haloes of galaxies provides valuable information about their accretion and evolutionary histories, offering clues about past merger events and interactions. Although this component has been studied in detail in the MW-mass regime, there are many unanswered questions concerning the low-mass regime, and recent advancements in instrumentation and numerical simulations have helped to address these. This approach also enables tests of the hierarchical structure formation model predicted by the Λ CDM paradigm, helping to assess whether its predictions hold true across different mass scales.

However, this is challenging to study in the low-mass regime due to the faintness of these dwarf galaxies' stellar haloes, and until recently it was not even clear whether they hosted such extended structures. With that in mind, the main objective of this thesis is to provide a characterisation of the stellar haloes of dwarf galaxies from a theoretical point of view, as well as a better understanding of their formation and evolution history.

In this thesis we used a new set of very high resolution hydrodynamical cosmological simulations from the Auriga project (Grand et al., 2017, 2024) to characterise and study properties of the stellar haloes of low-mass galaxies ($3.06 \times 10^{10} M_{\odot} \leq M_{DM} \leq 3.73 \times 10^{11} M_{\odot}$). We also studied their evolution through time and their possible formation mechanisms. The resolution of these new simulations is of $5 \times 10^4 M_{\odot}$ in DM mass and $\sim 6 \times 10^3 M_{\odot}$ in baryonic mass, which allows us to resolve galaxies within a stellar mass range of $3.28 \times 10^8 M_{\odot} \leq M_{*} \leq 2.08 \times 10^{10} M_{\odot}$ with more than 10000 particles. We set a definition for the stellar haloes in these galaxies, which considers all the stellar material located outside an ellipsoid with semi-major axes $a = b = 4R_h$ (being R_h the half-light radius) to be part of the stellar halo. Our sample contains 17 dwarf galaxies. These simulated galaxies vary significantly in size and their outer regions reach very low surface brightness values ($\mu > 32 \text{ mag arcsec}^{-2}$, see Figs. 3.1.2 and 2.3.2). The main conclusions of this thesis are summarised in the following paragraphs.

In Chapter 3, we showed that the inner stellar haloes ($\sim 4 - 6R_h$) of all the galaxies analysed in this thesis are dominated by in-situ stellar material (see Fig. 3.2.1 and Table 2.2.1). We also found that the stellar haloes ($4 - 10R_h$) of the least massive dwarf galaxies ($M_{*} < 4.54 \times 10^8 M_{\odot}$) are dominated by in-situ stellar material at all radii (see Fig. 3.2.1). Regarding the accreted component, we found that more massive dwarf galaxies have a greater amount of accreted stellar material contained in their stellar haloes, which dominates beyond $\sim 5R_h$ (see Fig. 3.2.1). Additionally, more massive dwarf galaxies ($M_{*} \geq 6.30 \times 10^9 M_{\odot}$) keep on accreting stellar material until later times (mean τ_{90} of 4.44 Gyr ago) than

less massive ones (mean τ_{90} of 8.17 Gyr ago, see Fig. 3.4.1). The formation time of their accreted stellar halo is also later than for less massive galaxies. In the case of the accreted stellar haloes of more massive dwarfs, this quantity is $\tau_{90} = 3.93$ Gyr ago, while for those of less massive galaxies is $\tau_{90} = 7.03$ Gyr ago. Moreover, galaxies that accreted more stellar material have obtained it by accreting more massive satellites (see Fig. 3.4.3), and the satellite galaxy that contributed the most to the accreted component of the stellar halo is also the one that contributed the most to the overall accreted stellar material of the dwarf galaxy (see Sec. 3.3). Overall, there are few satellites that contribute to the accreted component of these low-mass galaxies. The number of significant progenitors, defined here as those satellite galaxies that contribute with up to 90% of the accreted stellar material, ranges from 1 to 7 (see Fig. 3.4.4).

We also showed in Chapter 3 some correlations we found involving properties of these stellar haloes. We found a strong correlation between the *accreted* stellar halo mass fraction and the total stellar mass of the galaxies, over a 3 dex range in stellar mass which extends to the MW-mass regime. Less massive galaxies have lower fraction of accreted stellar halo material (see Fig. 3.2.3). Furthermore, the correlation found in MW-mass galaxies that indicates that more massive stellar haloes are also more metal rich than less massive ones is also present in this low-mass range, but only when considering the accreted component of the stellar haloes (see Fig. 3.3.3). In addition, when comparing with MW-mass galaxies, at a given accreted stellar halo metallicity, galaxies with a larger dark matter halo have a more massive accreted stellar halo (see Fig. 3.3.3). As for the significant progenitors, we found that there is no clear correlation between the number of them and the total stellar mass or the accreted stellar mass of dwarf galaxies (see Fig. 3.4.4).

In Chapter 4 we analysed the metallicity and age of the galaxies in our sample, as well as those of their stellar haloes. We found that the galaxies analysed in this thesis have negative $[\text{Fe}/\text{H}]$ gradients, ranging from -0.24 to -0.1 , indicating that their outskirts are more metal-poor than their central regions. The centres of less massive dwarfs ($M_* < 6.30 \times 10^9 M_\odot$) are in general more metal-poor than those of more massive dwarfs. We found no correlation between the metallicity gradients of the galaxies and their stellar mass, their accreted stellar mass, their accreted mass fraction and the number of significant progenitors they have. This implies that the link between the evolution of the galaxies and their resulting metallicity gradients is not so straightforward to measure in the low-mass regime. As previously mentioned, more massive accreted stellar haloes ($M_{acchalo} \geq 10^8 M_\odot$) are also more metal-rich (median $[\text{Fe}/\text{H}]$ values ≥ -1.22). In addition, in this Chapter we found a correlation between the metallicity of the accreted stellar haloes and the infall time of their most dominant satellite: at a given accreted stellar halo mass, the dwarf galaxies that accreted satellites at later times have a more metal-rich accreted stellar halo. This is due to the fact that satellites accreted at later times had more time to chemically evolve and enrich their stellar populations before being disrupted.

Regarding the age, in Chapter 4 we showed that the mean ages of the main body of the galaxies (i.e. within $4R_h$) are generally lower than the mean ages of their total stellar haloes (see Table 4.3.1). Additionally, the majority of the galaxies (12 out of 17) present a prominent U-shape in their radial age profiles. This U-shape is mainly driven by the in situ stellar population and located within $4R_h$. In those galaxies with a U-shaped radial age profile, the radial location of the minimum age before the upturn matches that of the peak of the star formation of young stellar material. In other words, in the cases where we found a U-shaped radial age profile, the age of the stellar material starts to radially increase beyond the radius where there is no recent star formation activity. Moreover, galaxies with and without a U-shape in their radial age profile undergo significant merger events (i.e. with M_{peak}/M_{200}

ratios between 0.1 and 1) at early times and late times. Hence, these alone are not enough to explain the redistribution of the old stellar material so as to generate the U-shaped radial age profiles. However, when this information is combined with the sSFR, we note that galaxies with a U-shape had formed a considerable amount of stellar material at early times that was already there to be kicked out when the mergers occurred. Furthermore, the galaxies without a U-shaped age profile present a continuous sSFR that increases monotonically up to $z = 0$, and they keep on forming stellar material at large distances from their centres, which contributes to the flattening of their profiles. Another finding presented in this Chapter is that more massive stellar halos are older than the less massive ones, indicating that less massive galaxies keep on forming in situ stellar material until later times, which can later end up comprising their stellar haloes. In contrast, when considering only the accreted component, more massive accreted stellar haloes have younger stars than less massive ones, given that the less massive galaxies accreted their stellar material earlier, leaving them with older accreted material in their stellar haloes. Finally, we found a strong correlation between the age and metallicity of the accreted stellar haloes of the analysed low-mass galaxies: more metal-rich accreted stellar haloes are younger, while more metal-poor ones are older. The results from this Chapter show us the wide variety in ages and metallicities when analysing low-mass galaxies and their stellar halos, reflecting the complex and non-uniform evolutionary pathways these systems can follow. Although these imprints on stellar haloes are difficult to confirm with current observational data, future facilities such as the Nancy Grace Roman Space Telescope will enable the detection of these extended components.

In Chapter 5 we focused on the formation scenario of the in-situ stellar halo. We found that the in-situ component of the stellar haloes is formed in the inner regions of the galaxies and subsequently kicked out into the outskirts as a consequence of interactions and merger events with satellite galaxies (see Fig. 5.1.1). Additionally, in some cases, the accreted satellite galaxies provide the main galaxy with gas, which can be used to form this in-situ stellar material that is found in the outskirts at $z = 0$. However, the contribution of stripped gas, provided by gas-rich satellites, to the formation of the in-situ halo stars may not be the same in every main dwarf galaxy. We thus analysed the $[\text{Fe}/\text{H}]$ distribution of the in-situ and accreted components of the stellar halo (see Fig. 5.1.4). We find a bimodal distribution in 8 out of 17 galaxies ($\sim 50\%$), indicating that in those galaxies the contribution to the stellar halo of in-situ particles born out of accreted gas is not significant. The remaining galaxies do not present a bimodality in their $[\text{Fe}/\text{H}]$ distribution, which means that the in-situ material born out of accreted gas significantly contributes to their in-situ stellar halo.

The numerical simulations used in this thesis present some limitations when working in the low-mass range. For example, the sub-grid models were originally designed for higher mass ranges, and while they provide some insights into the assembly of low-mass galaxies, the results obtained in this low-mass regime may be affected by the sub-grid physics involved since the resolution may not be sufficient to capture all relevant physical processes. In addition, dwarf galaxies in the Auriga low-mass simulations reach as low stellar masses as $M_* = 5 \times 10^4 M_\odot$ with a baryonic mass resolution of $\sim 10^3 M_\odot$. Even though the resolution is indeed very high for cosmological hydrodynamical simulations, the smallest mass probes leave us just few hundreds to few thousands of particles per galaxy. Studying the stellar haloes of these galaxies, which have much fewer particles, is not reliable in this regime. It is also worth noticing that the resolution limitation will affect the satellite galaxies involved in the evolution history of our simulated sample as well, especially those with very low stellar masses ($M_* < 10^7 M_\odot$).

We highlight that these findings are based on a ΛCDM cosmology, the current standard model for

structure formation in the Universe. As such, they may serve as valuable predictions for comparison with upcoming observational data. Any significant discrepancies between these results and observations could provide insight into possible deviations from the Λ CDM paradigm, potentially offering constraints on the nature of dark matter and alternative cosmological models.

In the coming years we will have access to large-scale surveys, such as the Large Synoptic Survey Telescope (LSST) from the Vera Rubin Observatory, and the Nancy Grace Roman Space Telescope, which will allow us to reach deeper and fainter surface brightness values, as well as farther regions when observing dwarf galaxies. All these unprecedented observational data will help shed light into the composition of the stellar haloes of low-mass systems, and will also put the numerical models and hypothesis regarding their formation to the test.

Chapter 7

Future work

In this final part of this thesis, some follow-up studies are introduced. These projects arise from questions and results that emerged during the analyses conducted throughout this work.

7.1 In-situ and accreted components of the stellar halo at higher z

In Chapter 3 (Sec. 3.2) we presented the in-situ and accreted stellar material's radial distribution at $z = 0$, and we found that the inner regions of the stellar haloes (i.e., between 4 and $\sim 6R_h$) comprise a considerable amount of in-situ stellar material. Additionally, in Fig. 3.2.1, we showed that the outskirts of most galaxies of our sample are dominated by accreted material, and also that there are some galaxies dominated by in-situ material at all radii.

As a follow-up study, it would be interesting to analyse when the stellar halo starts to form at higher z and when it becomes more or less dominated by accreted material. Probably, the galaxies will have accreted less material at earlier times, but it is also possible that less of the in-situ stellar material will have reached the stellar halo at those z . Thus, this analysis will help shed light into the evolution of the stellar halos in low-mass systems.

To do so, we will select different snapshots (corresponding to different z) and compute the R_h of the galaxies in each one of them. Based on the obtained R_h , we will define the galaxies' stellar halo at those times and analyse the amount of accreted and in-situ material they have.

7.2 Environmental effects on shaping the stellar haloes

In this work we have studied isolated low-mass galaxies, focusing on their properties, their stellar content and their evolution through time without the influence of more massive neighbours. This helped us understand the intrinsic formation and evolution of these galaxies' stellar haloes. As part of a future work, we will analyse how the properties of the stellar haloes in low-mass galaxies differ between isolated and satellite/interacting galaxies.

This can be achieved by using numerical simulations in which dwarf galaxies are not isolated but are satellites of a more massive galaxy, such as the IllustrisTNG simulations (Nelson et al., 2019). However, due to the lower resolution of these simulations ($m_{\text{baryon}} = 8.5 \times 10^4 M_\odot$) compared to Auriga

($m_{\text{baryon}} = 6 \times 10^3 M_{\odot}$), we will focus on satellite dwarfs with $M_* \geq 8.5 \times 10^8 M_{\odot}$ to ensure reliable results and compare with isolated dwarfs in Auriga above this threshold. Taking this into account, we will compute the formation time of the stellar halos in satellite dwarf galaxies and compare it to that of isolated dwarfs found in this thesis. This will help determine whether the proximity to a more massive galaxy significantly impacts the formation of stellar halos in low-mass systems. Moreover, we will also examine the in-situ stellar mass fractions in the outskirts of these galaxies to determine whether this proximity affects the amount of in-situ material in their stellar halos. This combined analysis will help determine the extent to which environmental factors influence the formation, structure, and stellar content of dwarf galaxies' outskirts.

7.3 Radial age profiles at higher z

In Chapter 4 we presented the radial age profiles at $z = 0$ of the galaxies of our sample, and we showed in Fig. 4.2.1 that the majority of them have a prominent U-shape. According to our results, this behaviour is driven by the in-situ stellar material, and it is caused due to the combination of a drop off in the SFR together with the ejection of stellar material from the inner to the outer region.

However, it would be interesting to see how this behaviour in the age profile changes with time. When considering higher z , younger stellar material will not have yet been born. In addition, the stellar material of the galaxies will have interacted with fewer satellite galaxies as we consider earlier times, and will not have had time to be redistributed to large distances. Therefore, we could expect this U-shape of the age profiles to not be present at high z . Furthermore, such an analysis could help identify the epoch at which this feature first emerges, offering valuable insight into the timing and processes driving the development of these age gradients.

To explore this, we will select different z and compute the radial age profiles in each one of them. We will then analyse the percentage of galaxies that have U-shaped age profiles at each epoch and investigate how this fraction evolves with redshift, providing insights into the conditions and timescales that favour the development of such features.

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