The stellar halo in Local Group Hestia simulations II.  

The accreted component

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ABSTRACT

In the Milky Way (MW), recent progress in the exploration of its assembly history is driven by the tremendous amount of high-quality data delivered by Gaia (ESA), which has revealed a number of substructures potentially linked to several ancient accretion events. In this work, aiming to explore the phase-space structure of accreted stars, we analyze six M31/MW analogues from the HESTIA suite of cosmological hydrodynamics zoom-in simulations of the Local Group. We found that all the HESTIA galaxies experience a few dozen mergers but only 1–4 mergers have the stellar mass ratio > 0.2 (relative to the host at the time of the merger) where, depending on the halo definition, the most massive merger contributes from 20% to 70% of the total stellar halo mass. Individual merger remnants show diverse density distributions at z = 0, significantly overlapping with each other and with the in-situ stars in the Lz – E1 – (V, V0) and (R, V0) coordinates. Moreover, the mergers debris often change their position in the Lz – E space with time due to the galactic mass growth and the non-axisymmetry of the potential. In agreement with previous works, we show that even individual merger debris exhibit a number of distinct Lz – E features. In the (V, V0) plane, all HESTIA galaxies reveal radially hot, non-rotating or weakly counter-rotating, Gaia-Sausage-like features, which are the remnants of the most recent significant mergers. We found an age gradient in Lz – E space for the individual debris, where the youngest stars, formed in the inner regions of accreting systems, deposit to the innermost regions of the host galaxies. The bulk of these stars is being formed during the last stages of accretion, making it possible to use the stellar ages of the remnants to date the merger event. In actions space (J, J, J), the mergers debris do not appear as isolated substructures but are instead scattered over a large parameters area and overlapping with the in-situ stars. We suggest that accreted stars can be best identified using \( \sqrt{J^2} > 0.2 – 0.3 \). We also introduce a new, purely kinematic space (J, J, −orbital eccentricity), where different merger debris can be disentangled better from each other and from the in-situ stars. Accreted stars have a broad distribution of the eccentricities, peaking at \( \epsilon \approx 0.6 – 0.9 \); also, the mean eccentricity of accreted stars tends to be smaller for the systems accreted more recently.

Key words. galaxies: evolution – galaxies: haloes – galaxies: kinematics and dynamics – galaxies: structure

1. Introduction

Thanks to a long dynamical timescale, the stellar halo serves as a fossil record, revealing the galactic assembly history (Helmi et al. 1999; Bullock & Johnston 2005; Abadi et al. 2006). Stars
stripped off from different dwarf galaxies can be identified as streams or moving groups in the halo (Ibata et al. 1994, 2001; Belokurov et al. 2007), which are visible on top of the in-situ stellar halo formed via either dissipative collapse (Eggen et al. 1962; Sandage & Fouts 1987) or by heating a pre-existing stellar disk (Zolotov et al. 2009; Parcell et al. 2010). Stars from accreted massive satellites result in large-scale stellar substructures in the halo which, not being spatially coherent at \(z = 0\), are expected to preserve their common origin imprinted in their chemical and kinematical properties (Bullock & Johnston 2005; Abadi et al. 2006; Stewart et al. 2008; De Lucia & Helmi 2008; Cooper et al. 2010; Font et al. 2011; Brook et al. 2012; Pillepich et al. 2015; Rodriguez-Gomez et al. 2016; Deason et al. 2016).

Although merger stellar remnants disperse across a large volume in the halo, it is believed that even after a long time they can still be identified in purely kinematic, phase-space coordinates or in, so-called, integrals of motion (energy-angular momentum, \(L_q = E\)). For instance, Helmi & White (1999) showed that there is a strong correlation between different velocity components of merger debris, making it possible to associate certain kinematic groups with particular mergers (see, also, e.g., Villalobos & Helmi 2009; Koppelman et al. 2019). Broadly speaking, a number of models suggest that individual merger remnants can be identified as coherent structures in the total energy-angular momentum components space \((L_q − E)\), see, e.g. Johnston et al. 1996; Re Fiorentint et al. 2005; Kepley et al. 2007; Helmi & de Zeeuw 2000; Choi et al. 2007; Morrison et al. 2009; Gómez et al. 2010; Gómez & Helmi 2010; Re Fiorentint et al. 2015). These results are based on the assumption that both energy and angular momentum are approximately conserved over the galaxy life-time and, thus, the merger debris stars follow trajectories as their progenitor system (see Sec.3.3 in Helmi 2020, for the caveats). However, simulations with evolving galactic potentials suggest that the merger remnants can be smeared significantly in the \(L_q − E\) coordinates due to dynamical friction, mass growth and the halo shape evolution, and this finding is valid both for the baryonic components (Knebe et al. 2005; Amorisco 2017; Jean-Baptiste et al. 2017; Tissera et al. 2018; Grand et al. 2019; Panthímpampa et al. 2021; Vasiliev et al. 2021a; Amarante et al. 2022) and dark matter (Knebe et al. 2005). Moreover, the finite size of accreting dwarf galaxies and their own self-gravity will also affect the coherence of their merger debris (Sanders & Binney 2013). It is worth mentioning that chaotic mixing may affect the tidal streams’ density on a rather short time scale, making it hard to isolate the debris, especially in a small volume of space (Vogelsberger et al. 2008; Price-Whelan et al. 2016). However, Maffione et al. (2015, 2018) showed that diffusion due to chaotic mixing in the neighbourhood of the Sun does not efficiently erase phase space signatures of past accretion events.

Nowadays, the MW is the best laboratory for studying the assembly history of a massive galaxy via the identification of merger debris, since the number of stars with 6D phase-space information has been boosted drastically by data from the Gaia (ESA) satellite (Gaia Collaboration et al. 2016, 2018b). These data complemented by the information from spectroscopic surveys make it possible to identify the merger remnants and disentangle them from the in-situ disc and halo populations not only in the kinematic space but also in the chemical abundances (Mackereth et al. 2019; Horta et al. 2020; Naidu et al. 2020; Zhao & Chen 2021; Matsuno et al. 2021; Simpson et al. 2021).

Prior to the Gaia mission, Nissen & Schuster (2010) and Schuster et al. (2012) were the first to identify the presence of two distinct halo populations at metallicity lower than that of the Galactic disc in the solar neighbourhood (see, also, Chiba & Beers 2000, 2001; Brook et al. 2003). More recently, using Gaia data, Belokurov et al. (2018) discovered stellar debris in the inner halo deposited in a major accretion event by a satellite between 8 and 11 Gyr ago (Gaia-Sausage, see also, Myeong et al. 2018; Deason et al. 2018). The Gaia-Sausage populations is the most distinct in the \((V_R, V_\phi)\) space at \(-2 < [\text{Fe/H}] < -1\) where it corresponds to the non-rotating component with a large radial orbital excursion. Second Gaia data release revealed a double color–magnitude sequence (Gaia Collaboration et al. 2018a) observed for the stars with high transverse velocities which were used to constrain the last significant merger in the MW history (Haywood et al. 2018; Helmi et al. 2018, Gaia-Enceladus) which, similar to Nissen & Schuster (2010), can be identified as a distinct low-[Fe/H] sequence in [\(\alpha/\text{Fe}\)]–[Fe/H] plane.

A number of recent works provide the estimates of the stellarmass of accreted GSE (Gaia-Sausage-Enceladus) satellite to be in the range of \(2 \times 10^6 – 5 \times 10^6 \text{ M}_\odot\) (Fernández-Alvar et al. 2018; Vincenzo et al. 2019; Fattahi et al. 2019; Mackereth et al. 2019; Feuillet et al. 2020). Theory suggests that such massive accretion events significantly perturb the pre-existing disc populations (Quinn et al. 1993; Velazquez & White 1999; Gómez et al. 2016; Grand et al. 2016; Gómez et al. 2017). In the MW the impact of the GSE merger is associated with the heating of the in-situ populations ("Splash" in Belokurov et al. 2020, or "Plume" as it was introduced in Di Matteo et al. (2019)). The stellar kinematic fossil record shows the imprint left by this accretion event which heated the (metal-rich) thick disc which is now found in the Galactic halo leaving a little room for the existence of in-situ stellar halo component (Di Matteo et al. 2019, but see recent findings by Belokurov & Kravtsov (2022)).

Analysis of the MW halo stars orbits suggest that GSE arrived in the Galaxy on a highly retrograde orbit (Helmi et al. 2018; Naidu et al. 2021), however, recently Vasiliev et al. (2021b) highlighted the importance of radialization of the stellar orbits due to angular momentum exchange between the host and massive satellite thus making it difficult to constrain the actual orbit of the GSE. This result also suggests that the individual merger debris could lead to the appearance of a number different phase-space (or energy-angular momentum) features (see, e.g. Helmi & de Zeeuw 2000; Choi et al. 2007; Morrison et al. 2009; Gómez et al. 2010, 2013; Jean-Baptiste et al. 2017; Grand et al. 2019; Naidu et al. 2021) because the satellite stars lost at different pericentre passages can escape their progenitor with different mean energies or angular momenta (see also the case of leading/trailing tidal debris analysis in cosmological context in Simpson et al. 2019). Gómez et al. (2013) showed that the fraction of the halo substructures that can be resolved using the integrals of motions and purely kinematic space varies from 31% to 82% while the rest of accreted mass to be smoothly distributed in the phase space.

Since the revolutionizing discovery of the GSE merger the presence of a number of other merger remnants is being discussed in the literature, e.g. Sequoia (Myeong et al. 2019), Kraken (Kruijssen et al. 2020), inner Galaxy structure (IGS in Horta et al. 2021, or Hercules in Horta et al. (2022)), Thamnos (Koppelman et al. 2019), Arjuna structure (Naidu et al. 2020) and others (see, Helmi 2020; Malhan et al. 2022, for review). All the above-mentioned discoveries reveal a number of the mergers remnants with similar (withing uncertainties) chemical abundances and substantial overlap in the phase-space and \(L_q − E\) coordinates thus making it difficult to uncover the actual MW assembly history (Buder et al. 2021; Feuillet et al. 2021; Horta et al. 2022). However, some hints on how to un-
Fig. 1. Morphology of individual mergers at the time of accretion for the five most significant events, for each M31/MW analogues in HESTIA. The merger accretion time, $\log_{10}(M_\ast)$, and the stellar mass ratio, $\mu_\ast$, relative to the main M31/MW progenitor are shown in the bottom of each panel. The colorbar represents stellar density, in units of $M_\ast/kpc^2$. The merger debris show diverse morphologies, likely caused by the different trajectories of accreting systems and internal mass/kinematics distributions.

To understand the complexity of the observational data can be taken from simulations. A nearly complete MW assembly history has been predicted by using the E-MOSAICS simulations where artificial neural networks have been used to link the phase-space parameters of the globular clusters in cosmological simulations with the ones measured in the MW (Kruijssen et al. 2019, 2020).

Thanks to the advances in subgrid physics implementation and increased spatial/mass resolution, modern cosmological hydrodynamic simulations make possible to study various galaxy-scale properties of accreted and in-situ stellar populations (see, e.g. Schaye et al. 2015; Wetzel et al. 2016; Sawala et al. 2016; Pillepich et al. 2018) see also the recent review by Vogelsberger et al. (2020). Using the EAGLE suite of simulations, Mackereth et al. (2019) studied the chemical composition of accreted satellites and the orbital eccentricity of their stellar remnants, suggesting that the low-$\alpha$ MW halo populations is associated with the debris of massive $10^{8.5} - 10^{9} M_\odot$ satellites, which is quite unusual for the MW-type galaxies in EAGLE. Auriga cosmological simulations of the MW-type galaxies (Grand et al. 2017) show that a small number of relatively massive destroyed dwarf galaxies dominate the mass of stellar haloes where 90% per cent of the mass in the inner 20 kpc is contributed by only three massive progenitors (Fattahi et al. 2020; Monachesi et al. 2019), however, the fraction of accreted stars is well below 1% in the galactic center (see also Fragkoudi et al. 2020). Fattahi et al. (2019) find that around 1/3 of the simulated galaxies have a significant population of stars which resemble the Gaia-Sausage structure at low-[Fe/H]. Grand et al. (2020) found evidence that the “Splash”-like component is produced from a gas-rich merger that dynamically heats stars from the Milky Way proto-disc onto halo-like orbits (see, also, Belokurov et al. 2020).

Although the mounting growth of evidence is in favour of a large number of building blocks of the MW stellar halo, their disentangling from each other and from the in-situ stars remains uncertain. Therefore, the aim of the paper is to investigate the structure of ancient mergers debris in a set of HESTIA\(^1\) cosmological simulations of the MW-type galaxies. (Grand et al. 2017) show that a small number of relatively massive destroyed dwarf galaxies dominate the mass of stellar haloes where 90% per cent of the mass in the inner 20 kpc is contributed by only three massive progenitors (Fattahi et al. 2020; Monachesi et al. 2019), however, the fraction of accreted stars is well below 1% in the galactic center (see also Fragkoudi et al. 2020). Fattahi et al. (2019) find that around 1/3 of the simulated galaxies have a significant population of stars which resemble the Gaia-Sausage structure at low-[Fe/H]. Grand et al. (2020) found evidence that the “Splash”-like component is produced from a gas-rich merger that dynamically heats stars from the Milky Way proto-disc onto halo-like orbits (see, also, Belokurov et al. 2020).

\(^1\) https://hestia.aip.de
logical simulations of the Local Group (LG). In particular, we analyse a set of six galaxies from three high-resolution HESTIA simulations (Libeskind et al. 2020). These simulations were tailored to reproduce the LG galaxies populations which resemble both realistic MW and M31 galaxies in terms of their halo mass, stellar disc mass, morphology separation, relative velocity, rotation curves, bulge-disc morphology, satellite galaxy stellar mass function, satellite radial distribution and the presence of a Magellanic cloud-like objects (Libeskind et al. 2020) thus making the HESTIA simulations the best tool for studying the assembly history relevant for the MW and M31 galaxies.

In a series of works based on a new set of the HESTIA high-resolution cosmological simulations of the Local Group galaxies we investigate the impact of the ancient mergers on the in-situ stellar populations (Khoperskov et al 2022a, hereafter Paper I) and the chemical abundance patterns as a function of stellar ages and kinematics of both accreted and in-situ stellar populations (Khoperskov et al 2022b, hereafter Paper III). In this paper, we investigate the present-day phase-space structure and evolution over time of the mergers debris in six M31/MW analogues from the high-resolution hydrodynamical HESTIA simulations.

The paper is structured as follows. The HESTIA simulations are briefly described in Section 2 where we also provide the merger histories and morphology of the stellar debris. In Section 3 we present stellar debris of the mergers in the integrals of motions. In Section 4 we present the Gaia-Sausage-like features in the HESTIA galaxies. Section 5 describes the action space and orbital properties of the mergers debris. In Section 6 we discuss the dual nature of the kinematically-defined stellar haloes. Finally, in Section 7 we summarise our main results.

2. Model

2.1. HESTIA simulations

In this work we analyze the three highest resolution HESTIA simulations of the LG. Each simulation is tailored to reproduce a number of the LG properties (Libeskind et al. 2020), including the massive disc galaxies resembling the Milky Way and Andromeda analogues with the population of smaller satellites at $z = 0$. 

Fig. 2. Same as Fig. 1, but merger debris are shown at $z = 0$ instead of at the time of accretion. At this time they appear well phased-mixed with some structure found for the most recent events. Note also that earlier mergers seem to be more compact compared to the later ones.
Fig. 3. Energy-angular momentum relation for the stellar remnants of the five most significant mergers (M1,...,M5; see Fig. 4 in Paper I) at the time of accretion (blue contours) and at $z = 0$ (red contours). The merger accretion time, $\log_{10}(M_\ast)$, and the stellar mass ratio, $\mu_\ast$, relative to the main M31/MW progenitor, are shown in the bottom of each panel. The colorbar represents stellar density, in units of $M_\ast/kpc^2$. Since the total host mass increases over time, the initial $L_z - E$ distributions have lower energies (upper half in each panel), while at $z = 0$ clumps at higher $|E|$. The density maps are transparent to distinguish the overlap for some of the most recent mergers. Both the energy and angular momentum of accreted systems are not conserved after the time of accretion, as often assumed in the literature. This energy change is caused by the mass growth of the host galaxy and the angular momentum transformations are due to the non-axisymmetric time-dependent potential of the galaxy with a certain contribution from the population of satellites orbiting the host.

The HESTIA simulations are performed by using the AREPO code (Springel 2005; Pakmor et al. 2016) where gravitational forces are computed using a hybrid TreePM technique (Springel 2005). The HESTIA simulations use the galaxy formation model from Grand et al. (2017), which is based on the Illustris model (Vogelsberger et al. 2013), and implements the most important physical processes relevant for the formation and evolution of galaxies. HESTIA simulations assume a cosmology consistent with the best fit values (Planck Collaboration et al. 2014): $c_s = 0.83$ and $H_0 = 100 \, h \, \text{km} \text{s}^{-1} \text{Mpc}^{-1}$ where $h = 0.677$. We adopt $\Omega_M = 0.682$ throughout and $\Omega_\Lambda = 0.270$ and $\Omega_b = 0.048$. Halos and subhaloes are identified at each redshift by using the publicly available AHF halo finder (Knollmann & Knebe 2009). For more details we refer the reader to the HESTIA simulations introductory paper (Libeskind et al. 2020) and Paper I.

In the rest of the paper, the term “in situ” refers to the stars formed in the most massive M31/MW galaxy progenitor, while “accreted” stars formed in other galaxies, which are then accreted onto the most massive one (see, e.g. Fattahi et al. 2020; Agertz et al. 2021).

3. Merger remnants in the energy-angular momentum space

3.1. Morphology of the merger debris

Before analysing the merger debris in various phase-space and energy-momentum coordinates, we take a look at the morphol-
Fig. 4. Block of top three rows: energy-angular momentum relation for all stars (first row), in-situ stars (main progenitor, second row), and accreted stars (third row) at $z = 0$. To focus on the stellar halo we select only stars with $|z| > 1$ kpc (away from the disc mid-plane). The corresponding stellar mass is shown in the bottom right of each panel. Block of bottom five rows: $L_E$ relation for the five most significant mergers at $z = 0$ ($M1, ..., M5$; see Fig. 4 in Paper I). Time of the merger, $\log_{10}(M_*)$, and the stellar mass ratio, $\mu_*$, relative to the main $M31/MW$ progenitor, are shown in the bottom left of each panel. All colorbars represent stellar density, in units of $M_\odot$. In-situ stars, being kicked out from the plane, show some net rotation with some overdensities/features similar to those of the accreted stars. The latter ones contain a number of overdensities, which are the relics of the different merger events. Some individual merger remnants are represented by a number of features/overdensities.

At redshift zero, most of the merger debris look flattened towards the galactic plane of the host galaxy, smooth stellar ellipsoids (see Fig. 2). Only a few debris are not featureless, which is typical behaviour for unrelaxed remnants from relatively recent mergers. Another interesting behaviour is that more ancient mergers tend to be more compact while more recent debris exhibit streams, tails and, in general, a more complex morphology. This morphological diversity of the remnants is likely because the galaxies merged at early epochs simply do not have enough time to evolve into internally-complex objects. Also, to be accreted earlier, they should appear relatively close to the main progenitor with a peculiar velocity much smaller than the escape one. The galaxies that merged later have more time to grow and, thus, they can have a more complex and long-term orbital evolution around the host galaxy ($M31/MW$).

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Fig. 5. Overlap of debris from different mergers in the $L_z$–$E$ plane. Each pixel is colored by the number of merger events contributing to that region, as given in the color bar. Top row: debris from all mergers for each HESTIA galaxy, as indicated above each panel. The maroon color corresponds to the largest overlap of mergers. Bottom row: Same as top row, but limited to the five most significant mergers. These maps suggest that the most crowded region of the $L_z$–$E$ space corresponds to the non-rotating region, which is where the Gaia-Enceladus merger was identified (Helmi et al. 2018). The number of debris decreases in the regions of substantial rotation.

Fig. 6. Energy-angular momentum relation for each of the two most significant mergers at $z = 0$ per galaxy in our sample: the left two columns show the density distributions of each of the two mergers, the middle two columns are colour-coded by the mean distance, $R_0$, of stars inside the dwarf galaxies before they accreted, and the two rightmost columns show the mean stellar age. This figure demonstrates that even a single merger event could result in a number of overdensities in the $E$–$L_z$ space. More recent events tend to show more substructures however even 9 – 10 Gyr ago merger remnants are not featureless at $z = 0$. The $R_0$-gradient suggests how the internal structure of dwarf galaxies is being mapped into the $L_z$–$E$ space once the system is accreted.
Fig. 7. Top: the mean age of stars accreted from the five most significant mergers as a function of galactocentric distance, $R_{\text{gal}}$, at $z = 0$. Bottom: corresponding age distributions, color-coded as above. The strongest burst of star formation is typically for the youngest stars in a given merger, thus corresponding to the time of accretion. Age estimates for accreted stars can, therefore, be used to time each merging event.

3.2. Evolution of the $L_z - E$ distribution

We demonstrated that since the merger time, the morphology of the merger debris changes drastically, where coherent tidal structures and streams are completely phase-mixed (see Fig. 1 and 2). We remind the reader that in the case of axisymmetric and time-independent gravitational potential, a given merger debris is expected to remain clustered in the $L_z - E$ coordinates if the dynamical friction is not taken into account (Jean-Baptiste et al. 2017). However, we already showed that the main M31/MW progenitors acquire a substantial amount of their mass since the very first mergers (see Fig. 4 in Paper I), suggesting that, at least, the energy of the stellar merger remnants can be changed, thus, affecting the initial phase-space configuration.

In order to study the impact of the galaxy mass growth on the merger debris in Fig. 3 we show the $L_z - E$ distribution for five of the most significant mergers. Each panel shows the distribution at the time of the merger (upper distributions, blue contours) and at $z = 0$ (bottom distributions, red contours). The vertical displacement in Fig. 3, or the energy change, is explained by the mass growth of the host. At early times a dwarf galaxy is being accreted into a low mass M31/MW progenitor and, thus, has larger energy in a shallow potential. Later on, the mass of the host galaxy increases (due to accretion of other systems and
Fig. 8. Top block of three rows: Stellar density distributions in the $V_R$-$V_{\phi}$ plane at redshift zero for stars in the range $1 < R_d < 3$ ($R_d$ is the disc scale-length) and $|z| > 2$ kpc including all stars (first row), only in-situ stars (second row), and only accreted populations (third row). The mass fractions of in-situ and accreted populations are shown at the bottom of the second and third rows, respectively.

Bottom block of five rows: as above, but for the five most significant mergers at $z = 0$ (M1,...,M5; see Fig. 4 in Paper I). Time of the merger, $\log_{10}(M_*)$, and the stellar mass ratio, $\mu_*$, relative to the main M31/MW progenitor are shown in the bottom left of each panel. The color-bar represents density and is in units of $M_\odot$ yr$^{-1}$ kpc$^{-2}$. All M31/MW HESTIA galaxies demonstrate the presence of Gaia-Sausage-like features, which, however, exhibit different individual shapes and radial velocity ranges.

Gas) and the total energy of the debris decreases. Thus, the mass growth of the main progenitor plays an essential role in the evolution of the total energy of any merger remnant. Another effect contributing to the change of the total energy is dynamical friction which is, however, the most important at the early phases of the merger when the cores of dwarf galaxies are still dense enough.

Another interesting feature seen in Fig. 3 is that the mergers debris do not conserve their initial (at the time of accretion) angular momentum $L_z$ distribution. The evolution of the angular momentum distribution can be understood because the galaxies are non-axisymmetric, and the potential is constantly perturbed by orbiting satellites. In this context, it is worth mentioning the work by Dillamore et al. (2022) where by using the ARTEMIS...
set of 45 high-resolution cosmological simulations the authors found a transformation of the merger debris caused by subsequent accretion of dwarf galaxies. Although most of the mergers show a little net rotation, we can see that the tails of the distribution may change the direction of rotation (see, e.g. M3 mergers in 09-18 M31/MW, M2 and M3 in 17-11 M31 and M4 in 37-11 MW). More generally, most of the different debris contribute to slowly co- or non-rotating stellar components near $L_z \approx 0$ where they overlap with each other. This overlap suggests that different merger remnants can not be disentangled from each other, at least by using their distribution in the $L_z - E$ plane at $z = 0$.

### 3.3. Individual mergers and in-situ stars in $L_z - E$

Next, we provide the structure of the $L_z - E$ space of the stellar haloes in the M31/MW HESTIA galaxies, including in-situ, all the accreted populations and some individual merger debris at $z = 0$. In Fig. 4 (top) we show $L_z - E$ plane for all the stars $> 1$ kpc away from the galactic plane at $z = 0$. In-situ stars (formed inside the main progenitor) are shown in the second row, and the third row corresponds to all accreted populations. Overall, the $L_z - E$ distributions look quite similar for all the M31/MW galaxies suggesting that slightly different accretion and mass growth histories (see Fig. 4 in Paper I) result in a rather similar halo composition. Using a simple spatial cut, we find the mass of accreted stellar components in the range of $34 - 61\%$ of the total stellar mass $> 1$ kpc away from the galactic plane. Therefore, about a half of stellar mass is made of the in-situ stars ($1.3 - 8 \times 10^8 M_\odot$).

Interestingly, the accreted stars $L_z - E$-distributions look very similar to all stars distributions making an impression that accreted stellar populations visually hide the in-situ halo, which, as we already showed in Paper I (see, also Gómez et al. 2017), is composed of the disc stars heated up by the mergers. Compared to the in-situ stars, the accreted populations span over the larger range of $L_z$ dominating in the counter-rotating tail ($L_z < 0$) of the distribution. Nevertheless, the averaged kinematics of the accreted stars shows slightly co-rotating or non-rotating behaviour, similar to the one observed in the MW. A single exception here is the MW galaxy from the 09-18 simulation where a very prominent counter-rotating debris appears (M5) as the result of a rather recent (3.7 Gyr ago) and massive (stellar mass $10^{9.5} M_\odot$) accretion event.

Another feature is that the accreted stars show a number of small-scale clumps or elongated overdensities (see, also, Helmi & de Zeeuw 2000; Choi et al. 2007; Morrison et al. 2009; Gómez et al. 2010; Re Fiorentini et al. 2015; Amarante et al. 2022) while the distributions of the in-situ stars seem to be almost featureless (except for the very high energies), suggesting that the individual mergers do not produce coherent substructures made of in-situ stars (but see Jean-Baptiste et al. 2017, regarding the substructures made of in-situ stars). The individual merger remnants distributions (4th to 8th rows in Fig. 3) show that not every particular feature in the $L_z - E$ plane corresponds to any particular merger debris. Almost all the merger remnants (with no exceptions) contribute to a non-rotating region ($L_z \approx 0$) and, at the same time, depict a number of different overdensities. Of course, more prominent features are made of the debris from the most recent mergers; however, even the very early mergers (from $9 - 10$ Gyr ago) show some distinct substructures. In some cases, the individual merger debris depict a sequence of small-scale overdensities or group of clumps along the energy axis while being stretched along the angular momentum.

To discuss more the overlap between the merger debris in Fig. 5 we show the $L_z - E$ plane colour-coded by a number of merger debris that can be found in a given range of parameters. The top row corresponds to all the merger debris we have identified, while the bottom row shows the maps based on the five most significant M1, ..., M5 mergers. The general trend is that most of the mergers contribute to the parameters of stellar halo with no prominent rotation, where the GSE merger remnant is found in the MW (see, e.g. Belokurov et al. 2018; Helmi et al. 2018; Belokurov et al. 2020; Naidu et al. 2020), while the edges of the $L_z - E$ distribution show the presence of a fewer number of merger debris. Roughly the same picture is observed for the most significant mergers (see bottom of Fig. 5).

### 3.4. Dissecting of individual debris in the $L_z - E$ by age and origin

Although it is expected that merger debris should be clustered in integrals of motion space (e.g., $L_z - E$), we have shown that
Fig. 10. Radial structure of the azimuthal velocity distribution for all stars (first row), in-situ (second) and accreted populations (third row) taken >1 kpc away from the galactic plane. All other rows below (4th to 8th) correspond to the most significant merger remnants. Time of the merger, \( \log_{10}(M_\ast) \) and the stellar mass ratio \( \mu_\ast \) relative to the main M31/MW progenitor are shown in each panel. Magenta lines in the individual merger debris distribution show the dispersion level along the radius. In-situ stars rotate faster around the galactic center and show the presence of diagonal ridges similar to the ones discovered in the MW (Antoja et al. 2018) which are likely to be the manifestation of spiral arms (Khoperskov & Gerhard 2021) and/or bar resonances (Fragkoudi et al. 2019). Accreted stars depict a number of radially-extended structures with no net rotation and multiple co- and counter-rotating components and small-scale overdensities. The important feature of the individual merger debris is that the azimuthal velocity dispersion remains nearly constant along the galactocentric distance, except for the innermost parts of the galaxies.

in the HESTIA galaxies, particular merger debris occupy a wide range of parameter space and consists of several prominent overdensities. Next, we focus on the variations of parameters across the merger debris in \( L_z - E \) coordinates. In Fig. 6 for each galaxy in our sample for simplicity we show two individual merger debris in \( L_z - E \) coordinates (first and second rows). The next two columns (third and fourth) show the distribution of the mean distance relative to the centre of a dwarf galaxy before the merger that results in a given stellar remnant. In other words, these columns show how far from the centre were the stars inside the dwarf galaxy before it merged into the host galaxy. The last two
Fig. 11. Top: X-Z projection of in-situ (left) and all accreted stars (middle) and survived satellites (right) in 09-18 M31 galaxy at $z = 0$. Density maps and the action space analysis are based on the stars (accreted and in-situ) > 1 kpc away from the galactic plane. Different survived satellites are shown in different colours. Second row: $J_z - J_r$ plane for in-situ (left), the fraction of accreted stellar mass (center) and survived satellites (right). Third row: $(J_r - J_z)/J_{tot} - J_\phi/J_{tot}$ plane for in-situ (left), fraction of accreted stellar mass (center) and survived satellites (right). Bottom row: $\sqrt{J_r - J_\phi}$ plane for in-situ (left), fraction of accreted stellar mass (center) and survived satellites (right). While both in-situ and accreted stars do not show any prominent features in the action space, the dwarf satellites, as expected, are seen as coherent structures. Accreted stars have on average larger radial and vertical actions but still substantially overlap with the in-situ populations at smaller values.
Fig. 12. Actions space for five of the most significant merger remnants in 09-18 M31 galaxy. From top to bottom: X-Z density maps, \( J_z - J_R \) space, \( (J_r - J_z)/J_{tot} - J_\phi/J_{tot} \) plane and \( \sqrt{J_r - J_\phi} \) plane. Similar to Fig. 11 where we presented the entire accreted population, the individual merger debris completely fill the \( (J_r - J_z)/J_{tot} - J_\phi/J_{tot} \) plane, where, nevertheless different remnants peak at slightly different regions of the diagram depending on the orbital parameters. The interesting feature, seen in the second row, is that the merger remnants show a different ratio of \( J_z \) and \( J_R \). Some substructures, however, can be seen at the very large radial/vertical actions, which correspond to the outer parts of the debris where the dynamical time is longer and, thus, phase mixing is not yet completed for the most recent mergers at \( z = 0 \).

Columns in Fig. 6 show the mean stellar age distribution of the individual mergers in \( L_z - E \) coordinates. Fig. 6 highlights that even a single merger can result in several prominent groups of stars isolated from each other in \( L_z - E \) space. In most cases, these groups can be found along the smooth density distribution stretched along the total energy. The next two columns show that stars in different \( L_z - E \) parts arrive from different distances inside the dwarf galaxy prior to the merger. In particular, the smallest total energy stars at \( z = 0 \) were captured from the outer parts of dwarf galaxies. The outer parts of the dwarf galaxies being less bound are captured earlier and do not penetrate much to the center of the host, thus building the (relative) outer parts of the stellar halo. The central parts of the...
Fig. 13. Density distribution in the $\Theta = \arctan(J_z/J_r)$-eccentricity plane for all stars (first row), in-situ (second row) and all accreted populations (third row). All other rows below (4th to 8th) correspond to the most significant merger remnants. The eccentricity values are multiplied by the sign of the angular momentum; thus, the counter-rotating stars have negative values of eccentricity and can be found in the right relative to the vertical magenta lines. To sharpen the structures, we present here only the stars located in the $(1-2)R_d$ radial range, where $R_d$ is the disc scale length. The figure shows how the anisotropy of actions correlates with the orbital eccentricity for different populations. The in-situ stars distribution shows the presence of vertically-cold (low $\Theta$ angles), low-eccentricity stars representing a disc component; at higher eccentricities, $\Theta$ remains roughly the same. The accreted stars distribution is even more interesting, where there are many substructures, and the overall distribution is different from the in-situ stars; moreover, different merger debris, in many cases, show different behaviour. The individual merger debris (4th to 8th) do not represent the entire complexity of the $\arctan(J_z/J_r)$-eccentricity space which is more complex in the third row where all the merger debris are taken into account.

The mean age maps in Fig. 6 (rightmost columns) seem do not imply a unique picture. However, in most cases, we can notice the age gradient as a function of the total energy. In particular, relatively older stars from the outer parts of dwarf galaxies appear to sink towards the center of the host galaxy due to dynamical friction where they have the smallest total energy. As the result, these populations dominate in the low-$E$ regions of the $L_z-E$ space.
tend to occupy the upper parts of the $L_z - E$ distribution while the mean age decreases towards the lower values of the total energy. Coupling this information with the previous result, one can explain the observed trends. Before the merger, stars formed earlier in the “upside-down” regime occupy the outer parts of dwarfs galaxies; therefore, once the galaxy is being accreted, these older stars are stripped first and appear at larger energies inside the host. At the same time, the cores of dwarf galaxies could have a more extended star formation history and, thus, be younger or, at least, have a larger fraction of younger stars. Therefore, being dragged towards the central parts of the hosts the stars from the cores of the dwarf galaxies populate lower energy levels where the mean age of stellar debris is relatively smaller. Of course, the strength of the age gradient in the $L_z - E$ space is rather low, especially for the very early mergers (see, e.g. the MW galaxy in the 17-11 simulation). However, typical age uncertainties for oldest MW stars may not allow to capture the age gradient of the merger debris but some parameters of stellar populations can change very quickly with the stellar age, e.g. chemical abundances (see the metallicity analysis in Paper III), and, thus can be detected in the observational data.

To explore a bit more on the age variations of the merger debris in Fig. 7 we show the mean stellar age as a function of the galactocentric distance (top) and the overall age distributions (bottom) for the individual merger debris. First, we confirm the results seen in the previous figure where the inner parts of the mergers debris tend to be younger (see also Monachesi et al. 2019). There is a number of exceptions, probably depending on the details of a particular merger evolution. However, the age gradient tends to be larger for the most recent mergers. Once we consider the overall age distribution (or the star formation history, see bottom of Fig. 7), we notice a substantial increase in the star formation rate just before the merger. Some merger remnants show a few peaks, possibly related to the pericentric passages (see, e.g. Di Cintio et al. 2021). This suggests that, in most cases, the age of the youngest stellar populations can be used as a proxy of the merger time, however, for better estimates, the stars from the inner galaxy should be considered (see also Monachesi et al. 2019; Dillamore et al. 2022).

If the relations we observe in the HESTIA galaxies are relevant to the MW, this may affect some of the conclusions regarding the merger history of the MW. In particular, the mean age of the GSE progenitor can be overestimated because its measurements are based on the stars in the solar suburb (see, e.g. Gallart et al. 2019; Feuillet et al. 2021; Borre et al. 2021; Montalbán et al. 2021), however, the youngest stars of the GSE will likely appear in the innermost galaxy, which is yet poorly covered by the existing spectroscopic surveys and the stellar age information is even more limited in that regions. Therefore, once we extend the analysis of the MW stellar halo towards its innermost regions, we may constrain even better the age distribution (and thus the merger time) of the GSE and possibly even infer the star formation history of its progenitor.

4. Gaia-Sausage-like features in HESTIA galaxies
4.1. Emerging of the Gaia-Sausage-like debris

We already mentioned in the Introduction that the last significant merger (GSE) in the MW was initially discovered as a horizontally-aligned structure in the $V_R$-$V_\phi$ coordinates with zero net rotation ($V_\phi \approx 0$) for low-[Fe/H] stars (Gaia-Sausage, Belokurov et al. 2018). Therefore, it is worth testing how much the HESTIA simulations able to reproduce this particular feature in a pure kinematic space. In Fig. 8 we show the density distribution in the $(V_R, V_\phi)$-plane for stars located in the radial range of $(1 - 3)R_d$ ($R_d$ is the disc scale length) and $> 1$ kpc away from the galactic mid-plane. In the plot, we also separate in-situ (second row) and accreted stellar populations (third row). In the adopted region the accreted halo constitutes from 34 to 81% of the mass while the rest is represented by the heated in-situ stars. First, we notice that in the M31/MW HESTIA galaxies, in-situ stars are represented by a single blob whose tail however spans to $V_\phi \leq 0$ km s$^{-1}$ (or even below in the case of the M31 galaxy in the 09-18 simulation). The in-situ stars distribution is almost featureless and shows a behaviour typical for thick-disc stars,
Fig. 15. Toomre diagram for all stars in \((1 - 3)R_d\) (\(R_d\) is the disc scale-length) and \(|z| > 2\) kpc (first row), in-situ stars (second row) and all accreted populations (third row). The mass fraction of in-situ and accreted populations are shown at the bottom in the second and third rows, respectively. Five rows below the gap correspond to the Toomre diagram for five of the most significant mergers at \(z = 0\) (M1,...,M5; see Fig. 4 in Paper I). Time of the merger, \(\log_{10}(M^*)\) and the stellar mass ratio \(\mu^*\) relative to the main M31/MW progenitor are shown in the bottom left of each panel. The colorbar is in \(M^*\) scale. The white circle corresponds to the thick disc selection: \(V_{\text{circ}} = \frac{180}{240} \text{km s}^{-1}\), where \(V_{\text{circ}}\) is the circular velocity value at \(2R_d\) for each galaxy, 180 km s\(^{-1}\) corresponds to the selection made for the Milky Way and 240 km s\(^{-1}\) is the Milky Way circular velocity. We suggest that the disc-like regions in the Toomre diagram are populated by the accreted stars. A single debris spans over a large volume, and, in some cases, the bulk of the accreted stars have (thick) disc-like kinematics.

however, with some asymmetry in 09-18 M31 and 17-11 M31 galaxies, caused by the very recent mergers (see Fig. 4 in Paper I).

The accreted stars distributions in the \(V_R-V_\phi\) plane are much more interesting. In particular, we notice the presence of multiple distinct kinematic components with a certain level of similarity between the galaxies. The morphology here can be described as a blob on top of the horizontally-aligned structure(s). The blobs for accreted stars have a larger radial velocity range compared to the in-situ populations and lower median azimuthal velocity (except for 37-11 MW where the \(\langle V_\phi \rangle\) are essentially
the same). This demonstrates a smooth transition from fast rotating in-situ stars to slower accreted ones.

Obviously, the most striking features in the accreted density distribution are the horizontally-aligned structure(s). The third row in Fig. 8 shows a diverse morphology of slowly-rotating components, which one can be described as horizontal features with zero (17-11 M31, 17-11 MW, 37-11 MW; similar to the Gaia-Sausage) and negative (37-11 MW) net rotation; and positively (09-18 M31) and negatively (09-18 MW, 37-11 MW) bent moustache-like features. Note that in the 37-11 MW galaxy we can directly identify two prominent features below the high-velocity dispersion ovals which have different but mostly positive (or prograde relative to the host component) bulk rotation. Gaia-Sausage-like horizontally-aligned features are rare in a given galaxy and they tend to correspond to the most recent mergers (09-18 M31/MW, 37-11 M31). In 17-11 MW galaxy accreted stars show a Gaia-Sausage-like feature but the corresponded merger is very recent (1-2 Gyr ago) with the relative mass smaller than M1, ..., M5 mergers.

The MW galaxy from the 37-11 simulation is an exceptional case because at least 4 (M1-M4) merger remnants are seen as flattened structures in the V_R-V_φ plane, with different bulk V_φ. In this galaxy, the relative mass of the mergers decreases with time thus each subsequent merger introduces less perturbation to the structure of the previous ones. More likely, the mergers are to be accreted with some angular momentum and settle in the galaxy with a certain bulk V_φ. Later on, the following mergers perturb the galaxy by heating up all the previous debris thus leading to an increase in the velocity dispersion, also in the azimuthal direction. Therefore, the transformation from the horizontally-aligned structures in the V_R-V_φ space can be caused by the subsequent mergers.

So far, we have presented only the most significant mergers; therefore, the V_R-V_φ space for accreted stars decomposition is not complete, and the variety of kinematic structures is not fully explored. In order to show a diversity of the accreted populations in the V_R-V_φ space, in Fig. 9 we show two different merger debris in each HESTIA galaxy which results in the structures the most similar to the Gaia-Sausage. Although we have a very large sample of mergers (> 60 for all the galaxies) we can see that only a single merger remnant from the MW in the 37-11 (see bottom right) simulation match precisely the Gaia-Sausage kinematics.

In order to understand the radial structure of accreted populations and the merger debris in Fig. 10 we show the stellar density map in (R,J_φ) plane for all the stars, in-situ, accreted and individual merger remnants for stars > 1 kpc away from the disc plane. The figure reveals a number of radially-extended nearly-horizontal overdensities which at large distances from the center occupy rather narrow V_φ ranges, and the azimuthal velocity dispersion (magenta contours) remains roughly constant along the radius. Some of the debris show a fine structure with some clumps or diagonal overdensities. Note an important difference between these accreted structures and the diagonal (R,J_φ)-ridges, discovered by the Gaia (Antoja et al. 2018). In HESTIA galaxies, accreted components have nearly constant V_φ while the (R,J_φ)-ridges typically have nearly constant energy/angular momentum (Ramos et al. 2018). Fig. 10 also suggests that the Galactic center is a very crowded region because all the different merger debris contribute there. However, the outer disc seems to be a promising region for the analysis of accreted components. Taking into account similarities between some individual merger remnants in Fig. 8 and the Gaia-Sausage structure one could expect that in the MW, the accreted populations should be seen as radially extended structures with certain values of the azimuthal velocity depending on the orbital parameters of the merger (see, e.g. recent works by Naidu et al. 2020; Amarante et al. 2022).

5. Action space (J_r, J_z, J_φ) and orbital analysis

In this section, we analyze the orbital composition and axisymmetric actions of the stellar component of the HESTIA galaxies. For all star particles, we have reconstructed their orbital eccentricity by integrating their orbits in the fixed galactic potential at z = 0 using the AGAMA code (Vasiliev 2019) which was also used to compute the actions (J_r, J_z, J_φ).
5.1. Action space for in-situ, accreted stars and satellite galaxies

The previous section demonstrated that the accreted stellar populations have a complex structure in $L_z - E, V_r-V_z, (R, \nu_\phi)$. In these kinematic coordinates, the mergers debris overlap with each other and with the in-situ stars heated up by merging events. In this section, we focus our analysis on the orbital actions, which are conserved under adiabatic changes of the gravitational potential of a galaxy (Binney & Tremaine 2008) and, thus, the merger debris should be clustered in the actions space. Although we already demonstrated that the last assumption is not exactly applicable for the HESTIA galaxies, it is still worth testing what we can learn about the mergers debris structure in the action space.

This section only analyses the M31 galaxy in the 09-18 M31 simulation; however, we have tested that the results are similar to other M31/MW HESTIA galaxies. For the reference, in Fig. 11 (top row) we show the $X = Z$ density distribution for the in-situ and all accreted stars at $z = 0$ together with a population of survived satellites (different colours correspond to different dwarf galaxies). Since we focus on the stellar halo, we remove from our sample in-situ and accreted stars located close to the galactic mid-plane ($|z| < 1$ kpc) where the disc stars dominate and the impact of spiral arms and bar is more important in shaping the orbital actions space (Trick et al. 2017, 2021).

In the second row of Fig. 11 we show the mass distribution for the in-situ stars (left) which are mostly confined near $J_z > 1000$ km s$^{-1}$ kpc$^{-1}$. In contrast to the smooth halo component, represented by the in-situ and the merger debris, despite some overlap, survived satellites demonstrate a clear clustering in the $(J_z, J_\phi)$ space (rightmost column in Fig. 11). We notice the clustering of the satellites in other actions spaces $(J_z - J_\phi)/J_{tot} - J_\phi/J_{tot}$ and $\sqrt{J_z - J_\phi}$; however, this analysis does not deliver much information since the satellites are the distinct objects in galactic halo (top right of Fig. 11).

Similar to $(J_z, J_\phi)$, we do not detect any prominent substructures of the merger debris neither in $(J_z - J_\phi)/J_{tot} - J_\phi/J_{tot}$ nor $\sqrt{J_z - J_\phi}$ coordinates, however, the fractional distribution of accretes stars allows to use of the actions space to disentangle between accreted and in-situ stars which substantially overlap in $L_z - E$ and other phase-space coordinates (see Sec. 3 and 4). This is better seen in $\sqrt{J_z - J_\phi}$ coordinates where stars above $\sqrt{J_z} > 0.3-0.4$ km s$^{-1}$ kpc$^{-1}$ certainly represent accreted populations. Nevertheless, we suggest that the application of advanced clustering algorithms in the actions space taking into account the chemical abundances of stars will make it possible to differentiated the merger remnants.

5.2. Individual merger debris in the actions space

In order to test how different mergers are mapped in the actions spaces, in Fig. 12 we show the stellar mass distribution for five of the most significant mergers (M1, ..., M5) from the M31 galaxy (09-18 simulation) in $XZ, (J_z, J_\phi), (J_z - J_\phi)/J_{tot} - J_\phi/J_{tot}$ and $\sqrt{J_z - J_\phi}$ coordinates. There is no much diversity in the morphology of the merger remnants at $z = 0$ however, different mergers show a certain level of differentiation in $(J_z, J_\phi)$ space. One can notice that the M5 merger is elongated in the galactic plane having possibly larger radial (in cylindrical coordinates) motions. This is clearly seen in $(J_z, J_\phi)$ where the density distribution is stretched along the $J_z$ compared to the $J_\phi$. A more spherical remnant M3 has nearly equal distribution in both $J_z$ and $J_\phi$ actions. Finally, the M1 merger seems to be puffed-up perpendicular to the plane, and as a result, its $(J_z, J_\phi)$ distribution is more elongated in $J_z$ compared to $J_\phi$. Since all the merger remnants slowly co-rotate with the galactic disc in $(J_z - J_\phi)/J_{tot} - J_\phi/J_{tot}$, all M1, ..., M5 mergers mainly contribute to the right corner with complete overlap. A similarity in the net rotation is also evident from the $\sqrt{J_z - J_\phi}$ plane where, except for the tails of the distributions, all the mergers occupy essentially the same region being practically indistinguishable from each other. Note that the unmixed tidal tails of the merger debris can be captured in the actions space, e.g. M3 and M4 mergers, where some features outside the bulk of the distribution can be seen.

To summarize, the actions space analysis of the HESTIA galaxies does not allow us to isolate accreted stars from the in-situ in $(J_z, J_\phi), (J_z - J_\phi)/J_{tot} - J_\phi/J_{tot}$ and $\sqrt{J_z - J_\phi}$ coordinates. However, some action ranges can be used to capture the accreted stellar populations. Different mergers debris show some systematic differences in the above-mentioned coordinates despite a substantial overlap with each other. Since the dwarf galaxies are isolated substructures in the actions space, the overlap between accreted populations suggests that the gravitational potential of the HESTIA galaxies grows non-adiabatically and/or dynamical friction significantly affects the trajectories of stars in the merger debris. Nevertheless, we suggest that some information from the actions still can be used to identify the merger debris.

We already noticed some differences in the behaviour of the merger debris in $(J_z, J_\phi)$ space, where the ratio between vertical-to-radial actions correlates with the shape of the merger debris in the halo, which likely depends on the orbit of the infall and the internal structure of merging galaxies. For instance, for a disc-like component, one could expect that the distribution of stars is stretched along $J_z$, while a sphere should have a similar ratio of the $J_z, J_\phi$ actions. Therefore we can introduce the angle between radial and vertical actions characterizing the shape of the debris $\Theta = \arctan(J_z/J_\phi)$. At the same time, stars from different debris could have different eccentricities in the galactic plane, also depending on the merger parameters. In Fig. 13 we combine these two parameters and present the distribution of all stars (top row), in-situ (second row) and all accreted stars (third row) together with five individual merger debris with a higher stellar mass ratio relative to the main progenitor at the time of accretion (M1, ..., M5). In order to separate prograde from the retrograde stars, we multiply the eccentricity by the sign of the angular momentum. The figure shows the density distribution of stars located in the galactocentric range on $(1 - 2)R_d$. Fig. 13 reveals a lot of substructures where the in-situ stars tend to have lower $\Theta$ and rather low eccentricities (mainly < 0.5), which is a typical behaviour of a regularly rotating disky component. Meanwhile, the accreted component shows a diverse morphology with some isolated clumps or overdensities with nearly constant or slightly varying eccentricity. The most important feature here is that in many cases we can notice very different features typical for different merger debris, which, especially in combination with some other parameters or chemical abundances, can be used to clean the samples of accreted stellar populations.
5.3. Merger remnants: combining orbital parameters and actions

A number of recent studies suggest that highly eccentric orbits characterise the stars in the accreted MW halo population (> 0.85) (see, e.g. Deason et al. 2018; Helmi et al. 2018; Belokurov et al. 2020). This result is supported by the analysis of the EAGLE simulations which shows that dwarf galaxies with mass in the range 10^{8.5} – 10^{9} M_☉ accreted around z ≈ 1.5 would result in similar orbital parameters of the merger debris (Mackereth et al. 2019). In Fig. 13 we can see that the debris have a broad range of eccentricities where the mean value could be different for different mergers. Since the EAGLE simulations include all types of galaxies with a small fraction of the MW-type objects (Mackereth et al. 2018), it is worth investigating the eccentricity distribution of accreted stars in the HESTIA simulations, which were tailored to the LG galaxies.

In Fig. 14 (left), we show the mean eccentricity of stars accreted from different satellite galaxies as a function of the accretion time/redshift. In the figure, we present all the mergers in all the M31/MW HESTIA galaxies colour-coded by the stellar mass of the merger. In agreement with Mackereth et al. (2019), we find that more recent mergers have larger masses and result in a broad distribution of eccentricities in the debris. It is worth noticing that the mean eccentricity values are larger than ≈ 0.6 indeed. At the same time, the left panel makes somewhat a misleading impression suggesting that the merger debris result only in high-eccentricity stars. This becomes evident once we consider the distribution of eccentricities for all the stars in the mergers debris. In the right panel of Fig. 14 we present the distribution of the eccentricity for the individual mergers debris (grey) where the sign of the eccentricity is negative for stars with the negative angular momentum. We find that overall (red lines) about 10 – 30% of accreted stars have eccentricities below 0.5. This result shows that the accreted stars do not necessarily have large eccentricities, and more recent events are more likely to produce populations with a disc-like kinematics.

6. Dual nature of kinematically-defined stellar halo: in-situ vs. accreted populations

In this section we discuss the relations between in-situ and accreted components of the stellar haloes in the HESTIA galaxies. In particular, we focus our analysis on the kinematically-defined stellar haloes, which is done, similar to a number of similar studies (see, e.g. Nissen & Schuster 2010; Helmi et al. 2018; Koppelman et al. 2019), by using a Toomre diagram. In Fig. 15 we show the Toomre diagram for all stars (top row), in-situ stars only (second row) and all stars from the merger remnants (third row) at z = 0. To enhance the structure of the distributions in Fig. 15 we consider only stars located in (1 – 3) R_☉ which is roughly accessible for the MW large-scale surveys. In all the galaxies in our sample, the distributions on top show the presence of two distinct components, where one is centered near the LSR (V₀ = 200 km s⁻¹, disk). In contrast, the others tend to show slow prograde to retrograde rotation with a larger peculiar velocity. The latter one is mainly made of stars from disrupted dwarf galaxies – mergers, presented in the third row. The properties and formation paths of the in-situ stellar halo components are discussed in Paper I.

To define the stellar halo in the Toomre diagrams we introduce a threshold separating stars with a halo-like kinematics from stars with a disc-like kinematics. We estimate the LSR velocity value V_{LSR} for each disc galaxy as the mean circular velocity value in the (1 – 3) R_☉ radial range. For the kinematically-defined stellar halo we require a peculiar velocity component V_{pec} = \sqrt{V_{R}^2 + V_{φ}^2 + (V_{LSR} - V_{φ})^2} to be larger than V_{LSR} × 180 km s⁻¹ / V_{MW}, where V_{LSR} = 240 km s⁻¹ and 180 km s⁻¹ are the values adopted in the MW to separate disc from the halo (see, e.g. Di Matteo et al. 2019). The boundary between the halo and disc kinematics is shown by the white lines in all the panels of Fig. 15. Similar to a number of phase-space coordinates presented above, in Fig. 15 the individual mergers debris (fifth to eighth rows) have a diverse morphology, but, interestingly, most of them show a significant contribution to the region usually associated with the disc inside the white circle. Remind that we present only the structure of the most significant mergers while some others are missing, but their total contribution can be inferred from the third row. The structure of the Toomre diagrams in Fig. 15 shows that in a given radial range (1 – 3)R_☉ a lot of accreted stars (> 17 – 40%) contribute to the kinematically-selected disc and, in contrary, the in-situ populations (20 – 50%) can be identified as the stellar halo. Suppose these numbers are relevant for the MW. In that case, more work should be done in searching for the merger debris in the disc-like region of the Toomre diagram, also because in some cases, the individual merger debris is only deposited to this region (e.g., M3 in the MW 09-18, M2 in the M31 17-11, M5 in the 17-11 MW and so on).

Fig. 15 nicely illustrates the dual nature of the kinematically-defined stellar halo, where it is made of both accreted and in-situ stellar populations demonstrating the complexity of the stellar halo and how its components overlap and affect each other. We already showed that in most of the HESTIA galaxies, there are only a few massive mergers in each galaxy (see Fig. 4 in Paper I). At the same time, it is believed that the GSE merger is the biggest accretion event over the lifetime of the MW (Belokurov et al. 2018; Helmi et al. 2018). Therefore, we can test how much the most massive merger contributes to the accreted component of the kinematically-defined stellar halo. In Fig. 16 (top) we show the fraction of the most massive merger mass (M_{mass}) among all accreted stars as a function of the most massive merger mass. The figure shows that 20 – 70% of the accreted mass in the M31/MW-type disc galaxies comes from a single merger with a median value of about 40% and the fraction of a single merger is larger for more massive accretion ones. Note that the correlation does not depend on the definition of the accreted component (either total or kinematically-defined halo).

Finally, in the bottom panel of Fig. 16 we show how the fraction of the in-situ kinematically-defined stellar halo depends on the total accreted stellar mass. With a single exception, MW in the 37-11 simulation, we find a positive correlation, which is somewhat counterintuitive because, in this case, the fraction of accreted halo component is lower for more massive ex-situ halo. Therefore, more accreted material results in a more heavily perturbed disc which deposits more stars to the kinematically-defined halo. Since these relations are based on the constrained simulations of the LG, they can be used to estimate the total accreted mass once the in-situ halo is constrained, e.g. by using chemical abundances.

7. Summary

In this work, we analysed six M31/MW analogues in the HESTIA suite of cosmological hydrodynamics zoom-in simulations. All the galaxies experienced 1 – 4 significant mergers with stellar mass ratios between 0.2 and 1 (relative to the host), where all the
significant mergers (with a single exception) happen between 7 and 11 Gyr ago. We studied the merger debris using integrals of motions (total energy - angular momentum), phase-space coordinates, orbital parameters and actions. Focusing our analysis on the most significant merger debris, with the larger stellar mass fraction relative to the host galaxy at the time of accretion, we arrived to the following conclusions:

- Different stellar merger debris show a diverse morphology at the time of accretion, varying from streams and shell-like structures to smoothly-looking nearly-spherical distributions (see Fig. 1). At redshift zero, the vast majority of stellar merger debris have similar and almost featureless density distributions, flattened towards the disc plane; some exceptions were found for the most recent mergers, which show some unmixed substructures (see Fig. 2). More ancient merger debris are more compact compared to more recent accretion events, likely due to the mass-growth of the galaxy over time, deepening the potential well.

- The self-consistent cosmological HESTIA simulations suggest the $L_z - E$ distributions of individual merger debris evolve in time due to the host’s mass growth and its non-axisymmetric gravitational potential (see Fig. 4). Therefore, we demonstrate that neither the energy nor angular momentum of the merger remnants is conserved after the merger has concluded. In some cases, we observe a substantial change in the direction of the angular momentum and noticeable changes in the energy distribution of the stellar debris.

- We showed that merger remnants from a single event are not clustered in the integrals of motions space, but cover a large area in these coordinates. At the same time, however, the $L_z - E$ distributions are not featureless, as a single merger remnant often contributes to a few overdensities (see Fig. 4).

- By dissecting the $L_z - E$ distributions by age and the location inside dwarf galaxies before the mergers, we found that inside the host galaxy, the accreted stars with smaller total energy are typically older and acquired from the outer parts of the dwarf galaxies (see Fig. 7). This variation of parameters is translated into a prominent radial positive age gradient for individual merger debris. However, the mean age of the debris is largely biased towards the time of accretion because most of the mergers are accompanied by an enhancement of star formation. Moreover, the most significant bursts of star formation inside the merger debris correspond to the merger time. This result also suggests that in the Milky Way the merger time estimation can be done by using the age distribution of the stellar debris but the accreted stars from the innermost disc should be taken into account.

- The merger remnants show a diverse appearance in phase-space coordinates with some examples similar to the ones discovered in the Gaia data. In particular, the HESTIA simulations reproduce the Gaia-Sausage-like features in the $(V_\phi, V_R)$ plane with prominent non-rotating or weakly counter-rotating components (see Fig. 8). Moreover, in some cases, we can see the presence of more than one Gaia-Sausage-like feature (see Fig. 9). We also demonstrate that the local $(V_\phi, V_R)$ Gaia-Sausage-like features are the parts of large-scale radially-extended components traceable across the entire disk (see Fig. 10).

- Apart from the dwarf galaxies population, the merger debris do not show any isolated structures in the actions space being distributed over a large area, as well as overlapping with each other and in-situ stars (see Figs. 11, 12). However, we suggest that accreted stars can more likely be identified with the cut $\sqrt{J_x J_y} > 0.2 - 0.3$. We also proposed that some merger debris can be disentangled from each other in the $(J_x/J_y - orbital eccentricity)$ space. Nevertheless, we showed that the actions, once combined with the orbital parameters (e.g. eccentricity), demonstrate different behaviour for different merger debris, thus making it possible to disentangle accretion events (see Fig. 13).

- The accreted stars in HESTIA have a broad distribution of eccentricities, peaking at $\approx 0.6 - 0.9$. The mean eccentricity of the accreted stars correlates with the mass of the accreted dwarf galaxy and the time of accretion. In particular, more massive mergers and more recent ones result in the smaller eccentricity of stars at $z = 0$.

- Finally, we showed that identifying stellar haloes in the Toomre diagram selects both accreted and in-situ stars, which in total represent 45 – 65% of the stellar mass of the galaxy (excluding dwarf galaxies). The accreted component of such kinematically-defined stellar haloes is mainly made of a single merger ($\approx 40 – 50\%$). The in-situ mass fraction also correlates with the total accreted mass (see Fig. 16).

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References

Abadi, M. G., Navarro, J. F., & Steinmetz, M. 2006, MNRAS, 365, 747
Agertz, O., Renaud, F., Feldling, S., et al. 2021, MNRAS, 503, 5826
Amarante, J. A., S. Debbastia, V. P., Berardo e Silva, L., Laporte, C. F. P., & Deg, N. 2022, arXiv e-prints, arXiv:2204.12187
Anorisco, N. C. V. 2017, MNRAS, 464, 2882
Antoja, T., Helmi, A., R. Gómez, M., et al. 2018, Nature, 561, 360
Astropy Collaboration, Price-Whelan, A. M., Sipćı, B. M., et al. 2018, AJ, 156, 123
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Belokurov, V., Enkli, D., Evans, N. W., Koposov, S. E., & Deason, A. J. 2018, MNRAS, 478, 611
Belokurov, V., Evans, N. W., Irmig, M. J., et al. 2007, ApJ, 658, 337
Belokurov, V. & Kravtsov, A. 2022, arXiv e-prints, arXiv:2203.04980
Belokurov, B., Sanders, J. L., Fattahi, A., et al. 2020, MNRAS, 494, 3880
Binney, J., & Tremaine, S. 2008, Galactic Dynamics: Second Edition
Borg, C. C., Aguirre Borsen-Koch, V., Helmi, A., et al. 2021, arXiv e-prints, arXiv:2111.01669
Brook, C. B., Kawata, D., Gibson, B. K., & Flynn, C. 2003, ApJ, 585, L125
Brook, C. B., Stinson, G. S., Gibson, B. K., et al. 2012, MNRAS, 426, 690
Buder, S., Lind, K., Ness, M. K., et al. 2021, arXiv e-prints, arXiv:2109.04059
Bullock, J. S. & Johnston, K. V. 2005, ApJ, 635, 931
Chiba, M. & Beers, T. C. 2000, AJ, 119, 2843
Chiba, M. & Beers, T. C. 2001, ApJ, 549, 325
Choi, J.-H., Weinberg, M. D., & Katz, N. 2007, MNRAS, 381, 987
Cooper, A. P., Cole, S., Frenk, C. S., et al. 2010, MNRAS, 406, 744
De Lucia, G. & Helmi, A. 2008, MNRAS, 391, 14
Deason, A. J., Belokurov, V., Koposov, S. E., & Lancaster, L. 2018, ApJ, 862, L1
Deason, A. J., Mao, Y.-Y., & Wechsler, R. H. 2016, ApJ, 821, 5
Di Cintio, A., Mostogiou, R., Knebe, A., & Navarro, J. F. 2021, MNRAS, 506, 531
