The Formation History of the Milky Way disc with high-resolution cosmological simulations

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ABSTRACT
We analyse from an observational perspective the formation history and kinematics of a Milky Way-like galaxy from a high-resolution zoom-in cosmological simulation that we compare to those of our Galaxy as seen by Gaia DR2 to better understand the origin and evolution of the Galactic thin and thick discs. The cosmological simulation was carried out with the GADGET-3 TreePM+SPH code using the MUlti Phase Particle Integrator (MUPPI) model. We disentangle the complex overlapping of stellar generations that rises from the top-down and inside-out formation of the galactic disc. We investigate cosmological signatures in the phase-space of mono-age populations and highlight features stemming from past and recent dynamical perturbations. In the simulation, we identify a satellite with a stellar mass of $1.2 \times 10^9 \, M_\odot$, i.e. stellar mass ratio $\Delta \approx 5.5$ per cent at the time, accreted at $z \approx 1.6$, which resembles the major merger Gaia-Sausage-Enceladus that produced the Galactic thick disc, i.e. $\Delta \approx 6$ per cent. We found at $z \approx 0.5 - 0.4$ two merging satellites with a stellar mass of $8.8 \times 10^8 \, M_\odot$ and $5.1 \times 10^8 \, M_\odot$ that are associated to a strong starburst in the Star Formation History, which appears fairly similar to that recently found in the Solar Neighbourhood. Our findings highlight that detailed studies of coeval stellar populations kinematics, which are made available by current and future Gaia data releases and in synergy with simulations, are fundamental to unravel the formation and evolution of the Milky Way discs.

Key words: Galaxy: kinematics and dynamics – Galaxy: disc – galaxies: formation – galaxies: evolution – galaxies: star formation – methods: numerical

1 INTRODUCTION

Many of the chemo-kinematic properties of the Milky Way (MW) and nearby galaxies are related to events that occurred a long time ago. The aim of Local Cosmology is to provide a link between the local scenario at redshift $z = 0$ and the distant Universe (e.g. Freeman & Bland-Hawthorn 2002).

In the era of precision astrometry, opened by the impressive improvement given by the Gaia Second Data Release (DR2, Gaia Collaboration et al. 2018a), the comparison between observations and high-resolution cosmological simulations of MW-like disc galaxies becomes mandatory to create a coherent laboratory for Local Cosmology studies. The standard cosmological ΛCDM model predicts that our Galaxy formed through the hierarchical merging of substructures, whose accretion history can be inferred from the chemo-kinematic signatures that we observe today in the stellar populations of the Galactic bulge, halo, thick and thin discs. With the advent of cosmological hydrodynamical zoom-in simulations of MW-like galaxies, we are able to analyse in detail the complex interplay of physical processes (e.g. dynamics of collisionless systems, gas flows, star formation, stellar nucleosynthesis, ...) that generated our Galaxy, which represents the Rosetta stone of galaxy evolution.

Recently, several studies have confirmed that our Galaxy experienced $\sim 10$ Gyr ago a major merger with a massive dwarf galaxy, named Gaia-Sausage-Enceladus (GSE, Belokurov et al. 2018; Helmi et al. 2018; Di Matteo et al. 2019; Vincenzo et al. 2019; Gallart et al. 2019). According to these studies, the stellar inner halo is mainly made up of stellar debris from the accreted satellite and heated disc stars. However, the actual origin of the present thick disc is not clear and it is a still matter of debate whether it derives mainly from the kinematic heating of the proto-disc, or from a starburst triggered by merging events and fed by the infall of a
gas-rich satellite (Broek et al. 2004, 2012). An extensive review of the early accretion history of the MW is described by Helmi (2020), while detailed comparisons with the chemo-dynamical properties of cosmological simulations are presented by Minchev et al. (2013), Stinson et al. (2013), Buck et al. (2019) and Grand et al. (2020).

Other authors have also produced and analysed high resolution simulations in order to reconstruct the formation history of our MW: some of these studies are listed in Table 1. Here, we provide a detailed analysis of Aquila-C-4 (AqC4), a hydrodynamical cosmological simulation of a MW-mass galaxy based on the MUPPI algorithm (Murante et al. 2010, 2015). The AqC series of simulations has been presented by Springel et al. (2008) and used, among other papers, in the Aquila comparison project (Scannapieco et al. 2012). The validity of the MUPPI algorithm has been confirmed by several studies (e.g. Monaco et al. 2012; Goz et al. 2015; Valentini et al. 2017). It consists of an unconstrained simulation, i.e. it is not designed to exactly mimic the dynamic history of our Galaxy as in simulations aimed to reproduce the Local Group environment (see for example Sawala et al. 2016; Carlesi et al. 2016). Thus, according to the precepts of Local Cosmology, AqC4 results as a typical cosmological product with mass and phase-space properties similar to the MW, and with a merging history comparable to a disc-like galaxy.

In this paper, we aim to compare AqC4, namely a theoretical ‘error-free’ catalogue predicted for a Milky Way-like galaxy, to our Galaxy as seen by Gaia DR2 (Gaia Collaboration et al. 2018a). Therefore, the analysis presented in this work is carried out as if the simulation were a real stellar survey of our Galaxy and we focus on the phase-space properties of stellar particles contained in a simulated region representative of the Solar Neighbourhood. We characterize the spatial and kinematical parameters of the stellar disc and investigate the Star Formation History (SFH) of AqC4 for redshift $0 < z < 2$, in order to identify signatures of past and recent merging events that can be used to disentangle the accretion history of our Galaxy.

In Sect. 2 we describe the simulation and summarize its main parameters. In Sect. 3 we characterize the spatial distribution of particles, focusing on the radial and vertical structures of the stellar disc, i.e. determining its scale length and scale height. We investigate the mono-age populations in order to study the flaring of the stellar disc. In Sect. 4 we analyse the kinematic properties of AqC4. We study the global rotation curve of AqC4 and we make a direct comparison with recent observational data of the MW as seen by Gaia. Then, we focus on the substructures of the stellar disc in the region defined as the Simulated Solar Ring (hereafter SRR). In Sect. 5 we link our previous findings to the formation and evolution of AqC4; specifically, we extensively compare the Star Formation History of the simulation with recent estimates for the MW, and then we extend our investigation to the accretion history. Finally, in Sect. 6 we summarize our findings and discuss our results.

### Table 1. Cosmological hydrodynamical simulations of MW-like disc galaxies. Main properties of recent high resolution zoom-in simulations.

| Project        | Mass particle | Softening | Reference       |
|----------------|---------------|-----------|-----------------|
| Eris           | $M_{DM} \sim 1 \times 10^5$ | $\epsilon_s \sim 120$ | Guedes et al. (2011) |
| Auriga         | $M_{DM} \sim 3 \times 10^5$ | $\epsilon_s \sim 369$ | Grand et al. (2017) |
| GIZMO          | $M_{DM} \sim 3 \times 10^5$ | $\epsilon_s \sim 50$  | Ma et al. (2017)   |
| Illustris      | $M_{DM} \sim 7 \times 10^6$ | $\epsilon_s \sim 740$ | Nelson et al. (2018) |
| TNG100         | $M_{gas} \sim 1 \times 10^6$ | $\epsilon_{gas} \sim 185$ |       |
| EAGLE          | $M_{gas} \sim 4 \times 10^5$ | $\epsilon_{gas} \sim 223$ | Mackereth et al. (2019) |
| AqC4           | $M_{gas} \sim 7 \times 10^5$ | $\epsilon_{gas} \sim 223$ | This work |

![Table 1](https://example.com/table1.png)
(n = 0.01 cm\(^{-3}\)) and its temperature drops below a temperature threshold (T = 10\(^{5}\) K).

A set of ordinary differential equations describes mass and energy flows among different components within each multiphase particle: for instance, radiative cooling moves mass from the hot into the cold phase, while a tiny fraction of the cold gas evaporates due to the destruction of molecular clouds. We rely on the phenomenological prescription by Blitz & Rosolowsky (2006) to estimate the fraction of cold gas which is in the molecular phase and which fuels star formation. Star formation is then modelled according to the stochastic algorithm introduced by Springel & Hernquist (2003): as a consequence, a multiphase gas particle can generate (up to four generations of) star particles.

The MUPPI model features stellar feedback both in thermal and kinetic forms (as described in Murante et al. 2015). Besides stellar feedback in energy, star formation and evolution also result in a chemical feedback, and galactic outflows generated by supernova (SN) explosions promote metal spread and circulation within the galaxy (Valentini et al. 2017, 2018).

Our model accounts for stellar evolution and chemical enrichment following Tornatore et al. (2007), where a thorough description can be found. In summary, each star particle is considered to be a simple stellar population. Assuming an initial mass function (Kroupa et al., 1993), as well as predictions for stellar lifetimes (Padovan & Matteucci 1993) and stellar yields (see Murante et al. 2015, for details), we evaluate the number of stars aging and eventually exploding as SNe, and the amount of metals injected in the ISM. Heavy elements released by star particles are distributed to neighbouring gas particles. The chemical evolution of 9 metals (C, Ca, O, N, Ne, Mg, S, Si, Fe) synthesized by different sources (namely asymptotic giant branch stars, SNe Ia and SNe II) is individually followed. The model also features metallicity-dependent radiative cooling (following Wiersma et al., 2009), and includes the effect of an ionizing cosmic background (Haardt & Madau 2001).

3 SPATIAL DISTRIBUTION OF THE DISC

Fig. 1 shows the face-on and edge-on projected density of stellar (upper panels) and gas (lower panels) particles. The reference system used is centred in the minimum of the gravitational potential and rotated to be aligned with the angular momentum vector of the stellar mass used is centred in the minimum of the gravitational potential plane which can be defined itself as the galactic plane. Finally, a small non-axisymmetric bar structure is visible in both the central region, a non-axisymmetric bar structure is visible in both components. The stellar disc is quite symmetric around the plane, while the XY plane is orthogonal to it. This reference system has been adopted for the entire analysis presented in this paper.

The presence of a disc structure is clear both in the stellar and gas distribution. This disc dominates the central part of the galactic volume and is extended until \( R \sim 10 \) kpc. In the innermost central region, a non-axisymmetric bar structure is visible in both components. The stellar disc is quite symmetric around the XY plane which can be defined itself as the galactic plane. Finally, a spiral pattern is visible in the outer part of the disc region, while the gas exhibits a warped shape at its edge.

We characterize the main components of AqC4 by means of the stellar mass distribution as a function of the orbit circularity of all star particles within \( R_{gal} \) for our simulation at redshift \( z = 0 \). The circularity of an orbit is defined as \( \epsilon = \epsilon_J / \epsilon_{circ} \), where \( \epsilon_J \) is the specific angular momentum in the direction perpendicular to the disc, and \( \epsilon_{circ} \) is the specific angular momentum of a reference circular orbit. The results are shown in Fig. 2.

The prominent peak at \( \epsilon \sim 1 \) demonstrates that AqC4 is characterized by a disc structure, with a bulge component corresponding to the smaller peak at \( \epsilon \sim 0 \). We compute the ratio of bulge-over-total stellar mass \( B/T \) by doubling the mass of the counter-rotating stars within \( R_{gal} \), under the hypothesis that the bulge is supported by velocity dispersion and thus has an equal amount of co- and counter-rotating stars. We highlight that this is a ‘dynamical’ value of the bulge-over-total stellar mass ratio as defined by Scannapieco et al. (2010). The resulting ratio is \( B/T = 0.34 \), fairly comparable with the upper limit estimated for the MW, \( B/T_{MW} = 0.15 \sim 0.33 \) (see e.g. Bland-Hawthorn & Gerhard 2016; Bell et al. 2017, and references therein).

3.1 Radial scale length of the stellar disc

It is common to describe the stellar disc of the MW with a double-component exponential profile with a radial scale length of \( h_{RI} = 2.6 \pm 0.5 \text{ kpc for the thin disc and } h_{RGT} = 2.0 \pm 0.2 \text{ kpc for the thick disc (Bland-Hawthorn & Gerhard 2016).} \)

In order to determine the radial extension of the stellar disc of AqC4, we first select all the star particles that lie within a height on the galactic plane \( |Z| \leq 1 \) kpc and compute the volume mass density (in \( \text{M}_\odot \text{pc}^{-2} \)) for cylindrical radial bins of \( 0.25 \text{ kpc as shown in Fig. 3.} \)

To infer the scale length, we limit the fit in the disc-dominated region between \( 2.5 < R \leq 9 \) (solid black lines).

Note that for this and the following analysis, we implement an MCMC Bayesian algorithm using the Python package PyMC3 (Salvatier et al. 2016) to take into account the mass of stellar particles, the weighted errors due to the Poissonian statistics within each bin and to check if the uncertainties induced by the bin size could be influenced by the softening resolution limit of the simulation, i.e. \( \epsilon = 0.163 \) kpc.

We analyse the stellar particles close to the galactic plane, i.e. \( |Z| \leq 1 \) kpc, and estimate a radial scale length of \( h_R = 2.058 \pm 0.002 \text{ kpc that is smaller by a factor of } \sim 21 \text{ per cent with respect to the MW thin disc.} \)

Thus, in the following we adopt a proportionally smaller Simulated Solar Ring (SSR) of \( 6 \leq R \leq 7 \) with respect to the distance between the Sun and the Galactic Centre, \( R_\odot = 8.122 \pm 0.033 \text{ kpc, as estimated by the Gravity Collaboration et al. (2018).} \)

3.2 Vertical distribution of the stellar disc in the SSR

The vertical mass distribution of the MW disc is modelled as a double-component exponential function.

As reported by Bland-Hawthorn & Gerhard (2016), the thin disc scale height at solar distance from the Galactic Centre is \( h_Z = 300 \pm 50 \) pc, while for the thick disc is \( h_Z = 900 \pm 180 \) pc. Moreover, several studies have tried to determine the relative density normalization \( f = f_T / f_R \) of the thick disc compared to the thin disc with estimates ranging from 6 to 12 per cent (e.g. Jurić et al. 2008; Just & Jahreiß 2010; Bovy et al. 2015).

In order to reduce the contamination from halo stars, we select

\( 3 \) We set the Credible Interval (CI) as the ±1\( \sigma \) equivalent range between the 16\% and 84\% percentile of the posterior distribution, i.e. the percentage equivalents of the 1\( \sigma \) range in a Gaussian distribution. From the posteriors, it results very narrow and thinner than the best-fitting line.
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Figure 1. Stellar (upper panels) and gas (lower panels) projected density for the AqC4 simulation (face-on and edge-on view on left and right panels, respectively). The $Z$-axis of the coordinate system is aligned with the angular momentum vector of multi-phase gas and stars enclosed within 8 kpc from the position of the minimum of the gravitational potential. The total box size is 50 kpc.

all the $320,354$ stellar particles in the SSR within $|Z| \leq 3$ kpc and fit simultaneously a double-component disc described as follows:

$$\rho(Z) = A \left( e^{-\frac{|Z|}{h_1}} + f \cdot e^{-\frac{|Z|}{h_2}} \right),$$

where $A$ is the total density normalization, $f$ is the relative density normalization, $h_i$, for $i = 1, 2$, is the scale height of the two components of the disc, and $Z$ is the vertical coordinate.

We estimate the scale heights, $h_1 = 0.305 \pm 0.005$ kpc that is in good agreement with the MW thin disc, and $h_2 = 1.33 \pm 0.02$ kpc that results $\sim 50$ per cent larger than what it is estimated for the MW thick disc (see Fig. 4). We also found a relative density parameter of $f = 22.6 \pm 0.7$ per cent that is 2-3 times larger with respect to the MW (Bland-Hawthorn & Gerhard 2016). These differences derive from the diverse accretion history of the MW and AqC4, as described in Sect. 5.

A better understanding of the stellar disc distribution is given by the stellar sub-samples formed in 2 Gyr time bins (see Table 2) shown as coloured lines in Fig. 4. We can distinguish four main com-
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Figure 2. Distribution of the stellar mass of AqC4 as a function of the orbit circularity for all stellar particles within $R_{gal}$ at redshift $z = 0$.

Figure 3. Radial density distribution (green dots) of stellar particles within $|Z| \leq 1$ kpc from the galactic plane computed in radial bins of $\Delta R = 0.25$ kpc. Error bars are smaller than the size of data point. Red line represents the best fit obtained from the posteriors of MCMC analysis. The CI is thinner than the best-fitting black line. Vertical black lines show the radial interval adopted for the fit.

Figure 4. Vertical density distribution (red dots) of stellar particles in the SSR with $|Z| \leq 3$ kpc computed in vertical bins of $\Delta Z = 0.25$ kpc. Black line represents the best fit obtained from the posteriors of MCMC analysis. The CI is thinner than the best-fitting black line. Colour lines represent mono-age stellar populations divided in bins of 2 Gyr as listed in Table 2.

Table 2. Age and relative weights of the mono-age populations with respect to the total stellar particles ($N_0$) in the SSR ($6 \leq R [kpc] \leq 7$) within $|Z| \leq 3$ kpc.

| Colour | Age [Gyr] | $N^*/N_0$ |
|--------|-----------|-----------|
| blue   | 0-2       | 0.22      |
| orange | 2-4       | 0.18      |
| green  | 4-6       | 0.12      |
| red    | 6-8       | 0.10      |
| purple | 8-10      | 0.22      |
| brown  | 10-12     | 0.10      |
| pink   | 12-14     | 0.07      |

Thick black line: $N_0$ = 320 354

These results reveal a SFH affected by significant changes over time, which are discussed in more detail in Sect. 5.1.

3.3 The radial disc flaring

Another important spatial feature which stems from the inside-out is the disc flaring (see e.g. Minchev et al. 2017, and references therein). Here, we investigate this property by studying the vertical distribution of AqC4 stellar particles as a function of the cylindrical radial distance for both the whole sample and for the mono-age populations listed in Table 2.

As shown in Fig. 5, we divided the star particles in rings of $\Delta R = 1$ kpc and $|Z| \leq 3$ kpc. In each ring we fit the vertical density distribution of the whole stellar sample with the double exponential model of Eq. (1) and determine the variation of $h_1$ and $h_2$ parameters along the disc. Then, we estimate the thickness of each mono-age population as the height, $h_Z$, where the density distribution decreases by a factor $e^{-1}$ with respect to the galactic plane, $Z = 0$ kpc.

The results of Table 3 report that flaring is present for all mono-age populations and occurs at smaller radii for older populations due to the inside-out formation of the disc. In particular, the youngest population (Age $\leq 2$ Gyr) lies close to the galactic plane ($h_Z \lesssim 0.5$ kpc) along the whole disc up to $R \approx 9$ kpc (cfr. Fig. 3), while the
intermediate old-thin disc population (4 ≤ Age[Gyr] ≤ 8) shows a significant flaring already at \( R = 6 \) kpc with a steep increase towards larger radii. We recall that in the SSR the stellar particles appear described by double-component exponential vertical profiles (Fig. 4): the presence of coeval stars evidences that heterogeneous populations were possibly formed by different progenitors.

The prominent thick disc population (i.e. 8 ≤ Age[Gyr] ≤ 10) shows a thickness \( h_Z \approx 1.0 - 1.2 \) kpc in the SSR at \( R = 6 - 7 \) kpc that is pretty close to the scale height \( h_2 \approx 1.33 \) kpc estimated in Sect. 3.2. A radial flaring is already apparent at \( R = 4 \) kpc, but it shows a milder increase at larger radii than the younger populations discussed above. These stellar particles were born in the same period of the starburst at \( z = 1.5 \) (see Sect. 5.1) and formed the primordial disc. In Sect. 5.2 we will see that this component may represent the signature of one of the most important mergers in the accretion history of AquC4.

In summary, our analysis of the spatial distribution of AquC4 confirms that a two-disc decomposition is a ‘simplified’ mathematical description of a more complex physical scenario which implies an overlapping of different mono-age profiles for several stellar generations. These results support the global top-down, inside-out disc formation model and are consistent with previous observations of the MW (e.g. Muñoz-Mateos et al. 2011; González Delgado et al. 2014; Bovy et al. 2016, where in the latter the authors used mono-abundance populations in the MW instead of mono-age ones) and simulations (Stinson et al. 2013; Grand et al. 2017; Valentini et al. 2019).

Table 3. The \( h_1 \) and \( h_2 \) scale heights, and relative density normalization \( f \) with the 1σ CI integrated over all the \( N_\ast \) stellar particles within each radial bin.

| \( R [\text{kpc}] \) | \( h_1 [\text{kpc}] \) | \( h_2 [\text{kpc}] \) | \( f \) [%] | \( N_\ast \) |
|----------------|----------------|----------------|--------|--------|
| 2-3            | 0.306^{+0.004}_{-0.003} | 0.899^{+0.005}_{-0.005} | 35.2^{+3.9}_{-4.3} | 767311 |
| 3-4            | 0.256^{+0.002}_{-0.002} | 1.016^{+0.007}_{-0.007} | 13.0^{+3.3}_{-1.3} | 687832 |
| 4-5            | 0.288^{+0.002}_{-0.002} | 1.09^{+0.02}_{-0.02} | 12.2^{+4.4}_{-6.4} | 592207 |
| 5-6            | 0.297^{+0.003}_{-0.003} | 1.17^{+0.02}_{-0.02} | 21.4^{+0.7}_{-0.5} | 436270 |
| 6-7            | 0.305^{+0.005}_{-0.005} | 1.34^{+0.02}_{-0.02} | 22.6^{+0.7}_{-0.7} | 320354 |
| 7-8            | 0.362^{+0.007}_{-0.006} | 1.81^{+0.05}_{-0.05} | 22.0^{+0.9}_{-0.9} | 234454 |
| 8-9            | 0.485^{+0.007}_{-0.007} | 2.6^{+0.1}_{-0.1} | 19.9^{+1.1}_{-1.1} | 171674 |
| 9-10           | 0.55^{+0.02}_{-0.02} | 2.9^{+0.1}_{-0.1} | 46^{+2}_{-2} | 96159 |
| 10-11          | 1.7^{+0.2}_{-0.2} | 2.8^{+0.7}_{-0.9} | 89^{+4}_{-4} | 46019 |

**4 KINEMATIC PROPERTIES**

Now, we extend the analysis of the galactic structure done in Sect. 3 to the kinematics of the stellar populations ‘observed’ at redshift \( z = 0 \) in AquC4.

**4.1 Rotation Curve**

The galactic Rotation Curve (RC) constitutes one of the key features that characterize disc galaxies like the MW. The significant discrepancy existing between the empirical curves observed (e.g. Sofue & Rubin 2001; Eilers et al. 2019; Crosta et al. 2020), and theoretical circular velocity profiles derived form the baryonic mass distribution (considering test particles that would move in an axisymmetric gravitational potential \( \Phi \) according to Newtonian theory) represents one of the main line of evidence of the presence of dark matter (DM) in haloes (e.g. Iocco et al. 2015; McMillan 2017; de Salas et al. 2019).

**Figure 5.** Variation of stellar height, |\( Z \)|, with \( R \). Flaring is present for all mono-age populations (colour code as in Table 2). Solid lines show when the density decays by a factor of e^{-1}. The \( h_1 \) and \( h_2 \) scale heights for each radial bin integrated over all stellar ages (see Table 3) are represented by circles and diamonds, respectively.

**Figure 6.** Circular velocity \( V_c(R) = \sqrt{2GM(< R)/R} \) for the total mass (black solid line), and for the individual component of DM (gray dashed), stars (gray dot-dashed), gas (dotted). As expected, after a steep linear increase for \( R \leq 3 \) kpc, the RC has an almost flat profile in the disc-dominated region for \( 3 \leq R[\text{kpc}] \leq 11 \), reaches its peak \( V_c = 280.6 \text{ km s}^{-1} \) at \( R = 6.25 \) kpc, and finally has a smooth decrease for \( R \geq 11 \) kpc in the halo dominated region. In the central region, for \( R \leq 5 \) kpc, the RC is dominated by the mass of stellar particles, while for \( R \geq 5 \) kpc the main contribution is due to DM. This is similar to what happens in the MW (e.g. see Fig. 1 in Crosta et al. 2020) taking into account the relative size of the MW disc which is more extended than the one of AquC4.

In the SSR, the mean circular velocity is 280.1 km s^{-1}, which is ~20 per cent faster than the value \( V_\odot = 234 \text{ km s}^{-1} \) measured at the Sun position \( R_\odot = 8.122 \) kpc by Crosta et al. (2020). However, if we scale the size (with the radial scale length estimated in Sect. 3.1) and the velocity, keeping constant the angular momentum \( L_Z \) at the Sun position, we can reasonably overplot the RC of the MW (green star symbols in Fig. 6) on that of AquC4.

Thus, AquC4 appears to be a disc galaxy fairly similar to the MW with a ~20 per cent faster rotating disc and a shorter pseudo-solar position location. The re-scaled Gaia data that describe the Galactic disc kinematics results in good agreement with the rotation curve of AquC4.

**4.2 Multi-component disc in the SSR**

In Sect. 3.2, we have modeled the stellar vertical distribution in the SSR with the superposition of a thin disc (\( h_1 = 0.305 \) kpc) and thick disc (\( h_2 \approx 1.33 \) kpc) that includes a residual contamination of halo star particles.

Here, we focus on the rotation velocity distribution of the stellar particles within the SSR in order to identify and characterize the
different components. This methodology is usually applied to real stellar surveys in order to select stellar samples belonging to the Galactic populations, e.g. the thin and thick disc, and inner halo (Bond et al. 2010; Spagna et al. 2010). Only a few authors have applied such kinematic decomposition to cosmological simulations (see Abadi et al. 2003a,b; Obreja et al. 2018, 2019, and references therein), as the high-resolution level required has been only recently achieved.

We select the 333 616 stellar particles in the SSR with \(|Z| \leq 4 \text{ kpc}\) to define the Probability Distribution Function (PDF), \(f(V_\phi)\), of the azimuthal velocity by normalizing to 1 the integral of the total sample. We adopt a model based on a Triplet Normal Mixture distribution (TNM), namely

\[
f(V_\phi) = \sum_{i=1}^{3} w_i N(V_\phi | V_{\phi,i}, \sigma_{V_{\phi,i}}),
\]

where \(0 \leq w_i \leq 1\) is the mixture weight of the \(i\)-th component and \(N\) is a Normal distribution with mean \(V_{\phi,i}\) and standard deviation \(\sigma_{V_{\phi,i}}\). The results of the MCMC analysis are listed in Table 4 and visualised in Fig. 7 (left panel), where the PDF model (red line) appears in good agreement with the observed velocity distribution (blue dots). Further information on the posterior probability of the fitted parameters are reported in Appendix A2.

We also tested alternative models with a different number of components. The results for a double Gaussian distribution such as halo+disc or disc+disc are not statistically significant and do not provide good curve fitting of the data. A four-component model, aimed to represent additional disc populations, produced non-significant improvements to the model.

We note that the weights of the two disc components listed in Table 4 correspond to the total mass of the young disc (Age \(\leq 4 \text{ Gyr}\)) and of the old disc/thick disc (4 \(\leq \text{Age[Myr]} \leq 10\)), respectively (cfr. Table 2 considering the different vertical cut applied). The comparison with the mono-age distributions shown in Fig. 7 (right panel) confirms that these two disc components represent the superposition of the stellar generations formed in the age intervals 0-4 Gyr and 4-10 Gyr. Note that the old thin disc and the thick disc populations are difficult to distinguish because of their very similar velocity distributions. Moreover, the difference between the mean rotation velocity of the AqC4 discs is

\[
\Delta V_\phi = 284.4 - 257.7 = 27 \text{ km s}^{-1}.
\]

Table 4. TNM model parameters: \(w_i\) is the mixture weight of the \(i\)-th component (i.e. young disc, old disc/thick disc, halo), while \(\langle V_\phi \rangle_{i}\) and \(\sigma_{V_{\phi,i}}\) are the corresponding mean and the standard deviation of the Normal distribution. Note that \(0 \leq w_i \leq 1\) and \(\sum_i w_i = 1\). 

| \(i\) | Component       | \(w_i\) | \(\langle V_\phi \rangle_{i}\) [\(\text{km s}^{-1}\)] | \(\sigma_{V_{\phi,i}}\) [\(\text{km s}^{-1}\)] |
|------|----------------|--------|---------------------------------|-------------------------|
| 1.   | young disc     | 0.389 ± 0.006 | 284.4 ± 0.2                  | 20.7 ± 0.2               |
| 2.   | old disc/thick disc | 0.467 ± 0.006 | 257.7 ± 0.3                  | 39.9 ± 0.1               |
| 3.   | halo           | 0.145 ± 0.001 | 35.6 ± 1.1                   | 159.6 ± 0.6              |

This value is smaller than in the MW, where \(\Delta V_\phi,\text{MW} = 197.2 - 159.2 = 38 \text{ km s}^{-1}\) (Han et al. 2020). Actually, this difference depends on the fact that in AqC4 the two main disc components represent the young and the old/thick discs instead of the whole thin disc and the thick disc, as in the MW. Moreover, the high rotation velocity of the AqC4 disc is consistent with its more compact structure with respect to the MW disc (Sect. 3.1).

Finally, the halo component shows a small prograde rotation as observed in the inner halo of the MW, while its velocity dispersion \(\sigma_{V_\phi} \approx 160 \text{ km s}^{-1}\) is about 70 – 100 per cent higher than in the Solar Neighbourhood (Re Fiorentini et al. 2015; Bland-Hawthorn & Gerhard 2016, and references therein).

In summary, here we robustly support what is discussed in Sect. 3: in the SSR, we can distinguish at least two kinematic disc components which rotate faster than what is measured in the Solar Neighbourhood (as discussed globally in Sect. 4.1), and with a smaller discrepancy between the mean values. These results extend the spatial characterisation of AqC4 stellar disc beyond the determination of the scale lengths and scale heights, allowing us to properly investigate the complete phase-space of mono-age populations, as usually done in Galactic surveys.

### 4.3 Kinematics of mono-age disc populations

Fig. 8 shows the three median velocity components \(\langle V_R, V_\phi, V_Z \rangle\) and the dispersions \(\sigma_{V_R}, \sigma_{V_\phi}, \sigma_{V_Z}\) as a function of \(R\), computed in radial annular bins of \(\Delta R = 0.25 \text{ kpc}\), for the mono-age stellar disc populations younger than 10 Gyr and with \(|Z| \leq 1 \text{ kpc}\). Error bars are derived via bootstrapping with 100 re-samples.

As in Sect. 4.1, we can identify three main regions based on the different kinematic properties of mono-age populations: (i) for \(R \leq 3 \text{ kpc}\) (blue area) we have the bulge/bar region characterized by high velocity dispersion and peculiar velocity patterns; (ii) for \(3 \leq R \lesssim 11 \text{ (white area)}\) the region dominated by the disc, where we have the lowest dispersions and the RC flat regime; (iii) finally, for \(R \geq 11 \text{ kpc}\) (grey area) the halo region where the velocity dispersions increase and, conversely, the rotation velocity decreases.

In the disc region, the median radial velocity turns out to be negative, i.e. \(\bar{V}_R = -10 \pm 0 \text{ km s}^{-1}\), for almost all mono-age populations (see Fig. 8, top-left panel), meaning that the system is out of equilibrium in contrast to what observed in the MW. Examining the last \(- 0.4 \text{ Gyr}\) dynamic history of AqC4, we found that this global inward motion of the stellar particles characterizes the disc at the...
present time only, since $\bar{V}_R \sim 0 \text{ km s}^{-1}$ in the previous snapshots of the simulation. Unfortunately, the nature of this kinematical signature cannot be easily investigated because it occurred only in the last snapshot of the simulation. The dynamical perturbation of the AqC4 disc may have been produced by the last satellite detected at redshift $z = 0.014$ (see next section for details), whose high velocity and retrograde orbit shows a perigalactic passage in the outer regions of the disc. Further investigations are necessary to confirm this hypothesis. Despite such zero-point offset in AqC4, we observe an ‘U-shape with a minimum at about the Sun position similar to the MW, although the Gaia data samples only a portion of the Galactic disc (Fig. 12 in Gaia Collaboration et al. 2018b).

The rotation velocity $\bar{V}_\phi$ is slower for the older stellar generations, as expected from asymmetric drift, as well as to the secular processes (e.g. spiral arms perturbations and bar resonances) and to merging events. The presence of significant dynamical disc perturbations may also explain why the young stellar particles with $6 < R[\text{kpc}] < 11$ and $|Z| \leq 1$ kpc rotate faster than $V_c$ (middle-left panel). These stars belong to the most angular-momentum sustained population and may be accelerated by the momentum of accreted gas.

As expected by the azimuthal averaging, the radial gradient of the vertical velocity is almost flat, with a median value $\bar{V}_Z \approx 0 \text{ km s}^{-1}$ and with larger fluctuations for younger populations (Fig. 8, bottom-left panel). Instead, the apparent radial increase of the mean vertical velocity, $\bar{V}_Z$, found in the outer disc of the MW by Poggio et al. (2018, Fig. 3) represents a local signature of the Galactic warp, due to the limited volume sampled by Gaia DR2 and to the peculiar Sun position close to the line of nodes.

In the disc region, the two velocity dispersion components $\sigma_{V_R}$ and $\sigma_{V_\phi}$ decrease from $R \approx 3$ kpc to $\sim 6$ kpc and then become almost constant until $R \approx 11$–12 kpc. The younger populations show stronger gradients $\partial \sigma_R / \partial R$ and cooler isothermal curves than the older populations. These results are consistent with the monotonous radial decrease of the velocity dispersions observed in our Galaxy, since the colder longer-scale length young disc is dominant in the outer disc.

The behaviour of $\sigma_{V_\phi}$ in AqC4 is different from the other two components and shows a positive radial gradient for mono-age populations between 2 and 8 Gyr old (i.e. the intermediate old disc population), while the youngest and oldest stellar particles are almost isothermal. We argue that this is a cosmological signature of a heating process due to mergers that occurred in the last 7 Gyr of the simulation as discussed below in Sect. 5.1.

Even though our investigation focuses on the disc region, we remark the peculiar velocity patterns within $R \leq 4$ kpc due to the presence of a central bar, which is easily visible in both the stellar and gas distributions (see left panels of Fig. 1).

In summary, the stellar disc of AqC4 is still evolving and shows the kinematic signatures of several past and recent dynamical perturbations, such as (a) the global inward $V_R$ systematic motion, (b) the faster rotation $V_\phi > V_c$ of the youngest stars, and (c) the peculiar velocity dispersions shown by mono-age populations. Moreover, the gas accretion in the external region of the disc shown in Fig. 1 highlights that the galaxy is still out-of-equilibrium, as discussed in Valentini et al. (2020). All these properties are consistent with the recent studies based on Gaia DR2 that show how the accretion history is the key to understanding the origin of the ancient thick disc and inner halo (e.g. Stinson et al. 2013; Helmi et al. 2018, and references therein), as well as to disentangle the signatures of the “dynamically young and perturbed MW disk” (Antoja et al. 2018).

### 5 GALAXY FORMATION AND EVOLUTION

Star Formation History (SFH) does enclose fundamental information about the origin and evolution of disc-like galaxies and of the MW, as well. In order to understand the phase-space properties of mono-age populations discussed in Sects. 3.2, 4.2 and 4.3, here we investigate the star formation and the accretion history of AqC4. Similarly to Bigonne et al. (2019) and Grand et al. (2020), we contrast the total Star Formation Rate (SFR) with the accretion history of our simulated galaxy. In addition, we consider the local SFR, as inferred by the stellar particles within the SSR, that we compare with the observational results recently derived by Mor et al. (2019).

#### 5.1 Star Formation History

First, we analyse the SFH of the stellar populations in AqC4 by investigating the SFR, which results $\sim 2.65 \text{ M}_\odot \text{yr}^{-1}$ for the whole
galaxy at redshift $z = 0$. This value is at least 1.5 times higher than what is measured for the MW by Robitaille & Whitney (2010) and Licquia & Newman (2015).

Fig. 9 shows the evolution of the SFR per unit of surface, for the star particles inside a spherical volume of $R_{\text{gal}}$ (red line) and in the SSR with $|Z| \leq 3$ kpc (blue line). Black symbols with corresponding error bars represent the recent stellar production in the Solar Neighbourhood as estimated by Mor et al. (2019) from Gaia DR2.

The apparent peak of the whole SFR at $z > 3.3$ represents the primordial phase of the galaxy formation that builds up the central bulge (as in Murante et al. 2015), while the smooth decrease after redshift $z \sim 2.5$ (i.e. during the last 10 Gyr) describes the disc formation.

The SFR of AqC4 shows a secondary peak at redshift $z \sim 1.6$ that corresponds to the thick disc formation discussed in Sects. 4.2–4.3. At this epoch, we estimate the total SFR $\approx 7 - 8 \, M_\odot \, \text{yr}^{-1}$, which appears more similar to value of $\sim 6.5 \, M_\odot \, \text{yr}^{-1}$ found in the EAGLE simulation studied by Bignone et al. (2019), than to...
the much stronger starburst up to $\approx 25$ $M_\odot$ yr$^{-1}$ resulting from the AURIGA simulation analysed by Grand et al. (2020).

Meanwhile, the subset of stellar particles within the SSR highlights an irregular SFH, quite different from the global SFR, that evidences the complex evolution of the galactic disc. The peak at cosmic times $T < 2$ Gyr clearly indicates that a fraction of the stars formed during the primordial starburst have moved from the inner galaxy to the SSR. Then, after a quenching phase, a double-peak event (at redshift $z = 2.1$ and $z = 1.4$) evidences the formation of the ancient thick disc. We point out the consistency between these bursts in the star formation at $T \approx 4$–$6$ Gyr and the relative weights of the mono-age populations reported in Table 2.

Because of the inside-out formation of the disc, for $T > 7$ Gyr we notice an increasing SFR in the SSR, as opposed to the decreasing SFR of the entire AqC4. Finally, we remark the very high SFR of $10 - 12$ $M_\odot$ Gyr$^{-1}$ pc$^{-2}$ for $T > 11$ Gyr, that formed a massive young disc, as already discussed in Sect. 3.2. Despite the large uncertainties, the SFR observed by Mor et al. (2019) in the Solar Neighbourhood results in very good agreement with our estimates for AqC4 in the SSR.

The large time-scale (almost 3.5 Gyr) and the large amount of mass that is involved suggest that this event is produced by an external factor. Indeed, lower panels of Fig. 1 show a large reservoir of gas both in the disc and falling from the halo. We argue that the low-redshift merging events shown in the next Section may have contributed to the recent gas accretion.

Although more significant in AqC4, this scenario is consistent with the results published by Mor et al. (2019) and supports the hypothesis that the increasing SFR in the Solar Neighbourhood of the MW may be due to the recent merging event claimed by Lian et al. (2020).

5.2 Accretion history

In order to understand the features found in the SFH of AqC4, we select seven snapshots with redshift $z = 1.637, 1.314, 1.154, 0.550, 0.401, 0.178$ and 0.014, corresponding to the time intervals of the main starbursts observed in Fig. 9.

For illustration purpose only, in Figs. 10 - 11 we show the face-on and edge-on stellar density distributions at the selected redshifts. The presence of one or more merging satellites is noticeable in all the panels.

For each snapshot, we estimate the total stellar mass of the main satellite, marked with a white circle, within a spherical radius, $r_{\text{sat}}$. A similar procedure is performed to estimate the mass of the main disc-like galaxy, but considering a cylindrical volume defined by the radial disc extension at that epoch, $R_{\text{disc}}$, within $|Z| < 2$ kpc. As reported in Table 5, the stellar mass ratio $\Delta = M_{\text{sat}}/M_{\text{disc}}$ varies from $0.5$ to $5.5$ per cent.

We focus our attention on the satellite at redshift $z = 1.637$, whose stellar mass of $1.2 \times 10^9$ $M_\odot$ is pretty similar to that estimated by Mackereth et al. (2019) and Fattahi et al. (2019) for the GSE progenitor. In fact, these authors claim a mass of a few $10^9$ $M_\odot$, assuming a $10^{10}$ $M_\odot$ stellar mass for the thick disc present at the time. We obtain a stellar mass ratio $\Delta \approx 5.5$ per cent which is quite consistent with the stellar mass ratio of $\sim 6$ per cent estimated by Helmi et al. (2018) and confirmed by Gallart et al. (2019) for GSE. This event is the main merger that can be associated with the starburst between 4 and 6 Gyr in cosmic time (see Fig. 9).

After this large merger, we find a few accretion events due to satellites with masses of $M_{\text{sat}} \lesssim 10^8$ $M_\odot$ corresponding to a mass ratio $\Delta \lesssim 2$ per cent. These minor accretions produced the secondary fluctuations of the SFR in the SSR after redshift $z \approx 1.5$. These results are consistent with the standard hierarchical formation scenario of the MW (Helmi 2020, and references therein).

We estimate a mass of $M_{\text{sat}} \approx 8.8 \times 10^8$ $M_\odot$ for the accreted satellite detected at $z = 0.550$, and a mass of $M_{\text{sat}} \approx 5.1 \times 10^8$ $M_\odot$ for the one detected at redshift $z = 0.401$. These low-redshift significant mergers may have produced an heating of the old disc population that explains the large scale height of the stellar particles with age 4-8 Gyr shown in Fig. 5. The presence of merging events during the intermediate phase of the disc formation is consistent with the late-accretion model proposed by Lian et al. (2020), who suggest that a recent merger event occurred in the MW at 8.2 Gyr in cosmic time (i.e. redshift $z \approx 0.6$). In particular, these authors estimate a mass of $M_{\text{sat}} < 10^9$ $M_\odot$ for the gas-rich dwarf galaxy involved.

Finally, we detect two more satellites at redshift $z = 0.178$ and 0.014 , with $M_{\text{sat}} \approx 4.0 \times 10^8$ $M_\odot$ and $2.6 \times 10^8$ $M_\odot$, respectively, which appear associated to the increasing SFR in the SSR of AqC4 during the last 2 Gyr.

In summary, the SFH and the accretion history of AqC4 are consistent with its spatial and kinematic properties described in Sects. 3 - 4 and, in particular, we clarify the formation of the peculiar features observed in the young disc and old disc populations.

Moreover, the overall formation and evolution of AqC4 and the MW appear fairly similar. Indeed, our findings are consistent with both the GSE scenario for the origin of the Galactic thick disc (Brook et al. 2004, 2012; Stinson et al. 2013; Helmi et al. 2018; Gallart et al. 2019), and with the recent accretion event proposed to explain the increasing SFR in the Solar Neighbourhood (Mor et al. 2019). We argue that the higher SFR of our simulated galaxy with respect to the MW depends on both the gas contribution from the late-accreted satellites and the infall of gas previously expelled by the strong starbursts and supernova explosions that occurred at high redshift.

6 SUMMARY AND CONCLUSIONS

In this work, we analysed the spatial and kinematic properties of stellar particles of the MW-like galaxy AqC4. Our approach consisted in considering such simulation as a real survey of the stellar contents of our Galaxy. Therefore we implemented methods of investigation usually applied to real stellar catalogues. Our aim was to identify cosmological signatures enclosed in the mono-age stel-

| $z$ | $r_{\text{sat}}$ [kpc] | $M_{\text{sat}}$ [$10^8 M_\odot$] | $R_{\text{disc}}$ [kpc] | $M_{\text{disc}}$ [$10^9 M_\odot$] | $\Delta$ [%] |
|-----|-----------------|-----------------|-----------------|-----------------|-------|
| 1.637 | 3.0 | 12.0 | 5.0 | 2.2 | 5.5 |
| 1.314 | 2.5 | 4.7 | 5.0 | 2.7 | 1.7 |
| 1.154 | 4.0 | 1.3 | 5.0 | 2.9 | 0.4 |
| 0.550 | 6.0 | 8.8 | 8.0 | 4.5 | 2.1 |
| 0.401 | 3.5 | 5.1 | 8.5 | 4.8 | 1.1 |
| 0.178 | 3.5 | 4.0 | 9.0 | 5.3 | 0.8 |
| 0.014 | 3.5 | 2.6 | 10.0 | 5.7 | 0.4 |

Table 5. Estimates of the total stellar mass of selected satellite galaxies and the main galactic disc, with corresponding mass ratios $\Delta = M_{\text{sat}}/M_{\text{disc}}$ at different redshift $z$. The spherical radius, $r_{\text{sat}}$, is centred on satellite galaxies, while the radial extension of the disc, $R_{\text{disc}}$, is in the reference frame of the main galaxy.
lar populations, defined as coeval particles sub-samples of 2 Gyr age bins, and compare their phase-space properties with the MW. We focused on the Simulated Solar Ring (SSR), an annular region within $6 < R \lesssim 7$ kpc, corresponding approximately to the Solar Neighbourhood, given the ~ 20 per cent smaller radial scale length of the thin disc of AqC4 with respect to the MW ($h_R \approx 2.1$ kpc wrt. 2.6 kpc), and where we were able to compare the spatial-kinematical distributions of the stellar populations to the SFH and accretion history of this simulated galaxy.

The high-resolution cosmological simulation we used is based on the Aquila-C suite presented by Springel et al. (2008) and the MUPPI algorithm to model the sub-resolution baryonic physics (see Murante et al. 2010, 2015, for more details). It is an unconstrained simulation with initial conditions chosen to reproduce a disc-like galaxy. Therefore, it should be interpreted as a cosmological product with mass and phase-space properties similar to the MW. The Plummer-equivalent softening length for the computation of the gravitational force is $\epsilon_{Pl} = 163 h^{-1}$ pc.

In the SSR, we confirmed the presence of at least two disc components with vertical exponential distribution (see Sect. 3.2). We estimated a scale height $h_1 \sim 0.3$ kpc that is in good agreement with the MW thin disc, and a scale height $h_2 \sim 1.33$ kpc that is ~ 50 per cent larger with respect to the MW thick disc.

The inspection of the vertical distributions of the mono-age stellar particles in the SSR clarified that the thin disc of AqC4 is mainly formed by a young disc population with $h_Z \sim 250 - 500$ pc and age $\leq 4$ Gyr (Sects. 3.2 - 3.3). In addition, we identified an old disc (age 4-8 Gyr) having intermediate thickness ($h_Z \sim 500 - 1000$ pc), and a prominent thick disc population with age 8-10 Gyr and $h_Z \sim 1200$ pc (Fig. 5).

We evidenced that the vertical scale heights and weights of the mono-age populations are strictly correlated with the SFH of AqC4. In fact, the large scale heights of the stellar particles in the SSR with age 4-8 Gyr cannot be explained by the secular disc evolution, and we argued that these values derive from the disc heating produced by the low-redshift mergers shown in Fig. 9.

The kinematic analysis of the stellar particles in the SSR (Sect. 4.2) revealed that the azimuthal velocity distributions correspond to two main kinematic disc components (i.e. the young disc and the old/thick disc), plus a slightly prograde inner halo. We pointed out that these discs rotate faster than the MW, and with a smaller velocity difference, $\langle V_{\phi,1} \rangle \approx 284.4$ km s$^{-1}$ and $\langle V_{\phi,2} \rangle \approx 257.7$ km s$^{-1}$. These results are consistent with the more compact structure of AqC4 with respect to the MW.

The median $V_R$ and $V_\phi$ components of mono-age stellar particles and their relative dispersions in Fig. 8 revealed that the stellar disc of AqC4 is out of equilibrium and shows the dynamical signatures of the perturbations due to both recent mergers, cosmic impact and gas accretion. Indeed, in the disc region $3 \leq R [\text{kpc}] \leq 11$, $V_R$ evidences a systematic inward motion for all the mono-age populations in contrast to what measured in the MW. We suppose that the very recent impact of the high-speed, counter-rotating satellite found at redshift $z = 0.014$ (see lower panels of Fig. 11) may have produced this dynamical perturbation. On the other hand, younger
stars show an higher median $\bar{V}_\phi$ than older ones as expected from inside-out formation and secular processes occurred in the disc, but also rotate faster than the circular velocity, accelerated by accreted gas.

These kinematic features are consistent with the recent studies based on Gaia DR2 data that show how the accretion history is the key to understand the origin of the ancient MW thick disc and inner halo (e.g. Brook et al. 2004, 2012; Stinson et al. 2013; Helmi et al. 2018; Gallart et al. 2019), as well as to disentangle the signatures of the “dynamically young and perturbed MW disk” (Antoja et al. 2018).

We suggest that the prominent thick disc population was generated by the major accreted satellite detected at redshift $z = 1.6$. Such merging event is associated to the starburst at redshift $1 < z < 2$ shown in Fig. 9, which attains a total SFR of $\sim 7 - 8$ M$_\odot$ yr$^{-1}$. This scenario is consistent with the results published by Bignone et al.
Figure 11. As Fig. 10 but at redshift $z = 0.550, 0.401, 0.178$ and $0.014$. 

*Formation History of the Milky Way disc*
starburst above discussed, which matches quite well the high SFR of the MW by Mor et al. (2019) till z ~ 0.2. The comparison with the accretion history of AqC4 supports the hypothesis that the starburst that occurred 2–4 Gyr ago in the Solar Neighbourhood may be due to a late merging event, as claimed for the MW at z ~ 0.6 by Lian et al. (2020).

The higher SFR of our simulated galaxy in the SSR with respect to the MW at low redshift may depend on a greater gas contribution from the last accreted satellites, as well as from the delayed infall of the gas outflows triggered by the strong starbursts at high redshift. Given this, our analysis sheds light on the complex scenario of the origin and evolution of the Galactic disc: it supports the global top-down, inside-out disc formation model and implies an overlapping of several stellar generations closely correlated with the accretion history of the Galaxy.

The negative median \( V_R \) trends represents an interesting starting point for future studies that will have to include chemo-dynamical analysis in order to improve and detail our knowledge of the MW thin and thick discs origin and evolution, as well as investigations on the in-situ/ex-situ star formation contributions and stellar back-time tracking in order to select halo streams and identify common progenitors to study the Galactic halo. In this respect, the use of constrained simulation (e.g. Carlesi et al. 2016) can be very promising.

There is no doubt that current and future Gaia data releases and the important synergies with spectroscopic ground surveys such as APOGEE (Majewski et al. 2017) and GALAH (De Silva et al. 2015) and detailed comparison with simulations will bring tremendous and fundamental contributions to the studies of Galactic Archaeology.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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APPENDIX A: POSTERIORS PDF

A1 Vertical distribution of stellar disc

Fig. A1 shows the posterior distributions of the parameters according to Eq. (1) for the vertical distribution of stellar particles. Dashed lines in each histogram refer to the 10th, 16th, 50th, 84th and 90th percentiles of the relative distribution, while numbers on top indicate the medians and the 1σ CIs. Thick black contours indicate the 1 and 2σ CIs of the two-dimensional correlations of the posteriors.

As for the radial scale length, the uncertainties take into account the Poissonian statistic within each bin and are smaller than the size of single data points in the plot. Consequently, the CIs are very narrow and we obtain well-peaked posteriors on the parameters estimates.

The analysis highlights that \( h_1 \) and \( h_2 \) are positively correlated, and they are both negatively correlated with the local density normalization parameter \( f \) indicating the intrinsic physical overlapping of the two disc components. The closest correlation is between \( h_2 \) and \( f \).

A2 TNM model

The posterior distributions of the parameters for TNM model are shown in Fig. A2. The means of the posteriors are indicated with a blue square, while dashed black lines and numbers on top of each histogram have the same meaning as in Appendix A1. The posteriors are well approximated by normal distribution, as the means and the medians are similar and the CI are pretty symmetric.

The closest correlations are between the arrays of parameters that describe the two discs components, i.e. the components with \( i = 1 \), \( 2 \). This is again a signature of the intrinsic overlap of the stellar generations that compose the two populations and is similar to what reported in Appendix A1. The last kinematic component with \( i = 3 \) represents the residual halo contribution and its parameters show almost no correlations with the other quantities.

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Figure A2. As in Fig. A1 for TNM model parameters according to Eq. 2. The blue square shows the mean value of each posterior distribution.