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# Bimodality of $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$ distributions is a natural outcome of dissipative collapse and disc growth in Milky Way-type galaxies

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## ABSTRACT

By using chemo-dynamical simulations of the Milky Way-type galaxies formation, we find that the two  $\alpha$ -sequences are formed in quite different physical environments. The high- $\alpha$  sequence is formed early from a burst of star formation in a turbulent, compact gaseous disc that forms a thick disc. The low- $\alpha$  stellar population is the result of quiescent star formation supported by the slow accretion of enriched gas on to a radially extended thin disc. Feedback-driven outflows during the formation of the thick disc are responsible for the enrichment of the surrounding gaseous halo, which subsequently feeds the disc on a longer time-scale. During the thin disc phase, chemical evolution reaches an equilibrium metallicity and abundance, where the stars pile-up. This equilibrium metallicity decreases towards the outer disc, generating the ridge line that forms the low- $\alpha$  sequence. We identify a second mechanism capable of creating a low- $\alpha$  sequence in one of our simulations. A rapid shutdown of the star formation due to feedback at the end of the thick disc phase, suppresses the chemical enrichment of the halo gas, which, once accreted on to the star-forming disc, dilutes the interstellar medium at the beginning of the thin disc formation. Therefore, the bimodality is independent of any particular merger history, suggesting that it could be much more widespread than has been claimed. We also find that radial migration has a negligible effect on the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  distribution over time, suggesting that  $\alpha$ -bimodality results purely from the presence of different star formation regimes over the galaxy’s formation.

**Key words:** Galaxy: abundances – Galaxy: disc – Galaxy: evolution – Galaxy: formation – galaxies: evolution – galaxies: formation.

## 1 INTRODUCTION

The Milky Way (MW) is a typical disc galaxy composed of thin and thick stellar discs, a central pseudo-bulge and an old stellar halo. The latter seems to be dominated by a single major merger at early epoch (Belokurov et al. 2018; Haywood et al. 2018; Helmi et al. 2018). For a long time, the bulge has been seen as an old classical spheroid, but models and observations now show that most of the mass is concentrated in a boxy-peanut pseudo-bulge made of disc(s) stars which passed through the phase of secular evolution driven by the buckling instability of the bar (Shen et al. 2010; Bekki & Tsujimoto 2011; Di Matteo et al. 2015; Athanassoula, Rodionov & Prantzos 2017; Debattista et al. 2017; Fragkoudi et al. 2018; Di Matteo et al. 2019a).

The MW stellar disc is a complex structure containing thick and thin components, a bar and spiral arms. The thick disc was recognized as a component of the MW distinct from the thin disc by Gilmore & Reid (1983). Thick disc stars are significantly older than those of the thin disc, which means that they contain a fossil record of the formation processes of the early phases of the MW evolution. However, parsing of thick/thin disc stars is quite problematic because they intersect much in phase space due to several dynamical effects, such as radial migration (Sellwood & Binney 2002), the presence of spiral arms and the bar evolution (Dehnen 2000; Quillen & Minchev 2005; Antoja et al. 2009; Minchev et al. 2011) and gravitational interactions with the environment (Weinberg & Blitz 2006; D’Onghia et al. 2010; Purcell et al. 2011; Gómez et al. 2013, 2017). In such a context, the dissection of thin/thick discs by chemical composition is the preferred tool. Moreover, the chemical composition of its stars is related to the star formation history (SFH) of a galaxy (Snaith et al. 2015), and therefore to the evolution of the gas content during galactic evolution.

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One of the most striking chemical patterns discovered in the MW disc is the two sequences visible in the abundance ratios of alpha elements as a function of metallicity for stars in the solar vicinity (Gratton et al. 1996; Fuhrmann 1998, 2004; Reddy, Lambert & Allende Prieto 2006; Adibekyan et al. 2011; Adibekyan et al. 2012; Bensby, Feltzing & Oey 2014; Hayden et al. 2020). Over the last few years a number of studies exposed the clear separation of  $\alpha$ -abundance for a given metallicity on larger spatial scales (Anders et al. 2014; Hayden et al. 2015; Queiroz et al. 2019), together with the prevalence of the high- $\alpha$  sequence in the inner Galaxy ( $R < 6$  kpc) and of the low- $\alpha$  sequence in the outer disc ( $R > 10$  kpc). The existence of a distinct  $[\alpha/\text{Fe}]$ -bimodality across the MW disc suggests two different formation paths for high- and low- $\alpha$  sequences but the mechanism by which this bimodal distribution appeared remains debated. Since it is traditionally accepted that high- and low- $\alpha$  sequences correspond to the thick and thin Galactic disc (see e.g. Fuhrmann 1998; Haywood et al. 2013), respectively, the problem of understanding the global chemical abundance patterns is ultimately linked to the understanding of the formation scenarios of the MW disc components.

Before going further, the ambiguity between two types of bimodality in the  $[\text{Fe}/\text{H}]$ – $[\alpha/\text{Fe}]$  distribution must be clarified. Bimodality (1), whose origin is addressed here, is the presence of two clearly defined  $[\alpha/\text{Fe}]$  sequences in this plane, and it is visible at all  $[\text{Fe}/\text{H}]$  of disc stars. This bimodality is evident even when not taking into account the density of stars along the two sequences. Bimodality (2) reveals itself only in the inner disc, with a bimodal distribution of  $[\alpha/\text{Fe}]$  abundances. This second bimodality (2) comes from the quenching phase that occurred between the formation of the thick disc and the inner thin disc (see Haywood et al. 2016). The two bimodalities are generated by different processes: the first bimodality (the existence of two  $[\alpha/\text{Fe}]$  sequences), cannot be generated by a simple gap in the SFH.

Several studies have tried to reproduce the observed  $[\alpha/\text{Fe}]$ -bimodality (1), proposing radically different solutions. For instance, Grisoni et al. (2017) tried to reproduce the bimodality as it is observed in the solar vicinity with a hiatus in the chemical track in the  $\alpha$ -metallicity plane generated by a gap between two sequential gas infalls (see also Chiappini, Matteucci & Gratton 1997; Chiappini 2009; Spitoni et al. 2019). Haywood et al. (2013) advocated that the inner and outer discs, dominant in the high and low- $\alpha$  sequences respectively, both present at the solar vicinity, cannot be represented by the same evolution, and for this reason they were described by two different models in Snaith et al. (2015). It was also claimed by these authors that sustained star formation activity must have formed the thick disc, as was confirmed by the measurement of the SFH in Snaith et al. (2014), the chemical homogeneity of this population at all ages implying a high level of turbulence in the gas (see also Haywood et al. 2015). This picture was completed more recently in Haywood et al. (2019), where they suggested that while the high- $\alpha$  sequence is a temporal sequence, the low- $\alpha$  sequence is made of parallel evolution occurring at different radii, starting at  $R \gtrsim 6$  kpc.

Brook et al. (2004, 2005) showed that the thin and thick disc stars can have parallel tracks in  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  plane in simulations with a very high star formation rates triggered by the early gas-rich merging epoch. More recent simulations emphasized the possible importance of external processes in the formation of the dichotomy in the  $[\alpha/\text{Fe}]$  distribution. By using Auriga cosmological simulations Grand et al. (2018) found only one galaxy with a clear  $[\alpha/\text{Fe}]$ -bimodality in the outer disc, produced when the gaseous disc shrinks after the high- $[\alpha/\text{Fe}]$  sequence forms, causing a decrease in SFR while the gas transitions to a low- $[\alpha/\text{Fe}]$  state. Subsequent low-metallicity gas accretion grows the low- $[\alpha/\text{Fe}]$  sequence in an

inside-out fashion at lower metallicities compare to the end of the high- $[\alpha/\text{Fe}]$  sequence. By analysing 133 simulated EAGLE MW-mass galaxies, Mackereth et al. (2018) found that a prominent disc bimodality is rare. They deduce from their analysis that a bimodality is established only when an early, first, rapid phase of gas accretion is followed by a slower, usually later, second phase, where the gas is mainly acquired from a galaxy merger. In an alternative approach both high- and low- $\alpha$  sequences can be formed in parallel (or simultaneously). Clarke et al. (2019) presented a galaxy formation simulation where gas clumps self-enrich in  $\alpha$ -elements due to their high star formation rate density and produce the high- $\alpha$  sequence while the low- $\alpha$  sequence is produced contemporaneously by the star formation in a smooth surrounding disc, implying a temporal overlap in the formation of the two  $\alpha$ -sequences. One of the most recent chemodynamical study of the  $[\alpha/\text{Fe}]$  bimodality in simulated galaxies has been made by Buck (2020) who conducted an in-depth analysis of chemical patterns in MW-type galaxies from the NIHAO-UHD project. In the four simulation analysed in their paper, Buck (2020) finds that the high- $\alpha$  sequence is formed first, and the low- $\alpha$  sequence is a generic consequence of a gas-rich merger at some point in the galaxy’s evolution. More recently Renaud et al. (2020a, b) and Agertz et al. (2020) presented a zoom-in simulation of the MW analogue where cosmological accretion leads to the rapid formation of an outer, metal-poor, low- $[\alpha/\text{Fe}]$  disc around the inner, metal-rich galaxy containing the old high- $[\alpha/\text{Fe}]$  stellar populations. In this scenario, the galaxy is fueled by two distinct gas flows that leads to a bimodality in  $[\alpha/\text{Fe}]$  over a range of  $[\text{Fe}/\text{H}]$ . Importance of the outflow-to-infall ratio of metals was also noticed by Vincenzo & Kobayashi (2020) who found an  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  dichotomy in a MW-mass galaxy with quiet formation history.

In this paper, we present a set of idealized galaxy formation models via cooling of gas within an evolving galactic dark matter halo. Our work aims to explore some basic chemodynamical processes that can lead to the formation of the  $[\alpha/\text{Fe}]$ -bimodality in simulated MW-type disc galaxies. We analyse isolated galaxy formation simulations where the gas is able to feed the disc, driving the evolution of chemical abundances of the different galactic components. The choice to study, in particular, galaxies that evolve in isolation is dictated by the desire to understand if and under what conditions a  $[\alpha/\text{Fe}]$  bimodality can be generated in a disc galaxy, even in the absence of mergers. The paper is structured as follows. In Section 2, we present our numerical methods, models setup and briefly summarize the global evolution of simulated galaxies. In Section 3, we explore the enrichment of the multiphase gaseous component feeding the galaxies over time. In Section 4, we explore the pathways to the  $[\alpha/\text{Fe}]$  bimodality as well as the spatial, kinematical, and age structure of the stellar populations. In Section 5, we describe the impact of stellar radial migration on the observed chemical abundance patterns across both thin and thick discs. Finally, the results are discussed and summarized in Sections 6 and 7, respectively.

## 2 SIMULATION SET UP

This section provides an overview of the simulations and their subgrid physics routines.

### 2.1 Models setup

Our models consist of a disc galaxy forming inside a hot corona of pressure-supported gas embedded in a dark matter halo, an approach that has been used extensively for studying isolated disc galaxy formation and evolution (see e.g. Cole et al. 2014; Aumer,

**Table 1.** Initial and final (at 10 Gyr) parameters of simulated galaxies: gaseous halo mass ( $M_{\text{g}}(0)$ ), gaseous halo scale length ( $R_{\text{gas}}$ ), initial gaseous halo spin ( $\lambda$ ); total stellar mass ( $M_{\text{stars}}$ ), total number of star particles ( $N_{\text{stars}}$ ),  $l$  is the radial disc scale,  $h$  is the vertical disc scale,  $\sigma_{\text{R}}$  and  $\sigma_z$  are the mean radial and vertical velocity dispersions, respectively. Upper indexes (1), (2) correspond to low- and high- $\alpha$  sequences, respectively, relative to the cuts shown in Fig. 8. Note that the velocity dispersion components are measured for stars across the entire galaxy and the values are not suitable for the direct comparison with the numbers in the Solar vicinity.

Model	Initial parameters			Morphology	$M_{\text{stars}}$ $10^{10} M_{\odot}$	$N_{\text{stars}}$ $10^6$	Final (at 10 Gyr) parameters				
	$M_{\text{gas}}(0)$ $10^{10} M_{\odot}$	$R_{\text{gas}}$ kpc	$\lambda$				$M_{\text{stars}}^{(1)}/M_{\text{stars}}^{(2)}$ $10^{10} M_{\odot}$	$l^{(1)}/l^{(2)}$ kpc	$h^{(1)}/h^{(2)}$ kpc	$\sigma_{\text{R}}^{(1)}/\sigma_{\text{R}}^{(2)}$ $\text{km s}^{-1}$	$\sigma_z^{(1)}/\sigma_z^{(2)}$ $\text{km s}^{-1}$
Model 1	6	3	0.0436	Barred	5.8	4.6	2.33 / 3.46	7.3 / 5.5	0.29 / 0.48	54 / 67	32 / 34
Model 2	9	5	0.0465	Barred	8.2	4.7	4.77 / 3.42	4.3 / 3.2	0.35 / 0.59	73 / 87	27 / 37
Model 3	9	3	0.049	Spirals	8.4	4.1	4.57 / 3.82	5 / 3.9	0.22 / 0.38	69 / 104	30 / 49
Model 4	6	5	0.0347	Spirals	3.4	2.4	– / 3.4	– / 3.3	– / 0.24	– / 51	– / 27

Binney & Schönrich 2016; Clarke et al. 2019) and simulations of mergers (Athanasoula et al. 2016). We believe that this approach may also be relevant specifically to the MW formation/evolution which did not experience any significant mergers over the last  $\approx 9$  Gyr (Haywood et al. 2018; Helmi et al. 2018; Di Matteo et al. 2019b; Kruijssen et al. 2020) implying that the MW stellar mass has grown mostly by gas accretion and *in situ* star formation (Snaith et al. 2015; Haywood et al. 2019).

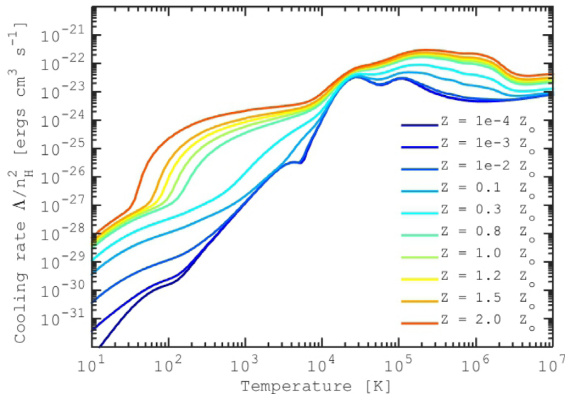
In this paper, we consider four models where the initial gaseous halo has different scale length, different initial mass and different  $\lambda$  spin parameters. These parameters are listed in Table 1. The gas is initially a Plummer sphere density distribution with a temperature profile to yield an approximate hydrostatic equilibrium (see e.g. Aumer & White 2013). The angular momentum follows a radial profile of  $j \propto r$ , where  $j$  is the specific angular momentum (see also Roskar et al. 2008; Cole et al. 2014; Clarke et al. 2019) which gives us a spin values consistent with those obtained from collisionless cosmological simulations (Bullock et al. 2001). Due to the large uncertainties in the actual gas metallicity at high redshift, we rely on the assumption of a primordial chemical composition of the gas, with a 24 per cent mass fraction of helium, and the rest of the mass in hydrogen. No star particles are present at the beginning of the simulations since all stars form out of gas that cools and reaches conditions to trigger star formation (see below). The initial state for the rotating gaseous halo embedded into the live DM halo has been generated using the iterative method described in Rodionov, Athanasoula & Sotnikova (2009). The dark matter halo is set up using a population of  $10^6$  collisionless particles following a Plummer distribution with a scale of 10 kpc and the spin values adopted as for the gas. We truncate the dark matter halo at 160 kpc. The particle mass is  $2.57 \times 10^5 M_{\odot}$ , and the gravitational softening length is set for DM to 250 pc.

The simulations were evolved with the  $N$ -body + Total Variation Diminishing hydrodynamical code (Khoperskov et al. 2014). For the  $N$ -body system integration and gas self-gravity, we used our parallel version of the TREE-GRAPE code (Fukushige, Makino & Kawai 2005) with multithread usage under the SSE and AVX instructions. In recent years, we already used and extensively tested our hardware-accelerator-based gravity calculation routine in several galaxy dynamics studies where we obtained accurate results with a good performance (Polyachenko, Berczik & Just 2016; Moetazedian et al. 2017; Saburova et al. 2017, 2018; Khoperskov et al. 2018b, c, 2019). For the time integration, we used a leapfrog integrator with a fixed step size of 0.1 Myr. In the simulation, we adopted the standard opening angle  $\theta = 0.7$ . Although we do not force a constant value of the initial mass of newborn star particles, the vast majority ( $> 90$  per cent) of them have a mass of  $\approx 3.8 \times 10^3 M_{\odot}$ . This allows us to use a constant value of gravitational softening parameter of 50 pc for star particles. The number of stellar particles

at the end of simulations for different models vary in the range of  $\approx (3-5) \times 10^6$  which makes our galaxies more detailed compared to similar studies based on large-scale cosmological simulations (e.g. Mackereth et al. 2018). Dynamics of the ISM is simulated on a Cartesian grid with static mesh refinement and a minimum cell size of 50 pc close to the galactic disc plane. The hydrodynamical part also includes radiative cooling (see next section) and heating terms and idealized magnetic field treatment with constrained transport approach (Khoperskov et al. 2014).

## 2.2 Subgrid physics

In our simulations a gaseous cell undergoes star formation if: (i) the gas mass is  $> 2 \times 10^5 M_{\odot}$ , (ii) the temperature  $T$  is lower than 100 K, and (iii) is part of a converging flow. The efficiency of star formation is set to 0.05, i.e. 5 per cent of the gas eligible to form a new star particle per dynamical time. There is no direct dependency of the star formation efficiency on the gas metallicity. Newborn stellar particles inherit the velocity and elemental abundances of their parent gas cells. Although in our models we allow the formation of new particles in a wide range of masses, we found that 95–98 per cent of particles have the mass of about  $4 \times 10^4$ , which does not contribute significantly to artificial heating due to constant softening. The mass of newborn stellar particles is not fixed in our simulations, however, about 95–98 per cent of particles have the mass of about  $4 \times 10^4$ , so each can be considered as a single stellar population. We assume the initial distribution of stellar masses (IMF) to be described by the parameters from Kroupa (2001), normalized between 0.1 and  $100 M_{\odot}$ . At each time-step, we calculate the amount of gas returned, the mass of the various species of metals, the number of SNII or SNIa for a given initial mass and metallicity, the cumulative yield of various chemical elements (O, Mg, Si, Fe, and H), the total metallicity, and the total gas released. Released mass of different elements are treated separately as passive scalars which obey non-homogeneous transport equations and thus are advected with the gas (see e.g. Mignone et al. 2012). Therefore, we consider the interstellar medium (ISM) as a mixture of several species (H, He, Si, Mg, O, Fe, and other metals) which is sufficient for modelling the galactic chemical evolution. Following standard approach for the passive scalars, these species are mixed within a given cell but abundances are allowed to be different in different cells. Following the chemical evolution models by Snaith et al. (2015), at each time-step, the mass and metals released from evolving stellar populations are transferred from stellar particles to their neighbours, with weights calculated using the initial, rather than current, mass of the particle. Feedback associated with the evolution of massive stars is implemented as an injection of thermal energy in a nearby gas cell proportional to the number of type II supernovae (SNII), type



**Figure 1.** Cooling functions adopted for the calculation of  $\Lambda/n^2$  (ergs  $\text{cm}^3 \text{s}^{-1}$ ) for different values of gas total metallicity ( $Z$ ).

I supernovae (SNI), and asymptotic giant branch stars. Outflows develop naturally without the need to specify an initial gas velocity and do not require that radiative cooling or hydrodynamic forces to be temporarily disabled (see also Kim et al. 2016). Such an approach was successfully used in a number of our previous studies (Khoperskov et al. 2016, 2018a; Khoperskov & Vasiliev 2017) and provides a realistic ISM treatment and Kennicutt–Schmidt-type relations for both low- and high- star formation regimes of galaxy evolution.

In the energy equation for hydrodynamics, we take into account cooling processes using the tabulated non-equilibrium cooling curves that depend on the metallicity of the gas (see Fig. 1). The full description of our method of cooling rate calculations and the references to the atomic data can be found in Vasiliev (2011, 2013). Although we do not consider the detailed chemical reactions network in the ISM, a tabulated metallicity dependent cooling rates provide us a reasonable agreement of the ISM structure (pressure–temperature relation, see Fig. A1) with widely used state-of-the-art gravito-hydrodynamics codes (Kim et al. 2016).

In brief, the non-equilibrium calculation includes the ionization kinetics of all ionization states for the following chemical elements H, He, C, N, O, Ne, Mg, Si, and Fe as well as molecular hydrogen kinetics at  $T < 10^4$  K. We take into account the following major processes in a collisional gas: collisional ionization, radiative, and dielectronic recombination as well as charge transfer in collisions with hydrogen and helium atoms and ions. In a low-temperature ( $T \leq 10^4$  K) gas the above-listed ionization states of the elements are supplemented by a standard set of species:  $\text{H}^-$ ,  $\text{H}_2$ ,  $\text{H}_2^+$ , D,  $\text{D}^+$ ,  $\text{D}^-$ , and HD, needed to model the  $\text{H}_2/\text{HD}$  gas-phase kinetics (Abel et al. 1997; Galli & Palla 1998). Note that the  $\text{H}_2/\text{HD}$  cooling is efficient in low metallicity gas,  $[\text{Z}/\text{H}] < -3$ .

The cooling rates are obtained for a gas cooled down isochorically from  $10^8$  down to 10 K. We calculate a grid of cooling rates covering the metallicity range from  $[\text{Z}/\text{H}] = -4$  to  $+0.3$ . The grid is constructed so that the difference of cooling rate between neighbouring values of metallicity is smaller than a factor of two for any temperature.

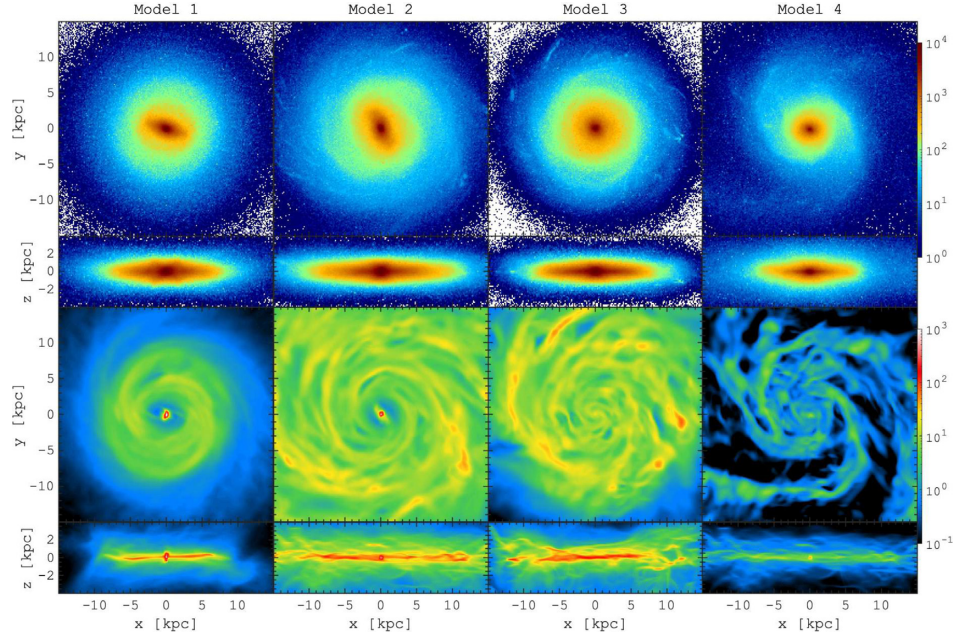
### 2.3 Overview of the star formation histories of simulated galaxies

As we described before, in this work we present the analysis of four MW-type disc galaxies with stellar masses in the range of  $(3.4\text{--}8.2) \times 10^{10} M_\odot$ . Two galaxies have bars with boxy/peanut pseudo-bulges (models 1 and 2) and the two other models present

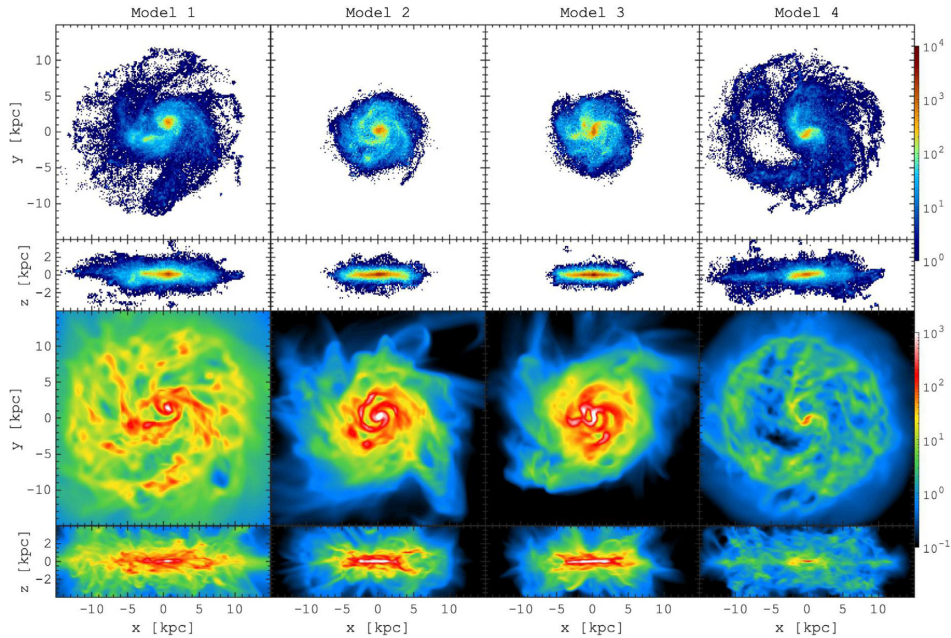
a spiral structure (model 3 with a weak pattern and model 4 with a more prominent one) at the end of the simulation (see Fig. 2). This set of simulations, although being limited, allows us to follow the main paths of chemodynamical evolution of MW-type disc galaxies.

At the beginning of the simulations, the primordial gaseous haloes rapidly settle into thick disc-like structures. The turbulent gaseous phase at the beginning of our discs formation somehow resembles the gas-rich merger phase observed in simulations with cosmological initial conditions (see e.g. Brook et al. 2004). In our models, the high mass of the gaseous disc leads to its rapid fragmentation and to the formation of clumpy discs with an enhanced SFR. The chains of massive clumps ( $10^8\text{--}10^9 M_\odot$ ) dominate the structure of the galaxies, similarly to some previous simulations (Noguchi 1999; Kroupa 2002; Bournaud, Elmegreen & Elmegreen 2007; Bournaud et al. 2014; Inoue et al. 2016; Clarke et al. 2019; Beraldo e Silva et al. 2020, see Fig. 3) and the analytical calculations of the MW stellar structure at high redshift (Assmann et al. 2011; Zonoozi, Mahani & Kroupa 2019). We observe that after the fragmentation phase, some clumps fall to the centre, but some of them are dissolved, preventing the formation of massive bulges. Our galaxies pass through a stage of a rapid collapse of gas and intense star formation activity in a thick turbulent disc, where a high level of turbulence is driven by the stellar feedback, leading to an efficient mixing of metals in the disc. Despite a short time-scale, this phase contributes significantly to the buildup of the stellar component. As can be seen in Fig. 3, the star formation rate density is sufficiently high to generate possible outflows (Lehnert et al. 2014) that may have contributed to polluting the surrounding extended gaseous halo (see e.g. Davé, Finlator & Oppenheimer 2011; Christensen et al. 2016; Gutcke et al. 2017). At later epochs, the evolution is more quiescent, and settles to structures similar to those observed in nearby disc galaxies and in the MW (see Fig. 2).

To understand the origin of the diversity of chemical patterns, and of the  $\alpha$ -bimodality in particular, we need to explore the star formation, stellar feedback, and the gas infall rates as a function of time. These are shown for the four simulations in Fig. 4. Similar to Nuza et al. (2019), we compute the gas accretion rates in units of solar masses per year by multiplying gas fluxes by their corresponding surface areas where the surface is defined by two parallel planes  $\pm 1$  kpc from the disc plane. Of course, the choice of the surface is arbitrary, but our selection provides a global view of the gas infall rate evolution. According to Fig. 4, during a short initial phase (1.5–3 Gyr, depending on the model) primordial gas is rapidly accreted, giving rise to the formation of a significant fraction of the disc component. This episode is followed by a less intense ( $0.5\text{--}5 M_\odot \text{yr}^{-1}$ ) new phase of gas accretion on much longer time-scales, resulting in the formation of a younger disc component. The SFH (see Fig. 4) shows a similar temporal evolution to the gas accretion rate, which suggests that in our simulations the star formation rate is supported by the gas accretion rate (or re-accretion, see e.g. Fraternali & Binney 2008; Marinacci et al. 2010). It seems to happen in two more or less distinct phases, namely, an early, initial intense period of star formation followed by a subsequent, lower star formation intensity phase. The SFH is also very much spatially segregated: the initial intense phase of star formation is limited to a few central kpcs, the early SFR intensity at 10 kpc being often less than 10 per cent its value in the inner regions of the discs. As we shall see in Section 4, these spatial and temporal dichotomies, which are defined by the accretion history and distribution of the gas, are at the origin of the large-scale bimodality of the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  distribution.



**Figure 2.** Face-on and edge-on density maps ( $M_{\odot} \text{pc}^{-2}$  in log-scale) of the stellar (top frames) and gaseous (bottom frames) components for the four simulated galaxies after 10 Gyr of evolution.

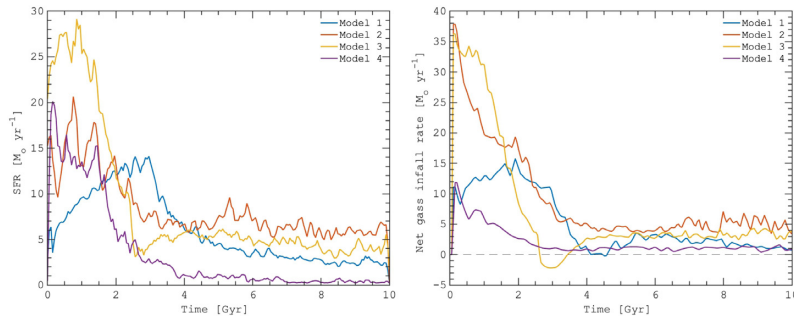


**Figure 3.** Same as in Fig. 2 but at early times of evolution,  $t = 500$  Myr. Our simulated galaxies went through a clumpy phase with rapid internal evolution, similar to that of progenitors of MW-type galaxies at high redshifts. Another important characteristic of the early evolution is the gaseous outflows caused by the stellar feedback (best visible in models 2 and 3 with a compact disc).

### 3 CHEMICAL ENRICHMENT OF THE MULTIPHASE ISM

In chemical evolution models, the chemical evolution history is determined by both the SFH, which determines the amount of metals that are rejected in the ISM as a function of time, and the ISM itself, which fixes the dilution of these elements. Both are controlled by the gas infall rate. As we have seen, the SFH of our galaxies is critically determined by their infall history. However, in our simulations, the physics of the gas, described by a multiphase ISM, introduces a more complex chemical cycle which is studied here.

In our simulations, the source of the accreted gas is a pre-existing extended, initially hot ( $T \sim 10^6$  K), gaseous halo. The most intense phase of mass and metals exchange between the disc ISM and this surrounding circumgalactic medium (CGM) is the thick disc formation at early epoch ( $\approx 8-10$  Gyr ago, see Fig. 3). During this phase and afterwards, the gas is heated through supernovae (SN) explosions, ejected in the halo through outflows, mixed by the induced turbulence in the disc. Fig. 6 illustrates the resulting complexity of the multiphase structure of the ISM in  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  plane at different times. To avoid some



**Figure 4.** Left: SFH of simulated galaxies. Right: net gas infall rate as a function of time. At early times, accretion rate is high, reaching values up to  $10\text{--}35 M_{\odot} \text{ yr}^{-1}$  and then decline towards net values within the range  $0.5\text{--}5 M_{\odot} \text{ yr}^{-1}$  at the end of evolution. The sharp decrease of the gas infall rate at the end of the initial intense phase of star formation is caused by the intensive stellar feedback, which, e.g. in model 3 leads to the short period of net outflow of the gas.

peculiarities in the chemical abundance evolution of individual elements we define  $[\alpha/\text{H}] = ([\text{Si}/\text{H}] + [\text{Mg}/\text{H}] + [\text{O}/\text{H}])/3$ . Already at very early stages ( $\approx 0.5\text{--}1$  Gyr), we find the presence of gas with solar abundances, however, it is characterized by a very high temperature ( $> 10^5\text{--}10^6$  K). This gas was likely released in several episodes of SN explosions in massive star-forming regions. It was then ejected from the galaxy by stellar feedback in the form of filaments flowing out of the stellar disc (see Fig. 3), carrying metals into the surrounding gaseous halo which can then be mixed with the pre-existing gas. However, due to the low density of the gaseous halo, the dilution of metals is limited, and the resulting CGM abundances can be very large compared to the newly formed stars. An important implication, is that the high-metallicity gas cannot take part in subsequent star formation for a considerable time. This means that there is a time delay between stars releasing metals and those metals returning to the ISM. On a longer time-scale, this mixture of pristine and recycled material with large angular momentum is then accreted by the existing stellar component, contributing to the formation of a thin disc. In particular in models with a high early-star formation rate (models 1–3) stellar feedback is strong enough to remove low-angular momentum gas from the disc and make it available in the halo where it is efficiently captured by the rotating gas, similar to the process noticed in a number of galaxy formation studies (see e.g. Oppenheimer & Davé 2008; Oppenheimer et al. 2010; Übler et al. 2014; Kretschmer, Agertz & Teyssier 2020). Then, after being mixed with surrounding CGM gas, the ejected gas falls back on to the disc, bringing more gas for further star formation during the thin disc formation epoch (Fraternali & Binney 2008; Binney, Nipoti & Fraternali 2009; Marinacci et al. 2010). To demonstrate this, in Fig. 5 we show the relation between the ISM metallicity and the spherical radial velocity, where negative velocities trace inflows while positive velocities trace outflow. At early stages of intense star formation, the high metallicity regions are found preferentially in outflowing gas while infalling gas has lower abundances (see also Peroux et al. 2020). Thereby, when this gas is re-accreted on to the disc, it is already enriched, and not pristine, which appears to confirm various observations in the MW (see e.g. Brook et al. 2014; Miller & Bregman 2015; Fox et al. 2016; Stern et al. 2016) and in external galaxies (see e.g. Tumlinson et al. 2011a, b). This overall cycle is also very similar to the one described in Huscher et al. (2020), who analysed EAGLE simulations of MW-like galaxies, in particular for what concerns the early-metal enrichment of the hot CGM by outflows, and the fact that most of the gas accretion during the thin disc phase is already recycled gas.

A notable feature in Fig. 6, is the two distinct areas of cold gas, that correspond to the formation of the thick disc, at high- $\alpha$  and

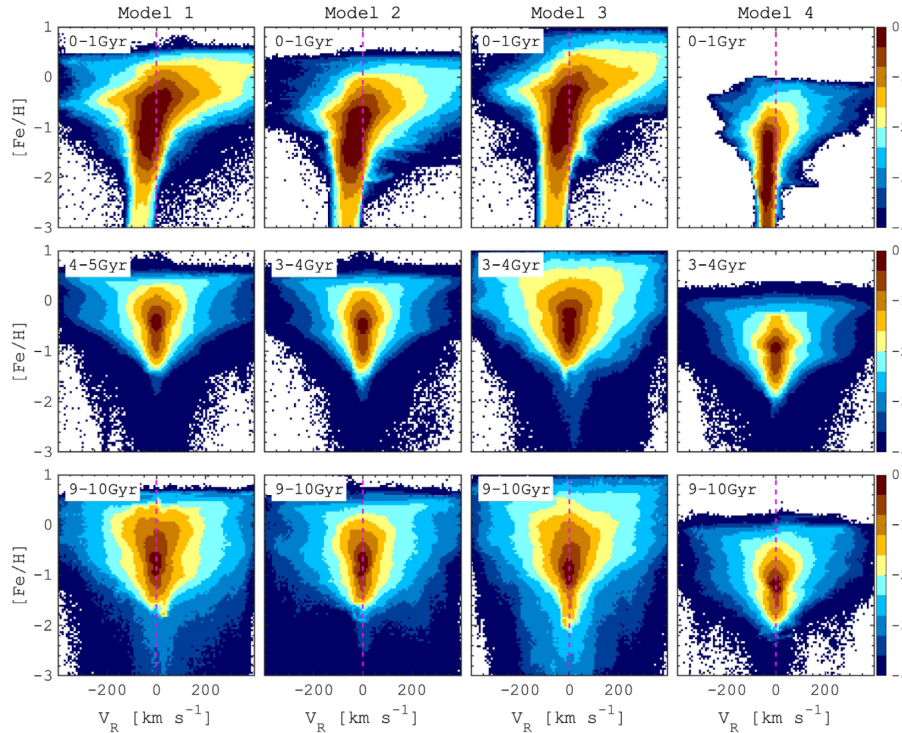
to the thin disc, at low- $\alpha$ . The high- $\alpha$  sequence is present as early as the first Gyr, as can be seen in the first row, while the low- $\alpha$  sequence appears later, at higher metallicity, indicating that the cold ISM has been gradually enriched in metals. Another notable feature is the absence of high- $\alpha$  abundances in the ISM after the thick disc formation (the two lower rows) which is likely caused by the mixing of metals in the CGM and the near galactic disc.

Fig. 7 illustrates the range of chemical abundances of the ISM that exist at any given time in the simulation, due to the presence of gas at very different temperatures. It shows the chemical abundance evolution of newly formed stars (yellow curves) and the ISM (colour density maps) in model 1 in four 1 kpc-width circular annuli, while the other models are presented in the Appendix A (see Fig. A3). As mentioned earlier, in all models the ISM abundances ( $[\text{Fe}/\text{H}]$  and  $[\alpha/\text{H}]$ ) can rapidly reach very high values, with a (moderate) fraction reaching solar metallicities already at  $t < 1$  Gyr. Meanwhile, stellar populations do not gain such a high metallicity before the firsts  $\approx 2$  Gyr, even in the galactic centre. At large galactocentric radii, the difference between stellar and ISM abundances is even more evident, most of the ISM being more enriched than the population of locally formed stars.

The large spread of ISM abundances at all radii clearly demonstrates that the assumption of instantaneous mixing (Spitoni et al. 2009; Matteucci 2014) used in chemical evolution models is a crude approximation because it assumes that all metals are available and well mixed in the gas that forms stars at all times. From Fig. 7 it can be seen, however, that stars can form in an ISM which is substantially less (at large radii) or more (at small radii) metal-rich than the majority of the gas. Hence, in chemical evolution models, this will lead to chemical evolutions that are either faster or slower, depending on the location, than what the evolutions really is in more elaborate models. In the inner and outer galaxy in particular, star formation occurs neither in the most enriched gas nor in the most widespread (in terms of the gas mass abundances). Such behaviour is explained by the complex multiphase structure of the ISM. Having illustrated the complex circulation of metals in the gas phase, we now turn to the emergence of the chemical patterns in stars.

#### 4 CHEMICAL ABUNDANCE PATTERNS

We begin by examining the global chemical abundance patterns in the simulated galaxies, in particular we focus on the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  distribution at the final snapshot  $t = 10$  Gyr. In Fig. 8, we show  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  relation for all the stars in the four models. The relation for each model is shown in a restricted range of metallicities ( $[\text{Fe}/\text{H}] > -2.5$  and,  $[\alpha/\text{Fe}] < 1$ , large frames) and for a



**Figure 5.** Gas metallicity as a function of spherical radial velocity, with the vertical line demarcating inflow ( $<0$ ) versus outflow ( $>0$ ). For top frames, we stack together 10 snapshots for the first 1 Gyr of evolution. Second row represents the relation based on 10 snapshots after the end of the high- $\alpha$  sequence formation. The bottom frames correspond to 10 snapshots at the end (9–10 Gyr) of the simulations. At early stages, during the burst of the star formation, models 1–3 show that outflows have preferentially higher metallicity than inflows (see Peroux et al. 2020), while in model 4 the outflows are less effective. At later stages of evolution, we observe a balance between inflow/outflow of metals because of the low star formation activity in our galaxies.

larger range of abundances ( $[\text{Fe}/\text{H}] > -5$ ,  $[\alpha/\text{Fe}] < 1.2$ ) where the most metal-poor first generations of stars, being minor contributors to the total disc mass, are clearly visible. This figure shows that three (models 1–3) among the four simulations produce clear low and high  $[\alpha/\text{Fe}]$  sequences in the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  plane, qualitatively similar to those observed in the MW (see e.g. Hayden et al. 2015; Queiroz et al. 2019). To further understand our results, we separate high- and low- $\alpha$  sequences (see black lines in Fig. 8) by a different lines for different models, except for model 4 that shows a single pattern similar to the high- $\alpha$  sequences of other models but shows no obvious low- $\alpha$  sequence. The low- and high- $\alpha$  sequences, as defined by this separating line, can be seen as tracing mostly the thin and thick discs, as is done in practice for observations of stars in the MW (see Brook et al. 2012, for simulated thin/thick discs analysis).

#### 4.1 Low and high- $[\alpha/\text{Fe}]$ sequences: relation to structures (thin and thick discs)

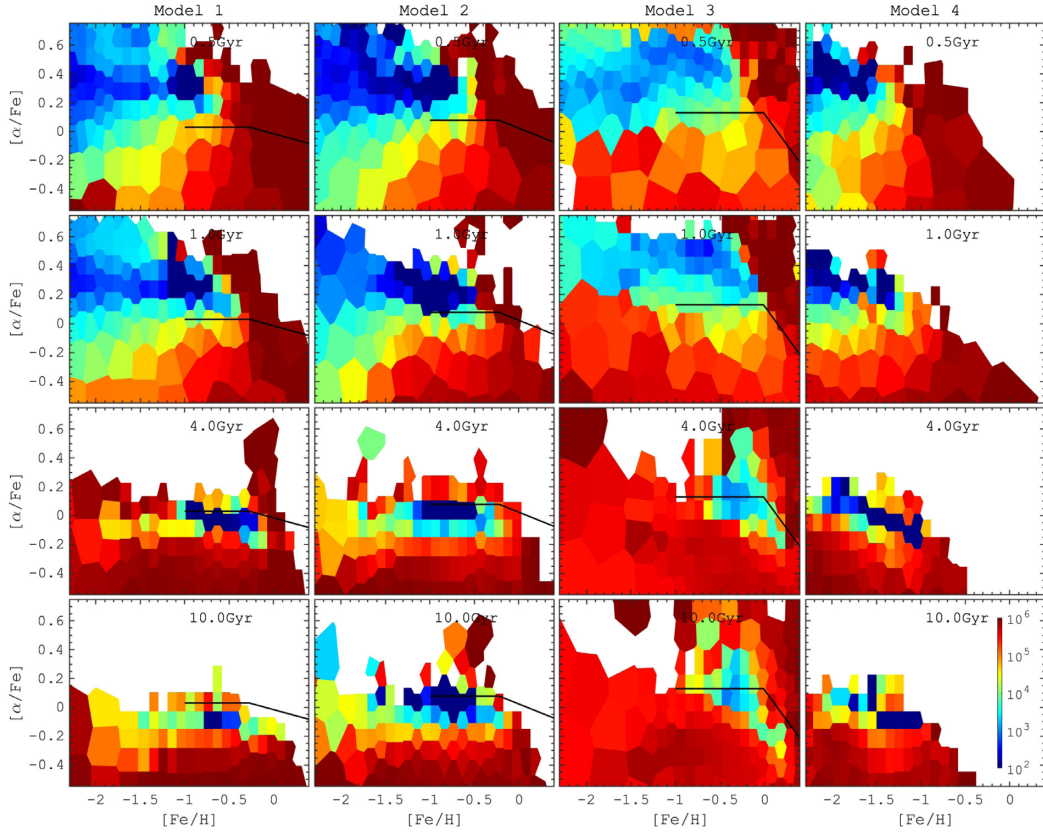
Discrimination between low- and high- $\alpha$  sequences allows us to connect the observed bimodality with structure and kinematics of these chemically defined stellar components of simulated galaxies. In particular, we look at spatial distributions of these populations and global differences in their kinematics. In Table 1, we summarize the main properties of simulated galaxies where we also compare some main parameters for stars belonging to low- and high- $\alpha$  sequences. Across different models, the mass of the high- $\alpha$  population is rather similar  $(3.4\text{--}3.8) \times 10^{10} M_{\odot}$  which correspond to 45–60 per cent of the entire galaxy stellar mass. Note that these numbers are somewhat arbitrary and depend on the definition of the low- and high- $\alpha$  sequences. However, in all cases, our models show a significant high-

$\alpha$  disc mass, which is in quantitative agreement with the estimate of Snaith et al. (2015) who found that 47 per cent of the stellar mass belongs to the high- $\alpha$  sequence in the MW. In all three galaxies with bimodality, the high- $\alpha$  components exhibit shorter radial extent compared to low- $\alpha$  stars, and is also vertically thicker and dynamically hotter in both radial and vertical directions (see Table 1, note that the velocity dispersion components ( $\sigma_R$ ,  $\sigma_z$ ) are measured for stars across the entire galaxy). Our simulations imply that, similarly to the MW, the high- $\alpha$  sequence in models 1–3 correspond to chemically defined compact thick discs, while the low- $\alpha$  stars form chemically defined extended thin discs (see e.g. Bovy et al. 2012; Hayden et al. 2015; Feuillet et al. 2019). It is also worth mentioning that, in our models, we find *in situ* formed stars with chemical abundances typical of the low- $\alpha$  sequence discussed in the observational data and typically interpreted as made of accreted stars (Nissen & Schuster 2010; Haywood et al. 2018; Helmi et al. 2018; Di Matteo et al. 2019b). In other words, our simulations suggest that *in situ* stellar populations of the MW could contribute to the low  $\alpha$ -populations at metallicities below  $\lesssim -0.5$ .

#### 4.2 Low- and high- $[\alpha/\text{Fe}]$ sequences: relation to age

The first question we want to address is related to the age differences between the two  $\alpha$ -sequences. In Fig. 9, we show the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  distribution for all stars in the simulated galaxies colour coded by the mean age of stars. The age structure of our galaxies is similar to the one observed in the solar vicinity (Haywood et al. 2013). In particular, all models (1–3) with bimodality have a high- $\alpha$  sequence mainly formed during the first 2–3 Gyr of evolution, implying that the thick discs in our simulations are made of old stars. Moreover, it can





**Figure 6.** Evolution of the median gas temperature distribution in  $[\alpha/\text{Fe}]$ - $[\text{Fe}/\text{H}]$  plane. The temperature value is measured at snapshots marked in each frame (0.5, 1, 4, and 10 Gyr from top to bottom). The temperature scale is the same across the frames and it is shown in the bottom right frame. In our simulations, star formation is allowed only in the cold ISM ( $T < 100$  K) which limits the inheritance of the chemical abundances of newly formed stars. Multiphase structure of the ISM demonstrates that the amount of cold gas decreases with time, suggesting that thick discs form in the epoch of molecular gas domination. The distributions also illustrate the presence of, even at early times, metal-enriched hot gas which is not involved in the star formation activity due to long cooling time-scale. A large fraction of metals in the hot phase decreases the speed of the chemical evolution, e.g. compared to standard chemical evolution models. Black lines separate low- and high- $\alpha$  sequences in three models except model 4 (right column) where we do not find a prominent bimodality (see Section 4 for details).

be seen that the high- $[\alpha/\text{Fe}]$  sequence is clearly an age sequence, in the sense that age decreases along the sequence. This is particularly true for model 3, where the sequence is tight. This is also illustrated in Fig. 12 where we present the chemical evolution tracks in the  $[\alpha/\text{Fe}]$ - $[\text{Fe}/\text{H}]$  plane in 1 kpc width circular annuli at different galactocentric distances built from recently formed stars (age  $< 10$  Myr) stars as a function of time (see Brook et al. 2012, fig. 8).

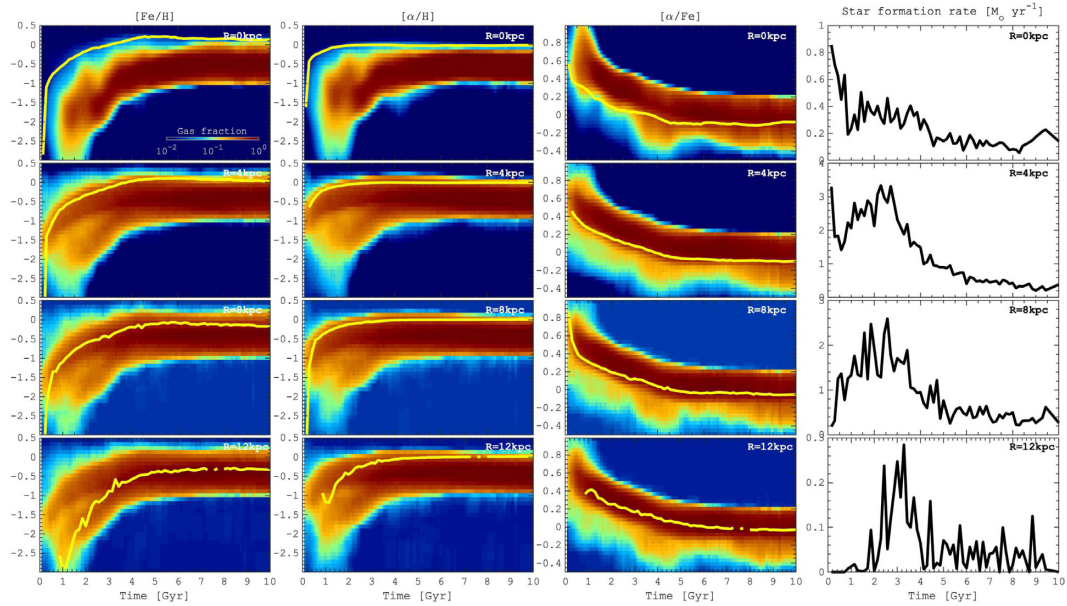
Thin discs (or low- $\alpha$  stars) contain stellar populations with a wider range of ages ( $\lesssim 6$ -8 Gyr) suggesting their formation on a longer time-scale after the thick disc formation. The sharp age transition is in favour of a rapid change of the star formation regime leading to different enrichment efficiencies during the formation of high- and low- $\alpha$  sequences. A rapid transition between thick and thin discs formation phases also implies that in our simulations, both  $\alpha$ -sequences are not formed concurrently as it has been suggested in Clarke et al. (2019). On the contrary, in our models, the thick and thin disc evolutions are sequential (see also Stinson et al. 2013). In the outer disc, however, where the thick disc does not exist, the star formation ignition will depend on the gas density, which will depend on a range of related processes, such as the accretion history at large radii, outflows from the inner disc, and/or the possible occurrence of a gas-rich merger.

Another feature related to the SFH is the width of the high- $\alpha$  sequence. This sequence is tightest for the model with the most intense SFR during the thick disc phase (model 3), due to the largest

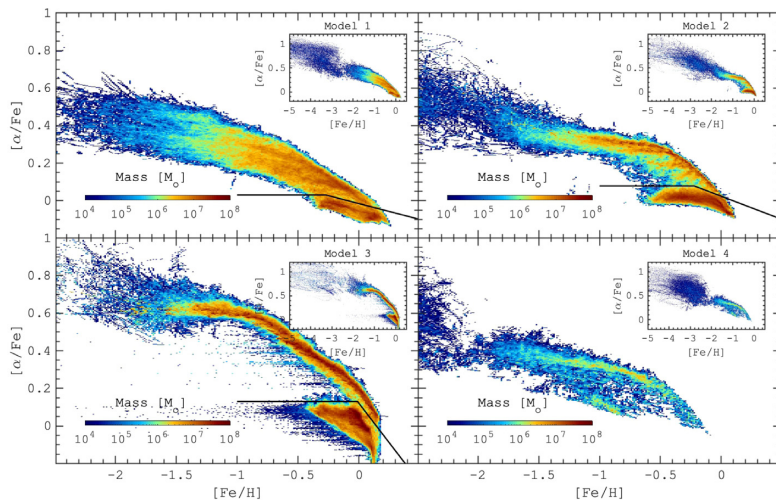
initial gas mass and smallest scale length. On the contrary, the model with the longest thick disc formation phase (model 1) has a wide high- $\alpha$  sequence. Model 1 has radial stellar scale length for the thick disc which is 40–70 per cent larger than for the other models, or less concentrated gas distribution, implying less intense star formation during thick disc formation. The consequence is that the formation of the thick disc is much less concentrated than for the other models, less well mixed, with a clear radial dependence of the formation of the thick disc. Hence, the high- $\alpha$  sequence is composed of parallel chemical tracks.

### 4.3 Low- and high- $[\alpha/\text{Fe}]$ sequences: relation to radius

Next we look at the radial distribution of stars of both  $\alpha$ -sequences. In Fig. 10, we show  $[\alpha/\text{Fe}]$ - $[\text{Fe}/\text{H}]$  distributions but now colour coded by the mean galactocentric distances for stars at the end of the simulation. Across all models, during the formation of high- $\alpha$  sequences, the chemical evolution is fast but slightly different at different radii due to the radial decrease of the star formation efficiency (see e.g. Nidever et al. 2014). In particular, we observe parallel tracks reaching the same values of the  $[\text{Fe}/\text{H}]$  delayed in time at a larger radius, stars forming more rapidly in the inner disc. This process is seen prominently in models 1, 2, and 4, where star formation intensity follows the decreasing gas density (and hence



**Figure 7.** Chemical evolution of stellar populations and the ISM enrichment history at different radii in model 1. From left to right: the average evolution of  $[\text{Fe}/\text{H}]$ ,  $[\alpha/\text{H}]$ ,  $[\alpha/\text{Fe}]$ , and total star formation rate in 1 kpc-width circular annuli: 0, 4, 8, and 12 kpc (different rows). Chemical abundance evolution of new born stars (age  $< 10$  Myr) is shown by yellow lines. Background colourmaps represent a mass fraction (normalized at each snapshot) of the gas according to the colour-bar plotted in the top left frame.



**Figure 8.**  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  maps of simulated galaxies at 10 Gyr colour coded by the stellar mass. Large frames correspond to a restricted chemical abundance range while smaller subframes depict the distribution on a larger metallicity scale to show where the oldest very metal-poor stars ( $[\text{Fe}/\text{H}] \lesssim -5 \dots -4$ ) can be found. Black lines separate low- and high- $\alpha$  sequences in three models except model 4 (bottom right) where we do not find a prominent bimodality.

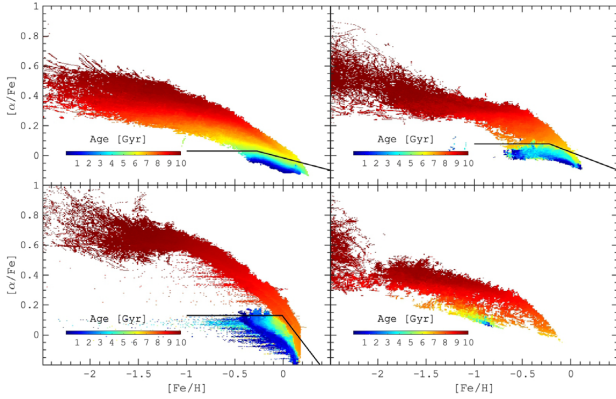
increasing distance to the Galactic Centre), leading to a chemical evolution that depends on radius. In model 3, the high star formation drives turbulent ISM conditions that contribute to a more uniform chemical abundance evolution across a range of radii. This leads to a tighter high- $\alpha$  sequence, but we still can distinguish parallel chemical evolution tracks (see Fig. 12).

Meanwhile, thin discs show (except for model 4) a negative radial metallicity gradient which is most prominent in models 1 and 2, the metallicity decreasing towards the outer disc as is apparent along the low- $\alpha$  sequence (see Fig. 10). In these models, the formation of the disc is clearly inside-out, in the sense that the peak of star formation occurs at earlier times and is more intense in the inner disc. This is illustrated for model 1 in Fig. 7 which shows the SFH at different radii, and for model 2 in the Appendix. Hence thick discs (high- $\alpha$ )

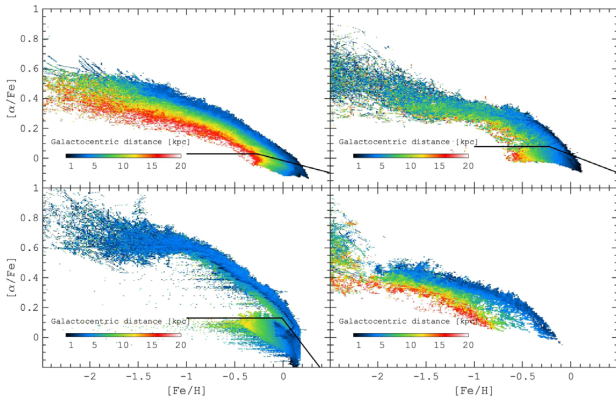
form initially in the inner galaxy, and thin stellar discs assemble later over a larger spatial scale. This is confirmed by Fig. 11, which shows the  $[\text{Fe}/\text{H}]$ – $[\alpha/\text{Fe}]$  distribution in different radial and vertical ranges. The figure clearly illustrates that the ridge line defining the high- $\alpha$  sequence is confined to the inner disc, while the full extent of the low- $\alpha$  sequence is visible only at larger radii, being restricted to high metallicities in the inner Galaxy. This behaviour is very similar to what is found in the MW with the APOGEE data (Hayden et al. 2015; Queiroz et al. 2019).

#### 4.4 Fine structures

Another interesting feature during the formation of the high- $\alpha$  sequence in model 2 is the horizontally aligned ‘spikes’. These



**Figure 9.** Mean stellar age maps of  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  relation in simulated galaxies at 10 Gyr. Black lines separate low- and high- $\alpha$  sequences, as in Fig. 8. The distributions show that high- $\alpha$  sequence stars formed at early epochs of the galaxy evolution while low- $\alpha$  is the result of later evolution.



**Figure 10.** Mean galactocentric distance maps in the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  plane in simulated galaxies at 10 Gyr. Black lines separate low- and high- $\alpha$  sequences, as in Fig. 8. Radial metallicity gradient is visible across all the models on the low- $\alpha$  sequence, but also on the high- $\alpha$  sequence for model 1, 4, and to a lesser extent, on model 2. It is essentially absent in model 3.

brief, low-amplitude  $[\text{Fe}/\text{H}]$  dilution episodes (see also in Fig. 8 as horizontal ridges) are likely associated with bursts of star formation during the thick disc formation phase ( $< 2$  Gyr, see Fig. 4 left). Note that similar patterns can be found when gas-rich mergers (Snaith et al. 2016; Buck 2020) stimulate the star formation in the low- $[\text{Fe}/\text{H}]$  gas accreted during the merger.

After the formation of the high- $\alpha$  sequences in models with bimodality (1, 2, 3), we observe a rapid decrease and subsequent slow increase of the metallicity creating a ‘loop’ similar to one predicted by the chemical evolution models by Grisoni et al. (2017), Spitoni et al. (2019, 2020). In our simulations, the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  loop is the result of the star formation quenching being induced by the sharp change of the gas infall rate into the galaxy controlled by the stellar feedback (winds). In Fig. 4, we can see that the star formation quenching is the most rapid ( $\approx 1$  Gyr) in model 3, being slower in model 1 ( $\approx 2$  Gyr) and model 2 ( $\approx 3$  Gyr). Thereby, the different quenching ‘speed’ (and likely the star formation ratio before and after the quenching) is clearly imprinted in the diversity of the loop shapes across the models. In particular, in model 1, with a slow decrease of the star formation rate, the loop amplitude is small and it results in a  $[\text{Fe}/\text{H}]$  dilution of  $\approx 0.1$  dex while in model 2 the loop is very evident, especially in the inner galaxy where the  $[\text{Fe}/\text{H}]$

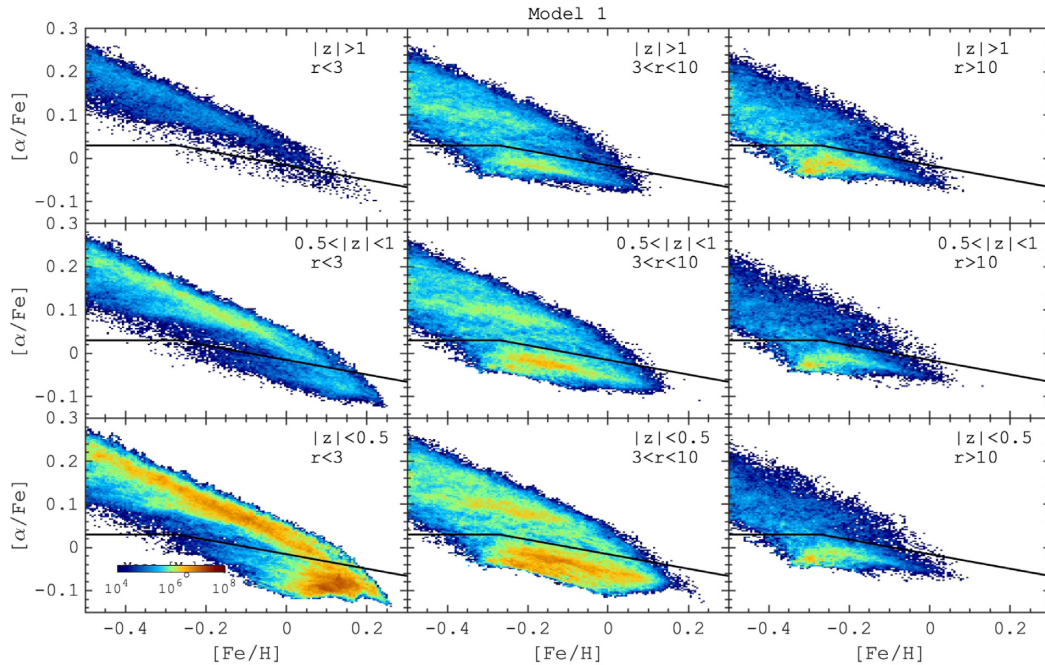
dilution is  $\approx 0.2$  dex. Finally, in model 3, we found a  $[\text{Fe}/\text{H}]$  dilution of 0.25–0.3 dex due to the fastest transition between the intense star formation during the thick disc phase and quiescent thin disc formation phase. Note also that the amplitude of the  $[\text{Fe}/\text{H}]$  dilution in our simulations is significantly smaller compared to 1.2 dex in Grisoni et al. (2017) who assumed primordial chemical composition of the infalling gas. In our simulations, the chemical composition of the infalling gas during the thin disc formation phase is not primordial because the gaseous halo has been significantly polluted during the thick disc formation, providing a tight connection between chemical abundance patterns in thick and thin discs.

#### 4.5 Origin of the bimodal sequence

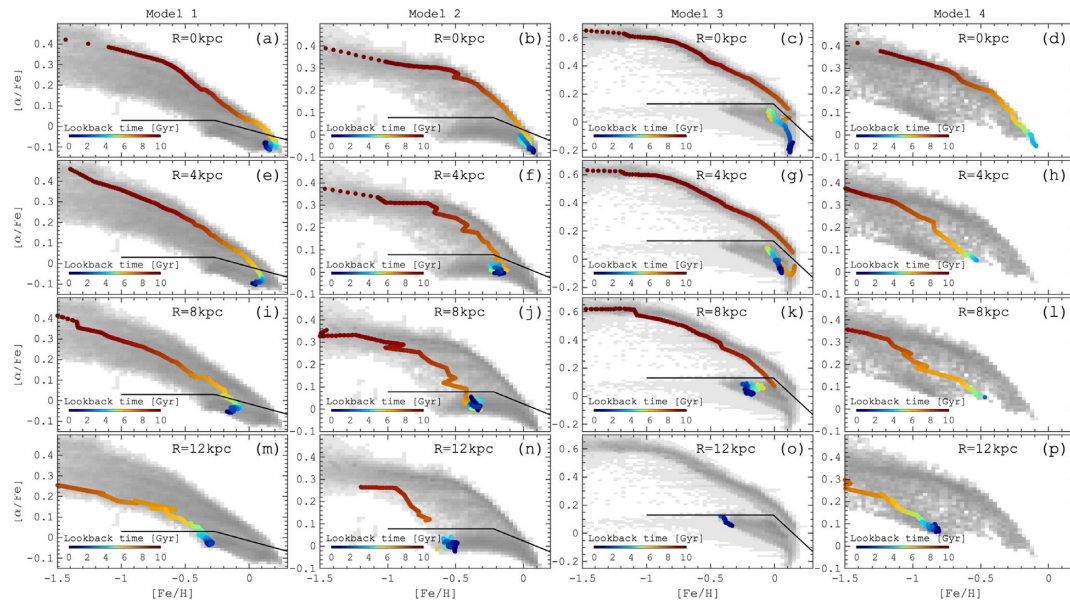
Although all models present a variety of chemical patterns, the first three have conspicuous bimodal sequences, and it is possibly embryonic in model 4 (weakly visible on Fig. 2). The high- $\alpha$  sequence is a temporal sequence because metallicity increases and alpha abundance decreases monotonically with time during this phase (see Figs 9 and 12). The low- $[\alpha/\text{Fe}]$  sequence is somewhat more complex and result from the combination of two different effects: the first is the accumulation of stars younger than 6–7 Gyr at the end of each chemical track. This is seen in Fig. 12 that shows the chemical evolution in different parts of the simulated galaxies. We measure the chemical evolution tracks as the evolution of the chemical abundances ( $[\text{Fe}/\text{H}]$ ,  $[\alpha/\text{Fe}]$ ) for young stars (age  $< 10$  Myr) in 1 kpc-width circular annuli at four galactocentric distances 0, 4, 8, and 12 kpc. Because metallicity and  $\alpha$ -abundance evolve little during the thin disc phase, reaching equilibrium values, thin disc stars pile up at the end of each track. The second effect contributing to the formation of the low- $\alpha$  sequence is the gradual shift of these equilibrium metallicities to lower values at larger radii. This gradual shift builds up a continuous sequence from low to high metallicity.

The existence of the low- and high- $\alpha$  sequences is a natural consequence of stars forming in two different ISM: one in which chemical species are produced in an intense episode of star formation and well mixed, which can occur only in primordial, concentrated discs, and the other in more extended discs, where the star formation efficiency is lower and follows the gas density, decreasing towards the outer disc. It is likely that these two types of ISM in galaxies are determined primarily by the presence of a substantially massive thick disc since the low- $\alpha$  sequence, and its ridge line should occur whenever the gas density decreases radially, which is expected in more or less all galaxies with a thin disc. Moreover, the bimodality goes with the dichotomy in radius, with the high- $\alpha$  dominating in the inner disc and the low- $\alpha$  at larger radii. When the infall rate provides only a limited amount of gas, as in model 4, it leads to the formation of a massive thick disc and no clear thin disc component. In which case the dichotomy in the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  plane is absent, or barely visible.

All four models illustrate that significant differences can arise in the chemical patterns because of the different SFHs, and spatial distribution of the star formation occurring within the modelled galaxies. The SFHs are themselves different because of the initial distribution of the gas and its total mass in each galaxy (see Table 1). These initial conditions result in a factor of 5 difference in gas surface densities, explaining the different star formation intensities reached in the first Gyrs of evolution by each galaxies. It clearly illustrates how differences of the order of 30 per cent in the initial gas mass and its spatial extent produce significant variations in the final chemical patterns.



**Figure 11.** Spatial variations of the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  maps in different parts of the disc at the end of the simulation in model 1. The low- $\alpha$  sequence disappears far away from the galactic plane, except in the outer disc due to flaring (see Minchev, Chiappini & Martig 2014), while the high- $\alpha$  sequence becomes barely visible at large galactic radii. This  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  variations show that similar to the MW (see e.g. Hayden et al. 2015; Queiroz et al. 2019), the high- $\alpha$  sequence corresponds to radially compact thick disc, while the low- $\alpha$  stars represent the radially extended thin disc component. We note that although the SFH shows no discontinuity, the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  shows clearly two distinct sequences dominated by the thick and thin discs. Spatial variations of the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  relation in other models are shown in Appendix A (see Fig. A2).

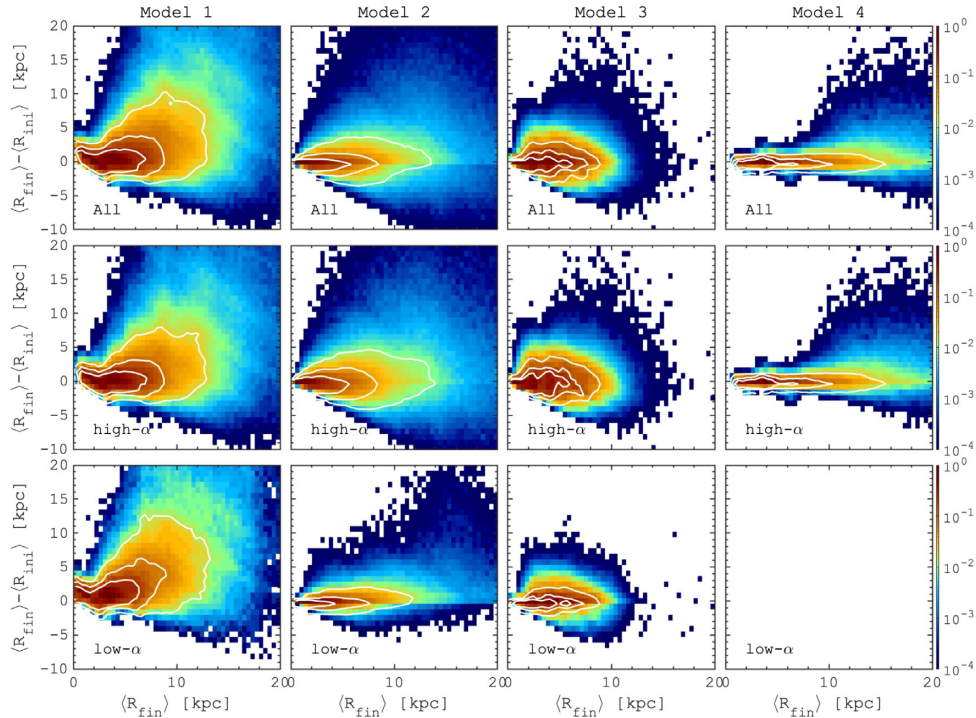


**Figure 12.** Chemical evolution tracks in  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  plane in 1 kpc width circular annuli at different galactocentric distances built from newly born (age  $< 10$  Myr) stars as a function of time. Grey background depicts the entire  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  relation for all the stars at the end of the simulation. Each galaxy formation model is shown in a separate column. Models with a clear bimodality (1–3) have endured a rapid (and moderate) dilution of  $[\text{Fe}/\text{H}]$  during the decrease of the star formation rate (see Fig. 4). This episode is imprinted as a non-monotonic stretch of the chemical evolution track, or even a loop (see also Grisoni et al. 2017; Spitoni et al. 2020) being the most prominent in models 2 and 3.

## 5 ROLE OF RADIAL MIGRATION

Although it is widely accepted that radial migration plays a role in reshaping the structure of galaxies over time (see e.g. Roskar et al. 2008; Schönrich & Binney 2009a; Loebman et al. 2011; Minchev et al. 2012; Roskar et al. 2012; Di Matteo et al. 2013; Kubryk,

Prantzos & Athanassoula 2013; Daniel et al. 2019), some studies suggest that, at least in the MW, the global characteristics of the stellar disc do not seem to require significant migration, if only to explain the few percent of metal-rich and metal-poor stars on circular orbits at the solar vicinity (Haywood et al. 2013; Halle et al. 2015,



**Figure 13.** Distributions of the mean change of the galactocentric distance  $\langle R_{\text{ini}} \rangle - \langle R_{\text{fin}} \rangle$  as a function of  $\langle R_{\text{ini}} \rangle$  for different models: top row corresponds to all stars while the middle and the bottom to high- and low- $\alpha$  sequences, respectively. Initial galactocentric position of star particles ( $\langle R_{\text{ini}} \rangle$ ) is measured as the mean position during the first 500 Myr after a star particle formation. Final galactocentric position of star particles ( $\langle R_{\text{fin}} \rangle$ ) is measured as the mean position during the last 500 Myr before the end of simulation (10 Gyr). Maps are shown in the same scale and colour coded according to the mass fraction relative the maximum value. Three white contours in each frame correspond to 90, 70, and 50 per cent of the enclosed mass. Across models, stellar radial migration is limited to 4–5 kpc for 90 per cent of the stars suggesting that only 10 per cent of stars are extreme migrators.

2018; Haywood et al. 2019; Khoperskov et al. 2020b). Very limited radial migration seems to be found in models where the coupled effects of bar and spiral arms is taken into account (see Monari et al. 2016, their fig. 11). Also recent works based on the analysis of GES data seem to suggest that migration is limited, with for example, only 2 per cent of stars in the solar vicinity being bona fide candidate migrators from the inner disc, these stars having both high metallicity ( $[\text{Fe}/\text{H}] > 0.1$ ) and circular orbits (Hayden et al. 2018).

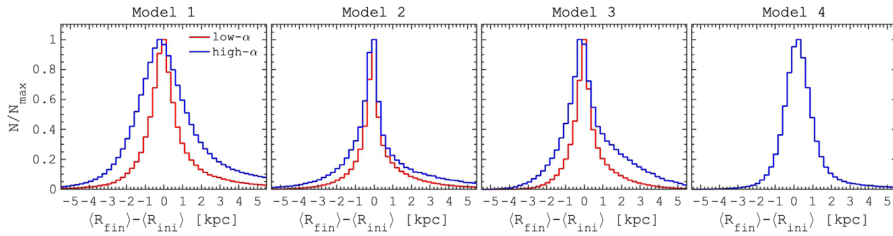
Our simulated galaxy sample includes galaxies with different morphologies (see Fig. 2), thus providing us with an opportunity to test how much radial migration is experienced by stars due to the different asymmetries and how they affect chemical patterns. In this section, we first take a brief look on the efficiency of radial migration for thin (low- $\alpha$ ) and thick (high- $\alpha$ ) disc stars and we study the impact of radial migration on the chemical abundance patterns, and in particular on the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  relation over time.

### 5.1 The intensity of radial migration in our simulations

First, we measure the amplitude of the radial displacement of stars in different models. In Fig. 13, we show the relation between the change of the galactocentric distance ( $\langle R_{\text{fin}} \rangle - \langle R_{\text{ini}} \rangle$ ) as a function of the initial galactocentric distance ( $\langle R_{\text{ini}} \rangle$ ). For this and the following figures, we define  $\langle R_{\text{ini}} \rangle$  as the mean galactocentric radius of stellar particles, averaged over a time interval of 500 Myr (50 snapshots) since their formation; in a similar way,  $\langle R_{\text{fin}} \rangle$  is the mean galactocentric radius of stellar particles, averaged over the last 500 Myr, before the end of simulation. This approach allows us to estimate the churning of stars in kpc independent of the angular momentum

calculation which can also experience periodic variations with zero net change, especially in the non-axisymmetric potential of the barred galaxies (see e.g. Ceverino & Klypin 2007). In Fig. 13, we see that half of the stars migrate only up to  $\approx 2$  kpc from their birthplaces, about 40 per cent can be churned up to  $\approx 4$ –5 kpc while the most extreme migrators ( $|\langle R_{\text{fin}} \rangle - \langle R_{\text{ini}} \rangle| > 5$  kpc) represent only  $\approx 10$  per cent of the total disc mass (see a similar behaviour in Minchev, Chiappini & Martig 2013). A notable feature is that radial migration is substantially more efficient in models with bars (models 1 and 2) where stars can migrate by more than 5 kpc. Model 3, without a prominent spiral structure, shows the less efficient overall churning, while in model 4, with spiral arms, migration is more efficient in the outer disc ( $> 8$ –10 kpc) where the resonance of slowly rotating spirals is located. In our simulations, bar formation causes considerable more angular momentum changes, especially in the inner disc, than those of spiral patterns.

In Fig. 14, we show how much radial migration is experienced by stars of both high- and low- $\alpha$  sequences or, as we showed above, chemically defined thick and thin stellar discs, respectively. It shows that the galactocentric distance change is dominated by thick disc stars (in particular in models 1 and 3), although the tails of the most substantial changes of guiding radii are almost equally extended in each population. This is in qualitative agreement with studies by Solway, Sellwood & Schönrich (2012) and Halle et al. (2018), who also found that churning in a thick disc is only mildly more important than the churning of thin disc stars. This figure shows that churning effects in the thin disc (as defined by stars belonging to the low- $\alpha$  sequence), is minimal, and affects a small number of stars. Finally, although we observe both inward and outward radial migration for both thick and thin disc stars, outward migration is



**Figure 14.** Distribution of the difference between the mean final ( $\langle R_{\text{fin}} \rangle$ ) and the mean initial ( $\langle R_{\text{ini}} \rangle$ ) galactocentric distance for high- $\alpha$  (blue) and low- $\alpha$  (red) stars in simulated galaxies. Difference between the mean final and initial positions of stars depicts the amplitude of the radial migration (churning). Both thick and thin disc stars experience churning of 2–4 kpc, but for a greater fraction of stars in the thick disc (high- $\alpha$  sequence), which likely suggests a higher radial migration efficiency during the early phases of the galaxy evolution. The skewness of the distributions reflects the dominance of the outward churning caused by the negative density gradient in stellar discs.

slightly more significant in all our models due to negative radial density gradient (see also Fig. 13).

## 5.2 Effect of radial migration on the chemical patterns

We now test how much chemical abundance patterns in the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  plane and metallicity distributions are affected by radial migration. Fig. 15 (top two rows) shows  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  distributions for stars at their time of formation (top row) and at the end of the simulations (middle row) in the middle disc region ( $5 < R < 10$  kpc) near the galactic plane ( $|Z| < 0.5$  kpc). Generally speaking in Fig. 15, radial migration only slightly smooths the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  distribution – mostly by bringing some stars from the inner and outer disc regions – but the distributions are only very marginally affected by migration, in all simulations, and whatever the structure dominating the asymmetries (bar or spiral arms).

The typical radial excursion due to blurring (epicyclic oscillation) is of the order of 2 kpc for an old high- $\alpha$  star. If radial mixing is due essentially to blurring, then chemical patterns sampled on a 2 kpc radius range will be unchanged. If churning has a significant effect, chemical patterns will be substantially modified due to contamination by stars churned to a certain disc region. Fig. 16 shows the same plots as the previous figure, sampled on a smaller radius range, going from 7.5 to 8 kpc. The comparison of the top and middle rows illustrate that churning has no significant impact. Similar to the Solar vicinity region in the MW; however, Figs 15 or 16 show that the most evident manifestation of the outward radial migration, visible in all models, is the presence of high-metallicity stars, likely formed in the innermost regions (see e.g. Grenon 1972; Hayden et al. 2015; Kordopatis et al. 2015; Hayden et al. 2018). To highlight this effect, the bottom rows of the two figures show the metallicity distributions of stars at their initial (dashed lines) and final radius (solid lines) for high- and low- $\alpha$  sequences separately. Apart from this small shift in metallicity, the impact of radial migration is barely visible when comparing  $[\text{Fe}/\text{H}]$  distributions of stars where they are formed and at the end of the simulation. The contribution of these metal-rich stars does not exceed 1–2 per cent of the total mass of both disc components, it is similar to the findings of other recent studies (Haywood et al. 2019; Khoperskov et al. 2020b).

These figures show why, in galaxies with a tight high- $\alpha$  sequence, such as in model 3, but also as in the MW, the effect of radial migration on chemical patterns is limited. The high- $\alpha$  sequence remains unchanged because of the formation of the thick disc is mostly independent of radius. Hence, even though stars can migrate on substantial distances after formation, the high- $\alpha$  chemical patterns will not be affected, since they are similar at all radii, because of the efficient mixing occurring at early times. On the contrary, the low- $\alpha$

sequence depends on the radius of formation of the stars, but it is left unaffected by radial mixing because churning is limited in the thin disc.

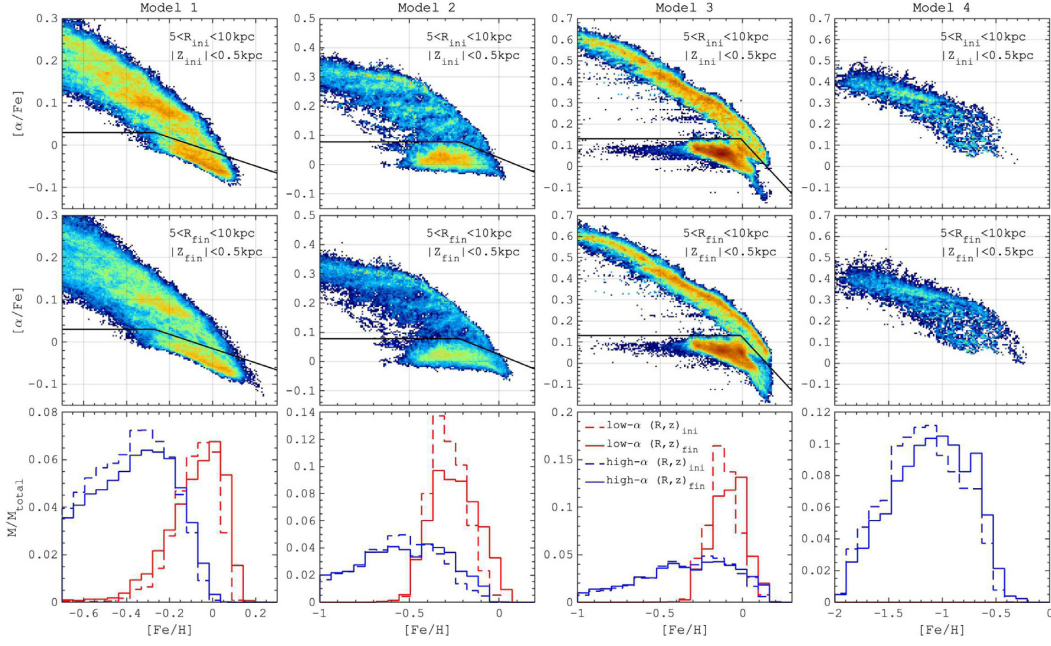
## 6 DISCUSSION

In this section, we first start by summarizing our results, then discuss the consequences of our findings.

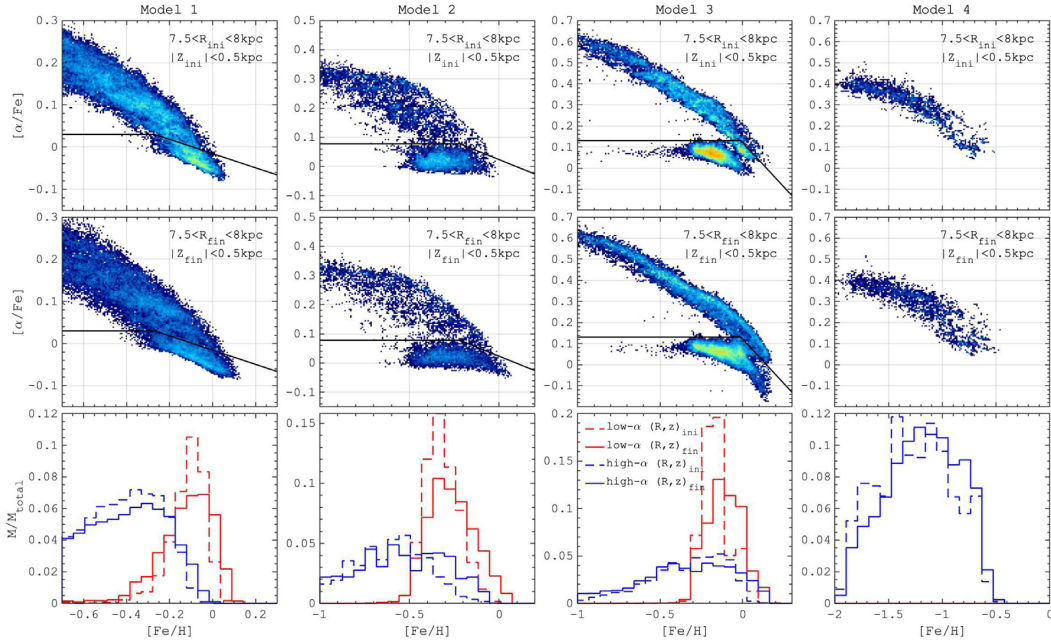
### 6.1 Our results

The existence of a high- $\alpha$  sequence with a clearly visible ridge line (Fig. 8) is related to the presence of a dense and massive disc of gas. Models 2–4, which all have this feature, have their high- $\alpha$  sequence associated with a disc of a scale length of 3.2–3.9 kpc, significantly smaller than the scale length of model 1, which is 5.5 kpc, nearly two times larger. The scatter of high- $\alpha$  sequence is more prominent in model 1, where the initial gas distribution is radially extended, thus leading to a progressive decline of the star formation efficiency with radius (see also Nidever et al. 2014) within the thick disc. Although, our models do not include the evolution of galaxies in cosmological context, our chemical abundance trends are in general agreement with several studies that include cosmological conditions with early mergers (Gibson et al. 2013; Stinson et al. 2013; Miranda et al. 2016). This similarity suggests that mergers are not required for the thin/thick discs  $\alpha$ -bimodality while being essential for the chemical trajectories of accreted and *in situ* halo stars of the MW (Nissen & Schuster 2010; Hayes et al. 2018; Haywood et al. 2018; Helmi et al. 2018; Gallart et al. 2019; Brook et al. 2020).

The evolution of the low- $\alpha$  sequence follows two possible paths. First, the low- $\alpha$  sequence is made of the ends of the chemical tracks that start at high- $\alpha$  and low metallicity and go to low- $\alpha$  and high metallicities (see Fig. 10). In the last 7–9 Gyr, change in metallicity and  $\alpha$  is limited, reaching an ‘equilibrium’ value, allowing stars to pile up at more or less the same position in the  $[\text{Fe}/\text{H}]$ – $[\alpha/\text{Fe}]$  plane. A negative gradient of the gas density drives a slower evolution towards the outer disc, the ends of the chemical tracks at larger  $R$  reaching lower values of metallicities. As a consequence of these two effects, the terminal metallicity at which the stars pile up gradually moves to lower values towards the outer disc, building the low-alpha sequence. Secondly, the low- $\alpha$  sequence may also result from a loop in the  $[\text{Fe}/\text{H}]$ – $[\alpha/\text{Fe}]$  plane, when the disc ISM metallicity decreases at the end of the thick disc phase. This dilution results from the abrupt quenching of the star formation activity, as best illustrated by model 3. The quenching induces a drop in the amount of metals ejected to the halo. Then this gas rains back on to the disc with a lower metallicity, inducing a dilution. From Fig. A3, it can be seen that the



**Figure 15.** Top row: [ $\alpha$ /Fe]–[Fe/H] distribution of stars formed in the middle part of the disc ( $5 < R_{\text{ini}} < 10$  kpc) near the galactic plane ( $|Z_{\text{ini}}| < 0.5$  kpc). Middle row: [ $\alpha$ /Fe]–[Fe/H] relation for stars located at the end of simulation in the middle part of the disc ( $5 < R_{\text{fin}} < 10$  kpc) near the galactic plane ( $|Z_{\text{fin}}| < 0.5$  kpc). Bottom row: metallicity distribution for both high- and low- $\alpha$  sequences for stars formed and located at the end in the same region. Black lines in the first two rows separate high- and low- $\alpha$  sequences. Comparison of two first rows demonstrates that stellar radial migration leads to a weak blurring of the [ $\alpha$ /Fe]–[Fe/H] relation. However, the global structure of high- and low- $\alpha$  sequences does not depend on radial migration. Migration of stars from the innermost region leads to a slight shift of the [Fe/H] distributions towards higher values for both thick and thin discs, but the fraction of these metal-rich stars does not exceed 1–2 per cent, being comparable to the estimates for the MW.



**Figure 16.** Same as previous figure, but for the distance range 7.5–8 kpc.

extension of the loop (and therefore of the low- $\alpha$  sequence) to low metallicity seems to be a direct function of the speed of the drop in the star formation activity. The drop in metallicity is about  $-0.5$  dex when the drop in the star formation rate is almost instantaneous, as is the case in the radius range centred on  $R = 8$  kpc.

When the formation of the low- $\alpha$  sequence results from the first path, the presence of these two sequences in a single galaxy is due

to two difference modes of star formation, mainly driven by the gas density. The formation of a tight high- $\alpha$  sequence, is due to the high star formation intensity reached in massive discs, and depends on the early accretion of a large quantity of gas. The formation of a low- $\alpha$  sequence (as described by the first process) is expected to occur as soon as star formation proceeds at lower gas densities, outside the compact gaseous disc that formed the thick disc. The formation of

a radially extended disc is expected in most cases independently of the particular merger history of the galaxy. Stars will then form at a rate that depends on the radius, and the mixing (mostly blurring) of stars in the disc will then generate a low- $\alpha$  sequence by blending together stars that are formed at different radii (hence at different metallicities).

Although we emphasize that nothing prevents the two sequences to be formed contemporaneously, stars will form first where the cold ISM reaches the necessary density, which occurs faster in the inner disc. This is visible looking at the SFHs at different radii in the first 3 models (see Fig. A3). In these models, the formation of the outer disc is delayed by a couple of Gyr. On the other hand, we do not confirm the parallel formation of both  $\alpha$ -sequences demonstrated in Clarke et al. (2019), which could possibly occur in our simulations if the multiphase structure of the ISM was not taken into account. In particular, allowing star formation in a warm ISM ( $T \sim 10^4$ ), we would obtain a similar result (see Fig. 6 where the low- $\alpha$  sequence appears to be filled by enriched hot gas at early times). However, our results suggest that chemical evolution models should include multiphase ISM evolution to correctly take into account the delayed metal enrichment of the star-forming gas (see e.g. Rybizki, Just & Rix 2017, and Snaith et al. in preparation).

What our simulations demonstrate is that the bimodality is a natural outcome in massive galactic discs. If early gas accretion has been sufficiently important in central regions of discs, and we argue below that this is probably the case for most MW-like galaxies (guaranteeing the formation of a high- $\alpha$  sequence), then bimodality is assured, because low-gas density is always present in the outskirts of exponential discs. We emphasize that bimodality is conspicuous even when the global SFH of a galaxy shows no obvious separation, or distinct phases (see for example model 2). This is because the two regimes of high- and low-star formation intensity are spatially separated, the high- $\alpha$  building up in the inner disc, while the low- $\alpha$  builds up mostly outside the inner disc.

## 6.2 How do these results help understanding the evolution of the Milky Way?

How do the simulations presented here help us to understand the evolution of the MW? The MW differs from all models in various ways, but some of its characteristics can be found in each model. For example, the tight high- $\alpha$  sequence observed in model 3, with weak deviations of the chemical evolution during high- $\alpha$  sequence formation observed at different radii, is very similar to the one we have in our Galaxy. In the MW, the small dispersion in  $[\alpha/\text{Fe}]$  at a given age is in favour of a thick disc formation in a well-mixed turbulent ISM (Haywood et al. 2013, 2015; Feuillet et al. 2019). This is also consistent with the fact that galaxies at high redshifts are known to be gas-rich, and to have high gas mass surface densities (Aravena et al. 2010; Daddi et al. 2010; Genzel et al. 2015; Papovich et al. 2016) and intense star formation (Lehnert et al. 2009, 2013; Swinbank et al. 2011).

On the other hand, the low- $\alpha$  sequence of the MW looks more like those seen in models 1 and 2, which in both cases are built through the first path described above: they are a composite of chemical tracks resulting from the evolution at each radius. This is the scenario described in Haywood et al. (2019) and confirmed by the simulations presented here. Haywood et al. (2019) found that while the high- $\alpha$  sequence is a temporal sequence, in the sense that age varies monotonically with metallicity and  $\alpha$ -abundance (see also Haywood et al. 2013), the low- $\alpha$  sequence is a spatial sequence, in the sense that, at a given age, metallicity varies with radius along the ridge line

of the sequence. This corresponds to the way the low- $\alpha$  sequence is built in models 1 and 2: it is a composite of evolutions that proceeded almost independently at each radius. Then radial wandering of stars effectively built a sequence visible where this mixing is sufficiently effective (for example at the solar radius). The formation of the two distinct sequences may be strengthened by internal dynamical effects. Hence, in Halle et al. (2015), we showed that the outer Lindblad resonance of the bar creates a separation between the inner and outer discs, thereby diminishing gas and star exchanges, fostering different evolution of the inner and outer discs. In simulations, stars form even at very low metallicities and very old ages in the outer disc, as illustrated by the chemical tracks of young stars shown in Fig. 12, and provide the metals for the younger generations that dominate the low- $\alpha$  sequence, at ages less than 7–8 Gyr. In the case of our Galaxy, there is yet no compelling evidence as to from where the oldest stars in the outer disc obtained their chemical abundances. Apart from the gas outflows expected during the thick disc formation (Lehnert et al. 2014) there is also ongoing, rapid cold gas accretion suggested by cosmological simulations (Birnboim & Dekel 2003; Dekel & Birnboim 2006; Agertz, Teyssier & Moore 2009; Woods et al. 2014; Cornuault et al. 2018). Another possible source is the gas deposited by early mergers [Sausage–Gaia–Enceladus (Belokurov et al. 2018; Haywood et al. 2018; Helmi et al. 2018), Sequoia (Myeong et al. 2019), and Kraken (Kruijssen et al. 2019)]. However, Di Matteo et al. (2019b) and Belokurov et al. (2020) found that the GES merger contributed to the heating of a fraction of the thick disc, which started to form before and continued its formation sometime after the last merger. Of course, some amount of gas could have been delivered by the previous mergers (Kraken, Sequoia); however, Kruijssen et al. (2019, 2020) estimated that these satellite galaxies were even less massive. Therefore, the MW-type galaxies had the same (still high) gas fraction, the amount of gas delivered by mergers should be an order of magnitude lower compared to the main progenitor.

## 6.3 Comparison with other recent studies

There is another example of chemodynamical simulations that clearly show two sequences in the distribution of stars in the  $[\text{Fe}/\text{H}]$ – $[\alpha/\text{Fe}]$  space (oxygen in this case) are the MAGICC simulations in Snaith et al. (2016). In this study, the authors study the effect of various feedback prescriptions on the evolution of disc galaxies and in particular on the chemical patterns, starting the evolution with the same initial conditions. The galaxy evolved with the strongest early feedback prescription shows chemical patterns that look very similar to what we have in the MW, with a high- $\alpha$  sequence that dominate their inner simulated galaxy, and a low- $\alpha$  sequence which is dominated by the thin disc at ages younger than 6–7 Gyr. Finally, the low- $\alpha$  is clearly radially dependent, as illustrated in their Fig. 6. Similar to our findings Kruijssen et al. (2019, 2020) show that smooth accretion supplies most of the gas for forming thin discs, while thick discs emerge from the much more turbulent gaseous phase at high redshift, fueled by gas-dominated mergers in their case.

More recently, Grand et al. (2018) explored the Auriga cosmological zoom simulations for a number of MW mass galaxies, but the bimodalities that are described by these authors in the inner or outer discs bear more resemblance to the second type of bimodality described in the introduction. That is, the bimodality is generated by two distinct phases of star formation, the gap in the star formation activity in the outer disc being induced and maintained by a contraction of the gaseous disc. The resulting general patterns are much less evocative of a high- and low- $\alpha$  sequence as can be seen, for example, in Snaith et al. (2016). In particular, the low- $\alpha$



sequence is not a ridge line that builds up progressively inside-out as the result of the accumulation of stars at an equilibrium metallicity, as is observed in Snaith et al. (2016), or in this study.

In our simulations, we showed that the low- $\alpha$  sequence forms when star formation efficiency ceases to be dominated by the formation of the thick disc, specifically in the radially extended thin disc. It de facto produces separate evolutions, even though the outflows generated by the thick disc may contribute to the metal enrichment of the outer disc. It is also the conclusion reached by Mackereth et al. (2018) that the pathways producing the two sequences in galaxies from EAGLE simulations are distinct. The formation of the two sequences, however, differs in several aspects from our work. For example in our simulations, and in the MW, the high- $\alpha$  sequence can be subdivided into two segments: the first corresponds to the formation of the thick disc, the second to the formation of the inner thin disc at high metallicities. In Mackereth et al. (2018), this second segment does not exist, and the evolution in the inner disc seems to halt after a few Gyr, and explains the relatively small extension of the high- $\alpha$  sequence in the simulations presented by these authors. In the MW, the highest metallicity stars are found in the inner disc ( $R < 6$  kpc) and are the endpoint of a two-stage evolution, the first stage being the thick disc formation. This is also the case in our simulations, when such high-metallicity stars exist (models 1 and 2). The pathway to the formation of high-metallicity stars in Mackereth et al. (2018) is different: they are the typical end product of a low- $\alpha$  evolution that occurs in the outer regions of these simulated discs. Finally, the formation of two distinct sequences in Mackereth et al. (2018) seems to hinge on two circumstantial conditions: the high- $\alpha$  sequence on an early and rapid accretion of gas, which seems to be a rare event in their simulations of MW-type galaxies, and the later accretion of gas due to the merger of a gas-rich galaxy. The consequence is that the authors conclude the formation of both sequences to be a rare event. We shall see in the next section that, on the contrary, we find that it must be relatively widespread.

Buck (2020) analysed the NIHAO-UHD cosmological zoom simulations, with results that are similar to ours. In particular, the low- and high- $\alpha$  sequences show clear bimodality, and the ridge defining the low- $\alpha$  sequence varies towards decreasing metallicity as a function of radius. Buck (2020) reached the same conclusion as Mackereth et al. (2018) by saying that the formation of low- $\alpha$  sequence is linked to gas-rich mergers. The link is obvious in some simulated galaxies, for instance the galaxy designated *g7.55e11*, which shows a spread in metallicity after the merger, but much less in some others. Another example, *g6.96e11* apparently suffers the greatest number of mergers, with no obvious bimodality. The most massive galaxy (*g2.79e12*) presents patterns very similar to those of our model 1. It is difficult to think that the two merger events linked to this galaxy (see Fig. 7 in Buck 2020), at times  $\sim 3.5$  and 10 Gyr, are directly linked to the low-alpha sequence, which stars start to form at 7 Gyr, even if the gas provided by the mergers probably fuels the star formation activity in the disc. Ultimately, these results raise the question of the origin of the gas that settles to form the low- $\alpha$  sequence. Although the aforementioned studies emphasize the role of gas-rich mergers we suggest that a gradual (re)-accretion of gas from the halo generically give rise to a low- $\alpha$  sequence of a thin disc.

#### 6.4 How common are these patterns?

In our simulations, a high- $\alpha$  sequence is always present at  $[\text{Fe}/\text{H}] > -1$  and is generated as a consequence of the intense star formation that occurs in the first Gyrs, reaching values of the order or higher than  $\sim 10 M_{\odot} \text{ yr}^{-1}$  for a few Gyrs. How widespread these high- $\alpha$

sequences are among galaxies will of course depend on the fraction of galaxies that start their evolution with a substantial amount of gas in their inner parts. Mackereth et al. (2018) advocate that this number is probably small, because galaxies with only a low-alpha sequence are much more typical in MW-like galaxies. This, however, is a potential problem, because MW-type galaxies are known to have a rapid mass growth, building about 50 per cent of their stellar mass before  $z \sim 1.5$  (see e.g. van Dokkum et al. 2013; Morishita et al. 2015; Papovich et al. 2015), implying typical SFR of about  $> 10 M_{\odot} \text{ yr}^{-1}$  for a few Gyrs. Hence, unlike what was found by Mackereth et al. (2018), we would expect high- $\alpha$  sequences to be a common feature of MW-like galaxies. This is also supported by the widespread of thick discs in the local universe (Yoachim & Dalcanton 2006; Comerón et al. 2011). A possible solution to this apparent contradiction is the criterion adopted by Mackereth et al. (2018) to classify the stars in low- and high- $\alpha$  stars, which is illustrated on their Fig. 5. The limit they choose to separate the two groups is relatively high in the  $[\text{Fe}/\text{H}]$ – $[\alpha/\text{Fe}]$  plane and seems to be a very conservative definition of the high- $\alpha$  stars, leading them to classify stars as ‘low- $\alpha$ ’ even when they have  $[\alpha/\text{Fe}]$  above 0.4 or 0.5. Another equally valid definition of high- $\alpha$  stars could be that  $[\alpha/\text{Fe}] > 0.4$ , which would include much more objects, and probably lead to different conclusions. Another possible explanation comes from the rather atypical SFHs of the EAGLE MW-like galaxies, illustrated by the fig. 5 in Mackereth et al. (2018), and which barely reach intensities above  $10 M_{\odot} \text{ yr}^{-1}$ , and for a limited amount of time (much less than a Gyr in the galaxy labelled ‘B’). This is not what is inferred from either observations (van Dokkum et al. 2013; Morishita et al. 2015; Papovich et al. 2015) or other simulations (Buck 2020).

According to Grand et al. (2018), Mackereth et al. (2018), and Buck (2020), the presence of bimodality is related to separate episodes of gas accretion, a significant part of the gas fueling the low- $\alpha$  sequence being related to gas-rich mergers. However, we expect that the building of discs with exponential profiles in dark matter haloes will generically give rise to low-star formation efficiency, independently of any particular gas accretion history. A low-star formation efficiency is observed in outer regions of discs (see e.g. Bigiel et al. 2010). These discs will give rise to the prolonged SFH of gradually decreasing intensity outwards, driven by the decreasing gas density. Therefore, we should expect bimodality to be a ubiquitous feature in MW-like galaxies. In some cases, however, the stage of prolonged star formation is never reached, most of the gas being consumed before the galaxy forms a substantial amount of stars on the low- $\alpha$  sequence. This is illustrated by the model 4, which may resemble what is expected from S0 galaxies.

#### 6.5 Radial migration

Radial migration is believed to be responsible for a number of observed chemical abundance patterns in the MW (Schönrich & Binney 2009b) and in the nearby galaxies (see e.g. Sánchez-Menguiano et al. 2016). However, as we discussed in Section 5 the current structure of the MW makes a spiral arms-driven migration possible only beyond the Solar radius because of its slow pattern speed and the corotation location in the outer disc. Alternatively, if we assume that spiral arms rotated much faster at the early epochs when most of the thin disc stars were not formed yet, spiral arms-induced churning could have had more impact on thick disc stars. However, once the thick disc stars formed as a dynamically hot structure, its stars were unlikely to be trapped by the spiral arm corotation due to the low fraction of stars on nearly circular orbits. Alternatively, the MW spirals can be corotating structures making possible radial migration everywhere

along them (Grand, Kawata & Cropper 2012a, b). Nevertheless, this assumption is not yet supported by the maser sources kinematics, which is in favour of a rigid rotation of the spiral structure (Reid et al. 2009, 2014), and a similar result was obtained using *Gaia* DR 2 data (Eilers et al. 2020; Khoperskov et al. 2020a). Recent *Gaia* DR 2 analysis also suggests that the MW bar can cause radial migration during its gradual slowdown (Chiba, Friske & Schönrich 2019), but even in this case the amount stars migrating outwards is rather modest and most of the stars (90 per cent) do not churn out more than 2–4 kpc over the last  $\approx 8$  Gyr, in agreement with some independent estimates (Frankel et al. 2018; Minchev et al. 2018). Note, however, that both mechanisms of radial migration (spiral arms scattering or bar-slowdown) are sufficient to explain the presence of high-metallicity stars ( $[\text{Fe}/\text{H}] > 0.2$ ) in the Solar vicinity migrated from the innermost galaxy (Kubryk et al. 2013; Minchev et al. 2013; Khoperskov et al. 2020b).

## 7 SUMMARY

In this paper, we present a set of self-consistent chemodynamical MW-type galaxy formation simulations without mergers. The simulations show two-phases SFHs that are not an input of the model but are driven by the two regimes of the gas infall that naturally arise from the pre-existing extended hot halo. The first infall is the result of a rapid collapse of the primordial gas which is halted (in 1–3 Gyr) by the intense stellar feedback leading to substantial removal of the gas from the galactic disc. Most of the released gas roughly conserves its angular momentum, but part of the ejected material to large radii gains significant angular momentum before re-accretion, participating to the infall of metal-richer gas on a longer time-scale, and which then contributes to the thin disc formation. Despite significant pollution of the disc–halo interface, there is a certain delay between the release of metals and their participation to the chemical evolution of the stellar disc. This leads to the existence of enriched (up to solar values) warm/hot gas which is however not involved in the star formation until it cools down via galactic fountain mechanism. We show that a proto-galaxy collapsing to a disc naturally leads to the formation of  $[\alpha/\text{Fe}]$ -bimodality. Our results and conclusions can be summarized as follows:

1. The  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  bimodality is observed in galaxies with two different regimes of star formation. In our simulations, this takes place as an initial burst ( $10$ – $30 M_{\odot} \text{ yr}^{-1}$ ) of star formation followed by a subsequent quiescent star formation phase ( $3$ – $6 M_{\odot} \text{ yr}^{-1}$ ). The high- $\alpha$  sequence is formed early on a short time-scale (2–4 Gyr) in a thick turbulent gaseous disc, and it is represented by a compact and kinematically hot thick stellar disc. The low- $\alpha$  sequence corresponds to the stars formed in the radially extended thin stellar disc, and is made of stars formed on a longer time-scale (last 6–7 Gyr) and which evolution at a given radius piles-up at a terminal (or equilibrium) metallicity and  $\alpha$  abundance. The sequence itself arises because the equilibrium metallicity and abundance vary gradually with radius, due to the decrease of the star formation efficiency with the gas density. Thereby, we demonstrate that different physical conditions are necessary for the formation of thick and thin galactic discs. In our simulations, the two components are formed one after the other, implying no significant overlap of ages of thick and thin disc stars, but this needs not to be always the case and must depend on how rapidly the gas density necessary for star formation is reached in the extended disc. Stars in the thick disc are older, have enhanced  $\alpha$ -element abundances and lower metallicity as well as hotter kinematic features. Note that, similar to what is observed in the MW, in our models with

$\alpha$ -bimodality, thick discs represent a substantial fraction of the total stellar mass of simulated galaxies ( $\approx 40$ – $60$  per cent). Contrary to the recent studies, however, we do not expect that bimodality is dependent on any particular accretion history. Bimodality is related to the massive and early accretion of gas that must be prevalent in MW-like galaxies to build the high- $\alpha$  sequence, and to the presence of lower star formation efficiency regions that are expected in the outer regions of all stellar discs. We therefore expect this to be a common feature in MW-like galaxies. We also find *in situ* formed stars with chemical abundances typical of the low- $\alpha$  sequence and typically interpreted as made of accreted stars. Therefore, our simulations suggest that *in situ* stellar populations of the MW could contribute to the low  $\alpha$ -populations at metallicities below  $\lesssim -0.5$ .

2. The thick disc formation phase plays a significant role in the enrichment of the CGM surrounding MW-type disc galaxies. The thin disc forms from a mixture of enriched material expelled from the thick disc and accreted gas low metallicity. When a sharp transition between thick and thin disc formation phases occurs, it is imprinted in the chemical abundances in a form of a loop (see Fig. 12) in the chemical evolution tracks in the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  plane. A sharper and efficient star formation quenching leads to a stronger dilution of  $[\text{Fe}/\text{H}]$  and a more prominent loop. The effect of this non-monotonic chemical evolution can somehow mimic the impact of stellar radial migration towards in the inner parts of the disc by producing thin disc stars of lower metallicity than the youngest thick disc stars.

3. Although radial migration plays a role in mixing stellar populations, in our simulations we do not find a significant impact on the global structure of the observed chemical abundance patterns. In particular, we found very little difference in the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  distribution over time in the solar-like radius (5–10 kpc or 7.5–8 kpc, see Figs 15 and 16) confirming that  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  bimodality in the MW is the outcome of the thin and thin disc formation process and is not produced by secular evolution. Nevertheless, the high- $[\text{Fe}/\text{H}]$  tail of the metallicity distribution, representing a few percent of the stars in the simulations, is explained by radial migration, as it is for stars in the solar vicinity. Outward churning dominates in all our simulations due to the negative density gradient of the discs. Models with a bar show a more substantial redistribution of stellar orbits in the inner disc (see models 1, 2 in Fig. 13) while spiral arms induced more prominent migration in the outer disc where the corotation radius is located (see model 4 in Fig. 13).

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## DATA AVAILABILITY

Data directly related to this publication and its figures are available by request from the corresponding author.

## REFERENCES

- Abel T., Anninos P., Zhang Y., Norman M. L., 1997, *New Astron.*, 2, 181
- Adibekyan V. Z., Santos N. C., Sousa S. G., Israelian G., 2011, *A&A*, 535, L11
- Adibekyan V. Z., Sousa S. G., Santos N. C., Delgado Mena E., González Hernández J. I., Israelian G., Mayor M., Khachatryan G., 2012, *A&A*, 545, A32
- Agertz O., Teyssier R., Moore B., 2009, *MNRAS*, 397, L64
- Agertz O. et al., 2020, preprint([arXiv:2006.06008](https://arxiv.org/abs/2006.06008))
- Anders F. et al., 2014, *A&A*, 564, A115
- Antoja T., Valenzuela O., Pichardo B., Moreno E., Figueras F., Fernández D., 2009, *ApJ*, 700, L78
- Aravena M. et al., 2010, *ApJ*, 718, 177
- Assmann P., Fellhauer M., Kroupa P., Brüns R. C., Smith R., 2011, *MNRAS*, 415, 1280
- Athanassoula E., Rodionov S. A., Peschken N., Lambert J. C., 2016, *ApJ*, 821, 90
- Athanassoula E., Rodionov S. A., Prantzos N., 2017, *MNRAS*, 467, L46
- Aumer M., White S. D. M., 2013, *MNRAS*, 428, 1055
- Aumer M., Binney J., Schönrich R., 2016, *MNRAS*, 459, 3326
- Bekki K., Tsujimoto T., 2011, *MNRAS*, 416, L60
- Belokurov V., Erkal D., Evans N. W., Koposov S. E., Deason A. J., 2018, *MNRAS*, 478, 611
- Belokurov V., Sanders J. L., Fattahi A., Smith M. C., Deason A. J., Evans N. W., Grand R. J. J., 2020, *MNRAS*, 494, 3880
- Bensby T., Feltzing S., Oey M. S., 2014, *A&A*, 562, A71
- Beraldo e Silva L., Debattista V. P., Khachatryan T., Nidever D., 2020, *MNRAS*, 492, 4716
- Bigiel F., Leroy A., Walter F., Blitz L., Brinks E., de Blok W. J. G., Madore B., 2010, *AJ*, 140, 1194
- Binney J., Nipoti C., Fraternali F., 2009, *MNRAS*, 397, 1804
- Birnboim Y., Dekel A., 2003, *MNRAS*, 345, 349
- Bournaud F. et al., 2014, *ApJ*, 780, 57
- Bournaud F., Elmegreen B. G., Elmegreen D. M., 2007, *ApJ*, 670, 237
- Bovy J., Rix H.-W., Liu C., Hogg D. W., Beers T. C., Lee Y. S., 2012, *ApJ*, 753, 148
- Brook C. B., Kawata D., Gibson B. K., Freeman K. C., 2004, *ApJ*, 612, 894
- Brook C. B., Gibson B. K., Martel H., Kawata D., 2005, *ApJ*, 630, 298
- Brook C. B. et al., 2012, *MNRAS*, 426, 690
- Brook C. B., Stinson G., Gibson B. K., Shen S., Macciò A. V., Obreja A., Wadsley J., Quinn T., 2014, *MNRAS*, 443, 3809
- Brook C. B., Kawata D., Gibson B. K., Gallart C., Vicente A., 2020, *MNRAS*, 495, 2645
- Buck T., 2020, *MNRAS*, 491, 5435
- Bullock J. S., Dekel A., Kolatt T. S., Kravtsov A. V., Klypin A. A., Porciani C., Primack J. R., 2001, *ApJ*, 555, 240
- Ceverino D., Klypin A., 2007, *MNRAS*, 379, 1155
- Chiappini C., 2009, in Andersen J., Nordström B., Bland-Hawthorn J., eds, Proc. IAU Symp. 254, The Galaxy Disk in Cosmological Context. Kluwer, Dordrecht, p. 191
- Chiappini C., Matteucci F., Gratton R., 1997, *ApJ*, 477, 765
- Chiba R., Friske J. K. S., Schönrich R., 2021, 500, 4710
- Christensen C. R., Davé R., Governato F., Pontzen A., Brooks A., Munshi F., Quinn T., Wadsley J., 2016, *ApJ*, 824, 57
- Clarke A. J. et al., 2019, *MNRAS*, 484, 3476
- Cole D. R., Debattista V. P., Erwin P., Earp S. W. F., Roskar R., 2014, *MNRAS*, 445, 3352
- Comerón S. et al., 2011, *ApJ*, 741, 28
- Cornuault N., Lehnert M. D., Boulanger F., Guillard P., 2018, *A&A*, 610, A75
- D’Onghia E., Springel V., Hernquist L., Keres D., 2010, *ApJ*, 709, 1138
- Daddi E. et al., 2010, *ApJ*, 713, 686
- Daniel K. J., Schaffner D. A., McCluskey F., Fiedler Kawaguchi C., Loebman S., 2019, *ApJ*, 882, 111
- Davé R., Finlator K., Oppenheimer B. D., 2011, *MNRAS*, 416, 1354
- Debattista V. P., Ness M., Gonzalez O. A., Freeman K., Zoccali M., Minniti D., 2017, *MNRAS*, 469, 1587
- Dehnen W., 2000, *AJ*, 119, 800
- Dekel A., Birnboim Y., 2006, *MNRAS*, 368, 2
- Di Matteo P., Haywood M., Combes F., Semelin B., Snaith O. N., 2013, *A&A*, 553, A102
- Di Matteo P. et al., 2015, *A&A*, 577, A1
- Di Matteo P., Fragkoudi F., Khoperskov S., Ciambur B., Haywood M., Combes F., Gómez A., 2019a, *A&A*, 628, A11
- Di Matteo P., Haywood M., Lehnert M. D., Katz D., Khoperskov S., Snaith O. N., Gómez A., Robichon N., 2019b, *A&A*, 632, A4
- Eilers A.-C., Hogg D. W., Rix H.-W., Frankel N., Hunt J. A. S., Fouvry J.-B., Buck T., 2020, *ApJ*, 900, 186
- Feuillet D. K., Frankel N., Lind K., Frinchaboy P. M., García-Hernández D. A., Lane R. R., Nitschelm C., Roman-Lopes A. r., 2019, *MNRAS*, 489, 1742
- Fox A. J. et al., 2016, *ApJ*, 816, L11
- Fragkoudi F., Di Matteo P., Haywood M., Schultheis M., Khoperskov S., Gómez A., Combes F., 2018, *A&A*, 616, A180
- Frankel N., Rix H.-W., Ting Y.-S., Ness M., Hogg D. W., 2018, *ApJ*, 865, 96
- Fraternali F., Binney J. J., 2008, *MNRAS*, 386, 935
- Fuhrmann K., 1998, *A&A*, 338, 161
- Fuhrmann K., 2004, *Astron. Nachr.*, 325, 3
- Fukushige T., Makino J., Kawai A., 2005, *PASJ*, 57, 1009
- Gallart C., Bernard E. J., Brook C. B., Ruiz-Lara T., Cassisi S., Hill V., Monelli M., 2019, *Nat. Astron.*, 3, 932
- Galli D., Palla F., 1998, *A&A*, 335, 403
- Genzel R. et al., 2015, *ApJ*, 800, 20
- Gibson B. K., Pilkington K., Brook C. B., Stinson G. S., Bailin J., 2013, *A&A*, 554, A47
- Gilmore G., Reid N., 1983, *MNRAS*, 202, 1025
- Gómez F. A., Minchev I., O’Shea B. W., Beers T. C., Bullock J. S., Purcell C. W., 2013, *MNRAS*, 429, 159
- Gómez F. A., White S. D. M., Grand R. J. J., Marinacci F., Springel V., Pakmor R., 2017, *MNRAS*, 465, 3446
- Grand R. J. J., Kawata D., Cropper M., 2012a, *MNRAS*, 421, 1529
- Grand R. J. J., Kawata D., Cropper M., 2012b, *MNRAS*, 426, 167
- Grand R. J. J. et al., 2018, *MNRAS*, 474, 3629
- Gratton R., Carretta E., Matteucci F., Sneden C., 1996, in Morrison H. L., Sarajedini A., eds, ASP Conf. Ser. Vol. 92, Formation of the Galactic Halo—Inside and Out. Astron. Soc. Pac., San Francisco, p. 307
- Grenon M., 1972, in Cayrel de Strobel G., Delplace A. M., eds, Proc. IAU Colloq. 17, IAU Colloq. 17, Age des Etoiles, p. 55
- Grisoni V., Spitoni E., Matteucci F., Recio-Blanco A., de Laverny P., Hayden M., Mikolaitis Š., Worley C. C., 2017, *MNRAS*, 472, 3637
- Gutcke T. A., Stinson G. S., Macciò A. V., Wang L., Dutton A. A., 2017, *MNRAS*, 464, 2796
- Halle A., Di Matteo P., Haywood M., Combes F., 2015, *A&A*, 578, A58
- Halle A., Di Matteo P., Haywood M., Combes F., 2018, *A&A*, 616, A86
- Hayden M. R. et al., 2015, *ApJ*, 808, 132
- Hayden M. R. et al., 2018, *A&A*, 609, A79
- Hayden M. R., et al., 2020, *MNRAS*, 493, 2952
- Hayes C. R. et al., 2018, *ApJ*, 852, 49

- Haywood M., Di Matteo P., Lehnert M. D., Katz D., Gómez A., 2013, *A&A*, 560, A109
- Haywood M., Di Matteo P., Snaith O., Lehnert M. D., 2015, *A&A*, 579, A5
- Haywood M., Lehnert M. D., Di Matteo P., Snaith O., Schultheis M., Katz D., Gómez A., 2016, *A&A*, 589, A66
- Haywood M., Di Matteo P., Lehnert M. D., Snaith O., Khoperskov S., Gómez A., 2018, *ApJ*, 863, 113
- Haywood M., Snaith O., Lehnert M. D., Di Matteo P., Khoperskov S., 2019, *A&A*, 625, A105
- Helmi A., Babusiaux C., Koppelman H. H., Massari D., Veljanoski J., Brown A. G. A., 2018, *Nature*, 563, 85
- Huscher E., Oppenheimer B. D., Lonardi A., Crain R. A., Richings A. J., Schaye J., 2021, *MNRAS*, 500, 1476
- Inoue S., Dekel A., Mandelker N., Ceverino D., Bournaud F., Primack J., 2016, *MNRAS*, 456, 2052
- Khoperskov S. A., Vasiliev E. O., 2017, *MNRAS*, 468, 920
- Khoperskov S. A., Vasiliev E. O., Khoperskov A. V., Lubimov V. N., 2014, *J. Phys. Conf. Ser.*, 510, 012011
- Khoperskov S. A., Vasiliev E. O., Ladeyschikov D. A., Sobolev A. M., Khoperskov A. V., 2016, *MNRAS*, 455, 1782
- Khoperskov S., Haywood M., Di Matteo P., Lehnert M. D., Combes F., 2018a, *A&A*, 609, A60
- Khoperskov S., Di Matteo P., Haywood M., Combes F., 2018b, *A&A*, 611, L2
- Khoperskov S., Mastrobuono-Battisti A., Di Matteo P., Haywood M., 2018c, *A&A*, 620, A154
- Khoperskov S., Di Matteo P., Gerhard O., Katz D., Haywood M., Combes F., Berczik P., Gomez A., 2019, *A&A*, 622, L6
- Khoperskov S., Gerhard O., Di Matteo P., Haywood M., Katz D., Khrapov S., Khoperskov A., Arnaboldi M., 2020a, *A&A*, 634, L8
- Khoperskov S., Di Matteo P., Haywood M., Gómez A., Snaith O. N., 2020b, *A&A*, 638, A144
- Kim J.-h. et al., 2016, *ApJ*, 833, 202
- Kordopatis G. et al., 2015, *MNRAS*, 447, 3526
- Kretschmer M., Agertz O., Teyssier R., 2020, *MNRAS*, 497, 4346
- Kroupa P., 2001, *MNRAS*, 322, 231
- Kroupa P., 2002, *MNRAS*, 330, 707
- Kruijssen J. M. D., Pfeffer J. L., Reina-Campos M., Crain R. A., Bastian N., 2019, *MNRAS*, 486, 3180
- Kruijssen J. M. D. et al., 2020, *MNRAS*, 498, 2472
- Kubryk M., Prantzos N., Athanassoula E., 2013, *MNRAS*, 436, 1479
- Lehnert M. D., Nesvadba N. P. H., Le Tiran L., Di Matteo P., van Driel W., Douglas L. S., Chemin L., Bournaud F., 2009, *ApJ*, 699, 1660
- Lehnert M. D., Le Tiran L., Nesvadba N. P. H., van Driel W., Boulanger F., Di Matteo P., 2013, *A&A*, 555, A72
- Lehnert M. D., Di Matteo P., Haywood M., Snaith O. N., 2014, *ApJ*, 789, L30
- Loebman S. R., Roskar R., Debattista V. P., Ivezić, Ž., Quinn T. R., Wadsley J., 2011, *ApJ*, 737, 8
- Mackereth J. T., Crain R. A., Schiavon R. P., Schaye J., Theuns T., Schaller M., 2018, *MNRAS*, 477, 5072
- Marinacci F., Binney J., Fraternali F., Nipoti C., Ciotti L., Londrillo P., 2010, *MNRAS*, 404, 1464
- Matteucci F., 2014, *The Origin of the Galaxy and Local Group, Saas-Fee Advanced Course (Berlin Heidelberg: Springer-Verlag)*, 37, 145
- Mignone A., Zanni C., Tzeferacos P., van Straalen B., Colella P., Bodo G., 2012, *ApJS*, 198, 7
- Miller M. J., Bregman J. N., 2015, *ApJ*, 800, 14
- Minchev I., Famaey B., Combes F., Di Matteo P., Mouhcine M., Wozniak H., 2011, *A&A*, 527, A147
- Minchev I., Famaey B., Quillen A. C., Di Matteo P., Combes F., Vlajić M., Erwin P., Bland-Hawthorn J., 2012, *A&A*, 548, A126
- Minchev I., Chiappini C., Martig M., 2013, *A&A*, 558, A9
- Minchev I., Chiappini C., Martig M., 2014, *A&A*, 572, A92
- Minchev I. et al., 2018, *MNRAS*, 481, 1645
- Miranda M. S. et al., 2016, *A&A*, 587, A10
- Moetazedian R., Polyachenko E. V., Berczik P., Just A., 2017, *A&A*, 604, A75
- Monari G., Famaey B., Siebert A., Grand R. J. J., Kawata D., Boily C., 2016, *MNRAS*, 461, 3835
- Morishita T., Ichikawa T., Noguchi M., Akiyama M., Patel S. G., Kajisawa M., Obata T., 2015, *ApJ*, 805, 34
- Myeong G. C., Vasiliev E., Iorio G., Evans N. W., Belokurov V., 2019, *MNRAS*, 488, 1235
- Nidever D. L. et al., 2014, *ApJ*, 796, 38
- Nissen P. E., Schuster W. J., 2010, *A&A*, 511, L10
- Noguchi M., 1999, *ApJ*, 514, 77
- Nuza S. E., Scannapieco C., Chiappini C., Junqueira T. C., Minchev I., Martig M., 2019, *MNRAS*, 482, 3089
- Oppenheimer B. D., Davé R., 2008, *MNRAS*, 387, 577
- Oppenheimer B. D., Davé R., Kereš D., Fardal M., Katz N., Kollmeier J. A., Weinberg D. H., 2010, *MNRAS*, 406, 2325
- Papovich C. et al., 2015, *ApJ*, 803, 26
- Papovich C. et al., 2016, *Nat. Astron.*, 1, 0003
- Péroux C., Nelson D., van de Voort F., Pillepich A., Marinacci F., Vogelsberger M., Hernquist L., 2020, *MNRAS*, 499, 2462
- Polyachenko E. V., Berczik P., Just A., 2016, *MNRAS*, 462, 3727
- Purcell C. W., Bullock J. S., Tollerud E. J., Rocha M., Chakrabarti S., 2011, *Nature*, 477, 301
- Queiroz A. B. A. et al., 2020, *A&A*, 638, 76
- Quillen A. C., Minchev I., 2005, *AJ*, 130, 576
- Reddy B. E., Lambert D. L., Allende Prieto C., 2006, *MNRAS*, 367, 1329
- Reid M. J. et al., 2009, *ApJ*, 700, 137
- Reid M. J. et al., 2014, *ApJ*, 783, 130
- Renaud F., Agertz O., Read J. I., Ryde N., Andersson E. P., Bensby T., Rey M. P., Feuillet D. K., 2020a, preprint([arXiv:2006.06011](https://arxiv.org/abs/2006.06011))
- Renaud F., Agertz O., Andersson E. P., Read J. I., Ryde N., Bensby T., Rey M. P., Feuillet D. K., 2020b, preprint([arXiv:2006.06012](https://arxiv.org/abs/2006.06012))
- Rodionov S. A., Athanassoula E., Sotnikova N. Y., 2009, *MNRAS*, 392, 904
- Roskar R., Debattista V. P., Stinson G. S., Quinn T. R., Kaufmann T., Wadsley J., 2008, *ApJ*, 675, L65
- Roskar R., Debattista V. P., Quinn T. R., Wadsley J., 2012, *MNRAS*, 426, 2089
- Rybizki J., Just A., Rix H.-W., 2017, *A&A*, 605, A59
- Saburova A. S., Katkov I. Y., Khoperskov S. A., Zasov A. V., Uklein R. I., 2017, *MNRAS*, 470, 20
- Saburova A. S., Chilingarian I. V., Katkov I. Y., Egorov O. V., Kasparova A. V., Khoperskov S. A., Uklein R. I., Vozyakova O. V., 2018, *MNRAS*, 481, 3534
- Sánchez-Menguiano L. et al., 2016, *ApJ*, 830, L40
- Schönrich R., Binney J., 2009a, *MNRAS*, 396, 203
- Schönrich R., Binney J., 2009b, *MNRAS*, 399, 1145
- Sellwood J. A., Binney J. J., 2002, *MNRAS*, 336, 785
- Shen J., Rich R. M., Kormendy J., Howard C. D., De Propriis R., Kunder A., 2010, *ApJ*, 720, L72
- Snaith O. N., Haywood M., Di Matteo P., Lehnert M. D., Combes F., Katz D., Gómez A., 2014, *ApJ*, 781, L31
- Snaith O., Haywood M., Di Matteo P., Lehnert M. D., Combes F., Katz D., Gómez A., 2015, *A&A*, 578, A87
- Snaith O. N., Bailin J., Gibson B. K., Bell E. F., Stinson G., Valluri M., Wadsley J., Couchman H., 2016, *MNRAS*, 456, 3119
- Solway M., Sellwood J. A., Schönrich R., 2012, *MNRAS*, 422, 1363
- Spitoni E., Matteucci F., Recchi S., Cescutti G., Pipino A., 2009, *A&A*, 504, 87
- Spitoni E., Silva Aguirre V., Matteucci F., Calura F., Grisoni V., 2019, *A&A*, 623, A60
- Spitoni E., Verma K., Silva Aguirre V., Calura F., 2020, *A&A*, 635, A58
- Stern J., Hennawi J. F., Prochaska J. X., Werk J. K., 2016, *ApJ*, 830, 87
- Stinson G. S. et al., 2013, *MNRAS*, 436, 625
- Swinbank A. M. et al., 2011, *ApJ*, 742, 11
- Tumlinson J. et al., 2011a, *Science*, 334, 948
- Tumlinson J. et al., 2011b, *ApJ*, 733, 111
- Übler H., Naab T., Oser L., Aumer M., Sales L. V., White S. D. M., 2014, *MNRAS*, 443, 2092

van Dokkum P. G. et al., 2013, *ApJ*, 771, L35  
 Vasiliev E. O., 2011, *MNRAS*, 414, 3145  
 Vasiliev E. O., 2013, *MNRAS*, 431, 638  
 Vincenzo F., Kobayashi C., 2020, *MNRAS*, 496, 80  
 Weinberg M. D., Blitz L., 2006, *ApJ*, 641, L33  
 Woods R. M., Wadsley J., Couchman H. M. P., Stinson G., Shen S., 2014, *MNRAS*, 442, 732  
 Yoachim P., Dalcanton J. J., 2006, *AJ*, 131, 226  
 Zonoozi A. H., Mahani H., Kroupa P., 2019, *MNRAS*, 483, 46

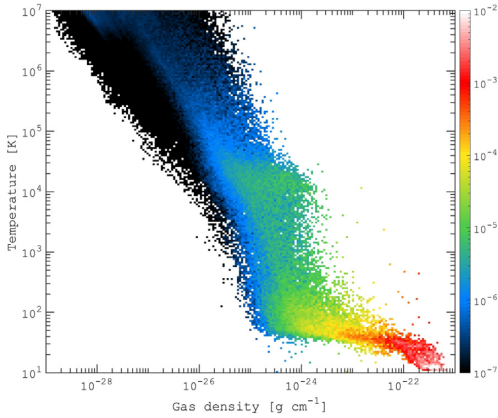
**SUPPORTING INFORMATION**

Supplementary data are available at [MNRAS](https://www.mnras.org) online.

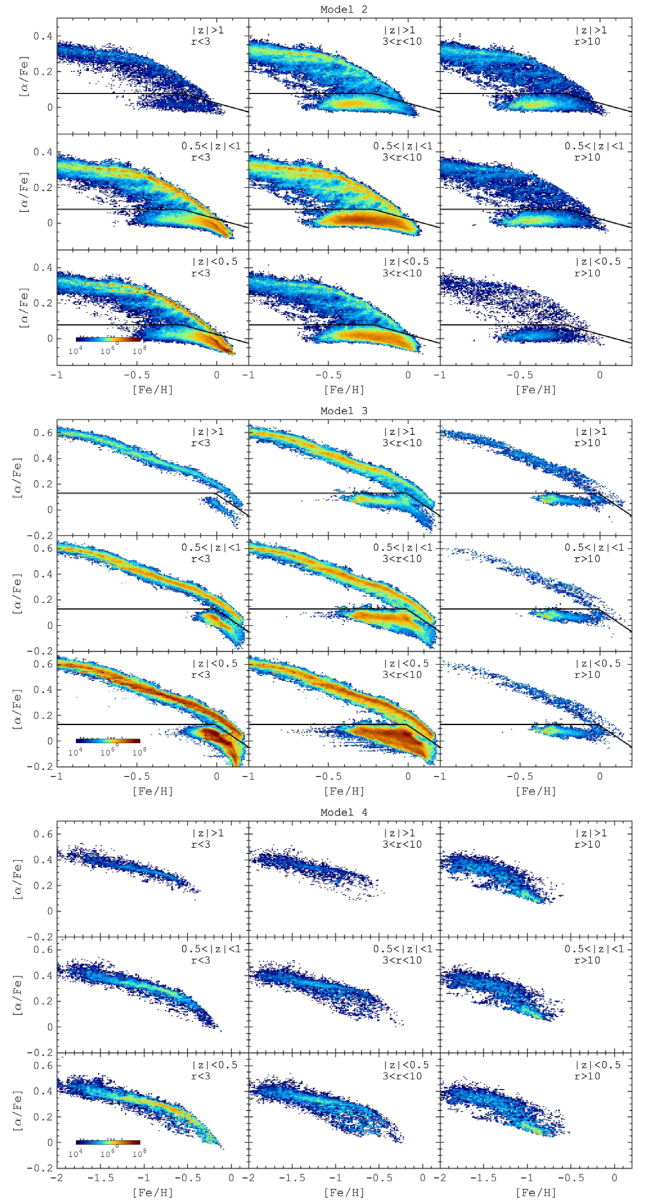
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**APPENDIX A: EXTRA PLOTS**

In this section, we provide the chemical abundance patterns ( $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$ ) at the end of simulation in models 2–4, similar to the Fig. 11 for model 1. In Fig. A3, we show the evolution of  $[\text{Fe}/\text{H}]$ ,  $[\alpha/\text{H}]$ ,  $[\alpha/\text{Fe}]$ , and the local star formation rate as a function of time in models 2–4, similar to Fig. 7 for model 1.

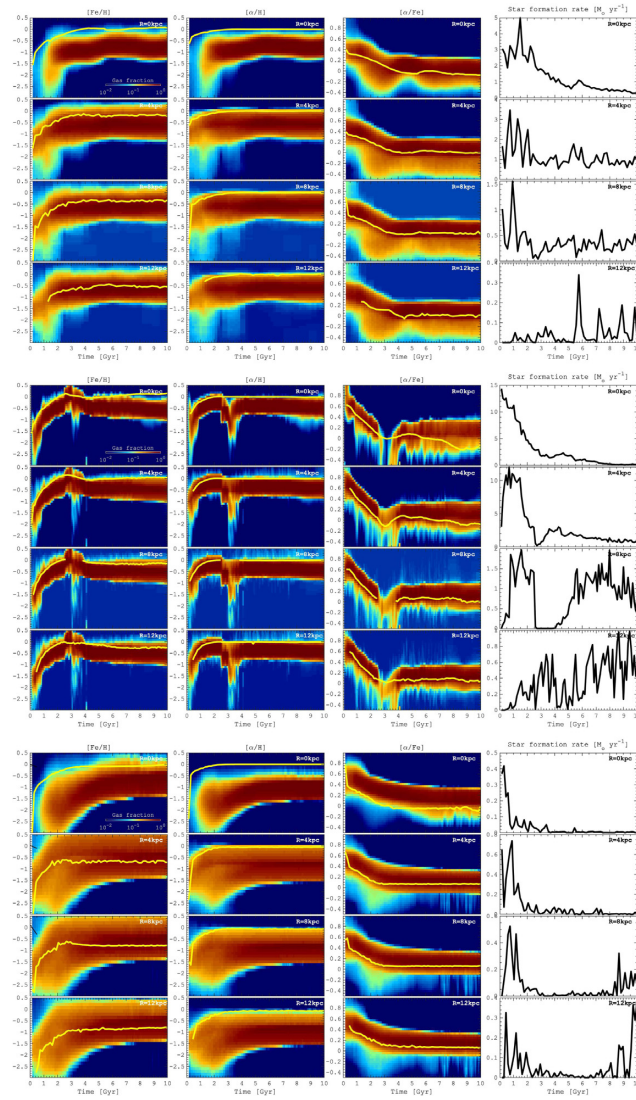


**Figure A1.** Example of 2D probability distribution function of density and temperature for the gas in model 1. Colours represent the total gas mass in each 2D bin.



**Figure A2.** Same as in Fig. 11 but for models 2–4.

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**Figure A3.** Same as in Fig. 7 but for models 2–4.

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