

# On the origin of globular clusters in a hierarchical universe

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Accepted 2024 April 8. Received 2024 March 5; in original form 2023 July 5

## ABSTRACT

We present an end-to-end description of the formation of globular clusters (GCs) combining a treatment for their formation and dynamical evolution within galaxy haloes with a state-of-the-art semi-analytic simulation of galaxy formation. Our approach allows us to obtain exquisite statistics to study the effect of the environment and assembly history of galaxies, while still allowing a very efficient exploration of the parameter space. Our reference model, including both efficient cluster disruption during galaxy mergers and dynamical friction of GCs within the galactic potential, accurately reproduces the observed correlation between the total mass in GCs and the parent halo mass. A deviation from linearity is predicted at low-halo masses, which is driven by a strong dependence on morphological type: bulge-dominated galaxies tend to host larger masses of GCs than their later-type counterparts. While the significance of the difference might be affected by resolution at the lowest halo masses considered, this is a robust prediction of our model and a natural consequence of the assumption that cluster migration into the halo is triggered by galaxy mergers. Our model requires an environmental dependence of GC radii to reproduce the observed low-mass mass distribution of GCs in our Galaxy. At GC masses  $> 10^6 M_{\odot}$ , our model predicts fewer GCs than observed, due to an overly aggressive treatment of dynamical friction. Our model reproduces well the metallicity distribution measured for Galactic GCs, even though we predict systematically younger GCs than observed. We argue that this adds further evidence for an anomalously early formation of the stars in our Galaxy.

**Key words:** stars: formation – globular clusters: general – galaxies: evolution – galaxies: formation – galaxies: star clusters: general.

## 1 INTRODUCTION

Globular clusters (GCs) are found in all galaxies in the local Universe down to galaxy stellar masses of  $\sim 10^8 M_{\odot}$ . GCs typically have old ages ( $\sim 10$  Gyr; Strader et al. 2005; Forbes & Bridges 2010; VandenBerg et al. 2013), nearly uniform sizes (e.g. Masters et al. 2010; Krumholz, McKee & Bland-Hawthorn 2019), and a peaked mass distribution that can be approximated by a lognormal function, with a characteristic peak mass that depends weakly on the host galaxy stellar mass (e.g. Jordán et al. 2007). The old ages and small sizes of GCs have long prevented direct observations of their formation – a situation that is changing rapidly with the new JWST finally in operation (see e.g. Mowla et al. 2022; Vanzella et al. 2022; Claeysens et al. 2023)

For decades, the origin of GCs has represented a largely unsolved problem that encompasses the fields of star and galaxy formation. First theoretical work on this subject envisioned that GC formation could be triggered by special conditions in the early Universe: e.g. Peebles & Dicke (1968) argued that GCs may have formed before the first galaxies, with masses determined by the Jeans mass. In a later work by Fall & Rees (1985), GCs were assumed to form during the collapse of protogalaxies due to thermal instabilities in the hot gaseous haloes. Alternative models pushed for a significantly later formation of GCs, possibly triggered by mergers between gas-rich disc galaxies that can compress and shock the interstellar medium (ISM; Schweizer 1987; Ashman & Zepf 1992). At present, none of these scenarios are thought to explain the origin of the majority of GCs (see Kruijssen 2014 and Forbes et al. 2018 for reviews).

Important information about the physical processes leading to GC formation can be inferred from their present day properties and from the formation of (young) massive stellar clusters in the local Universe.

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A key insight has been that young GCs are observed to form in the local Universe whenever conditions are present that mimic those in high-redshift galaxies, such as high gas pressures and densities (e.g. Elmegreen & Efremov 1997). This has led to the formulation of a family of models in which GCs are the byproduct of normal star and galaxy formation throughout cosmic history (e.g. Kruijssen 2015; Keller et al. 2020).

In our current standard paradigm for structure formation, galaxies form at the centre of dark matter haloes that collapse in a bottom-up fashion, with small systems forming first and later merging into progressively more massive structures. In this framework, galaxy formation is a complex physical process that involves both gas condensation at the centre of dark matter haloes, as well as galaxy mergers and interactions either with other galaxies or with the central regions of dark matter haloes (for a classical reference, see e.g. Mo, van den Bosch & White 2010). This means that an end-to-end description of the formation process of today’s GCs should include an explicit treatment of both their formation and their dynamical evolution within their evolving host galaxy haloes.

In the past years, different attempts have been made to study the dynamical evolution of GCs within their host galaxy haloes. These include largely analytical studies that focused on the effects of two-body relaxation, gravitational shocks, and mass-loss by stellar evolution on the mass function of star clusters, starting from an initial distribution approximated by a power law (e.g. Fall & Zhang 2001; Prieto & Gnedin 2008; Elmegreen 2010; Kruijssen 2015); work that has tried to constrain the physical processes leading to the formation of GCs by using their observed metallicity distributions in the local Universe and a combination of empirical relations and/or merger trees extracted from  $N$ -body simulations (e.g. Tonini 2013; Li & Gnedin 2014; Choksi, Gnedin & Li 2018; Chen & Gnedin 2022); and other empirical approaches that combine numerical merger trees with the assumption, based on observations in the local Universe, of a power-law relation between halo mass and mass in GCs (Ramos-Almendares et al. 2020; Valenzuela et al. 2021). This previous work either focused on specific aspects of GC evolution/formation or neglected important physical mechanisms of GC evolution.

Resolving the process of GCs formation directly within galaxy formation simulations is prohibitively expensive, because it would require extremely high resolution (particle masses/cells below  $10^3 M_\odot$ , and sub-parsec force resolution to resolve the bulk of the GC population and the scales at which they form), as well as an appropriate treatment of the star formation and stellar feedback processes. While some work has begun to resolve aspects of GC formation in cosmological simulations (e.g. Mandelker et al. 2017; Kim et al. 2018; Lahén et al. 2020; Ma et al. 2020; Meng & Gnedin 2020; Li et al. 2022), the approach remains limited to small volumes and a narrow range in redshifts, preventing a detailed comparison with the wealth of observational data in the local Universe.

An alternative approach is that of modelling GC formation and evolution within their parent galaxy haloes resorting to ‘sub-grid’ or ‘semi-analytic’ models. The important advantage, in this case, is that the limited computational costs allow an efficient investigation of the influence of different specific assumptions, as well as a rapid exploration of the parameter space. Coupling these techniques to dark matter-only and high-resolution cosmological volumes provides access to a large dynamic range in halo and galaxy masses allowing statistical analysis as a function of redshift, galaxy properties, and environment. Efforts in this direction include post-processing analyses of dark matter simulations with the inclusion of baryons through scaling relations inspired by observational data or physical

models (Tonini 2013; Kruijssen 2015; Choksi et al. 2018; El-Badry et al. 2019).

In more recent years, direct simulations of galaxy formation have been used to model the formation and evolution of GCs. For instance, the E-MOSAICS project (Pfeffer et al. 2018; Kruijssen et al. 2019a) couples an analytic model that describes the formation, evolution, and disruption of stellar clusters to the EAGLE galaxy formation model. Over the past years, the E-MOSAICS simulations have been used to provide context, interpretation, and predictions for a wide range of GC properties, such as their numbers (e.g. Bastian et al. 2020), metallicity distribution (e.g. Usher et al. 2018; Pfeffer et al. 2023), formation histories (Reina-Campos et al. 2019), mass function (Hughes et al. 2022), spatial distribution and kinematics (Trujillo-Gomez et al. 2021; Reina-Campos et al. 2022a), origin (Pfeffer et al. 2019; Trujillo-Gomez et al. 2023), and their use in tracing galaxy formation and assembly (Hughes et al. 2019; Kruijssen et al. 2019a, 2020; Pfeffer et al. 2020; Dolfi et al. 2022). The success of this approach has motivated several similar initiatives (e.g. Rodriguez et al. 2023; Reina-Campos et al. 2022b; Doppel et al. 2023; Grudić et al. 2023). The big hurdle faced by all of these models is one of statistics, as the requirement of resolving galaxy formation implies that cosmological volumes larger than  $\sim 50$  Mpc (see e.g. Bastian et al. 2020) remain out of reach.

In this work, we adopt an approach very similar to that used in the E-MOSAICS project, but take advantage of a state-of-the-art semi-analytic galaxy formation model to describe the evolution of the galaxy population across a much larger cosmological volume that can be spanned by spatially resolved hydrodynamical simulations. Specifically, we build on the GC model presented in Kruijssen (2015) that explains the observed properties of GCs as the natural outcome of star and cluster formation in high-redshift galaxies, and include its basic assumptions in the GALaxy Evolution and Assembly (GAEA) semi-analytic model (De Lucia et al. 2014; Hirschmann, De Lucia & Fontanot 2016), coupled to a large dark matter-only cosmological simulation. In this paper, we provide the details of our model and discuss how its basic predictions for the GC population compare with available data.

The layout of the paper is as follows: we present the simulation and the galaxy formation model used in our study in Section 2. Section 3 provides a detailed description of how we have included in our semi-analytic model the formation of young stellar clusters, how we have modelled their evolution, and how we have tested various physical descriptions of these physics. In Section 4, we present a case study of two model galaxies to illustrate how the mass distribution of GCs evolves as a function of time. Sections 5 and 6 show the basic predictions of our model and compare them to observational estimates. Finally, in Section 7, we discuss our results and present our conclusions.

## 2 THE SIMULATION AND THE GALAXY FORMATION MODEL

The model predictions presented in this work are based on dark matter merger trees extracted from the Millennium Simulation (Springel et al. 2005). This dark matter-only simulation follows  $2,160^3$  particles in a comoving box of  $500 \text{ Mpc } h^{-1}$  on a side, and assumes cosmological parameters consistent with WMAP1 ( $\Omega_\Lambda = 0.75$ ,  $\Omega_m = 0.25$ ,  $\Omega_b = 0.045$ ,  $n = 1$ ,  $\sigma_8 = 0.9$ , and  $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). In previous work (Wang et al. 2008), we have shown that (small) modifications of the cosmological parameters do not significantly affect model predictions, once the model parameters are retuned to reproduce a given set of observational results in the local Universe.

Therefore, we do not expect significant changes with an updated cosmological model. We will verify this in future work, where we plan to extend our analysis to higher resolution simulations and an updated cosmological model.

In this work, we take advantage of the GALaxy Evolution and Assembly (GAEA) model of galaxy formation<sup>1</sup>, described in detail in Hirschmann et al. (2016), with the updated modelling for disc sizes described in Xie et al. (2017). While the latter modification does not affect significantly the basic predictions of our model, it leads to a better agreement between model predictions and observational data for galaxy sizes – an element that we deem important for the stellar cluster model discussed in this paper. We refer to Hirschmann et al. (2016) and references therein for full details about the modelling adopted for all physical processes considered. Briefly, we have four different baryonic components (plus an equivalent number of metal components) associated to each model galaxies: hot gas at temperature  $> 10^4$  K that; cold gas that is only associated with galaxy discs in which star formation takes place; stars; and an ejected component that stores material that is outside the star forming phase because of stellar feedback. Star formation occurs, in galaxy discs, at a rate that is proportional to the amount of cold gas available above a surface density threshold that is modelled following De Lucia & Helmi (2008). The interstellar medium of galaxies is enriched by metals released by stellar winds and supernovae explosions. Our galaxy formation model includes a sophisticated treatment for the non-instantaneous recycling of gas, metals and energy that accounts for the finite lifetimes of stars and allows us to follow individual metal abundances (full details about the approach adopted can be found in De Lucia et al. 2014). The adopted stellar feedback model is partly based on scaling relations extracted from hydro-dynamical simulations. Specifically, these relations are used to parametrize the rate at which cold gas in discs can be reheated and then, assuming energy conservation arguments, to quantify the rate at which reheated gas can be ejected in a galactic outflow. This ejected component can be eventually re-incorporated onto the hot gas, on a time-scale that depends on the halo mass, and can then later cool onto the central galaxy of the halo. Full details about the stellar feedback scheme can be found in Hirschmann et al. (2016). Galaxy mergers trigger starbursts episodes and lead to the formation of stellar bulges; the gas converted into stars is proportional to the baryonic mass ratio of the two merging galaxies, with model parameters being calibrated against results from controlled numerical experiments. We further assume that in case of major mergers, that occur when the mass ratio is larger than 0.3, the disc is completely disrupted and all the stars put in a bulge component. Full details about these prescriptions can be found in De Lucia & Blaizot (2007) and De Lucia et al. (2010).

In previous work, we have shown that our reference model is able to reproduce a large number of important observational constraints, including the galaxy stellar mass function up to  $z \sim 7$  and the cosmic star formation rate density up to  $z \sim 10$  (Fontanot, Hirschmann & De Lucia 2017), the relation between galaxy stellar mass and gas metallicity and its secondary dependence as a function of star formation rate and gas mass (De Lucia et al. 2020), as well as the observed evolution of the galaxy mass–gas/star metallicity relations (Hirschmann et al. 2016; Fontanot et al. 2021).

For the analysis presented in this paper, we have used only a small fraction (about 10 per cent) of the entire volume of the Millennium Simulation. On the basis of previous work, we consider this sub-volume representative (it includes a few of the most massive haloes

that can be identified in the entire simulation volume). In addition, we have used the same parameter set adopted in Hirschmann et al. (2016) with only one modification: in our published reference model, we had assumed that galaxies at the centres of haloes with masses below  $5 \times 10^{10} M_{\odot}$  would inject most of the newly synthesized metals (95 per cent) directly into the hot gas phase. This modification had been included in previous work focused on faint satellites of our Milky-Way (Li, De Lucia & Helmi 2010) to better reproduce their metallicities, and was motivated by results of hydro-dynamical simulations of dwarf galaxies (Mac Low & Ferrara 1999). While not affecting significantly galaxy (and GC) properties on larger scales, it does enter a critical resolution regime for the dark matter simulation used in this work: the particle mass is  $m_p = 8.6 \times 10^8 M_{\odot}$ , which means that a halo of  $5 \times 10^{10} M_{\odot}$  is resolved with only about 40 particles. Therefore, in this work, we assume that all new metals are immediately mixed with the cold gas in the disc, and explicitly show when this has some influence on our model predictions (see Section 6).

### 3 A TWO-PHASE MODEL FOR THE ORIGIN OF GLOBULAR CLUSTERS

To model the abundance and properties of GCs, we build on the ‘two-phase’ model introduced by Kruijssen (2015), including additional implementations that we detail in the following. We refer to the original study by Kruijssen (2015) for a detailed review of the approach, which attempts to provide an end-to-end description of the origin of GCs, from their formation at high redshift until the present day. In summary:

- (i) young stellar clusters are assumed to form in the high-pressure discs hosted by high-redshift galaxies;
- (ii) the clusters undergo rapid disruption by tidal perturbations from molecular clouds and clumps in the host galaxy disc;
- (iii) the disruption continues until clusters migrate into the halo of the galaxy, following e.g. a merger event;
- (iv) finally, clusters undergo a slow evolutionary phase, in the host galaxy halo, due to tidal evaporation.

In the following subsections, we describe the specific prescriptions adopted to include each of the four elements listed above in our galaxy formation model. As we explain in detail below, we assume stellar clusters form in the host galaxy disc, and migrate into the galaxy halo after galaxy mergers. In practice, we have associated to each model galaxy two three-dimensional arrays storing the information about the stellar clusters that are associated with the disc and the halo of the galaxy. The three dimensions of each array correspond to bins of stellar cluster mass (we consider  $N_{MBINS} = 50$  mass bins, logarithmically spaced between  $10^2$  and  $10^{10} M_{\odot}$ ),  $[Fe/H]$  ( $N_{ZBINS} = 20$ , linearly spaced between  $-3.5$  and  $0.68$ ), and formation time ( $N_{TBINS} = 27$ , linearly spaced between 0 and 13 Gyr). The disc and halo arrays are initialized and evolved as detailed in the next sections.

#### 3.1 Formation of young stellar clusters

In our galaxy formation model, star formation can take place in a ‘quiescent’ mode (from cold gas associated with the galaxy disc), and during merger driven starbursts. We assume that a (small) fraction of the star formation occurring only through the quiescent channel leads to the formation of young massive clusters, that inherit the metallicity of the star forming gas. We suppress the formation of new stellar clusters during merger-driven starbursts, as they are expected to be

<sup>1</sup><https://sites.google.com/inaf.it/gaea/>

associated with very strong tidal perturbations (See Section 3.3). A new population of stellar clusters is initialized for each new episode of star formation: if  $\Delta M_{\text{star}}$  is the mass of stars formed during a code time-step<sup>2</sup>, we assume that the corresponding mass in stellar clusters is  $\Gamma \Delta M_{\text{star}}$ , where  $\Gamma$  quantifies an environmentally dependent cluster formation efficiency (CFE). We have computed this quantity using the analytic model presented in Kruijssen (2012), in which bound stellar clusters collapse in the highest-density regions of the interstellar medium. In the framework of this model, the CFE can be expressed as the product of the fraction of star formation that results in bound structure and the fraction thereof that survives the ‘cruel cradle effect’, i.e. the tidal disruption of star-forming regions or young stellar clusters by encounters with in the natal environment. We refer to the original paper by Kruijssen (2012) for full details on the derivation of these quantities.

The CFE is determined by galaxy scale physics, and can be expressed in terms of the cold gas surface density, the galaxy angular velocity, and the Toomre (1964)  $Q$  instability parameter. For this calculation, and throughout this paper, we have set the Toomre instability parameter ( $Q$ ) equal to 1. This value is within the typical range observed in star-forming galaxies at  $z \sim 2$ ,  $Q = 0.2\text{--}1.6$  (Genzel et al. 2014). The cold gas surface density and galaxy angular velocity are given by:

$$\Sigma_{\text{gas}} = M_{\text{cold}} / \pi r_{\text{half}}^2 \quad \text{and} \quad \Omega = V_{\text{max}} / r_{\text{half}}.$$

In the above equations,  $M_{\text{cold}}$  is the cold gas mass, and  $r_{\text{half}}$  is the disc half mass radius. The latter is computed as  $1.68 \times R_{\text{d}}$  (assuming an exponential disc), where  $R_{\text{d}}$  is the scale radius of the disc and is computed by tracing the specific angular momentum of the gas as described in detail in Xie et al. (2017).  $V_{\text{max}}$  is inherited from the subhalo catalogue and is the maximum circular velocity of the parent dark matter substructure for each model galaxy (for orphan satellites, i.e. those that are no longer associated with an existing substructure, this is the value at the last time there was a distinct parent subhalo). The CFE resulting from the model by Kruijssen (2012) is found to increase with the gas surface density, from  $\Gamma \sim 1$  per cent in low-density galaxies up to  $\Gamma \sim 70$  for surface gas densities  $\sim 10^3 M_{\odot} \text{pc}^{-2}$ . This provides a good match to cluster formation efficiencies that are observed in the local Universe, ranging from a few per cent to as much as 50 per cent in high-density starburst environments (e.g. Adamo et al. 2015, 2020a, b; Johnson et al. 2016).

A proper calculation of  $\Gamma$  requires several integrations that would slow down significantly our galaxy evolution code. In order to speed up our computation, we have used tabulated values of  $\Gamma$  (on a  $30 \times 30$  grid) corresponding to different values of the gas surface density and of the angular velocity. The entries of the table are then linearly interpolated at each star formation episode, to compute the corresponding CFE. We have verified that values obtained using our approach are very close to those that would be obtained using a full integration calculation.

Observations of young stellar cluster populations (Zhang & Fall 1999; Hunter et al. 2003; Larsen 2009; Portegies Zwart, McMillan & Gieles 2010) have shown that the initial cluster mass function

(ICMF) is well described by a power law with index  $\alpha = -2$ , which is consistent with expectations from gravitational collapse in hierarchically structured clouds (Elmegreen & Falgarone 1996; Guszejnov, Hopkins & Grudić 2018). At low masses, a fiducial truncation corresponding to  $M_{\text{min}} = 100 M_{\odot}$  is typically adopted (Lada & Lada 2003; Kruijssen 2015, and references therein). However, this assumption appears in contrast with findings that very large fractions (up to about 50 per cent) of low-metallicity stars in some nearby dwarf galaxies are bound to their GCs (Larsen et al. 2018), which implies that few low-mass clusters (or possibly none) could have formed coevally with these GCs. In fact, an ICMF extending down to  $100 M_{\odot}$  in these galaxies would require the majority of low-mass clusters to have been disrupted, returning their mass to the field population. This would allow for a maximum of 10 per cent of the low-metallicity stars to reside in surviving GCs, contrary to observations. At the high-mass end, an exponential truncation of the ICMF is often assumed. Observational studies find truncation masses varying from  $M_{\text{max}} = 0.5$  to  $10^5 M_{\odot}$  (Gieles et al. 2006; Larsen 2009; Bastian et al. 2012; Konstantopoulos et al. 2013).

In this work, we assume that the ICMF is well described by a power law, with exponential truncations at both the high- and low-mass ends (Trujillo-Gomez, Reina-Campos & Kruijssen 2019):

$$\frac{dN}{dM} \propto M_i^{\alpha} \exp\left(\frac{-M_{\text{min}}}{M}\right) \exp\left(\frac{-M}{M_{\text{max}}}\right). \quad (1)$$

We assume  $\alpha = -2$ , and that  $M_{\text{max}}$  is determined by evaluating the mass fraction of a centrifugally limited region that can collapse before stellar feedback is able to halt star formation, as detailed in Reina-Campos & Kruijssen (2017). In this study, the resulting upper truncation mass is expressed in terms of the cold gas surface density, the galactic angular velocity, and the Toomre parameter  $Q$ , with the latter having a limited impact on the cluster mass scale. The model predicts that more massive clusters are formed in environments characterized by larger gas surface densities, providing a natural explanation for the existence of more massive clumps at higher redshift.

As for  $M_{\text{min}}$ , we adopt the model presented in Trujillo-Gomez et al. (2019), based on empirical scaling relations of molecular clouds in the local Universe, and on the hierarchical nature of star formation in clouds regulated by stellar feedback. Specifically, the minimum mass of stellar clusters is evaluated by estimating the time-scale required for stellar feedback to halt star formation, against the collapse time of clouds with a given mass spectrum. This allows an estimate of the range of cloud masses that can achieve the minimum star formation efficiency required to remain bound after feedback has blown out the remaining gas. The resulting values of  $M_{\text{min}}$  vary by orders of magnitude from local and quiescent discs to high-redshift starbursting systems, with a strong dependence on the surface density of the ISM and no significant dependence on the galaxy angular velocity and the Toomre parameter  $Q$ . Below, we will test explicitly the impact of assuming an environmentally dependent  $M_{\text{min}}$ .

Both  $M_{\text{min}}$  and  $M_{\text{max}}$  can be expressed as a function of the gas surface density and of the galaxy angular velocity, as in the case of CFE, which for all of these quantities reflects an underlying physical dependence on the gas pressure. For the sake of computational time, we have generated pre-computed tables giving the minimum and maximum truncation mass over the same grid used to pre-compute  $\Gamma$ . The tables are linearly interpolated to evaluate equation (1) each time the cluster mass function needs to be initialized or updated, due to a new episode of star formation.

<sup>2</sup>The differential equations governing the evolution of the baryonic components associated with model galaxies are solved dividing the time interval between two subsequent snapshots (the available simulation outputs) into 20 time-steps, each corresponding to  $\sim 10\text{--}19$  Myrs up to  $z = 3$ , and even smaller timescales at higher redshift (where the snapshots are closer in time). We have verified, in previous work, that the number of sub-steps adopted is enough to achieve numerical convergence.



### 3.2 Cluster evolution during the rapid disruption phase

After their formation, stellar clusters evolve within the host galaxy disc, and are subject to frequent and strong tidal perturbations by dense gas clumps (e.g. Gieles et al. 2006; Elmegreen & Hunter 2010; Kruijssen et al. 2011). Following Kruijssen (2015, see original paper and references therein), we describe the rapid disruption phase driven by these tidal shocks in terms of a mass-loss rate

$$(dM/dt)_{\text{cce}} = -M/t_{\text{cce}}, \quad (2)$$

where the subscript ‘cce’ stands for ‘cruel cradle effect’ (Kruijssen et al. 2012a). The disruption time-scale can be expressed as (Kruijssen 2015)

$$t_{\text{cce}} = t_{5,\text{cce}} \left( \frac{f_{\Sigma}}{4} \right)^{-1} \left( \frac{\rho_{\text{ISM}}}{M_{\odot} \text{pc}^{-3}} \right)^{-3/2} \left( \frac{M}{10^5 M_{\odot}} \right) \Phi_{\text{ad}}^{-1} \quad (3)$$

where  $t_{5,\text{cce}} = 176 \text{ Myr}$  is a proportionality constant,  $f_{\Sigma}$  is the ratio between the surface density of giant molecular clouds and the mean gas surface density in the galactic mid-plane, and  $\rho_{\text{ISM}}$  is equated to the mean density in a galactic disc mid-plane for an equilibrium disc (Krumholz & McKee 2005):

$$\rho_{\text{ISM}} = 3\Omega^2/\pi G.$$

Finally,  $\Phi_{\text{ad}}$  is a correction factor that accounts for the absorption of tidal energy by adiabatic expansion. Following Kruijssen (2015), we assume

$$f_{\Sigma} = 3.92 \left( \frac{10 - 8f_{\text{mol}}}{2} \right)^{1/2}$$

with

$$f_{\text{mol}} = 1/(1 + 0.025 \Sigma_{\text{gas},2}^{-2}).$$

In the last equation,  $\Sigma_{\text{gas},2}$  is the surface density of the gas in units of  $100 M_{\odot} \text{pc}^{-2}$ . The adiabatic correction is expressed as follows

$$\Phi_{\text{ad}} = \left[ 1 + 9 \left( \frac{\rho_{\text{h}}/\rho_{\text{ISM}}}{10^4} \right) \right]^{-3/2},$$

where  $\rho_{\text{h}} = 3M/8\pi r_{\text{h}}^3$ .

In the following, we will consider two different assumptions for the cluster radius. In one case, we will assume that it is independent of the cluster mass, and equal to  $r_{\text{h}} = 1.5 \text{ pc}$ . Alternatively, and this will be the fiducial assumption in our reference run, we will assume that  $r_{\text{h}}$  depends on the cluster mass. Specifically, we adopt equation (13) of Gieles & Renaud (2016):

$$r_{\text{h}} \simeq 3.8 \text{ pc} \left( \frac{\gamma_{\text{GMC}}}{12.8 \text{ Gyr}} \right)^{2/9} \left( \frac{M}{10^4 M_{\odot}} \right)^{1/9}, \quad (4)$$

where

$$\gamma_{\text{GMC}} \simeq 6.5 \text{ Gyr} \left( \frac{\sigma}{10 \text{ km s}^{-1}} \right) \left( \frac{10 M_{\odot}^2 \text{ pc}^{-5}}{f_{\Sigma} \cdot \Sigma_{\text{gas}} \cdot \rho_{\text{ISM}}} \right) \quad (5)$$

and, assuming an equilibrium disc and  $Q = 1$ :

$$\sigma = \frac{\pi G \Sigma_{\text{gas}}}{2 \Omega} \quad (6)$$

When considering environmentally dependent cluster radii, we multiply our expression for  $t_{\text{cce}}$  by a factor:

$$(r_{\text{h}}/r_{\text{h},0})^{-3}, \text{ with } r_{\text{h},0} = 1.5 \text{ pc}. \quad (7)$$

This makes disruption much faster (up to a factor 15) in low-density environments, and is justified by the fact that more extended clusters would be more susceptible to tidal perturbations, as observed.

To implement the rapid disruption phase in our galaxy formation model, we need to account for the dependence of equation (3) on

both the stellar cluster mass and on the physical properties of the host galaxy. Practically, equation (3) must be evaluated for each galaxy, at each time-step of the evolution, and for each value of the cluster mass considered. To limit the computational overhead, we have adopted an approach that is sketched in Fig. 1, and that can be summarized as follows

(i) for each bin boundary of the mass grid considered at a given time  $t$ , we use equations (2) and (3) to compute the evolved values at the following time-step  $t'$ . In Fig. 1, this forward integration is illustrated by the dashed red lines, and  $M'_i$  (with  $i = 1, 2, \dots, 6$ ) represent the evolved values of the grid boundaries ( $M_i$ ) at the time  $t'$ .

(ii) We then get the interpolated indices for which  $M'_i = M_i$  at the time  $t'$ . These indices are used to compute the mass values at the time  $t$  that would evolve into the fixed boundaries of the bins at the time  $t'$ . This ‘backward’ integration is illustrated in Fig. 1 by the dashed-dotted blue lines.  $M''_i$  (with  $i = 1, 2, \dots, 6$ ) correspond to the values that would evolve into the fixed grid boundaries at the time  $t'$ .

(iii) The values obtained as described above can be used to compute the evolved cluster mass function at time  $t'$  (i.e. the number of stellar clusters in each mass bin considered) starting from the mass distribution at time  $t$ . In the example shown in Fig. 1, the evolved number of stellar clusters in the first mass bin (between  $M_1$  and  $M_2$  at time  $t'$ ) can be computed by taking the number of stellar clusters in the unevolved array between  $M''_1$  and  $M''_2$  at time  $t$ . The evolved number of clusters in the second mass bin would be equal to the number of stellar clusters between  $M''_2$  and  $M''_3$  at the time  $t$ , etc.

To simplify our calculation, we assume that stellar clusters are distributed uniformly<sup>3</sup> in each mass bin. We have verified that our results do not change significantly when increasing the number of mass bins considered, so a more sophisticated treatment is not expected to change significantly our results.

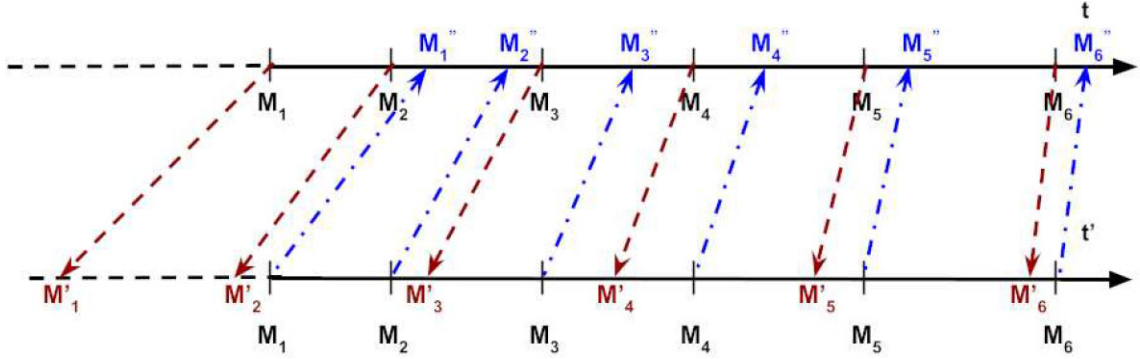
### 3.3 Cluster migration into the galaxy halo

The rapid disruption phase continues until the stellar clusters that form in (and are associated with) the galaxy disc migrate into the halo. Following Kruijssen (2015), we assume that the migration agent is represented by (minor and major) galaxy mergers. Major mergers occur when the baryonic mass ratio between the merging galaxies is larger than 0.3. In this case, we assume that all stellar clusters in the discs of both the accreted and accreting galaxies migrate into the halo of the merger remnant. In case of a minor merger, we assume that only the clusters in the disc of the accreted galaxy migrate into the halo of the remnant, whereas the main progenitor instead retains the stellar clusters in its own disc. During both minor and major mergers, the clusters in the haloes of both progenitor galaxies are always transferred to the halo of the remnant galaxy.

In our model, galaxy mergers can trigger starbursts (for details, see De Lucia & Blaizot 2007; De Lucia et al. 2010). We have suppressed the formation of a new stellar cluster population during this star formation channel, because it is expected to be associated with tidal perturbations stronger than those that characterize quiescent star formation episodes. We note that this specific assumption does not affect significantly our model results, as merger driven starbursts only contribute to a minor fraction of the total star formation in our model (Wang et al. 2019).

In addition, we also consider the possibility that the rapidly changing tidal field during galaxy interactions can lead to an efficient

<sup>3</sup>This assumption is correct in the case of infinitesimally small mass bins.



**Figure 1.** A sketch of our implementation of the rapid disruption evolutionary phase of star clusters in our galaxy formation model. The two horizontal lines show the mass projection of the three-dimensional array associated with each model galaxy, at two subsequent time-steps.  $M_i$  (with  $i = 1, 2, \dots, 6$ ) represent the boundaries of the mass bins considered;  $M'_i$  (end-points of dashed arrows) show the corresponding evolved values at the following time-step  $t'$  (these are computed using equations 2 and 3). Finally,  $M''_i$  (end-points of dot-dashed arrows) correspond to the mass values that would evolve into the fixed grid values at  $t'$  (see the text for details). The latter values can be used to compute the evolved cluster mass function at time  $t'$  from the unevolved distribution at time  $t$ .

cluster disruption in the galaxy disc, before the merger is completed. To model this, we use results from Kruijssen et al. (2012b), based on numerical simulations of merging disc galaxies. In particular, we use their equation (10) to compute the survival fraction of clusters (this is applied to all star clusters independently of their mass):

$$f_{\text{surv}} = 4.5 \times 10^{-8} M_{\text{min},2}^2 \left( \frac{t_{\text{depl}}}{\text{yr}} \right)^{0.77 - 0.22 \log(M_{\text{min},2})}, \quad (8)$$

and assume  $M_{\text{min},2} = M_{\text{min}}/10^2 M_{\odot} \sim 1$ . In the work by Kruijssen et al. (2012b),  $t_{\text{depl}}$  is parametrized as the ratio between the amount of gas available during the merger and the peak star formation rate. We evaluate the latter quantity simply as the ratio between the amount of stars formed during the burst associated with the merger and the corresponding internal code time-step.

### 3.4 Cluster evolution during the slow disruption phase

After their migration into the galaxy halo, stellar clusters lose mass due to different physical processes: mass-loss by stellar evolution and by dynamical effects, like two-body relaxation and stripping of stars due to the tidal field in which the star cluster is immersed and shocks (see e.g. Lamers, Baumgardt & Gieles 2010). Following Kruijssen (2015, we refer to the original paper for more details), we also describe the slow tidal evaporation phase in terms of a mass loss rate:

$$(dM/dt)_{\text{evap}} = -M/t_{\text{evap}}, \quad (9)$$

with (Lamers et al. 2005):

$$t_{\text{evap}} = t_{5,\text{evap}} \left( \frac{M}{10^5 M_{\odot}} \right)^{\gamma}. \quad (10)$$

In the last equation,  $\gamma = 0.7$  and  $t_{5,\text{evap}}$  depends on the stellar cluster metallicity:

$$[\text{Fe}/\text{H}] = -1.03 - 0.5 \log(t_{5,\text{evap}}/10 \text{ Gyr}).$$

This semi-empirical relation was adopted by Kruijssen (2015) so that the near-universal characteristic mass-scale of GC is reproduced as a function of  $[\text{Fe}/\text{H}]$  at  $z = 0$ . It reflects the idea that the globular cluster metallicity correlates with the binding energy of the galaxy in which it formed, which was proposed to be approximately preserved during migration. The above relation between  $[\text{Fe}/\text{H}]$  and the disruption time is shown by Kruijssen (2015) to be consistent with the observed metallicity gradient of the Galactic GC population.

To implement the slow evaporation phase in our galaxy evolution model, we have adopted an approach similar to that outlined in Section 3.2 for the rapid disruption phase, but taking advantage of the fact that equation (10) does not depend on the physical properties of the host galaxy and therefore does not need to be evaluated at each code time-step. From the practical point of view, this allows us to reduce the number of calculations and pre-compute a mass-loss grid at each new snapshot<sup>4</sup> rather than for each internal time-step of our model. Specifically:

- (i) for each boundary of the mass bins considered, and for each metallicity corresponding to central values of the metallicity bins considered, we have pre-computed the time-scales given by equation (10) and the mapping needed to evolve the star clusters;
- (ii) we have then used this pre-computed mass-loss grid to evolve the mass function of the clusters associated with the galaxy halo at each internal time-step.

As for the rapid disruption phase, we assume that clusters are distributed uniformly within each mass, metallicity, and formation time-bin. As mentioned earlier, we have checked that results do not change significantly when increasing the number of mass bins considered.

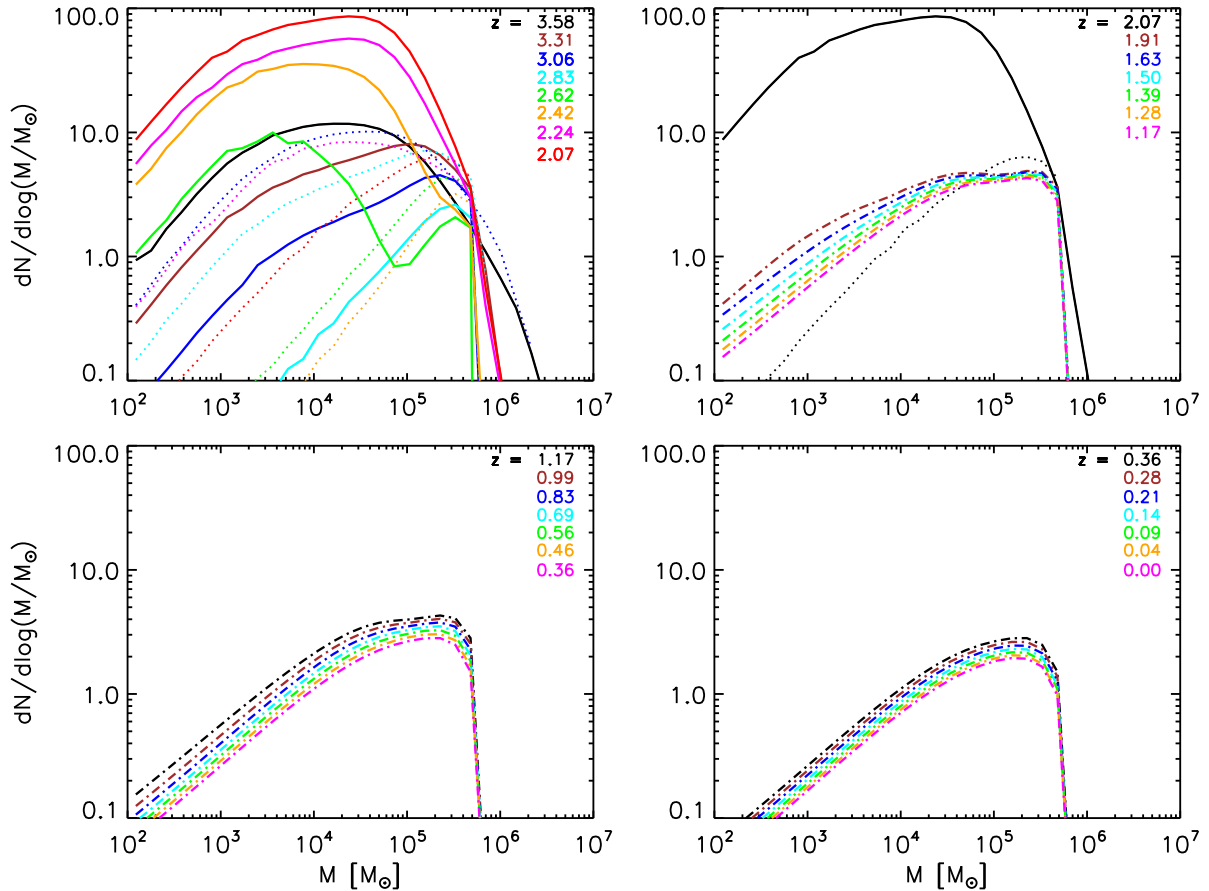
### 3.5 Dynamical friction

When computing the evolution of the most massive clusters in the galaxy disc, it is important to account for the effect of dynamical friction, which can cause them to spiral in to the centre of the host galaxy. Following Kruijssen (2015, see their equation 18), we evaluate the dynamical friction time-scale for each central value of the mass bins considered:

$$t_{\text{df}} = 2 \text{ Gyr} \left( \frac{10^6 M_{\odot}}{M} \right) \left( \frac{R}{2 \text{ kpc}} \right)^2 \left( \frac{V}{200 \text{ km s}^{-1}} \right)$$

where we assume  $R$  is equal to the half-mass radius of the galaxy disc and  $V = V_{\text{max}}$ . We then simply set equal to zero the number of stellar clusters in all those bins of our three-dimensional array

<sup>4</sup>This is necessary because the spacing between subsequent snapshots, and therefore also the internal time-step, are not constant. Otherwise, it would have been sufficient to compute the mapping only once.



**Figure 2.** Evolution of the mass distribution of stellar clusters associated with a model galaxy that has a stellar mass of  $\sim 1.3 \times 10^9 M_{\odot}$  at  $z = 0$ , and that experiences a single major merger at  $z \sim 1.8$ . The top left panel shows the mass distribution of stellar clusters associated with the two progenitors of the final galaxy, over the redshift range indicated in the legend. Solid and dotted lines indicate the stellar clusters associated with the disc of each progenitor, respectively. The top right panel shows again the mass distribution of the stellar clusters in the two progenitors right before the merger, and the evolution of the mass distribution of clusters associated with the halo of the remnant galaxy as dot-dashed lines. The same distribution, evolved down to  $z = 0$ , is shown in the bottom panels.

that have experienced more than one dynamical friction time-scale, integrated over their lifetimes.

As we will see in the following, our implementation of dynamical friction might be too aggressive. This might be due to the fact that our implementation does not account for the mass-loss of the clusters as they spiral in: the environment gets increasingly disruptive, which causes them to lose more mass and spiral in more slowly.

### 3.6 Alternative physics

To study the impact of the physics discussed in this section, we have run alternative models in which we have switched off specific processes one by one. In particular, we have considered the following cases:

- (i) no environmental dependence of GC radii (equations 4–7);
- (ii) no efficient cluster disruption in the galaxy disc during galaxy mergers (see equation 8);
- (iii) no dynamical friction (see Section 3.5);

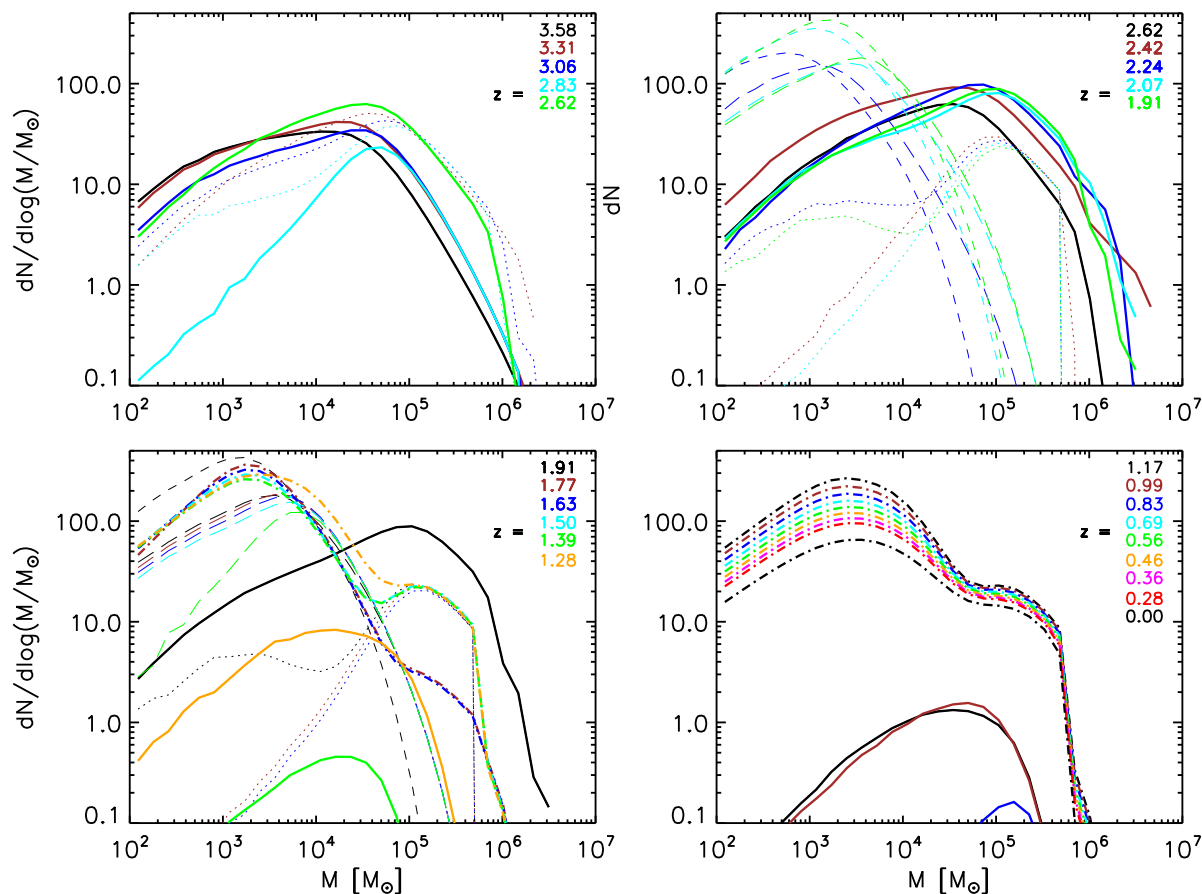
Additionally, we have considered a run where we assume that the minimum cluster mass scale ( $M_{\min}$ ) is always equal to  $10^2 M_{\odot}$ . We find that, for the range of masses considered in this work, this assumption gives results that are indistinguishable from those obtained using our reference run, that assumes the model presented

in Trujillo-Gomez et al. (2019) to determine  $M_{\min}$ . Finally, as anticipated above, we have also considered a run where metal ejection in small haloes is treated as in the model published in Hirschmann et al. (2016), i.e. almost all newly synthesized metals (95 per cent) are directly injected into the hot gas component in haloes less massive than  $5 \times 10^{10} M_{\odot}$ .

## 4 CASE STUDIES: EVOLUTION OF THE GC MASS FUNCTION

Before analysing the predictions of our model in detail, we discuss two ‘case studies’ to show how the mass distribution of stellar clusters evolves due to the physical mechanisms discussed in Section 3 and implemented in our model. Our case studies correspond both to relatively low-mass galaxies because this allows us to visualize in some detail the evolution of their stellar cluster population. The corresponding history for more massive galaxies becomes more difficult to visualize, depending on the number of merger events suffered.

Fig. 2 corresponds to a low-mass galaxy (the galaxy stellar mass at  $z = 0$  is  $\sim 1.3 \times 10^9 M_{\odot}$ ) that experiences one single major merger event between  $z = 1.91$  and  $z = 2.07$ . The top left panel of Fig. 2 shows the mass distribution of stellar clusters associated with the two



**Figure 3.** As in Fig. 2, but for a galaxy that has a stellar mass of  $\sim 3.2 \times 10^9 M_{\odot}$  at present, and that suffered one minor merger at  $z \sim 1.6$  (with a galaxy of mass  $\sim 2.7 \times 10^8 M_{\odot}$ ) and two major merger events at  $z \sim 1.3 \sim 1.8$  (in this case, the merging galaxies have mass  $\sim 3$  and  $\sim 5 \times 10^8 M_{\odot}$ , respectively). The mass distributions of stellar clusters discs are shown by solid, dotted, dashed, and long dashed lines (solid is for the main progenitor, while other linestyles are used for other progenitors when present). The mass distribution of clusters in the halo is shown with dot-dashed lines.

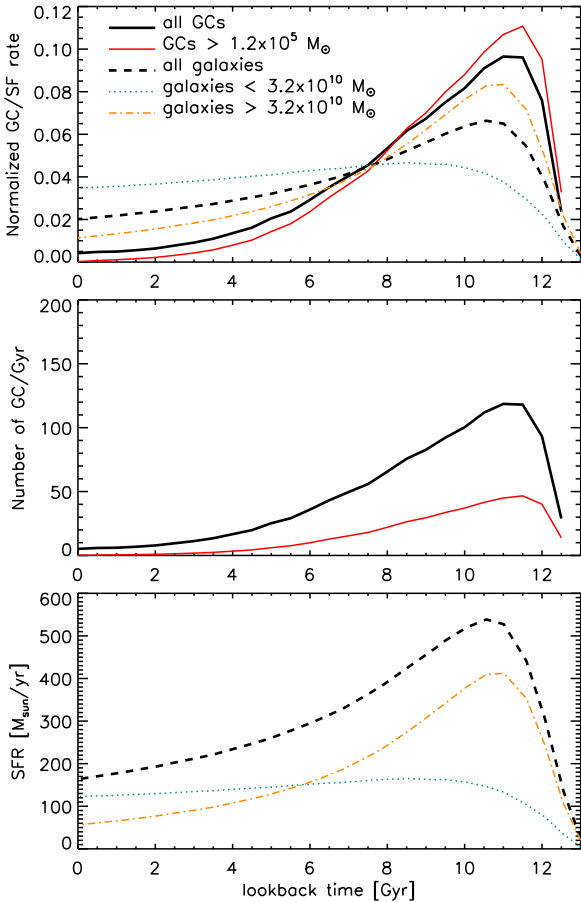
progenitors of the final galaxy at high redshift (a second progenitor exists only for those snapshots where a dotted line is plotted, i.e. from  $z = 3.06$  to  $z = 2.07$ ). At these early times, the distribution of young stellar clusters (those that are associated with the disc of our model galaxies) results from a ‘competition’ between ongoing star formation and the efficient rapid disruption of clusters by tidal shocks. At the final redshift shown in this panel, the total mass in stellar clusters is actually larger than that predicted at even higher redshift for the most massive progenitor (compare the red solid line with the black solid line). The distributions shown in this panel also highlight the strong effect of our dynamical friction implementation, which we will return to below. The top-right panel again shows the distribution of stellar clusters in both progenitors at  $z = 2.07$  (solid and dotted black lines) and the distribution of clusters associated with the halo of the remnant galaxy after the major merger (dot-dashed lines). As detailed in Section 3.3, we assume that the rapidly changing tidal field during the interaction leads to an efficient cluster disruption before the stellar clusters associated to the merging galaxies migrate to the halo of the remnant galaxy (dot-dashed brown line). At this point, the evolution of stellar clusters is driven by the slow evaporation phase described in Section 3.4. This slow evolution of the cluster mass function can be appreciated, down to  $z = 0$ , in the bottom panels of Fig. 2. At present, the mass distribution of the clusters associated with the model galaxy considered in this example peaks at  $\sim 1.5 \times 10^5 M_{\odot}$ , and corresponds to a specific frequency of  $\sim 13.8$

( $\sim 6.3$  when considering only stellar clusters more massive than  $10^5 M_{\odot}$ ).

Fig. 3 corresponds to a just slightly more massive galaxy (the stellar mass at present is  $\sim 3.2 \times 10^9 M_{\odot}$ ) with a more complex merger history. Specifically, the galaxy considered in this case has suffered one minor merger episode at  $z \sim 1.5$  and two major mergers (one at  $z \sim 1.8$  and the second at  $z \sim 1.3$ ). At the redshifts shown in the top left and top right panels, there are two and four progenitors for this galaxy. The mass distribution of star clusters in the disc evolves rapidly because of disruption and new star formation. The three merger events occurring during the redshift interval shown in the bottom-left panel lead to the formation of a stellar cluster component, associated with the halo of the model galaxy, which then evolves slowly as a result of evaporation. At present, the mass distribution of GCs associated with the example galaxy considered shows a double peak, one at a mass slightly larger than  $\sim 10^5 M_{\odot}$  and one at a mass  $\sim 3.6 \times 10^3 M_{\odot}$ . The specific frequency of GCs measured for this galaxy is  $\sim 235$  if we consider all stellar clusters down to  $10^2 M_{\odot}$ , and  $\sim 16.5$  when we consider only stellar clusters more massive than  $10^5 M_{\odot}$ .

In the two example cases considered above, GCs form at early cosmic times and migrate to the halo, where they are no longer subject to rapid disruption, at  $z > 1 - 1.5$ . Since the merger activity peaks at high redshift, most of the surviving GCs associated with model galaxies will be old. Fig. 4 compares the formation history of





**Figure 4.** Formation history of GCs (solid lines) compared to the star formation history of all model galaxies in the simulated volume considered. The thick dashed black line corresponds to galaxies more massive than  $\sim 10^9 M_{\odot}$ , while the thinner dotted and dash-dotted lines correspond to galaxies more and less massive than  $3.2 \times 10^{10} M_{\odot}$ , respectively. In the top panel, all lines have been normalized to unity to ease their relative comparison, whereas the middle and bottom panels show the actual formation rate of GCs and stars, respectively.

surviving GCs (solid lines, with the red line showing the formation history of GCs more massive than  $10^5 M_{\odot}$ ) with the star formation history of all model galaxies in the simulated volume considered. The black dashed line shows the average star formation history obtained considering all model galaxies more massive than  $10^9 M_{\odot}$ , while the orange and cyan lines correspond to galaxies more and less massive than  $3.2 \times 10^{10} M_{\odot}$  respectively. All lines have been normalized to unity in the top panel to ease the comparison, while the middle and bottom panels show the actual values of the GC and star formation rate, respectively. The figure shows that surviving GCs correspond to the oldest stellar component formed in our model galaxies: the formation history of GCs peaks at lookback time  $\sim 11.5$  Gyr, about one Gyr earlier than the peak of the star formation when considering all surviving galaxies (above our mass limit). The figure also shows a trend for more massive GCs forming earlier than their less massive counterparts. This is a survivor bias – low-mass clusters are disrupted more rapidly, and any surviving low-mass GCs are therefore more likely to be young. In Section 6, we will analyse in more detail the age (and metallicity) distribution of GCs associated with galaxies of different stellar mass.

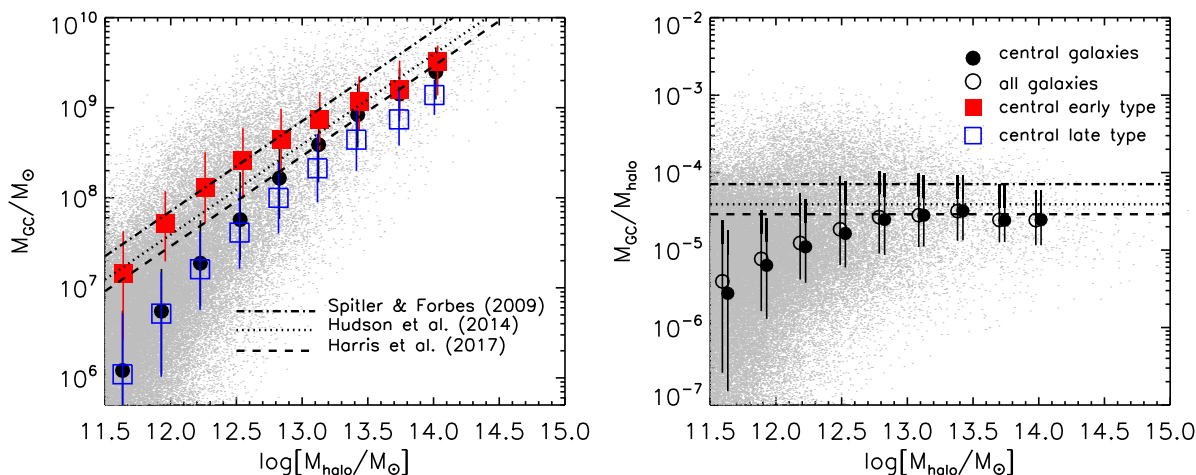
## 5 SCALING RELATIONS AND SPECIFIC FREQUENCY OF GLOBULAR CLUSTERS

Several observational studies have highlighted the existence of well-defined scaling relations between the GC population and the properties of their host galaxies. In particular, the total mass in GCs scales almost linearly with the host galaxy’s halo mass across at least three or even four orders of magnitude in halo mass (from  $\sim 10^{11}$  to  $\sim 10^{15} M_{\odot}$ ; Blakeslee, Tonry & Metzger 1997; Spitler & Forbes 2009; Hudson, Harris & Harris 2014; Harris, Blakeslee & Harris 2017). The relation possibly extends for another two orders of magnitude (down to halo masses  $\sim 10^9 M_{\odot}$ ), with no significant deviation from linearity but an increased scatter towards low-halo masses (Forbes et al. 2018).

The observed correlation appears surprising because, if GC formation is related to star formation, one would expect a more natural correlation between the total mass/number of GCs and the stellar mass of the galaxy. Virtually all studies mentioned above interpreted the strong quasi-linear relation observed as an indication that GCs formed at early times, with the process being unaffected by the stellar/AGN feedback that introduces a non-linear correlation between galaxy stellar mass and halo mass. An alternative explanation was provided by Kruijssen (2015), who argued that the nearly constant ratio ( $\eta$ ) between the total mass in GCs and the halo mass arises from the combination of galaxy formation within dark matter haloes and strongly environmentally dependent cluster disruption. Recent work by El-Badry et al. (2019), based on a semi-analytic model for GC formation coupled to dark matter merger trees, has argued that a constant value of  $\eta$  is a natural consequence of hierarchical assembly, with the relation being sensitive to the details of GC formation at low-halo masses ( $< 10^{11.5} M_{\odot}$ ). These arguments have been revisited in a recent work by Bastian et al. (2020), based on the E-MOSAICS simulation suite. In particular, the latter study argues that the normalization of the relation is primarily set by cluster disruption, while the downturn also predicted by El-Badry et al. (2019) at low-halo masses is imprinted by the underlying relation between galaxy stellar mass and halo mass.

Fig. 5 shows our model predictions. The left panel shows the predicted correlation between the total mass in GCs and the parent halo mass, for all model central galaxies in the simulated volume considered (solid circles with error bars show the 25th and 75th percentiles of the distributions). We have considered only central galaxies because observational work typically uses scaling relations that are calibrated on central galaxies to infer the parent halo mass. In addition, to have a fair comparison with observational data, we considered all stellar clusters with masses  $> 1.2 \times 10^5 M_{\odot}$ , age  $> 7$  Gyr, and  $-2.54 < [\text{Fe}/\text{H}] < 0.34$ . These limits are motivated by the properties of the Galactic GC population (e.g. Kruijssen et al. 2019b). We also show results obtained when splitting our model galaxies into two subsamples according to their bulge-to-total stellar mass ratio (solid and open squares correspond to bulge/disc-dominated systems, respectively). In the right panel of the same figure, we show how the ratio between the total mass in GCs and the halo mass varies as a function of the halo mass. Empty symbols with error bars correspond to the median and percentiles of the distribution obtained including also satellite galaxies. In this case, the plotted halo mass is obtained by multiplying the number of bound particles associated with the parent dark matter subhalo<sup>5</sup> by the particle mass. Lines with different

<sup>5</sup>For ‘orphan’ galaxies, i.e. galaxies that are no longer associated with a distinct dark matter substructure, we have considered the number of particles associated with the last identified parent substructure.



**Figure 5.** Left panel: total mass in globular clusters as a function of the parent halo mass. Circles with error bars show the median and percentiles (25th and 75th) of the distributions obtained considering all central model galaxies. Individual values are shown as grey symbols. Filled and open squares show the median and percentiles obtained for galaxies with bulge-to-total stellar mass ratio larger than 0.8 and smaller than 0.4, respectively. Different observational estimates are shown with lines of different styles, as indicated in the legend. Right panel: as for the left panel but this time showing the ratio between the total mass in globular clusters and halo mass. Empty symbols with error bars show the median and percentiles of the distribution obtained when including satellite galaxies.

styles in both panels show observational estimates, as indicated in the legend.

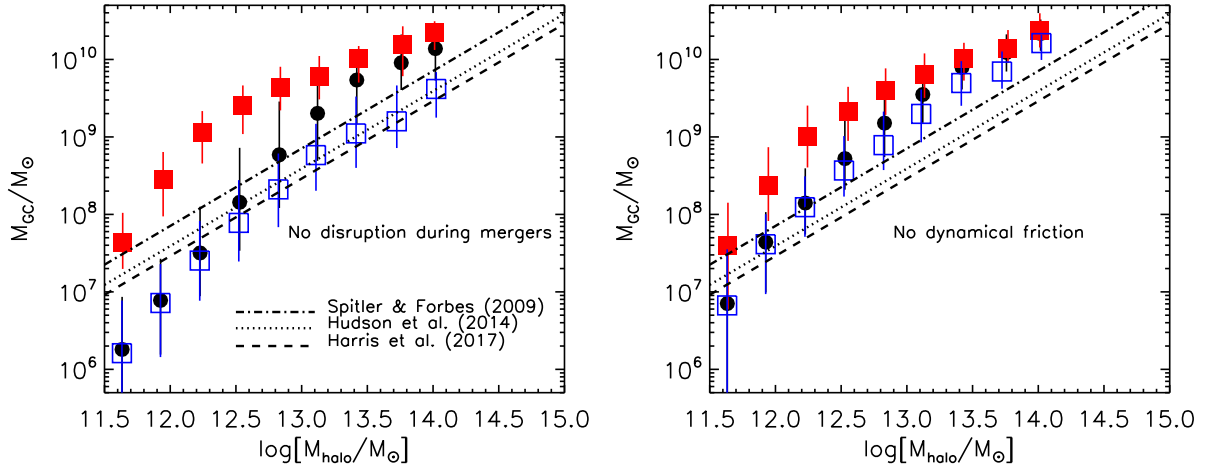
Fig. 5 shows that our model predicts a quasi-linear relation between the total mass in GCs and halo mass, for haloes more massive than  $\sim 3 \times 10^{12} M_{\odot}$ . A deviation from linearity is predicted for lower-mass haloes. As mentioned above, a curvature at low-halo masses has been found in previous work (e.g. Choksi et al. 2018; El-Badry et al. 2019; Bastian et al. 2020). In our model, the curvature is not affected by the alternative physical models considered (see Section 3.6 and the discussion below). The curvature is also only slightly weakened by the inclusion of satellite model galaxies. The latter has a more pronounced effect in the E-MOSAICS simulation suite (Bastian et al. 2020). We note here that haloes with mass  $\sim 10^{12} M_{\odot}$  are resolved with about 850 particles in the Millennium Simulation, so it would be interesting to verify the trends predicted with a higher resolution volume – a higher resolution would allow smaller mergers to be resolved, and these could potentially bring into the halo a larger number of GCs from lower mass accreted galaxies. In addition, one should bear in mind that observed halo masses of low-mass galaxies are affected by relatively large uncertainties, which limits the statistical significance of a downturn in observational data (see discussion in Bastian et al. 2020).

Our model also predicts that bulge-dominated galaxies are typically characterized by a larger total mass in GCs compared to galaxies of similar stellar mass but later morphological type. This is not surprising given that the main channel for bulge formation in our model is represented by galaxy mergers (De Lucia et al. 2011), and that we have assumed that mergers trigger the migration of stellar clusters from the disc to the halo. A positive correlation between the number of GCs and the number of mergers was also found in the E-MOSAICS simulation suite (Kruijssen et al. 2019a). Early observational studies did not find any significant dependence of  $\eta$  on the environment or the morphological type of the galaxy (Spitler & Forbes 2009; Hudson et al. 2014). Larger statistical samples and revised analysis methods have highlighted a second-order difference between ellipticals and spirals (Harris, Harris & Hudson 2015) in the same sense that is predicted by our model, but less pronounced. This could suggest a weaker correlation between

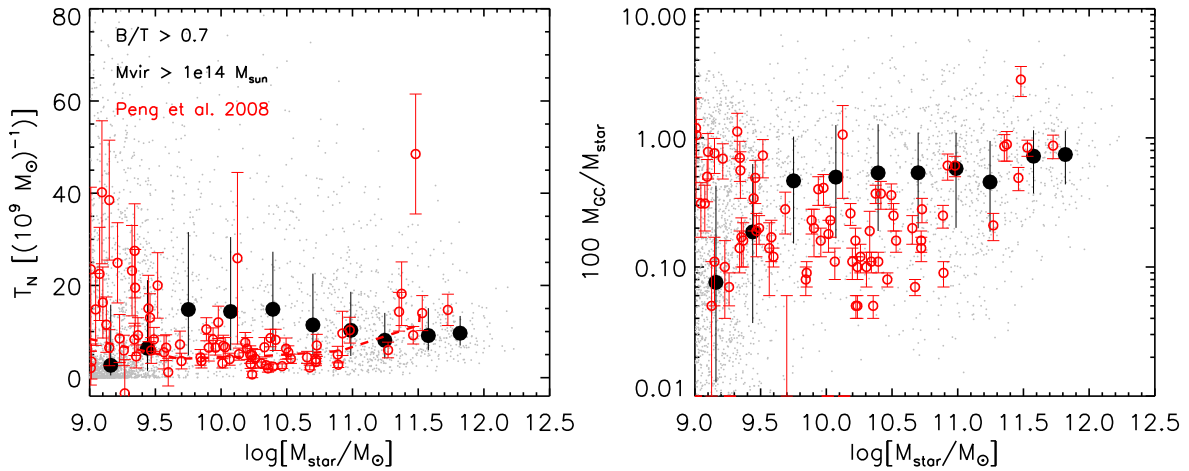
bulge formation and stellar cluster migration than that assumed in our model.

Analysing our results based on alternative physical prescriptions, we find that both efficient cluster disruption and a treatment for dynamical friction are needed in our model to predict both the correct slope and normalization of the relation. Fig. 6 shows the impact of efficient cluster disruption during mergers (left panel) and dynamical friction (right panel) on the relation between the total mass in GCs as a function of the parent halo mass. As in Fig. 5, we plot the median relation (and percentiles) obtained for all model galaxies (filled circles), and for different morphological types (filled and empty squares). Switching off both physical modifications cause an increase of the number (and total mass) of GCs associated with model galaxies. This affects the overall normalization of the predicted relation. Since galaxy mergers are, by construction, more important for early-type galaxies, the lack of an efficient cluster disruption during mergers has a stronger impact for early-type rather than late-type galaxies, thus further strengthening the morphological dependence and implying that our fiducial model is more consistent with observations. Since early-type galaxies represent a larger fraction of the overall population with increasing galaxy stellar mass, these particular physical ingredients also affect the predicted slope of the relation. Our treatment for dynamical friction reduces the mass of GCs that is associated with model galaxies, more or less independently of the galaxy type. This translates into a significant effect only on the overall normalization of the relation, but a negligible effect on its shape.

Fig. 7 shows the predicted dependence of the GCs' specific frequency, as a function of galaxy stellar mass. For this comparison, we have considered the same cuts in GC mass, age, and metallicity indicated above, and we have only considered galaxies (both centrals and satellites) with bulge-to-total stellar mass ratio larger than 0.7 and residing in haloes more massive than  $10^{14} M_{\odot}$ . These limits have been considered to have a fair comparison with the observational data by Peng et al. (2008, empty symbols with error bars in the figure), based on the Virgo Cluster Survey conducted with the *Hubble Space Telescope*. Our simulated sample considered here consists of about 3000 galaxies, i.e. about 40 times larger than the number of galaxies



**Figure 6.** As in the left panel of Fig. 5 but for a model in which no efficient cluster disruption during galaxy mergers has been considered (on the left), and for a model where no dynamical friction has been considered (on the right).



**Figure 7.** Left panel: specific frequency of globular clusters as a function of galaxy stellar mass. All galaxies with bulge-to-total larger than 0.7 and residing in haloes more massive than  $10^{14} M_{\odot}$  have been considered in this case, so as to have a fair comparison with observational estimates by Peng et al. (2008, empty circles). Filled symbols with error bars show the median and percentiles (25th and 75th) of the distributions of all model galaxies (these are shown as dots in the background). Right panel: ratio between the total mass in GCs and galaxy stellar mass for the same model galaxies considered in the left panel, compared to observational estimates.

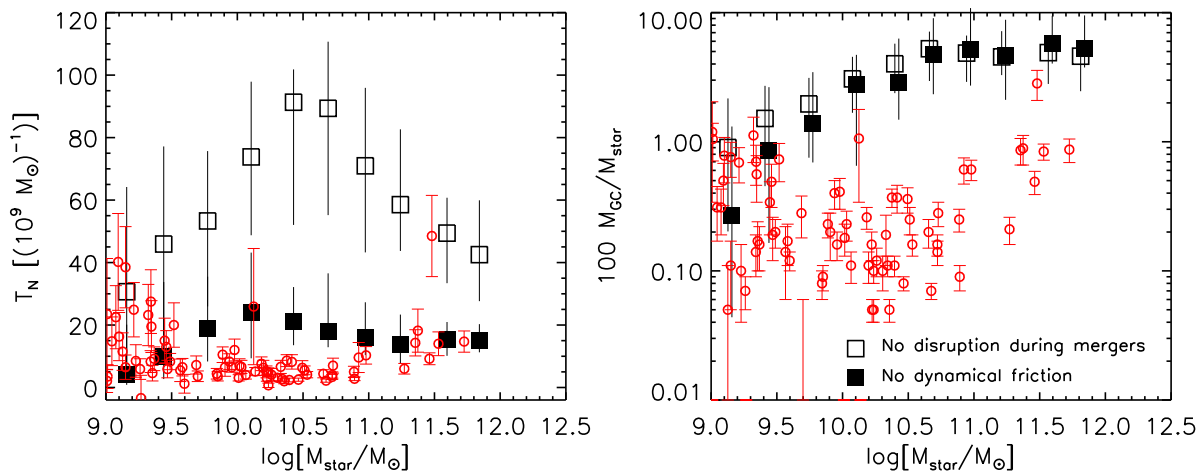
included in the observational data set over the same stellar mass range.

Fig. 7 shows that the model predictions cover the same region of observational estimates, with a few noticeable differences. In particular, for the lowest-mass galaxies considered, the observational estimates tend to be larger than our model predictions. The latter exhibits a significant bending of the median GC mass per galaxy stellar mass towards lower values. This might be due to resolution, i.e. to the fact that an artificially low number of mergers are resolved in this stellar mass range. For galaxies with intermediate stellar masses (between  $\sim 10^{10}$  and  $10^{11} M_{\odot}$ ), the median values of our model predictions lie systematically above the observational measurements, with a large number of model galaxies that are characterized by a specific frequency larger than that measured for Virgo galaxies of comparable stellar mass. We note that model predictions shown in Fig. 7 correspond to an ensemble of massive haloes. By contrast, the observational data sample is based on one galaxy cluster only. Given the large variations of halo mass accretion histories, and the large expected stochasticity in the merger history of their hosted galaxies,

cosmic variance can significantly affect the comparison illustrated in this figure.

An interesting result shown in Fig. 7, which is valid in general and not specific to the cluster environment, is the relatively large scatter of the predicted specific frequency/mass in GCs at fixed galaxy stellar mass. This result, which can be appreciated already considering the two specific case studies discussed in Section 4, is a natural consequence of the stochasticity of the merger events and of the large scatter of galaxy physical properties and GC population at the time of mergers. While a general trend as a function of galaxy stellar mass (see also the next section) exists and is expected (the average number of galaxy mergers increases as a function of galaxy mass), this scatter is important and needs to be taken into account to correctly interpret the observational results.

As discussed above, the mass in GCs (and as a consequence also the specific frequency of GCs) increases significantly without an efficient cluster disruption, or when no treatment for dynamical friction is included. Fig. 8 shows that, when these two physical processes are switched off, both the number and the total mass in



**Figure 8.** As in Fig. 7, but showing results for two alternative models where no efficient cluster disruption during galaxy mergers (empty squares) or no dynamical friction (filled squares) is considered.

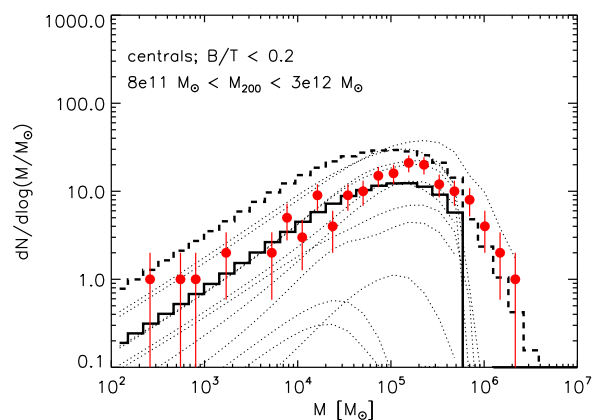
GCs associated with model galaxies increase significantly to values that are considerably larger than current observational estimates. The left panel of the figure shows that the difference is larger for the specific frequency, suggesting a different shape of the cluster mass function in these alternative models. We will come back to this in the next section.

## 6 MASS, METALLICITY, AND AGE DISTRIBUTIONS OF GLOBULAR CLUSTERS

In this section, we analyse the physical properties of GCs and their distributions in terms of mass, metallicity, and age. We will compare these with available observational measurements for the Milky Way and analyse how the distributions vary as a function of galaxy stellar mass. For the analysis presented in this section, we have considered only model galaxies that host at least one GC. This does not significantly affect the results presented below, except for the two lowest galaxy stellar mass bins considered. For such low-mass galaxies, the large number of model galaxies with zero GCs (likely due to resolution limits) has a non-negligible effect on the median distributions presented.

Fig. 9 shows the mean (dashed line) and median (solid line) mass distributions of GCs associated with Milky Way-like model galaxies, compared with the observed GC mass function of the Milky Way (filled circles with error bars; from Harris 1996). The model sample used for this figure consists of 16916 galaxies that are disc dominated (the bulge-to-total mass ratio is smaller than 0.2) and that are centrals of haloes with mass between  $8 \times 10^{11}$  and  $3 \times 10^{12} M_{\odot}$ . The dotted lines show a few individual (random) examples. These highlight the existence of a large galaxy-to-galaxy variance (in terms of normalization, peak mass, presence of a double peak), which is determined by the different merging histories and physical properties of galaxies at the time of GC formation/migration, even though we consider only a limited halo mass range and galaxies with a low number of mergers (as reflected by the cut in morphological type). For example, when considering individual MW-like galaxies, we find that the peak mass varies between  $\sim 10^3 M_{\odot}$  and  $\sim 4.5 \times 10^5 M_{\odot}$ .

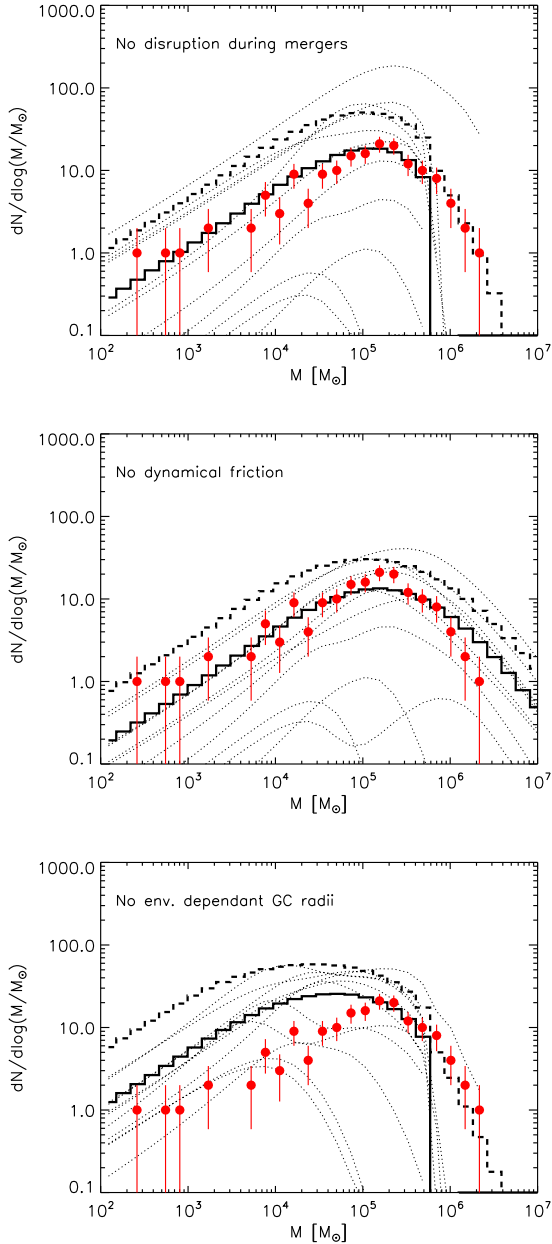
The median distribution obtained for model galaxies follows the observational measurements quite well, with a small deficit of GCs at the peak of the distribution, and a more significant deficit at masses larger than  $\sim 6 \times 10^5 M_{\odot}$  that could be improved by using a less



**Figure 9.** Mass distribution of globular clusters associated with Milky-Way like galaxies. Only model central galaxies of haloes in the mass range indicated in the legend have been considered. In addition, only galaxies with a bulge-to-total mass ratio smaller than 0.2 (i.e. disc dominated galaxies) have been selected. The solid and dashed lines show the median and mean of the distribution, respectively. Dotted lines show only a few individual ‘Milky-Way’ like galaxies, which have been randomly selected. Filled circles with Poisson error bars correspond to observational estimates (Harris 1996).

‘aggressive’ treatment for dynamical friction (see Section 3.5). This can be seen in the middle panel of Fig. 10, where we show the same model predictions, but from a run without a treatment for dynamical friction. In this run, the predicted GC mass distribution for Milky Way-like galaxies extends up to  $\sim 10^8 M_{\odot}$ , with a gradual decrease for masses larger than  $\sim 2 \times 10^5 M_{\odot}$ . At variance with model predictions discussed in the previous section, we find that the results shown in Fig. 9 are not significantly affected if no efficient cluster disruption during galaxy mergers is considered (see the top panel of Fig. 10). This is not surprising, given that the sample of galaxies considered in this case is dominated by late-type galaxies, i.e. galaxies that did not experience a significant number of mergers. Switching off this physical ingredient actually brings model results in somewhat better agreement with the observed peak of the mass distribution. However, as we have discussed in the previous section, an efficient cluster disruption during galaxy mergers is needed to reproduce the normalization of the relation between the total mass in GCs and halo mass. Finally,

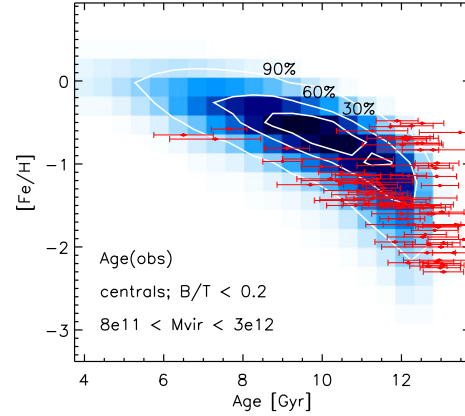




**Figure 10.** As Fig. 9 but (i) in the top panel no efficient cluster disruption in the galaxy disc during galaxy mergers is considered; (ii) in the middle panel no model for dynamical friction is considered; (iii) in the bottom panel no environmental dependence of cluster radii is considered.

the bottom panel of Fig. 10 shows that, when the assumption of an environmental dependence of cluster radii is relaxed, the peak of the mass distribution is moved to lower masses (for the Milky-Way like galaxies considered here, it moves to  $\sim 5 \times 10^4 M_\odot$ ), and the number of GCs below the peak increases by a factor of 2–3. This is a consequence of the treatment adopted (see Section 3.2 and equations 4–7), which leads to longer survival times for stellar clusters less massive than  $10^4 M_\odot$  if a constant, compact radius is adopted.

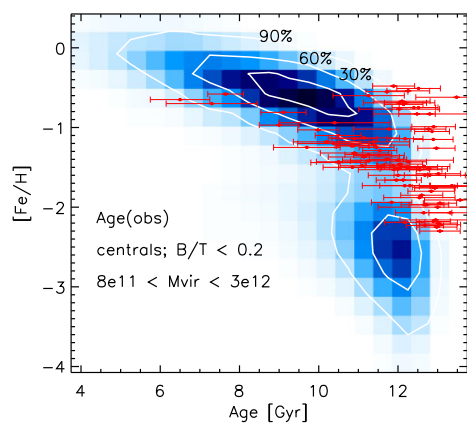
Fig. 11 shows the age-metallicity distribution of GCs associated with the same Milky Way-like model galaxies considered above and compares it with observational estimates of GCs in our Galaxy (circles with error bars). Considering that observations are cut at



**Figure 11.** Age–metallicity distribution of GCs associated with model Milky-Way like galaxies. Circles with error bars correspond to individual measurements of GCs in our Galaxy (compilation presented in Kruijssen et al. 2019b).

$[\text{Fe}/\text{H}] = -0.5$ , the agreement in terms of the metallicity distribution is fairly good. As for ages, our model predictions are systematically younger than the observational estimates by  $\sim 0.75$  Gyr, on average. A similar shift was found for the E-MOSAICS simulations (Kruijssen et al. 2019b, 2020). Specifically, Kruijssen (2019) found a median value of  $\tau_{25}$  (the assembly time of 25 per cent of the final halo mass) of 10.78 Gyr, against 11.5 Gyr estimated for the MW. The same was found for the GCs: the median age of GCs in the MW is 12.26 Gyr, whereas for galaxies in E-MOSAICS the median GC age was found to be 10.73 Gyr. This shift might be explained by an anomalously early formation time of our Galaxy. In fact, there are several further observations confirming the idea that the Milky-Way is not a ‘typical’ galaxy for its stellar mass, such as the offset from the Tully–Fisher relation (Hammer et al. 2007), the unusual satellite population (e.g. Geha et al. 2017; Nashimoto et al. 2022), and the tension between the early formation of the Milky Way’s disc inferred from galactic archaeology and state-of-the-art numerical simulations (Semenov et al. 2023). In order to verify if this is a generic prediction of the model, or if there are a subset of haloes that would reproduce the data, we have considered only those MW-like model galaxies that have an age distribution ‘similar’ to that measured for our Galaxy. To do so, we have computed, for each model galaxy the Kolmogorov–Smirnov statistics and associated probability that the model age distribution is significantly different from the observed distribution. Considering only galaxies with a low-KS probability, we obtain a GC metallicity distribution that is still very similar to the one observed for our Galaxy. However, the resulting GC mass distribution has a significantly different shape and lower normalization than observed, as a consequence of the earlier formation and longer time available for disruption.

We have tested the impact of all relevant parameters in the GC model (see Section 3.6), and we find that the only physical process that has a significant impact on the age–metallicity distribution shown in Fig. 11 is the treatment of chemical enrichment (more specifically metal ejection) in small haloes. Fig. 12 shows the age–metallicity distribution of GCs associated with MW-like galaxies, in a model in which 95 per cent of the metals in small haloes are ejected directly into the hot gas phase. The figure shows a bimodal distribution of metallicities with a second peak at very low values ( $[\text{Fe}/\text{H}] \sim -2.5$ ). These GCs all have very old ages ( $\sim 13$  Gyr) and are therefore associated with very early episodes of star formation in low-mass haloes. The ‘bimodality’ that is observed in Fig. 12 could



**Figure 12.** As in Fig. 11 but for a model in which 95 per cent of the metals in small haloes are ejected directly into the hot gas phase.

be affected by the limited resolution of the simulation adopted: a higher resolution would resolve a larger number of mergers with lower mass galaxies. This could increase the number (and total mass) of GCs associated with low-mass galaxies and affect the metallicity distribution. Although we plan to investigate this in future work, we note here that this feature suggests the prescriptions adopted for chemical enrichment within low-mass haloes may need revisiting. A similar conclusion was also reached independently by studies focusing on the abundances and properties of Damped Ly  $\alpha$  absorbers predicted by our GAEA model (Di Gioia et al. 2020).

Finally, we consider the mass distributions and age–metallicity distributions for model galaxies in bins of galaxy stellar mass, independently of the parent halo mass and morphology. Fig. 13 shows that the peak of the mass distribution increases weakly with galaxy stellar mass, varying between  $\sim 1 \times 10^5$  and  $\sim 2 \times 10^5 M_{\odot}$  over two orders of magnitudes in galaxy stellar mass, in qualitative agreement with findings by Jordán et al. (2007) based on the Virgo Cluster Survey. Fig. 14 shows the median mass distribution obtained in runs where different physical ingredients in our model have been switched off. The left panel corresponds to a run with no efficient cluster disruption during mergers; the middle panel to a run with no dynamical friction; the right panel to a run with no environmental dependence of cluster radii. The impact of these model prescriptions is consistent with what was discussed for the mass distribution of GCs in Milky Way-like galaxies. In addition, the figure shows that the lack of a prescription for dynamical friction virtually removes the already weak dependence of the peak of the mass distribution on the stellar mass of the galaxy for galaxies more massive than  $\sim 10^{10.5} M_{\odot}$ .

Fig. 15 shows the age–metallicity distribution of GCs associated with model galaxies of increasing galaxy stellar mass, as indicated in the different panels. For the lowest mass galaxies considered, most of the GCs have very old ages and a relatively narrow range of metallicities. As the galaxy stellar mass increases, both the ranges of ages and metallicities widen, extending to younger ages and larger metallicities (the two are of course correlated: younger GCs are formed in gas that has been enriched by previous generations of stars, and therefore also have larger metallicities).

Fig. 16 shows the age–metallicity distribution of GCs associated with galaxies of different stellar mass, for a model where 95 per cent of the metals in low-mass haloes are ejected directly into the hot gas phase. The figure shows that this different assumption about metal enrichment in small haloes leads to the development of

secondary density peaks around very old ages and low metallicities, for all galaxy masses considered. This secondary peak at very low metallicities and old ages is dominant in the least massive galaxies considered, supporting the warning given above that this result might be affected by resolution.

## 7 DISCUSSION AND CONCLUSIONS

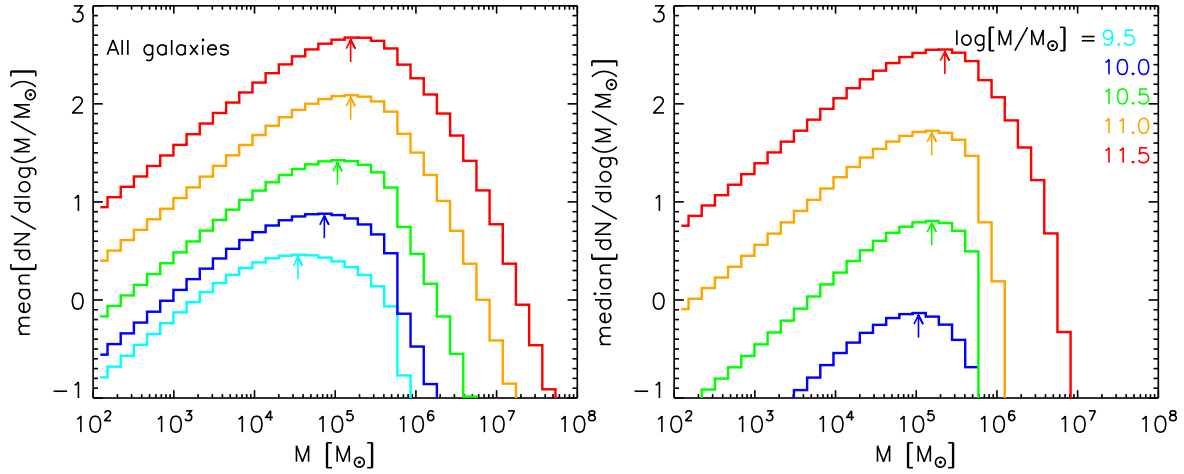
In this paper, we present an end-to-end description of the formation process of GCs, that combines a treatment for their formation and dynamical evolution within galaxy haloes with a modelling of the latter through a state-of-the-art semi-analytic model of galaxy formation and evolution. This theoretical framework has been constructed by effectively coupling the GC model presented in Kruijssen (2015) and the GALaxy Evolution and Assembly (GAEA) semi-analytic model (De Lucia et al. 2014; Hirschmann et al. 2016). A similar approach has been recently used in the framework of the E-MOSAICS project (Pfeffer et al. 2018; Kruijssen et al. 2019a). Being based on hydrodynamical simulations, however, these studies are limited to relatively small cosmological boxes ( $\sim 50$  Mpc on a side) or to a few individual resimulations. Our fully semi-analytic approach requires significantly shorter computational times, allowing us to:

- (i) efficiently explore the coupling between the galaxy and star cluster formation physics parameter space by running a large number of model variants;
- (ii) model large populations of galaxies to study the effect of environment and assembly history with exquisite statistics;

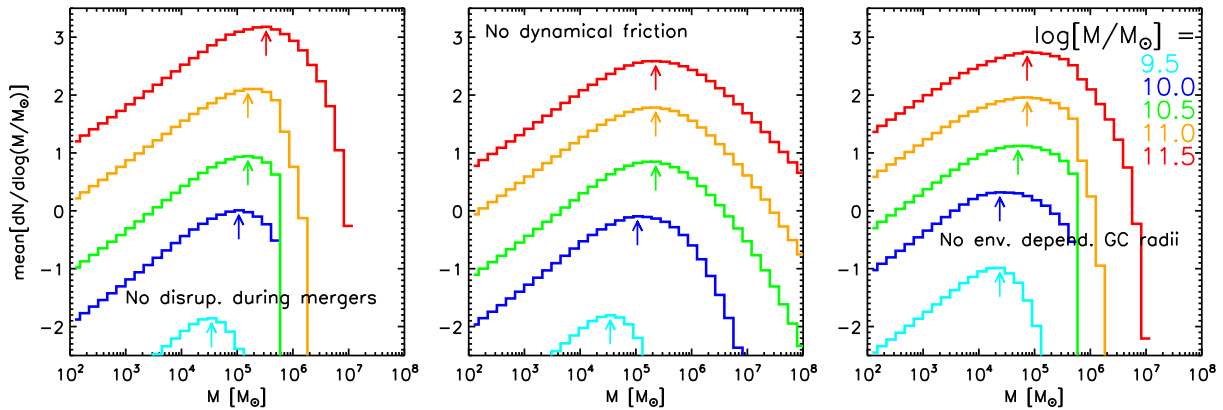
Our approach also improves upon previously published models that parametrize the formation of the GC populations using dark matter accretion histories extracted from cosmological simulations (e.g. Kruijssen 2015; Choksi et al. 2018; El-Badry et al. 2019), by including an explicit treatment for galaxy formation and the effect of the evolving galactic environment on star cluster formation and disruption.

Our model reproduces naturally the observed correlation between the total mass in GCs and the parent halo mass (Spitler & Forbes 2009; Harris et al. 2017). The predicted relation is linear for haloes more massive than  $\sim 3 \times 10^{12} M_{\odot}$ , with a deviation from linearity for lower halo masses. In the framework of our model, such a deviation is not affected by GC formation physics, at least not by the processes that we have explicitly varied: a fixed/varying value for the minimum cluster mass scale, the environmental dependence of GC radii, the efficiency of cluster disruption during mergers, and dynamical friction. In our model, the turnover at low masses is driven by a significant dependence on morphological type in this mass range: bulge dominated galaxies host, on average, larger masses of GCs than their late-type counterparts resulting in a closer to linear behaviour at low-halo masses. This dependence is a natural consequence of our assumption that cluster migration from the disc to the halo is triggered by galaxy mergers, and that bulges are predominantly built through mergers. Although a similar dependence is seen in the observational data, the observed effect is not as strong as predicted by our model, which might suggest a weaker correlation between bulge formation and the migration of stellar clusters than predicted by our model.

One caveat to bear in mind is that haloes with mass  $\sim 10^{12} M_{\odot}$  are resolved with  $\sim 800$  particles in the Millennium Simulation that we have employed in our study. This might result in merger trees that are not resolved well enough to give convergent results for the corresponding central galaxies: increased resolution would lead to



**Figure 13.** Mass distribution of globular clusters associated with model galaxies of different stellar mass, as indicated in the legend. The left and right panels show the mean and median of the distributions, respectively. The vertical arrows correspond to the peaks of the corresponding distributions.



**Figure 14.** Median mass distributions of globular clusters associated with model galaxies of different galaxy stellar mass (as indicated in the legend), for three alternative models considered. The left panel corresponds to a run where no efficient cluster disruption in the galaxy disc during mergers is considered; the middle panel corresponds to a run with no dynamical friction; the right panel corresponds to a run where no environmental dependence of cluster radii is assumed.

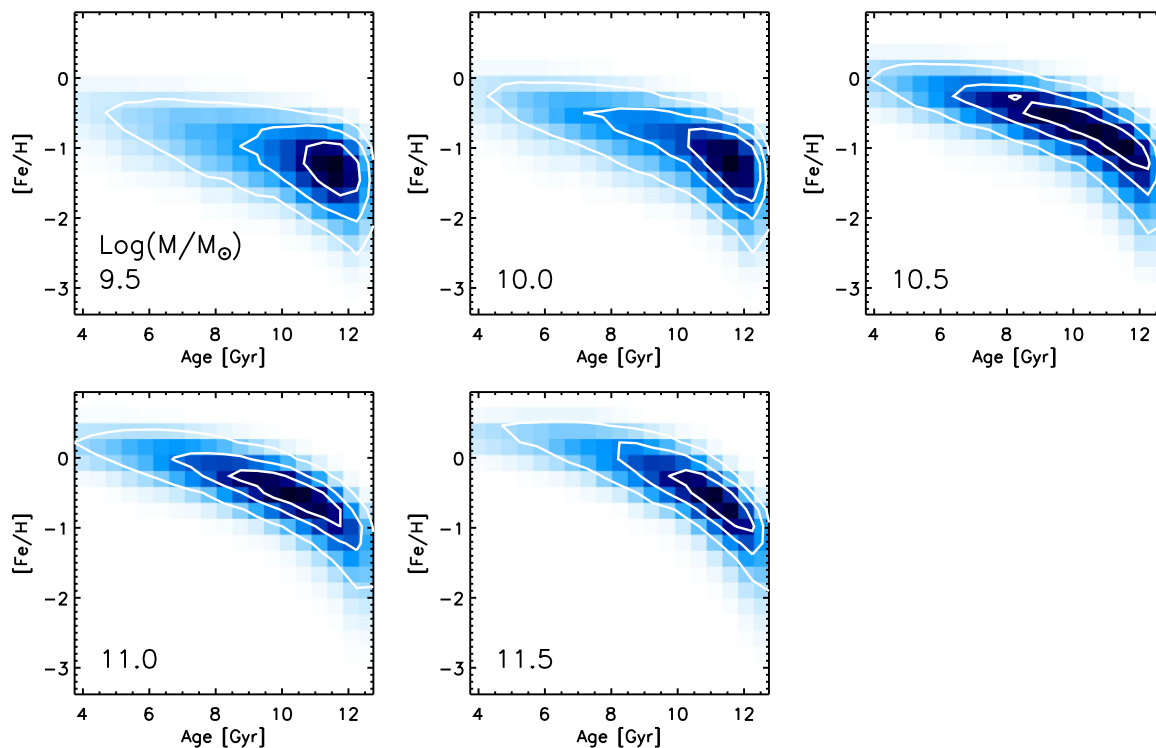
a larger number of mergers (with smaller haloes) and these could potentially bring in a larger number of GCs from accreted galaxies. This could reduce the bending of the predicted relation at low-halo masses, and potentially also the different mass of GCs predicted for the corresponding central galaxies that have late and early-type galaxies. Such a difference is, however, predicted also for galaxies that are well resolved within the simulation employed in this study, and therefore represents a robust prediction of our model.

We find that both the slope and the normalization of the predicted relation between halo mass and total mass in GCs depend on cluster physics. In particular, our model requires both an efficient cluster disruption during galaxy mergers and a rather aggressive treatment for dynamical friction to bring model predictions in close agreement with observational results: the former affect both the slope and the normalization of the relation because of the stronger impact on early-type galaxies and the varying fraction of these galaxies as a function of galaxy stellar mass; the latter has a significant effect on the overall normalization but a negligible impact on the slope.

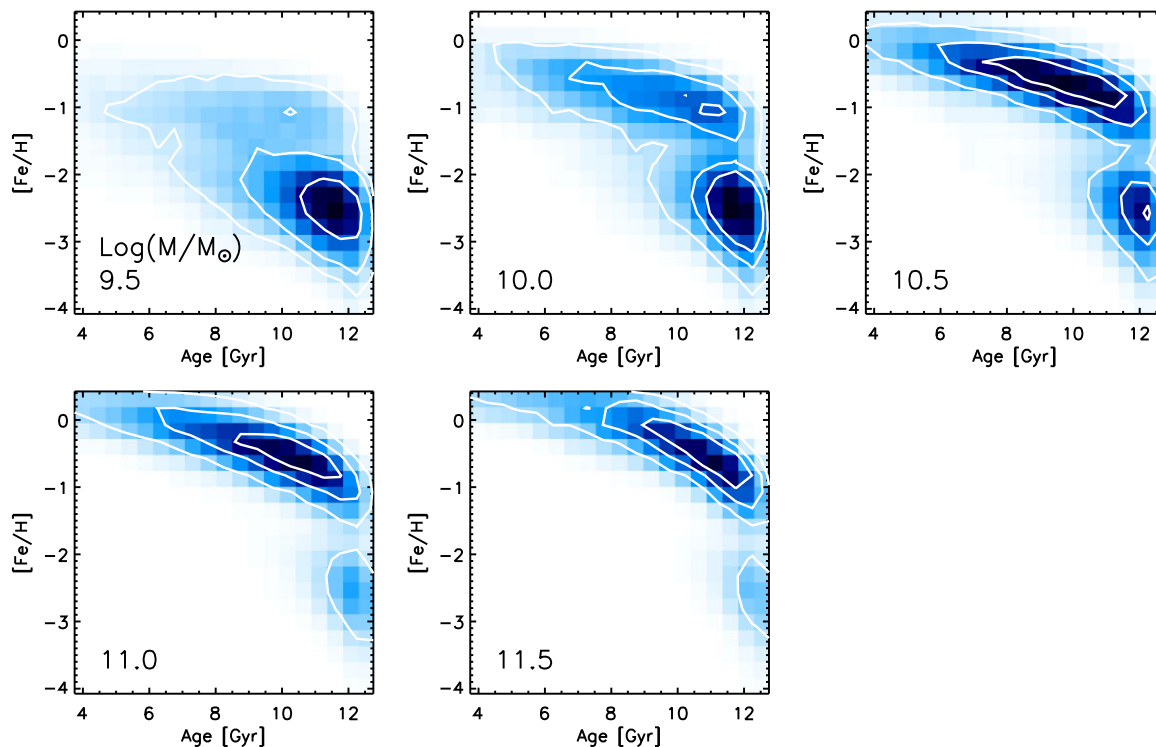
Our reference model reproduces quite well the observed mass distribution of GCs in our Galaxy, with a deficit at GC masses larger than  $6 \times 10^5 M_{\odot}$  that could be improved with a less aggressive treatment for dynamical friction. At lower GC masses,

our model requires an environmental dependence of GC radii (i.e. lower survival times for less massive clusters) to bring model predictions in agreement with observational data. The model GCs in Milky-Way galaxies tend to be systematically younger (by  $\sim 1$  Gyr) than those observed in our Galaxy. A similar result was found in the E-MOSAICS simulations (Kruijssen et al. 2019b, 2020) and could be explained by an anomalously early formation of our Galaxy. The metallicity distribution is unimodal, with a peak at  $[\text{Fe}/\text{H}] \sim -0.5$ . When considering the overall galaxy population, our model also predicts a weak increase of the peak of the GC mass distribution with increasing galaxy stellar mass, in qualitative agreement with observational results. The predicted age–metallicity distribution depends significantly on galaxy mass: both the age and metallicity ranges widen for more massive galaxies, that include younger and more metal rich GCs. Again, there is no clear sign of bimodality in either the age or metallicity distributions obtained when considering the entire galaxy population in the simulated volume.

As mentioned above, the large volume of the simulation translates into large statistical samples of galaxy populations. Our sample of Milky-Way like galaxies, selected only on the basis of halo mass and bulge-to-total mass ratio and using only about 10 per cent of



**Figure 15.** Age–metallicity distributions of globular clusters associated with model galaxies of different stellar mass, as indicated in the legend.



**Figure 16.** As in Fig. 15 but for a model where 95 per cent of the newly synthesized metals in small haloes are ejected directly into the hot gas phase.

the Millennium Simulation volume, is made up of about 600 000 galaxies. Our results highlight the existence of a very large galaxy-to-galaxy variance, even in the limited halo mass bin of Milky-Way like haloes, that is driven by the different galaxy merger histories and physical conditions at GC formation and migration. When

considering individual galaxies, bimodal or multi-modal metallicity and age distributions become not uncommon. In future studies, we plan to investigate in further detail how the predicted properties of GCs depend on the mass accretion and merger history of their parent galaxy/halo.



## ACKNOWLEDGEMENTS

GDL gratefully acknowledges support from the Alexander von Humboldt Foundation, and the hospitality of Heidelberg University, where part of this work was carried out. JMDK gratefully acknowledges funding from the DFG through an Emmy Noether Research Group (grant number KR4801/1-1). STG gratefully acknowledges the generous and invaluable support of the Klaus Tschira Foundation. JMDK and STG gratefully acknowledge funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme via the ERC Starting Grant MUSTANG (grant agreement number 714907). COOL Research DAO is a Decentralized Autonomous Organization supporting research in astrophysics aimed at uncovering our cosmic origins. MH acknowledges funding from the Swiss National Science Foundation (SNF) via the PRIMA Grant PROOP2 193577 'From cosmic dawn to high noon: the role of black holes for young galaxies'.

## DATA AVAILABILITY

The model data underlying this article will be shared on request to the corresponding author. An introduction to GAEA, a list of our recent work, as well as data files containing published model predictions, can be found at: <https://sites.google.com/inaf.it/gaea/>

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