The origin of the Milky Way globular clusters

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ABSTRACT
We present a cosmological zoom-in simulation of a Milky Way-like galaxy used to explore the formation and evolution of star clusters. We investigate in particular the origin of the bimodality observed in the colour and metallicity of globular clusters, and the environmental evolution through cosmic times in the form of tidal tensors. Our results self-consistently confirm previous findings that the blue, metal-poor clusters form in satellite galaxies which are accreted onto the Milky Way, while the red, metal-rich clusters form mostly in situ or, to a lower extent in massive, self-enriched galaxies merging with the Milky Way. By monitoring the tidal fields these populations experience, we find that clusters formed in situ (generally centrally concentrated) feel significantly stronger tides than the accreted ones, both in the present-day, and when averaged over their entire life. Furthermore, we note that the tidal field experienced by Milky Way clusters is significantly weaker in the past than at present-day, confirming that it is unlikely that a power-law cluster initial mass function like that of young massive clusters, is transformed into the observed peaked distribution in the Milky Way with relaxation-driven evaporation in a tidal field.

Key words: galaxies: formation — galaxies: star clusters: general — methods: numerical

1 INTRODUCTION
Globular clusters are among the oldest astrophysical objects. They form in the early Universe in highest density peaks (e.g. Diemand et al. 2005; Boley et al. 2009) and because of their high density, they survive tidal harassment from their host(s). Hence, they witness most of the formation and evolution processes of galaxies, and can be used to probe them (Brodie & Strader 2006). The globular clusters populations of most (if not all) massive galaxies display a colour bimodality: the so-called blue and red clusters (see e.g. Zinn 1985; Gebhardt & Kissler-Patig 1999; Larsen et al. 2001; Peng et al. 2006, and references therein). Due to their extended distribution in space, blue clusters used to be referred to as halo clusters. They are metal-poor (with the distribution peaking at $[\text{Fe/H}] \approx -1.5$ for the Milky Way, Harris 1996, but this value varies from galaxy to galaxy) and show no sign of rotation as a population, contrary to the red clusters which are more metal-rich (peak at $[\text{Fe/H}] \approx -0.5$ in the Milky Way), more spatially concentrated and which are rotating with the galaxy (see a review in Brodie & Strader 2006).

Such bimodality suggests two formation mechanisms for globular clusters. For instance, it has been proposed that blue clusters form in galaxies in the early Universe that merge later. In such (wet) merger process, starbursts would generate the red population (Schweizer 1987; Ashman & Zeff 1992). The resulting massive galaxy would then exhibit its own red population together with the blue clusters of its progenitors. This scenario is supported by the observed ability of wet mergers to produce young massive clusters (Whitmore & Schweizer 1995; Mengel et al. 2005; Bastian et al. 2009; Herrera et al. 2011, see also Renaud et al. 2014, 2015 for a theoretical perspective) which could share the same physical properties as (present-day observed) globular clusters when they formed. However this scenario faces issues, mainly in matching the specific frequency of globular clusters, in particular in massive elliptical galaxies (e.g. McLaughlin et al. 1994). Forbes et al. (1997) propose instead that blue globulars form when the proto-galaxy itself collapses, in a metal-poor and turbulence media. The red population would form later, once the galactic disc has settled. The formation of globular clusters would then be a multiphase process, with the first phase being interrupted possibly by cosmic reionisation (Beasley et al. 2002).

Kravtsov & Gnedin (2005) and Li & Gnedin (2014) advocate that major mergers are at the origin of both sub-populations: blue clusters form during early mergers ($z > 4$) while the red ones appear in mergers at lower redshifts (even after $z = 1$). Although this scenario combined with star formation enhancement in mergers seems appropriate in dense galactic environment leading to the assembly of massive elliptical galaxies, like in the Virgo Cluster as tested by Li & Gnedin (2014), it does not apply to Milky-Way like systems where no recent major merger took place (Wyse 2001; Deason et al. 2013; Ruchti et al. 2014, 2015). Finally, Côté et al. (1998) argue that red clusters form in situ while the blue ones are accreted, either via merging satellite galaxies, or by tidal capture of the clusters themselves (see also Tonini 2013).
Because of the age-metallicity degeneracy (e.g. Worthy 1994), determining the physical origins of the two populations is an observational challenge (see Marin-Franch et al. 2009; Leaman et al. 2013; Forbes et al. 2015), and the numerical approach has been followed by several pioneer works to shed more light on this topic. There, the difficulty consists in the wide range of scales (space and time) spanning both the cosmological context of galaxy formation and evolution, and the internal physics of clusters. For this reason, all previous studies focus on a specific aspect of the problem. For instance, following Kravtsov & Gnedin (2005), Li et al. (2016) use parsec-resolution cosmological simulations to explore the physics of globular cluster formation, in particular the shape of the cluster initial mass function, leaving aside the environment-dependent cluster evolution.

Modelling the evolution of clusters requires to resolve their internal physics driven by stellar evolution and interactions between individual stars (and/or binary and multiple systems, see e.g. Heggie & Hut 2003), which is still out of reach of large scale galactic and cosmological simulations. However, several works develop and use coupling methods in which the cosmological environment is (partially) accounted for in dedicated N-body star-by-star simulations of clusters (Fujii et al. 2007; Renaud et al. 2011; Renaud & Gieles 2015a). Studies consider either the full cosmological context (Rieder et al. 2013), or focus on specific aspects of galaxy evolution like major mergers (Renaud & Gieles 2013), accretion of satellites (Miholics et al. 2014; Bianchini et al. 2015) or the secular growth of the host galaxy’s dark matter halo (Renaud & Gieles 2015b). All these works point out the mild effects of the cosmological context and the galactic events on the short time-scale evolution of clusters (≲Gyr, as opposed to local perturbations like encounters with molecular clouds Elmegreen 2010; Gieles & Renaud 2016). However, these evolutions modify the context itself (e.g. the galactic mass distribution) and/or the orbits of the clusters, which influence their evolution over longer time-scales (≳Gyr). Connecting the theory on cluster formation and their response to the evolution of their environment over several Gyr to the observation of globular clusters is thus an on-going process in the understanding of origin of galaxies and of their stellar populations.

Using a cosmological zoom-in simulation of the formation of a Milky Way-like galaxy, we explore both the formation and the evolution of star clusters, tracking their orbits and the tidal field they experience since their formation, in the Milky Way and its progenitors. We particularly focus on the bimodality of globulars retrieved in our simulation and explore the differences between the two sub-populations along their evolutions to propose a consistent scenario of their origins.

2 METHODOLOGY

We carry out a cosmological hydrodynamic+\(N\)-body zoom-in simulation of a Milky Way mass galaxy using the adaptive mesh refinement (AMR) code RAMSES (Teysseier 2002), assuming a flat \(\Lambda\)-cold dark matter cosmology with \(H_0 = 70.2 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_m = 0.272\), \(\Omega_{\Lambda} = 0.728\), and \(\Omega_{\Lambda} = 0.0455\). A dark matter only simulation was performed beforehand using a simulation cube of size 85 Mpc. At \(z = 0\), a halo of \(R_{200m} = 334 \text{ kpc}\) (radius within which the mass density is 200 times the mean matter density) and \(M_{200m} = 1.3 \times 10^{12} M_{\odot}\) was selected for re-simulation at high resolution. Particles within \(5R_{200m}\) at \(z = 0\) were traced back to \(z = 100\), and the Lagrangian region they defined was regenerated at high resolution, still embedded within the full lower-resolution volume, using the MUSIC code (Hahn & Abel 2011). This is the same initial conditions as the “m12i” halo from Hopkins et al. (2014) and Wetzel et al. (2016).

The dark matter particle mass in the high resolution region is \(2.1 \times 10^6 M_{\odot}\) and the adaptive mesh is allowed to refine if a cell contains more than eight dark matter particles. This allows the local force softening to closely match the local mean inter-particle separation, which suppresses discreteness effects (e.g. Romeo et al. 2008). A similar criterion is employed for the baryonic component, where the maximum refinement level is set to allow for a mean constant physical resolution of 218 pc.

The adopted star formation and feedback physics is presented in Agertz et al. (2013) and Agertz & Kravtsov (2015, 2016). Briefly, star formation proceeds in gas denser than \(1 \text{ cm}^{-3}\). At our working resolution, choosing a threshold better representative of molecular (\(10^4 \text{ cm}^{-3}\), Krumholz et al. 2009) or self-gravitating gas (\(10^5 \text{ cm}^{-3}\), Renaud et al. 2013) would not provide a good match of the star formation rate, in particular in the low-mass haloes. Above this threshold, our star formation prescription is based on the local abundance of molecular hydrogen following Krumholz et al. (2009), and each formed stellar particle is treated as a single-age stellar population with a Chabrier (2003) initial mass function. We account for injection of energy, momentum, mass and heavy elements over time via type II and type Ia supernovae (SNe), stellar winds and radiation pressure (allowing for both single scattering and multiple scattering events on dust) on the surrounding gas. Each mechanism depends on the stellar age, mass and gas/stellar metallicity, calibrated on the stellar evolution code STARBURST99 (Leitherer et al. 1999). Feedback is done at the appropriate times, taking into account the lifetime of stars of different masses in a stellar population through the metallicity dependent age-mass relation of Raiteri et al. (1996).

Furthermore, we adopt the SN momentum injection model recently suggested by Kim & Ostriker (2015, see also Martizzi et al. 2015; Gatto et al. 2015; Simpson et al. 2015). Here we consider a SN explosion to be resolved when the cooling radius in gas of density \(\rho > Z\text{, and the Lagrangian region they defined was regenerated at high resolution, still embedded within the full lower-resolution volume, using the MUSIC code (Hahn & Abel 2011). This is the same initial conditions as the “m12i” halo from Hopkins et al. (2014) and Wetzel et al. (2016).\n
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in order to account for enrichment from unresolved population III star formation (e.g. Wise et al. 2012).

By accounting for the above processes, and allowing for star formation to be locally efficient, Agertz & Kravtsov (2015, 2016) demonstrated that feedback regulation resulted in a galaxy corresponding to a realistic late-type galaxy that matches the evolution of basic properties of late-type galaxies such as stellar mass, disc size, the presence of a thin and thick stellar disc, stellar and gas surface density profiles, the Kennicutt-Schmidt relation, the stellar mass-gas metallicity relation (and its evolution), and a specific angular momentum typical of spiral galaxies of the Milky Way mass (stellar mass of \( \sim 5 \times 10^{10} \, M_\odot \)).

The simulation is run until it reaches \( z = 0.5 \) (i.e. a lookback time of about 5 Gyr), i.e. long after the last major merger event which occurs at \( z \approx 2 \) (see Section 3.1). The simulation has been performed on the Carre supercomputer hosted at the Très Grand Centre de Calcul (TGCC).

We identify galaxies using the friend-of-friend algorithm HOP (Eisenstein & Hut 1998) on the stellar component only, with the parameters \( 10^5 \), \( 10^4 \), \( 10^2 \, M_\odot \, \text{kpc}^{-3} \) for the peak, saddle, and outer densities respectively, chosen to agree with a visual examination of stellar density maps. For convenience, hereafter we refer as the Milky Way to the most massive progenitor of the most massive galaxy in our simulated volume at \( z = 0.5 \). We identify the plane of its disc using the total angular momentum vectors of all stars within 10 kpc from its centre of mass, and use the prime notation for quantities projected into the cylindrical coordinate system defined by the plane of the disc and its spin axis. We defined stars formed in situ those which have formed in the most massive progenitor of the Milky Way, and are still in the progenitor of the Galaxy at a given time, thus excluding stars that formed in the Milky Way but have been ejected later on, without being re-accreted. Accreted stars are all other stars in the Milky Way.

The originality of our study consists in combining both the formation and the evolution of star clusters. From the formation point of view, details on the structure of the interstellar medium (ISM) and the propagation of stellar feedback at the scale of molecular cloud are not resolved in our simulation, which thus affects the mass and size of our stellar objects. The mass of our stellar particles (\( \sim 10^5 \, M_\odot \)) forbids the direct identification of star clusters. Not being able to resolve stellar systems less massive then several times this mass resolution, and with the gravitation affected by softening at the resolution of the AMR grid which introduces artefacts on the boundness of aggregates of such particles into “clusters”, we do not seek an identification of star clusters and rather use our stellar particles as tracers of both the conditions and epochs of their formation and of their orbits. Therefore, we refer to them as “star cluster candidates” in the following. Among this group, we further qualify the subset of particles formed before a lookback time of 10 Gyr (\( z \gtrsim 1.8 \)) as “globular cluster candidates”, in line with observational definitions (e.g. Portegies Zwart et al. 2010). From the evolution perspective, our simulation does not capture the internal dynamics of the clusters, which is known to be an important driver of their evolution (Hénon 1961; Gieles et al. 2011). A full coupling of the internal and external physics of star clusters is still out of reach due to technical limitations, but previous works provide an estimate of the gravitational (tidal) effect of a non-regular galactic or cosmological environment on star clusters (e.g. Renaud et al. 2011; Rieder et al. 2013). We adopt this approach by computing the tidal tensor along the orbits of our cluster candidates (See Appendix A for details). The tensors are evaluated as the first order finite differences of the gravitational acceleration on the AMR cell containing the particle, as in Renaud et al. (2014). By doing this at the (local) resolution of the grid (instead of interpolating the acceleration at smaller scales), we ensure that the gravitational information we extract is not strongly affected by the artificial softening of the gravitational acceleration (see also Renaud 2010, Chapter 1 for details). Following all stellar particles to trace their formation, orbit and tidal history would be numerically costly. In particular, the computation of the tidal tensors and its output for all particles at a high frequency (about every Myr) would significantly slow down the simulation. Instead, we defined a subset of about 15,000 stellar particles in the region of the Milky Way progenitor and extract tidal data for the selected subset only. This is done at every coarse timestep, i.e. \( \sim 0.5–5 \, \text{Myr} \). We have checked that the subset is representative of the environment of the Milky Way by ensuring it follows the same distributions in space, age and metallicity.

### 3 RESULTS

#### 3.1 Galaxy and star formation

Fig. 1 shows the morphology of the Milky Way neighbourhood at four epochs along the course of galaxy formation\(^2\). As a complement, Fig. 2 shows the merger tree of the Milky Way, based on the stellar component only. At \( z = 4 \), the intergalactic filaments can still be clearly identified. The main galaxies are found at their intersection (as expected, see e.g. Zeldovich et al. 1982) and are fuelled with gas and smaller galaxies. At \( z \approx 3.5 \), the main two gaseous filaments (almost vertical thin blue structures in the top-left panel of Fig. 1) collide, further fuelling galaxies with gas and producing shocks that trigger an episode of star formation. At \( z \approx 2 \), our Milky Way experiences its last major merger (i.e. with a mass ratio higher than 1:10), but is still surrounded by numbers of small satellites. The starbursts and stirring of the ISM following (major and minor) mergers allows the injection of metals by stellar feedback and their propagation in the interstellar and intergalactic media. At \( z = 1 \), most of the growth of the Milky Way is done, but several small satellites remain in the vicinity of the Galaxy. Most of them are accreted before \( z = 0.5 \). At \( z = 0.5 \) (which corresponds to the end of our simulation), the simulated Milky Way has a stellar mass of \( 4.1 \times 10^{10} \, M_\odot \).

Fig. 3 displays the star formation history (SFH) of the Milky Way and tells apart the in situ and accreted populations\(^3\). The SFH starts by being dominated by the accreted population, indicating that the Milky Way progenitor assemblies mostly through the merging of smaller galaxies. Until \( z \approx 2 \), maxima in the stellar accretion rate (corresponding to the discrete events of major mergers) are of the same order as the SFR, i.e. \( \approx 1–3 \, M_\odot \, \text{yr}^{-1} \). At later

\(^2\) Movies are available at [http://personal.ph.surrey.ac.uk/~fr0005/movies.php](http://personal.ph.surrey.ac.uk/~fr0005/movies.php)

\(^3\) The jump in star formation rate (SFR) at \( z \approx 1.5 \) originates from the activation of an additional refinement level: refinement is artificially blocked when the gas mass in the AMR cells is too low compared to the mass of the stellar particle. This happens at high redshift and is suddenly deactivated, as already noted by Agertz et al. (2011). In reality (and at higher resolution), this jump would be replaced by a slower increase of the SFR, starting at higher redshift and reaching the maximum value at the epoch of the jump we detect. The SFR and other quantities presented in this paper are thus altered by this artefact but only a few 100 Myr before the jump, which does not affect our conclusions.
stages, the accretion rate peaks at comparable values, which indicates that the satellite galaxies merging with the Milky Way remain of comparable mass throughout the evolution. However, because the Milky Way itself keeps growing from accretion and in situ star formation, the late mergers become minor and have less influence on the mass budget and dynamics of the main galaxy. We note that, according to our definition of formation before a lookback time of 10 Gyr, globular cluster candidates form during this merger-dominated phase, in contrast with the more quiet period of secular evolution taking place after. The SFR reaches its maximum

Figure 1. Morphology of simulated neighbourhood of the Milky Way at four epochs, showing the gas density (blue), dark matter (red), stars (yellow) and iron density (green).

Figure 2. Stellar merger tree of Milky Way. Dots mark the earliest detection of a stellar clump. Colours and line widths indicate the stellar mass of the galaxy. Triangles mark major mergers, i.e. mergers with a mass ratio greater than 1:10. The tree is computed at the output frequency of the simulation, i.e. \( \approx 150 \) Myr.
between $z = 1$ and 2, in line with observational data of galaxies in the mass range of the Milky Way (e.g. Lettner 2012; van Dokkum et al. 2013).

Fig. 4 shows the evolution of the stellar mass, compared to the model of Behroozi et al. (2013)\(^4\). Except at very high redshift ($z \gtrsim 4 – 5$) when it is sensitive to the (poorly constrained) merger history, the build up of the simulated galaxy corresponds well to the model data.

The bottom panel of the Fig. 4 displays the fraction of stars formed in situ. Rapid drops in this fraction denote a “dilution” of the in situ stars following the accretion of an external galaxy by the Milky Way, while its slow increase indicates the secular conversion of gas into stars inside the galaxy. We note that, as expected from the merger tree (Fig. 2), rapid changes associated with major mergers dominate the evolution before $z \approx 2$, while a more regular behaviour is found later, in line with the SFH of the two sub-populations (Fig. 3). At $z = 0.5$, 95\% of the stars in the Milky Way have formed in situ, which is compatible with the model of Behroozi et al. (2013). This is however higher than the value of 75\% (at $z = 0$) found in the “Eris” simulation (Guedes et al. 2011) by Pillepich et al. (2015), likely because of their intense ex situ SFR, and not because of the galactic interaction history which is qualitatively comparable to that of our model (see their figure 3).

Fig. 5 displays the evolution of the stellar density profile of the galaxy. Incoming galaxies are visible as oblique patterns in the outer regions (highlighted by the contours), and redistribution of the mass in the inner regions during the major merger events ($z \gtrsim 2$). The main growth phase by accretion ends at $z \approx 2$. Later the stellar component gets denser (i.e. more massive but not more extended) because of in situ star formation. This figure suggests the formation of the disc at $z \approx 1.2 – 1.5$.

In short, the formation history, merger tree and build-up of our Milky Way are in-line with literature on the formation of the Milky Way (1.3 $\times$ 10$^{12}$ $\odot$ and 6.4 $\times$ 10$^{10}$ $\odot$, McMillan 2011).

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\(^4\) scaled for a stellar mass of 4.9 $\times$ 10$^{10}$ $\odot$ and a halo mass of 10$^{12}$ $\odot$ at $z = 0$, which corresponds to the same stellar mass to halo mass as that of the Milky Way (1.3 $\times$ 10$^{12}$ $\odot$ and 6.4 $\times$ 10$^{10}$ $\odot$, McMillan 2011).
Galaxy (see e.g. Freeman & Bland-Hawthorn 2002, and references therein). In particular, the absence of major mergers after $z \approx 2$ agrees with predictions from the observed structures of the disc(s) and the lack of tidal signatures in the real Galaxy (Wyse 2001; Brodie & Strader 2006).

### 3.2 Stellar distributions, metallicities and kinematics

Figs. 6 and 7 show distributions of the stellar populations of the Milky Way at the end of the simulation. The in situ population is more centrally concentrated and vertically thinner than the accreted one. The accreted population dominates the mass profile beyond $\approx 17$ kpc in the plane of the disc and $\approx 7$ kpc above. We note that the density profiles are the same for the entire accreted population and for its oldest component only (globular cluster candidates) indicating that early accretion combined with long evolution inside the Milky Way cannot be distinguished from late accretion. This is confirmed by the remarkably flat radial profile of the age of the accreted stars. The globular cluster candidates formed in situ yield comparable distributions than the accreted ones in the inner galaxy ($\leq 10$ kpc), but their fraction drops in the outer parts, making their overall population more centrally (radially and vertically) concentrated than the accreted one.

Star formation being active in the densest regions of the galaxy, the youngest in situ population is mostly found in the central part of the Milky Way. This age gradient is associated with a metallicity gradient of the in situ population, while the accreted one yields very little variation with galactic radius. A comparable behaviour is seen in the vertical profiles (not shown). In the innermost $10$ kpc of the simulated galaxy, the metallicity gradient of the Milky Way is $\approx -0.06$ dex/kpc, in good agreement with observational data ($\approx -0.05$ dex/kpc, Kewley et al. 2010). In the simulation, the two sub-populations are clearly separated: clusters (globulars and all) formed in situ are more metal-rich and younger than the accreted ones, at all radii in the galaxy. We note that the populations of globular cluster candidates do not yield strong metallicity gradients. However, due to their different spatial distributions, the transition from in situ-dominated in the inner regions to accreted-dominated in the outer areas makes the whole globular population (black solid line in Fig. 6) yielding a net metallicity gradient between $\approx 1$ and $20$ kpc. This qualitatively agrees with the findings of a decreasing [Fe/H] with radial distance in the inner halo and the absence of a [Fe/H] gradient in the outer halo by Searle & Zinn (1978). The latter formed a crucial ingredient in their idea on how the Milky Way (halo) grows via (hierarchical) accretion and our model confirms that all globular cluster candidates beyond $\approx 30$ kpc are indeed accreted and have similar (average) [Fe/H].

Details on the intensity of this gradient and its radial position depend on how our cluster candidates are representative of real clusters, which is the main uncertainty of our study (see below).

The top panel of Fig. 8 shows the distributions of metallicities for the globular cluster candidates (i.e. older than 10 Gyr at $z = 0$). The average values of $[\text{Fe/H}] = -0.8$ and $-1.2$ for the in situ and accreted populations of globular cluster candidates respectively are close to the values of $-0.5$ and $-1.5$ observed for the metal-rich and metal-poor globulars in the real Milky Way (Harris 1996). The Galaxy counts twice more metal-poor ($[\text{Fe/H}] < -1$) globular clusters than metal-rich ones (Harris 1996), while in our simulation this ratio is only 0.6. The differences are discussed below.

We note that the simulation produces an overall too large number of cluster candidates, but recall that our “clusters” are mere stellar particles and that we do not take any cluster evolution processes into account in this study. First, the most massive clusters are likely made of many of our $\sim 10^4 \, M_\odot$ particles, which would thus significantly reduce the number of clusters. Properly inferring the binding energy and thus membership of star clusters would require an unbiased (i.e. non-softened) treatment of gravity at the sub-parsec scale, as shown in Renaud et al. (2015). Second, it has been suggested that cluster formation is more efficient in low-metallicity...
environments than in enriched media (Peebles 1984; Fall & Rees 1985; Bromm & Clarke 2002; Kimm et al. 2016). In this case, the initial cluster mass function would be different for the accreted (i.e. mostly formed in low-metallicity dwarfs) and in situ clusters, making the former more resistant to external disruptions like tides, which could lower the over-abundance of metal-rich objects in our simulation. In addition, we note that at the spacial and mass resolutions of our simulation, we likely underestimate the number of accreted clusters with respect to those form in situ. Furthermore, the stronger tidal field experienced by in situ candidates with respect to the accreted ones (see next Section) could lead to their preferential disruption or even the dissolution of the fragile, low-density end of their distribution, once these aspects would be accounted for.

The bottom panel of Fig. 8 indicates the locii of our globular cluster candidates in the age-metallicity plane. Despite clusters lying on a rather continuous distribution, we note a clear difference of slope between the two ends of the metallicity distribution, making two branches in this diagram. By fitting them by eye, we find that the most metal-rich cluster candidates (with 74 per cent of those with lower metallicities (mainly the accreted clusters) present a much more shallow relation: age $\propto -1.4$ Gyr/dex [Fe/H].

The transition between the two branches originates from the ability of galaxies to produce and retain enriched material. The Milky Way being the most massive member of its “local group” already at high redshift ($z \approx 5 – 6$, see Fig. 2), its escape velocity rapidly becomes higher than that of its satellites, which participates in retaining ejecta from feedback, while dwarf galaxies (which have a lower SFR and thus a slower metal enrichment) rather launch outflows and do not efficiently retain metal-enriched medium. Indeed, effective yields of dwarf galaxies are observed to be much lower than that of higher mass galaxies (Tremonti et al. 2004), indicating efficient removal of metals in outflows. This translates in the age-metallicity diagram as follows.

In the young and low-mass Milky Way, early in situ formation produces a few, relatively metal-poor, objects ([Fe/H] $< -1$, see Forbes et al. 2011 in the context of elliptical galaxies). Rapidly, the galaxy becomes massive enough to produce and retain metals, and it evolves along the shallow branch toward higher metallicities. Then, at an increased SFR, most of the in situ formation proceeds along the steep branch, i.e. at almost constant metallicity. Furthermore, the accretion of low-mass (pristine) galaxies brings metal-poor clusters to the Milky Way. The galaxy population is thus the sum of the in situ group which are mostly metal-rich, and these accreted metal poor clusters, hence making a bimodal distribution. Finally, any galaxy with a mass similar to that of the Milky Way
is likely to share a comparable evolution, and thus to yield its own bimodality. Therefore, when such a galaxy merges with the Milky Way, it brings a bimodal accreted population (thus sharing properties with the “young halo” cluster population discussed by Mackey & van den Bergh 2005). In the merger history of our Milky Way, such an event occurs at the last major merger, at $z \approx 2$ (recall Fig. 2).

In short, in agreement with the semi-analytic model of Tonini (2013), our work suggests that metal-poor clusters form in low-mass, metal-poor galaxies, while the metal-rich ones originate from massive galaxies able to self-enrich their ISM, i.e. mainly the Milky Way and its most massive progenitor galaxies. A merger of two massive enough galaxies (thus typically at late epochs) induces a mixing of accreted and in situ clusters in the high-metallicity mode. Combining the observed distributions of metallicities to that of other tracers of the in situ and accreted populations like the space distribution (see above) could bring constraints on the merger history of the Galaxy.

As noted above, our derived metallicities are slightly off compared to the observational data of Milky Way globular clusters: on average, our metal-poor population is too metallic and our metal-rich one is too metal poor. In addition, our simulation underestimates the relative number of very low metallicity objects ([Fe/H] $\leq -1.6$) compared to the real Milky Way. These discrepancies are likely due to the uncertainties in simulating the assembly of the galaxy, especially at these high redshifts, the imperfections in our modelling of the enrichment at our working resolution (star formation and feedback recipes), the unresolved initial enrichment by population III stars (recall Section 2), and the lack of evolution mechanism for our cluster candidates. Furthermore, the resolution of the simulation does not allow us to capture the formation of low-mass dwarf galaxies, which would contribute to the lowest end of the metallicity distribution. However, we notice comparable trends between our age-metallicity relation (Fig. 8) and that observed by Leaman et al. (2013, see their Fig. 2). In particular, in the age range we probe, we note a similar slope for our accreted clusters and their halo clusters. Furthermore, there is a remarkable steepening of this relation for Leaman et al.’s disc clusters (at about an age of 12.5 Gyr and [Fe/H] $\approx -1.3$), which could corresponds to the knee in our distribution of in situ cluster candidates (at an age of $\approx 11.5$ Gyr and [Fe/H] $\approx -0.8$). Although the position of the clusters and the features in their distributions are sensibly different in our simulation and in reality, the fact that global trends are retrieved indicates the likelihood of the formation scenario we describe, in particular the fact that the bimodality is already in place at $z = 2$ (see also Dotter et al. 2011, their Figure 10).

Finally, Fig. 9 highlights the kinematic differences between the in situ and accreted components. Accreted stars retain signatures of their pre-accretion orbital motions for several Gyr. As noted by the small rotation velocity, the weak alignment with the galactic spin, and the large dispersion of these quantities, these motions are preferentially radial, unlikely to be aligned with the spin of the Milky Way and rather isotropic. Only subtle differences are found between the young and older components (globular clusters) in the outer parts of the galaxy ($R_{2D} \gtrsim 10$ kpc), where the earliest epoch is likely to share a comparable evolution, and thus to yield its own bimodality. Therefore, when such a galaxy merges with the Milky Way, it brings a bimodal accreted population (thus sharing properties with the “young halo” cluster population discussed by Mackey & van den Bergh 2005). In the merger history of our Milky Way, such an event occurs at the last major merger, at $z \approx 2$ (recall Fig. 2).

In short, in agreement with the semi-analytic model of Tonini (2013), our work suggests that metal-poor clusters form in low-mass, metal-poor galaxies, while the metal-rich ones originate from massive galaxies able to self-enrich their ISM, i.e. mainly the Milky Way and its most massive progenitor galaxies. A merger of two massive enough galaxies (thus typically at late epochs) induces a mixing of accreted and in situ clusters in the high-metallicity mode. Combining the observed distributions of metallicities to that of other tracers of the in situ and accreted populations like the space distribution (see above) could bring constraints on the merger history of the Galaxy.

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Stars formed in situ have a faster rotation and a spin better aligned with that of the galaxy than the accreted ones. Since the galactic disc is not in place at very high redshift (and is very turbulent and thick in the earliest phases of its evolution), the population of globular clusters formed in situ has kinematic properties closer to that of the accreted globulics than the stars formed more recently in the disc. They however rotate slightly faster and closer to the (final) plane of the disc than the accreted population, especially $\gtrsim 5$ kpc from the galactic centre, probably indicating an early influence of the organised dynamics of the galaxy.

### 3.3 Tidal histories

For the volumes considered here, probing the internal physics of the star clusters, or even details of their formation, is still out of reach: the space and time resolutions are not sufficient, and codes treating galaxy evolution lack the physics of clusters like detailed stellar evolution and treatment of the multiple stars. However, by considering our particles as tracers, we can explore the history of the tidal field experienced by our clusters candidates along their orbits. In a forthcoming study, we will complement this analysis with a description of individual clusters and populations of clusters to actually infer their evolution in the environments we consider here.
Evolution of the instantaneous maximum tidal eigenvalue $\lambda_1$, averaged over members of the sub-populations of particles formed in situ and those being accreted (dotted lines), and only globular clusters (solid lines). This quantity is normalised to $\bar{\lambda}_\odot$, which represents a rough proxy of the intensity of the present-day tidal field at the position of the Sun (see text). All curves have been smoothed using a non-parametric local regression method (LOWESS), for the sake of clarity. Shaded areas around the curves represent 0.1 times the standard deviation (non-smoothed). Shaded vertical stripes correspond to the epochs discussed in the text.

The formalism and quantities used below are defined in Appendix A, where we present a brief reminder about tides. We base our analysis on tidal tensors and their ordered eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3$. For convenience, we normalise the strength of the tidal tensor of a point of which mass is that enclosed within the orbit of the Sun (considered circular), and evaluated at the position of the Sun in the real Galaxy. We use the approximate values for the Local Standard of Rest of $r_\odot = 8$ kpc and $v_\odot = 220$ km s$^{-1}$, which leads us to

$$\bar{\lambda}_\odot \equiv \frac{2GM(<r_\odot)}{r_\odot^3} = \frac{2v_\odot^3}{r_\odot^2} \approx 1600 \text{ Gyr}^{-2}. \quad (1)$$

Fig. 10 shows the evolution of the average strength of the tidal field experienced by cluster candidates in our simulation. Reasons for this evolution can be roughly estimated by analysing the average radius $\langle r \rangle$ of the clusters in the Milky Way, the total mass enclosed in this radius $\langle M(< r) \rangle$, and the enclosed density $\rho(< r)$ in $3M(<r)/(4\pi r^3)$, as plotted in Fig. 11. (Recall that the tidal field generated by a point-mass galaxy of mass $M$ at a distance $r$ would lead to $\lambda_1 = 2GM/r^3$. See Appendix A for details.) In addition, Fig. 11 displays the evolution of the specific total angular momentum, computed as the sum of angular momenta for all the stellar particles in the Milky Way divided by the stellar mass of the galaxy, as in Agerzt & Kravtsov (2016).

For simplicity, we focus here on the candidate clusters formed in situ. We identify 5 epochs in the evolution:

(i) At high redshift ($z \gtrsim 5, \gtrsim 12.4$ Gyr), the immediate environment of the Milky Way consists of tens of galaxies within a few 10 kpc. The superposition of their gravitational potentials (mainly that of their dark matter halos) generates cores spanning several kpc, like those noted during galaxy mergers by Renaud et al. (2009). This topology corresponds to compressive tides which favour star formation (Renaud et al. 2014). As the Universe expands and the immediate satellites of the Milky Way get accreted, the number density of galaxies decreases, the Milky Way dominates the gravitational potential, the above-mentioned inter-galactic cores tend to disappear and the tidal fields becomes mostly extensive.

(ii) During the next $\approx 2$ Gyr ($2 \lesssim z \lesssim 5$, between $\approx 10.4$ and $12.4$ Gyr), the growth of the Milky Way is dominated by discrete but repeated major mergers. The mass of the galaxy rapidly increases, and the transfer of angular momentum leads to a growth in size: both $\langle r \rangle$ and $\langle M(< r) \rangle$ increase, resulting in a roughly constant average tidal field strength.

(iii) Later ($1.2 \lesssim z \lesssim 2$, between $\approx 8.5$ and $10.4$ Gyr), the SFR reaches its maximum value (Fig. 3), with star formation taking place preferentially in the central (dense) regions of the galaxy. The contribution of these newly formed stars reduces the average radius of the ensemble of in situ stars, while $\langle M(< r) \rangle$ varies little as the result of disc growth (visible as the steady increase of specific total angular momentum, see also Fig. 5). As a result, the average tidal field strength starts to increase.

(iv) At $z \approx 1.2$ ($\approx 8.5$ Gyr), as the disc continues to grow and form stars, the enclosed mass increases while the radius keeps on decreasing. This combine effects translates in the acceleration of the strengthening of tides.

(v) At $z \approx 0.6$ ($\approx 5.4$ Gyr), the decrease in SFR (recall Fig. 3).
imply that the evolution of both \( \langle r \rangle \) and \( \langle M(<r) \rangle \) slows down. Most of the building up of the Milky Way is done and thus the tidal field is roughly constant. We assume that it would remain constant between the end of the simulated period and the present-day. Local variations might occur in the case of formation of strong substructures like bar(s) and spirals, but we expect the tidal field to remain roughly unchanged when averaged over the entire galaxy.

A similar evolution is expected for the accreted clusters, but only after their accretion. Since this sub-population is made of cluster candidates accreted at different epochs (Fig. 3), their average tidal history encompasses both that of the Milky Way as described above (which dominates the statistics of accreted population after the end of the major merger epoch), and that of the satellites galaxies where the clusters formed.

Between the initial phase and the steady increase (1.2 \( \lesssim z \lesssim 5 \)), the average tidal field of the in situ cluster candidates is comparable to that of the accreted population. This indicates that, before their accretion, clusters experience similar tides whatever their host is. At later times, in situ clusters (all and globular only) become more centrally concentrated in the massive Milky Way, which significantly increases the strength of the tides they experience with respect to their accreted counterparts.

To further characterise the nature of the tidal field experienced by the cluster candidates, Fig. 12 shows the ratio of the minor eigenvalues to the main one \( \lambda_1 \). In the non-spherically symmetric configurations we consider, it is not possible to tell apart the physical meaning of \( \lambda_3 \) from that of \( \lambda_1 \), and thus we rather consider the average of the two \( \lambda_{2,3} = (\lambda_2 + \lambda_3)/2 \). Therefore, keeping in mind that the eigenvalues are sorted in descending order, the quantity \( \Lambda \equiv \lambda_{2,3}/\lambda_1 \) can be:

- greater than unity (i.e. \( 0 > \lambda_1 > \lambda_{2,3} \)), in the case of compressive tides,
- between 0 and 1 (i.e. \( \lambda_1 > \lambda_{2,3} > 0 \)), in rare occasions \(^7\).

\(^7\) Because of Poisson’s law, it is impossible that all three eigenvalues are

Figure 12. Ratio of the average of the minor two eigenvalues of the tidal tensor \( \lambda_2 \) from \( \lambda_3 \) to the main one \( \lambda_1 \). Horizontal lines indicates the limits of the tidal regimes (see text for details and interpretation). Shades stripes corresponds to the evolution epochs identified in Fig. 10.

\[ \Lambda = (\lambda_2 + \lambda_3)/(2\lambda_1) \]

Most of the building up of the Milky Way is done and thus the tidal field is roughly constant. We assume that it would remain constant between the end of the simulated period and the present-day. Local variations might occur in the case of formation of strong substructures like bar(s) and spirals, but we expect the tidal field to remain roughly unchanged when averaged over the entire galaxy.

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Figure 13. Average maximum tidal eigenvalue \( \lambda_1 \) (normalised to \( \lambda_{10} \), see text) experienced by stars since their birth, i.e. at a given time \( t \), the quantity \( \langle \lambda(t) \rangle \) is the average \( \lambda_1 \) between the star formation epoch and time \( t \).

- between -1 and 0 (i.e. \( \lambda_1 > 0 > \lambda_{2,3} \) and \( \lambda_1 > -\lambda_{2,3} \)), which is the classical case for non-fully compressive tides,
- smaller than -1 (i.e. \( \lambda_1 > 0 > \lambda_{2,3} \) and \( \lambda_1 < -\lambda_{2,3} \)), which also represent non-fully compressive tides, but with the compression along the minor axes being stronger than the extension along the main axis \(^8\).

The textbook example of the tides generated by a point-mass yields \( \Lambda = -1/2 \). Smaller (more negative) values can be reached in shallower density profiles. (See also Appendix A3 for details.)

In the simulation, the early evolution of \( \Lambda \) confirms the compressive nature of tides at the formation phase of the oldest clusters. Quickly, the tidal field jumps to the extensive regime (\( \Lambda < 0 \)). In the major merger dominated phase (\( 2 \lesssim z \lesssim 5 \)), \( \Lambda \) is mostly smaller than -1, which likely indicates complex substructures in the potential, likely merger-induced, inducing strong transversal compression, in a similar fashion as the effect of spiral arms in a disc (as mentioned above). Later (\( 1.2 \lesssim z \lesssim 2 \)), \( \Lambda \) rises between -1 and 0 for the in situ population. This corresponds to rather steep density profiles for the Milky Way, that are replaced by shallower ones at the end of the simulation (\( z \lesssim 1 \)), when \( \Lambda \) becomes smaller than -1, once the disc has formed (recall Fig. 11). For the accreted population, \( \Lambda \) represents a mix of pre- and post-accretion cases and remains close to -1 after the major merger phase.

We note that after \( z \approx 1 \), the tidal field of any population is highly incompatible with that of the point-mass galaxy (\( \Lambda = -1/2 \)), in contrast with the assumption often made in the literature when modelling Galactic tides.

Finally, Fig. 13 shows, at each time \( t \), the value of the average \( \lambda_1 \) between the formation time and current time \( t \). (If, for the purpose of another study, one has to assume a constant tidal field, one should use the final value of this quantity.) The weak tidal field at positive (equation A2). However, \( \lambda_{2,3} \) is positive when only \( \lambda_3 \) is negative and \( \lambda_2 > -\lambda_3 \). This situation is found e.g. in a spiral arm within a disc: the main tidal axis points toward the galactic centre but the field generated by the arm adds to the compression from the galactic monopole along the perpendicular axes, making it potential stronger then the radial extension.
early stages (mainly due to the low galactic mass) drags down the average of globular cluster candidates, while populations formed later experience stronger fields. Note that both the in situ and accreted globular cluster candidates yield an average smaller than the present-day tidal strength for the Sun ($\lambda_\odot$).

Furthermore, the present-day tidal field is stronger than the past average, over any period. For in situ cluster candidates, the present-day average tidal field is $\approx 6.3\lambda_\odot$ (Fig. 10), while its time-average value ($\approx 1.9\lambda_\odot$, over the simulated period) is 3.3 times smaller (Fig. 13). This ratio jumps to 6.5 for the accreted population. When considering globular cluster candidates only, the present-day values are about 6.8 times stronger than the time-average, for both the in situ and accreted groups, making the present-day value even less representative of the average tides for the globulars than for all clusters candidates. In other words, using the present-day tidal field to model the evolution of clusters over several Gyr, as it is often done, strongly over-estimates the effects of the environment, which significantly affect the conclusions on e.g. cluster mass-loss. When modelling the tidal environment of clusters with a constant field, adopting time-averaged values like those in Fig. 13 would lead to significantly more accurate estimates, as those obtained by the majority of studies. We however argue that a time-dependent environment, with tides varying with time as the cluster itself evolves might lead to yet different and more precise results.

Using a disruption rate based on the present-day tidal field of the Milky Way, studies argue that the observed peaked cluster mass function could not originate from an initial power-law with index -2 as that observed for young massive clusters (e.g. Baumgardt 1998; Vesperini 2001; Gieles & Baumgardt 2008; Portegies Zwart et al. 2010). The strong assumption of time-independent galactic tides makes several author question the validity of this claim, arguing that tides could have a stronger impact on clusters in the earlier Universe (Fall & Zhang 2001; McLaughlin & Fall 2008; Kravtsov & Gnedin 2005; Muratov & Gnedin 2010). Our results show however that the average tidal field is significantly weaker in the past than at present-day for all cluster populations, and thus that a sole tidal effect cannot explain a depletion of the low-mass end of the cluster mass function and thus a transition from an initial power-law cluster mass function into a peaked one (see also Renaud & Gieles 2015b). Other mechanisms like the early disruption via encounters with gas clouds might participate in such evolution under extreme conditions (e.g. in gas-rich and clumpy galaxies, see Elmegreen 2010; Kruijssen 2015, but see also Gieles & Renaud 2016). We will explore this point in more details in a forthcoming paper.

4 DISCUSSION AND CONCLUSIONS

We present a cosmological zoom-in simulation of a Milky Way-like galaxy to explore the origins of its star cluster populations. For our study, the most important aspects of the modelled galaxy is the formation of a disc and the absence of major mergers after $z \approx 2$. We characterise the dynamical properties of star cluster populations and their evolution histories. Our main results are as follows.

- The observed bimodality of globular clusters is reproduced in our model. The physical properties of the modelled sub-populations of globular cluster candidates match those of the observed blue and red groups. Blue, metal-poor clusters originate from low-mass galaxies that are accreted onto the Milky Way. The red, metal-rich clusters form in galaxies massive enough to retain their enriched media, i.e. mostly in the Milky Way itself (in situ clusters), but also in high-mass accreted companions (accreted clusters during late major mergers).
- The simultaneous formation of the two sub-populations, with differences between them originating from the more rapid growth of the Milky Way than its satellites, implies that all quantities we measure (e.g. space distribution, age, metallicities, tides) yield rather continuous transitions between the two groups, as opposed to the clear separations induced by distinct formation epochs in other scenarios.
- At high redshift ($z \geq 5$), the high number density of galaxies implies significant overlaps of their gravitational potential wells, making tidally compressive regions over several kpc, in a comparable way as in present-day interacting galaxies. This could affect the star (cluster) formation efficiency.
- The average tidal field of star cluster candidates remains relatively weak during the early galactic growth phase dominated by major mergers ($z \leq 2$). It strengthens later during the secular build-up through centrally concentrated star formation.
- The tidal field experienced by accreted clusters is almost always weaker than that of clusters formed in situ. This is due to their early life in a low-mass (satellite) galaxy and their evolution at large galacto-centric radii (on average) following their accretion onto the Milky Way. Accreted clusters experience tides about four times weaker than those formed in situ (on average over their lifetime).
- Due to galaxy growth, present-day tidal effects are significantly stronger than their average, over any period in the past, except during the very early phase of galaxy formation when tides are strongly compressive due to the high concentration of galaxies and the overlap of their dark matter halos.
- Therefore, using the present-day tidal field of the Milky Way to study the dynamical evolution of its star clusters leads to strong over-estimates of their disruption and dissolution rates.

These conclusions correspond to the formation history of the galaxy modelled here, but would certainly change when considering other cases. In particular, different merger histories including major mergers at low redshift ($z \lesssim 2$) would significantly alter the distributions of in situ and accreted stars and the relative weight of these sub-populations, as proposed by e.g. Li & Gnedin (2014). For instance, a recent major merger would possibly trigger a starburst activity during which hydrodynamical shocks and compression would lead to the formation of young massive clusters like those observed in the Antennae galaxies (see e.g. Whitmore & Schweizer 1995; Mengel et al. 2005; Bastian et al. 2009; Herrera et al. 2011, and Barnes 2004; Renaud et al. 2014, 2015). The merger remnant would then form a massive elliptical galaxy. (Reforming a disc is possible but would take several Gyr, see e.g. Athanassoula et al. 2016.) The pre-existing clusters are likely to survive the merger event, as shown in Renaud & Gieles (2013). In this picture, the population of blue globular clusters would form in the progenitor galaxies and would get spatially redistributed by the collision(s). Depending on the orbits and inclinations of the galaxies, a fraction of the pre-existing clusters would be ejected from the remnants (possibly into the tidal debris), and their orbits would span a larger volume after the collision than in the isolated galaxies. On the contrary, metal enriched red clusters would form during the gas-rich merger, in the densest gaseous regions of the merger, and would thus be more centrally concentrated (although starbursting mergers harbour intense star formation activity over several kpc, e.g. Wang et al. 2004). This would lead to a cluster bimodality, as
suggested by Ashman & Zepf (1992), and comparable to the observations of sub-populations in M 87 by Larsen et al. (2001, but see the discussion in Forbes et al. 1997).

However, this would not explain the bimodality in galaxies which do not experience a recent major merger, like the Milky Way. The scenario we present here allows to form the bimodality with a more quiescent merger history, in line with that of the Milky Way, following Côté et al. (1998). It is thus likely that the origins of the globular cluster populations vary from one galaxy to the next, being mainly influenced by the galaxy build-up itself. From the hierarchical galaxy formation perspective, a given galaxy would thus encompass the cluster populations of its progenitors, possibly each bringing their own, pre-existing bimodalities. Dynamical mixing during the merger event could then make difficult the identification of sub-populations. For instance, by extending the scenario we propose, a massive elliptical galaxy with mergers throughout its formation history is likely to harbor a rather continuous distribution of accreted clusters, from metal-poor to metal-rich, on top of its in-situ population. Thus, we expect the metallicity distribution to be at least as wide as that of the Milky Way, but with no clear separation between two modes. Yoon et al. (2006) showed that such an uni-modal metallicity distribution could still translate into a bimodal colour distribution due to the non-linearity of the colour-metallicity relations (as observed by, e.g. Usher et al. 2012).

The fully compressive nature of the tidal field over large volume at high redshift suggests to draw a parallel between this epoch and the present-day interacting galaxies, where tides become compressive during encounters (Renaud et al. 2009). As noted above, in addition to stopping the destructive effect of classical tides, this mode promotes enhanced star formation, in particular in the form of young massive clusters and is thought of triggering a significant fraction of starburst activity in close galactic pairs (Renaud et al. 2014, 2015). Our simulation lacks the resolution to probe the propagation of this tidal effect down to the scale of star forming clouds (∼1–10 pc) in the early Universe, but we can speculate that such mechanism does participate in the assembly and collapse of such clouds leading to the formation of massive stellar objects. In that respect, and up to differences due to the extremely low metallicities at high redshift (Fall & Rees 1985; Kimm et al. 2016), young massive clusters and globular clusters would share similar formation triggers. We note however that their respective evolutions due to early disruption by giant molecular clouds and secular tides would likely differ, implying that currently young massive clusters observed in a few Gyr from now would probably not resemble present-day globulars.

When averaged over the sub-populations, the tidal field experienced by our accreted cluster candidates is significantly weaker than that of the in situ group, partly because of the larger average galactocentric radius of the former. In addition, at a given galactocentric radius in the Milky Way, the time-average tides are also weaker for an accreted cluster, due to its formation in a low mass galaxy. Along those lines, it has been proposed that accretion onto the Milky Way could explain the observed extended size of accreted globulars, compared to those formed in situ (Mackey & Gilmore 2004). This question has been investigated using N-body star-by-star simulations of clusters accounting for both the internal evolution and a time-dependent tidal field mimicking the accretion onto the Milky Way. Theses studies show that clusters rapidly adjust to their new tidal environment once they are accreted onto the Milky Way, such that no distinction between the in situ and accreted population could be made based on their size only (Bianchini et al. 2015; Miholics et al. 2016). Therefore, the observed larger size of accreted objects is more likely a signature of their formation and/or early evolution, rather than a result of their accretion event itself (Elmegreen 2008).

Because of resolution limitations, this work misses a detailed description of the properties of the clusters at the epoch of their formation. Modelling the mass and size of star clusters implies a proper treatment of turbulence and cooling mechanisms within their formation sites, which requires at least parsec resolution. (See the non-convergence of star formation rates when the turbulence cascade is not resolved at least up to the supersonic scale, as illustrated in Fig. 1 of Renaud et al. 2014. See also Teyssier et al. 2010). Such resolutions are now commonly reached in galaxies simulations neglecting the cosmological context, and start to be in range of full cosmological setup, as demonstrated by Li et al. (2016, which is however limited to high redshifts).

Furthermore, all the clusters we consider are mere candidates since we do not model their mass-loss and potential dissolution. Our results are thus biased towards over-estimating the contribution of clusters that would get disrupted early, like low-density clusters and those in strong tidal fields. However, it is likely that typical tides would only have moderate effects on the dense, resistant globular clusters. Using the tidal information extracted from this simulation, we will study the response of individual clusters and entire populations to these tidal perturbations in a forthcoming contribution.

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MNRAS (2016)
APPENDIX A: A BRIEF REMINDER ON TIDES, TIDAL TENSORS AND TIDAL RADII

Galactic tides are treated from many different perspectives in the literature, which is causing confusion, especially on the validity range of formulae and the equivalence of various formalisms. Here, we provide a brief reminder.

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we attempt a clarification, starting from the most general formalism offered by tidal tensors.

At any given point in space and time, the tidal field can be fully and exactly described by the tidal tensor, which is minus the Hessian matrix of the gravitational potential \( \phi \). Its component for the \( i \)-th and \( j \)-th space coordinates reads

\[
T^{ij} = -\frac{\partial^2 \phi}{\partial x_i \partial x_j}.
\]  

(A1)

A1 Eigenvalues of the tidal tensor

It is often convenient to write a tidal tensor in its diagonal form, where the three eigenvalues \( \lambda_1 \geq \lambda_2 \geq \lambda_3 \) represent the intensity of the tidal field along the corresponding eigenvectors\(^9\).

In spherically symmetric potentials, the eigenvector associated with the maximum eigenvalue points toward the centre of potential, and the other two eigenvalues are strictly equal. In a classical situation like tides generated by a point-mass (e.g. the Moon on the Earth), the maximum eigenvalue is positive and the other two are negative. These additional terms would then represent the acceleration of the eigenbase in an inertial reference frame.

It is useful to note that the trace of the tidal tensor, i.e. the sum of its eigenvalues, is minus the Laplacian of the gravitational potential and thus, from Poisson’s law, one has

\[
\text{Tr}(T) = -\left( \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} \right) = -\nabla^2 \phi = -4\pi G \rho \leq 0
\]  

(A2)

where \( \rho \) is the local density. Therefore, it is impossible to have three strictly positive eigenvalues.

Negative eigenvalues represent tidal compression along the corresponding axis. When all eigenvalues are negative (i.e. the tensor is negative definite), the potential is convex (or cored) and the tidal field is fully compressive (see e.g. Renaud et al. 2008, 2009).

A2 Inertial reference frame and tidal radius

For a star cluster of mass \( m \) embedded in a tidal field, the inertial tidal radius is

\[
r_{t,\text{in}} = \left( \frac{Gm}{\lambda_3} \right)^{1/3}.
\]  

(A3)

(Note that obtaining this expression, and all the following, requires to linearise the tidal field at the position of the cluster, and to assume the potential of the cluster itself can be considered as that of a point-mass at the distance \( r_t \) from its centre.) Using this definition for a cluster at a distance \( R \) from a point-mass galaxy of mass \( M \), one gets

\[
r_{t,\text{point}} = R \left( \frac{m}{3M} \right)^{1/3},
\]  

(A4)

as in e.g. von Hoerner (1957, his equation 33, see also Spitzer 1987).

The tidal radius is however often written as

\[
r_{t,\text{e}} = \left( \frac{Gm}{\Omega^2 - \frac{\varpi^2}{\varpi_0}} \right)^{1/3},
\]  

(A5)

using the angular velocity \( \Omega \) (King 1962), which implies that the expression for a point-mass potential is

\[
r_{t,\text{e, point}} = R \left( \frac{m}{3M} \right)^{1/3} = R \left( \frac{Gm}{3M^2} \right)^{1/3},
\]  

(A6)

which is different from equation (A4) by a factor \((2/3)^{1/3} \approx 0.87\).

The difference between the equations (A3) and (A5) is that no assumption is made on the cluster orbit in the former case (which thus does not include non-inertial terms), while the latter is a specific case including the centrifugal force along a circular orbit. This centrifugal effect is represented by the \( \Omega^2 \) term in equation (A5). This can also be expressed in term of eigenvalues of the inertial tidal tensor by noting that, for any circular orbit in a spherically symmetric potential, \( \Omega^2 = -\lambda_2 = -\lambda_3 \). Thus, equation (A5) is strictly equivalent to

\[
r_{t,\text{e}} = \left( \frac{Gm}{\lambda_1 - \lambda_2} \right)^{1/3}.
\]  

(A7)

Note that \( \lambda_1 - \lambda_2 \) is called the effective eigenvalue, noted \( \lambda_{e,1} \) in Renaud et al. (2011) for circular orbits in spherically symmetric potentials only.

In other words, equation (A3) represents the tidal radius in an inertial reference frame, while equations (A5) and (A7) correspond to a frame co-rotating with the cluster, along a circular orbit. (Because of the complexity introduced by Coriolis terms, there is no analytical expression for an effective tidal radius along an elliptical orbit, but see an approach based on perturbation theory by Bar-Or et al., in preparation, and its numerical counterpart in Cai et al. 2016, following Baumgardt & Makino 2003.)

Since both expressions for the tidal radius are valid for clusters on circular orbits, which should be considered when studying, e.g., the mass-loss of clusters in a tidal field? None. In such problem, the orbital motion of individual stars in the cluster should be considered. For instance, prograde orbits (i.e. the angular momentum of the star within the cluster is aligned with the angular momentum of the cluster in the galaxy) yield a stronger effective centrifugal effect, which allows stars on these orbits to escape the cluster with a lower energy than those on retrograde orbits (see e.g. Read et al. 2006; Tiongco et al. 2016). In other words defining a global tidal radius (or equivalently, an escape energy level) for the cluster cannot correctly describe the actual escape of cluster members. The tidal radius (or the tidal energy at the Lagrange point \( L_1 \)) is a global quantity defined by considering the cluster as a single object. Thus, it cannot be used to assess the properties of some constituents of this object, like the escape rate. Such shortcut is one of the reasons for the existence of potential escapers (i.e. stars with an energy above that of the Lagrange point \( L_1 \), but still within the Jacobi surface for several orbits, see Hénon 1969; Fujikoshi & Heggie 2000; Baumgardt 2001, Claydon et al., submitted).

A3 Anisotropy of the tidal field

Because the three eigenvalues can never be all strictly positive (equation A2), an isotropic tidal field can only be found in fully compressive tides (\( \lambda_1 = \lambda_2 = \lambda_3 < 0 \)), or a tide-free environment (\( \lambda_1 = \lambda_2 = \lambda_3 = 0 \)). In all other cases, the ratios of eigenvalues

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Figure A1. Ratio $\Lambda = (\lambda_2 + \lambda_3)/(2\lambda_1)$ for several analytical density profiles. The radius is normalised to the scale-radius of the profile (see Appendix B of Renaud 2010, for details). Vertical dotted lines are the asymptotes marking the transition from compressive to extensive regime for the Plummer and logarithmic profiles. The shaded area indicates the “forbidden” regime, corresponding to negative densities.

Define the anisotropy of the tidal field, which can be pictured using the flattening of the Jacobi surface (see e.g. Renaud et al. 2011, their Figure 1 and equation 14).

Fig. A1 shows the ratio $\Lambda = (\lambda_2 + \lambda_3)/(2\lambda_1)$ derived analytically for some classical density profiles (which is exactly $= \lambda_2/\lambda_1 = \lambda_3/\lambda_1$ for these spherically symmetric profiles). For a given $\lambda_1$, different $\Lambda$’s would have different effects on the object embedded in the tidal field.

For instance, Tanikawa & Fukushige (2010) show that, for star clusters orbiting in a power-law density profile and for a given tidal radius, the shallower the profile, the slower the mass-loss. In term of eigenvalues, this statement translates into: for a given $\lambda_1$, the smaller $\Lambda$ (i.e. negative with a large absolute value), the slower the mass-loss. Again, this can be pictured using the Jacobi surface. By setting the tidal radius, one fixes the position of the Lagrange point $L_1$. Varying the slope of the density profile (or equivalently the ratio $\Lambda$) produces different flattening of the surface: a shallow density profile (i.e. a small, very negative, $\Lambda$) corresponds to a flattened surface and a smaller aperture around $L_1$ and $L_2$ in the equipotential surface for the stars to escape through (for a given energy above that of $L_1$). This is illustrated in figure 3 of Renaud et al. (2011). Following Fukushige & Heggie (2000), and in the special case of circular orbits, Renaud et al. (2011) estimate the dissolution time of a cluster (their equation 29) to go as

$$t_{\text{diss}} \propto r_{\text{c,e}}^{3/2} \left( 1 - \frac{\lambda_{\text{c,e},3}}{\lambda_{\text{c,e},1}} \right)^{1/8} \propto r_{\text{c,e}}^{3/2} \left( 2 + \frac{1}{\Lambda - 1} \right)^{1/8},$$

(A8)

confirming that shallower galactic profiles induce longer dissolution times (see also Claydon et al., submitted).