Simulating the Spatial Distribution and Kinematics of Globular Clusters within Galaxy Clusters in Illustris

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ABSTRACT
We study the assembly of globular clusters (GCs) in 9 galaxy clusters using the cosmological simulation Illustris. GCs are tagged to individual galaxies at infall time and their tidal removal and distribution within the cluster is followed later self-consistently by the simulation. The method relies on the simple assumption of a single power-law relation between halo mass ($M_{\text{vir}}$) and mass in GCs ($M_{\text{GC}}$) as found in observations. We find that the GCs specific frequency $S_N$ as a function of $V$-band magnitude naturally reproduces the observed “U”-shape, due to the combination of a power law $M_{\text{GC}}-M_{\text{vir}}$ relation and the non-linear $M_*-M_{\text{vir}}$ relation from the simulation. Additional scatter in the $S_N$ values are traced back to galaxies with early infall times due to the evolution in the $M_*-M_{\text{vir}}$ relation with redshift. GCs that have been tidally removed from their galaxies form today the intra-cluster component from which about $\sim 60\%$ were brought in by galaxies that orbit today within the cluster potential. The remaining “orphan” GCs are contributed by satellite galaxies with a wide range of stellar masses that are fully tidally disrupted at $z = 0$. This intra-cluster component is a good dynamical tracer of the dark matter potential providing an estimate of the velocity dispersion of the dark matter with $25\%$ accuracy. As a consequence of the accreted nature of most intra-cluster GCs, their orbits are fairly radial with a predicted orbital anisotropy $\beta \geq 0.5$. However, local tangential motions may appear as a consequence of localized substructure, providing a possible interpretation to the $\beta < 0$ values suggested in observations of M87 or NGC 1407.

Key words: galaxies: clusters: general – galaxies: haloes – galaxies: star clusters: general

1 INTRODUCTION

Galaxy clusters are populated by tens of thousands of globular clusters (GCs) that distribute around galaxies as well as in the intra-cluster space. However, little is known about their assembly history or their connection to the cluster build up within the cosmological framework. GCs are among the densest stellar systems in the Universe, with typical stellar masses in the range $[10^4-10^6 M_\odot]$ and sizes of only a few parsecs (Harris & Racine 1979; Brodie & Strader 2006). Because of their inferred old ages (Vandenberg et al. 1996) clustered distribution around galaxies, they are believed to be surviving probes of the early star formation in the universe.

GCs are, however, more metal poor than the bulk of the stars in their host galaxy. In fact, GCs display a wide range of colors and metallicities suggestive of a separation where the youngest and more metal rich GCs are formed in situ –and perhaps associated to major mergers– while the metal poor component is likely acquired hierarchically via the accretion of smaller galaxies (e.g., Harris 1991; Ashman & Zepf 1992; Zepf & Ashman 1993; Côté et al. 1998; Kissler-Patig et al. 1998; Gebhardt & Kissler-Patig 1999). This is
consistent with the exquisite GCs data around the Milky Way (MW), other galaxies in the Local Group (Harris 1996; Gaia Collaboration et al. 2018; Johnson et al. 2015) and in massive ellipticals (Forbes et al. 2011; Usher et al. 2012; Taylor et al. 2017). But in terms of numbers, the rich environment of nearby galaxy clusters, due to their high matter density and wide range of galaxy masses and morphologies, offer the best opportunity to understand the connection between GCs, galaxies and ultimately their dark matter halos.

Significant effort and resources in the community have focused on the generation of comprehensive GC maps in nearby galaxy clusters such as Virgo (Jordán et al. 2009; Durrell et al. 2014a), Fornax (Liu et al. 2019) and Coma (Madrid et al. 2018b). Along with other studies, these data have raised a number of interesting discoveries that shed light on the formation of GCs. First, the relation between the total mass in GCs (MGC) and the estimated dark matter halo mass (Mvir) for galaxies follows a single and relatively tight power-law correlation (Harris et al. 2015; Hudson et al. 2014; Harris et al. 2013; Blakeslee et al. 1997; Peng et al. 2008; Georgiev et al. 2010; Spitler & Forbes 2009; Forbes et al. 2018) that contrasts the complex and non-linear correlation of stellar galaxy mass (M*) and halo mass suggested by abundance matching models (Moester et al. 2013; Behroozi et al. 2013). Second, the specific frequency of GCs (SN), defined as the number of GCs normalized to the galaxy luminosity, is also highly non-linear, with dwarf galaxies in clusters that show high SN > 5 values which are at odds with dwarf galaxies of similar mass located in the field and that are characterized by SN ~ 2 (Peng et al. 2008; Georgiev et al. 2010).

Some of the observed trends in GCs can be explained in models where they trace the most turbulent, high density and gas rich star formation episodes in galaxies (Gnedin et al. 2004; Prieto & Gnedin 2008), and analytical calculations support such view (Kruijssen & Cooper 2012; Kruijssen 2015; Elmegreen 2017). Other scenarios where GCs are placed at the centers of their own dark matter halo (Peebles 1984; Rosenblatt et al. 1988) and form completely independent of their host galaxy are, although compelling, currently disfavoured due to the large degree of tidal stripping expected and the observationally constrained abundances and radial distribution of GCs around galaxies (Carlberg 2018; Creasey et al. 2019).

While other mechanisms such as baryonic flows in the early universe may suggest the possible formation of GC-like objects (Naoz & Narayan 2014; Chiou et al. 2019), the most dominant formation channel for GCs seems therefore to be related to galaxies undergoing high-density and violent star formation activity. Additional observational support in this direction comes from the observed correlation between star formation density and an increased fraction of stars born in bound stellar clusters in nearby star forming galaxies (Goddard et al. 2010; Adamo et al. 2011; Bastian et al. 2013).

Due to the low mass and small sizes of GCs, resolving these systems in hydrodynamical simulations of galaxy formation is a daunting task, especially when embedded within the cosmological framework. Encouragingly, Kim et al. (2018) reports the formation of at least one GC-like object in a full cosmological zoom-in simulation. However, due to the expensive calculations the run is stopped at high redshift (z = 5) and is not suitable for comparisons of nearby GCs in the local Universe. Several theoretical efforts are currently underway that couple the formation and evolution of stellar clusters to the star particles formed in cosmological hydrodynamical simulations (Li et al. 2017; Renaud et al. 2017; Li et al. 2018; Pfeffer et al. 2018; Li & Gnedin 2019). However, the price to pay for such an approach is high, as it requires resolving the necessary conditions for molecular clouds formation and their posterior tidal evolution at the sub-pc level. Currently this is only possible at the scale of individual ~ L, and dwarf galaxies, but not for larger systems such as groups and clusters. To take advantage of the richest set of observational data of GCs available to date, which is collected from all nearby galaxy clusters, one must therefore look for alternative and numerically more efficient techniques.

One possibility is to study the abundance and chemical properties of GCs by following their formation, evolution and destruction via semi-analytical modeling built on top of cosmological N-body simulations (El-Badry et al. 2019; Choksi & Gnedin 2019b). Such models are powerful since they allow to make quick predictions over a wide range of halo masses and assembly histories by simultaneously sample the large parameter space that is inherent to following the formation of GCs. But it is also desirable to make predictions on the spatial distribution or kinematics of these simulated GCs. A possible avenue to achieve the latter is by implementing tagging techniques, where GCs are “painted” on top of other particle type in the simulation, i.e. dark matter or stars, and use their dynamical evolution to follow self-consistently the phase space information expected for the GCs within the hierarchical assembly of structures in ΛCDM. Such an approach, reminiscent of the insightful Bullock & Johnston (2005) technique used in stellar halos analysis, has been implemented to study the stripping of GCs within clusters (Bekki et al. 2003b; Ramos et al. 2015; Ramos-Almendares et al. 2018) or the large specific frequency of dwarf ellipticals in clusters (Mistani et al. 2016).

In this work, we apply a similar technique to that presented in Ramos-Almendares et al. (2018) but instead of using a single N-body only zoom-in simulation of a galaxy cluster we couple it to 9 galaxy clusters selected from the hydrodynamical cosmological simulation Illustris (Vogelsberger et al. 2014b,a). This allows for the first time to make predictions on the connection between GCs and the properties of galaxies, for which the stellar mass build up and gas evolution is naturally followed from the hydrodynamical treatment in the simulations. Our work is different from that presented in (Mistani et al. 2016) (which was also using Illustris) in that the abundances of GCs are calculated from the dark matter halo mass by calibrating the model to the observed MGC-Mvir relation presented in Harris et al. (2015), instead of modeling the GC formation by using the individual star formation histories of galaxies as given by the simulation. Furthermore, our model extends that in Mistani et al. (2016) in that all galaxies ever entering the galaxy clusters are tagged with GCs instead of looking only at surviving dwarf galaxies and by assigning GC red/blue colors following observational fractions Harris et al. (2015).

Our technique delivers GC maps in galaxy clusters that can be directly compared to observations in Virgo and the Fornax cluster. In this paper, the first of a series, we will introduce the technique (Sec. 2) and study the resulting
specific frequency $S_N$ of galaxies (Sec.3) as well as the predictions for the radial distribution and kinematics of the intra-cluster GC component (Sec. 4). We conclude by summarizing our main results in Sec. 5.

2 METHODS

The Illustris suite of simulations consists of a series of cosmological boxes with 106 Mpc on a side that follow the assembly of tens of thousands of halos and galaxies from $z = 127$ until present day (Vogelsberger et al. 2014b,a; Genel et al. 2014). The simulation adopts a cosmology consistent with the Wilkinson Microwave Anisotropy Probe (WMAP)-9 measurements (Hinshaw et al. 2013) and is run using the arepo hydrodynamical code (Springel 2010). Cooling, star formation, stellar feedback and stellar evolution are modeled following the implementations described in Vogelsberger et al. (2013), while black hole growth and feedback is modeled following Sijacki et al. (2015). Relevant to the science presented in this paper, Illustris has been proven to reproduce several of the observables at the galaxy population level, including the scaling relations and angular momentum content (Genel et al. 2019), the estimated merger rates (Rodriguez-Gomez et al. 2015), general morphology diversity (Snyder et al. 2015; Rodriguez-Gomez et al. 2017) and color evolution of satellite galaxies (Sales et al. 2015), among others.

The Illustris suite is composed of three different resolution levels and sibling runs with/without the inclusion of baryons. We use for our study the highest resolution run (Illustris-1 referred to as Illustris hereafter for simplicity) achieving a mass per particle $m_{pl} = 1.3 \times 10^6 M_\odot$ and $m_{pxdm} = 6.3 \times 10^6 M_\odot$ for gas and dark matter, respectively, and a gravitational softening that is kept always smaller than 700 pc for the collisionless components (dark and stars). Note that the high resolution gas typically resolve much smaller scales due to the adaptive Voronoi mesh construction, reaching a typical cell size $\sim 50$ pc at the centers of galaxies.

We use galaxy and halo catalogs from subfind (Springel et al. 2001; Dolag et al. 2009) which run over pre-identified Friends-of-Friends (FoF) groups (Davis et al. 1985). We will use the commonly accepted terminology of “centrals” vs. “satellites” to refer either to the main galaxy sitting at the center of the gravitational potential (a.k.a central) or to the rest of the galaxies associated to the same FoF group (satellites). Further details on the simulations data products can be found in Nelson et al. (2015).

2.1 Galaxy sample and infall time

We analyze 9 galaxy clusters from Illustris selected to have present day virial mass $M_{200} \geq 8 \times 10^{13} M_\odot$. In what follows, we use 200 times the critical density of the universe to define all virial quantities. Although 10 objects satisfy our criteria at $z = 0$, group 5 is not included in our sample due to problems in tracing the central galaxy of the group backwards in time. Our sample then comprises 9 galaxy clusters with virial masses consistent with those of Virgo and Fornax.

We use the subLink merger trees (Rodriguez-Gomez et al. 2015) to follow all galaxies that ever interacted with each of our clusters. For GC tagging, we choose all galaxies with stellar mass above $M_\star = 10^9 M_\odot$ at infall time, ensuring that our galaxies are numerically well resolved ($\geq 60$ stellar particles). We define the infall time as the last snapshot where a galaxy is a central of its own FoF group. We note that such definition does not necessarily correspond to the time when they join the cluster but can instead be earlier if a galaxy joins a different group before falling onto the cluster. However, choosing a different infall time will not impact significantly our results as the dark matter halo of any galaxy (which in our model is what determines the amount and distribution of GCs) stops growing after they become satellites of any system. On average, our selection criteria results on $\sim 300$ galaxies with GCs tagged per galaxy cluster.

2.2 GC Tagging

In order to select dark matter particles as tracers of globular cluster systems we use the technique outlined by Bullock & Johnston (2005) and Peiraniuba et al. (2008). This technique allows to select a sub sample of particles to follow a chosen spatial density profile, and has been used by these authors to simulate stellar populations in dark matter only simulations. This method has been already successfully implemented to model the GC systems of galaxies in dark matter only simulations by our team (Ramos et al. 2015; Ramos-Almendares et al. 2018). Briefly, the procedure is as follows.

First we find the best Navarro-Frenk-White Navarro et al. (1996, NFW) fit that describes the density profile of the dark matter in a given infalling halo:

$$
\rho_{\text{NFW}}(r) = \frac{\rho_{\text{NFW}}^0}{(r/r_{\text{NFW}})(1+r/r_{\text{NFW}})^2}
$$

where $\rho_{\text{NFW}}^0$ and $r_{\text{NFW}}$ are the dark matter halo characteristic density and scale length, respectively. We assume that $r_{\text{NFW}}$ can be approximated by $r_{\text{max}} = \alpha r_{\text{NFW}}$ (Bullock et al. 2001), where $\alpha = 2.1623$ and $r_{\text{max}}$ is the radius of the maximum circular velocity, a parameter provided by the subfind catalog in the Illustris database.

As in Ramos et al. (2015) and Ramos-Almendares et al. (2018), we choose the density profiles of globular cluster systems to follow a (Hernquist 1990) profile:

$$
\rho_{\text{HQ}}(r) = \frac{\rho_{\text{HQ}}^0}{(r/r_{\text{HQ}})(1+r/r_{\text{HQ}})^3}
$$

where $\rho_{\text{HQ}}^0$ and $r_{\text{HQ}}$ are the (Hernquist 1990) characteristic density and scale length, respectively. We take $r_{\text{HQ}} = \beta r_{\text{NFW}}$, with $\beta = 3.0$ and $\beta = 0.5$ for blue and red globular clusters, respectively. This choice is calibrated to reproduce the projected density profiles of red and blue GCs in observations at $z = 0$ (for details please see Ramos et al. 2015).

Once we have the right scale lengths for these density profiles, we compute the distribution function for dark matter ($f_{\text{NFW}}$) and globular cluster systems ($f_{\text{HQ}}$) using the equation

$$
f(\epsilon) = \frac{1}{8\pi} \left[ \int_0^\epsilon \frac{d^2P}{\sqrt{\epsilon - \psi}} + \frac{1}{\sqrt{\epsilon}} \frac{dP}{d\psi} \right]_{\psi = 0}
$$

MNRA 000, 1–13 (2019)}
where $\psi$ and $\epsilon$ are the relative gravitational potential and the relative energy, respectively (Binney & Tremaine 1987).

This leaves us in the position to select, in bins of relative energy $(\epsilon, \Delta\epsilon)$, a fraction $f_{HQ}/f_{NFW}$ of particles as candidate GC particles.

We assume that the GC systems are more concentrated than the dark matter halo, so we truncate the selection to a radius $r_{\text{CutOff}} = r_{50,h}/3$, where $r_{50,h}$ is the half mass radius of the halo (Bekki et al. 2003a; Ramos et al. 2015; Ramos-Almendares et al. 2018).

### 2.3 GC Mass

In order to assign mass to particles tagged as GCs, we use Harris et al. (2015) as observational constraints.
authors found that, at $z=0$, the total mass of globular clusters inside a galaxy can be described by

$$M_{GC,0} = a M_{vir,0}^b$$  \hspace{1cm} (4)

where $M_{GC,0}$ and $M_{vir,0}$ are the mass of GCs and the halo mass of the galaxy at $z=0$, respectively, and taking $(a, b) = (4.9 \times 10^{-3}, 0.96)$ for blue and $(a, b) = (2.6 \times 10^{-3}, 1.2)$ for red GCs. Harris et al. (2015) estimate $M_{vir,0}$ from the stellar mass of the galaxies using the empirical star-halo mass relation from lensing results by Hudson et al. (2015) (see their Appendix C, eq. C1).

We use this result to compute the GC mass at infall in our simulated galaxies using:

$$M_{GC,inf} = a_{inf} M_{vir,inf}^b$$  \hspace{1cm} (5)

where $M_{GC,inf}$ and $M_{vir,inf}$ are the mass of GCs and the halo mass of the galaxy at infall time, respectively. Since our definition of infall time ensures that the galaxy is a central galaxy of a FoF group at this time, we take $M_{vir,inf} = M_{vir}$.

The values of $a_{inf}$ and $b_{inf}$ in Eq. 5 need to be calibrated so that, at redshift $z=0$ the resulting correlation between $M_{vir,0}$ and $M_{GC,0}$ reproduces the observed normalization from Harris et al. (2015). This exercise gives us $a_{inf} = 3.5 \times 10^{-4}$ (2.0 $\times 10^{-7}$) and $b_{inf} = 0.9$ (1.15) for blue (red) GC, respectively. We note that because at $z=0$ the simulated galaxies are satellites within the cluster potential (and therefore their halo/virial mass is ill defined) to make a fair comparison to Harris et al. (2015), we compute the $z=0$ halo mass using the same procedure as the authors and implement the star-mass relation from Hudson et al. (2015) using the stellar mass of the galaxies at $z=0$ as provided by the simulation.

Blue (red) points of figure 2 shows the resulting blue (red) GCs mass associated to galaxies in sample as a function their halo mass at $z=0$. Blue and red lines indicate the observational relation by Harris et al. (2015). For comparison, we also show in green the relation reported by Burkert & Forbes (2019) for a combination of all GCs, and shows that our results are in the ballpark of those observations as well. Once $M_{GC}$ is known for each of our galaxies, we take the number of candidate dark matter particles associated to each object, $N_{tag}$, and assign a mass $M_{GC,inf}/N_{tag}$ to each tagged particle. In this way, all GC particles with the same original host galaxy have the same mass.

With this method, each particle tagged as a GC has usually a mass of $\sim 10^3 M_{\odot}$, far below the typical mass of a observed GCs. This happens because the number of tagged candidate particles that are consistent with the right distribution function of the GCs distribution is greater than the expected number of real GCs in galaxies. Although this procedure allows us to have a better sampling of the phase-space of GCs around each galaxy, there are certain applications where the number of GCs is important (for instance, specific frequency estimations). In those cases, it is not adequate to use all the candidate GCs to compare to observations, but...
instead we re-sample. This is done by adding back all the GC mass (previously distributed among all tagged particles) and dividing by the typical GC mass chosen to be $m_{\text{GC}} = 10^5 M_\odot$ (Brodie & Strader 2006). This gives us the number of particles that need to be considered per galaxy as “realistic” GC numbers. We then randomly select from all candidate GC particle, the needed number of realistic GCs.

One of the important features of our method is that the early destruction of GCs due to tides, evaporation and infant mortality is automatically accounted for. This is because our model is calibrated to reproduce the $z = 0$ content of GCs around galaxies, meaning that those GCs that were disrupted after birth are never part of our sample. This is advantageous since the modeling of such destruction processes can be cumbersome and requires many free parameters (Pfeffer et al. 2018; El-Badry et al. 2019; Choksi & Gnedin 2019b). Therefore, although our method is not able to inform about such processes affecting the early lifetime of GCs, it is also free from the uncertainties inherent to their modeling. Fig. 1 shows as an example the most massive galaxy cluster in our simulations indicating in gray scale the stellar density and highlighted in magenta the tagged GC candidates.

3 GCS AROUND GALAXIES IN CLUSTERS

After tagging the corresponding GC candidate particles, our technique self-consistently follows the orbits and tidal stripping experienced by each galaxy and their population of GCs after they infall onto the cluster. As a result of that, the number of GCs that remain associated to a given galaxy today may differ from the one that was originally assigned. We start by quantifying the distribution and number of GCs that remain associated to a given galaxy to- 

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We note in Fig. 3 that some small stellar clumps are visible in the grayscale map and have no associated green circle. These correspond to galaxies that remained below the minimum mass for tagging ($M_* < 10^8 M_\odot$) throughout their history and will consequently not be considered in the analysis that follows. In a few exceptional cases a galaxy will be above our minimum mass criteria but are identified by the merger tree as having been a satellite of another system at all times. Because the tagging is done at infall, defined as the last time that a galaxy was a central of its own group, those objects cannot be tagged and therefore will also be

Figure 4. Specific frequency ($S_N$) as a function of V-band absolute magnitude $M_V$ for all GCs (gray points). The simulation naturally reproduces the observed “U”-shape. Magenta stars are observed $S_N$ values in galaxies from the Virgo cluster by Peng et al. (2008). Dark green curves were obtained analytically by assuming the Harris et al. (2015) $M_{\text{GC}}$ vs $M_*$ power law fit, a constant mass to light ratio $M/L_V = 2$ and the stellar mass - halo mass relation described by either Guo et al. (2010) (solid) and Moster et al. (2013) (dashed) or Behroozi et al. (2013) (dotted).

Figure 5. Virial mass at infall as a function of the present day stellar mass in our cluster galaxies. The points are color coded by their $z = 0$ specific frequency and show that large $S_N$ values are associated to larger halo masses at infall. This can be explained as the result of the evolution in the stellar mass-halo mass relation. Black/green lines show the median $M_* - M_{\text{halo}}$ relation of galaxies with infall times in the ranges $t_{\text{inf}} = [13, 13.5]$ and $t_{\text{inf}} = [2.5, 3.5]$ Gyr respectively. Since the GC mass scales with halo mass (and not $M_*$), that helps explain the larger GC content of galaxies with earlier infall times. Additionally, tidal stripping contributes to the scatter. Gray symbols highlight objects that lost more than 90% of the stars (see text for details).
excluded from the analysis (an example of it can be seen near the (−50, −250) kpc position in the figure, with a few blue GCs that were acquired as some smaller companion merged to it). The fraction of such objects in our sample is below ∼ 2% of the galaxies and therefore will not strongly impact our results.

3.1 The GC specific frequency $S_N$

In observations of galaxy clusters, the specific frequency of GCs $S_N$, which is defined as the number of GCs per unit $M_V = −15$ of galaxy luminosity, shows a strong dependence on galaxy brightness; with a characteristic “U”-shape indicating large specific frequencies in bright as well as in dwarf galaxies ($S_N ≥ 5$, Durrell et al. 1996; Lotz et al. 2004; Peng et al. 2008). The origin of this behaviour is not well understood. In particular, in light of the results on field and late type galaxies, which suggest $S_N ∼ 1$ (Harris 1991; Miller et al. 1998). Although the large specific frequencies in the central galaxies may not be surprising given their ability to capture GCs from orbiting and merged galaxies in the cluster (Coenda et al. 2009); the upturn of $S_N$ in the dwarf scale regime is less well understood.

We use our tagging technique to gain insight on the possible cause for such trends. Fig. 4 shows $S_N$ as a function of absolute $V$-band magnitude for our simulated galaxies. $S_N$ is computed as,

$$S_N = N_{GC} × 10^{0.4(M_−M_⊙ + 15)}$$

(Harris & van den Bergh 1981), where $N_{GC}$ is the number of GCs within $r < 3r_{h_*}$ of a galaxy (and assuming an average mass per cluster $10^5 M_⊙$, see Sec. 2.3). Encouragingly, the GCs specific frequency in our simulated galaxies, shown in black small dots, follow the familiar “U”-shape trend found in observations. For comparison we include in magenta starred symbols a set of observed $S_N$ values for galaxies in the Virgo cluster from Peng et al. (2008). Although our simulations tend to underestimate $S_N$ on the bright end, an effect driven by the inefficiency of feedback to shut down star formation in high mass halos for galaxies in Illustris (see Fig. 2 in Genel et al. 2014) artificially lowering our $S_N$ calculations, the good agreement with intermediate and low mass dwarfs is a notable success of the GC model.

Our GCs tagging method relies mostly on one specific assumption: a single power-law relation between the mass in GCs and the halo virial mass at infall. The $S_N$ characteristic “U”-shape in our model arises as a consequence of this assumption combined with the well known non-linear relation between stellar mass (and, consequently, luminosity) and halo virial mass. Notice that for the latter we use the information on stellar mass and luminosity directly from the Illustris hydrodynamical run and it is not an input of our GC model. This conclusion is consistent with previous independent results using semi-analytical catalogs or analytic models of GCs formation (e.g., Peng et al. 2008; Harris et al. 2013; Choksi & Gnedin 2019a).

To guide the eye, we add in Fig. 4 green curves that are the results of a toy model, as follows. We vary the halo mass $M_{vir}$ in the range $\log(M_{vir}/M_⊙) = [10, 15]$. For halos in this mass range, following the $M_{GC} - M_{vir}$ relation from Harris et al. (2015) we determine the mass in GCs. As a second step, assuming three different abundance matching relation $M_* - M_{vir}$ (Guo et al. 2010; Moster et al. 2013; Behroozi et al. 2013, with solid, dashed and dotted, respectively) we estimate their $M_*$. Adopting a uniform mass-to-light ratio $γ = 1$ to go from stellar mass to $V$-band magnitude and an average GC mass $M_{GC} ∼ 10^5 M_⊙$ we compute the resulting $S_N$ for a galaxy with $M_∗$ magnitude. This simple model seems to capture the essence of the simulated and observed trend, providing a possible interpretation for the $S_N$ shape.

Our simulations also shed light on the origin on the scatter of the $S_N - M_∗$ relation. Fig. 5 show that for a given stellar mass today $M_*$, the corresponding virial mass at infall can vary substantially (and therefore, the initial mass of GCs assigned). As expected, objects with a larger halo mass at a given present-day stellar mass should display larger specific frequencies today, as confirmed by the color coding of the points.

Interestingly, we find that the bulk of the scatter in this plot is due to an evolving $M_* - M_{vir}$ relation with redshift in our simulations. To illustrate this, we show the median $M_* - M_{vir}$ relation of those points selected in very narrow ranges of infall times: $t_{inf} = [2.5, 3.5]$ Gyr (green) and $t_{inf} = [13, 13.5]$ Gyr (black). For halos infalling earlier into the cluster, the same halo mass is populated by a smaller stellar mass content, resulting on an increased $S_N$ value today. Such evolution in the $M_* - M_{vir}$ relation seen in our simulations is also consistent with that determined via abundance matching studies (Moster et al. 2013; Behroozi et al. 2013).

We have checked that for those points well above the green curve in Fig. 5 tidal disruption plays a major role. Gray circles highlight objects where more than 90% of the stars have been tidally removed. In most cases tides remove stars and GCs and are conducive to a small $S_N$ (blue points). However, there is a small subset of heavily tidally stripped galaxies where the specific frequency increases to $S_N ≥ 8$. These galaxies, located in the dwarfs regime in Fig. 4, have retained less than 10% of their stellar budget but have held on to at least 10 GCs resulting on large specific frequencies at $z = 0$. Because the distribution of stars follows naturally a shallower profile than the cuspy Hernquist profile selected for GCs, once a galaxy has been significantly depleted of stars, enters a regime where more stars are lost than GCs, explaining the rise on $S_N$. However, this might be a direct consequence of our specific choice of a cuspy radial profile for the tagged GCs and we prompt the reader to consider $S_N ≥ 10$ values and above with caution.

Although our assumption of an almost constant slope in the $M_{GC} - M_{vir}$ relation with redshift partially drives some of these results, it is reassuring to see that estimates of GCs formation as a result of mergers might support such assumption (see Choksi & Gnedin 2019a), together with a factor ∼ 10 redshift evolution in the normalization, as needed by our calibration. Moreover, our model makes a testable prediction: dwarf galaxies with the largest $S_N$ values within galaxy clusters will correspond to the earliest infalling halos and therefore should be located preferentially in the inner regions of clusters. We note that our results are in line with those presented in Mistani et al. (2016) with an independent GCs analysis in the Illustris clusters. In their study, Mistani et al. (2016) conclude as well that earlier infalling dwarfs have larger $S_N$ values, an effect partially driven by their larger dark matter halo mass—in agreement with our
Figure 6. Projected density profiles for the red and blue intra-cluster GCs (red and blue curves), using thin lines for the 9 individual clusters and thick solid for the median in our sample. Encouragingly, the profiles are steeper than that of the dark matter in the clusters (gray) and comparable to that of the intra-cluster light (stars not associated to galaxies, shown in cyan). We compare with measurements in the Virgo cluster from the work in Lee et al. (2010). The simulated red component is shallower than detected in Virgo. Normalizations for the dark matter and the intra-cluster light are as quoted.

results— and a more bursty star formation that may increases the chances of GCs formation. Encouragingly, observational evidence seems to suggest an increase of $S_N$ for dwarfs near the cluster center (see Fig. 10 & 11 in Peng et al. 2008), in good agreement with our predictions.

We hasten to add that our prediction for field dwarfs would place them at $S_N \sim 5$ at $M_V = -16$ (i.e. near the green curves in Fig. 4) but they will not scatter upwards. We defer the comparison to field objects to future work.

4 DISTRIBUTION & KINEMATICS OF INTRA CLUSTER GCs

GCs that lay beyond $3r_h$, from the center of a galaxy (and are therefore not considered in the $S_N$ calculations of the previous section) constitute a diffuse and extended intracluster GC (ICGC) component. They are seemingly not connected to any galaxy today but are instead linked to the gravitational potential of the host galaxy cluster. In observations, hints to such intracluster GC population can be found in early work (e.g. Forte et al. 1982; Muzzio et al. 1984; White 1987) and confirmed in more recent observations of nearby galaxy clusters such as Virgo (Lee et al. 2010; Durrell et al. 2014b), Fornax (Bassino et al. 2003) or Coma (Madrid et al. 2018b). We use our simulated GCs catalog to study this diffuse intracluster component, understand its origin and determine their potential as dynamical tracers of the dark matter.

4.1 Building the intracluster GCs component

Fig. 6 shows the projected radial profile of red and blue intracluster GCs. Thin lines indicate individual simulated galaxy clusters in Illustris whereas thick solid curves represent the median. ICGCs have a radial distribution that roughly follows that of the intracluster light (cyan curves) and that are steeper than the dark matter (shown in gray), with a surface density profile scaling $\Sigma_{GC} \sim r^{-2.5}$. A complete census of this diffuse component in observations is extremely challenging, and as a result only a few estimates are available to date. We compare in Fig. 6 with the SDSS measurement for ICGCs in Virgo by Lee et al. (2010) shown with starred symbols.

The blue GCs intracluster component in our simulated clusters seems in reasonable agreement with Lee et al. (2010) although we note that our model predicts a shallower profile for the red (or metal rich) distribution than observed. This is likely due to an insufficient initial segregation between red and blue components already set at infall time of individual galaxies in our GCs tagging method. However, given the non-linearity required on building the ICGC and the simplicity of our tagging method, the good agreement between the radial distribution of observed and simulated GCs is remarkable. To be conservative, in what follows, we will not distinguish between red and blue ICGC components and consider it as a single unit.
GCs in galaxy clusters

Figure 8. Top: Distribution of the (stellar) mass of the galaxy progenitors that contributed GCs to the total (black) and intra-cluster component (green) in all our simulated clusters. These are number weighted distributions, meaning that a galaxy is counted as many times as candidate GCs it contributed, and all simulated clusters have been added to a single histogram. The ICGC component is formed in its majority from galaxies with stellar mass comparable to the Milky Way and above ($M_\ast \geq 10^{10.5}$). Within the ICGC, the orphan population is also dominated by large progenitors (blue curve). However this changes from cluster to cluster. Bottom: individual distribution of $M_\ast$ of the galaxy progenitors for the orphan population for each simulated cluster. Although in most cases orphan GCs were brought in by dwarf-like progenitors with $M_\ast \sim 10^{9.5} M_\odot$, in 5 of our 9 clusters orphans are mostly contributed by major merger events with progenitor galaxies $M_\ast \sim 10^{11} M_\odot$.

What is the origin of this ICGCs? We find two main contributors to building the ICGC component, the GCs that were tidally stripped from (surviving) galaxy satellites in the cluster as well as GCs that were initially associated to galaxies that still survive today as satellites in the cluster\(^1\). Vertical arrows indicate the half number radius split by components.

GCs initially associated to the central galaxy dominate only in the inner region and their contribution is not significant beyond $r/r_{\text{vir}} \geq 0.1$. From the rest of the intracluster component, orphans are more centrally concentrated compared to those from surviving galaxies. This is consistent with orphan GCs having having had their progenitor galaxies totally disrupted, which explains their segregation towards the center of the cluster. For completeness, we show in Fig. 7 the total 3D median profile of GCs (black). The difference between ICGCs and the total curve indicates, as expected, that in the outskirts of the galaxy clusters most GCs are still associated to their host galaxies.

Because the chemical composition of GCs is linked to that of their progenitor galaxy (e.g., Côté et al. 1998; Liu et al. 2016; Pastorello et al. 2015), it is of interest to identify the spectrum of galaxy masses contributing GCs within a galaxy cluster. The top panel in Fig. 8 shows the added distribution of progenitor galaxy masses for GCs in all our simulated clusters, divided according to the different populations. Taken as a whole, most GCs today in clusters are linked to massive galaxies with $M_\ast \sim 10^{10.5} M_\odot$ and above

\(^1\) The exact contribution of surviving satellites to the ICGC component is only weakly dependent on the adopted cutoff of $3r_{\text{vir}}$, to consider a GC as not associated to a galaxy. For example, this changes to 54% if the cutoff is extended to $5r_{\text{vir}}$, instead
objects, with median masses orphans population is dominated instead by dwarf-like for the other half of the clusters, the contribution to the nated by orphans brought in by one or two very massive find that about half of the galaxy clusters are heavily domi-

components of the velocity, in a spherical coordinates sys-

for our ICGC component. matter and GCs as well as the orbital structure predicted potential will then depend on relative biases between dark And how well GCs are expected to trace the gravitational own Galaxy, the kinematical information will be projected. of several dozens to hundreds of GCs in the intra-cluster luminous tracers are scarce. Obtaining spectroscopic data to galaxies (contributing to the all curve in black), we con-

cider the present-day mass of their host galaxy. In the case of orphans GCs, we count the mass of the galaxy progenitor at their infall time, since they have totally merged to the cluster by \(z = 0\) by definition.

4.2 Intracluster GCs as kinematic tracers of the dark matter

This population of free floating GCs provides also a unique opportunity to trace kinematically the gravitational potential of the galaxy cluster in regions where stars or other luminous tracers are scarce. Obtaining spectroscopic data of several dozens to hundreds of GCs in the intra-cluster medium of nearby clusters like Virgo or Fornax is, although expensive, within current to near-future capabilities of observational campaigns (e.g., Subaru/PFS, Maunakea Spectroscopic Explorer). In the MW itself, 3D information of GCs have been used to estimate the enclosed dark matter mass out to 100 kpc, well beyond the stellar and gaseous disk (Watkins et al. 2019). However, for systems outside our own Galaxy, the kinematical information will be projected. And how well GCs are expected to trace the gravitational potential will then depend on relative biases between dark matter and GCs as well as the orbital structure predicted for this ICGC component.

Fig. 9 compares the global kinematics of the ICGCs (green) to that of the underlying dark matter halo (black) for our 9 simulated clusters. We show the three spherical components of the velocity, in a spherical coordinates sys-

tem centered at each cluster. For this we have stacked the information of all individual clusters, by scaling the distances and velocities by their respective virial quantities. The results from individual clusters are not different from the overall ensemble. We find that the velocity dispersion for the ICGCs in all three directions is comparable to that of the dark matter component in the host cluster halo (solid black line). Thick lines correspond to the median of the stacked sample of our galaxy clusters and reproduces several observational measurements in the MW (Watkins et al. 2019; Creasey et al. 2019) or inner regions of M87 (Zhu et al. 2014). However, tangentially biased orbits as measured in observations of NGC 1407 (Spitler et al. 2012) or the outskirts of M87 (Zhu et al. 2014; Spitler et al. 2012) are difficult to obtain. The tension may be alleviated by considering the effects of substructure. Thin solid blue lines show the intra-cluster GCs for each individual cluster in our simulation, where we have correlated the “dips” in \(\beta\) to the presence of infalling groups/substructure. Notice that the odd external orbital distribution inferred for M87 traces quite closely one of our clusters.

Figure 10. Predicted anisotropy profile \(\beta\) for the stacked sample of red and blue simulated intra-cluster GCs (thick solid red, blue lines, respectively). We predict a very radial (\(\beta \approx 0.5\)) orbital structure that is comparable to that of the dark matter component in the host cluster halo (solid black line). Thick lines correspond to the median of the stacked sample of our galaxy clusters and reproduces several observational measurements in the MW (Watkins et al. 2019; Creasey et al. 2019) or inner regions of M87 (Zhu et al. 2014). However, tangentially biased orbits as measured in observations of NGC 1407 (Spitler et al. 2012) or the outskirts of M87 (Zhu et al. 2014; Spitler et al. 2012) are difficult to obtain. The tension may be alleviated by considering the effects of substructure. Thin solid blue lines show the intra-cluster GCs for each individual cluster in our simulation, where we have correlated the “dips” in \(\beta\) to the presence of infalling groups/substructure. Notice that the odd external orbital distribution inferred for M87 traces quite closely one of our clusters.

\[
\beta = 1 - 2\frac{\sigma_r^2}{\sigma_t^2}, \quad \text{where} \quad \sigma_r^2 = \sigma_{\theta}^2 + \sigma_{\phi}^2 \quad \text{(Binney & Tremaine 1987)}.
\]

Thick solid lines show the median \(\beta\) profiles for the ICGC separated in red and
blue component (although no significant difference is seen between both populations).

We find that the orbits of GCs are expected to be highly radially biased \( (\beta \geq 0.3) \) at all radii within the cluster. This agrees with the accreted nature of the intracluster population, where galaxies in radial orbits result preferentially tidally disrupted, donating their GCs to the cluster potential. Dark matter halos in ACDM galaxy clusters have long been known to be radially biased (Wojtak et al. 2009). Fig. 10 also shows the median \( \beta \) profile of the host dark matter halos (black curve) and confirms that the ICGC component is comparable and even slightly more radially biased than the dark matter in the clusters. Large \( \beta \) values seem therefore an unavoidable prediction for any scenario where structure grows hierarchically and tidal stripping plays a major role (Diemand et al. 2005; Abadi et al. 2006; Creasey et al. 2019; Loebman et al. 2018).

A few observational estimates of \( \beta \) are currently available in the literature and offer important constraints to theoretical models of GC assembly. For instance, GCs around the MW seem to suggest \( \beta \sim 0.4 \) (Watkins et al. 2019) in reasonable agreement with our predictions\(^2\). Interestingly, the kurtosis of the line of sight velocity dispersion in combination with an estimate of the circular velocity can be used as an indication of the orbital anisotropy of a luminous tracer (stars, PNe, GCs) in extragalactic objects (Gerhard 1993; van der Marel & Franx 1993; Napolitano et al. 2009). Such measurements are challenging, in particular, due to projection effects and the availability of a discrete number of GCs.

Applying the kurtosis technique to GCs around M87 and NGC1407 suggests a very different orbital structure for GCs in these two systems (Spitler et al. 2012). For M87, the estimates place GCs in significantly radial orbits consistent with our predictions (magenta triangles in Fig. 10). On the other hand, the results on NGC1407, the central galaxy on a moderate massive galaxy group \( M_{\text{vir}} \sim 6 \times 10^{11} \, M_{\odot} \) (Romanowsky et al. 2009), is consistent instead with highly tangentially biased orbits for its GCs throughout the whole radial range explored, with \( \beta \leq -0.5 \) at \( r \sim 0.1 \, r_{\text{vir}} \). Furthermore, an independent analysis of the GCs around M87 presented in Zhu et al. (2014) argues for a \( \beta < 0 \) beyond \( r \geq 100 \) kpc also in Virgo. Such preferentially tangential orbits for GCs are difficult to reconcile with the accretion origin for the ICGC component explored here (see Creasey et al. 2019, for a similar conclusion).

As discussed in Spitler et al. (2012), a possible origin for the negative anisotropy values found in NGC 1407 would be the preferential tidal disruption of GCs in radial orbits, which would create an orbital distribution that favors preferentially tangential orbits. Our method is not well suited to test such hypothesis since our model is calibrated to reproduce the \( f_{\text{GC}} \) final GCs content in halos and the destruction of individual GCs is not explicitly modeled. Instead, our simulations suggest an alternative explanation for negative \( \beta \) values.

Thin blue lines in Fig. 10 show the individual anisotropy profile for each of our simulated clusters and confirm that local deviations toward lower \( \beta \) values are not uncommon. We have associated such dips in the profiles with the presence of infalling group of galaxies, not yet virialized into the cluster, with GCs that are mostly tracing the orbit of the substructure within the cluster (and hence the tangential motion) and are not directly tracing the cluster potential.

The fact that tangential orbits appear at very small radii for NGC 1407 is perhaps a compelling argument in favor of the preferential disruption of GCs in radial orbits. On the other hand, the substructure explanation seems more aligned with GCs on possible tangential orbits in M87, since the Virgo cluster is known to be not fully relaxed. Moreover, substructure in the kinematics of planetary nebulae in the Virgo cluster have already been identified (Longobardi et al. 2018). Although differentiating between these two mechanisms may probe difficult, our results indicate that localized tangentially biased orbits are not inconsistent with the accretion build up of the ICGC component. However, such \( \beta < 0 \) values should be local, not extending for more than a few hundred kiloparsecs. We highlight that the orbital structure of objects like NGC 1407 is interesting and warrants further exploration with simulations as well as other observational attempts at constraining the orbits of GCs in galaxies as well as groups and clusters.

5 CONCLUSIONS

We present a novel method to follow the evolution of GCs within galaxy clusters in cosmological simulations. The method relies on the observational single power-law relation between mass in GCs and halo mass to determine the number of GCs associated to a galaxy. By following the cluster assembly, we trace back all galaxies at infall time and by means of a particle tagging technique we are able to follow the posterior dynamical evolution of its associated GCs within the cluster potential. We apply this technique to 9 of the most massive cluster halos with \( M_{\text{vir}} \sim 10^{14} \, M_{\odot} \) in the cosmological hydrodynamical simulation Illustris, providing useful constraints to observations of GCs in systems such as the Virgo cluster.

The successes of this model include reproducing, (i) the “U”-shape relation between specific frequency of GCs, \( S_N \), and stellar mass or magnitude, and (ii) the build up of an intracluster population of GCs that is spatially distributed following a steeper profile than the dark matter, in agreement with observations. We find that \( S_N \sim 5 \) values are naturally expected for dwarf galaxies with \( M_{\odot} > -18 \) as a result of the non-linear relation between halo mass and stellar mass. Furthermore, dwarfs that scatter upwards in the \( S_N-M_{\odot} \) relation correspond to the early accreting subhalos onto the cluster, and their large specific frequency stands from the lower galaxy formation efficiency at fixed halo mass expected at higher redshifts. This result is in line with observational evidence of large \( S_N \) values distributed preferentially near the center of the Virgo cluster (Peng et al. 2008).

We use our simulations to make predictions about the galaxy progenitors that are expected to be the main contributors to the intracluster population of GCs. We find that in numbers the ICGC population is dominated by galaxies like the MW and above, with masses \( M_{\star} \sim 10^{10.5} \, M_{\odot} \) contribut-
ing about 80% of the GCs in this extended and diffuse component. Furthermore, we find that the tidal origin for the ICGC translate, on average, into a very radial ($\beta \sim 0.5$) orbital structure for the GCs. However, the anisotropy profile can present localized deviations towards tangentially biased orbits as a result of surviving substrate of galaxies within the otherwise virialized cluster. It would be interesting to explore this possibility in light of the tangentially biased orbital structure measured by the galaxy group centered at NGC 1407 (Spitler et al. 2012) and for M87 according to Zhu et al. (2014).

Fully self-consistent models of GC formation and their evolution within the local interstellar medium embedded within the cosmological context are the ultimate goal to understand the GC connection to halos and galaxies. However, the wide dynamical range needed to be resolved (from subpc to several mega-pc scales) are outside the reach of current numerical simulation capabilities. Important efforts to follow the formation of stellar clusters are starting to shed light on such connection, but are limited to the scale of individual galaxies (Pfeffer et al. 2018; Li et al. 2017; Renaud et al. 2017; Carlberg 2018; Kruissink et al. 2019), higher redshifts (Kim et al. 2018) or idealized galaxy mergers set-ups (Karl et al. 2011).

We argue that tagging techniques like the one presented here, when coupled to fully hydrodynamical simulations that follow the formation of galaxies within $\Lambda$CDM such as Illustris, offer a unique opportunity to make predictions on the properties of GCs on the scales of galaxy groups and clusters. This approach is complementary to the aforementioned theoretical strives on smaller scales and can potentially be informed by them if more complex modeling is required. Our current predictions cover the need for a theoretical framework to interpret the wealth of existing observational data of GCs in nearby groups and clusters such as Virgo (Jordán et al. 2009; Durrell et al. 2014a), Coma (Madrid et al. 2018a), Fornax (Liu et al. 2019) and CenA (Taylor et al. 2017) among others.

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