

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

Felipe Ramos-Almendares^{1*}, Laura V. Sales^{2†}, Mario G. Abadi^{1,3}, Jessica E. Doppelt², Hernan Muriel^{1,3}, and Eric W. Peng^{4,5}

¹ CONICET-Universidad Nacional de Córdoba, Instituto de Astronomía Teórica y Experimental (IATE), Córdoba, Argentina

² University of California Riverside, 900 University Ave., Riverside CA 92521, USA

³ Observatorio Astronómico, Universidad Nacional de Córdoba, Córdoba, Argentina

⁴ Department of Astronomy, Peking University, 5 Yiheyuan Road, Beijing, China 100871

⁵ Kavli Institute for Astronomy and Astrophysics, Peking University, 5 Yiheyuan Road, Beijing, China 100871

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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 their infall time. The tidal removal of GCs from their galaxies and the distribution of the GCs within the cluster is later followed self-consistently by the simulation. The method relies on the simple assumption of a single power-law relation between halo mass (M_{vir}) and mass in GCs (M_{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 the power law $M_{\text{GC}}-M_{\text{vir}}$ relation and the non-linear stellar mass (M_*) - halo mass relation from the simulation. Additional scatter in the S_N values is traced back to galaxies with early infall times due to the evolution of the M_*-M_{vir} relation with redshift. GCs that have been tidally removed from their galaxies form the present-day intra-cluster component, from which about $\sim 60\%$ were brought in by galaxies that currently orbit 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. 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.

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 intra-cluster space. However, little is known about their assembly history and 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). Be-

cause of their inferred old ages (Vandenberg et al. 1996) and clustered distribution around galaxies, they are believed to be surviving probes of the star formation in the early 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 that suggests different origins. One possible interpretation is that the youngest and more metal rich GCs are formed *in-situ* while the metal poor component is likely acquired hierarchically via the accretion of smaller galaxies

* E-mail: fframes@oac.unc.edu.ar

† Hellman Fellow

(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). In terms of numbers, however, 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 (M_{GC}) and the estimated dark matter halo mass (M_{vir}) 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 galaxy stellar mass (M_*) and halo mass suggested by abundance matching models (Moster et al. 2013; Behroozi et al. 2013). Second, the specific frequency of GCs (S_N), defined as the number of GCs normalized to the galaxy luminosity, is also highly non-linear, with dwarf galaxies in clusters that show high $S_N \geq 5$ values which are at odds with dwarf galaxies of similar mass located in the field and that are characterized by $S_N \sim 2$ (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 (Kravtsov & Gnedin 2005; Prieto & Gnedin 2008), and analytical calculations support this 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 (Naoy & 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, full cosmological zoom-in simulations are starting to resolve the formation

of individual GC-like objects (Kim et al. 2018; Ma et al. 2019; Lahén et al. 2019). However, due to the expensive calculations the runs are necessarily stopped at high redshift ($z = 5$) or they focus on very low mass dwarfs, making them not fully suitable for predictions of GCs in nearby galaxies and groups 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 $\sim L_*$ 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; Muratov & Gnedin 2010; Tonini 2013; Li & Gnedin 2014; Boylan-Kolchin 2017; Choksi et al. 2018). Such models are powerful since they make quick predictions over a wide range of halo masses and assembly histories by simultaneously sampling 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 types in the simulation, i.e. dark matter or stars, and use their dynamical evolution to self-consistently follow the phase space information expected for the GCs within the hierarchical assembly of structures in Λ CDM. Such an approach, reminiscent of the insightful Bullock & Johnston (2005) technique used in stellar halo analysis, has been implemented to study the stripping of GCs within clusters (Bekki et al. 2003; Ramos et al. 2015; Ramos-Almendares et al. 2018) and 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). For the first time, this allows us 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 by the hydrodynamical treatment in the simulations. Our work is different from that presented in (Mistani et al. 2016) (which also used Illustris) in that the abundances of GCs are calculated from the dark matter halo mass by calibrating the model to the observed $M_{GC}-M_{vir}$ 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 of Mistani et al. (2016) in that all galaxies ever entering the galaxy clusters

are tagged with GCs rather than looking only at surviving dwarf galaxies and that the red/blue GC colors are assigned following observational fractions of [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 106 Mpc on one 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 shown 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 $m_{p,g} = 1.3 \times 10^6 M_\odot$ and $m_{p,dm} = 6.3 \times 10^6 M_\odot$ 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 resolves much smaller scales due to the adaptive Voronoi mesh construction, reaching a typical cell size ~ 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 $M_{vir} \geq 8 \times 10^{13} M_\odot$. 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 $M_* = 10^8 M_\odot$ at infall time, ensuring that our galaxies are numerically well resolved (≥ 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 a 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 infalling onto the cluster. However, choosing a different infall time will not impact our results significantly, 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. The central galaxy of each cluster requires a different treatment as their infall times are not well defined. We choose to tag them at the time when they reach 5% of their final virial mass in an attempt to capture their individual GC population separated from that resulting from the later hierarchical assembly of the clusters. With this definition, we find $z \sim 2.5$ -3.0 as the typical tagging redshifts for our centrals. We have explicitly checked that our results are not sensitive to this particular choice. On average, our selection criteria results in ~ 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 [Peñarrubia et al. \(2008\)](#). This technique selects a subsample of particles that follow a chosen spatial density profile, and it has been used by the above 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:

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

where ρ_{NFW}^0 and r_{NFW} are the dark matter halo characteristic density and scale length, respectively. We assume that r_{NFW} can be approximated by $r_{max} = \alpha r_{NFW}$ ([Bullock et al. 2001](#)), where $\alpha = 2.1623$ and r_{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 sys-

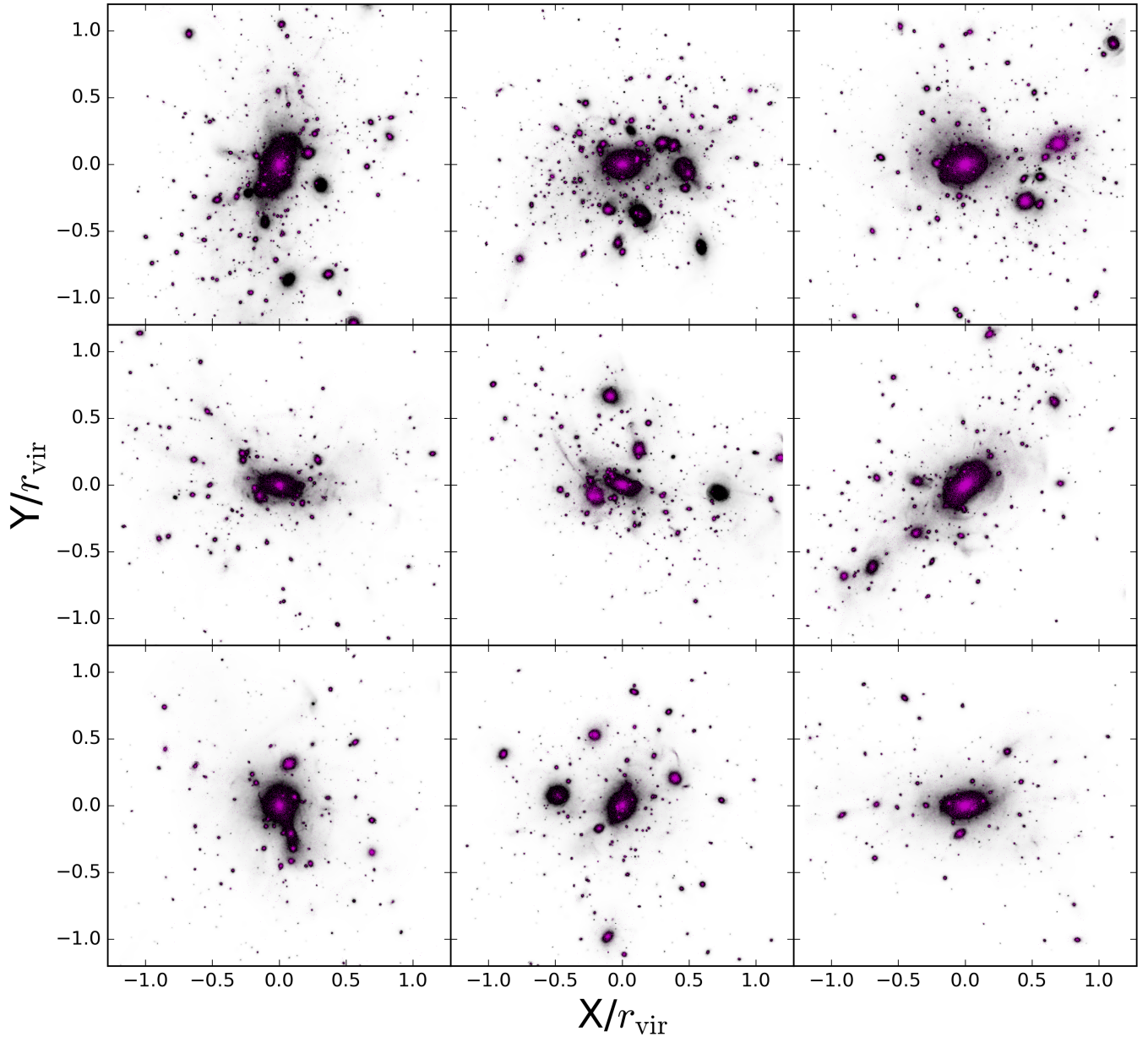


Figure 1. Projected map of our simulated clusters in Illustris selected with $M_{\text{vir}} \sim 10^{14} M_{\odot}$. Gray scale shows the stellar density distribution and in magenta we highlight the generated catalog of GCs. Note that GCs tend to cluster around galaxies, but are also found at present day in an extended and diffuse intra-cluster component (see also Fig. 3 for a zoom-in of the top-right panel cluster).

tems to follow a [Hernquist \(1990\)](#) profile:

$$\rho_{HQ}(r) = \frac{\rho_{HQ}^0}{(r/r_{HQ})(1+r/r_{HQ})^3} \quad (2)$$

where ρ_{HQ}^0 and r_{HQ} are the ([Hernquist 1990](#)) characteristic density and scale length, respectively.

The radial distribution of GCs around galaxies have been studied in observations ([Dirsch et al. 2003a,b](#); [Bassino et al. 2006](#); [Coenda et al. 2009](#)) and shown to be spatially

more extended than the stars but less extended than the inferred underlying dark matter halo ([Abadi et al. 2006](#); [Hudson & Robison 2018](#)). Furthermore, for the Milky Way galaxy there seems to be a *dichotomy* of GC properties: a more centrally concentrated distribution of red, younger and more metal rich GCs, and a more extended old and metal poor population of “blue” GCs with presumably accreted origins. Interestingly, this dichotomy or bi-modality may not hold true in other external galaxies, which instead may be

better explained by a *continuous gradient* on their GC population (Harris et al. 2017; Forte 2017; Forte et al. 2019).

Regardless of this dichotomy vs. gradient discussion – which is in itself worth of in-depth theoretical investigations that is beyond the scope of this paper– observational evidence suggests that the redder GC component tends to be more centrally clustered compared to the bluer GCs. In this work, we attempt to model this spatial segregation by tagging two different GC populations, “blue” and “red”, with different radial distributions. Notice, however, that this does not require the GC systems to be bi-modal, but instead can be interpreted as a rough description of the “redder” and “bluer” parts of a continuous distribution.

In Eq. 2 take $r_{HQ} = \beta r_{NFW}$, with $\beta = 3.0$ and $\beta = 0.5$ for blue and red globular clusters, respectively. The specific values for β were obtained as least square fits to 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_{NFW}) and globular cluster systems (f_{HQ}) using the equation

$$f(\epsilon) = \frac{1}{8\pi} \left[\int_0^\epsilon \frac{d^2\rho}{d\psi^2} \frac{d\psi}{\sqrt{\epsilon-\psi}} + \frac{1}{\sqrt{\epsilon}} \left(\frac{d\rho}{d\psi} \right)_{\psi=0} \right] \quad (3)$$

where ψ and ϵ 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.

To guarantee that the GC system is more concentrated than the dark matter halo as inferred from observations, we truncate the selection to a radius $r_{CutOff} = r_{50,h}/3$, where $r_{50,h}$ is the half mass radius of the dark matter halo. This choice has been used in previous work and it is inspired on the typical radius for the Milky Way GCs (Yahagi & Bekki 2005; Ramos et al. 2015; Ramos-Almendares et al. 2018).

2.3 GC Mass

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

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

where $M_{GC,0}$ and $M_{vir,0}$ are the mass of GCs and the halo mass of the galaxy at $z = 0$ in solar mass units (M_\odot), respectively, and taking $(a, b) = (4.9 \times 10^{-5}, 0.96)$ for blue and $(a, b) = (2.6 \times 10^{-8}, 1.2)$ 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:

$$M_{GC,inf} = a_{inf} M_{vir,inf}^{b_{inf}} \quad (5)$$

where $M_{GC,inf}$ and $M_{vir,inf}$ are the mass of GCs and the halo mass of the galaxy at infall time in solar mass units, respectively. Since our definition of infall time ensures that the

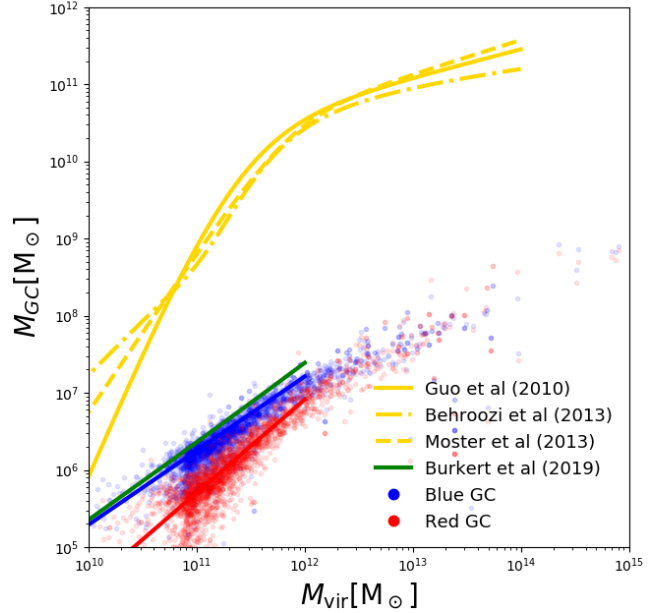


Figure 2. Mass in GCs at the present day in our galaxies as a function of their halo mass. The method is calibrated to reproduce the Harris et al. (2015) measurements for the red and blue components (solid lines). Green solid line shows the combined mass from both populations taken from the compilation in Burkert & Forbes (2019). For comparison, we also display in yellow lines the relation between halo mass and stellar mass in galaxies following the abundance matching models presented in Guo et al. (2010) (solid), Moster et al. (2013) (dashed) and Behroozi et al. (2013) (dotted). The stellar mass - halo mass relation is markedly different from the power law found in the GCs mass relation to halo mass, a fact that might drive the characteristic “U”-shape in the specific frequency of galaxies as a function of their luminosity (see Fig. 4).

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 $a_{inf} = 3.5 \times 10^{-4}$ (2.0×10^{-7}) and $b_{inf} = 0.9$ (1.15) for blue (red) GC, respectively. This calibration is needed to account for the average fraction of GCs lost by each galaxy to tidal stripping in the cluster potential. We note that because at $z = 0$ the simulated galaxies are satellites within the cluster (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.

For simplicity, we have chosen an infall relation that is independent of redshift (a_{inf} and b_{inf} in Eq. 5 are the same for all infalling galaxies). Theoretical models give different predictions regarding a possible evolution of the $M_{GC}-M_{vir}$ relation with redshift, from nearly no evolution (Kruijssen 2015) to changes by factor ~ 10 (Choksi & Gnedin 2019a) between $z \sim 3$ and present day. The lesson learned from our

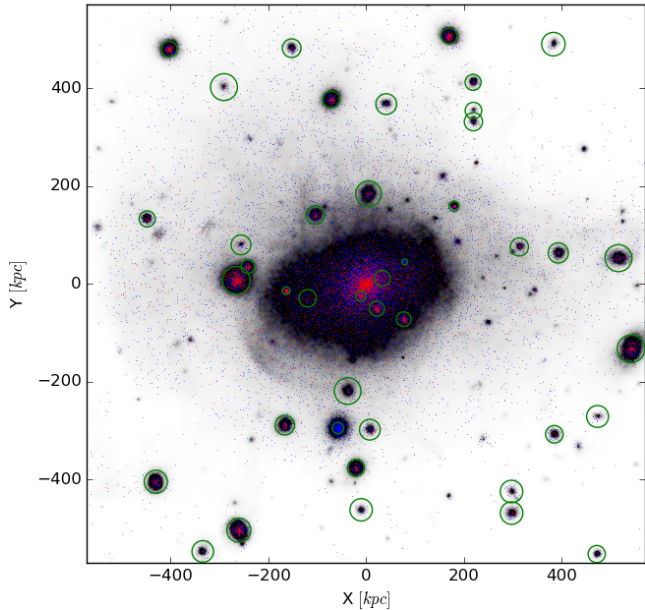


Figure 3. Zoom-in into our most massive galaxy cluster in the sample. Gray scale shows the stellar density and red/blue the tagged GCs candidates. GCs are considered associated to a galaxy if they are within 3 times the stellar half mass radius $3r_{h,*}$ (green circles).

model is that such evolution is not *needed* based on available observations, besides a calibration that accounts for the average fraction of GCs lost to tidal removal by the cluster. However, this does not mean that normalization of the $M_{GC}-M_{vir}$ relation cannot change with time (see discussions in e.g., [El-Badry et al. 2019](#); [Choksi & Gnedin 2019a](#)). It only means that, given the fair amount of free parameters in our model, we choose to adopt an unevolving infall relation and defer an exploration of changing this hypothesis to future work and plausible observational evidence that may justify better such assumption.

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 $z = 0$. We define a GC as “associated” to a galaxy if it lays within three times the stellar half mass radius of a galaxy, i.e., $r < 3r_{h,*}$. This choice is inspired by the typical values used in observations ([Peng et al. 2008](#)). However, replicating the exact procedure done on real galaxies is non-trivial and involves the fitting of parametrized profiles to account for an uniform background of not-associated GCs. Instead, here we adopt a simpler definition that scales the size with that of the central galaxy. We have explicitly checked that our main conclusions are not changed significantly by this choice by varying the criteria of association between $2-4r_{h,*}$.

Blue and red lines in Fig. 2 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,

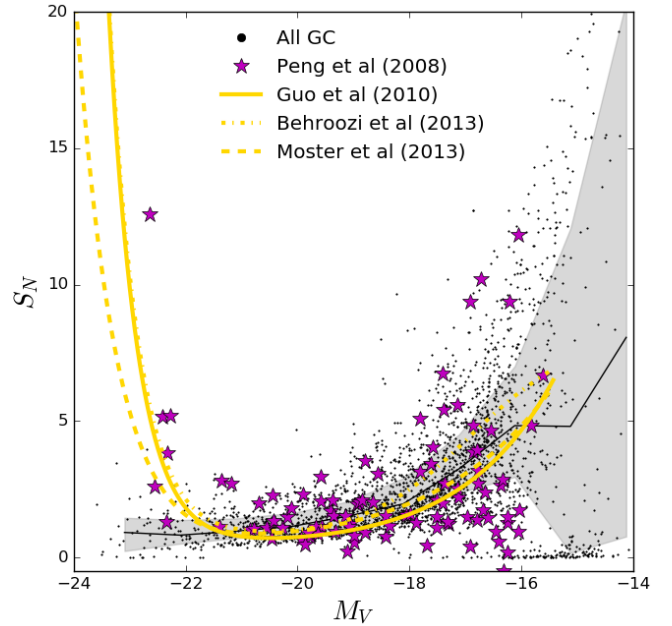


Figure 4. Specific frequency (S_N) as a function of V-band absolute magnitude M_V for all GCs (gray points). The simulation naturally reproduces the observed “U”-shape. Magenta stars are observed S_N values in galaxies from the Virgo cluster by [Peng et al. \(2008\)](#). Yellow curves were obtained analytically by assuming the [Harris et al. \(2015\) \$M_{GC}\$ vs \$M_{vir}\$ 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 \[Behroozi et al. \\(2013\\)\]\(#\) \(dotted\). The solid black curve indicates the median \$S_N\$ in bins of \$M_V\$ for our simulated galaxies. The grey area shows the 25%-75% quartiles range.](#)

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 an 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 $m_{GC} = 10^5 M_\odot$ ([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 particles, the needed number of realistic GCs. 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.

One of the caveats of our method is that the early destruction of GCs due to tides, evaporation and infant mor-

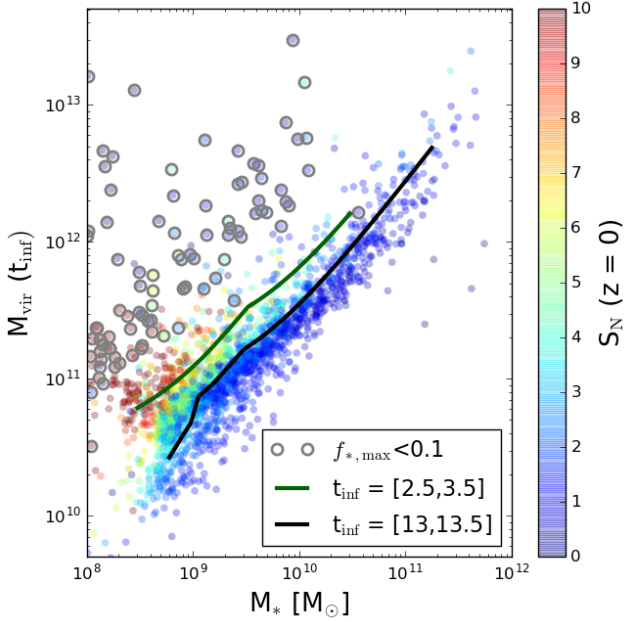


Figure 5. Virial mass at infall as a function of the present day stellar mass in our cluster galaxies. The points are color coded by their $z = 0$ specific frequency and show that large S_N values are associated to larger halo masses at infall. This can be explained as the result of the evolution in the stellar mass-halo mass relation. Black/green lines show the median M_* - M_{vir} 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).

tality is not explicitly followed. Instead, 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 a necessary compromise, since the modeling of such destruction processes can be not only cumbersome, requiring many free parameters (Pfeffer et al. 2018; El-Badry et al. 2019; Choksi & Gnedin 2019b), but also requires a numerical resolution that is currently prohibitive for the study of GCs on the scale of galaxy clusters. Consequently, our method is not able to inform us about the early destruction mechanisms of GCs and it has been designed, instead, as a tool to study the predictions of the surviving population at $z = 0$ within the cosmological assembly of structures.

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 join their 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 around galaxies in our 9 simulated galaxy clusters in Illustris-1.

Fig. 3 shows a zoom-in of the most massive galaxy cluster within half the virial radius. The background gray scale map corresponds to the stellar distribution. Superimposed in blue and red are the tagged *candidate* GCs. A close inspection of this figure indicates that most GCs are found today heavily clustered around the central and satellite galaxies. As introduced in Sec. 2, GCs are considered associated to a galaxy if they lay within $3r_{h,*}$. We indicate this criteria with a green circle.

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, these objects cannot be tagged and therefore will also be 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 $\sim 2\%$ 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 ($S_N \geq 5$, 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 of field and late type galaxies, which suggest $S_N \sim 1-2$ (Harris 1991; Miller et al. 1998). Although the large specific frequencies of 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 into 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,

$$S_N = N_{GC} \times 10^{0.4(M_v + 15)} \quad (6)$$

(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 $10^5 M_\odot$, see Sec. 2.3). Encouragingly, the GC specific frequency in our simulated galaxies, shown in black small dots, follow a similar the familiar 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 GC 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 yellow curves that are the results of a toy model, as follows. We vary the halo mass M_{vir} in the range $\log(M_{\text{vir}}/M_{\odot}) = [10, 15]$. For halos in this mass range, following the $M_{\text{GC}} - M_{\text{vir}}$ relation from Harris et al. (2015), we determine the mass in GCs. As a second step, assuming three different abundance matching relations $M_* - M_{\text{vir}}$ (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 $\gamma = 2$ to go from stellar mass to V-band magnitude and an average GC mass $M_{\text{GC}} \sim 10^5 M_{\odot}$, we compute the resulting S_N for a galaxy with M_V magnitude. This simple model seems to capture the essence of the simulated and observed trend; thus, it provides a possible interpretation for the S_N shape.

Our simulations also shed light on the origin on the scatter of the $S_N - M_V$ relation. The S_N scatter increases substantially towards the low mass galaxies in our model, in good agreement with observational findings (e.g. Peng et al. 2008; Forbes et al. 2018). In particular, we note the existence of several dwarf galaxies that at $z = 0$ have no associated GCs. A closer inspection of those objects reveal that their full GCs content has been tidally stripped by the gravitational potential of the host cluster. A more detailed analysis of the scatter in the $S_N - M_V$ relation suggests differences in the infall properties of surviving galaxies at $z = 0$. Fig. 5 shows 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 $M_* - M_{\text{vir}}$ relation with redshift in our simulations. To illustrate this, we show the median $M_* - M_{\text{vir}}$ relation of those points selected in very narrow ranges of infall times: $t_{\text{inf}} = [2.5, 3.5]$ Gyr (green) and $t_{\text{inf}} = [13, 13.5]$ Gyr (black). For halos infalling earlier into the cluster, the same halo mass is populated by a smaller stellar mass content, resulting in an increased S_N value today. Such evolution in the $M_* - M_{\text{vir}}$ 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 $S_N \geq 8$. These galaxies, located in the dwarf regime in Fig. 4, have retained less than 10% of their stellar budget but have held on to at least 10 GCs resulting in large specific frequencies at $z = 0$. The distribution of stars follows naturally a shallower profile than the cuspy Hernquist profile selected for GCs. Therefore, once a galaxy has been significantly depleted of stars, it may enter a regime where more stars are lost than GCs, explaining the rise in 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 $S_N \approx 10$ values and above with caution.

Although our assumption of an almost constant slope in the $M_{\text{GC}} - M_{\text{vir}}$ relation with redshift partially drives some of these results, it is reassuring to see that estimates of GC formation as a result of mergers might support such an assumption (see Choksi & Gnedin 2019a). 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. Mistani et al. (2016) also conclude that earlier infalling dwarfs have larger S_N values, an effect partially driven by their larger dark matter halo mass—in agreement with our results—and that more bursty star formation may increase 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 INTRACLUSTER 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) and 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

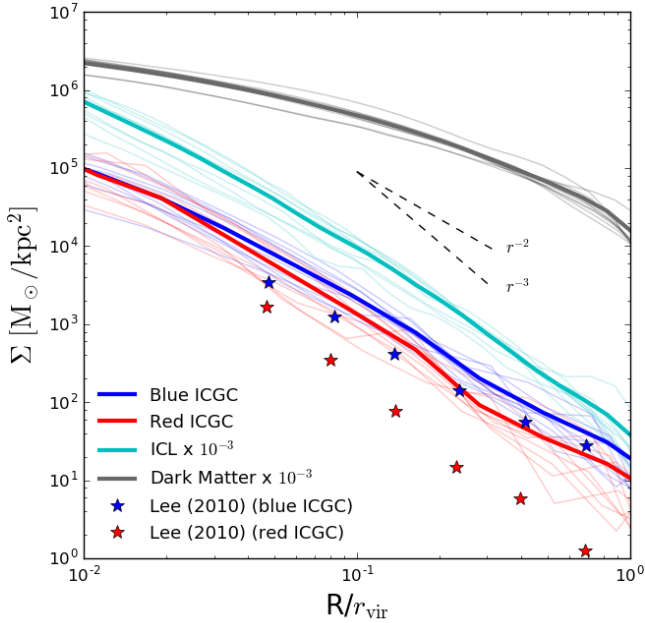


Figure 6. Projected density profiles for the red and blue intra-cluster GCs (red and blue curves), using thin lines for the 9 individual clusters and thick solid for the median in our sample. Encouragingly, the profiles are steeper than that of the dark matter in the clusters (gray) and comparable to 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.

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 $\Sigma_{\text{GC}} \sim r^{-2.5}$. A complete census of this diffuse component in observations is extremely challenging, and as a result only a few estimates are available to date. For reference, 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 for building the ICGC and the simplicity of our tagging method, the good agreement between the radial distribution of observed and simulated GCs is encouraging. To be conservative, in what follows, we will not distinguish between red and blue ICGC components and consider it as a single population.

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 brought in by galaxies that had fully merged to the central potential. We will refer to them in what follows as “orphan” GCs since their progen-

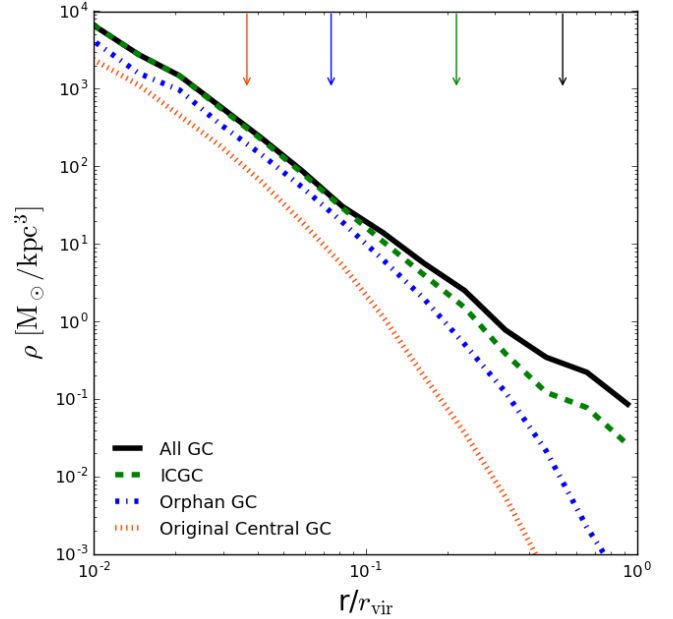


Figure 7. Median (stacked) 3D radial density profiles of simulated GCs separated in different populations: all GCs (solid black curve), intra-cluster GCs (dashed green), orphan GCs (defined as those brought into the clusters by a galaxy that has been fully tidally disrupted, blue dot-dashed) and GCs originally tagged to the central galaxies in each cluster (dotted red). As shown by the half mass radius of each component (matching colors vertical arrow at the top of the panel), the intra-cluster component is more centrally concentrated than considering all GCs, indicating that the majority of GCs in galaxy clusters today are still associated to their host galaxies, in particular, those orbiting in the cluster outskirts.

itors not longer exist today. Fig. 7 allows a closer look to this contribution as a function of radius from the cluster center. We show the 3D median density profile of the ICGC component in a stacking sample of our simulated clusters. ICGCs are shown in dashed green and it is split into contributions from orphans (blue dashed-dotted) and those that were originally assigned to the central galaxy (dotted red). The remaining contribution to the ICGCs, accounting for about 62% of this component, originates from GCs initially associated to galaxies that still survive today as satellites in the cluster¹. 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 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

¹ The exact contribution of surviving satellites to the ICGC component is only weakly dependent on the adopted cutoff of $3r_{h,*}$ to consider a GC as not associated to a galaxy. For example, this changes to 54% if the cutoff is extended to $5r_{h,*}$ instead

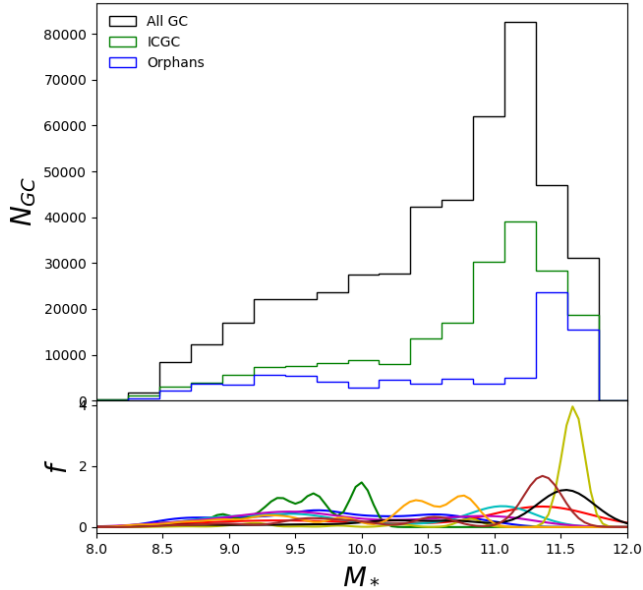


Figure 8. *Top:* Distribution of the (stellar) mass of the galaxy progenitors that contributed GCs to the total (black) and intra-cluster component (green) in all our simulated clusters. These are number weighted distributions, meaning that a galaxy is counted as many times as *candidate* GCs it contributed,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

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 $M_* \sim 10^{10.5} M_\odot$ and above (black solid curve), which seems to also apply for the intra-cluster component (green line). We have checked that this is the case when we look individually to each of the simulated clusters.

On the other hand, the orphan population seems quite diverse. Although adding all clusters hints to a highly skewed distribution towards massive progenitors for the orphan population (blue line, top panel), when analyzed separately, each cluster may show a different behavior. We demonstrate this in the bottom panel of Fig. 8, which shows for each

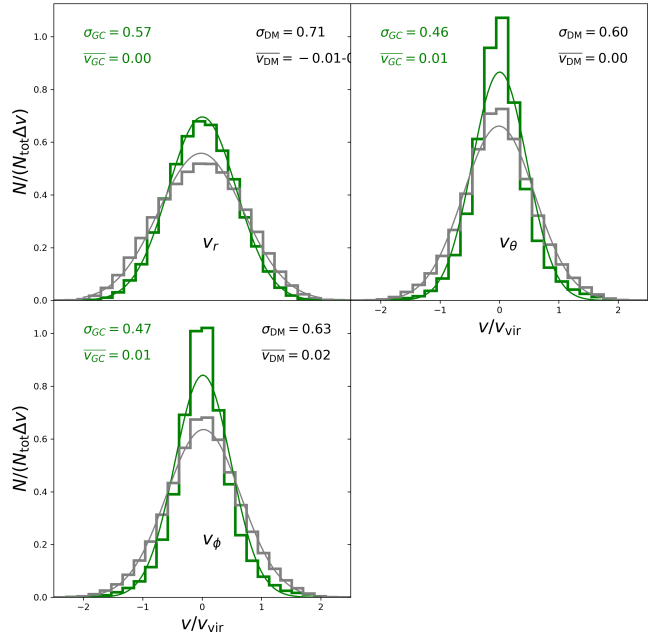


Figure 9. Distribution of the spherical velocity components V_r , V_θ , and V_ϕ for the stacked sample of GCs (green) compared to that of the dark matter in the cluster halos (gray). In general GCs are good tracers of the underlying dark matter distributions, with velocities well described by a Gaussian function. We quantify the similarity of the distributions by quoting the velocity dispersion in each component for the GCs and for the dark matter (left/right labels, respectively). Note also the larger dispersion in the radial direction compared to the other two tangential components.

cluster the progenitor stellar mass distribution for their orphan population. Because the number of orphans may vary from object to object, each histogram has been normalized such that the bins add up to 1 to ease the comparison. We find that about half of the galaxy clusters are heavily dominated by orphan GCs brought in by one or two very massive $M_* \geq 10^{11} M_\odot$ progenitors (major merger events). However, for the other half of the clusters, the contribution to the orphan GCs population is dominated instead by dwarf-like objects, with median masses $M_* \sim 10^{9.5} M_\odot$. Such variations should be imprinted in the chemical signatures of the ICGC component, providing clues to unravel the past accretion histories of their cluster hosts.

Therefore, our simulations indicate an interestingly broad distribution of galaxy masses that contributed to the build up of the ICGC component. As such, a heterogeneous range of metallicities and ages are expected to be found in observations, albeit modulated by the radial trends shown in Fig. 7. We note that histograms in the top panel of Fig. 8 are number-weighted, meaning that each candidate GC counts individually and the same galaxy progenitor is counted as many times as GCs it contributed. For GCs still associated to galaxies (contributing to the *all* curve in black), we consider 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.

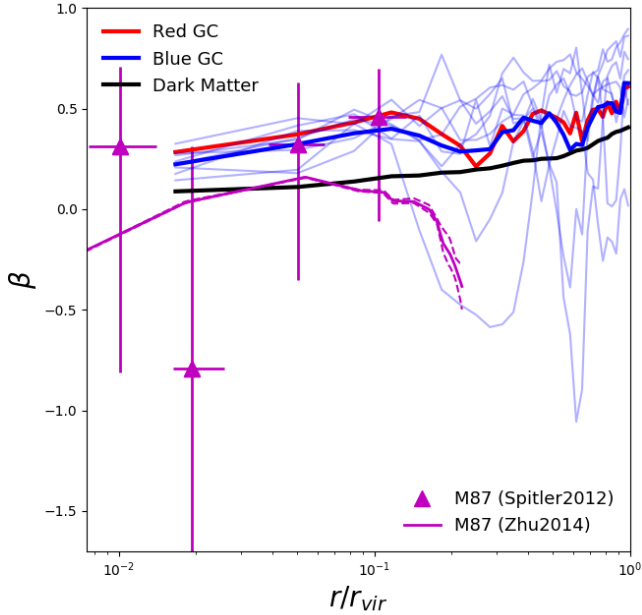


Figure 10. Predicted anisotropy profile β for the stacked sample of red and blue simulated intra-cluster GCs (thick solid red, blue lines, respectively). We predict a very radial ($\beta \sim 0.5$) orbital structure that is comparable to that of the dark matter component in the host cluster halo (solid black line). Thick lines correspond to the median of the stacked sample of our galaxy clusters and reproduces observational in inner regions of M87 (Zhu et al. 2014). However, tangentially biased orbits as measured in the outskirts of M87 (Zhu et al. 2014) are more 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 β to the presence of infalling groups/substructure. Notice that the odd external orbital distribution inferred for M87 traces quite closely one of our clusters.

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 system 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, albeit systematically smaller by ~ 20 -25%. The more concentrated radial distribution found for GCs compared to the dark matter in Fig. 6 is a possible explanation for this difference. Values for the r.m.s dispersion in all coordinates are quoted individually in each panel for both components to ease the comparison. In all cases, the distributions are well described by a Gaussian function with the measured r.m.s dispersion (indicated by the thin lines).

The radial velocity component for the ICGC as well as for the dark matter exceeds that of the θ and ϕ components, suggesting the prominence of radial orbits over tangential ones. This is shown in more detail in Fig. 10 by means of the orbital anisotropy parameter $\beta = 1 - 2\sigma_r^2/\sigma_t^2$, where $\sigma_t^2 = \sigma_\phi^2 + \sigma_\theta^2$ (Binney & Tremaine 1987). Thick solid lines show the median β 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 are preferentially tidally disrupted, thus donating their GCs to the cluster potential. Dark matter halos in Λ CDM galaxy clusters have long been known to be radially biased (Wojtak et al. 2009). Fig. 10 also shows the median β profile of the host dark matter halos (black curve) and confirms that the ICGC component is comparably and even slightly more radially biased than the dark matter in the clusters. Large β values therefore seem an unavoidable prediction for any scenario where structure grows hierarchically and tidal stripping plays a mayor role (Diemand et al. 2005; Creasey et al. 2019).

A few observational estimates of β are currently available in the literature and offer important constraints to theoretical models of GC assembly. In particular, 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 particularly challenging due to projection effects and the availability of a discrete number of GCs.

Applying the kurtosis technique to GCs around M87 suggests that their orbits are radially biased ($\beta > 0$), consistent with our predictions (magenta triangles in Fig. 10 compared to solid lines). Interestingly, an independent analysis of the GCs around M87 presented in Zhu et al. (2014) argues for a $\beta < 0$ beyond $r \geq 100$ kpc. 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 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 *final* GC content in halos and the destruction of individual GCs is not explicitly modeled. Instead, our simulations suggest an alternative explanation for negative β 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 β values are not uncommon. We have associated such dips in the profiles with the presence of infalling galaxies that have not yet virialized into the cluster. The GCs of these infalling objects mostly trace the substructure of the cluster (and hence the tangential motion), and they are not directly tracing the cluster potential.

The substructure explanation suggested by our simulations seems well aligned with GCs on possible tangential orbits in M87, as 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). 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, offering a path to proving or disproving such explanation.

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 large scatter in the specific frequency of GCs, S_N for dwarf galaxies, helping build the observed “U”-shape in the S_N -stellar mass or magnitude relation; 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 $M_V > -18$ as a result of the non-linear relation between halo mass and stellar mass. Furthermore, dwarfs that scatter upwards in the S_N - M_V 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 $M_* \sim 10^{10.5} M_{\odot}$ 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 substructure 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).

An important caveat of our analysis is that the GC content and distribution for each galaxy is not computed *ab-initio*, but instead parametrized based on empirical relations following Eq. 2 and 5. This means that only surviving GCs are tagged, providing no valuable insights on the formation, dynamics and destruction mechanisms of GCs at birth. 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 sub-pc 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 connections, but they are limited to the scale of individual galaxies (Pfeffer et al. 2018; Li et al. 2017; Renaud et al. 2017; Carlberg 2018; Kruijssen 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 Λ CDM such as Illustris, offer a unique opportunity to make predictions on the properties of GCs on the scales of galaxy groups and clusters until more sophisticated models become available. 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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