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The Formation of Globular Clusters in a Cosmological Context

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Abstract

Globular Clusters (GCs) are among the oldest gravitationally bound stellar systems, as they are characterised by stellar populations with ages of 11.5 to 12.5 Gyr. They probably formed during, or just after, the epoch of reionisation. Therefore, the study of these systems at high redshift can not only give insight into the processes and environments that governed star formation at that time, but they can also represent valuable probes of the reionisation epoch itself. However, the exact phases of GC formation are still unknown. Due to their compact sizes, the ability to directly observe the ancestors of present-day GCs at high redshift is still difficult; thus, we must turn to cosmological simulations. In this doctoral thesis, I utilised a suite of numerical simulations of a cosmological volume from the First Billion Years (FiBY) Project and I also ran a set of simulations of isolated galaxy environments down to $z \sim 2$.

As a first step, I performed an “agnostic exploration” of the demographics of low-mass stellar systems within the FiBY simulations. Specifically, I identified a population of dense objects with a stellar component of up to a hundred thousand solar masses and such that their fraction of baryons (over the total mass of baryons and dark matter) is close to unity; these objects are possible “infant GC candidates”. Compared to their present-day counterparts in the local Universe, these infant stellar clusters have a higher gas fraction and appear to be more extended, consistent with the properties of the few examples of proto-globular clusters currently observed at high redshift. They are compact systems, with densities higher than the average population of FiBY systems at the same stellar mass. The infant GC candidates appear to be more massive and more abundant in massive host galaxies, indicating that the assembly of galaxies via mergers may play an important role in building several GC-host scaling relations. I assessed the present-day GC mass (GC number) – halo mass relation and found it offers a satisfactory description of the behaviour of the infant GC candidates at high redshift, suggesting that such a relation may be set at formation. I also reported a new relation between the specific star formation rate of a host galaxy and the mass of the most

massive GC that holds across a large range of redshifts, thus providing a way to probe both the evolution of GCs as well as their host galaxy across time.

As a second step, I examined the origin of these infant GC candidates through the use of energy-angular momentum phase-space characterisation to identify bound structures within the simulations. By analysing the evolution in phase-space, I determined the redshift at which the infant GCs first became gravitationally bound. By studying the collapse of both the gaseous and stellar components of the objects, I found evidence that they undergo radial infall and that the collapse itself is driven by the internal self-gravity of the infant GC candidates. The phase-space characterisation also revealed that some infant GC candidates shared certain features in the energy-angular momentum plane, allowing them to be grouped by their behaviour in phase-space. This classification is reflected in the formation environment: infant GC candidates of the same phase-space class are found in hosts of similar morphology, the majority of which are located in clumpy, irregular proto-galaxies. Within the set of infant GC candidates studied, there are two which consist only of stars by $z = 6$. By analysing these particular objects, I found that supernova feedback is the main physical mechanism behind expelling the gas and halting star formation. These candidates best represent the local Universe GCs and provide a possible future for the gas-rich infant GC candidates beyond $z = 6$.

Finally, I explored the subsequent evolution of these infant GC candidates within their host galaxies by performing a new set of isolated, cutout numerical simulations evolved to redshift $z \sim 2$. These simulations were designed to focus on the three main groupings of infant GC candidates and to investigate whether they would survive within their hosts, without the influence of large-scale external factors. Three host galaxies were selected, containing a total of 11 infant GC candidates; most of these candidates are gas-rich, with a single object being composed only of stars by $z = 6$ (the time at which the previous FiBY simulations ended). I found that all gas-rich candidates are destroyed: their star formation activity peaks at $z \sim 6$ and, once the supernovae release their feedback and expel the gas, the remaining stars in the candidates can not adjust to the new potential and the objects dissolve. By comparing the destruction of the gas-rich candidates with the history of the star-only candidate (which had previously lost its gas due to supernovae as well, but survived), I found that a key factor in whether a candidate would survive the feedback phase is the ratio of gas mass to stellar mass. If this factor is too large, then the survival of the candidate is unlikely. This observation is further reinforced when comparing this ratio with the timescale for dissolution: on average, objects with a lower gas to stellar mass fraction live longer. To complete this analysis, I examined the evolution of the star-only candidate and its trajectory around

its host galaxy's barycentre. I found that the object is on an infalling orbit towards the centre of the host and, eventually, it begins to merge with the central part of the galaxy, in agreement with the GC infall formation scenario for nuclear star clusters.

Lay Summary

All large galaxies, including our own Milky Way, contain hundreds of globular clusters. Each is a dense group of about a million stars held together by their mutual gravity. They are local relics of the ancient Universe, as they were among the first stellar structures to emerge at the dawn of the formation of galaxies. Understanding how globular clusters formed and evolved through time can therefore allow for a deeper understanding of how galaxies came to be.

This thesis presents a computational investigation into the formation and early evolution of this class of ancient stellar systems. Thanks to an in-depth analysis of a suite of numerical simulations focused on the first billion years of the Universe, I identified a group of promising infant globular cluster candidates that could be the early ancestors of the star clusters that we observe in the local Universe today. These candidates are the densest stellar objects in the simulations, with masses and sizes comparable to the preliminary observations of globular clusters at high redshift. This area of investigation is blooming, with early detections by the James Webb Space Telescope already becoming available.

By studying the position and velocities of the gas and stars belonging to the infant globular cluster candidates, I concluded that the primary mechanism for their formation and early evolution is the collapse of the stars and gas themselves, as driven by their own self-gravity. I also found that there is a strong relationship between the properties of the candidates and the characteristics of their host galaxy. This result suggests the existence of a link between the formation pathway of the infant globular clusters and their natal galactic environment.

Finally, I conducted my own numerical simulations to study the evolution of the infant globular cluster candidates beyond the first billion years of the Universe, to evaluate their likelihood to survive to the present day. I found that, for a globular cluster candidate to survive, it needs to have an appropriate amount of gas and it must form its

stars very efficiently, otherwise the violent burst of energy determined by the explosion of the first massive stars in the cluster can be fatal.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Chapter 2 of this work has been published in [Phipps et al. \(2020\)](#), and Chapter 3 has been submitted to Monthly Notices of the Royal Astronomical Society and is currently under review.

(Frederika Phipps, August 2022)

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Chapter 1

Introduction

In the rich context of contemporary research in astrophysics, the formation and evolution of galaxies is one of the key problems that has yet to be fully understood. The currently favoured standard paradigm for the formation of structures in the Universe is the Lambda Cold Dark Matter (Λ CDM) model, where Λ is the cosmological constant which is a candidate for dark energy. Dark energy is believed to be responsible for the accelerated expansion of the Universe which has been observed through Type Ia supernova measurements ([Riess et al., 1998](#); [Perlmutter et al., 1999](#)). Within the Λ CDM model, potential wells generated by dark matter (DM) haloes drive the gravitational collapse of baryons. Once the gas is dense enough, self-gravity starts taking over, and gas clouds collapse further to form stars, stellar clusters, and galaxies. As baryons collapse, DM haloes continue to grow via accretion and mergers, which lead to the hierarchical growth of cosmic structures. While this general picture is now consolidated, important details still remain to be understood (e.g., see [Somerville & Davé, 2015](#); [Naab & Ostriker, 2017](#)). Specifically, the behaviour of key astrophysical processes on progressively smaller scales can now be assessed thanks to the gradual increase in numerical resolution of cutting-edge cosmological simulations (e.g., see [Johnson et al., 2013a](#); [Paardekooper et al., 2015](#); [Cullen et al., 2017](#); [Kim et al., 2018](#); [Ma et al., 2020](#)). This type of progress creates the opportunity to attack a number of long-standing questions related to the formation and evolution of low-mass stellar systems in the early Universe. Given the wealth of data expected from current and forthcoming observational facilities focused on the exploration of the high-redshift Universe, it is imperative to deepen our theoretical understanding of the formation process of star clusters at high redshift and their evolution to be able to provide an interpretation of observational data and testable predictions.

1.1 Observational studies of globular clusters

Globular clusters (GCs) are among the most ancient gravitationally bound stellar systems. They are ubiquitous in the way that they can be found around any type of galaxy, from dwarf to elliptical (e.g. see [Harris & Racine, 1979](#); [Harris, 2016](#)). They are massive ($10^4 - 10^7 M_{\odot}$), compact, roughly spherical, and extremely dense (e.g. see [Harris, 1996](#); [Renaud, 2018](#)). The shapes, masses, and densities of these objects are likely linked to their internal stellar dynamics. Because stellar populations of GCs are extremely old ($\sim 11.5 - 12.5$ Gyr, which corresponds to $z \sim 4 - 6$), it is assumed that they formed during or shortly after the epoch of reionisation (e.g. see [Ricotti, 2002](#); [Katz & Ricotti, 2014](#)). Hence, for this reason, studying these systems at high redshift can not only give insight into the processes and environments that governed star formation at that time, but can also represent valuable probes of the reionisation epoch itself (e.g. see [Paardekooper et al., 2013](#); [Boylan-Kolchin, 2018](#)). Investigating the formation of GCs also allows one to constrain the dynamical and chemical conditions in forming galaxies, and, through comparisons with local Universe observations, this can impart constraints on models relating to, for example, merger and assembly histories (e.g., see [Kruijssen et al., 2019b](#); [Renaud, 2018](#)).

GCs have been most extensively studied observationally. The most well-examined ones are those which orbit the Milky Way (MW) which have been studied with the Hubble Space Telescope among other observational facilities (e.g., see [Harris, 1996](#); [McLaughlin & van der Marel, 2005](#)), but projects have been pushed out to study star clusters around local group galaxies and beyond (e.g., see [Harris et al., 2013](#); [Bastian et al., 2013b](#); [Fouesneau et al., 2014](#); [Ryon et al., 2015](#); [Chandar et al., 2016](#); [Fahrion et al., 2020a,b](#); [Brown & Gnedin, 2021](#); [Bouwens et al., 2021](#)) and improvements to models of, for example, the colour-magnitude diagram allow for more accurate determination of physical properties of extragalactic GCs - see Figure 1.1 ([Cabrera-Ziri & Conroy, 2022](#)). Through these observations, several interesting features of GCs have been uncovered and studied in further detail.

The most distinctive feature of GCs is the presence of multiple populations (MPs) in their stellar content. This feature is deemed to be so unique to this class of clusters that it is often used as the defining factor for classifying objects as GCs. Every globular whose stellar population can be examined in detail has at least two distinct populations of stars, typically referred to as the first (1P) and second (2P) populations ([Bastian & Lardo, 2018](#)). 1P stars are characterised as having a low-metallicity chemical composition and can be linked to field-like stars in the host galaxy. Conversely, 2P stars seemed

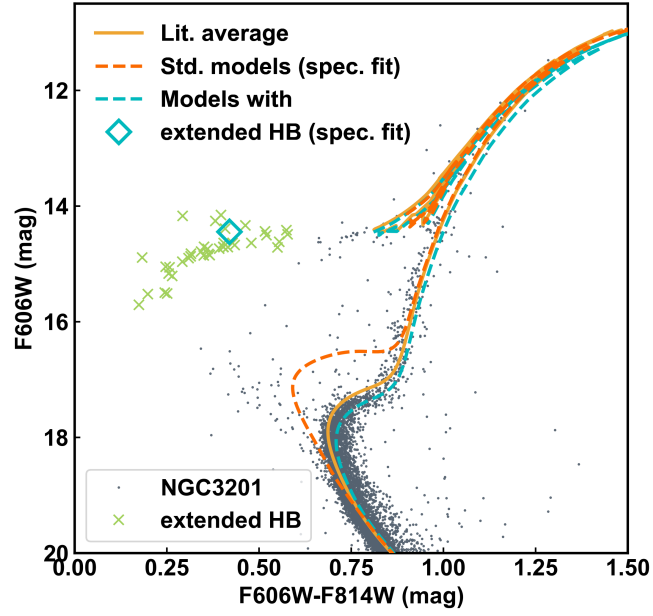


Figure 1.1 Figure extracted from [Cabrera-Ziri & Conroy \(2022\)](#), showing the colour-magnitude diagram of NGC 3201, confronted with a best-fitting representative model from the literature (orange dashed), and their new model, which includes a revised treatment of the extended horizontal branch stars (blue dashed).

to have formed later, as shown by their more enriched metal content ([Milone et al., 2017](#)). This population also exhibits anti-correlations in some of their lighter elements - for example Na-O (see Figure 1.2), N-C, and Mg-Al ([Carretta et al., 2009a,b](#); [Pancino et al., 2017](#)). MPs are identified by examining the chromosome maps of GCs (Figure 1.3). These analyses usually focus on a specific phase in stellar evolution, such as the Red Giant Branch phase, to identify the different populations (e.g., see [Piotto et al., 2015](#); [Soto et al., 2017](#); [Milone et al., 2017](#)).

There have also been some suggestions that the differences between these generations of stars extend beyond just their chemical compositions. In some clusters, it is found that the younger stars (2P) are preferentially located within the inner most regions of the clusters ([Lardo et al., 2011](#); [Simioni et al., 2016](#)), however not all GCs appear to show this trend ([Larsen et al., 2015](#); [Lim et al., 2016](#)). It has also been observed for some clusters that the 2P stars form the dominant fraction of total stars in the GC ([Milone et al., 2017](#)). Several recent studies have confirmed and characterised the multiple population phenomenon in GCs (e.g., see [Lagioia et al., 2019](#); [Milone et al., 2020](#); [Tang et al., 2021](#); [Dondoglio et al., 2022](#)).

Not only can the stellar populations of GCs be split into different populations, but so can the GCs themselves. Through studying metallicities, ages, kinematics, density

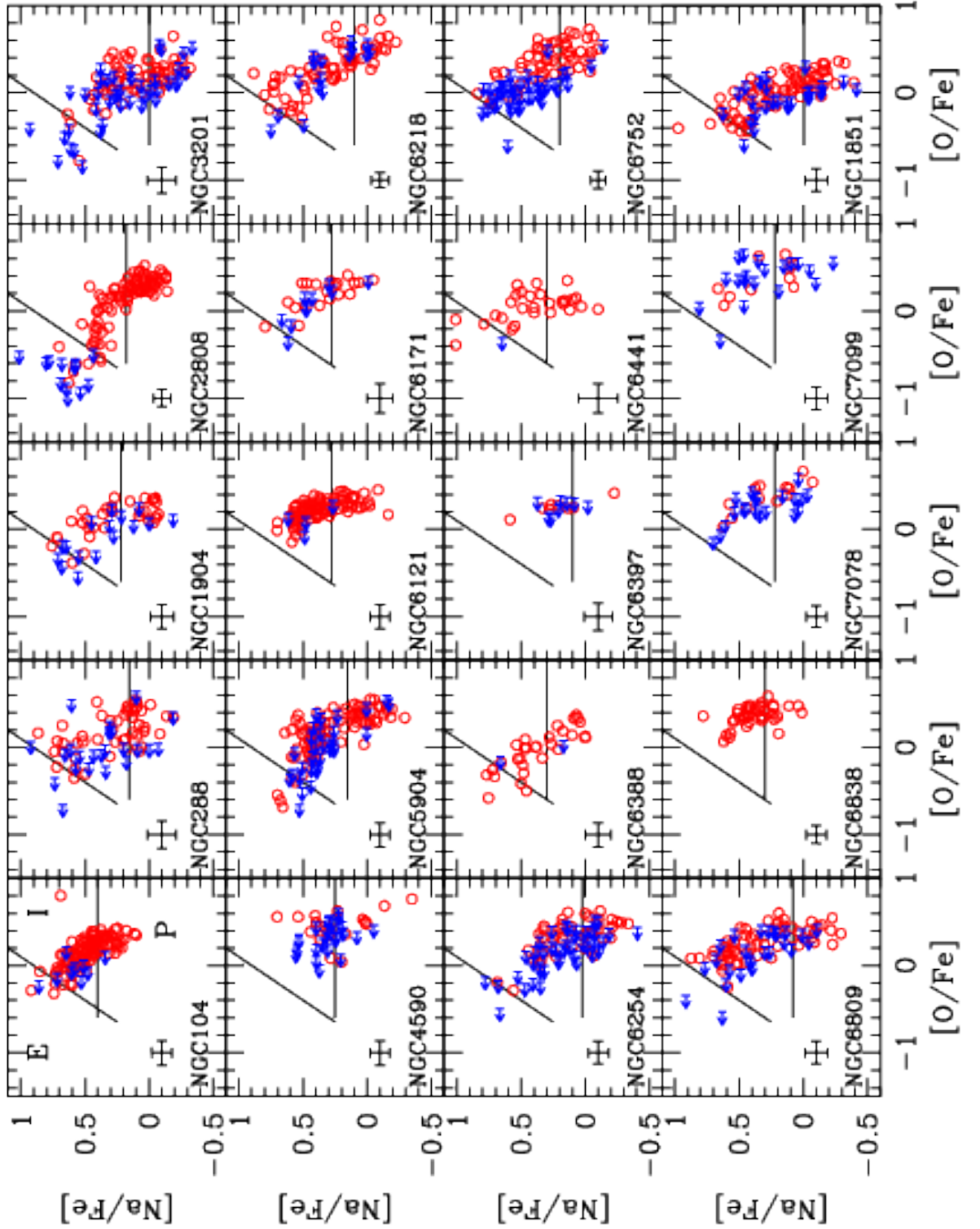


Figure 1.2 Figure extracted from the review by [Gratton et al. \(2012\)](#), showing the Na-O anticorrelations for a sample of GCs which were studied in one of the first comprehensive spectroscopic surveys of the multiple populations phenomenon, conducted by Carretta and collaborators with FLAMES. ([Carretta et al., 2009a](#)).

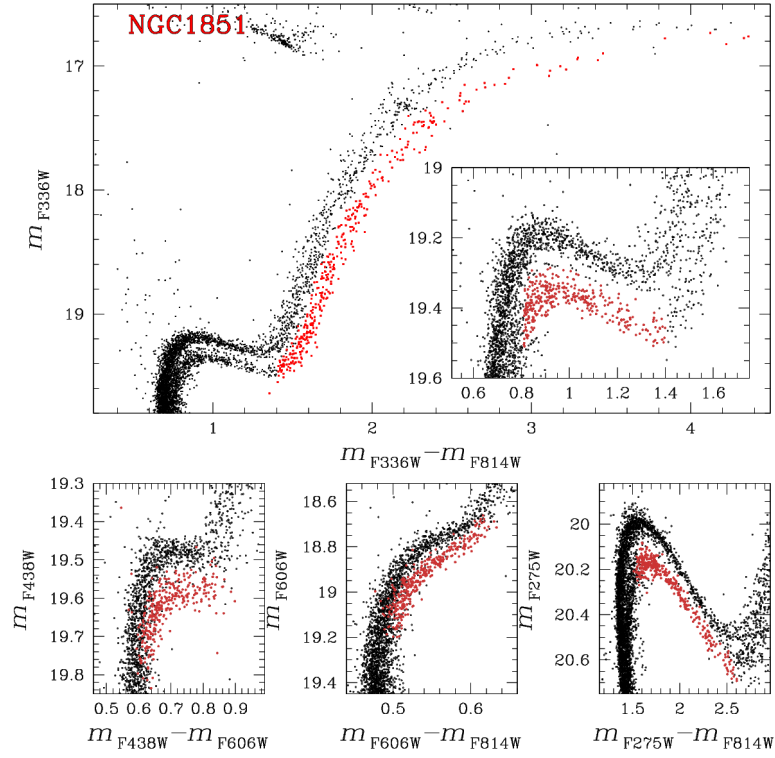


Figure 1.3 Figure extracted from [Milone et al. \(2017\)](#), showing a representative chromosome map for NGC 1851.

profiles, and distributions of the globulars in the MW halo, it is found that they can be split into two groups. In general, one can separate GCs into metal-poor and metal-rich through their location on the age-metallicity relation (AMR - see Figure 1.4) ([Forbes & Bridges, 2010](#); [Leaman et al., 2013](#)), which is also reflected as a colour bimodality of red (metal-rich) and blue (metal-poor) clusters ([Larsen et al., 2001](#); [Peng et al., 2006](#)). An in-depth study of the MWs system of globulars shows that the differences between these two groups extend beyond metallicity and colour.

It is found that the blue, metal-poor clusters are commonly found in the halo of the MW and show no net rotation as a population, indicating they were unlikely to have formed at the same time or in the same environment. On the other hand, the red, metal-rich clusters are preferentially found near or within the galactic disk, and they rotate with the MW ([Renaud et al., 2017a](#); [Renaud, 2018](#)). These differences between red and blue clusters implied that red GCs were likely formed in-situ (i.e., formed during the formation of the MW), whilst blue GCs were brought into the system later through mergers with dwarf galaxies ([Côté et al., 1998](#); [Tonini, 2013a](#); [Renaud et al., 2017a](#); [Recio-Blanco, 2018a](#)). This hints that there are at least two modes of formation for GCs. The different environmental conditions of low-mass and high-mass galaxies may lead to the formation of blue and red populations. The colour bimodality has also been

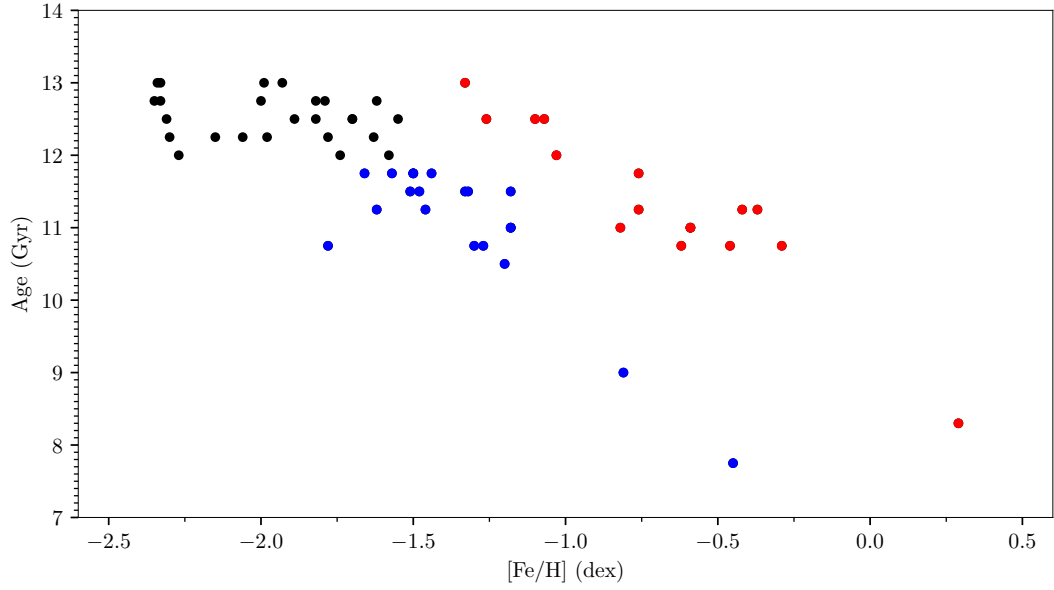


Figure 1.4 *Figure 1 from [Recio-Blanco \(2018a\)](#) showing the AMR using data from [Leaman et al. \(2013\)](#). The metal-rich and metal-poor clusters are shown in red and blue respectively and there is a clear split between the populations.*

observed in other systems of GCs beyond the Milky Way. For example, in [Fahrion et al. \(2020a,b\)](#), they examined the GCs in the Fornax cluster system and also find a colour bimodality. The red GCs in Fornax, in general, traced the stellar metallicity profile of the inner regions of the host galaxy - again hinting at in-situ formation. They find a non-linear fit for the colour-metallicity relation of the GCs in this system - the exact form of the colour-metallicity relation is debated ([Kim et al., 2021](#)) - and the metallicity distribution function predicted by this relation supports different formation origins for metal-poor and metal-rich GCs.

Beyond the in-depth population studies of GCs and their stellar content, the relationship between GCs and their hosts has been looked into. As suggested previously, there are some links between the metallicities and/or motions of a subset of GCs and their hosts. However, there are also relationships between the physical properties of a galaxy and the system of GCs it hosts. These relationships are important to examine as they may provide clues to the potential co-evolution of GCs and their hosts. One such relationship exists between the total mass (or number) of GCs in a system and the halo mass of the host galaxy (e.g., see [Spitler & Forbes, 2009](#); [Harris et al., 2015, 2017](#); [Saifollah et al., 2021](#); [Eadie et al., 2022](#)). This is a linear relation that can be characterised by a simple equation:

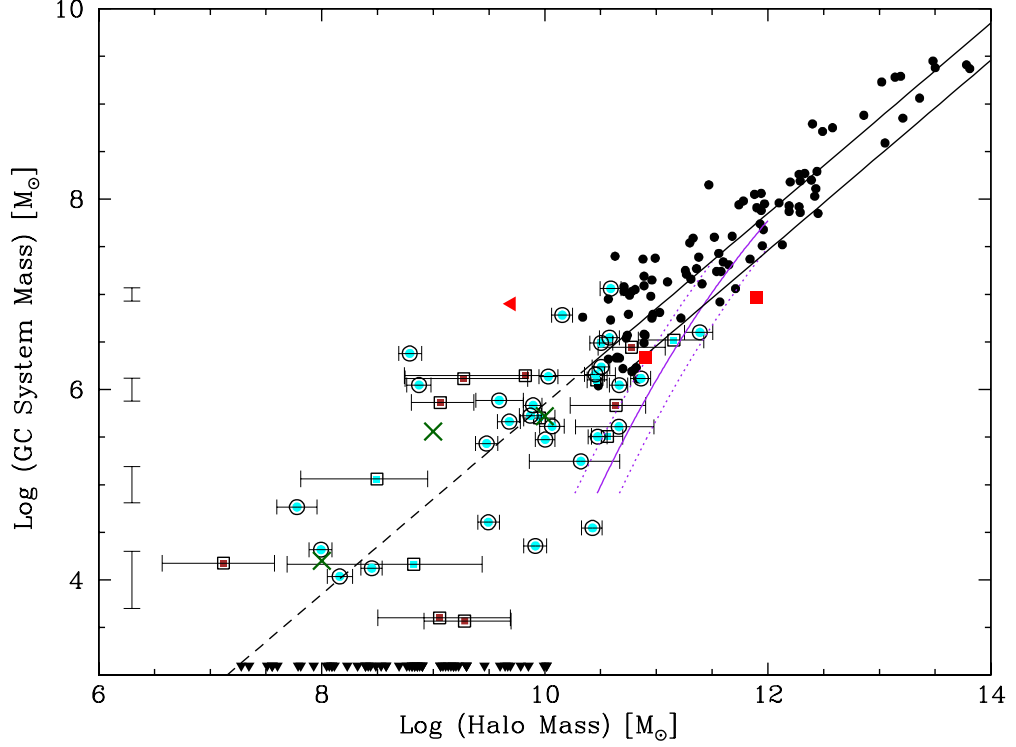


Figure 1.5 Figure extracted from [Forbes et al. \(2018b\)](#) showing the GC system mass – halo mass relation for low (cyan points) and high (black points) mass hosts.

$$\log \left(\frac{M_{\text{GC}}}{M_{\text{Halo}}} \right) = -C \quad (1.1)$$

where M_{Halo} is the mass of the host halo, M_{GC} is the sum of the GC masses in that halo and C is a constant derived from a fit to data. This relationship is shown to hold for both high and low-mass galaxies ([Forbes et al., 2018b](#)) (Figure 1.5), hence any model of GC formation needs to reproduce Eqn 1.1 at low redshift. The above result implies that, regardless of environment, all GCs undergo either similar formation processes or evolutionary histories in order to produce a self-consistent relation across a wide range of masses. Whether Eqn 1.1 undergoes an evolution with redshift is not constrained observationally due to current limitations with telescope facilities being unable to resolve and measure individual GC masses around galaxies at higher redshifts, although hopefully with the launch of JWST we can get a better handle on the observational evolution of this relationship. However Equation 1.1 can be investigated computationally or analytically (e.g., see [Bastian et al., 2020](#); [Chen & Gnedin, 2022](#)). The presence of the $M_{\text{GC}} - M_{\text{Halo}}$ relationship at high redshift would

be a strong indication that the formation of GCs goes hand-in-hand with the formation of the host, rather than one being formed before the other (see Section 1.2) and it would also suggest that the formation of GCs is primarily dependent on physical properties of the host galaxy. Another relationship that has been studied is the specific frequency of GCs as a function of galaxy mass. The GC specific frequency follows a U-shaped trend, which is likely due to the different modes of feedback that are operating at different masses during galaxy formation (Harris et al., 2013). It is clear, therefore, that the evolution history of the host galaxy has an impact on the population of GCs it hosts (whether by destroying them or by increasing their number due to mergers). As we go to higher redshifts, it is more difficult to study GCs in detail. These relationships between the host and GC system are therefore vital to understand in order to use the host galaxy to trace GC evolution observationally.

The mass function of GCs at present-day can be approximated as a log-normal function with a critical mass of $10^{5.3} M_{\odot}$ (Elmegreen, 2010). Therefore, there are some GCs in the local Universe whose masses are similar to those of some dwarf galaxies (see Figure 1.6 taken from Bouwens et al. 2021), which has sparked some debate on how to distinguish a star cluster from a low-mass galaxy. One suggestion has been to look at the mass segregation in these objects. The process of mass segregation takes a few relaxation times, and due to the density and size of globular clusters, they should display mass segregation (as their relaxation times are shorter), whereas low-mass dwarf galaxies would not (Baumgardt et al., 2022). Another potential separating factor is to examine the DM content of these low-mass objects. By studying the mass-to-light ratios of known GCs, they have been found to have ratios near to unity (e.g., see Weidner et al., 2004; Baumgardt, 2017; Baumgardt et al., 2020) implying that GCs have no DM content or halo. By examining the velocity profiles of low-mass stellar objects, one could determine whether there is a DM halo for the object and, if so, one can conclude that it must be a low-mass galaxy rather than a GC. However, this second method comes with its own problems, as recently there have been some studies conducted that focus on the outskirts of GCs, utilising astrometric data from Gaia. They have found interesting signatures in the velocity dispersion profiles that hint at an extended DM halo for, at least, some of these objects (e.g., see Ibata et al., 2013; Penarrubia et al., 2017; Bianchini et al., 2019a), hence care needs to be taken when using such a method.

All these observational studies of GCs in the local Universe provide hints and clues to the possible formation channels for GCs. Theories surrounding GC formation are vast, and I will explain the main ones in the next Section.

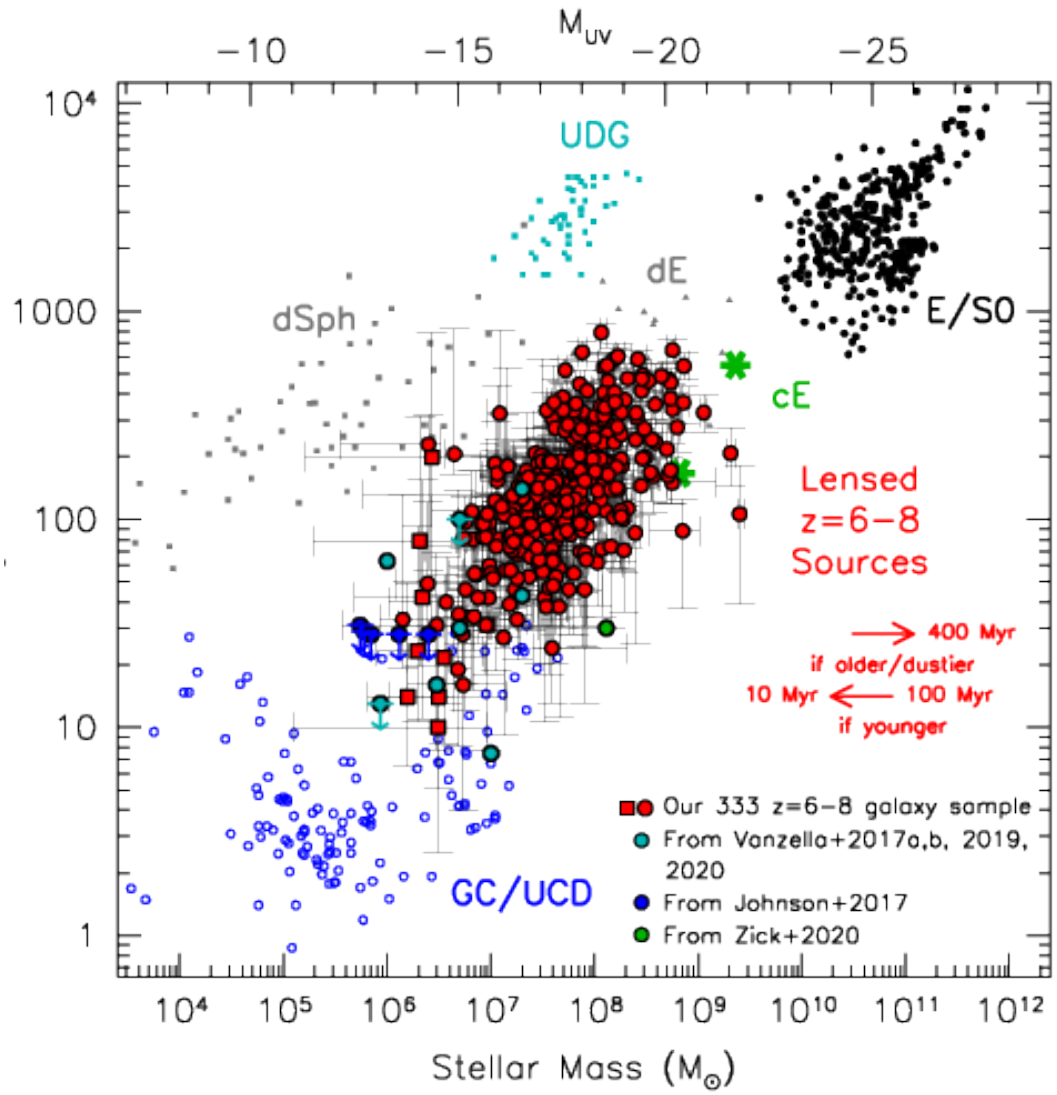


Figure 1.6 Figure extracted from [Bouwens et al. \(2021\)](#) showing the masses and sizes of different stellar systems in the local Universe including GCs (blue) and a variety of dwarf galaxies (red, grey, cyan) as well as ellipticals (black).

1.2 Formation scenarios for globular clusters

The path through which GCs are formed is still unknown, however, many different theories have been proposed. There is a possibility that some GCs formed through different channels, as GC formation can occur from $z > 6$ down to at least $z = 3$ (e.g., see [Katz & Ricotti, 2013](#); [Kruijssen, 2015a](#)). Over this vast period of cosmic time, the Universe changed drastically, thus the conditions under which star and cluster formation occurred evolved significantly as well. Any theory put forward to explain GC formation has to satisfy a number of observational constraints - detailed in the previous subsection. The observed colour bi-modality and the age-metallicity relation of GCs have led astronomers to believe that a fraction of GCs form in-situ within their host galaxy, whilst the remaining globulars in the system might have been accreted from in-falling dwarf galaxies (e.g., see [Côté et al., 1998](#); [Tonini, 2013b](#); [Renaud et al., 2017b](#); [Recio-Blanco, 2018b](#)). Whilst the in-situ vs. ex-situ operational framework can not provide the fine details on the exact formation mechanism of these stellar systems, it does provide empirical evidence that there could be at least two different channels of formation for GCs. If blue GCs do indeed originate in dwarf galaxies, then, the environment they formed in could be different from those of red GCs. When considering the metallicities of the blue and red populations, it is deduced that the blue GCs formed earlier than the red GCs (as inferred from their lack of metals). Some early theories already attempted to address the constraint imparted by colour bi-modality. The first investigations in this remit by [Schweizer \(1987\)](#) and [Ashman & Zepf \(1992\)](#) proposed a two-step formation process to account for the age difference between the red and blue GCs. They suggested that the blue GCs form in the early Universe, in metal-poor environments, before the formation of the first galaxies (see also [Peebles & Dicke, 1968](#)). These early, blue GCs then enrich the gas in their host galaxies with metals, and the galaxies themselves eventually merge with other hosts. This merging process triggers starburst activity from which the red GCs emerge.

Over the years, there have been some further developments, using this theory as a foundation. One perspective that has been taken is that the red GCs form in gas-rich discs and that galaxy mergers further enhance their formation ([Kravtsov & Gnedin, 2005](#); [Shapiro et al., 2010](#)). However, a caveat to this interpretation is presented by the cosmic merger history itself, as the extent of the distinction between the two GC populations strongly depends upon the merger activity. In this regard, since mergers can proceed at any redshift, one would expect the present-day GCs to ultimately achieve a continuous and uni-modal colour distribution. Another two-step formation channel

for GCs has been proposed by [Forbes et al. \(1997\)](#), with attention to the role of the interstellar medium (ISM). The first step occurs during the collapse of the proto-galaxies, which is when the blue GCs are pinpointed to form. This phase likely ends when reionisation occurs, as this process quenches star formation ([Beasley et al., 2002](#)). The second step is identified as the phase when GCs formation is then resumed, once the ISM becomes dense enough, due to the formation of galactic discs. This scenario naturally accounts for the bi-modality observed. However, from the age constraints of both the blue and red population of GCs ([Forbes et al., 2015](#)), the redshifts at which these two steps occur can be determined only approximately, with the second one thought to take place at $z \sim 3$.

In more recent years, it has been suggested that the GC population is just a consequence of standard clustered star formation in high redshift environments (e.g., see [Kruijssen, 2015a](#); [Keller et al., 2020](#)). Stars and star clusters form from gravitationally bound gas structures called giant molecular clouds (GMCs) ([McKee & Ostriker, 2007](#); [Dobbs et al., 2014](#)). GMCs in the local Universe typically have masses $M \geq 10^4 M_\odot$ ([Williams et al., 2000](#)), but, in more distant galaxies, they have been observed to have masses up to $10^7 M_\odot$ ([Vogel et al., 1988](#); [Sakamoto et al., 1999](#)). Therefore, when studying the formation of low-mass stellar systems, one needs to consider the effects of large-scale gas dynamics and the evolution of cloud properties. It is possible that the early stages of GC formation are similar to those of GMC formation. GMCs typically form either in a “bottom-up” or “top-down” process. Summarised, the bottom-up process involves a series of inelastic collisions of cold clouds of HI. The mean size and mass of the overall cloud then increases gradually until it reaches the size of a GMC ([Field & Salpeter, 1965](#); [Kwan, 1979](#)), however, this process is slow. When considering the timescales of individual collisions, the total procedure exceeds the estimated GMC lifetime, hence the “top-down” process was proposed. This theory involves large-scale instabilities in a diffuse ISM ([Elmegreen, 1979, 1995](#)) - instabilities such as the Parker instability ([Parker, 1966](#)) or the Jeans instability. Recently, [Ma et al. \(2020\)](#) used zoom-in simulations to study high-redshift globular clusters, they found that both the bottom-up and top-down scenarios were observed.

Another crucial aspect that any formation theory of GCs needs to address concerns their expected amount of DM content, both at formation as well as at their present-day conditions. GCs could have potentially formed as a result of gravitational instabilities driven by baryons without the need for DM. However, another possibility is that GCs were formed at the centres of their own DM haloes. The DM halo can be removed from the GC through an interplay between external (e.g. see [Moore, 1996](#); [Saitoh](#)

et al., 2006; Creasey et al., 2019) and internal dynamical processes (e.g. see Bromm & Clarke, 2002; Mashchenko & Sills, 2005; Hurst & Zentner, 2019), as well as feedback processes (Pontzen & Governato, 2012; Davis et al., 2014). In the model employed by Creasey et al. (2019), they conclude that the present-day GC should still lie within an extended DM halo, but the material within their core radius should remain DM free - to confirm this scenario, a positive detection of extended DM haloes around present-day GCs would be needed. In order to address these questions in the local Universe, detailed astrometric and spectroscopic observations of member stars in the peripheries of GCs are required and the structural and kinematic properties of these stellar systems in their very outer regions must be explored. These empirical assessments have become possible only recently, thanks to the ongoing mission Gaia (Gaia Collaboration et al., 2018). It could be possible that some remnant of the DM halo is still preserved in the peripheries of present-day GCs (e.g. see Heggie & Hut, 1996; Baumgardt et al., 2009; Lane et al., 2010; Conroy et al., 2011; Ibata et al., 2013; Penarrubia et al., 2017; Bianchini et al., 2019a).

Due to the high redshifts at which GCs are expected to form, it is possible that they contribute significantly to the reionisation of the Universe (e.g., see Ricotti, 2002; Schaerer & Charbonnel, 2011; Katz & Ricotti, 2013, 2014; Boylan-Kolchin, 2018). However, it is still unknown what the escape fraction of ionising photons would be for such objects, although efforts have been made to estimate this figure (e.g., see Paardekooper et al., 2015; Howard et al., 2017, 2018; Kimm et al., 2019; He et al., 2020). Another significant era in the history of the Universe that could be related to the formation of GCs is that of recombination. At that time, the baryons and photons are coupled, resulting in the DM particles cooling and collapsing more efficiently than the baryons. Once the baryons are decoupled from the photons, there is a difference between the velocities of baryons and DM particles (Naoz & Barkana, 2005). This difference between the stream velocities of baryons and DM particles increases as the baryons cool and the relative velocity becomes large enough for the baryons to become supersonic. This results in an offset between the DM halo and the baryons that reside within it. Thus, in theory, a DM-free object at very high redshift can exist - these objects are known as “SIGOs - Supersonically Induced Gas Objects” (Naoz & Narayan, 2014; Tseliachovic & Hirata, 2010; Tseliachovich et al., 2011). Recently, it has been suggested that these objects could be an early progenitor of present-day GCs, and this could be one potential formation channel for globulars or low-metallicity star clusters (Popa et al., 2016; Chiou et al., 2018, 2019, 2021; Lake et al., 2021). There are many questions surrounding this theory, however. Preliminary studies have found the supersonically induced objects to be relatively low in mass and very metal-poor,

therefore it is uncertain whether many of these objects would survive to low redshift, and, even if they do, they may not resemble the local Universe globulars we see today.

A majority of the formation theories discussed so far are concerned with recreating the global properties of GCs from observational studies, yet most are unable to explain the presence of MPs and other small-scale physical details of GCs. Whilst the mechanisms through which MPs are formed have been discussed in the literature (e.g., see [Prantzos & Charbonnel, 2006a](#); [Decressin et al., 2007a,b](#); [D’Ercole et al., 2008](#); [Bastian et al., 2013a](#); [D’Ercole et al., 2016](#); [Bekki, 2017](#); [Elmegreen, 2017](#)), this thesis focuses more on the global formation of GCs, but, for completeness, some of the main MP formation theories are outlined here below. A popular model for the formation of multiple populations is the Asymptotic Branch (AGB) scenario. The first population of stars are formed with the same age and a single abundance spread; after ~ 30 Myr, many of these stars enter the AGB phase of stellar evolution. The winds of the AGB stars can enrich the surrounding gaseous medium with heavier metals. Due to the combination of low-velocity winds and a large potential well, the enriched material cools and condenses to the centre of the cluster. This is when the second population of stars is formed ([D’Ercole et al., 2008, 2016](#); [Bekki, 2017](#)). Another model, by [Bastian et al. \(2013a\)](#), is based upon observations and constraints from young massive clusters (YMCs) in the local Universe. Enriched material is ejected from high mass stars and pollutes the low mass stars ($< 2M_{\odot}$), which were formed at the same time. For this model to be efficient, the timescales for wind transfer and accretion would have to be of order $\sim 10^7$ years and simulations have since shown that accretion occurs on much smaller timescales ($\sim 10^4$ years) rendering this model unfeasible ([Wijnen et al., 2016](#)). The Extended Cluster Formation Event model ([Prantzos & Charbonnel, 2006b](#); [Elmegreen, 2017](#)) requires multiple generations of stars to form before the first stars formed in the cluster go supernova. This model would occur in high-density environments where the envelopes of massive stars are stripped and subsequently mixed into the gas enriching later generations of stars. However, this model also fails to reproduce all the observables for MPs in GCs at present-day ([Lochhaas & Thompson, 2017](#)). Fast Rotating Massive Stars (FRMS) have also been suggested as a mechanism behind MPs in GCs. The heavy metals in the cores of the FRMS can be brought up to the surface and disseminated into the surrounding medium. This model is similar to that of the AGB model, except the FRMS scenario can only occur for clusters younger than 20 Myr, hence, it results in a “mass budget problem”, as not enough material is processed from the 1P stars to explain the observed 2P stars.

The difficulty in determining the formation channel (or channels) of GCs is primarily

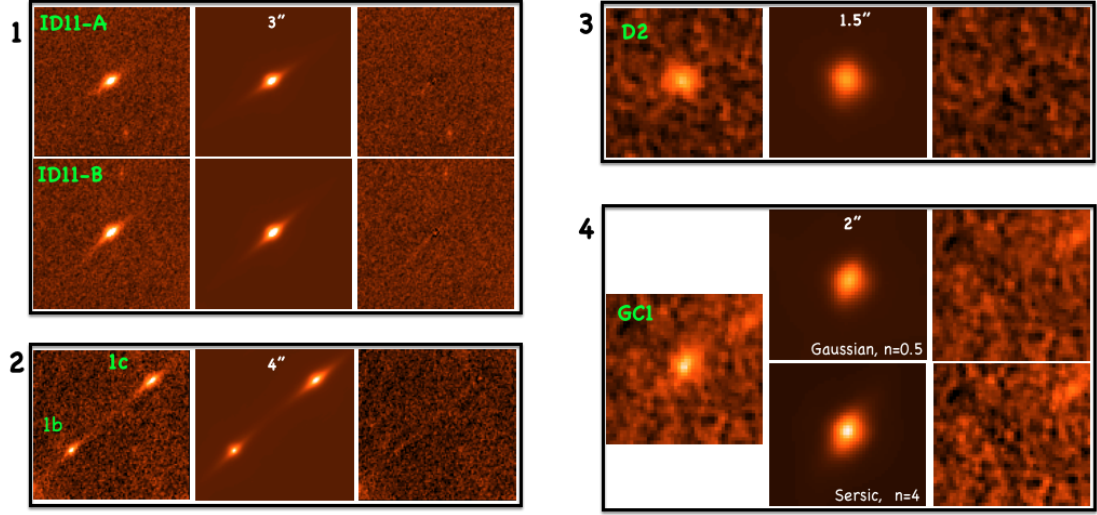


Figure 1.7 *Figure extracted from Vanzella et al. (2017), showing the four most compact and magnified objects in their VLT/MUSE study. The sources are located at $z > 3$ and are deemed to be proto-GCs.*

due to the lack of observations of proto-GCs at high redshift. Whilst there is evidence of such objects being detected (see Figure 1.7) (see Vanzella et al., 2017, 2019, 2020; Meštrić et al., 2022; Elmegreen & Elmegreen, 2017; Bouwens et al., 2017a, 2021; Bouwens et al., 2022; Kawamata et al., 2018; Kikuchihara et al., 2020, among others), these observations do not yet have the required depth or detail needed in order to provide constraints on different formation scenarios for GCs. With the launch of JWST, there will soon be new observations of star clusters forming at high redshift (Coe et al., 2021; Vanzella et al., 2021) which can be examined and compared to the theoretical predictions. In fact, some preliminary results from JWST of high-redshift star clusters have already been shared (Vanzella et al., 2022; Mowla et al., 2022; Faisst et al., 2022) and a preliminary detection of proto-GCs can be seen in Figure 1.8. However, numerical simulations are an alternative way to study and assess these formation channels, in preparation for more stringent observational constraints. In the next Section, some of the studies of GCs in simulations are discussed.

1.3 Globular clusters in simulations

Numerical simulations offer an alternative tool to study the formation of low-mass stellar systems and to test current theoretical models. Over recent years, the resolution of cosmological simulations has increased greatly and the models describing the underlying physics have been significantly improved. Various studies have been

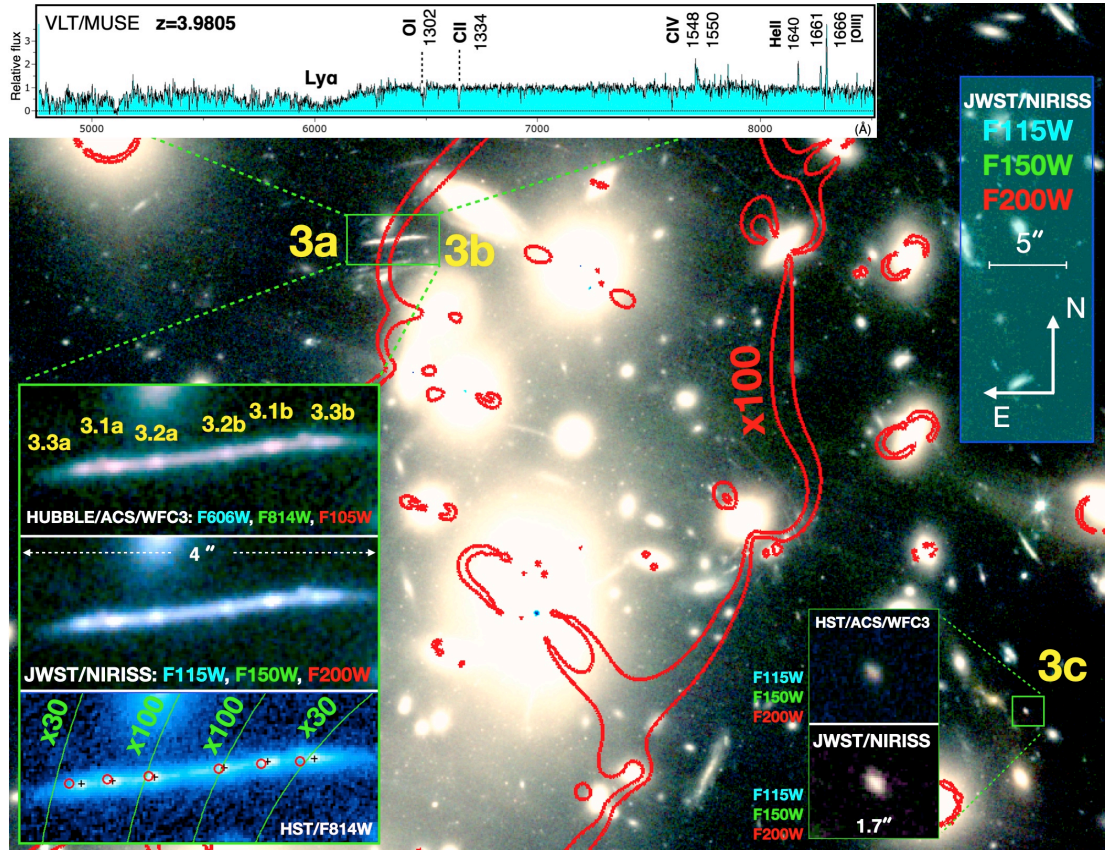


Figure 1.8 Figure extracted from [Vanzella et al. \(2022\)](#), showing a colour composition of an image taken by JWST/NIRISS of cluster A2744. The region highlighted by a green rectangle outlines a magnified arc at $z = 4$, which is zoomed in upon in the insets on the lower left-hand side. The compact star clusters are numbered and the lower left-hand insets show the Hubble colour image (top), JWST/NIRISS colour image (middle) and Hubble F814W image (bottom). The lower right-hand side insets show the colour images in Hubble (top) and JWST/NIRISS (bottom) for cluster 3c. The top inset shows the VLT/MUSE spectrum for the magnified arclet.

conducted using a wide range of simulations from local (e.g. Nakasato et al., 2000; Bate et al., 2003) to cosmological settings (e.g. Kravtsov & Gnedin, 2005; Prieto & Gnedin, 2008). Several groups now use a variety of simulation suites to study the formation of GCs (e.g. Ishiyama et al., 2013; Rieder et al., 2013; Ricotti et al., 2016a; Kim et al., 2018; Carlberg, 2018; Reina-Campos et al., 2019; Li & Gnedin, 2019; Ma et al., 2020). Some of these studies rely on present-day observational criteria to identify and characterise possible progenitors of globular clusters.

One recent example is the study conducted by Halbesma et al. (2020) to identify GC candidates within the Auriga simulations. They were interested in assessing whether the galaxy and star formation models implemented in their simulations were able to also reproduce a realistic GC population. They identified GC candidates by selecting star particles that had an age older than 10 Gyr, which would imply that all stars present in their simulations at $z \geq 6$ are GC members. One local observational property of GC systems that has been used to identify GCs at high- z in simulations is the GC system - halo mass relation. In their work, Creasey et al. (2019) assumed that a GC formed within any halo which had a virial mass $\geq 10^8 M_{\odot}$.

Other approaches include looking at gravitationally bound star clusters of a given mass in zoom-in simulations throughout cosmic time (e.g. Ma et al., 2020). Whilst these approaches are effective in selecting promising candidates, they could lead to biases in any predictions that are made, because of the intrinsic limitations in capturing the dynamical evolution of the GCs. This evolution has a significant impact on their total mass function, individual mass function, as well as their detailed phase-space structure (for an overview see, e.g. Elson et al. 1987; Meylan & Heggie 1997; Heggie & Hut 2003, and, more recently, Portegies Zwart et al. 2010; Kruijssen 2014; Bastian & Lardo 2018; Renaud 2018; Gratton et al. 2019). Also, it is not evident that all bound objects in a given mass range can be uniformly and reliably classified as GCs. Ideally, one would like to combine different criteria to produce a selection approach for infant GC candidates that matches physical constraints on them, both in the early and local Universe.

Understanding the formation and evolution of star clusters, and, in particular, GCs has also been explored extensively in direct N-body simulations (Heggie & Hut, 2003). N-body simulations of this kind offer an accurate way to explore the dynamical evolution of collisional stellar systems. They can be used to study the dynamics and interactions of individual particles and, currently, they can finally reach a high resolution, modelling clusters with an order of a million particles (Heggie, 2014; Wang et al., 2016). This is particularly useful when wanting to understand the collisional processes that lead

to, for example, mass segregation and energy equipartition (Trenti & van der Marel, 2013; Webb & Vesperini, 2017; Pavlík & Vesperini, 2021, 2022). Collisional and collisionless N-body investigations have also been extensively used to study complex features of GCs, such as stellar stripping and tidal tails (Lee & Ostriker, 1987; W. et al., 2010; Amorisco et al., 2016; El-Falou & Webb, 2022; Webb & Bovy, 2022), or to gain a deeper understanding of the roles that dynamical friction or other subhaloes (e.g. dwarf galaxies) have in modifying the orbits of GCs within their host system (Garrow et al., 2020; Bílek et al., 2021). Due to the technical limitations of both collisional and collisionless N-body simulations, it is often difficult to use them to understand the relations between gas and stars in the early stages of cluster formation, although certain physical processes can be modelled via analytical models (for an overview, see e.g. Varri et al. 2018 and references therein). These types of simulations can be particularly useful in understanding the survival rates of star clusters after the gas has been expelled or consumed. Domínguez et al. (2021), for example, recently looked into how the dissolution process of star clusters changes depending on the level of primordial mass segregation of the stars. They find that the initial distribution of masses has no role in whether the cluster remains bound after gas expulsion and that two-body interactions cause the cluster to become dynamically mass segregated regardless of the initial conditions that were set. The results from N-body simulations are important to our understanding of how, dynamically, GCs evolved to their current state. These types of dynamical processes are difficult (and in some cases) impossible to follow in hydrodynamical simulations, due to resolution issues (among other factors such as computational cost).

There are drawbacks to N-body simulations; they often lack the physical prescriptions and/or the large-scale influences that are incorporated into cosmological hydrodynamic simulations. This means the early stages of cluster formation, where large amounts of gas are still present, can not be modelled accurately (e.g. in the case of Domínguez et al. 2021, they modelled their gas via either a Plummer or uniform distribution, which is not realistic). There have been recent works that aim to combine the high-resolution of direct N-body, to understand the dynamics of the systems, with galaxy-scale hydrodynamic simulations, to examine the early stages of GC formation more accurately. For example, the works of Dobbs et al. (2022) and Rieder et al. (2022) begin with galaxy-scale smoothed-particle hydrodynamic (SPH) simulations, which include models for gas dynamics and also allow them to study the galaxy-scale effects on star formation (Figure 1.9). Within this simulation, they employ a method to form individual stars in order to be able to follow the N-body dynamics of star clusters - similar methods of star formation at this resolution have also been employed in the

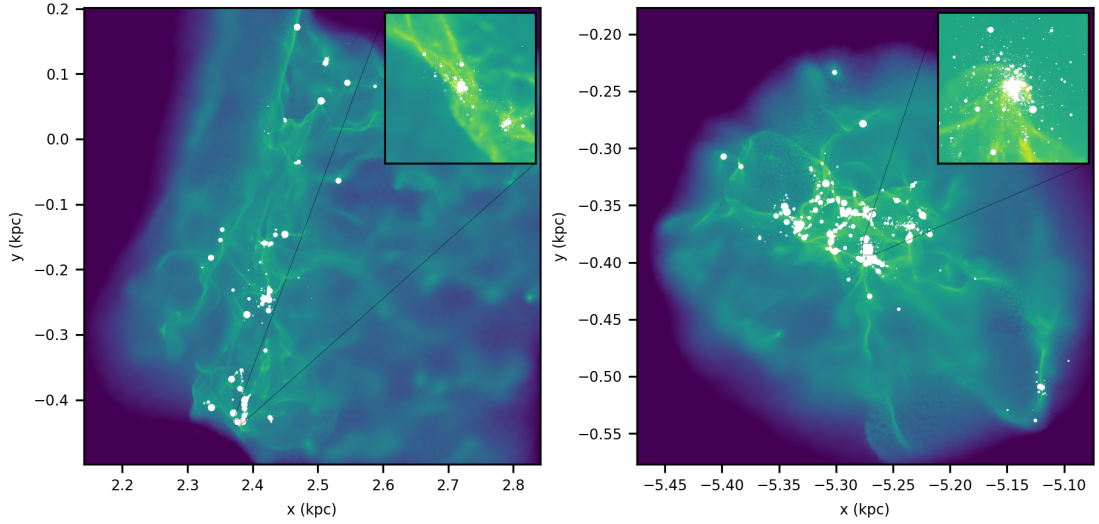


Figure 1.9 *Figure extracted from [Rieder et al. \(2022\)](#) showing star formation in a spiral arm (left) and a cloud (right). The insets in each panel are 10 pc wide and the sizes of the stars (white dots) are proportional to their radius.*

SIRIUS project ([Hirai et al., 2021](#); [Fujii et al., 2021a,b](#)). Once an area of interest is identified, they further increase the resolution of the star particles through particle splitting. However such studies have some drawbacks, the most crucial being that several forms of feedback (radiative, supernovae, and winds) are not included as the mass resolution of their gas particles makes this impractical. They can only follow the evolution of their proto-clusters for a few Myr (before supernova feedback would kick in) and can not give a detailed account of the full early stages of formation - these steps after feedback would kick in are also crucial to understanding the behaviour of the gas as well as the formation of potential multiple populations (see Section 1.1).

Other groups, rather than looking into the small-scale dynamical processes, study the evolution of GCs across time as a global population. One such group, E-MOSAICS ([Pfeffer et al., 2018](#); [Kruijssen et al., 2019a](#)), is particularly concerned with the global and average properties of globulars and their relations with their host galaxies. Their study combines semi-analytical models for star cluster formation and evolution (MOSAICS) with the EAGLE cosmological simulations ([Crain et al., 2015](#); [Schaye et al., 2015](#)). The underlying semi-analytical models are based on work from [Kruijssen & Lamers \(2008\)](#); [Kruijssen \(2009\)](#); [Kruijssen et al. \(2011\)](#); [Kruijssen \(2012\)](#); [Reina-Campos & Kruijssen \(2017\)](#) and account for the environmental dependence of the cluster formation efficiency on cluster mass. The E-MOSAICS results have been utilised for a variety of studies relating to GC formation and evolution ([Reina-Campos et al., 2018](#); [Usher et al., 2018](#); [Pfeffer et al., 2019a,b](#); [Reina-Campos et al., 2019](#); [Bastian et al., 2020](#); [Hughes et al., 2020](#); [Keller et al., 2020](#); [Pfeffer et al., 2020](#); [Reina-](#)

Campos et al., 2020; Trujillo-Gomez et al., 2021; Reina-Campos et al., 2021). Most recently, these simulations were used to train a neural network in order to predict the accretion properties (e.g., the accretion redshift) of satellites around the MW from the GC population and consequently reconstruct the merger tree of the MW (see Kruijssen et al. 2020, Figure 9). Whilst E-MOSAICS body of results can reproduce global GC-halo trends, they mainly suffer from a resolution issue: in their zoom-in simulations, the highest resolution they reach for SPH particles is of the order of $10^5 M_{\odot}$, i.e. many of their GCs are modelled by a single particle, thus a detailed analysis of formation channels, or the exact impact of evolution on their internal structure, can not be undertaken.

Whilst studies like the ones outlined above can give us insight into how GCs evolve as a population, the lack of resolution means that they can not be studied on a case-by-case basis, and the finer details related to their formation and evolution might be missed. Other groups focus on simulating isolated galaxy systems at high resolution to examine sites of star formation - and in particular - clustered star formation to assess what this could tell us about the nature of GC formation. A popular scenario that is often simulated in isolation is a galaxy-galaxy merger, in order to analyse the impact of this merger on the giant molecular clouds and star cluster formation (Hopkins et al., 2013). In cases where the resolution is high enough, some studies go on to track the initial evolution of these young star clusters, and assess some of their internal properties (e.g., how bound they are) in order to make predictions on their likelihood of becoming GCs (Bournaud et al., 2008; Renaud et al., 2015; Kim et al., 2018; Lahén et al., 2019, 2020a,b). However, whilst these simulations reach a high resolution, they lack a variety of host environments, as well as the cosmological context. Furthermore, due to computational costs, they can not be extended to low redshift, hence an equally detailed study of the clusters' later evolution is not possible.

The work I present in this thesis offers a complementary approach to many of the cosmological ones outlined above, with the aim of closing the gap between the large volume, low-resolution simulations and the high-resolution, limited-volume, limited-time evolution ones. In essence, my goal is to examine the small-scale physics concerning the formation of low-mass stellar systems, especially GCs, whilst keeping the representation of the cosmological context as truthful as possible.

1.4 The FiBY simulations

The numerical framework within which the present study is conducted are simulations from the First Billion Years (FiBY) project (e.g. [Johnson et al., 2013b](#); [Paardekooper et al., 2015](#)). These are a suite of high-resolution cosmological hydrodynamics simulations. They have been performed by using a modified version of GADGET-3 ([Springel, 2005](#); [Schaye et al., 2010](#)) which includes specific physics relevant for the onset of galaxy formation in the high-redshift Universe (e.g. Population III star formation, see below) ([Johnson et al., 2013b](#)). These simulations run until $z = 6$. All substructures within the simulations are identified with the SUBFIND algorithm ([Springel et al., 2001](#); [Dolag et al., 2009](#); [Neistein et al., 2011a](#)). The FiBY simulations are suitable for the work proposed here as they recover a number of established observational trends, including the stellar mass function and star formation rate of galaxies at $z > 6$. They also reproduce the expected trends in the metallicity evolution of galaxies, and they provide appropriate evidence that low-mass galaxies can reionise the Universe ([Paardekooper et al., 2013](#); [Paardekooper et al., 2015](#); [Cullen et al., 2017](#)).

For Chapters 2 and 3, a simulated box of volume $(4 \text{ Mpc})^3$ with 2×684^3 particles is used - see Figure 1.10. The mass resolution of particles is $1250 M_\odot$ and $6160 M_\odot$ for SPH and DM particles, respectively. The co-moving Plummer-equivalent gravitational softening length is $\epsilon = 234 \text{ pc}$ or $\leq 33 \text{ pc}$ in physical units at $z \leq 6$. In the following, I give a brief summary of the implemented physics ([Johnson et al., 2013b](#); [Paardekooper et al., 2015](#); [Cullen et al., 2017](#)). In the simulation suite, star formation occurs at a threshold density of $n = 10 \text{ cm}^{-3}$ and has a prescription based on a pressure law designed to be consistent with the observed Schmidt-Kennicutt Law ([Schmidt, 1959](#); [Kennicutt, 1998](#); [Schaye & Dalla Vecchia, 2008](#)). The simulation forms both Population II and III stars. For each of the populations, a different IMF is assumed. For Population III stars, a power-law with a Salpeter slope ([Salpeter, 1955](#)) is assumed for a mass range of $21 M_\odot - 500 M_\odot$. The adopted stellar IMF for Population II stars is that of [Chabrier \(2003\)](#). There is a “critical metallicity” at which the stellar IMF transitions between that for Population III and II stars ([Maio et al., 2011](#)). The value of this metallicity in FiBY is $Z_{\text{crit}} = 10^{-4} Z_\odot$. This value is consistent with prevailing theory and inferred metallicities of the most metal-poor stars ([Frebel et al., 2007](#); [Caffau et al., 2011](#)). The stellar feedback is modelled via an injection of thermal energy from star particles to neighbouring particles ([Dalla Vecchia & Schaye, 2012](#)). Once a star particle (for a Population II star) has reached an age of 30 Myr, a supernova

is injected with energy of 10^{51} erg. This age is chosen as it corresponds to the maximum lifetime of stars that end their lives as core-collapse supernova (Heger et al., 2003). A similar technique is applied to model feedback from Population III stars, however, a distinction is made between Type II SNe (Population II stars, occurs for initial stellar masses $8 \lesssim M_* \lesssim 100$) and PISNe (Population III stars, occurs for initial stellar masses $140 \lesssim M_* \lesssim 260$). For the latter, the energy of 3×10^{52} erg per SN is injected. For metal pollution, FiBY tracks 11 elements: H, He, C, N, O, Ne, Mg, Si, S, Ca, and Fe. Cooling of the gas is based on line-cooling in photoionisation equilibrium for these elements (Wiersma et al., 2009), using tables from the CLOUDY v07.02 code (Ferland et al., 1998). Also incorporated into the simulations are full non-equilibrium primordial chemistry networks (Abel et al., 1997; Galli & Palla, 1998; Yoshida et al., 2006), including molecular cooling for H_2 and HD. In Chapter 3, I utilised a simulation from the FiBY suite that had a much finer time resolution between the output snapshots (in Chapter 2 $\delta t \sim 50\text{Myr}$, while for Chapter 3 it is $\sim 2\text{Myr}$). The two simulations were run with the same initial conditions, box size, and mass resolution as described above. I performed a consistency check on the outputs from both simulations and I found similar numbers of objects being formed in both.

For Chapter 4, I utilised an updated version of the modified GADGET-3 code used previously for the FiBY simulations (full details can be found in Yajima et al. 2022). The primary modifications were made to the star formation and the supernova feedback models, following the results from the EAGLE project (Schaye et al., 2015). Models were added to calculate the radiative feedback from young stars, the kinetic feedback from massive black holes, and the growth/destruction of dust grains. I have personally performed a set of simulations, with the same resolution as the previous FiBY simulations ($1250 M_\odot$ per SPH and $6160 M_\odot$ per DM) detailed above. Rather than being of a cosmological volume, these simulations are isolated cases of the individual galaxy-infant GC systems, chosen specifically for their different environments (see Chapters 3 and 4). I performed these simulations in isolation until $z \sim 2$ in order to assess the probability of GCs survival in different galactic environments and to study the interplay between the host and GC candidates.

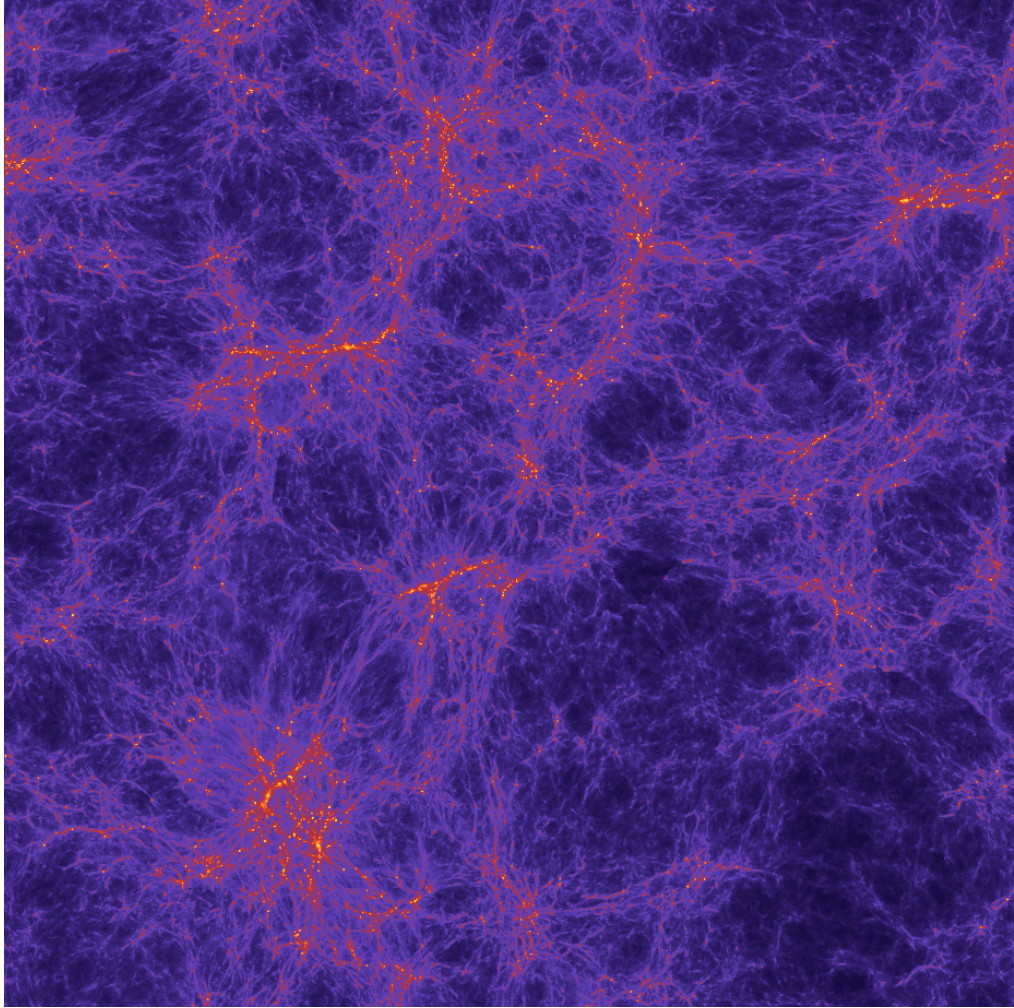


Figure 1.10 *Gas surface density of the FiBY $(4 \text{ Mpc})^3$ volume at $z = 6$. This is an illustration of the simulation used for the analyses presented in Chapters 2 and 3.*

Chapter 2

Identifying globular clusters at $z = 6$

In this Chapter, I explore the suite of high-resolution cosmological simulations from the First Billion Years (FiBY) project at $z \geq 6$ to identify progenitors of present-day old, low-mass stellar systems with a particular focus on GCs. The simulation used in this Chapter has mass resolutions of $6160 M_{\odot}$ and $1250 M_{\odot}$ for DM and SPH particles respectively with a gravitational softening length of ≤ 33 pc at $z \leq 6$. The gravitational softening length is the minimum scale gravitational forces are calculated on in order to prevent unrealistic particle motions within the simulation. A box of volume $(4 \text{ Mpc})^3$ is studied. There have been several recent studies that examine GCs in simulations which are complementary in terms of spatial resolution and cosmic volume they simulate and the analysis presented in this Chapter aims to close the gap between them. For example, [Ricotti et al. \(2016a\)](#) uses cosmological simulations to study the origins of GCs and satellite galaxies in a high-resolution simulation at $z > 9$ with a spatial resolution of 1 pc and a simulation volume of $1 h^{-1} \text{ Mpc}$. This volume is 20 times smaller than the one of the simulations presented here. Additionally, as shown below, I find a large population of GC candidates that form at $z < 9$, indicating the need to run simulations to lower redshifts. Other groups that utilise large volume simulations such as EAGLE ([Reina-Campos et al., 2019](#)) or simulate to a lower redshift ([Kim et al., 2018](#); [Li & Gnedin, 2019](#)) generally have a lower mass resolution ($\sim 200\times$ lower) compared to the FiBY simulation suite.

The Chapter is laid out as follows. In the next Section, I discuss the two groups of objects that emerge from these simulations and I present my initial results. In Section 4, I describe the galactic environments within which the objects of the first group are found. I compare such objects to high-redshift observations in Section 5. Finally, I

discuss and summarise my findings in Section 6. Throughout this Chapter I assume $H_0 = 71 \text{ kms}^{-1}\text{Mpc}^{-1}$, $\Omega_M = 0.265$, $\Omega_\Lambda = 0.735$ and $\Omega_b = 0.0448$.

2.1 Results

2.1.1 Classifying low-mass stellar systems

To assess the demographics of the low-mass stellar systems within the simulations, I extract all SUBFIND identified substructures in the simulated box within the stellar mass range $10^4 - 10^8 M_\odot$. SUBFIND is a halo finder which identifies substructures through local over-densities. Here, I consider exclusively SUBFIND objects with more than 80 particles. Out of these objects, I focus on the structures with the stellar mass range stated above, as their star formation rate is resolved by more than 10 star particles, which I adopt as my lower limit. For each of the substructures, their total baryon fraction:

$$f_b = \frac{(M_* + M_{\text{gas}})}{M_{\text{total}}}, \quad (2.1)$$

is calculated where M_{total} is the sum of baryonic and dark matter masses, M_* the stellar mass and M_{gas} the mass in gas. Equation 2.1 gives the fraction of mass contained in baryonic material. Also calculated for each of the objects is the stellar fraction. This quantity defines the amount of baryonic mass found in stars:

$$f_* = \frac{M_*}{(M_* + M_{\text{gas}})}. \quad (2.2)$$

All the objects that were extracted from the simulations are plotted within the plane drawn out by f_b and f_* . This plane can be seen in each of the panels of Figure 2.0¹.

In Figure 2.0, I discriminate between different masses of individual objects through the size of the data point. Each panel has a different colour bar to add further information about the objects. In the top panel, the colours indicate the stellar metallicity of the substructure. In the middle and bottom panels, the colour bar represents the total stellar and dark matter (DM) mass of the parent friend-of-friends (FOF) halo that the object belongs. can As seen in Figure 2.0, two distinct groups of objects emerge with respect to the general population.

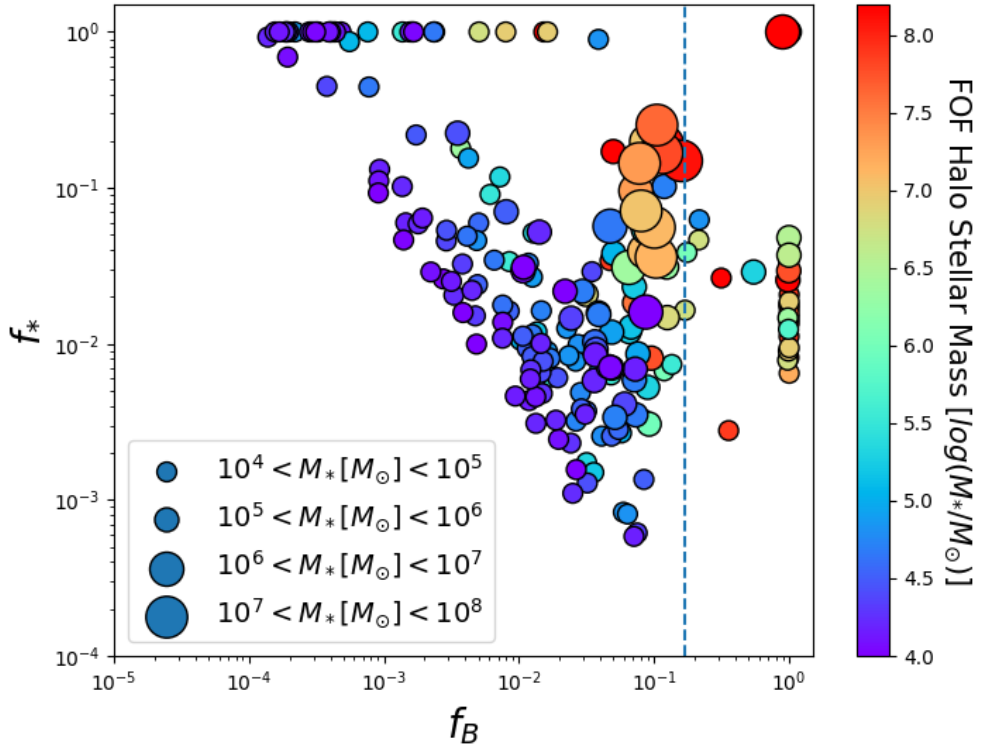
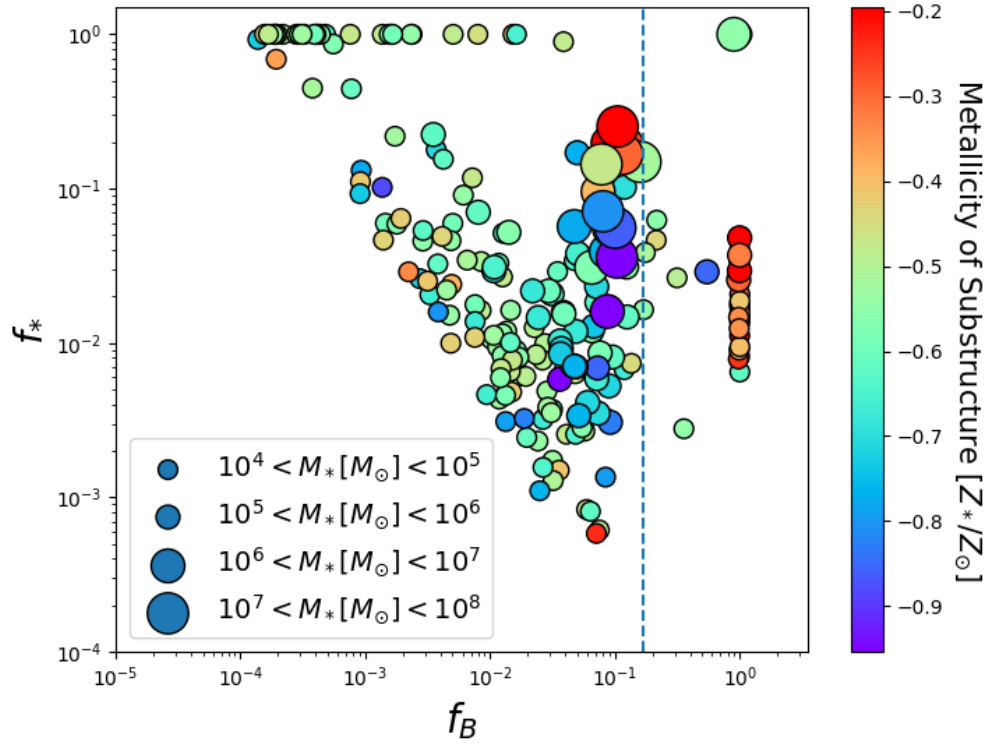
¹I note that the sharp edge at large dark matter fractions is a result of the imposed mass limits on the stellar mass of the objects and follows the expected $f_* \propto 1/f_b$ behaviour.

The first of these groups can be seen as a vertical line where $f_b = 1$, that is to say, the total mass of these objects is in the form of baryons. Hence, from their very definition, these objects have low DM fractions. They all seem to have masses in the range of $10^4 - 10^6 M_\odot$. From the top panel, it can be seen that a majority of these objects have a stellar metallicity which is about half solar. These objects appear to be lying within an environment that contains either a much larger host galaxy, or many other objects of a similar mass (see middle panel of Figure 2.0). The total stellar mass within the parent halo for all these objects exceeds $10^6 M_\odot$. Whilst these individual substructures appear to have a low concentration of DM within them, they lie within an extended DM halo environment (see bottom panel of Figure 2.0).

The second distinct group of objects lie horizontally in the plane along the $f_* = 1$ line. These objects are similar in mass to those along the $f_b = 1$ strip, yet they are vastly different from each other. For this second group of objects, all their baryonic matter is tied up in stars. However, their baryon fraction itself is low, indicating a large concentration of DM within these objects. When looking at their stellar metallicities, they are more metal-poor than the $f_b = 1$ objects. They have a stellar metallicity about a quarter of the solar metallicity. The $f_* = 1$ substructures appear to be isolated systems - this can be seen when looking at the middle panel of Figure 2.0. The stellar component of the host FOF halo for these objects seems to be of similar mass to the $f_* = 1$ objects. The $f_* = 1$ group also lies within an extended DM halo, but this halo is on average two orders of magnitude smaller than the halo of the $f_b = 1$ group.

An interesting feature of the $f_b = 1$ and $f_* = 1$ groups is that they are separated from the main distribution of substructures by a distinct gap, which is more apparent for the $f_b = 1$ group of objects. Shown in the bottom panel of Figure 2.0 is a histogram of the distribution of objects with certain values of f_b . There is a clear valley between the universal baryon fraction and the $f_b = 1$ objects, indicating that these objects likely are characterised by different amounts of DM at birth. The non-continuous nature of the distribution argues for a distinct formation process of $f_b = 1$ objects.

I hypothesise that the objects along the $f_b = 1$ line could be associated with infant GC systems, whilst the $f_* = 1$ objects might be akin to proto-ultra-faint dwarfs (UFDs), as I discuss in the following. In order to test these hypotheses, I compare the $f_b = 1$ and $f_* = 1$ groups and three subsamples of objects which have been chosen based on observational constraints in the local Universe. The first of these subsamples is stellar mass limited within the range $10^4 \leq M_\odot \leq 10^7$. Whilst not all the objects in this mass range are either an infant GC or a UFD, being able to compare the properties of these two distinct groups of objects to a more general population can help evaluate how



unique they are. The second subsample contains objects within the same mass range as before, but that also have a dark matter fraction ≤ 0.2 . Such a condition was chosen in order to allow a broader assessment of stellar systems in the regime of relatively low DM fraction, without imposing a strict requirement of a complete absence of DM (see Chapter 1 for some phenomenological considerations on this specific issue). Therefore, whilst it is likely that GCs formed within an extended dark matter halo, here I focus on the analysis of objects with a relatively low intrinsic DM content. The final subsample has a gas fraction of ≤ 0.2 and stellar masses in the range $10^4 \leq M_{\odot} \leq 10^7$. This constraint comes from the current understanding of UFDs. Such a class of satellite galaxies appears to have a very low gas content (Brown et al., 2014; Westmeier et al., 2015; Simon, 2019). From current studies of the internal kinematics and the resulting values of their mass-to-light ratios, UFDs are found to have a high DM content (e.g. see Kleya et al., 2005; Martin et al., 2007; Simon & Geha, 2007), akin to the low baryon fractions observed for the $f_* = 1$ group (see Figure 2.0). Thus, it would be interesting to assess how the properties of the $f_* = 1$ group compare to a subsample with a small gas mass. In the rest of this Chapter, the main focus is placed on the $f_b = 1$ objects, but I also analyse some of the properties of the $f_* = 1$ objects.

2.1.2 Number density of the $f_b = 1$ objects

As a first step, I compare the number density of present-day GCs with those of the different populations that I have identified at $z = 6$. I also analyse the build-up of the $z = 6$ population of infant GCs.

In Figure 2.1, I show the evolution of the number density (ϕ) as a function of redshift for both the $f_b = 1$ and the $f_* = 1$ objects. The number density is calculated by dividing the total number of objects in each subsample by the volume of the simulated box (see Section 1.4). A recent estimate of the local number density of GCs is illustrated with a horizontal dot-dashed line (at 0.77 Mpc^{-3} ; for further details of such a calculation see Appendix 1 in Rodriguez et al. 2015).

By comparing these findings to the local Universe literature, I see that the potential infant GC candidates are characterised by a lower value for ϕ . However, GCs are expected to still be able to form until $z \sim 3$ (Katz & Ricotti, 2013; Kruijssen, 2015b). The value of ϕ I estimate in the simulations at $z = 6$ for the $f_b = 1$ systems is about half of that quoted by Rodriguez et al. (2015), suggesting that a significant fraction of GCs might still form after $z = 6$. Through extrapolation of the number density to $z = 3$, as based on the trend seen in number densities for both $f_b = 1$ ($d\phi/dz = -0.19$)

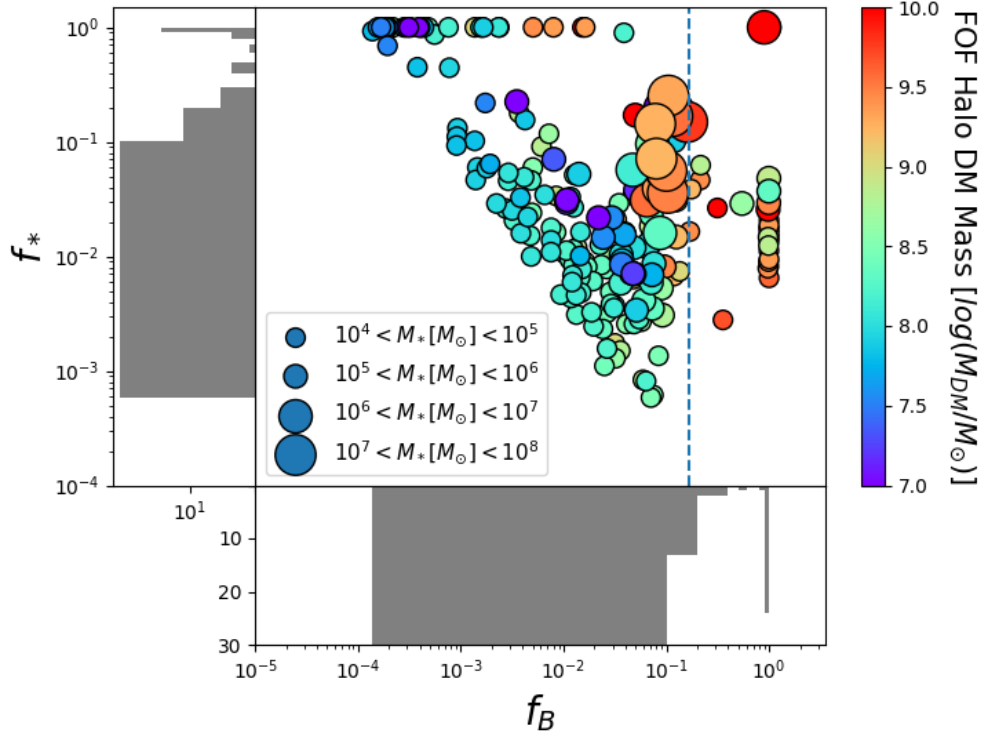


Figure 2.0 *Fraction of baryons in stars (f_*) against the total fraction of baryons (f_b) for all substructures identified by SUBFIND in the stellar mass range of $10^4 \leq M_* [M_\odot] \leq 10^8$ at $z = 6$. The sizes of the symbols indicate the mass range of the substructures. The vertical line represents the WMAP 7-year universal baryon fraction value of 0.167 (Komatsu et al., 2011). From top to bottom, the colour bars represent the stellar metallicity of the substructures, the stellar mass of the parent friend-of-friends (FOF) halo, and the dark matter mass of the parent FOF haloes.*

and $f_* = 1$ ($d\phi/dz = -0.12$) objects between $z = 8$ and 6 , I easily match the locally observed number densities of GCs. However, I wish to stress that such an extrapolation does not take into account any disruption of GCs. On the basis of this approximated approach, only $\sim 80\%$ of the population at $z = 3$ would need to survive to ensure agreement with local observations.

An interesting result that arises from Figure 2.1 is that the number density for the $f_b = 1$ and $f_* = 1$ objects matches the ones for the DM (blue dots) and gas (green dots) constrained subsamples based on local-Universe observations of GCs and UFDs. This is not surprising when recalling the results from the bottom panel of Figure 2.0. As noted, there is a distinct gap between the $f_b = 1$ and $f_* = 1$ objects and the other substructures I have identified. Therefore, any cut in baryon fraction above 0.167 would result in a subset of objects which would contain the infant GCs. As a follow-up study (see Chapter 5), I suggest to focus on the origin of this gap in the context of the formation and evolution of these objects. A large separation may be noticed in the number density between the red dots and the rest of the data displayed in Figure 2.1. This feature is due to these objects having the least restrictive criteria in order to be selected for this subsample.

2.1.3 Global properties of the $f_b = 1$ objects

I proceed by studying the global properties of the potential infant GC candidates. These properties allow me to further analyse the difference between the $f_* = 1$ and $f_b = 1$ group of objects and support the hypothesis that the $f_b = 1$ objects are possible infant GCs. In addition, such a global characterisation may provide initial constraints and predictions for future high-redshift observations of GCs. I wish to focus on the following global properties; stellar half-mass radius (R_*), stellar density (ρ_*), stellar metallicity (Z_*) and stellar velocity dispersion (σ_*).

I established two distinct groups of objects covering a similar mass range in the $f_b - f_*$ plane in Figure 2.0. In Figure 2.2, I investigate whether a clear separation exists for global properties when split up by stellar mass (M_*).

The general picture emerging from Figure 2.2 is that the two distinct groups of objects found in Section 2.1.1 (denoted by stars and triangle symbols, respectively) continue to be well separated in terms of their sizes, metallicity and velocity dispersion. However, within each group, a dependence on the stellar mass of all examined global properties can be noted. As discussed in the previous Section, it appears that the $f_b = 1$ objects

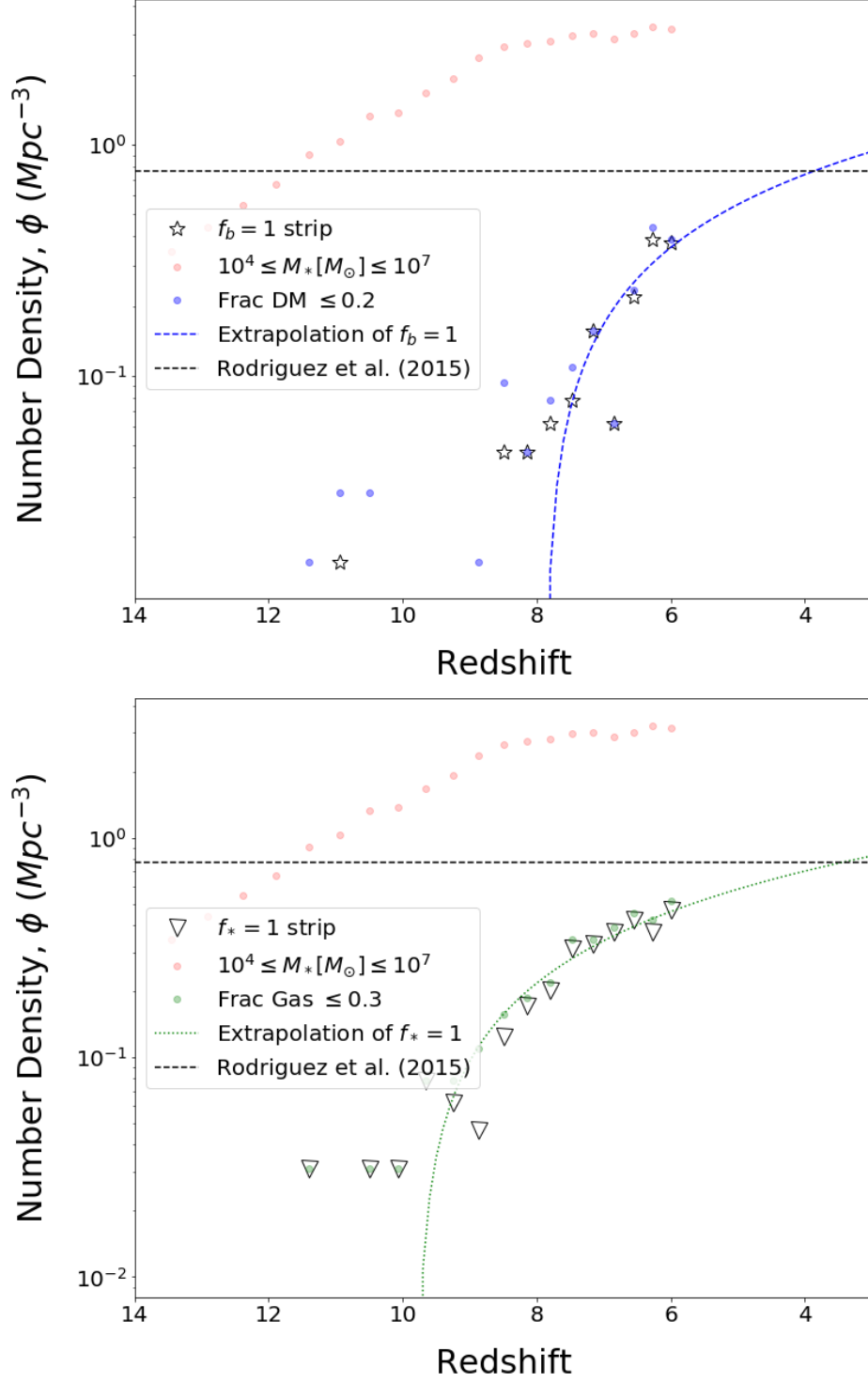


Figure 2.1 Redshift evolution of the number density of potential infant GC candidates in the simulation. Stars and triangles represent the $f_b = 1$ and $f_* = 1$ groups. The red, green and blue coloured dots indicate the three other subsamples described in Section 2.1.1. The solid and dot-dash lines are predicted values of ϕ taken from the literature (see legend and Section 2.1.2).

and the DM fraction-limited sample consist of the same objects, as they overlap within the same regions of the parameter spaces illustrated in Figure 2.2. The same can be said for the objects in the $f_* = 1$ group and gas fraction-limited sample. I interpret this equivalence mainly as a consequence from the gap that appears in Figure 2.0 (see Section 2.1.1 for more details).

The top left panel in Figure 2.2 shows the reference mass-size plane (R_* vs M_*). For the simulation data, R_* is calculated by using particle information as follows. For each of the objects, the coordinates of the most bound particle are obtained (star, gas or dark matter particle). This most bound particle represents the minimum of the potential well for a given object and I identify this as its centre. By assuming spherical symmetry, the number of star particles within a spherical shell of a given size is counted. The radius of the shell is increased from zero in increments of 0.1 pc. The value of R_* is then obtained by plotting a cumulative stellar mass profile for the object as a function of radius and then choosing the radius which encloses 50% of the stellar mass. From such a mass-size plane, it can be seen that the objects I am associating with infant GCs candidates ($f_b = 1$ objects) are the most concentrated and have the smallest radii out of all identified objects in the simulation. They all have radii < 90 pc, with a majority of the infant GCs having radii in the range 40 – 60 pc². The systematically lower value of R_* for these objects holds across a broad range of stellar masses, indicating that this is a general property for objects of this classification. Confirmation that these objects are compact is further evidence to support the notion that the $f_b = 1$ objects are plausible infant GC candidates. The $f_* = 1$ group appears to span a broad range of stellar radii ($\sim 60 - 300$ pc, with two objects < 60 pc) for a given stellar mass, showing that these objects are more diverse but crucially different to the objects in the $f_b = 1$ and DM fraction-limited samples. By comparing the objects from the $f_b = 1$ and $f_* = 1$ groups, one can see that the majority of the latter are $\sim 1.5 - 7\times$ larger than the former. In the local Universe, GCs are typically observed to have half-light radii of the order of ~ 10 pc (Harris, 1996; Larsen et al., 2002; Masters et al., 2010, e.g. see) and for UFDs $\sim 30 - 100$ pc (e.g. see Bechtol et al., 2015; Koposov et al., 2015; Simon et al., 2015). Thus the ratio of sizes I find between the potential infant GCs and proto-UFDs is similar to the ratio of sizes of these objects at $z = 0$.

In the top-right panel of Figure 2.2 the stellar density, ρ_* is plotted. With reference to the approach described above to calculate the stellar half-mass radius, I estimate ρ_* by using the mass within R_* . Consistent with their behaviour in the mass-size plane, the

²The gravitational softening (33 pc at $z = 6$) is of similar order as the size of these objects. I, therefore, expect the sizes to be overestimated, especially for the most compact objects. General relative trends between populations, however, should be robust.

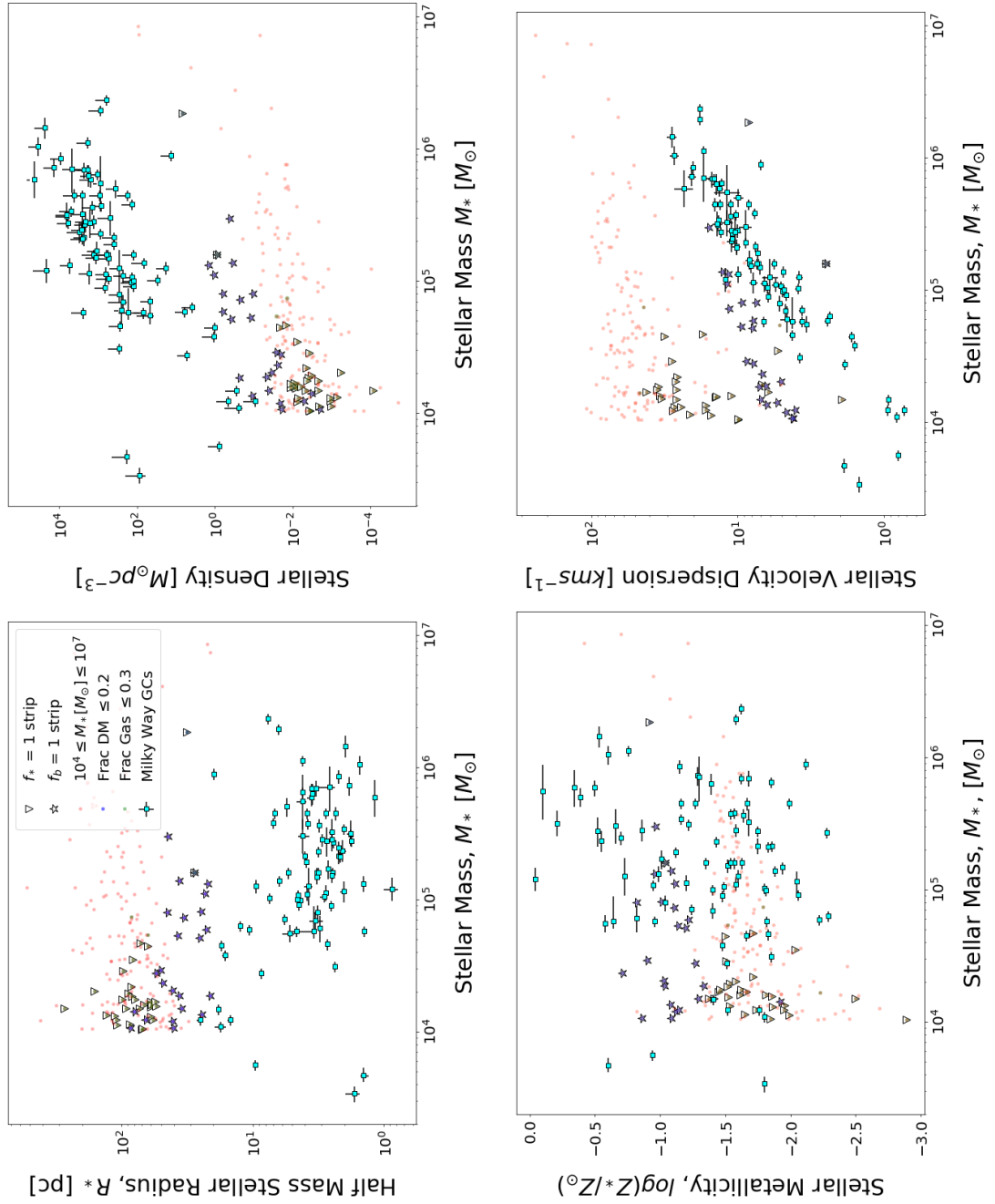


Figure 2.2 From top left to bottom right (viewed landscape): stellar radius, stellar density, stellar metallicity, and stellar velocity dispersion as a function of stellar mass. Pale dots indicate the subsamples defined by applying one selection criterion at a time, using observable properties of present-day GCs for stellar mass, dark matter and gas fraction (see Section 2.1.1). Stars and triangles represent the $f_b = 1$ and $f_* = 1$ samples. The stellar density is calculated assuming spherical symmetry, whilst the stellar velocity dispersion is calculated using the virial theorem (see Section 2.1.3). Corresponding quantities for Galactic GCs are overlaid as filled turquoise-coloured squares, taken from [McLaughlin & van der Marel \(2005\)](#). Sizes for the $f_b = 1$ sample are upper limits due to the spatial resolution of the simulation. However, $f_b = 1$ objects show a separation from the general population of simulated objects at $z = 6$. They are more compact, dense, metal-rich, and have lower velocity dispersions due to a lack of dark matter.

objects in the $f_b = 1$ group appear to be the densest identified in the simulation. There is also a trend that the more massive objects in this group are denser by about one order of magnitude compared to other objects of the same mass, again fitting with the behaviour observed for stellar radii. The $f_b = 1$ objects have higher stellar densities compared to the other substructures extracted from the simulations, this further reinforces the intuition that these objects are infant GC candidates. Local measurements of GC densities (e.g. see [McLaughlin & van der Marel, 2005](#)) are typically larger than those in this simulation. This is a consequence of the force resolution in the FiBY simulation which results in the radii being over-estimated.

The bottom left panel of Figure 2.2 shows stellar metallicity, Z_* against stellar mass. Amongst the simulated objects, there appears to be a clear distinction between the $f_b = 1$ group and the $f_* = 1$ group. The infant GC candidates (star symbols) appear to be a factor two more metal-rich than the general population and show a spread of ~ 1 dex - consistent with what can be seen in the top panel of Figure 2.0. The range of metallicities I am finding for the potential infant GCs is consistent with the measurement of metallicities of present-day Galactic GCs (see Fig. 2.2, bottom left panel, where the cyan squares depict values taken from [McLaughlin & van der Marel 2005](#)). Although in the local Universe, there are some Galactic GCs which have a higher metallicity than what I find by ~ 0.5 dex (e.g. see [Brodie & Huchra, 1991](#); [McLaughlin & van der Marel, 2005](#); [Muratov & Gnedin, 2010](#)).

The final panel in Figure 2.2 shows the stellar velocity dispersion - mass plane (σ_* vs. M_*). A simple estimate based on the virial theorem:

$$\sigma_* = \sqrt{\frac{1}{2} \frac{G}{R_{\text{half}}} \frac{M}{2}}, \quad (2.3)$$

was used to calculate the value of the velocity dispersion. There is a slight positive correlation between σ_* and M_* , which results mainly from the virial theorem itself.

In each of the panels of Figure 2.2, I have also plotted the corresponding data for the Milky Way GCs as taken from [McLaughlin & van der Marel \(2005\)](#) (with reference to their analysis based on [King 1966](#) models). The $f_b = 1$ objects show the most similarity to the Milky Way GCs, although they have a systematic offset due to larger sizes. The sizes of the simulated objects are effectively limited by the gravitational softening length used in the simulation and hence should be considered as strict upper limits, especially for the $f_b = 1$ objects which are close to the resolution limit. However, sizes above the resolution limit are numerically robust. This allows a comparison of the $f_b = 1$ objects to the general population of stellar systems. I find that the $f_b = 1$ population mirrors

the observed trends of GCs compared to that of general stellar systems. They are more dense and compact at a fixed stellar mass than the rest of the population, as seen, for example in the top two panels of Figure 2.2. Furthermore, they also show no clear scaling of their sizes with stellar mass, in agreement with the observed trend shown in the top left panel of Figure 2.2.

In Figure 2.3, I present the size – total mass plane for a selection of compact stellar systems. From the simulations, I plot the $f_b = 1$ and $f_* = 1$ groups of objects. I contrast these with a compilation of observational data from the local Universe of different stellar systems. These include local group GCs (McLaughlin & van der Marel, 2005), young massive clusters (Portegies Zwart et al., 2010) and ultra-compact dwarf galaxies (Forbes et al., 2014), represented with square, circle and diamond symbols respectively. The $f_b = 1$ objects are not quite as massive in terms of stellar mass as present-day GCs or young massive clusters but they do have a greater total cluster mass due to the presence of copious amounts of gas. This indicates the potential for further star formation and mass growth before feedback clears out all gas, pushing the candidates into the stellar mass regime observed for GCs in the local Universe.

I wish to emphasise that any comparison between the properties of simulated objects at $z = 6$ and present-day stellar systems should be taken with caution. Many internal and external processes (see Introduction) determine a significant evolution of all low-mass systems identified in this study, including the $f_b = 1$ objects. For this reason, I see it as appropriate to interpret such objects only as “candidate infant GCs” (see Sect. 2.4 for a more extensive discussion on this point) and I regard the comparison to the currently available high-redshift more robust (see Sect. 2.3).

2.1.4 GC system - halo mass relations

An observational scaling law of GCs that has been looked at in depth is that between the total mass of GCs associated with a host galaxy (M_{GC}) and the mass of the host halo (M_{Halo}). This is a linear relation (e.g. see Spitler & Forbes, 2009; Hudson et al., 2014; Kruijssen, 2015b; Harris et al., 2015, 2017), showing that more massive galaxies have a greater GC system mass. So far, only low-redshift observations of such a scaling relation exist. Knowledge of the shape of this relation around the epoch when the GCs formed the majority of their stars ($z \geq 6$) put constraints on the subsequent evolution of GC systems and the connection to their host galaxies. Also, if this relation is already established at high redshift, then this could hint at conformity across all different masses of GC systems in terms of their future evolution.

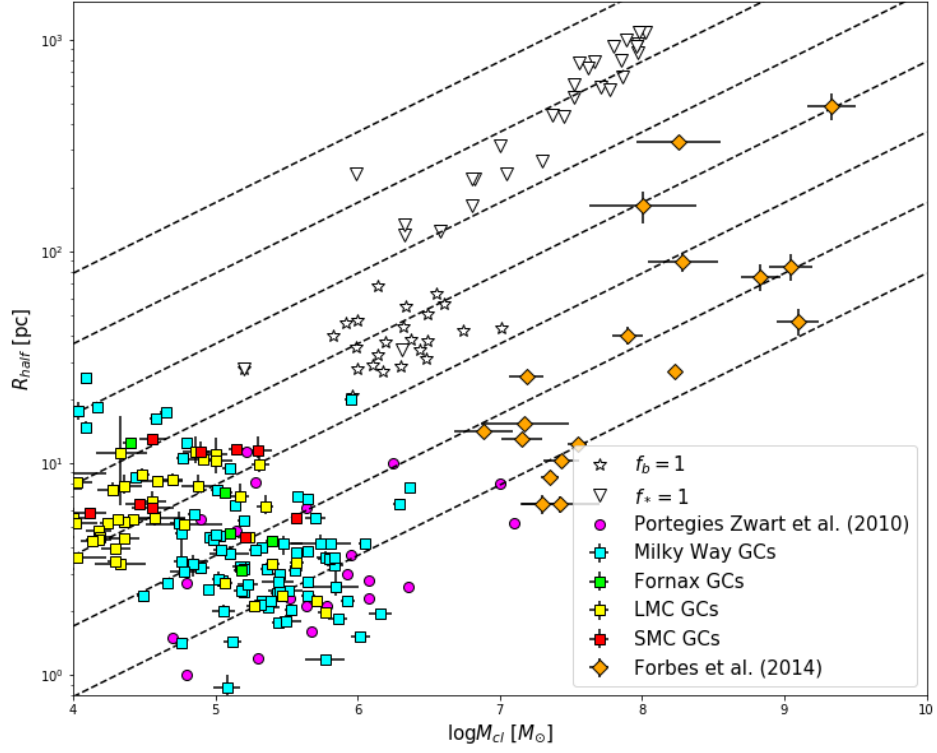


Figure 2.3 *Stellar half-mass radius against total (stars and gas) cluster mass. Star and triangle symbols represent the $f_b = 1$ and $f_* = 1$ samples. The square, circle, and diamond symbols represent a selection of local Universe data for GCs, young massive clusters, and ultra-compact dwarfs, taken from the literature (see legend for further details). The dashed lines represent lines of constant density from $0.1 m_h \text{ cm}^{-3}$ - $10 m_h \text{ cm}^{-3}$ (from top left to bottom right).*

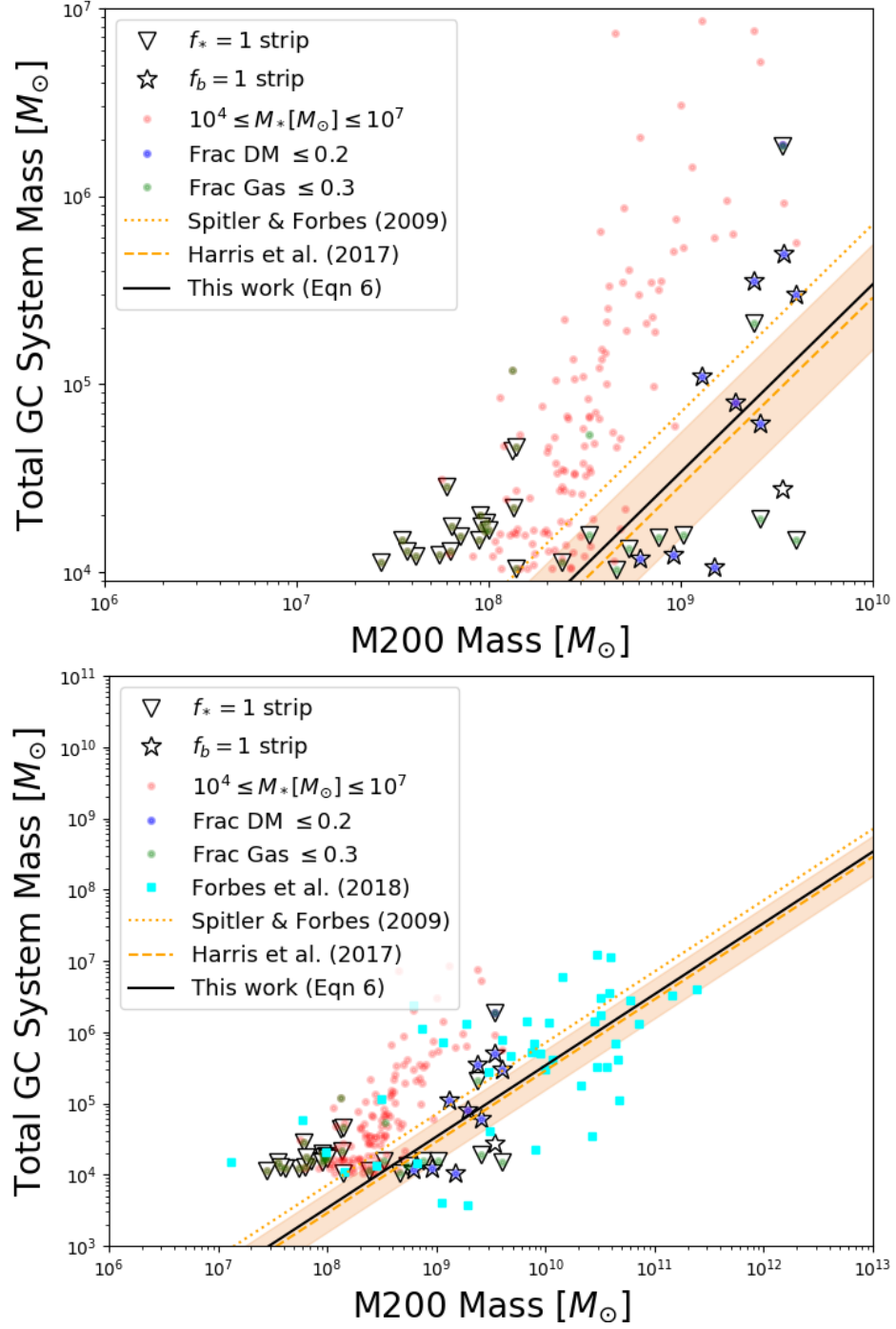


Figure 2.4 *Top: total stellar mass of potential GC systems against their parent halo mass. Pale dots indicate subsamples defined using observable properties of present-day GCs. Stars and triangles represent the $f_b = 1$ and $f_* = 1$ samples, respectively. Two of the relations plotted are taken from Spitler & Forbes (2009) (solid) and Harris et al. (2017) (dash). The black line shows the relation I find for the simulated data. Bottom: same as top plot, except the turquoise squares are the GC systems examined in Forbes et al. (2018b)*

In Figure 2.4, I have depicted the estimated GC system (stellar) mass against the FOF halo mass from the simulation (M_{200}). The GC system masses were computed by identifying infant GC candidates that belong in the same FOF halo and adding their masses together. On this plot, illustrated as the dashed lines are the system mass – halo mass relations from Spitler & Forbes (2009), SF09, and Harris et al. (2017), H17. The relation found in SF09 is a simple linear relation between the two quantities:

$$\log \left(\frac{M_{\text{GC}}}{M_{\text{Halo}}} \right) = -4.15, \quad (2.4)$$

In their work, M_{GC} is calculated by multiplying the number of GCs per galaxy by an average GC mass of $4 \times 10^5 M_{\odot}$. M_{Halo} is defined as the total mass (baryonic plus dark matter) within a sphere containing an over-density of 180 times the background.³

The relation found in H17 is close in appearance to that of SF09:

$$\log \left(\frac{M_{\text{GC}}}{M_{\text{Halo}}} \right) = -4.54, \quad (2.5)$$

where the values M_{GC} and M_{Halo} are calculated in a similar way as in SF09. In H17, however, they assume a mean GC mass which varies with galaxy luminosity. There is a residual RMS scatter in the H17 relation of ± 0.28 dex (shown as the grey shaded region in Figure 2.4).

For the $f_b = 1$ sample (i.e. the likely GC candidates) each of the relations could be regarded as a reasonable fit, although the limited range in the mass of M_{GC} probed in the sample restricts how well this can be quantified, particularly at masses $M_{\text{GC}} \geq 10^6 M_{\odot}$. The latter is mainly due to the limited simulation volume.

I find evidence suggesting that the $M_{\text{GC}} - M_{\text{Halo}}$ relation exists at $z = 6$ in the simulation. Such a relation is similar to the one observed at $z = 0$, with

$$\log \left(\frac{M_{\text{GC}}}{M_{\text{Halo}}} \right) = -(4.47 \pm 0.15), \quad (2.6)$$

although a larger mass range would help support these claims. The fit for this relation and its errors were calculated using a non-linear least squares function using the Python Scipy module. My relation only needs to be modified slightly to match those of SF09

³This is slightly different to the halo mass I use, which is the M_{200} mass, a sphere containing an over-density 200 times the background. I looked into the difference when using M_{180} and found very little change. I, therefore, decided to present the relation for M_{200} which is commonly used in numerical studies.

and H17. In fact, the modification required for Equation 2.6 to match Equation 2.5 is within the errors quoted for my relation. The individual observations presented by Forbes et al. (2018b) agree well with the simulated data in terms of actual values and scatter. Interestingly, for the rest of the simulated population, however, the observed relations appear to underestimate the system mass, further supporting that the selection of objects adopted in this analysis, based on their dark matter fraction identifies potential infant GC candidates.

The comparison to the local relation puts bounds on the future evolution of the different groups identified in this analysis, especially regarding the mass evolution of individual objects, as resulting from internal and external processes. The $f_b = 1$ population of objects leave little room for such processes to take place if they are to match the local relation without the formation of new GCs at $z < 6$ or residual star formation from existing gas in infant GCs. In contrast, the general population (the pale red dots) of objects in the corresponding mass range would need to lose up to one order of magnitude in mass and/or grow significantly slower in mass than their hosting halo to be consistent with the local relation. From the bottom panel of Figure 2.4, there is a good indication that a relation between M_{GC} and M_{Halo} is already in place by $z = 6$.

As both the SF09 and H17 relations are linear, the expectation is that, as the haloes of infant GC systems merge with other haloes, the resultant relation continues to follow the local one. The $M_{GC} - M_{Halo}$ scaling relation observed in the local Universe would result from the variation in the growth history of the GC systems and any processes related to the stripping of stars and ongoing star formation. The scatter I find in the relation at $z = 6$ is 0.46 dex. This is larger than the 0.28 dex scatter H17 found for the $z = 0$ relation. However, continued merger during the hierarchical growth of the host might result in a decrease of the scatter due to the central limit theorem (Hirschmann et al., 2010; Jahnke & Macciò, 2011).

2.2 Galactic environments of the $f_b = 1$ objects

Next, I move on to the analysis of the environments for the most likely infant GC candidates. By gaining insight into the formation environments of globulars, one can begin to establish which channel they formed through (see Introduction). In the local Universe, GCs are often found to be members of collective systems associated with a host galaxy (e.g. see Harris, 1991; van den Bergh, 2000; Harris et al., 2013). In Local Group galaxies, the general expectation is that GC systems are composed of both

in-situ and accreted star clusters, but the fraction of GCs accreted at low redshift is still under intense evaluation (e.g. see [Côté et al., 1998](#); [Tonini, 2013a](#); [Renaud et al., 2017a](#); [Recio-Blanco, 2018a](#)). Therefore, it is important to include in this study an environmental analysis. Indeed, I have already shown in this work that the likely infant GC candidates lie within extended dark matter haloes (see Figure 2.0, Section 2.1.1). Many of them also already seem to be part of a larger GC system which follows the known GC system mass – halo mass relation (Figure 2.4, Section 2.1.4). In this Section, I look deeper at the current ($z = 6$) environments of the infant GC candidates.

For each of the candidates identified in Section 2.1.1, their parent FOF halo was located. The 24 candidates are distributed across 10 different FOF haloes. The largest system contains 6 potential infant GCs whilst some haloes only contain 1 candidate. Within each FOF halo, the largest SUBFIND member was identified. This member is labelled as the host galaxy of the GC system. In Figure 2.5, I show the positions of the infant GC candidates (star symbols) in the x-y plane of the simulation. The positions of the candidates are illustrated in a frame of reference centred on the centre of mass of the host FOF halo as well as the (likely) parent galaxy (orange crosses and purple dots, respectively). The R_{200} of the FOF halo and half-mass radius R_{half} of the host galaxy are plotted as circles of orange and purple colour, respectively.

In Figure 2.6, I plot the surface density distribution of both stars (left) and gas (right) for the galaxy in panel (a) of Figure 2.5. This particular galaxy hosts six $f_b = 1$ objects, the details of which can be seen in the second entry of Table 2.1. When examining such objects in the surface density maps, they appear for the most part to be clumpy and compact, consistent with my findings for their size in previous Sections. The $f_b = 1$ objects have a higher gas surface density than the stellar one, due to their high gas content, which results in an easier distinction of these objects in the bottom panel of Figure 2.6. However, in both panels, these low-mass stellar systems are located in the spiral arms of the host galaxy. Such a localisation in regions which are rich in giant molecular clouds, high-density gas and clustered star formation (e.g. see [Kim & Ostriker, 2002](#); [Kim et al., 2006](#); [Mo et al., 2010](#)), further supports the interpretation that the $f_b = 1$ objects could be associated with progenitors of globular clusters.

When considering the DM density distribution for each of the infant GC systems, I found that the infant GCs were preferentially located at the density peaks for their respective FOF halo. This is consistent with the expectation that structures form in density fluctuations ([Blumenthal et al., 1984](#); [Kaiser, 1984](#); [Peebles, 1984](#); [Davis et al., 1985](#); [Springel et al., 2005](#)), however, I note that the infant GC candidates (as identified and characterised on the basis of the SUBFIND algorithm) contain a low number of DM

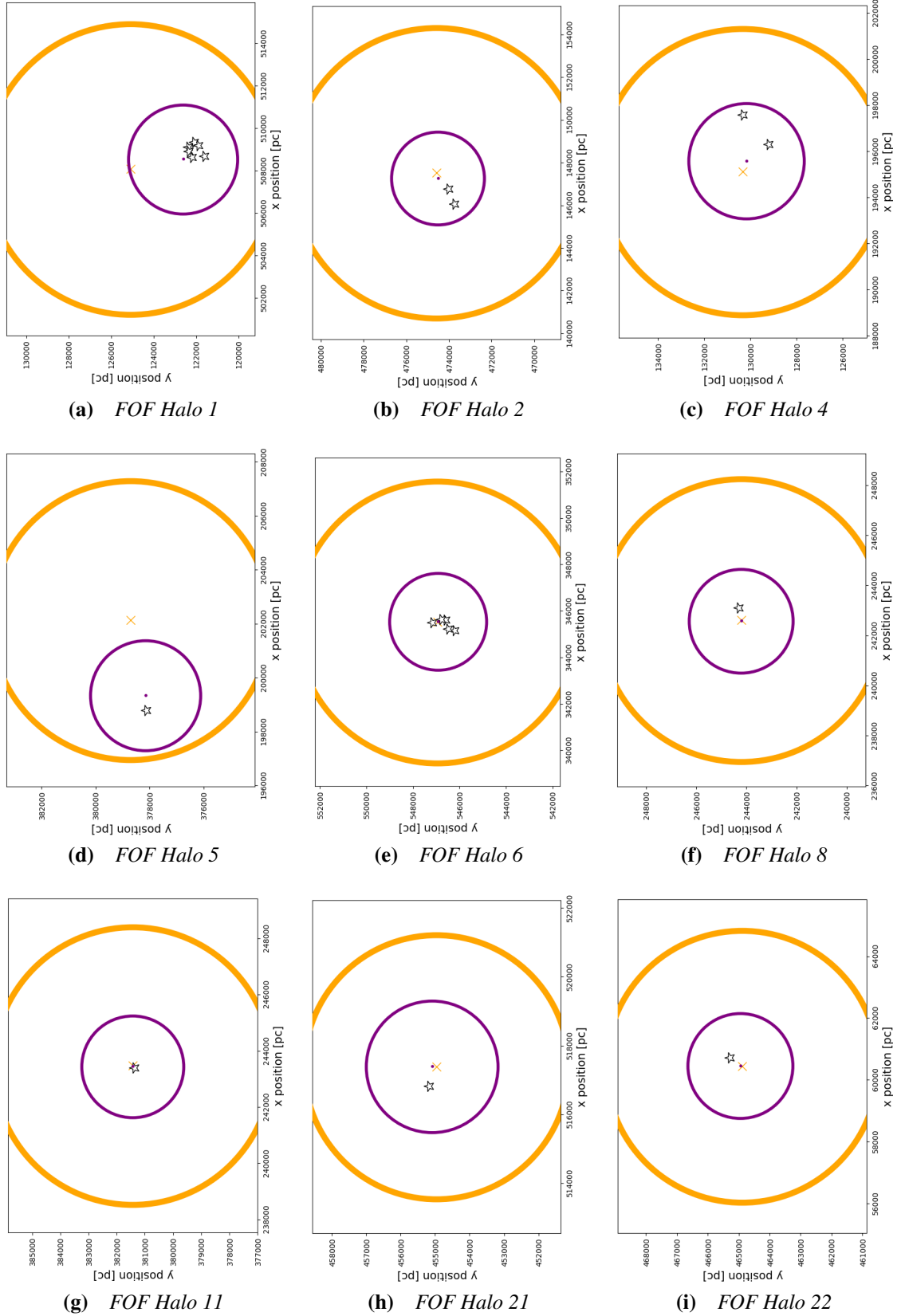


Figure 2.5 *Positions of the most likely infant GC candidates within their parent FOF halo. The star symbols represent the infant GCs identified in Section 2.1.1. The orange and purple circles represent the positions and radii of the FOF halo and the parent galaxy (see text for details).*

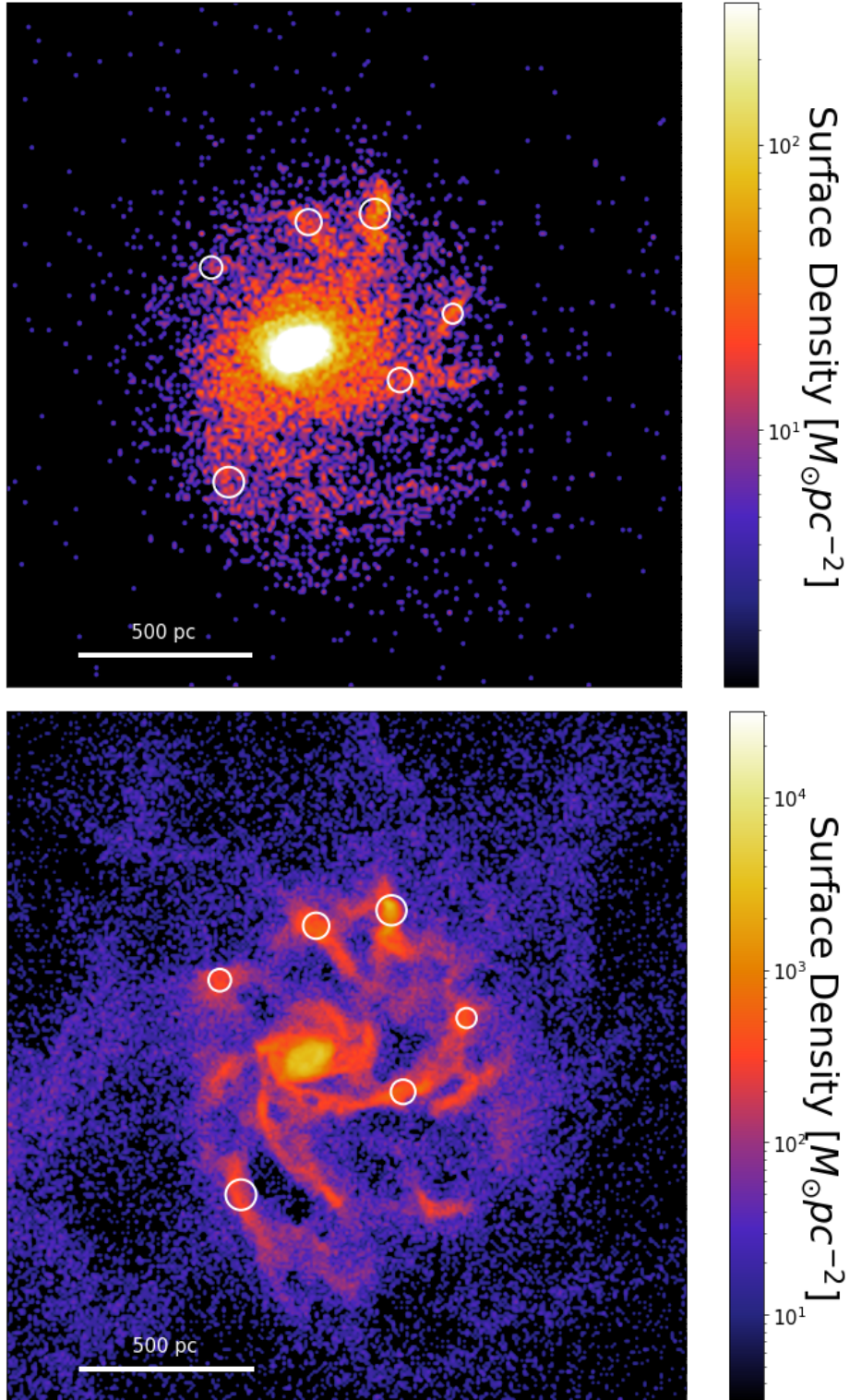


Figure 2.6 *Surface density distribution of the stars (top) and gas (bottom) at $z = 6$ for a galaxy in the FiBY simulation that hosts six $f_b = 1$ objects - see Table 2.1, entry 2. The $f_b = 1$ positions are shown with white circles.*

FOF ID	FOF R_{200} (kpc)	Gal ID	Gal R_{half} (kpc)	Gal M_* ($M_\odot$)	Num of GCs	$M_{\text{cl, gas}}$ ($M_\odot$)	$M_{\text{cl, *}}$ ($M_\odot$)	R_* (pc)	d_{gal} (kpc)	v (km/s)
0	7.20	0	2.62	9.40×10^7	4	5.22×10^6	1.38×10^5	41.9	14.58	21.3
						3.99×10^6	7.25×10^4	5.6	13.53	18.4
						3.52×10^6	2.91×10^4	63.4	14.27	26.5
1	6.84	68	2.57	6.14×10^7	6	1.23×10^6	5.88×10^4	28.9	14.03	14.8
						9.85×10^6	2.99×10^5	43.1	0.6202	20.2
						3.05×10^6	5.29×10^4	37.5	0.45587	20.1
						2.05×10^6	2.32×10^4	44.0	1.05	23.0
						1.93×10^6	8.05×10^4	28.7	0.94701	19.4
						1.36×10^6	1.87×10^4	32.3	0.41287	24.2
2	6.81	141	2.18	1.21×10^7	2	9.62×10^5	2.03×10^4	35.3	0.96094	17.3
						2.16×10^6	1.41×10^4	54.6	1.62	24.6
4	6.21	261	2.50	4.10×10^6	2	9.08×10^5	1.35×10^4	20.9	0.79688	17.6
						1.42×10^6	5.13×10^4	27.1	1.26	5.75
5	5.17	286	2.04	4.27×10^7	1	1.34×10^6	1.07×10^4	68.1	2.10	7.77
6	6.07	316	2.08	7.25×10^6	5	6.67×10^5	1.07×10^4	40.1	0.55959	16.1
						3.05×10^6	2.77×10^4	50.7	0.81133	9.63
						2.60×10^6	1.31×10^5	34.4	0.27059	8.87
						1.56×10^6	1.49×10^4	37.4	0.55919	11.9
						9.76×10^5	1.86×10^4	28.0	0.37954	21.7
8	5.65	392	2.07	2.11×10^7	1	0	1.59×10^5	27.8	0.29052	10.9
11	4.94	472	1.81	8.51×10^6	1	2.25×10^6	8.02×10^4	38.4	0.59289	12.0
21	3.84	714	1.91	2.03×10^6	1	2.88×10^6	1.11×10^5	30.9	0.16266	7.00
22	4.40	737	1.70	4.97×10^5	1	7.98×10^5	1.19×10^4	45.8	0.86058	4.73
						9.79×10^5	1.23×10^4	46.9	0.42662	4.63

Table 2.1 A table giving the identifiers for each of the FOF halo, parent galaxy and infant GC candidate as identified in the simulation. For each FOF halo, the R_{200} radius is given. For each of the (assumed) parent galaxies, the galaxy's half-mass radius (R_{half}), stellar mass (M_*) and the number of infant GCs belonging to the system are given. I provide for the potential infant GCs, their total gas mass ($M_{\text{cl, gas}}$), total stellar mass ($M_{\text{cl, *}}$), their stellar half-mass radius (R_*) as described in Section 2.1.3, distance from the parent galaxy centre (d_{gal}) and their orbital velocity (v).

particles which are energetically bound to the system. Keeping in mind the limitations determined by the numerical resolution and volume of the cosmological simulation (see Section 1.4), I compare the number of DM particles bound to the infant GCs and the number of DM particles that lie within the half-mass radius of the candidates. Whilst there are only relatively few stellar particles bound to each of these infant GCs, there is also a low number (< 40) of DM particles in the underlying medium. For the most extreme case, if the underlying population of DM particles were included in the calculation of f_b then the fraction would decrease from 1.0 to 0.8, hence this object would still be dominated by baryonic matter and classified as an infant GC candidate. Thus it needs to be understood how these candidates can form in such a DM-rich region and yet be void of DM matter themselves. This could possibly be due to the physical mechanism underpinning the evolution of these objects. Indeed, initially, the DM density peak could have resulted in a coalescence of gas at that point. As the gas cooled and contracted, star formation could begin. As the cluster then evolved, the cooperation between internal dynamical processes and external interactions with its environment (for example with its host galaxy) could result in the DM being removed from the stellar system. This is an evolutionary scenario that could be explored further in future work (see Chapter 5).

For all the probable infant GC systems - apart from the first entry in Table 2.1 - their individual objects lie within the half-mass radius of the host galaxy. This is indicative that tidal and dynamical interactions may have occurred during the formation of these infant GCs. I provide complementary information to Figure 2.5 in the form of Table 2.1. As one can see from Table 2.1, the majority of the infant GCs (excluding those in FOF halo 0) lie < 1 kpc from the centre of the (assumed) parent galaxy. The close proximity to the galaxy centre further supports the idea that these systems undergo many interactions during their first few Myr of evolution. However, the distances between the presumed GCs and the galactic centres are much smaller than what is observed in the local Universe for the Milky Way and its GC system.

A relation is present when comparing the masses of the infant GCs to the stellar masses of their host galaxies. The amount of stellar mass present in a host galaxy that is required to host the most massive cluster of mass, M_{cl} , increases linearly with M_{cl} (see also Ma et al. (2020)). This can be seen both in Table 2.1 and also in Figure 2.7. In this Figure, I plot the stellar mass of the parent galaxies against the number of $f_b = 1$ objects per system (top), the total mass of the potential infant GC system (middle) and the total mass (stellar and gas) of most massive infant GC candidate (bottom). In the middle and bottom panels, I have also provided the one-to-one relations (red) and my

own fits to the data (blue). The bottom panel displays the linear relation between parent galaxy's stellar mass and the most massive infant GC. This relation has the form:

$$\log(M_{\text{cl}}) = (0.31 \pm 0.15) \log(M_{*,\text{gal}}) + (4.17 \pm 1.06). \quad (2.7)$$

Another interesting connection between the infant GC candidates and their host galaxy is shown in Figure 2.8. There I plot the mass of the most massive GC per system against the specific star formation rate (sSFR) of the host galaxy. Overlaid on this Figure is a selection observational data taken from [Larsen & Richtler \(2000\)](#) - Tables 1 and 2 - and [Larsen \(2002\)](#) - Table 6. These tables provided SFR density, area and magnitudes of the host galaxy, and magnitude of the most massive cluster. The magnitudes of the host galaxy were converted to a mass using a mass-to-light ratio relation from [Bell et al. \(2003\)](#). For the observed clusters, their magnitudes were converted to masses using three different mass-to-light ratios all taken from [Weidner et al. \(2004\)](#). The different colours of the observational data relate to the different age populations of stars (see Table 1 in [Weidner et al. 2004](#)). I find that there does seem to be a relation between the sSFR of the host and the most massive cluster in the system. I have quantified this relation for each of the observational sets of points:

$$\log(M_{\text{cl}}) = (0.85 \pm 0.30) \log(s\text{SFR}) + \alpha, \quad (2.8)$$

where the sSFR is in units of Gyr^{-1} and α represents the normalisation factor for the different mass-to-light ratios used. The values of α found were 6.27 ± 0.30 , 5.07 ± 0.30 and 5.27 ± 0.30 for the orange, green and red lines in Figure 2.8, respectively. The sample of data used for deriving the fits is consistent with those from the original source. In addition to the fits, the observational data from the local Universe seems to follow continuously from the simulation data providing a link between the early and late Universe. This is a relation that could be investigated further at different redshifts with observations.

Finally, I discuss FOF halo 0. This system appears to be a merger between two galaxies. To confirm this, I look at this system through different projections and at different times in its evolution. From this analysis, I conclude that the system is likely an ongoing merger. However, this classification results in a different problem. It needs to be determined whether the parent galaxy initially identified is the original parent of the potential infant GC system or whether the GC candidates in the system are going to be accreted by this galaxy. From Table 2.1, it can be seen that the average distance between the infant GCs in FOF halo 0 and the parent galaxy is ~ 14 kpc. Whilst this

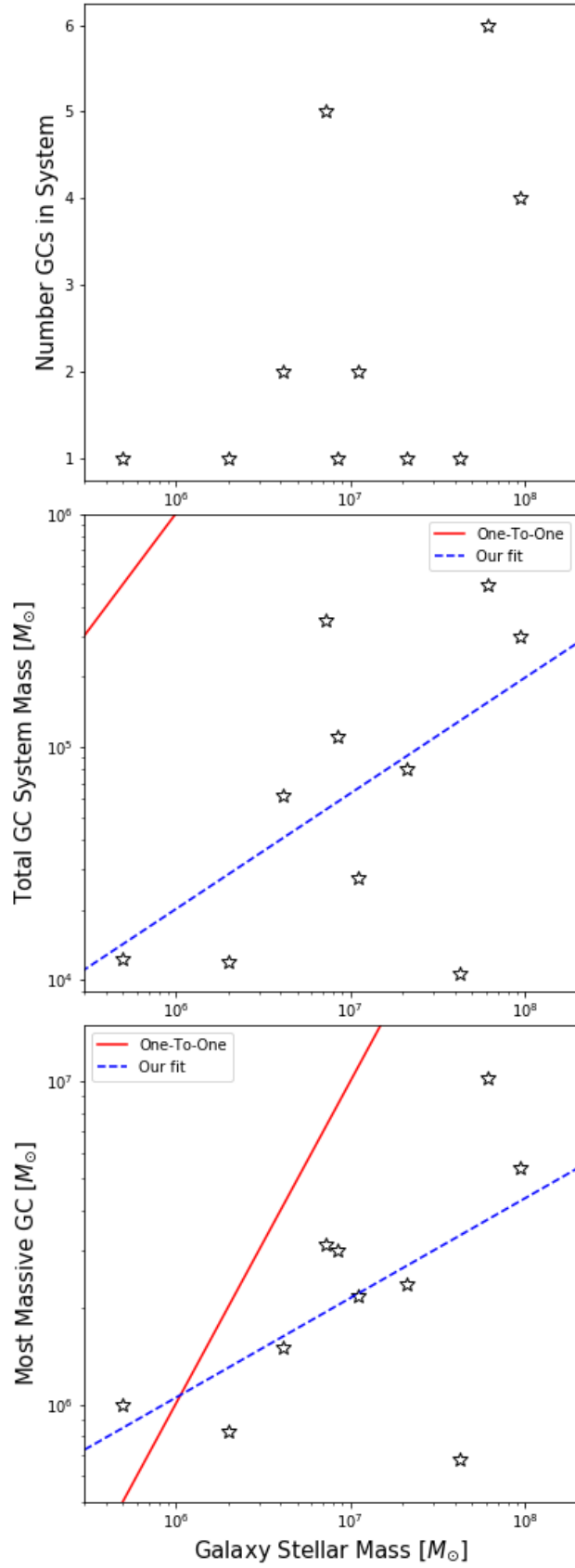


Figure 2.7 GC system number (top), GC system mass (middle), and total mass (stellar and gas) of the most massive GC (bottom) against the stellar mass of the parent galaxy. In the middle and bottom panels, I also display the one-to-one relation (red) and my own fits to the data (blue) (see Section 3.3). 45

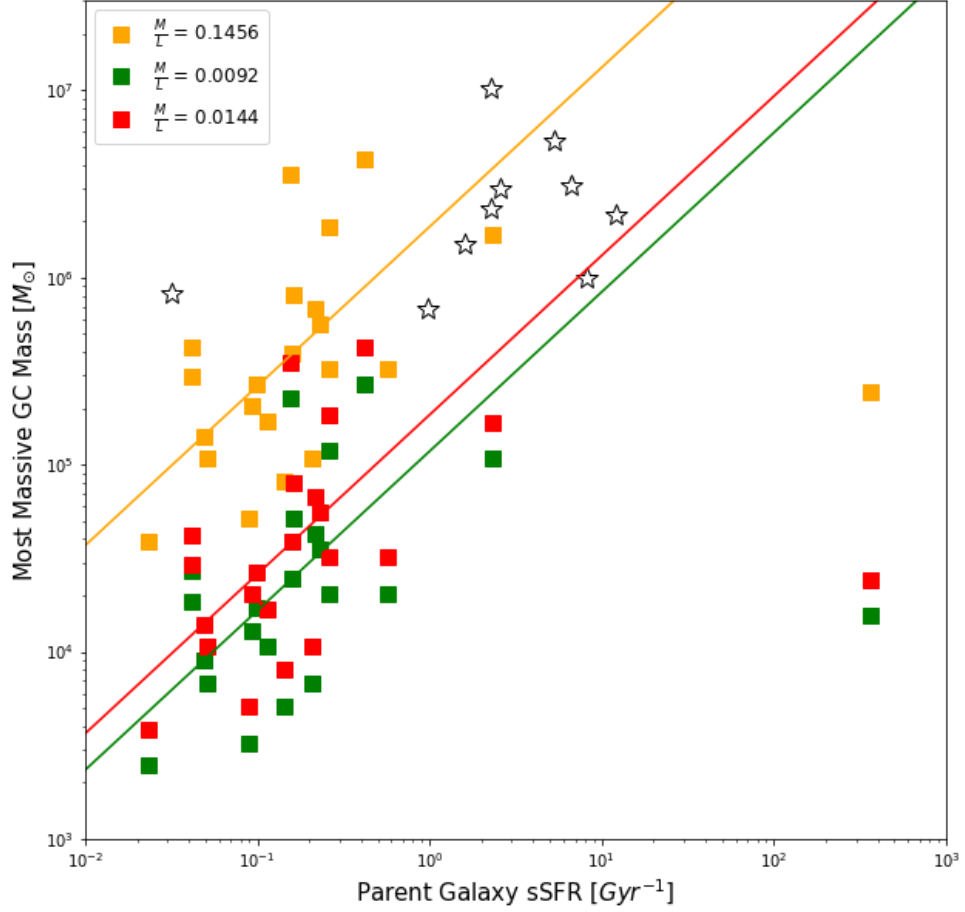


Figure 2.8 *Most massive infant GC against the sSFR of the parent galaxy. Star symbols represent data from this work and the coloured squares (red, orange and green) come from observations (see Section 3.3 for details). The straight lines are fit to each of the sets of observations.*

value is consistent with local Universe observations, it is much larger than the distances I am finding for the other systems, further suggesting that the parent galaxy initially identified by the method outlined previously for FOF halo 0 is not the original parent of these infant GCs. Instead, this will be the future parent of the clusters once the merger is complete.

2.3 Comparison with high-redshift observations

Observations in the early Universe of infant GCs are currently limited by the intrinsic difficulties posed by the detection and characterisation of low-mass stellar systems at high redshifts. Even in the local Universe, it is hard to accurately measure the mass and luminosity of GCs surrounding their parent galaxies. This task becomes laborious

when moving to higher redshift. However, with JWST on the horizon, the potential for studying these systems at formation looks promising (see Introduction and especially the recent studies by [Renzini, 2017](#); [Forbes et al., 2018a](#); [Pozzetti et al., 2019](#)).

There has been some preliminary work in observing candidate GCs at $z > 3$. For example, [Vanzella et al. \(2017\)](#) identified a selection of objects at redshifts, $z = 3.1169, 3.235$ and 6.145 . A few of these objects are very promising potential infant GCs (see magenta squares in Figure 2.9). Table 1 in [Vanzella et al. \(2017\)](#) summarises the physical properties and magnification factors for the most magnified images in the systems they studied. In particular, GC1 and ID11 are the most likely infant GC candidates in their sample. They have half-light radii consistent with what I am finding in the simulation (i.e. ≤ 50 pc). However, the measured masses of GC1 and ID11 are more than an order of magnitude larger than the masses of the $f_b = 1$ strip objects being identified in the present study. This is due to the limited volume of the simulations, which does not allow to probe massive systems.

Three of the five objects studied by [Vanzella et al. \(2017\)](#) are also included in the sample of objects investigated by [Bouwens et al. \(2017b\)](#). In their study, a sample of 307 faint sources from the Hubble Frontier Fields (HFF) is examined, with all sources located at $z = 6 - 8$. A selection of such objects (see their Table 2) have half-light radii ≤ 40 pc. It is likely that some of these objects could be infant GCs, especially when compared to observational data from the local Universe (their Figure 10). Whilst some of these objects are more extended than a typical GC, these sizes are consistent with what I am finding in the FiBY simulations. Taking these results at face value, I would not expect the radii of infant GCs to evolve greatly during the epoch of the high-redshift Universe given the values found in this work and the works of [Vanzella et al. \(2017\)](#) and [Bouwens et al. \(2017b\)](#).

Due to their relatively short relaxation times, as well as tidal interactions with their host galaxies, GCs evolve significantly in mass and size, due to the cooperation of internal and external processes, giving origin to the structural and kinematic properties measured at $z = 0$. Therefore, the consistency I am finding with preliminary observations of high redshift GCs and the potential candidates in the FiBY simulations indicates that the masses and sizes seen in Figure 2.2 are encouraging and can serve as an upper limit when making predictions for future observations. In this respect, the detection and characterisation of the gas content of such early objects can be of interest to the community. Some first results on the gas structure at small scales within possible proto-Giant Molecular Clouds at $z = 1$, as obtained by [Dessauges-Zavadsky et al. \(2019\)](#) with ALMA, appear particularly promising.

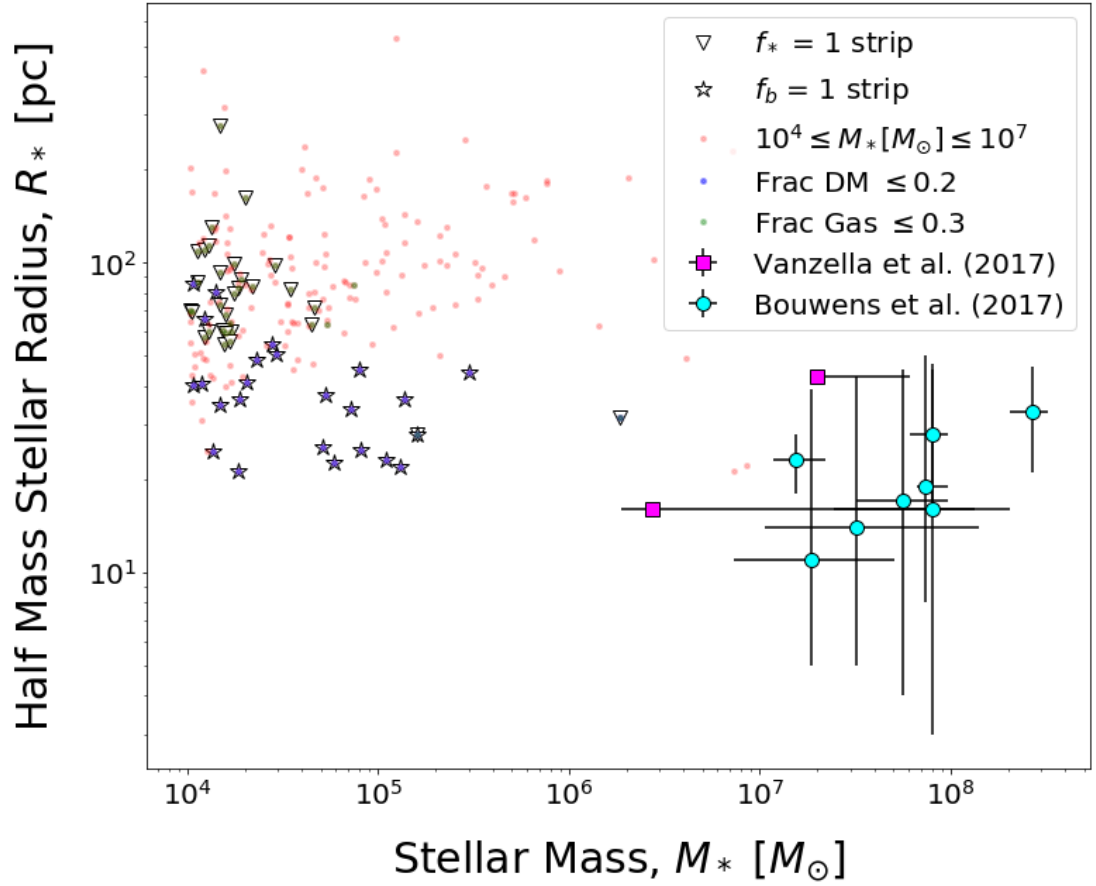


Figure 2.9 *Stellar radius against stellar mass. The green, blue and red pale dots indicate subsamples defined using observable properties from the local Universe. Stars represent the likely infant GC candidates and triangles the proto-UFDs. The magenta circles and cyan squares are high redshift observations from Vanzella et al. (2017) and Bouwens et al. (2017b). For the Bouwens et al. (2017b) data, I have taken objects from their Table 2 which had a radius < 50 pc, including errors.*

2.4 Discussion and conclusions

2.4.1 The astrophysical interpretation of the $f_b = 1$ objects

I explored a suite of high-resolution cosmological simulations from the First Billion Years (FiBY) project at $z \geq 6$ to identify potential globular cluster (GCs) candidates during their infant stages. Two distinct groups of objects were identified within the simulations. The objects in the first group have a high baryon fraction and appear to lie within an extended DM environment. I hypothesised that these objects could be possible infant GCs candidates. The second group of objects, which are characterised by high stellar fractions, exhibit similarities to ultra-faint dwarf galaxies (UFDs).

Studying their global properties, as well as looking into their environments, I explored the possibility that the objects with high baryon fraction ($f_b = 1$ objects) could be infant GCs. I started by comparing the number density of infant GC candidates which I found in the simulations with values obtained from observations at $z = 0$.

As well as investigating consistency with low-redshift observations, I now compare what I found in Figure 2.1 with theoretical predictions from the literature for the number density at $z = 6$. This can be seen in Figure 2.10. The horizontal lines overlaid on Figure 2.10 represent two predictions for $z = 6$ from the literature for the value of ϕ as based on a combination of model assumptions on top of present-day observations of GCs; [Boylan-Kolchin \(2017\)](#) (solid) and [Elmegreen et al. \(2012\)](#) (dot-dashed). I briefly discuss how each author came to their predicted value. [Boylan-Kolchin \(2017\)](#) gives a value of $\sim 2.2 \text{ Mpc}^{-3}$ for N_{GC} at high redshift. To obtain this value, they assumed the mass function of GCs to be log-normal. [Elmegreen et al. \(2012\)](#) focus on metal-poor GCs and they estimate a high-redshift number density of 8 Mpc^{-3} by evolving the present-day value of N_{GC} from [Portegies Zwart & McMillan \(2000\)](#), with some considerations about the behaviour of metal-poor GCs. They assume that metal-poor GCs make up two-thirds of the GC population and that, by $z = 0$, half of the GCs have evaporated. The apparent discrepancy between the model predictions and the simulations suggest that evolutionary trends in the simulations are different from the model assumptions used in both studies. In particular, assumptions based on global properties at $z = 0$ seem not to translate directly to high-redshift behaviours, as currently observed. Therefore, once more observations of GCs at high redshifts progressively become available, a direct comparison between the N_{GC} assessed from such observations and the corresponding estimates based on simulations and theory

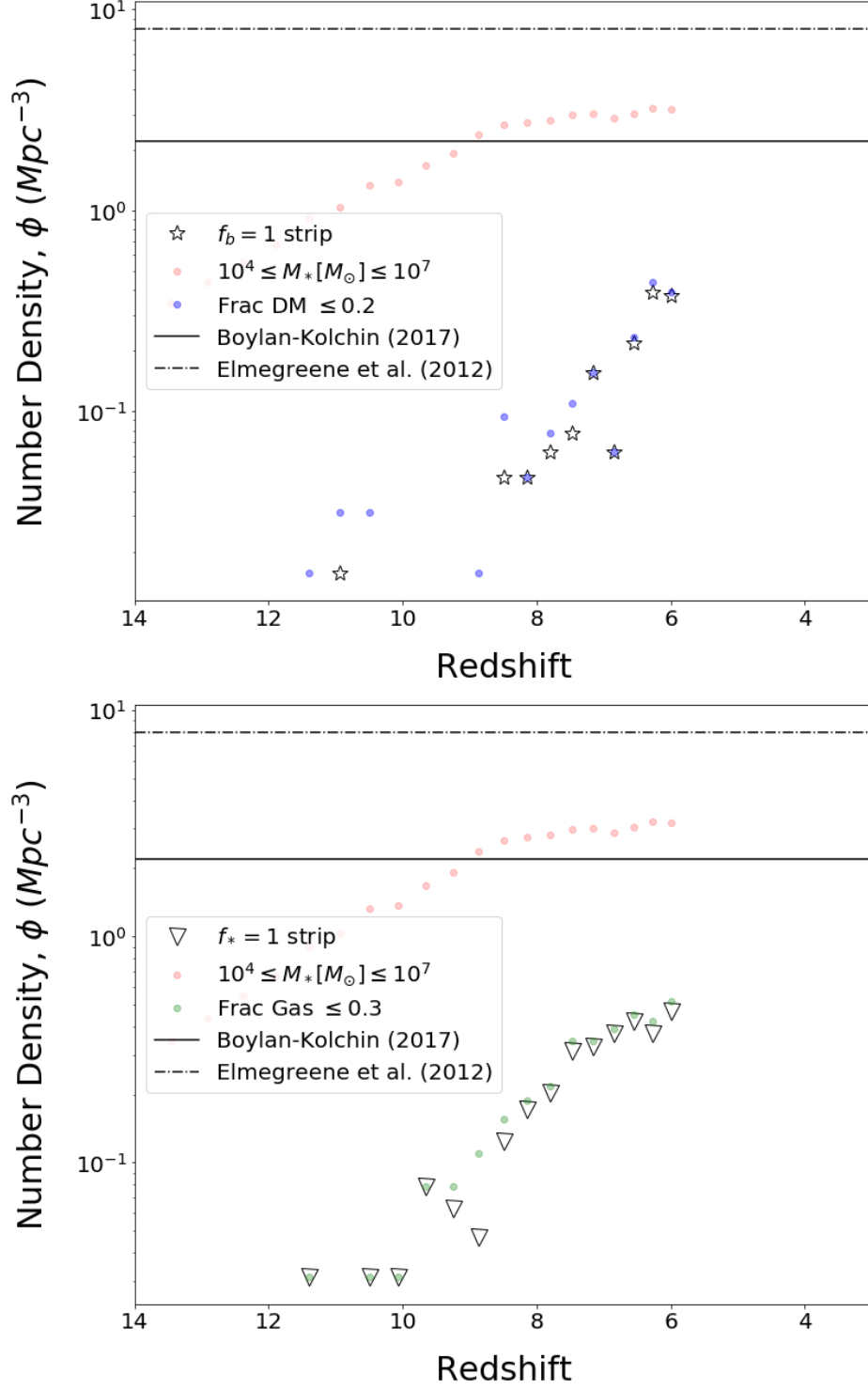


Figure 2.10 *Redshift evolution of the number density of potential candidate GCs in the simulation. Stars and triangles represent the $f_b = 1$ and $f_* = 1$ groups. Pale coloured dots indicate the observationally constrained subsamples I am comparing to. The solid and dot-dash lines are predicted values of ϕ taken from the literature (see legend and Section 2.4).*

should be made to constrain the physics at play.

When studying the global properties of low-mass stellar systems in the cosmological simulation, I found that the $f_b = 1$ objects have relatively higher stellar densities when compared to other substructures. However, the densities calculated are lower than those found in the local Universe for the Galactic GCs. This is due to a limitation of the simulations. The values of R_* determined here are likely overestimated due to the finite spatial resolution of FiBY. As well as investigating stellar density, I also looked into stellar half-mass radii, stellar velocity dispersion and stellar metallicity. When considering Z_* , I found that the $f_b = 1$ objects are a factor of two more metal-rich than the rest of the substructures extracted from FiBY. These values of Z_* are in fair agreement with the metallicities inferred for local Galactic GCs. However, I do find that the simulations are giving slightly higher metallicities than those found at low redshift. This is primarily due to the enrichment process in FiBY acting too rapidly (Cullen et al., 2019).

I also investigated the GC system mass – halo mass relation: the very good agreement between the local and the $z = 6$ relation in the simulations is somewhat surprising given that evolution of the GCs is still expected past $z = 6$. Most likely, the number density of infant GCs is still increasing at $z < 6$, which would increase the GC system mass per halo. Contributing to a further increase is the fact that many of the infant GCs have significant gas fractions that could lead to star formation at $z < 6$, if feedback effects are not sufficiently efficient. On the other hand, the cooperation between internal collisional processes and external tidal effects determine the mass loss of the individual infant GC candidates as they orbit around the centre of mass of their host galaxy. In addition, stellar evolution also likely play a significant role. The mean mass I find for the infant GC objects is 6×10^4 (i.e., about 10 times smaller than that used in SF09), which would allow for a significant contribution from newly formed GCs and subsequent star formation. In any case, the balance between the latter processes and those leading to mass loss in the GC system would require a dedicated investigation.

When presenting these results I proceeded with caution, referring to the $f_b = 1$ objects as infant GC candidates rather than definitively branding them as predecessors to present-day GCs. The reasoning behind this choice of vocabulary is two-fold. First, a comparison to observations in the local Universe will not necessarily provide conclusive evidence that the $f_b = 1$ objects are infant GCs. The objects that I am studying in this work have been taken from a snapshot in the simulation at $z = 6$. Thus, by $z = 0$, the $f_b = 1$ objects could look vastly different from their high-redshift counterparts, as a result of evolution driven by both internal and external effects (see Introduction for an

extended discussion). Concurrently, there is no guarantee that all the low-mass stellar systems identified in this Chapter will survive to the present day, as they might get disrupted or merge (Forbes et al., 2018a). Furthermore, some of the candidates are in a phase of their evolution when they are still gas-rich and star formation has not yet fully ceased, thus allowing for further evolution of their stellar mass and metallicity.

The second reason behind the terminology of “candidates” is the practical limitations of the simulations. The FiBY simulations used in this work reproduce both the star formation rate and stellar mass function for galaxies at $z \geq 6$ (Cullen et al., 2017) and the resolution is high enough to be able to study the global properties of gravitationally collapsing giant molecular clouds with Jeans masses of $\sim 10^6 M_\odot$ in the simulations in terms of star formation, feedback and metal enrichment. What they lack, however, is both time duration (as FiBY stops at $z = 6$) and a much finer spatial resolution. Both of these aspects would allow me to make detailed statements on the internal dynamical and kinematic structure of these objects as well as being able to compare them self-consistently to present-day GCs. These elements would, in turn, allow me to further support the hypothesis that the $f_b = 1$ objects are infant GCs. I also note that, when comparing the $f_b = 1$ group to high-redshift observations of candidate proto-GCs (see Figure 2.9), the findings are consistent. Thus the use of the terminology “candidate” for the infant GC objects is appropriate.

2.4.2 Conclusions

I explored a suite of high-resolution cosmological simulations from the First Billion Years (FiBY) project at $z \geq 6$ to study low-mass stellar systems with a particular focus on potential globular cluster (GC) candidates. The main results of this Chapter can be summarised as follows:

- I conducted an analysis of the demographics and global properties of low-mass stellar systems at high redshift, within the numerical framework of the FiBY cosmological simulations. I identified a population of $f_b = 1$ objects with a relatively low fraction of mass in the form of dark matter, which I suggest as possible infant GC candidates.
- I explored how the stellar half-mass radius, density, metallicity and velocity dispersion vary as a function of the stellar mass for the likely infant GC candidates. For comparison, I also investigated these properties for other groups of low-mass stellar systems identified in the simulations. I believe the $f_b = 1$ objects are

plausible infant GC candidates as they are characterised, among other properties, by high stellar densities when compared to the general population of substructures identified in the cosmological simulations.

- I fitted the redshift-zero globular system mass – halo mass relation and found it provides a reasonable fit to the $f_b = 1$ objects, indicating that this relation is set at formation. Due to its linearity, I speculate that, as these cluster - galaxy systems evolve, they move along the GC system mass – halo mass relation and be in good agreement with the present-day observations
- I found a previously not reported correlation between the specific star formation rate of galaxies and the stellar mass of the most massive GC. This correlation extends several orders of magnitude in sSFR and appears to hold for data at $z = 0$ and $z = 6$.
- I compared the sizes and masses of the $f_b = 1$ objects identified in FiBY to preliminary high-redshift observations of possible proto-GCs from [Vanzella et al. \(2017\)](#) and [Bouwens et al. \(2017b\)](#). In both cases, I found a relatively good agreement. Whilst the infant GC candidates are rather dense objects, they appear to be more extended than typical present-day GCs in the local Universe, consistently with the properties of the infant globulars currently observed at high redshifts.
- I investigated the morphology and the galactic environments that the $f_b = 1$ objects reside in. I found that these objects lie within the DM density peaks for their given parent halo, but they contain a low fraction of energetically bound DM particles. Most of the $f_b = 1$ objects lie within 1 kpc from the centre of their parent galaxy. This suggests that even in their first few Myr of evolution these objects have undergone many interactions.

In the next Chapter, I will investigate how the $f_b = 1$ objects came to be. I will look into their past evolution, star formation history and how the potential infant GCs and their environments have changed over time until $z = 6$. This will be done in order to be able to distinguish a particular formation pathway for infant GCs.

In Chapter 4, I will then focus on the evolution of the potential GCs candidates I have identified to redshifts $z < 6$. These objects have a high gas fraction, therefore I will investigate how much of this gas is used in subsequent star formation. In addition, the $f_b = 1$ objects appear to be in close proximity to the centre of mass of their

parent galaxy: this could have an impact on their likelihood of survival and subsequent evolution.

Chapter 3

Forming infant globular clusters in FiBY

In this Chapter, I build upon the work just laid out ([Phipps et al., 2020](#)) and utilise the same suite of simulations. In Chapter 2, two distinct groups of low-mass stellar systems within the simulations were identified. One group has a high fraction of stars and DM, with much larger radii; these objects were hypothesised to be proto-ultra faint dwarf (UFD) galaxies. The second group were considered to be infant GC candidates. They have a low dark matter (DM) fraction, a high stellar density, and small half-mass radii. The low DM content of these infant GCs raises questions about how the formation of these dense objects proceeded at higher redshift. Since there is no underlying DM structure for the infant GCs, understanding the instability mechanism behind the collapse of these objects is important. Previously, some infant GC candidates were found to be located in the disk of their host galaxy, therefore disk instabilities (e.g., see [Romeo & Agertz, 2014](#); [Bournaud, 2016](#); [Romeo et al., 2020](#)) could be the main trigger behind forming these objects. The infant GCs have a high fraction of gas, thus thermal instabilities ([Field, 1965](#); [McKee & Ostriker, 1977](#)) and/or turbulence could also have an effect. The motivation behind this Chapter is to analyse the infant GC candidates from Chapter 2 at redshift $z > 6$ in order to gain an understanding of the physical processes behind their formation. Whilst there are studies that are complementary to the one being conducted here in terms of spatial resolution ([Ricotti et al., 2016b](#)), they do not match the cosmic volume or the physically rich nature of the sub-grid models used in FiBY. Vice-versa, there are simulations of larger cosmic volume (e.g., see [Kim et al., 2018](#); [Li & Gnedin, 2019](#); [Pfeffer et al., 2018](#); [Kruijssen et al., 2019a](#)) but they simply cannot match the resolution achieved with FiBY. Thus this study provides a

complementary view.

The Chapter is laid out as follows. In Section 3.1, I introduce the way I classify bound structures and how I utilise this to identify and track GC-like objects at high redshift. Section 3.2 describes the collapse of these objects whilst Section 3.3 details the impact of the host-galaxy environment on their formation. In Section 3.4, I examine the effects of stellar feedback and the potential future evolution of the candidates. Finally, I discuss and summarise the findings in Sections 3.5 and 3.6. Throughout this Chapter I assume $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.265$, $\Omega_\Lambda = 0.735$ and $\Omega_b = 0.0448$.

3.1 Globular cluster formation in phase-space

Halo finders typically concern themselves with identifying matter that is gravitationally bound together in a single substructure, close to virialisation (e.g. [Springel et al., 2001](#); [Knollmann & Knebe, 2009](#); [Knebe et al., 2011](#); [Behroozi et al., 2013](#)). In the previous Chapter, the substructures were identified through the SUBFIND algorithm ([Springel et al., 2001](#); [Dolag et al., 2009](#)) and followed through time using a merger tree ([Neistein et al., 2011b](#)). Once such structures are identified, a list of their properties is given, with particular attention to their mass and radius. While this basic characterisation is informative at the final stages of formation, it lacks a clear identification of the various components that are involved in the formation of GCs; in particular, the baryonic material that is subject to feedback and dissipational effects may be difficult to capture. To overcome this limitation, here I take into account all the matter that is present in a given region, the identification of which is initially guided by the location of the particles that are bound at $z = 6$. Equipped with this information, I explore the formation of bound structures by studying the time evolution in the energy-angular momentum plane for all relevant matter components, as detailed below.

3.1.1 Energy-angular momentum diagram

The main tool adopted in this analysis is a representation of the phase-space of a substructure of interest in terms of the energy and modulus of the angular momentum vector of its individual constituents (sometimes referred to as the “Lindblad diagram”). A characteristic example of the diagram of one infant GC candidate identified in Chapter 2 can be seen in the left-hand panels of Figure 3.1, where gas and stellar particles are plotted as blue dots and red stars. The particles illustrated in this diagram are located

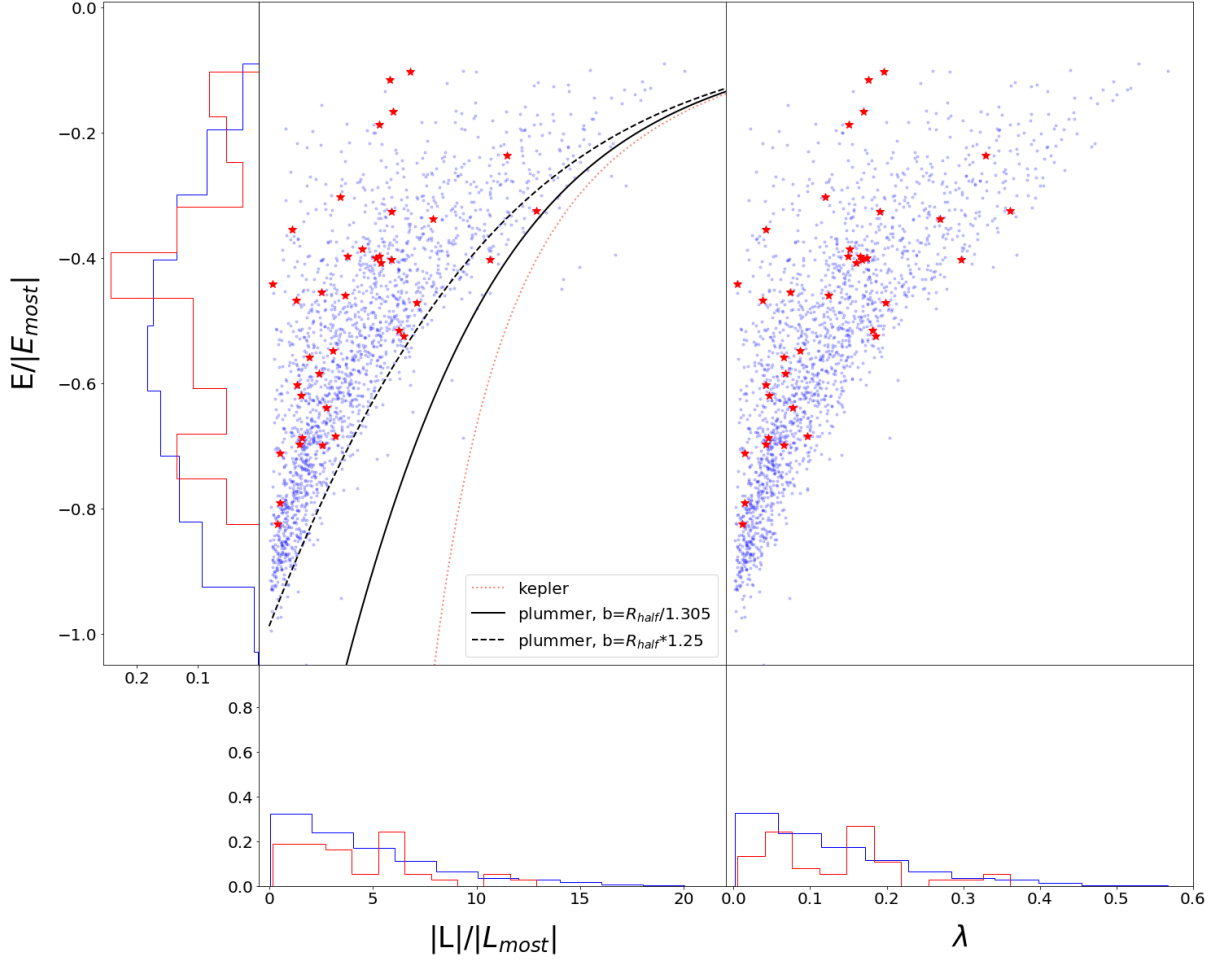


Figure 3.1 *Left: Representation of a GC candidate in the energy-angular momentum plane (“Lindblad diagram”); for details on the adopted normalisation, see main text. Gas particles are represented by blue points whilst stars are shown with red star symbols. The solid, dashed, and dotted lines represent the maximum allowed angular momentum for given energy in three different spherical potentials (for further details, see Section 3.1.1). Right: Alternative diagram in which the angular momentum is expressed by means of the dimensionless spin parameter (Bullock et al., 2001). On the axes, I show histograms of the distributions of the particles by type, with the same colour scheme.*

within a sphere of radius $R_{\text{sph}} = R_{\text{half}}$, where R_{half} is the half-mass radius of the candidate at the final redshift of $z = 6$. The sphere is centred on the centre of mass of the system, which, in turn, is calculated through a convergence method. Initially, I identify a GC candidate, its associated particles, and the relevant centre of mass by using SUBFIND. I then recalculate the centre of mass by using all particles (within a sphere of radius R_{sph}) that have negative total energy. I repeat this process iteratively, each time calculating the percentage difference between the calculated centre of masses. Once this difference is 10% or less, I consider the centre of mass as converged. The total energy (E) of each particle is defined as the sum of the kinetic energy and the gravitational potential energy. The kinetic energy is given by:

$$E_k = \frac{1}{2} m_i v_{i,\text{rel}}^2 \quad (3.1)$$

where m_i is the mass of a given particle and $v_{i,\text{rel}}$ is the magnitude of the velocity vector of the particle relative to the centre of mass of the infant GC candidate. I calculate the gravitational potential energy as the sum of the two-body interactions of a particle with all other particles within a given sphere of radius R_{sph} , centred on the centre of mass

$$E_{\text{grav}} = -G \sum_{i,j,i \neq j} \frac{m_i m_j}{r_{ij}} \quad (3.2)$$

where r_{ij} is the magnitude of the distance vector between particles i and j . As illustrated in Figure 3.1, for each GC candidate I normalise the total energy of the particles to $|E_{\text{most}}|$, i.e. the average energy of the 10 most bound particles within the sphere of radius R_{sph} , as obtained at the end of the convergence method described above¹. As the second dimension of the Lindblad diagram, I consider $|L|$, i.e. the magnitude of the total angular momentum vector of the individual particles, calculated in the same frame of reference centred on the centre of mass of the GC candidate. For consistency with the normalisation adopted for the energy, I also normalise $|L|$ of each particle to $|L_{\text{most}}|$, i.e. the magnitude of the average angular momentum of the 10 most bound particles within the sphere of radius R_{sph} .

From a dynamical point of view, in the case of a system characterised by spherical symmetry, the Lindblad diagram as defined above represents a complete catalogue of the orbits that are supported by the corresponding mean-field potential. All orbits must lie within the region enclosed by the vertical axis $|L| = 0$, which represents the radial

¹Such a normalisation has been chosen by analysing the average energy of the most bound particles as a function of the number of particles considered; for all GC candidates, an average over $N = 10$ particles allowed to identify numerically stable normalisation values.

orbits, and the curve denoting the angular momentum and energies for a circular orbit (L_c and E_c); beyond such a “centrifugal barrier”, which, under these assumptions, is a function of the spatial derivative of the potential under consideration, the diagram is formally inaccessible. For illustrative purposes, in Figure 3.1 I include three different options for the $L_c - E_c$ barrier. Two are determined by considering a Plummer potential (Plummer, 1911)

$$\Phi = -\frac{GM}{\sqrt{r^2 + b^2}}, \quad (3.3)$$

with appropriate values of the scale radius b . In the first case, which is shown as a solid black line, the scale radius is determined by the half-mass radius of the system, i.e. $b = R_{\text{half}}/1.35$ (for a derivation of this approximate expression, see Heggie & Hut, 2003). In the second case (dashed black line), the value of the scale radius is such that the corresponding centrifugal barrier encloses the majority of the particles, as illustrated in the diagram. Finally, the third curve corresponds to a Keplerian potential, which is fully specified by the total mass M , and, therefore, has no further spatial degree of freedom available in the determination of the associated centrifugal barrier. I wish to emphasise that this characterisation of the $L_c - E_c$ curves in terms of analytical potentials is not intended to be realistic and it has been introduced exclusively to offer a simple parameterisation of the energy-angular momentum distribution of a GC candidate at the final redshift $z = 6$; this will provide a convenient visual reference in the analysis of the time evolution of such diagrams, presented in the next subsection.

For completeness, in the right-hand panels of Figure 3.1, I display also an alternative version of the Lindblad diagram, by evaluating the total energy of particles (as defined above) against the individual spin parameter, λ . Here I have adopted the definition proposed by Bullock et al. (2001), but I note that this dimensionless parameter was first introduced by Peebles (1969) to characterise the angular momentum of bound stellar structure of cosmological relevance.

An interesting feature of Figure 3.1 is the distribution of the various species of particles: the gas and star particles appear to have a similar spread in both energy and angular momentum. In this representative infant GC candidate, as in most of the others identified in this study, the number of star particles is lower compared to gas particles; this seems to suggest that gas is the dominant contribution to the local gravitational potential and that stars adjust to it. As implied by the adopted GC candidate selection criterion (see Chapter 2, Section 2.1), only very few DM particles are present in these systems. I also note that such DM particles, whilst having negative total energies, are usually located on the far right-hand side of the Lindblad diagram, which signifies a high angular momentum content. This location in the diagram suggests that they

might have been initially associated with the extended DM halo of the host galaxy and subsequently captured gravitationally by the GC candidate.

3.1.2 Formation and evolution before $z = 6$

I can now explore the formation and early evolution of the infant GC candidates by assessing the time evolution of their Lindblad diagram before $z = 6$. I follow this evolution through 21 snapshots of the FiBY simulation, covering a time span of 56 Myr, which, for all the infant GC candidates, corresponds to several dynamical times.

To compute the Lindblad diagram through time, as displayed in Figure 2, I apply the following approach. First, for a given GC candidate, I consider the particles that, at $z = 6$, are located within a sphere of radius R_{sph} and trace them back through time. At each snapshot, I use the positions of these particles at an earlier time to determine an initial centre of mass as well as a half-mass radius ($R_{\text{half},z}$) for the ancestors of the objects. To determine the appropriate centre of mass of the systems at the earlier redshifts, I apply a similar convergence method as for the analysis conducted at $z = 6$; in the first step of the iteration, I choose all particles that are bound within the sphere of radius defined by the particles bound at $z = 6$. After this step, I then calculate the energy and angular momentum for each particle within $R_{\text{sph},z}$. For this work, I choose $R_{\text{sph},z} = R_{\text{half},z}$. Ultimately, this conservative choice is made because, at $z = 6$, the particles within the half-mass radius represent the core of the infant GC candidate and can be safely associated with it. Also, this collection of inner particles will most likely evolve to become the core of the GC at later times and, therefore, it is less prone to be disrupted by external environmental effects.

When calculating the total energy and angular momentum, I use every bound particle within a sphere of radius $R_{\text{half},z}$, however, in Figure 3.2, even at earlier times, I display only particles that are part of the bound object at $z = 6$. This visualisation choice is made in order to concentrate on examining the phase-space assembly and evolution of the core itself, as it appears at the final redshift. As before, the axes of the diagrams presented in Figure 3.2 are normalised to the 10 most-bound displayed particles at each given redshift, and the curves denote the “centrifugal barriers” corresponding to the spherical potentials assessed exclusively at $z = 6$, as introduced in the previous subsection. For visual clarity, I show only the gas particles, as they dominate the potential of the system; at all times, the stars follow approximately the distribution of the gas particles, as demonstrated in the case of the Lindblad diagram at $z = 6$ (see Figure 3.1).

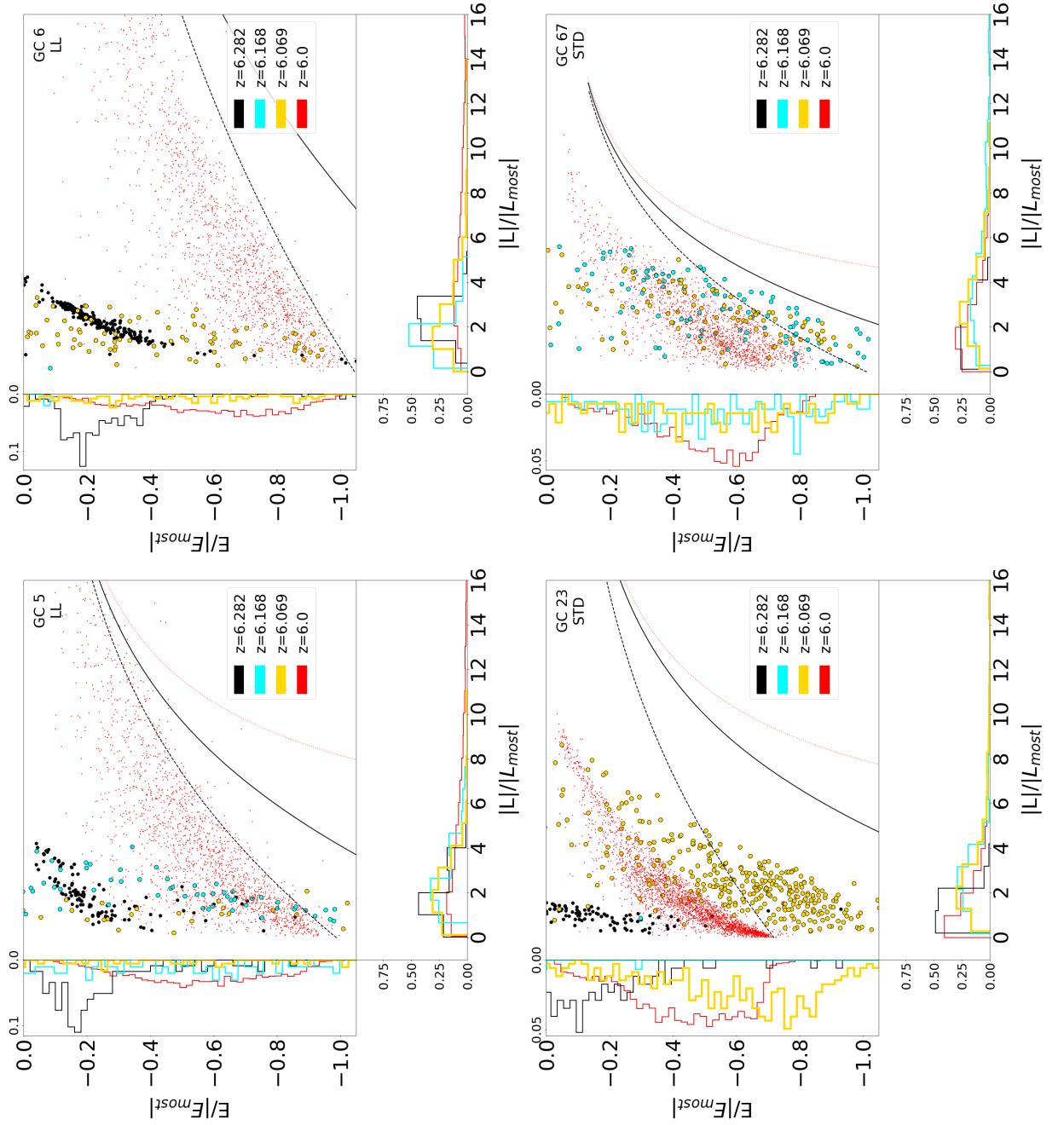


Figure 3.2 *Time evolution of the Lindblad diagram for GC candidates 5, 6, 23 and 67. Particle energies and angular momenta are normalised to the corresponding average of the 10 most bound particles at each redshift. Displayed are only the gas particles that are bound to the object at $z = 6$; different colours indicate different redshifts. Gas particles appear to be on nearly radial orbits, suggesting infall at early times. At later times, the system tends to become isotropic, as the angular momentum of the gas spreads out (see x -axis histograms), and the distribution in the energy of the gas settles into the configuration observed at $z = 6$.*

When examining the Lindblad diagrams as a function of time, I can identify different phases of dynamical evolution, relating to the infall and collapse of the systems. For most instances, ~ 56 Myr ago, the infant GC candidate had not yet formed but the gas is in the process of collapsing. This can be seen through the column of gas particles (black and blue data points in Figure 3.2) at very low angular momentum, but high energies. The gas particles at these early times are on nearly radial orbits, which indicate infall. Also, the little variation one can see across time in angular momentum (compared to the energy of the gas) may indicate that angular momentum is conserved during the early formation stages and suffers little re-distribution. After a few Myr, the distribution in energy still occupies a wide range (blue and yellow data points) and the distribution in angular momentum also progressively spreads out.

It appears that, as the collapse proceeds, the distribution in energy approaches more negative values as the gas becomes gravitationally self-bound and settles into the characteristic configuration observed at $z = 6$. This behaviour in the Lindblad diagram coincides with the point at which nearly all of the gas reaches high densities, beyond the star formation threshold. The general evolution depicted in the diagram suggests that, after an initial period of radial infall, the systems tend to become more isotropic, as the distribution of the angular momentum of the gas and star particles becomes more extended. This happens on timescales well within the dynamical time of the candidates and supports the notion that the initial orbital structure of GCs is set during a short time window that coincides with the onset of star formation. I also note that there are a few particles (in all infant GC candidates) that temporarily experience a large excursion in energy. The most probable cause of this behaviour in these simulations is supernovae in the nearby environment imparting thermal energy to neighbouring SPH particles and increasing the gas particles' kinetic energy.

I find that different candidates can be grouped on the basis of their evolution in the Lindblad diagram. In general, objects with a similar phase-space evolution are found to belong to the same galaxy or to be located in host galaxies of similar morphology. In Table 3.1 these groupings are indicated, as identified on the basis of their Lindblad diagram evolution. The panels in Figure 3.2 illustrate a representative candidate of each of the main classes presented in Table 3.1. The last column of the Table gives the group designations, which I expand upon here. When comparing the angular momentum distribution of GC candidates I find a clear separation into two distinct populations (see Figure 3.3), one with a distribution that shows a large range in angular momentum, which I label *LL*. The other population that I find, which is more common (labelled *STD*), shows a smaller spread in angular momentum, and, in addition, appears to have

GC ID	z_{form}	M_{T} [$M_{\odot}$]	M_{G} [$M_{\odot}$]	M_{J} [$M_{\odot}$]	R_{J} [pc]	fracDM	R_{half} [pc]	$\log(Z/Z_{\odot})$	λ_{global}	Star Formation?	Group
5	6.042	5.37×10^5	3.85×10^5	5.43×10^5	69	0.26	16.60	-0.93	0.003	Y	LL
6	6.042	1.72×10^6	1.24×10^6	5.04×10^5	56.9	0.24	23.30	-1.03	0.003	Y	LL
8	6.083	1.44×10^5	1.19×10^5	5.43×10^5	99.2	0.17	13.80	-1.15	0.003	N	LL
9	6.154	5.98×10^5	4.29×10^5	5.31×10^5	91.6	0.28	25.40	-1.20	0.01	Y	LL
15	6.111	3.57×10^5	3.16×10^5	5.26×10^5	76.2	0	15.80	-1.04	0.002	Y	ZDM
16	6.028	6.70×10^4	6.10×10^4	5.57×10^5	102.4	0	11.0	-1.29	0.007	Y	ZDM
22	6.125	3.02×10^6	1.66×10^6	4.99×10^5	51.3	0.40	31.90	-1.04	0.001	Y	STD
23	6.097	6.14×10^5	5.20×10^5	5.28×10^5	64.2	0.13	14.40	-1.19	0.0007	Y	STD
24	6.097	2.12×10^5	1.62×10^5	5.99×10^5	132.9	0.23	19.30	-1.22	0.003	N	STD
25	6.111	3.24×10^5	3.15×10^5	5.62×10^5	104.9	0.019	23.90	-2.16	0.004	N	STD
34	6.125	4.73×10^5	3.16×10^5	5.50×10^5	99.8	0.33	19.9	-1.24	0.006	Y	STD
42	6.139	2.24×10^6	1.63×10^6	4.67×10^5	14.9	0.003	4.50	-0.43	0.0001	Y	STD
47	6.083	2.00×10^5	1.57×10^5	5.39×10^5	83.2	0.22	12.60	-1.64	0.002	N	STD
65	6.055	1.22×10^5	1.04×10^5	5.65×10^5	102.4	0.15	12.50	-1.69	0.003	Y	STD
67	6.182	4.01×10^5	3.64×10^5	5.99×10^5	142.9	0.09	31.20	-2.46	0.002	N	STD
10	6.014	7.84×10^4	0	-	-	0.16	7.90	-	0.013	Y	SO
35	6.014	1.99×10^5	0	-	-	0.12	11.60	-	0.033	Y	SO
3	>6.282	6.94×10^7	3.78×10^7	4.47×10^5	9.4	0.05	12.0	-0.12	0.0004	Y	NSC

Table 3.1 Selected physical properties of the infant GC candidates at their “formation redshift”. They are divided into groups of objects that show similar evolution in their Lindblad diagram. From left to right: ID of the candidate, formation redshift, total mass within R_{half} , total gas mass within R_{half} , Jeans mass, Jeans length, DM fraction, half-mass radius, average gas metallicity, global spin parameter [Bullock et al. \(2001\)](#), whether any stars present within R_{half} at $z = 6$ have already formed at z_{form} . The final column indicates the group designation, as based on their evolution in phase-space. The groups are: nuclear star cluster (NSC), largest range in angular momentum (LL), zero-dark matter (ZDM), standard (STD) and star-only (SO). For clarity, I find the following candidates in the same host galaxy: 5 to 10, 22 to 25, 15 & 16 and 34 & 35.

GC ID	M_T [$M_\odot$]	M_G [$M_\odot$]	frac _{DM}	R_{half} [pc]	Galaxy Morphology	Galaxy ID	Host Mass [$M_\odot$]	Group
5	2.39×10^6	2.34×10^6	0.0026	8.80	Proto-Merging Spiral-like	1	3.26×10^9	LL
6	2.37×10^6	2.32×10^6	0.0026	7.50	Proto-Merging Spiral-like	1	3.26×10^9	LL
8	1.25×10^6	1.22×10^6	0.0049	15.50	Proto-Merging Spiral-like	1	3.26×10^9	LL
9	8.22×10^5	8.10×10^5	0	10.30	Proto-Merging Spiral-like	1	3.26×10^9	LL
15	1.56×10^6	1.54×10^6	0	9.0	Rotating Spiral-like	71	3.19×10^9	ZDM
16	7.15×10^5	7.04×10^5	0	10.30	Rotating Spiral-like	71	3.19×10^9	ZDM
22	5.10×10^6	4.89×10^6	0.003	7.90	Clumpy Proto-Galaxy	235	2.29×10^9	STD
23	3.56×10^6	3.47×10^6	0.005	8.70	Clumpy Proto-Galaxy	235	2.29×10^9	STD
24	1.14×10^6	1.12×10^6	0.066	10.50	Clumpy Proto-Galaxy	235	2.29×10^9	STD
25	8.38×10^5	8.27×10^5	0	14.90	Clumpy Proto-Galaxy	235	2.29×10^9	STD
34	1.20×10^6	1.18×10^6	0.24	10.70	Clumpy Proto-Galaxy	360	2.14×10^9	STD
42	2.65×10^6	0	0.04	6.60	Clumpy Proto-Galaxy	458	1.84×10^9	STD
47	1.38×10^6	1.31×10^6	0	10.80	Clumpy Proto-Galaxy	472	1.54×10^9	STD
65	7.95×10^5	7.21×10^5	0.23	12.70	Clumpy Proto-Galaxy	649	4.68×10^8	STD
67	2.10×10^6	2.04×10^6	0.11	16.40	Clumpy Proto-Galaxy	676	8.12×10^8	STD
10	4.41×10^5	0	0.15	7.90	Proto-Merging Spiral-like	1	3.26×10^9	SO
35	3.91×10^5	0	0.12	11.60	Clumpy Proto-Galaxy	360	2.14×10^9	SO
3	8.44×10^6	5.14×10^6	0.009	3.60	Proto-Merging System	0	3.85×10^9	NSC

Table 3.2 Selected properties of the infant GC candidates at $z = 6$. They are divided into groups of objects that show similar evolution in their Lindblad diagrams. From left to right the columns show: the ID of the candidate, DM fraction and half-mass radius, morphology of the host galaxy, the total mass of the host galaxy, and the group designation from the phase-space evolution.

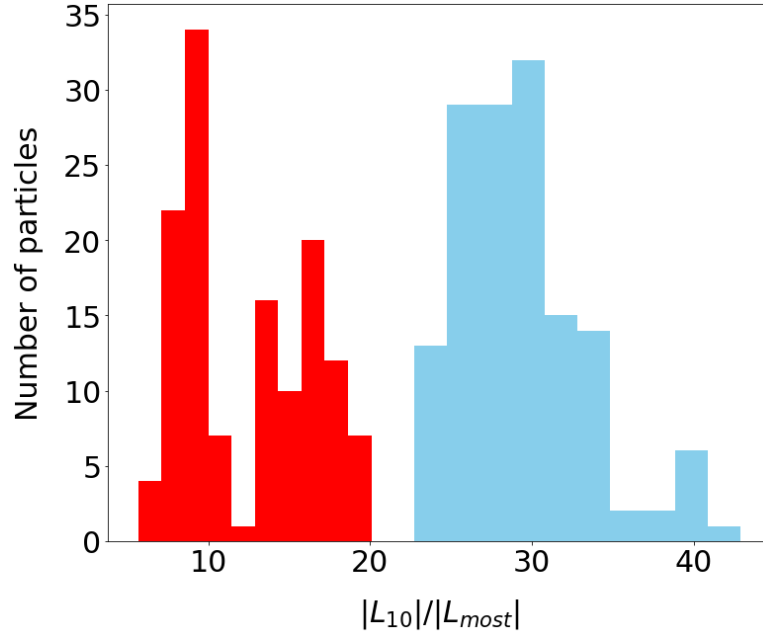


Figure 3.3 *Histogram of the top ten percent of gas particles per candidate with the highest angular momentum, normalised to the angular momentum of the most bound particles at $z = 6$. The blue histogram represents particles in the LL group of GC candidates, whilst the red is the STD group.*

a very distinct evolution in energy. During the collapse phase, the gas becomes more bound than the expectation based on the reference Plummer profile identified at $z = 6$. This indicates that the gas cloud ancestor of these candidates collapsed further, which is a reflection of the lower initial angular momentum of the gas cloud compared to the LL class. I also identify another sub-group, zero dark matter candidates (labelled ZDM), that have a similar evolution to the large angular momentum class LL , but in contrast, no DM associated with their phase-space evolution at any time. Again, in these cases, the initial angular momentum of the gas cloud prohibits deep collapse which is seen in the STD class.

For completeness, I wish to mention three GC candidates that stand out from the overall sample. The first is candidate 3 (labelled NSC). This candidate is the most massive one identified, with a total mass of $M_T = 6.94 \times 10^7 M_\odot$ and, across the 21 snapshots I have studied, its Lindblad diagram had already settled into an evolved configuration in the energy - angular momentum plane, indicating that its formation time is much earlier than $z = 6.28$. Given such phase-space appearance and its mass, I speculate that this candidate might be a potential ancestor of a nuclear star cluster. The other two interesting candidates are 10 and 35 (SO candidates). These two candidates are the only ones that consist only of stars at $z = 6$, and they appear to be gas-poor throughout most of their evolution. I will come back later to the SO candidates in Section 3.4 to

discuss how feedback might have shaped their properties.

The Lindblad diagram also gives an approximate indication of the formation time of the infant globular cluster candidates observed at $z = 6$. Here “formation” refers to the moment at which the Lindblad diagram of a given infant GC candidate settles into the characteristic configuration in the energy - angular momentum plane, as observed at $z = 6$. It is interesting to note that this moment coincides closely with the time at which the number of the most bound particles converges towards the number recorded at $z = 6$, and the majority of stars, which later are observed at $z = 6$, start to form. In Table 3.1, I list all these formation redshifts, denoted as z_{form} .

3.2 Collapse of infant GCs

3.2.1 Collapse of the gas

Having established the approximate formation redshift of all infant GC candidates, I can look into how the gas in the objects collapses and characterise its overall evolution, pre- and post-formation. At formation, in all GC candidates, the majority of the gas particles are above the star formation density threshold adopted in the FiBY simulations, thus, they are in the process of being converted into stars. This provides further evidence that z_{form} is a good proxy for the formation of a gravitationally bound infant GC, as almost all gas has reached density values which are appropriate for giant molecular clouds.

The evolution of the gas at density values which are beyond the adopted star formation threshold is governed by an effective equation of state, to ensure the Jeans mass is always resolved. Therefore, studying the evolution of the gas post-formation redshift will not help to gain much insight into its collapse. However, pre-formation most of the gas has densities less than the star formation threshold, thus I can study its collapse and the evolution of its density during this time frame to gain some physical insight.

I wish to reiterate, as already stated in the previous Section, that “formation redshift” simply refers to the operational definition I am adopting. In reality, the process of formation for these objects might have started at earlier times, with the initial infall of the gas; here “formation redshift” just marks the time at which the GC candidates can be considered as gravitationally bound objects.

The simplest way for the gas to collapse is under the influence of its own gravity. In

an idealised setting where the only force at play is gravity, the gas collapses on a free-fall timescale. Comparing a free-fall model to the dynamics of the gas pre-formation ($z > z_{\text{form}}$) can offer some insight into whether forces other than gravity are at work during the gas collapse. I compare the evolution of the gas density in the simulation to a basic free-fall model (Larson, 1969; Penston, 1969; Omukai, 2000) given by

$$\frac{d\langle\rho\rangle}{dt} \approx \frac{\langle\rho\rangle}{t_{\text{dyn}}} \quad (3.4)$$

where I approximate the dynamical time as $t_{\text{dyn}} = 1 / \sqrt{G\langle\rho\rangle}$, with G as the gravitational constant and $\langle\rho\rangle$ an average density estimate based on the density distribution of the gas in each infant GC candidate.

Specifically, I wish to confront the dynamical timescale with δt , which is the time required to reach z_{form} . As I compare these two timescales over a range of different redshifts, during periods when the collapse is purely driven by gravitational free-fall, one would expect to find $t_{\text{dyn}} \sim \delta t$, as dictated by the solution of Equation 3.4. Figure 3.4 shows as solid lines the evolution I find for the collapse of the GC candidates in the FiBY simulation. In most cases, the ratio t_{dyn} over δt is close to unity, which suggests that the dominant force acting on the objects is gravity and, whilst there could be some internal pressure support, it is insufficient to prevent collapse on a free-fall time. Also, all GC candidates - for a majority of the time - do collapse on a timescale that is slower than t_{dyn} , which means that additional, external factors are not influencing the formation and collapse of these objects. At the earliest times, for a number of GC candidates, the ratio is much greater than the analytical prediction. This implies that the trigger for the collapse in these objects is not self-gravity, but an external process sourced by the environment in the host galaxy. I wish to note, however, that self-gravity does quickly take over and subsequently drives the collapse dynamics.

Interestingly, the infant GC candidates that have a similar $t_{\text{dyn}}/\delta t$ evolution (*LL* & *ZDM* vs *STD*) are the ones which I identified earlier as being grouped on the basis of similarity in their Lindblad diagram evolution (see Table 3.1); these groupings are displayed in Figure 3.4 with lines of the same colour. Although, in general, all infant GC candidates do undergo dynamical collapse, the subtle nuances in the time evolution of the ratio of the dynamical time over δt are still hinting at possible differences during the collapse, for which I also see some evidence for in the evolution of the Lindblad diagrams. In particular, the low angular momentum *STD* population shows an evolution that continuously declines in $t_{\text{dyn}}/\delta t$, before going through a phase of roughly constant $t_{\text{dyn}}/\delta t$. In contrast the, *LL* and *ZDM* classes show an extended period of constant

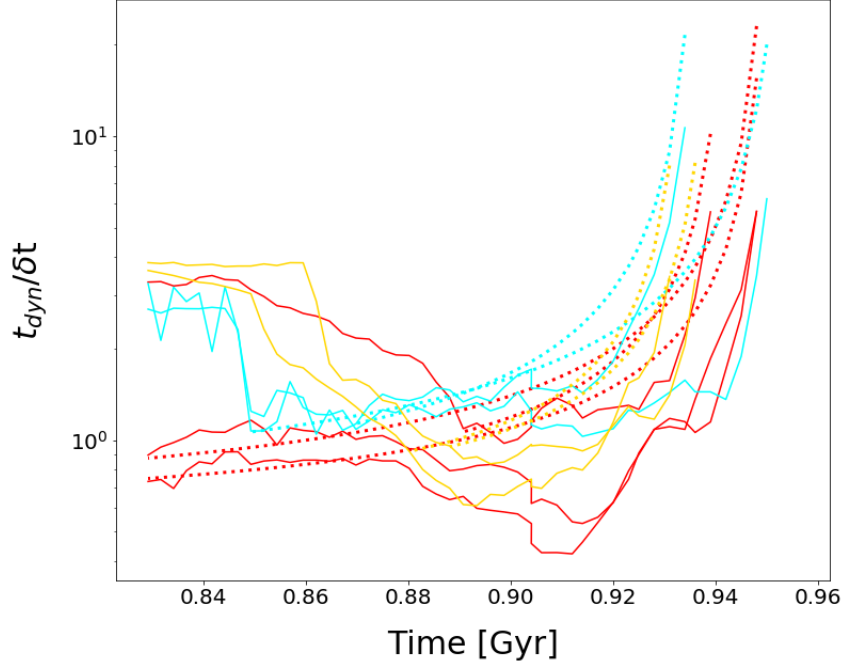


Figure 3.4 *Evolution of the ratio of the dynamical time over δt - the time until “formation” - for a selection of candidates that represent each of the main groupings: LL (red), ZDM (blue) and STD (orange). The dotted lines indicate the analytic prediction (see text). Proximity to the dotted lines indicates free-fall collapse. However, at early times, some of the GC candidates show ratios greater than the analytical prediction, which suggests that other forces besides self-gravity are at play at the collapse inception.*

$t_{\text{dyn}}/\delta t$.

To further confirm that the dynamics of the collapse are consistent with the effect of self-gravity, I calculate the analytic solution of Equation 3.4 for each candidate, by starting at a time when $t_{\text{dyn}}/\delta t \sim 1$ and using the average density of the GC candidate at that time. For the first tens of Myrs, the analytic solutions (displayed as dotted lines in Figure 3.4) are in good agreement with the numerical results from the FiBY simulation, then there is a deviation. However, such a deviation from the expectation of the free-fall model is not too substantial, especially when the density of the gas at that state is taken into account.

Even for the infant GC candidates that display signs of star formation at $z > z_{\text{form}}$, this activity does not seem to affect the collapse of the gas. This lack of impact on the gas dynamics is likely due to the fact that any such star formation activity is recent, hence any stellar feedback (e.g., winds due to supernovae feedback) is still of a minor entity.

3.2.2 Infall of the stars

For a majority of the infant GC candidates, a fraction of the stars that, by $z = 6$, are located in the core of the object have already formed by the time I consider the candidates to be gravitationally bound objects. From an examination of the time evolution of the stellar mass enclosed within a sphere of radius R_{half} , I find that not all of the stars that exist before redshift z_{form} are formed locally within R_{half} . This may be partly due to the adopted method of determining the centre of mass, as, between snapshots, the position of the barycentre fluctuates slightly. However, this effect does not account for the total infall of the stars that is observed in Figure 3.5. This Figure displays the interparticle distance for the star particles which are present in the GC candidates at $z = 6$. When considering the stellar component of the infant GC candidates, I only show the average interparticle distance as a proxy for the extent of the stars in the object as the stellar component is resolved by a lower number of particles compared to the gas. Solid lines represent all stars, whereas the dashed lines correspond to the stars that are already present in the previous snapshot. This illustration highlights the impact on the interparticle distance of stars which are formed between snapshots. Most of the infant GC candidates show a constant decrease in interparticle distance over time, which can be interpreted as the particles moving toward each other during collapse.

When comparing the time evolution of interparticle distance with the Jeans length of the gas in the GC candidates (see Figure 3.6), I find that, initially, the Jeans length is smaller than the interparticle distance between star particles and that the ratio of interparticle distance to the Jeans length becomes roughly constant around z_{form} . The Jeans length in this Figure is calculated at each snapshot by using the average density and temperature of the gas particles within a sphere of radius R_{half} at that time. These results, partnered with evidence of the gas collapsing on the dynamical timescale, suggest that the formation of the infant GC candidates is primarily driven by gravitational instabilities. The physical size of the GC candidates in the FiBY simulation is, therefore, likely set at early times by the Jeans length and then, subsequently, by further infalling material. I emphasise that the Jeans length, as well as the sizes I calculate for the objects, should be interpreted only as upper limits due to the resolution limits of the FiBY simulation.

By studying the gas distribution over time, the star formation histories, and distance between star particles, I have determined that self-gravity dictates the timescales of the collapse of the GC candidates as well as the reference length scales they form on through the Jeans instability. The onset of gravitational instabilities in some cases, however, requires an external trigger that quickly becomes sub-dominant to self-gravity.

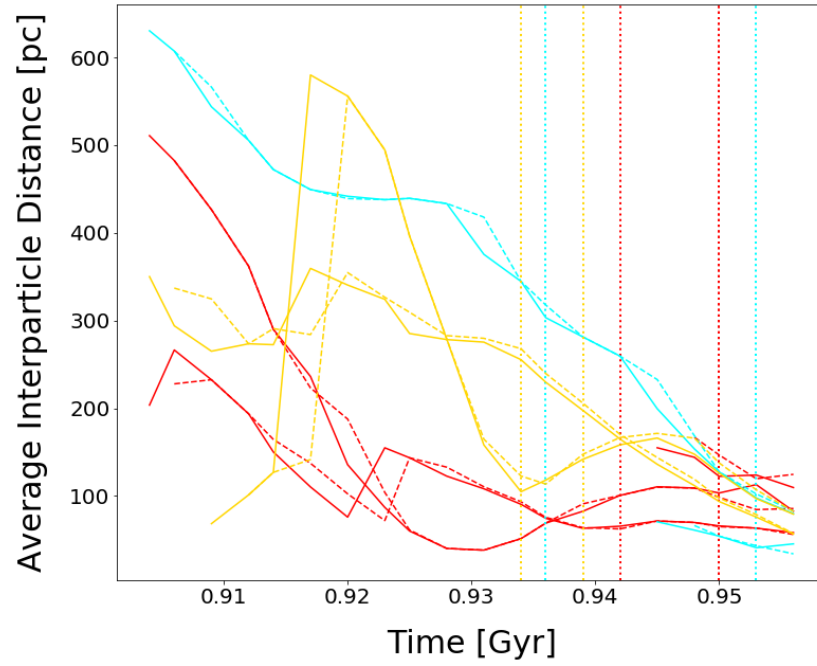


Figure 3.5 *Evolution of the average interparticle distance between the stars present in the infant GC candidates at $z = 6$. All stars are shown with solid lines whilst stars that were present in the previous snapshot are shown with dashed lines. Vertical lines indicate the formation times of each of the candidates. The similarity between the solid and dashed lines shows that the new stars form consecutively closer together with time. The red (LL), blue (ZDM) and orange (STD) lines show candidates from each of the main groupings as in Figure 3.4.*

3.3 The infant GCs - host connection

In the local Universe, GCs are most often found as populations of clusters in the haloes of galaxies. As presented in Chapter 2 and confirmed in the high-frequency simulation used here, the infant GC candidates that I identify are typically located within the half-mass radius of their host galaxy. Given that most of such objects formed just recently, they are indeed still located close to their birth site. Interactions and mergers with other galaxies at lower redshift likely relocate the surviving GC candidates to the haloes of new host galaxies. The prime epoch for these events to happen is expected to be toward $z \sim 2$, when the merger rate of galaxies peaks (Khochfar & Burkert, 2001).

I find that the infant GC candidates that belong to the same class, as attributed based on their phase-space properties (see Table 3.1), also reside in hosts of similar morphology, e.g. the STD candidates are all found in clumpy host galaxies. In Figure 3.7 I present gas surface density maps for three GC-host galaxy systems. I refer to these systems by

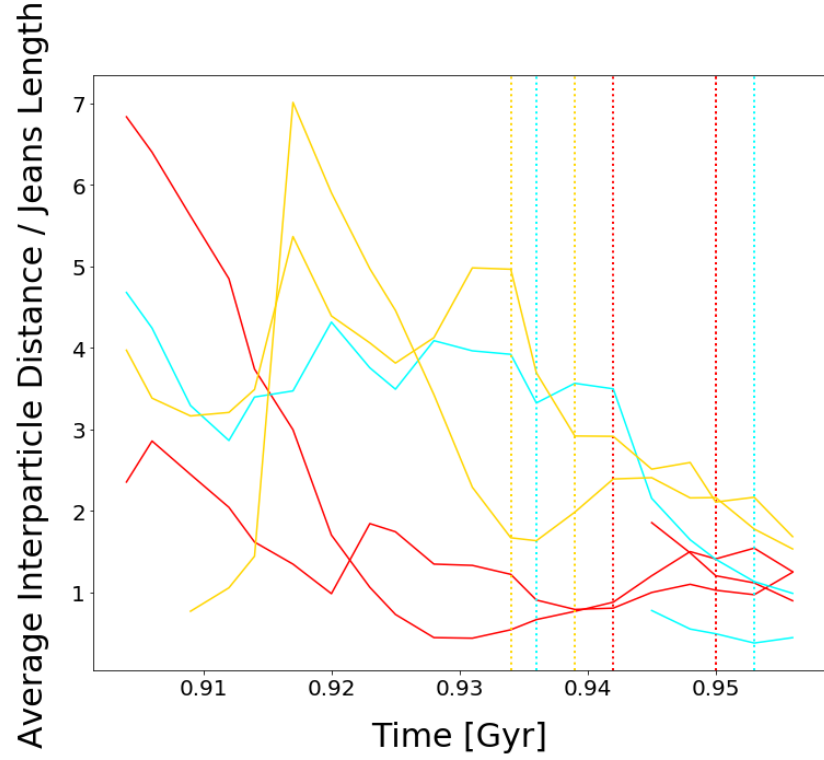


Figure 3.6 *Evolution of the ratio of the average interparticle distance between the stars present in the infant GC candidates at $z = 6$ and the Jeans length of the gas. Line colours are the same as in Figure 3.4. Vertical lines indicate the formation times of each of the candidates. The evolution of this ratio is similar to that in Figure 3.5 as the Jeans length evolution is roughly constant. By $z = 6$ this ratio is equal to 1, implying that the physical size of the candidates is set at early times by the Jeans length of the gas.*

their parent galaxy ID: 1, 71 and 235. The location of the infant GC candidates in each of the galaxies is indicated by a black circle. One of the host galaxies is undergoing a major merger, whilst the infant GC candidates are forming and evolving (top left panel - Galaxy 1). In the bottom panels, I present a host (Galaxy 71) which contains two infant GC candidates, displayed at their corresponding formation redshifts. This host galaxy is a rotating spiral-galaxy-like system, as can be seen by the change in orientation of the spiral arms from one snapshot to the other; the infant GC candidates are located in the spiral arms. Finally, the last host galaxy (top right panel - Galaxy 235) appears to be a clumpy proto-galaxy that has no distinct morphology as of yet and it is characterised by many high-density knots of gas. This clumpy case is the most common host for the infant GC candidates in Table 3.1. In the following Sections, I will examine the impact that these different types of host galaxy environment might have on the formation and early evolution of the infant GC candidates.

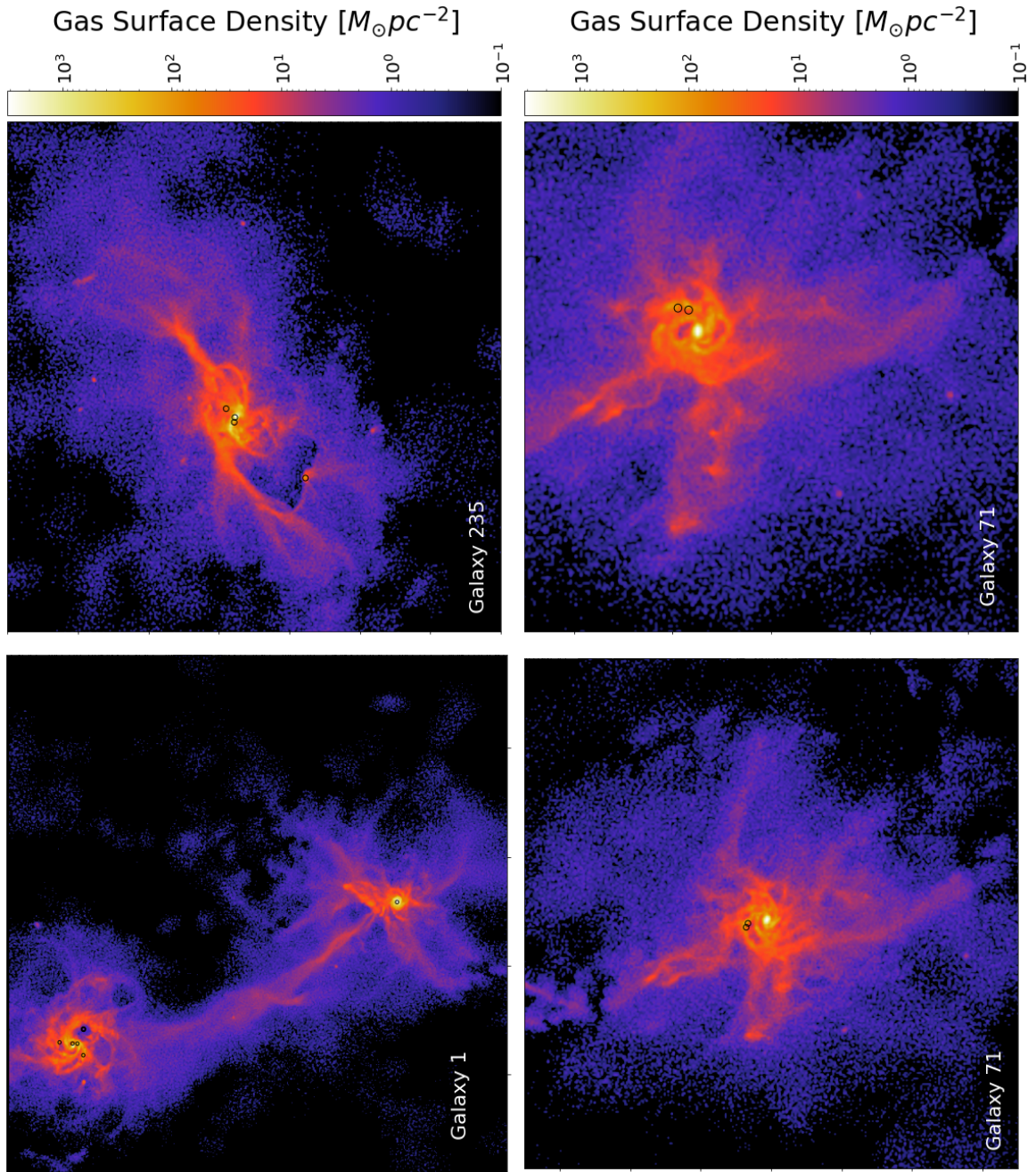


Figure 3.7 *Gas surface density maps of selected host galaxies, evaluated at the formation time of one of the GC candidates in the system. As viewed from landscape, top left: Galaxy 1 hosts five candidates (it is merging with Galaxy 0, which hosts one candidate). Top right: Galaxy 235 hosts four candidates. Bottom: Galaxy 71 hosts two candidates. This system is displayed at two different redshifts, that correspond to the formation times of the two GC candidates in the galaxy.*

3.3.1 Disk-like galaxies

The *LL* and *ZDM* (see Table 3.1) candidates are located in host galaxies that show a clear disk structure and, for the latter, also spiral arms (see Figure 3.7, bottom two panels). For the two *ZDM* candidates (GCs 15 and 16), there is a difference in their formation times of about ~ 17 Myr, but they form close to each other and have similar masses and Jeans lengths. The candidates appear to form in one of the spiral arms of the host galaxy. This is the natural place for their formation given that spiral arms are regions rich in molecular gas clouds and are known to host high-density gas, as well as clustered star formation (e.g., see Kim & Ostriker, 2002; Kim et al., 2006; Mo et al., 2010). Spiral arms themselves can trigger gravitational instabilities in the gas clouds (e.g., see Elmegreen, 2009).

To further explore the possible role of the angular momentum of the host galaxy in defining the environment of the different classes of infant GC candidates, I evaluate λ , i.e. the global spin parameter of the host galaxies, computed at the formation times of their infant GC candidates. I begin by following the method of Lagos et al. (2017) to calculate the radial λ_R profile (see their Equations 1 - 4). In their work, such profiles only take into account the baryonic components; here, I wish to apply this method to both the baryons and the DM particles. So Equation 4 from Lagos et al. (2017) becomes:

$$\lambda_R(r) = \frac{\sum_{i=1}^{N(r)} m_i r_i V_{rot}(r_i)}{\sum_{i=1}^{N(r)} m_i r_i \sqrt{V_{rot}^2(r_i) + \sigma_{1D}^2(r_i)}} \quad (3.5)$$

where $N(r)$ is the number of radial bins enclosed within radius, r , and the sum is taken over all of the radial bins from the inner most one until radius, r . The values V_{rot} and σ_{1D} are the rotational velocity and the component of velocity vector above parallel to the angular momentum vector of the particles. To calculate the radius of each shell, I assume a Lagrangian-based approach, such that each shell contains the same number of particles ($N = 4000$). Once the radial profile is computed, the global λ is found by summing the λ_R value in each shell and then dividing the total by the number of shells in other words $\lambda = (\sum \lambda_R)/N$.

The global λ value for both the galaxies in the proto-merging system (Galaxy 1) and the “standard” proto-galaxy (Galaxy 235) decreases with redshift, whereas the rotating spiral (Galaxy 71, bottom panels, Figure 3.7) has a constant value for λ across the formation redshifts of its infant GC candidates. This indicates that the angular momentum in this system is being conserved. However, the value of the total λ of Galaxy 71 is not the highest out of the galaxies analysed here. The reason for this is

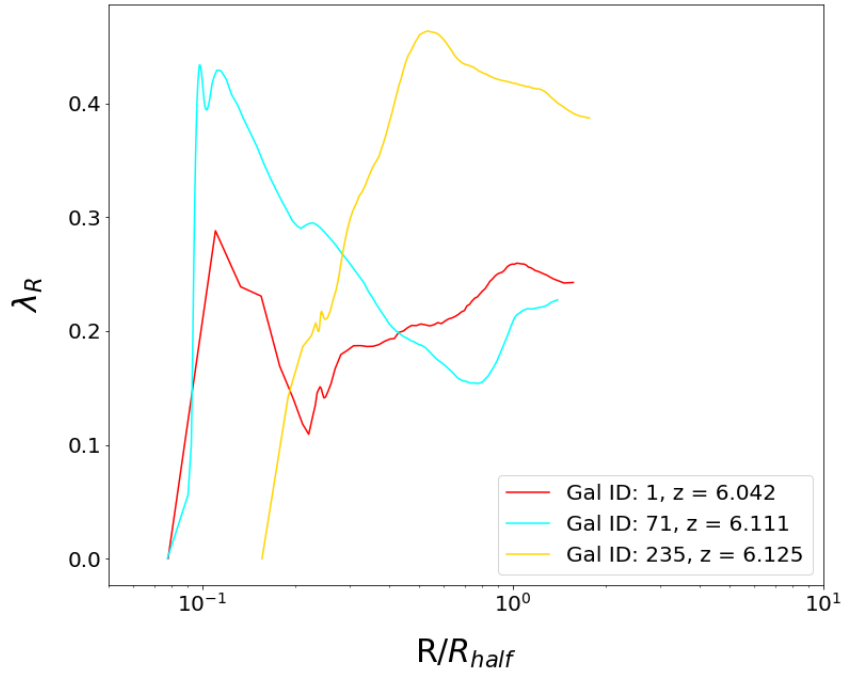


Figure 3.8 *The radial profile of the dimensionless spin parameter for three representative host galaxies of the main groups of GC candidates where the x-axis is normalised to the half-mass radius of the host galaxy. The host for LL is displayed in red, ZDM in blue, and STD in yellow (see Table 3.1). The redshift at which the profile is calculated is indicated in the legend.*

clear when inspecting the λ_R profiles (see Figure 3.8). While baryons dominate the inner parts of the galaxies analysed here, the decision to include dark matter particles in the calculation has resulted in a flattening of the profile out to large radii for Galaxy 235, thus inflating the global value of λ . If one focuses instead on scales < 1 kpc (which would pertain to the stellar disk for the spiral galaxy), it is clear that Galaxy 71 has a much higher value of angular momentum.

The GC candidates with the largest range in angular momentum (class *LL*, see Table 3.1) happen to be in the same host galaxy (Galaxy 1). This galaxy also hosts one of the *SO* candidates, making it the galaxy with the most GC candidates in this study. This host also has a defined disk-like structure and, when moving out to larger scales, I find that it is about to engage in a galaxy-galaxy merger. I investigate now whether this future galaxy-galaxy merger already has an impact on the formation of infant GC candidates within this host galaxy. A number of previous studies have indeed looked into the impact that interacting and merging galaxies could have on the formation of GCs (e.g., see Kennicutt & Chu, 1988; Ashman & Zepf, 1992; Whitmore & Schweizer, 1995; Whitmore et al., 1999; Bekki et al., 2002; Whitmore et al., 2010; Miah et al., 2015; Kim et al., 2018).

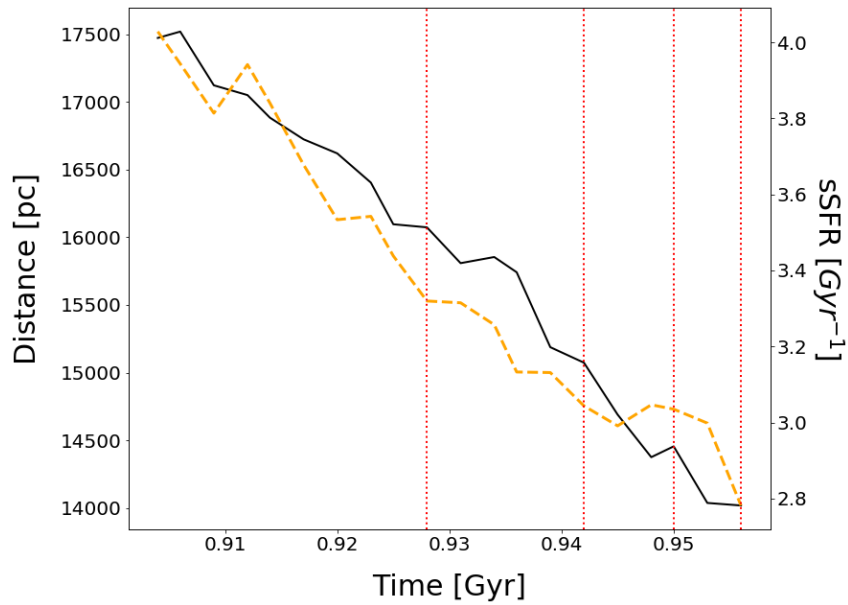


Figure 3.9 *Evolution of the $sSFR$ of Galaxy 1 (orange, dashed) compared with its distance from Galaxy 0 (black, solid). The vertical lines indicate times when infant GC candidates belonging to Galaxy 1 “form”.*

Although at a very early stage of the merger, the proximity between these two galaxies may result in a higher number of candidates for host Galaxy 1. To investigate this further, I examine the specific star formation rate ($sSFR$) across time for Galaxy 1 (orange dashed line in Figure 3.9), as well as the evolution of the distance between the two galaxies (black solid line in Figure 3.9). If the onset of the merger is having an impact on the star formation in Galaxy 1, one would expect to see spikes in the $sSFR$ as the two galaxies approach each other (e.g., see [Springel et al., 2005](#); [Di Matteo et al., 2008](#)). I do not see evidence for the existence of such a correlation in Figure 3.9, which suggests that the merger is still in its very early stages. There is no substantial orbital evolution and the two galaxies have not yet gone through their first pericentre passage, therefore, it would be premature to see the typical starburst event associated with the advanced stages of a merger.

However, infant GC candidates start to form with higher frequency as the two galaxies approach each other, suggesting that instabilities are already triggered in the disc of Galaxy 1. As it can be seen in Figure 3.7, there is a bridge of gas connecting these two galaxies. An investigation at higher redshifts of the galaxies taking part in this event shows that the bridge begins to form before the formation of any of the candidates in Galaxy 1 (by more than one redshift). In the future, I would want to look into the effect that this assembling bridge may have on the existing candidates in this system, as well as the bridge’s capacity to host further GC candidates.

In summary, during the early stages of a major merger, before the onset of any starburst, I already find that the frequency of GC formation increases as the merging galaxies approach each other.

3.3.2 Clumpy irregular proto-galaxies

In the FiBY simulations, I find that most of the galaxies hosting GC candidates are not yet well-developed spiral galaxies, but rather “standard” high-redshift clumpy proto-galaxies with no distinct disk or bulge; they do consist of high-density clumps of gas within a structure of irregular morphology. As one moves to galaxies with fewer and fewer GC candidates, the hosts become less massive and more diffuse. When compared to the two other hosts previously discussed in Section 3.3.1, these galaxies also appear to have lower stellar and gas masses, which helps explain their dominance, due to the steep power-law slope of the stellar mass function.

I analyse these high-redshift hosts in a similar fashion to the previous two cases (see Table 1 for the resulting properties). These hosts do not appear to have exceptionally large values of the spin parameter, nor do they have any signs of previous or future mergers. I study the sSFR over time for all hosts considered in this work and compare this quantity to the star formation histories of the infant GC candidates, as well as their “formation times”. When analysing the sSFR of the host galaxies I recover the results from Chapter 2, where I established a relationship between the sSFR of the host galaxy and the mass of the most massive globular in a system. In general, these clumpy host galaxies have higher sSFR (orange solid lines, Figure 3.10) compared to the rotating spiral hosts or the disk galaxy involved in a merger, by at least an order of magnitude. Such a difference in sSFR is reflected in the masses of the GC candidates belonging to these systems (see Table 3.1). For instance, candidates 15 and 16, which are located in the rotating spiral galaxy, have lower masses, on average, than the GC candidates in the clumpy hosts.

In summary, I find that the sSFRs of the “standard” clumpy proto-galaxies are, in general, larger and more varied than those I find for the more disk-like hosts. These clumpy high-redshift galaxies, in turn, produce more massive infant GC candidates, consistent with my relation from Chapter 2, although the hosts themselves are typically lower in mass compared to the other host galaxies. This suggests that the morphology of the host is a good proxy for the mode of star formation as indicated by the sSFR, and, in turn, this mode affects the mass of individual infant GC candidates at formation.

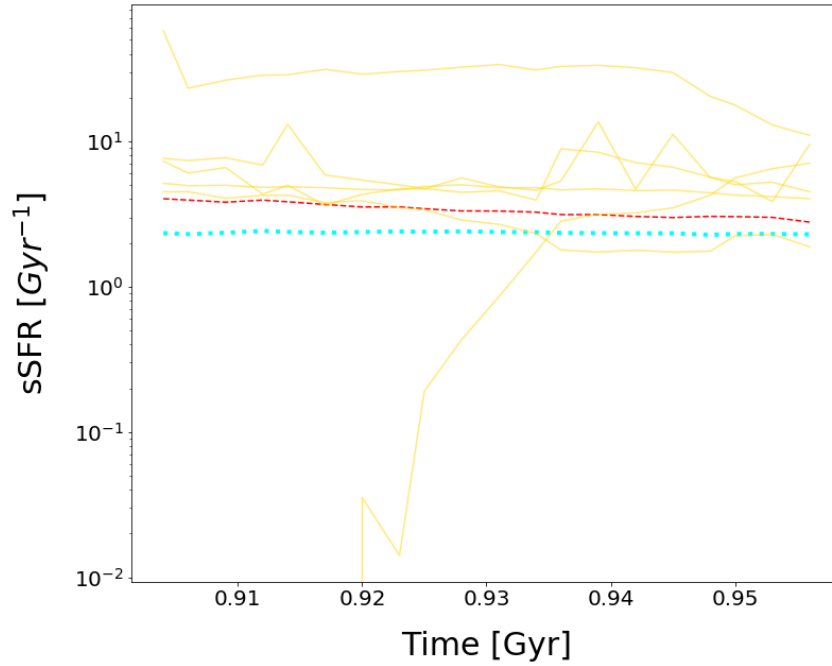


Figure 3.10 *The evolution of $sSFR$ for all galaxies hosting candidates in the FiBY simulation. The clumpy high-redshift proto-galaxies (orange solid lines) in general have higher $sSFR$ than the rotating spiral hosts (blue dotted line) or the disk galaxy involved in a merger (red dashed line).*

3.4 Feedback effects and subsequent evolution

As previously anticipated, I identify two GC candidates, labelled as *SO*, that, at $z = 6$, are composed exclusively of stars. They are, physically, the most similar to the GCs observed in the local Universe. One of the most interesting features of the *SO* candidates' evolution in phase-space is the distinct lack of gas for most of the snapshots studied. At earlier redshifts, the gas appears to be gravitationally bound, but, suddenly, the energy of the gas increases substantially, and, eventually, all the gas is blown out of the half-mass radius. In the FiBY simulations, this is caused by stellar feedback as a result of SN explosions. The prescription for SN feedback in the FiBY simulations (see Chapter 1) means that thermal energy is imparted to the surrounding gas, which, in turn, increases the outward velocity of the gas in the vicinity of multiple SN. To evaluate whether the energy injected by SN is enough to disrupt the gas component in these GC candidates and drive a wind, I compare the cumulative SN energy with the potential energy of the system over time. This is shown in Figure 3.11, where it appears that the cumulative energy of the SN at earlier times is smaller than the potential energy of the infant GC. As the number of SN increase with time, the energy deposited into the surrounding gas slowly increases. Eventually, it increases in an almost exponential

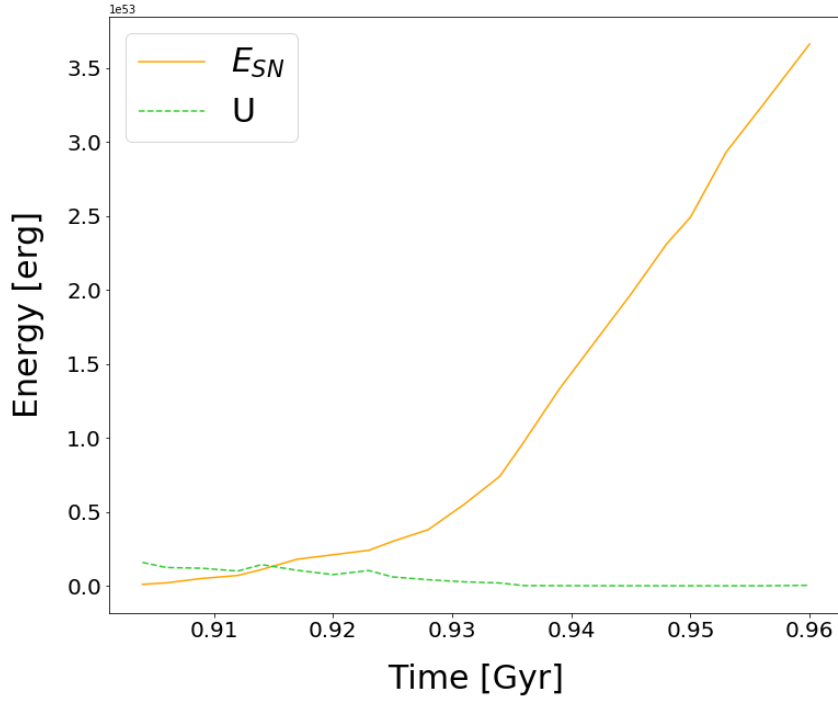


Figure 3.11 *Energy evolution of the particles within the half-mass radius of one of the SO candidates (GC 10). The green dashed line shows the potential energy of the gas particles in the half-mass radius and the orange line shows the cumulative SN energy.*

fashion; by this point, the gas particles in the GC candidate have been blown out. The cross-over point past which the potential energy becomes significantly lower than the SN contribution coincides with the redshift where the gas particles in phase-space rapidly increase in energy and become unbound from the infant GC. This shows that SN feedback is the main physical mechanism behind the gas depletion in this candidate (see also [Davis et al., 2014](#)) and not gas consumption by star formation.

The removal of such a large quantity of mass in a short amount of time has an impact on the remaining star particles in the GC candidate. To investigate this further, in Figure 3.12 I compute the interparticle distance for the gas (purple solid) and star (orange lines) particles. The gas and star interparticle distances are very similar at earlier times, which is consistent with the gas condensing and forming stars. The evolution of the gas abruptly ends at the time when the gas is expelled from the half-mass radius. After this moment, the interparticle distance between the stars increases; the removal of mass violently changes the potential of the infant GC candidate, thus causing the GC to expand.

To quantify this interpretation, I use the prescription of [Blumenthal et al. \(1986\)](#), which

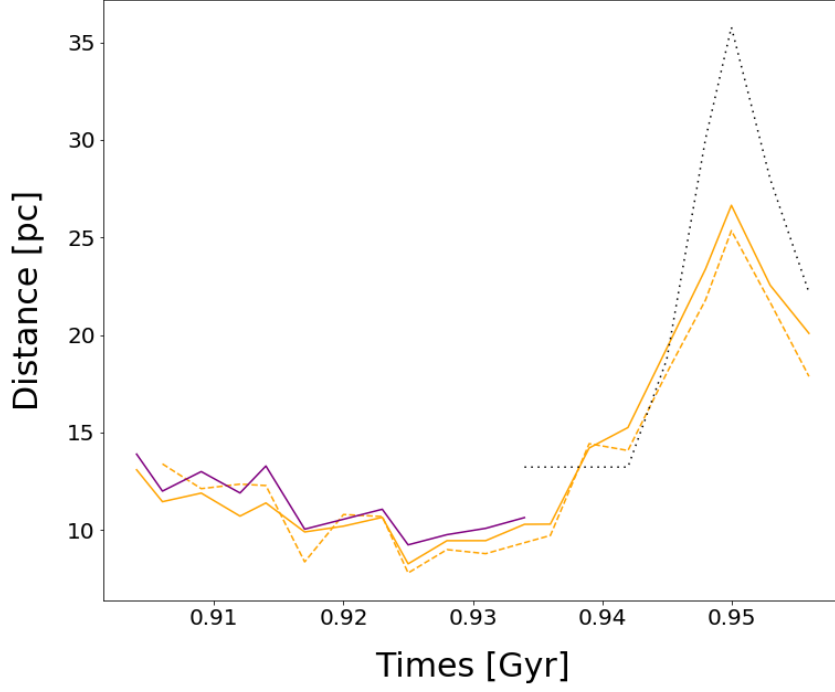


Figure 3.12 *Evolution of the average interparticle distance for the gas (purple) and star (orange) particles for one of the SO candidates (GC 10). All stars are shown with solid lines whilst stars that were present in the previous snapshot are shown with dashed lines to highlight the impact of newly formed stars between snapshots. The black dotted line shows the prediction due to adiabatic expansion given in Equation 3.6.*

has later been expressed by Arraki et al. (2014) as

$$r_f = \frac{r_i}{\alpha(r_i)}, \quad (3.6)$$

where r_i is the radius of the object at the final snapshot before all the gas is expelled, $\alpha(r_i)$ is the fraction of mass within this radius at a later time (once the gas has been removed) and r_f is the radius I expect at this time. In these calculations, r_i is constant, but $\alpha(r_i)$ changes with redshift. By examining the theoretical prediction illustrated in Figure 3.12 (dotted black line), the behaviour of the star particles in this GC candidate at later redshifts appears to be approximately consistent with an adiabatic expansion.

In summary, in the SO candidates I find that the stellar feedback due to SN is strong enough to blow out the gas component. Once the gas is removed, there is a period of time during which the star particles resettle themselves into the new potential, and this appears to happen in an adiabatic fashion. I suggest that the gas-rich GC candidates that have been identified in other hosts might follow a similar evolution beyond $z = 6$. The most likely reason why GC candidates 10 and 35 have already reached this more

advanced dynamical stage is that they start forming stars earlier and, therefore, the associated stellar feedback is in effect sooner.

3.5 Discussion

3.5.1 Implications of the infant GCs-host connection

I presented a connection between the morphology of the host galaxy and the internal properties of the infant GC candidates during their early evolution. Host galaxies with little global angular momentum, but very clumpy morphology, appear to host infant GC candidates that have less internal rotation compared to those formed in more developed spiral galaxies (see Section 3.3). These results suggest an avenue to generate two populations of GCs with different internal properties, as a consequence of their host environments at formation. It is interesting to note that galaxies with a high number of clumps and velocity dispersion (e.g. [Förster Schreiber et al., 2009](#); [Khochfar & Silk, 2009](#)) are expected to be common at higher redshifts due to the high accretion rates of gas; only beyond $z \sim 2$ a population of disk-like galaxies starts appearing.

If GC formation is indeed a natural by-product of ongoing star formation (e.g., see [Kruijssen, 2015a](#)), the FiBY simulations would suggest that the GC candidates that are progressively formed at later redshifts are characterised by a higher internal angular momentum content, as their host becomes more regular and less clumpy. The sSFR of the clumpy hosts appear to be, on average, higher than those of the more disk-like galaxies; this is consistent with the fact that clumpy hosts also display higher accretion rates per unit mass and it suggests a higher specific GC formation rate. The evidence for the latter is only tentative, as it is based on the relatively limited statistics of the present study.

3.5.2 External triggers for infant GCs collapse

These results support a picture in which the size evolution of the infant GCs, as measured by the average interparticle distance of stars, is driven to first order by internal properties, i.e. the Jeans length of the gas component, as long as gas dominates the local gravitational potential (see Sections 3.1 and 3.2). The final size of the infant GC is then set at the point when SN feedback clears the gas abruptly and the infant GC

settles into the new potential, with an approximately adiabatic transition (see Section 3.4).

While there is sufficient evidence that self-gravity regulates the collapse dynamics for all GC candidates (see especially Figure 3.4), the physical event triggering the collapse is likely to be different, given the variety of conditions under which one sees the GC candidates emerge. The precise nature of the triggering instabilities is difficult to determine due to the uncertainties in pinpointing the exact time at which the gas begins to collapse. However, it is clear that a trigger external to the infant GC is initially needed. The variety of environments that I find the infant GC candidates in implies that it may not be the same instability from host to host. The larger scale environment also appears to impact the number of infant GC candidates that can form in a given host galaxy, as well as when they form (as it can be seen from Sections 3.3.1 and 3.3.2).

3.5.3 Impact of stellar feedback and gas expulsion

The impact of stellar feedback on high-density gas regions (e.g. for molecular clouds in merging galaxies) has been found to be less efficient at clearing the gas, thus high-density gas clouds could have multiple episodes of star formation (Rahner et al., 2017; Guillard et al., 2018). To test this idea, I examined the evolution of the gas morphology of the two galaxies hosting the SO candidates, before and after the expulsion of gas from the candidates.

For GC 10, I see that, at earlier times, the object appears as a dense knot of gas within a tightly furled spiral arm. As time progresses, the galaxy rotates and the candidate moves with the spiral arm. In the few snapshots before the gas expulsion from this object, the knot of gas appears to become gradually less dense. This behaviour is also consistent with what is observed for the behaviour of the gas in the Lindblad diagram for this object. After $z = 6.111$ (the redshift at which the gas is expelled from this candidate), the spiral arm appears to “unfurl” and a cavity of low-density gas grows around the location of the GC candidate. This suggests that such a cavity might be a result of stellar feedback from the infant GC candidate. It is known that stellar feedback in molecular cloud structures can determine the expulsion of gas - in some cases removing it completely - which, in turn, can halt star formation (Murray et al., 2010; Krumholz, 2014; Hopkins et al., 2014); gas expulsion can also affect the density structure of the surrounding environment (Grisdale et al., 2017; Semenov et al., 2017).

When examining the evolution of the environment surrounding GC 35, I find that the

infant GC appears to maintain a position near the centre of the clumpy proto-galaxy. Prior to the redshift at which the gas is expelled from GC 35, I note only minor variations in the morphology of the gas of the host. After that moment, I note an expansion of the high-density core and also the appearance of two low-density cavities on either side of the location of the GC candidate. To summarise, after the moment in which the gas is expelled from the *SO* candidates, there appears to be also a change in the density of the gas within the host galaxy on the order of a few hundreds of parsecs around the location of the *SO* candidates.

3.5.4 Future observational studies

A significant finding from this work is the confirmation of the relation between the specific star formation rate of the host galaxy and the mass of the most massive GC in the system. As presented in Chapter 2 (Phipps et al., 2020), this relation appears to hold at low and high redshift, for the simulated and observational data sets I studied. The fact that the relation persists in the high-frequency FiBY simulation offers evidence that this result is impervious to the stochastic modelling of star formation between different numerical realisations. Such a relation can be utilised in current and forthcoming observations of high-redshift galaxies to predict the masses of the largest infant GCs expected to form at a given redshift; therefore, it can offer a guide to identify particularly promising host galaxies to target in future observational campaigns.

3.5.5 Numerical caveats

The evidence from the FiBY simulations used here is that feedback due to SN is efficient at removing gas from the young stellar clusters and hence halting star formation. However, in FiBY the only type of stellar feedback prescribed is that due to SN. The effects of other types of stellar feedback that could be happening early in the infant GC candidates' lives have not been included. The inclusion of other types of feedback would likely affect the results I presented here as it has been shown that some forms of stellar feedback can have a big effect on the gas cloud / stellar cluster before the first SNe even occur. In the work of Grudić et al. (2022), they study a very high-resolution simulation of an individual giant molecular cloud from its initial collapse until its dispersal. The simulation includes protostellar jets, radiation, wind and SN. They find that during star formation, the jets are the dominant form of feedback but they cannot disrupt the gas cloud completely on their own. Once winds and radiation from massive

stars come into play, the cloud is successfully disrupted and star formation is halted. This occurs on a timescale of ~ 8 Myr but the first SN in their simulation does not occur until ~ 8.3 Myr into the simulation, showing that in their simulations if you include early forms of stellar feedback the SN feedback becomes redundant in halting star formation. Similar results were presented in [Verliat et al. \(2022\)](#), who found that ionising radiation is needed to disperse the gas cloud but protostellar jets are important in regulating star formation. These simulations, however, do not include the effects of stellar winds or SN. Based on the recent works in the literature, it is likely that including early stellar feedback mechanisms would affect the way the candidates evolve in their early infancy, however, it must also be noted that the resolutions used in these recent works ([Grudić et al., 2022](#); [Verliat et al., 2022](#)) are much finer and they only focus on a singular isolated gas cloud, hence they can resolve the formation of individual stars. In the future, it would be important to consider incorporating other forms of feedback into the FiBY simulations and comparing results to the ones I have presented here.

3.6 Conclusions

I built upon the previous results from Chapter 2 ([Phipps et al., 2020](#)) and utilised a high-frequency ($\Delta t \sim 2$ Myr) simulation from the First Billion Years project to explore the possible formation channels of a group of low-mass stellar systems which are likely ancestors of the low-redshift globular clusters - I call these stellar systems “infant GC candidates”. The main results of this Chapter can be summarised as follows:

- I harnessed the behaviour of the infant GC candidates in the energy and angular momentum plane (“Lindblad diagram”) as a technique to examine the formation of small structures in a changing galactic environment (Figure 3.1). This analysis of the phase-space evolution over time allowed me to identify the redshift at which these systems first became gravitationally bound (“formation redshift”), as well as to show evidence of radial infall of gas onto the object at early times (Figure 3.2).
- Before this “formation redshift”, the gas in the infant GC candidates collapses on a dynamical timescale. Further analysis of the infall of the star particles revealed that the ratio of the Jeans length of gas to the interparticle distance between stars is of order unity, which suggests that the size of infant GCs during the early stages is set by the Jeans length of the gas.

- The phase-space behaviour of the infant GC candidates allowed me to identify some characteristic groupings of objects (Table 3.1), which may indicate the existence of multiple formation channels. Such a phase-space classification is also reflected in the formation environment: GC candidates which belong to the same class are located in host galaxies of similar morphology (Table 3.2 and Figure 3.7)
- The majority of the infant GC candidates (i.e., those with lower angular momentum) are located in “standard” clumpy high-redshift proto-galaxies which have no distinct morphology yet. Furthermore, I found that the relation between the sSFR of the host galaxy and the mass of the most massive candidate in a system (established in Chapter 2 Phipps et al., 2020) persisted here, supporting the argument that these candidates are a natural product of star formation in high-redshift galaxies.
- Finally, I examined the potential future evolution for the general population of infant GC candidates through the analysis of two GC candidates that contains only stars by $z = 6$. Such candidates most closely resemble the GCs observed in the local Universe. I found that, at earlier times, the feedback energy from SN expels the gas from the half-mass radius of the systems and, subsequently, the remaining star particles relax into the new potential via an approximately adiabatic expansion.

This latter point will be investigated further in the next Chapter, by means of tailored numerical simulations which extend beyond $z = 6$. Specifically, I will assess whether the evolutionary path discussed in Section 3.4 is common for the majority of the GC candidates. Most importantly, it will be essential to first evaluate if these infant GC candidates will survive until $z = 0$ and how closely they will resemble to present-day GCs, as observed in the local Universe.

Chapter 4

Evolution beyond $z = 6$

This Chapter explores the evolution of a selection of candidates beyond $z = 6$. To this end, I ran a suite of new numerical simulations with the same sub-grid physical models used in the First Billion Years (FiBY) simulations but evolving smaller volumes to lower values of redshift. The main goal of this investigation is to assess the fate of the selected sample of candidates: if they survive, if they display properties which are consistent with the ones of present-day globular clusters or if they get destroyed. The simulations I have performed for this Chapter have the same framework and physical prescriptions as the FiBY ones, as described in the previous Chapters, and I summarise the key features here. For the work conducted below, I used the same resolution as the simulations in Chapters 2 and 3, i.e. $1250 M_{\odot}$ and $6160 M_{\odot}$ for SPH and DM particles, respectively. The code is built upon GADGET-3 ([Springel, 2005](#); [Schaye et al., 2010](#)), and it includes prescriptions to form both Population II and III stars, as well as tracing 11 elements for metal pollution; for full details of these prescriptions please see the Introduction. The simulations include a few modifications compared to the original FiBY simulations that are based on results from the EAGLE project ([Schaye et al., 2015](#); [Yajima et al., 2022](#)). These modifications include adding models to calculate the radiative feedback from young stars, kinetic feedback from massive black holes, and the growth/destruction of dust grains.

I set up a suite of isolated, “cutout” simulations that focus on individual haloes and the GC candidates within them, to understand whether the infant GCs can survive in their natal environments without any external influences that might disrupt them. One further advantage of performing an isolated simulation is that I can keep the resolution level of the simulations relatively high, whilst being able to evolve them to reach much

lower redshifts at a moderate computational cost. First, I considered the three GC-galaxy systems that I studied in Chapter 3. These are Galaxies 1, 71 and 235 which host 5, 2, and 4 infant GC candidates, respectively. Galaxy 1 is a disk-like galaxy that is in the early stages of a merger with Galaxy 0. The candidates in Galaxy 1 are all characterised by the LL group (see Chapter 3, Tables 3.1 and 3.2) apart from a single SO candidate. This host was chosen for this evolutionary study as it is the largest, it contains the most candidates, and is the only one undergoing a merger. It also hosts a diverse range of infant GCs. Therefore, it is possible to examine whether differences in their early evolution result in long-term differences in their subsequent development. The second host, Galaxy 71, is another disk-like galaxy that shows apparent rotation and distinct spiral arms, it hosts a subset of the LL group, named as ZDM (zero dark matter). This galaxy was chosen due to the uniqueness of the candidates it hosts and the clear morphology of the host. An examination of how this GC-galaxy system evolves at later redshifts should give a clear picture of how the presence of a disk and spiral arms affect the evolution of gas-rich infant GCs beyond $z = 6$. The final host I chose is Galaxy 235. This is a “standard”, clumpy, high-redshift proto-galaxy and it hosts the most common type of infant GC - the STD group - which are characterised by their lower angular momentum. This host was chosen because, from the work conducted in the previous Chapters, it represents the most prevalent formation channel for infant GC candidates in the FiBY simulations. Understanding if and how the objects survive in a host environment, which is yet to form a distinct morphology and is still undergoing an intense period of star formation, informs us about the processes that can destroy GCs.

To generate the initial conditions for these isolated simulations, a region centred on the centre of mass of the host galaxy with a width of three times the virial radius of the host galaxy was chosen - see Figure 4.1 for the extraction region. All the particles (gas, star, dark matter) within this area were extracted along with all the significant data attached to them - not just their positions and velocities but also masses, metallicities, and all other data that was stored in the snapshot files for the FiBY simulations. This extraction was conducted at $z = 6$ on the simulation used in Chapter 3; the extracted particles were then stored in a new HDF5 file to be used as the initial conditions for the new simulations. I then set up the parameter file needed to conduct the simulations. Within this parameter file, I specified the cosmological parameters to be used, as well as the output frequency of snapshots and the format the data should be stored in. Snapshots were produced at intervals of about $\Delta t \sim 10$ Myr and stored in HDF5 files. I ran the isolated cutout simulations on Cuillin, a computing cluster hosted at the Royal Observatory Edinburgh for the University of Edinburgh. They were run on a single node of 32 CPUs for $\sim 156,000$ core hours and the haloes reached a redshift of ~ 2 in

that time.

The Chapter is laid out as follows. In Section 4.1, I give an overview of what happens to the sample of candidate infant GCs in the three host galaxies, then, in Section 4.2, I focus on the evolution of the gas-rich candidates from Chapter 3. In Section 4.3 an examination of the star-only candidate is presented and, finally, in Section 4.4, I offer my discussion and conclusions. Throughout this Chapter, I assume $H_0 = 71 \text{ kms}^{-1}\text{Mpc}^{-1}$, $\Omega_M = 0.265$, $\Omega_\Lambda = 0.735$ and $\Omega_b = 0.0448$.

4.1 Demographics of the evolved GC candidates

I begin by discussing the demographics of the surviving candidates across the three host galaxies, and I give a qualitative description of their evolution towards $z = 0$. Of the selection of candidates chosen for further study in this Chapter, only one candidate appears to survive. This is GC 10 - the SO candidate. Although it may not necessarily be evolving towards a GC-like object, in fact, it currently appears to be on track to form part of the nuclear star cluster (NSC) of its host; in turn, such a galaxy was formed from the merger of Galaxies 0 and 1. This candidate will be explored in greater detail in Section 4.3. All remaining candidates (which are all gas-rich), appear to dissolve after a few Myr, but the details for the dissolution process seem to differ between host halo and candidate classification. In general, there are two distinct destructive evolutionary paths which depend on the nature of the relationship with the host throughout the later stages of evolution. In Figure 4.2, I illustrate the time variation of the distance between the centre of masses of the candidates and their host galaxy. The destroyed candidates belonging to Galaxies 1, 71 and 235 are shown in red, blue and orange, whilst the purple line indicates the surviving candidate (GC 10).

In Scenario 1, as the dissolution of the candidates proceeds, they also seem to move or “wander away” from their host galaxy in a rapid fashion. Such is the case for the gas-rich candidates in Galaxies 1 and 235 (red and orange lines). Focusing on the LL candidates in Galaxy 1, in Figure 4.2, one can see that, initially, the distance between the centre of mass of the host and the candidates decreases, as the merger continues to progress. However, after less than 0.5 Gyrs, the red lines start to steeply increase, as the candidates move quickly away from the merger, which, by now, is approaching its second pericentre passage. After this point, the LL candidates continue to drift further and further away from the interacting galaxies. In Galaxy 235, the STD candidates follow a similar evolutionary path (see orange line, Figure 4.2). They very quickly

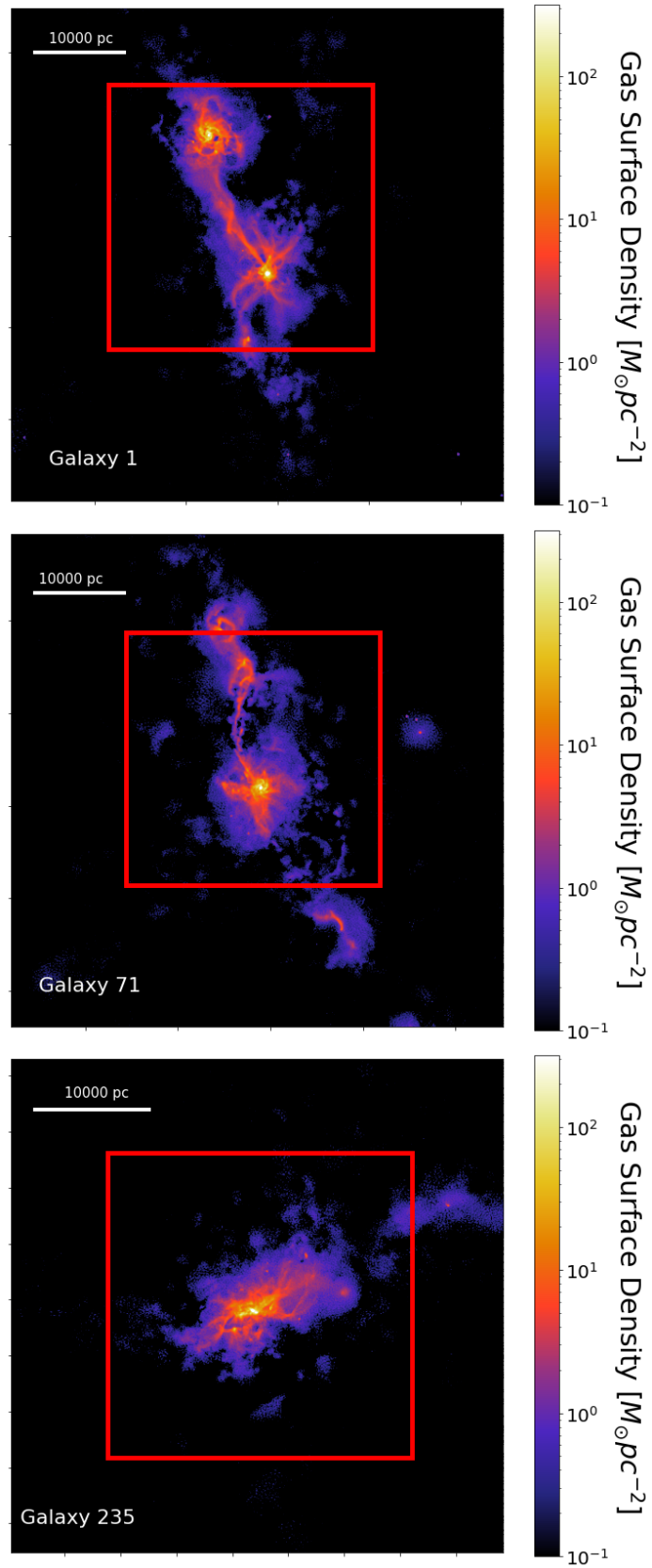


Figure 4.1 *Gas surface density maps of the haloes chosen for the isolated cutout simulations to run to lower redshift. The red square indicates the extraction region within which all the particles are used to form the initial conditions file for the cutout simulations.*

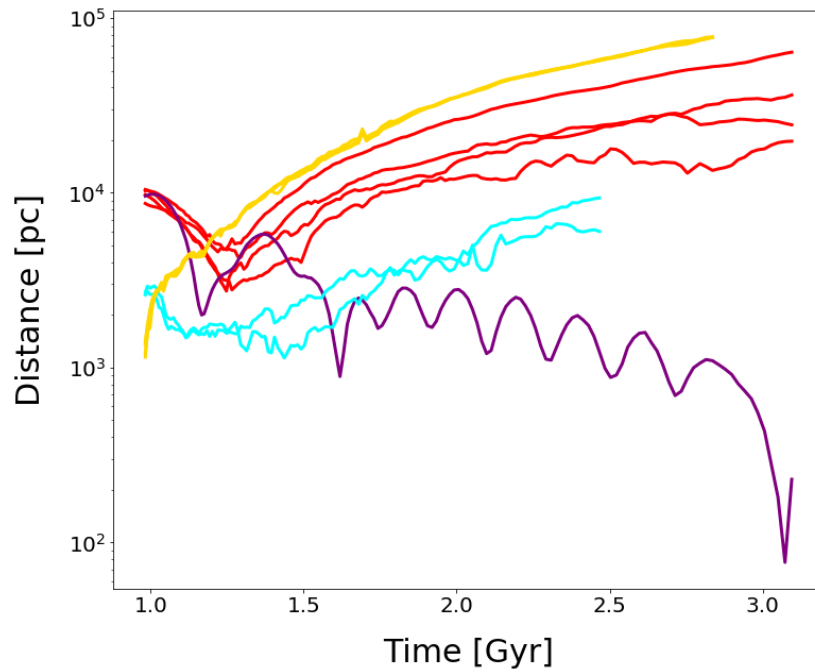


Figure 4.2 *Evolution of the distance between the centre of masses of the candidates and their host galaxy for $z < 6$. The destroyed candidates belonging to Galaxies 1, 71, and 235 are shown with red, blue, and orange lines. The purple line indicates the single candidate (GC 10) that survives to $z \sim 2$.*

(i.e, in the first few Myr after $z = 6$) begin to move away from the centre of the host galaxy and proceed to the outer reaches of the halo, or even beyond - to regions of the simulated box with very little gas. The behaviour of the LL and STD candidates is similar, even though they have different values of internal angular momentum, and, initially, they originate from different galactic environments. However, for Galaxy 1, once the merger has reached its advanced stages, the morphology becomes less distinct and more clumpy, mimicking the environment of the “standard” high-redshift proto-galaxies. Hence, this wandering behaviour could be tied to a more turbulent and chaotic host environment where the forces acting upon the candidates result in an orbit out to progressively larger radii rather than a stable or infalling orbit.

The second case of destruction, Scenario 2, occurs for the ZDM candidates in Galaxy 71 (Figure 4.2, blue lines). For these candidates, rather than them wandering away from their host galaxy, the host appears to blow most of its gas out due to SN feedback which causes a change in the centre of mass of the host; this, in turn, results in the increase in distance, as shown in Figure 4.2 with blue lines. This increase in distance is due to the host galaxy potential decreasing significantly as the galaxy loses mass resulting in an apparent shift of its centre of mass relative to the fairly stable positions of the candidates. It should be noted that these two scenarios are distinct from each

other, as the evolution of distance from the galaxy with time is different, in terms of both smoothness and rapidity of the distance increase. The non-destructive case of GC 10 (Figure 4.2, purple line) has an oscillating radial excursion, where the distance progressively decreases with time, which indicates infall. This will be examined in greater detail later in Section 4.3.

In the previous Chapter, where the SO candidates' early evolution was studied in detail, the expectation was that they would resemble the future evolution of the gas-rich ones. However, this does not seem to be the case, perhaps due to the gas-rich candidates being of larger mass and, therefore, the feedback in these objects may have been stronger, resulting in destruction. This possibility will be discussed later in this Chapter. The rapidity of the dissolution of the gas-rich candidates implies that the methods applied in the previous Chapter (such as the convergence method and calculations of energy and angular momentum) are not feasible for a meaningful application here when trying to examine the path of their destruction. To demonstrate this statement, in Figure 4.3, I illustrate the evolution of the half-mass radius for all the candidates studied beyond $z = 6$, by adopting the same colour scheme as for Figure 4.2. All the gas-rich candidates evolve rapidly from radii of the order of tens of parsecs (at $z = 6$) to beyond hundreds of parsecs, in less than 0.5 Gyr. These radii only continue to inflate until they reach values $> 10^4$ pc, by which point it is fairly certain they have fully dissolved. This meteoric increase in radius for the gas-rich candidates results in a larger number of particles being “associated” with the candidates whose membership is more difficult to be determined. Henceforth, when discussing and studying these candidates, I only focus on the particles which formed the central core of the objects at $z = 6$. The surviving SO candidate also experiences an increase in radius - although not to the same extent as the others. This increase in radius, combined with the apparent infall observed in Figure 4.2, may imply that this infant GC is to become part of the NSC itself. In this case, I can still apply some of the methods used previously (with caution).

To summarise, the three GC-galaxy systems chosen for further study hosted a total of 11 infant GC candidates. Out of these 11, only 1 candidate appears not to be destroyed. In the next Section, I will discuss the dissolution of the gas-rich candidates: I will examine the evolution of their gas, whether any further SF took place, and if one can discern any difference between the low and high-angular momentum objects.

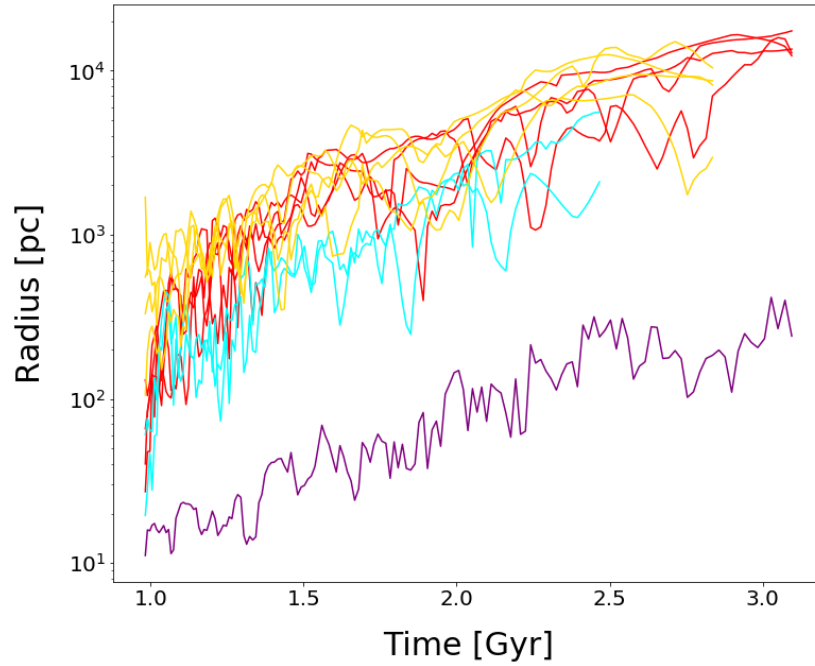


Figure 4.3 *Evolution of the half-mass radius of candidates evolved beyond $z = 6$. The destroyed candidates belonging to Galaxies 1, 71, and 235 are shown in red, blue, and orange. The purple line indicates the single candidate that survives to $z = 2$.*

4.2 Evolution of gas-rich candidates

As discussed in the previous Section, in consideration of the rapid dissolution of the gas-rich candidates, it is not appropriate to apply the methods from Chapter 3 to track the subsequent evolution. Instead, the analysis focuses on the particles that were within the half-mass radius of the infant GCs at $z = 6$. In this Section, I explore in greater detail which processes are behind the dissolution of these objects and whether there are any differences in destruction between the high LL and low LL candidates. As already seen, there seems to be a difference in the interaction with the host galaxy for the destroyed candidates (Scenario 1 versus Scenario 2) but these cases do not seem to be separated by candidate group.

The most likely cause behind the dissolution of the candidates appears to be feedback from the stars. However, for all of the gas-rich candidates, star formation before $z = 6$ had been minimal, so, as a first step, I looked into whether any of the gas particles that were energetically bound at $z = 6$ underwent further star formation, and upon which timescale. In Figure 4.4, I display the star formation rate for the gas-rich candidates, where the red, blue and orange lines correspond to candidates in Galaxies 1, 71 and

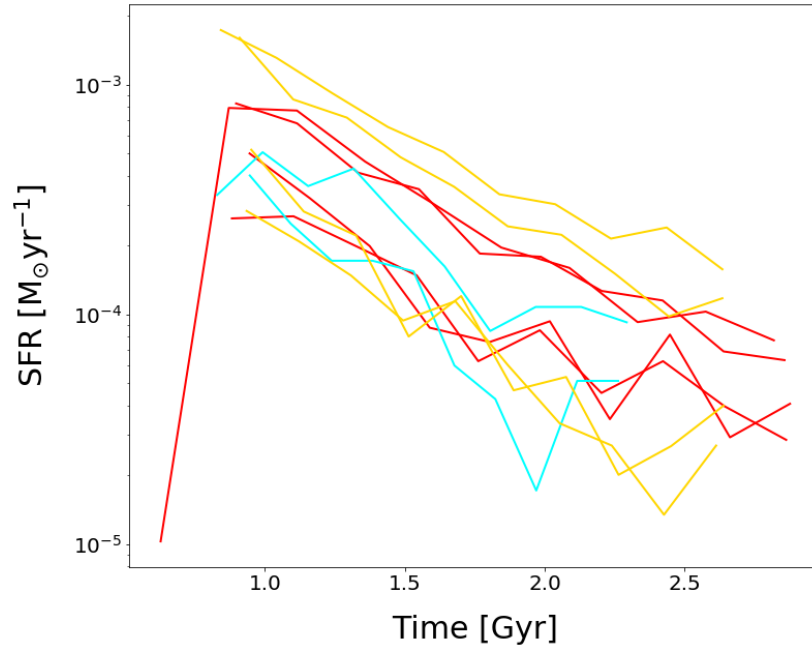


Figure 4.4 *The star formation rate for the gas-rich infant GC candidates that were destroyed. The plot shows the star formation rates for the particles that belonged to the candidates at $z = 6$. The candidates belonging to Galaxies 1, 71, and 235 are shown in red, blue, and orange.*

235. From this illustration, there does not seem to be any difference between the star formation histories for different groups of candidates, and they all seem to follow the same pattern. All candidates peak in their star formation at around 1 Gyr: in other words, just after the old FiBY suite ended. Therefore, all the gas-rich candidates form their largest mass of stars at the start of the suite of new simulations. From the physical prescriptions applied in this work, once stellar particles reach the age of 30 Myr, SN energy is injected into the immediate vicinity of the particles. So, for these particular infant GCs, not only do they form a large number of stars at $z \sim 6$, but, a short time later (concerning the time-span of the simulations), these candidates are injected with a vast amount of energy. This SN energy is decimated in the simulation as thermal energy imparted on the gas particles, therefore, if the potential of the object is sufficiently shallow, this SN energy could drive the gas out of the candidate. To confirm whether this is the case for the gas-rich candidates, I compare the SN energy injected into the systems with the evolution of the potential energy of the core particles over time. I show a few examples for some candidates in Figures 4.5 - 4.7, where the orange line shows the cumulative injected SN energy and the green line is the potential of the $z = 6$ core particles. Each of the candidates shown in Figures 4.5 - 4.7 is an example of a destroyed gas-rich candidate, in each of the different host galaxy systems. Here it is evident that at times earlier than ~ 1 Gyr, in the infant GC candidates there are very

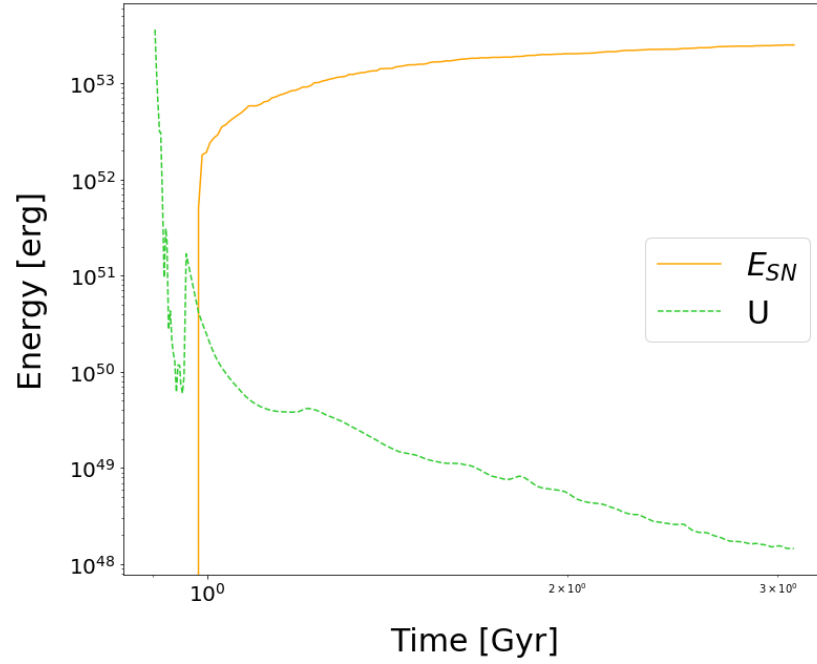


Figure 4.5 *Energy evolution of the $z = 6$ only particles for gas-rich candidate: GC 8. The green dashed line shows the potential energy of all particles within the half-mass radius at $z = 6$, and the orange line is the cumulative supernova energy.*

few stars that are old enough to inject any SN feedback into the surrounding medium. However, as the age of the Universe approaches 1 Gyr, more gas particles have been converted to stars, and the SN energy begins to build up. Eventually, the energy due to SN bypasses the potential energy of the candidate, and it continues to increase until it converges. The potential energy, however, once the SN energy surpasses it, continues to decrease in an exponential-like fashion.

This rapid build-up of feedback most likely resulted in the expulsion of the gas to large radii, as was observed in Section 3.4 for the SO candidates. However, a natural question is why the SO candidates survived the removal of their gas, whilst these gas-rich candidates do not. To answer this question, I introduce and define significant phases in their evolution and their relevant timescales. First, t_{cross} is defined as the time at which the SN energy surpasses the potential energy of the candidate, as observed in Figures 4.5 - 4.7. Second, I define t_{halflife} which is the timescale on which the candidates are destroyed (when applicable). To calculate these timescales, I first fit an exponential function to the potential curve in Figures 4.5 - 4.7 (green line), t_{halflife} is then defined as the time it takes (according to the exponential fit) for the energy has decayed by approximately half. Finally, t_{diss} , is the time at which the candidates can be considered to be destroyed which is found by adding the half-life timescale to t_{cross} .

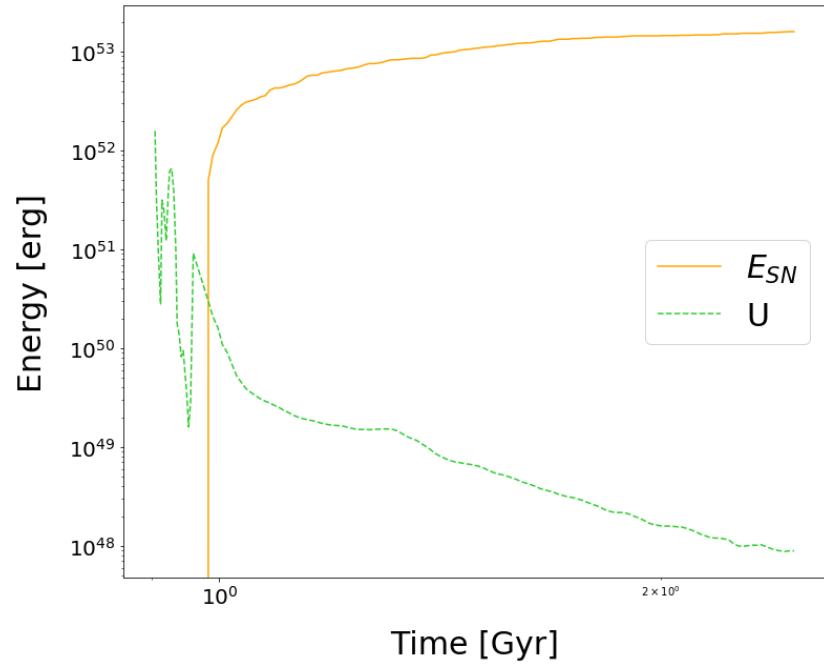


Figure 4.6 Same as Figure 4.5 but for GC 16.

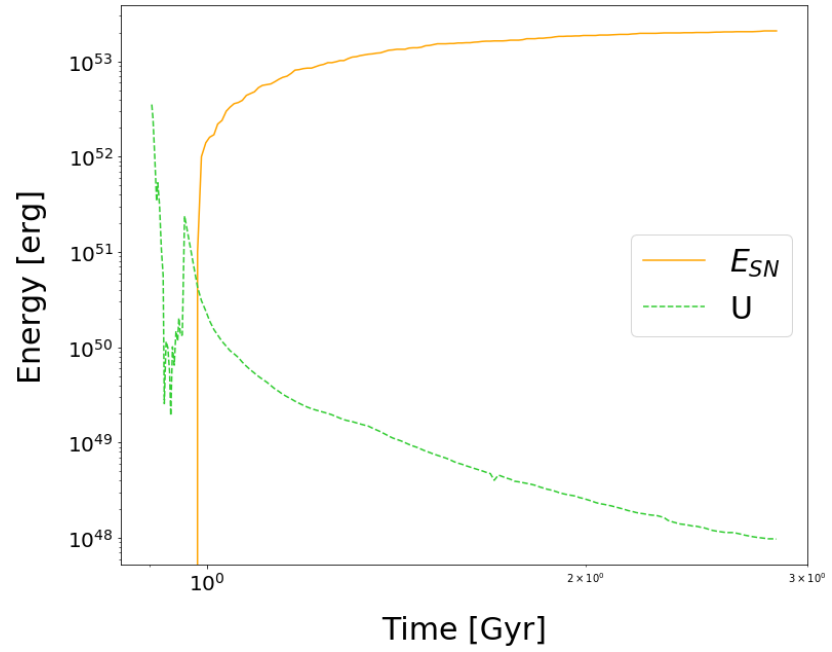


Figure 4.7 Same as Figure 4.5 but for GC 24.

GC ID	Group	Galaxy ID	Survived?	t_{cross} [Gyr]	$E_{*,\text{potential}}$ [Erg]	f_{gas}	t_{halflife} [Gyr]	t_{diss} [Gyr]
5	LL	1	No	0.983	2.55×10^{48}	58.18	0.1928	1.1758
6	LL	1	No	0.983	2.19×10^{48}	52.78	0.1818	1.1419
8	LL	1	No	0.983	4.12×10^{47}	62.66	0.1788	1.1618
9	LL	1	No	0.960	1.53×10^{47}	78.80	0.1805	1.1405
15	ZDM	71	No	0.960	6.61×10^{47}	75.21	0.1303	1.0903
16	ZDM	71	No	0.983	2.50×10^{47}	71.89	0.1424	1.1254
22	STD	235	No	0.983	1.98×10^{49}	28.30	0.1583	1.1413
23	STD	235	No	0.983	5.39×10^{48}	54.89	0.1515	1.1345
24	STD	235	No	0.983	1.87×10^{47}	79.35	0.1509	1.1339
25	STD	235	No	0.983	1.51×10^{47}	85.62	0.1384	1.1214
10	SO	1	Yes	0.912	9.53×10^{49}	9.57	-	-

Table 4.1 *Selection of properties relating to the survival or destruction of the GC candidates. They are divided into groups of objects that show similar evolution in their Lindblad diagrams (see Chapter 3). From left to right, the columns show: ID of the candidate, group designation based on phase-space evolution, the ID of the host galaxy, whether the candidate survived or not, the time where the cumulative supernova energy is greater than the potential energy (t_{cross}), the potential energy of the stars at t_{cross} , the gas to stellar mass ratio at t_{cross} , the time for the potential of the particles to drop by half (t_{halflife}), and, finally, the time at which the candidate can be considered fully destroyed ($t_{\text{diss}} = t_{\text{cross}} + t_{\text{halflife}}$). The value of t_{cross} is similar for many of the candidates due to the output spacing of the snapshots from the simulation.*

These moments and timescales are listed for each candidate in Table 4.1. Almost all of the candidates have the same, or similar, values for t_{cross} , apart from the SO candidate for which this phenomenon occurs earlier. Due to the similarities not only in t_{cross} , but also in t_{halflife} , most of the gas-rich candidates are “destroyed” at around the same time¹, but these times are consistent with the behaviour observed in Figures 4.2 and 4.3. When comparing the half-life timescale to the dynamical time of the candidates at $z = 6$ (see Table 4.2), the former is about one order of magnitude greater than the dynamical timescales. Considering that t_{dyn} is calculated for the half-mass radius, it is likely that its true value for the candidates at $z = 6$ is much higher, therefore, it is still physically feasible for a candidate to have $t_{\text{halflife}} \sim t_{\text{dyn}}$ and yet to be dissolved.

I now use the different timescales (as defined above and shown in Table 4.1) to understand why the SN feedback destroyed the gas-rich candidates, but not GC 10 (the SO candidate). I examine certain properties of the candidates at the time t_{cross} - the point when the SN energy is dominant over the potential - to understand why removing the gas for GC 10 was not fatal when in all other cases examined in this Chapter it was.

¹It should be noted the similarities in t_{cross} is primarily due to the output spacing of the simulations

GC ID	Group	Galaxy ID	M_T [$M_\odot$]	R_{half} [pc]	$\log(Z_*/Z_\odot)$	t_{dyn} [Gyr]
5	LL	1	2.39×10^6	8.8	-0.78	0.0066
6	LL	1	2.37×10^6	7.5	-0.83	0.0048
8	LL	1	1.25×10^6	15.5	-1.23	0.022
9	LL	1	8.22×10^5	10.3	-1.13	0.013
15	ZDM	71	1.56×10^6	9.0	-1.04	0.009
16	ZDM	71	7.15×10^5	10.3	-1.19	0.014
22	STD	235	5.10×10^6	7.9	-0.99	0.004
23	STD	235	3.56×10^6	8.7	-0.77	0.006
24	STD	235	1.14×10^6	10.5	-1.05	0.009
25	STD	235	8.38×10^5	14.9	-1.45	0.021
10	SO	1	4.41×10^5	7.9	-0.87	-

Table 4.2 *Selection of properties (as measured at $z = 6$) for the candidates that are evolved beyond $z = 6$. They are divided into groups of objects that show similar evolution in their Lindblad diagrams (see Chapter 3). From left to right: ID of the candidate, group designation based on phase-space evolution, the ID of the host galaxy, the total mass of the candidate (within R_{half}), half-mass radius, stellar metallicity, and the dynamical timescale of the gas.*

First, I look into $E_{*,\text{potential}}$, which is defined as the potential energy calculated from the star-star pairs within each candidate. If one was to assume that all the gas was to be removed instantaneously at t_{cross} , then the survival of the candidate would depend on the strength of the potential energy of the stars. Looking at Table 4.1, it is clear that GC 10 has the largest value of $E_{*,\text{potential}}$ at t_{cross} compared to any other candidate, therefore increasing its chances of survival. The SO candidate builds up its stellar mass much faster than the gas-rich candidates, and, therefore, once SN feedback for these particles is injected, the stellar particles have already developed a deep potential well. However, the values of $E_{*,\text{potential}}$ for the gas-rich candidates are not vastly different from GC 10, and all the candidates formed within dense gaseous environments. So why did GC 10 survive the feedback at these earlier redshifts? It could be that, by t_{cross} , if the fraction of gas in GC 10 compared to the number of stars was much smaller, the removal of gas would have a smaller impact on the potential well of GC 10. To look into this further, I have calculated f_{gas} (the fraction of gas mass to stellar mass) for each of the candidates at t_{cross} - see Table 4.1. The gas-rich candidates all have fractions > 20 , despite having their most active phase of SF occurring at $z \sim 6$. On the contrary, GC 10 has $f_{\text{gas}} < 10$. This confirms the interpretation outlined above, that GC 10 had less gas to lose and, therefore, it was less affected by its removal (although, as shown in Figure 3.12 in Chapter 3, the stars undergo some adiabatic adjustment to a new potential). It seems that, for a young, forming GC to survive its natal environment, it

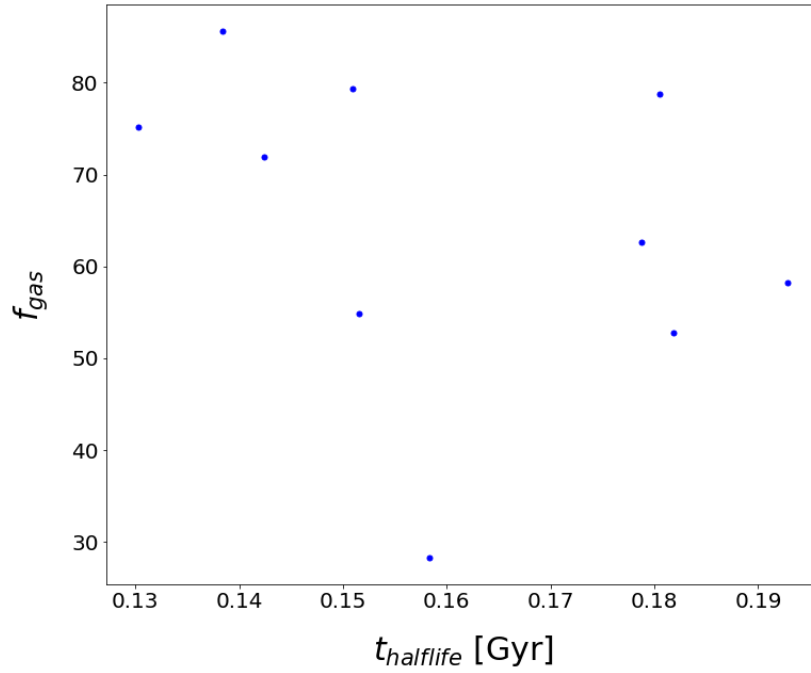


Figure 4.8 *The ratio of gas mass to stellar mass (f_{gas}) as a function of $t_{\text{half-life}}$ for the candidates which are destroyed in the simulations.*

has to undergo efficient SF in the early stages to balance out its gas mass to stellar mass ratio. In Figure 4.8, I have illustrated the f_{gas} versus $t_{\text{half-life}}$. Due to the small number of candidates being tracked in these low-redshift simulations, statistically significant trends are hard to discern, however, in general, it appears that the larger the gas fraction the faster the candidate dissolves. This is not surprising: if f_{gas} is large, then the gas is the largest contributor to the potential of the object, and the removal of its mass changes the potential greatly. If the dynamical timescale is too long for the stars to adjust to this new potential, then the structure “unravels”.

In summary, the gas-rich candidates undergo their period of highest star formation at $z \sim 6$; this results in a massive injection of supernova feedback into the surrounding medium ~ 30 Myr later. The energy from this feedback quickly dominates over the potential energy of the particles that belonged to the core of the candidates at $z = 6$, and, ultimately, it is the cause of their dissolution. When examining the evolution in the energy-angular momentum phase-space (“Lindblad diagram”) for the particles in these objects, very quickly after $z = 6$ the shape of the distribution becomes tighter in angular momentum, but increases in the range of energies. The shape observed is similar to the radial infall seen in the early stages of Figure 3.2 in Chapter 3, but, this time, rather than indicating infall of particles, it shows the stripping of them from the core, as the infant GC candidate “unravels”. Comparing the cases of the gas-rich candidates to that

of GC 10 (the SO candidate) which managed to survive despite losing its gas at $z > 6$, it was found that stars in GC 10 likely formed more efficiently as the ratio of gas mass to stellar mass was much lower at the point when the SN feedback dominated the system. Hence, the removal of the gas for GC 10 has less impact on the overall potential of the candidate, when compared to those which were destroyed. In Chapter 3, the gas-rich candidates could be split in general between those with low angular momentum and those with high angular momentum. I investigated whether there were any differences in the destruction paths for these two groups, however, I could not find any. This could be due to the relatively short timescales for destruction, compared to the runtime of the simulation.

4.3 Evolution of the star-only candidate

In this Section, I explore the evolution of the only infant GC candidate that survives beyond $z = 6$. This candidate is the SO object, also denoted as GC 10. The star formation in this object occurs earlier than for the gas-rich ones discussed above and, hence, it ejects its gas at $z > 6$. As explored in the previous Section, the fraction of gas-to-stellar mass at t_{cross} is much lower for the SO candidate; this allows the stars to adjust to the new, lower potential, without the entire object dissolving. This candidate is located in the galaxy system that is undergoing a merger, it is the only candidate in that host that does not wander away from the host. As the merger between the two galaxies progresses, the SO object appears to infall to the centre of the galaxies, orbiting around the common centre of mass for the galaxies. This behaviour is reflected in Figure 4.9, which shows the distance between the centre of masses of the SO object and the merging galaxies. This distance declines over time, but in an oscillating fashion, indicating a circular, orbital motion to the infall of the SO object. After ~ 2 Gyr of evolution from $z = 6$, the SO candidate lies within the central region of the (now) merged host galaxies. Due to the large number of snapshots from $z = 6$ to $z = 2.185$, I have selected only a few snapshots for the subsequent discussion which reflect several, key points in the evolution of the SO object. The times at which these snapshots correspond are shown in Figure 4.9 by the vertical dashed lines.

In Figures 4.10 and 4.11, I display these key snapshots in terms of the gas surface density and stellar surface density maps as a visual aid for the reader to inspect the evolution of the merging galaxies and the spatial evolution of the SO candidate, as it infalls into the centre. The first pair of maps shows the system at about 23 Myr after $z = 6$: the two galaxies are still distinct from each other. GC 10 is located in an

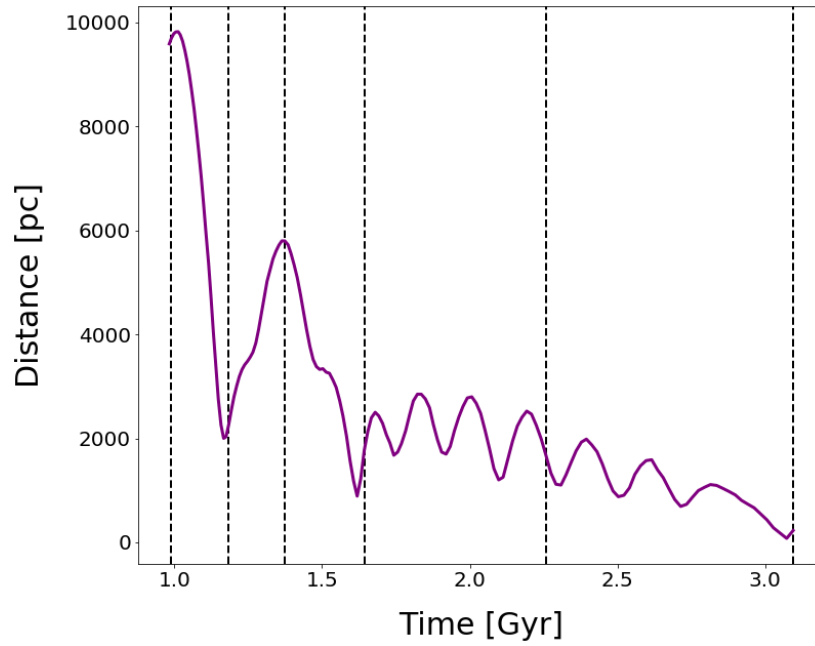


Figure 4.9 *The distance between the centre of mass of the SO object and the common centre of mass for the merging galaxies. The vertical lines indicate the snapshots which are displayed in subsequent Figures.*

under-dense gas cavity in the galaxy on the upper left-hand side of the panel, reflective of the candidates gas-poor properties. The next snapshot ($z = 5.091$) shows the first pericentre passage of the two galaxies: by this point, the gas-rich candidates are located in the outer regions of the system, whereas GC 10 lies close to the peaks in both star and gas surface density. In the third snapshot, the two galaxies have passed by for the first time and have just reached their apocentre. The SO object (GC 10) during this time has orbited across the centre of the galaxy in the lower part of the plot and can be discerned as a small blob of high stellar surface density located on the left-hand side of the galaxy. As the two galaxies continue on a head-on collision towards each other, GC 10, once again, transits across the centre of its original host galaxy. The two highest density peaks for the galaxies (both in gas and stellar components) come into extremely close contact, and GC 10 passes through this highest density point, as can be seen in the fourth snapshot. By the fifth snapshot, the centres of the two galaxies have merged completely to form a large stellar surface density peak, and GC 10 orbits this centre in a circular fashion, with a declining radius; by the last snapshot, it has settled into the centre of the merged galaxy.

For each of the key snapshots shown in Figure 4.10 - 4.11, I display the corresponding energy-angular momentum phase-space diagram for GC 10. The Lindblad diagrams for this object have only been calculated for the particles that belonged to the candidate

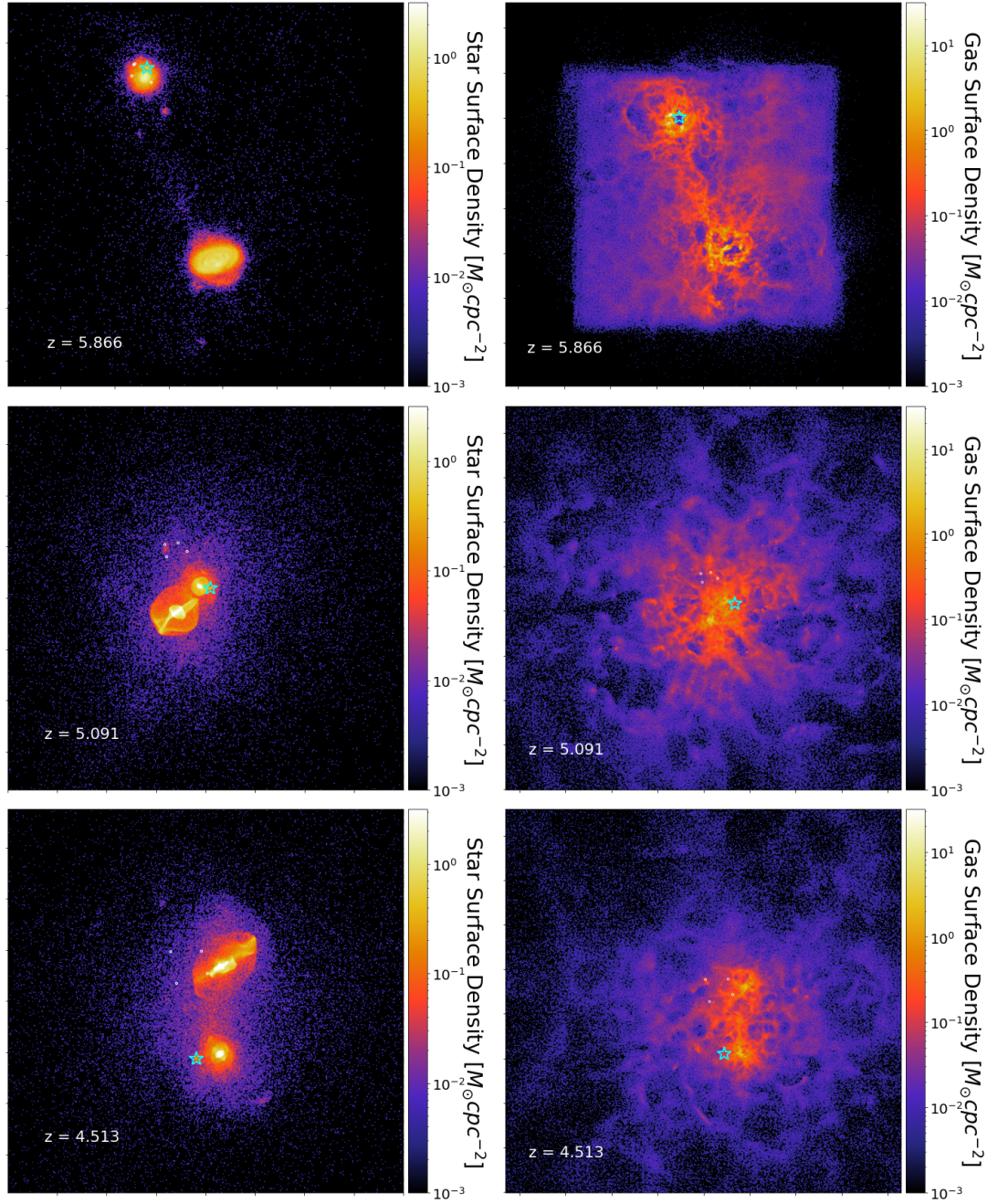


Figure 4.10 *Stellar (left) and gas (right) surface density maps of the merging galaxy system at key points in time. Each snapshot corresponds to a vertical line in Figure 4.9. The SO candidate (GC 10) is shown with a cyan star marker; whilst the gas-rich candidates in this system which are eventually destroyed are shown with small white circle markers.*

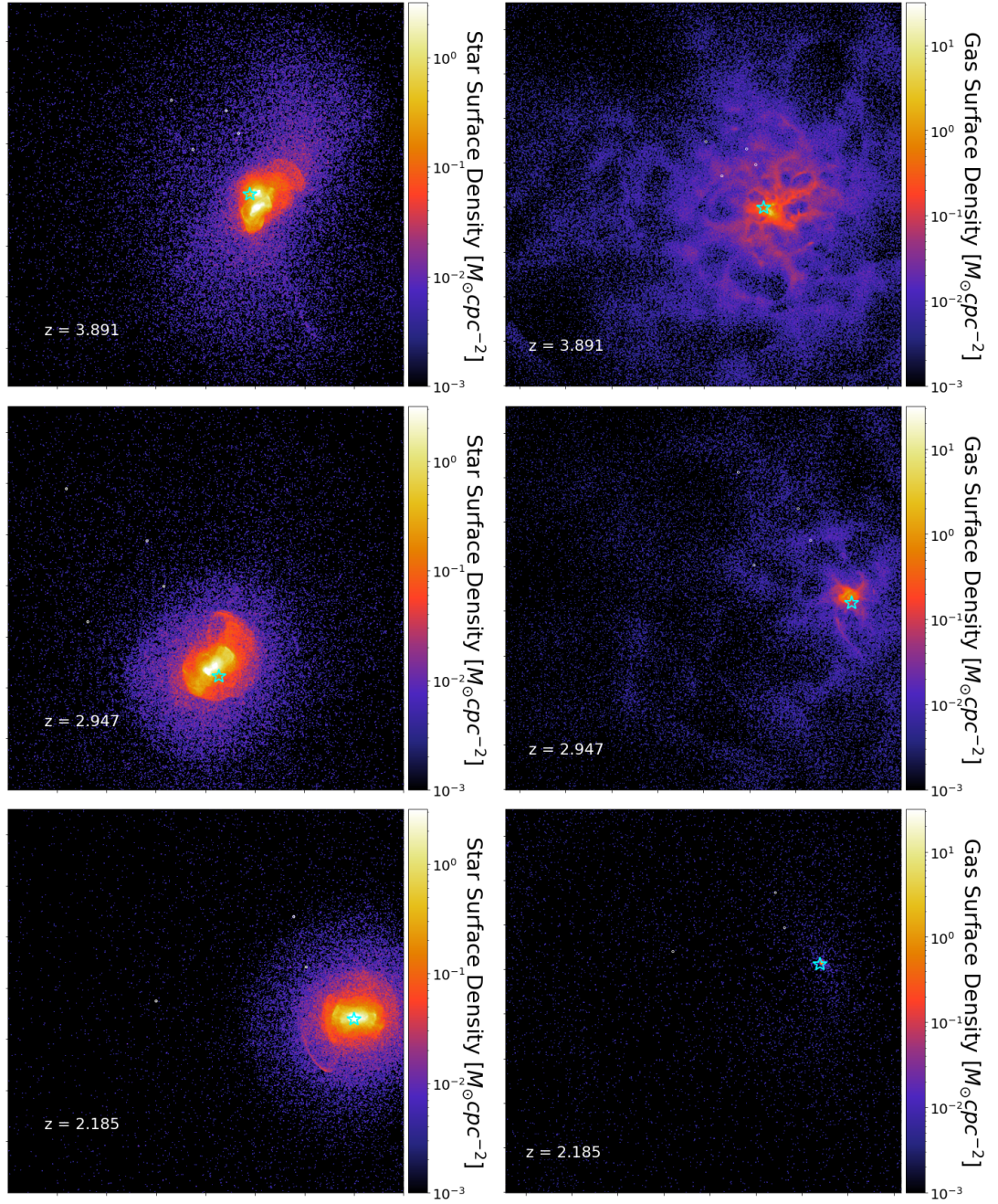


Figure 4.11 Continuation from the previous Figure. Stellar (left) and gas (right) surface density maps of the merging galaxy system at key points in time. Each snapshot corresponds to a vertical line in Figure 4.9. The SO candidate (GC 10) is shown with a cyan star marker, whilst the gas-rich candidates in this system which are eventually destroyed are shown with small white circle markers.

at $z = 6$. This was done to maintain consistency with Chapter 3 and to show that the original structure remains bound to lower redshifts. Based on the morphology evolution observed (especially for the stellar component), I do not show any phase-space diagrams for $z < 3$, as, by this point in time, the candidate has settled into the central region of the merged galaxy and an accurate determination of the centre of mass of the object (which is separate from the galaxy’s centre of mass) would be difficult. Therefore, any energy or angular momentum calculation that is done at these redshifts can not be fully reliable. In Figure 4.12, the phase-space diagrams for the particles within R_{half} at $z = 6$ for GC 10 are shown for the selected “key” snapshots. In these diagrams, I do not overlay the spherical potentials calculated in Chapter 3 for Figure 3.2, as, for $z < 6$, these are not an accurate representation of the object (or of the changes it underwent). Initially, at $z = 5.866$, the particles still follow the distribution observed for all infant GC candidates at $z = 6$ which demonstrates that there is still an underlying bound structure for the SO object. As time progresses, the distribution becomes more narrow (between $z = 5.091$ and $z = 4.513$) and, eventually, by $z = 3.891$, the “Lindblad” diagram resembles some of the early stages (for example, at $z \sim 6.282$) observed in Figure 3.2 in Chapter 3. In the previous Chapter, the collimated particles indicated radial infall of the gas during the early phases of the evolution of the candidate. In the case of the SO object, the changes in phase-space observed for $z < 6$ are indicative of the changing environment for GC 10. This object is inspiralling to the centre of the system; such a centre is still undergoing many changes, as the two galaxy bulges continue to merge. This system is far from settled, and the particles in the SO object are constantly adjusting to a new, increased potential, which is reflected in their behaviour in Figure 4.12.

The adjustment to the new potential which was observed in Figure 4.12 is also reflected in the evolution of the half-mass radius for GC 10. As can be seen from the purple line in Figure 4.3, this candidate undergoes an inflation in radius as time evolves. This increase is not as dramatic, or as large, as that observed for the gas-rich candidates which are destroyed, but it is still significant, especially given the compact size of GC 10 at $z \geq 6$ (Table 4.2). The half-mass radius displayed in Figure 4.3 is calculated via the convergence method used in Chapter 3; this method is dependent upon the energies of the particles, but it also requires a continuous calculation of the centre of mass. Due to the infall of the candidate into this larger potential and the adjustments the particles undergo during this time, it was found that most of the particles within the half-mass radius become unbound from each other. This is likely due to the difficulties in accurately determining the centre of mass for the SO object, as well as the fluctuating potential affecting the energies of the particles in the centre of the merger. Therefore,

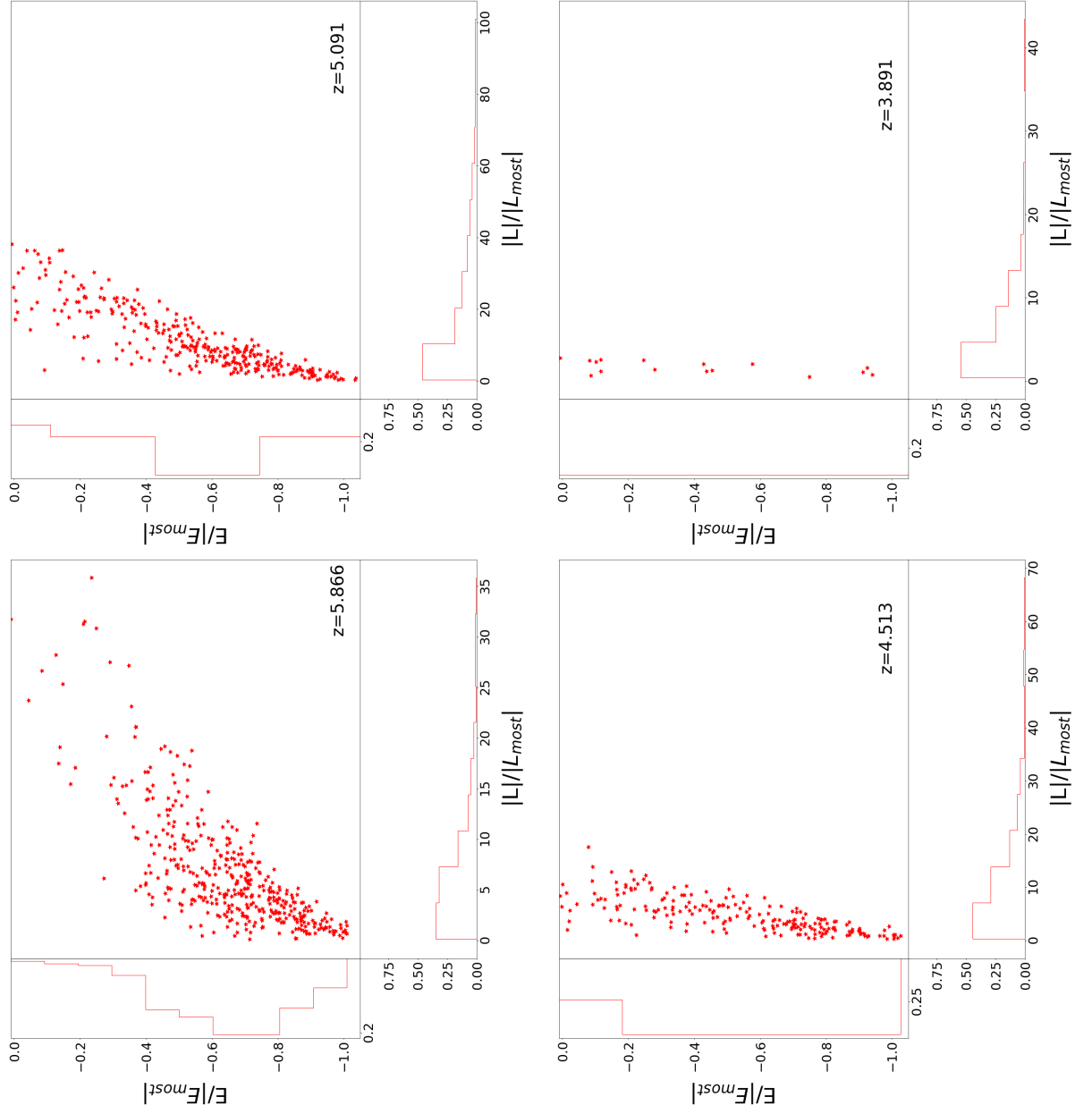


Figure 4.12 *Phase-space diagram of energy and angular momentum for the particles within R_{half} at $z = 6$ for the star-only candidate (GC 10) at the key snapshots as shown in Figure 4.10 - 4.11.*

one can relate the increase in the half-mass radius with the orbital evolution and infall of GC 10; this interpretation is further supported when exploring the mass evolution of this object. I show this in Figure 4.13 which illustrates the stellar (red dashed line) and gas (blue solid line) mass evolution until the Universe is 3 Gyr old. The masses are calculated within a sphere of three times the half-mass radius for GC 10. This was done to account for the adjustment of particles to the new potential and the increase in the size of the infalling object. As can be seen from Figure 4.13, there is a gradual increase in the stellar mass with time, which is consistent with what was observed in the stellar surface density plots in Figures 4.10 - 4.11. What is also seen is an increase in the gas mass of the object. At earlier times, the gas mass fluctuates between zero and $\sim 10^4 M_{\odot}$, however, from ~ 2 Gyr, the gas mass starts to steadily increase, with very little fluctuation. This behaviour is also in line with what is known about the infall of the SO object, as, by $z < 3$, the centres of the two galaxies are almost completely merged and the candidate has reached the outskirts of the central region of the system, where a majority of the stars reside, but also where almost all of the remaining gas sits. Between $t = 1.5 - 2.5$ Gyr, the stellar and gas masses residing within $3 R_{\text{half}}$ are approximately equal. When examining the density maps at these times, at the locations of the candidate the surface densities for gas and stars are comparable, which translates into similar mass values.

In summary, from analysing the subsequent evolution of the SO candidate beyond $z = 6$, it is clear that the object is infalling into the centre of the merger in a spiral-in fashion (see Figure 4.9). Key points in the candidate's trajectory evolution have been analysed in terms of the gas and stellar surface density as well in phase-space. It was found that the evolution of the phase-space diagrams is reflective of the infall of the small candidate into a much larger gravitational well, and the particles adjust to the new potential by relaxing out to larger separations. This has also been noted in the half-mass radius evolution (Figure 4.3, purple line), which increases as the SO candidate approaches the central bulge of the merged galaxies. The increase in stellar and gas mass for the object within 3 half-mass radii offers further evidence of infall and implies that the candidate is en route to become to be part of the galactic bulge.

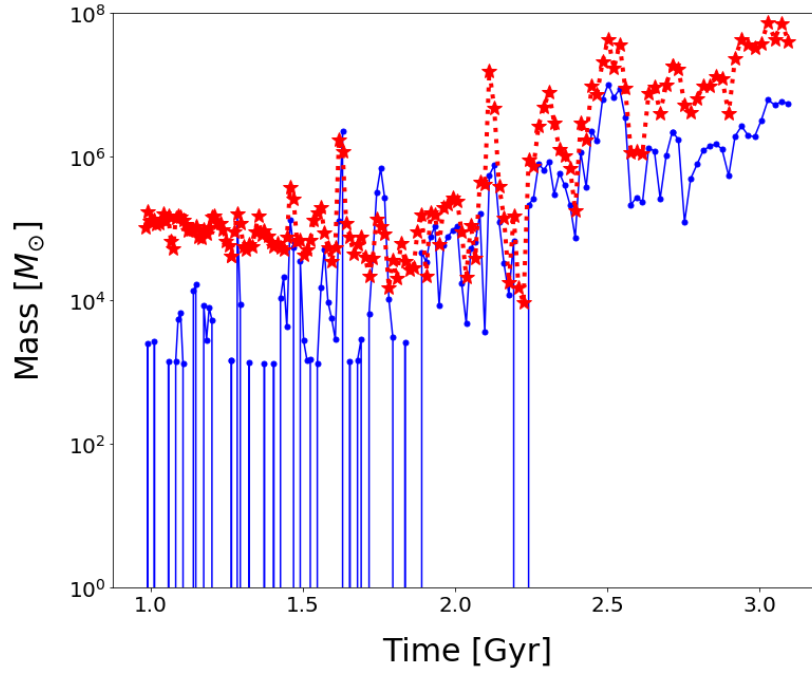


Figure 4.13 *The evolution of stellar (red stars, dashed line) and gas (blue dots, solid line) mass for the SO object. The mass is calculated within $3R_{\text{half}}$.*

4.4 Discussion and conclusions

4.4.1 Discussion

In this Chapter, I presented a suite of new simulations which utilised the same sub-grid physical models as applied in the FiBY simulations that were used in Chapters 2 and 3 of this work. These evolved to $z < 6$. The suite consists of three “isolated” simulations of galaxies, which have been extracted from the FiBY simulation analysed in Chapter 3. These galaxies were chosen as they represented the primary environments in which the infant GC candidates were found, and they hosted the widest variety of candidates. In total, there were 11 GC-like objects across all three galaxies. Out of this group, only one candidate survives, whilst the others are all destroyed. The surviving candidate is the only one in the cutout simulations which consists only of stars by $z = 6$, all the destroyed candidates are gas-rich. I explored the physics behind the destruction of the gas-rich candidates and found that SN feedback from the first stars formed in the objects clears out the gas. As the gas mass is much greater than the stellar component, the remaining stars can not adjust to the new potential, hence dissolving. For the surviving SO candidate, through examination of its subsequent evolution, it was found to infall into the centre of the merging-galaxy host system and eventually become part of the

central bulge. In this Section, I discuss the physical implications of these results.

The behaviour of GC 10 (the SO candidate), in particular its infall as documented by Figures 4.9 - 4.11, implies that this candidate can no longer be considered a GC ancestor by $z \sim 2$, but it is, instead, more likely part of the nuclear star cluster (NSC) for the newly formed galaxy from the major merger. The infall of GCs and young massive clusters as a pathway for the formation of NSCs has long been discussed in the literature (e.g., see Tremaine et al., 1975; Agarwal & Milosavljević, 2011; Antonini, 2013; Neumayer et al., 2020). It is supported by observational evidence, such as the presence of metal-poor stars in some NSCs (e.g., see Mucciarelli et al., 2017; Alfaro-Cuello et al., 2019), the deficit of massive GCs in the inner parts of many galaxies (e.g., see Lotz et al., 2001; Capuzzo-Dolcetta & Mastrobuono-Battisti, 2009), and the equal mass/luminosity in GCs and NSCs for early-type galaxies (e.g., see Côté et al., 2006; den Brok et al., 2014). The main idea of this theory is that massive star clusters (such as GCs) formed in their host galaxy get dragged to the centre, due to dynamical friction of the cluster moving through the stellar background of the host. Many studies (both numerical and analytical) have looked into the strength and efficiency of the dynamical friction force required, as well as the timescales over which a GC could be pulled into the central bulge (e.g., see Oh & Lin, 2000; Hartmann et al., 2011; Antonini, 2013; Neumayer et al., 2011). In the works of Neumayer et al. (2011) and Bekki (2010), they find that a cluster of $M \sim 10^5 M_\odot$ falls into the centre on a time scale of $\lesssim 2$ Gyr. These values are consistent with what I have computed for the SO candidate; this object has a mass of $\sim 4 \times 10^5 M_\odot$ and, after about 2 Gyr, it has almost completely settled into the centre of the host galaxy. Therefore, it is likely that this object ends its life as a GC ancestor, but begins a new one as part of the NSC. This is an avenue that would be interesting to explore further in the future through zoom-in simulations of higher resolution, as this would allow for a more accurate determination of the centre of mass of the infalling object and the corresponding particle association. This future avenue is discussed further in Chapter 5.

The destruction of all the gas-rich candidates presents a problem for some theories concerning GC formation, but it also highlights the duality of high-redshift environments. I have previously determined in Chapters 2 and 3 that a substantial amount of high-density gas is needed for star cluster formation to proceed at $z > 6$ - a property that is common for high-redshift galaxies. However, the results in this Chapter from the cutout simulations also demonstrate that the gas-rich environments of early Universe galaxies also make them ideal environments for destroying star clusters, due to the impact stellar feedback (such as SN) has on the gaseous environment. This

contradictory feature of high-redshift galaxies has also been commented on by the E-MOSAICS group in [Keller et al. \(2020\)](#), who found that GCs in their simulations are most efficiently formed in the gas-rich discs of high-redshift galaxies, but they are also most efficiently destroyed in these regions too.

In the case of the gas-rich infant GC candidates studied in this work, the driving physical mechanism behind their destruction is the feedback from the SNe of the first stars formed in the clusters. This presents a problem for some of the theories surrounding the creation of multiple populations (MPs) in GCs, in particular a subset of theories that come under the AGB scenario category (see Section 1.2). In the works of [D’Ercole et al. \(2008\)](#); [Calura et al. \(2019\)](#); [Lacchin et al. \(2021\)](#), the set-up of their simulations begins after the first generation of stars formed in the clusters have released the feedback from all Type II SN, removing gas from the system before the AGB ejecta is released into the surrounding medium. At some point prior to the formation of the second generation of stars, some pristine gas re-enters the system, diluting the ejecta from AGB stars of the first generation. However, given the results from Section 4.2; the first generation of stars would unlikely survive this initial expulsion of gas, and, even if they did, the potential well they provide may not be large enough to support the re-accretion of pristine gas at a later time. The contradiction to this theory is under the assumption of a high gas fraction, and, therefore, it cannot be ruled out completely based on the work here.

However, one theory of GC formation that has been presented in recent years depends heavily on a high gas fraction to be successful and that is the “Supersonically Induced Gas Objects” (SIGOs) theory. As discussed this in the Introduction, SIGOs are objects of little to no dark matter which are formed at the time of recombination, in areas of the Universe where the relative velocity between baryons and dark matter is high enough for them to become “detached”, resulting in gas-rich haloes. If star formation then proceeds in these objects, they could be plausible ancestors for a subset of present-day GCs ([Naoz & Narayan, 2014](#); [Chiou et al., 2019](#); [Lake et al., 2021](#)). In the works of [Chiou et al. \(2019\)](#) and [Lake et al. \(2021\)](#), the SIGO objects in their simulations are classified as gas-primary subhaloes (as identified by FOF) that have a gas fraction greater than 40% and lie outside the virial radius of the closest DM halo. Given this high gas fraction and the low level of star formation that proceeds in these gas-primary subhaloes in the simulations (not the assumed level calculated in post-processing), it is unlikely that SIGOs are a viable formation route for present-day GCs.

When considering the results presented in this Chapter, such a high fraction (40%) is what was observed for the infant GC candidates that were destroyed in the cutout

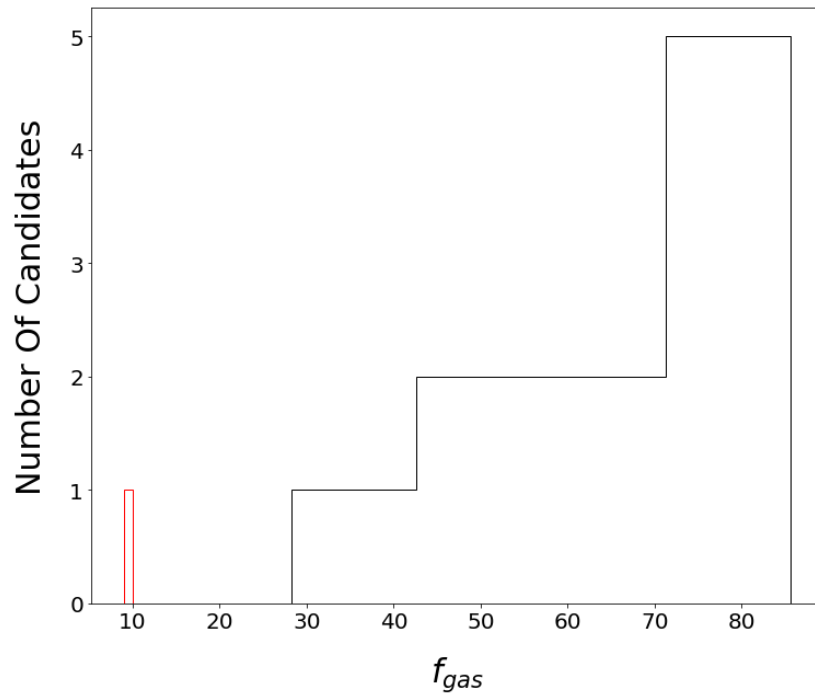


Figure 4.14 *A histogram showing the distribution of f_{gas} for the destroyed candidates (black histogram) compared to the one of the surviving candidate (red histogram).*

simulations run here. In Figure 4.14, I report the distribution of f_{gas} for destroyed candidates versus survived. There is a clear dichotomy between the two groups, implying there is an ideal gas-to-stellar mass fraction that is required to guarantee efficient cluster formation without destruction, or in other words, an empirical limit on f_{gas} . One way to get from the destruction regime to the survival one could be to increase the star formation efficiency of the gaseous object. In the case of the SO candidate, its star formation history is a very short, spike-like burst which is very contrasting to the gas-rich objects (see Figure 4.4) whose histories are flatter and drop off very smoothly. The implication is that the SO candidate formed stars much more efficiently than the gas-rich objects, which resulted in the value of f_{gas} being lowered significantly in a short period of time, and, hence, the object was able to stay gravitationally bound once the gas was removed.

The destruction of the gas-rich candidates may have been enhanced due to numerical issues within the simulations themselves. Here I discuss the caveats to the work presented above that should be considered in the future. One clear caveat to the work presented here is the resolution of the simulations used to run to lower redshift. I chose to keep the resolution of the cutout simulations the same as those I used previously in Chapters 2 and 3 to maintain consistency, as I was studying the same objects in

these new simulations. However, increasing the resolution may have been beneficial in studying the gas-rich candidates as, at a higher resolution, the simulation would be able to resolve much higher gas densities. The gas in the disrupted candidates may have been able to withstand the initial burst of SN at these higher densities allowing for further star formation in the candidates, potentially resulting in a bound stellar cluster at later times. These higher resolutions would also have enabled the study of the progress of the infalling candidate, as the spatial resolution would have been finer, thus the analysis of the small object within the bulk of the central bulge would have been more manageable.

Another improvement that could have been made to the cutout simulations would have been to take a larger region around the galaxies to study in isolation. Whilst this would have had the drawback of increasing the running time of the simulations, a larger radius of the cutout to include more particles would have allowed for some of the intergalactic and interstellar medium to be “modelled” better. Hence, the gaseous medium further from the host galaxies, where some of the candidates found themselves, would have been rendered with more particles, potentially allowing for new gas to fall into the systems preventing destruction.

Some of the physical prescriptions used in the FiBY simulations may also have caused the dissolution of candidates to occur at a higher rate than it should have been. As discussed, the stellar feedback due to SN is what destroys the candidates, hence the recipe for SN feedback applied in FiBY might be too strong or might need to be implemented differently. The issue could also lie in the star formation prescription; as mentioned above, the difference between survival and destruction is dependent upon the ratio of gas to stellar mass, which, in turn, relies on the efficiency of star formation for the gas cloud. In the FiBY simulations, gas particles which reach the star formation threshold density lie along the effective equation of state, until the timestep when they are chosen to be transformed into a stellar particle. The gas particles are chosen in a probabilistic fashion (the probability of a gas particle being converted is given by Equation 21 in [Schaye & Dalla Vecchia 2008](#)), therefore, not all of the “star-forming” gas is forming stars.

For comparison, I briefly discuss the work of [Ma et al. \(2020\)](#): they perform high-resolution, zoom, re-simulations of galaxies at $z \geq 5$ taken from the FIRE project. They find several star clusters born from high-density, high-pressure gas clouds, which are likely proto-GC objects. Their clusters survive the duration of the simulation, even though they are also formed in gas-rich environments like the ones studied in this Chapter. However, their simulations have a number of numerical differences:

(1) the resolution of their work is much finer ($m_b = 119.3 M_\odot$), (2) most of the re-simulations adopt a local star formation efficiency of unity, (3) the SN feedback is implemented probabilistically (see [Hopkins et al. 2018](#) for further details). These differences in resolution and physical prescriptions could result in their simulations producing clusters that are more likely to be bound at birth and also survive for longer. Although, it should be noted that the re-simulations studied in [Ma et al. \(2020\)](#) are only run for a short period of time. The timescales covered by these simulations are shorter than the timescales for dissolution in Table 4.1, hence it could be a case of the simulations studied in [Ma et al. \(2020\)](#) not covering the period of destruction for the proto-GC candidates. For future directions of research (see Chapter 5), I will consider these numerical factors to make improvements to the simulations.

4.4.2 Conclusions

In this Chapter, I explored the subsequent evolution of some of the infant GC candidates studied in Chapter 3, by setting up and running a suite of isolated “cutout” simulations to study the progress of the objects to $z < 6$. The main results can be summarised as follows:

- I selected three host galaxies (see Figure 4.1) for further simulation. These galaxies were good representatives of the different environments that the infant GC candidates were found in Chapter 3; each host galaxy hosted multiple infant GC candidates.
- In total, there were 11 candidates across the 3 galaxies for the isolated cutout simulations. Out of those 11, only a single candidate survived to lower redshifts. The surviving candidate was the only one to be a gas-free stellar cluster already by $z = 6$; all the destroyed candidates were still gas-rich by the end of the original FiBY simulations.
- I explored the cause of the dissolution of the gas-rich candidates and found that they experienced a peak in star formation at $z \sim 6$. The resultant SN feedback from this star formation period resulted in the expulsion of the remaining gas in these objects, as the feedback energy built the potential of the objects dropped (see Figures 4.5 - 4.7).
- I defined the following timescales: t_{cross} (the time at which the SN feedback energy exceeded the potential energy), t_{halflife} (the timescale it took for the

potential energy to drop by half) and t_{diss} (the time in the simulation at which the candidates could be considered fully destroyed) - see Table 4.1. When comparing the potential energy of the stars at t_{cross} for the gas-rich and SO candidates, it was found that the SO candidate's stars were more bound at the moment when SN feedback is stronger. I also examined the ratio of gas to stellar mass at t_{cross} (f_{gas}) and found that the destroyed candidates had a much higher value of f_{gas} than the SO candidate.

- When comparing the values of f_{gas} with t_{halflife} (Figure 4.8), in general, it was found that the lower the gas fraction the longer the half-life. This offers a further indication that the amount of gas in a GC candidate has a significant impact on its ability to survive. This implies that there is an empirical limit on the value of f_{gas} a GC candidate should have to survive. To enter this regime the efficiency of star formation for the gas cloud should be high.
- Finally, I examined the evolution of the surviving SO candidate. By studying its evolving position in time with reference to the common centre of mass of the merging host galaxies, I found that the candidate was infalling into the centre of the system (Figure 4.9). Upon examination of phase-space diagrams for this candidate, it was determined that the candidate was on a path to merge with the bulge, supporting the GC infall formation theory for nuclear star clusters.

I wish to emphasise that the results presented in this Chapter are preliminary and they would require further work: in the first instance, it would be important to improve upon the foundations these cutout simulations have provided by addressing the numerical issues discussed in Section 4.4.1.

Chapter 5

Conclusions and outlooks

5.1 Conclusions

This doctoral thesis aimed to study the early evolutionary stages of globular cluster (GC) formation by utilising a suite of numerical simulations of a cosmological volume from the First Billion Years (FiBY) project, as well as a set of new simulations extending the timescale of interest from $z = 6$ to $z = 2$.

In Chapter 2, I explored the FiBY simulations at $z = 6$, to identify potential GC candidates during their infant stages. Indeed, a group of objects with a high baryon fraction, but appearing to lie within an extended dark matter (DM) environment, were identified. I hypothesised such objects to be possible infant GC candidates, and I explored this possibility by studying their global properties and host galaxy environments. An exploration of the stellar half-mass radius, density, metallicity and velocity dispersion as a function of stellar mass for the infant GC candidates provided further support for the above hypothesis, as such objects are characterised by high stellar densities when compared to the general populations of substructures of similar mass. These infant GC candidates already appeared to resemble the GC systems observed in the local Universe, as multiple candidates were found to be located in the same host galaxy. Hence, I explored any relationships that might exist between the host and the candidates. I started with the well-studied redshift-zero globular system mass – halo mass relation, and I found that it provided a reasonable fit for the infant GC candidates, indicating that this relationship is likely set at formation. This relationship is linear, hence, it is likely that, as these GC - galaxy systems evolve, they will move along

the relation and remain in good agreement with the present-day observations. I also found a previously not reported correlation between the specific star formation rate (sSFR) of the host galaxy and the stellar mass of the most massive globular. This relationship extends over several orders of magnitude in sSFR, and, when compared to local Universe literature data, was shown to hold across redshifts. Such a correlation provides a link between the low and high-redshift Universe and it can be utilised in the future to study GC evolution observationally. These relations imply a close connection between the host galaxy and the forming GC. When investigating the morphology and galactic environments of the infant GC candidates, they were found to lie within the DM density peaks of their host, but to contain a low fraction of energetically bound DM particles. Most candidates are located within 1 kpc from the centre of the parent galaxy, suggesting that, during their early evolution, they may have undergone many interactions. Finally, I compared the sizes and masses of these candidates identified in FiBY to preliminary high-redshift observations of possible proto-GCs from [Vanzella et al. \(2017\)](#); [Bouwens et al. \(2017a\)](#) and found relatively good agreement. The analysis conducted in Chapter 2 imply that these high-baryon-fraction objects are plausible early ancestors of local Universe GCs.

Building upon the results in Chapter 2, I utilised a high-frequency snapshot simulation from the FiBY project to explore, in Chapter 3, the possible formation channels for the infant GC candidates. I utilised the distribution in the energy – angular momentum phase-space (“Lindblad diagram”) as a technique to examine the formation of small structures in a changing galactic environment. Such an analysis allowed for the identification of the redshift at which these systems first became gravitationally bound (“formation redshift”). Before this redshift, the gas in these objects falls radially to the centre of the object and collapses on the dynamical timescale. An analysis of the infall of the star particles showed that the ratio of the interparticle distance between stars to the Jeans length of the gas is of order unity, suggesting that the size of the infant GCs is set in the early stages by the Jeans length. The phase-space behaviour of the infant GCs was further examined, and I identified that the candidates could be characterised into groups of a similar evolution, indicating the existence of multiple formation channels. The classification in phase-space is reflected in the formation environment: candidates in the same class are located in hosts of similar morphology. The most common class of infant GCs are characterised by lower angular momentum and are located in “standard” clumpy high-redshift proto-galaxies, with no distinct morphology. These hosts have the highest sSFR, and the relation between sSFR and cluster mass discussed in Chapter 2 persisted here, supporting the argument that these candidates are a natural product of star formation in high-redshift galaxies. A small set of the infant GC candidates

were classified as “star-only” (SO) and could potentially represent the end product of the gas-rich candidates. I examined the prospective future evolution of the general population through analysis of these SO candidates, and I found that, at earlier times, the feedback from supernova (SN) expels the gas from the half-mass radius of the systems and, subsequently, the remaining star particles relax into the new potential via an approximate adiabatic expansion.

Finally, in Chapter 4, I performed my own suite of simulations to study how the candidates evolve in their host galaxies, without external influences from the larger environment. These simulations are isolated, “cutouts” of three different galaxies, which were extracted from the FiBY simulation analysed in Chapter 3. These galaxies were chosen for the variety of infant GC candidates they hosted and for the diverse range of host environments they presented. In total, 11 candidates were examined, as located across three host galaxies, and the new simulations were run until $z \sim 2$. I found that only one candidate survives (an SO candidate), whilst all the remaining gas-rich objects are destroyed. The main physical cause of the dissolution of the gas-rich clusters is SN feedback from the stars that were formed in these objects at $z \sim 6$. This feedback clears out the remaining gas; the stars try to adjust to the new potential, but they are unable to remain bound, and the cluster unravels. Through a comparison of the properties of the destroyed candidates and the surviving one at the moment when the SN feedback starts to exceed the potential energy of the object, it was determined that the ratio of gas mass to stellar mass (f_{gas}) is vital in understanding whether an object would survive. If f_{gas} is too large, then the gas dominates the potential of the candidate, resulting in its death once the gas is removed. This observation is further supported by finding that, in general, the time it takes for the gas-rich objects to dissolve decreases with increasing f_{gas} . A gas-rich environment is needed for the efficient formation of clusters, however, the local star formation efficiency also needs to be high to reduce the probability of the cluster being destroyed, once stellar feedback kicks in. Finally, I studied the evolution of the SO candidate and found that it is on an infalling orbital trajectory to the centre of the merging galaxy system, supporting the GC infall formation theory for nuclear star clusters.

5.2 Future work

The next immediate step would be to restart the cutout simulations used in Chapter 4, but with a larger extraction region and to extend those simulations until $z = 0$. This would allow me to address some of the numerical caveats that were presented in Chapter 4,

Section 4.4 and to assess the impact these might have had on the results presented in that Chapter. I would also want to run the zoom-in simulations of a Milky Way mass halo for which the initial condition and parameter files I had already set up, but, unfortunately, I did not have the time to run to a redshift of use. It would be interesting to examine the results from these zoom-in simulations, as they would be of higher resolution than the cutouts used in Chapter 4. There could be a chance that more of the infant GC candidates would survive in these additional simulations. There are other directions I would like to explore as well, building upon and extending the work here into several avenues. Below I will discuss a few of them that I believe are particularly interesting to consider.

5.2.1 Formation of nuclear star clusters

In Chapter 4, I presented some preliminary evidence that a fraction of the infant GC candidates in the new cutout simulations infall onto the central bulge of the galaxy, thus forming part of the nuclear star cluster (NSC). While there is some debate surrounding the formation process of NSCs, the consensus is that multiple accretion events of GCs play a significant role in their early growth (e.g., see [Guillard et al., 2016](#); [Neumayer et al., 2020](#); [Fahrion et al., 2021](#)). From the work presented in this thesis, I have evidenced that multiple GCs can form close to one another. These formation sites are often located in the disk (for a galaxy with an already defined morphology) or within the highest density gas knots of irregular-looking, high-redshift galaxies. Thus, a fraction of the infant GC candidates identified in the FiBY simulations (at $z = 6$) may go on to form the central NSC for their host galaxies. In fact, in Chapter 4, it was uncovered that a candidate which is on an infalling orbit, by $z \sim 2$ in the simulation, had begun to merge with the centre of the host galaxy. Further investigations could be done directly, if one is to perform a set of zoom-in smoothed particle hydrodynamical (SPH) simulations with high enough resolution such that the star clusters are represented by ideally tens of thousands of star and gas particles. This high resolution would need to be combined with a large enough cosmological volume to account for other factors that could influence the star clusters' evolution, e.g. tidal effects from the host galaxy. In particular, it would be important to pay attention to (i) the role played by the gas during accretion events, especially as the infant GC candidates identified in this work are much more gas-rich than their present-day counterparts; (ii) the evolution of the angular momentum of the resulting NSC, with reference to both the internal and orbital momentum of the accreting GCs.

5.2.2 The bridge between GCs and dwarf galaxies

When examining the size-mass plane of low-mass stellar systems, there is an apparent gap between the locations of GCs and dwarf galaxies. Currently, the criteria for making the distinctions between these two groups of objects are primarily DM-dependent (see discussion in Introduction). However, recent studies by [Ibata et al. \(2013\)](#); [Parrubia et al. \(2017\)](#); [Bianchini et al. \(2019b\)](#) have shown that GCs may have an extended DM halo, although such an old-standing proposal is still lacking clear observational evidence. To fully delineate between the two classes, a careful dynamical interpretation of the density profiles and internal kinematics of these systems is needed. In Chapter 2, I have identified a further population of low-mass objects with a broad range of DM content - from sub-dominant to fully dominating their total mass budget. I propose that a worthwhile future avenue for further research would be to examine these objects in greater detail. Performing a similar analysis on these “proto-UFDs” as was done in Chapter 3 for the infant GCs would be ideal. Beyond this, it would be prudent to perform isolated simulations, similar to such ones conducted in Chapter 4, but addressing the numerical caveats discussed in Section 4.4.1, on selected galaxies hosting low-mass objects of interest. In this way, one could assess their evolution, especially regarding their DM content and their structural and kinematical properties. The results of such a numerical investigation could directly be compared to specific compact objects at various redshifts – in particular cases where it is difficult to classify the object as a star cluster or a low-mass galaxy. In addition, such an investigation could provide insight into the possibility of the existence of “free-floating” or intergalactic GCs, of which some tentative detections have been claimed by [Jang et al. \(2012\)](#), [Harris et al. \(2020\)](#), and, most recently, [Lee et al. \(2022\)](#), on the basis of JWST observations. A key challenge here is to distinguish such an object from a small satellite galaxy.

5.2.3 Exploring the connection between low and high redshift observations of star clusters

With the launch of JWST, new observations of forming star clusters at high redshift are already becoming available (see the very recent results by [Vanzella et al. 2022](#); [Mowla et al. 2022](#); [Faisst et al. 2022](#)). Even in the first cycle, there are at least two programmes that are focused on the early ancestors of GCs ([Coe et al., 2021](#); [Vanzella et al., 2021](#)). Understanding the connection between these upcoming high-redshift objects and the GCs we observe locally will give deeper insight into the probability of

survival of low-mass stellar systems that form in the early Universe, as well as providing a complementary perspective to the simulations that study the evolution of such objects over time. One way to approach this problem is to exploit well-known relations between GCs and their environments. In Chapter 2, I showed that the GC system mass – halo mass relation holds at $z = 6$ in cosmological simulations; an observational confirmation of such a theoretical result would allow us to better understand the process of creation and destruction of GCs over cosmic time. Also, in Chapter 2, I reported a new relation between the mass of the most massive cluster and the specific star formation rate of the parent galaxy. This relation has already been shown to hold at both low and high redshift and, therefore, can provide an upper limit on the mass evolution of larger GCs in a GC-galaxy system. Combining archival data, new observations, and models for galaxy evolution found in the simulations studied here could provide a route to understand the connection between the present-day GCs and their ancestors, as well as an evaluation of how GC-galaxy relations evolve.

5.2.4 Population III-only star cluster

The model of a Population III star cluster is often used in theories surrounding the formation of intermediate-mass black holes (IMBHs) and the seeding of the supermassive black holes (SMBHs) which we observe today (e.g., see [Woods et al., 2019](#); [Alister et al., 2020](#); [Vergara et al., 2021](#)). In such numerical models, these clusters are assumed to be of high density (to ensure multiple star-star collisions) and they are assumed to be present in the early Universe. However, the formation of such a stellar cluster has not been studied in detail in high-resolution cosmological simulations. In the research conducted for this thesis, I found that a fraction of stars forming in the infant GC candidates have metallicities consistent with the ones of Population III star models employed in FiBY. We know that GCs have low metallicities, but there is no evidence of GCs with metallicities below $1 \times 10^{-3} Z_{\odot}$. Is there a fundamental physical reason for the absence of low-metallicity GCs, i.e. a “metallicity floor”, or have we simply not yet discovered these types of objects, including Population III star clusters? If such clusters do form, can they survive to the present day? Are these objects related to the formation of SMBH seeds? These questions could be answered by running high-resolution, zoom-in simulations of the very early Universe, and then applying similar methods as used in Chapters 3 and 4. The results of such a study can be used to determine more accurate initial conditions in N-body codes modelling the formation of IMBHs and SMBH seeds through runaway collisions, which may take place in these types of clusters. Furthermore, applying radiative transfer solutions to the resulting

snapshots of such a study can allow for the assessment of ionising photon escape fractions from such metal-poor stellar systems and their contribution to reionisation.

5.2.5 Globular clusters in extreme environments

Due to their ubiquitous nature, GCs can be found around any type of galaxy. Thus, some of them can be located in extreme, hostile environments and, as shown in Chapter 3, the host galaxy environment does have an impact on the early stages of GC formation. Hence, it would be intriguing to investigate the effect such environments might have on the formation and evolution of GCs over time, and how it could affect their physical properties at redshift $z = 0$, as this could inform us about the history of the host galaxy. There is observational evidence of quasars at $z > 5$ (e.g., see [Mazzuchelli et al., 2017](#); [Decarli et al., 2018](#)), which are redshifts at which GCs are also expected to form. If GCs form in the haloes of active galaxies, it is possible that energetic feedback from the SMBH could affect the forming stellar systems. Previous works have shown that the outflows from SMBHs can change the physical properties (such as temperature, density, and metallicity) of the gas throughout the host galaxy, as well as its halo (e.g., see [Ciotti et al., 2017](#); [Maiolino et al., 2017](#); [Hahn et al., 2020](#)). In this work, I have shown that the early ancestors of GCs are likely to be gas-rich. Thus, such outflows could impact these structures in several ways: for instance, by changing the initial mass function of the stars forming in the clusters, by affecting the light-element variations or by removing gas from the object and stunting star formation. If the effects of SMBH outflows on forming or early GCs can be detected in simulations, then this information could be used to observationally assess the formation pathway of low-redshift GCs and, simultaneously, to infer the previous activity of the SMBH in the host galaxy.

Bibliography

- Abel T., Anninos P., Zhang Y., et al. 1997, *NewA*, 2, 181
- Agarwal M., Milosavljević M., 2011, *ApJ*, 729, 35
- Alfaro-Cuello M., Kacharov N., Neumayer N., et al. 2019, *ApJ*, 886, 57
- Alister S. P. J., Schleicher D. R. G., Boekholt T. C. N., et al. 2020, *MNRAS*, 493, 2352
- Amorisco N. C., Gómez F. A., Vegetti S., et al. 2016, *MNRAS*, 463, L17
- Antonini F., 2013, *ApJ*, 763, 62
- Arraki K. S., Klypin A., More S., Trujillo-Gomez S., 2014, *MNRAS*, 438, 1466
- Ashman K. M., Zepf S. E., 1992, *ApJ*, 384, 50
- Bastian N., Lardo C., 2018, *ARA&A*, 56, 83
- Bastian N., Lamers H. J. G. L. M., de Mink S. E., Longmore S. N., Goodwin S. P., Gieles M., 2013a, *MNRAS*, 436, 2398
- Bastian N., Cabrera-Ziri I., Davies B., et al. 2013b, *MNRAS*, 436, 2852
- Bastian N., Pfeffer J., Kruijssen J. M. D., et al. 2020, *MNRAS*, 498, 1050
- Bate M. R., Bonnell I. A., Bromm V., 2003, *MNRAS*, 339, 577
- Baumgardt H., 2017, *MNRAS*, 464, 2174
- Baumgardt H., Cote P., Hilker M., et al. 2009, *MNRAS*, 396, 2051
- Baumgardt H., Sollima A., Hilker M., 2020, *PASA*, 37, id. 46
- Baumgardt H., Faller J., Meinhold N., et al. 2022, *MNRAS*, 510, 3531
- Beasley M. A., Baugh C. M., Forbes D. A., Sharples R. M., Frenk C. S., 2002, *MNRAS*, 333, 383
- Bechtol K., Drlica-Wagner A., Balbinot E., et al. 2015, *ApJ*, 807, 50
- Behroozi P. S., Wechsler R. H., Wu H. Y., 2013, *ApJ*, 762

Bekki K., 2010, MNRAS, 401, 2753

Bekki K., 2017, MNRAS, 469, 2933

Bekki K., Forbes D. A., Beasley M. A., Couch W. J., 2002, MNRAS, 335, 1176

Bell E. F., McIntosh D. H., Katz N., et al. 2003, ApJS, 149, 289

Bianchini P., Ibata R., Famaey B., 2019a, ApJL, 887, L12

Bianchini P., Ibata R., Famaey B., 2019b, ApJ, 887, L12

Bílek M., Zhao H., Famaey B., et al. 2021, A&A, 653, A170

Blumenthal G. R., Faber S. M., Primack J. R., et al. 1984, Nature, 311, 517

Blumenthal G. R., Faber S. M., Flores R., Primack J. R., 1986, ApJ, 301, 27

Bournaud F., 2016, ASSL, 418, 355

Bournaud F., Duc A. P., Emsellem E., 2008, MNRAS, 389, L8

Bouwens R. J., Illingworth G. D., Oesch P. A., Maseda M., Ribeiro B., Stefanon M., Lam D., 2017a, eprint

Bouwens R. J., Illingworth G. D., Oesch P. A., et al. 2017b, eprint arXiv:1711.02090

Bouwens R. J., Illingworth G. D., van Dokkum P., et al. 2021, ApJ, 162, id. 255

Bouwens R. J., Illingworth G. D., van Dokkum P. G., Oesch P. A., Stefanon M., Ribeiro B., 2022, , 927, 81

Boylan-Kolchin M., 2017, MNRAS, 472, 3120

Boylan-Kolchin M., 2018, MNRAS, 479, 332

Brodie J. P., Huchra J. P., 1991, ApJ, 379, 157

Bromm V., Clarke C J., 2002, ApJ, 566, L1

Brown G., Gnedin O. Y., 2021, MNRAS, 508, 5935

Brown T M., Tumlinson J., Geha M., et al. 2014, ApJ, 796

Bullock J. S., Dekel A., Kolaff T. S., et al. 2001, ApJ, 555, 240

Cabrera-Ziri I., Conroy C., 2022, MNRAS, 511, 341

Caffau E., Bonifacio P., Francois P., et al. 2011, Nature, 477, 67

Calura F., D’Ercole A., Vesperini E., et al. 2019, MNRAS, 489, 3269

Capuzzo-Dolcetta R., Mastrobuono-Battisti A., 2009, A&A, 507, 183

Carlberg R. G., 2018, ApJ, 861, 69

Carretta E., et al., 2009a, *A&A*, 505, 117

Carretta E., Bragaglia A., Gratton R., Lucatello S., 2009b, *A&A*, 505, 139

Chabrier G., 2003, *PASP*, 115, 763

Chandar R., Whitmore B. C., Dinino D., et al. 2016, *ApJ*, 824, id. 71

Chen Y., Gnedin O. Y., 2022, eprint arXiv 2203.00599

Chiou Y. S., Naoz S., Marinacci F., et al. 2018, *MNRAS*, 481, 3108

Chiou Y. S., Naoz S., Burkhardt B., et al. 2019, *ApJ*, 878, L23

Chiou Y. S., Naoz S., Burkart B., et al. 2021, *ApJ*, 906, id. 25

Ciotti L., Pellegrini S., Negri A., Ostriker J. P., 2017, *ApJ*, 835, 15

Coe D., Acebron A., Avila R., et al. 2021, p. JWST Proposal 2282 Cycle 1

Conroy C., Loeb A., Spergel D. N., 2011, *ApJ*, 741, 72

Côté P., Marzke R. O., West M. J., 1998, *ApJ*, 501, 554

Côté P., Piatek S., Ferrarese L., et al. 2006, *ApJS*, 165, 57

Crain R. A., Schaye J., Bower R. G., et al. 2015, *MNRAS*, 450, 1937

Creasey P., Sales L. V., Peng E. W., et al. 2019, *MNRAS*, 482, 219

Cullen F., McLure R. J., Khochfar S., et al. 2017, *MNRAS*, 470, 3006

Cullen F., McLure R. J., Dunlop J. S., et al. 2019, *MNRAS*, 487, 2038

D’Ercole A., Vesperini E., D’Antona F., McMillan S. L. W., Recchi S., 2008, *MNRAS*, 291, 825

D’Ercole A., D’Antona F., Vesperini E., 2016, *MNRAS*, 461, 4088

Dalla Vecchia C., Schaye J., 2012, *MNRAS*, 426, 140

Davis M., Efstathiou G., Frenk C. S., et al. 1985, *ApJ*, 292, 371

Davis A. J., Khochfar S., Dalla Vecchia C., 2014, *MNRAS*, 443, 985

Decarli R., Walter F., Venemans B. P., et al. 2018, *ApJ*, 854, 97

Decressin T., Meynet G., Charbonnel C., Prantzos N., Ekstrom S., 2007a, *A&A*, 464, 1029

Decressin T., Charbonnel C., Meynet G., 2007b, *A&A*, 475, 859

Dessauges-Zavadsky M., Richard J., Combes F., et al. 2019, *Nature*, 3, 1115

Di Matteo P., Bournaud F., Martig M., et al. 2008, *A&A*, 492, 31

- Dobbs C. L., Krumholz M. R., Ballesteros-Paredes J., Bolatto A. D., Fukui Y., Heyer M., Low M. M. M., Ostriker E. C., 2014, *Protostars and Planets*, pp 3–26
- Dobbs C. L., Bending T. J. R., Pettitt A. R., et al. 2022, *MNRAS*, 509, 954
- Dolag K., Borgani S., Murante G., et al. 2009, *MNRAS*, 399, 497
- Domínguez R., Farias J. P., Fellhauer M., et al. 2021, *MNRAS*, 508, 5410
- Dondoglio E., Milone A. P., Renzini A., et al. 2022, *ApJ*, 927, id. 207
- Eadie G. M., Harris W. E., Springford A., 2022, *ApJ*, 926, id. 162
- El-Falou N., Webb J. J., 2022, *MNRAS*, 510, 2437
- Elmegreen B. G., 1979, *ApJ*, 231, 372
- Elmegreen B. G., 1995, *Molecular Clouds and Star Formation*, p. 149
- Elmegreen B. G., 2009, *The Galaxy Disk in Cosmological Context*, *Proceedings of the International Astronomical Union*, IAU Symposium, 254, 289
- Elmegreen B. G., 2010, *ApJL*, 712, L184
- Elmegreen B. G., 2017, *ApJ*, 836
- Elmegreen D. M., Elmegreen B. G., 2017, *ApJ*, 851, L44
- Elmegreen B. G., Malhorta S., Rhoads J., 2012, *ApJ*, 757
- Elson R., Hut P., Inagaki S., 1987, *ARA&A*, 25, 565
- Fahrion K., Lyubenova M., Hilker M., et al. 2020a, *A&A*, 637, id. A26
- Fahrion K., Lyubenova M., Hilker M., et al. 2020b, *A&A*, 637, id. A27
- Fahrion K., Lyubenova M., van de Ven G., et al. 2021, *A&A*, 650, A137
- Faisst A. L., Chary R. R., Brammer G., et al. 2022, p. eprint arXiv:2208.05502
- Ferland G. J., Korista K. T., Verner D. A., et al. 1998, *PASP*, 110, 761
- Field G. B., 1965, *ApJ*, 142, 531
- Field G. B., Salslaw W. C., 1965, *ApJ*, 142, 568
- Forbes D. A., Bridges T., 2010, *MNRAS*, 404, 1203
- Forbes D. A., Brodie J. P., Grillmair C. J., 1997, *AJ*, 113, 1652
- Forbes D. A., Norris M. A., Strader J., et al. 2014, *MNRAS*, 444, 2993
- Forbes D. A., Pastorello N., Romanowsky A. J., Usher C., Brodie J. P., Strader J., 2015, *MNRAS*, 452, 1045

Forbes D. A., Bastian N., Gieles M., et al. 2018a, *Proceedings of the Royal Society A*, 474

Forbes D. A., Read J. I., Gieles M., Collins M. L. M., 2018b, *MNRAS*, 481, 5592

Förster Schreiber N. M., Genzel R., Bouché N., et al. 2009, , 706, 1364

Fouesneau M., Johnson L. C., Weisz D. R., et al. 2014, *ApJ*, 786, id. 117

Frebel A., Johnson J. L., Bromm V., 2007, *MNRAS*, 380, L40

Fujii M. S., Saitoh T. R., Wang L., et al. 2021a, *PASJ*, 73, 1057

Fujii M. S., Saitoh T. R., Hirai Y., et al. 2021b, *PASJ*, 73, 1074

Gaia Collaboration Helmi A., van Leeuwen F., et al. 2018, *A&A*, 616, A12

Galli D., Palla F., 1998, *A&A*, 335, 403

Garrow T., Webb J. J., Bovy J., 2020, *MNRAS*, 499, 804

Gratton R. G., Carretta E., Bragaglia A., 2012, *A&ARv*, 30, 50

Gratton R. G., Bragaglia A., Carretta E., et al. 2019, *A&ARv*, 27, 8

Grisdale K., Agertz O., Romeo A. B., Renaud F., Read J. I., 2017, *MNRAS*, 466, 1093

Grudic M. Y., Guszejnov D., Offner S. S. R., et al. 2022, *MNRAS*, 512, 216

Guillard N., Emsellem E., Renaud F., 2016, *MNRAS*, 416, 3620

Guillard N., Emsellen E., Renaud F., 2018, *MNRAS*, 477, 5001

Hahn O., Abel T. Choi E., Brennan R., Somerville R. S., et al. 2020, *ApJ*, 904, 8

Halbesma T. L. R., Grand R. J. J., Gomez F. A., et al. 2020, *MNRAS*, 496, 638

Harris W. E., 1991, *ARA&A*, 29, 543

Harris W. E., 1996, *AJ*, 112, 1487

Harris W. E., 2016, *AJ*, 151

Harris W. E., Racine R., 1979, *ARA&A*, 17, 241

Harris W. E., Harris G. L. H., Alessi M., 2013, *ApJ*, 772

Harris W. E., Harris G. L., Hudson M. J., 2015, *ApJ*, 806

Harris W. E., Blakeslee J. P., Harris G. L., 2017, *ApJ*, 836

Harris W. E., Brown R. A., Durrel P. R., et al. 2020, *ApJ*, 890, 105

Hartmann M., Debattista V. P., Seth A., et al. 2011, *MNRAS*, 418, 2697

- He C. C., Ricotti M., Green S., 2020, MNRAS, 492, 4858
- Heger A., Woosley S. E., Fryer C. L., et al. 2003, *From Twilight to Highlight: The Physics of Supernovae*, p. 3
- Heggie D. C., 2014, MNRAS, 445, 3435
- Heggie D. C., Hut P., 1996, IAUS, 174, 303
- Heggie D., Hut P., 2003, Cambridge University Press, p. 372
- Hirai Y., Fujii M. S., Saitoh T. R., 2021, PASJ, 73, 1036
- Hirschmann M., Khochfar S., Burkert A., et al. 2010, MNRAS, 407, 1016
- Hopkins P. F., Cox T. J., Hernquist L., et al. 2013, MNRAS, 430, 1901
- Hopkins P. F., Kereš D., Oñorbe J., et al. 2014, MNRAS, 445, 581
- Hopkins P. F., Wetzel A., Kereš D., et al. 2018, MNRAS, 477, 1578
- Howard C. S., Pudritz R. E., Harris W. E., 2017, MNRAS, 470, 3346
- Howard C. S., Pudritz R. E., Harris W. E., et al. 2018, MNRAS, 473, 3121
- Hudson M. J., Harris G. L., Harris W. E., 2014, ApJL, 787, L5
- Hughes M. E., Pfeffer J. L., Martig M., et al. 2020, MNRAS, 491, 4012
- Hurst T. J., Zentner A. R., 2019, arXiv, 1910, 00665
- Ibata R., Nipoti C., Sollima A., et al. 2013, MNRAS, 428, 3648
- Ishiyama T., Rieder S., Makino J., et al. 2013, ApJ, 767, 146
- Jahnke K., Macciò A. V., 2011, ApJ, 734
- Jang I. S., Lim S., Park H. S., Lee M. G., 2012, ApJ, 751, L19
- Johnson J. L., Dalla Vecchia C., Khochfar S., 2013a, MNRAS, 428, 1857
- Johnson J. L., Dalla Vecchia C., Khochfar S., 2013b, MNRAS, 428, 1857
- Kaiser N., 1984, ApJL, 284, L9
- Katz H., Ricotti M., 2013, MNRAS, 432, 3250
- Katz H., Ricotti M., 2014, MNRAS, 444, 2377
- Kawamata R., Ishigaki M., Shimasaku K., Oguri M., Ouchi M., Tarigawa S., 2018, ApJ, 855, 4
- Keller B. W., Kruijssen J. M. D., Pfeffer J., et al. 2020, MNRAS, 495, 4248
- Kennicutt R. C. J., 1998, ARA&A, 36, 189

Kennicutt R C. J., Chu Y.-H., 1988, AJ, 95, 720
 Khochfar S., Burkert A., 2001, , 561, 517
 Khochfar S., Silk J., 2009, , 700, L21
 Kikuchihara S., et al., 2020, ApJ, 893, 60
 Kim W. T., Ostriker E. C., 2002, ApJ, 570, 132
 Kim C. G., Kim W. T., Ostriker E. C., 2006, ApJL, 649, L13
 Kim J., Ma X., Grudic M. Y., et al. 2018, MNRAS, 474, 4232
 Kim S., Yoon S. J., Lee S. Y., et al. 2021, ApJS, 256, id. 29
 Kimm T., Blaizot J., Garel T., et al. 2019, MNRAS, 486, 2215
 King I. R., 1966, AJ, 71
 Kleyna J. T., Wilkinson M. I., Evans N. W., et al. 2005, ApJ, 630, L141
 Knebe A., Knollmann S. R., Muldrew S. I., et al. 2011, MNRAS, 415, 2293
 Knollmann S. R., Knebe A., 2009, ApJs, 182, 608
 Komatsu E., Smith K. M., Dunkley J., et al. 2011, ApJS, 192
 Kopolov S. E., Belokurov V., Torrealba G., et al. 2015, ApJ, 805, 130
 Kravtsov A. V., Gnedin O. Y., 2005, ApJ, 623, 650
 Kruijssen J. M. D., 2009, A&A, 507, 1409
 Kruijssen J. M. D., 2012, MNRAS, 426, 3008
 Kruijssen J. M. D., 2014, CQGra, 31, 244006
 Kruijssen J. M. D., 2015b, MNRAS, 454, 1658
 Kruijssen J. M. D., 2015a, MNRAS, 454, 1658
 Kruijssen J. M. D., Lamers H. J. G. L. M., 2008, A&A, 490, 151
 Kruijssen J. M. D., Pelupessy F. I., Lamers H. J. G. L. M., et al. 2011, MNRAS, 414, 1339
 Kruijssen J. M. D., Pfeffer J. L., Crain R. A., et al. 2019a, MNRAS, 486, 3134
 Kruijssen J. M. D., Pfeffer J. L., Reina-Campos M., et al. 2019b, MNRAS, 486, 3180
 Kruijssen J. M. D., Pfeffer J. L., Chevance M., et al. 2020, MNRAS, 498, 2472
 Krumholz M. R., 2014, PhR, 539, 49

Kwan J., 1979, *ApJ*, 229, 567

Lacchin E., Calura F., Vesperini E., 2021, *MNRAS*, 506, 5951

Lagioia E. P., Milone A. P., Marino A. F., et al. 2019, *AJ*, 158, id. 202

Lagos C. P., Theuns T., Stevens A. R. H., et al. 2017, *MNRAS*, 464, 3850

Lahén N., Naab T., Johansson P. H., et al. 2019, *ApJ*, 879, L18

Lahén N., Naab T., Johansson P. H., et al. 2020a, *ApJ*, 891, 2

Lahén N., Naab T., Johansson P. H., et al. 2020b, *ApJ*, 904, 71

Lake W., Naoz S., Chiou S. Y., et al. 2021, *ApJ*, 922, id. 86

Lane R. R., Kiss L. L., Lewis G. F., et al. 2010, *MNRAS*, 406, 2732

Lardo C., Bellazzini M., Pancino E., et al. 2011, *A&A*, 525

Larsen S. S., 2002, *AJ*, 124, 1393

Larsen S. S., Richtler T., 2000, *A&A*, 354, 836

Larsen S. S., Brodie J. P., Huchra J. P., et al. 2001, *AJ*, 121, 2974

Larsen S. S., Brodie J. P., Sarajedini A., Huchra J. P., 2002, *AJ*, 124, 2615

Larsen S. S., Baumgardt H., Bastian N., Brdoie J. P., Grundahl F., Strader J., 2015, *ApJ*, 804

Larson R. B., 1969, , 145, 271

Leaman R., VandenBerg D. A., Mendel J. T., 2013, *MNRAS*, 436, 122

Lee H. M., Ostriker J. P., 1987, *ApJ*, 322, 123

Lee M. G., Bae J. H., Jang I. S., et al. 2022, p. eprint arXiv:2208.05124

Li H., Gnedin O. Y., 2019, *MNRAS*, 486, 4030

Lim D., Lee Y. W., Pasquato M., Han S. I., Roh D. G., 2016, *ApJ*, 832

Lochhaas C., Thompson T. A., 2017, *MNRAS*, 470, 977

Lotz J. M., Telford R., Ferguson H. C., et al. 2001, *ApJ*, 552, 572

Ma X., Grudic M. Y., Quataert E., et al. 2020, *MNRAS*, 493, 4315

Maio U., Khochfar S., Johnson J. L., Ciardi B., 2011, *MNRAS*, 414, 1145

Maiolino R., Russell H. R., Fabian A. C., et al. 2017, *Nature*, 544, 202

Martin N. F., Ibata R. A., Chapman S. C., et al. 2007, *MNRAS*, 380, 281

Mashchenko S., Sills A., 2005, *ApJ*, 619, 243
 Masters K. L., Jordan A., Cote P., et al. 2010, *ApJ*, 715, 1419
 Mazzuchelli C., Baados E., Venemans B. P., et al. 2017, *ApJ*, 849, 91
 McKee C. F., Ostriker J. P., 1977, *ApJ*, 218, 148
 McKee C. F., Ostriker E. C., 2007, *ARA&A*, 45, 565
 McLaughlin D. E., van der Marel R. P., 2005, *ApJS*, 161, 304
 Meštrić U., et al., 2022, arXiv e-prints, p. arXiv:2202.09377
 Meylan G., Heggie D. C., 1997, *A&ARv*, 8, 1
 Miah J. A., Sharples R. M., Cho J., 2015, *MNRAS*, 447, 3639
 Milone A. P., Piotto G., Renzini A., et al. 2017, *MNRAS*, 464, 3636
 Milone A. P., Marino A. F., Da Costa G. S., et al. 2020, *MNRAS*, 491, 515
 Mo H., van den Bosch F. C., White S., 2010, Cambridge University Press, p. 424
 Moore B., 1996, *ApJ*, 461, L13
 Mowla L. A., Iyer K. G., Desprez G., et al. 2022, p. eprint arXiv:2208.02233
 Mucciarelli A., Bellazzini M., Ibata R., et al. 2017, *A&A*, 605, A46
 Muratov A. L., Gnedin O. Y., 2010, *ApJ*, 718, 1266
 Murray N., Quataert E., Thompson T. A., 2010, *ApJ*, 709, 191
 Naab T., Ostriker J. P., 2017, *ARA&A*, 55, 59
 Nakasato N., Mori M., Nomoto K., 2000, *ApJ*, 535, 776
 Naoz S., Barkana R., 2005, *MNRAS*, 362, 1047
 Naoz S., Narayan R., 2014, *ApJ*, 791, L8
 Neistein E. L. C., Khochfar S., Weinmann S. M., et al. 2011a, *MNRAS*, 416, 1486
 Neistein E., Li C., Khochfar S., et al. 2011b, *MNRAS*, 416, 1486
 Neumayer N., Walcher C. J., Andersen D., et al. 2011, *MNRAS*, 413, 1875
 Neumayer N., Seth A., Boker T., 2020, *A&ARv*, 28, 4
 Oh K. S., Lin D. N. C., 2000, *ApJ*, 543, 620
 Omukai K., 2000, *ApJ*, 534, 809
 Paardekooper J. P., Khochfar S., Dalla C. V., 2013, *MNRAS*, 429, L94

Paardekooper J. P., Khochfar S., Dalla Vecchia C., 2015, MNRAS, 451, 2544

Pancino E., et al., 2017, A&A, 601

Parker E. N., 1966, ApJ, 145, 811

Pavlík V., Vesperini E., 2021, MNRAS, 504, L12

Pavlík V., Vesperini E., 2022, MNRAS, 509, 3815

Pearrubia J., Varri A. L., Breen P. G., et al. 2017, MNRAS, 471, L31

Peebles P. J. E., 1969, ApJ, 155

Peebles P. J. E., 1984, ApJ, 277, 470

Peebles P. J. E., Dicke R. H., 1968, ApJ, 154, 891

Penarrubia J., Varri A. L., Breen P. G., et al. 2017, MNRAS, 471, L31

Peng E. W., Jordán A., Côté P., et al. 2006, ApJ, 639, 95

Penston M. V., 1969, , 144, 425

Perlmutter S., Aldering G., Goldhaber G., et al. 1999, ApJ, 517, 565

Pfeffer J., Kruijssen J. M. D., Crain R. A., et al. 2018, MNRAS, 475, 4309

Pfeffer J., Bastian N., Crain R. A., et al. 2019a, MNRAS, 487, 4550

Pfeffer J., Bastian N., Kruijssen J. M. D., et al. 2019b, MNRAS, 490, 1714

Pfeffer J. L., Trujillo-Gomez S., Kruijssen J. M. D., et al. 2020, MNRAS, 499, 4863

Phipps F., Khochfar S., Varri A. L., Dalla Vecchia C., 2020, A&A, 641, A132

Piotto G., Milone A. P., Bedin L. R., et al. 2015, AJ, 149

Plummer H. C., 1911, MNRAS, 71, 460

Pontzen A., Governato F., 2012, MNRAS, 421, 3464

Popa C., Naoz S., Marinacci F., et al. 2016, MNRAS, 460, 1625

Portegies Zwart S. F., McMillan S. L. W., 2000, ApJ, 528, L17

Portegies Zwart S. F., McMillan S. L. W., Gieles M., 2010, ARA&A, 48, 431

Pozzetti L., Maraston C., Renzini A., 2019, MNRAS, 485, 5861

Prantzos N., Charbonnel C., 2006a, A&A, 458, 135

Prantzos N., Charbonnel C., 2006b, A&A, 458, 135

Prieto J. L., Gnedin O. Y., 2008, ApJ, 689, 919

Rahner D., Pelligrini E. W., Glover S. C. O., Klessen R. S., 2017, MNRAS, 470, 4453

Recio-Blanco A., 2018a, A&A, 620

Recio-Blanco A., 2018b, A&A, 620, A194

Reina-Campos M., Kruijssen J. M. D., 2017, MNRAS, 469, 1282

Reina-Campos M., Kruijssen J. M. D., Pfeffer J., et al. 2018, MNRAS, 481, 2851

Reina-Campos M., Kruijssen J. M. D., Pfeffer J. L., et al. 2019, MNRAS, 486, 5838

Reina-Campos M., Hughes M. E., Kruijssen J. M. D., et al. 2020, MNRAS, 493, 3422

Reina-Campos M., Trujillo-Gomez S., Deason A. J., et al. 2021, p. eprint arXiv:2106.07652

Renaud F., 2018, New Astronomy Reviews, 81, 1

Renaud F., Bournaud F., Duc P. A., 2015, MNRAS, 446, 2038

Renaud F., Agertz O., Gieles M., 2017a, MNRAS, 465, 3622

Renaud F., Agertz O., Gieles M., 2017b, MNRAS, 465, 3622

Renzini A., 2017, MNRAS, 469, L63

Ricotti M., 2002, MNRAS, 336, L33

Ricotti M., Parry O. H., Gnedin N. Y., 2016a, ApJ, 831

Ricotti M., Parry O. H., Gnedin N. Y., 2016b, ApJ, 831, 204

Rieder S., Ishiyama T., Langelan P., et al. 2013, MNRAS, 436, 3695

Rieder S., Dobbs C. L., Bending T. J. R., et al. 2022, MNRAS, 509, 6155

Riess A. G., Filippenko A. V., Challis P., et al. 1998, AJ, 116, 1009

Rodriguez C. L., Morscher M., Pattabiraman B., et al. 2015, Physical Review Letters, 115

Romeo A. B., Agertz O., 2014, MNRAS, 442, 1230

Romeo A. B., Agertz O., Renaud F., 2020, arXiv, p. 2006.09159

Ryon J. E., Bastian N., Adama A., et al. 2015, MNRAS, 452, 525

Saifollah T., Trujillo I., Beasley M. A., et al. 2021, MNRAS, 502, 5921

Saitoh T. R., Koda J., Okamoto T., et al. 2006, ApJ, 640, 22

Sakamoto K., Okumura S. K. ad Ishizuki S., Scoville N. Z., 1999, ApJS, 124, 403

Salpeter E. E., 1955, ApJ, 121, 161

Schaerer D., Charbonnel C., 2011, MNRAS, 413, 2297

Schaye J., Dalla Vecchia C., 2008, MNRAS, 383, 1210

Schaye J., Dalla Vecchia C., Booth C. M., et al. 2010, MNRAS, 402, 1536

Schaye J., Crain R. A., Bower R. G., et al. 2015, MNRAS, 446, 521

Schmidt M., 1959, ApJ, 129, 243

Schweizer F., 1987, Nearly Normal Galaxies. From the Planck Time to the Present. The Eighth Santa Cruz Summer Workshop in Astronomy and Astrophysics, p. 18

Semenov V. A., Kravtsov A. V., Gnedin N. Y., 2017, ApJ, 845, 133

Shapiro K. L., Genzel R., Förster S., Natascha M., 2010, MNRAS, 403, L36

Simioni M., Milone A. P., Bedin L. R., Aparicio A., Piotto G., Vesperini E., Hong J., 2016, MNRAS, 463, 449

Simon J. D., 2019, ARA&A, 57, 375

Simon J. D., Geha M., 2007, ApJ, 670, 313

Simon J. D., Drlica-Wagner A., Li T. S., et al. 2015, ApJ, 808, 95

Somerville R. S., Davé R., 2015, ARA&A, 53, 51

Soto M., et al., 2017, AJ, 153

Spitler L. R., Forbes D. A., 2009, MNRAS, 392, L1

Springel V., 2005, MNRAS, 364, 1105

Springel V., Yoshida N., White S. D. M., 2001, New Astronomy, 6, 79

Springel V., White S. D. M., Jenkins A., et al. 2005, Nature, 435, 629

Tang B., Wang Y., Huang R., et al. 2021, ApJ, 908, id. 220

Tonini C., 2013a, ApJ, 762

Tonini C., 2013b, ApJ, 762, 11

Tremaine S. D., Ostriker J. P., Spitzer L. J., 1975, ApJ, 196, 407

Trenti M., van der Marel R., 2013, MNRAS, 435, 3272

Trujillo-Gomez S., Kruijssen J. M. D., Reina-Campos M., et al. 2021, MNRAS, 503, 31

Tseliachovich D., Barkana R., Hirata C. M., 2011, MNRAS, 418, 906

Tseliakhovic D., Hirata C., 2010, PhysRevD, 82, 083520

Usher C., Pfeffer J., Bastian N., et al. 2018, MNRAS, 480, 3279

Vanzella E., Calura F., Meneghetti M., et al. 2017, MNRAS, 467, 4304

Vanzella E., et al., 2019, MNRAS, 483, 3618

Vanzella E., et al., 2020, MNRAS, 491, 1093

Vanzella E., Adamo A., Annibali F., et al. 2021, p. JWST Proposal 1908 Cycle 1

Vanzella E., Castellano M., Bergamini P., et al. 2022, p. eprint arXiv:2208.00520

Varri A. L., Cai M. X., Concha-Ramírez F., et al. 2018, Computational Astrophysics and Cosmology, 5, 2

Vergara M. Z. C., Schleicher D. R. G., Boekholt T. C. N., et al. 2021, A&A, 649, A160

Verliat A., Hennebelle P., González M., et al. 2022, A&A, 663, A6

Vogel S. N., Kulkarni S. R., Scoville N. Z., 1988, Nature, 334, 402

W. K. A. H., Kroupa P., Baumgardt H., et al. 2010, MNRAS, 401, 105

Wang L., Spurzem R., Aarseth S., et al. 2016, MNRAS, 458, 1450

Webb J. J., Bovy J., 2022, MNRAS, 510, 774

Webb J. J., Vesperini E., 2017, MNRAS, 464, 1977

Weidner C., Kroupa P., Larsen S. S., 2004, MNRAS, 350, 1503

Westmeier T., Staveley-Smith L., Calabretta M., et al. 2015, MNRAS, 453, 338

Whitmore B. C., Schweizer F., 1995, AJ, 109, 960

Whitmore B. C., Zhang Q., Leitherer C., et al. 1999, AJ, 118, 1551

Whitmore B. C., Chandar R., Schweizer F., et al. 2010, AJ, 140, 75

Wiersma R. P. C., Schaye J., Smith B. D., 2009, MNRAS, 393, 99

Wijnen T. P. G., Pols O. R., Pelupessy F. I., Portegies Zwart S., 2016, A&A, 594

Williams J. P., Blitz L., McKee C. F., 2000, Protostars and Planets, p. 97

Woods T. E., Agarwal B., Bromm V., et al. 2019, PASA, 36, 27

Yajima H., Abe M., Khochfar S., et al. 2022, MNRAS, 509, 4037

Yoshida N., Omukai K., Hernquist L., et al. 2006, ApJ, 652, 6

den Brok M., Peletier R. F., Seth A., et al. 2014, MNRAS, 445, 2385

van den Bergh S., 2000, PASP, 112, 932