Tracing the Quenching History in Galaxy Clusters in the EAGLE Simulation

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ABSTRACT

We use the EAGLE hydrodynamical simulation to trace the quenching history of galaxies in its 10 most massive clusters. We use two criteria to identify moments when galaxies suffer significant changes in their star formation activity: i) the instantaneous star formation rate (SFR) strongest drop, $\Gamma_{\text{SFR}}$, and ii) a “quenching” criterium based on a minimum threshold for the specific SFR $\lesssim 10^{-11}$ yr$^{-1}$. We find that a large fraction of galaxies ($\gtrsim 60\%$) suffer their $\Gamma_{\text{SFR}}$ outside cluster viral radius. This “pre-processed” population is dominated by galaxies that are either low mass and centrals or inhabit low mass hosts ($10^{10.5}M_\odot \lesssim M_{\text{host}} \lesssim 10^{11.0}M_\odot$). The host mass distribution is bimodal, and galaxies that suffered their $\Gamma_{\text{SFR}}$ in massive hosts ($10^{13.5}M_\odot \lesssim M_{\text{host}} \lesssim 10^{14.0}M_\odot$) are mainly processed within the clusters. Pre-processing mainly limits the total stellar mass with which galaxies arrive to the clusters. Regarding quenching, galaxies preferentially reach this state in high-mass halos ($10^{13.5}M_\odot \lesssim M_{\text{host}} \lesssim 10^{14.5}M_\odot$). The small fraction of galaxies that reach the cluster already quenched have also been pre-processed, linking both criteria as different stages on the quenching process of these galaxies. For the $z = 0$ satellite populations, we find a sharp rise in the fraction of quenched satellites at the time of first infall, highlighting the role played by the dense cluster environment. Interestingly, the fraction of pre-quenched galaxies rises with final cluster mass. This is a direct consequence of the hierarchical cosmological model used in this simulations.

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

1 INTRODUCTION

Since the first half of the twentieth century, it is well known that galaxy colors reflect the predominant stellar population of galaxies and that is related to their morphology (Morgan & Mayall 1957). Color-morphology (Roberts & Haynes 1994) and color-magnitude relations (Chester & Roberts 1964; Faber 1973) are now widely used to study the properties of galaxies. As a result, rather than selecting objects according to their early- or late-type morphology, galaxies can be separated between red and blue, which naturally relates with their star formation and metal-enrichment history. Studies in the local universe show that, in general, galaxies present a strong bimodal color distribution (Strateva et al. 2001; Baldry et al. 2006; Cassata et al. 2008), regardless of the environment in which they reside (Hogg et al. 2004; Baldry et al. 2006). This suggests different mechanisms driving the evolution of galaxies on each of these regimes (Menci et al. 2005; De Lucia et al. 2007). Reproducing this bimodality, and understanding the role played by the environment, has become an important goal for galaxy-evolution theories (Trayford et al. 2015; Nelson et al. 2018).

One of the first indications that the environment plays a fundamental role in driving the evolution of galaxies was
the morphology-density relation (Dressler 1980, 1984). It is observed that in high density environments there is a greater fraction of galaxies with early-type morphology than in the field, and the fraction of early-type galaxies in clusters rises toward the center (Brough et al. 2017; Cava et al. 2017).

In addition, observations in the last decades show that dense environments can also affect the star formation history of galaxies (Gunn & Gott 1972; Dressler 1980; Moore et al. 1996; Poggianti et al. 2001; Boselli et al. 2005). Naturally, the cores of galaxy clusters are an ideal laboratory to study how the environment affects the evolution of galaxies in dense regions and at various redshifts (Cayatte et al. 1990; Smail et al. 1997; Bravo-Alfaro et al. 2000; Boselli et al. 2005). Evidence of global transformations for galaxies over look-back time is given by the increasing fraction of spiral galaxies in clusters up to z ∼ 0.5 (Dressler et al. 1997; Pasano et al. 2000; Desai et al. 2007) and thanks to the fact that high-z clusters are observed to contain more star-forming galaxies compared to present-day (Butcher & Oemler 1984; Poggianti et al. 2006).

It is also well known that there are differences between the physical and internal properties of galaxies in the inner and outer regions of galaxy clusters. Some authors (Kodama et al. 2001; Treu et al. 2003), suggest that this is a result of a variety of different mechanisms that can act in different regions of the clusters, driving the galaxy evolution in different timescales. Moreover, it is observed (e.g. Dressler et al. 2013; Hou et al. 2014; Bianconi et al. 2018) that in the outer regions of galaxy clusters there are infalling galaxies toward the cluster environment from infalling groups. In addition, theoretical works (e.g. Mc Gee et al. 2009; De Lucia et al. 2012) suggest that ∼ 25–40% of galaxies belonging to a massive cluster (M_{halo} ≈ 10^{14.5}–10^{15.0}(M_\odot)) at z = 0 have been accreted from galaxy groups. In this sense, according to the hierarchical scenario, galaxy groups are thought to be the buildings blocks of today’s rich clusters. For this reason, the study of galaxy properties in the outer regions of clusters, where these systems are still in an assembling process, has captured the interest of the astronomers principally in the last decade (e.g. Just et al. 2010; Cybulski et al. 2014; Jaffé et al. 2016). In particular, some authors (e.g. Hou et al. 2014; Haines et al. 2015; Bianconi et al. 2018) studied the fraction of quiescent galaxies as a function of the distance from the cluster centre and they found a high fraction of quiescent galaxies in the outer region of galaxy clusters even at 3R_{200}. This observational result cannot be explained only by the effect of mechanisms that can act inside clusters, it is necessary that quiescent galaxies in the outer regions of clusters, stopped their star formation within galaxy groups before their infall into the cluster environment, this scenario is known as pre-processing (Zabludoff & Mulchaey 1998; Fujita 2004). Thereby, galaxy groups can constitute a fundamental stage in galaxy evolution thanks to the “pre-processing” of their members before the accretion into the main final cluster. These groups provide another suitable laboratory to study the physical processes that change the morphology and other observable properties of galaxies, such as colour and star-formation rate (e.g. Dressler et al. 2013; Bianconi et al. 2018; Olave-Rojas et al. 2018).

In support of the morphology-density relation, several authors have shown that, at z ∼ 0, the specific star-formation rate of galaxies in dense environments is in general significantly smaller than those observed galaxies located in lower density regions (Hashimoto et al. 1998; Lewis et al. 2002; Kauffmann et al. 2004; Gray et al. 2004; Balogh et al. 2007) and a higher fraction of quiescent or passive galaxies are found in dense regions of the Universe (Poggianti et al. 1999; Baldry et al. 2006; van den Bosch et al. 2008; Gavazzi et al. 2010; Haines et al. 2013). These studies also provide evidences that the star-formation activity and the morphology of the galaxies can be correlated with stellar mass of the galaxy at z ∼ 0. Less massive galaxies also are more susceptible to environmental effects, indicating that the quenching of star formation can be accelerated in dense environments, and that galaxies are quenched as clusters grow hierarchically with cosmic time (De Lucia et al. 2012; Muzzin et al. 2012; Jaffé et al. 2016).

In spite of the strong observed correlation between environment and cessation of formation activity, i.e. “environmental quenching”, it is important to take into account internal processes that can drive galaxy quenching. This process, known as “mass quenching” or “internal quenching”, can arise as a result of, e.g. internal gas consumption, supernova and AGN feedback, star formation feedback or halo gas heating (see e.g. Peng et al. 2010, Efstathiou 2000, Croton et al. 2006, Dekel & Birnboim 2008, Cantalupo 2010). The dominance of one mechanism over the other is where the dichotomy of “nature versus nurture” was born, and has been one of the main subjects of study for extragalactic astronomy in the last years.

According to Oesch et al. (2016), quenching may start shortly after the first appearance of the galaxies, at roughly z ∼ 11, but the environment does not play an important role until z ∼ 1.6, with the environmental quenching rising by a factor of ∼ 3.5 between z ∼ 1.6 and z ∼ 0.9 (Nantais et al. 2016, 2017). Nevertheless, a study of the sSFR and the fraction of star forming galaxies in clusters at z ∼ 1 from the GCLASS survey (Muzzin et al. 2012) shows that the mass quenching dominates over environmental quenching, at least at this redshift. Balogh et al. (2016) using another sample of clusters from GCLASS, found that the quenching of the star formation at z > 1 may be due to different mechanisms than those at z ∼ 0. On one hand, at high redshift, the cessation of the star formation is driven mainly by a combination of gas consumption due to an enhancement of star formation and gas outflows as a result of supernovae and AGN feedback. On the other hand, at low redshift, dynamical mass removal mechanisms (due to environment) may be the main driver for the quenching of galaxies in clusters.

A detailed description of the main mechanisms that lead to environmental quenching is provided by Boselli & Gavazzi (2006). Jaffé et al. (2016) separated these mechanisms in three broad categories:

- Gravitational interactions between galaxies (Toomre & Toomre 1972; Barnes & Hernquist 1996; Walker et al. 1996; Moore et al. 1999);

- Interactions between galaxies and the intra-cluster medium (Gunn & Gott 1972; Abadi et al. 1999; Quilis et al. 2000; Vollmer et al. 2001; Jaffé et al. 2015; Benitez-Llambay et al. 2013);

- Gravitational interactions between clusters and galax-
Quenching history in Galaxy Clusters

Figure 1. Examples of the selection criteria used on this work to determine if a galaxy was processed or quenched, for a random galaxy in our sample. Panel (a) shows the star formation rate against redshift. The red ellipse highlights the strongest drop on the star formation activity, and the blue dashed line correspond to the time of the first infall into the final cluster $R_{200}$. Panel (b) shows the specific star formation rate of the galaxy against redshift. The red solid line shows the critical star formation rate imposed by our selection criteria to define quenched galaxies. The blue dashed line correspond to the first infall into the $R_{200}$. Panel (c) shows the growth of the galaxy stellar mass through cosmic time. The blue star indicates the moment when the processing started. We can see that the growth of the stellar mass is suppressed after the strongest drop, and that the specific star formation rate decreases abruptly after the infall to within $R_{200}$ of the cluster center.

It is precisely because of this complex nature of the environmental quenching that it is difficult to separate the aforementioned processes, and it is expected that at least some of these processes act simultaneously and that they are effective in different overlapping regions of the cluster. Some studies show that the effectiveness of these processes is linked to the galaxy’s clustercentric distance (Moran et al. 2007).

A good approach to study the mechanisms that impact galaxy evolution is through cosmological models (Fujita 2004; Wetzel et al. 2013; Vijayaraghavan & Ricker 2013; Schaye et al. 2015; Nelson et al. 2018). Several works have used simulations to understand the properties of galaxies in different environments, and how their story changes their properties, such as colors, stellar mass and star formation rate (Trayford et al. 2015, 2016; Katsianis et al. 2017; Tescari et al. 2018; Nelson et al. 2018). Hydrodynamical simulations can be used to define and test different criteria that can be used to understand the processes that drive galaxies to be quenched. Simulations also allow us to follow the evolution of galaxies in different environments and the evolution of their properties from $z = 0$ to $z \sim 20$. Since clusters at $z > 1.5$ are difficult to detect due to the fact that they are still in assembling process, simulations are a helpful tool to study the role that environment plays at such high redshift (see e.g. Overzier 2016).

In this paper we use the public database from the state-of-art EAGLE hydrodynamic simulations (Schaye et al. 2015; Crain et al. 2015; McAlpine et al. 2016), to trace the evolution history of the galaxies that belong to the ten most massive clusters at $z = 0$. We aim to identify the environment in which galaxies preferentially cease their star formation and identify signatures that could be used to determine the main physical mechanism leading to the cessation of star formation of cluster satellite galaxies. We compare the results obtained from two different criteria to identify when star formation in galaxies significantly drops. The hydrodynamic simulations of the EAGLE project are perfectly suited for this study since they provide the possibility to study the evolution of galaxies and their properties.

The outline of this paper is organized as follows: in Section 2 we describe the EAGLE simulation, its main characteristics and the main potentialities that it provides for this study. In section 3 we define the two criteria used on this work to locate those moments when the galaxy suffer an important variation in their star formation; in section 4, we describe the results obtained using our two approaches, we put special interest in the environment where these events take place. Finally in section 5 we summarizes our main conclusions and compare our results with both, observational and theoretical works. A brief discussion of some future projects are presented in this section as well.

2 THE EAGLE SIMULATION

The EAGLE project, is a suite of cosmological hydrodynamical N-body simulations. These simulations were run with a modified version of the GADGET-3 code, which is an improved version of GADGET-2 (Springel 2005). All the simulations adopt a flat $\Lambda$CDM cosmology whose parameters were calibrated with the data obtained by the
initially containing 1504 particles, with a mass of $9.70 \times 10^3$ mass of $1.81 \times 10^3$ consists of a periodic box with a volume of $(100\text{cMpc})^3$ from the main simulation, referred to as L100N1504, which in particular, for this work we select our sample of galaxies in the mass range $0.1 \ M_\odot$ - $100 \ M_\odot$, with a Chabrier (2003) initial mass function in the stellar mass function and size-mass relation for galaxies in a mass clusters ($\Omega = 0.693$, $\Omega_m = 0.307$, $\Omega_b = 0.04825$, $\sigma_8 = 0.8288$, $Y = 0.248$ and $h_0 = 67.77 \text{ km s}^{-1}$).

In particular, for this work we select our sample of galaxies from the main simulation, referred to as L100N1504, which consists of a periodic box with a volume of $(100\text{Mpc})^3$, initially containing $1504^3$ gas particles, with an initial mass of $1.81 \times 10^6 \ M_\odot$ and the same amount of dark matter particles, with a mass of $9.70 \times 10^9 \ M_\odot$.

Each simulation counts with 29 discrete snapshots from redshift 20 to 0, with a time span ranging from 0.3 to 1Gyr. Radiative cooling and photoheating are implemented following Wiersma et al. (2009a), assuming an optically thin X-Ray/UV background (Haardt & Madau 2001). Star formation is implemented stochastically, following Schaye & Dalla Vecchia (2008) and using the metallicity-dependent density threshold shown in Schaye (2004). This reproduces the observed Kennicutt-Schmidt law (Kennicutt 1998). Each particle is assumed to be a single age stellar population, with a Chabrier (2003) initial mass function in the range $0.1 \ M_\odot$ - $100 \ M_\odot$.

Stellar evolution is modelled as shown in Wiersma et al. (2009b), chemical enrichment is produced by the 11 elements that most contribute to radiative cooling from massive stars (Type II supernovae and stellar winds) and intermediate-mass stars (Type Ia supernovae and AGB stars). Following Dalla Vecchia & Schaye (2008) the thermal-energy product of stellar feedback is stochastically distributed among the gas particles surrounding the event without a preferential direction.

The EAGLE project calibrated the free parameters associated with stellar feedback to match the observations for stellar mass function and size-mass relation for galaxies in a range of $10^9 \ M_\odot$ - $10^{11} \ M_\odot$. (Furlong et al. 2015, 2017).

The appropriate calibration of the subgrid physics and the good agreement with the observational data make these simulations our best tool to study the evolution in the star formation of galaxies in these mass ranges for different environments.

### 3 THE END OF THE STAR FORMING PHASE: DEFINITIONS

According to Peng et al. (2010), the quenching of a galaxy is the result of a process with two different components. A continuous component associated with internal galactic process such as star formation and AGN feedback, and a “once-only” component due to environmental processes. Note, however, that other mechanisms like mergers may also have an important effect on the star formation activity.

To determine the moment when the star formation activity in a galaxy drops in a significant way, two different criteria are introduced; one based on the maximum drop of the SFR between two consecutive snapshots of the simulation, and the other based on a minimum threshold for specific star formation rate (sSFR). The first criterion seeks to identify the mechanisms that abruptly reduce star formation in galaxies, while the second one is meant to define when a galaxy is actually quenched, that is, it is no longer forming stars (e.g. Weinmann et al. 2010; De Lucia et al. 2012; Wetzel et al. 2012). The aim of using these two definitions of quenched galaxy is to clearly determine the main mechanisms that affect the evolution of the star formation and the role played by the environment in quenching.

#### 3.1 SFR Strongest Drop

One of our goals is to identify the mechanisms that can abruptly reduce the star formation of galaxies. For this purpose, we first calculate for each galaxy the variation of the star formation rate between two different snapshots on the simulation, normalized by the star formation in the earliest

**Figure 2.** Distribution of $\Gamma_{\text{SD}}$ (normalized instantaneous strongest drop of the SF activity), as function of the redshift when it takes place. Blue dots correspond to galaxies that suffer their $\Gamma_{\text{SD}}$ outside the cluster R200 (pre-processed), while red dots to those that suffer their $\Gamma_{\text{SD}}$ inside R200 (processed in-situ). The median for both samples are indicated by the dashed lines. The boxes are separated from left to right as high mass clusters $(14.6 < \log_{10} M_{\text{host}} [M_\odot] < 14.8)$, intermediate mass clusters $(14.3 < \log_{10} M_{\text{host}} [M_\odot] < 14.6)$ and low mass clusters $(14.0 < \log_{10} M_{\text{host}} [M_\odot] < 14.3)$ respectively.
Figure 3. Mass distribution of galaxies and their hosts at key moments related to the to the $\Gamma_{\text{SD SFR}}$. Each row shows the results obtained after stacking the distribution of galaxies associated to clusters within different mass ranges. Column (a) shows the mass distribution of the host of each galaxy at the moment of their $\Gamma_{\text{SD SFR}}$. Column (b) shows the total mass distribution of the galaxies at their $\Gamma_{\text{SD SFR}}$. Column (c) shows the baryonic mass fraction distributions at $\Gamma_{\text{SD SFR}}$. Column (d) shows stellar mass distribution of galaxies at the time of their first infall into the cluster they belong at $z = 0$. Blue, red and greed bars correspond to galaxies pre-processed, in-situ processed, and processed as centrals, respectively. The dashed lines indicate the median of each distribution.

\[ \Gamma_{\text{SFR}} = \frac{\text{SFR}_{i+1} - \text{SFR}_i}{\text{SFR}_i}, \]  

where the subindex $i$ indicates the simulation snapshot. $\Gamma_{\text{SFR}}$ is computed only if the SFR value in both snapshots is larger than $1 \times 10^{-3} \text{M}_\odot \text{yr}^{-1}$. This is done to avoid divergence or spurious drops on the value of $\Gamma_{\text{SFR}}$. We then define $\gamma_{\text{SD}}$ as the moment when the strongest drop occurs, i.e.

\[ \gamma_{\text{SD}} = \max \Gamma_{\text{SFR}}. \]  

We refer to this method as the “Strongest drop selection criterion”. $\gamma_{\text{SD}}$ takes into account the moments when a “once-only” event affects the star formation activity of the galaxies but does not take into account any rejuvenation scenario that could take place afterwards. For this reason, it is not a good tracer of definitive quenching. However, the information gathered by this criterion allows us to find the epochs in which the galaxy suffers a “processing” event, in particular the most significant one. An example of this selection criterion is shown in Figure 1, panel (a), where we plot, as a function of time, the star formation rate of a random galaxy in our sample. The red ellipse highlights the moment when $\gamma_{\text{SD}}$ takes place. In particular for this galaxy, the $\gamma_{\text{SD}}$ is the result of several processes that heat and remove its cold gas content, producing an stagnation in the evolution of the stellar mass and a small decrease in the total gas mass of the galaxy. Unfortunately, we cannot isolate the different mechanisms that produce this processing event due to the lack of temporal resolution. We will further explore this in a future work using a better suited simulation.

3.2 Critical sSFR criterion

In addition, we wish to define a criterion that aims to identify the moment when the galaxies reach a definitive state of “quenching”. Several different definitions of “quenched galaxy” have been proposed in the literature. Here we used the criterion used in Wetzel et al. (2013). According to this criterion, a galaxy can be considered effectively quenched once it reaches an $s\text{SFR}^Q = 10^{-11} \text{[yr}^{-1}]$. At this point the galaxy is considered to be passive. From now on we will refer as “quenched galaxies” to those galaxies with an $s\text{SFR}$ lower than $s\text{SFR}^Q$, and we will call this selection criterion “Critical sSFR Selection Criterion”. When using this semi-observational definition, we will only focus on galaxies that are quenched at redshift $z = 0$. This is to ensure that the selected galaxies will not suffer a rejuvenation process during their evolution. From each of our quenched galaxies, we
will extract information about the environment and the time when the quenching state is reached.

An example of this selection criterion is shown in Figure 1, panel (b), where the sSFR is shown for the same galaxy from the previous example as a function of time. The red line indicates the sSFR threshold established in previous works (Weinmann et al. 2010; De Lucia et al. 2012; Wetzel et al. 2012, 2013) for passive galaxies. In particular for the galaxy shown in the example, the critical star formation is reached once it crosses the $R_{200}$ of the cluster for the first time, showing the importance of dense environments in the quenching of the star formation.

4 RESULTS

We wish to study the dependencies of star formation quenching on environmental processes and in galaxies internal physics, focusing on dense environments such as those that can be found on galaxy clusters. For this it is necessary to characterize the properties of individual galaxies such as stellar mass, specific star formation rate (sSFR), gas fraction, total mass and colors, as well as the overall properties of the host cluster such as total mass and virial radius. We will study how these properties evolve as a function of look-back time and focus on those moments where individual galaxies experience sharp falls in their star formation rates.

As previously discussed in Section 1, in this work we focus on the population of galaxies associated with the 10 most massive clusters of the EAGLE simulations. To increase the statistics in the properties of these galaxies as a function of mass, the clusters where stacked in three different bins according to their total mass at $z = 0$:

- high mass: $14.6 < \log_{10} M_{\text{host}} [M_\odot] < 14.8$,
- intermediate mass: $14.3 < \log_{10} M_{\text{host}} [M_\odot] < 14.6$,
- low mass: $14.0 < \log_{10} M_{\text{host}} [M_\odot] < 14.3$.

We will refer to these three categories as HMC, IMC and LMC, respectively. The number of cluster that fall on each bin are 2 for the HMC, 5 for the IMC and 3 for the LMC. In this section we present our results based on the two previously defined criteria to identify the time at which the star formation activity of a galaxy is significantly altered. From now on, we will refer to as “pre-processed galaxies”, those galaxies that suffer sharp decreases in their star formation rate, or ceased their star formation activity, before being accreted into the main cluster. On the other hand, galaxies
that satisfy those conditions inside the cluster viral radius will be referred to as “processed in-situ”.

4.1 Strongest Drop Selection Criterion

We first focus on abrupt changes of the SFR activity. We start by computing $\Gamma_{\text{SD,SFR}}$ for all galaxies that belong to the 10 most massive clusters at $z = 0$. Our goal is to asses where and when they suffer their most significant processing event. The total number of galaxies in the HMC, the IMC and the LMC bins are $N_{\text{gal}} = 846$, $N_{\text{gal}} = 1430$ and $N_{\text{gal}} = 421$, respectively. Note that the differences in the number of galaxies is mainly due to the number of clusters that fall in each mass bin.

In Figure 2 we show $\Gamma_{\text{SD,SFR}}$ for all galaxies as a function of the redshift when this event takes place. The blue and red dots correspond to pre-processed and in-situ galaxies, respectively. The different panels show the results for the different mass bins. We can clearly see that, for the pre-processed population, there is no preferential redshift for $\Gamma_{\text{SD,SFR}}$ to take place. Note as well that there is no clear correlation between redshift and the typical value of $\Gamma_{\text{SD,SFR}}$ for both populations. This indicate that these “once-only” events that significantly affect star formation activity are not associated to any preferential epoch.

In all mass bins, the majority of the galaxies have been pre-processed. Interestingly, for in-situ processed galaxies, $\Gamma_{\text{SD,SFR}}$ typically occurs at lower values of redshift than for pre-processed galaxies. This can be seen from the dashed vertical lines, which indicate the median redshift for each population. Note as well that the pre-processed fraction grows with the mass of the clusters, but the median in redshift for pre-processing remains the same regardless of the mass bin. This shows that, even though more massive clusters accrete a greater number of pre-processed galaxies, the redshift at which $\Gamma_{\text{SD,SFR}}$ typically takes place is independent of the mass of clusters in which galaxies reside at $z = 0$.

To understand how the pre-processing affects the evolution of galaxies and which is the role played by the environment, we characterize the mass distribution of the hosts on which these galaxies resided when they suffer their $\Gamma_{\text{SD,SFR}}$. On Figure 3, panels a), we show the fraction of pre-processed galaxies against the mass of the host halo, $M_{\text{host}}$, at the time of $\Gamma_{\text{SD,SFR}}$. Note that we also include central galaxies in this analysis. On these cases, the mass of the host represents the mass of the galaxy itself. We can clearly see two well separated populations on these distributions, one corresponding to the pre-processed (blue bars) population and the another corresponding to the in-situ processed population (red bars). The median $M_{\text{host}}$ of each population is indicated with dashed lines. As we can see, according to the criteria $\Gamma_{\text{SD,SFR}}$, pre-processing tends to happen in low mass halos, preferentially in halos with a total mass between $10^{10.5} \lesssim M_{\text{host}}[M_\odot] \lesssim 10^{11.0}$. On the other hand, the processing in-situ preferentially occurs in higher mass halos, with a total mass between $10^{11.5} \lesssim M_{\text{host}}[M_\odot] \lesssim 10^{12.0}$.

To explore this relation between $\Gamma_{\text{SD,SFR}}$ and environment we compute, for the overall processed galaxy population, the distribution of total mass ($M_{\text{galaxy}}$) and the baryonic mass fraction ($M_{\text{baryon}}/M_{\text{galaxy}}$), at the time they suffer their $\Gamma_{\text{SD,SFR}}$. These are shown on panels b) and c) of Figure 3, respectively. In general we find that in-situ processed galaxy tend to have a marginally larger $M_{\text{galaxy}}$ than pre-processed galaxies. Interestingly, the difference in ($M_{\text{baryon}}/M_{\text{galaxy}}$) for these two populations is significantly more clear, with the pre-processed galaxies showing the lowest baryonic mass fractions. This is in agreement with the results shown in Figure 2, where we show that $\Gamma_{\text{SD,SFR}}$ for the in-situ population occur at lower redshift, thus giving more time for these galaxies to grow in mass. Note as well that there is a strong preference for pre-processing to occur in galaxies when they still remain as centrals, as shown by the green bars. As expected for central galaxies, the $M_{\text{host}}$ and $M_{\text{galaxy}}$ distributions are the same. On Figure 3, panels d), we show the distribution of stellar mass ($M_\star$) for all galaxies at the time of the first $R_{200}$ crossing. We can clearly see that the difference in $M_\star$ between in-situ and pre-processed galaxy is not only present at the time of $\Gamma_{\text{SD,SFR}}$, but pre-processed galaxies tend to arrive to the cluster with a significantly lower stellar mass. These results suggest that one of the strongest effect associated with these pre-processing is to limit the final stellar mass of satellites in galaxy clusters. As an example, in Figure 1, panel c), we show how the $\Gamma_{\text{SD,SFR}}$ significantly affects the subsequent growth of $M_\star$ on this galaxy.

It is clear from this figure that centrals dominate the population of pre-processed galaxies. Isolated and low mass galaxies can suffer from several mechanisms that can significantly affect their star formation history and current activity. Examples are photo-reionization, which limits their gas reservoir to star form (Hopkins et al. 2014; Chan et al. 2018), or supernova feedback which, thanks to the injection of large amounts of kinetic energy into the intergalactic medium, can eject significant fractions of the available gas (Dekel & Silk 1986; Davé et al. 2011; Biernacki & Teyssier 2018). In addition, as shown by Benítez-Llambay et al. (2013), ram-pressure stripping from the gas distribution within the cos-
mic web can efficiently remove the gas content of isolated low mass galaxies. Pre-processing on galaxies that were not central at the time of $\Gamma_{\text{SD SFR}}$ is generally associated with ram pressure stripping within the corresponding host. However, Figure 3 shows that the environment associated with a massive host galaxy plays a minor role in the pre-processing of low-mass galaxies.

As discussed before, the fraction of galaxies processed in-situ is rather low ($\lesssim 30\%$), and these galaxies tend to be more massive than the pre-processed population at the time of their corresponding $\Gamma_{\text{SD SFR}}$. Their most significant drop in star formation activity took place within the $R_{200}$ of the main cluster. Thus, the main mechanisms acting are tidal and ram pressure stripping within the cluster itself. These highlights the role played by the denser environments associated with galaxy clusters.

There is a small fraction of pre-processed galaxies for which $\Gamma_{\text{SD SFR}}$ takes place on high mass halos different from the main cluster. These haloes correspond to objects that belong to massive galaxy-groups, in the mass range of $10^{13.5} M_\odot \lesssim M_{\text{host}} \lesssim 10^{14.0} M_\odot$, that are later accreted into the main cluster.

### 4.2 Critical sSFR Selection Criteria

In Section 4.1 we focused on the the properties of galaxies when they suffer their strongest drop in their star formation, $\Gamma_{\text{SD SFR}}$. These drops do not need to be correlated with a cease in star formation activity. Rather, as shown in Section 4.1, on average pre-processed galaxies arrive to the galaxy cluster with a significantly lower stellar mass than those galaxies processed in-situ. Thus, instead than cease the star formation activity, an early $\Gamma_{\text{SD SFR}}$ constrains the final galactic stellar mass.

In this Section we will focus on the moment when galaxies become effectively quenched. Within $R_{200}$ of each cluster, we search for galaxies with sSFR values lower than $\text{sSFR}^Q$, defined in Section 3.2, and track their specific star formation history to identify the moment when this threshold is crossed. As before, we separate our galaxy sample in three bins according cluster mass. The number of quenched galaxies in each bin is $N_{\text{gal}} = 780$, 1282 and 374 for the HMC, IMC and LMC, respectively. Note that, in general, the number of quenched galaxies on each bin is $\lesssim 12\%$ smaller than those that have suffer some type of processing.

On the left panels of Figure 4 we show the distribution of host mass associated to each galaxy at the time they became quenched. As before, for galaxies that quenched while being centrals (green bars), this mass corresponds to their own halo mass. Contrary to what is found with the $\Gamma_{\text{SD SFR}}$ criteria, we find that, independently of the cluster mass bin, the vast majority of galaxies become quenched within massive hosts with $10^{13.5} \lesssim M_{\text{host}}[M_\odot] \lesssim 10^{14.5}$. This highlights the important role played by the denser environment of massive clusters on the overall quenching of its galaxy members. As an example we show, in Figure 5, the time evolution of the sSFR of a handful for galaxies as they approach the central galaxy of one of our clusters. The dashed lines show the time evolution of the clusters $R_{200}$ and the color bar the sSFR of each galaxy. Note that, as they approach the cluster, their sSFR slowly decreases. However, the change in sSFR just after the first $R_{200}$ crossing is significantly more abrupt, in some cases rapidly resulting in quenching. On the other hand, galaxies that quenched in low mass halos, i.e. $10^{10.0} \lesssim M_{\text{host}}[M_\odot] \lesssim 10^{11.0}$, did it as centrals, highlighting the regime where internal quenching processes are most relevant.

The red bars on Figure 4 indicate the distributions of the in-situ quenched galaxies population. Interestingly, we find that the fraction of galaxies that arrived to the cluster already quenched (i.e., pre-quenched population) decreases with cluster mass. For comparison we find 73% of the galax-
ies were quenched in-situ in the LMC bin, but only 45% in the HMC bin. This apparent relation between fraction of pre-quenched galaxy with cluster mass is further explored below. As in the case of the SFR criteria, we find the total mass distribution of pre and in-situ quenched galaxies to be very similar (medium left panels), but they show a significant offset on their stellar masses at the moment of quenching (medium right panels). As expected, we find that most pre-quenched galaxies (~95%) have also been pre-processed, indicating the important role played by the pre-processing on the quenching of low-mass objects. The right panels of Figure 4 show the distribution of quenching times. We find a preference for in-situ quenched galaxies to become so at later times. However this difference is only of the order of 1 to 2 Gyr.

In Figure 6 we show the time evolution of the cumulative fraction of quenched galaxies, Nq/NTot, as function of cluster centric distance. Here, Nq represent the number of quenched galaxies within a given radius, R, and NTot the total number of galaxies within the same distance. The different lines correspond to the different cluster mass bins.

Interestingly we see that at early times, between z = 1 and z ~ 0.5, the fraction of quenched galaxies grows towards the cluster outskirts. However, at later time this trend reverses, showing a decreasing fraction of quenched galaxies with distance. During the last decade surveys such as WINGS (Cava et al. 2017) and SAMI (Brough et al. 2017) have shown that:

(i) the fraction of quenched galaxies grows towards z = 0. This is attributed to the environment having more time to act on the galaxies within a cluster.

(ii) the fraction of quenched galaxies decreases with cluster centric distance. Thanks to the denser environments that can be found in the inner cluster region, galaxies, specially those with lower masses, can be more efficiently depleted of their gas reservoir.

Our results are in good agreement with these observations. We have previously highlighted a correlation between the fraction of pre-quenched galaxies and cluster mass. We further explore this correlation on Figure 7. Here we show how the cumulative fraction of quenched galaxies, with respect to the total number of all galaxies that can be found within R200 at z = 0, grows as a function of the normalized time, t − t_{infall}. To obtain this plot we first compute, for each galaxy within R200 at z = 0, the time when they crossed R200 for the first time. Second, for each galaxy we define the variable t − t_{infall} and identify the moment when it became quenched on this new time scale. Finally, we compute the cumulative quenched galaxy fraction as a function of t − t_{infall}. This figure allows us to study how the fraction of quenched galaxies changes as a function of the time they remain either outside (negative t − t_{infall}) or inside (positive t − t_{infall}) the cluster R200. The different lines are associated to the galaxy populations of different cluster. The colors indicate the mass of each cluster at z = 0. Note that, in all clusters, the fraction of quenched galaxies slowly grows as they approach the cluster R200, again highlighting the role of pre-processing. Interestingly, there is an abrupt change in the slope of this cumulative function around the time of the first R200 crossing, i.e. −1 Gyr ≤ t − t_{infall} ≤ 1 Gyr. During this period, the fraction of quenched galaxies raises more rapidly than during any other epoch. This is in agreement with the behaviour of the sSFR observed in Figure 5, and clearly displays the role played by the cluster environment. We can also observe a large dispersion on the fraction of galaxies that arrive quenched to the cluster R200, with values that go from 20 to 60%. More importantly, this fraction shows a dependency with final cluster mass, with larger values for more massive clusters.

To study the origin of this trend we compute the mass distribution of the structures, M_{host}, where the quenched galaxy population at z = 0 were located at the moment just before their first R200 crossing. This is shown on Figure 8, panels a). As before, each row corresponds to the results obtained from a different cluster mass bin. The blue bars indicate the fraction of pre-quenched galaxies, while the white bars shows all the quenched galaxies found within the cluster at z = 0. The dashed lines indicate the median for the pre-quenched population. Interestingly, pre-quenched galaxies on the LMC bin tend to arrive on lower mass structures than in the rest of the cluster mass bins. However, no significant difference is observed on both the distribution of total (M_{galaxy}) and stellar masses (M_{*}) of the pre-quenched galaxy populations at infall, shown in panels b) and c), respectively.

Our results indicate that the larger fraction of pre-quenching in larger mass clusters is the result of the hierarchical nature of the CDM cosmological model used in this work, in which larger mass object can accrete more massive substructures. These more massive the substructures are naturally more efficient on quenching their own galaxy satellite population, thus resulting on larger fraction of pre-quenching at z = 0.

5 DISCUSSION AND CONCLUSIONS

On this paper we have presented our study of the different environmental-quenching and processing scenarios undergone by the satellite galaxies of the ten most massive
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Figure 8. Mass distribution of galaxies and their hosts at the moment before crossing the clusters $R_{200}$. Each row shows the results obtained after stacking the distribution of galaxies associated to clusters within different mass ranges. Column (a) shows the mass distribution of the host of each galaxy. Column (b) shows distribution of galaxies total mass. Column (c) shows the distributions of stellar mass. The blue bars correspond to the galaxies quenched before the first infall and the white bars correspond to all galaxies in our sample. Dashed lines correspond to the median of the pre-quenched population.

clusters in the state-of-the-art EAGLE hydrodynamical simulation. Two different criteria were defined to explore the different processes that significantly affect the SFR of these galaxies along their history. Our goal is to quantify and characterize the role played by environment on these processes.

For the instantaneous strongest drop in SFR, we find that the majority of galaxies suffer their $\Gamma_{SD}^{\text{SFR}}$ outside the clusters $R_{200}$ (pre-processing $\gtrsim 60\%$). This fraction grows with cluster mass. We find that there is no correlation between the strength of the $\Gamma_{SD}^{\text{SFR}}$ and the time at which occurs, nor a preferential redshift for this process to occur. Nonetheless, for galaxies processed in-situ, $\Gamma_{SD}^{\text{SFR}}$ tends to happen at lower redshift than for the pre-processed population. In terms of the environment, while in-situ processing mainly occurs on massive hosts, pre-processing shows a strong preference to take place in galaxies that are either low mass and central or in low mass hosts, i.e. $10^{10.5}M_\odot \lesssim M_{\text{host}} \lesssim 10^{11.0}M_\odot$. Our results are in good agreement with those published by Bianconi et al. (2018), which observationally studied a sample of 23 massive clusters ($M_{200} = 10^{15.0}[M_\odot]$) with 34 infalling groups ($\log_{10}M_\star [M_\odot] = 10.75$), which are located in outer cluster regions. They found that at cluster centric distances $R \sim 1.3R_{200}$ the fraction of star-forming galaxies in infalling groups is half of that in the clusters. According to this, Bianconi et al. (2018) suggest that the pre-processing in groups is the responsible for these results.

Interestingly, for galaxies with similar total mass, at the time of arrival to the main cluster, the in-situ processed population shows in general a larger stellar mass than those pre-processed. This highlights the important role of pre-processing on limiting the star formation activity of low mass galaxies. The origin of this pre-processing event can be explained by a variety of different internal mechanisms such as supernovae feedback, photo-reionization, interactions and starburst-phases. Unfortunately, due to the poor time resolution available in this simulation, it is hard to identify what
is the main mechanism acting on each galaxy. In addition, ram-pressure from the cosmic web can also cause an accelerated depletion of the gas reservoirs on low mass galaxies, producing abrupt changes in their star formation (Benítez-Llambay et al. 2013).

In the case of the Critical sSFR criteria, contrary to our results for $t_{\text{SDSFR}}$, we find that quenching presents a strong preference for high mass halos to take place. This is a strong indicator that dense environments promote the definitive cessation of the star formation. Our results are in agreement with the observations presented by Olave-Rojas et al. (2018), who finds that the fraction of high-mass ($M_\star \geq 10^{10.5} [M_\odot]$) red (i.e. passive) galaxies in clusters (i.e. quenched in-situ) is higher than the fraction of high-mass red galaxies in accreted groups (i.e. pre-quenched). We find that most of the pre-quenched galaxies ($\gtrsim 95\%$) have also been pre-processed, evidencing the importance of pre-processing in the quenching of low mass galaxies. In general we find a slight preference for pre-quenching to take place at earlier times than quenching in-situ. The difference in the median of the quenching time distribution is only of the order of 1 to 2 Gyr. As a function of clustercentric distance, close to $z = 0$ the fraction of quenched galaxies grows toward the cluster center. This is in good agreement with the results obtained from observational studies based different surveys such as WINGS (Cava et al. 2017) and SAMI (Brough et al. 2017). However, at earlier times, between $z \sim 1$ and $z \sim 0.5$, this trend reverts, showing a fraction of quenched galaxies that grows towards the cluster outskirts.

In general, we find that in comparison to the in-situ quenched population, on average pre-quenched galaxies have lower stellar-masses. This result appears in disagreement with those presented by Hou et al. (2014) who found that, independent of the mass of galaxies, the fraction of quiescent galaxies is higher in groups than in the clusters and field. However, we can reconcile our findings with those of Hou et al. (2014) by noting that these authors only studied galaxies with stellar masses in the range $9.5 < \log_{10} M_\star [M_\odot] < 10.5$ and with $10^{12.0} \lesssim M_{\text{halo}} [M_\odot] \lesssim 10^{14.0}$. In these massive and dense substructures the environmental quenching effects are stronger.

We find a sharp rise in this fraction at the time of the first infall, highlighting the role played by the dense cluster environment. It is interesting to note that, although galaxies prefer denser environments to reach their quenching state, the fraction of pre-quenched galaxies in our sample grows with the total mass of the cluster at $z = 0$. We find that 73% of galaxies were quenched in-situ in the low-mass clusters, but only 45% were quenched in-situ for the high-mass clusters. To explain why high-mass clusters show higher fractions of pre-quenched galaxies, we explore the mass distribution of the structures where the cluster satellite galaxies reside at the moment of accretion. We find that high-mass clusters preferentially accrete their satellites through structures and groups that are significantly more massive than accreted by low-mass clusters. This is a direct consequence of the hierarchical cosmological model used in this simulations. More massive cluster tend to accrete more massive substructures. Due to their own intracluster dense environments, these massive substructures arrive to the clusters with their satellite population already quenched.

Cora et al. (2018a) explored the quenching time of galaxies, and the relevance of the environment on this process, using the semi-analytic model SAG (Cora et al. 2018b). A similar criteria to our sSFR threshold was imposed. According to their results, environmental effects dominate the star formation quenching of low-mass satellite galaxies ($M_\star < 10^{10.1} [M_\odot]$). These results are in good agreement with our results. Panels a) and c) of Figure 4 show that we also find an important fraction of low stellar mass galaxies that are quenched within the cluster $R_{200}$. Note that a significant fraction of the low-mass star galaxies that arrive in the cluster as quenched galaxies were actually quenched in the dense environments of massive groups. This exemplifies the relevance of the environment in the quenching of the clusters satellite population.

We also find a that there is fraction of low-mass star mass galaxies that are quenched as centrals. According to Benítez-Llambay et al. (2013), this can be explained through a combination of different mechanisms that are acting simultaneously on dwarf galaxies. Processes such as supernovae feedback and photo-reionization can reheat the cool gas of these galaxy inducing the quenching of their star formation activity, an scenario commonly referred to as mass quenching. In addition, as previously discussed, ram-pressure stripping taking place within the cosmic web filaments can also deplete the gas reservoir of dwarf galaxies, producing a quenching state due to the environment.

Unfortunately, due to the limited number of snapshots available in the simulation, we do not have the capabilities to separate and distinguish the different overlapping processes that are influencing the star formation history of the galaxies. In a follow-up project we plan to explore these different mechanisms using more detailed hydrodynamical simulations from the C-EAGLE project, which possess better temporal resolution, of 125 Myr Barnes et al. (2017). Since these simulation suite also counts with a sample of 30 clusters with a $M_{200}$ in the range between of $10^{13.5} < M_{200} [M_\odot] < 10^{15.5}$, this study will also allow us to explore in more detail the dependency between cluster mass and fraction of pre-quenched galaxies.

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