The strong correlation between post-starburst fraction and environment

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ABSTRACT
We examine a magnitude limited ($M_B \leq -18.7$) sample of post-starburst (PSB) galaxies at $0.03 < z < 0.11$ in the different environments from the spectroscopic data set of the Padova Millennium Galaxy Group Catalog and compare their incidence and properties with those of passive (PAS) and emission line galaxies (EML). PSB galaxies have a quite precise life-time ($<1 - 1.5\,$Gyr), and they hold important clues for understanding galaxy evolution. While the properties (stellar mass, absolute magnitude, color) of PSBs do not depend on environment, their frequency increases going from single galaxies to binary systems to groups, both considering the incidence with respect to the global number of galaxies and to the number of currently+recently star-forming galaxies. Including in our analysis the sample of cluster PSBs drawn from the WIdefield Nearby Galaxy-cluster Survey presented in Paccagnella et al., we extend the halo mass range covered and present a coherent picture of the effect of the environment on galaxy transformations. We find that the PSB/(PSB+EML) fraction steadily increases with halo mass going from 1% in $10^{11}M_\odot$ haloes to $\sim 15\%$ in the most massive haloes ($10^{15.5}M_\odot$). Our analysis does not allow us to definitely identify the main mechanisms responsible for the appearance of the PSB spectrum. However, the higher incidence of PSB galaxies in the densest environments suggests that the processes operating in the most massive haloes, such as ram pressure stripping, are more effective in producing such population than the processes operating in the sparest environments, most likely galaxy interactions.

Key words: galaxies: general — galaxies: formation — galaxies: evolution — galaxies: groups: general

1 INTRODUCTION

Post-starburst galaxies are a distinct class of objects, whose main spectroscopic characteristics are strong Balmer absorption lines with a lack of emission lines due to star formation. They were identified for the first time by Dressler & Gunn (1983) and, since then, they have been largely analyzed also through extensive spectrophotometric modeling (e.g. Couch & Sharples 1987; Newberry, Boroson & Kirshner 1990; Poggianti & Barbaro 1996; Abraham et al. 1996; Poggianti & Barbaro 1997; Bekki, Shioya & Couch 2001; Poggianti 2004; Poggianti et al. 2004). The physical explanation for the post-starburst spectra is that these galaxies had a large burst of star formation (or had at least active star formation, in the weakest cases) at some point during the $\sim 1\,$Gyr before the time of observation and then suddenly quenched, showing very little ongoing star formation (Couch & Sharples 1987). The stellar population in these galaxies is old enough that the massive, short-lived O- and B-stars have all died (showing no nebular emission lines), and young enough that A-stars dominate the optical spectrum (showing strong Balmer absorption). Given their properties, different studies have suggested different origins for the post-starburst galaxies. It has been proposed that these objects are in a transitional stage between star-forming blue cloud galaxies and quiescent red sequence galaxies (e.g. Caldwell et al. 1996; Zabludoff et al. 1996; Norton et al. 2001; Pracy et al. 2009; Zwaan et al. 2013; Yesuf et al. 2014; Pattarakijwanich et al. 2016; Paccagnella et al. 2017) and there-

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fore might be closely related to the “green valley” galaxies. Nonetheless, not all green valley galaxies have the spectroscopic signature of post-starburst galaxies (e.g. Wong et al. 2012; Vulcani et al. 2015). These galaxies may also represent a key stage in the formation of a large fraction of the passive population (Wild et al. 2016), be rejuvenating from the quiescent population (e.g. Dressler et al. 2013; Abramson et al. 2013) or returning to the star forming population (Rowlands et al. 2015; French et al. 2015; Wild et al. 2016).

Two main scenarios have been proposed to explain the formation of post-starburst galaxies, which most likely describe their existence in different environments.

The first scenario justifies the presence of post-starbursts in clusters, where Dressler & Gunn (1982) first observed them, hypothesizing that they lay exclusively in over-dense regions. In this picture, the main mechanism is a cluster-related process such as ram-pressure stripping. Gas-rich star-forming galaxies fall into clusters and their gas is removed by the interaction with the hot intra-cluster medium, suddenly quenching their star formation (Dressler & Gunn 1982; Couch & Sharples 1987; Dressler & Gunn 1992; Poggianti et al. 1999; Balogh, Navarro & Morris 2000; Tran et al. 2003, 2004, 2007; Poggianti et al. 2009; Paccagnella et al. 2017). The resulting post-starburst galaxies would still resemble disk galaxies, since nothing apart from gas loss would disturb their morphologies. This explanation holds also for post-starburst galaxies in massive groups, where ram pressure is still effective (e.g. Poggianti et al. 2009).

The second scenario was introduced to explain the presence of post-starburst galaxies in lower density regions such as poor groups and the field (Blake et al. 2004; Goto 2005; Zabludoff et al. 1996; Quintero et al. 2004). These galaxies might be associated with galaxy interactions, mergers or AGN feedback (Bekki, Shioya & Couch 2001; Quintero et al. 2004; Blake et al. 2004; Goto 2005; Hogg et al. 2006; Coil et al. 2011; Mahajan 2013; Trouille et al. 2013; Yesuf et al. 2014). In this picture, when gas-rich galaxies go through a merger phase, the gas is disturbed and collapses form stars, leading to a large scale starburst. The same disturbance also channels the gas to the galactic center, resulting in both a central starburst and AGN activity. Then, either the galaxies run out of gas and stop forming stars, or the rest of the gas receives enough heating from supernova or AGN feedback that it becomes too hot to collapse further or is expelled altogether. Either way, these galaxies go through a starburst phase that stops quickly. Within this picture, their morphologies should be disturbed and show prominent signs of recent interactions such as tidal tails (Zabludoff et al. 1996; Yang et al. 2004; Yang, Mo & van den Bosch 2008; Blake et al. 2004; Tran et al. 2004; Goto 2005; Pracy et al. 2009), even though the faint merger remnant features might decay much more rapidly than the post-starburst features (Pawlik et al. 2016).

Spatially resolved kinematics and stellar population analysis suggest that mergers are the dominant mechanism in the field (Pracy et al. 2012, 2013). In particular, Balmer line enhancement in the central regions of post-starburst galaxies might be indicative of young central merger-induced star bursts (Swinbank et al. 2011; Whitaker et al. 2012; Pracy et al. 2013).

Another type of galaxies with spectral characteristics similar to post-starbursts, but with important differences, are those with both emission-lines and strong H$\alpha$ (>4Å) in absorption, the so-called “e(a)” galaxies (Dressler et al. 1999; Poggianti et al. 1999; Poggianti & Wu 2000; Miller & Owen 2001; Yesuf et al. 2014). Poggianti et al. (1999) suggested that this kind of galaxies are almost dust-enshrouded starburst galaxies, and Poggianti & Wu (2000) showed that this type of spectra are in fact common among Luminous and Ultraluminous Infrared galaxies. In this picture, the ongoing star formation is hidden behind a large amount of dust and gas and therefore the emission lines are strongly extinguished. Balmer absorption lines, on the other hand, originate from A-stars, which are long-lived enough to migrate out of the star-forming gas cloud and become visible. It is instead still debated what fraction of the post-starburst spectra (with no emission lines) are dust-enshrouded starbursts (Goto 2004; Chang et al. 2001; Dressler et al. 2009; Nielsen et al. 2012). A number of galaxies with both Balmer strong absorption and emission lines have also been found to be “shocked Poststarburst galaxies”, in which the nebular lines are excited via shocks, that have been interpreted as an earlier phase in galaxy transformations than traditional post-starburst galaxies (Alatalo et al. 2016, 2017; Baron et al. 2018).

Few papers have started comparing samples of post-starburts in clusters and in the field, but only at intermediate redshift. Poggianti et al. (2009) performed a spectral analysis of galaxies in a wide range of environments (from clusters to the field) at $0.4 < z < 0.8$, exploiting the ESO Distant Cluster Survey. They found that the incidence of $k+a$ galaxies depends strongly on environment: the poststarburst fraction is higher in clusters and in a subset of groups showing a low fraction of [OII] emitters. In these environments, 20-30% of star-forming galaxies have had their star formation activity recently truncated. In contrast, $k+a$ galaxies are proportionally less frequent in the field, in poor groups and with a high [OII] fraction. Also Dressler et al. (2013), examining the full range of environments sampled by the IMACS Cluster Building Survey at $0.31 < z < 0.54$ (Oemler et al. 2013), found that post starburst galaxies strongly favor denser environments and that their incidence increases going from the field to groups and clusters.

In the local universe, a coherent picture of the properties and incidence of post-starburts in the different environments in an homogeneous sample is still lacking. Paccagnella et al. (2017) presented the first complete characterization of post-starburst galaxies in clusters at low-redshift. They investigated the incidence, properties of the stellar populations and the spatial location of post-starburst galaxies within clusters, in a sample at $0.04 < z < 0.07$, based on the Wide-field Nearby Galaxy-cluster Survey (WINGS) (Pasano et al. 2006; Moretti et al. 2014) and OmegaWINGS (Gullieuszik et al. 2015; Moretti et al. 2017) data. They found that considering a magnitude limited sample including all galaxies with an apparent V magnitude brighter than 20, post-starbursts are $7.2 \pm 0.2\%$ of cluster members within 1.2 virial radii. Their frequency raises from the outskirts toward the cluster center and from the least toward the most luminous and massive clusters. Post starburst magnitudes, stellar masses, morphologies and colors typically show an intermediate behavior between passive and emission line galaxies, indication of a population in transition from being star forming to passive. These results, together...
Post-starburst galaxies in the field

with the phase-space analysis and velocity dispersion profile, made Paccagnella et al. conclude that post starburst galaxies represent cluster galaxies that accreted onto clusters quite recently. Ram-pressure stripping was proposed as the main responsible for the rapid truncation of star formation required to explain the spectral features observed in post starburst galaxies.

In this work we extend the analysis presented in Paccagnella et al. (2017), by characterizing the incidence and stellar population properties of post-starburst galaxies in lower-density environments, specifically in groups, binaries and single systems, and contrast their incidence to the same population in clusters. We base our analysis on the Padova-Millennium Galaxy and Group Catalogue (PM2GC, Calvi, Poggianti & Vulcani 2011), a spectroscopically complete sample of galaxies at 0.03 ≤ z ≤ 0.11 with $M_B ≤ −18.7$. This group catalog has been already successfully exploited to investigate the role of the group environment in driving galaxy transformations (e.g. Vulcani et al. 2011; Calvi et al. 2012, 2013; Poggianti et al. 2013; Guglielmo et al. 2015; Vulcani et al. 2015).

Vulcani et al. (2015) already briefly investigated the incidence of post-starburst galaxies in a mass limited sample (log($M_*/M_\odot$) ≥ 10.25) of galaxies drawn from the PM2GC. They found that, in the general field, 4.5% of all galaxies can be classified as post-starbursts. However, when considering the relative number of post-starburst and blue galaxies (used as a proxy of currently star-forming galaxies), this fraction is much lower in binaries and singles (13 ± 5%) than in groups (22 ± 6%), suggesting a higher efficiency of sudden quenching in groups compared to lower mass haloes. Here we build on their findings, characterizing in detail the stellar population properties of the post-starburst galaxies, and exploiting a more accurate definition of environment. We also combine the PM2GC and WINGS+OmegaWINGS samples, with the aim of characterizing the incidence of post-starbursts over a wide range of halo masses, namely $10^{11}M_\odot < M_{\text{halo}} < 10^{15.5}M_\odot$.

Throughout the paper, we adopt a Salpeter (1955) initial mass function (IMF) in the mass range 0.1−125 $M_\odot$. The cosmological constants assumed are $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2 THE DATA SAMPLES

2.1 The field sample

The main sample of this analysis is the PM2GC (Calvi, Poggianti & Vulcani 2011), a spectroscopically complete sample of galaxies at 0.03 ≤ z ≤ 0.11 brighter than $M_B = −18.7$. The galaxy sample was built on the basis of the Millennium Galaxy Catalogue (MGC) (Liske et al. 2003; Cross et al. 2004; Driver et al. 2005), a deep and wide B-imaging survey along an equatorial strip of 0.6deg × 73deg covering an area of ~ 38deg$^2$ obtained with the Isaac Newton Telescope (INT) and consisting of 144 overlapping fields.

A sample of galaxies included in the MGCz catalog, the spectroscopic extension of the MGC, was selected. ~86% of the MGCz spectra of the sample come from the SDSS (~2.5 Å resolution, median signal-to-noise per pixel 15, Abazajian et al. 2003), 12% from the 2dF Galaxy Redshift Survey (2dFGRS, ~ 9 Å resolution, median signal-to-noise per pixel 13, Colless et al. 2001) and 2% from the 2dF follow-up obtained by the MGC team (Driver et al. 2005). The fibre diameters are 3” for the SDSS and 2.16” for the 2dF setup, corresponding to the inner 1.3 to 6 kpc of the galaxies. While SDSS spectra were already flux-calibrated, for all 2dF spectra a relative flux calibration was performed. We used the response curve provided by the 2dF team. We refined the curve using the ratio between the 2dF spectra and the corresponding SDSS spectra for objects with both spectra available, as done by Cava et al. (2009).

The approach adopted to identify galaxy groups is based on a friends-of-friends (FoF) algorithm (Calvi, Poggianti & Vulcani 2011). A galaxy is considered a member of a group if its spectroscopic redshift lies within ±3σ (velocity dispersion) from the median group redshift and if it is located within a projected distance of 1.5R$^2_{200}$ from the group geometric center. R$^2_{200}$ is defined as the radius delimiting a sphere with interior mean density 200 times the critical density of the universe at that redshift, and is commonly used as an approximation of the group virial radius. The R$^2_{200}$ values are computed from the velocity dispersions as in Poggianti et al. (2006). The result is a catalog of 176 groups of galaxies with at least three members, in the redshift range 0.04 ≤ z ≤ 0.1, containing in total 1057 galaxies and representing 43% of the total general field population at that redshift. Most of the groups contain fewer than 10 members, 63% have less than 5 members and 43% have only three members. The median redshift and velocity dispersion of the sample are $z = 0.0823$ and $σ = 191.8$ km/s respectively. The range of velocity dispersion is between 100 km/s and 800 km/s.

Galaxies that do not satisfy the group membership criteria at 0.03 ≤ z ≤ 0.11 and with no friends (1141) were classified as field-single, those with only one friend within 1500 km/s and 0.5 $h^{-1}$ Mpc (490) were called field-binary. All galaxies in the environments described above are collected in the “general field” sample.

2.2 Probing the environments with mock catalogs in the PM2GC

Due to projection effects, in observations any method adopted to identify groups and their members produces some fraction of false positives, that is interlopers selected as members that do not belong to a group, and false negatives, that is true members missed by the selection procedure.

To test the performance of the FoF algorithm adopted to define the different environments (Calvi, Poggianti & Vulcani 2011), we exploit mock catalogs drawn from the Millennium Simulation (Springel et al. 2005). We also use the same simulations to assign estimates of halo masses to the PM2GC structures, as described in the following.

2.2.1 The simulation

We base our analysis on the publicly available catalogs from the semi-analytic model of De Lucia & Blaizot (2007) run on the Millennium Simulation (Springel et al. 2005). The simulation has a spatial resolution of 5 $h^{-1}$ kpc, uses 10$^{10}$ particles of mass 8.6 × 10$^6 h^{-1} M_\odot$ and traces the evolution of the matter distribution in a cubic region of the universe of 500 $h^{-1}$ Mpc, on a side from $z = 127$ until $z = 0$. 

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The De Lucia & Blaizot (2007) model builds on the methodology and prescriptions originally introduced by Springel et al. (2001); De Lucia, Kauffmann & White (2004) and Croton et al. (2006). We refer to the original papers for details.

We exploit the extractions presented in Vulcani et al. (2014), which were used to reproduce the PM2GC field. 10 portions of “simulated sky” corresponding to square boxes of $\sim 38 \text{deg}^2$ (30x30 Mpc) at $z = 0.06$ each were selected. The boxes extracted were 323 physical Mpc deep. No pre-selection on halo mass was applied to these boxes.

The model provides information on halo masses, virial radii, velocity dispersions, number of galaxies, galaxy stellar masses, galaxy positions in the box, and galaxy magnitudes. In what follows, we refer to an output value of the simulations either as a “simulated” or a “sim-projected” quantity. The former are the 3D estimates provided by the simulations, we compute stellar masses in an homogeneous way either as a “simulated” or a “sim-projected” quantity. The latter are computed from the simulation with the same methods that has been used observationally and are projected on the $xy$ plane.

To reduce the biases between observations and simulations, we compute stellar masses in an homogeneous way for the sim-projected and the observed sample. We therefore adopt the Bell & de Jong (2001) prescription and corredata the stellar mass-to-light ratio with the optical colors of the integrated stellar population:

$$\log(M/L_B) = -0.51 + 1.45(B-V)$$

valid for a Bruzual & Charlot model with solar metallicity and a Salpeter (1955) IMF (0.1-125 $M_\odot$). The typical uncertainty on mass estimates is 0.2-0.3 dex. For simple-projections, we use the rest-frame Vega magnitudes from the models; for the PM2GC, we use the B-band photometry taken from the MGC, and the rest-frame B-V color computed from the Sloan g-r color corrected for Galactic extinction (see Calvi, Poggianti & Vulcani 2011, for details). Vulcani et al. (2014) performed a comparison between the masses provided by the model and those obtained following the Bell & de Jong (2001) formulation, highlighting a good agreement, with an absolute median difference of 0.08 dex.

### 2.2.2 Contamination and incompleteness of the sim-projected groups

To estimate the contamination and incompleteness in our observed group catalog, we run our FoF algorithm on each of the ten extractions of the sim-projected sample, limited at $M_B = -18.7$, separately, and identify sim-projected-groups, sim-projected-binary systems and sim-projected-single galaxies.

We then compare these outputs to the catalogs of structures obtained from the simulated samples using the real memberships. The number of systems in the two different samples, averaged over the 10 fields, are given in Tab. 1. It appears evident that the FoF recovers many more groups than the real ones, suggesting a high level of contamination in the observed catalog.

We can call $N_{\text{true}}$ the number of real members recovered by the FoF, $N_{\text{true}}$ the intersection between $N_{\sim} \text{ and } N_{sp}$ and $N_{sp} = N_{\text{true}} − N_{\text{true}}$ the number of interlopers. The “contamination” is defined as the fraction of interlopers: $f_i = N_{sp}/N_{\text{true}}$.

In the sim-projected samples, more than 50% of the sim-projected groups have a contamination higher than 0.5. Figure 1 shows the velocity dispersion of sim-projected groups $\sigma$ as a function of the total stellar mass of group members, $\log(M_{\text{tot}}^\ast/M_\odot)$. The latter has been computed including only galaxies brighter than the PM2GC magnitude limit of $M_B = -18.7$. While groups with $f_i \geq 0.3$ are spread all over the plane, a quite tight correlation emerges for groups with $f_i < 0.3$, which are preferentially found at

$$\log(M_{\text{tot}}^\ast/M_\odot) > 0.003 \cdot \sigma + 10.40$$

Groups above this line have a fraction of interlopers of $\sim 0.2$, and from now on we will refer to them as “real” groups. In contrast, groups below this line (from now on “fake” groups) have a fraction of interlopers of $\sim 0.6$.

The “incompleteness” is defined as the number of lost members $N_{\text{sp}} = N_{\text{true}} − N_{\text{true}}$. In the sim-projected samples, 7% of the sim-projected groups have an incompleteness higher than 0.5. The incompleteness will be used in the following Section to determine the halo mass of sim-projected groups.

### Table 1. Mean number of groups, binary systems and single galaxies in the simulated and sim-projected samples.

| Catalog      | Groups   | Binaries   | Singles    |
|--------------|----------|------------|------------|
| simulated    | 87±1     | 133.5±0.5  | 1893.3±0.5 |
| sim-projected| 165.7±0.7| 212.5±0.4  | 969.2±0.6  |

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1 These magnitudes include the effect of dust in the Buser (1978) system, calculated using the models of Bruzual & Charlot (2003).
We assign halo masses to the sim-projected-groups with at least three members. For each sim-projected group, we select the simulated halo that includes the majority of its members. Then, we calculate the incompleteness of the system. If \( N_{\text{lost}} > N_{\text{tot}} \), we select the second most common simulated halo present in the sim-projected group and recalculate the incompleteness. If \( N_{\text{lost}}' < N_{\text{tot}} \), with \( N' \) indicating the second simulated halo, we reject the first halo and assume that the second one better corresponds to the sim-projected group and iterate the process, otherwise we keep the first one. At the end, we assign to each sim-projected group the mass of the simulated halo that better represents it.

We note that in 38% of the sim-projected groups, all galaxies belong to different simulated halos. In these cases we assign to the group the halo mass of the halo where the most massive galaxy (MMG) is located.

For galaxies in the sim-projected binary systems, if the two members do not belong to the same simulated halo, we use the mass of the halo hosting the MMG.

For single galaxies the associated halo mass is the one of the simulated halo that contains the galaxy.

In what follows, we will refer to this halo mass estimate as \( M_{\text{halo}}^\text{MS} \).

### 2.2.4 The Total Stellar-to-halo Mass Relation

Our aim is to derive an halo mass estimate for each system in our observed group catalog. Therefore, we have to link our observables to a quantity derived from simulations.

As demonstrated in Yang, Mo & van den Bosch (2003); Yang et al. (2005, 2007); Yang, Mo & van den Bosch (2008), the mass of a dark matter halo associated with a group is tightly correlated with the total stellar mass of member galaxies. Such relation holds also in our sim-projected samples, as illustrated in Figure 2, where the correlations between the halo mass \( \log(M_{\text{halo}}^\text{MS}) \) and the total stellar mass \( \log(M_{\text{tot}}^\text{MS}/M_\odot) \) for the 10 sim-projected fields are shown. Real groups,\(^2\) binaries and single systems are here considered all together.

We fit the relation in each sim-projected sample using an analytic equation with four free parameters

\[
\log M_{\text{halo}}^\text{tot} = a + d \left[ \arctan \left( \frac{\log M_{\text{halo}}^\text{MS} - b}{c} \right) \right]
\]

implementing a nonlinear least-squares Marquardt-Levenberg algorithm (Marquardt 1963).

The typical scatter of the relation increases with halo mass, but is always < 0.4 dex along the whole mass range. Clearly, the scatter will result in errors in the inferred group masses.

We then average the outputs of the ten fields, obtaining the following values: \( a = -13.13 \pm 0.05 \), \( b = 11.51 \pm 0.04 \), \( c = 1.59 \pm 0.04 \), \( d = 2.19 \pm 0.07 \).

2 Including also fake groups would increase the scatter in the determination of the halo masses.

### 2.2.5 Halo masses for the PM2GC

The procedure described above has been applied to groups identified by the same group finder algorithm run on the observations, thus already contains the scatter introduced with projection effects and interlopers on the estimation of the final halo masses. We can now apply Eq.3 to the observed sample, in order to obtain halo mass estimates for the PM2GC structures.

Before doing so, we have to consider that the observed sample is affected by survey geometry. Indeed, a group whose projected area straddles one or more survey edges may have members that fall outside of the survey area, thus causing an incompleteness that affects the mass estimate of the group. The geometry used to quantify this issue is a simplification of the real one. Following Yang et al. (2007), we correct using a rectangular mask that contains the whole field of view. To start, we estimate the total stellar mass\(^3\) for each group without taking into account edge effects. We then randomly distribute 200 points within the corresponding halo radius \( R_{200} \). Next we apply the rectangular mask and compute the number of points that fall within the field region, \( N_r \), and define \( f_{\text{edge}} = N_r/200 \) as a measure for the volume of the group that lies within the survey edges. Afterwards, we corre-

\(^3\) To take into account the different cosmology adopted in the PM2GC and in the Millennium Simulation, we first apply a correction of 0.09 to the PM2GC magnitudes, which translates into a factor of ~ 0.032 on stellar masses.
rect the total stellar mass by $1/f_{\text{edge}}$ to take into account the “missing members” outside the edges. This correction works well for groups with $f_{\text{edge}} > 0.6$, that in the PM2GC sample constitute the 96% of the whole sample.

Finally, we calculate the dark matter halo masses for the whole PM2GC catalog (groups, binaries and single galaxies) exploiting equation 3 and flag as real those groups with $\log M_* > 0.003 \cdot \sigma + 10.4$ that, according to the statistics derived in section 2.2.3, should be the ones with the lower fraction of interlopers.

Figure 3 shows the distribution of the inferred halo masses for single galaxies, binary systems and groups in the PM2GC. Single galaxies span a halo mass range between $10^{10.9}M_\odot$ and $10^{13.9}M_\odot$, with a median value of $10^{11.58\pm0.02}M_\odot$. Binary systems span a halo mass range between $10^{11.2}M_\odot$ and $10^{12.9}M_\odot$, with a median value of $10^{12.03\pm0.03}M_\odot$. Groups span a halo mass range between $10^{11.6}M_\odot$ and $10^{14.8}M_\odot$, with a median value of $10^{12.68\pm0.05}M_\odot$. If we consider only real groups, the halo mass ranged spanned by the systems narrows, being $10^{12.0} - 10^{14.8}M_\odot$, with a median value of $10^{12.88\pm0.04}M_\odot$.

The entire catalog of the halo mass estimates is described in Appendix A and is given in the online version of the article.

### 2.3 The cluster sample

The secondary sample of our analysis is the WIde-field Nearby Galaxy-cluster Survey (WINGS) (Fasano et al. 2006; Moretti et al. 2014) and its recent extension, OmegaWINGS (Gullieuszik et al. 2015; Moretti et al. 2017), which quadruples the area covered. The two surveys together observed 76 clusters X-ray selected from ROSAT All Sky Survey data (Ebeling et al. 1996, 1998, 2000) at $0.04 < z < 0.07$. The clusters span a wide range in X-ray luminosity ($L_X \sim 0.2 - 5 \times 10^{44}$ erg/s) and velocity dispersion ($\sigma$ typically between 500 and 1100 km s$^{-1}$). They therefore probe the massive tail of the halo mass distribution.

Details on the target selection, redshift determinations, geometrical and magnitude incompleteness can be found in Paccagnella et al. (2017).

Halo masses have been estimated from the cluster velocity dispersion $\sigma_{\text{cl}}$, by means of the virial theorem, following Poggianti et al. (2006)

$$M_{200} = 1.2 \times 10^{15} \left( \frac{\sigma_{\text{cl}}}{1000 \text{km/s}} \right)^3 \frac{1}{\sqrt{(2\Lambda + 3\Omega_M(1 + z_{\text{cl}})^3)}} h^{-1} (M_\odot)$$

(4)

### 3 GALAXY PROPERTIES AND SAMPLE SELECTION

In the PM2GC, we convert the observed SDSS photometry into rest-frame absolute magnitudes running INTERREST (Taylor et al. 2009). This code is based on a number of template spectra and carries out an interpolation from the observed photometry in bracketing bands (see Rudnick et al. 2003). We then derived rest-frame colors from the interpolated rest-frame magnitudes.

In WINGS+OmegaWINGS, rest-frame B and V absolute magnitudes are directly obtained from the observed ones (Varela et al. 2009; Gullieuszik et al. 2015).

As presented by Poggianti et al. (2013); Paccagnella et al. (2017), for both samples we exploit the spectrophotometric model SINOPSIS (SimulatIng Optical Spectra wth Stellar population models, Fritz et al. 2007, 2011, 2014) to obtain estimates of stellar masses and galaxy equivalent widths (EWs) for the most prominent spectral lines, both in emission and in absorption. The code is based on a stellar population synthesis technique that reproduces the observed optical galaxy spectra.

In this paper, we will use stellar masses locked into stars, including both those that are still in the nuclear-burning phase, and remnants such as white dwarfs, neutron stars, and stellar black holes.

Observed EWs will be converted in rest frame values dividing the measurements by $(1 + z)$. We will adopt the usual convention of identifying absorption lines with positive values of the EWs and emission lines with negative ones. Fritz et al. (2007) found that SINOPSIS is able to reliably measure emission and absorption lines in spectra with $S/N > 3$, computed across the whole spectral range. In spectra with $S/N < 3$, SINOPSIS can misinterpret noise as an emission. This happens especially for the [O II] emission line, which is located in a spectral range where the lines of the Balmer series (in absorption) crowd. Therefore, a peak between two such absorption lines can be misinterpreted as an [O II] emission. Simulations from the Fritz et al. (2007) have shown that a fair threshold value to get a reliable [O II] detection is -2 Å. Lines with an EW higher (in absolute value) than this, are properly measured.

We will use the morphological classification performed by MORPHOT (Fasano et al. 2012), an automatic tool designed to reproduce the visual classifications. The code was
applied to the B-band MGC images and V-band OmegaCAM images to identify ellipticals, lenticulars (S0s), and later-type galaxies (Calvi et al. 2012, Fasano et al. in prep).

The projected local galaxy density was derived by Vulcani et al. (2012) for each galaxy in the PM2GC survey from the circular area A that, in projection on the sky, encloses the 5th nearest projected neighbours within ±1000 km/s brighter than $M_V = -19.85$, which is the V absolute magnitude limit at which the sample is spectroscopically complete. The projected density is then $\Sigma = N/A$ in number of galaxies per Mpc$^2$.

3.1 The spectral classification

We follow the same classification scheme presented in Paccagnella et al. (2017), based on the measurement of the rest frame EWs. Briefly, we use the rest frame EWs of [OII], [OIII], H$\alpha$ in emission and H$\delta$ in absorption to subdivide the sample into the following three classes.

- Emission Line Galaxies (EML): galaxies whose spectra show any line in emission. These galaxies have $|\text{EW}/\text{err(EW)}| \geq 3$ for at least one line present in the spectrum;
- Passive Galaxies (PAS): galaxies whose spectra show no emission lines and weak H$\delta$ in absorption (EW(H$\delta$)<3 Å). These galaxies are typically characterized by spectra resembling those of K-type stars, lacking emission lines and with weak H$\delta$ in absorption, $(k$ spectra), which is typical of passively evolving galaxies with neither current nor recent star formation activity normally found in passively evolving elliptical galaxies;
- Post Starburst Galaxies (PSB): galaxies whose spectra show no emission lines and strong H$\delta$ in absorption. These galaxies are typically characterized by $k+a$ ($3 <$ EW(H$\delta$) < 8) and $a+k$ (EW(H$\delta$)>8) spectra, and display a combination of signatures typical of both K and A-type stars.

Before proceeding with the analysis, we visually inspected all the spectra where only one emission line was detected and changed the galaxy spectral type where necessary. We also visually inspected all the PSB candidates and remeasured the H$\delta$ EW for those with an automatic measure higher than 5 Å or with a S/N$<1$. Note that our classification scheme assumes that any emission line would be coming from star-forming regions. If this assumption is not correct - for instance, when the contribution of [O II] from AGNs is significant - the PSB sample would be incomplete because AGNs would be mistakenly discarded as star-forming galaxies (e.g. Yan et al. 2006; Lemaux et al. 2017).

Figure 4 shows some spectra of galaxies in the PM2GC sample. Both typical SDSS and 2dF spectra for EML, PSB and PAS galaxies are shown.

3.2 The sample selection

For the PM2GC, in the redshift range $0.03 < z < 0.11$, we consider all galaxies entering the sample with $M_B \leq -18.7$,

which is the survey magnitude completeness limit. We use galaxies in the three different environments: groups, binary and single systems. This sample includes 2642 objects.

For the WINGS+OmegaWINGS sample, we consider the redshift range $0.04 < z < 0.07$ and include in the analysis only the 32 clusters with a global spectroscopic completeness higher than $\sim$50% (Paccagnella et al. 2017). Cluster members within 1$R_{200}$ from the Brightest Cluster Galaxy enter the final sample. While in Paccagnella et al. (2017) we selected galaxies with a V magnitude brighter than 20, here, to directly compare the different data sets, we apply the same magnitude cut of the PM2GC ($M_B = -18.7$). The main results of Paccagnella et al. (2017) still hold with the current selection.

Note that in both samples we neglect the contribution from AGN in our analysis. Alatalo et al. (2016) showed that this assumption could in principle bias the results. Indeed, galaxies in which emission lines are excited by the AGN mechanism or shocks rather than by star formation, are excluded from the PSB sample. Nonetheless, to investigate the incidence of AGNs in the PM2GC sample, we have matched it with an AGN catalog from SDSS, based on emission line ratios, finding that overall 51 galaxies (2.0±0.3%) that enter our selection are most likely hosting an AGN.

For the cluster sample, Guglielmo et al. (2015) found that in a mass-limited sample extracted from the WINGS survey the AGN contribution in the star-forming galaxy population is approximately 1.6% and (Paccagnella et al. 2017) estimated that this fraction does not change in the entire WINGS+OmegaWINGS sample.

Thus, including these galaxies in the EML population should not considerably affect the results.

4 RESULTS

4.1 Properties of the different galaxy populations

We begin our analysis by examining the relative fractions of each spectral type in the different environments, as summarized in Table 2. In the general field, EML galaxies represent $\sim$ 73% of the whole galaxy population, PAS galaxies $\sim$25%, while PSB galaxies are 2% of the total. The incidence of each spectral type depends on environment, even though EMLs always dominate the population, followed by PAs and PSBs. Overall, the incidence of EMLs increases going from the more massive (i.e. groups) to the less massive (i.e. single) systems, while the incidence of PAs has the opposite behavior. These trends are even more outstanding if we consider only real groups. This result corroborates our distinction between fake and real groups: indeed fake groups are most likely just either binary or single systems that due to projection effect appear as group members, and are characterized by a higher fraction of EML galaxies. PSBs are always very rare, but in groups (both real and fake) they are more than twice as numerous as in single systems (3% vs 1.1%). In binaries they represent the 2%. Therefore, the group environment seems to boost the presence of PSBs, confirming what previously found by Vulcani et al. (2015).

\[http://www.sdss3.org/dr10/spectro/spectro_access.php\]
Figure 4. Examples of spectra of PAS, PSB and EML galaxies in our samples are shown. Left panels show SDSS spectra, right panels show 2dF spectra.

Table 2. Number and percentage of the different spectral types in the general field and its finer environments. Errors are binomial. The cluster sample is drawn from Paccagnella et al. (2017) and will be discussed in Sec. 4.3. Numbers are weighted for spectroscopic incompleteness, while raw numbers are given in brackets.

| Environment     | PAS   | %    | PSB   | %    | EML   | %    |
|-----------------|-------|------|-------|------|-------|------|
| General field   | 652   | 25±1 | 53    | 2.0±0.3 | 1937 | 73±1 |
| Groups          | 373   | 36±1 | 31    | 3.0±0.6 | 629  | 61±1 |
| Real groups     | 280   | 42±2 | 25    | 3.7±0.7 | 364  | 54±2 |
| Binaries        | 111   | 23±2 | 10    | 2.0±0.6 | 365  | 75±1 |
| Single galaxy   | 105   | 15±1 | 12    | 1.1±0.4 | 943  | 84±1 |
| Clusters        | 3125  | 60.9±0.6 | 229 (119) | 4.5±0.3 | 1776 (1026) | 34.6±0.6 |
Figure 5: Stellar mass (upper), absolute B magnitude (central) and rest-frame (B-V) color (bottom) distribution for PAS (red, solid line histogram), EML (blue, hatched histogram) and PSB (green, filled histogram) galaxies. The main panel shows distribution in the general field, the subpanels show the distributions in the different environments. Median values are reported in Tab.3.

As results are robust against the inclusion of the fake groups, in what follows we will keep them in the analysis, so to have a better statistics.

The trends already detected from the single systems to the groups extend to clusters: the fraction of PAS galaxies is much higher in clusters (> 60%) than in groups (~ 40%), while the fraction of EML galaxies is much lower (35% vs. 60%). The fraction of PSB galaxies grows from the poorest (only 1% in single galaxies) to the richest environments (4.5% in clusters).

We define the “active” population (PSB+EML galaxies) as the population of galaxies that were star-forming \( \lesssim 2 \) Gyr before the epoch of observation; the PSB/active fraction can be therefore considered as a sort of quenching efficiency in truncating star formation in star-forming galaxies. PSB galaxies represent 11.4 \( \pm \) 0.8% of the active population in clusters (Paccagnella et al. 2017), 5 \( \pm \) 1% of the active population in groups (6 \( \pm \) 2% if only real groups are considered), and their incidence decreases in binaries (3 \( \pm \) 1%) and single galaxies (1.3 \( \pm \) 0.6%), suggesting that in clusters and groups the suppression of the star formation is more efficient than in other environments.

Figure 5 shows the stellar mass, the B-band absolute magnitude and the rest-frame (B-V) color distributions for the different spectral types both in the general field and in its finer environments, for galaxies in the magnitude limited sample. The median values are given in Tab.3. Errors are computed as 1.253\( \sigma/\sqrt{n} \) with \( \sigma \) standard deviation and \( n \) number of objects. First focusing on the general field, EML and PAS galaxies have quite different mass/magnitude/color distributions, dominating respectively the low and high mass/luminosity and blue/red tails. PSB galaxies are characterized by mass, luminosity and color distributions that are overall intermediate between that of the PAS and EML galaxies, lacking both the least and most massive objects and the reddest and the bluest ones. No different trends emerge for galaxies in the finer environments and the median values of both stellar mass and magnitude of the different spectral type galaxies do not depend on environment.

Similarly, in clusters, PSB magnitudes, stellar masses, and colors typically show an intermediate behavior between passive and emission line galaxies, indication of a population in transition from being star forming to passive (Paccagnella et al. 2017).

The different mass distribution of the different spectral types is mainly driven by the fact that we are analyzing a magnitude limited sample. To obtain a mass complete sample, we should disregard galaxies with \( \log(M/\text{M}_\odot) < 10.44 \). Figure 5 shows the the vast majority of galaxies below this threshold are EML galaxies. This cut would however considerably lower our sample statistics of 40%.

4.1.1 Morphologies of the different galaxy populations

The analysis of the morphologies of the different galaxy populations can shed light on their formation.

Figure 6 shows the fine morphological distribution of galaxies in the general field. PAS galaxies are clearly skewed towards earlier morphologies, mainly ellipticals and S0s. PSBs include a wide range of morphologies, ranging from ellipticals to intermediate spirals. Most of EMLs are intermediate and late-type spirals, even though few objects show...
**Table 3.** Median values along with errors of stellar mass and absolute B magnitude for galaxies of different spectral type in the different environments.

| Environment     | PAS | PSB | EML |
|-----------------|-----|-----|-----|
| logM$^*$        | logM$^*$ | (B-V)$_{df}$ | logM$^*$ | (B-V)$_{df}$ | logM$^*$ | (B-V)$_{df}$ |
| General field   | 10.94$\pm$0.02 | -19.91$\pm$0.04 | 0.81$\pm$0.01 | 10.76$\pm$0.06 | -19.28$\pm$0.09 | 0.77$\pm$0.03 | 10.42$\pm$0.02 | -19.54$\pm$0.02 | 0.52$\pm$0.01 |
| Groups          | 10.93$\pm$0.03 | -19.90$\pm$0.05 | 0.81$\pm$0.01 | 10.76$\pm$0.09 | -19.21$\pm$0.01 | 0.78$\pm$0.04 | 10.48$\pm$0.03 | -19.61$\pm$0.04 | 0.55$\pm$0.01 |
| Binaries        | 11.01$\pm$0.04 | -20.01$\pm$0.08 | 0.81$\pm$0.01 | 10.76$\pm$0.15 | -19.25$\pm$0.11 | 0.8$\pm$0.1 | 10.44$\pm$0.04 | -19.59$\pm$0.05 | 0.51$\pm$0.01 |
| Singles         | 10.92$\pm$0.04 | -19.87$\pm$0.07 | 0.81$\pm$0.01 | 10.91$\pm$0.11 | -19.47$\pm$0.22 | 0.76$\pm$0.03 | 10.38$\pm$0.02 | -19.50$\pm$0.02 | 0.51$\pm$0.01 |

**Table 4.** Morphological fractions for galaxies of different spectral type in the different environments. Errors are binomial.

| GROUPS     | S0 | LATE | E | S0 | LATE | E | S0 | LATE |
|------------|----|------|---|----|------|---|----|------|
| PAS        | 0.42$\pm$0.03 | 0.43$\pm$0.03 | 0.15$\pm$0.02 | 0.39$\pm$0.05 | 0.41$\pm$0.05 | 0.20$\pm$0.04 | 0.39$\pm$0.05 | 0.39$\pm$0.03 | 0.22$\pm$0.03 |
| PSB        | 0.3$\pm$0.1 | 0.4$\pm$0.1 | 0.3$\pm$0.1 | 0.3$\pm$0.2 | 0.7$\pm$0.2 | 0.4$\pm$0.2 | 0.3$\pm$0.3 | 0.4$\pm$0.2 | 0.4$\pm$0.2 |
| EML        | 0.08$\pm$0.01 | 0.18$\pm$0.02 | 0.74$\pm$0.02 | 0.07$\pm$0.01 | 0.14$\pm$0.02 | 0.79$\pm$0.02 | 0.09$\pm$0.01 | 0.14$\pm$0.01 | 0.77$\pm$0.01 |

**Figure 6.** Fine morphological distribution of galaxies of the different spectral types for galaxies in the general field.

an early type morphology (as discussed in Vulcani et al. 2015).

Table 4 presents the morphological distribution of galaxies of the different spectral types, in the different environments. As expected, PAS, EML, and PSB galaxies have different morphologies. However, there is not a one-to-one correspondence between spectral type and morphology, suggesting that in many cases star-formation properties and galaxy appearance must change on different timescales, in agreement with previous studies (e.g., Dressler et al. 1999; Fritz et al. 2014; Vulcani et al. 2015; Pawlik et al. 2016), or that these galaxies are actually rejuvenating and about to return to the blue sequence (e.g., Dressler et al. 2013; Abramson et al. 2013; Rowlands et al. 2015; French et al. 2015; Wild et al. 2016).

In all the environments, 74-79% of EML galaxies present a late-type morphology, 14-18% of them are classified as S0s, less than 10% as ellipticals. These fractions suggest that the morphology of EMLs does not vary with the environment. Similarly, within the errors, also the morphologies of PSB galaxies seem to not depend on the environment: ~30% of them are ellipticals, ~40–70% are S0s, 0-40% are late types. Similar fractions are also found in local clusters (Paccagnella et al. 2017). Finally, the environment has also little influence on PAS galaxies: ~15-20% of them are late types, while the others are evenly split between S0 and ellipticals. There is a hint that in groups the fraction of late types is smaller, suggesting that this environment accelerates morphological transformations after the shut off of the star formation, but the evidence in only marginal (< 2σ, with r binomial error on the fractions).

**4.2 Properties of the different galaxy populations at different local densities in the general field**

The local density is a parametrization of the environment based on the number of nearby galaxy companions, therefore it should better trace processes like harassment and galaxy–galaxy interactions. If, as discussed in Sec.1, field post-starburst galaxies are indeed associated with galaxy interactions and mergers (Bekki, Shioya & Couch 2001; Quintana et al. 2004; Blake et al. 2004; Goto 2005; Hogg et al. 2006; Mahajan 2013), we should find them at relatively higher local densities, where this kind of processes are favored (Fakhouri & Ma 2008).

Figure 7 shows the distribution of the projected local density for galaxies of the different spectral types in the different environments. Median values along with errors are provided in Tab.5. As expected, galaxies in singles and binaries are shifted toward lower density values than galaxies in groups, and in any given environment EML galaxies tend to be found at lower density values than PAS galaxies. Trends for PSBs are more interesting. In binary and singles, the distribution of PSBs is skewed toward larger local density values than the other two populations, supporting the scenario according to which PSBs are the result of interaction effects (Fakhouri & Ma 2008).

Finally, the K-S is not able to conclude that PSBs and PASs are significantly different from EMLs in groups and singles, while the K-S is not able to robustly determine differences in binaries, maybe due to the low number statistics. Finally, the K-S is not able to conclude that PSBs and PASs are drawn from different distributions.
Table 5. Median local density values along with errors for galaxies of different spectral type in the different environments.

|        | PAS     | PSB     | EML     |
|--------|---------|---------|---------|
| Groups | 0.69±0.05 | 0.6±0.2 | 0.16±0.04 |
| Binaries | -0.3±0.1 | -0.2±0.2 | -0.46±0.03 |
| Singles | -0.51±0.06 | -0.3±0.1 | -0.64±0.02 |

Figure 7. Projected local density distribution for galaxies of the different spectral types (PAS: red, PSB: green, EML: blue), in the different environments (singles: upper panel, binaries: middle panel, groups: bottom panel).

These results therefore suggest that EMLs in high density environments most likely quench, turning into PSBs and eventually PASs.

4.3 Post-starburst galaxies as a function of halo masses

In the previous section we have investigated the incidence and the properties of galaxies of the different spectral types in the different environments, ranging from the single systems to the clusters.

We are now in the position of studying the PSB population as a function of the mass of the dark matter halo. Considering the different environments together, namely single galaxies, binaries, groups and clusters, the halo mass range covered goes from $10^{11} M_\odot$ to above $10^{15} M_\odot$.

The upper panel of Fig. 8 shows the fraction of PSBs as a function of the halo mass. A clear trend emerges: the fraction of PSB galaxies increases with the halo mass. If only real groups are considered, this trend is even more pronounced. Not only the incidence of PSB galaxies becomes more important going to higher halo masses, but also the quenching efficiency ($N_{PSB}/N_{PSB+EML}$) significantly increases, as shown in the lower panel of Fig. 8. It therefore appears clear that the environment plays a major role in inducing the formation of PSB galaxies, which are more frequent in massive haloes, as discussed in the next Section.

Note that these results still hold when applying a common cut in stellar mass in the two samples, implying that the different mass distribution can not be responsible for the observed trends.

5 DISCUSSION

In this work we have characterized the PSB population in the general field at $0.03 < z < 0.11$ and investigated their incidence as a function of environment. We also contrasted their properties to those of PSB galaxies in clusters at similar redshift (Paccagnella et al. 2017). Overall, PSBs have properties (stellar mass, rest-frame B magnitude, B-V color) intermediate between those of PAS and EML galaxies, suggesting that these objects are in a transitional stage between star-forming blue cloud galaxies and quiescent red sequence galaxies (in agreement with e.g. Caldwell et al. 1996;
Our main result is that the frequency of PSB galaxies strongly depends on halo mass.

The quenching efficiency is enhanced in more massive systems: the ratio of PSBs to PSBs+EMLs in clusters (∼ 11%) is twice the same ratio in groups (∼ 6%). The same ratio is halved in binary systems (∼ 3%) and further reduced among single galaxies (∼ 1%). These trends are even more outstanding when the fraction of PSBs is plotted as a function of halo mass (Fig. 8). Therefore, massive environments boost the presence of PSBs.

These results are in agreement with those presented by Gavazzi et al. (2010) for the PSB population within the Coma supercluster. They found that the PSB fraction significantly increases from the cosmic web to groups, to the cluster center.

These findings suggest that any physical mechanism that produces PSB galaxies must depend in some way on the global environment.

We remind the reader that the PSB signature in a galaxy spectrum is the consequence of a truncation of the star formation on time-scales as short as or shorter than ∼100 Myr, but there are no signs on the spectrum that allow us to distinguish among the different mechanisms responsible for the abrupt shut down of the star formation.

Different scenarios have been proposed to explain the formation of PSB galaxies in the different environments. In clusters, the truncation of the star formation is most likely due to the interaction of the galaxy with the intracluster medium (e.g. Dressler & Gunn 1982; Couch & Sharples 1987; Poggianti et al. 2009; Paccagnella et al. 2017). As already discussed and extensively modeled (see for example Boselli et al. 2008 and references therein), ram pressure stripping could be the driving mechanism. This mechanism is expected to be strongest in the most massive clusters (e.g. Gunn & Gott 1972; Jaffé et al. 2015), and this can explain the observed trend with halo mass. Trends in groups can be explained as the natural sequence of intergalactic medium (IGM), with more massive systems having a denser IGM.

When smaller systems as small groups, binaries or single galaxies are included in the global picture, other processes might need to be considered. In these environments, the most obvious candidate mechanisms are close galaxy interactions or mergers. According to numerical simulations (e.g. Barnes & Hernquist 1991, 1996; Bekki, Shioya & Couch 2001; Bekki et al. 2005; Hopkins et al. 2006, 2008; Suyder et al. 2011), gas-rich major mergers can induce strong starbursts that quickly exhaust a substantial amount of the gas reservoir (Di Matteo, Springel & Hernquist 2005), and can transform late-type galaxies into early types both structurally and kinematically (Toomre & Toomre 1972; Naab & Burkert 2003). Many works support this scenario, from both the theoretical and observational point of view (Bekki, Shioya & Couch 2001; Goto 2005; Blake et al. 2004, and references therein). Theoretical simulations indeed indicate that the PSB spectrum marks a late stage of the merging event, when the merging companion is no longer identifiable as the morphological signatures of the merging.

The signs of morphological disturbance found in many PSB galaxies provides strong evidence sustaining this statement (Zabludoff et al. 1996; Blake et al. 2004; Goto 2005; Yang, Mo & van den Bosch 2008).

Galaxy-galaxy interactions are traced by local density estimates and our analysis considering the projected local density (Fig. 7) shows that the distribution of PSB is skewed toward larger local density values than the other two populations, supporting the scenario according to which PSB are the result of galaxy interactions.

However, we did not detect any signs of disturbance in the morphology distribution of the PSBs in low mass halos, in agreement e.g. with Zabludoff et al. (1996); Blake et al. (2004); Yang, Mo & van den Bosch (2008). These results suggest that possibly less disruptive events, like minor mergers and accretion, are at play (see also Dressler et al. 2013). This conclusion is supported also by the fact that the redshift-evolution of the PSB number density found by Wild et al. (2009) is ~100 times that of the major-merger rate estimated by de Ravel et al. (2009).

Even though our analysis can not definitely state the main mechanisms responsible for the appearance of the PSB spectrum, the higher ratio of PSBs in cluster than in the field suggests that the process operating in the most massive systems, which most likely is ram pressure stripping, is more efficient than the processes operating in the sparest environments, most likely galaxy interactions, in producing this population.

The trends we have detected in the local universe seem to hold also at higher redshifts. Poggianti et al. (2009) performed a spectral analysis of galaxies in a wide range of environments (from clusters to the field) at 0.4 < z < 0.8, exploiting the ESO Distant Cluster Survey. They found that the incidence of k+a galaxies depends strongly on environment: PSBs reside preferentially in clusters and in a subset of groups showing a low fraction of [OII] emitters. In these environments, 20-30% of star-forming galaxies have had their star formation activity recently truncated. In contrast, k+a galaxies are less numerous in the field, in poor groups and with a high [OII] fraction. Also Dressler et al. (2013), examining the full range of environments sampled by the IMACS Cluster Building Survey at 0.31 < z < 0.54 (Oemler et al. 2013), found that PSB galaxies strongly favor denser environments and that their incidence increases going from the field to groups and clusters.

In this work, we have shown that the variation of the PSB fraction with environment is a smooth, monotonic function of the host halo mass.

6 SUMMARY AND CONCLUSIONS

Exploiting an absolute magnitude limited sample of galaxies (M_R ≤ −18.7) at 0.03 < z < 0.11 in the general field drawn from the PM2GC (Calvi, Poggianti & Vulcani 2011), we have investigated the occurrence and the properties of galaxies of different spectral types in different environments. We used different parameterizations of the environment, in order to have a broad understanding of its influence in shaping galaxy properties. First, we exploited the outputs of a FoF algorithm, which subdivided galaxies into single, binary and group systems. Second, we used projected local density estimates and third we adopted halo mass estimates, obtained exploiting mock catalogs drawn from the Millennium
et the most massive clusters (e.g. Gunn & Gott 1972; Jaffe mechanism. This mechanism is expected to be strongest in Therefore, ram pressure stripping is the most likely driving

Galaxies were classified based on the different features detected in their spectra (presence/strength of [OII], [OIII], H$\alpha$ and H$\beta$) into passive (PAS), post starburst (PSB) and emission line (EML) galaxies. We studied the stellar population properties of the different subpopulation with the aim to shed light on the physical processes responsible for the star formation quenching.

The main results can be summarized as follows.

- PSBs have properties (stellar mass, magnitude, color) intermediate between those of PAS and EML galaxies, suggesting that these objects are in a transitional stage between star-forming blue cloud galaxies and quiescent red sequence galaxies.
- The environment drives the incidence of PSBs: while PSBs are always quite rare compared to the other populations, their fraction decreases from clusters (4.5%), to groups (3%), to binaries (2%), to single systems (1.1%).
- Trends are even more outstanding when using the estimates of halo masses: the PSB fraction increases monotonically with halo mass.
- In binaries and singles the distribution of PSB is skewed toward larger local density values than the other two populations, while in groups strong trends do not emerge.

Our results can be explained advocating two different scenarios for the formation of PSB galaxies.

In clusters and in (at least the massive) groups, the truncation of the star formation is most likely due to the interaction of the galaxy with the intracluster medium (e.g. Dressler & Gunn 1982; Couch & Sharples 1987; Poggianti et al. 2009; Paccagnella et al. 2017) or intergroup medium. Therefore, ram pressure stripping is the most likely driving mechanism. This mechanism is expected to be strongest in the most massive clusters (e.g. Gunn & Gott 1972; Jaffe et al. 2015), and this can explain the observed trend with halo mass.

In binaries and singles the most obvious candidate mechanisms are close galaxy interactions or mergers, which can exhaust in a short time the available gas and thus give rise to a PSB spectrum. Our findings with the local density support this scenario. As we did not detect any signs of disturbance in the morphological distribution of the PSBs little disruptive events, like minor mergers and accretion, are expected to be at play (see also Dressler et al. 2013).

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Table A1. Subsample of 10 galaxy groups with their properties. The full table is available with the online version of the paper (see Supporting Information). Columns: (1) PM2GC group serial number; (2, 3) geometric centre right ascension and declination in degrees; (4) Halo mass estimate; (5) Error on the halo mass estimate.

| ID_GR | RA_GR (deg) | DEC_GR (deg) | log $M_{halo}^{tot}$ ($M_\odot$) | $\Delta$log $M_{halo}^{tot}$ ($M_\odot$) |
|-------|-------------|-------------|---------------------------------|----------------------------------|
| 1000  | 170.3258    | -0.2097     | 14.0                            | 0.1                              |
| 1001  | 197.1675    | 0.0623      | 12.53                           | 0.03                             |
| 1002  | 161.6724    | -0.0394     | 12.95                           | 0.05                             |
| 1003  | 175.4628    | 0.223       | 12.80                           | 0.04                             |
| 1004  | 154.4308    | -0.0772     | 13.53                           | 0.09                             |
| 1006  | 150.2518    | -0.1296     | 12.85                           | 0.05                             |
| 1007  | 151.4264    | 0.0807      | 12.75                           | 0.04                             |
| 1008  | 155.8879    | -0.2185     | 13.89                           | 0.1                              |
| 1009  | 169.9662    | 0.0633      | 12.62                           | 0.03                             |
| 1011  | 150.259     | -0.1726     | 14.29                           | 0.2                              |

Table A2. Subsample of 10 binary systems with their properties. The full table is available with the online version of the paper (see Supporting Information). Columns: (1) PM2GC binary serial number; (2, 3) PM2GC serial numbers of the two galaxies of the system; (4) Halo mass estimate; (5) Error on the halo mass estimate.

| ID_BIN | IDMGC_1 (deg) | IDMGC_2 (deg) | log $M_{halo}^{tot}$ ($M_\odot$) | $\Delta$log $M_{halo}^{tot}$ ($M_\odot$) |
|--------|---------------|---------------|---------------------------------|----------------------------------|
| 1      | 19714         | 19621         | 11.98                           | 0.01                             |
| 2      | 29003         | 28996         | 11.62                           | 0.01                             |
| 3      | 9715          | 9645          | 12.39                           | 0.02                             |
| 4      | 23444         | 23429         | 12.24                           | 0.01                             |
| 5      | 11804         | 96374         | 11.66                           | 0.04                             |
| 6      | 61222         | 61196         | 11.54                           | 0.01                             |
| 7      | 27171         | 27176         | 12.15                           | 0.01                             |
| 8      | 64057         | 64105         | 12.79                           | 0.04                             |
| 9      | 16794         | 16813         | 11.44                           | 0.01                             |
| 10     | 64907         | 64887         | 11.34                           | 0.01                             |

APPENDIX A: THE HALO MASS CATALOGS

We release a catalog with the halo mass estimates for the single, binary and group systems in the PM2GC, as computed in the previous section. Table A1 provides the information for a subset of 10 groups, extracted from the main catalog; Table A2 provides the information for a subset of 10 binary systems; Table A3 provides the information for a subset of 10 single galaxies. The full tables are available with the online version of the paper (see Supporting Information).

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Table A3. Subsample of 10 single galaxies with their properties. The full table is available with the online version of the paper (see Supporting Information). Columns: (1) PM2GC galaxy serial number; (2) Halo mass estimate; (3) Error on the halo mass estimate.

| ID  | \( \log M_{\text{halo}}^{\text{tot}} (M_\odot) \) | \( \Delta (\log M_{\text{halo}}^{\text{tot}}) (M_\odot) \) |
|-----|---------------------------------|-----------------|
| 61514 | 11.96                           | 0.01            |
| 27280 | 11.63                           | 0.01            |
| 11383 | 11.56                           | 0.01            |
| 66778 | 11.41                           | 0.01            |
| 52268 | 11.86                           | 0.01            |
| 56234 | 11.58                           | 0.01            |
| 16076 | 11.95                           | 0.01            |
| 13606 | 11.44                           | 0.01            |
| 57725 | 11.34                           | 0.01            |
| 25661 | 11.63                           | 0.01            |