The impact of global environment on galaxy mass functions at low redshift

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ABSTRACT

We study the galaxy stellar mass function in different environments in the local Universe, considering both the total mass function and that of individual galaxy morphological types. We compare the mass functions of galaxies with $\log_{10} M_*/M_\odot \geq 10.25$ in the general field and in galaxy groups, binary and single galaxy systems from the Padova-Millennium Galaxy and Group Catalogue at $z = 0.04 - 0.1$ with the mass function of galaxy clusters of the WIde-field Nearby Galaxy-Cluster Survey at $z = 0.04 - 0.07$. Strikingly, the variations of the mass function with global environment, overall, are small and subtle. The shapes of the mass functions of the general field and clusters are indistinguishable, and only small, statistically insignificant variations are allowed in groups. Only the mass function of our single galaxies, representing the least massive haloes and comprising less than a third of the general field population, is proportionally richer in low-mass galaxies than other environments. The most notable environmental effect is a progressive change in the upper galaxy mass, with very massive galaxies found only in the most massive environments. This environment-dependent mass cut-off is unable to affect the Schechter parameters and the K-S test, and can only be revealed by an ad-hoc analysis. Finally, we show how, in each given environment, the mass function changes with morphological type, and that galaxies of the same morphological type can have different mass functions in different environments.

Key words: galaxies: formation: general – galaxies: groups environments – galaxies: stellar masses

1 INTRODUCTION

The formation and evolution of galaxies is a subject of great complexity. If on the one hand the cosmological framework of the structure formation in the Universe is well in place and in agreement with observations, on the other hand the significant differences that emerge between galaxy models and the observed trends leave open many unsolved problems and intriguing scenarios on the physical processes involved.

Studies of the galaxy mass function (MF hereafter) are expected to provide important clues in this context because the MF, in addition to constraining the baryonic content of galaxies, is the result of the hierarchical mass assembly of dark matter halos, the intrinsic physical processes and the transformation processes that galaxies experience during their lifetimes (Brinchmann & Ellis 2000).

In recent years, the combination of spectroscopic catalogs with large photometric (especially infrared) surveys such as 2dF, SDSS, 2MASS has made possible to explore the distribution of galaxy stellar masses in the local universe over the mass range $M_* = 10^7 - 10^{12} M_\odot$ (Yang et al. 2009, Li & White 2009, Baldry et al. 2012) and as a function of the galaxy environment. There are two main ways to characterize the environment. One is to refer to the “global” structure to which a galaxy belongs (from clusters, to groups, to lower mass haloes). The second one is based on “local” galaxy density which can be parametrized following different techniques, for example by the number density of objects within some distance or measuring the distance of a galaxy to the $N_{th}$ nearest neighbour, with $N_{th}$ typically between 5-10.

Various studies have found that the galaxy MF depends on local galaxy density, with denser environments hosting on average more massive galaxies, both in the nearby universe (Bamford et al. 2009, Baldry et al. 2006, Vulcani et al. 2012) and at higher redshifts (Bolzonella et al. 2010, Vulcani et al. 2012). These works have analyzed galaxies in the general field, measuring the galaxy local density based on the 5th nearest neighbours. Vulcani et al. (2012) have also shown the importance of the local density in reg-

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ulating the mass distribution within galaxy clusters at low and intermediate redshift.

In contrast, the variation of the MF with global environment, and consequently halo mass, has not been fully understood. In the local universe, the study from [Balogh et al. 2001] finds a different mass function in clusters compared to the field, while other works detect no difference [von der Linden 2010; Mercurio et al. 2010].

The MF in distant clusters and its evolution from z ∼ 0.8 to z ∼ 0 have been analyzed for the first time in [Vulcani et al. 2011]. They found that the MF evolves with redshift: clusters at high-z show proportionally more massive galaxies than clusters at low-z, probably as a consequence of the mass growth of galaxies due to star formation in both cluster galaxies and, most of all, in galaxies infalling from the cluster surrounding areas.

A preliminary comparison with the field MFs taken from literature did not find evidence for an environmental mass segregation.

Performing an additional study on cluster and field data at 0.3 ≤ z ≤ 0.8, [Vulcani et al. 2013] found that the mass distribution at these redshifts does not show a dependence on global environment, being the global environment defined as clusters, groups or general field. As a consequence, the evolution of the MF between z ∼ 0.8 and today is similar in clusters and the general field. Differences in the MF of galaxies at intermediate redshifts become evident when comparing group and isolated galaxies, as found for the the xCOSMOS sample by [Kovac et al. 2010]. At similar redshifts, [Giodini et al. 2012] analysing a sample of X-ray galaxy groups, found that the MF of passive galaxies shows a difference from groups to field while the star-forming MF is similar in all environments.

The dependence of the MF on local density and its invariance from clusters to groups to general field led these authors to conclude that at least at z ≤ 0.8 local density is more important than global environment in determining the galaxy stellar mass distribution, suggesting that galaxy properties are not much dependent of halo mass, but do depend on local scale processes.

On the theoretical side, [Moster et al. 2010] found a correlation between the stellar mass of the central galaxy and the mass of the dark matter halo in N-body simulations. Indeed, observationally, at cluster scales the mass distribution of central galaxies appears to be a function of halo mass [Yang et al. 2009] but whether the total mass function depends on global environment is still an open question for both observations and simulations. As far as the dark matter component is concerned, high resolution numerical simulations predict that dark matter haloes contain a population of subhaloes whose mass function is found to be universal, independently of the mass of the host halo [Giocoli, Tormen & van den Bosch 2008]. Several authors have found that simulations coupled with semi-analytic models are not able to reproduce the mass function of low-mass galaxies (e.g. [Fontanot et al. 2009; Guo et al. 2011]). A detailed theoretical investigation for different halo masses has not been carried out yet and is currently underway (Vulcani et al. in prep.).

In this work we analyze the MF of galaxies at low redshift (0.04 − 0.1) as a function of “global” environment. We study both the general field MF and, for the first time, its variation in progressively less massive “haloes” from clusters, to groups, to binary systems and single galaxies, covering a range of system masses from 10^{12}M_⊙ to systems that are expected to be of the order of a few times 10^{12}M_⊙. Our aim is to understand if and how the MF varies with the global environment in the local Universe, where we are able to perform a detailed analysis isolating also low mass environments.

In addition, we study the MF of different morphological types: ellipticals, lenticulars and later-type galaxies. Our aim here is twofold: to characterize the differences in MF between a morphological type and the other, in each given environment, and to investigate whether the MF of a given type changes with environment.

The paper is structured as follows: after presenting our datasets in §2, we present our mass measurements and methods in §3.1 and 3.2, respectively. §3.3 shows a comparison of our general field MF with previous literature results. Our main results are presented in §4. The galaxy MFs by morphological types, how they differ with environment and from each other, are given in §5. We discuss our results in §6 and summarize them in §7. Throughout this paper we consider a ΛCDM cosmology with ΩM = 0.3, ΩΛ = 0.7 and Hubble constant of H_0 = 70 km s^{-1} Mpc^{-1}, a Kroupa (2001) IMF and Vega magnitudes.

2 GALAXY SAMPLES AT LOW-Z

In order to present a complete overview of how galaxies properties vary in different environments, we used two galaxy samples in the local universe: group, binary, single and, all together, general field galaxies were selected from the Padova Millennium Galaxy and Group Catalog (PM2GC) [Calvi, Poggianti & Vulcani 2011], while cluster galaxies were selected from WINGS [Pasano et al. 2006].

2.1 PM2GC

The PM2GC (Calvi et al. 2011) is a database built on the basis of the Millennium Galaxy Catalogue (MGC), a deep and wide B-imaging survey along an equatorial strip of ∼ 38deg^2 obtained with the INT (Isaac Newton Telescope). The design, execution, reduction, object detection and preliminary analysis of this survey are described in [Liske et al. 2003]. The MGC field lies within the 2dFGRS Northern Galactic Cap region and the SDSS region and a detailed comparison of the MGC with these surveys is described in [Cross et al. 2004].

We constructed the PM2GC catalogue restricting ourselves to galaxies brighter than M_B = -18.7 with a spectroscopic redshift in the range 0.03 < z < 0.11 (3210 galaxies), taken from the MGC2 catalogue, the spectroscopic extension of the MGC that has a 96% spectroscopic completeness at these magnitudes [Driver et al. 2005].

By applying a friends-of-friends algorithm we were able to identify a catalogue of 176 galaxy groups with at least three members in the redshift range 0.04 < z < 0.1 containing in total 1057 galaxies (PM2-G, hereafter groups). We consider members of the groups only those galaxies that after several iterations are within 1.5R_vir (from the group centre and 3σ (velocity dispersion) from the group redshift. Galaxies that do not satisfy the group linking criteria adopted have been placed either in the catalogue of single field galaxies (PM2-FS, hereafter single), that comprise the isolated galaxies, or in the catalogue of binary field galaxies (PM2-FB, hereafter binary) which comprise the systems with two galaxies within 1500 km s^{-1} and 0.5 h^{-1} Mpc. The redshift range of these catalogues is 0.03 < z < 0.11. All galaxies in the environments described

1 R_200 is the approximation of the virial radius computed as in [Finn et al. 2005].
above and galaxies excluded from the final virialized groups by the FoF procedure are collected in the "general field" sample (PM2-GF, hereafter general field). The methods and the presentation of catalogues are described in Calvi, Poggianti & Vulcani (2011) and the samples are available online on the web page of the MNRAS paper and of the MGC.

For the analysis discussed in this paper we decided to limit the single, binary and general field catalogues to the same redshift range of groups (0.04<z<0.1) and for general field we also excluded galaxies in group with edge problems. Moreover, in this paper we considered as "group" galaxies only members of groups with a velocity dispersion $\sigma < 500\,\text{km s}^{-1}$, to eliminate from our group sample a possible contamination from clusters.

### 2.2 WINGS

Designed to investigate the properties of galaxies in clusters and their connection with the cluster properties, WINGS\footnote{http://web.oapd.inaf.it/wings} (Fasano et al. 2006) is a multipurpose survey based on deep optical (B,V) wide field images ($\sim 35'$×$35'$) of 76 clusters at 0.04<z<0.07. The targets were selected in the X-ray from the ROSAT Brightest Cluster Sample, and its extension (Ebeling et al. 1998) in the northern hemisphere, and the X-ray Brightest Abell-type Cluster sample (Ebeling et al. 1996) in the southern hemisphere, and span a wide range in velocity dispersion ($\sigma$ typically between 500-1100 km s$^{-1}$) and X-ray luminosity ($L_X$ between 0.2-5×$10^{44}$ erg s$^{-1}$).

In addition to the optical imaging data a number of follow-up observations were carried out to obtain a large set of homogeneous informations for galaxies in WINGS clusters. WINGS-SPE is the spectroscopic survey conducted with the spectrographs WYFFOS@WHT and 2df@AAT for a subsample of 48 clusters for galaxies with a fiber aperture magnitude V<21.5 (Cava et al. 2009). In addition, near-infrared (J, K) observations of 28 clusters with WFCAM@UKIRT (Valentinuzzi et al. 2009) and U-band imaging for a subsample with wide-field cameras at different telescopes (INT, LBT, Bok, Omizzolo et al. in prep.) have been obtained. An Omegacam/VST U,B and V follow-up of about 50 WINGS clusters is underway.

For our analysis, we have considered 21 of the 48 clusters with spectroscopy. This is the subsample that provides a spectroscopic completeness larger than 50% (see Table 1 in Vulcani et al. (2011)). Only spectroscopically confirmed members within 0.6R$_{200}$ (the largest radius generally covered in clusters) will be considered. For our analysis, WINGS galaxies were weighted for spectroscopic incompleteness using the ratio between the number of galaxies with a spectroscopic redshift and the number of galaxies in the parent photometric catalogue, as a function of galaxy magnitude, as described in Cava et al. (2009). A detailed description of redshift measurements, cluster membership and completeness level is given in Cava et al. (2009).

### 2.3 Morphological classification

All galaxies in our samples have been morphologically classified using MORPHOT, an automatic non parametric tool designed to obtain morphological type estimates of large galaxy samples (Fasano et al. 2006, 2011), which has been shown to be able to distinguish between ellipticals and S0 galaxies with unprecedented accuracy. It combines a set of 11 diagnostics, directly and easily computable from the galaxy image and sensitive to some particular morphological characteristic and/or feature of the galaxies, providing two independent estimates of the morphological type based on: (i) a Maximum Likelihood technique; (ii) a Neural Network machine. The final morphological estimator combines the two techniques and the comparison with visual classifications of SDSS images provides an average difference in Hubble type $\Delta T$ ($< 0.4$) and a scatter ($< 1.7$) comparable to those among visual classifications of different experienced classifiers.

The classification process has been performed using B-band images for PM2GC galaxies and V-band images for WINGS, after testing that no significant systematic shift in broad morphological classification (ellipticals E, lenticulars S0 or late-types LT) exists between the V and B WINGS images (see Calvi et al. 2012 for details). In Table 1 we list the morphological fractions of elliptical, S0, early-type (ellipticals + S0s) and late-type galaxies in each sample for galaxies with $log_{10} M_*/M_\odot \geq 10.25$.

The morphological catalogue is available online as Table 7 in the electronic version of the journal. The different columns indicate: (1) galaxy serial number in MGC; (2) MORPHOT classification, see Fasano et al. (2012) for a detailed classification scheme. Here, TypeMOR $< -4.25$ Ellipticals, $-4.25 \leq$TypeMOR $\leq 0$ S0s, TypeMOR$> 0$ Late-types, TypeMOR=9.0 for objects that MORPHOT was not able to classify, mostly because suffering of edge problems.

### 3 THE GALAXY MF

#### 3.1 Estimate of galaxy stellar masses and definition of the samples

As argued by Bell & de Jong (2001), the galaxy stellar M/L ratio is a function of color according to the relation

$$\log_{10}(M_*/L_\lambda) = a_\lambda + b_\lambda \text{Color}$$

which is robust to uncertainties in stellar populations and galaxy evolution modeling, including the effects of modest bursts of recent star formation.

As described in Calvi, Poggianti & Vulcani (2011) using equation (1) we derived the stellar masses for PM2GC and WINGS galaxies considering the rest frame $(B-V)$ color, computed from the SDSS Galactic extinction-corrected model magnitudes in $g$ and $r$ (for the PM2GC) and the observed B and V WINGS magnitudes, with $a_B = 0.51$ and $b_B = 1.45$ for the Bruzual & Charlot model, solar metallicity and a Salpeter (1955) IMF (0.1-125 M$_\odot$). Subsequently the masses have been scaled to a Kroupa (2001) IMF

| Envir.  | Ellipticals | S0s     | Late-type | Early-type |
|--------|------------|---------|-----------|------------|
| WINGS  | 33.8±1.5%  | 50.7±1.5%| 15.4±1.0% | 85.4±1.0%  |
| gen.field | 27.0±1.3%  | 28.7±1.3%| 44.3±1.5% | 55.7±1.5%  |
| groups  | 31.8±2.4%  | 31.3±2.4%| 36.9±2.5% | 63.0±2.5%  |
| binary  | 25.3±3.5%  | 25.8±3.6%| 48.8±4.0% | 51.1±4.0%  |
| single  | 21.5±2.3%  | 24.2±2.5%| 54.2±2.8% | 45.7±3.0%  |

Table 1. Fractions of each morphological type in the PM2GC and WINGS mass-limited samples with $M_*/M_\odot = 10^{10.25}$, WINGS = clusters (corrected for completeness). Early-type galaxies comprise ellipticals and S0s. Errors are binomial. Data taken from Calvi et al. (2012) with the correction for groups which now comprises only groups with a velocity dispersion $\sigma < 500\,\text{km s}^{-1}$.
Table 2. Number of galaxies in the PM2GC and WINGS mass-limited samples with $M_\star \geq 10^{10.25} M_\odot$. The WINGS number between brackets is weighted for spectroscopic incompleteness.

| Red. range | Environment | Num. of galaxies |
|------------|-------------|------------------|
| 0.04 < z < 0.07 | clusters | 690 (1056) |
| 0.04 < z < 0.1 | general field | 1188 |
| " | groups | 409 |
| " | binary | 174 |
| " | single | 334 |

The galaxy stellar mass completeness limit was computed as the logarithm of the characteristic stellar mass at which the MF exhibits a rapid change in the slope, and $\Phi^*$ is the normalization.

3.3 Comparison with previous works

First of all we compare our MF with previous results from the literature to check if they are in agreement. Fig. 1 shows the comparison between the MFs of the PM2GC general field and the MFs from 2dFGRS-2MASS (Table 4 in Cole et al. 2001), SDSS-2MASS (Table 5 in Bell et al. 2003), SDSS-DR7 Li & White 2009 and the recent GAMA result from Baldry et al. 2012. All the MFs in this plot are given in units of number per h^{-3} Mpc^3 per decade of mass (dex⁻¹). Masses in $M_\odot$ are all converted to a Kroupa IMF.

For our work, Cole’s, Bell’s and Baldry’s we plot the binned MFs (symbols) and the best-fitting Schechter functions, while for Li & White’s we can only show the Schechter fit they provide (the black short dashed line in the plot).

The shape of our MF is in very good agreement with all previous estimates. As for the absolute normalization, the only MF that tends to be slightly lower is the one from Baldry et al. 2012. The excess of very massive galaxies ($\log_{10} M_\star/ M_\odot > 11.7$) with respect to the Schechter function is similar in our sample and in GAMA, and is present in many previous studies (e.g. Panter et al. 2004; Li & White 2009).

The agreement among the MFs is confirmed by the Schechter parameters. Our $\log_{10} M_\star/ M_\odot = 10.96 \pm 0.06$, $\alpha = -1.1 \pm 0.1$ and $\phi^* = 0.011 \pm 0.004$ are fully consistent with Cole's $\log_{10} M_\star/ M_\odot = 10.97 \pm 0.01$, $\alpha = -1.18 \pm 0.03$ and $\phi^* = 0.009 \pm 0.0014$, Li’s $\log_{10} M_\star/ M_\odot = 10.85 \pm 0.53$, $\alpha = -1.155 \pm 0.008$ and $\phi^* = 0.0083 \pm 0.0002$, and Bell’s $\log_{10} M_\star/ M_\odot = 11.02 \pm 0.02$, $\alpha = -1.10 \pm 0.02$ and $\phi^* = 0.0102 \pm 0.0005$ when they are all converted to our units. Baldry et al. fit their data with a double Schechter therefore parameters cannot be compared.

4 RESULTS: THE MF IN DIFFERENT ENVIRONMENTS

In this section we focus our attention on how the galaxy MF changes with galaxy “global environment” in the local Universe comparing PM2GC and WINGS above our completeness limit of $M_\star = 10^{10.25} M_\odot$. An analysis of the WINGS’s MF down to $M_\star = 10^{9.8} M_\odot$ can be found in Vulcani et al. 2011.

As the presence of Brightest Cluster Galaxies (BCGs), defined as the single brightest galaxy in each galaxy cluster, could alter the total mass distribution we investigated the MFs also excluding the BCGs in the WINGS sample. We remind the reader that, in the case of WINGS, each galaxy is weighted by its correction for spectroscopic incompleteness.

4.1 General field versus clusters

Fig. 2 shows the comparison between the mass distribution of galaxies in the general field and the mass distribution of all cluster galaxies.

Looking at the plot, the overall similarity of the shape of the mass functions of clusters and general field is rather striking. For galaxies with masses up to $\log_{10} M_\star/ M_\odot \sim 11.5$ the MFs overlap, while in at least two of the four most massive bins at $M_\star > 10^{11.5} M_\odot$ the WONGS sample exhibits an excess of
galaxies compared to the PM2GC. This excess is due to the presence of BCG galaxies. Removing the BCGs, the MFs of general field and clusters are similar within the errors at all masses. The K-S test also finds no difference both when we include the BGCs ($P_{K-S} \sim 69\%$) or not ($P_{K-S}^{BCG} \sim 72\%$).

The similarity of the cluster and general field MFs is also confirmed by the Schechter fits shown in Fig. 1 and by the analysis of the best fit parameters, that are similar (inset in Fig. 2 and Table 3). Indeed, taking into account the fact that the two parameters are correlated, we explored a grid of ($\alpha$, $M_\star$) parameters, finding the corresponding $\chi^2$ values and the likelihood of having the same couple of values and found that MFs are in agreement within $1\sigma$. We note that, as seen in previous works (e.g. Panter et al. 2004; Li & White 2009; Baldry et al. 2012), the Schechter function is unable to fit the very massive end.

The general field sample is the sum of group galaxies, (which dominate the general field, and whose MF is very similar to the general field mass function, for its shape, Schechter fit and K-S test), binary system galaxies, single galaxies and galaxies that, although located in a trial group, did not make it into the final group sample. In the following section our aim is to understand if differences in the galaxy MF become appreciable when considering these finer division of environments.

### 4.2 The MF in groups, binaries, singles and clusters

Fig. 3 shows the mass distribution of galaxies comparing different pairs of environments. Also in this case we use the WINGS sample both with and without BCGs. The fact that we consider as group galaxies only those galaxies which are in groups with a velocity dispersion less than 500 km s$^{-1}$ makes us confident that our findings for groups are not influenced by galaxies in structures as massive as WINGS’s, therefore the group and cluster distributions sample truly different environments.

The shapes of the MFs of groups and clusters show a rather similar trend, as expected given the results shown above and the similarity of the general field and group MF. At masses $\log_{10} M_\star / M_\odot < 11.2$ the distributions overlap, while in intermediate mass bins the distribution in groups tends to be higher than the cluster one (top left panel). The K-S test is not able to reveal difference being $P_{K-S} \sim 34\%$ and $P_{K-S}^{BCG} \sim 16\%$ with and without BCGs, respectively. The compatibility of cluster and group MFs is also confirmed by the Schechter fit parameters (Table 3). In addition, we note that both in clusters and groups galaxies more massive than $\log_{10} M_\star / M_\odot > 11.5$ are found, but the cluster MF extends to even higher masses than the groups when including BCGs.

Considering the MF of the single, that is the extreme “low-mass halo” environment, we note that the slope of the single MF in Fig 3 appears steeper than any other environment (groups, binaries and clusters). The K-S test is able to conclude that the MFs of group and isolated galaxies are statistically different ($P_{K-S} < 1\%$). Quite low K-S probabilities (of the order of 7-8%) are also suggesting that the visual differences between the MF of single galaxies and that of clusters and binaries might be real. Indeed, single galaxies have the steepest value of $\alpha$ in the Schechter fit, although the differences with the other environments are not statistically robust given the errors.

For binary galaxies it is difficult to quantify the differences...
given the low number statistics and the fact that the upper mass of binary is lower than the others, as discussed in the next section. From the slope of the binary MF there may be a hint that this is flatter than others at low masses, but no statistically robust difference can be found based on the KS test, and the Schechter parameters are unconstrained for binaries.

To conclude, no statistically significant difference has been found between the galaxy MF in groups and clusters, while a variation with global environment starts to be appreciable when considering single galaxies, that show a steeper MF, therefore are proportionally richer in lower-mass galaxies, than other environments. It is worth noting that single galaxies represent less than a third (28%) of the general field population above our mass limit, as can be inferred from Table 2, therefore their influence on the total general field MF is small.

### 4.3 Cut-off in mass

In addition to the similarities and differences described above, it is interesting to observe that in binary and single systems there are no galaxies with masses \( M_* \geq 10^{11.2} \, M_\odot \) and \( M_* \geq 10^{11.5} \, M_\odot \), respectively, while in groups and clusters there are galaxies up to \( M_* \sim 10^{13.75} \, M_\odot \) and \( M_* \sim 10^{12} \, M_\odot \), respectively, even excluding cluster BCGs. This might suggest that galaxies in different environments could reach different upper masses.

To better quantify the differences, in Table 4 we show the number of galaxies in each environment above and below \( M_* = 10^{11.2} \, M_\odot \) (the upper limit of masses for binary system galaxies), and their number ratio. The ratio varies with environment being higher in clusters, than groups, than single and binary galaxies.

In order to assess the significance of the variation of the upper mass limit we performed a Montecarlo simulation to understand whether this effect could be due to low number statistics in the least massive environments.

Using each time 1000 simulations, we extracted from the group sample the same number of galaxies once as in the single sample and once as in the binary sample, and then extracted from the single sample the same number of galaxies as in binary systems.

In Table 5 we show the median upper masses for the different simulations: they are always significantly higher than the cut-off mass observed in singles and binaries.

| Environment          | Median upper mass \((M_*)\) |
|----------------------|-----------------------------|
| groups-bin           | 10^{11.7}                   |
| groups-sim           | 10^{11.8}                   |
| sin-bin              | 10^{11.4}                   |

### Table 3. Best-fit Schechter parameters for the different samples.

| Environments | \(\alpha\) | \(\log_{10} M^*\) | \(\phi^*(h^3 \text{Mpc}^{-3} \log_{10}(M^{-1}))\) |
|--------------|-----------|-----------------|-----------------------------------------------|
| WINGS        | -1.1 ± 0.3 | 10.96 ± 0.15    | \ldots                                      |
| WINGsexBCG   | -1.1 ± 0.2 | 10.90 ± 0.09    | \ldots                                      |
| general field| -1.1 ± 0.1 | 10.96 ± 0.06    | (1.1 ± 0.4) \times 10^{-2}                  |
| groups       | -1.2 ± 0.1 | 11.05 ± 0.08    | (0.3 ± 0.1) \times 10^{-2}                  |
| single       | -1.3 ± 0.1 | 10.94 ± 0.04    | (0.3 ± 0.1) \times 10^{-2}                  |
| binary       | -0.6 ± 0.5 | 10.75 ± 0.23    | (0.3 ± 0.1) \times 10^{-2}                  |

### Table 4. Number of galaxies in the PM2GC and WINGS mass-limited samples with mass \( M_* \geq 10^{11.2} \, M_\odot \) and \( M_* < 10^{11.2} \, M_\odot \) and their ratio as a percentage.

| Environment          | \(M_* \geq 10^{11.2} \, M_\odot\) | \(M_* < 10^{11.2} \, M_\odot\) | \(M_\odot(11.2)/M_\odot(11.2)\) |
|----------------------|-------------------------------|-------------------------------|---------------------------------|
| WINGS(exBCGs)        | 46 (34)                       | 644                           | -                              |
| general field        | 52                            | 1136                          | 7.1 ± 1.15\% (5.2 ± 0.9\%)      |
| groups               | 23                            | 386                           | 6.0 ± 1.2\%                    |
| binary               | 0                             | 174                           | 0.0 ± 1.1\%                    |
| single               | 12                            | 322                           | 3.7 ± 1.1\%                    |

Table 5. Fractions of simulations which reach an upper mass at least as low as the observed mass +0.1dex and values of the median upper mass reached in the Montecarlo simulations comparing group and binary, group and single, single and binary samples.
5 THE GALAXY MF BY MORPHOLOGICAL TYPE

In the previous sections we found the somewhat unexpected result that the MF is similar in different global environments, except when analyzing single galaxies separately and when studying in detail the cut-off mass.

Now we attempt to examine the MF of different morphological types, to address two main questions: how the MF differs from a galaxy type to the other, and whether the MF of each given type varies with environment.

5.1 The galaxy MF of different morphological types in each given environment

We start analyzing the MFs of different morphological types in each given environment. In this case, we don’t apply any normalization to the MFs, to show which morphological type dominates in number as a function of mass. Table 6 gives the best fit Schechter parameters and Fig. 4 shows the mass distributions of galaxies in each environment.

In the general field (bottom left panel), the total MF is dominated by late-type galaxies at low masses ($\log(M_*/M_\odot) \lesssim 11$), and by a mix of late-types and ellipticals at higher masses. Instead, in the single and binary systems (central and right upper panels), it is dominated by late-type galaxies at all masses. In groups (upper left panel), the most numerous types at masses $\lesssim 11$ are late-types and S0s, except in the first mass bin (10.25 – 10.5) where late-type
Figure 4. Mass distribution of galaxies in the groups (top left panel), single (top middle panel), binary (top right panel), general field (bottom left panel), clusters (bottom right panel). The K-S probabilities are shown. Red triangles are elliptical galaxies, green squares S0s and blue crosses late-type galaxies. Lines represent Schechter fits. Errors are poissonian errors in the $y$ direction and are equal to the bin size in the $x$ direction. Numbers in brackets are the number of galaxies in each morphological class, above the respective mass limit and are weighted for WINGS.

From Fig. 4 it is clear that the shape of the MF depends on the morphological type in most environments. This is confirmed by the K-S test, which finds incompatible distributions for ellipticals, S0s and late-types in the general field, in groups and in clusters, with the exception of cluster S0s and late-types whose MFs are less distinguishable. These conclusions are generally confirmed by the Schechter fit parameters shown in the insets of Fig. 4.

For binary system galaxies, the K-S test and the analysis of the Schechter fits are inconclusive due to low number statistics, but in the plot the late-type MF appears to be significantly different from the MFs of the other types ($P_{K-S} = 5.9$ and 12.0 for ellipticals-late-types and S0-late-types, respectively).

For single galaxies, the shape of the MF varies little between late-type galaxies and ellipticals, and may differ for S0s, as suggested also by the Schechter fit parameters. The K-S test is always inconclusive.

We note from Table 6 that in all environments the S0’s $M^*$ value is significantly lower than those of ellipticals and late-types, except in clusters where the late-type $M^*$ is almost as low as that...
of S0s. The lowest S0 $M^*$ value is reached in the single and binary samples. The $M^*$ values of ellipticals and late-type galaxies are similar in all environments, except in clusters where the elliptical $M^*$ is significantly higher.

We conclude that in general field the shape of the MF changes from one morphological type to another, but in a way that depends on global environment. The cluster morphological MFs have a peculiar behaviour, both for the MF shape of the various types and their relative numbers. In the next section we examine in detail the MF of each morphological type in different environments.

5.2 The MF of ellipticals, S0s, early-type and late-type galaxies in the general field versus clusters

The comparison between the mass distribution of elliptical, S0, early and late-type galaxies of general field and clusters is shown in Fig. 5.

In all cases, the K-S test is unable to detect any significant difference between general field and clusters. The analysis of the Schechter parameters (Table 6) and the inspection of the plot, instead, reveal a few differences.

Ellipticals in clusters, even when excluding the BCGs, have a higher $M_e$ and a lower value of $\alpha$ than ellipticals in the general field. This is due to the excess of ellipticals with masses $\log M_*/M_\odot > 11.5$ in clusters compared to the field visible in the top left panel of Fig. 5.

The Schechter parameters for S0s in clusters and general field are instead statistically indistinguishable. We note that, given the large errorbars, the S0 Schechter $\alpha$ is essentially unconstrained, and a visual inspection of the plot may suggest a steeper low-mass end in clusters.

When ellipticals and S0s are considered together, the early-type MF is similar in clusters and in the general field, and also the Schechter parameters are compatible. The environmental variation of the MF of ellipticals seen in the top left panel gets diluted when adding them up with lenticulars, and no significant difference with environment is left when considering all early-type galaxies. Looking at the numbers in the plots, one can notice that the general field consists of a similar number of ellipticals and S0s, while WINGS clusters are dominated by S0s. The morphological fractions are given in Table 1, and a detailed study of the variation of the morphological mix with environment can be found in Calvi, Poggianti & Vulcani (2011).

Coming to late-type galaxies, at low masses the shape of their mass function in WINGS is slightly flatter than in general field. As also indicated by the Schechter $\alpha$ parameter, there is a small relative deficit of low-mass late-type galaxies in clusters compared to the general field.

In conclusion, the only variations we are able to detect are an excess of massive ellipticals and a small deficit of low mass late-type galaxies in clusters compared to the general field. We cannot exclude that, with better statistics, environmental variations of the S0 MF could be found.

5.3 The shape of the galaxy MF of each morphological type in different environments

As for the total galaxy MFs, now we investigate the variation of the MF of elliptical, S0, early and late type galaxies in clusters, groups, binaries and singles. Fig. 6 shows the distributions of each morphological class. Subdiving our samples in both morphological type and detailed environment, the statistics get worse, and in most cases the errors on the Schechter parameters become too large to draw robust conclusions. In particular, the binary sample is always too poor to be compared with the others, and is not included in the following analysis. Schechter parameters are anyway listed for completeness for all environments in Table 7.

Comparing clusters and groups, which are the two environments with the best statistics, we find small differences in the MF of ellipticals, as seen in Fig. 6 from the K-S and the Schechter fits. Ellipticals in the single sample, instead, show a steeper MF than those in groups and clusters, as seen in the plot and, marginally, found by the K-S for groups.

The mass distribution of S0 galaxies in clusters and groups is indistinguishable on the basis of the K-S test and of the Schechter parameters, although the inspection of Fig. 6 shows a possible steepening at low masses in clusters. The S0 MFs of single galaxies is too noisy to draw secure conclusions, but the plot is suggestive of a steep fall-off at high masses.

For the early-type MF small differences start to be appreciable between clusters and groups especially when excluding cluster BCs; both the K-S and the Schechter $\alpha$ show differences at the 1-2$\sigma$ level. Moreover, the differences in the MF of singles and groups are now statistically significant and differences singles-clusters are clearly visible in the plot.

Finally, we consider the mass distributions of late-type galaxies. The shape of their MF is very similar in groups and singles, while in clusters there is a flattening at masses $\log 10 M_*/M_\odot < 10.65$, corresponding to a much higher Schechter $\alpha$ value. This may correspond to the steepening in the MF of cluster S0s at these masses, if preferentially low-mass late-types are transformed in S0s by the cluster environment.

To summarize, the MFs of ellipticals and S0 galaxies show small differences between clusters and groups, while their distributions appear much steeper in the single galaxy sample. Therefore, isolated elliptical have on average lower masses than cluster and group ellipticals.

The mass distribution of late-type galaxies is similar in all environments, except for a deficit of low-mass late-types in clusters. These environmental variations are consistent with those found in the previous section between general field and clusters, where we observed an excess of massive ellipticals in clusters compared to the general field, obviously driven by the steep high-mass fall-off of the elliptical MF in single galaxies, and the deficit of low-mass late-types in clusters.

6 DISCUSSION

Our most important result is the intriguingly weak environmental dependence of the galaxy stellar MF. Above $\log 10 M_*/M_\odot = 10.25$, the MF in the general field, and in groups – which are the dominant component of the general field – is similar to that in clusters.

It is important to emphasize that our sample consists of galaxies with masses at least half of our Milky Way, and that stronger variations of the MF with global environment can exist at lower galaxy masses than those considered in this study.

Our results disagree with the conclusions of Balogh et al. (2011), while agree with von der Linden (2010). Balogh et al. (2011) found a much higher $M^*$ and a much lower $\alpha$ in clusters than in the general field in a sample that uses 2MASS photometry and Las Campanas Redshift Survey spec-
Figure 5. Comparison of the mass distribution of general field and WINGS for elliptical galaxies (top left panel), S0 galaxies (top right panel), early-type galaxies (bottom left panel) and late-type galaxies (bottom right panel). Errors are defined as poissonian errors in the $y$ direction and equal to the bin size in the $x$ direction. Numbers in the brackets are the number of galaxies of each type above the mass limit (for WINGS the number is weighted for incompleteness). The K-S probabilities are also shown in the bottom left corner. Mass distributions are normalized using the total integrated stellar mass, above the mass completeness limit.

7 SUMMARY

We have analyzed the low-z stellar MF of galaxies with masses $\log_{10} M_*/M_\odot \geq 10.25$ in different global environments, from clusters, to groups, binary and single galaxies, and the general field.

The main result of our work is the overall striking independence of the shape of the MF on global environment. Contrary perhaps to most expectations, the MF in the general field is indistinguishable from that in clusters. The cluster and the group MFs are also very similar, with only subtle differences allowed at best.

The only environment where the MF differs significantly is the sample of single galaxies, representing the lowest mass haloes containing the most isolated galaxies and comprising about one third of the general field population. The single galaxy MF is steeper, proportionally richer in lower-mass galaxies, than other environments.

What varies with global environment is the maximum mass reached by galaxies: the upper MF cut-off varies from $1.6-3.5 \times 10^{11} M_\odot$ in binaries and single galaxies, to $5.6 \times 10^{12} M_\odot$ in groups and $10^{12}$ in clusters, even excluding the cluster BCGs.

In line with theoretical expectations, this indicates that the most massive galaxies are only formed in the most massive environments/haloes.

We stress that a stronger dependence of the MF on environment may of course exist at lower galaxy masses than those considered in this study, and that our sample includes galaxies down to masses about half of our Milky Way.

Our results resemble those at higher redshifts of [Vulcani et al. 2012], that found a similar MF in clusters, groups and general field.
at $z = 0.4 - 0.8$, and a surprisingly similar evolution of the MF in clusters and the field between $z \sim 0.8$ and today. Their study could not discriminate single galaxies. In fact, our results are also in agreement with those at intermediate redshifts of [Kovac et al. (2010)], that found a difference in the mass function of group and isolated galaxies (their Fig. 7).

In the second part of our paper we have presented the MF of different morphological types (ellipticals, S0s and late-types) in different environments. We have shown how the MF changes from one type to another in each environment, and that the mass function of a given morphological type may vary with environment. The strongest environmental dependence is for the (massive) ellipticals, while only very small differences are observed for spirals. These findings imply that both galaxy mass and environment must play some role in establishing the distribution of morphological types we observe in the local Universe.

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Table 6. Best fit Schechter parameters for PM2GC groups, binary systems, single, general field and WINGS clusters.

| Environment | morph. type | $\alpha$ | $\log_{10} M^* / M_\odot$ | $\phi^*$ | $h^3 \text{Mpc}^{-3} \log_{10} (M^{-1})$ |
|-------------|-------------|----------|--------------------------|---------|-----------------------------------|
| WINGS       | E           | -1.5 ± 0.2 | 11.62 ± 0.25             | 53.2 ± 39.4 | ..... |
|             | EnoBCG      | -1.4 ± 0.2 | 11.54 ± 0.27             | 64.9 ± 51.6 | ..... |
|             | S0          | -0.6 ± 0.3 | 10.61 ± 0.10             | 849.8 ± 154.2 | ..... |
|             | late        | -0.6 ± 0.5 | 10.77 ± 0.20             | 206.6 ± 78.2 | ..... |
|             | early       | -1.1 ± 0.3 | 10.91 ± 0.16             | 712.2 ± 332.8 | ..... |
|             | earlynoBCG  | -1.0 ± 0.2 | 10.89 ± 0.11             | 775.1 ± 248.0 | ..... |
| general field | E           | -1.0 ± 0.2 | 11.06 ± 0.10             | 208.9 ± 61.2 | (2.8 ± 0.8) × 10^{-3} |
|             | S0          | -0.4 ± 0.4 | 10.63 ± 0.12             | 520.4 ± 93.1 | (7.1 ± 1.2) × 10^{-3} |
|             | late        | -1.4 ± 0.1 | 11.03 ± 0.08             | 271.9 ± 77.0 | (3.7 ± 1.0) × 10^{-3} |
|             | early       | -0.9 ± 0.1 | 10.90 ± 0.07             | 612.8 ± 112.0 | (8.3 ± 1.5) × 10^{-3} |
| groups      | E           | -1.1 ± 0.2 | 11.26 ± 0.16             | 57.4 ± 27.8 | (0.8 ± 0.4) × 10^{-3} |
|             | S0          | -0.5 ± 0.3 | 10.70 ± 0.09             | 178.0 ± 29.1 | (2.4 ± 0.4) × 10^{-3} |
|             | late        | -1.4 ± 0.3 | 11.10 ± 0.26             | 65.0 ± 56.7 | (0.9 ± 0.8) × 10^{-3} |
|             | early       | -1.1 ± 0.1 | 11.09 ± 0.09             | 156.8 ± 42.1 | (2.1 ± 0.6) × 10^{-3} |
| binary      | E           | -0.5 ± 1.7 | 10.85 ± 0.85             | 48.2 ± 62.1 | (0.6 ± 0.8) × 10^{-3} |
|             | S0          | 0.7 ± 0.7  | 10.41 ± 0.14             | 64.1 ± 18.3 | (0.9 ± 0.2) × 10^{-3} |
|             | late        | -1.3 ± 0.4 | 11.00 ± 0.30             | 53.6 ± 47.4 | (0.7 ± 0.6) × 10^{-3} |
|             | early       | 0.1 ± 0.8  | 10.58 ± 0.21             | 137.7 ± 17.4 | (1.9 ± 0.2) × 10^{-3} |
| single      | E           | -1.4 ± 0.5 | 11.00 ± 0.30             | 38.2 ± 39.9 | (0.5 ± 0.5) × 10^{-3} |
|             | S0          | -0.2 ± 0.9 | 10.42 ± 0.20             | 158.2 ± 27.8 | (2.1 ± 0.4) × 10^{-3} |
|             | late        | -1.5 ± 0.1 | 11.08 ± 0.09             | 76.4 ± 23.7 | (1.0 ± 0.3) × 10^{-3} |
|             | early       | -1.1 ± 0.2 | 10.82 ± 0.10             | 147.7 ± 42.3 | (2.0 ± 0.6) × 10^{-3} |

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Figure 6. Mass distribution for different pairs of environments for ellipticals, S0s, early-types and late-types. Errors are defined as poissonian errors in the \( y \) direction and are equal to the bin size in the \( x \) direction. Mass distributions are normalized using the total integrated stellar mass, above the mass completeness limit. Numbers in the brackets are the number of galaxies above the mass limit and are weighted for WINGS.
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