NO EVIDENCE FOR A DEPENDENCE OF THE MASS–SIZE RELATION OF EARLY-TYPE GALAXIES ON ENVIRONMENT IN THE LOCAL UNIVERSE

M. Huertas-Company1,4, F. Shankar1,4, S. Mei1,4, M. Bernardi2, J. A. L. Aguerr3,5, A. Meert2, and V. Vikram2

1 GEPI, Paris Observatory, 77 Avenue, Denfert-Rochereau 75014, Paris, France
2 Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
3 Instituto de Astrofisica de Canarias, E-38200 La Laguna, Tenerife, Spain

ABSTRACT

The early-type galaxy (ETG) mass–size relation has largely been studied to understand how these galaxies assembled their mass. One key observational result of the last years is that massive galaxies increased their size by a factor of a few at fixed stellar mass from $z \sim 2$. Hierarchical models favor minor mergers as a plausible driver of this size growth. Some of these models predict a significant environmental dependence in the sense that galaxies residing in more massive halos tend to be larger than galaxies in lower mass halos, at fixed stellar mass and redshift. At present, observational results of this environmental dependence are contradictory. In this paper we revisit this issue in the local universe, by investigating how the sizes of massive ETGs depend on a large-scale environment using an updated and accurate sample of ETGs in different environments—field, group, and clusters—from the Sloan Digital Sky Survey DR7. Our analysis does not show any significant environmental dependence of the sizes of central and satellite ETGs at fixed stellar mass at $z \sim 0$. The size–mass relation of early-type galaxies at $z \sim 0$ seems to be universal, i.e., independent of the mass of the host halo and of the position of the galaxy in that halo (central or satellite). The result is robust to different galaxy selections based on star formation, morphology, or central density. Considering our observational errors and the size of the sample, any size ratio larger than 30%–40% between massive galaxies ($\log(M_*/M_\odot) > 11$) living in clusters and in the field can be ruled out at 3σ level.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: halos

Online-only material: color figures

1. INTRODUCTION

The study of scaling relations at low and high redshift (e.g., Bernardi et al. 2010, 2011; Shankar et al. 2010) is a powerful tool to constrain models of galaxy evolution. The mass–size relation has largely been studied in recent literature. One key observational result arising from many of these works is that massive galaxies experienced a strong size evolution in the last 10 Gyr, e.g., a significant fraction of them increased their size by a factor of two to three from $z \sim 1$ and by three to five from $z \sim 2$ (e.g., Daddi et al. 2005; Trujillo et al. 2006; van der Wel et al. 2008; van Dokkum et al. 2008; Buitrago et al. 2008; Damjanov et al. 2011; Cimatti et al. 2012; Huertas-Company et al. 2013; Raichoor et al. 2012; Mei et al. 2012).

Models of galaxy formation have proposed two main mechanisms to increase the size of early-type galaxies (ETGs). Fan et al. (2008) proposed mass loss from active galactic nucleus feedback as the main process responsible for galaxy expansion (expansion scenario), while Hopkins et al. (2009) and Naab et al. (2009) argued that minor dry mergers are the most efficient mechanism (see also Shankar et al. 2013a). Since both mechanisms act in different timescales (e.g., Ragone-Figueroa et al. 2012) and leave different imprints in the galaxy structure (e.g., Hopkins et al. 2009), these observables are largely used to constrain the models. Observational evidence supporting one of the above theoretical proposals is still debated in the literature. On the one hand, Trujillo et al. (2011) reported that the low scatter in the ages of galaxies is difficult to reconcile with the fast growth predicted by the expansion scenario and van Dokkum et al. (2010) and Patel et al. (2012) showed that galaxies grow inside-out and increase their Sersic index, which are clear predictions of the merger models. Alternatively, Ascario et al. (2011) claim significant evolution in size but no change in Sersic index for the brightest cluster galaxies, supporting an expansion scenario rather than a merger-driven one. Also, Newman et al. (2012) reported recently that only when a short dynamical timescale is assumed, can mergers alone explain the growth shown by the data from $z \sim 1$ (see also López-Sanjuan et al. 2012). Huertas-Company et al. (2013) showed that several state-of-the-art semi-analytical models struggle to fully reproduce the size evolution for galaxies at fixed $\log(M_*/M_\odot) > 11.2$ (see also Nipoti et al. 2012). The exact abundance of compact galaxies in the local universe is still debated (e.g., Valentinuzzi et al. 2010; Poggianti et al. 2012; Trujillo et al. 2009) and the impact of newly born galaxies is not fully understood (e.g., Newman et al. 2012; López-Sanjuan et al. 2012; Kaviraj et al. 2013). The morphological evolution of these massive galaxies and how it affects size evolution is also unclear (e.g., Buitrago et al. 2011; Huertas-Company et al. 2013; van der Wel et al. 2011; van Dokkum et al. 2011).

Environment is another powerful observable that can shed new light into the puzzle. Some hierarchical models predict a significant environmental dependence in that galaxies residing in more massive halos tend to be larger than galaxies in lower mass halos, at fixed stellar mass and redshift (e.g., Shankar et al. 2013a). Observational studies at different redshifts however have led to controversial results. Three works at $z \sim 0$, $z < 0.4$ and $z \sim 1.2$ (Weinmann et al. 2009; Maltby et al. 2010; Rettura...
et al. 2010) did not find any significant trend of the mass–size relation with environment. Valentinuzzi et al. (2010) found, however, a high fraction of super dense galaxies in clusters in the local universe, a result that is confirmed by Poggianti et al. (2012), who also claimed that early-type galaxies in clusters are slightly smaller than those in the field at fixed stellar mass. At $z \approx 1.3$, Raichoor et al. (2012) studied a sample of morphologically selected early-type galaxies in three different environments (field, cluster, and groups) and found that, on average, for masses $10 < \log(M/M_\odot) < 11.5$, cluster galaxies have either the same size or appear to be smaller at fixed stellar mass than field galaxies, depending on the stellar population model used. More recently, Huertas-Company et al. (2013) did not detect any correlation with environment below $z \sim 1$ up to the group scale ($\log(M_h/M_\odot) < 14$). In the same stellar mass range, but using a different definition for environment, Cooper et al. (2012) found exactly the opposite trend. Larger sizes in the cluster environment are also observed at $z = 1.62$ by Papovich et al. (2012) for passive galaxies with stellar masses larger than $\log(M/M_\odot) \sim 10.5$ and by Delaye et al. (2013) in a sample of clusters at $0.8 < z < 1.5$ with a similar selection (see also Lani et al. 2013). The differences between these works are still to be understood and might come from different sample selections, the way environment is measured, and low statistics at high redshift.

In this paper, we revisit this issue by studying the mass–size relation of central and satellite ETGs in different environments selected from the Sloan Digital Sky Survey (SDSS) DR7 (Abazajian et al. 2009) with an updated and accurate sample. The large statistics available make the SDSS the best sample to probe the environmental dependence of galaxy sizes. We probe a halo mass range $12 < \log(M_h/M_\odot) < 15$.

2. ETG SAMPLE SELECTION

We select our ETG galaxy sample from the SDSS DR7 spectroscopic sample (Abazajian et al. 2009). We select galaxies with an early-type morphology based on the galaxy morphological classification from Huertas-Company et al. (2011).6 We perform a Bayesian automated classification of the full SDSS DR7 spectroscopic sample based on support vector machines and associate to every galaxy a probability to be in four morphological classes (E, S0, Sab, and Scd). In this work, we select as ETGs those objects with a probability to be early-type (E or S0) greater than 0.8. Results do not change significantly if the probability threshold is changed between 0.5 and 0.8.

To probe halos of different mass, we use the group and cluster galaxy sample from Yang et al. (2007), updated to the DR7.7 This catalog of $\sim 300,000$ clusters and groups ($\sim 30,000$ with more than two members) was built using an automated halo-based group finder and provides an estimate through abundance matching of the halo mass in which galaxies are located. For this work, we restricted the analysis to groups with $z < 0.09$ (for completeness reasons) and at least two members and removed those objects affected by edge effects ($f_{\text{edge}} < 0.6$). With this selection, we expect that $\sim 80\%$ of these groups have less than $\sim 20\%$ contamination from interlopers (Yang et al. 2007). We use as halo mass estimate HM1, which is based on the characteristic luminosity of the group, but results remain unchanged when using a halo mass estimate based on the characteristic stellar mass. The expected uncertainties on halo masses are $0.2–0.3$ dex according to Figure 7 of Yang et al. (2007) in which they compare estimated to true halo masses from a mock catalog. The abundance matching using luminosity (or stellar mass) through which the halo masses are derived might have an impact on the results. We discuss the implications of these uncertainties in our main results.

Galaxy sizes are circularized effective radii obtained from the two-dimensional Sersic fit using the PyMorph package (Vikram et al. 2010), which can fit two convolved components models to observed surface brightness profiles. We perform bulge-to-disk and single Sersic decompositions to $\sim 7 \times 10^5$ galaxies from the SDSS DR7. The algorithm is described and tested in Meert et al. (2012). The sky estimate and how it affects size measurements is fully discussed in the mentioned work (see Section 3.6). Through extensive simulations, we show that the sky estimate with PyMorph is underestimated by 0.1%, which has no major impact in the size estimate (<10%). It is also shown that a bias in the sky value larger than 0.5% is required to have a significant impact on the size (>10%). For what concerns our work, the important result is that sizes are unbiased with a typical scatter <0.1 dex (which depends on luminosity). For consistency with high redshift works, we use the sizes estimated from single Sersic fits, which are shown to be less accurate than the ones obtained with two component models (Bernardi et al. 2012). Our results are not affected by this choice.

Mass-to-light ratios are obtained from the MPA-JHU DR7 release.8 They are derived through spectral energy distribution fitting using BC03 synthesis population models (Bruzual & Charlot 2003) and a Kroupa initial mass function (IMF) following the procedure presented in Kauffmann et al. (2003) and Salim et al. (2007). We then convert to stellar masses by multiplying the M/L of each galaxy by its luminosity estimated from the best fit Sersic model. To compare with models, we also apply a 0.05 dex shift to convert to a Chabrier IMF following Bernardi et al. (2010). The typical error expected for photometrically derived stellar masses is $\sim 0.2$ dex, which is the value that is used (e.g., Bernardi et al. 2010).

The final sample contains $\sim 12,000$ ETGs with $\log(M_*/M_\odot) > 10.5$ and $z < 0.09$, located in groups and clusters with halo masses from $M_h/M_\odot \sim 10^{12.5}$ to $M_h/M_\odot \sim 10^{15}$.

3. RESULTS

3.1. Mass–Size Relation of ETGs in Different Environments

Figure 1 shows the observational median stellar-mass relation for centrals, satellites, and all galaxies in halos of increasing mass, typically corresponding with field, group and cluster environments. Central galaxies are defined in all this work as the most massive galaxies in a given halo. For some groups, the central is not the same galaxy defined by Yang et al. (2007) because we reprocessed stellar masses using the Sersic luminosity, as explained in Section 2. The main results remain, however, unchanged when using the original definition. Our first result is that the mass–size relation of satellite and central galaxies do not show any significant trend with environment; they present similar mass–size relations independently of the mass of the host. We confirm the preliminary results with Weinmann et al. (2009), but with a much larger sample and better defined sizes and morphological classification. We notice, however, that, in a recent work using an independent dataset, Poggianti et al. (2012) found that the mass–size relation of
cluster galaxies lies slightly below (∼1σ) the relation for field galaxies (see also Valentinuzzi et al. 2010). It is still unclear what makes the difference and requires further investigation. Morphological selection could, for example, play a role since the Poggianti et al. (2012) sample seems to be dominated by lenticular galaxies, which have been shown to be systematically smaller than elliptical galaxies at fixed stellar mass (Bernardi et al. 2012; Huertas-Company et al. 2013; see also Section 4.1) when the size is estimated with a single Sersic profile and then circularized. In the Poggianti et al. (2012) sample, there are ∼50% S0s in clusters but only ∼30% in the field (private communication), which would partially explain why they find smaller galaxies in clusters. What seems to arise from these works is that, if there is a difference with environment at z ∼ 0, then it must be small. Moreover, at fixed halo-mass, satellites and centrals present similar mass–size normalizations (Figure 2) and scatter, which suggests that the mass–size relation is universal, independent of the position of the galaxy in the halo.

3.2. Mh–γ Relation of Massive ETGs

Though galaxies of similar mass share similar size distributions irrespective of their environment, we cannot directly rule out some intrinsic environmental dependence. The intrinsic scatter of the mass–size relation for massive ETGs (∼0.2 dex; e.g., Bernardi et al. 2011, 2012; see also Figure 1) puts an upper limit to that effect, i.e., galaxies in massive halos can be, at most, a factor three (2 × 10^{0.2}) times larger than the same galaxies living in small halos. As a result, the detection of the signal might be difficult given the observational uncertainties in the different variables at play (sizes, halo masses, galaxy classification, and stellar masses), which can reduce any observed trend (see Sections 4.2).

In the next two sections we focus on the high-mass end of the mass function (where the impact of mergers should be more pronounced) and look in detail for environmental effects, taking into account as much as possible the effects of observational biases and errors.

To this purpose, we analyze the Mh–Re relation, which gives the median size of ETGs at fixed stellar mass as a function of environment. While there is a well known correlation between the mass of the halo and the stellar mass of galaxies populating it (e.g., Lin & Mohr 2004), the scatter of that relation is large enough so that galaxies of a fixed stellar mass populate a large range of halos (Figure 3), allowing a study of environmental effects at fixed stellar mass.

Our main results are shown in Figure 4 for central galaxies in two stellar mass bins (11 < log(M∗/M⊙) < 11.5 and 11.5 < log(M∗/M⊙) < 12) and for satellite galaxies in one single stellar mass bin (massive satellites only exist in massive halos). We use large stellar mass bins to increase statistics and minimize the impact of errors in stellar mass (∼0.2 dex). However, this choice could induce false correlations between
size and environment, since more massive galaxies and hence larger galaxies are prone to existing in massive halos given the existing correlation between $M_h$ and $R_e$. To get rid of this effect, we use normalized sizes ($\gamma$) following a similar procedure to the one explained in Newman et al. (2012) and Cimatti et al. (2012):

$$\log_{10}(\gamma) = \log_{10}(R_e) + \beta(11 - \log_{10}(M_*/M_0)), \tag{1}$$

where, $\beta$ is the slope of the $M_*/R_e$ relation in the considered mass interval and $R_e$ is the effective radius. We use a value of $\beta = 0.83$, which is the slope measured in the mass–size relation for galaxies with $\log(M_*/M_0) > 11$.

Finally, since we are interested in relative differences between the different environments, we normalize all sizes to the median size in the halo mass bin $M_h/M_0 = 10^{12.5} - 10^{13}$. That way, by definition, all median sizes in that halo are equal to one. Uncertainties on the median values are computed through bootstrapping, i.e., we repeat the computation of each value 1000 times, removing one element each time, and compute the error as the scatter error of all the measurements.

The most striking result is that the $\gamma-M_h$ relation is essentially flat, independent of the stellar mass and of the position of the galaxy in the halo, i.e., sizes of massive EGTs are the same at all environments within the errors. In the next section, we discuss the robustness of this result to observational errors and selection effects.

4. DISCUSSION

4.1. Selection Effects

In the previous sections, we show results for galaxies selected at fixed stellar mass and with early-type morphology. We investigate, in this section, the impact of the selections in our results.

4.1.1. Stellar Mass Selection

While in the expansion scenario (see Section 1), galaxies puff-up at constant stellar mass, in the merger model, galaxies contemporarily also grow in mass by a factor two to three (Naab et al. 2009). Studying environmental dependence at fixed stellar mass may thus not be the ideal choice to test hierarchical scenarios, though we expect this to have a small effect in our results given the large bins of stellar mass used (0.5 dex). To be effective, it seems, in increasing sizes, minor mergers should preferentially increase the outskirts of the stellar distributions, leaving the central regions more or less intact. Therefore, one alternative way to probe environmental effects could be to fix central-mass density instead of total stellar-mass. Results are shown in Figure 5 for central galaxies with central densities that roughly correspond to galaxies of $\sim 10^{11}$ solar masses. Projected central densities are computed in the inner 1 Kpc, using the best fit profiles as done, for instance, by Saracco et al. (2012). The observed trend in the $M_h-\gamma$ plane is still consistent with no environmental dependence. The $\beta$ normalization factor to compute $\gamma$ (see Equation (1)) is larger than the one used at fixed stellar mass since the mass–size relation is steeper when the central mass density is fixed (see middle panel of Figure 5).

4.1.2. Morphology Selection

An observational signature of merger models (see Section 1) should be a systematic increase in the Sersic index with time, while the expansion scenario tends to preserve the original profile, at least up to 50% of mass loss (Ragone-Figueroa et al. 2012). Thus, in a hierarchical scenario, more evolved systems (those with more mergers) are expected to have, on average, higher Sersic indices (e.g., Hopkins et al. 2009).

By selecting only early-type galaxies in our study, we might be biased toward higher values of the Sersic index, and might not be properly considering a wide enough dynamic range to probe different growth histories. Our selection of EGTs might artificially flatten the signal since we might be preferentially selecting objects with high Sersic index, with an assembly history possibly dominated by mergers, and missing objects with lower Sersic index, mostly grown in situ (which could be more common in low density environments). If we do not apply any morphological selection, however, we might detect an environmental signal if the morphological mixing changes significantly with environment, since it is known that size and morphologies correlate. In Figure 6, we show that the Sersic index distribution of the selected galaxies is broad (even if dominated by high values), indicating that we are probing different formation histories. The distributions change slightly if the selection is based on stellar mass or star formation (instead of morphology) as expected but, most importantly, our main results discussed previously remain unchanged. In Figure 7, we show the $\gamma-M_h$ plane for different selections in the stellar mass range $11 < \log(M_*/M_0) < 11.5$ (ETGs, lenticulars, ellipticals, passive, or no selection at all). The selection of passive galaxies is based on the total median specific star formation rates (sSFRs), computed by Brinchmann et al. (2004). More precisely, we select as passive galaxies those objects with $-15 < \log(sSFR(\gamma^{-1})) < -11.5$ based on the bimodal distribution of the sSFR. We do not normalize here to explicitly measure the different normalizations between

---

http://www.mpa-garching.mpg.de/SDSS/DR7/sfrs.html.
Figure 5. $M_h - \gamma$ plane at fixed central-mass density. Left panel shows the relation between stellar mass and central density for central ETGs. Red lines indicate the range of central mass densities considered to produce the plots on the middle and right panels. The middle panel shows the mass–size relation for the selected galaxies in three environments. The right panel shows the $M_h - \gamma$ plane for ETGs with $10^{9.8} < \rho < 10^{10.1}$. The trend is still consistent with no environmental dependence.

Values have been normalized so that, by definition, the field observed value at a halo mass of $\log(M_h/M_\odot) = 12.5$–13 is equal to 1. Errors in models and observations are errors on the median values computed through bootstrapping.

(A color version of this figure is available in the online journal.)

Figure 6. Sersic index distribution for galaxies with $\log(M_*/M_\odot) > 11$ for different selections.

(A color version of this figure is available in the online journal.)

the different selections. All selections show a behavior consistent with no environmental dependence. The samples without morphological selection present slightly higher sizes due to the contamination of spiral galaxies. The most noticeable difference appears in the lenticular population which is systematically $\sim 15\%$ smaller than all the other selections (including ellipticals). This fact has already been noticed by Bernardi et al. (2012) and Huertas-Company et al. (2013) at $z \sim 1$ and it is consistent with the recent claims that the most compact galaxies have a disk component (e.g., Trujillo et al. 2012; van der Wel et al. 2011; Chang et al. 2013). Most of this effect is because of the way sizes are computed, i.e., we use a single Sersic to model the light of a galaxy with two components by definition and the radii are circularized with values of $b/a$, which are smaller on average since S0s are better identified when they present high inclinations.

4.2. Can Errors Wash Out the Signal?

As previously stated, the scatter of the mass–size relation for massive galaxies is not large, a factor of 1.5–2, typically. Therefore, the environmental signature is bounded to a factor three to four at most. We must learn if the lack of dependence on environment we measure is a consequence of observational errors in the different parameters involved ($M_h, M_*, R_e$), which could wash out the signal or a real signature.

We investigate, in this section, through Monte Carlo simulations, what the global effect of statistical errors is on a possible existing signal. To that purpose, we create an artificial trend with environment within the constraints imposed by the scatter of the real mass–size relation, i.e., at fixed stellar mass, ETGs living in low mass halos can at most be $\sim 3$ times smaller than their counterparts living in the most massive halos (twice the scatter of the mass–size relation). Therefore, to each galaxy, given its measured stellar mass, size, and halo mass from the real data, we add a positive shift to its size, which scales linearly with its halo mass:

$$R_e^{\text{sim}} = R_e + (\log(M_h) - 12) \times \kappa.$$  (2)

Increasing values of $\kappa$ will produce larger environmental effects. Smaller galaxies at fixed stellar mass will then preferentially be associated with smaller halos. We then investigate the
effect of adding increasing Gaussian random errors to stellar mass, size, and halo mass. With this procedure we are assuming that the observed mass–size relation is the intrinsic one (before convolution with errors), which is an approximation since it already contains errors. Nevertheless, the conclusions drawn from our Monte Carlo experiments are independent of the exact choice of the initial condition, as long as all the variables are properly updated after convolution with errors.

The way errors correlate with the three variables is not a trivial question and depends on the dataset and the way the three parameters are derived from an observational point of view. We explore two extreme cases in this work that fully bracket the whole range of meaningful possibilities. First, we consider a scenario in which errors in the three variables are completely independent. Then, we work out a second possibility characterized by the three variables being, instead, fully correlated, following the constraints imposed by how our sample of (central and satellite) galaxies was built.

We find that, if errors are uncorrelated, then the signal with the environment is preserved independent of the errors or even enhanced in the case of central galaxies (Figures 8 and 9). The reason for this is that halos are not populated in a uniform way by central galaxies in terms of stellar mass (Figure 3) in the sense that, below $10^{11}$ solar masses, central galaxies are more likely to populate small halos. Adding errors to stellar mass (without updating the other variables) will systematically add a population of new small galaxies in small halos, which will maintain or enhance an environmental signal.

The independence assumption does not seem to be realistic, at least for our sample, in which halo masses are determined using abundance matching with the group stellar mass function (Yang et al. 2007). Next we focus on a scenario with correlated errors.

Stellar masses and sizes are also correlated since the choice of a given model light profile with respect to another to fit the image will translate into an error in the total luminosity, which is converted into an error in stellar mass. Bernardi et al. (2013) estimate that the maximum systematic error on magnitude can be for luminous galaxies of the order of 0.5 mag (see their Figure 1), which translates into 0.2 dex in luminosity, thus a 0.2 dex in stellar mass. On the other hand, the same systematic shift produces up to 0.2 dex in size, and thus a correlation of the type $\Delta \log R_e \sim \Delta \log M_\star$. This is the maximum correlation possible reported in the literature so far between $\log M_\star$ and $\log R_e$. This systematic error is at least one order of magnitude larger than the statistical error on size (Meert et al. 2012), which we neglect.

Concerning halo masses, Yang et al. (2007) use abundance matching between the total stellar mass of the group or cluster and the halo mass to assign friends-of-friends halo masses to galaxies. Thus, halo mass and galaxy mass are fully correlated.
Figure 10. Results of Monte Carlo tests to assess the sensitivity to observational errors of an eventual environmental effect on the sizes of central ETGs when errors are correlated. The left column shows different simulated $M_h - \gamma$ relations without errors (see the text for details). The right column shows the resulting $M_h - \gamma$ plane after adding expected uncertainties on halo masses, stellar masses, and sizes as explained in the text. An environmental effect larger than 30% should be detected at 3\(\sigma\) level, given the errors in our sample.

by the cumulative relation between stellar mass function and halo mass function. When we assign Gaussian errors in our simulations, we convolve the stellar mass function with a Gaussian, thus increasing the number density of massive galaxies. This changes the mapping between stellar mass and halo mass. To properly take this effect into account, we use the Millennium simulation and the Guo et al. model (2010). We compute the stellar mass function of centrals with and without statistical and systematic errors, as described in the previous paragraph, and, each time, compute the median $M_* - M_h$ relation to quantify the median shift in the halo mass at fixed stellar mass. Both the stellar mass function and cosmology used in Yang et al. (2007) will be a little different, but we do not expect these changes to make any major impact in our conclusions given that we are interested in the median shift, not in the absolute value of $M_h$.

Figures 10 and 11 show the results for decreasing values of $\kappa$ for centrals and for all galaxies respectively. The left column shows the signal before adding errors and the right column shows the same signal once errors are incorporated as described. When correlated errors are included, the environmental signal tends to be washed out. Thus, a size ratio between cluster and field galaxies of $\sim 1.4$ or larger will be detected at more than 3\(\sigma\), even after maximizing the potential effect of correlated errors. Size ratios lower than 1.4 would be detected with small significance or not detected at all.

These simulations show that, despite the different systematics involved in the determination of stellar masses, sizes, and specially halo masses in the sample used in this work, we should be able to detect any size difference greater than a factor of 1.4 between galaxies in extreme environments.

4.3. Effects of Interlopers

As an additional check to estimate the effects of errors in halo mass and interlopers in the membership selection, we define a smaller but robust control sample of spectroscopically confirmed members of massive clusters based on the selection of Aguerri et al. (2007). The sample is made of 88 clusters with known redshift at $z < 0.1$ from the catalogs of Abell et al. (1989), Zwicky et al. (1961), Böhringer et al. (2000), and Voges et al. (1999) that have been mapped by the SDSS-DR4 (York et al. 2000). Cluster membership is obtained using the velocity information from SDSS-DR4, by a combination of two algorithms. In the first step, the ZHG algorithm is applied. In the second step, the cluster membership is refined by the applications of the KMM algorithm. The final sample contains a total of 10865 galaxies as cluster members (see Aguerri et al. 2007 for more details). Halo masses of those clusters were estimated independently, based on numerical $N$-body simulations using Equation (2) of Biviano et al. (2006) rescaled for cluster redshift and cosmology. The errors in the mass estimations were obtained by propagating the errors in this equation. Sizes, stellar masses, and morphologies come from the same
catalogs as those from the main sample (see Section 2). We find similar results using this independent sample. The Pearson correlation coefficient between halo mass and size is $\gamma \sim 0.1$ proving that there is no correlation at the cluster scale and that the values of $\gamma$ are consistent with the ones measured from the field SDSS sample (Figure 12).

5. CONCLUSIONS

We analyze a sample of $\sim$12,000 local ETGs from the SDSS DR7, selected in different environments. Our main results are as follows.

1. The mass–size relation of ETGs in the local universe does not significantly depend on the environment. At fixed stellar mass (or fixed-central stellar-mass density), galaxies in clusters have similar sizes than the ones in the field.

2. The mass–size relation does not depend on the position of the galaxy in the halo; satellite and central galaxies follow similar mass–size relations.

3. If we focus on the high-mass end of the galaxy population ($\log(M_*/M_\odot) > 11$), then our estimated observational uncertainties and the size of our sample, we can rule out any size difference between cluster and field ETGs larger than 30%–40% at $3\sigma$. The flatness of the $R_s-M_*$ relation is, therefore, an intrinsic property and not a consequence of observational uncertainties.

4. The result is also robust to different galaxy selections. If galaxies are selected based on morphology, star formation, stellar mass, or central densities, the correlation of sizes with environment is always inexisten.

Several recent works have studied the effect of environment on the mass–size relation of massive early-type galaxies in the local universe. Maltby et al. (2010) reported no size difference between ETGs in nearby clusters ($z < 0.4$) and those in the field with similar stellar mass. In the same line, Fernández Lorenzo et al. (2013) studied a sample of isolated ETGs in the SDSS and found no difference in size when compared with less isolated galaxies. Poggianti et al. (2012) also tackled this issue with an independent sample and found a trend (though not statistically significant, i.e., 1σ) pointing toward smaller galaxies in clusters. Given that the difference is not statistically significant, it should not be considered as a real discrepancy with the present work. We also show that the small difference might be a consequence of the environmental selection. All these results, seem to converge toward a picture in which the effect of environment in the structure of nearby ETGs at low redshift is negligible.

If the recent results pointing toward larger sizes of ETGs in cluster environments at $z > 1$ are confirmed (e.g., Delaye et al. 2013; Papovich et al. 2012; Lani et al. 2013), our results suggest that the effect has to disappear between $z \sim 1$ and $z \sim 0$. We reserve a full theoretical study of current predictions from hierarchical models in a companion paper (Shankar et al. 2013b) in which we will show how environment can be used to put constraints on the physical processes behind mass assembly of early type galaxies. Overall, a variety of parameters contribute to the environmental dependence of sizes in the models, from the exact choice of dynamical friction timescale, to the level of stripping in merging satellites. A detailed investigation of this is beyond the scope of the present work and will be presented in a dedicated work.

F.S. acknowledges support from a Marie Curie grant. M.B., A.M. and V.V. acknowledge support from a NASA grant ADP/NNX09AD02G and NSF/0908242. We also thank I. Trujillo, G. Mamom, and B. Poggianti for interesting discussions.

REFERENCES

Abazajian, K. N., Adelman-McCarthy, J. K., Aguérès, M. A., et al. 2009, ApJS, 182, 543
Abell, G. O., Corwin, H. G., Jr., & Olowin, R. P. 1989, ApJS, 70, 1
Aguerri, J. A. L., Sánchez-Janssen, R., & Muñoz-Tuñón, C. 2007, A&A, 471, 17
Angulo, R. E., & White, S. D. M. 2010, MNRAS, 405, 143
Ascaso, B., Aguerri, J. A. L., Varela, J., et al. 2011, ApJ, 726, 69
Bernardi, M., Meert, A., Sheth, R. K., et al. 2013, MNRAS
Bernardi, M., Meert, A., Vikram, V., et al. 2012, arXiv:1211.6122
Bernardi, M., Roche, N., Shankar, F., & Sheth, R. K. 2011, MNRAS, 412, L6
Bernardi, M., Shankar, F., Hyde, J. B., et al. 2010, MNRAS, 404, 2087
Biviano, A., Murante, G., Borgani, S., et al. 2006, A&A, 456, 23
Böhringer, H., Voges, W., Huchra, J. P., et al. 2000, ApJS, 129, 435
Brinchmann, J., Charlot, S., White, S. D. M., et al. 2004, MNRAS, 351, 1151
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Buitrago, F., Trujillo, I., Conselice, C. J., & Haeussler, B. 2011, MNRAS, 428, 1460
Buitrago, F., Trujillo, I., Conselice, C. J., et al. 2008, ApJL, 687, L61
Chang, Y.-Y., van der Wel, A., Rix, H.-W., et al. 2013, ApJ, 762, 83
Cimatti, A., Nipoti, C., & Cassata, P. 2012, MNRAS, 422, L6
Cooper, M. C., Griffith, R. L., Newman, J. A., et al. 2012, MNRAS, 419, 3018
Daddi, E., Renzini, A., Pirkal, N., et al. 2005, ApJ, 626, 680
Damjanov, I., Abraham, R. G., Glazebrook, K., et al. 2011, ApJL, 739, L44
Delaye, L., Huertas-Company, M., Mei, S., et al. 2013, arXiv:1307.0093
Fan, L., Lapi, A., De Zotti, G., & Danese, L. 2008, ApJL, 689, L101
Fernández Lorenzo, M., Sulpten, J., Verdes-Montenegro, L., & Argudo-Fernández, M. 2013, MNRAS, 434, 325
Gao, Q., White, S., Li, C., & Boylan-Kolchin, M. 2010, MNRAS, 404, 1111
Hopkins, P. F., Hernquist, L., Cox, T. J., Keres, D., & Wuyts, S. 2009, ApJ, 691, 1424
Huertas-Company, M., Aguerri, J. A. L., Bernardi, M., Mei, S., & Sánchez Almeida, J. 2011, A&A, 525, A157
Huertas-Company, M., Mei, S., Shankar, F., et al. 2013, MNRAS, 428, 1715
Kauffmann, G., Heckman, T. M., White, S. D. M., et al. 2003, MNRAS, 341, 33
Lani, C., Almaini, O., Hartley, W. G., et al. 2013, MNRAS, 435, 207
Lin, Y.-T., & Mohr, J. J. 2004, ApJL, 617, 879
López-Sanjuan, C., Le Fèvre, O., Ilbert, O., et al. 2012, A&A, 548, A7
