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# The mass-size relation of LRGs from BOSS and DECaLS

Ginevra Favole<sup>1\*</sup>, Antonio D. Montero-Dorta<sup>2</sup>, Francisco Prada<sup>3</sup>, Sergio A. Rodríguez-Torres<sup>4,5,6</sup>, David J. Schlegel<sup>7</sup>

<sup>1</sup>*European Space Astronomy Centre (ESAC), 28692 Villanueva de la Cañada, Madrid, Spain*

<sup>2</sup>*Instituto de Física, Universidade de São Paulo, São Paulo, SP, Brazil*

<sup>3</sup>*Instituto de Astrofísica de Andalucía (IAA)/ CSIC, Granada, E-18008, Spain*

<sup>4</sup>*Instituto de Física Teórica (IFT) UAM/CSIC, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*

<sup>5</sup>*Campus of International Excellence UAM/CSIC, Cantoblanco, E-28049 Madrid, Spain*

<sup>6</sup>*Departamento de Física Teórica M-8, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain*

<sup>7</sup>*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720, USA*

## ABSTRACT

We use the DECaLS DR3 survey photometry matched to the SDSS-III/BOSS DR12 spectroscopic catalog to investigate the morphology and stellar mass-size relation of luminous red galaxies (LRGs) within the CMASS and LOWZ galaxy samples in the redshift range  $0.2 < z < 0.7$ . The large majority of both samples is composed of early-type galaxies with De Vaucouleurs profiles, while only less than 20% are late-type exponentials. We calibrate DECaLS effective radii using the higher resolution CFHT/MegaCam observations and optimise the correction for each morphological type. By cross-matching the photometric properties of the early-type population with the Portsmouth stellar mass catalog, we are able to explore the high-mass end of the distribution using a large sample of 313,026 galaxies over  $4380 \text{ deg}^2$ . We find a clear correlation between the sizes and the stellar masses of these galaxies, which appears flatter than previous estimates at lower masses. The sizes of these early-type galaxies do not exhibit significant evolution within the BOSS redshift range, but a slightly declining redshift trend is found when these results are combined with  $z \sim 0.1$  SDSS measurements at the high-mass end. The synergy between BOSS and DECaLS has important applications in other fields, including galaxy clustering and weak lensing.

**Key words:** galaxies: distances and redshifts — galaxies: evolution — galaxies: photometry — galaxies: structure — galaxies: statistics — cosmology: observations — cosmology: theory — large-scale structure of Universe

## 1 INTRODUCTION

The SDSS-III/Baryon Oscillation Spectroscopic Survey (BOSS; Eisenstein et al. 2011; Dawson et al. 2013) provided unprecedented statistics at the high-mass end by measuring the spectra of about 1.5 million luminous red galaxies (LRGs; Eisenstein et al. 2001) over  $10,000 \text{ deg}^2$  of sky down to magnitude  $r \sim 22.2$  and within the redshift range  $0.2 < z < 0.7$ . This data set has been used not only to accurately measure the baryon acoustic oscillation feature (BAO; Eisenstein et al. 2005; Anderson et al. 2014; Alam et al. 2017), but also to study the massive galaxy population at  $z \sim 0.55$ . BOSS allowed us to characterise the red/blue color bimodality observed in LRGs (Tojeiro et al. 2013; Ross et al. 2014; Favole et al. 2016; Montero-Dorta et al. 2016b), to constrain the high-mass end of the stellar mass and luminosity functions of these massive galaxies (Maraston et al. 2013; Bernardi et al. 2013; Leauthaud et al. 2016; Bernardi et al. 2016, 2017; Montero-Dorta et al. 2016b) and to mea-

sure the intrinsic relation between galaxy luminosity and velocity dispersion (Montero-Dorta et al. 2016a, 2017). Despite these achievements, the morphological and structural properties of BOSS LRGs have been difficult to probe due to the poor SDSS image quality (median seeing of  $2''$ ).

More recently, the Dark Energy Camera Legacy Survey<sup>1</sup> (DECaLS) of the SDSS Equatorial Sky has been designed to obtain high-quality images that cover  $6700 \text{ deg}^2$  in three optical bands ( $g, r, z$ ). With a limiting magnitude of  $r \leq 23.4$  and a median seeing of  $1.2''$ , it allows a narrower and more efficient target selection for the DESI survey (Comparat et al. 2013, 2016). DECaLS improves dramatically the quality of the SDSS data set, providing also deeper photometry.

Besides the classification of galaxies through their morphology and shape parameters, the stellar mass-size relation has been explored in a number of works as a powerful scaling law to connect fundamental galaxy properties. Bernardi et al. (2010) studied the distribution of stellar mass ( $M_*$ ),

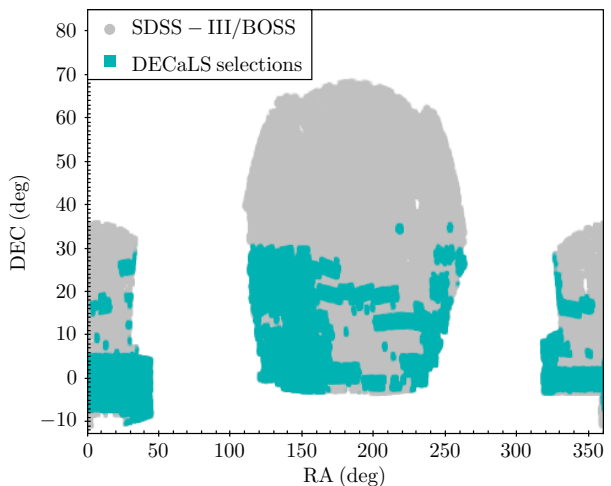
\* E-mail: gfavole@sciops.esa.int

<sup>1</sup> <http://legacysurvey.org/decamls/>

size, velocity dispersion, luminosity and color as a function of galaxy morphology and concentration index for SDSS massive early-type galaxies. They claimed that sample selections based on colour or concentration lead to significantly different scaling relations. [Bernardi et al. \(2011\)](#) investigated further these dependencies in a sample of SDSS early-type galaxies (ETGs) and found that there is a particular stellar mass scale ( $M_{\star} \sim 2 \times 10^{11} M_{\odot}$ ) beyond which major mergers start to dominate the assembly histories of these massive galaxies. [Cappellari \(2013\)](#) identified the same mass scale as the transition point between two processes that regulate the mass-size distribution of galaxies in dense environments and in the field. From one side, spiral galaxies are replaced by bulge-dominated fast-rotator ETGs, with the same mass-size relation and mass distribution as in the field. On the other hand, the slow-rotator ETGs are segregated in mass from the fast ones, and their size increases proportionally to their mass. These evidences suggest that bulge growth (outside-in evolution) and bulge-related environmental quenching dominate in the low-mass end, while dry mergers (inside-out evolution) and halo-related quenching shape the mass and size growth at the high-mass end.

[Huertas-Company et al. \(2013b\)](#) investigated the impact of different large-scale environments (i.e., field, group and clusters) on the size of massive ETGs at  $z \sim 0$ . At fixed stellar mass, they did not find any significant dependence of the central and satellite ETG sizes on the environment. The mass-size relation of these galaxies is independent of the host halo mass and the galaxy position within the halo. This result is not sensitive to different galaxy selections based on morphology, star formation, or central density. [Trujillo et al. \(2011\)](#) studied the buildup of the mass-size relation of elliptical galaxies from  $z \sim 0$  up to  $z \sim 1$ , using observations from SDSS and HST/GOODS. They did not find any evidence for age segregation at fixed stellar mass. This rules out the scenario of a present-day mass-size relation progressively established through a bottom-up sequence in which older galaxies populate its lower tail, remaining in place since their formation. Their result supports instead the hypothesis that the local mass-size relation is defined at  $z \sim 1$ , with all galaxies occupying a region half of the size of the present-day distribution. [Shen et al. \(2003\)](#) explored the connection between galaxy size and luminosity (or stellar mass) using  $z \sim 0.1$  SDSS data and found a trend which is significantly steeper for early- than for late-type galaxies.

Recently, [Zhang & Yang \(2017\)](#) analysed the dependence of the luminosity- or mass-size relation on galaxy concentration and morphology in the SDSS DR7 Main galaxy sample. They found a clear trend of smaller sizes and steeper slope for early-type elliptical galaxies. [Masters et al. \(2011\)](#) studied the morphology and size of BOSS luminous massive galaxies using HST/COSMOS photometry and found that about 74% of them are early-type elliptical or lenticular, while the rest are late-type spirals. [Beifiori et al. \(2014\)](#) compared galaxy size measurements in SDSS, SDSS-III/BOSS and COSMOS data at  $0.1 \lesssim z \lesssim 0.7$  to derive accurate corrections for the galaxy effective radii (i.e. sizes). [Hill et al. \(2017\)](#) investigated the redshift-size relation in massive ETGs in the UltraVISTA and CANDELS surveys. They found evidence of a significant mass build up at  $r < 3$  kpc beyond  $z > 4$ , and a clear evolutionary change at  $z \sim 1.5$ , when the galaxy progenitor stops growing in-situ through disk star formation and accretes minor mergers. [Somerville et al. \(2017\)](#) explored the ratio between galaxy size and dark



**Figure 1.** Footprint of the cross-matched DECaLS-BOSS galaxy sample (green area) versus the original SDSS-III/BOSS coverage (grey).

matter halo virial radius at  $z \lesssim 3$  using data from GAMA and CANDELS. They found very little dependence on stellar mass and lower ratios at high redshift for more massive galaxies.

In this work, we aim to characterise the morphology and the stellar mass-size relation of the well-known SDSS-III/BOSS DR12 CMASS and LOWZ galaxy samples ([Anderson et al. 2012](#); [Bolton et al. 2012](#); [Anderson et al. 2014](#); [Alam et al. 2015](#)) within the redshift range  $0.2 < z < 0.7$ . To this purpose, we match these BOSS spectroscopic samples to the DECaLS DR3 photometric catalog. We calibrate DECaLS sizes using the high-resolution (0.6'' median seeing) CFHT/MegaCam observations and optimise the correction individually for each morphological type. By cross-matching our DECaLS selections with the Portsmouth ([Maraston et al. 2013](#)) stellar mass catalog at  $0.2 < z < 0.7$ , we are able to constrain the  $M_{\star}$ -size relation of very massive LRGs in a sample of unprecedented size at these redshifts. Our cross-matched BOSS-DECaLS galaxy samples with CFHT calibrated sizes are made publicly available for the community on the SKIES AND UNIVERSES<sup>2</sup> database.

The paper is organised as follows: Section 2 describes the data sets used in our analysis. In Section 3 we explain how the DECaLS effective radii are calibrated using CFHT observations. In Section 4 we present our results: the morphology of BOSS galaxies, their stellar mass-size relation and their size evolution. We compare with previous studies in Section 5 and summarize our conclusions in Section 6. For the analysis we adopt the cosmology:  $h = 0.6777$ ,  $\Omega_m = 0.3071$ ,  $\Omega_{\Lambda} = 0.6929$ ,  $n = 0.96$ ,  $\sigma_8 = 0.8228$  ([Planck Collaboration et al. 2014](#)).

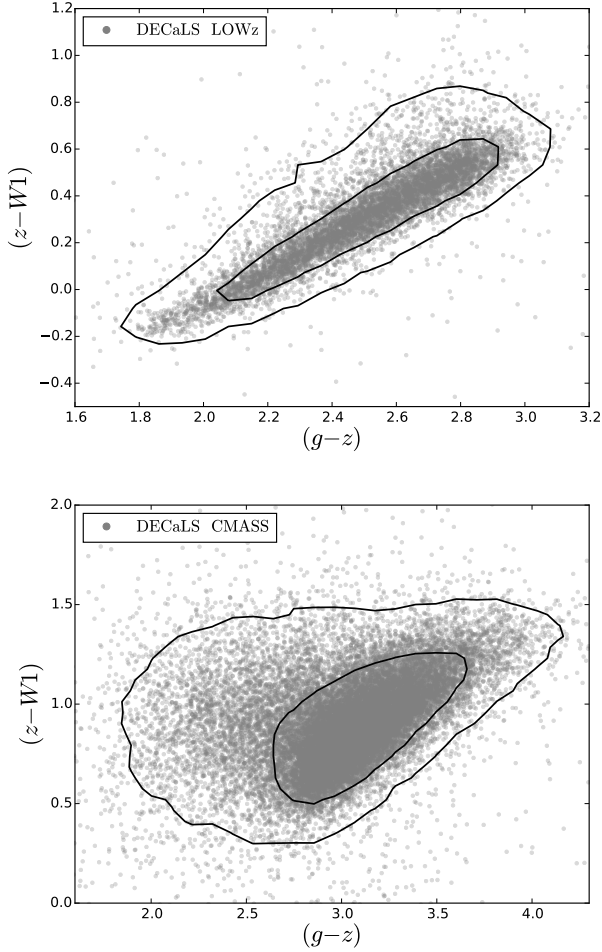
## 2 DATA AND GALAXY SELECTIONS

We use the DECam Legacy Survey (DECaLS) DR3 photometric catalog<sup>3</sup> row-by-row-matched to the SDSS DR12 spectroscopic galaxy sample<sup>4</sup>. DECaLS is an optical survey

<sup>2</sup> <http://www.skiesanduniverses.org/>

<sup>3</sup> <http://legacysurvey.org/dr3/files/>

<sup>4</sup> <https://data.sdss.org/sas/dr12/sdss/spectro/redux/>



**Figure 2.**  $(z - W1)$  vs.  $(g - z)$  color distributions of the cross-matched DECaLS-BOSS LOWZ (top) and CMASS (bottom) samples. The contours denote the  $1\sigma$  and  $2\sigma$  uncertainty regions.

on the 4m Blanco telescope at Cerro Tololo Inter-American Observatory designed to complement the SDSS, SDSS-III, SDSS-IV and DESI surveys with high-quality images from  $6700\text{ deg}^2$  of extragalactic sky in the equatorial region in three optical bands ( $g$ ,  $r$ ,  $z$ ). The DECaLS DR3 photometric catalog also includes the infrared WISE bands (W1, W2, W3, W4). The sky coverage lies within  $-18^\circ < \delta < +34^\circ$  in celestial and  $|b| > 18^\circ$  in Galactic coordinates. DECaLS has improved dramatically the quality of the SDSS imaging data, providing a deeper photometry with limiting magnitude of  $r \leq 23.4$  and a median seeing of  $1.2''$ .

In the cross-matched catalog introduced above, we select the BOSS CMASS and LOWZ galaxy samples of LRGs (hereafter our “parent samples”) using the SDSS spectroscopic flags<sup>6</sup>. We further exclude point-like sources from the parent samples by imposing the DECaLS condition `TYPE!=“PSF”`. We recover 238,008 CMASS and 75,018 LOWZ galaxies, respectively, i.e., about 31% and 23% of the original BOSS samples. The missing galaxies are not observed by DECaLS DR3,

which has an effective area of  $4380\text{ deg}^2$ , much smaller than the  $9376\text{ deg}^2$  of the SDSS-III/BOSS, as shown in Figure 1. In Figure 2, we display our LOWZ (top panel) and CMASS (bottom) parent samples in the DECaLS color-color plane. We use the  $g$  and  $z$ -band magnitudes from DECaLS and the W1 infrared magnitude from WISE to highlight the color properties of BOSS LRGs in DECaLS photometry.

Beside DECaLS magnitudes, for the analysis we adopt DECaLS effective radii, surface brightness profiles and galaxy morphologies. We perform galaxy size calibrations using data from two different surveys: the MegaPrime/MegaCam<sup>7</sup> at CFHT and the Cosmic Evolution Survey (COSMOS)<sup>8</sup>. The first one has a  $1\text{ deg}^2$  field-of-view with a resolution of  $0.187''$  per pixel and a median seeing of  $\sim 0.7''$ . It provides much better imaging quality, which is key to precisely determine galaxy sizes and morphological types. The second survey was originally designed to probe galaxy formation and evolution over a  $2\text{ deg}^2$  equatorial field with imaging by most of the major space-based telescopes and a number of large ground based telescopes.

We adopt Maraston et al. (2013) stellar masses for the galaxies in our parent samples to study the mass-size relation of LRGs at  $0.2 < z < 0.7$ . These are estimated by fitting model spectral energy distributions to the BOSS observed magnitudes.

### 3 GALAXY SIZE CALIBRATION

In order to correct our galaxy size measurements from seeing effects (Saglia et al. 1993; Bernardi et al. 2003; Beifiori et al. 2014), we calibrate DECaLS effective radii with the latest CFHT (see Section 2) observations. We cross-match our CMASS and LOWZ samples with the data available in the four CFHT fields. Only galaxies with De Vaucouleurs and exponential profiles are employed. For those objects surviving the matching (4721 in CMASS and 2050 in LOWZ), we compare their radii measured in both surveys. We define the DECaLS circularized radius as  $R_{\text{DECaLS}} = R_{\text{eff}} \sqrt{(b/a)}$ , where  $R_{\text{eff}}$  is the DECaLS effective radius, while  $a$  and  $b$  are the semi-major and semi-minor ellipse axes, respectively. For the calibration we use the following functional form:

$$R_{\text{DECaLS}}^{\text{calib}} = R_{\text{DECaLS}} \times f(R_{\text{DECaLS}}), \quad (1)$$

where  $f(R_{\text{DECaLS}})$  is the calibration function depending on DECaLS size defined as:

$$f(R_{\text{DECaLS}}) = \left( \frac{R_{\text{DECaLS}}}{R_0} \right)^\alpha. \quad (2)$$

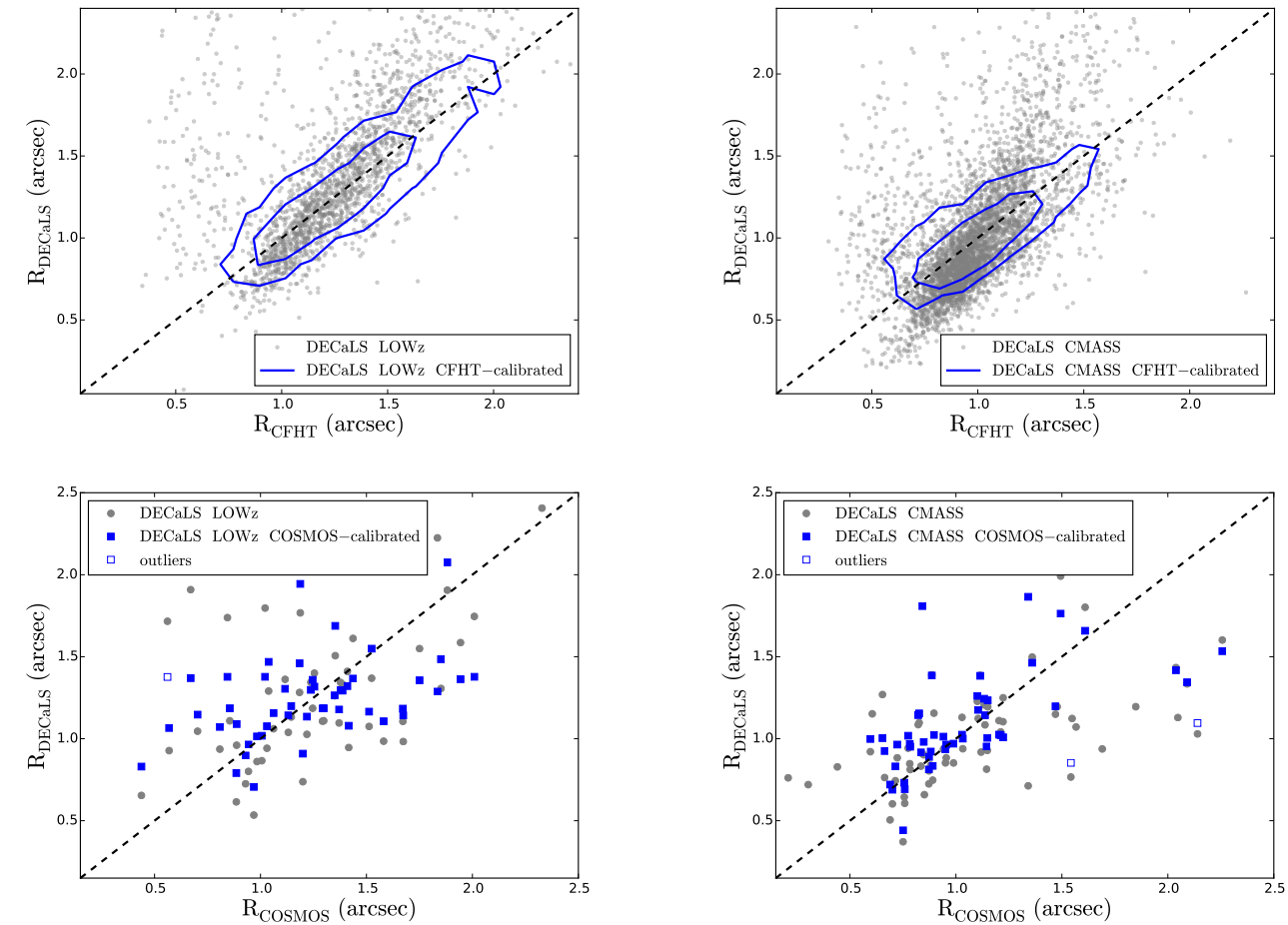
We separately fit CMASS and LOWZ galaxies with De Vaucouleurs and exponential profiles to find the optimal parameters  $\alpha$  and  $R_0$ . As part of the fitting procedure, we perform sigma-clipping, rejecting those objects located more than  $2\sigma$  away from the mean of the  $R_{\text{CFHT}}/R_{\text{DECaLS}}$  distribution. The excluded points are considered outliers in what follows. The best-fit parameters are reported in Table 1. In the top panels of Figure 3, we display DECaLS versus CFHT effective radii of the LOWZ (left) and CMASS (right) samples, respectively. The grey points are DECaLS original radii

<sup>5</sup> <http://wise.ssl.berkeley.edu/index.html>

<sup>6</sup> [http://www.sdss.org/dr13/algorithms/boos\\_galaxy\\_ts/](http://www.sdss.org/dr13/algorithms/boos_galaxy_ts/)

<sup>7</sup> <http://www.cfht.hawaii.edu/Instruments/Imaging/MegaPrime/>

<sup>8</sup> <http://cosmos.astro.caltech.edu/>



**Figure 3.** DECaLS LOWZ (left column) and CMASS (right column) effective radii as a function of the corresponding CFHT (top row) and COSMOS (bottom row) sizes in arcsec. The dashed diagonal line corresponds to the 1:1 relation for each case.

DECaLS LOWZ				
	$0.15 \leq z < 0.3$		$0.3 \leq z < 0.43$	
	$R_0$ [arcsec]	$\alpha$	$R_0$ [arcsec]	$\alpha$
CFHT DeV	$1.226 \pm 0.020$	$-0.324 \pm 0.014$	$1.141 \pm 0.009$	$-0.395 \pm 0.011$
CFHT Exp	$1.370 \pm 0.168$	$-0.672 \pm 0.154$	$1.292 \pm 0.094$	$-0.652 \pm 0.143$
COSMOS DeV	$1.241 \pm 0.289$	$-0.079 \pm 0.166$	$1.556 \pm 0.168$	$-0.439 \pm 0.128$
COSMOS Exp	—	—	—	—
DECaLS CMASS				
	$0.43 < z \leq 0.55$		$0.55 < z < 0.7$	
	$R_0$ [arcsec]	$\alpha$	$R_0$ [arcsec]	$\alpha$
CFHT DeV	$1.009 \pm 0.006$	$-0.469 \pm 0.009$	$0.952 \pm 0.006$	$-0.547 \pm 0.011$
CFHT Exp	$2.085 \pm 0.147$	$-0.276 \pm 0.020$	$2.123 \pm 0.143$	$-0.247 \pm 0.018$
COSMOS DeV	$1.256 \pm 0.126$	$-0.186 \pm 0.083$	$1.847 \pm 0.356$	$-0.832 \pm 0.344$
COSMOS Exp	—	—	—	—

**Table 1.** Best-fit coefficients for the calibration factor  $f(R_{\text{DECaLS}})$  given in Eq. 2. The COSMOS correction for the DECaLS CMASS and LOWZ samples with exponential profile is omitted due to the lack of statistics.



before the CFHT calibration; the blue contours are the corrected sizes. The effect of the CFHT calibration lowers DECaLS effective radii by a  $\sim 40\%$  factor, fully consistent with the statistical correction made by Masters et al. (2011) using the Zurich Estimator of Structural Types (ZEST; Scarlata et al. 2007) measurements. In what follows, we extrapolate and apply this calibration to the entire CMASS and LOWZ parent samples.

In order to test the CFHT calibration, we also derive an independent correction by cross-matching DECaLS with COSMOS data. Even though the overlap between the two data sets is very small – only 67 galaxies survive the matching for CMASS and 56 for LOWZ – the result is consistent with the CFHT analysis, as shown in the bottom panels of Figure 3. Here we show DECaLS LOWZ on the left and CMASS on the right side. The grey points are the DECaLS radii before correction and the blue filled squares are the sizes calibrated using COSMOS data. The blue empty squares are the outliers, i.e. those objects located more than  $2\sigma$  away from the mean of the corrected distribution.

## 4 RESULTS

In this section, we present our main results: the morphology of the cross-matched BOSS-DECaLS CMASS and LOWZ samples and the stellar mass-size relation for their early-type galaxy population.

### 4.1 The morphology of BOSS LRGs

We use the DECaLS surface brightness profile classification as an indicator of the morphology of CMASS and LOWZ galaxies. In DECaLS, the following profiles have been fitted to individual objects:

- De Vaucouleurs: Sérsic (Sérsic 1968) profile with  $n = 4$ .
- Exponential: Sérsic profile with  $n = 1$ .
- Composite: linear combination of a De Vaucouleurs and an exponential profile with the same source center.
- Simple: exponential profile with a fixed 0.45" effective radius and circular shape.

We find that 64% (89%) of CMASS (LOWZ) galaxies have De Vaucouleurs profiles; 14% (4%) are exponentials; 17% (1%) are simple and 5% (6%) are composite. Galaxies with De Vaucouleurs profiles are typically early-type/ellipticals, while exponentials correspond to late-type/spirals (see e.g., Caon et al. 1993; D’Onofrio et al. 1994; Andredakis et al. 1995; Bernardi et al. 2005; Shao et al. 2007; Tempel et al. 2011). Composite profiles are a mixture of the two previous configurations. Simple profiles are used when any other profile with varying radius does not yield a significantly better  $\chi^2$  (note that the number of parameters is penalized in the determination of the goodness of fit).

The CMASS selection allows for a fraction of bluer objects in the sample, which increases with redshift (Eisenstein et al. 2001; Montero-Dorta et al. 2016b). This explains the presence of galaxies with exponential profiles. Interestingly, the fraction of galaxies with De Vaucouleurs profiles increases significantly from the LOWZ to the CMASS sample, as the fraction of exponentials decreases. In Figure 4, we show the  $(g - z)$  color distributions in both the LOWZ (left) and CMASS (right) samples for De Vaucouleurs and elliptical galaxies separately. In the CMASS sample, galaxies with De Vaucouleurs profiles are significantly redder than

those showing an exponential profile, as expected from the early-late type association. Interestingly, this separation is less obvious in the LOWZ sample, which might be due to the presence of more dusty spirals having an exponential profile. Note that the red/blue separation in the CMASS sample is more evident in the  $(g - i)$  color distribution (i.e.,  $(g - i) = 2.35$ ), as shown in Masters et al. (2011), Dawson et al. (2013), Maraston et al. (2013), Ross et al. (2014), Favole et al. (2016), and Law-Smith & Eisenstein (2017).

The fraction of late-type and early-type galaxies that we find in our samples is approximately consistent, given the uncertainties and differences between different methods, with results from Masters et al. (2011), Maraston et al. (2013) and Montero-Dorta et al. (2016b) using the SDSS photometry.

In Figure 5, we show the effective radius distribution of the LOWZ (left) and CMASS (right) samples, highlighting the contribution from the different morphologies. In both populations, the early-type De Vaucouleurs galaxy distribution peaks at  $R_{\text{DECaLS}} \sim 7$  kpc, exponentials around 8 kpc, composite at 12 kpc and simple below 5 kpc. Most of the galaxies classified as “composite” have a companion nearby preventing to accurately measure their effective radius. Due to this configuration, composite galaxies have on average larger radii and wider size distributions compared to the other morphologies. The number of galaxies and the number density (per unit  $\text{deg}^2$ ) of each sample are reported in Table 2.

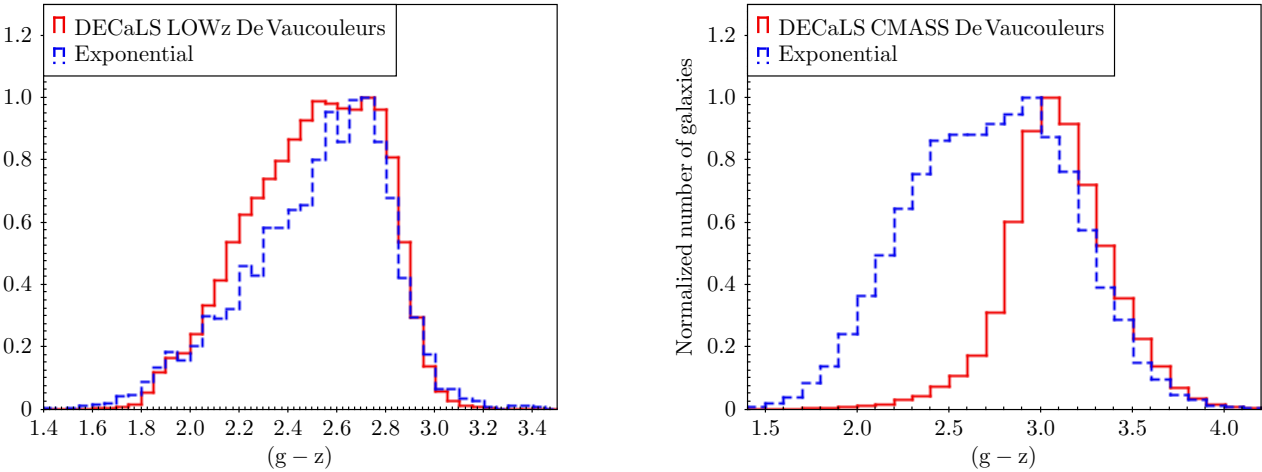
In Figure 5, the median seeing at the corresponding redshift of each sample is represented by a solid vertical line. The DECaLS PSF is dominated by seeing on scales of  $1\text{--}1.2''$ , which corresponds to a FWHM of about 2.8 kpc at the mean redshift of LOWZ ( $z \sim 0.3$ ) and about 3.9 kpc at the mean redshift of CMASS ( $z \sim 0.55$ ). This makes the effective radius distribution fall sharply at small radii. For LOWZ galaxies, however, this effect is less pronounced due to their larger angular size compared to CMASS objects. In what follows, we exclude from our samples those objects classified as “simple”, which have effective radius significantly lower than these thresholds.

### 4.2 The mass-size relation of LRGs at $0.2 < z < 0.7$

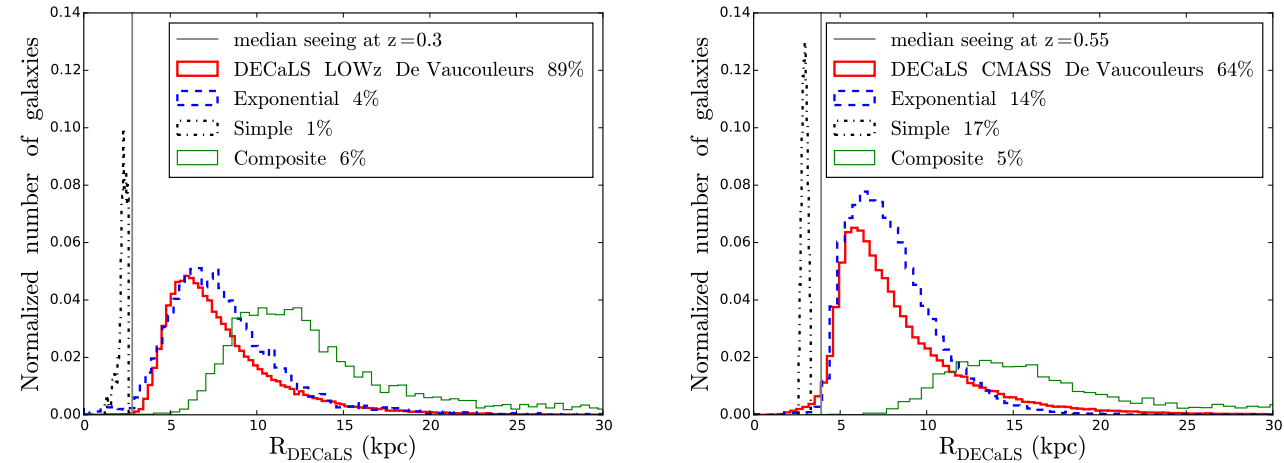
Hereafter, we will focus only on LRGs with De Vaucouleurs profiles. Figure 6 displays the circularized effective radius as a function of stellar mass for the DECaLS LOWZ (upper row) and CMASS (lower row) samples, respectively, in four bins of redshift ( $0.2 \leq z < 0.3$  and  $0.3 \leq z < 0.4$  for LOWZ;  $0.43 \leq z < 0.55$  and  $0.55 \leq z < 0.6$  for CMASS). The density contours are approximately corrected from stellar-mass incompleteness using the analytic formula from Leauthaud et al. (2016):

$$c = \frac{f}{2} \left[ 1 + \text{erf} \left( \frac{\log M_*/M_1}{\sigma} \right) \right], \quad (3)$$

where the parameter values are chosen at the mean redshift of our samples, see Table 3. As expected, we find a correlation, although mild, between effective radius and stellar mass in our cross-matched BOSS-DECaLS samples. The mean size estimates in bins of stellar mass are displayed on top of each distribution as blue points; the error bars correspond to the  $\pm 1\sigma$  dispersion around the mean. A linear fit of the form  $\log(R_{\text{DECaLS}}/\text{kpc}) = A \log(M_*/M_\odot) + B$  is also shown in each panel of Figure 6 as a blue solid line; the



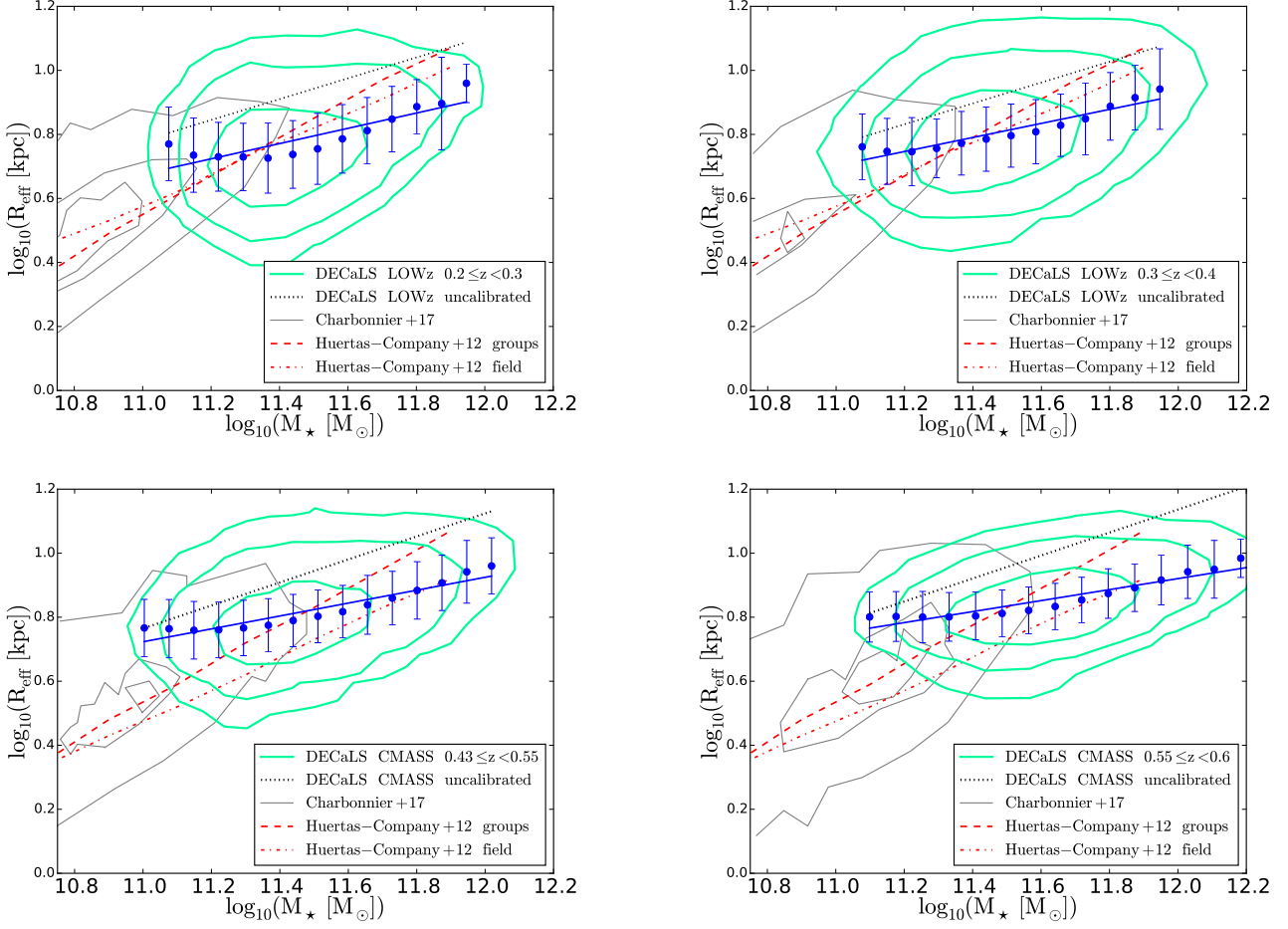
**Figure 4.**  $(g - z)$  color distribution of the cross-matched DECaLS-BOSS LOWZ (left) and CMASS (right) samples. The contributions of galaxies with De Vaucouleurs and exponential profiles are shown as red, solid and blue dashed histograms, respectively.



**Figure 5.** DECaLS LOWZ (left) and CMASS (right) effective radius. The large majority (89% in LOWZ and 64% in CMASS) of both samples is composed by galaxies with De Vaucouleurs profiles. Only 4% (14%) of LOWZ (CMASS) galaxies in DECaLS have an exponential profile. Objects classified as “simple” have exponential profiles and round shape, with fixed effective radius. Galaxies classified as “composite” are fitted by a combination of De Vaucouleurs and exponential profiles. The vertical dashed lines represent the median DECaLS seeing at the mean redshift of each sample.

	DECaLS LOWZ			DECaLS CMASS		
	$N_{\text{gal}}$	$n_{\text{dens}} [\text{deg}^{-2}]$	fraction [%]	$N_{\text{gal}}$	$n_{\text{dens}} [\text{deg}^{-2}]$	fraction [%]
Total	84,986	19.4	100	239,431	54.7	100
De Vaucouleurs	75,441	17.2	89	154,004	35.2	64
Exponential	3464	0.8	4	33,681	7.7	14
Simple	1062	0.3	1	41,292	9.4	17
Composite	5019	1.1	6	10,454	2.4	5

**Table 2.** The number, number density (per unit  $\text{deg}^2$ ) and fraction of De Vaucouleurs, exponential, simple and composite galaxies in the DECaLS LOWZ and CMASS samples.



**Figure 6.** Stellar mass–size relation for the DECaLS LOWZ (top row) and CMASS (bottom row) samples, considering only galaxies with De Vaucouleurs profiles. DECaLS effective radii are calibrated using CFHT data as explained in Section 3. We show in green the  $1\sigma$  (innermost),  $2\sigma$  (median) and  $3\sigma$  (outermost) contours of each distribution, weighted against stellar mass incompleteness by applying the correction from Leauthaud et al. (2016). The blue points are the mean radii in bins of stellar mass and the error bars are the  $\pm 1\sigma$  scatter. The blue solid line is a linear fit to these mean values. The black dotted line is the linear fit to the uncalibrated relation. The grey thin contours correspond to previous observations of less massive quiescent galaxies in CFHT SDSS Stripe 82 (Charbonnier et al. 2017). The red dashed and dot-dashed lines are the results for COSMOS ETGs in groups and in the field environment from Huertas-Company et al. (2013a).

	DECaLS LOWZ		DECaLS CMASS	
	$0.2 \leq z < 0.3$	$0.3 \leq z < 0.4$	$0.43 \leq z < 0.55$	$0.55 \leq z < 0.6$
$f$	1.00	0.87	0.57	1.0
$\sigma$	0.12	0.20	0.20	0.22
$\log(M_1/M_\odot)$	11.24	11.27	11.24	11.36
$A$	$0.238 \pm 0.044$	$0.219 \pm 0.022$	$0.202 \pm 0.021$	$0.172 \pm 0.015$
$B$	$-1.947 \pm 0.509$	$-1.706 \pm 0.263$	$-1.493 \pm 0.241$	$-1.141 \pm 0.178$

**Table 3.** *Top:* Parameters used in Eq. 3 from Leauthaud et al. (2016) to correct for stellar-mass incompleteness. *Bottom:* Parameters of the linear fits  $\log(R_{\text{DECaLS}}/\text{kpc}) = A \log(M_\star/M_\odot) + B$  to the stellar mass-size relations shown in Figure 6.



corresponding parameters are given in Table 3. The slope of the mass-size relation increases mildly across our redshift range  $0.2 \leq z < 0.7$ , with values of  $A \sim 0.17 - 0.24$ .

BOSS provides unprecedented statistics at the high-mass end, as compared to previous surveys and samples at similar redshifts. Establishing a fair comparison at these stellar masses is therefore tricky. Instead, in Figure 6, we show results from two relatively large lower-mass samples. The first one is a selection of quiescent galaxies observed in CFHT SDSS Stripe 82 (Charbonnier et al. 2017), with stellar masses from the S82 Massive Galaxy Catalog<sup>9</sup> (S82-MGC; Bundy et al. 2015). The second one is composed by early-type galaxies detected using COSMOS (Huertas-Company et al. 2013a). When combined, the BOSS mass-size relation appears as a natural higher-mass continuation of those lower-mass relations, but displaying a significantly flatter slope (the typical slope at lower-masses is  $A \sim 0.47 - 0.61$ ).

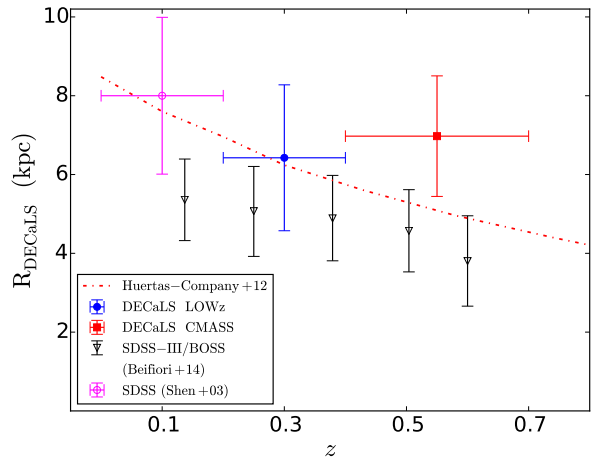
The apparent flattening observed in the mass-size relation might be due to residual incompleteness and selection effects that we could not take into account in the analysis, and to the CFHT size calibration. In Figure 6, we overplot the linear fit to the uncalibrated relation (black dotted line), which is flatter ( $A \sim 0.20 - 0.45$ ) than the lower-mass measurements, but steeper than the corrected relation, especially towards higher redshifts. By comparing these two fits, one can appreciate the effect of the CFHT calibration on the DECaLS size estimates, which are reduced by a factor  $\sim 0.5 - 0.25$  dex. Note also that the size correction has a stronger effect on the higher redshift bins (i.e., CMASS), as expected from the right panel of Figure 3.

The possibility remains that the apparent flattening of the mass-size relation towards the high-mass end is related to the well-documented curvature of scaling relations for early-type galaxies (see e.g., Desroches et al. 2007; Hyde & Bernardi 2009; Bernardi et al. 2011; Kormendy & Bender 2013; Cappellari et al. 2013b,a; Montero-Dorta et al. 2016b,a, 2017). In BOSS, particularly, this phenomenon was reported by Montero-Dorta et al. (2016a) when analysing the intrinsic  $L - \sigma$  relation for the red sequence population. In Section 5, we discuss possible interpretations of this result.

#### 4.3 The redshift-size relation of LRGs at $0.2 < z < 0.7$

We have analysed the redshift evolution of the average size of massive LRGs from the BOSS-DECaLS cross-matched samples. This measurement, due to the mass-size relation itself, is very sensitive to the particular stellar mass range observed, so comparisons with previous results should be taken with caution.

Figure 7 displays the mean effective radius of our LOWZ (blue point) and CMASS (red square) samples, in which only galaxies with De Vaucouleurs profile are considered; the error bars correspond to  $\pm 1\sigma$  scatter around the mean. Our results are obtained by integrating over the entire stellar mass range. The empty black triangles represent previous estimates from SDSS and SDSS-III/BOSS (Beifiori et al. 2014) calibrated against HST/COSMOS data and selected in a narrow bin of stellar mass.



**Figure 7.** Redshift-size relation of our DECaLS CMASS (red filled square) and LOWZ (blue filled point) galaxies, compared to the SDSS-III/BOSS (black empty triangles) results from Beifiori et al. (2014). We also show the  $z \sim 0.1$  SDSS Main galaxy sample measurement from Shen et al. (2003) (magenta empty point) which, combined with our results, suggests a mildly declining redshift trend. The dot-dashed line is the fit to the COSMOS ETGs with  $11.2 < \log(M_*/M_\odot) < 12$  (Huertas-Company et al. 2013a).

The redshift evolution of the DECaLS early-type galaxy sizes calibrated using CFHT data is overall consistent with a flat trend, i.e. no evolution. This is in good agreement with CFHT observations in Stripe 82 of quiescent ETGs (Charbonnier et al. 2017). However, when we combine our nearly flat results with the SDSS measurements at  $z \sim 0.1$  (Shen et al. 2003, empty magenta point), the evolutionary trend mildly declines with redshift and reconciles with Beifiori et al. (2014). The effective radius estimates presented by Beifiori et al. (2014) are systematically smaller than our results and their evolutionary trend is overall similarly flat.

Interestingly, when we limit our measurements to very high masses,  $\log(M_*/M_\odot) > 11.8$ , we find a slope steeply declining with redshift. This is in line with current estimates for very massive ETGs in ULTRAVISTA and CANDELS/3D-HST (Hill et al. 2017) and with the massive ETGs at  $11.2 < \log(M_*/M_\odot) < 12$  observed in COSMOS (Huertas-Company et al. 2013a).

## 5 COMPARISON WITH PREVIOUS STUDIES

We have measured the stellar mass-size relation for massive early-type galaxies within the redshift range  $0.2 < z < 0.7$ . When compared with lower-mass results, our measurement shows a relative flattening of this relation, especially at higher redshift.

At face value, it seems that the observed flattening of the mass-size relation could be related to the well-documented curvature of the scaling relations towards the high-mass end, which has been extensively addressed in the literature for early-type galaxies (Hyde & Bernardi 2009; Desroches et al. 2007; Bernardi et al. 2011; Kormendy & Bender 2013; Cappellari et al. 2013b,a; Montero-Dorta et al. 2016a). In particular, Hyde & Bernardi (2009) studied the stellar mass-size relation in a sample of  $\sim 50,000$  SDSS

<sup>9</sup> <http://www.icolick.org/~kbundy/massivegalaxies/>

ETGs at  $z \sim 0.1$  and found evidence for a deviation from the linear behaviour: galaxies with  $\log(M_*/M_\odot) \gtrsim 11.5$  have larger sizes than expected. The slope of the regression line depends on the weighting scheme adopted to correct from survey incompleteness and ranges from  $A \sim 1$  (unitary weights) to  $A \sim 0.47$  ( $1/V_{\max}(L)$  weights). [Bernardi et al. \(2011\)](#) demonstrated that different scaling relations for ETGs all point to two preferential mass scales,  $3 \times 10^{10}$  and  $2 \times 10^{11} M_\odot$ , as places where fundamental physical processes happen. [Kormendy & Bender \(2013\)](#) investigated the Faber-Jackson correlation between velocity dispersion  $\sigma$  and total galaxy luminosity separately for elliptical galaxies with and without cores. Using the mass-to-light ratio, they related  $\sigma$  to the stellar mass. They found that the velocity dispersion of core ellipticals increases much more slowly with luminosity and mass, compared to the coreless galaxies. They claimed that this is an evidence for dry major mergers as the dominant growth mode of the most massive elliptical galaxies. [Montero-Dorta et al. \(2016a\)](#) found a steep slope and small scatter for the  $L$ - $\sigma$  relation of the massive red sequence population at  $z \sim 0.55$  using the CMASS sample.

Although our measurement, in combination with lower-mass results, seems generally consistent with the curvature of the scaling relations towards the high-mass end, it is noteworthy that this behaviour appears to go in the opposite direction to what is reported by [Hyde & Bernardi \(2009\)](#) at low redshift. As mentioned above, they find that SDSS ETGs at the high-mass end are progressively larger than expected (from a linear relation). Establishing a fair comparison is, however, hindered by sample differences. Besides focusing on a different redshift range, their conclusion is drawn mostly from an intermediate-mass sample (the high-mass end corresponds to the tail of the distribution), whereas our results are obtained from a larger sample covering exclusively the high-mass end (and after comparing with independent lower-mass measurements at the same redshift). Follow-up work will be specifically devoted to addressing this question.

We have also measured the redshift evolution of the average size of massive early-type galaxies from  $z = 0.7$ . Our results are consistent with a non-evolving scenario. This conclusion is in agreement with results from [Bundy et al. \(2017\)](#), who detected no growth in the stellar mass of massive (i.e.,  $\log(M_*/M_\odot) > 11.2$ ) galaxies over  $0.3 < z < 0.65$ . [Montero-Dorta et al. \(2016a\)](#) also found results generally consistent with no evolution of the high-mass end of the  $L$ - $\sigma$  relation all the way to  $z = 0$ .

## 6 SUMMARY AND FUTURE WORK

We have studied the morphology, the stellar mass-size relation and the size evolution of the SDSS-III/BOSS DR12 CMASS and LOWZ spectroscopic galaxy samples cross-matched with the DECaLS DR3 ( $g, r, z$ ) deeper and higher-quality image photometry. The resulting CMASS and LOWZ selections include about 31% and 23% of the original BOSS samples. We find that the large majority of both populations is composed of early-type galaxies with De Vaucouleurs profiles, while only less than 20% of them are late-type spirals with exponential profiles. The fraction of ETG clearly increases from LOWZ to CMASS. We calibrate the DECaLS sizes of these galaxies against the available observations from CFHT/Megacam and COSMOS with better image quality. We obtain an excellent agreement between these two independent corrections and our

results are fully consistent with [Masters et al. \(2011\)](#) using ZEST ([Scarlata et al. 2007](#)) data. By cross-matching our CMASS and LOWZ galaxies with De Vaucouleurs profiles with the Portsmouth ([Maraston et al. 2013](#)) stellar mass catalog for SDSS-III/BOSS LRGs at  $0.2 < z < 0.7$ , we are able to study the high-mass end of the distribution up to  $\log(M_*/M_\odot) \sim 12.2$  with unprecedented statistics for 313,026 galaxies over  $4380 \text{ deg}^2$ . Our main results can be summarized as:

(i) the BOSS-DECaLS mass-size relation for massive early-type galaxies exhibits a clear correlation with an apparent flattening in the slope compared to previous estimates from ETGs in CFHT SDSS Stripe 82 at lower masses ([Huertas-Company et al. 2013a](#); [Charbonnier et al. 2017](#)). Further analysis is needed to determine what causes this behaviour. The apparent flattening might be explained by the fact that scaling relations for the most massive early-type galaxies can be systematically different from the same relations at lower masses (e.g., [Montero-Dorta et al. 2016a](#); [Hyde & Bernardi 2009](#); [Bernardi et al. 2011](#); [Kormendy & Bender 2013](#)).

(ii) we find no evolution in the BOSS-DECaLS ETG sizes over  $0.2 < z < 0.7$ . This result is consistent with the non-evolving scenario found by [Montero-Dorta et al. \(2016a\)](#) in the high-mass end of the  $L$ - $\sigma$  relation all the way to  $z = 0$ . In addition, it is consolidated by the no-growth detection in the stellar mass of Stripe 82 Massive galaxies within  $0.3 < z < 0.65$  ([Bundy et al. 2017](#)). If we focus only on the most massive galaxies at  $\log(M_*/M_\odot) > 11.8$ , the slope of their evolution changes to steeply declining with redshift. This is in agreement with current estimates for very massive ETGs in ULTRAVISTA and CANDELS/3D-HST ([Hill et al. 2017](#)) and in COSMOS ([Huertas-Company et al. 2013a](#)).

(iii) combining our BOSS-DECaLS size measurements with the SDSS results at  $z \sim 0.1$  ([Shen et al. 2003](#)), the evolutionary trend mildly declines with redshift and reconciles with [Beifiori et al. \(2014\)](#). This is consistent with a passive evolution scenario for LRGs from  $z \sim 0.55$  ([Maraston et al. 2013](#); [Montero-Dorta et al. 2016b,a](#); [Bundy et al. 2017](#)).

This work provides a galaxy sample with unprecedented statistics that can be used to further investigate morphological and size-related aspects in the evolution of LRGs. In addition, this cross-matched sample can be used to study the dependence of clustering on morphological and size-related properties of LRGs. Our cross-matched BOSS-DECaLS CMASS and LOWZ samples with CFHT calibrated sizes are made publicly available for the community on the SKIES AND UNIVERSES<sup>10</sup> database.

In a follow-up study, we will attempt to deconvolve the uncertainties on the effective radius and the residual incompleteness effects present in the mass-size relation using a similar forward-modeling Bayesian method as the one presented in [Montero-Dorta et al. \(2016b,a\)](#). Within this framework, we will be able to measure the mass-size relation for the *intrinsic* red sequence population photometrically identified in [Montero-Dorta et al. \(2016b\)](#). We also plan to look at the dust properties and star formation history of these

<sup>10</sup> <http://www.skiesanduniverses.org/>

galaxies by cross-matching them with the available data from the infra-red Herschel<sup>11</sup> ESA mission.

In the near future, the Subaru HSC-CCP<sup>12</sup> Collaboration will provide ultra-deep multicolor images down to  $r_{AB} \sim 28$  with 0.6'' median seeing, which will be key to improve the current constraints on galaxy size and morphology. New-generation spectroscopic surveys such as SDSS-IV/eBOSS (Dawson et al. 2016), DESI (Schlegel et al. 2015) and Euclid (Laureijs et al. 2011; Sartoris et al. 2015) will produce enormous data sets with high-resolution out to redshift  $z \sim 2$ . These observations will allow us to better understand the galaxy formation paradigm on small scales, and to coherently link it to the evolution of the large scale structure of our Universe.

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<sup>11</sup> <http://sci.esa.int/herschel/>

<sup>12</sup> <http://hsc.mtk.nao.ac.jp/ssp/>

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