Galaxy Populations in the 26 most massive Galaxy Clusters in the South Pole Telescope SZE Survey

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ABSTRACT

We present a study of the optical properties of the 26 most massive galaxy clusters selected within the SPT-SZ 2500 deg\textsuperscript{2} survey. This Sunyaev-Zel’dovich effect selected sample spans a redshift range of 0.10 < z < 1.13. We measure the galaxy radial distribution, the luminosity function (LF), and the halo occupation number (HON) using optical data with a typical depth of m\textsuperscript{*} + 2 within the band that lies just redward of the 4000 Å break at the cluster redshift. The stacked radial profiles are consistent with a Navarro-Frenk-White profile with a concentration of 2.8\textsuperscript{1+0.6}_{-0.4} for the red sequence and 2.36\textsuperscript{+0.38}_{-0.35} for the total population. Stacking the data in multiple redshift bins shows a hint of redshift evolution in the concentration when both the total population is used, and when only red sequence galaxies are used (at 2\textsigma{} and 2.8\textsigma{}, respectively). The stacked LF shows a faint end slope α\textsubscript{σ} = \text{-1.66}\textsuperscript{+0.04}_{-0.03} for the total and α\textsubscript{σ} = \text{-0.80}\textsuperscript{+0.04}_{-0.03} for the red sequence population. The redshift evolution of the characteristic magnitude m\textsuperscript{*} is found to be consistent with a passively evolving Composite Stellar Population (CSP) model over the full redshift range. By adopting the CSP model predictions for the characteristic magnitude m\textsuperscript{*}, we explore the redshift evolution in the faint end slope α and characteristic galaxy density ρ\textsuperscript{*}. We find α for the total population to be consistent with no evolution (0.29\textsigma{}), while evidence of evolution for the red galaxies is mildly significant (1.08–2.10\textsigma{}), with a steeper faint end at low redshifts. The data show that the density ρ\textsuperscript{*} / E\textsuperscript{2}(z) of galaxies with characteristic magnitude m\textsuperscript{*} decreases with redshift, in tension with the self-similar expectation at a 2.3\textsigma{} level for the total population, when m\textsuperscript{*} is fixed to the model. The measured HON–mass relation for our sample-wide redshift range has a lower normalization than previous studies at low redshift. Finally, our data support HON redshift evolution at a 2.1\textsigma{} level, with clusters at higher redshift containing fewer galaxies per unit mass to m\textsuperscript{*} + 3 than their low-z counterparts.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: formation – cosmology: observations – Sunyaev-Zel’dovich Effect
1 INTRODUCTION

Clusters have long been recognised as important laboratories for the study of galaxy formation and evolution (e.g., Spitzer & Baade 1951; Dressler 1980; Butcher & Oemler 1984; De Propris et al. 2003; Andreon 2010). With the advent of the new generation of mm-wave survey telescopes like the South Pole Telescope (Carlstrom et al. 2011), the Atacama Cosmology Telescope (ACT, Fowler et al. 2007) and Planck (Planck Collaboration et al. 2011b), it has become possible to select galaxy clusters over large fractions of the extragalactic sky using the thermal Sunyaev-Zel’dovich effect (SZE), which arises from the inverse Compton scattering of CMB photons off the hot electrons in the intracluster medium (Sunyaev & Zel’dovich 1972). For the SPT-SZ survey, it has been demonstrated that the cluster samples selected using this signature are close to mass limited (Reichardt et al. 2013), extend to at least redshift $z = 1.47$ (Bayliss et al. 2014) and have purity exceeding 95% from the SZE selection alone (Song et al. 2012b; Bleem et al. 2015). These cluster samples, selected using cluster gas signatures as opposed to cluster galaxy signatures, are ideal for evolutionary studies of the cluster galaxy populations.

By studying the evolution of the cluster galaxy luminosity function (LF) we can address the changes in the cluster populations in a statistical manner. It has been shown, that while the bright population is consistent with a passive evolution of the stellar population, the faint-end of the red sequence LF (rLF) becomes increasingly shallow at higher redshifts (e.g De Lucia et al. 2007; Gilbank et al. 2008; Rudnick et al. 2009). Furthermore, the same studies hint at a weak correlation of the luminosity function faint end slope $\alpha$ with mass. At the same time, previous studies have shown that the Halo Occupation Number (HON), or the integral of the LF per unit mass, seems to be invariant with redshift (Lin et al. 2004, 2006), which points to continuous galaxy transformation within the cluster. This transformation can also be tracked as a function of the radius, using the concentration evolution of the different species. Literature values at different redshifts seem to indicate no evolution when all galaxies within the virial radius are considered (e.g., Carlberg et al. 1997; Capozzi et al. 2012), and while the expectation is that the brightest red sequence galaxies, which dominate the bright-end of the LF, would be more concentrated than the fainter component, it is not known whether this effect is present already at high redshift. All these components are also used in the framework of the Halo Occupation Distribution (HOD; Berlind et al. 2003), which describes how galaxies occupy the cluster as a function of the location, velocity distribution, and luminosity.

In this work, we extract the radial distribution, luminosity function and the HON of galaxies in SZE selected cluster sample to address cluster galaxy evolution questions cleanly within a uniformly selected sample of the most massive clusters in the Universe. This work is complementary to that of Hennig, C. et al. (2016), a study of optical properties of a larger sample of 74 SZE selected clusters with a lower average mass within a limited sky area of 200 deg$^2$. Our goal is to study how the galaxy components, separated into the red subsample and the full sample within the virial radius, change over cosmic time. By making reference to previous studies that have been carried out on X-ray and optically selected cluster samples, we have the opportunity to begin to address the importance of sample selection in these studies.

The paper is organized as follows: Section 2 describes the observations and data reduction. In Section 3, we describe our tools and the simulations used to test them. In Section 4 we present the main results of the study of the galaxy populations in the SPT selected massive cluster sample. Conclusions of this study are presented in Section 5. Magnitudes are quoted in the AB system. We assume a flat, $\Lambda$CDM cosmology with $H_0 = 70.2$ km s$^{-1}$ Mpc$^{-1}$, and matter density $\Omega_M = 0.272$, according to WMAP7 + BAO + H0 data (Komatsu et al. 2011). Masses are defined as $M_{\Delta,\text{crit}} = 4\pi \Delta \rho_{\text{crit}}$, where $\rho_{\text{crit}} = 3H^2/8\pi G$ is the critical density of the Universe.

2 OBSERVATIONS AND DATA REDUCTION

In this work we use a sample of the most massive galaxy clusters in the total 2500 deg$^2$ SPT survey area that was originally presented in Williamson et al. (2011). The sample consists of 26 galaxy clusters with masses $M_{200,\text{crit}} > 1.2 \times 10^{15}h^{-1}M_{\odot}$ extending to redshift $z = 1.13$.

The optical photometric and spectroscopic data used in this paper come from multiple observatories and they have been processed using several pipelines. The data reductions for a portion of the dataset are outlined in several papers (High et al. 2010; Williamson et al. 2011; Song et al. 2012b). In the following subsections we summarize the data and the processing and calibration.

2.1 mm-wave Observations

The clusters presented here are the most massive systems in the SPT-SZ survey area, which consists of a contiguous 2500 deg$^2$ region defined by the boundaries $20^h \leq R.A. \leq 24^h, 0^\circ \leq B.R. \leq 7^\circ$ and $-65^\circ \leq \text{decl.} \leq -40^\circ$. Mass estimation for the clusters has been carried out in a staged manner, first using simulations (Vanderlinde et al. 2010),
and then using a small number of X-ray $Y_X$ measurements (Benson et al. 2013; Reichardt et al. 2013). For details on the SPT data processing there are several papers that describe the method in detail (Staniszewski et al. 2009; Vanderlinde et al. 2010; Shirokoff et al. 2011).

2.2 Redshifts and Cluster Masses

Cluster redshifts first appeared in the discovery paper (Williamson et al. 2011), but since then additional spectroscopic redshifts have become available for six of these systems (Song et al. 2012b; Ruel et al. 2014; Sifón et al. 2013; Planck Collaboration et al. 2011a). Where possible we use spectroscopic redshifts. The redshifts are listed in Table 1. This table contains the SPT cluster name (with reference to other names where they exist), the SPT sky position of the cluster (R.A. and Decl.), the redshift (with two significant digits if a photo-z and with three if a spectroscopic redshift), the SPT S/N, $\xi$, the estimated cluster mass, the virial radius in arc minutes, and the Brightest Cluster Galaxy (BCG) position (R.A. and Decl.).

Although Williamson et al. (2011) reported $M_{200,\text{mean}}$ and $M_{500,\text{crit}}$ masses for each cluster, we update the values of $M_{500,\text{crit}}$ using the Bocquet et al. (2015) code. We convert the $M_{500,\text{crit}}$ to $M_{200,\text{crit}}$ (hereafter $M_{200}$), using a Navarro-Frenk-White profile (NFW; Navarro et al. 1997) and a concentration-mass relation from Duffy et al. (2008). Masses are shown in Table 1 along with the corresponding angular projected radii at which the cluster density reaches $200 \times \rho_{\text{crit}}$, hereafter $r_{200}$, given the assumed cosmology.

2.3 Optical Imaging

The present cluster sample has been imaged with several instruments and telescopes, and with different goals in mind: from shallow photometry for photometric redshift estimations to deep observations for weak lensing analysis (see Table 2 for a list of the telescopes/instruments used). Those observations led to a heterogeneous dataset. To ‘homogenize’ such observations, we set a common luminosity limit of $m_\ast$ for each cluster, re-observing several of them in order to achieve this goal. The data reduction is performed using three different pipelines, and they are summarized below.

2.3.1 Mosaic2 Imager

The Mosaic2 imager was a prime focus camera on the Blanco 4m telescope until 2012 when it was decommissioned in favour of the new wide field DECam imager. Mosaic2 contained eight $2048 \times 4096$ CCD detectors. However, one of the amplifiers of CCD # 4 had been non-operational for the last three years coinciding with these observations. Given the fast optics at the prime focus on the Blanco, the pixels subtend $0.27''$ on the sky. Total field of view is $36.8'$ on a side for a total solid angle per exposure of $\sim 0.4$ deg$^2$. More details on the Mosaic2 imager can be found in the online CTIO documentation\(^1\).

The data from the Mosaic2 imager for this analysis is reduced using a development version of the Dark Energy Survey Data Management Pipeline (DESDM) (Desai et al. 2012). In the DESDM pipeline the data from each night first undergoes detrending corrections, which includes cross-talk correction, overscan correction, trimming, and bias subtraction, as well as fringe corrections for $z$ and $z$ bands. Astrometric calibration is done using SCAMP (Bertin 2006) and using the USNO-B catalog as the astrometric reference. Co-addition is done using SWARP (Bertin et al. 2002). The single epoch images contributing to the coadd are brought to a common zeropoint using stellar sources common to pairs of images. The final photometric calibration of the coadd images is carried out using the stellar color-color locus, with reference to the median SDSS stellar locus (Covey et al. 2007), as a constraint on the zeropoint offsets between neighboring bands, while the absolute calibration comes from 2MASS (Skrutskie et al. 2006).

Mosaic2 data has been acquired over the period of 2005 to 2012, both for the Blanco Cosmology Survey (BCS\(^2\) Desai et al. 2012) and for the SPT targeted cluster followup. A detailed description of the image corrections, calibration and typical photometric and astrometric quality appears in Desai et al. (2012).

2.3.2 WFI, IMACS, and Megacam

Clusters outside the BCS footprint were observed using various instruments, including WFI, IMACS and Megacam. For such observations, the strategy adopted was to adjust the exposure time to reach a depth of $0.4L^\ast(m_\ast-1)$ at $8\sigma$, to obtain robust red-sequence photometric redshifts (Bleem et al. 2015). This study required somewhat deeper imaging than this photometric redshift estimation strategy, so the Wide Field Imager (WFI) on the MPG 2.2-meter telescope at La Silla was used to acquire deeper imaging in $B-$, $V-$, $R-$, and $I-$ filters. The initial imaging from IMACS on Magellan (Dressler et al. 2003; Osip et al. 2008) was typically deep enough to use in this study, and did not require additional observations. We also use $g$, $r$, and $i$ band data acquired with the Megacam imager on Magellan (McLeod et al. 1998) for an ongoing cluster weak lensing program (High et al. 2012; Dietrich et al. in prep).

The processing of the WFI and IMACS data were done with the PHOTPIPE pipeline (Rest et al. 2005; Garg et al. 2007; Miknaitis et al. 2007). WFI data were calibrated in a procedure analogous to the Mosaic2 data. The colors of stars in the science data were calibrated via the Stellar Locus Regression (SLR; e.g., High et al. 2009) technique to a stellar sequence locus generated from a catalog of synthetic stellar spectra from the PHOENIX library (Brott & Hauschildt 2005). The synthetic stellar locus was calculated in the WFI instrument magnitude system using CCD, filter, telescope, and atmospheric throughput measurements.

\(^1\) http://www.ctio.noao.edu/mosaic/manual/index.html
\(^2\) The BCS was a NOAO Large Survey project that covered $\sim 80$ deg$^2$ over 60 nights between 2005 and 2008:
2.3.3 FORS2

The nominal exposure times for the different bands were 1000 s (b), 2000 s (I), and 1000 s (z). These were achieved by coadding dithered exposures with 160 s (b), 175 s (I), and 120 s (z). Deviations from the nominal exposure times are present for some fields due to repeated observations when conditions violated specified constraints or when observing sequences could not be completed during the semester for which they were allocated. Data reduction and calibration was performed with the THELI pipeline (Erben et al. 2005; Schirmer 2013). Twilight flats were used for flatfielding. The I−z−band data were defringed using fringe maps made with night sky flats constructed from the data themselves. To avoid over-subtracting the sky background, the background subtraction was modified from the pipeline standard as described by Appleage et al. (2014).

The FORS2 field-of-view is so small that only a few astrometric standards are found in the common astrometric reference catalogs. Many of them are saturated in our exposures. While we used the overlapping exposures from all passbands to map them to a common astrometric grid, the absolute astrometric calibration was done using mosaics of F606W images centered on our clusters from the complimentary ACS/HST programs 12246 (PI Stubbs) and 12477 (PI High).

Because the data were generally not taken under photometric conditions, the photometric calibration was also carried out using data from the HST programs. We derived a relation between F814W magnitudes and the FORS2 I−band with Schirmer et al. 2013, 2011(a) [note: the citation is likely missing a year or another reference]. The data were then corrected for Galactic extinction using the Schlegel et al. (1998) values.

### Table 1. SPT Cluster List

| Object Name | R.A. [deg] | Decl. [deg] | z | S/N | $M_{200}$ | $M_{200}$ | R200 | R.A.BCG | Decl.BCG |
|-------------|------------|-------------|---|-----|---------|---------|------|---------|----------|
| SPT-CL J0040-4408 | 10.202 | −44.131 | 0.350 | 19.34 | 16.61 | 2.78 | 7.33 | 10.2083 | −44.1305 |
| SPT-CL J0102-4915 | 15.722 | −49.257 | 0.870 | 19.39 | 25.12 | 2.44 | 4.34 | 13.8721 | −49.2530 |
| SPT-CL J0232-4421 | 38.070 | −44.351 | 0.284 | 23.96 | 19.26 | 2.74 | 9.09 | 39.0680 | −44.3466 |
| SPT-CL J0234-5831 | 38.670 | −58.520 | 0.415 | 14.66 | 13.25 | 2.04 | 5.96 | 38.6762 | −58.5235 |
| SPT-CL J0243-5833 | 40.910 | −58.557 | 0.500 | 13.90 | 12.96 | 2.14 | 5.15 | 40.9120 | −58.5807 |
| SPT-CL J0245-5302 | 41.378 | −53.036 | 0.300 | 15.95 | 14.75 | 2.41 | 7.96 | 41.3354 | −53.0292 |
| SPT-CL J0254-5856 | 43.563 | −58.949 | 0.438 | 14.13 | 12.87 | 2.11 | 5.67 | 43.5365 | −58.9717 |
| SPT-CL J0304-4401 | 46.064 | −44.030 | 0.458 | 15.69 | 14.10 | 2.21 | 5.65 | 46.0878 | −44.0438 |
| SPT-CL J0411-4819 | 62.811 | −48.321 | 0.422 | 15.26 | 13.47 | 2.20 | 5.92 | 62.8154 | −48.3174 |
| SPT-CL J0417-4748 | 64.340 | −47.812 | 0.590 | 14.24 | 12.43 | 2.06 | 4.52 | 64.3463 | −47.8132 |
| SPT-CL J0438-5419 | 69.569 | −54.321 | 0.421 | 22.88 | 17.59 | 2.54 | 6.48 | 69.5738 | −54.3223 |
| SPT-CL J0549-6205 | 87.326 | −62.083 | 0.368 | 25.81 | 20.12 | 2.90 | 7.64 | 87.3332 | −62.0870 |
| SPT-CL J0555-6406 | 88.851 | −64.099 | 0.345 | 12.72 | 12.99 | 2.67 | 6.76 | 88.8534 | −64.1055 |
| SPT-CL J0615-5746 | 93.957 | −57.778 | 0.972 | 26.42 | 17.96 | 2.31 | 3.66 | 93.9656 | −57.7801 |
| SPT-CL J0628-4143 | 97.201 | −41.720 | 0.176 | 13.89 | 13.87 | 2.30 | 12.17 | 97.2073 | −41.7269 |
| SPT-CL J0638-5358 | 99.693 | −53.574 | 0.226 | 22.69 | 19.14 | 2.38 | 10.95 | 99.6882 | −53.9730 |

As with the other data, the absolute calibrations were measured with respect to 2MASS point sources in each field. The Megacam data reduction was carried out at the Smithsonian Astrophysical Observatory (SAO) Telescope Data Center using the SAO Megacam reduction pipeline, and also calibrated using the SLR technique. See High et al. (2012) for a more detailed description of the observation strategy and data processing.

#### 2.3.3 FORS2

For two clusters at $z = 0.87$ and $z = 1.132$ in this sample, we acquired VLT/FORS2 data in $b$−, $I$−, and $z$−band under program Nos. 087.A-0843 and 088.A-0796(A) (PI Bazin), 088.A-0889(A,B,C) (PI Mohr) and 286.A-5021(A) (DDT, PI Carlstrom). Observations were carried out in queue mode, and were in clear, although generally not photometric, conditions. The nominal exposure times for the different bands are 480 s ($b$), 2100 s ($I$), and 3600 s (z). These were achieved by coadding dithered exposures with 160 s ($b$), 175 s ($I$), and 120 s (z). Deviations from the nominal exposure times are present for some fields due to repeated observations when conditions violated specified constraints or when observing sequences could not be completed during the semester for which they were allocated. Data reduction and calibration was performed with the THELI pipeline (Erben et al. 2005; Schirmer 2013).
other bands were fixed using a stellar locus regression in the $(m_r, m_{F606W}, m_t, m_z)$ color-space. The inclusion of F606W data in this process was necessary because the stellar locus in $(m_t, m_z, m_s)$ colors has no strong breaks as in the $(g - r, i - z)$ diagrams.

2.4 Completeness

In the majority of cases the photometry is complete to a 1σ level or better to a depth of $m^* + 2$ and no correction due to incompleteness is necessary. For the small fraction of the sample for which this limit is not reached, a correction is applied to enable analysis to a common depth relative to the cluster galaxy characteristic magnitude. The correction follows our previous work in Zenteno et al. (2011): We compare the griz count histograms to the deeper Canada-France-Hawaii-Telescope Legacy Survey (CFHTLS, Brimouille et al. 2008, private communication) by dividing both count histograms. The resulting curve is fit by an error function, which is used to account for the missing objects as we approach the $m^* + 2$ common depth. All clusters covered by WFI-BVRI and VLT-Iz bands reach $m^* + 2$ to a 10σ level and no correction is applied in those cases.

3 CLUSTER GALAXY POPULATIONS: TOOLS

Song et al. (2012b) showed that if the SPT positional error distribution is taken into account, BCGs in the SPT cluster sample are distributed similarly to BCGs in X-ray selected samples. Furthermore, several studies have shown the BCG to be a good proxy for the cluster center, as defined by X-ray (e.g., Lin & Mohr 2004; Mann & Ebeling 2012) and by weak lensing (e.g., Oguri et al. 2010), for the general cluster population. For the following analysis we use the position of the observed BCG (selected within $r_{200}$ following Song et al. 2012b) as a proxy for the cluster center (coordinates listed in Table 1) and its luminosity as a limit on the bright end, to reduce the foreground contamination. Error bars in variables are estimated with $\chi^2$ statistics, where the confidence limits are defined as constant $\Delta \chi^2$ boundaries (Press et al. 1992).

3.1 Radial Distribution of Galaxies

While simulations of dark matter (DM) present a consistent and clear picture of the DM density profiles where the concentration depends strongly on redshift but only weakly on mass (e.g., c(z) = 5.71 × (1+z)$^{-0.47}$($M/M_{200}$)$^{-0.084}$, Duffy et al. 2008), simulations of subhaloes, where the galaxies are expected to live, are less clear. In DM simulations it is found that the radial distribution of subhaloes is roughly independent of host halo mass and redshift. Also, as massive haloes sink more rapidly in the cluster potential due to dynamical friction, they lose mass more rapidly due to tidal stripping (e.g., Angulo et al. 2009). When baryon physics is included, the cores of the radial profiles steepen as the more tightly bound baryons survive better in the central regions than DM only subhaloes (Nagai & Kravtsov 2005; Dolag et al. 2009). These processes may have an effect on the observed galaxy radial profile as well as on the luminosity distribution.

On the observational side, no clear redshift trends have been found to date. Observations of the galaxy distribution have been carried out in clusters with different redshifts and masses. For example, using a local sample of 93 groups and clusters with masses in the $3 \times 10^{13}M_\odot - 2 \times 10^{15}M_\odot$ range, and at $z < 0.06$, Lin et al. (2004, hereafter L04) found a concentration of $c_{g,200c} = 2.9^{+0.21}_{-0.22}$ with no evidence of a mass dependence. At a higher redshift, $0.15 < z < 0.4$, Budzynski et al. (2012) found $c_{g,200c} \approx 2.6$ independently of both cluster mass and redshift, using 55,121 groups and clusters from the SDSS-DR7.

Muzzin et al. (2007), using 15 CNOC clusters at $0.19 < z < 0.55$, found a concentration of $4.13 \pm 0.57$. At a much higher redshift ($z \approx 1$), Capozzi et al. (2012), using 15 clusters with an average mass of $M_{200} = 3.9 \times 10^{14}M_\odot$, found a concentration of $c_{g,200c} = 2.8^{+1.0}_{-0.8}$, completely consistent with the lower redshift cluster samples.

Recently, van der Burg et al. (2014, 2015) studied the evolution of the concentration comparing 60 clusters at $0.04 < z < 0.26$ and 10 clusters at $0.86 < z < 1.34$, finding galaxy density concentrations of $c_{g,200c} = 2.31^{+0.22}_{-0.18}$ (for the $M^* > 10^{12}M_\odot$ haloes) and $c_{g,200c} = 5.14^{+0.54}_{-0.63}$, respectively. While the low redshift sample agrees with the literature, the concentration found for the high redshift sample is higher than expected. As mentioned above, Capozzi et al. (2012) found a concentration of $c_{g,200c} = 2.8^{+1.0}_{-0.8}$ at similar redshifts but with masses only twice as large as van der Burg et al. (2015). A larger sample at high redshift is needed to test if this disagreement is due to strong mass dependence in the concentration of galaxies in clusters, or due to other causes. With the exception of van der Burg et al. (2014), these results appear to point to no evolution in the concentration up to a redshift of 1. We use the SPT-SZ selected sample to test this picture using a uniformly selected sample over a broad redshift range. The radial surface density profiles are constructed for both the full population and the red population. The outer projected radius ranges from one to three $r_{200}$, which is the case for most clusters. Red galaxies are selected if their colour lies within a $\pm 3\sigma (\pm 0.22)$ range around the observed red sequence for that redshift (López-Cruz et al. 2004, see § 4.2.2 for details). In a larger sample it is possible to measure the red sequence as a function of redshift, and then take a more restrictive approach to defining the red sequence population (see Hennig, C. et al. 2016).

The radial binning is done in two ways, depending on how the data are combined and fit. In one configuration all the data are stacked and fitted to a common radius $R_{200}$, and in another a simultaneous fitting on subsamples of individual profiles (multi-fit hereafter) is performed. We use $\chi^2$ statistics (with a number of members per bin of $\ge 15$) with a different binning for each case. For the multi-fit method, which involves fitting multiple individual cluster radial profiles, we bin the data in $0.05 \times r_{200}$ with the first bin and bins beyond $r_{200}$ being twice as wide. For the stacked case, in which the individual cluster bins can be much finer, we use bins of $0.02 \times r_{200}$ size with the first one being twice as wide, up to $R_{200}$. In addition, as a cross check, we perform individual fits on single clusters. For the single cluster fit we use bins
of width $0.02 \times r_{200}$ size and beyond $r_{200}$ double the width. As in the latter case, the bins are scarcely populated, and we use Cash (1979) statistics and a Markov chain Monte Carlo (MCMC) Ensemble sampler emcee from Foreman-Mackey et al. (2013). The results are shown in Fig. 2 and Fig. 3.

As in Zenteno et al. (2011), we have masked the saturated stars in the field and corrected for the effective area covered. This is done by gridding the data within a radial bin tangentially by using an angular bin of 2 degrees (i.e., dividing the radial bin into 180 tangentially arranged bins). Bins that fall within masked areas are discarded from the radial area calculation. Also, as a quality control, if two thirds or more of the area of the annulus is lost, then the annulus is discarded. This typically happens at the detector edges.

To compare with previous studies we fit a projected NFW profile to our radial distribution. This density is modeled as the number of galaxies in a cylinder within rings divided by the ring area. The number of galaxies in a cylinder of radius $r$ can be described analytically by integrating the NFW profile along the line of sight (e.g., Bartelmann 1996):

$$N_{\text{cyl}}(r) = 4\pi \rho_s r_s^3 f(x)$$

$$f(x) = \begin{cases} \ln \frac{x}{c_g} + \frac{2}{\sqrt{x^2-1}} \arctan \sqrt{\frac{x^2-1}{x^2+1}} & \text{if } x > 1, \\ \ln \frac{x}{c_g} + \frac{2}{\sqrt{1-x^2}} \arctanh \sqrt{\frac{1-x^2}{1+x^2}} & \text{if } x < 1 \end{cases}$$

where $\rho_s$ is the central density, $r_s = r_{200}/c_g$ is the scale radius, $c_g$ is the galaxy concentration and $x = c_g r / r_{200}$. We can parametrize this as a function of the number of galaxies within a cylinder of radius $r_{200}$:

$$N_{\text{cyl}}(r) = 4\pi \rho_s r_s^3 f(c_g).$$

Combining this with Eq. 1 we can write the projected number of galaxies within $r_{200}$ as a function of $N_{\text{cyl}}$:

$$N_{\text{cyl}}(r) = N_{\text{cyl}}^{r_{200}} f(x) / f(c_g)$$

Thus, in the end we fit $c_g$, $N_{\text{cyl}}^{r_{200}}(M)$ plus a flat background $N_{\text{bkg}}$ to our data. Note that even if all cluster galaxy distributions had the same shape, we would still expect the number of galaxies within the virial region $N_{\text{cyl}}^{r_{200}}(M)$ to exhibit a cluster mass dependence.

Due to the heterogeneity of our optical imaging dataset we have radial profiles extending from one to several $r_{200}$, and it is not possible to define a region for background estimation that is uncontaminated by the cluster. We approach this problem in two ways: (1) we simply discard the background information and combine the data over the region where all clusters have coverage ($\sim r_{200}$, see Fig. 2) and (2) we simultaneously fit all clusters making use of the common NFW shape parameters while marginalizing over individual cluster backgrounds. That is, we fit each cluster by fixing a common $c_g$ and $N_{\text{cyl}}^{r_{200}}$ but marginalizing over the individual cluster background $N_{\text{bkg}}$. While in the former case the $\chi^2_{\text{stack}}$ comes from the single fit, in the latter, the stack $\chi^2_{\text{stack}}$ is calculated as the sum of the individual cluster $\chi^2$ contributions. Errors are reported as the projection of the 1σ contour for 1 parameter ($\Delta \chi^2_{\text{stack}} = 1$; Press et al. 1992) for $c_g$ and $N_{\text{cyl}}^{r_{200}}$.

Although the mass range in the current sample is small there are mass dependencies which need to be accounted for in the stacking and multi-fit processes. We do this by varying $N_{\text{cyl}}^{r_{200}}$ from Eq. 2 as a function of the cluster mass $M$ in the following way:

$$N_{\text{cyl}}^{r_{200}}(M) = N_{\text{cyl}}^{r_{200}} \left[ \frac{M}{\frac{\gamma}{M_{\text{piv}}}} \right]^{\gamma}$$

where $\gamma = 0.87$ (L04) and the pivotal mass is $M_{\text{piv}} = 10^{13} M_\odot$. 

| Site            | Telescope           | Aperture [m] | Camera | Filters | Field [′ × ′] | Pixel scale [″] |
|-----------------|---------------------|--------------|--------|---------|--------------|----------------|
| Cerro Tololo    | Blanco              | 4.0          | MOSAIC-II | griz    | 36 × 36      | 0.27           |
| Las Campanas    | Magellan/Baade      | 6.5          | IMACS i/2 | griz    | 27 × 27      | 0.20           |
| Las Campanas    | Magellan/Clay       | 6.5          | Megacam | gri     | 25 × 25      | 0.16           |
| La Silla        | 2.2 MPG/ESO         | 2.2          | WFI    | BVRI    | 34 × 33      | 0.24           |
| Paranal         | VLT Antu            | 8.2          | FORS2  | bJrz    | 7 × 7        | 0.25           |

Figure 2. Radial profile of the stacked sample up to $r_{200}$, using all galaxies (black) and red sequence galaxies (red). These profiles are well fit by NFW profiles with the red subsample somewhat more concentrated than the full sample, with concentrations of $2.84_{-0.37}^{+0.40}$ and $2.36_{-0.35}^{+0.38}$, respectively.

Table 2. Optical Imagers Employed in this Study
The individual cluster LF is constructed using sources within a projected $r_{200}$, centered on the BCG. We perform a statistical background subtraction using a background region at $r > 1.5r_{200}$. In general, we make use of the photometry up to a 10σ level at an $m^* + 2$ depth or even deeper. The projected, background-corrected LF is then de-projected using an NFW profile with a concentration of $c_{\text{corr}} = 2.36$ and $c_{\text{corr}} = 2.84$, which corresponds to the stack value in Fig. 2 for the full and the red populations, respectively. Finally, the cluster LF is divided into the different magnitude bins and scaled by the cluster volume in Mpc.

Corrections due to masked regions and background over-subtraction are applied here as well. In the case of masked regions within $r_{200}$ we correct for the missing cluster galaxies using the NFW profile with the concentration $c_{\text{corr}}$. Also, using the same model, we correct for the over subtraction due to cluster galaxies contaminating the background dominated region. This over subtraction can be expressed by an extra term $N_{\text{clus, true}}^{>1.5r_{200}}$ in the background:

$$N_{\text{clus, true}}^{>r_{200}} = N_{\text{clus, true}}^{>r_{200}} - AN \times (N_{\text{back}}^{>1.5r_{200}} + N_{\text{clus, true}}^{>1.5r_{200}})$$ (3)

where $A_N$ is the area normalization between cluster and background. Under the assumption that there is no luminosity segregation and that the galaxy distribution is well described by an NFW model with a given concentration, we can connect the over subtraction to the galaxies within $r_{200}$ as $N_{\text{clus, true}}^{>1.5r_{200}} = \tau(c_g)N_{\text{clus, true}}^{>r_{200}}$. Combining Eq. 3 we have a correction:

$$N_{\text{clus, true}}^{>r_{200}} = \frac{N_{\text{clus, obs}}^{>r_{200}} - \tau(c_g)N_{\text{clus, obs}}^{>1.5r_{200}}}{1 - AN \times \tau(c_g)} = N_{\text{clus, obs}}^{>r_{200}}.$$ (4)

The average correction $C$ is of the order of 1.11.

Finally, two of the clusters have only imaging from VLT/FORS2 with a FOV of $7' \times 7'$, covering less than 1.5$r_{200}$. For SPT-CLJ2106-5844 at $z=1.131$, the background area is re-defined as the area at $r > r_{200}$ with a corresponding correction C, of 1.49. For the cluster SPT-CLJ1012-4915, this re-defined area is at the detector edge and an external background is used. As a background area we use the Cosmic Evolution Survey (COSMOS, Scoville et al. 2007a) data, avoiding regions with known large scale structures at the cluster redshift (Scoville et al. 2007b)\textsuperscript{4}.

Once the LF is constructed we fit it by the three parameter Schechter function (SF) (Schechter 1976),

$$\phi(m) = 0.4 \ln(10) \phi^* 10^{0.4(m^* - m)/(\alpha + 1)} \exp(-10^{0.4(m^* - m)}).$$

We fit the SF to the stack, and to the individual luminosity functions. In the single cluster case, simulations show that there is little constraint on $m^*$ if the three variables are allowed to float within our typical luminosity range (see §3.4), so our approach is to extract the parameters $\phi^*$, $m^*$, and $\alpha$ by fixing one parameter and leaving the other two to float. Specifically, for the $m^*$ evolution analysis, we fix $\alpha$. We note that the three parameters of the Schechter function are correlated, so fixing one variable to the wrong value will have an impact on the free parameter.

\textsuperscript{4} $149.4^\circ \leq R.A. \leq 150.2^\circ$ and $1.5^\circ \leq \text{decl.} \leq 2.2^\circ$
For the stacked LF we fit all three parameters. We bring the data to a common frame fitting in the space of \( m - m_{\text{model}} \), using a Composite Stellar Population model (see § 4.2.2 for details). Once the data are brought to this common frame, they are stacked using an inverse variance weighted average:

\[
N_j = \frac{\sum_i N_{ij}^*=0 / \sigma_{ij}^2}{\sum_i \sigma_{ij}^2}
\]

where \( N_{ij}^*=0 \) is the number of galaxies per volume per magnitude at redshift zero, in the \( j \)th bin corresponding to the \( i \)th cluster’s LF and \( \sigma_{ij} \) is the statistical poisson error associated. We obtain \( N_{ij}^*=0 \) by correcting it by the evolutionary factor \( E^2(z) \), where \( E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_k} \). This scaling is appropriate for self-similar evolution where the characteristic density within the cluster virial region will scale with the critical density of the universe.

The errors of the stacked profile are computed as

\[
\delta N_j = \frac{1}{(\sum_i \sigma_{ij}^2)^{1/2}}
\]

We adopt \( \alpha \) from the stacked LF for the evolution study of the single cluster characteristic magnitudes \( m^* \).

## 3.3 Composite Stellar Population Models

Several studies have shown that \( m^* \) evolution can be well described by a passively evolving stellar population that has formed at high redshift (e.g., De Propris et al. 1999; Andreon 2006; Lin et al. 2006; De Propris et al. 2007; Mancone et al. 2010). Empirically, these Simple Stellar Population (SSP) models have been used to predict red sequence colors that are then used to estimate cluster redshifts with characteristic uncertainties of \( \delta z \sim 0.025 \) (e.g., Song et al. 2012a,b).

Generally speaking, in an analysis of cluster galaxy populations over a broad redshift range it is helpful to have a model within which the evolution and \( k \)-corrections are self-consistently included to simplify the comparison of cluster populations at different redshifts within the observed bands.

In this analysis we create red sequence CSP models for Mosaic2 and IMACS griz, WFI BVRI, and VLT BIz bands using the Bruzual & Charlot (2003) SSP models and the EzGal python interface (Mancone & Gonzalez 2012). The models consist of an exponentially falling star formation rate with a decay time of 0.4 Gyr, Salpeter IMF, and a formation redshift of 3. We use in total six different metallicities to introduce the tilt in galaxy red sequence within the color-magnitude space. To calibrate these models we adopt the measured metallicity-luminosity relation for Coma cluster galaxies (Poggianti et al. 2001; Mobasher et al. 2003). This procedure then requires a further adjustment of the Coma \( L^* \) luminosity (Iglesias-Páramo et al. 2003) brightening it by 0.2 magnitudes to reproduce the observed colour of the Coma cluster. This calibrated set of CSP models allows us to predict the apparent magnitudes and colors of all our cluster populations within the range of relevant observed bands. As described in § 4 below, by using the full sample of clusters we can test whether this set of models is consistent with the real galaxy populations.

### 3.4 Simulated Galaxy Catalogs

To test our methods, find the best stacking strategy and quantify possible biases, we create simulated galaxy catalogs of a typical cluster. We re-create a galaxy cluster using the number of galaxies in a cluster of mass \( M_{200} = 1.3 \times 10^{14} M_\odot \), given the expected number of galaxies from measurements of the halo occupation number (HON at low redshift, L04) and with a concentration of 3 over a typical angular region on the sky. This corresponds to a spherical number of galaxies, within \( r_{200} \) and up to a magnitude of \( m^* + 3 \), of \( N_{200}^* = 335 \) and its projected value \( N_{200}^\phi = 443 \). Although \( m^* + 2 \) is our typical depth we extend the cluster counts to \( m^* + 5 \) for testing purposes. No luminosity segregation is included. We assign galaxy magnitudes to match an LF with \( \alpha = -1.2 \) and \( m^* = m_{\text{model}}^*(z = 0.35) \), while \( \phi^* \) is set by \( N_{200}^\phi \). The number of background galaxies used corresponds to 45,000 sources in the \( m^* - 3 \) to \( m^* + 5.5 \) luminosity range with a brightness distribution equivalent of the CFHTLS \( r \)-band count histogram used in § 2.4. The construction of the radial profiles and luminosity functions is done using the same tools as for the real clusters, accounting for the masked areas due to CCD gaps, stars and missing CCDs.

As we mention in § 3.1, the multi-fit stack approach uses a typical bin size of 0.05\( r_{200} \), while the first bin and the bins beyond \( r_{200} \) are twice as wide. This configuration is chosen to balance a good number of galaxies (\( \gtrsim 15 \)) per bin with the need to have narrow enough bins to be able to constrain \( c_\alpha \). We fit for \( c_5 \) and \( N_{200}^\phi \) and marginalize over each individual cluster background. We demonstrate this with the multi-fit method on five clusters using the region extending up to 3\( r_{200} \) over 20 realizations, the concentration is recovered within 1\( \sigma \) (3.09 ± 0.00).

Another way to use the data is to stack the cluster data up to a common maximum radius. In this case there are more galaxies per bin than in the single cluster case, giving us the chance to explore finer bins and to test that our results are not biased due to the chosen bin size. The common maximum radius is reached at \( \sim r_{200} \), set by the lowest redshift cluster. We use a bin set of 0.04, 0.02 and 0.1\( r_{200} \) for the first bin, the bins below \( r_{200} \) and the bins at \( > r_{200} \) respectively. Simulations show that in the case of 25 clusters in the stack, the input concentration is recovered within 1\( \sigma \) (3.62 ± 0.48). In comparison, when the same data are stacked up to 3\( r_{200} \), the input values are recovered well within 1\( \sigma \).

Using the multi-fit stack binning configuration, we also test the individual results. Fitting for the radial profile parameter \( c_\alpha \), \( N_{200}^\phi \) and background in each individual simulated cluster, over the 100 realizations, the weighted mean of the concentration is recovered well within 1\( \sigma \) (\( c_\alpha = 2.97 \pm 0.12 \)). These tests give us confidence that our binning strategy and our scripts are suited for use in extracting measurements of the concentration of the galaxy clusters in this study with biases that are at or below the statistical uncertainty.

In the case of the luminosity function, we use and apply the configuration and corrections described in § 3.2 (0.5 mag bin, count correction due to background over subtraction, star-masked areas, CCD gaps, etc.) to test our scripts and assess the level of bias and or scatter under this configuration.

Simulations demonstrate that simultaneously fitting all
three SF parameters provides only weak constraints on $m^*$, given that the typical depth pushes to $m^* + 2$. To overcome this we fix one of the three parameter and explore the other two: when $\alpha$ is fixed the weighted mean value recovered for $m^*$ is within 1.6$\sigma$. Conversely, if $m^*$ is fixed, $\alpha$ is recovered well to within 1$\sigma$. In the case of the HON, when $m^*$ is fixed, the true HON is recovered to 0.6$\sigma$ and to 3.2$\sigma$ when $\alpha$ is the variable fixed to the input value. Accordingly our first choice is to fix $m^*$ when studying the HON.

4 RESULTS

4.1 Radial Profile

The composite profiles for the full and red sequence selected galaxies in the full sample of clusters are shown in Fig. 2. The lines trace out the best fit NFW profiles, which provide a good description of the stacked galaxy profiles in both cases. The best fit concentration for the red galaxy sample is $2.84^{+0.40}_{-0.37}$, which is somewhat higher than that for the total population of $2.36^{+0.38}_{-0.35}$. The higher concentration for the red subsample is consistent with the radial variations of red fraction found in optical studies of other cluster samples (e.g., Goto et al. 2004; Verdugo et al. 2012; Ribeiro et al. 2013; Gruen et al. 2013).

Our measured concentration for the full sample $2.36^{+0.38}_{-0.35}$ is somewhat lower when compared to previous estimates $2.9^{+0.24}_{-0.21}$ at redshift zero (L04) and $2.8^{+0.19}_{-0.16}$ at $z \sim 1$ (Capozzi et al. 2012). Given the high masses of our sample, one may wonder if the differences reflect a mass dependence on the concentration. While in DM simulations more massive halos have lower concentration, the same simulations do not show such a trend with galaxies. Some analyses have shown a steep inverse mass dependence with concentration (Hansen et al. 2005), while other analyses (including many of the same clusters Budzynski et al. 2012) found no such trend. They attribute the difference to different approaches in defining the radius in the two studies. van der Burg et al. (2015) did find a steep mass-concentration relation, although the two cluster samples are at very different redshifts. Nevertheless, for the high mass, low-redshift sample, the concentration found by van der Burg et al. (2015) of $c_{200c} = 2.31^{+0.22}_{-0.18}$ is in excellent agreement with ours. Hennig, C. et al. (2016) used an SPT selected sample with a lower mass average finding higher concentrations of $3.59^{+0.20}_{-0.18}$ and $5.37^{+0.24}_{-0.22}$ for the total and the red galaxy population, respectively. This overall picture seems to point to a mass-concentration relation steeper than DM only simulations.

The concentration measured as a function of redshift for the SPT sample is shown in Fig. 3. The individual cluster fits are shown in light grey, pointing to an apparent evolution. The multi-fit over five bins with five clusters in each bin confirms this picture. Fitting a slope and intercept to the red sample and full subsample we find $c_{\text{red}} = 6.05^{+1.23}_{-1.55} \times (1 + z)^{-1.74^{+0.66}_{-0.64}}$ and $c_{\text{all}} = 5.01^{+1.05}_{-1.29} \times (1 + z)^{-1.21^{+0.59}_{-0.49}}$ which correspond to 2.81$\sigma$ and 2.05$\sigma$ significance respectively, of a possible evolution. Also, the result from the stack over all redshifts is consistent with this formula within the errors, as expected.

4.2 Luminosity Function

Several studies have found that the steepness of the faint end depends on the band chosen (e.g., Goto et al. 2002, 2005), as bands bluer than the 4000Å break are more sensitive to younger populations. We systematically select the nearest band redward of the 4000Å break. The two excluded clusters included the lowest redshift system where our imaging is not adequate and another system that has a foreground star field, making it difficult to identify the faint galaxy population. The BCGs are excluded. The weighted averaged luminosity function appears below. In black the total population is shown, and in red the red-sequence population is displayed. Bins with at least two contributing clusters are shown. The fit for the all galaxies stacked is $\phi^*_{\text{fit}} = 2.24^{+0.23}_{-0.20}$ and $\alpha_{\text{fit}} = -1.06^{+0.04}_{-0.03} \chi^2_{\text{all,red}} = 2.96$. The fit for red-sequence galaxies is $\phi^*_{\text{red}} = 2.21^{+0.16}_{-0.15}$ and $\alpha_{\text{red}} = -0.80^{+0.04}_{-0.05} \chi^2_{\text{rs,red}} = 1.31$.

Figure 4. We plot 24 of the 26 individual LFs (top) versus $m - m^*_{\text{model}}$, where $m^*_{\text{model}}$ is the predicted CSP characteristic luminosity at the redshift of the cluster. Each individual LF is extracted using the band redward of the 4000Å break. The two excluded clusters included the lowest redshift system where our imaging is not adequate and another system that has a foreground star field, making it difficult to identify the faint galaxy population. The BCGs are excluded. The weighted averaged luminosity function appears below. In black the total population is shown, and in red the red-sequence population is displayed. Bins with at least two contributing clusters are shown. The fit for the all galaxies stacked is $\phi^*_{\text{fit}} = 2.24^{+0.23}_{-0.20}$ and $\alpha_{\text{fit}} = -1.06^{+0.04}_{-0.03} \chi^2_{\text{all,red}} = 2.96$. The fit for red-sequence galaxies is $\phi^*_{\text{red}} = 2.21^{+0.16}_{-0.15}$ and $\alpha_{\text{red}} = -0.80^{+0.04}_{-0.05} \chi^2_{\text{rs,red}} = 1.31$. 

Galaxy Populations in the 26 most massive Galaxy Clusters in the South Pole Telescope SZE Survey

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4.2.1 Stacked Luminosity Function

For the stacked LF we use 24 clusters. The two excluded clusters are SPT-CL J2201-5956 which, with a redshift of 0.098 and 1.5 × 10^12 M_{⊙} mass, has a projected r_{200} outside of the field-of-view, making it all but impossible to estimate the background contribution, and SPT-CL J0555-6406, which has a star field as a foreground that makes the cluster normalization unreliable.

As we mentioned in § 3.4, fitting all three variables in the LF produces large errors in the parameter exploration. To address this problem, we use m* from the model or α from the stacked LF to explore the remaining two LF parameters. In spite of the large errors during three parameter SF fits, we need at a minimum to check that the m* evolution is consistent with our passively evolving CSP model. Doing this we find that a linear fit to the observed m* distribution as a function of redshift has a zero point of 0.250±0.041 and a slope of 0.53±0.20 for the total population. That is, the normalization of our model is consistent to within the uncertainties with the data, and the dataset over this broad range of redshifts provides no evidence for a deviation from the model. We also compare our model to red only galaxies spanning a large range of redshift is consistent with measurements using variously selected samples at different redshifts (Gaidos 1997; Paolillo et al. 2001; Piranomonte et al. 2001; Barkhouse et al. 2007; Popesso et al. 2005, which provided measurements of α = −1.09 ± 0.08, −1.11 ± 0.09, −1.01 ± 0.08, −1.07, −1.09 ± 0.05, −1, and −1.05 ± 0.13, respectively).

Initially φ* seems lower than in L04, a previous study. L04 found a best fit for their data of φ* = 4.43 ± 0.11 h^2 Mpc^{-3} for α = −0.84 ± 0.02 (best fit), but found a lower φ* = 3.00 ± 0.04 h^2 Mpc^{-3} when α is fixed to = −1.1, noting that both α’s described well their data. As our systems are more massive and the slope of the HON is less than unity it is expected that our φ* solution would be lower than that measured for lower mass systems. L04 also explore this possibility, using their 25 most massive systems, with mean mass of M_{200} = 5.3 × 10^{14} M_{⊙} finding α = −0.84 ± 0.03 and φ* = 4.00 ± 0.16 h^2 Mpc^{-3}. Given the dependence of α and φ* shown and the mass range, this result using a redshift zero sample of clusters and 2MASS photometry seems to be consistent with our result. A larger cluster mass range is needed to carry out a more precise test.

\[ \phi^* = (\frac{2}{\sqrt{2\pi}}) \int \exp\left(\frac{-(m-m_0)^2}{2\sigma^2}\right) \, dm \]

Figure 5. LF parameter evolution with redshift. As noted before, the LFs are extracted using the band redward of the 4000 Å break. We fit a line in each case, marking the allowed 1σ region. Panel (a): There is no significant evolution in Δmag = (m_{model} − m*), indicating the CSP model provides a good description of galaxy evolution across this redshift range. Panel (b): Evolution of α is suggested by the data with best fit line having intercept −1.05±0.05 and slope = −0.04±0.14. Panel (c): φ/E^2(z) extracted when fixed m* is consistent with no evolution at 2.38σ level. Panel (d): Ratio of HON deviates from this work and the redshift independent L04 prediction. Slope and intercept are found to be = −0.89±0.38 and = −1 at 1σ respectively, which indicate a mild evolution where z = 1 clusters have typically 30% fewer galaxies than their low redshift counterparts of the same mass.
Several previous studies have shown that the evolution of \( m^* \) for cluster galaxy populations can be described by a passively evolving stellar population formed at high redshift (e.g., De Propris et al. 1999; Andreon 2006; De Propris et al. 2007; Šuhada et al. 2012; Stalder et al. 2013). We test this result by fitting the LF using \( m^* \) and \( \phi^* \) as free parameters while fixing \( \alpha \) to the measurement from the stack. We compare the obtained \( m^* \) to a CSP model that is produced as described in Sec. 3.3 above. In panel (a) of Fig. 5 we show a comparison between the observed \( m^* \) and our CSP model. From this figure and the 1σ (grey) area, it is clear that the data and our CSP model is in good overall agreement. A linear fit with redshift yields an intercept of \( 0.11^{+0.12}_{-0.13} \) and a slope of \( -0.12^{+0.30}_{-0.29} \). Thus, our CSP model of an exponential burst of star formation at \( z=3 \) with a decay time of 0.4 Gyr and a Salpeter IMF tuned with a range of metallicities to reproduce the tilt of the red sequence population at low redshift provides a good description of the evolution of the cluster galaxy populations over a broad range of redshift. It is important to emphasize that our \( m^* \)’s are extracted from the band that is just redward of the 4000 Å break, a band that would be expected to be relatively insensitive to recent star formation. If red sequence galaxies are used a similar result is obtained. The top panel of Fig. 6 shows \( m^* \) not evolving within the sample redshift range (the slope found is \( -0.25^{+0.15}_{-0.18} \)). While there is no evidence for evolution of \( m^* \) for the red population, a non-zero weighted average overall offset of 0.46 is found (and applied to the panel (a) of Fig. 6). We attribute this difference to the \( m^* - \alpha \) covariance and we apply this correction for the red galaxies only model by dimming the models by the corresponding value. This correction in the model normalization is important, as by fixing a wrong \( m^* \) model we would infer, for example, an incorrect \( \alpha \). As a sanity check we remind the reader that in § 4.2.1 we found an intercept of \( 0.54^{+0.17}_{-0.17} \) for a three parameters SF fitting, in full agreement with the correction described above.

### Evolution of \( \phi^* \)

The LF normalization (\( \phi(\nu) \)) is the number of galaxies per Mpc\(^3\) per unit magnitude, and it informs us, once the universal evolution of the critical density is scaled out, about possible evolution of the number density of galaxies near the characteristic magnitude in cluster environment. In our study we are using the SZE data to give us the cluster mass \( M_{200} \), the mass within the region of the cluster that has a mean density of 200 times the critical density. Because the critical density evolves with redshift as \( \rho_{\text{crit}} \propto E^2(z) \) where \( H(z) = H_0E(z) \), we expect to see a higher characteristic galaxy density at high redshifts. Thus, to explore for density evolution beyond this we examine measurements of \( \phi(\nu)/E^2(z) \) in the case where \( \alpha \) is a free parameter and \( m^* \) comes from the CSP model. Results appear in panel (c) of Fig. 5 for all galaxies, and Fig. 6 for the red sequence subsample. By fitting a linear relation for both sets of measurements, using \( m^* \) fixed to the model we find best fit parameters for the slope to be \( -0.47^{+0.30}_{-0.29} \) for the red population, consistent with no evolution. On the other hand, the total population with a slope equal to \( -0.81^{+0.34}_{-0.20} \) hints to a possible evolution at the 2.38σ level, with clusters having a lower density of \( m^* \) galaxies at higher redshift.

As already mentioned in § 4.2.1, our LF normalization is consistent with values in the low redshift regime when accounting for the high masses of our clusters. At high redshift this is among the first study of its kind. Our approach to studying the characteristic galaxy density \( \phi^* \) requires good mass estimates, and until recently these were not available at redshifts \( z \sim 1 \).

### Evolution of the Faint End Slope \( \alpha \)

The redshift evolution of the faint end slope \( \alpha \) for all galaxies and for red galaxies is shown in panels (b) of Fig. 5 and Fig. 6. It can be seen that \( \alpha \) changes to less negative values at higher redshift with 0.29σ and 2.10σ significance.
for all and red population, respectively. That is, for the red population there is weak evidence for fewer low luminosity cluster galaxies relative to high luminosity cluster galaxies at high redshift than in the local Universe. The best fit linear relation has intercept $-1.05_{-0.05}^{+0.05} / -0.87_{-0.04}^{+0.04}$ and slope $-0.04_{-0.14}^{+0.14} / 0.21_{-0.10}^{+0.09}$ for all and red population, respectively.

Comparing the results from the total population with low-z Abell Clusters, in bands redward of the 4000 Å break, we find a consistent picture. For example, Gaidos (1997) observed 20 Abell Clusters in the $R$-band obtaining $\alpha = -1.09 \pm 0.08$. Paolillo et al. (2001) constructed the LF using 39 Abell Clusters and found $\alpha = -1.11_{-0.09}^{+0.09}$, in Gunn $r$-band. Barkhouse et al. (2007) studied 57 Abell Clusters, in $R_C$ band, constructing the red, blue and total LF. For the total LF they find an agreement with $\alpha = -1$ in the region just fainter than $m^*$ and a steeper $\alpha$ as the photometry gets deeper, in the range that is not covered by this study. Also, Piranomonte et al. (2001) examined 80 Abell Clusters finding $\alpha = -1.01_{-0.07}^{+0.09}$ in Gunn $r$-band.

At higher redshifts, in agreement with low-z studies, Popesso et al. (2005) used X-ray selected samples at redshift $\leq 0.25$ and found a faint end slope $\alpha = -1.05 \pm 0.13$, in $r$-band, for the brighter part of the LF and with a background subtraction method similar to our approach. Also, in the same redshift range, Hansen et al. (2005) showed qualitatively that $\alpha = -1$ is a good fit to X-ray selected clusters in $r$-band using SDSS data.

At even higher redshift, the observational efforts to obtain the LF are more common in the infrared, as it is expected to track the stellar mass without great sensitivity to recent star formation. Lin et al. (2006) used 27 clusters at redshifts $0 < z < 0.9$ to find the low-redshift faint-end slope of $\alpha = -0.9$ qualitatively consistent with their high redshift sample. Muzzin et al. (2007) found a similar slope $\alpha = -0.84 \pm 0.08$ with a sample of 15 clusters at redshifts $0.2 < z < 0.5$. Using Spitzer, Mancone et al. (2012) found also shallower slopes, with $\alpha_{2\mu m} = -0.97 \pm 0.28$ and $\alpha_{5\mu m} = -0.91 \pm 0.28$ in lower mass clusters or groups at $< z > \sim 1.35$. Recently, Chiu et al. (2016b) also used Spitzer 3.6μm to construct the LF of 46 low mass systems, within a wide redshift range. They found an LF faint slope of $\alpha \sim -0.9$, within $0.1 < z < 1.02$, consistent with no evolution albeit with large error bars.

The literature points to little evolution of $\alpha$, with high-z cluster LFs being shallower (albeit with redder rest frame bands). Our results show $\alpha$ evolution for the full population consistent with no evolution up to redshift 1.1. For the red population, there are several studies that show that the red sequence LF slope evolves strongly with shallower $\alpha$ at higher redshifts (e.g., De Lucia et al. 2004; Goto et al. 2005; Tanaka et al. 2005; Barkhouse et al. 2007; Stott et al. 2007; Gilbank et al. 2008; Rudnick et al. 2009). Our findings show an evolutionary trend on $\alpha_{red}$ as reported in previous works at the 2.10σ level. Nevertheless, a closer inspection of panel (b) of Fig. 6 seems to show that at the high redshift end the trend is dominated by a single cluster, SPT-CLJ0102-4915, observed with VLT and with a background subtraction done with COSMOS data. To estimate the impact of the cluster we perform a bootstrap resampling of the data, revealing a similar positive trend in $\alpha$ evolution of $0.15 \pm 0.14$, but with a lower significance ($1.08\sigma$). A larger sample of SZE selected clusters is needed to strengthen our results, especially in the high redshift end.

### 4.3 Halo Occupation Number

We use a homogeneously selected cluster sample to characterize the HON as a function of mass and redshift and then to examine possible evolutionary trends. The Halo Occupation Number is obtained by integrating the Schechter Function.

$$ N = 1 + N^*, \quad \text{with} \quad N^* = V \phi^* \int_{\phi_{low}}^{\infty} y^\alpha e^{-y} \, dy $$

where the first term accounts for the BCG, which is not part of the LF, $V$ is the cluster virial volume, $\phi_{low} = L_{low} / L^*$, and $\alpha$ and $\phi^*$ are the values obtained in previous sections. To compare to previous studies such as L04 we integrate the LF to $m^* + 3$.

As can be seen in Fig. 7 the range of masses in our sample is quite small, and so it is not possible to constrain both normalization and slope of the HON-mass relation. Therefore, we adopt the slope of 0.87 reported in the literature for a large sample of low redshift clusters (L04). With this slope, we measure a normalization of $223.87_{-10.36}^{+15.22}$ (1σ uncertainties), which is lower than the value found by L04 of $267 \pm 22$.

Furthermore, we look for possible evolution by examining the ratio between our measured HON and the value at the same mass obtained at low redshift (L04). In this analysis we enhance the HON errors using the mass uncertainties and the adopted mass slope of 0.87. Fitting a linear relation in log space (see panel (d) in Fig. 5) we obtain $-0.80_{-0.38}^{+0.38}$ and $0.06_{-0.05}^{+0.06}$ for the slope and intercept, respectively. Thus, we find evidence at the 2.11σ level that galaxy clusters at high redshift have fewer galaxies per unit mass to $m^* + 3$ than their low-z counterparts. This result is consistent with Capozzi et al. (2012), where the HON was found to exhibit a mild evolution.

One concern we have is that our VLT cluster LFs suffer from background over-subtraction. As we mentioned in § 3.4 we use the NFW profile to correct for cluster galaxies in the defined background region. While in the non-VLT data the background is defined at $r > 1.5 r_{200}$, for the VLT clusters it is defined at $r > r_{200}$, which means that a larger correction is being made to the measured background. This correction is at the $12 \pm 4$% level for 23 clusters, while for SPT-CLJ2106-5844 at $z = 1.131$, this correction is at the 49% level. In the case of SPT-CLJ0102-4915 at $z = 0.87$ an external background is used (COSMOS), rendering a much lower HON compared to the best fit (see circled right point in Fig. 7), although not constituting a clear outlier. This suggests that the contamination corrections we apply to the VLT backgrounds are not resulting in biased HON estimates. However, in the complementary analysis of Hennig, C. et al. (2016), which uses DES imaging data over large regions so that the background subtraction is less problematic, there is a statistically lower significant evidence for redshift evolution.
5 CONCLUSIONS

We have studied a cluster sample consisting of the 26 most massive galaxy clusters selected in the 2500 deg^2 SPT-SZ survey. The masses range between $M_{200,c} = 1.2 \times 10^{15} M_\odot$ and $2.7 \times 10^{15} M_\odot$, and the redshift range is broad $0.10 < z < 1.13$. We use the SZE based cluster mass to define the virial region within which we study the optical properties such as the radial profile, the luminosity function and the Halo Occupation Number.

The stacked radial profile of the whole sample is well described by an NFW model with a concentration of $c_g = 2.36 \pm 0.38$, which is low compared to the majority of the results found in the literature. Differences between our study and previous works include the mass range, the redshift extent and the selection. Using SDSS clusters and groups, Hansen et al. (2005) found a strong inverse correlation between mass and concentration which may explain the lower concentration we see in our high mass sample, although Budzynski et al. (2012) did not find such correlation using a different radius definition on the same dataset. Furthermore, our low concentration measurement is driven by clusters in the higher redshift bin, which are not represented in most previously published samples (Carlberg et al. 1997; Lin et al. 2004; Budzynski et al. 2012). A more similar sample to compare to our higher redshift sample is that in Capozzi et al. (2012). Although having a lower average mass than our sample, the concentration found is $c_g = 2.84 \pm 0.40$, which is consistent with our findings.

We also stack the red galaxy population—defined using a colour bin of $±0.22$ centered on the red sequence at each redshift, finding them to be more concentrated than the total population at $c_{g,\text{red}} = 2.84 \pm 0.40$. A higher NFW concentration in the red population is expected from the observed radial distribution of the fraction of red galaxies, which increases toward the center of the cluster (e.g., Goto et al. 2004; Verdugo et al. 2012; Ribeiro et al. 2013; Gruen et al. 2013).

Evidence for the redshift evolution of the concentration for the full population is weak at the $2.05\sigma$ level. In the case of the red sequence population the redshift evolution index is $-1.74 \pm 0.04$, which provides evidence for evolution at the $2.81\sigma$ level, a trend qualitatively in line with DM only simulations (e.g., Duffy et al. 2008). As can be seen in Fig. 3, this result is strongly dependent on the lowest
redshift cluster bin. A larger sample, in number of clusters and area coverage, is required to further examine this issue. The Dark Energy Survey (DES) is ideally suited to address this question.

The stacked total luminosity function (LF) is well fit by a Schechter function with Schechter parameters: \( \alpha_{\text{all}} = -1.06_{-0.03}^{+0.04} \) and \( \phi^*_{\text{all}} = 2.24_{-0.20}^{+0.23} \). The faint end slope is found to be consistent with previous studies of local clusters (e.g., Gaidos 1997; Paolillo et al. 2001; Piranomonte et al. 2001; Barkhouse et al. 2007) and cluster at somewhat higher redshifts (e.g., Popesso et al. 2005; Hansen et al. 2005). Also,\( \alpha_{\text{all}} \) value found is somewhat lower than previous work (\( L_04, \phi^* = 4.00 \pm 0.16 \ h_{70}^2 \ Mpc^{-3} \) for the case of the 25 most massive systems, which has a median mass lower than ours), although when considering the \( \phi^* - \alpha \) covariance they are in qualitative agreement. The stacked red-sequence LF (rLF) is well fit in the ratio of bright/dwarf galaxies. Nevertheless, this significant \( \alpha_{\text{all}} \) found is consistent with previous studies (Gilbank et al. 2008; Rudnick et al. 2009).

We also fit the LF of individual clusters using \( \alpha_{\text{all}} = -1.06_{-0.03}^{+0.04} \) from the stacked result to study the single cluster \( m^* \) evolution. We use the band which probes the region of the galaxy spectrum redward of the 4000 Å break over the full redshift range. The \( m^* \) behaviour with redshift yields a slope of \( -0.12_{-0.26}^{+0.26} \), indicating that the evolution of the characteristic luminosity in this uniformly selected sample does not deviate from the CSP model to which we compare. This model is an exponential burst at \( z = 3 \) with decay time of 0.4 Gyr and a Salpeter IMF. This is broadly in agreement with previous work, which has shown cluster galaxies are generally well modeled by a passively evolving stellar population that formed at redshift \( z > 1.5 \) (e.g., De Propris et al. 1999; Lin et al. 2006; Andreon et al. 2008; Mancone et al. 2010).

We used this result, fixing \( m^* \) to the CSP model predictions in the LF fit to explore the \( \alpha \) and \( \phi^* \) evolution. In the case of \( \alpha \) evolution, we find a slope of \( -0.04_{-0.14}^{+0.14} \), indicating no evolution. In the rLF \( \alpha_{\text{red}} \) case, it is found to evolve as \( 2.10_{-0.10}^{+0.09} \), at a 2.10σ level evidence for low redshift clusters having a steeper faint end, indicating an evolution in the ratio of bright/dwarf galaxies. Nevertheless, this significance is greatly reduced if we do a bootstrap resampling of the data (1.08σ). The normalization \( \phi^*/E^2(z) \) measurements provide no significant evidence of redshift evolution when \( m^* \) is fixed to the model for the red population, and some evidence (2.38σ) for evolution of the total population.

We measure the HON, the number of galaxies within the virial region more luminous than \( m^* + 3 \), comparing it to the literature using a \( N \propto M^{\gamma} \) parametrization, and probing for redshift trends. Due to the small mass range in our sample, a simultaneous fit of both the normalization and the slope does not provide useful constraints. Therefore, we adopt a slope of \( \gamma = 0.87 \) from the literature (\( L_04 \)) and fit for the normalization. We find a normalization of 223.87 ± 15.22 at a mass \( M_{200} = 10^{13.5} M_\odot \), which is lower than the normalization of 267 ± 22, found in L04 from local clusters.

HON evolution with redshift is found to have a slope of \( -0.80_{-0.38}^{+0.38} \), providing some evidence (2.11σ) of a preference for high redshift clusters to be less populated than their lower redshift counterparts as suggested by Capozzi et al. (2012) findings. A bigger sample is needed to investigate further the HON.

These results are to be further tested as the Dark Energy Survey is completed, enabling us to probe the galaxy population variations not only with redshift but also with mass.

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