

Clustering properties of g -selected galaxies at $z \sim 0.8$

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ABSTRACT

Current and future large redshift surveys, as the Sloan Digital Sky Survey IV extended Baryon Oscillation Spectroscopic Survey (SDSS-IV/eBOSS) or the Dark Energy Spectroscopic Instrument (DESI), will use Emission-Line Galaxies (ELG) to probe cosmological models by mapping the large-scale structure of the Universe in the redshift range $0.6 < z < 1.7$. With current data, we explore the halo-galaxy connection by measuring three clustering properties of g -selected ELGs as matter tracers in the redshift range $0.6 < z < 1$: (i) the redshift-space two-point correlation function using spectroscopic redshifts from the BOSS ELG sample and VIPERS; (ii) the angular two-point correlation function on the footprint of the CFHT-LS; (iii) the galaxy-galaxy lensing signal around the ELGs using the CFHTLenS. We interpret these observations by mapping them onto the latest high-resolution MultiDark Planck N-body simulation, using a novel (Sub)Halo-Abundance Matching technique that accounts for the ELG incompleteness. ELGs at $z \sim 0.8$ live in halos of $(1 \pm 0.5) \times 10^{12} h^{-1} M_{\odot}$ and $22.5 \pm 2.5\%$ of them are satellites belonging to a larger halo. The halo occupation distribution of ELGs indicates that we are sampling the galaxies in which stars form in the most efficient way, according to their stellar-to-halo mass ratio.

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

1 INTRODUCTION

By investigating the properties of galaxy clustering within the cosmic web, it is possible to constrain cosmology and infer the growth of structure and the expansion history of the Universe (Weinberg et al. 2013). In fact, galaxy clustering measurements using last-generation large-volume red-

shift surveys, as the Sloan Digital Sky Survey (SDSS; York et al. 2000; Gunn et al. 2006; Smee et al. 2013) and the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS; Eisenstein et al. 2011; Dawson et al. 2013) provide robust information about both the evolution of galaxies and the cosmological framework in which these complex structures live. In order to interpret such measurements, we need to understand the relation between the theory-predicted dark matter field and its luminous counterpart i.e., the discrete galaxy map (Cooray & Sheth 2002).

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Luminous low-redshift galaxies have already been connected to their dark matter halos in a precise manner, through weak lensing and clustering analysis as a function of galaxy luminosity and stellar mass. Baldry et al. (2004), Zehavi et al. (2011) and Guo et al. (2015) measured the clustering properties of the SDSS “blue cloud” and “red sequence” in the local Universe (SDSS median redshift $z \sim 0.1$; Abazajian et al. 2009), as a function of magnitude and color. Their results show that at a given luminosity, the blue sample has a lower clustering amplitude and a smaller correlation length compared to the red one.

Guo et al. (2014) investigated the clustering luminosity and colour dependence of BOSS CMASS DR10 (Anderson et al. 2014), and found that more luminous galaxies are more clustered and hosted by more massive halos. For luminous red galaxies (LRGs), these masses are $\sim 10^{13} - 10^{14} h^{-1} M_{\odot}$, at fixed luminosity, progressively redder galaxies are more strongly clustered on small scales, which can be explained by having a larger fraction of these galaxies in the form of satellites in massive haloes. Favole et al. (2015) measured galaxy clustering in the BOSS CMASS DR11 (Anderson et al. 2014) sample at $z > 0.55$ as a function of color, and proposed a new statistic to extract robust information about small-scale redshift-space distortions and large-scale galaxy bias. Consistent with many previous results (e.g., Wang et al. 2007; Zehavi et al. 2005; Swanson et al. 2008), they found that, compared to the blue population, red galaxies reside in more massive halos, show a higher clustering amplitude, and their large-scale bias and peculiar velocities are lower.

This type of clustering analysis has recently been extended to higher redshifts thanks to the VIMOS Public Extragalactic Survey (VIPERS; Guzzo et al. 2014; Garilli et al. 2014) and DEEP2 survey (Newman et al. 2013). Compared to DEEP2, VIPERS has a much larger volume but has a lower redshift limit however, the signal-to-noise ratio in its spectroscopic measurements is higher. Using VIPERS data, Marulli et al. (2013) measured the clustering properties of galaxies at redshift $z = 0.8$ as a function of their luminosity and stellar mass, and found that the clustering amplitude and the correlation length increase with these two quantities; see also the PRISM Multi-object Survey (PRIMUS) results by Skibba et al. (2015) and Bray et al. (2015). Mostek et al. (2013) measured the clustering of the red sequence and the blue cloud at $z = 0.9$, as a function of their stellar mass and star formation history, using DEEP2 data. They argued that blue galaxies are more clustered in the local Universe than at $z = 0.9$, and red galaxies are much more clustered locally than at high redshift. They also suggested that the clustering trend observed with star formation rate (SFR) can be explained mostly by the correlation between stellar mass and clustering amplitude for blue galaxies. Coil et al. (2008) studied the DEEP2 clustering dependence on color and luminosity, and found that the dependence on color is much stronger than with luminosity, and is as strong with color at $z \sim 1$ as locally. They claimed no dependence of the clustering amplitude on color for galaxies in the red sequence, but a significant dependence for galaxies within the blue cloud. Cooper et al. (2008) investigated the connection between star formation (SF) and environment in DEEP2 data at $z \sim 0.1$, and $z \sim 1$. Their results indicate that, locally, galaxies in regions of higher overdensity have lower star formation rates (SFRs), and their stars form more slowly than

in their counterparts in lower density regions. At $z \sim 1$, this SFR-overdensity relation is inverted; this is in part due to a population of bright, blue galaxies in dense environments, which lacks a counterpart in the local Universe, and is thought to evolve into members of the red sequence from redshift 1 to 0.

The combination of clustering with weak galaxy-galaxy lensing (see e.g., Bartelmann 1999) allows one to gain insight on the large-scale structure formation, and directly probe the stellar-to-halo mass relation (SHMR; Leauthaud et al. 2011). The galaxy-halo connection has been measured at $z < 1$ by Leauthaud et al. (2012), Shan et al. (2015), and Coupon et al. (2015), using three different weak lensing surveys (COSMOS: Scoville et al. (2007); CFHT-Stripe82 and CFHTLenS¹: Heymans et al. (2012a); Erben et al. (2013a)); all obtained consistent results. Leauthaud et al. (2012) performed the first joint analysis of galaxy-galaxy weak lensing, galaxy clustering, and galaxy number densities using COSMOS data, and provided robust constraints on the shape and redshift evolution of the SHAM relation in the redshift range $0.2 < z < 1$. At low stellar mass, the halo mass scales proportionally to $M_{\star}^{0.46}$; this scaling does not evolve significantly with redshift. At $M_{\star} > 5 \times 10^{10} M_{\odot}$, the SHMR rises sharply, causing the stellar mass of a central galaxy to become a poor tracer of its parent halo mass. Combining observations in the CFHT-LenS/VIPERS field from the near-UV to the near-IR, Coupon et al. (2015) found that the SHMR for the central galaxies peaks at $M_{h,peak} = (1.9^{+0.2}_{-0.1} \times 10^{12} M_{\odot})$, and its amplitude decreases as the halo mass increases. Hearin et al. (2014) presented new measurements of the galaxy two-point correlation function and the galaxy-galaxy lensing signal from SDSS, as a function of color and stellar mass, and demonstrated that the age-matching model (Hearin & Watson 2013), which states that older halos tend to host galaxies with older stellar populations, exhibits remarkable agreement with these and other statistics of low-redshift galaxies.

Current (Sub)Halo-Abundance Matching (SHAM; Conroy et al. 2006; Trujillo-Gomez et al. 2011; Klypin et al. 2013; Nuza et al. 2013) and Halo Occupation Distribution (HOD; Berlind & Weinberg 2002; Kravtsov et al. 2004; Zheng et al. 2005, 2007) models correctly reproduce the clustering measurement mentioned above. SHAM maps observed galaxies onto dark matter halos directly from N-body cosmological simulations, according to a precise monotonic correspondence between halo and galaxy number densities. The HOD method is an analytical prescription to populate simulated halos with galaxies, in which the assignment is performed by interpolating the halo occupation distribution at the values of the desired halo masses. In this sense, the SHAM approach returns a model which is built directly on the considered simulation box.

Next generation high-redshift surveys as SDSS-IV/eBOSS (Dawson et al. 2015, in prep.), Subaru Prime Focus Spectrograph (PFS; Sugai et al. 2012; Smee et al. 2014), DESI (Schlegel et al. 2015), 4MOST² and Euclid³ (Laureijs et al. 2011; Sartoris et al. 2015) will use emission-line galaxies (ELGs) as BAO tracers to explore the Uni-

¹ <http://www.cfht.hawaii.edu/Science/CFHTLS/>

² <https://www.4most.eu/cms/>

³ <http://sci.esa.int/euclid/>

verse large-scale structure out to $z \sim 2$. Observing ELGs, learning how to model their clustering properties and understanding how they populate their host halos are therefore crucial points that we need to understand in order to select the targets for future experiments. From the observational point of view, the recent increment of available ELG spectroscopic data (Guzzo et al. 2014; Comparat et al. 2015) allows one to measure their clustering properties over about 12 deg^2 at $z = 0.8$ (corresponding to a comoving volume of $V \sim 10.6 \times 10^6 h^{-3} \text{ Mpc}^3$ in the Planck cosmology; see Section 3 for details), which represents a dramatic improvement.

Comparat et al. (2013) demonstrated that neither a standard HOD nor a traditional SHAM technique are able to reproduce the angular clustering of ELGs on small scales. In fact, both techniques are based on the assumption that the galaxy sample to model is complete, but this is not the case of the ELGs, which are highly incomplete in stellar mass. One could instead use semi-analytic models of galaxy formation and hydrodynamic simulations, but they lack of mass resolutions to model emission line galaxies.

The aim of this work is to provide a modified version of the standard SHAM prescription, directly based on the latest MultiDark N-body simulation with Planck cosmology, that accounts for the ELG incompleteness and returns suitable mock galaxy catalogs able to accurately predict the ELG angular and redshift-space clustering, respectively, on small and larger scales. These mock catalogs are released to the public.

The paper is organized as follows. Section 2 describes the data sets and the MultiDark simulation box used in our analysis. In Section 3 we present our ELG clustering and weak lensing measurements. In Section 4 we explain how we model the ELG clustering and we present our main results. Section 5 discusses the implications of our ELG clustering analysis in a galaxy evolution perspective, and Section 6 summarizes our main results.

Throughout the paper, we assume the Planck cosmology (Planck Collaboration et al. 2014) and magnitudes in the AB system (Oke & Gunn 1983).

2 DATA AND SIMULATION

2.1 Data sets

We build our ELG galaxy sample using the Canada-France-Hawaii Telescope Legacy Survey (CFHT-LS) Wide T0007⁴ photometric redshift catalog (Ilbert et al. 2006; Coupon et al. 2009). We apply a g -band magnitude cut, $20 < g < 22.8$ (Fukugita et al. 1996), to select galaxies with bright emission lines and low dust at $z < 1$. We also apply a color selection, $-0.5 < (u - r) < 0.7(g - i) + 0.1$, to remove the low-redshift galaxies. For details on the selection function, see Comparat et al. (2015). Then, to obtain the largest possible area, we convert the i -selection into the new Megacam

i -band filter⁵. For the W1, W3 and W4⁶ fields, we derive an average density of about 500 ELGs per deg^2 , 70% of which have a photometric redshift in the range $0.6 < z < 1$. The densities of each field are reported in Table 1, and the errors on the photometric redshift are $\sigma_z < 0.05(1+z)$ for $i < 22.5$ and $z < 1$. The $ugri$ ELG selection is brighter than $i < 22.5$.

We match the photometric targets to the available spectroscopic surveys – BOSS DR12, DEEP2, VIPERS (Bolton et al. 2012; Alam et al. 2015; Newman et al. 2013; Guzzo et al. 2014) – within $1''$ radius; see Table 2. Based on KS-tests, the VIPERS, BOSS and DEEP2 spectroscopic selections constitute fair sub-samples of the complete selection: the hypothesis that they are drawn from the same distribution cannot be rejected at the 90% confidence level. For these samples, we create random catalogs with the same redshift distribution of the data and 30 times denser. Figure 2 displays the ELG spectroscopic redshift distribution per unit volume for the three Wide fields (solid histograms), and their mean (dashed line). Two thirds of the galaxy density is located in the redshift range $0.7 < z < 0.9$, while both the intervals $0.6 < z < 0.7$ and $0.9 < z < 1$ contain one sixth of the sample.

2.2 MultiDark simulations

The MultiDark Planck simulation (MDPL, Klypin et al. 2014; www.MultiDark.org) contains 3840^3 particles in a $1 h^{-1} \text{ Gpc}$ box, and was created adopting Planck ΛCDM cosmology (Planck Collaboration et al. 2014). Halos are identified based on density peaks including substructures using the Bound Density Maximum (BDM) halo finder (Klypin & Holtzman 1997; Riebe et al. 2013).

⁵ <http://www4.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/en/megapipe/docs/filt.html>

⁶ <http://www.cfht.hawaii.edu/Science/CFHTLS/T0007/T0007-docsu10.html>

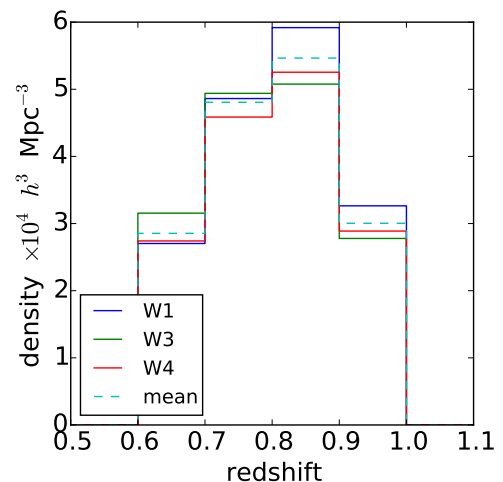
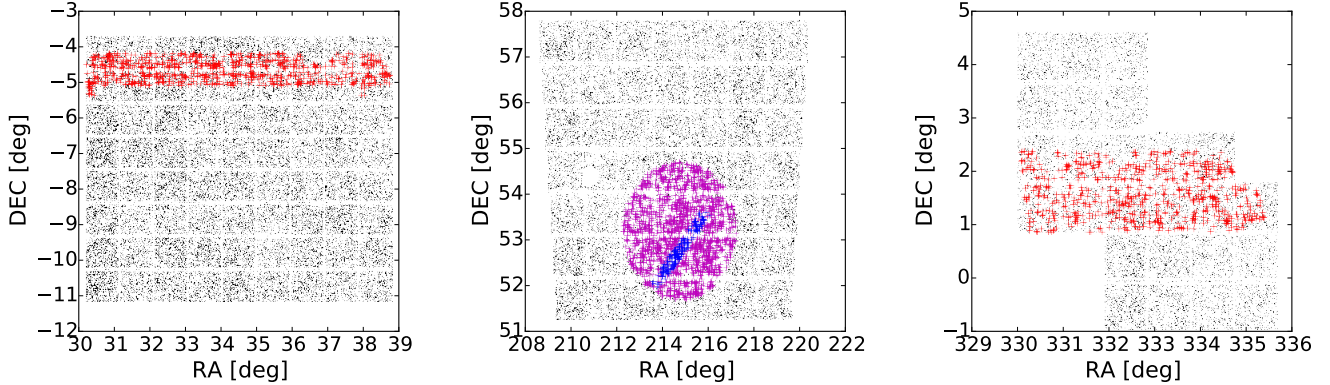


Figure 2. ELG weighted spectroscopic redshift distribution per unit volume for the W1, W2, and W3 Wide fields (solid histograms), and their mean value (dashed line).

⁴ <http://www.cfht.hawaii.edu/Science/CFHTLS/>

Table 1. ELG photometric data per CFHT-LS Wide field after applying the bright star and bad field mask.

Field	W1	W3	W4	all
Center α, δ	35°, -7°	215°, 54°	333°, 2°	-
area [deg ²]	63.75	44.22	23.3	131.27
N	32,808	22,195	11,025	66,028
N [deg ⁻²]	514.64	501.92	473.18	502.99
z_{phot} quartiles	0.78 / 0.88 / 1.03	0.77 / 0.88 / 1.05	0.78 / 0.88 / 1.03	0.78 / 0.88 / 1.03
z_{phot} Deciles D10, D90	0.7 / 1.24	0.68 / 1.29	0.69 / 1.25	0.69 / 1.26
N ($0.6 < z_{phot} < 1$)	23,433	15,242	7,861	46,536
N ($0.6 < z_{phot} < 1$) [deg ⁻²]	367.58	344.69	337.38	354.51
z_{phot} quartiles	0.75 / 0.83 / 0.9	0.74 / 0.81 / 0.89	0.75 / 0.83 / 0.89	0.75 / 0.82 / 0.89

**Figure 1.** Photometric (black) and spectroscopic (VIPERS: red; BOSS: magenta; DEEP2: blue) coordinates of our ELG sample in the three CFHT-LS Wide fields.

We use the MDPL halo catalogs to build a mock light-cone that matches the mean ELG redshift distribution shown in Figure 2. Given the high density of the ELG tracers and their expected low-mass host halos, the MDPL box is an excellent compromise between numerical resolution and volume. We apply the SURvey GenerAtor code (SUGAR; Rodriguez-Torres et al. (2015), in prep.) to the 11 snapshots available from MDPL to construct a light-cone with a volume ten times the observations that covers the redshift range $0.6 < z < 1$ ($\sim 1h^{-1}$ Gpc depth). The procedure used is analogous to the method presented by Blaizot et al. (2005) and Kitzbichler & White (2007), and can be summarized as follows:

(i) Set the properties of the light-cone: angular mask, radial selection function (number density) and number of snapshots within the redshift range considered. Each slice of the light-cone is constructed by selecting all halos from every MDPL snapshot. The thickness of a slice at redshift z_i is given by $[(z_i + z_{i-1})/2, (z_i + z_{i+1})/2]$

(ii) Place an observer (i.e., $z = 0$) inside the box and shift the cartesian coordinates of the box in such a way that the observer occupies the central point of the box at $z = 0.8$

(iii) Convert from cartesian (x, y, z) to spherical (α, δ, r_c) coordinates, where r_c is the comoving distance in real space.

The redshift of each point will be:

$$r_c(z) = \int_a^b \frac{cdz'}{H_0 \sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} \quad (1)$$

(iv) From each snapshot, select the (sub)halos so that $(z_i + z_{i-1})/2 < z < (z_i + z_{i+1})/2$ and α/δ lie inside the sky window. Since the ELG observational data represent halos with typical masses $\sim 10^{12}h^{-1}M_\odot$, in the light-cone we include all halos for which the simulation is complete i.e., $\log(M_h/h^{-1}M_\odot) > 11.2$

(v) Using the halo velocities, v_p , we compute the peculiar velocity contribution for each object along the line-of-sight and derive its distance in redshift-space as

$$s = r_c + (v_p \cdot r_c)/(aH(z)), \quad (2)$$

where $a = (1+z)^{-1}$ is the scale factor and $H(z)$ is the Hubble parameter at redshift z

(vi) Finally, select objects from the light-cone using our selection function.

Throughout the paper we will designate our lightcone as “MDPL-LC”. Section 4 describes in detail the halo selection and the (Sub)Halo-Abundance Matching modeling adopted to determine the halo occupation distribution of our ELG sample.

Table 2. ELG spectroscopic data.

survey	match	good z	$0.6 < z < 1$	area [deg ²]	\bar{z}
VIPERS W1	1,223	942	760	5.478	0.803
BOSS W3	2,145	1,876	1,357	6.67	0.803
DEEP2 W3	225	222	156	0.5	0.803
VIPERS W4	1,148	846	680	5.120	0.795
All	4,741	3,886	2,953	17.668	0.803

3 MEASUREMENTS

Using the ELG sample described in Section 2.1, we measure both galaxy clustering and galaxy-galaxy lensing. The following provides a detailed description of our measurements.

3.1 Galaxy Clustering

We estimate both the angular, $w(\theta)$, and the redshift-space, $\xi(s)$ (hereafter ξ^s), two-point correlation functions following

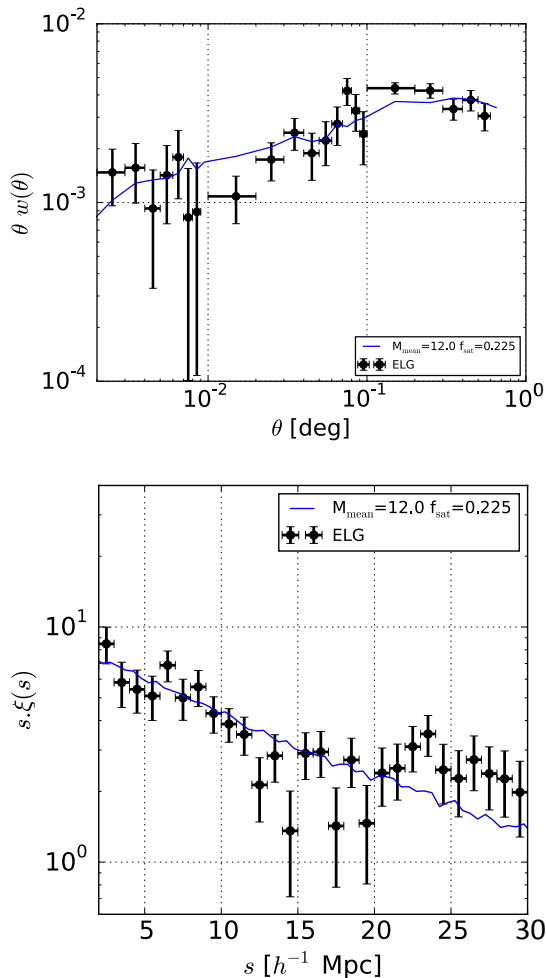


Figure 3. Two-point angular (top panel) and redshift-space (bottom panel) ELG correlation functions (points), together with our best-fit model (blue line), which corresponds to the point highlighted by a star in Figure 6.

the procedures described by Landy & Szalay (1993), Coupon et al. (2012) and de la Torre et al. (2013).

To compute ξ^s on the VIPERS and the BOSS ELG samples (see Table 2), independently, we create linear bins in separations of $1 h^{-1} \text{Mpc}$ at $s < 10 h^{-1} \text{Mpc}$, and $4 h^{-1} \text{Mpc}$ for $10 < s < 40 h^{-1} \text{Mpc}$. We then correct the impact of redshift errors and catastrophic redshifts to recover the correlation function down to $1 h^{-1} \text{Mpc}$. Finally, we combine the two measurements weighted by the projected density of each field. The resulting redshift-space correlation function is displayed in Figure 3 (bottom panel); fitting a power-law model, $\xi(s) = (s/s_0)^\alpha$, in the separation range $2 < s < 30 h^{-1} \text{Mpc}$, we find $s_0 = (5.3 \pm 0.2) h^{-1} \text{Mpc}$ and $\alpha = -1.6 \pm 0.1$.

Analogously, we calculate the angular 2PCF, $w(\theta)$, using photometric redshifts from the W1, W3 and W4 CFHT-LS fields. The points are corrected from the integral constraint following Coupon et al. (2012) and Tinker et al. (2010). On scales $\theta < 0.05^\circ$, all three fields provide consistent measurements. At larger scales, there are signs of possible systematics in W1 and W4, since the clustering signal does not decrease as rapidly as expected. We therefore use only the measurement on the W3 field, which appears the most robust (see Figure 3, top panel). The $w(\theta)$ of the W3 field is in perfect agreement with Figure 9 (panel 4) in Comparat et al. (2013). This result was computed on the Stripe 82 region (Stoughton et al. 2002), with three times larger area. At the mean redshift of the sample, $z = 0.8$, one degree corresponds to $18.847 h^{-1} \text{Mpc}$; thus, $w(\theta)$ spans the range from $\sim 40 h^{-1} \text{kpc}$ up to $\sim 20 h^{-1} \text{Mpc}$.

To estimate the errors on our galaxy clustering measurements, since the simulated light-cone area is larger than the data ($\sim 560 \text{ deg}^2$), we divide the best MDPL-LC model in different realizations of our data (15 for the photometric and 30 for the spectroscopic samples), and obtain sample variance diagonal errors that we use rather than Poisson errors.

We compare the combined ξ^s measurement from BOSS and VIPERS to previous measurements by Marulli et al. (2013) to provide a first interpretation. Our result matches both the clustering signal of galaxies selected in the stellar mass range $9.5 < \log(M_*/h^{-1} M_\odot) < 11$, and the clustering of galaxies selected by absolute magnitude in the interval $-22 < M_B - 5 \log(h) < -20.5$. Using the stellar-to-halo mass relation from Leauthaud et al. (2012), Shan et al. (2015) and Coupon et al. (2015), we can deduce a rough estimate of the halo masses populated by our ELG sample i.e., $11.6 < \log(M_h/h^{-1} M_\odot) < 12.7$. These halo masses are typical of Milky-Way size halos, being much less massive than those hosting the LRG sample, see Nuza et al. (2013).

In the angular clustering measurement, the change of slope occurs at $\theta \sim 0.01^\circ$, corresponding to $\sim 200 h^{-1} \text{kpc}$. Using MDPL, we derive the relation between halo mass and virial radius at $z \sim 0.8$; halos with virial radius $\sim 200 h^{-1} \text{kpc}$ occupy the mass range $M_h = (0.5 - 1) \times 10^{12} h^{-1} M_\odot$. Since a single galaxy per halo would not induce such a change in the $w(\theta)$ slope, this result implies a satellite fraction of approximately 22.5% (see Section 4). Figure 3 displays a good agreement between our clustering measurements and predictions for ELG halos of mass $10^{12} h^{-1} M_\odot$ with this satellite fraction.

3.2 Weak lensing

We use the latest weak lensing catalogs produced by the Canada-France-Hawaii Telescope Lensing Survey (CFHTLenS; Heymans et al. 2012b; Erben et al. 2013b) on the W1 and W3 fields to measure the galaxy-galaxy lensing around 47,485 ELG lenses. This measurement allows one to constrain the halo masses. We follow Gillis et al. (2013) and apply only the multiplicative correction, m_s , to the shear measurement and avoid the $c2$ correction. We measure the tangential shear, γ^t , around the photometric ELG sample as a function of the radial distance from the lenses using the (Velandier et al. 2011) estimator:

$$\Delta\Sigma = \left[\frac{\sum_{ls} w_{ls} \gamma_{ls}^t \Sigma_c}{\sum_{ls} w_{ls}} \right] / \left[\frac{\sum_{ls} w_{ls} (1 + m_s)}{\sum_{ls} w_{ls}} \right], \quad (3)$$

where the sum runs over the lens - source pairs (ls) and the w_{ls} values are the weight obtained by lensfit.

The lenses being at higher redshift compared to the source catalog, and the fact that ELGs are expected to live in “low” mass halos, tends to a low signal-to-noise ratio around 2 for $R < 1 \text{ Mpc}$. We measure only the 1-halo term.

We model the measurement using a truncated Navarro, Frank & White (NFW) halo profile (Baltz et al. 2009) and the mass-concentration relation from Neto et al. (2007) to truncate halos at half their concentration (Wright & Brainerd 2000). The best-fit model suggests typical halo masses of $M_{200} = 1.25 \pm 0.45 \times 10^{12} h^{-1} M_\odot$. The lower and upper mass limits are, respectively, $M_{200} = 5.61 \pm 7.20 \times 10^{11} h^{-1} M_\odot$ and $M_{200} = 1.41 \pm 0.51 \times 10^{12} h^{-1} M_\odot$; see Fig. 4. This measurement is in good agreement with the first interpretations based on the clustering (see Section 3).

4 HALO OCCUPATION FOR EMISSION LINE GALAXIES

The (Sub)Halo-Abundance Matching (SHAM; e.g., Conroy et al. 2006; Trujillo-Gomez et al. 2011) technique is a straightforward method to link observed galaxies with dark-matter-only simulated halos. It relies in a monotonic correspondence between halo and galaxy number densities, which is based on the assumption that more luminous galaxies reside in more massive halos. Such association is performed by choosing suitable proxies for both halos and galaxies (e.g., the halo maximum circular velocity and the galaxy luminosity or stellar mass) and includes some scatter (see Trujillo-Gomez et al. (2011) for details). The advantage of using N -body simulations, compared to analytical models, is given by the accuracy achieved in the predictions of the

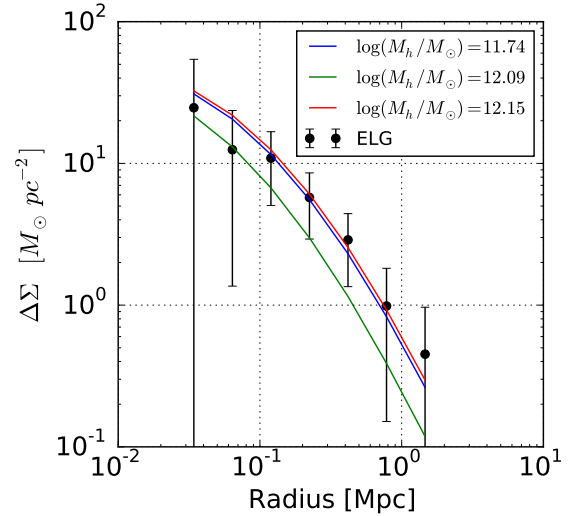


Figure 4. ELG surface density ($\Delta\Sigma$) as a function of the physical scale for different lens models.

clustering for a given halo population. Many state-of-the-art clustering measurements have been modeled using a SHAM technique that maps the observations onto suitable high-resolution N -body simulations, allowing the interpretation of the halo occupation distribution and bias (de la Torre et al. 2013; Nuza et al. 2013; Carretero et al. 2015). Watson et al. (2015) recently presented a method to upgrade SHAM models to account for differences between quenched and star-forming galaxies.

In the specific case of the emission-line galaxies, the traditional SHAM approach cannot be applied since it requires a complete galaxy sample, and ELGs are far from being complete in any parameter space, even in terms of their emission line luminosity, see Comparat et al. (2013). We therefore must modify the standard SHAM procedure to take into account the ELG incompleteness and match their clustering amplitude. To this purpose, we selected halos and subhalos by mass (for the subhalos we considered only the mass of the bound particles, to avoid ambiguities) to be able to compare directly with the weak lensing measurements. In the future, provided a high signal-to-noise ratio in the clustering measurement, we will properly select (sub)halos by their maximum circular velocity at accretion, (e.g., Behroozi et al. 2013b).

In order to model both the 1-halo and the 2-halo terms in the ELG two-point correlation functions and the weak lensing measurement, we use the MultiDark Planck $1h^{-3} \text{Gpc}^3$ box (see Section 2.2), which represents the best compromise between high resolution and volume, as previously described in Section 3.

We parametrize the probability of selecting a halo hosting an ELG as follows:

$$P(M_h, M_{mean}, \sigma_M, f_{sat}) = f_{sat} \mathcal{N}(M_h, M_{mean}, \sigma_M, \text{flag} = \text{sat}) + (1 - f_{sat}) \mathcal{N}(M_h, M_{mean}, \sigma_M, \text{flag} = \text{cen}) \quad (4)$$

where \mathcal{N} is a Gaussian distribution with the variable being M_h , the halo mass. The parameters are: M_{mean} , the mean

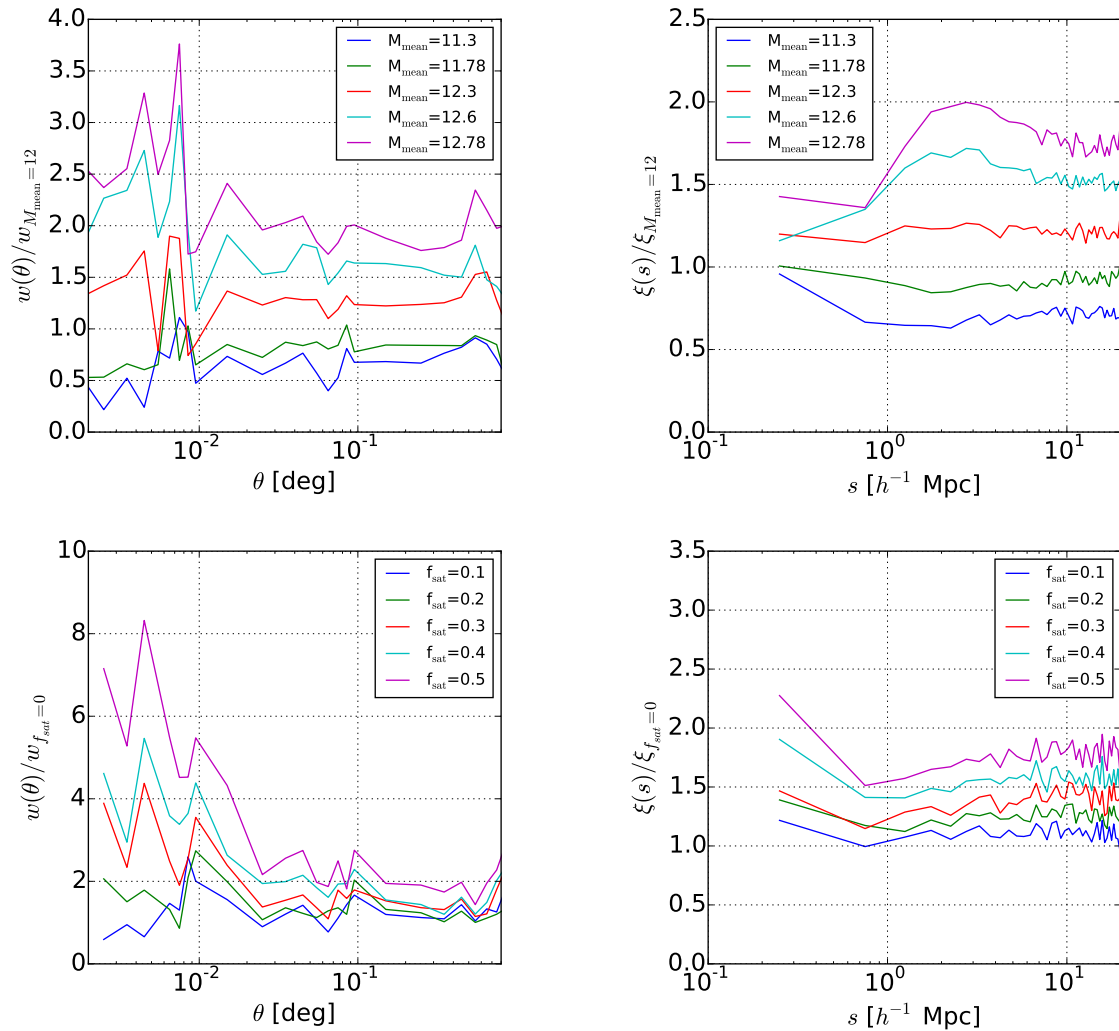


Figure 5. *Left column:* ratio of the angular correlation functions of the MDPL-LC halos selected by mass, with varying satellite fraction, to $w(\theta)$ computed at $M_{\text{mean}} = 10^{12} h^{-1} M_{\odot}$ (top row) and at $f_{\text{sat}} = 0$ (bottom). *Right column:* same for the monopole. The top row presents our first experiment (see the text for details) on the lightcone: we impose different halo mass thresholds to the MDPL-LC and apply a standard SHAM. The bottom row displays SHAM in the mass bin $M_h = (1 \pm 0.5 \times 10^{12} h^{-1} M_{\odot})$ with varying satellite fractions.

halo mass of the sample including both host and satellite halos; σ_M , the dispersion around the mean halo mass; f_{sat} , the satellite fraction. The additional parameter “flag” enables to identify among the halos the ones that are centrals (flag=cen) or the ones that are satellites (flag=sat).

To qualitatively understand the dependence of clustering on M_{mean} and f_{sat} , we impose (i) a maximum halo mass threshold to the MDPL-LC by removing all halos with $M_h > M_{\text{max}}$ and we apply the standard SHAM procedure. The higher-mass ($M_{\text{max}} > 10^{13} h^{-1} M_{\odot}$) models reproduce well the observed $w(\theta)$, and that the lower-mass models ($M_{\text{max}} < 10^{13} h^{-1} M_{\odot}$) match the large-scale clustering, but not the small-scale amplitude witnessed below $\theta \sim 0.01^\circ$. The top row in Figure 5 displays the ratio between the angular (left panel) and the monopole (right) correlation functions of the lower-mass models and the model with $M_{\text{mean}} = 10^{12} h^{-1} M_{\odot}$. We see a mild variation in $w(\theta)$ as a function of the physical scale, and a flatter trend in the monopole.

We next (ii) fix the halo mass by selecting all the halos in the mass bin $M_h = (1 \pm 0.5 \times 10^{12} h^{-1} M_{\odot})$, and vary the satellite fraction. We split this halo catalog into two catalogs, one containing only central halos ($f_{\text{sat}} = 0$) and one with satellites; then downsample both mocks to match the ELG $n(z)$. The bottom panels in Figure 5 present the variation of the angular and monopole clustering as a function of the scale. At small scales the amplitude of $w(\theta)$ with more than 30% satellite fraction is strongly enhanced compared to the 10–20% cases. In the monopole there is almost no variation with the scale. We then combine these two products to build galaxy mock catalogs that contain a f_{sat} fraction of satellites (taken from the satellite-only mock) and $(1-f_{\text{sat}})$ centrals (from the central-only mock). Satellite fractions between 20% and 30% account for the clustering signal on both small and large scales; see Figure 6. All the selections above are done on the halo mass defined as M_{200} , which correspond to an overdensity threshold of $\Delta_{200} = 200\rho_c$ (Prada et al. 2012), where ρ_c is the critical density of the Universe.

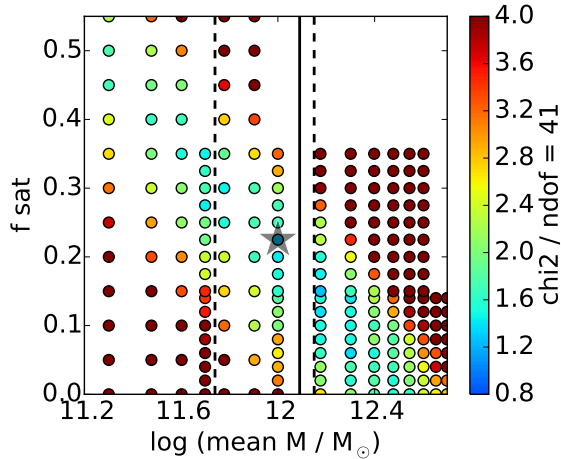


Figure 6. The two parameters driving the model: fraction of satellite (f_{sat}) and mean halo mass (M_{mean}). The spread around the mean halo mass is fixed at the value $\sigma_M = M_{mean}/2$. The vertical black lines represent the constraints by weak lensing (dashed: lower and upper limits; solid: mean), which rule out the majority of the low-mass and high-mass models. Our best-fit model is highlighted by the star symbol.

To produce a mock catalog, we randomly select halos from the light-cone according to the probability distribution P , defined in Eq. 4, until the ELG redshift distribution $n(z)$ in Figure 2 is achieved. We then construct a grid of mocks by selecting M_{mean} in the range $10^{11.2} - 10^{12.7} h^{-1} M_\odot$, σ_M between the values $M_{mean}/[1., 2., 4.] h^{-1} M_\odot$ (the sampling space is three times larger), and the satellite fraction in the interval $0 < f_{sat} < 0.5$, to obtain predictions for both ξ^s and $w(\theta)$. Finally, we compare these model predictions with our measurements by computing a combined χ^2 on scales $2 < s < 22 h^{-1} \text{Mpc}$ for the monopole, and $0.002^\circ < \theta < 0.55^\circ$ for the angular clustering, as follows:

$$\chi^2 = \frac{N_\xi \chi_\xi^2 + N_w \chi_w^2(\theta)}{N_\xi + N_w}, \quad (5)$$

where

$$\chi_w^2(\theta) = \frac{1}{N_w} \sum_i \frac{|w_{observed}(\theta_i) - w_{halos}(\theta_i)|^2}{\sigma^2(w_{observed}(\theta_i))}, \quad (6)$$

and

$$\chi_\xi^2 = \frac{1}{N_\xi} \sum_i \frac{|\xi_{observed}(s_i) - \xi_{halos}(s_i)|^2}{\sigma^2(\xi_{observed}(s_i))}. \quad (7)$$

The possible models accounting for the ELG clustering are degenerate with respect to the mean halo mass and the satellite fraction. In fact, Figure 6 shows that a plethora of $(\log M_{mean}, f_{sat})$ models fit the data: from $(11.3, 0.45)$ by $(12, 0.2)$ to $(12.5, 0)$. Given the 41 degrees of freedom we have, we consider acceptable those models with $\chi^2 < 1.25$. Models with a higher χ^2 value are rejected at the 90% level.

The combination with the weak lensing results breaks this degeneracy and rules out the higher- and lower-mass models. However, among these latter, there is one with $\chi^2 = 1$ and parameters: $\log M_{mean} = 12$, $\sigma_M = M_{mean}/2$, $f_{sat} = 22.5\%$ (star symbol in Figure 6). The angular and

redshift-space correlation functions of this best-fit mock are displayed in Figure 3 (blue line), together with the ELG measurements. The weak lensing measurement are perfectly compatible with this best-fit model.

We provide our best-fit MDPL mock catalog to the ELG clustering measurements at http://eboss.ft.uam.es/~comparat/website/ELG_mock_z08/.

5 RESULTS AND DISCUSSION

5.1 ELG clustering trends as a function of magnitude, flux, luminosity and stellar mass

We employ the complete VIPERS data sample at $z \sim 0.8$, which has about 30,000 reliable redshifts in the range $0.6 < z < 1$, to investigate trends of the clustering amplitude (bias) with observed or rest frame broad band magnitude or emission line flux. To this purpose, we measure the emission line properties in the VIPERS spectra and find a significant [OII] flux in about two thirds of them; the rest does not show emission lines (Comparat et al., in prep.). We bin the data according to apparent and absolute magnitude, [OII] flux and luminosity, and measure the clustering in each sample (the binning scheme was set to contain between 9000 and 10,000 data points). Consistent with previous analyses (e.g., Marulli et al. 2013; Mostek et al. 2013), we find that the brighter the selection in the i -band, either observed or rest-frame, the higher the bias. Analogously, the fainter the g -band limit, either observed or rest-frame, the higher the bias. The anti-correlation between [OII] flux and bias is only seen in the observed frame (the difference is ~ 1.4); in the rest frame it is not significant. It would be interesting to further investigate the correlation between [OII] luminosity and g -band magnitude in the small-scale clustering, but with the resolution of current data we are not able to push the analysis to scales $\sim 200 h^{-1} \text{kpc}$, which is the typical virial radius of a halo of mass $10^{12} h^{-1} M_\odot$. New data from eBOSS will be able to address this issue. The results above indicate that if we have a g -selected ELG sample and [OII] fluxes for a certain number of its galaxies, in order to maximize its clustering signal, we should select the ELGs with brighter i -band magnitudes.

To investigate the clustering dependence on stellar mass, we map the host halo masses for ELGs at $z \sim 0.8$, $M_h \sim 10^{12} h^{-1} M_\odot$, onto stellar mass values using the stellar-to-halo-mass relation by Leauthaud et al. (2012), see their Figure 11. Our data are right before the “knee” at $M_* \sim 3.5 \times 10^{10} h^{-1} M_\odot$.

5.2 Star formation efficiency

From our analysis, the typical halo masses hosting ELGs at $z \sim 0.8$ are $M_h \sim (1 \pm 0.5) \times 10^{12} h^{-1} M_\odot$, and $22.5\% \pm 2.5\%$ of them are satellites belonging to a larger halo, whose central is a quiescent galaxy. Figure 7 provides a schematic representation of the possible ELG configurations. A total of 22.1% ELGs are single satellites belonging to a parent halo with mass $M_{hQ} \sim 2.5 \times 10^{13} h^{-1} M_\odot$; only in 1.3% of the cases the parent halo hosts more than one satellite ELG. The maximum number of satellites, $n = 1.8$, is achieved in the highest-mass case, where $M_{hQ} \sim 6.8 \times 10^{13} h^{-1} M_\odot$. These

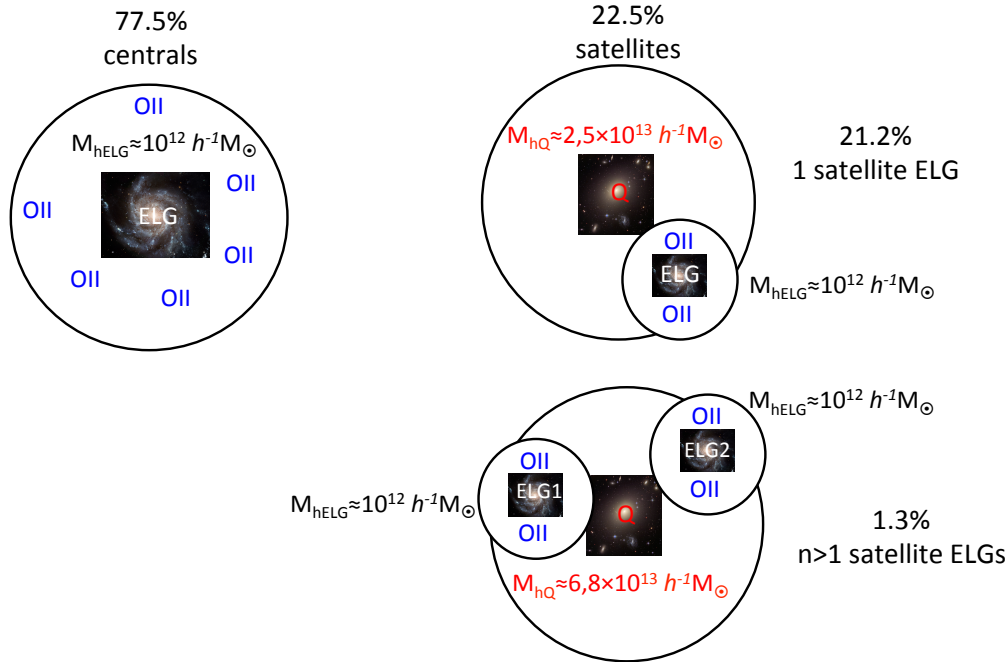


Figure 7. Schematic diagram of possible ELG configurations. ELGs at $z \sim 0.8$ typically live in halos of mass $M_h \sim (1 \pm 0.5) \times 10^{12} h^{-1} M_{\odot}$ and 22.5% are satellites belonging to larger halos, whose central galaxy is quiescent. Among these satellite configurations, 21.2% of parent halos with $M_{\text{hQ}} \sim 2.5 \times 10^{13} h^{-1} M_{\odot}$ host one satellite ELG, and only 1.3% of parents host more than one satellite ELG. The maximum number of satellites, $n = 1.8$, is achieved in the highest-mass case, $M_{\text{hQ}} \sim 6.8 \times 10^{13} h^{-1} M_{\odot}$. See the text for details.

results imply that the mean number of ELG satellites is only slightly larger than unity (~ 1.01). The quiescent galaxies at the center of the parent halos are not included in the sample, since the stellar masses for ELGs from the SHMR discussed above are too low for halos of $10^{13} h^{-1} M_{\odot}$.

The typical masses for halos hosting ELGs suggest that we are sampling halos ($\sim 10^{12} h^{-1} M_{\odot}$) that form stars in the most efficient way, according to the stellar-to-halo mass ratio discussed by Behroozi et al. (2013a) (see their Figure 1, bottom panel). This result opens a new science field and, hopefully, in the near future, integrated models combining N-body simulations with semi-analytic models (SAMs) will be able to probe star formation and shed some light on the correlations between [OII] flux and magnitude in the clustering of galaxies.

6 SUMMARY

We have presented an analysis of the halo occupation distribution for emission line galaxies, which jointly accounts for three measurements: the angular correlation function, the monopole, and the weak lensing signal around ELGs (see Section 3). Our procedure can be summarized in the following points:

- Apply the SUGAR (Rodríguez-Torres et al. (2015), in prep.) algorithm to the 11 snapshots available from the MDPL simulation to construct a light-cone (Section 2.2), with the same geometry and angular footprint of the ELG data.

- Modify the traditional SHAM technique (Section 4), to account for the ELG incompleteness, by selecting model galaxies by mass, until we match the observed ELG $n(z)$. In this way, our mock is constrained by the observed ELG redshift distribution, and represents a reliable model.

- Parametrize the probability of selecting a halo hosting an ELG with Eq. 4, in terms of the mean halo mass of the sample (M_{mean}), the dispersion around the mean (σ_M), and the satellite fraction (f_{sat}). The additional parameter “flag” enables to distinguish central and satellite halos.

- We perform two experiments (see Section 4) on the MDPL light-cone to derive information on which are the halo mass and satellite fraction ranges of values we need to input in our modified SHAM model to correctly fit the ELG clustering signal.

- Construct a grid of models based on these values, and jointly fit both angular and redshift-space clustering (see Section 4). Our best-fit models (see Figure 6) are degenerate with respect to M_{mean} and f_{sat} . The combination with the weak lensing analysis (see Section 3.1) breaks this degeneracy and rules out the highest and lowest mass models. Our best-fit ($\chi^2 = 1$) model is shown in Figure 3 together with the ELG measurements, and is given by $\log M_{\text{mean}} = 12$, $f_{\text{sat}} = 22.5\%$, $\sigma_M = M_{\text{mean}}/2$.

To conclude, we have built and released to the community a reliable galaxy mock catalog that correctly fits the clustering amplitude of the *ugri* ELG sample constructed by matching spectroscopic redshifts from BOSS

DR12, VIPERS and DEEP2 (for details see Section 2). With these tools, we can begin building many realizations of the density field to predict errors on the BAO measurement.

The measured halo masses for halos hosting emission-line galaxies indicate that we are sampling the halos that form stars in the most efficient way, according to the stellar-to-halo mass ratio discussed by Behroozi et al. (2013a) (see their Figure 1, bottom panel). This is an important point for the future, and opens the path to further studies to understand the correlation between clustering and the strength of emission lines. With the resolution available from current data, we are not able to push the analysis to the typical scales ($\sim 200h^{-1}\text{Mpc}$) of halos of $10^{12}h^{-1}M_{\odot}$; however, next-generation surveys, as eBOSS and DESI, will provide better resolution, and in the near future we should be able to build robust combinations of N-body simulations and SAMs that will address those questions.

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