Do model emission line galaxies live in filaments at z~1?
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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
Current and future cosmological surveys are targeting star-forming galaxies at z ~ 1 with nebular emission lines. In this work we use a state-of-the-art model of galaxy formation and evolution to explore the large scale environment of star-forming emission line galaxies (ELGs). Model galaxies are selected with cuts such that the samples can be directly compared with the DEEP2, VVDS, eBOSS-SGC and DESI surveys. Their large scale environment have been classified using a velocity-shear-tensor and a tidal-tensor algorithms. Half of model ELGs live in filaments and about a third in sheets. Model ELGs in knots have the largest satellite fractions. We find that the shape of the mean halo occupation distribution of model ELGs varies widely for different large scale environments. To put these results in context, we have compared fixed number density samples of galaxies, generated by either imposing an extra cut in stellar mass, star formation rate (SFR) or L[O II] to the ELGs, or by imposing a single cut in these quantities to the total model galaxy population. For the fixed number density samples, ELGs are close to L[O II] and SFR selected samples for densities above $10^{-4} h^{-3} \text{Mpc}^{-3}$. ELGs with an extra cut in stellar mass to fix their number density, present differences in sheets and knots with respect to the other samples. ELGs, SFR and L[O II] selected samples with equal number density, have similar large scale bias but their clustering below separations of $1h^{-1}\text{Mpc}$ is different.

Key words: galaxies: evolution – galaxies: formation – cosmology: large-scale of the Universe

1INTRODUCTION
The distribution of matter in the Universe is highly inhomogeneous at Mpc scales, at which the Filamentary structure of the cosmic web arises (e.g. Colless et al. 2001; Gott et al. 2005; Cui et al. 2018). In the prevalent theory of hierarchical formation of structure, gas cools following the cosmic web (e.g. White & Rees 1978). Galaxies at different separations from the Filamentary structures have been found to have different properties that cannot be explain by density alone (e.g. Laigle et al. 2018; Kraljic et al. 2018).

Here we aim to study the large scale environment of star-forming emission line galaxies (hereafter ELGs). These galaxies have spectra characterised by strong nebular emission lines, which allow for a robust determination of their redshift. Cosmological surveys have started to target ELGs to study the epoch around when the expansion of the Universe become dominated by dark energy, z ~ 1 (e.g. Comparat et al. 2013a). Understanding the connection between ELGs and their host dark matter haloes is a crucial step to maximally exploit these surveys. Cosmological surveys that have targetted or plan to target ELGs include: ATLAS

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Star-forming ELGs at around $z = 1$, have been found to populate haloes of masses $\sim 10^{12} h^{-1} M_\odot$ (Favole et al. 2016; Khostovan et al. 2018; Guo et al. 2018a) and have linear bias around 1.5 (Comparat et al. 2013b; Guo et al. 2018a). Using our previous semi-analytical model for galaxy formation and evolution (Gonzalez-Perez et al. 2018, hereafter GP18) we found model ELGs living in haloes with masses consistent with the observations but less clustered at large scales. As we found the percentage of model satellite ELGs to be below that in Favole et al. (2016), we argued that this could drive the difference in clustering. The fraction of model star-forming satellite galaxies is related to the modelling of the gas cycle (cooling, accretion, star formation, death of stars, etc). Nevertheless, the lack of assembly bias in the models used to interpret the observations of star-forming ELGs might be partly responsible to this difference (Contreras et al. 2019).

Both observations and models show that star-forming galaxies in general, and ELGs in particular, populate dark matter haloes in a different way than mass selected samples (e.g. Zheng et al. 2005; Cochrane & Best 2018; Favole et al. 2016; Guo et al. 2018a; Gonzalez-Perez et al. 2018; Alam et al. 2019; Contreras et al. 2019).

Here we aim to understand model [O II] emitters as tracers of the cosmic web using the results form a semi-analytical model of galaxy formation and evolution. We use an updated version of the model presented in GP18. In Fig. 12 from that paper we showed that, qualitatively, model [O II] emitters trace better filaments than mass selected galaxies.

The distribution of matter at large scale can be segmented into four dynamically distinct environments: knots, filaments, sheets, and voids. These four different cosmological structures are a natural outcome of gravitational collapse. Many methods have been developed to classify/identify these cosmological structures and we refer the reader to Libeskind et al. (2018) for a detailed description. Here, we measure the large-scale environment of the dark matter simulation using two algorithms, one using a shear tensor, VWEB, and the other a tidal one, PWEB. Both methods use the eigenvalues of the Hessian matrix for the indicator field (velocity and potential respectively) to spatially separate out these structures.

The plan of this paper is as follows. In § 2.1 we introduce an updated version of the GALFORM semi-analytical model for galaxy formation and evolution. The VWEB and PWEB

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1. Astrophysics Telescope for Large Area Spectroscopy, http://atlas-probe.ipac.caltech.edu/ (Wang et al. 2018).
2. Dark Energy Spectroscopic Instrument, http://desi.lbl.gov/ (Levi et al. 2013).
3. http://www.euclid-ec.org/ (Laureijs et al. 2011).
4. Hobby-Eberly Telescope Dark Energy Experiment http://hetdex.org/ (Hill et al. 2008).
5. Javalambre Physics of the Accelerating Universe Astrophysical Survey http://www.j-pas.org/ (Benitez et al. 2014).
6. MaunaKea Spectroscopic Explorer https://mse.cfht.hawaii.edu/ (Percival et al. 2019).
7. Prime Focus Spectrograph, http://sumire.ipmu.jp/en/2852 (Takada et al. 2014).
8. eBOSS survey, http://www.sdss.org/surveys/eboss/ (Ahumada et al. 2019).
9. Wide Field Infrared Survey Telescope, https://www.nasa.gov/wFIRST (Honsell et al. 2018).
10. WiggleZ Dark Energy Survey http://wigglez.swin.edu.au/site/ (Drinkwater et al. 2010, 2018).
11. 4-metre Multi-Object Spectroscopic Telescope, https://www.4most.eu/ (de Jong et al. 2014).
12. The programs used to generate the plots presented in this paper can be found in https://github.com/viogp/plots4papers/cv/
Table 1. Differences between the model presented here and the Gonzalez-Perez et al. (2018), GP18, GALFORM implementation.

| GALFORM parameter | GP18  | This work |
|-------------------|-------|-----------|
| Ram-Pressure Transfer Fraction | 0.1   | 0.01      |
| $M_{\text{strip}}(h^{-1} M_\odot)$ | 0     | 10.0      |
| $f_{\text{fdd}}$ | 0.039 | 0.01      |
| $\epsilon_{\text{cool}}$ | 0.016 | 0.02      |
| $\alpha_{\text{cool}}$ | 0.9   | 0.8       |

PWEB methods, used to characterize the large-scale environment are described in § 2.2 and in Appendix A. The selection of model [O ii] emitters is presented in § 3. The results on how [O ii] emitters populate the cosmic web can be found in § 3.2. Fixed number density samples are defined in § 4 and their properties in different large-scale environment are presented in § 4.2.2. In § 5 we summarise our results.

2 METHODS

In this work we analyse the $z = 0.83$ and $z = 1$ outputs from the MS-W7 N-body simulation (Guo et al. 2013; Jiang et al. 2014; Gonzalez-Perez et al. 2014). This N-body simulation is run within a box of 500 $h^{-1}$ Mpc comoving side and it assumed a cosmology consistent with the 7th year release from WMAP (Komatsu et al. 2011): matter density $\Omega_m = 0.272$, cosmological constant $\Omega_{\Lambda} = 0.728$, baryon density $\Omega_b = 0.0455$, a normalization of density fluctuations given by $\sigma_8 = 0.810$, $n_s = 0.967$ and a Hubble constant today of $H(z = 0) = 100 $ km s$^{-1}$ Mpc$^{-1}$ with $h = 0.704$.

The MS-W7 simulation has been populated with galaxies following a semi-analytical model for galaxy formation and evolution, based on that described in Gonzalez-Perez et al. (2018). This model is introduced in § 2.1.

The large-scale environment of the whole simulation box has been classified into knots, filaments, sheets and voids using two algorithms: VWEB, using a velocity-shear-tensor, and PWEB, which uses a tidal-tensor. These algorithms are described in § 2.2 and their resolution and threshold setting are further discussed in Appendix § A.

2.1 The GALFORM galaxy model

Semi-analytical models use simple, physically motivated rules to follow the fate of baryons in a universe in which structure grows hierarchically through gravitational instability (see Baugh 2006; Benson 2010; Somerville & Davé 2015, for an overview of hierarchical galaxy formation models).

GALFORM was introduced by Cole et al. (2000) and since then it has been enhanced and improved (e.g. Baugh et al. 2005; Bower et al. 2006; Lagos et al. 2011; Lacey et al. 2016; Griffin et al. 2019). GALFORM follows the physical processes that shape the formation and evolution of galaxies, including: (i) the collapse and merging of dark matter haloes; (ii) the shock-heating and radiative cooling of gas inside dark matter haloes, leading to the formation of galaxy discs; (iii) quiescent star formation in galaxy discs which takes into account both the atomic and molecular components of the gas (Lagos et al. 2011); (iv) feedback from supernovae, from active galactic nuclei (Bower et al. 2006) and from photo-ionization of the intergalactic medium; (v) chemical enrichment of the stars and gas (assuming instantaneous recycling); (vi) galaxy mergers driven by dynamical friction within dark matter haloes. GALFORM provides a prediction for the number and properties of galaxies that reside within dark matter haloes of different masses.

Currently there are two main branches of GALFORM: one with a single initial mass function (IMF, Gonzalez-Perez et al. 2014, 2018, and this work) and one that assumes different IMFs for quiescent and bursty episodes of star formation (Lacey et al. 2016). These two models have also been re-calibrated to run on a dark matter simulation with a Planck cosmology (Planck Collaboration et al. 2014; Baugh et al. 2018). In this work we have modified the semi-analytical model described in Gonzalez-Perez et al. (2018), hereafter GP18, to better match the observed passive fraction at $z = 0$ and to include the updated treatment of the evolution of supermassive black holes (SMBHs) introduced by Griffin et al. (2019). These two aspects are described in more detail in § 2.1.1 and § 2.1.2, respectively. The parameters that have been modified are summarised in Table 1, other free parameters have been inherited from the model described in GP18.

The free parameters presented in Table 1 have been calibrated against observations at $z = 0$: the luminosity function in the $b_J$ and $K$-bands (focusing on the region around the knee), the observed black hole–bulge mass relation (Fig. 1) and the local passive fraction (Fig. 2). When calibrating the model presented here, our aim was to make the smallest number of changes to the GP18 model parameters, despite the introduction of the new scheme for the black-hole growth.

2.1.1 The treatment of gas in satellite galaxies

The model we present here has been modified to achieve a local passive fraction closer to observations. To this end, we have reduced the rate at which the gas is removed from satellite galaxies due to ram-pressure stripping by a factor of 10. This has been done by setting to 0.01 the parameter 'ram-pressure transfer fraction'. This parameter is equivalent to $\epsilon_{\text{strip}}$ described in § 2.9 by Benson & Bower (2010). The ram-pressure transfer fraction represents the time-averaged stripping rate after the initial pericentre (see also Font et al. 2008). In the model used here, the ram-pressure stripping happens in larger time-scales than in GP18. Smaller values of the ram-pressure transfer fraction have no impact on the passive fraction at $z = 0$.

The separation of galaxies into quiescent and star-forming is done using the specific star formation rate (sSFR,
Figure 1. The predicted luminosity functions at $z=0$, in the $b_J$-band ($\lambda_{eff} = 4500\AA$, left) and in the $K$-band ($\lambda_{eff} = 2.2\mu m$, middle), compared with observations from Norberg et al. (2002) and Driver et al. (2012), respectively. The right panel shows the super massive black hole mass versus bulge stellar mass relation at $z=0$ compared to observational data from McConnell & Ma (2013). The lines in the right panel represent the median of the predicted super massive black hole mass in bins of bulge mass and the shading the 10-90 percentiles of the model distributions. The blue dashed lines show the predictions from the GP18 model, while the red solid lines show the predictions from the model presented here. These data sets were used to calibrate the free parameters of the model.

Figure 2. The fraction of passive galaxies at $z=0$, i.e. those with sSFR < 0.3/t_Hubble(z) = 0, for this work (thick lines) and the GP18 model (thin lines), compared to the observational results from Gilbank et al. (2010), circles, and Bauer et al. (2013), triangles, as extracted and presented in Furlong et al. (2015). The solid lines show the total passive fraction, the contribution from satellite galaxies is shown by dashed lines and that from centrals by dotted lines.

i.e. the ratio between SFR and stellar mass) boundary proposed by Franx et al. (2008): sSFR = 0.3/t_Hubble(z).

Fig. 2 shows that a slower removal of hot gas in satellites reduces the number of passive satellite galaxies. These dominate the least massive end. Around masses $\log_{10}(M_*/h^{-1}M_\odot) \sim 10$ at $z=0$, the model passive fraction presents a plateau dominated by the contribution of disks. This region of model masses is found to be very sensitive to the efficiency of the model AGN feedback. A more detailed exploration of the impact of the treatment of gas in models of galaxy formation will be developed in a future paper.

2.1.2 The growth of model Supermassive Black Holes

Griffin et al. (2019) presented a flavour of galform with and updated modelling of the growth and spin evolution for supermassive black holes (SMBHs). This model assumes that SMBHs can grow in three different ways: i) during starbursts triggered by either galaxy mergers or by disc instabilities; ii) accreting gas from the hot atmosphere of massive haloes; and iii) by SMBH-SMBH mergers after galaxy merge. The model takes into account how the angular momentum of both the SMBH and the accretion disk affects the consumption of gas.

In this updated model, SMBHs grow from seeds with mass $M_{seed}$. When a galaxy is formed in the model, it is assigned a black hole mass of $M_{seed}$. The value of this $M_{seed}$ is a free parameter set to 10 $h^{-1}M_\odot$ in this work (see also Table 1). For $M_{seed} > 0$, the black hole properties rapidly converge (for further discussion see Griffin et al. 2019).

The angular momentum of the gas in the inner accretion disk is assumed to be periodically randomised with respect to the angular momentum of the SMBH, i.e. we assume a 'chaotic accretion mode' (King et al. 2008).

This updated model includes the evolution of the SMBHs’ spins. This evolution affects the growth of SMBHs and therefore the AGN activity. Griffin et al. (2019) showed the new AGN luminosity functions for a range of wavelengths. The SMBH mass versus bulge mass relation at $z=0$ is shown in the right panel of Fig. 1. The updated model has a distribution consistent with that from the GP18 model.

2.1.3 The emission line model

Nebular emission lines are produced by gas heated by newly formed stars and by nuclear activity. Here we only model the star-forming contribution. In galform, the ratio between
the [O ii] luminosity and the number of Lyman continuum photons is calculated using HII region models of Stasińska (1990). The GALFORM model uses by default eight HII region models spanning a range of metallicities but with the same uniform density of 10 hydrogen particles per cm$^{-3}$ and one ionising star in the center of the region with an effective temperature of 45000 K. The ionisation parameter of these HII region models is around $10^{-3}$, with exact values depending on their metallicity in a non-trivial way. These ionisation parameters are average within the grid of HII regions provided by Stasińska (1990). Further details on the emission line model can be found in GP18.

Nebular emission lines are assumed to be attenuated by dust in a similar way to the stellar continuum (Gonzalez-Perez et al. 2013; Lacey et al. 2016).

The model properties of emission line galaxies derived when using the Stasińska (1990) default models are consistent to those derived using the Anders & Fritze-v. Alvensleben (2003) model for typical HII regions. The model emission line luminosity functions are also in reasonable agreement with the results derived from a model that assumes a large range of HII regions (Comparat et al. 2015). The nebular emission luminosity functions at different redshifts derived from this emission line model were found to be in agreement with observations (Lagos et al. 2014; Gonzalez-Perez et al. 2018).

### 2.2 The Cosmic Web

Here, we apply two algorithms, VWEB and PWEB, to classify the large-scale environment of the whole simulation box into knots, filaments, sheets and voids (Cui et al. 2018, 2019).

The VWEB method uses a velocity dimensionless shear tensor as the tracer to classify the large-scale environment. Following Hoffman et al. (2012), at a given redshift, $z$, the velocity, $\vec{v}(\vec{r})$, shear tensor is defined as:

$$\Sigma_{ij} = \frac{1}{2H(z)} \left( \frac{\partial v_i}{\partial r_j} - \frac{\partial v_j}{\partial r_i} \right).$$

where, $H(z)$ is the Hubble constant at redshift $z$. The eigenvalues of $\Sigma_{ij}$ are denoted as $\lambda_i^H$ ($i = 1, 2$ and 3).

The PWEB method classifies the large-scale environment based on the tidal tensor, which is measured with the Hessian matrix of the gravitational potential field, $\phi(\vec{r})$. The gravitational potential is calculated from the matter density distribution via the Poisson equation, $\nabla^2 \phi = 4G \rho$, where $\rho$ is mean density and $\delta$ is the density fluctuation. The tidal tensor is defined as follow, with units $r^{-2}$ (Hahn et al. 2007):

$$P_{ij} = \frac{\partial^2 \phi}{\partial r_i \partial r_j}.$$  

The computation of the eigenvalues for both matrices is performed on the particles of the MS-W7 dark matter only simulation split in regular $512^3$ cells grids. The typical side of a grid cell is $\sim 1$ h$^{-1}$Mpc. We use a triangular-shaped cloud in cell prescription for obtaining a smoothed density and velocity distribution at each point on the grid. These are smoothed further over a scale of $\sim 5$ h$^{-1}$Mpc. Then, the eigenvalues of the velocity shear tensor (tidal tensor for PWEB) are computed according to Eq. (1) (Eq. 2) for every grid cell. Note that although neither VWEB nor PWEB use the dark matter particles for their calculations, the larger number of particles per cell, the more accurate the velocity or potential fields will be. The large smoothing scale, $\sim 5$ h$^{-1}$Mpc, provides a robust velocity and density field in the real space, and thereby reliable tensors.

Each individual cell is then classified as either ‘void’, ‘sheet’, ‘filament’, or ‘knot’ according to the eigenvalues $\lambda_1 > \lambda_2 > \lambda_3$:

1. Void, if $\lambda_1 < \lambda_{th}$,
2. Sheet, if $\lambda_1 \geq \lambda_{th} > \lambda_2$,
3. Filament, if $\lambda_2 \geq \lambda_{th} > \lambda_3$,
4. Knot, if $\lambda_3 \geq \lambda_{th}$,

where $\lambda_{th}$ is a free threshold parameter (Hoffman et al. 2012; Libeskind et al. 2012, 2013). Following Carlesi et al. (2014) and Cui et al. (2018), we find that the threshold adopted for VWEB at $z = 0$, $\lambda_{th} = 0.1$, is also suitable for the simulation results at higher redshift (see Cui et al. 2019, for the redshift evolution of the mass and volume fractions of these large-scale structures with this fixed threshold). This value gives very convincing structures, which are visually comparable with the density field (see Appendix A for further details).

We find that the threshold $\lambda_{th} = 0.01$ at $z = 0$ for the PWEB method gives slightly larger voids and Sheet structures at the two redshifts investigated in this paper, $z = 0.83, 0.99$. Therefore, we lower the threshold to 0.005 for PWEB to provide consistent structures to VWEB. Note that the same threshold for PWEB is applied to both redshifts because the time difference is small.

The effects of resolution and the choice of different thresholds for the cosmic web classification are discussed in detail in the Appendix A.

### 3 MODEL ELGS

A range of cosmological surveys, such as SDSS/BOSS-SCG (Dawson et al. 2016) and DESI (DESI Collaboration et al. 2016), are or will be targeting star-forming ELG galaxies to probe the nature of dark energy using spectroscopic redshifts. ELGs selected with optical instruments at $z \sim 1$ are dominated by [O ii] emitters (Comparat et al. 2015). As we previously did in GP18, we select [O ii] emitters from the semi-analytical model described in §2.1 mimicking the samples from different surveys, §3.1. We then explore how these model galaxies trace the large-scale environment in §3.2.

In this work we use a model that strips the gas in satellite galaxies slower than in GP18. This modification has a strong impact on decreasing the passive fraction of galaxies with masses below $10^{10} h^{-1} M_\odot$, however, this merely changes the fraction of model [O ii] emitters by up to 5 per cent. Model ELGs at $z \sim 1$ are mostly centrals, with a satellite fraction between 4 and 9 per cent, dominated by star forming galaxies with $sSFR > 0.3/\mathcal{H}^\text{obs}(z)$.

#### 3.1 Model ELGs sample selection

We select model ELGs using the cuts specified in Table 2 in apparent magnitude, [O ii] flux and colour. The magnitude and flux cuts reproduce the limits in the DEEP2 (Newman et al. 2013) and VVDS (Le Fèvre et al. 2013) surveys, applied to select the corresponding model [O ii] emitters.
Table 2. The cuts applied to the model galaxies in order to mimic the selection of $[\text{O} \text{II}]$ emitters in the corresponding observational survey are the same as those summarised in Table 2 from Gonzalez-Perez et al. (2018), except for the eBOSS-SGC survey. We apply here the colour cuts described in Raichoor et al. (2017) for the eBOSS-SGC selection (further details can be found in Appendix B) plus a cut in $[\text{O} \text{II}]$ flux to mimic the instrumentation limitation of the eBOSS-SGC survey. The magnitudes are on the AB system. The particular filter response used for the different cuts is indicated by a superscript on the magnitude column.

| Cuts to mimic | Apparent magnitude | $[\text{O} \text{II}]$ flux ($\text{erg s}^{-1}\text{cm}^{-2}$) | Colour selection |
|---------------|-------------------|--------------------------|-----------------|
| DEEP2         | $K_{\text{DEIMOS}}^{\text{DEEP2}} < 24.1$ | $2.7 \times 10^{-17}$ | None |
| VVDS-Deep     | $i_{\text{CFHT}}^{\text{VVDS}} \leq 24$ | $1.9 \times 10^{-17}$ | None |
| VVDS-Wide     | $i_{\text{CFHT}}^{\text{VVDS}} \leq 22.5$ | $3.5 \times 10^{-17}$ | None |
| eBOSS-SGC     | $21.825 < i_{\text{DECam}}^{\text{eBOSS-SGC}} < 22.825$ | $1 \times 10^{-16}$ | $-0.068(r - z) + 0.457 < (g - r) < 0.112(r - z) + 0.773$ & $0.218(g - r) + 0.571 < (r - z) < -0.555(g - r) + 1.901$ |
| DESI          | $i_{\text{DECam}}^{\text{DESI}} < 23.4$ | $8 \times 10^{-17}$ | $(r - z) > 0.3$ & $(g - r) > -0.3$ & $(g - r) < 1.1 \cdot (r - z) - 0.13$ & $(g - r) < -1.18 \cdot (r - z) + 1.6$ |

Figure 3. The luminosity function of $[\text{O} \text{II}]$ emitters at $z = 0.83$ and $z = 0.99$ for model galaxies selected with the DEEP2 (dark blue lines, mostly over-plotted), VVDS-DEEP (light blue lines), VVDS-Wide (green lines), eBOSS-SGC (yellow lines) and DESI (red lines) cuts given in Table 2. The grey solid lines the model total dust attenuated $L[\text{O} \text{II}]$ luminosity function, the intrinsic one is shown by the dotted grey lines. The data from DEEP2 and VVDS are colour coded like the model galaxies selected to mimic both surveys. The observational errors come from jackknife resampling (Comparat et al. 2016a) and in some cases are smaller than the corresponding symbol.

No further colour cuts are applied to the model DEEP2 and VVDS selections, as observationally the colour cuts were applied to restrict the redshift range and here we are limiting our study to two single simulation outputs at $z = 0.83$ and $z = 0.99$. We have additional colour cuts to select model DESI (DESI Collaboration et al. 2016) and SDSS-IV/eBOSS (Raichoor et al. 2017) ELGs. These colour cuts were set observationally, targeting for an spectroscopic galaxy sample with colours that minimally overlap with those from stars (further details can be found in appendix B).

Here we focus on two simulation outputs at $z = 0.83$ and $z = 0.99$, which are separated by 717 Myr. The lowest of these two redshifts is close to the effective redshift of the SDSS/eBOSS-SGC sample (Raichoor et al. 2017), $z = 0.84$, which in turn is close to the average redshift of VVDS-DEEP (Comparat et al. 2015). The VVDS-Wide sample has a lower average redshift and will not be included in the clustering and environment analysis presented later in this work. The DESI ELG sample is designed to have a redshift baseline between 0.6 and 1.7 and an anticipated effective redshift of $z \sim 1$ (DESI Collaboration et al. 2016). The clean sample of DEEP2 ELGs has a mean redshift of 0.97 (Comparat et al. 2017). Both values are close to the redshift $z = 0.99$ of the simulation output.

3.1.1 $[\text{O} \text{II}]$ luminosity function

Model $[\text{O} \text{II}]$ emitters are selected in numbers that are in reasonable agreement with observational selections, as shown in Fig. 3. Note that the dust attenuation in this model is such, that it mostly affects the most luminous and massive $[\text{O} \text{II}]$ emitters. As reported in GP18, the change in slope of the luminosity functions shown in Fig. 3 are due to galaxies with an ongoing star-burst that dominate the bright end, $L[\text{O} \text{II}] > 10^{42} \text{erg s}^{-1}$. The bright end is also dominated by galaxies with a bulge to total mass above 0.5 (spheroids) and compact, with half mass radii smaller than 0.5 kpc. The luminosity functions shown in Fig. 3 are similar to those in GP18 and accompany Errata.13

The number density of model SDSS/eBOSS-SGC ELGs at $z \sim 0.83$, $\sim 1.58 \times 10^{-4} \text{h}^3 \text{Mpc}^{-3}$, is below the current observational estimations $\sim 2.67 \times 10^{-4} \text{h}^3 \text{Mpc}^{-3}$ (Raichoor et al. 2017). In Guo et al. (2018b) it was presented an empirical

13 Due to a problem with filter naming, the selection for VVDS was effectively done with in the $r$-band, instead of the indicated i-band. This discrepancy has been corrected in this work.
model directly calibrated with SDSS/eBOSS-SGC data and they compared their results directly against the model galaxies presented here. From this comparison it appears that besides lacking satellite ELGs, as it was concluded in GP18, there might be a lack of massive central galaxies. This is also suggested by the results presented in Comparat et al. (2017) for DEEP2. Although dust attenuation affects the most luminous and massive galaxies, there might be other physical processes contributing to the discrepancies found, from the simplicity of our emission line modelling to a more fundamental aspect of the growth of massive galaxies (Mitchell et al. 2018).

### 3.2 Model ELGs in the cosmic web

The large-scale environment has been classified using the algorithms described in §2 into: voids, sheets, filaments and knots. Table 3 summarise how model ELGs are distributed within the different structures of the cosmic web, as classified by the VWEB algorithm, although similar results are found when using PWEB. We find that about 80% of model ELGs live in either filaments or sheets, with half of them in filaments.

The distribution of ELGs in the cosmic web, summarised in Table 3, is also reflected in the split of the [O ii] luminosity function. This is shown in Fig. 4, for DESI model galaxies at $z = 0.99$, classified using the VWEB algorithm (similar results are found for PWEB). The [O ii] luminosity function varies in normalisation for the different large-scale environment structures, but the shape changes minimally. The brightest model [O ii] emitters are found in the structures where they are most dominant: filaments and sheets.

As the [O ii] luminosity function, the SFR function also shows different normalisations but similar shapes for galaxies in different cosmic web structures. Fig. 5 shows the case for DESI model galaxies at $z = 0.99$ classified with VWEB. Note that in GALFORM all galaxies have a SFR above zero, even if very small in some cases.

Fig. 5 also shows the distribution of model galaxies in the SFR-stellar mass plane. It is clear from here, that model ELGs are not directly equivalent to imposing a cut in SFR. This was also reported in GP18 and is common to all the studied ELG selections.

The galaxy stellar mass function for DESI model galaxies is also contained in Fig. 5. In this case and at high masses, there is a clear change in the shape for galaxies in knots. Model ELGs in knots tend to be more massive. This is also found for the other ELG selections. This might be related with the larger fraction of satellite galaxies found in knots, as summarised in Table 3.

As knots appear in dense regions, haloes there are expected to be more massive and, thus, able to host several

Table 3. Fraction of ELGs in the different large-scale environment structures as classified by the VWEB algorithm. The percentage of satellite galaxies for each selection is shown in brackets.

| $z$ | VVDS-DEEP (11%) | eBOSS-SGC (5%) |
|-----|----------------|----------------|
| voids | 0.05 (3%) | 0.04 (1%) |
| sheets | 0.34 (6%) | 0.32 (3%) |
| filaments | 0.48 (11%) | 0.51 (5%) |
| knots | 0.13 (24%) | 0.12 (13%) |

| $z=0.99$ | DEEP2 (7%) | DESI (4%) |
| voids | 0.04 (2%) | 0.04 (2%) |
| sheets | 0.32 (4%) | 0.34 (2%) |
| filaments | 0.51 (7%) | 0.51 (4%) |
| knots | 0.13 (15%) | 0.12 (8%) |

Figure 4. The [O ii] luminosity function for the model DESI model galaxies at $z = 0.99$, thick line, and the contribution of the different large-scale environment structures, thin lines, as classified by the VWEB algorithm (see the legend).

Figure 5. The $z = 0.99$ distribution of galaxies in the SFR-stellar mass plane for all DESI model galaxies, thick line, and those living in different large-scale environment structures, thin lines as classified by the VWEB algorithm. The sSFR-stellar mass plane has been collapsed into the galaxy stellar mass function, top sub-panel, and the SFR function, right sub-panel. The corresponding densities shown are $\Phi(h^3\text{Mpc}^{-3}\text{dex}^{-1})$. 

Do ELGs live in filaments?
galaxies. We have found that the distribution of satellite galaxies as a function of stellar mass largely varies for model ELG (not shown). Given an ELG selection, knots tend to host more satellites at all bins of stellar mass, however, the differences are largest for satellite galaxies with masses around $10^{10}h^{-1}M_\odot$. This is the value above which the galaxy stellar mass function in knots starts to differ from the other cosmic web structures, as it can be seen in Fig. 5.

In knots, the gas fuelling star formation in satellite galaxies will be removed with time and little new gas will be fuel to those galaxies, as in the model, this gas will feed the central galaxy. We defer to the future studying the evolution of the star formation in model galaxies populating different cosmic web structures.

3.2.1 The mean halo occupation distribution of ELGs

Fig. 6 shows the mean halo occupation distribution (HOD) for the DESI model galaxies at $z = 0.99$. This HOD is well below having one galaxy per halo. The HOD of model central ELGs is close to an asymmetric Gaussian with maybe a plateau (see also GP18). Galaxy mock catalogues from HOD models usually assume a very different shape from that seen in Fig. 6. The shape usually assumed for HOD models is that characteristic for mass-selected samples, this will be further explored in § 4.

Fig. 6 shows that the distribution of central galaxies peak decreases for different large-scale environment structures, following the trend in density reported in Table 3. The minimum mass to host an ELG remains practically independent of the cosmic web, except for voids, for which there is a slight increase in mass. The number of ELGs in voids are quite low and there are mostly central galaxies in these structures. Note that the minimum mass of the model HOD shown in Fig. 6 is not affected by resolution effects.

In voids and sheets there are almost no satellite ELGs. This can also be appreciated by looking to their corresponding, as those in Fig. 6 for DESI model galaxies. The contribution of satellite galaxies is so small in voids and sheets, that the global shape of the HOD for these environments can be described as an asymmetric Gaussian.

The shape of the mean HOD does change with environment. The HOD for central galaxies has a plateau in filaments and knots. There is a clear increase in the power law followed by model satellite ELGs in knots. The differences among the cosmic web structures highlight the importance of environmental processes in the evolution of galaxies. These will impact the small scale clustering derived for galaxies populating different large scale environments.

3.2.2 The clustering of ELGs

Here we study the clustering of ELGs living in different large-scale environment. Model galaxies come from a simulated box which is assumed to be periodic and thus, the configuration space auto-correlation two-point correlation func-

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**Figure 6.** The mean halo occupation distribution (HOD) as a function of host halo mass for the model DESI galaxies at $z = 0.99$, thick line, and the contribution of the different large-scale environment structures, thin lines, as classified by the Vweb algorithm (see the legend). Solid lines show the total mean HOD, the contribution from satellite galaxies is shown as dashed lines.

**Figure 7.** The real-space two point correlation function, top panel, and ratio between the correlation functions of galaxies and the dark matter one, $\xi_{\text{ALL}/\text{DM}}$. The dark matter auto-correlation function is shown as a dotted line. The auto-correlation function for all DESI model galaxies at $z = 0.99$ is shown as thick solid lines. Thin solid lines show the cross-correlation, $\xi_{\text{ALL}/\text{DM}}$, between the whole ELG sample and ELGs in different large-scale environment structures as classified by the Vweb algorithm (see the legend). The logarithm of the absolute value of negative $\xi_{\text{ALL}/\text{DM}}$ is shown with dashed thin lines. Poisson error bars are shown in both panels.
tion, $\xi$, is calculated using a simple estimator: $1 + \xi(r) = 2DD/(n^2VdV)$, where $DD$ is the number of distinct model galaxy pairs with separation between $r$ and $r+dr$ and the denominator is the average number of neighbours found in the volume $dV$ of the spherical shell of radius $r$ and thickness $dr$ (see also Gonzalez-Perez et al. 2011). The dark matter two-point correlation function is calculated using the particles from the MS-W7 dark matter only simulation. The calculation of the two-point auto-correlation functions has been done using the publicly available code CUTE14.

The 3-D pair-counts, $DD_{\text{eff}}$, needed to estimate the cross-correlation, $\xi_{\text{ELX}}$, between the whole ELG sample and the sub-samples populating different large-scale environment structures is obtained with the publicly available Python package Corrfunc.theory.DD15. The two point cross-correlation is then estimated as $1 + \xi_{\text{ELX}}(r) = DD_{\text{eff}}/(N_{\text{all}}N_{\text{efl}}dV/V)$, where $N_{\text{all}}$ is the number of all ELGs and $N_{\text{X}}$ those ELGs in a given large-scale environment structure, within the simulation volume, $V$. The Poisson errors for the cross-correlation are estimated as $(1 + \xi_{\text{ELX}})/DD_X$, where $DD_X$ is the number of unique pairs of the sub-sample of ELGs, living in either voids, sheets, filaments or knots.

Fig. 7 shows the real-space two point auto-correlation function for all DESI model galaxies at $z = 0.99$ compared with that for the dark matter. At large scales, $r > 1h^{-1}\text{Mpc}$, DESI ELGs trace the dark matter clustering, with a linear bias close to 1. Table 4 presents the bias for each of the ELG samples studied here (see Table 2), which are all close to 1.

Model galaxies explored here are naturally affected by assembly bias, i.e., the dependency on other properties beside halo mass of the evolution of dark matter haloes (e.g. Zentner et al. 2014). Thus, the bias we measure is the combination of the cosmological one and that derived from the assembly bias. The latter is expected to have a negative effect for star forming samples, such as the ELGs we study here (Contreras et al. 2019). This implies that the bias measured from a catalogue of galaxies constructed with a halo occupation distribution model without considering assembly bias, will be larger than the values reported here.

Fig. 7 also shows the cross-correlation between all DESI ELGs at $z = 0.99$ and those living in large-scale environment as classified by the VWEB algorithm. At small scales, $r \leq 0.5h^{-1}\text{Mpc}$, the clustering of ELGs in different large-scale environment follows closely the auto-correlation function. This is clearer for the DEEP2 and VVDS-DEEP samples (not shown here), for which pairs of galaxies are found at separations smaller than $0.03h^{-1}\text{Mpc}$, extending the one halo term clustering to smaller scales than the DESI one. At larger scales, $r \geq 0.5h^{-1}\text{Mpc}$, differences are found for the clustering of ELGs living in different large-scale environment. ELGs in filaments are the ones clustered most closely to the two point auto-correlation function.

ELGs living in knots are the most clustered for separations $1 \leq r(h^{-1}\text{Mpc}) \leq 10$. This can be seen in Fig. 7 for DESI model galaxies, but it is also the case for the other ELG selections. The fraction of satellite ELGs in knots is the largest found for the explored cosmic web structures (see Table 3). The large number of satellites might explain the reported boost in the clustering at intermediate scales, corresponding to the transition between the 1-halo and 2-halo terms.

For all the studied ELG samples, at large scales, $r > 1h^{-1}\text{Mpc}$, galaxies living in voids are less clustered than in any other environment, with cross-correlations having negative values and thus, negative bias values. There are few model ELGs found in voids (see Table 3), which are also the least dense regions, producing a low clustering at large scales.

Similar results to those described above for the VWEB classification are found when using the PWEB algorithm to classify the large-scale environment.

### 4 ELGS IN CONTEXT

We have previously quantified how model ELGs trace the large-scale environment. ELGs are expected to trace less dense regions than mass selected galaxies, such as Luminose Red Galaxies (e.g., Alam et al. 2019). Here we aim to compare ELGs to stellar mass selected galaxies and different selections of star-forming galaxies. To make a fair comparison between different galaxy samples, we generate fixed number density samples with $n_{\text{gal}} = 10^{-2}, 10^{-3}, 10^{-4.2} h^3\text{Mpc}^{-3}$. These fixed number density samples are generated by either imposing a single cut in stellar mass, SFR or $L(O \ \text{II})$ or starting with the ELG samples described in § 3.1 and then imposing an extra cut in one of the three mentioned properties.

Given either the effective or mean redshifts of the different surveys considered in this study, as described in § 3, the analysis is done at $z = 0.83$ for the eBOSS-SGC and VVDS-DEEP samples and at $z = 0.99$ for the DEEP2 and DESI ones.

#### 4.1 Fixed number density samples

Fig. 8 presents the cumulative abundance of the whole galaxy population and the ELGs subsamples ranked by their stellar mass, star formation rate and $L(O \ \text{II})$. From here, making cuts in these three properties, fixed number density samples are constructed with $n_{\text{gal}} = 10^{-2}, 10^{-3}, 10^{-4.2} h^3\text{Mpc}^{-3}$, for the all model galaxies and the four ELG selections shown in Fig. 8.

Fig. 9 shows the SFR-stellar mass plane, galaxy stellar function and SFR function for samples with 3 different

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14 https://github.com/damonge/CUTE (Alonso 2012).
15 https://github.com/manodeep/Corrfunc (Sinha & Garrison 2020)
Figure 8. The cumulative abundance of all galaxies, black lines, and ELGs selected as summarised in Table 2 and indicated in the legend, ranked by stellar L\([\text{O\,II]}\), left, SFR, middle, and stellar mass, right, at \(z = 0.83\), top panel, and \(z = 0.99\), bottom panel. The three number density cuts used to define similar samples, \(n_{\text{gal}} = 10^{-2}, 10^{-3}, 10^{-4} h^3\text{Mpc}^{-3}\), are indicated by the dashed horizontal lines.

Figure 9. The \(z = 0.83\) distribution of galaxies in the SFR-stellar mass plane for galaxies with the number densities indicated in the legend, selected by either imposing a single cut to the whole population of model galaxies (left panel) or an extra cut to the ELGs samples summarised in Table 2 (the right panel shows VVDS-DEEP galaxies at \(z = 0.83\)). The properties used for selecting the fixed number density samples are: stellar mass (dotted lines), SFR (dashed lines) and \(\text{L}[\text{O\,II}]\) (solid lines). The sSFR-stellar mass plane has been collapsed into the galaxy stellar mass function, top subpanels, and the SFR function, right subpanels. The corresponding densities shown are \(\Phi/h^3\text{Mpc}^{-3}\text{dex}^{-1}\).
number densities selected either imposing cuts on the stellar mass, the SFR or L\([\text{O} \, ii]\) on either the global population or the ELGs. Fig. 9 only shows the results for the model VVDS-DEEP sample, but similar trends are found for the other ELG selections studied here and summarised in Table 2. Galaxies selected by their SFR have stellar masses spreading a large range. This is also the case for galaxies selected with a cut in L\([\text{O} \, ii]\). However, in this case, galaxies tend to have lower masses and SFR than the fixed number density sample selected with cuts in the SFR. Fig. 9 shows that, as reported in GP18, the model ELG selection is not equivalent to imposing a cut in SFR.

The median mass of the host haloes increases with stellar mass limit (not shown), which decreases the number density of the galaxy sample. This trend is not found as clearly when either the SFR or L\([\text{O} \, ii]\) are used to select the fixed number density samples. In this case, the selected galaxies spread a large range of stellar masses even for low number densities, as can be seen in Fig. 9.

The median L\([\text{O} \, ii]\) for fixed number density galaxy samples selected with a single cut in their stellar mass is below $10^{40.5} \, h^{-2} \, \text{erg s}^{-1}$, while all the ELG fixed number density selections and those made with a single cut in SFR and L\([\text{O} \, ii]\) have median L\([\text{O} \, ii]\) above $10^{40.5} \, h^{-2} \, \text{erg s}^{-1}$. Fixed number density ELGs have SFR $> 10^8 \, h^{-1} \, \text{M}_\odot \, \text{Gyr}^{-1}$ at the studied redshifts (Gonzalez-Perez et al. 2018). The median SFR increases with decreasing number density when galaxies are selected by their SFR and their L\([\text{O} \, ii]\).

### 4.1.1 Mean HOD of fixed number density samples

The mean halo occupation distribution (HOD) for fixed number density central galaxies selected with a cut in their stellar mass follows a soft step function, reaching unity: at least one galaxy of a given mass will be found in large enough haloes (see the top panel in Fig. 10). This is very different from the behaviour of fixed number density SFR selected central galaxies (Zheng et al. 2005; Contreras et al. 2013; Cochrane et al. 2017, 2018). As shown in Fig. 10, these follow a shape closer to an asymmetric Gaussian plus a shallow power law (Cochrane & Best 2018; Gonzalez-Perez et al. 2018). A star forming galaxy is not found in all haloes above a certain mass. The top panel in Fig. 10 shows that the same is true for fixed number density galaxies selected with a single cut in L\([\text{O} \, ii]\). In this case, the suppression in the number of central galaxies found in massive haloes is even larger than for fixed number density samples selected with a SFR cut.

Fig. 10 shows that the HOD of fixed number density samples of ELGs is very similar to that of SFR or L\([\text{O} \, ii]\) selected samples, independently of the extra selection in either stellar mass, SFR or L\([\text{O} \, ii]\). This is because the ELGs we are studying are a sub-sample of star forming galaxies. It is interesting to note that a brighter [O ii] emitters, have a reduced number of central galaxies in massive haloes, compared to fixed number density ELGs with an extra cut in SFR or stellar mass.

As it is shown in Fig. 10, the HOD of samples selected by their SFR or L\([\text{O} \, ii]\) have a larger number of central galaxies with low masses and a lower number of satellites at larger masses, when compared with stellar mass selected samples. This difference gets larger for decreasing number densities.

Such difference is reduced for the ELG samples with fixed number densities. Fig. 10 also shows that fixed number density L\([\text{O} \, ii]\) selected samples populate slightly less massive haloes than the SFR selected samples. This difference is reduced for the fixed number density ELG samples, in particular for lower number densities.

Although Fig. 10 only shows the results for the fixed number density VVDS-DEEP sample, similar trends are found for the other fixed number density ELG selections explored here, except for the DESI one. In this case, the differences between applying the different cuts are negligible.

Compared to the global population, the minimum halo masses needed to host an ELG selected with a fixed number density are closer among the the cuts using the three properties studied here, stellar mass, SFR and L\([\text{O} \, ii]\). Despite the similarities, the effective bias for these samples are different, as it is described in the next section, §4.1.2.

For the fixed number density stellar mass selections, the minimum halo mass needed to find a galaxy increases for smaller number densities. This trend is also reflected in the increase of the effective bias from fixed number density stellar mass selected samples, as it can be seen in Table 5. This is not as clear for fixed number density SFR and L\([\text{O} \, ii]\) selections.
Table 5. Bias for the fixed number density samples described in §4, at \( z = 0.83 \) and \( z = 0.99 \). The bias is tabulated for the stellar mass, SFR and [O II] selected samples separated by a comma. The bias, \( b \), and associated error have been obtained as described in §3.2.2 in the range \( 8 \leq r (h^{-1}\text{Mpc}) \leq 50 \).

| \( z \) | Survey | \( 10^{-2}h^{3}\text{Mpc}^{-3} \) | \( 10^{-3}h^{3}\text{Mpc}^{-3} \) | \( 10^{-4}h^{3}\text{Mpc}^{-3} \) |
|---|---|---|---|---|
| 0.83 | All | 1.90±0.01, 1.27±0.01, 0.99 ±0.01 | 2.56±0.03, 1.21±0.03, 0.97 ±0.05 | 4.36±0.06, 1.48±0.06, 1.76 ±0.96 |
| | VVDS-DEEP | 1.26±0.01, 1.13±0.01, 0.99 ±0.01 | 1.50±0.04, 1.18±0.02, 0.96 ±0.09 | 2.35±0.40, 1.11±0.71, 1.83 ±0.91 |
| | eBOSS-SGC | \( \cdots \) | 1.23±0.01, 1.12±0.01, 1.05 ±0.01 | 1.42±0.02, 1.20±0.01, 1.22 ±0.69 |
| 0.99 | All | 2.00±0.01, 1.39±0.01, 1.06 ±0.01 | 2.70±0.03, 1.29±0.06, 1.15 ±0.01 | 4.28±0.45, 1.97±0.95, 1.80±0.29 |
| | DEEP2 | 1.28±0.01, 1.21±0.01, 1.06 ±0.01 | 1.57±0.06, 1.29±0.01, 1.16±0.04 | 2.95±0.63, 1.36±0.76, 1.52 ±0.68 |
| | DESI | 1.09±0.01, 1.08±0.01, 1.05 ±0.01 | 1.28±0.04, 1.17±0.06, 1.08 ±0.06 | 1.27±0.80, 1.70±0.96, 1.85 ±1.09 |

Figure 11. The real-space two point correlation function for model galaxies with a number density of \( 10^{-3}h^{3}\text{Mpc}^{-3} \) at redshift \( z = 0.99 \), selected using different criteria, as indicated in the legend. Bottom panel: The real space ratio \( \xi_{gg}/\xi_{DM} \). Poisson error bars are shown in both panels.

4.1.2 Clustering of fixed density samples

The real-space two point correlation function for galaxies with a fixed number density of \( 10^{-2}h^{3}\text{Mpc}^{-3} \) at redshift \( z = 0.99 \), is shown in Fig. 11. The calculation of the two point correlation function has been done following the description in §3.2.2.

Fig. 11 shows that at large scales, \( r > 8 h^{-1}\text{Mpc} \), the two point correlation function of fixed number density SFR and [O II] selected galaxies remain close, independently of starting with the whole galaxy population or ELGs. In fact, at a given number density, the bias of SFR and [O II] cut samples for all galaxies and ELGs at \( z = 0.83 \) and \( z = 0.99 \) remain within a 0.6 range (0.3 if only number densities above \( 10^{-4}h^{3}\text{Mpc}^{-3} \) are considered). The bias of all studied samples can be seen in Table 5. The bias has been calculated in the range \( 8 \leq r (h^{-1}\text{Mpc}) \leq 50 \), as \( \sqrt{\xi_{gg}/\xi_{DM}} \).

Both Fig. 11 and Table 5 show that galaxies selected with a single cut in stellar mass are more clustered than the rest of the samples (solid red line versus the rest in Fig. 11). Although this is also true at large scales for fixed number density ELGs selected with an extra cut in stellar mass, in these cases the differences are much smaller (see the dashed and dotted red lines versus the blue ones in Fig. 11, for the case of DEEP2 selected galaxies). There is one exception to this: the least dense DESI sample, for which the all selections are consistent at large scales.

Table 5 shows that, except for the DESI sample, the bias of mass selected galaxies grow with lower number densities. Such a trend does not seem to exist for the other galaxy selections.

At large scales, the SFR and [O II] cut samples trace closely the dark matter clustering, with biases, between 0.95 and 1.4 for samples with number densities above \( 10^{-2}h^{3}\text{Mpc}^{-3} \) (see Table 5). For these number densities, the [O II] sample has bias slightly lower than the SFR one, being closer to 1. The clustering in the lowest studied number density bin becomes very noisy and despite the biases reaching values close to 2, their corresponding error bars are close to 1.

The bias of galaxies selected with a single cut in either SFR or [O II] are comparable to that of ELGs with a fixed number density.

As shown in Fig. 11, at small scales, the clustering of ELGs and galaxies selected with a single cut in SFR are different, except for the DESI-like sample. The clustering of this sample is consistent within the Poisson error bars for both mass and SFR selected samples. Fig. 11 shows that pairs of galaxies selected by their [O II] are not found at the shortest separations found for the stellar mass or SFR samples. This is the case for all the studied selections. At \( z = 0.99 \) and \( 10^{-2}h^{3}\text{Mpc}^{-3} \), the case shown in Fig. 11, no pairs of [O II] selected galaxies are found with \( r \lesssim 0.04 h^{-1}\text{Mpc} \). At \( z = 0.83 \) for the same number density, no [O II] selected galaxies are found with \( r \lesssim 0.03 h^{-1}\text{Mpc} \). This values increase for decreasing number densities, a trend also seen for the other selections. The difference seen in Fig. 11 although striking, is reduced for VVDS-DEEP at \( z = 0.83 \) and for lower number density samples. Nevertheless, this difference is worth exploring as its origin is unclear. In Fig. 9, different galaxy selections are compared in the SFR-stellar mass plane. From here it is clear that very different ranges of stellar mass and SFR are covered by the different samples. These will cause differences in the clustering. We defer to an other study the
4.2 Fixed number density samples in the Cosmic Web

Here we study the fixed-number-density samples constructed above, §4, to understand ELGs compared to mass and SFR selected samples. Fig. 12 presents a $100 \times 100 \times 10 h^{-3} \text{Mpc}^3$ slice of the whole simulation box at redshift $z = 0.99$, highlighting in grey the cosmic web of the dark matter, together with the location of galaxies with a fixed number density, $10^{-2} h^3 \text{Mpc}^{-3}$, selected with single cuts on their stellar mass, SFR or [O II] and ELGs with and extra cut on these properties, as described previously. Fig. 12 shows that, at least qualitatively, even when the number density is fixed, star forming galaxies tend to trace less dense environments than mass selected samples. In Fig. 12 it is unclear if there are significant differences between the large-scale environment traced by ELGs and galaxies selected by their SFR to have the same number density. In this section we attempt to quantify the large-scale environment of ELGs and galaxies selected by their stellar mass and SFR.

4.2.1 Large scale environment distribution

Following the methods described in § 2.2, we classify the large-scale environment into voids, sheets, filaments and knots using a velocity-shear-tensor algorithm, VWEB, with a 0.1 threshold, for the samples of galaxies with fixed number density constructed in §4. Fig. 13 compares selections in stellar mass, SFR and [O II] with the same number density. About half of these galaxies populate filaments with few exceptions. The exceptions correspond to the mass selected sample with number densities below $10^{-2} h^3 \text{Mpc}^{-3}$ and for DEEP2 and VVDS-DEEP galaxies with an extra cut in stellar mass to achieve the lowest number density studied here, $10^{-4} h^3 \text{Mpc}^{-3}$.

As expected, samples based on a single stellar mass cuts have a higher presence in knots than the rest of the selections, which are star forming galaxies. For all samples, the presence in knots increases for lower number densities. [O II] selected samples trace the same large-scale environment structures, independently of being selected with just a single cut in [O II] or not. This stresses that, at least for the studied number densities, the particular magnitude and colour cuts applied to select ELGs are secondary to the [O II] limits.

[O II] selected samples are, in general, more present in sheets, $\sim 30\%$, than galaxies selected with a single cut in SFR. For number densities below $10^{-2} h^3 \text{Mpc}^{-3}$, [O II] galaxies are about 5% more present in sheets, and less present in knots, than ELGs selected in other ways. This appears to be in agreement with with difference in the 1-halo term for their clustering, reported in § 4.1.2.

All the studied ELG selections are distributed in the cosmic web close to that of samples with the same number density based on a single SFR cut for number densities above $10^{-4} h^3 \text{Mpc}^{-3}$, with difference in fraction below a value of 0.11. ELGs selected with a number density of $10^{-2} h^3 \text{Mpc}^{-3}$ are about 5% more present in sheets than the sample selected only by a cut in SFR.

The ELG sample with an extra cut in SFR to fix the number density, closely follow the distribution of the SFR sample, with differences in fractions up to 0.07. The differences between the ELG sample with an extra cut in stellar mass and the SFR one increase with decreasing number densities. At the lowest studied number density, the ELGs with an extra stellar mass cut have a much larger presence in knots, with difference in fractions up to 0.48, than the SFR sample.

Above 70% of the model ELG samples with number densities $10^{-2} h^3 \text{Mpc}^{-3}$ and $10^{-3} h^3 \text{Mpc}^{-3}$ are found in either filaments or sheets and about half of them are indeed in filaments. For the samples with a number density of $10^{-4} h^3 \text{Mpc}^{-3}$, this is only true for ELG samples with an extra cut in SFR or [O II]; for stellar mass selected ELG samples, the percentage drops for all the ELGs, except for the eBOSS-SGC.

The environmental split does agree with the differences in the clustering amplitudes reported in § 4.1.2. Fig. 11 shows that when more galaxies are found in knots the 1-halo term of the two point correlation function is much higher in SFR than in [O II].

We have done a similar analysis but classifying the large-scale environment with a tidal-tensor algorithm, PWEB, with a 0.005 threshold. The results with PWEB are quantitatively similar to those described above and can be seen in the Appendix C.

ELGs and [O II] selected galaxies tend to occupy ei-
ther filaments or sheets. ELGs and L\([\text{O}\,\text{II}]\) selected galaxies roughly populate the same large-scale environment as galaxies selected based on their SFR, for number densities above or equal to \(10^{-3} h^3\text{Mpc}^{-3}\). Below this number density, the differences can be large for stellar mass selected ELGs, in particular in knots and voids.

### 4.2.2 Comparison of global properties

For a given galaxy sample, the median stellar mass is comparable for galaxies in knots, filaments, sheets and voids. As expected, the maximum stellar mass of galaxies decreases towards less dense environments, i.e., it decreases from knots to voids. A similar trend is seen for the host halo mass of the galaxies, shown in the left panel in Fig. 14 for galaxies selected at \(z = 0.99\) with \(10^{-3} h^3\text{Mpc}^{-3}\). This trend does affect the distribution of host halo masses, such that median halo masses can decrease from knots to voids.

The median SFR is comparable for a given sample of galaxies in knots, filaments and sheets. In voids, stellar mass selected galaxies have minimum SFR above those for knots, filaments and Sheet. For example, galaxies with \(10^{-3} h^3\text{Mpc}^{-3}\) at \(z = 0.99\) in voids have SFR> \(10^9 h^{-1}\text{M}_\odot\text{Gyr}^{-1}\), while in the other large-scale structures galaxies with SFR< \(10^7 h^{-1}\text{M}_\odot\text{Gyr}^{-1}\) can be found. This suggests that galaxies in voids at \(z \sim 1\) are less affected by the quenching of the star formation than in other large-scale environment. A similar difference between voids and the other large-scale structures is found for the distribution of mass selected samples as a function of specific SFR, as shown in the middle panel of shown in Fig. 14 for galaxies selected with \(10^{-3} h^3\text{Mpc}^{-3}\) at \(z = 0.99\). However, the distribution as a function of specific SFR of galaxies selected with a single stellar mass cut has a larger variation with the large-scale structure. In Fig. 14 the differences between filaments, sheets and voids are clear for galaxies selected with a single cut in stellar mass. This trend is in agreement with star formation being quenched more effectively in the densest large-scale structures for a mass selected sample. This is not as clear for star forming galaxies, for which a minimum SFR or L\([\text{O}\,\text{II}]\) has already been imposed.

The right panel in Fig. 14 shows as a function of L\([\text{O}\,\text{II}]\) the distribution of galaxies with \(10^{-3} h^3\text{Mpc}^{-3}\) at \(z = 0.99\). The distributions are comparable for galaxies in different large-scale structures.

The trends discussed above are found for the classifi-
The percentage of satellite galaxies in different large-scale environment are comparable between the VWEB and PWEB classifications.

5 CONCLUSIONS

Star-forming emission line galaxies (ELGs) are being targeted by current and future cosmological surveys. Here we have studied how they populate the cosmic web structure within a semi-analytical model (SAM) of galaxy formation and evolution.

We have used a new flavour of the semi-analytical model galform run on the MS-W7 dark matter only simulation, with a WMAP7 cosmology and a simulation box of side 500 Mpc. This new flavour improves the model presented in Gonzalez-Perez et al. (2018) by (i) stripping the gas in satellites more slowly, such that the observed passive fraction at z = 0 is better matched (see § 2.1); and (ii) including the updated treatment of the evolution of supermassive black holes introduced in Griffin et al. (2019). This last point is relevant for this work as this improvement results in a different evolution of the AGN feedback. The model has been calibrated against local observations.

Model star-forming ELGs are selected by imposing cuts in apparent magnitude and [O ii] flux to mimic five observational surveys: DEEP2, VVDS-Deep, VVDS-Wide, eBOSS-SGC and DESI (see Table 2). Further colour cuts are imposed for the latter two, to mimic the spectroscopic selection that avoids galaxies with colours that can be confused with stars.

The large scale bias of model ELGs is close to 1 (see § 3.2.2). These model galaxies are naturally affected by assembly bias, as the semi-analytical model of galaxy formation and evolution includes the effect of different physical processes. Thus, the bias measured from galaxy catalogues...
constructed with a halo occupation distribution model without considering assembly bias, is expected to be larger than those values reported here.

The large-scale environment at $z = 0.83, 0.99$ has been classified into voids, sheets, filaments and knots using: (i) a velocity-shear-tensor algorithm, $V_{\text{WEB}}$, with a threshold of 0.1; and (ii) a tidal-tensor algorithm, $P_{\text{WEB}}$, with a threshold of 0.005. Similar conclusions are reached with both algorithms.

Half of the model ELGs live in filaments and a third in sheets (see § 3.2). Model ELGs in knots have the largest percentage of satellite galaxies and a tail of massive galaxies that set them apart when comparing the galaxy stellar mass function per environment. We find that the shape of the mean halo occupation distribution (HOD) of model ELGs varies widely with large-scale environment, partly due to the different presence of satellite ELGs in different cosmic web structures. The mean HOD of voids and sheets, where almost all galaxies are centrals, has a shape close to an asymmetric Gaussian. The mean HOD of central galaxies in filaments and knots have a plateau. The presence of satellite galaxies is most important among ELGs in knots, for which the mean satellite HOD follows a typical power law.

We have explored the cross-correlation between the whole ELG sample and those living in voids, sheets, filaments of knots. We find that, for all the studied ELG samples, the clustering of ELGs in knots is boosted at $1 \leq r/h^{-1}\text{Mpc} \leq 10$, while those ELGs in voids are largely under-clustered at large scales, $r > h^{-1}\text{Mpc}$.

To put in context the results obtained for model ELGs, we have defined samples with three fixed number densities, $10^{-2}, 10^{-3}, 10^{-4.2}h^{3}\text{Mpc}^{-3}$. These samples have been selected by imposing an extra cut in either stellar mass, SFR or $[\text{O} \ II]$ for ELGs or by imposing a single cut in one of these three properties to the whole sample of model galaxies. The median $[\text{O} \ II]$ for galaxies selected only by their stellar mass is below $10^{40.5}h^{-2}\text{erg s}^{-1}$, while all the other selections are much brighter, with median $[\text{O} \ II]$ above $10^{40.5}h^{-2}\text{erg s}^{-1}$.

The mean HODs of model ELGs with fixed number densities have shapes close to those of star forming samples, selected either based on a SFR or $[\text{O} \ II]$ cut. The studied ELGs are indeed a subsample of the star forming population.

For a fixed number density, we find that, in general, star forming galaxies are less clustered than stellar mass selected ones. Fixed number density ELG, SFR and $[\text{O} \ II]$ selected samples have very close large scale bias, however their clustering differ below separations of $1h^{-1}\text{Mpc}$. For instance, no pairs of $[\text{O} \ II]$ selected samples are found at the smallest separations considered. This might have implications for the expectations of redshift-space distortions derived assuming that ELGs are equivalent to galaxies selected by a single cut in [O II].

As expected, fixed number density samples selected with a single stellar mass cut have a higher presence in knots than either ELGs or galaxies selected by their SFR or $[\text{O} \ II]$.

For a fixed number density, the distribution of star forming ELGs in the cosmic web follows closely that of samples selected with a single cut in either SFR or $[\text{O} \ II]$. Differences are more significant for low number density samples, at least with respect to SFR selected samples. Over 70% of the model ELG samples with number densities $10^{-2}h^{3}\text{Mpc}^{-3}$ and $10^{-3}h^{3}\text{Mpc}^{-3}$ are found in either filaments or sheets. About half of them are in filaments. For samples with lower number densities, this percentage drops, except for the eBOSS-SGC sample.

The maximum stellar mass and host halo mass decreases from knots to voids for both star forming and stellar mass selected samples with fixed number densities. The specific star formation of fixed number density model samples is largely independent of the large-scale environment for star forming galaxies, but increases from knots to voids for galaxies selected with a single cut in stellar mass. For a fixed number density model sample, the $L([\text{O} \ II])$ appears to be independent of the large-scale environment.

The agreement between the properties of the ELGs, SFR and $L([\text{O} \ II])$ selected samples, at least for number densities above $10^{-4.2}h^{3}\text{Mpc}^{-3}$, shows the robustness of our results. For large scales, one could use the dispersion in the two point correlation function among these 'star forming' samples, as a reasonable error to produce mock catalogues. For small scales, variations are found among star-forming galaxies selected in different ways.

ACKNOWLEDGEMENTS

The authors would like to thank the help provided by Nuala McCullagh, Lee Stothert and Alex Smith to run CUTE on hdf5 files. VGP acknowledges support from the European Research Council grant No. 769130 and past support from the University of Portsmouth through the Dennis Sciama Fellowship award. WC was supported by the Ministerio de Economía y Competitividad and the Fondo Europeo de Desarrollo Regional (MINECO/FEDER, UE) in Spain through grant AYA2015-63810-P. WC further acknowledges the support from the European Research Council under grant number 670193. SC acknowledges the support from the Juan de la Cierva Formación Fellowship (FJCI-2017-33816). AG acknowledges support from the STCF studentship ST/N50404X/1. CGL and CMB acknowledge support from the STFC grant ST/P00541/1. AK is supported by MINECO/FEDER (Spain) under research grants AYA2015-63819-P and PGC2018-094975-C2. He further acknowledges support from the Spanish Red Consolider MultiDark FPA2017-90566-REDC and thanks Tocotronic for the red album. PN acknowledges the support of the Royal Society through the award of a University Research Fellowship, and the European Research Council, through receipt of a Starting Grant (DEGAS-259586). This work used the DiRAC@Durham facility managed by the Institute for Computational Cosmology on behalf of the STFC DiRAC HPC Facility (www.dirac.ac.uk). The equipment was funded by BEIS capital funding via STFC capital grants ST/P002293/1, ST/R002371/1 and ST/S002502/1, Durham University and STFC operations grant ST/R000832/1. DiRAC is part of the National e-Infrastructure. This work has benefited from the publicly available programming language PYTHON (https://www.python.org/) and the package matplotlib (https://matplotlib.org/).
and to the regions delimited by the eBOSS-SGC Raichoor et al. (2017) and DESI colour cuts DESI Collaboration et al. (2016). These colour cuts are summarized in Table 2. The colours of model galaxies are roughly consistent with the regions defined for eBOSS-SGC Comparat et al. (2016b) and DESI (DESI Collaboration et al. 2016) to select ELGs in the range 0.6 < z < 1.7. Further details on the colour cuts can be found in Gonzalez-Perez et al. (2018).

APPENDIX C: LARGE-SCALE ENVIRONMENT WITH PWEB

Fig. C shows the fraction of galaxies in voids, sheets, filaments and knots when the large-scale environment is classified using the PWeb algorithm described in § 2.2, with a 0.005 threshold. Very similar fractions are found when imposing a 0.01 threshold. This figure is qualitatively equivalent to Fig. 13, in terms of global trends, however, quantitatively there are differences that become more pronounced for the samples with the lowest number density, in particular for the mass selected ones.

This paper has been typeset from a TeX/LATEX file prepared by the author.

APPENDIX A: RESOLUTION AND THRESHOLD CHECKING

In Fig. A1, we compare the results with two different mesh numbers $256^3$ (corresponding to a cell size of $\sim 2 h^{-1}\text{Mpc}$) and $512^3$ ($\sim 1 h^{-1}\text{Mpc}$ cell size). Both meshes adopt the referenced thresholds: $\lambda = 0.1$ for VWeb and $\lambda_h = 0.005$ for PWeb. The smoothing length in all cases is set to $5h^{-1}\text{Mpc}$ (see § 4.2). It is clear that more details are revealed with the finer meshes. However, we do not go beyond the $512^3$ number of meshes, as finer mesh cells will have less particles which will provide noisier fields. We confirm here that with these two thresholds we have very similar volume fractions (see Table A1 for details) between VWeb and PWeb classified large-scale structures. Furthermore, we can see that these classified large-scale structures with both methods match the density fields shown in the right-hand side panels well.

We further investigated the effects of varying the two thresholds within two times of the reference values. They are either too large – $\lambda = 0.05$ ($\lambda_h = 0.025$) – with more knots regions, or too small – $\lambda = 0.2$ ($\lambda_h = 0.1$) – with most of the space is occupied by Void. However, it is interesting to see that our main conclusions are basically unchanged.

APPENDIX B: EBOSS-SGC AND DESI COLOUR CUTS

Fig. B1 presents the location of model galaxies with $\text{Flux}_{\text{OIII}} > 8 \times 10^{-17}\text{erg s}^{-1}\text{cm}^{-2}$ at redshifts $z = 0.62, 0.83, 1, 1.5$ in the $(g - r)\text{DECam}$ vs. $(r - z)\text{DECam}$ colour-colour space. These distributions are compared to the location of stars (Leauthaud et al. 2007), grey filled symbols in Fig. B1

| mesh number | method | Knot | Filament | Sheet | Void |
|-------------|--------|------|----------|-------|------|
| 256$^3$     | VWeb   | 0.028| 0.209    | 0.469 | 0.296|
| 512$^3$     | VWeb   | 0.029| 0.227    | 0.474 | 0.270|
| 256$^3$     | PWeb   | 0.022| 0.217    | 0.480 | 0.281|
| 512$^3$     | PWeb   | 0.019| 0.218    | 0.495 | 0.269|

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Do ELGs live in filaments?

Figure A1. The projected structures for a slice of the simulations with $256^3$ meshes (upper panels, $\sim 2 \, h^{-1}\text{Mpc}$ thickness) and $512^3$ meshes (lower panels, $\sim 1 \, h^{-1}\text{Mpc}$ thickness). The large-scale structures: knots, filaments, sheets and voids regions are shown as red, green, blue and black colours, respectively. From left-hand panel to right-hand panel, we show the results from $V_{\text{WEB}}$ and $P_{\text{WEB}}$ as well as the density fields. The same threshold $\lambda_{t,h} = 0.1$ for $V_{\text{WEB}}$ ($\lambda_{t,h} = 0.005$ for $P_{\text{WEB}}$) is applied to both meshes.
Figure B1. DECam (g-r) vs (r-z) parameter space with the isodensity lines at \( \log_{10}(\Phi/Mpc^{-3}h^{-3})d\log_{10}(L) = -4.5, -1.5, 1 \) for model galaxies, with \( \text{Flux}_{\text{OII}} > 8 \times 10^{-17}\text{erg s}^{-1}\text{cm}^{-2} \) at the redshifts indicated in the legend. The polygon with solid lines shows the eBOSS-SGC colour selection and the one with dashed lines that for DESI, as summarized in Table 2. Note that the flux limit difference between the eBOSS-SGC and DESI selections is about a 20 per cent and thus, the distribution of model galaxies in this plot is very similar for both cuts, \( \text{Flux}_{\text{OII}} > 8 \cdot 10^{-17}\text{erg s}^{-1}\text{cm}^{-2} \) and \( \text{Flux}_{\text{OII}} > 10^{-16}\text{erg s}^{-1}\text{cm}^{-2} \). The location of stars are shown by the grey symbols.
Do ELGs live in filaments?

Voids, Sheets, Filaments, Knots

| Fraction | Mass cut, All | Mass cut, VVDS-DEEP | Mass cut, eBOSS-DEEP | SFR cut, All | SFR cut, VVDS-DEEP | SFR cut, eBOSS-DEEP |
|----------|---------------|---------------------|---------------------|--------------|---------------------|---------------------|
| z = 0.83; 10 Mpc | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
| z = 0.99; 10 Mpc | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |

Figure C1. Histograms with the fraction of galaxies in voids, sheets, filaments and knots, similar to Fig. 13. In this case the large-scale environment has been classified using Pweb (see § 2.2).