The galaxy-halo connection of emission-line galaxies in IllustrisTNG

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ABSTRACT

We employ the hydrodynamical simulation IllustrisTNG-300-1 to explore the halo occupation distribution (HOD) and environmental dependence of luminous star-forming emission-line galaxies (ELGs) at $z \sim 1$. Such galaxies are key targets for current and upcoming cosmological surveys. We select model galaxies through cuts in color-color space allowing for a direct comparison with the Extended Baryon Oscillation Spectroscopic Survey and the Dark Energy Spectroscopic Instrument (DESI) surveys and then compare them with galaxies selected based on star-formation rate (SFR) and stellar mass. We demonstrate that the ELG populations are twice more likely to reside in lower-density regions (sheets) compared with the mass-selected populations and twice less likely to occupy the densest regions of the cosmic web (knots). We also show that the color-selected and SFR-selected ELGs exhibit very similar occupation and clustering statistics, finding that the agreement is best for lower redshifts. In contrast with the mass-selected sample, the occupation of halos by a central ELG peaks at $\sim 20\%$. We furthermore explore the dependence of the HOD and the auto-correlation on environment, noticing that at fixed halo mass, galaxies in high-density regions cluster about 10 times more strongly than low-density ones. This result suggests that we should model carefully the galaxy-halo relation and implement assembly bias effects into our models (estimated at $\sim 4\%$ of the clustering of the DESI color-selected sample at $z = 0.8$). Finally, we apply a simple mock recipe to recover the clustering on large scales ($r \gtrsim 1$ Mpc/$h$) to within 1% by augmenting the HOD model with an environment dependence, demonstrating the power of adopting flexible population models.

Key words: cosmology: large-scale structure of Universe – galaxies: haloes – methods: numerical – cosmology: theory

1 INTRODUCTION

In the current cosmological paradigm, the Universe is made up of a dense network of filaments shaped by gravity. Embedded in these filaments are dark matter structures, called halos, which correspond to overdense regions that have evolved by gravitational instability and interactions with other halos. According to this framework, galaxy formation takes place within these halos. Baryonic matter sinks to the center of their gravitational potential wells and condensation of cold gas allows for galaxies to form and evolve (White & Rees 1978). A detailed understanding of the galaxy-halo connection would enable us to use the galaxy field to place stringent constraints on cosmological parameters.

The evolution and distribution of the dark matter halos can be modeled effectively using cosmological ($N$-body) simulations, which incorporate various assumptions of the cosmological model. These simulations have the benefit of encompassing very large volumes ($\sim 1$ Gpc/$h$), but they lack prescriptions for determining the evolution and distribution of the baryonic content. To probe the effect of baryons in such large volumes, cosmologists often adopt alternative schemes for populating the dark matter halos with galaxies through a posteriori models of varying complexity. The simplest of them are phenomenological approaches such as halo occupation distribution (HOD) and subhalo abundance matching (SHAM), which rely on basic assumptions of how galaxies are connected to their halos.

The HOD framework (Benson et al. 2000; Peacock & Smith 2000; Scoccimarro et al. 2001; Yang et al. 2004) provides an empirical relation between halo mass and the number of galaxies it hosts, which is expressed as the probability distribution $P(N|M_h)$ that a halo of virial mass $M_h$ hosts $N$ galaxies satisfying some selection criteria. This method can thus be used to study galaxy clustering (Berlind & Weinberg 2002; Zheng et al. 2005; Conroy et al. 2006; Zehavi et al. 2011; Wechsler & Tinker 2018). Since the HOD parameters are tuned so as to reproduce only a limited set of observables such as the two-point correlation function and the galaxy number density, HOD modelling is one of the most efficient ways to “paint” galaxies on top of $N$-body simulations of large volumes and produce the many realizations required for, e.g., estimating covariance matrices using mock galaxy catalogs (e.g. Norberg et al. 2009; Manera et al. 2013). Such mock catalogs are crucial for developing new algorithms that will be used for the next generation of surveys such as DESI and Euclid. However, in their most stripped-down versions, empirical approaches such as the mass-only HOD have been shown to lead to significant discrepancies with observations and more detailed galaxy formation models, so one should proceed with caution when adopting them (Croton et al. 2007; Paranjape et al. 2015; Beltz-Mohrmann et al. 2019). For example, several recent works have shown that local halo environment as a secondary HOD parameter yields a better agreement with simulations than mass-only prescriptions (Hadzhiyska et al. 2020b; Xu & Zheng 2020; Hadzhiyska et al. 2020a).

Alternatively, other more complex empirical models that study the relationship between the properties of galaxies and their host...
halos have been an area of keen interest (Behroozi et al. 2013; Tacchella et al. 2013; Moster et al. 2013, 2018; Tacchella et al. 2018; Behroozi et al. 2019). A particularly well-developed route for assigning galaxies to dark-matter halos is through semi-analytical models of the galaxy formation (SAMs). SAMs provide a physically motivated mechanism for evolving galaxies and studying the processes that shape the evolution of baryons. These are built on top of halos extracted from an $N$-body simulation and employ various physical prescriptions to make predictions for the abundance and clustering of galaxies (Cole et al. 2000; Baugh 2006; Somerville & Davé 2015). A disadvantage to these models is that their outputs are highly sensitive to the particular choices of calibration parameters, which in turn depend on many physical processes that are still poorly understood.

Hydrodynamical simulations, on the other hand, are an example of an *ab initio* approach to gaining insight into the formation and evolution of galaxies (e.g. Vogelsberger et al. 2014; Schaye et al. 2015), incorporating baryonic effects such as stellar wind, supernova feedback, gas cooling, and black hole feedback. While these models are computationally expensive and cannot (at present) be run over the large volumes needed for future cosmological galaxy surveys, they can still be used to inform us of the galaxy-halo connection on large scales, having recently reached sizes of several hundred megaparsecs (Chaves-Montero et al. 2016; Springel et al. 2018). In particular, we can test the accuracy of empirical approaches such as the HOD model by applying them to the dark-matter-only counterpart of a hydro simulation and comparing various statistics of the galaxy field (Bose et al. 2019; Hadzhiyska et al. 2020b; Contreras et al. 2020). Such analyses have been performed extensively for galaxy populations above a certain stellar mass cut, but not as much for the study of other galaxy populations targeted by future surveys such as emission-line galaxies (ELGs). Both observations and models indicate that star-forming galaxies in general, and ELGs in particular, populate halos in a different way than mass-selected samples (e.g. Zheng et al. 2005; Cochrane & Best 2018; Favole et al. 2017; Guo et al. 2016; Gonzalez-Perez et al. 2018; Alam et al. 2019).

Emission-line galaxies (ELGs), targeted for their sensitivity to the Universe expansion rate during the epoch dark energy starts to dominate the energy budget of the Universe ($z \sim 1$), are characterized by nebular emission lines produced by ionized gas in the interstellar medium. The gas gets heated either by newly formed stars, evolved stars, or by nuclear activity due to black hole accretion. In this work, we focus only on luminous star-forming ELGs with a high line luminosity, as this is the population targeted by many current cosmological surveys such as DESI, Euclid, SDSS-IV/eBOSS, and the Nancy Grace Roman Space Telescope (Levi et al. 2013; Amendola et al. 2018; Ata et al. 2018; Spergel et al. 2015). The presence and strength of the emission lines depends on a number of factors, including star formation rate (SFR), gas metallicity, and particular conditions of the HII regions (e.g. Orsi et al. 2014). Despite the fact that ELG samples are related to star formation, they are not equivalent to SFR-selected samples. Nevertheless, the HOD method can still be adopted to study them (Geach et al. 2012; Cochrane et al. 2017; Cochrane & Best 2018; Avila et al. 2020). For both galaxy populations, the shape of the HOD is more complex than that of the more widely studied stellar-mass selected samples (Contreras et al. 2013; Gonzalez-Perez et al. 2018). For example, the occupation function of central galaxies does not follow a step-like form but rather peaks at low halo-mass values and decays promptly after.

Understanding the connection between ELGs and their host dark matter halos will help us obtain more realistic mock catalogs, which are crucial for the analysis of future observational samples. Observations concentrating on star-forming ELGs around $z \sim 1$ have studied their occupancy as a function of halo mass (Favole et al. 2016; Khosrovani et al. 2018; Guo et al. 2019) as well as their clustering function (Comparat et al. 2013; Jimenez et al. 2020). There have been efforts to match these findings through SAMs (Gonzalez-Perez et al. 2018; Favole et al. 2017), which despite being able to recover the occupation function, have found the clustering to be inconsistent with observations on large scales. A possible explanation is the lack of “assembly bias” in the models interpreting the observations (Contreras et al. 2019), where we define “assembly bias” to be the additional properties of halos which affect the galaxy clustering beyond halo mass. Another set of assumptions that these results rely upon is the particular calibration scheme adopted by the SAM. It is, therefore, worth exploring these questions in hydrodynamical simulations, which implement detailed baryonic physics processes during the simulation run instead of once the run has completed assuming gravitation-only interactions.

In this work, we study the clustering, galaxy bias and occupation function of ELG samples obtained by applying the color-space selection criteria proposed by DESI and eBOSS to the output of the hydrodynamical simulation IllustrisTNG (Pillepich et al. 2018a; Nelson et al. 2019a). We further construct a mock catalog using the HOD model augmented with an environmental dependence in order to recover the two-point correlation function on large scales. In Section 2, we introduce the DESI and eBOSS galaxy surveys, the hydrodynamical simulation IllustrisTNG, and a description of the steps we take to synthesize the galaxy colors. In Section 3, we show the main results of our analysis. We first compare the color-selected ELGs with galaxy samples selected based on SFR in terms of their three-dimensional distributions in $(g-r)-(r-z)-$SFR space. We then study their spatial distribution in the cosmic web, comparing it with that of a stellar mass-selected sample, with which we aim to mimic a luminous red galaxy (LRG) sample. We confirm that ELGs are more likely to reside in filamentary structures. We then derive and study in detail the occupation distribution and auto-correlation function of both the SFR- and color-selected ELG-like samples and investigate their differences and similarities. In particular, we explore the dependence of both statistics on the density of the local environment. Finally in Section 4, we propose an HOD prescription augmented with a secondary environment parameter, which captures well the clustering across all scales. In Section 5, we summarize our results and comment on their implications for future galaxy surveys.

2 METHODOLOGY

In this section, we describe the two ELG target selection strategies employed by the DESI and eBOSS surveys, the hydrodynamical simulation IllustrisTNG (TNG) used in this study, as well as the procedure we follow to synthesize the colors of the TNG galaxies. We also present an alternative ELG selection approach based on SFR and a single photometric band cut, which mimics the logic of the cuts in color-color space.

2.1 DESI

DESI is a ground-based experiment that aims to place stringent constraints on our models of dark energy, modified gravity and inflation, as well as the neutrino mass by studying baryon acoustic oscillations (BAO) and the growth of structure through redshift-space distortions (RSD). The DESI instrument will conduct a five-year survey of the sky designed to cover 14,000 deg$^2$. To trace the underlying dark matter distribution, several classes of spectroscopic samples
Table 1. Color-space cuts applied to the model galaxies in order to mimic the selection in the corresponding observational survey. The eBOSS selection is taken from Raichoor et al. (2017), while the DESI selection is as stated in the Final Design Report (DESI Collaboration et al. 2016). All magnitudes are reported in the AB system. The filter response used for the different cuts corresponds to the DECam camera.

| Galaxy survey | Magnitude limit | Magnitude cut | Color selection |
|---------------|-----------------|---------------|----------------|
| eBOSS-SGC     | $g < 24.7 \& r < 23.9 \& z < 23.0$ | $21.825 < g < 22.825$ | $-0.068(r-z) + 0.457 < (r-g) < 0.112(r-z) + 0.773 \& 0.218(g-r) + 0.571 < (r-z) < -0.555(g-r) + 1.901$ |
| DESI          | $g < 24.0 \& r < 23.4 \& z < 22.5$ | $20.0 < g < 23.6$ | $0.3 < (r-z) < 1.6 \& (r-g) < 1.15 \cdot (r-z) - 0.15 \& (g-r) < -1.2 \cdot (r-z) + 1.6$ |

will be selected including luminous red galaxies (LRGs), emission-line galaxies (ELGs), quasars, and bright galaxies around $z \approx 0.2$, totaling more than 30 million objects. The ELG sample will probe the Universe out to redshifts of $z = 1.6$, targeting galaxies with bright [O II] emission lines (DESI Collaboration et al. 2016). The ELG DESI targets are selected using optical $grz$-band photometry from the Dark Energy Camera Legacy Survey (DECaLS), the Beijing-Arizona Sky Survey (BASS), and the Mayall $z$-band Legacy Survey (MzLS) (Zou et al. 2017; Dey et al. 2019; Burleigh et al. 2020). The imaging depth is at least $24.0, 23.4, 22.5\, AB$ (for an exponential profile $r_{\text{half-light}} = 0.45\,''$) in $g$, $r$, and $z$. The Final Design Report (DESI Collaboration et al. 2016) color cuts are listed in Table 1.

2.2 eBOSS

eBOSS is one of three surveys from the SDSS-IV experiment (Blanton et al. 2017). It focuses on four different tracers, which significantly expand the volume covered by BOSS, spanning a redshift range of $0.6 < z < 2.2$. The four tracers are LRGs (Prakash et al. 2016), ELGs (Raichoor et al. 2017), ‘CORE’ quasars (Myers et al. 2015), and variability-selected quasars (Palanque-Delabrouille et al. 2016). The 255 000 ELG targets are centered around $z \approx 0.8$ and are observed through 300 plates with the BOSS spectrograph, obtaining a 2% precision distance estimate. The eBOSS ELG footprint is divided into two regions: South Galactic Cap (SGC) and North Galactic Cap (NGC), covering ~620 deg$^2$ and ~600 deg$^2$.

The eBOSS ELG target selection is based on an earlier data release of the ongoing imaging survey DECaLS (Raichoor et al. 2017; Delubac et al. 2017). The cuts applied in color-color space to obtain the ELG sample are shown in Table 1.

2.3 IllustrisTNG

For modeling the galaxy population, we consider the hydrodynamical simulation IllustrisTNG (TNG, Pillepich et al. 2018b; Marinacci et al. 2018; Naiman et al. 2018; Springel et al. 2018; Nelson et al. 2019a, 2018; Pillepich et al. 2019; Nelson et al. 2019b). TNG is the largest high-resolution hydrodynamical simulation from the suite. The size of its periodic box is $205\, Mpc/h$ with $2500^3$ gas particles and $2500^3$ gas cells, implying a DM particle mass of $3.98 \times 10^7\, M_\odot/h$ and baryonic mass of $7.44 \times 10^8\, M_\odot/h$. We also employ its DM-only counterpart, TNG300-Dark, which was evolved with the same initial conditions and the same number of dark matter particles ($2500^3$), each with particle mass of $4.73 \times 10^7\, M_\odot/h$. The halos (groups) in TNG are found with a standard friends-of-friends (FoF) algorithm with linking length $b = 0.2$ (in units of the mean interparticle spacing) run on the dark matter particles, while the subhalos are identified using the SUBFIND algorithm (Springel et al. 2001), which detects substructure within the groups and defines locally overdense, self-bound particle groups. We analyze the simulations at redshifts $z = 0.8, z = 1.1$ and $z = 1.4$, considering galaxies with minimum stellar mass of $M_\star = 10^{10}\, M_\odot$, which are deemed to be well-resolved (i.e. more than 1000 stellar particles).

2.4 Modeling galaxy colors

2.4.1 Stellar population synthesis and dust model

For all galaxies in a given snapshot, we predict the DESI and eBOSS photometries ($g$, $r$- and $z$-band) using the Flexible Stellar Population Synthesis code (FSPS, Conroy & Gunn 2010a,b). We adopt the MILES stellar library (Vazdekis et al. 2015) and the MIST isochrones (Choi et al. 2016). We measure the star-formation history (SFH) in the simulation from all the stellar particles in a subhalo within $30\, kpc$ of its center. We split the star-formation history (SFH) of each galaxy into a young (stellar ages $< 30\, Myr$) and old (stellar ages $> 30\, Myr$) component. We use the young SFH component to predict the nebular continuum emission and emission lines, assuming the measured gas-phase metallicity from the simulation and $-1.4$ for the ionization parameter (fiducial value in FSPS). We feed the old SFH component along with the mass-weighted stellar metallicity history to FSPS in order to predict the stellar continuum emission. For the galaxies studied here, the latter component dominates the flux in the DESI photometric bands.

An additional key ingredient in predicting the photometry is the attenuation by dust. There are several different ways of how to model dust attenuation in the simulation (e.g. Nelson et al. 2018; Vogelsberger et al. 2020). We use an empirical approach by basing our attenuation prescription on recent observational measurements. Specifically, we assume that the absorption optical depth follows:

$$
\tau_\nu = \gamma \left( \frac{Z_{\text{gas}}}{Z_\odot} \right)^{\alpha} \Sigma_\star^{\beta},
$$

where $Z_{\text{gas}}$ is the gas-phase metallicity and $\Sigma$ is the normalized stellar mass density ($\Sigma \equiv \Sigma_\star / (\Sigma_\star)$) with $\Sigma_\star = M_\star / (\pi r_\epsilon^2)$, where $r_\epsilon$ is the half-mass radius. Both quantities are obtained directly from the simulations. The parameters $\alpha$, $\beta$ and $\gamma$ have been roughly tuned to reproduce observed $z \sim 0$ scaling relations between $\tau_\nu$, SFR and $M_\star$ by Salim et al. (2018), which is based on GALEX, SDSS and WISE photometry. Specifically, we find $\alpha$, $\beta$ and $\gamma$ to be $-0.6, 0.2, 0.4$, respectively. We also vary the additional dust attenuation toward younger stars (dust1 in FSPS) and the dust index (shape of the dust
2.4.2 Adding photometric uncertainties

To make the synthetic sample more observationally realistic, we add photometric scatter to each of the $grz$ bands. At the faint magnitudes we are working with, the noise is limited by the background rather than the source, so the scatter can be assumed constant, i.e. independent of the source.

To determine the amount of scatter we need to add, we first convert the 5σ limiting magnitudes to fluxes and divide by 5 to get the RMS. This step is often complicated by the fact that the 5σ limit depends on the angular size of the galaxy – point sources will have a fainter limit than extended sources. For that purpose, the Legacy Survey quotes the depths in terms of the standard reference galaxy (0.45′ half-light exponential). We then set the ratio between the three bands to be constant and empirically scale the scatter until we match the width of the color distribution in the data. As will be discussed next, it turns out that the observed scatter can be matched in a satisfactory manner even without having to perform the second step of empirically matching the scatter (see Fig. 1).

2.4.3 Comparison of color distribution with DEEP2-DECaLS

The DEEP2 Galaxy Redshift Survey (Newman et al. 2013) is a large spectroscopic redshift survey. The survey was conducted on the Keck II telescope using the DEIMOS spectrograph (Faber et al. 2003) and measured redshifts for ~32000 galaxies from $0 < z < 1.4$. The DEEP2 targets were selected via a combination of magnitude ($R_{AB} < 24.1$) and color cuts (BRI) to efficiently select galaxies with $z > 0.7$. The DEEP2 survey has been particularly relevant for DESI, as its data has been used for calibration and refinement of the DESI target selection.

Here, we perform cross-matching between the DECaLS data release 8 (DR8) and DEEP2 in order to compare the synthesized TNG colors at $z = 0.8$, $z = 1.1$ and $z = 1.4$ with the observed colors and examine the dust parameters in the FSPS model. The matching is performed by first applying the DEEP2 window functions and the Tycho-2 mask¹ and then bijectively matching the DEEP2 and DR8 catalogs while testing for any astrometric discrepancies.

In Fig. 1, we show the cross-matched catalog between DEEP2 and DECaLS DR8 in red, and the TNG galaxies augmented with FSPS-synthesized colors in blue for the three redshift samples considered $z = 0.8$, $z = 1.1$ and $z = 1.4$. The median redshifts for the DEEP2-selected samples are $z = 0.83$, $z = 1.08$ and $z = 1.37$, respectively. We see that the $g-r$ vs. $r-z$ distributions are consistent between the two samples and are within 0.05, 0.2 and 0.1 mag for the three redshifts, respectively. These differences can be attributed to the observation that the TNG-predicted spectral energy distributions (SEDs) are fainter in the $r$-band for a given $g-z$ color than the observed data, which yields galaxies bluer in their $g-r$ and redder in their $r-z$ bands. The $r$-band rest-frame frequencies at these redshifts

¹ The Tycho-2 catalog is an astronomical reference catalog of more than 2.5 million of the brightest stars. For more information, see www.cosmos.esa.int/web/hipparcos/tycho-2.
correspond to the UV regime. The UV SED in the population synthesis model is sensitive to our choice for a dust attenuation model. In particular, changes in the dust law (concerning the slope as well as the UV bump) could introduce such effects, and in principle, one could experiment more with the dust attenuation model to bring better agreement between observations and simulations, but the insight would be minimal. Another possibility is related to the variability of star formation: since the UV (and in particular the far-UV) traces the SFR on short timescales (e.g., Caplar & Tacchella 2019), the UV luminosity might be underpredicted in TNG because of too smooth (not bursty enough) SFHs (Sparre et al. 2015; Iyer et al. 2020). We also note an overall shift of the SEDs towards the lower left corner, as we increase the samples redshift. In addition, the photometric scatter is quite similar as can be seen in the width of the red and blue curves in Fig. 1, which validates our heuristic approach to adding observational realism to the TNG sample.

2.5 SFR-selected sample

Many of the current and future cosmological surveys will target star-forming ELGs whose spectrum is characterized by prominent [O II] and [O III] emission lines as well as other less prominent features such as [Ne III] and Fe II emission lines. These surveys will apply a combination of color-color cuts as well as magnitude cuts (see Table 1 for the particular selection choices applied to the DESI and eBOSS ELG samples). A direct output of hydrodynamical simulations such as IllustrisTNG is the SFR, which is available at every snapshot for each galaxy. The ELG target selection in color-color space aims to isolate galaxies with vigorous star formation. Therefore, it is important to validate that indeed the selected objects have a significant overlap with the “true” star-forming objects as found in the simulation. In the following sections, we compare the color-selected ELG samples with samples of SFR-selected galaxies. In addition to satisfying a SFR limit, we also require of the star-forming sample to be within the chosen magnitude cut for the ELGs in the survey. The SFR threshold is selected so that the number of galaxies in the SFR-selected sample matches that of the color-selected one. This corresponds to $21.825 < g < 22.825$ and $20.0 < g < 23.6$ for eBOSS and DESI, respectively. We next study and compare the occupation function, two-point clustering, bias and cross-correlation coefficient of both samples.

3 RESULTS

Here we present an analysis of the ELG-like galaxies extracted from TNG300 using the methods described in the previous section. In particular, we study the ELG populations derived after applying the cuts in color space proposed by the DESI survey at $z = 0.8$, $z = 1.1$ and $z = 1.4$ and by eBOSS at $z = 0.8$. We also make use of the SFR-selected sample, which combines both a SFR cut and a magnitude cut matching that of the respective survey (see Section 2.5). First, we study the color-SFR distribution of the TNG300 galaxies to test the robustness of the DESI cuts. Next, we demonstrate the two-dimensional distribution of the ELGs in the cosmic web, comparing it with that of the most massive galaxies at the same number density. Importantly, we also study the galaxy occupations of the halos hosting ELGs and their dependence on the local halo environment. Finally, we study the clustering properties of the samples, focusing on their dependence on environment, as well as their galaxy bias and cross-correlation coefficient.

### 3.1 Number densities of ELGs

The expected number densities of ELGs at various redshifts for DESI and eBOSS can be found in DESI Collaboration et al. (2016) and Raichoor et al. (2017). For the three redshifts we consider ($z = 0.8$, $z = 1.1$, and $z = 1.4$), the number densities of ELGs for the DESI survey are $n_{\text{gal}} = 9 \times 10^{-4} [\text{Mpc}/h]^{-3}$, $n_{\text{gal}} = 4 \times 10^{-4} [\text{Mpc}/h]^{-3}$ and $n_{\text{gal}} = 1 \times 10^{-4} [\text{Mpc}/h]^{-3}$, respectively, and for the eBOSS ELGs at $z = 0.8$, it is $n_{\text{gal}} = 6 \times 10^{-4} [\text{Mpc}/h]^{-3}$. After applying the cuts in Table 1 on the synthesized galaxies in our hydro simulation box TNG300 ($V_{\text{box}} = 205^3 [\text{Mpc}/h]^3$), we find 8637 ($n_{\text{gal}} \approx 10.0 \times 10^{-4} [\text{Mpc}/h]^{-3}$), 4632 ($n_{\text{gal}} \approx 5.4 \times 10^{-4} [\text{Mpc}/h]^{-3}$), and 1539 ($n_{\text{gal}} \approx 1.8 \times 10^{-4} [\text{Mpc}/h]^{-3}$) DESI ELG-like objects at $z = 0.8$, $z = 1.1$, and $z = 1.4$, respectively, and 8112 ($n_{\text{gal}} \approx 9.4 \times 10^{-4} [\text{Mpc}/h]^{-3}$) eBOSS ELGs at $z = 0.8$. These are in good agreement with the expected number densities of the surveys stated above. These numbers are also shown in Table 2 for clarity.

| Survey   | Redshift | Target number density | Achieved number density |
|----------|----------|-----------------------|-------------------------|
| eBOSS    | $z = 0.8$ | $6 \times 10^{-4} [\text{Mpc}/h]^{-3}$ | $9.4 \times 10^{-4} [\text{Mpc}/h]^{-3}$ |
| DESI     | $z = 0.8$ | $9 \times 10^{-4} [\text{Mpc}/h]^{-3}$ | $10.0 \times 10^{-4} [\text{Mpc}/h]^{-3}$ |
| DESI     | $z = 1.1$ | $4 \times 10^{-4} [\text{Mpc}/h]^{-3}$ | $5.4 \times 10^{-4} [\text{Mpc}/h]^{-3}$ |
| DESI     | $z = 1.4$ | $1 \times 10^{-4} [\text{Mpc}/h]^{-3}$ | $1.8 \times 10^{-4} [\text{Mpc}/h]^{-3}$ |

3.2 Color-SFR dependence

An intriguing question to pursue is what the distribution of the TNG300 galaxies in SFR-color and sSFR-color space looks like in relation to the ELG cuts performed by galaxy survey analyses. Here, sSFR is the specific SFR, which is defined as the SFR per stellar mass. It is a key quantity in understanding the impact of stellar mass on star formation. For instance, studies have shown that galaxies with higher sSFR tend to be more massive and have more efficient star formation processes.

In Fig. 2, we visualize the SFR- and sSFR-color three-dimensional diagrams for the TNG300 galaxies at $z = 0.8$ alongside the DESI color-color cuts. The top panel demonstrates that the SFR values are much more evenly distributed across the galaxy population compared with the sSFR ones, as expected. There are two modes corresponding to the rapidly star-forming young galaxies, which are captured well by the DESI cuts, and the very massive red galaxies that also undergo significant amounts of star formation. However, as can be seen in the bottom panel, their SFRs are negligible compared with their masses.
Furthermore, the majority of the cold gas, which is needed for star formation to take place, is located in filaments and sheets at \( z \sim 1 \), which provides insight into why ELGs and star-forming galaxies are overwhelmingly found in these regions (Cui et al. 2012, 2014, 2019).

 Conventionally, the cosmic web is classified into voids, sheets, filaments and knots (Geller & Huchra 1989). To characterize the large-scale distribution of our simulation, we follow the traditional characterization into tidal environments (Doroshkevich 1970; Hahn et al. 2007; Forero-Romero et al. 2009). First, we evaluate the discrete density field, \( \delta(x) \), using cloud-in-cell (CIC) interpolation on a 128^3 cubic lattice of all particles in TNG300-3-Dark. We then apply a Gaussian smoothing kernel with a smoothing scale of \( R_{\text{smooth}} = 4 \text{ Mpc}/h \). Next, we solve the Poisson equation \( \nabla^2 \psi = \delta \) and obtain the second derivative, \( \psi_{ij} = \delta^2 \psi / \partial x_i \partial x_j \), which defines the tidal tensor in Fourier space. Finally, we compute the eigenvalues of this tensor \( \lambda_1 \leq \lambda_2 \leq \lambda_3 \) and define the four standard environment types:

- **peaks**: all eigenvalues below the threshold (\( \lambda_{\text{th}} \geq \lambda_1 \))
- **filaments**: one eigenvalue below the threshold (\( \lambda_1 \geq \lambda_{\text{th}} \geq \lambda_2 \))
- **sheets**: two eigenvalues below the threshold (\( \lambda_2 \geq \lambda_{\text{th}} \geq \lambda_3 \))
- **voids**: all eigenvalues above the threshold (\( \lambda_3 \geq \lambda_{\text{th}} \)).

The choice of the threshold value for the eigenvalues, \( \lambda_{\text{th}} \), is somewhat arbitrary. Here, we pick \( \lambda_{\text{th}} = 0.1 \), which yields a balanced distribution that agrees qualitatively with a rough visual classification into the four tidal field components (Carlesi et al. 2014).

In Fig. 3, we show the two-dimensional distribution of the ELG galaxy sample along with the mass-selected one. The ELG sample displayed in the figure corresponds to the color-selected galaxies at \( z = 0.8 \), following the DESI \( g - r \) and \( r - z \) cuts. The stellar-mass cut has been made so that the number density of the objects in both samples is the same, at \( n_{\text{gal}} = 9 \times 10^{-4} \text{ [Mpc}/h]^{-3} \) (see Table 2). The stellar-mass selected sample serves as a proxy for an LRG-like sample. In agreement with previous studies, most of the galaxies in the star-forming and mass-selected samples populate filaments. The mass-selected sample is roughly twice as likely to be present in knots and half as likely to be found in sheets. Across the entire volume of the simulation, we find that 4.8%, 34.4%, 48.3%, and 12.5% of the color-selected galaxies live in voids, sheets, filaments, and knots, respectively, whereas the corresponding percentages for the mass-selected sample are 0.7%, 17.8%, 55.5%, and 26.0%. This clearly demonstrates that ELGs have a stronger preference to occupy the less dense regions of the simulation. We also observed that choosing a lower bound on the galaxy number density, i.e. including fewer galaxies, leads to a more pronounced presence in knots in both the mass-selected and ELG samples.

### 3.3 Spatial distribution of ELGs

A large number of observational studies such as GAMA (Kraljic et al. 2018), VIPERS (Malavasi et al. 2017), and COSMOS (Laigle et al. 2018) have found that star-forming and less massive galaxies are more likely to reside in filamentary regions than quiescent and more massive galaxies. Filaments are also believed to assist gas cooling, thus enhancing star-formation processes in galaxies (Vulcani et al. 2020). Similar results have been found in hydrodynamical simulations (e.g. Liao & Gao 2019). These results can be explained as a combination of two effects: accretion in filaments is predominantly smooth (e.g. Kraljic et al. 2019), and their outskirts are very rich (Laigle et al. 2015). Furthermore, the majority of the cold gas, which is needed for star formation to take place, is located in filaments and sheets at \( z \sim 1 \), which provides insight into why ELGs and star-forming galaxies are overwhelmingly found in these regions (Cui et al. 2012, 2014, 2019).

The HOD represents a useful approach for the construction of mock catalogs because it assumes a simple and readily implementable relation between halo mass and occupation number. It is also one of the fundamental statistics used to study the galaxy-halo connection, as it provides information about the average number of galaxies as a function of halo mass.

The HOD is usually broken down into the contribution from central and satellite galaxies. In Fig. 4, we present the SFR- and color-selected ELG-like galaxies for the DESI and eBOSS surveys for the three redshift samples of interest \( z = 0.8 \), \( z = 1.1 \) and \( z = 1.4 \). For each redshift choice, the number density is the same as that stated in Table 2. The thick and thin curves show separately the contribution to the halo occupation from centrals and satellites, respectively, which
Figure 3. Galaxy distribution of DESI color-selected ELGs (in blue) and stellar-mass-selected galaxies (in red) at $z = 0.8$ with a number density of $n_{gal} = 1.0 \times 10^{-3} \ [\text{Mpc}/h]^{-3}$, shown as a horizontal cross section of the TNG300 box ($L_{box} = 205 \text{ Mpc}/h$) of depth $\sim 3 \text{ Mpc}/h$. On the top panel, the galaxies are displayed on top of the smoothed dark matter density field (with a Gaussian smoothing scale of $R_{\text{smooth}} = 1.5 \text{ Mpc}/h$) in gray. The bottom panel shows the galaxies painted over the four traditional tidal environment types – knots in black, filaments in dark gray, sheets in light gray, and voids in white, as defined in Section 3.3. This slice has a thickness of $1.6 \text{ Mpc}/h$. We see that the ELG sample of star-forming galaxies is distributed predominantly in filamentary structures, while the stellar-mass selected galaxies are mostly found in the highest density regions, i.e. the knots. Across the entire volume of the simulation, for the color-selected sample, we find that 4.8%, 34.4%, 48.3%, and 12.5% of the galaxies live in voids, sheets, filaments, and knots, respectively, whereas the analogous percentages for the mass-selected sample are 0.7%, 17.8%, 55.5%, and 26.0%. This clearly demonstrates that ELGs have a stronger preference to inhabit the less dense regions of the simulation.

appears to be distinct from that of a stellar-mass selected sample. The HOD shape of mass-selected centrals is typically similar to a smoothed step function, in which halos gradually transition to being guaranteed to host a central galaxy above a certain mass threshold. Both in our ELG-like HODs as well as in the traditional mass-selected samples, the satellite occupation roughly follows a power law above some halo mass limit.

Each HOD is computed in logarithmic mass bins of width 0.1 dex, and the average occupation number is plotted at the central value of each bin. The galaxies in both our ELG-like samples correspond mainly to blue star-forming galaxies and exclude luminous red galaxies with high stellar mass but low SFR. While the ranking of galaxies in order of their emission-line luminosity is not equivalent to a SFR ranking due to dust attenuation, i.e. the most rapidly star-forming galaxies may not have the brightest emission lines, the additional magnitude cut that we apply (see Section 2.5) makes the two samples extremely congruous. This can be seen in Fig. 4, which demonstrates the striking similarity between the color- and SFR-selected samples (blue and red curves, respectively). The worst agreement between the two is found for the DESI $z = 1.4$ and the eBOSS $z = 0.8$ samples. For the DESI sample, this is likely the case since at higher redshifts, the color-color distribution of galaxies shifts towards the DESI ELG-targeting boundaries, and a large number of red galaxies with relatively lower SFRs are selected (see Fig. 1). Furthermore, the magnitude selection in the $g$-band is picking intrinsically more luminous objects at higher redshifts. This results in an extra bump to the HOD of centrals for more massive halos relative to the SFR-selected sample. Studying the eBOSS color-color-SFR plot (analogously to Fig. 2), we found that our synthetic eBOSS color-selected sample includes a significant number of massive quiescent galaxies, resulting in a larger contribution to the halo occupation of massive halos relative to the SFR-selection choices, which tend to select smaller halos.

A notable feature is that the fraction of halos containing a central falls short of reaching unity in all cases shown, suggesting that a large number of the halos hosting ELG-like galaxies do not actually contain a central since its emission lines are too weak. This has also been inferred in studies involving SFR-selected samples in SAMs (e.g. Contreras et al. 2013, 2019; Gonzalez-Perez et al. 2018) as well as blue galaxies in observations (e.g. Zehavi et al. 2011). In Fig. 5, we demonstrate the cumulative occupation distribution of both satellites and centrals for the DESI color-selected sample (in blue) and the SFR-selected sample (in red) for the three redshifts $z = 0.8, z = 1.1$, and $z = 1.4$. We measure this quantity as the total number of galaxies per mass bin, $(N_g)(dn/dM_{halo})$. This is a useful quantity as it clearly demonstrates that the largest number of galaxies are found in relatively low-mass halos ($M_{halo} \sim 10^{12} \ M_{\odot}/h$), while the most massive halos contribute only a modest fraction to the total number of galaxies. As indicated in Fig. 5 and in Table 2, the total number of selected objects decreases with redshift uniformly across all scales, as their detection through the DESI experiment becomes more challenging. We also see that with increasing redshift, the cumulative occupation distributions shift to higher halo masses for all mass scales, suggesting that the selection cuts become more sensitive to more massive ELGs. This is the case since at earlier times, massive galaxies in TNG300 are less quiescent and their emission lines are stronger, which renders them eligible for our SFR- and color-selection criteria.
Studying the dependence of halo occupation on secondary properties besides halo mass can provide us with useful insights into the effects of assembly bias on galaxy clustering. Previous works have studied in detail the connection between the occupation function and assembly bias for various halo parameters such as environment and concentration (e.g. Zehavi et al. 2018; Contreras et al. 2019). Bose et al. (2019) perform such an analysis performed for IllustrisTNG, finding that at fixed halo mass, there are significant differences between the HOD shape for halos with varying concentration, formation epoch, and local environment.

In Fig. 6, we show what the environment dependence looks like for the color-selected sample of ELG-like galaxies at redshift \( z = 0.8 \) (top panel) obtained after applying the DESI cuts (see Table 1) as well as for the stellar-mass-selected sample (bottom panel) at the same number density (stated in Table 2). We define halo environment here as the Gaussian-smoothed matter density over a scale of \( R_{\text{smooth}} = 1.4 \) Mpc/h. The smoothing scale is chosen to be in the transition regime between the one- and two-halo terms, making it sensitive to cluster dynamics (e.g. accretion and merger events) on the outskirts of large halos. The black curves in both panels show the HOD for the full sample, while the blue and red curves correspond to the average occupation numbers of halos living in the 20% highest and 20% lowest density environments, respectively. In both cases, we see that the environment plays a significant role in determining the number of galaxies contained in a halo, although the effects are more pronounced for halos of lower mass, while the environment plays a significant role in determining the number of galaxies contained in a halo, although the effects are more pronounced for halos of lower mass, although their numbers are much more limited. Almost uniformly, halos living in denser environments tend to host a larger number of both central and satellite
ELGs. It is intriguing to note that there is a slight trend indicating an inversion of that relation for the higher mass halo hosts, so that low-density environments seem to be marginally more conducive to hosting central ELGs.

3.5 The clustering of ELGs

The spatial two-point correlation function, $\xi(r)$, measures the excess probability of finding a pair of galaxies at a given separation, $r$, with respect to a random distribution. It is a central tool in cosmology for studying the three-dimensional distribution of objects and thus constraining cosmological parameters. We compute the two-point correlation function of the galaxy samples using the Landy-Szalay estimator (Landy & Szalay 1993):

$$\xi_{LS}(r) = \frac{DD(r)}{RR(r)} - 1$$  \hspace{1cm} (2)

via the package CORRFUNC (Sinha & Garrison 2020) assuming periodic boundary conditions. We estimate the uncertainties of the correlation function using jackknife resampling (Norberg et al. 2009), dividing the simulation volume into 27 equally sized boxes and adopting the standard equations:

$$\bar{\xi}(r) = \frac{1}{n} \sum_{i=1}^{n} \xi_i(r)$$ \hspace{1cm} (3)

$$\text{Var}[\xi(r)] = \frac{n-1}{n} \sum_{i=1}^{n} (\xi_i(r) - \bar{\xi}(r))^2,$$ \hspace{1cm} (4)

to calculate the mean and jackknife errors of the correlation functions, where $n = 27$ and $\bar{\xi}(r)$ is the correlation function value at distance $r$ for subsample $i$ (i.e. excluding the galaxies residing within volume element $i$ in the correlation function computation).

In Fig. 7, we show the clustering of the ELG-like samples using the
Figure 7. Clustering of the color- (in blue) and SFR- (in red) selected ELGs. The color selections are done using the DESI (top left and bottom panels) and eBOSS proposed cuts (top right panel), detailed in Table 1, while the procedure for obtaining the SFR sample is laid out in Section 2.5. In each of the four plots, the upper section shows the two-point correlation function, $\xi(r)r^2$, while the lower section shows the fractional difference in the clustering relative to the SFR-selected objects. The eBOSS sample presented uses the $z = 0.8$ TNG galaxies, while the samples for DESI are taken at $z = 0.8$, $z = 1.1$, and $z = 1.4$. We see that the agreement between the color- and SFR-selected samples is best for the DESI $z = 0.8$ sample and worsens with redshift. The largest discrepancies are seen on small scales ($\sim 1 \text{ Mpc}/h$). Significant differences on large scales of about 50% can be observed at $z = 1.4$, where the color-color distribution of galaxies has shifted towards the DESI ELG-targeting boundaries and a larger number of red quiescent galaxies are selected (see Fig. 1 and Fig. 4).

various selection criteria outlined in Section 2. In blue, we show the color-selected samples using the DESI (top left and bottom panels) and eBOSS (top right) cuts (see Table 1), while in red we show the SFR-selected samples at the same galaxy number density (see Section 2.5 for a description and Table 2 stating the number densities). The top panels show the redshift samples at $z = 0.8$ and the bottom panels correspond to $z = 1.1$ and $z = 1.4$ (left and right, respectively). Each panel displays the two-point correlation function $\xi(r)r^2$ and beneath it the ratio of the color-selected sample with respect to the SFR-selected one.

We see that the agreement between the two ELG-selection strategies (i.e. based on color cuts and SFR cuts) is very good for all cases,
although the deviations are more apparent for the higher redshift samples. For the DESI \( z = 0.8 \) panel, the largest discrepancies appear on small scales, but the difference is consistent with zero on large scales. The top right panel demonstrates that the eBOSS ELGs are biased high compared with the SFR-selected sample. The behavior in the bottom right panel, which displays the \( z = 1.4 \) sample, is similar. These findings can be explained by considering the right panels of Fig. 4, which show that the color-selected samples find slightly more centrals than the SFR-selected ones (and also fewer satellites since the number density is constant between the two). Fig. 1 hints at an explanation of this effect: with increasing redshift the galaxies color-color distribution moves towards the ELG target selection boundaries, allowing a larger number of red quiescent galaxies to enter the sample. As a result, the clustering on large scales increases since the presence of a larger number of centrals contributes to the two-halo term. Conversely, a larger number of satellites enhances the one-halo term.

### 3.5.1 Environment dependence of ELG clustering

In Fig. 8, we show the dependence of the galaxy clustering on environment. We split the galaxies into belonging to high- and low-density environments using a similar approach to that adopted in Section 3.4.1 for obtaining an HOD augmented with an environment parameter. For each halo mass bin of size \( \Delta \log(M_{\text{halo}}) = 0.1 \) dex, we have chosen the top and bottom 20% halos ordered by their environment factor (as defined in Section 3.4.1). We then compute the two-point clustering of the galaxies living inside them. We display these results in Fig. 8 for the \( z = 0.8 \) redshift sample, as it hosts a larger number of objects (see Table 2). As before, we define halo environment as the Gaussian-smoothed matter density over a scale of \( R_{\text{smooth}} = 1.4 \) Mpc/h.

The two panels show the clustering, \( \xi(r) r^2 \), using the DESI and eBOSS selection criteria, respectively (see Table 1). The clustering of the low-environment galaxies is denoted by a dotted line, while that of the high-environment ones by a solid line. We see that the galaxies living in denser environments are more strongly clustered than their low-density counterparts, suggesting that at fixed mass, clustering is dependent on additional assembly bias properties pertaining to the halo environment. Indeed, recognition of the importance of this effect has motivated a number of recent “augmented” HOD models that, in addition to halo mass, also incorporate secondary and tertiary parameters in the galaxy-halo connection, such as environment and concentration assembly bias (e.g. Hadzhiyska et al. 2020b; Xu et al. 2020a; Yuan et al. 2020).

### 3.6 Bias and correlation coefficient

Most of the cosmological information of the matter distribution is encoded in the power spectrum (or correlation function) of the matter density fluctuations as a function of scale and redshift. However, galaxies are not perfect tracers of the underlying mass distribution, and thus, it is important to understand the relationship between the large-scale distribution of matter and that of galaxies. The galaxy auto-correlation function, \( \xi_{gg}(r) \) is related to the matter correlation function, \( \xi_{mm}(r) \), through the real-space galaxy bias, \( b \), in the following way:

\[
\xi_{gg}(r) = b^2(r) \xi_{mm}(r).
\]  

(5)

One can furthermore study the bias through the galaxy-matter cross-correlation function, \( \xi_{gm}(r) \), which can be related to the matter two-point correlation function through \( \tilde{b} \) and the real-space cross-correlation coefficient between matter and galaxy fluctuations, \( \tilde{\rho} \) (Hayashi & White 2008; Desjacques et al. 2018):

\[
\xi_{gm}(r) = \tilde{b}(r) \tilde{\rho}(r) \xi_{mm}(r)
\]  

(6)

where the galaxy bias is:

\[
\tilde{b}(r) = \left( \frac{\xi_{gg}(r)}{\xi_{mm}(r)} \right)^{1/2}
\]  

(7)
and the correlation coefficient is:

$$\tilde{r}(r) = \frac{\xi_{gm}(r)}{[\xi_{gg}(r) \xi_{mm}(r)]^{1/2}}.$$  

The equations above are general and may be taken as definitions of the scale-dependent galaxy bias $b(r)$ and cross-correlation coefficient $\tilde{r}(r)$. We note that the quantity $\tilde{r}(r)$ in real space is not constrained to be less than or equal to one. However, one expects $\tilde{r}(r)$ to approach unity on large scales, where the observed correlation should be sourced from the gravity field of the total matter.

In Fig. 9, we demonstrate what these look like for the color-selected sample using the DESI ELG targeting criteria (see Table 1), the SFR-selected sample (see Section 2.5 for a detailed description of the selection procedure), and a mass-selected sample matching the galaxy number density of the other two (stated in Table 2). The TNG redshift sample used in this figure corresponds to $z = 0.8$. From the top plot, we can infer that the galaxy bias roughly approaches a constant on large scales for the SFR- and color-selected samples, where $\tilde{r}(r) \approx 1.4$, while the bias of the mass-selected sample is much higher, $\tilde{b}(r) \approx 2.1$. This difference in the bias of the two samples is most likely a consequence of the fact that the most massive galaxies live predominantly in the densest regions (knots, see Fig. 3), while the ELG-like galaxies are more likely to be found in filamentary regions, which are less strongly biased (see e.g. Zentner 2007, for a review on Excursion Set Theory). We find the average bias on large scales ($1 \text{Mpc}/h < r < 20 \text{Mpc}/h$) for the other two redshift samples to be $\tilde{b}(r) \approx 2.3$, 1.5, and 1.5 for the mass-, SFR- and color-selected samples, respectively, at $z = 1.1$, and $\tilde{b}(r) \approx 2.9$, 1.7, and 2.0 for the mass-, SFR- and color-selected samples, respectively, at $z = 1.4$. The fact that on large scales the galaxy bias tends to a constant value suggests we can use the linear bias approximation to infer the underlying matter distribution (Peebles 1980; Mo & White 1996; Mandelbaum et al. 2013). For the linear bias approximation to be valid, the cross-correlation coefficient needs also be scale-independent on large scales, approaching unity (Baldauf et al. 2010). We can see from the lower panels that this is indeed the case and $\tilde{r}(r) \approx 1$ on large scales, implying that as long as one considers large-scale galaxy clustering on scales much greater than 1 Mpc, the observed correlation should be sourced from the gravity field of the total matter.

However, it is important to note that while on large scales the linear bias approximation appears to be viable, it certainly breaks down on smaller scales ($\sim 1 \text{Mpc}/h$). This has important implications for analyses using mock catalogs created via phenomenological approaches such as the HOD framework. The small-scale signal encodes a lot of information about cosmological parameters such as $\Omega_m$ and $\sigma_8$. In addition, modeling these scales correctly is a key requirement for weak lensing shear analysis. Finally, the small-scale data provide an important window for probing different DM models and understanding the effects of baryonic physics. It is reassuring to see that the galaxy bias is in a very good agreement between the two ELG-like samples (red and blue) in Fig. 9. Furthermore, the cross-correlation coefficients derived for the ELG-like samples exhibit a very similar behavior across all scales, suggesting that the galaxy-matter cross correlation relates similarly to the galaxy and matter clustering regardless of the underlying population model. The minimum point of the cross-correlation coefficient is around ($r \sim 1 \text{Mpc}/h$), which corresponds to the outskirts of halos, between the one- and two-halo terms, where the dark matter outweighs the luminous component, which has sunk to the halo center, as it radiates gas and dissipates energy. Note that the mass-selected galaxies tend to be larger and therefore the border between the one- and two-halo terms is pushed back to slightly larger scales ($r \sim 2 \text{Mpc}/h$).

**Figure 9.** Bias and correlation coefficient at $z = 0.8$ for the following three samples: one selected based on a stellar-mass cut (shown in gray solid), one selected using the proposed DESI cuts (shown in blue solid and described in Section 2.1), and one selected using the SFR cuts (shown in red solid and described in Section 2.5). Top panel shows the galaxy bias, $\tilde{b}(r)$, defined as the square root of the ratio of the galaxy and matter auto-correlation functions, while the bottom panel shows the real-space correlation coefficient, $\tilde{r}(r)$. The galaxy bias goes to a constant on large scales, and the correlation coefficient approaches 1, suggesting that a linear bias approximation on scales beyond 10 Mpc$/h$ is appropriate. We see that the agreement between the galaxy bias of the SFR-selected sample and that of the ELG sample is excellent, as expected from the two-point clustering plots, and their real-space cross-correlation coefficients are also compatible with each other. On the other hand, the mass-selected sample has a substantially higher galaxy bias ($\tilde{b}(r) \approx 2.1$) than the ELG-like samples ($\tilde{b}(r) \approx 1.4$), and the cross-correlation coefficient between galaxies and matter is also slightly higher.

### 4 MOCK CATALOGS

In this section, we provide motivation for an HOD population mechanism that incorporates environment by measuring the galaxy assembly bias of the DESI ELG-like sample as well as the SFR- and mass-selected ones. We then analyze the satellite distributions of the DESI ELGs and compare it with that of the subhalos rank-ordered by 6 different subhalo properties. Finally, we propose a detailed procedure for obtaining a mock catalog incorporating an environmental dependence and show its success in recovering the large-scale clustering of the various samples examined in this work.
4.1 Galaxy assembly bias

A standard way for assessing the amount of assembly bias of a given galaxy sample is to compare the two-point correlation function of the sample with that of a shuffled sample, where the galaxy occupation numbers of halos are randomly reassigned to halos belonging to the same mass bin (Croton et al. 2007). The goal of this shuffling procedure is to erase the link between the halo occupation and assembly history, thus eliminating the dependence on any secondary properties other than halo mass. Since in this section we are only interested in measuring the large-scale galaxy assembly bias, we do not need to adopt a realistic prescription for populating halos on small (intra-halo) scales. Instead, when we transfer galaxies from their original halo into their newly assigned host, we move their locations in a way which maintains their relative positions with respect to the halo center (defined as the spatial position of the particle with the minimum gravitational potential energy). When shuffled in this way, the contribution of the one-halo term to the auto-correlation function is preserved. The size of the halo mass bins within which we shuffle the halo occupations is $\Delta \log (M_{\text{halo}}) = 0.1 \text{ dex}$.

In Fig. 10, we present the results of performing the shuffling procedure applied to three galaxy samples of interest (preserving the relative positions of the galaxies with respect to the halo centers): a DESI-selected ELG sample (see Section 2.1), an SFR-selected sample (see Section 2.5), and a mass-selected sample, where we apply a stellar mass cut to the galaxies chosen in a way so that the number of galaxies in all three cases is equal. Here we apply this analysis to $z = 0.8$, where we have the largest expected number of ELGs (see Table 2). One can also notice that the clustering ratio of the mass-selected sample is consistent with 1 until slightly larger scales than for the ELG-like samples (shown in blue and red). The reason is that the mass-selected galaxies tend to live in larger halos, so the transition between the one- and two-halo terms happens at larger radial distance ($r \sim 1 \text{ Mpc}/h$). In dotted lines, we show the average ratio in the range of $2 - 10 \text{ Mpc}/h$. We find that the deviation of the stellar mass sample is the most substantial, at $\sim 10\%$, while that of the other two samples is within $5\%$. This suggests that while assembly bias imparts a smaller effect on ELGs, careful modeling is still necessary to achieve the required amounts of precision.

4.2 Satellite distribution

One of the key components of modeling the galaxy-halo connection is deciding upon an algorithm to internally assign galaxies in halos, i.e. once the number of centrals and satellites has been picked, one needs to determine how the satellites are distributed spatially within their host halos. This is vital for recovering accurate small-scale clustering on scales of $\leq 1 \text{ Mpc}/h$ (the one-halo term).

Typically, satellite positions are assigned by one of three commonly-adopted schemes: (i) assuming that satellites trace the dark-matter profile of the halo, to which one typically fits an NFW curve and mimics its shape through the satellites; (ii) placing satellites on a randomly-selected dark matter particle; (iii) assuming they follow the radial distribution of the dark-matter-only subhalos (typically adopting an abundance matching technique conditioned on some subhalo property). In hydrodynamical simulations, the knowledge of the “true” positions of the galaxies is provided since the simulations are evolved self-consistently, accounting for baryonic physics. We can therefore compare each of these methods before deciding upon the best strategy to populate the one-halo term. For the abundance matching step, we select the locations of satellite galaxies according to the following set of subhalo properties:

- $V_{\text{max}}$, the maximum circular velocity of the subhalo at the final time ($z = 0.8$),
- $V_{\text{peak}}$, the maximum circular velocity the subhalo reaches throughout its history,
- $V_{\text{disp}}$, the dispersion velocity of the subhalo,
- $M_{\text{SUBFIND}}$, the total mass of all bound particles in the subhalo as identified by SUBFIND (Springel et al. 2001),
- $M_{\text{max}}$, the total mass (of all components) of the subhalo contained within the radius at which it attains its maximum circular velocity,
- $M_{\text{twice}}$, the total mass (of all components) of the subhalo contained within twice the stellar halfmass radius.

In the two left panels of Fig. 11, we present the radial profiles of the satellite ELGs found by applying the DESI cuts to the $z = 0.8$ snapshot of the TNG300. In particular, we show the radial number density of ELG satellites and compare it with the radial number density obtained by abundance matching the subhalos in the full-physics (top left) and dark-matter-only (bottom left) simulations. For reference, we also include a curve (in dashed black) that shows the density profiles of the dark matter particles residing in all halos hosting ELG-like objects.

The abundance matching for the subhalos in full-physics is performed by rank-ordering the subhalos in each halo by one of the six properties listed above and selecting the top $N_s$ entries, where $N_s$ corresponds to the number of ELG satellites in the halo. For the dark-matter-only case, we first identify the ELG hosting halos in the full-physics run and their counterparts in the dark-matter-only simulations.
The radial distance is measured in units of $R_{200m}$, the halo radius at 200 times the mean density. For reference, we also show the number density profiles of the dark matter particles in dashed black. Right panels: Clustering ratio of samples populated by rank-ordering the six subhalo properties with respect to the “true” ELG positions. The shaded regions denote the 1σ errors. The top two panels refer to the full-physics run of TNG300 (FP), while the bottom panels refer to the dark-matter-only (DMO) run of the same box. In the top left panel, we see that $V_{\text{max}}$ matches the satellite distribution of ELGs best over all scales. The other 5 parameters diverge on smaller scales ($r/R_{200m} \leq 0.3$) with $V_{\text{peak}}$ and $V_{\text{disp}}$ being the next best-performing parameters. However, these small-scale differences have little effect on the clustering, which we study on scales of $10^{-1} \text{Mpc}/h < r < 10 \text{Mpc}/h$. We also see that the dark matter profile (dashed black) follows the ELG distribution quite well. The top right panel demonstrates that the full-physics ELG clustering is matched better (within ~15%) by $V_{\text{max}}$, $V_{\text{disp}}$, and $M_{\text{twice}}$, compared with the other three parameters. On large scales, the clustering of all samples agrees with that of the ELGs. This is as expected since the choice of a mechanism for populating the one-halo term should not affect the two-halo term clustering. In the bottom left panel, we have illustrated that for all parameters, the satellite distributions in the dark-matter-only simulation tend to flatten on small scales ($r/R_{200m} \leq 10^{-1}$) and are unable to provide a fit to the number density profile of DESI ELGs in that regime. This is least the case for the $V_{\text{peak}}$ parameter followed by $V_{\text{disp}}$ and $V_{\text{max}}$, which appear to be steeper than the mass-based parameters on these scales. On the scale of interest for the clustering comparison ($r > 10^{-1} \text{Mpc}/h$), the parameters that exhibit the most evident deviation are the mass-based ones ($M_{\text{SUBFIND}}$, $M_{\text{max}}$, $M_{\text{twice}}$), while the other three behave similarly. Similarly to the full-physics case, the dark matter profile (dashed black) is in close agreement with the ELG distribution. In the bottom right panel, we see that the dark-matter-only subhalo parameter displaying the smallest discrepancy from the ELG clustering is $V_{\text{peak}}$ followed by $V_{\text{disp}}$ and $V_{\text{max}}$. It is interesting to notice that in all cases, the small-scale clustering is slightly overpredicted when placing the galaxies in a halo according to a rank-ordered list.

Figure 11. Left panels: Number density profile as a function of distance from the halo center for the DESI color-selected ELGs at $z = 0.8$ (see Table 1) and the subhalos selected based on several velocity- and mass-based properties: $V_{\text{max}}$, $V_{\text{peak}}$, $V_{\text{disp}}$, $M_{\text{SUBFIND}}$, $M_{\text{max}}$, and $M_{\text{twice}}$ (see definitions in Section 4.2). The radial distance is measured in units of $R_{200m}$, the halo radius at 200 times the mean density. For reference, we also show the number density profiles of the dark matter particles in dashed black. Right panels: Clustering ratio of samples populated by rank-ordering the six subhalo properties with respect to the “true” ELG positions. The shaded regions denote the 1σ errors. The top two panels refer to the full-physics run of TNG300 (FP), while the bottom panels refer to the dark-matter-only (DMO) run of the same box. In the top left panel, we see that $V_{\text{max}}$ matches the satellite distribution of ELGs best over all scales. The other 5 parameters diverge on smaller scales ($r/R_{200m} \leq 0.3$) with $V_{\text{peak}}$ and $V_{\text{disp}}$ being the next best-performing parameters. However, these small-scale differences have little effect on the clustering, which we study on scales of $10^{-1} \text{Mpc}/h < r < 10 \text{Mpc}/h$. We also see that the dark matter profile (dashed black) follows the ELG distribution quite well. The top right panel demonstrates that the full-physics ELG clustering is matched better (within ~15%) by $V_{\text{max}}$, $V_{\text{disp}}$, and $M_{\text{twice}}$, compared with the other three parameters. On large scales, the clustering of all samples agrees with that of the ELGs. This is as expected since the choice of a mechanism for populating the one-halo term should not affect the two-halo term clustering. In the bottom left panel, we have illustrated that for all parameters, the satellite distributions in the dark-matter-only simulation tend to flatten on small scales ($r/R_{200m} \leq 10^{-1}$) and are unable to provide a fit to the number density profile of DESI ELGs in that regime. This is least the case for the $V_{\text{peak}}$ parameter followed by $V_{\text{disp}}$ and $V_{\text{max}}$, which appear to be steeper than the mass-based parameters on these scales. On the scale of interest for the clustering comparison ($r > 10^{-1} \text{Mpc}/h$), the parameters that exhibit the most evident deviation are the mass-based ones ($M_{\text{SUBFIND}}$, $M_{\text{max}}$, $M_{\text{twice}}$), while the other three behave similarly. Similarly to the full-physics case, the dark matter profile (dashed black) is in close agreement with the ELG distribution. In the bottom right panel, we see that the dark-matter-only subhalo parameter displaying the smallest discrepancy from the ELG clustering is $V_{\text{peak}}$ followed by $V_{\text{disp}}$ and $V_{\text{max}}$. It is interesting to notice that in all cases, the small-scale clustering is slightly overpredicted when placing the galaxies in a halo according to a rank-ordered list.
simulation. Once we have ordered the subhalos by a particular property, as is typically done, we add a scatter in logarithmic space for the velocity-based properties of $\Delta \log(V) = 0.1$ and none for the mass-based ones. Finally, we again select the top $N_s$ subhalos in the dark-matter-only halo. The radial distances in the number density profiles are measured in units of $R_{200m}$, the halo radius containing 200 times the mean density of the Universe. The most significant visual correspondence of the satellite distributions on the left panels with the one-halo term on the right panels can be seen around $r/R_{200m} \approx 1$, where we can identify a direct correlation between the density profiles and the clustering ratios. This observation is in agreement with the intuitive expectation that if the radial distribution of object is matched well, the one-halo term would also be consistent (see Zheng & Weinberg 2007, for details of the correlation function calculation).

From the left panels of Fig. 11, we see that the “true” satellite distribution is best traced by the full-physics subhalos ordered by $V_{\text{max}}$ (on all scales) and also by the dark-matter-only subhalos ordered by $V_{\text{peak}}$ and $V_{\text{max}}$. The curves in the dark-matter-only case (bottom left panel) are noticeably flatter than the full-physics ones with the three velocity-based parameters appearing to visually fit the ELG radial distributions best on scales of $r/R_{200m} < 1$. An important finding is also that the dark-matter profiles visually provide a very good match to the ELG distribution. This implies that mock catalogs that “paint” ELGs on top of particles may provide a good approximation to the true distribution of galaxies. We further study this in the next section, where we delve into the details of creating a realistic mock catalog.

To further test which abundance matching property yields a one-halo term that is consistent with the true ELG satellites, we compute the auto-correlation function of the “true” ELG sample and that of a sample where we have preserved the occupation numbers in each halo but have “painted” the galaxies on top of the subhalos ranked by one of the six properties. This is shown in the right panels of Fig. 11, which again correspond to the full-physics and dark-matter-only runs (top and bottom panels, respectively). The top right panel demonstrates that the one-halo term (i.e. $r \leq 1$ Mpc$/h$) is better matched when using one of three parameters: $V_{\text{max}}, V_{\text{disp}}$, and $M_{\text{twice}}$, compared with the rest of the parameters. This result corroborates the findings of the number density profiles.

In the bottom right panel, we can see that the parameter that performs best is $V_{\text{peak}}$ followed by $V_{\text{disp}}$ and $V_{\text{max}}$. It is interesting to notice that all 6 parameters slightly overpredict the one-halo term contribution. On large scales (i.e. $r \geq 1$ Mpc$/h$), the clustering of all samples and in both runs agrees with that of the ELGs as expected, since the choice of a mechanism for populating the one-halo term should not affect the two-halo term clustering. There are noticeable differences between the subhalo distributions in the full-physics and dark-matter-only runs, which are attributable to the differences in the physical processes governing them (e.g., stellar and AGN feedback, gas cooling, etc. in the full-physics TNG box; see Hadzhiyska et al. 2020a, for a discussion).

The analysis in this section provide a solid motivation for adopting a satellite population technique based on rank-ordered lists (by a particular property) of the subhalos or by “painting” galaxies onto particles in the halo, as we have seen that the dark matter profile follows closely the ELG radial distribution. In particular, when creating mock catalogs, (see details of our prescription in the next section), we apply the abundance-matching model to assign the locations of satellites within halos based on either the subhalo property $V_{\text{max}}$, as it performs well in matching the full-physics radial profile and auto-correlation of the ELGs on scales of $r > 1$ Mpc$/h$, or their dark-matter distribution, for which we randomly select particles in the halo.

### 4.3 Constructing HOD catalogs

The most commonly-adopted formalism to building mock galaxy catalogs is the HOD. In this section, we provide a prescription for implementing environment assembly bias effects into mock catalogs utilizing the HOD method and test its efficacy by comparing the derived catalogs with the “true” TNG300 galaxies. The purpose of this is to demonstrate that indeed incorporating halo environmental properties can help recovered the observed clustering in hydro simulations. The approach that we take utilizes halo occupation information as a function of both halo mass and environment as measured directly in the simulation and follows a similar procedure as that outlined in Xu et al. (2020b) and Contreras et al. (2020). The benefit of this method is that it is parameter-free and remains agnostic about the particular shape of the HOD, which is advantageous for any analyses working with non-standard occupation distributions. As illustrated in Section 3.4, ELGs and star-forming galaxies do not follow the traditional steadily increasing HOD shape and thus require specialized modeling.

The steps for obtaining such a mock catalog are outlined below:

1. We split the halos belonging to each mass bin (of size $\Delta \log(M_{\text{halo}}) = 0.1$ dex) into 5 bins based on their environment parameter (ranging from the 20% halos in the bin belonging to the least dense environments to the 20% belonging to the most dense environments), where we define environment as the Gaussian-smoothed dark-matter density over a scale of $R_{\text{smooth}} = 1.4$ Mpc$/h$.
2. Within each environment bin, we measure the average number of centrals and the average number of satellites and store the information in the form of a two-dimensional array per mass bin per environment bin.
3. To construct the mock catalog, for each halo in the dark-matter-only catalog (TNG300-1-Dark), we ascribe it the appropriate number of central and satellite galaxies, drawing from a binomial and a Poisson distribution, respectively, with probability and mean determined by the particular mass bin and environment bin the halo belongs to.
4. We populate the halos on small scales by either a) assigning the new galaxy positions to the locations of the top subhalos rank ordered by their $V_{\text{max}}$ with a scatter of $\log(V_{\text{max}}) = 0.1$. This choice is informed by our finding that the number density profile of ELGs is traced well by that of the subhalos with the highest values of $V_{\text{max}}$ (see Fig. 11); b) “painting” galaxies on top of randomly selected particles in the halo. This approach is motivated by the left panels of Fig. 11, where we found very good agreement between the ELG radial distribution and that of the dark matter particles in the halo, and is particularly useful in cases where we do not have subhalo catalog information (which is becoming increasingly expensive to store with current simulation volumes).

We do not require that every halo that has galaxies hosts a central galaxy since the ELG selection criteria disqualify quiescent large galaxies. Working with non-standard occupation distributions. As illustrated in Section 3.4, ELGs and star-forming galaxies do not follow the traditional steadily increasing HOD shape and thus require specialized modeling.

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In Fig. 12, we show the ratio of the clustering between our mock catalogs and the “true” TNG300 galaxies at $z = 0.8$ for three scenarios. The top panel shows the mock catalog ratios obtained by using a rank-ordered list of the subhalos based on $V_{\text{max}}$ to assign the new galaxy locations, whereas in the bottom panel, galaxies are “painted” on top of randomly selected particles in the halo (also see the left panels of Fig. 11). We show that both methods produce congruent
results, which is useful for creating mock catalogs when subhalo data are not available or not trusted (e.g., in the proximity of large clusters). In each of these scenarios, we use the two-dimensional HOD array derived from the corresponding “true” galaxy population to obtain the mock catalogs. For the first case, we compare the mock catalog with the TNG300 galaxies selected by applying the color selection criteria from the DESI survey. We observe that the small discrepancy between the “true” and shuffled clustering noted in Fig. 12 has been reconciled after supplying the HOD model with knowledge about the halo environment. Next, we compare the sample selected by applying a SFR cut (as described in Section 2.5) with the mock catalog of that SFR-selected sample, finding that the agreement between the two is again reasonable and within the expected error margins of near-future galaxy surveys. For the third case, we select galaxies by applying a stellar mass cut chosen so as to keep the number of galaxies equal to that in the other two cases (see Table 2). We demonstrate that the mock catalog for that sample recovers successfully the clustering of the “true” galaxies on large scales, significantly reducing the 10% differences found when employing the mass-only HOD formalism seen in Fig. 10.

5 DISCUSSION & CONCLUSIONS

Current and future cosmological surveys are actively targeting luminous star-forming ELGs. In this paper, we have studied how they populate the dark matter halos formed inside the cosmic web structure using the state-of-the-art hydrodynamical simulation IllustrisTNG. We model the star-forming ELGs by imposing cuts in apparent magnitude and color-color space in an attempt to mimic the galaxy surveys eBOSS and DESI (see Table 1). An additional sample is obtained by applying both a magnitude cut as well as a star-formation rate (SFR) threshold, which we have similarly designed to isolate blue star-forming galaxies such as those targeted by the surveys under consideration (see Fig. 2). We have studied the spatial distribution of the DESI-selected ELG sample at \(z = 0.8\) and compared it with a stellar-mass-selected sample (see Fig. 3). We have demonstrated that ELGs are likely to populate filamentary and sheet regions, defined via the traditional tidal environment classification scheme (i.e. using the eigenvalues of the tidal field to split the cosmic web into peak, filaments, sheets, and voids). On the other hand, the galaxies in the mass-selected sample tend to reside in the highest density regions (i.e. peaks, filaments).

Furthermore, we have shown that both the SFR- and color-selected samples behave very similarly when compared with each other in terms of their HODs and cumulative occupation distributions (see Fig. 4 and Fig. 5). As found by previous studies, we report that the occupation fraction of central ELGs does not reach 100% for any mass scale, but rather peaks around 10% at low masses (\(\log(M_{\text{halo}}) \approx 12\)). Central ELGs tend not to reside in more massive halos, while the satellite contribution follows the typical power law curve seen in traditional stellar-mass selected samples.

We also compare the auto-correlation functions for the color- and SFR-selected samples and find that their large-scale clustering is in good agreement, with the largest differences occurring for the eBOSS redshift sample at \(z = 0.8\) and the DESI redshift sample at \(z = 1.4\), both of which have a lower number of objects (see Fig. 7 and Table 2). The auto-correlation function on small scales exhibits more notable discrepancy particularly for the \(z = 0.8\) and \(z = 1.1\) DESI samples. We then study their relative clustering to a sample with shuffled halo occupations, which mimics a mass-only HOD population model and find that it affects ELG-like samples at about 4% (see Fig. 10). On the other hand, for mass-selected samples, the deviation is around \(\sim 10\)% in agreement with previous works (e.g. Hadzhiyska et al. 2020b).

We also study the large-scale bias and cross-correlation coefficient of model ELGs and find it to be close to \(b(r) \approx 1.4\) and roughly constant at \(z = 0.8\) (see Fig. 9), while the cross-correlation coefficient \(\hat{r}(r)\) approaches unity around \(r \sim 10\) Mpc/h. This suggests that on these scales, baryon physics does not affect the galaxy distribu-

Figure 12. Clustering ratio between the two-dimensional HOD approach augmented with environment information described in Section 4.3 and the “true” galaxies for the following three samples: one selected based on a stellar-mass cut (shown in gray solid), one selected using the proposed DESI cuts (shown in blue solid), and one selected using the SFR cuts (shown in red solid). The top panel shows a mock catalog ratio obtained by using a rank-ordered list of the subhalos based on \(V_{\text{max}}\) to assign the new galaxy locations, whereas in the bottom panel, galaxies are “painted” on top of randomly selected particles in the halo (also see the left panels of Fig. 11). We show that both methods produce congruent results, which is useful for creating mock catalogs when subhalo data are not available. In dotted lines, we show the large-scale values for the three cases averaged between \(r = 0.8\) Mpc/h (\(r = 2\) Mpc/h for the mass-selected sample) and 10 Mpc/h. Compared with Fig. 10, we see that the discrepancies with the “true” distributions are now smaller, which demonstrates the efficacy of environment as an assembly bias parameter. On average they deviate to within \(\sim 1\)% for the color-selected ELGs and the mass-selected samples, which is a much more palatable systematic effect to marginalize over in future mock challenges.
tion, and the dominant source that governs the galaxy distribution is gravity. We also find that the ELG-like samples exhibit a much weaker bias compared with the mass-selected one. This result can be attributed to the fact that the mass-selected galaxies preferably populated the higher density regions, which are also more strongly biased (see Section 3.6 for a discussion).

Many recent analyses have found that a halo parameter that accounts for the majority of galaxy assembly bias effects is halo environment. It has been shown that including it as an essential ingredient in mock recipes for mass-selected samples is of utmost importance in order to model galaxy clustering to a sufficiently high level of accuracy. In this work, we define environment by applying a Gaussian smoothing kernel to the dark matter field with a smoothing scale of $R_{\text{smooth}} = 1.4$ Mpc$/h$. By splitting the halos in each mass bin into those occupying low and high density regions, we have demonstrated (see Fig. 6) that the occupation function is highly dependent on environment both for the mass-selected sample as well as for our DESI ELG-like sample, clearly showing that high-environment halos are more likely to be hosting ELGs particularly in the low halo-mass regime. We also study the dependence of galaxy clustering on environment, which is presented in Fig. 8, and find that indeed galaxies living in high-environment halos are more clustered than their low-environment counterparts at fixed halo mass.

Implementing secondary properties into our HOD prescription affects the two-halo term, as it changes the number of galaxies within a halo at fixed halo mass and thus the pair counts, but it cannot inform us of sub-megaparsec processes. To construct more accurate population models devoid of substantial inherent biases, it is also important to probe the galaxy-halo relationship in the one-halo regime. In Fig. 11, we explore several different subhalo properties ($V_{\text{max}}$, $V_{\text{peak}}$, $V_{\text{disp}}$, $M_{\text{subfind}}$, $M_{\text{max}}$, and $M_{\text{wise}}$) to use as proxies for determining the placement of ELG satellites in both the full-physics and dark-matter-only runs of the TNG300 simulation box. In addition, we also display the density profile of halos using dark matter particles and find that this provides a reasonably good fit to the ELG radial distribution. For the full-physics run, we find that all parameters perform reasonably well with $V_{\text{max}}$, $V_{\text{disp}}$, and $M_{\text{wise}}$ exhibiting the smallest amounts of discrepancy for the clustering study (top right panel).

On the other hand, in the dark-matter-only simulation the satellite distribution displays a lot more sizeable differences particularly on small scales, where we see a notable flattening of the curves, which are attributable to the differences in the dynamics governing the two runs. Nevertheless, we find that after adding a scatter of $\log(V) = 0.1$ to the velocity-based parameters when performing the rank-ordering procedure, we can recover the clustering better. The parameters providing the best match are the velocity-based ones ($V_{\text{peak}}$, $V_{\text{disp}}$, and $V_{\text{max}}$). In our recipe for constructing mock catalogs, we adopt $V_{\text{max}}$ as well as a random particle selection method, which is useful in cases where we do not have reliable subhalo information.

Finally, we have applied a two-dimensional approach (similar to Xu et al. 2020b; Contreras et al. 2020) for incorporating halo environment effects into HOD recipes and have shown that it manages the large number of galaxies contained in these larger volume runs, such simulations will enable us to capture the large-scale behavior even better by possibly introducing a multidimensional approach to the HOD model.

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DATA AVAILABILITY

The IllustrisTNG data is publicly available at www.tng-project.org, while the scripts used in this project are readily available upon request.

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