

The DESI One-Percent Survey: Modelling the clustering and halo occupation of all four DESI tracers with UCHUU

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ABSTRACT

We present results from a set of high-fidelity simulated lightcones for the DESI One-Percent Survey, created from the UCHUU simulation. This $8 h^{-3} \text{Gpc}^3$ N -body simulation comprises 2.1 trillion particles and provides high-resolution dark matter (sub)haloes in the framework of the Planck base- Λ CDM cosmology. Employing the subhalo abundance matching (SHAM) technique, we populate the UCHUU (sub)haloes with all four DESI tracers (BGS, LRG, ELG and QSO) to $z = 2.1$. Our method accounts for redshift evolution as well as the clustering dependence on luminosity and stellar mass. The two-point clustering statistics of the DESI One-Percent Survey align reasonably well with our predictions from UCHUU across scales ranging from $0.1 h^{-1} \text{Mpc}$ to $100 h^{-1} \text{Mpc}$. Some discrepancies arise due to cosmic variance, incompleteness in the massive end of the stellar mass function, and a simplified galaxy-halo connection model. We find that the UCHUU BGS and LRG samples are adequately described using the standard 5-parameter halo occupation distribution model, while the ELGs and QSOs show agreement with an adopted Gaussian distribution for central halos with a power law for satellites. We observe a fair agreement in the large-scale bias measurements between data and mock samples, although the data exhibits smaller bias values, likely due to cosmic variance. The bias dependence on absolute magnitude, stellar mass and redshift aligns with that of previous surveys. These results improve simulated lightcone construction from cosmological models and enhance our understanding of the galaxy-halo connection, with pivotal insights from the first DESI data for the success of the final survey.

Key words: cosmology: observations – cosmology: theory – large-scale structure of the Universe – surveys – galaxies: haloes

1 INTRODUCTION

Since the discovery of the accelerating expansion of the universe (Riess et al. 1998; Perlmutter et al. 1999), there has been a significant emphasis within cosmology on ascertaining its underlying physical principles. The initial measurement, facilitated by type Ia supernovae (SNe Ia) as standardizable candles, has been substantially extended (e.g. Betoule et al. 2014; Scolnic et al. 2018; DES Collaboration 2019; Scolnic et al. 2022). Measurements of cosmic expansion have also been obtained using other methods, most notably data from the cosmic microwave background (CMB), such as that obtained from the Planck satellite (Planck Collaboration et al. 2020). As these

measurements have improved, a noticeable discrepancy has emerged when comparing the local Hubble constant value (H_0) from SNe Ia with that projected from CMB measurements (Verde et al. 2019; Freedman 2021; Mörtzell et al. 2022). This discrepancy, currently exceeding a significant level of 4σ , continues to be investigated for potential hidden systematic effects or evidence of new physics (see Dainotti et al. 2021, and references therein). Although measurements of cosmic expansion and dark energy have been tested using additional methods, including the large-scale clustering of galaxies, the tension remains. Beyond addressing this question, understanding the specific behavior of dark energy, such as whether it manifests as a cosmological constant or arises from new physics, are key questions we must try to answer.

The large-scale structure of the universe becomes evident through the measurements of galaxy clustering obtained from large redshift

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surveys. This structure naturally emerges from primordial fluctuations that originated in the early universe. The propagation of baryon acoustic oscillations (BAO) generates matter density fluctuations that are frozen at the cosmic epoch of recombination. The characteristic BAO distance scale between galaxies provides a standard ruler, allowing us to investigate the expansion history of the universe. BAO analysis has emerged as a successful cosmological probe (Cole et al. 2005; Eisenstein et al. 2005), as demonstrated by its sensitivity to the BAO distance scale highlighted in the results obtained from the latest SDSS-III/BOSS (Alam et al. 2017) and SDSS-IV/eBOSS (Alam et al. 2021) large spectroscopic surveys. Combining BAO measurements with studies of redshift-space distortions (RSD; see e.g. Gil-Marín et al. 2017, 2018, for BOSS and eBOSS) provides a critical complement to supernova and CMB results enabling us to measure the expansion of the universe and constrain cosmological models.

Spectroscopic surveys greatly improve cosmological constraints in comparison to photometric surveys due their precise 3D measurements of galaxy clustering (Patrignani et al. 2016). The Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration et al. 2016a,b) seeks our most precise measurements of the cosmic expansion history by using almost 40 million galaxy spectra to map the matter distribution across an unprecedented redshift range of $z < 3.5$ (Levi et al. 2013). Four different galaxy tracers will be used to cover this entire range. DESI is forecast to achieve sub-percent precision on the BAO distance scale, and an order of magnitude improvement in constraints on the dark energy equation of state compared to previous surveys (DESI Collaboration et al. 2016a), and DESI is currently on target to meet these goals (DESI Collaboration et al. 2023a). This advancement will enable DESI to meet its Dark Energy Task Force (DETF) Stage IV figure-of-merit performance goals (Albrecht et al. 2006).

The cosmic expansion history and cosmological parameters inferred from BAO and RSD results reflect gravitational effects on dark matter and baryonic matter. Baryonic physics associated with astrophysical processes plays a crucial role in placing observable galaxies within dark matter halos. However, it introduces a galaxy clustering bias relative to halos and determines which galaxies are detectable. This bias hinders our ability to establish a direct connection between our observations of galaxies and their haloes, thereby obscuring the underlying cosmology. Consequently, removing this bias is a prerequisite of cosmological measurements. The challenging baryonic physics connecting the galaxies to haloes must be carefully modelled (see Wechsler & Tinker 2018, for a review). Furthermore, it is essential that the uncertainties arising from these models on BAO measurements are controlled (see de Mattia et al. 2021). Although hydrodynamical cosmological simulations encompass such physics (e.g. Pakmor et al. 2022), their computational demands make them prohibitive for larger volumes required to probe the BAO scale ($> 100 h^{-1} \text{Mpc}$). Instead, large volume N -body cosmological simulations are employed to populate galaxies within well-resolved dark matter halos and subhalos. Empirical methods that rely on the halo occupation distribution (HOD) statistics are popular in cosmological surveys (see Wechsler & Tinker 2018, and references therein). This approach involves fitting the observed two-point clustering statistics of galaxies (e.g. Zehavi et al. 2011; White et al. 2011; Avila et al. 2020) and generating mock galaxies accordingly (e.g. White et al. 2014). Another technique, known as subhalo abundance matching (SHAM), offers a more precise and extensively validated approach for populating simulated (sub)haloes with observed galaxies. SHAM matches the number density of observed galaxies selected by luminosity or stellar mass with the calculated density for haloes and subhaloes in the simulation, using a reliable proxy of halo mass

(Conroy et al. 2006; Trujillo-Gomez et al. 2011). SHAM has been successfully used in numerous studies to accurately reproduce the clustering properties of observed galaxies in large-scale surveys (e.g. Nuza et al. 2013; Reddick et al. 2013; Rodríguez-Torres et al. 2016; Contreras et al. 2023). The depth and volume of the DESI survey poses computational challenges when generating the N -body cosmological simulations required for these empirical methods. It is crucial for the mass resolution of the N -body simulations to be able to match the scales probed by the survey tracers. To address this, the 2.1 trillion particle UCHUU simulation provides the necessary combination of a low particle mass and a large box size (Ishiyama et al. 2021). This simulation allows us to account for dark matter haloes and subhaloes, including those on the scale of dwarf galaxies, across the entire volume covered by the DESI survey.

In this paper, we present clustering and halo occupancy results based on high-fidelity, simulated lightcones created from the UCHUU simulation in the Planck base- Λ CDM cosmology for the DESI One-Percent Survey (DESI Collaboration et al. 2023a,b). These lightcones encompass all four DESI tracers (BGS, LRG, ELG and QSO) up to a redshift of 2.1. We provide an overview of the DESI early data in Section 2. Section 3 details the properties of each of the four tracer types and the specific SHAM prescriptions employed to generate the UCHUU-DESI lightcones for each tracer. In Section 4, we present the galaxy clustering measurements obtained from the UCHUU-DESI lightcones, along with the resulting halo occupation distributions and linear bias measurements for each tracer. Finally, our conclusions are summarized in Section 5.

This work is part of a collection of papers released with the DESI Early Data Release, which examine the galaxy-halo connection for different tracers using various methodologies. This includes studies using the ABACUS-SUMMIT (Maksimova et al. 2021) simulations to obtain LRG and QSO HOD models (Yuan et al. 2023), and ELG HOD models (Rocher et al. 2023). Yu et al. (2023) presents a modified SHAM analysis for LRGs, ELGs and QSOs based on the UNIT simulation (Chuang et al. 2019). Abundance matching was also employed in Gao et al. (2023) to analyze the cross-correlations between LRGs and ELGs using the COSMICGROWTH (Jing 2019) simulation.

2 DESI AND EARLY DATA RELEASE

To achieve the DETF Stage IV science goals, DESI is a highly multiplexed, robotically fibre-positioned spectroscopic array installed on the Mayall 4-meter telescope at Kitt Peak National Observatory (DESI Collaboration et al. 2016a). DESI is capable of obtaining nearly 5000 simultaneous spectra in a 3 deg field-of-view (DESI Collaboration et al. 2016b; Silber et al. 2022; Miller et al. 2023). Each of the ten spectrographs covers the entire UV-to-near-IR spectral range with three arms: 3600 – 5930 Å, 5660 – 7720 Å and 7470 – 9800 Å. Each arm is equipped with a $4k \times 4k$ CCD. Galaxy tracers are identified using spectroscopic features, such as the [OII] doublet visible for emission-line galaxies (ELGs; Comparat et al. 2013). Currently, DESI is conducting a five-year survey spanning a 14,000 deg² sky footprint, designed to yield approximately 40 million galaxy and quasar spectra to measure cosmological parameters to sub-percent precision over $0 < z < 3.5$.

The survey is supported by several software and data processing pipelines. The imaging from the public DESI Legacy Imaging Surveys (Zou et al. 2017; Dey et al. 2019; Schlegel et al. 2023) supports the target selection pipeline for spectroscopic follow-up. Target selection employs quality cuts, as well as various colour selections and machine learning classification tools, tailored to provide a highly

complete and low contamination sample for each tracer type. Identification and prioritization of all targets are described in Myers et al. (2023). Specific details are provided for the Bright Galaxy Survey (BGS; Ruiz-Macias et al. 2020), luminous red galaxies (LRGs; Zhou et al. 2020, 2023), emission line galaxies (ELGs; Raichoor et al. 2020, 2023b), and quasars (QSOs; Yèche et al. 2020; Chaussidon et al. 2023). A planning pipeline optimizes the tiling of observations throughout the survey (Schlafly et al. 2023). Fibres are assigned to targets for each pointing in another pipeline (Raichoor et al. 2023a). Resultant spectra are processed with a ‘spectroperfectionist’ (Bolton & Schlegel 2010) data reduction pipeline (Guy et al. 2023) followed by a template fit yielding redshifts and a final classifications for each source (Bailey et al. 2023).

Since DESI will probe the galaxy distribution substantially deeper than prior large area surveys, a 4-month Survey Validation (SV) observing period was conducted to evaluate the science program (DESI Collaboration et al. 2023a). A substantial effort was dedicated to the attainment of deeper spectra with substantially higher target densities than expected for the main survey. Deeper spectra allowed the parent redshift distribution to be probed, and the determination of the number of tracers versus redshift that should be expected to be observed in the survey. The many exposures required for the deeper spectroscopy were used to characterize the exposures and establish the statistical performance of the redshifts, including their statistical uncertainties, completeness after classification, and purity. The SV period was valuable for testing and finalizing calibration procedures for the observations. A large number of sky fibers were used, which was crucial in testing the sky subtraction. DESI aims to classify and measure redshifts for galaxies near the Poisson noise limit, which requires an excellent sky subtraction. SV allowed a determination of how many sky fibres will be required in the main survey. As an essential element of observing, DESI employs a dynamic exposure time calculation (Kirkby, D. et al. 2023) that utilizes *in situ* real-time measurements of observing conditions to optimize exposure times, minimizing overheads and inefficient data taking. SV observing in a full range of atmospheric and Galactic extinction environments allows for calibration of the models used by the calculator. The exposure times were optimized to facilitate completion of the main survey in the designed 5 years. An extensive visual inspection regime was also carried out using the SV data to verify the performance of the instrument, as well as the data reduction pipeline and target selection algorithms. For galaxies, more details can be obtained in Lan et al. (2023), while quasars are described in Alexander et al. (2023). Overall, SV has been invaluable in providing inputs for subsequent modeling and analysis.

The final month of SV was dedicated to the One-Percent Survey, covering 140 deg^2 at the intended main survey spectroscopic depth. A total of 239 (214) dark (bright) time tiles were observed over 33 (35) nights, with 375 (287) exposures and 88.2 (15.9) hours of effective exposure time. The BGS sample was split into two samples: BGS-BRIGHT with $r \leq 19.5$ and BGS-FAINT with $19.5 < r \leq 20.175$, with the bulk of the sample in BGS-BRIGHT. Target selection was optimized for high completeness and low background contamination. Stars and galaxies were distinguished by comparing G_{Gaia} from *Gaia* (Gaia Collaboration et al. 2018) with r from the DR9 Legacy Imaging Survey (Schlegel et al. 2023) and removing sources that were bright in *Gaia*. In order to isolate galaxies, colour cuts using z, g, r and $W1$ from WISE (Wright et al. 2010; Lang et al. 2016) were used. Further details can be obtained from Hahn et al. (2023). LRG selection was optimized to yield uniform comoving number density in the redshift range of $0.4 < z < 0.8$, while WISE photometry was used to effectively veto stars. z, g, r and $W1$ filters were utilized

Sample	Redshift	A_{eff} (deg^2)	N_{eff}	$10^2 \times V_{\text{eff}}$ ($h^{-3} \text{Gpc}^3$)
BGS-BRIGHT	$0.05 < z < 0.5$	173.5	142341	3.72
LRG	$0.45 < z < 0.85$	166.9	58764	7.97
ELG	$0.88 < z < 1.34$	168.6	156891	12.95
QSO	$0.9 < z < 2.1$	174.6	23085	1.87

Table 1. Basic properties of the DESI One-Percent Survey samples used in this work: the redshift interval, effective area of the sky footprint weighted by completeness (A_{eff}), number of galaxies (N_{eff}), and effective volume (V_{eff}).

to remove lower redshift and bluer galaxies. LRGs have a lower priority than QSOs but a higher priority than ELGs, ensuring high completeness. Further details on LRG final selection can be found in Zhou et al. (2023). Our final ELG selection was divided into two redshift bins due to their potential overlap with LRGs. A higher priority ‘ELG_LOP’ sample covers the range of $1.1 < z < 1.6$, which is inaccessible to LRGs, while a low priority ‘ELG_VLO’ sample covers the entire range of the DESI ELG targets $0.6 < z < 1.6$. Quality cuts were applied to reject bright stars, and g, z, r and g_{fib} filters were used to select star-forming instead of passive galaxies. Further details on ELG selection can be found in Raichoor et al. (2023b). Selection of quasars relies on colors from z, g, r as well as $W1, W2$ bands. The near-infrared fluxes are valuable to separate bluer stars from redder QSOs. Ten colours from these 5 bands are used and employ a Random Forest technique to improve efficiency. Quasars are observed at highest priority, and DESI achieves 99% efficiency. Further details on the selection of all tracers can be found in Myers et al. (2023). From the One-Percent Survey footprint, DESI projects number densities of 988 deg^{-2} , 533 deg^{-2} , 1121 deg^{-2} and 205 deg^{-2} for BGS, LRG, ELG, and QSO, respectively.

DESI has demonstrated excellent performance in the One-Percent Survey. Redshift comparisons to other surveys indicate offsets of 6.5 km s^{-1} , $< 10 \text{ km s}^{-1}$ and 1 km s^{-1} for LRGs, ELGs and QSOs, respectively. Our results have enabled a redirection of fibres from LRGs and QSOs, and an expectation to obtain redshifts for 36 million unique galaxies and 2.8 million unique quasars in the main survey. The achieved performance in many areas substantially surpasses prior projections. Catastrophic redshift failures $> 1000 \text{ km/s}$ should be $< 5\%$ for LRGs and ELGs, and 0.2% has been achieved. Random redshift errors need to satisfy $< 2 \times 10^{-4}(1+z)$ for ELGs and $< 4 \times 10^{-4}(1+z)$ for QSOs. Measurements achieve $3.3 \times 10^{-6}(1+z)$ and $8.7 \times 10^{-5}(1+z)$ for these populations, respectively. SV results also allow us to better project the main survey’s performance on cosmological parameter precision. DESI forecasts a statistical precision of $\delta H(z) \sim 0.28\%$, of RSD figure of merit $\delta R(z) \sim 0.24\%$, and of $\delta f\sigma_8 \sim 1.56\%$ for $z < 1.1$. At higher redshift, $\delta H(z)$ will reach a precision of 0.39% and 0.46% in $1.1 < z < 1.9$ and $z > 1.9$ ranges, respectively. For further details about Survey Validation, the One-Percent Survey, and the projected DESI Survey results, refer to DESI Collaboration et al. (2023a).

3 COSMOLOGICAL MODELLING OF THE DESI ONE-PERCENT SURVEY

This section details the process by which the UCHUU One-Percent high-fidelity lightcones were generated for each tracer to closely match the clustering properties of the DESI One-Percent Survey. The

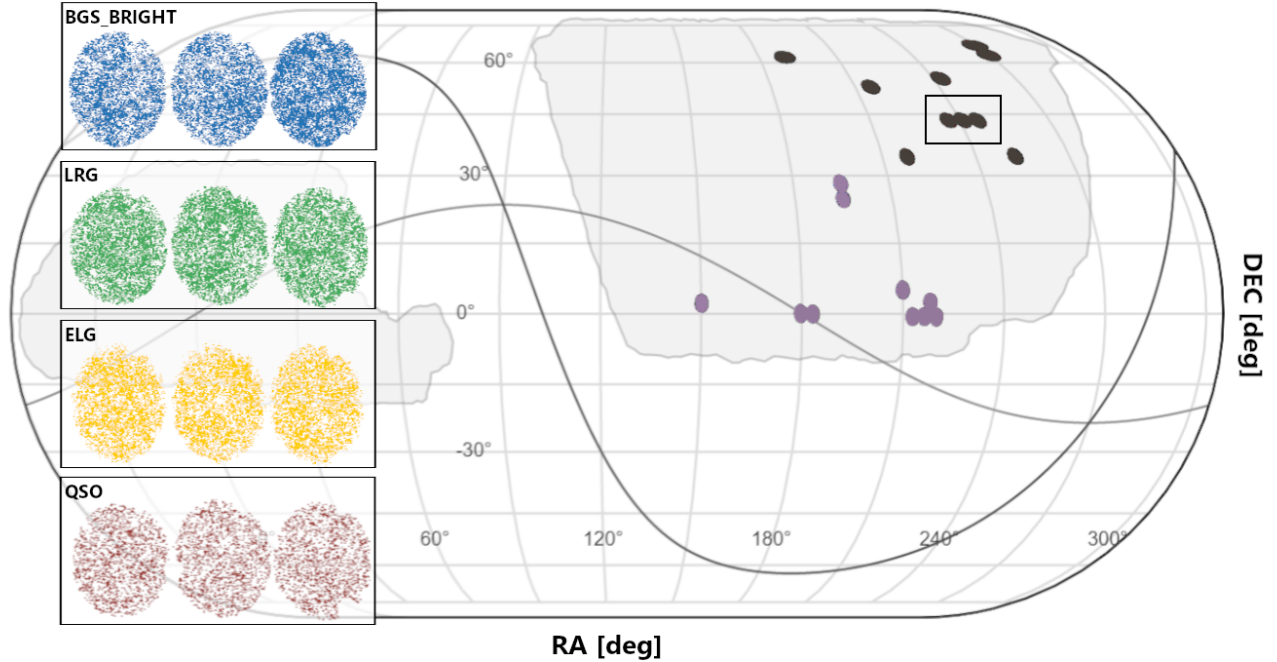


Figure 1. The sky coverage of the DESI One-Percent Survey for the BGS-BRIGHT, LRG, ELG, and QSO cosmological tracers used in this analysis. The 20 rosettes that make up the One-Percent footprint are split into ‘North’ (in black) and ‘South’ (in purple). The grey-shaded regions indicate the expected DESI Year-5 sky coverage. The four small panels are zoomed in on a section of the footprint covered by 3 rosettes, for each tracer. The color-coding represents the angular weighted number density, where darker colors indicate a higher density.

basic properties of the DESI One-Percent data, such as sky coverage and number densities of each tracer, are presented in Section 3.1. Section 3.2 describes the high-resolution UCHUU N -body simulation that was used to create our simulated lightcones. An overview of the SHAM method adopted to populate galaxies and quasars into the UCHUU halo catalogues to build lightcones for each of the DESI tracers is provided in Section 3.3.

3.1 Properties of the One-Percent Survey

Figure 1 shows the sky coverage of the DESI One-Percent BGS-BRIGHT, LRG, ELG, and QSO samples.¹ We list the basic properties of these samples as used in our analysis in Table 1, which includes information such as the redshift ranges, sky area, total number of galaxies, and effective volume as a measure of constraining power. The effective volume (equation 1 of Wang et al. 2013) is calculated as

$$V_{\text{eff}} = \sum_i \left(\frac{n(z_i)P_0}{1 + n(z_i)P_0} \right)^2 \Delta V(z_i), \quad (1)$$

where $n(z_i)$ is the weighted number density of galaxies and $\Delta V(z_i)$ is the comoving survey volume at redshift bin z_i . We adopt P_0 (the power spectrum at the scale where we desire to minimize the variance) equal to $7000 h^{-3} \text{Mpc}^3$, $10000 h^{-3} \text{Mpc}^3$, $4000 h^{-3} \text{Mpc}^3$ and $6000 h^{-3} \text{Mpc}^3$ for BGS, LRG, ELG, and QSO, respectively.

¹ This figure was created with the help of the web interface provided by D. Kirkby (<https://observablehq.com/@dkirkby/desi-tutorial>)

The four cosmological tracers cover a wide redshift range, extending from $z = 0.05$ to $z = 2.1$, with the BGS-BRIGHT and QSO samples having the highest and lowest densities, respectively. Figure 2 displays the comoving number density for the BGS-BRIGHT, LRG, ELG, and QSO samples taken from the DESI One-Percent Survey. We utilize the entire data sample taken during the One-Percent Survey, including areas only tiled to partial completeness, leading to a larger effective area than the 140 sq. degrees reported in DESI Collaboration et al. (2023a). This necessitates the inclusion of weighting schemes to correct for the incompleteness which we discuss in Section 4.1. We converted the redshifts of the One-Percent galaxies and quasars to comoving distances using a fiducial flat Λ CDM cosmological model with the Planck-15 parameters $h = 0.6774$, $\Omega_m = 0.3089$, $\Omega_b = 0.0486$, $n_s = 0.9667$, $\Omega_\Lambda = 0.6911$, and $\sigma_8 = 0.8159$ (Planck Collaboration et al. 2016).

3.2 The UCHUU simulation

In order to model the clustering signal of the DESI One-Percent Survey in the flat Λ CDM Planck cosmology, we utilized the UCHUU N -body simulation (Ishiyama et al. 2021). Designed specifically to model the DESI survey, UCHUU boasts high numerical resolution which enables the resolution of dark matter haloes and subhaloes down to small masses on a very large volume. This resolution, in turn, allows us to apply the SHAM technique to populate the UCHUU haloes and subhaloes with DESI galaxies and quasars, generating high-fidelity lightcones that reproduce the number density and clustering of each DESI tracer. Section 3.3 provides a more detailed description of the construction of these UCHUU-DESI lightcones. In Section 4,

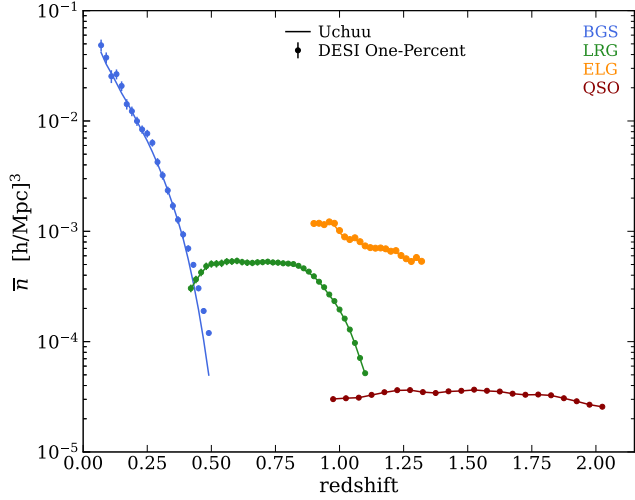


Figure 2. The comoving number density of the four DESI One-Percent tracer samples (points) and the average of the corresponding high-fidelity UCHUU-DESI lightcones (solid line) over the entire redshift range $0.1 < z < 2.1$. Data error bars are obtained from the ensemble of UCHUU One-Percent lightcones built in this work.

we provide a thorough comparison of the predicted clustering signal of these lightcones in the Planck cosmology to that observed in the DESI One-Percent survey. This comparison allows us to further investigate the halo occupation distribution and large-scale bias of all four tracers.

The UCHUU simulation was run using the TreePM code GREEM (Ishiyama et al. 2009, 2012). The box has a comoving side length of $2 h^{-1}\text{Gpc}$, with $12,800^3$ dark matter particles. The mass resolution and gravitational softening length are $3.27 \times 10^8 h^{-1}M_{\odot}$ and $4.27 h^{-1}\text{kpc}$, respectively. The initial conditions were generated using the second-order Lagrangian Perturbation Theory (2LPT) approximation at $z_{\text{init}} = 127$, and the simulation followed the growth of cosmic structures in the Planck-15 flat ΛCDM cosmology. We saved 50 snapshots of the particle distribution from $z = 14$ to $z = 0$, and identified bound structures using the ROCKSTAR phase-space halo/subhalo finder (Behroozi et al. 2013a). We constructed merger trees for these structures using a parallel version of the CONSISTENT-TREES algorithm (Behroozi et al. 2013b). Additionally, we obtained the peak value of the maximum circular velocity over the history of each (sub)halo, denoted as V_{peak} . We measure the maximum circular velocity at each of the 50 redshift outputs, and take the maximum value as V_{peak} . We used this to implement the SHAM method for populating UCHUU haloes with DESI galaxies and quasars. For more information on the simulation methodology and performance, we refer the reader to Ishiyama et al. (2021). All UCHUU data products are publicly available through SKIES & UNIVERSES.²

3.3 UCHUU One-Percent Lightcones

In the following, we provide a brief overview of the creation of the high-fidelity UCHUU lightcones for DESI One-Percent galaxies and quasars in the Planck cosmology. Further details will be provided in forthcoming papers on each tracer type utilizing first year of the observations of the DESI main survey to conduct a comprehensive study of the clustering signal, including the BAO scale. This dataset

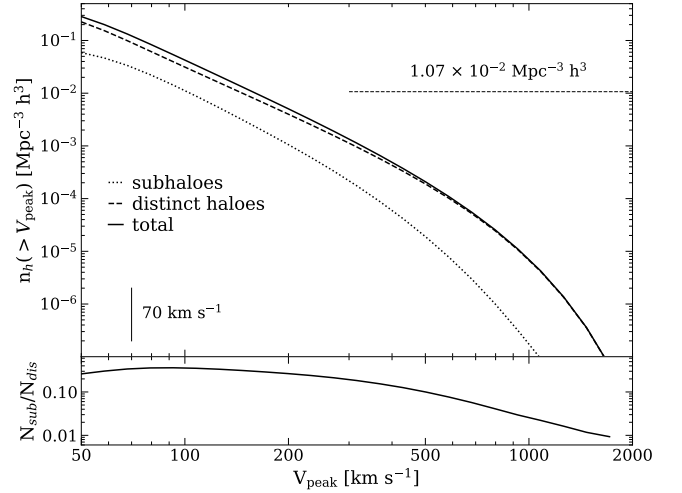


Figure 3. *Top panel:* Cumulative number density of distinct haloes (N_{dis}) (dashed curve), subhaloes (N_{sub}) (dotted curve), and all haloes (solid curve) as a function V_{peak} in the UCHUU simulation box at $z = 0.2$, the median redshift of the BGS-BRIGHT sample in the DESI One-Percent Survey. The horizontal line indicates the mean number density of the BGS-BRIGHT sample. The vertical line indicates the completeness threshold for UCHUU. *Bottom panel:* Cumulative subhalo fraction measured as a function of V_{peak} .

covers a much larger sky area than the One-Percent survey, yielding over an order of magnitude more galaxies.

3.3.1 Subhalo abundance matching

We employ the SHAM algorithm to construct lightcones for each DESI tracer from the UCHUU simulation boxes. For the BGS and LRG samples, the SHAM method assigns luminosities or stellar masses to all UCHUU (sub)haloes in the simulation boxes. Specifically, we match their V_{peak} cumulative distribution function to our chosen BGS-BRIGHT luminosity and LRG stellar mass functions, with a certain level of intrinsic scatter σ as the only free parameter when creating our UCHUU One-Percent BGS-BRIGHT and LRG lightcones in the Planck cosmology. We present the methodology in Sections 3.3.2 and 3.3.3. For the ELG and QSO tracers, we incorporate additional parameters to account for incompleteness, which we describe in Sections 3.3.4 and 3.3.5.

In this work, we adopt the peak maximum circular velocity V_{peak} as a proxy for (sub)halo mass. V_{peak} has been extensively used in numerous studies to accurately reproduce the properties of observed galaxies in large-scale surveys (e.g. Conroy et al. 2006; Trujillo-Gomez et al. 2011; Nuza et al. 2013; Reddick et al. 2013; Chaves-Montero et al. 2016; Rodríguez-Torres et al. 2016; Safonova et al. 2021).

We are able to reach the lowest luminosities and smallest stellar masses in the BGS-BRIGHT and LRG DESI galaxy samples, respectively, thanks to the high completeness level of subhaloes and distinct haloes in UCHUU. As estimated previously (Ishiyama et al. 2021; Dong-Páez et al. 2022) in comparisons with the much higher-mass resolution SHIN-UCHUU simulation, subhaloes in UCHUU have a completeness of 90% down to $V_{\text{peak}} \sim 70 \text{ km s}^{-1}$. Haloes have a completeness level of 90% down to $V_{\text{peak}} \sim 50 \text{ km s}^{-1}$.

Figure 3 illustrates in the top panel the cumulative number density of (sub)haloes vs. V_{peak} in the UCHUU box at $z = 0.2$, which is the median redshift of BGS-BRIGHT galaxies. At this redshift, we use

² <https://www.skiesanduniverses.org/Simulations/Uchuu/>

$V_{\text{peak}} > 170 \text{ km s}^{-1}$ for abundance matching with the BGS-BRIGHT sample, which is well above the completeness limit of UCHUU. The mean number density of the BGS-BRIGHT sample at its median redshift is indicated by the horizontal dotted line. This indicates that (sub)haloes hosting BGS-BRIGHT galaxies are well-resolved with the UCHUU simulation. The cumulative subhalo fraction, measured from the cumulative number densities in Figure 3, is shown as a function of V_{peak} in the bottom panel. For values of V_{peak} greater than 170 km s^{-1} , the cumulative subhalo fraction is approximately 25%. Note that at redshifts lower than $z = 0.2$, the faintest galaxies live in (sub)haloes with smaller V_{peak} than this, but only a small fraction have $V_{\text{peak}} < 100 \text{ km s}^{-1}$, which are still well resolved. For more insight, Figure 4 in Nuza et al. (2013) presents the number density of (sub)haloes in the MultiDark simulation at $z = 0.53$. This is similar to the BOSS-CMASS LRG sample, corresponding to (sub)haloes with V_{peak} above 370 km s^{-1} , consistent with typical DESI LRGs living in much more massive haloes than BGS-BRIGHT galaxies. In this case, the subhalo fraction is typically about 10%. In the following sections, we will present the results obtained from our analysis of the halo occupation distribution of all four DESI tracers provided by our UCHUU lightcones.

3.3.2 UCHUU BGS BRIGHT

We follow the SHAM methodology as outlined in Section 3.2 of Dong-Páez et al. (2022), which has been successfully applied to SDSS, to construct our UCHUU One-Percent BGS lightcones. SHAM assumes that the most massive (sub)haloes host the most luminous galaxies. To generate our simulated flux-limited BGS sample, we utilize a parameterized luminosity function from both SDSS and GAMA (see Smith et al. 2017, 2022b, for the creation of a DESI-BGS lightcone from the Millennium-XXL simulation).

We assigned galaxy magnitudes as a function of halo V_{peak} using a SHAM algorithm with intrinsic scatter, based on McCullagh et al. (2017) and Safonova et al. (2021). For simplicity, we adopt a constant scatter parameter of $\sigma = 0.5 \text{ mag}$. This value is calibrated to match the observed SDSS clustering (Dong-Páez et al. 2022).

We apply SHAM to the (sub)halo catalogues from UCHUU boxes at redshifts 0, 0.093, 0.19, 0.3, 0.43, and 0.49. The implementation details of the SHAM algorithm, and adopted scatter, are described in Dong-Páez et al. (2022). Finally, we combine the snapshots to create the UCHUU lightcone (see Section 3.3.6 for more details).

3.3.3 UCHUU LRG

To construct the UCHUU-LRG lightcones, we follow the SHAM approach introduced in section 4.1 of Rodríguez-Torres et al. (2016), which has been previously applied to the BOSS survey. This method assumes the most massive galaxies are hosted by the most massive (sub)haloes.

In Figure 4, we present the stellar mass function of LRG obtained from the DESI One-Percent survey using the CIGALE tool Boquien et al. (2019) to estimate individual stellar masses (Siudek et al. 2023). To fit the spectral energy distribution (SED), we used three optical photometry bands (g, r, z) from the DESI Legacy Survey (DECaLS; Dey et al. 2019), complemented by four WISE mid-infrared bands (W1, W2, W3, and W4) from the NEOWISE-Reactivation project (NEOWISER; Mainzer et al. 2014). The CIGALE SED-fitting tool is based on the principles of the energetic balance between the absorbed stellar emission in the ultraviolet and optical bands and its

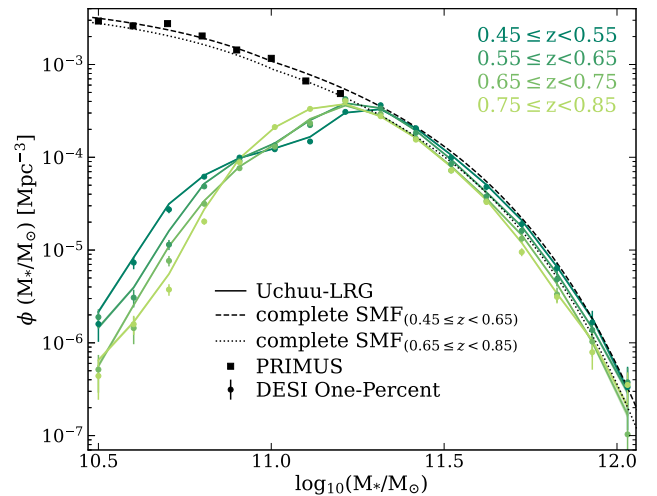


Figure 4. Stellar mass functions for LRG in the DESI One-Percent Survey (points) and the mean of our UCHUU-LRG lightcones (solid curves) are shown for several redshift bins within the range $0.45 < z < 0.85$. The dashed curves represent the complete SMF adopted in each redshift range, indicated in the legend. Data error bars and the model shaded area represent the standard deviation of our set of 102 UCHUU lightcones.

re-emission in the infrared by dust. We adopted a grid of stellar population models with a delayed star formation history (SFH), including an optional exponential burst, a Chabrier (2003) initial mass function (IMF), and solar metallicity. To model the effect of dust extinction, we used the reddening law of Calzetti et al. (2000), and we adopted the updated dust templates from Draine et al. (2014) to model the IR emission from dust reprocessed from the absorbed UV/optical stellar emission. We also incorporated the standard nebular emission model from Inoue (2011) and the AGN emission models from Fritz et al. (2006). We performed a Bayesian-like analysis to fit the SEDs of these models to the DESI galaxy SEDs. The quality of the fit is expressed by the reduced χ^2 , and we used the stellar masses of galaxies with reduced $\chi^2 < 10$ to ensure reliable stellar properties. Siudek et al. (2023) will provide a detailed description of the SED fitting procedure.

Although we were able to estimate the LRG stellar mass function (SMF), we lack information on the shape of the SMF at low masses due to the selection function. To supplement our analysis, we incorporate the SMF measurements obtained from PRIMUS presented by Moustakas et al. (2013), see Figure 4. It is worth noting that we do not consider the redshift evolution of the PRIMUS SMF in our analysis, as it has been shown to have a negligible impact on our results and is consistent with the findings of the PRIMUS survey.

To account for the observed evolution in the shape of the SMF with redshift (as shown in Figure 4), we have employed two different complete SMFs in our SHAM method: one that characterizes a complete population at $0.45 \leq z < 0.65$ (low- z , represented by the dashed line), and another that characterizes a complete population at $0.65 \leq z < 0.85$ (high- z , represented by the dotted line).

We apply SHAM to the (sub)halo catalogues from UCHUU boxes at redshifts 0.49, 0.63, 0.78, and 0.86 to cover the interval $0.45 \leq z < 0.85$. To ensure a consistent approach, we generate LRGs in the first two boxes using the low- z complete SMF, and the remaining two boxes with the high- z complete SMF. However, as the LRG DESI One-Percent stellar mass distribution is incomplete, we account for this by randomly down-sampling galaxies from the complete SMF in each UCHUU box to match the observed DESI One-Percent SMF.

We then combine the resulting snapshots to generate the UCHUU lightcone (see Section 3.3.6).

3.3.4 UCHUU ELG

To model DESI ELGs, we adopt a ‘modified SHAM’ approach as described in section 3.1 of Rodríguez-Torres et al. (2017), which was previously applied to the BigMultiDark Planck simulations to build eBOSS-QSO lightcones. This modification allows the use of SHAM-like methods to model incomplete tracers for which normal SHAM would not typically be possible such as both ELGs and QSOs. However, instead of using V_{\max} , the maximum circular velocity supportable by the halo for a single snapshot (as done in Rodríguez-Torres et al. 2017), we use V_{peak} , which is the maximum circular velocity that a halo can support at any point in its accretion history. This modification accounts for the incompleteness of the tracer population in terms of halo mass or luminosity/stellar mass (see also Favole et al. 2017, for the same method applied to [OII] galaxy emitters).

This methodology is implemented by selecting (sub)halo samples from UCHUU adopting two Gaussian distributions with the same mean V_{peak} (V_{mean}) and standard deviation σ_V , for central and satellite galaxies. Both Gaussian distributions are normalized to match the observed ELG number densities, with the satellite fraction (f_{sat}) treated as a free parameter. Over the range $5 h^{-1}\text{Mpc} < s < 30 h^{-1}\text{Mpc}$, we then fit the monopole of the two-point correlation function (2PCF) of ELGs in the DESI One-Percent data to the 2PCF of a full 4π lightcone for an array of V_{mean} and f_{sat} values (see Section 4.1 for the clustering comparisons). The best-fit V_{mean} and f_{sat} parameters used to generate our UCHUU One-Percent high-fidelity lightcones for ELGs are listed in the first row of Table 2. The subsequent rows show the best fit parameters for each box used in the construction of the mocks fit separately. σ_V was fixed at 30 km s^{-1} as in Rodríguez-Torres et al. (2017). This was due to the relative lack of effect of σ_V on the clustering in the mocks. The above scheme will be explained in more detail in a paper on Year 1 data. We apply the modified SHAM method to the (sub)halo catalogues from UCHUU boxes at redshifts 0.94, 1.03, and 1.22 to cover the interval $0.88 < z < 1.34$. These boxes cover an irregularly spaced set of redshifts designed to equipartition the ELG data sample.

3.3.5 UCHUU QSO

To model the QSO sample, we employ the same ELG SHAM methodology described in Section 3.3.4. We then fit the two-point correlation functions of QSOs (see Section 4.1) to obtain the best-fit V_{mean} and f_{sat} parameters, listed in Table 3, used to generate our UCHUU One-Percent high-fidelity lightcones for QSO. For the same reasons as in Section 3.3.4, we fixed σ_V at 30 km s^{-1} . We work with the (sub)halo catalogues from UCHUU boxes at four different redshifts, namely $z = 1.03, 1.32, 1.65, \text{ and } 1.9$ to cover the redshift range of the QSO sample (0.9 to 2.1). Estimates of quasar redshift have large uncertainties (Chaussidon et al. 2023) of a few hundred km s^{-1} due to the broadness of the emission lines and the intrinsic shifts from other emission lines (Youles et al. 2022). Hence we introduce Gaussian redshift errors such that

$$z_{\text{final}} = z + \mathcal{G}(0, \sigma). \quad (2)$$

Here, z_{final} is the final redshift distribution for the mock quasar catalogs, and $\mathcal{G}(0, \sigma)$ is the Gaussian random error added to the initial redshift distribution z . The dispersion σ was set as 500 km s^{-1} for the One-Percent sample.

3.3.6 Constructing the UCHUU lightcones

After applying the SHAM method to populate the simulation catalogues with galaxies and quasars, we generate the UCHUU-DESI lightcones for each tracer by joining together the cubic boxes in spherical shells (see Smith et al. 2022b, for a detailed explanation of this method). The following steps are involved in creating the lightcone:

- (i) The (x, y, z) Cartesian coordinates of each galaxy/quasar cubic-box snapshot are transformed so that the observer is at the origin. We used the corner of the box as the observer position.
- (ii) The cubic box is cut into a spherical shell, with the observer at the centre. The comoving distance between the observer and the inner/outer edges of the shell corresponds to the redshift halfway between this snapshot and the next/previous snapshot. In cases where the outer edge of the shell is bigger than the cubic box, periodic replications are applied. If this shell is at a high enough redshift, the inner edge will also be bigger than the central box.
- (iii) The spherical shells from each snapshot are joined together to make the lightcone.
- (iv) The Cartesian coordinates are converted to (RA, Dec, z). When computing the redshift, we also include the effect of peculiar velocities of galaxies along the line of sight.
- (v) Depending on the tracer, an extra step is applied to make sure the correct number density of galaxies/quasars is achieved in the lightcone, and to avoid discontinuities at the interfaces between shells.

To obtain an r -band luminosity function that evolves smoothly with redshift for the BGS lightcone, we apply a rescaling to the magnitudes in the final step. This rescaling is described in Dong-Páez et al. (2022) and ensures that the correct number density of galaxies is achieved in the lightcone, while avoiding any discontinuities at the interfaces between shells. Next, we assign a $g - r$ colour to each galaxy using the method and colour distributions presented in Smith et al. (2022a). To convert the absolute r -band magnitudes to the observed apparent magnitude, we use a set of colour-dependent k -corrections from the GAMA survey (see Smith et al. 2022a). Finally, we apply a magnitude cut of $r < 19.5$ to match the faint apparent magnitude limit of the BGS-BRIGHT survey.

For the LRG lightcone, we apply a smoothing to the redshift distribution $n(z)$ after joining the spherical shells to avoid a step function behaviour. We also randomly downsample the redshift ranges where the lightcone’s redshift distribution is above the observed one. In this step, we extend our lightcone up to redshifts 0.4 and 1.1 for the sole purpose of producing Figures 2 and 5.

For the ELG and QSO lightcones, we adopt a different approach to match the observed $n(z)$ in each redshift bin. Specifically, we select only the required number of galaxies such that the resulting $n(z)$ matches the observed one in all redshift bins. The bin width is set to be $\Delta z = 0.02$ for ELGs and $\Delta z = 0.05$ for QSOs.

We applied the aforementioned steps to each of the four DESI tracers to create their respective full-sky lightcones. The lightcones were then cut to match the northern and southern areas of the DESI One-Percent Survey footprint, as shown in Figure 1. In this study, we retained all objects within the survey footprint, regardless of completeness, for all tracers. Since our methods emulate an observed catalogue rather than a parent catalogue, applying any correction for fibre collisions or the effects of applying fibre assignment on the mock catalogue would be incorrect and lead to an underselection of tracers.

Figure 5 presents a visual representation of all four DESI tracers

z_{\min}	z_{\max}	N_{eff}	V_{eff}	$n_{\text{g}}^{\text{ELG}}$	$\chi^2/\text{d.o.f}$	V_{mean}	f_{sat}	$f_{\text{sat}}^{\text{Uchuu}}$	b^{ELG}	b^{Uchuu}
0.88	1.34	200997	0.259	0.776×10^{-3}	2.33	156.5 ± 4.2	0.131 ± 0.012	0.131	1.34 ± 0.03	1.34 ± 0.01
0.88	1.00	66699	0.059	1.13×10^{-3}	4.88	133.2 ± 6.1	0.179 ± 0.029	—	1.35 ± 0.04	1.27 ± 0.01
1.00	1.16	69110	0.089	0.78×10^{-3}	3.62	156.5 ± 6.9	0.131 ± 0.023	—	1.25 ± 0.06	1.35 ± 0.01
1.16	1.34	65187	0.111	0.60×10^{-3}	2.04	127.8 ± 5.4	0.246 ± 0.034	—	1.43 ± 0.01	1.42 ± 0.01

Table 2. Best-fit modified SHAM parameters for the ELGs for each redshift bin and for the entire mock. The first two columns show the minimum and maximum redshift used to define the different ELG samples. The following columns give, for each redshift bin, the number of galaxies, the effective volume (in $h^{-3}\text{Gpc}^3$) and the galaxy number density (in $h^3\text{Mpc}^{-3}$). The $\chi^2/\text{d.o.f}$ is obtained by fitting the monopole of the two-point correlation functions of the ELGs to the DESI One-Percent sample, in the separation range $\sim 5 h^{-1}\text{Mpc}$ to $\sim 30 h^{-1}\text{Mpc}$. This is further used to obtain the best-fit V_{mean} (in km s^{-1}), and f_{sat} parameters used to generate our UCHUU One-Percent high-fidelity lightcones. The last two columns show the bias calculated from the data and the mocks respectively (b^{ELG} and b^{Uchuu}). The errors reported for the data are statistical only from the fitting code, the errors reported for the mocks are the standard error in the mean of the 102 independent footprint mocks.

z_{\min}	z_{\max}	N_{eff}	V_{eff}	$n_{\text{g}}^{\text{QSO}}$	$\chi^2/\text{d.o.f}$	V_{mean}	f_{sat}	$f_{\text{sat}}^{\text{Uchuu}}$	b^{QSO}	b^{Uchuu}
0.9	2.1	23085	0.66	3.52×10^{-5}	1.49	309 ± 16	0.14 ± 0.05	0.14	2.13 ± 0.20	2.29 ± 0.02
0.9	1.2	4605	0.12	3.84×10^{-5}	0.47	280 ± 44	0.15 ± 0.13	—	1.74 ± 0.11	1.86 ± 0.01
1.2	1.5	6241	0.17	3.67×10^{-5}	0.94	307 ± 29	0.14 ± 0.09	—	2.19 ± 0.22	2.11 ± 0.02
1.5	1.8	6583	0.19	3.46×10^{-5}	1.70	305 ± 26	0.13 ± 0.09	—	2.44 ± 0.18	2.44 ± 0.02
1.8	2.1	5656	0.17	3.33×10^{-5}	1.30	333 ± 39	0.12 ± 0.11	—	2.95 ± 0.18	2.74 ± 0.02

Table 3. Same as Table 2 but for QSOs. The $\chi^2/\text{d.o.f}$ is obtained by fitting the monopole of the two-point correlation functions of QSO to the DESI One-Percent samples in the separation range $\sim 5 h^{-1}\text{Mpc}$ to $\sim 30 h^{-1}\text{Mpc}$.

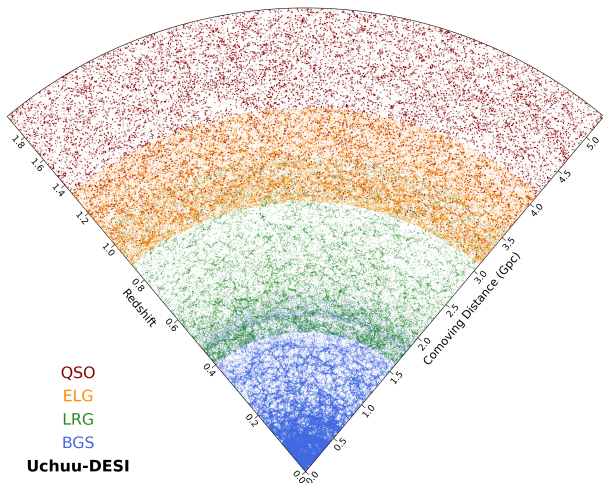


Figure 5. Slice through the UCHUU-DESI catalogues with objects coloured by tracer type: BGS (blue), LRG (green), ELG (orange), QSO (red). The slice shows an 80 deg wedge projected into comoving coordinates using a Planck background cosmology, extending out to a maximum redshift of 2. The projected thickness is 1 deg for QSOs and 0.5 deg for ELGs. The thickness for the BGS and LRG samples is adjusted with redshift to achieve a constant average projected number density. The transparency of points out of the projection plane falls off with Gaussian weighting.

within a thin slice of an UCHUU-DESI lightcone. The slice shows an 80 deg wedge projected into comoving coordinates using a Planck background cosmology, extending out to a maximum redshift of 2. Since the effective volume of the DESI One-Percent Survey is small, its footprint can be replicated over the full sky to generate a significant number of UCHUU One-Percent lightcones for each tracer, enabling us to compute covariance errors for the clustering measurements.

This is achieved by first moving the position of rosettes into a

small rectangular region, where the separation of the rosettes is only conserved for closely separated rosettes (i.e. the triplet of rosettes highlighted in Figure 1, the three close pairs of rosettes, and the cluster of five rosettes at $\text{RA} \sim 0$). This rectangular region is then replicated across the sky, and for each mock, the rosettes (or clusters of closely separated rosettes) are taken from different copies of the rectangular region. Finally, the positions of the rosettes are transformed back to match the One-Percent footprint. This enables us to make 102 One-Percent lightcones for each tracer. However, since the relative positions of the rosettes were not fixed, we only trust clustering measurements on scales smaller than the clusters of rosettes. For the BGS tracer at $z \sim 0.2$, this corresponds to a comoving separation of $\sim 100 h^{-1}\text{Mpc}$, and is larger for the other tracers at higher redshifts. It is worth noting that the mocks are not fully independent above $z = 0.36$, due to periodic replications of the box. Nevertheless, we checked the degree of overlap by tracking repeated halo IDs within the footprint of the mocks. We found that, for all four tracers and for the effective volume we are considering, the overlap is less than 5%. Therefore, we treat the 102 lightcones as if they were completely independent. The area on the sky of each of our 102 lightcones is 191.4 deg^2 . This is larger than the area of the data catalogues, since the Uchuu lightcones are complete, and no regions are masked.

Figure 2 shows a comparison between the comoving number density of the DESI One-Percent Survey (points) and the mean comoving number density of the high-fidelity UCHUU One-Percent lightcones (solid lines) constructed for each of the four tracer samples. Overall, the agreement between UCHUU and DESI is good, with the differences in the number density being within the error bars for all four tracers.

In Figure 6, the top panel displays the distribution of r -band absolute magnitude for the BGS sample in the DESI One-Percent Survey (hexagonal bins) and one of the UCHUU-BGS lightcones (contours). The same colour-dependent k -correction has been applied to the galaxies in the data and mock (see Smith et al. 2017), as well as

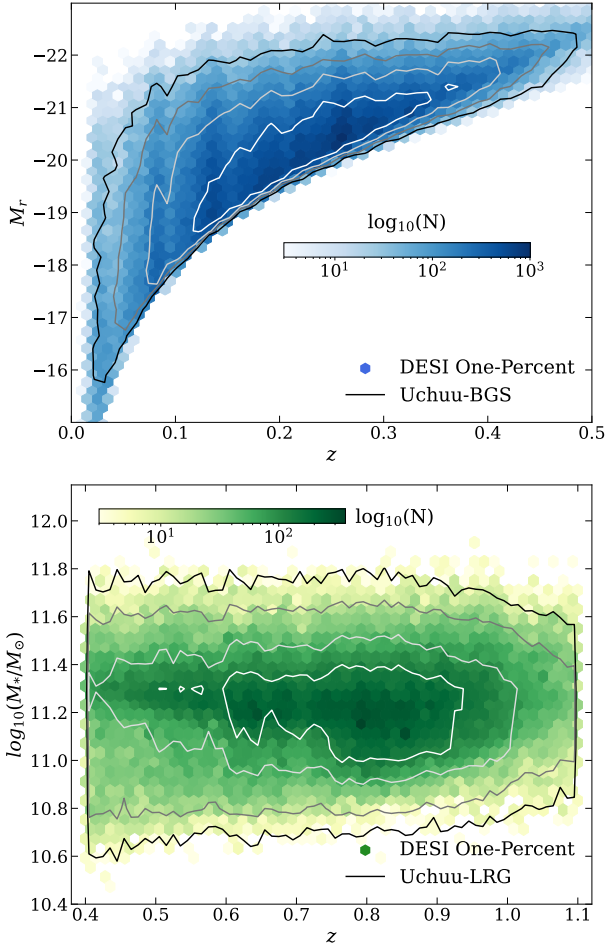


Figure 6. *Top panel:* Absolute magnitude vs. redshift for the DESI One-Percent BGS sample (hexagonal bins), compared to one of the UCHUU-BGS lightcones (contours). Absolute magnitudes have been k - and E -corrected. *Bottom panel:* Logarithm of the stellar mass vs. redshift for the DESI One-Percent LRG sample (hexagonal bins), compared to one of the UCHUU-LRG lightcones (contours).

the same E -correction, $E(z) = Q_0(z - z_0)$, where $Q_0 = 0.97$ and $z_0 = 0.1$. Figure 4 shows the stellar mass function for LRGs in the data and UCHUU One-Percent lightcones for several redshift bins. The UCHUU lightcones account for the incompleteness in the stellar mass function by randomly downsampling galaxies from the complete SMF adopted from Rodríguez-Torres et al. (2016), represented by a dashed line. The stellar mass function is observed to vary with redshift. This trend can also be seen in the bottom panel of Figure 6, where the logarithm of the stellar mass versus redshift is plotted for the DESI One-Percent LRG sample. The completeness of the SMF measured in each redshift bin is studied in Section 4.1. Both the luminosity and stellar mass included in our UCHUU galaxy catalogues allow us to study the dependence of the two-point correlation function on these properties for BGS and LRG in the DESI One-Percent survey.

4 RESULTS

In this section, we compare the clustering signal measured for each of the galaxy and quasar samples in the DESI One-Percent Survey

with that predicted by the Planck cosmology using our high-fidelity UCHUU One-Percent lightcones, as described in the previous section. Additionally, we explore the dependence of the galaxy clustering on luminosity and stellar mass for BGS and LRG, the dependence of the galaxy clustering on redshift for ELGs and QSOs, and estimate the halo occupancy and large-scale bias for all four targets.

4.1 Clustering statistics: DESI vs. UCHUU

While a more detailed description of the calculation of the clustering statistics will be given in Lasker, J. et al. (2023), we provide a brief overview specifically tailored to our analysis.

We use the Landy-Szalay (Landy & Szalay 1993) estimator to measure the two-dimensional correlation function, $\xi(s, \mu)$, in bins of s and μ , where s represents the separation between a pair of objects in units of h^{-1} Mpc, and μ is the cosine of the angle between the pair separation vector and the line-of-sight. The Landy-Szalay estimator is given by the following equation:

$$\xi(s, \mu) = \frac{DD(s, \mu) - 2DR(s, \mu) - RR(s, \mu)}{RR(s, \mu)} \quad (3)$$

where the normalized pair counts in the correlation function estimate consist of DD , representing the counts of data galaxies with other data galaxies, DR indicates counts of data galaxies with random points, and RR are the counts of random points with other random points.

We then decompose $\xi(s, \mu)$ into Legendre polynomials,

$$\xi_\ell(s) = \frac{2\ell + 1}{2} \int_{-1}^1 \xi(s, \mu) P_\ell(\mu) d\mu. \quad (4)$$

We measure the monopole and quadrupole ($\ell = 0, 2$), which are the first non-zero Legendre multipoles of the redshift-space two-point correlation function. To account for the selection function, we generate uniform random samples that are 50 times larger than the One-Percent data and use them to estimate the data-random and random-random pair counts for each tracer. We estimate the two-point correlation functions using the Python package PYCORR³, which is a wrapper for correlation function estimation wrapping a modified version of CORRFUNC (Sinha & Garrison 2020).

The data sample is primarily weighted using the Pairwise Inverse Probability (PIP) weights (Lasker, J. et al. 2023), which reflect whether pairs of galaxies would have been observed in 128 alternate realizations of DESI, in addition to which pairs are observed in the actual survey. The PIP weights are combined with FKP weights, w_{FKP} , to account for the inhomogeneous sampling density of the data sample, which are defined as:

$$w_{\text{FKP}} = \frac{1}{1 + P_0 n(z)}, \quad (5)$$

where $n(z)$ is the weighted number density, and P_0 is the power spectrum at the scale where we desire to minimize the variance. We adopt $P_0 = 7000 h^{-3} \text{Mpc}^3$ for BGS, $P_0 = 10000 h^{-3} \text{Mpc}^3$ for LRG, $P_0 = 4000 h^{-3} \text{Mpc}^3$ for ELG, and $P_0 = 6000 h^{-3} \text{Mpc}^3$ for QSO.

For ELG and QSO data clustering measurements, we apply angular upweighting based on the angular clustering of the parent and data catalogues (Mohammad et al. 2020). Random points, on the other hand, are only weighted by FKP weights.

For the BGS, we correct for incompleteness using Individual Inverse Probability weights (IIP) weights instead of PIP weights. These

³ <https://github.com/cosmodesi/pycorr>

weights were computed from the same 128 alternate realizations of DESI as the PIP weights. However, where PIP weights up-weight galaxy *pairs* by the inverse of the fraction of realizations in which the *pairs* are observed, IIP weights up-weight *individual galaxies* by the inverse of the fractions of realizations in which the *individual galaxies* were observed. The difference in the 2PCF monopole over the separation range used in the fit is $\sim 2\%$.

We use only FKP weights to measure the clustering in our UCHUU lightcones, with the same P_0 values as for the data measurements. The $n(z)$ is estimated from the mock.

Figure 7 presents the measurements of the redshift-space correlation function for the four tracers drawn from the DESI One-Percent parent samples. The monopole, $\xi_0(s)$, and quadrupole, $\xi_2(s)$, are shown for different redshift intervals indicated in the legends. The points with errors indicate the DESI One-Percent clustering measurements, and the solid curves represent the theoretical predictions based on Planck cosmology, determined from the mean of the UCHUU One-Percent lightcones, in the redshift intervals indicated in the figure caption, see also Table 1. The 1σ errors are estimated from the diagonal component of the covariance matrix obtained from our sample of UCHUU One-Percent lightcones generated for each tracer. Overall, the data is consistent with theoretical predictions.

For the BGS, we find excellent agreement between UCHUU lightcone and DESI One-Percent monopole measurements on scales smaller than $\sim 40 h^{-1}\text{Mpc}$. However, on larger scales larger cosmic variance becomes a factor, as the BGS One-Percent sample has a small volume. We also see good agreement for the quadrupole on small scales, with differences above $\sim 1 h^{-1}\text{Mpc}$.

For the LRG sample, we observe a good agreement between UCHUU lightcones and DESI One-Percent monopole and quadrupole measurements at scales larger than $5 h^{-1}\text{Mpc}$. However, on scales below $\sim 5 h^{-1}\text{Mpc}$, we find a systematically low prediction of UCHUU compared to DESI. This finding is consistent with the results obtained from our study of the dependence of clustering on stellar mass and redshift we discuss below (lower panels of Figure 8).

For the ELG sample, we find good agreement of both the monopole and the quadrupole within the region used to fit the mock monopole ($5 h^{-1}\text{Mpc} < s < 30 h^{-1}\text{Mpc}$) and excellent agreement at scales larger than $20 h^{-1}\text{Mpc}$. The smallest scales that we show here are subject to baryonic physics which we do not attempt to account for in this model.

For the QSO sample, once we account for the redshift errors, we find good agreement of both the monopole and the quadrupole within the fit region ($5 h^{-1}\text{Mpc} < s < 30 h^{-1}\text{Mpc}$) and excellent agreement at scales larger than $20 h^{-1}\text{Mpc}$. Like in ELGs, the smallest scales are subject to baryonic physics which we do not attempt to account for in this model.

The upper panels of Figure 8 illustrate the luminosity-dependent clustering for the BGS sample. We show the monopole and quadrupole for the different BGS volume-limited samples, with the redshift cuts for each absolute magnitude threshold provided in Table 4. Although we have calculated the clustering measurements for nine different volume-limited samples, we only display five in the figure to enhance clarity, with a vertical offset applied between samples. We see good agreement between the mock and BGS data for the intermediate $M_r < -20$ sample. For the brighter samples, the monopole of the mock shows stronger clustering than the data. The magnitude threshold used to define these samples is bright, where the luminosity function drops rapidly, so any small changes in the magnitudes due to e.g. errors in the E-corrections will have a large effect on the number density and clustering. Currently, we apply E-corrections to the data which come from luminosity function measurements from

the GAMA survey (McNaught-Roberts et al. 2014). We leave it for future work to improve the E-corrections in the data by measuring how the BGS luminosity function evolves with redshift, and apply a consistent evolution to the luminosity function of the mock. We have checked that adjusting the magnitude thresholds for the data by 0.1 mag brings the clustering into better agreement with the mock. For the fainter samples, which are unaffected by uncertainties in the E-corrections, the clustering in the mock is also stronger than in the One-Percent data. This difference is due to cosmic variance in this small volume, and the One-Percent data happens to have a low clustering amplitude by chance. We have verified this by comparing the clustering of the UCHUU-BGS lightcones with a larger dataset, consisting of the first 2 months of DESI observations, and we find good agreement with the UCHUU mock.

For the LRG sample, the lower panels of Figure 8 reveal a good agreement between the UCHUU lightcones and DESI One-Percent for stellar masses $\log M_* > 11.4$ (in red) in the redshift range $0.65 < z < 0.85$ (left panel), indicating that the LRG population in DESI One-Percent is complete in that range. However, at $0.45 < z < 0.65$ (middle panel), we note that UCHUU predictions remains above the data clustering signal, suggesting that the observed SMF is incomplete in that redshift range. We see a very good agreement between UCHUU and DESI for $M_* > 11.2$ and 11.3 (orange and green lines respectively) in all redshift ranges. However, for $M_* > 10.8$, the UCHUU monopole is slightly below the data. This result suggests that the complete SMF, which we have defined in the stellar mass range between 10.8 and 11.2, yields a $n(z)$ that surpasses that of the actual complete LRG population. We have verified this by measuring the clustering of galaxies with stellar masses in the specified range in the UCHUU-LRG lightcones and DESI One-Percent. The results confirm that the UCHUU signal is lower than that from the data. To estimate the complete LRG population in the $10.8 < \log_{10} M_* < 11.2$ range, we make use of the complete PRIMUS galaxy sample presented in Moustakas et al. (2013) (squares in Figure 4). Nonetheless, some discrepancies between DESI and PRIMUS samples may account for this discrepancy, such as the use of spectroscopic and photometric redshifts, respectively.

The correlation function of the ELGs, split into redshift bins, is shown in Figure 9. The apparent visual agreement of the ELG monopole and quadrupole is much better in all panels of Figure 9 compared to Figure 7, due to the reduced separation range at which we can calculate the 2PCF when the data is binned. The under-prediction of the clustering in the mocks at the smallest scales that we can see here becomes worse as redshift increases. This could point to, among other things, an increase in conformity-like effects with increasing redshift.

For QSOs, Figure 10 shows the correlation function in redshift bins. We find good agreement between UCHUU and the DESI One-Percent data in the respective bins, for both the monopole and quadrupole. The large error bars are due to the low statistics of the QSOs, since splitting the full sample into bins reduced the number of QSOs in each sample.

We also measure the power spectrum monopole, $P_0(k)$, and quadrupole, $P_2(k)$, with the Python package `pypower`⁴ which is based on the estimator from Hand et al. (2017). Similarly as for the correlation function measurements, incompleteness weights are applied to the survey data, and for both the survey data and UCHUU lightcones, FKP weights calculated from $n(z)$ and the same fiducial

⁴ <https://github.com/cosmodesi/pypower/>

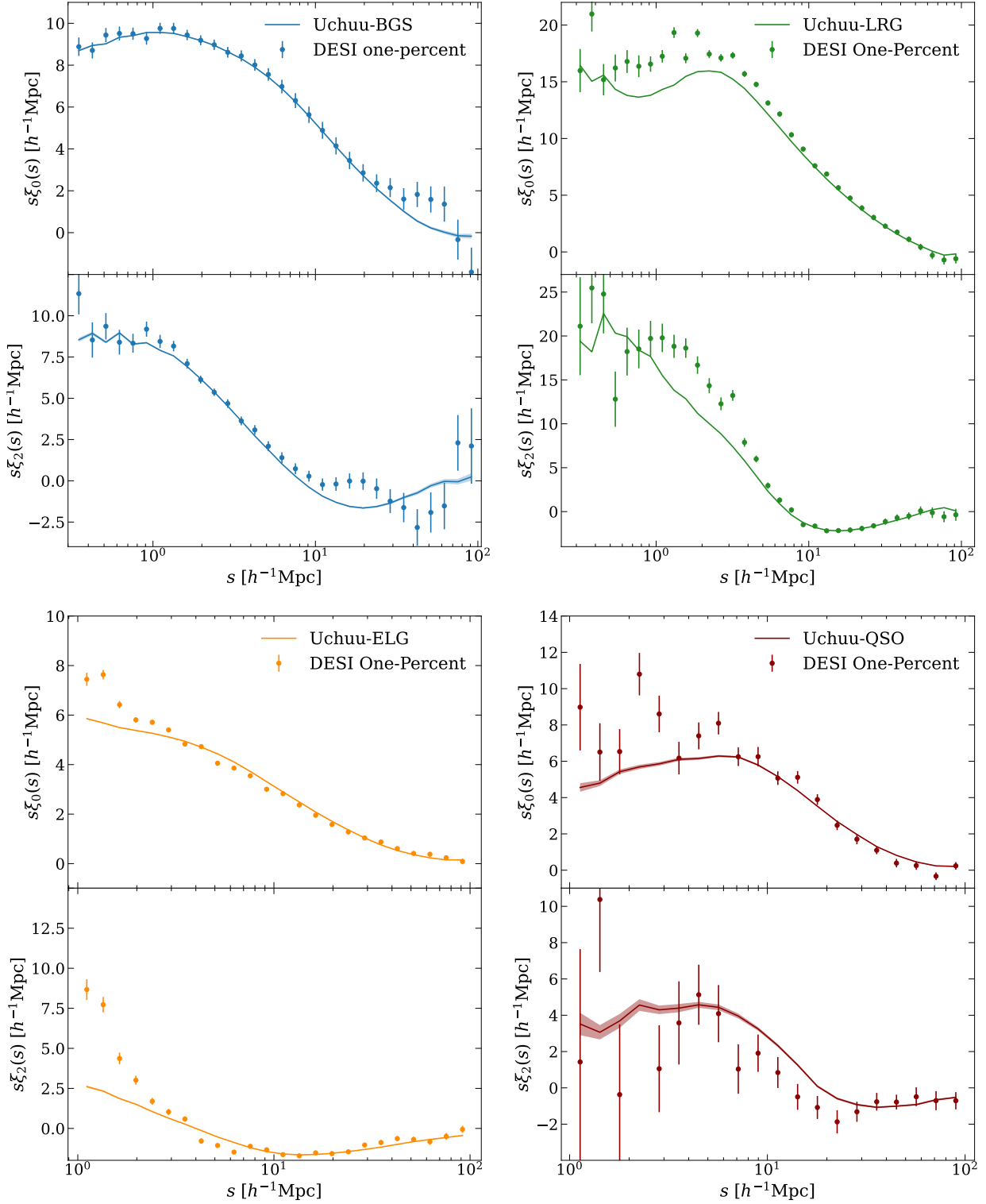


Figure 7. Measurements of the monopole and quadrupole of the redshift-space correlation function for all four tracers from the DESI One-Percent samples, in the redshift intervals $0.1 < z < 0.3$ (BGS), $0.45 < z < 0.85$ (LRG), $0.88 < z < 1.34$ (ELG) and $0.9 < z < 2.1$ (QSO). The theoretical predictions in Planck cosmology from the mean of the independent UCHUU-DESI lightcones generated for each tracer are shown as solid curves, while the shaded areas indicate the error on the mean from the 102 mocks, which is very small. The clustering measurements for the BGS, LRG, ELG and QSO are shown in blue, green, orange and red, respectively, with the monopole and quadrupole shown in the upper and lower panels. The points with error bars represent the measurements from the DESI One-Percent Survey, where the errors are the 1σ scatter between mocks. The results show good agreement between theory and observation, anticipating the power of DESI in constraining cosmological models.

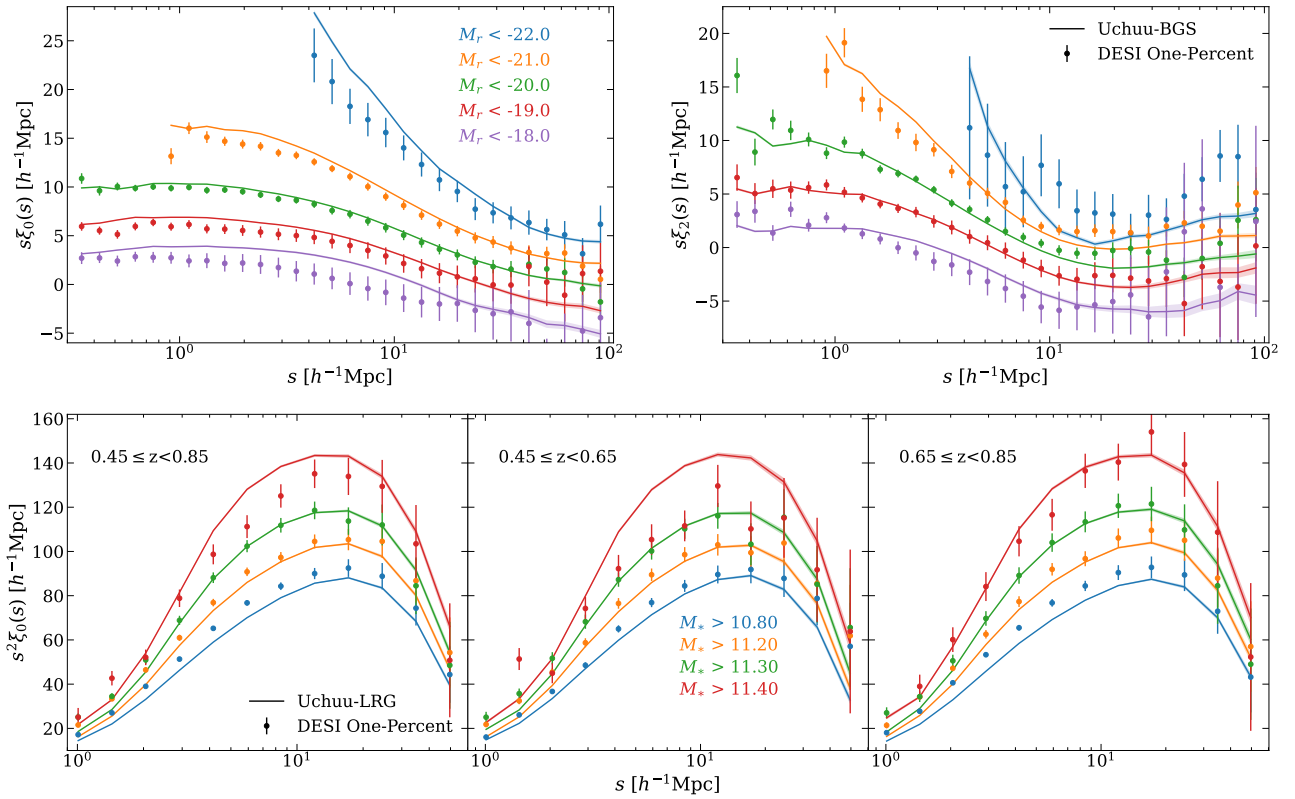


Figure 8. Top left: The monopole of the correlation function for BGS galaxies in volume-limited samples. The legend shows different magnitude thresholds with corresponding colours. The solid curves represent the mean of 102 independent UCHUU One-Percent mocks, while the shaded region denotes the error on the mean, which is small. DESI One-Percent clustering measurements are indicated by the points with error bars, where the errors are the 1σ scatter between the mocks. Each magnitude threshold sample is vertically offset relative to the $M_r < -20$ sample. Top right: The corresponding correlation function quadrupoles for BGS volume-limited samples. Bottom: The monopole of the correlation function for LRG galaxies, in stellar mass threshold samples and for different redshift bins. The legend shows different stellar mass thresholds with corresponding colors, and the redshift ranges are $0.45 \leq z < 0.85$, $0.45 \leq z < 0.65$, and $0.65 \leq z < 0.85$ from left to right.

power P_0 as above are also applied to each tracer. To minimise the amount of aliasing from discrete Fourier sampling, we have used the piecewise cubic spline (PCS) mesh assignment scheme with a grid number $N_{\text{grid}} = 1024$ in each dimension with interlacing (Sefusatti et al. 2016). For each of the four tracers, Figure 11 shows the power spectrum multipoles over the wavenumber range $k \in [0.005, 0.505] h\text{Mpc}^{-1}$ in 50 uniform bins. The solid lines show the mean power spectrum over 102 UCHUU lightcones, and the data points show the measurements from the DESI One-Percent samples with error bars given by the standard deviation of the UCHUU lightcone measurements. The shaded regions correspond to the error on the mean of the UCHUU lightcone measurements calculated from the standard deviation rescaled by $\sqrt{102}$.

The power spectrum measurements performed here are similar to the BOSS and eBOSS power spectra (Beutler et al. 2017; Gil-Marín et al. 2020; de Mattia et al. 2021; Neveux et al. 2020), where the local plane-parallel approximation is adopted to account for a varying line of sight (Feldman et al. 1994; Yamamoto et al. 2006). The local line of sight is chosen to be the end-point vector to one of the galaxies in a pair, which enables fast, FFT-based evaluations to be carried out (Bianchi et al. 2015). A minor difference here is that the normalisation factor is computed directly from the mesh field instead of relying on the angularly uniform quantity, $n(z)$. Besides the fact that the DESI One-Percent samples are smaller in area with stronger window effects on large scales, and smaller in size resulting in higher

shot noise (which is subtracted accordingly), the power spectrum estimates are comparable to those from BOSS and eBOSS for the LRG, ELG and QSO samples. For the BGS sample, a comparison can be made with the main galaxy sample (MGS) from the SDSS survey in Tegmark et al. (2004), Percival et al. (2007) and Ross et al. (2015). However, it is worth noting that Tegmark et al. (2004) measures a different combination of the power spectrum multipoles with a minimum-variance quadratic estimator; focusing on the monopole only, Percival et al. (2007) has combined the MGS dataset with the 2dFGRS sample, and Ross et al. (2015) has moreover restricted MGS galaxies to those residing in high-mass haloes resulting in a larger clustering amplitude.

4.2 Mean Halo-Occupancy of DESI One-Percent tracers

The abundance matching technique implemented in UCHUU provides a complete determination of the distribution and properties of all four DESI tracers within their host dark matter haloes. This allows us to estimate the mean number of galaxies or quasars within a dark matter (sub)halo of virial mass M_{halo} for each tracer sample. In Figure 12, we present the mean halo occupancy as a function of halo mass for BGS BRIGHT, LRG, ELG, and QSO tracers, obtained from our independent set of UCHUU lightcones. The clustering signal of the same samples for the One-Percent survey is shown in Figure 7). In our simulation, we can distinguish between central galaxies/quasars

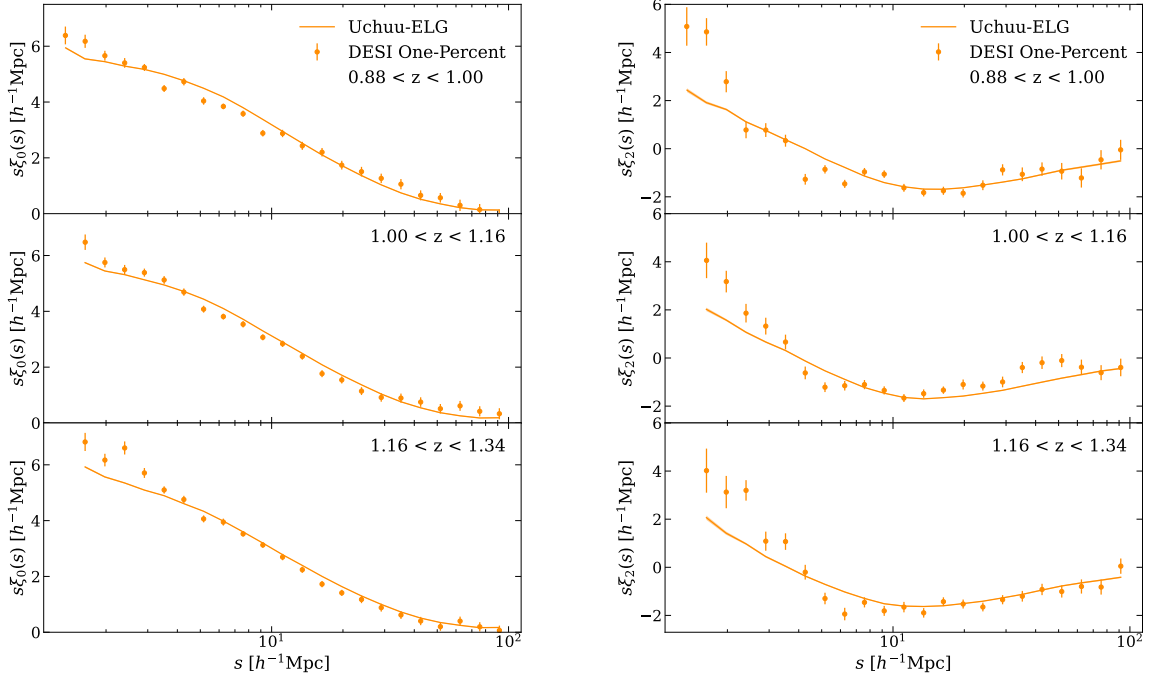


Figure 9. Measurement of the monopole and quadrupole of the redshift-space correlation function for ELGs from the DESI One-Percent parent samples in their respective redshift bins. The solid curves show the mean of the 102 UCHUU One-Percent mocks, where the shaded region is the error on the mean. DESI One-Percent clustering measurements are indicated by the points with error bars, where the errors are the 1σ scatter between the mocks. We note the good agreement between data and model on scales larger than $2 h^{-1}\text{Mpc}$, and the noticeable discrepancy on the smallest scales, see text.

residing in their host haloes and satellite galaxies/quasars that live in subhaloes. By doing so, we are able to measure the HOD separately for centrals and satellites. These are shown by the dotted and dashed curves in Figure 12, respectively, for each tracer.

The central and satellite HODs for the BGS sample show different behaviours. The central HOD increases smoothly as halo mass increases, with all high mass haloes containing a central BGS galaxy, while at low masses, the occupancy is zero, and there is a smooth transition in between due to scatter in the relationship between halo mass and galaxy luminosity. The satellite HOD, on the other hand, follows a power law that drops off more rapidly at low masses. For galaxy samples such as the BGS, where there is a monotonic relationship between halo mass and luminosity (with scatter), the HOD is commonly described using a 5-parameter form (e.g. see Zehavi et al. 2011), where for central and satellite galaxies,

$$\begin{aligned} \langle N_{\text{cen}} \rangle &= \frac{1}{2} \left[1 + \text{erf} \left(\frac{\log M - \log M_{\text{min}}}{\sigma_{\log M}} \right) \right] \\ \langle N_{\text{sat}} \rangle &= \langle N_{\text{cen}} \rangle \left(\frac{M - M_0}{M_1} \right)^\alpha. \end{aligned} \quad (6)$$

In this HOD parametrisation, the position and width of the central galaxy step function are set by M_{min} and $\sigma_{\log M}$. The satellite power-law slope is denoted by α , M_1 the normalisation, and M_0 represents the low mass cutoff.

For the LRG sample, the shape of the HOD is similar to the BGS. Since LRG lives in more massive haloes, the central HOD is shifted to higher masses compared with the BGS. However, at very high

masses, the central occupancy is less than 1. As can be seen in Figure 4, at very high stellar masses there seems to be an incompleteness in the observed galaxy population, so that the complete SMFs assumed in the SHAM remains above the data, resulting in the HOD dropping below 1 when the incompleteness is added. We use the same 5-parameter HOD to model the LRG occupation function, which is discussed in Section 4.2.2.

For the ELG and QSO samples, the central HOD strongly shows the influence of our model with the occupation fraction resembling a Gaussian in M_{halo} . This is expected due to the strong correspondence between V_{peak} and M_{halo} . The satellite component rises more quickly at high M_{halo} for ELGs than QSOs. This is a result of the ELG sample having a lower best-fit V_{mean} than the QSO sample as shown in Table 3 as well as the much larger sample size of ELGs.

In upcoming sections, we will explore how the halo occupation distribution of the various tracers depends on luminosity or stellar mass as well as redshift.

4.2.1 BGS HOD: luminosity dependency

We have obtained the HOD for nine different volume-limited samples, in addition to the full BGS-BRIGHT sample presented in Figure 12. The first two columns of Table 4 provide the magnitude thresholds and maximum redshifts defining these samples. We display five of these HODs using coloured curves in the left panel of Figure 13. Although the HOD for each sample has a shape that is very similar to the total sample shown in Figure 12, the HOD shifts

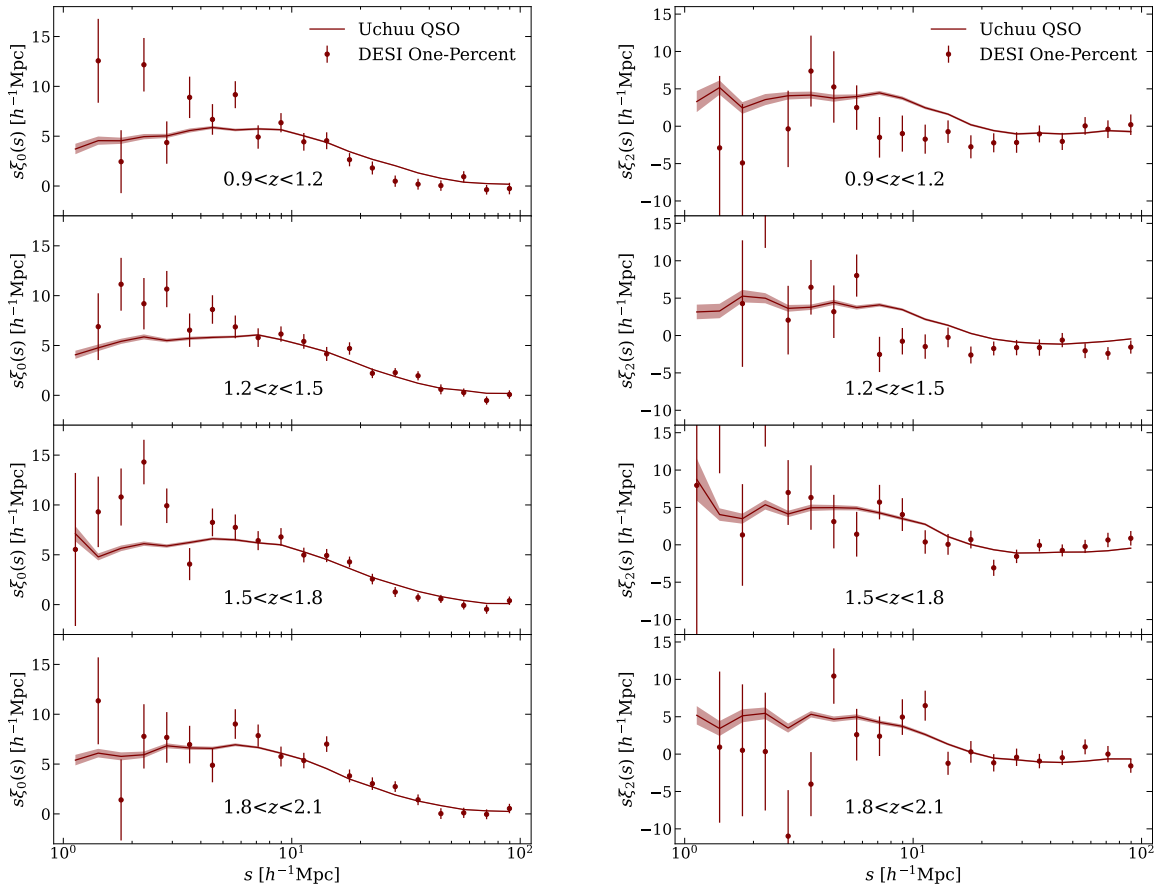


Figure 10. The same as Figure 9 but showing the clustering of the QSOs. The left panels show the monopole, the right panels show the quadrupole, and each row is for a different redshift bin. The good agreement between DESI and UCHUU suggests that our modeling of the QSO distribution is accurate.

to higher masses for the brighter samples, because bright galaxies live in more massive haloes.

To investigate the dependence of the HOD on the absolute magnitude threshold of our galaxy samples, we fit the 5-parameter HOD form from Equation 6 to the HODs obtained from the full-sky UCHUU BGS mock. Since the area of the full-sky mock is roughly twice as large as the combined area of the 102 smaller mocks, our HOD statistics are improved, particularly at the high-mass end. We separately fit the HOD for central and satellite galaxies using the non-linear least squares method, taking into account the uncertainty in the Uchuu HOD measurements as estimated from splitting the full sky into 100 jackknife regions. We split the area of the full sky into 100 equal area jackknife regions based on cuts in right ascension and declination, and we measure the HOD with each subvolume omitted once. We restrict the HOD fit to halo masses M_{halo} between 10^{11} and $3 \times 10^{15} h^{-1} M_{\odot}$, and where the occupation number $\langle N \rangle$ is greater than 10^{-2} . The resulting best-fitting HODs are shown as black dotted curves in Figure 13.

The top row of Table 4 shows the best-fit HOD of the full BGS

sample, as shown in Figure 12, while the remaining rows list the HOD parameters for the nine volume-limited samples. We also provide the satellite fractions in Table 4 calculated from our HOD fits, and also measured directly from the UCHUU mocks. Since the uncertainties in the HOD measurements from the full-sky mock are very small, we also obtain very small uncertainties in the best-fit HOD parameters, and quoting them would be misleading. To provide a more realistic estimate of the HOD uncertainties, one needs to consider the uncertainties in the luminosity function and intrinsic scatter parameter used in the SHAM procedure to construct the lightcone. However, since we only have one UCHUU simulation, we cannot estimate these uncertainties.

Figure 13 compares the best-fitting BGS HODs for five of the volume-limited samples to the HODs measured from the UCHUU lightcone. Although the 5-parameter HOD form provides reasonable fits by eye, the small uncertainties in the HOD measurements from the mock lead to very large χ^2/dof values, indicating poor fits. While the simple 5-parameter parametrisation approximates the HODs reasonably well, it fails to fully capture the shape predicted

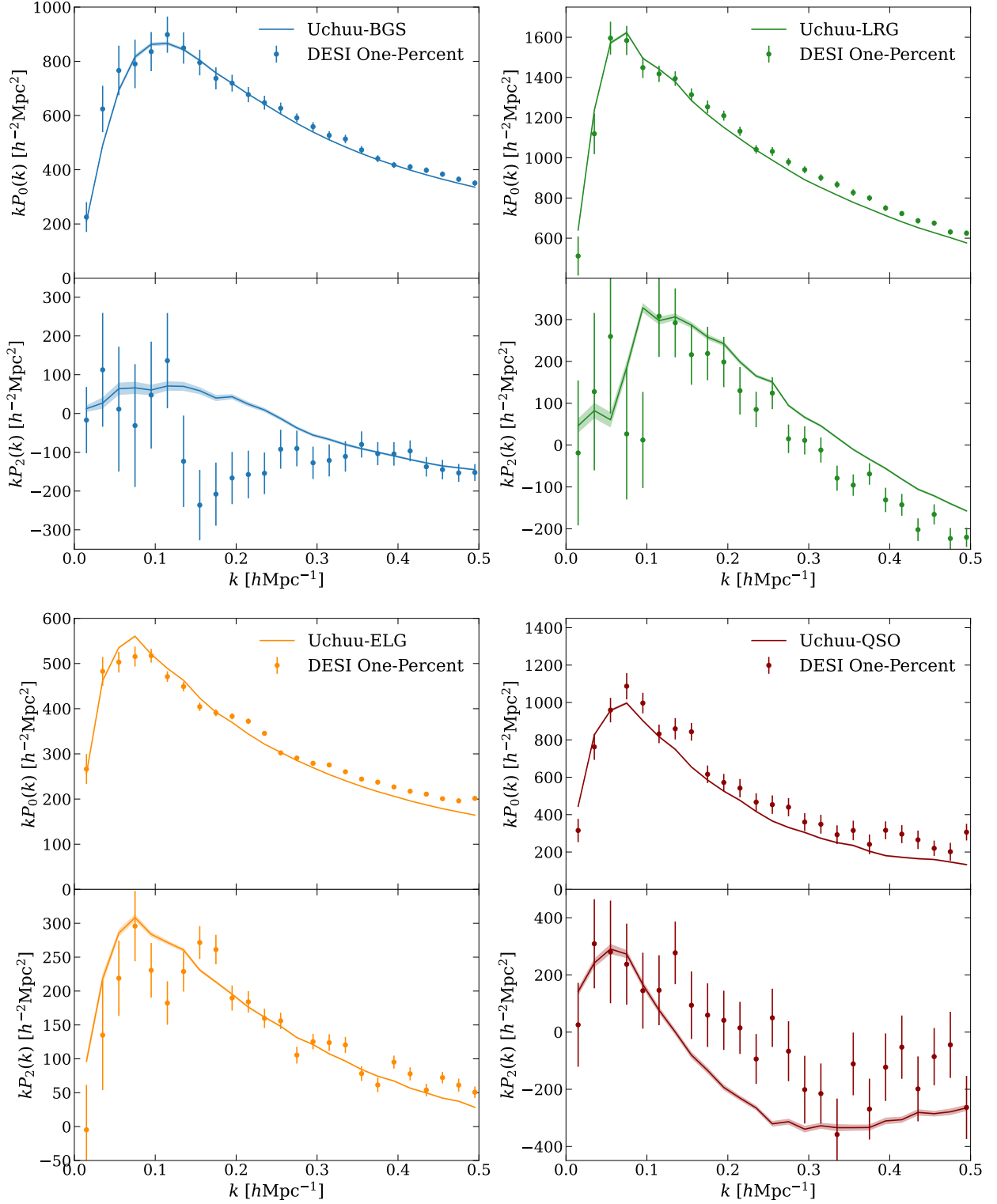


Figure 11. Power spectrum monopole and quadrupole measurements of the four DESI tracers, for the same samples as in Figure 7. The BGS, LRG, ELG and QSO samples are shown in blue, green, orange and red, respectively, with the power spectrum monopole in the upper panels, and quadrupole in the lower panels. The solid lines and the points with error bars show the measurements from UCHUU and the One-Percent Survey data, respectively. Error bars represent the 1σ scatter between the 102 mocks.

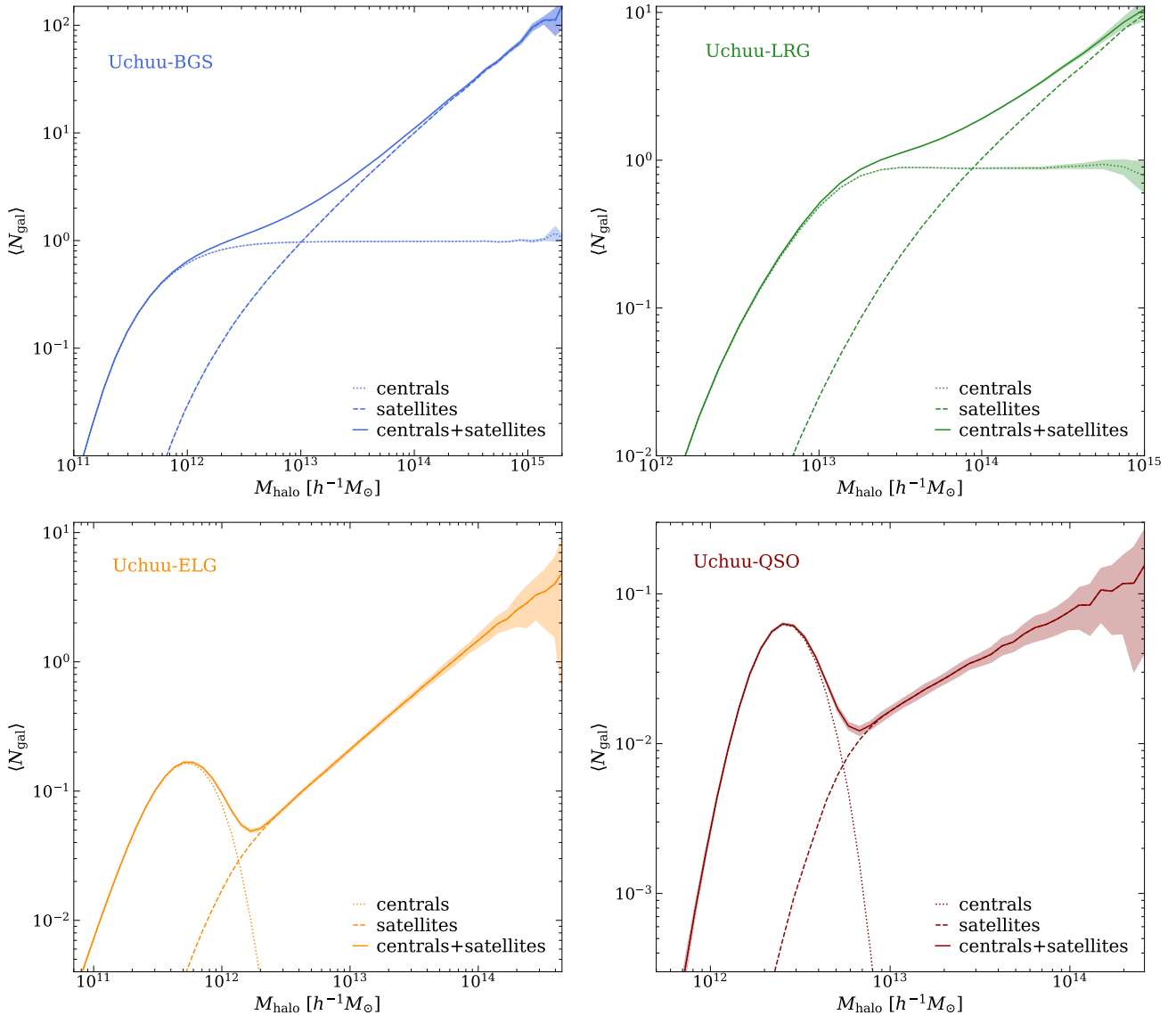


Figure 12. Mean halo occupancy of BGS (top-left panel), LRG (top-right panel), ELG (bottom-left panel), and QSO (bottom-right panel) samples, as determined from our UCHUU lightcones. The mean number of galaxies of a halo with a given mass M_{halo} is denoted by $\langle N_{\text{gal}} \rangle$. The solid lines represent the combined centrals and satellite occupation, while the dotted and dashed lines show the mean halo occupancy for centrals and satellites, respectively. The shaded area indicates the 1σ uncertainty of the occupation measured from the UCHUU lightcones. For BGS, this is a jackknife error from the full-sky mock, split into 100 jackknife regions. For the other tracers, this is the 1σ scatter between the 102 mocks. The best-fit HOD model parameters for BGS and LRG are listed in Tables 4 and 5, respectively.

by the UCHUU BGS lightcone. Specifically, the shape of the smooth central step function does not perfectly match the shape of the error function, and the satellite power-law slope is not strictly a simple power law.

The trends in the best-fitting HOD parameters and satellite fractions as a function of BGS luminosity are shown in Figure 14 (solid symbols). These trends are consistent with previous SDSS studies such as Zehavi et al. (2011) and Dong-Páez et al. (2022), as indicated by the dashed line obtained from the latter. The three mass parameters increase for brighter samples, which is expected since brighter galaxies typically reside in more massive haloes. The scatter parameter $\sigma_{\log M}$, also increases for the brighter samples, as the SHAM method applies a constant intrinsic scatter to the assigned magnitudes. This constant scatter leads to a wider step function for central

galaxies at brighter magnitudes, as the galaxy luminosity function falls off exponentially at the bright end. The agreement between the satellite fractions obtained from the HOD analysis and UCHUU is remarkable, with a decreasing trend expected as the luminosity (and hence host halo mass) of the galaxies in the sample increases. The power-law slope $\alpha \approx 1$ for all BGS samples, but it decreases for the brightest sample. Interestingly, we do not observe an increase of α for the largest luminosities as reported in previous studies such as (e.g. Zehavi et al. 2011) for SDSS. It is worth noting that for the $M_r < -22$ sample, as previously mentioned, the parameter M_0 is unconstrained. Notably for this sample, the low-mass cutoff in the satellite HOD is well modeled by the central HOD, and therefore, the additional M_0 parameter is not necessary.

We describe the relation between the mass scales in our HOD

M_r^{th}	z_{max}	N_{eff}	V_{eff}	$\log n_{\text{g}}^{\text{BGS}}$	$\log n_{\text{g}}^{\text{Uchuu}}$	$\log M_{\text{min}}$	$\sigma_{\log M}$	$\log M_0$	$\log M'_1$	α	$f_{\text{sat}}^{\text{HOD}}$	$f_{\text{sat}}^{\text{Uchuu}}$	b^{BGS}	b^{Uchuu}
$r < 19.5$	0.3	101909	10.48	-1.99	-1.86 ± 0.01	11.88	0.51	11.65	13.02	1.04	0.226	0.223	1.04 ± 0.05	1.110 ± 0.005
-18.0	0.10	12159	0.42	-1.52	-1.54 ± 0.04	11.31	0.28	11.49	12.59	0.99	0.267	0.26	0.76 ± 0.19	1.027 ± 0.018
-18.5	0.12	16764	0.76	-1.66	-1.66 ± 0.03	11.44	0.30	11.59	12.69	1.00	0.259	0.25	0.81 ± 0.17	1.065 ± 0.016
-19.0	0.15	24089	1.49	-1.73	-1.80 ± 0.03	11.59	0.33	11.69	12.82	1.00	0.251	0.246	1.02 ± 0.12	1.110 ± 0.012
-19.5	0.20	38522	3.46	-1.92	-1.97 ± 0.02	11.76	0.35	11.79	12.96	1.01	0.239	0.237	0.98 ± 0.09	1.144 ± 0.009
-20.0	0.25	44867	6.45	-2.14	-2.18 ± 0.02	11.99	0.39	11.96	13.14	1.01	0.225	0.225	1.17 ± 0.07	1.206 ± 0.007
-20.5	0.30	39591	10.37	-2.38	-2.46 ± 0.02	12.30	0.46	12.10	13.39	1.02	0.204	0.209	1.20 ± 0.06	1.289 ± 0.006
-21.0	0.35	25511	14.29	-2.74	-2.83 ± 0.02	12.73	0.57	12.21	13.73	1.02	0.179	0.188	1.33 ± 0.10	1.414 ± 0.010
-21.5	0.425	13184	16.78	-3.21	-3.36 ± 0.01	13.31	0.73	11.95	14.15	0.97	0.151	0.160	1.51 ± 0.10	1.638 ± 0.010
-22.0	0.50	3600	5.82	-3.79	-4.14 ± 0.02	14.05	0.86	—	14.73	0.86	0.111	0.128	1.81 ± 0.16	2.003 ± 0.016

Table 4. HOD parameters and bias factors of the BGS parent and volume-limited samples. The first two columns show the absolute magnitude threshold and the maximum redshift used to define the volume-limited samples. All volume-limited samples have a minimum redshift $z_{\text{min}} = 0.05$, while for the $r < 19.5$ sample, the redshift range is $0.1 < z < 0.3$. The following columns give for each sample the number of galaxies, the effective volume (in $10^6 h^{-3} \text{Mpc}^3$), \log_{10} of the galaxy number density (in $h^3 \text{Mpc}^{-3}$), the 5 parameters of the HOD model fit to its mean halo occupancy, displayed in the left panel of Figure 12. Halo masses are in units of $h^{-1} M_{\odot}$. $f_{\text{sat}}^{\text{HOD}}$ is the satellite fraction calculated using the best-fitting 5 parameter HOD, while $f_{\text{sat}}^{\text{Uchuu}}$ is the satellite fraction measured directly from the UCHUU BGS mock. The last two columns provide the bias factors at the median redshift of each sample measured from the UCHUU-BGS lightcones and One-Percent data, as shown in Figure 15.

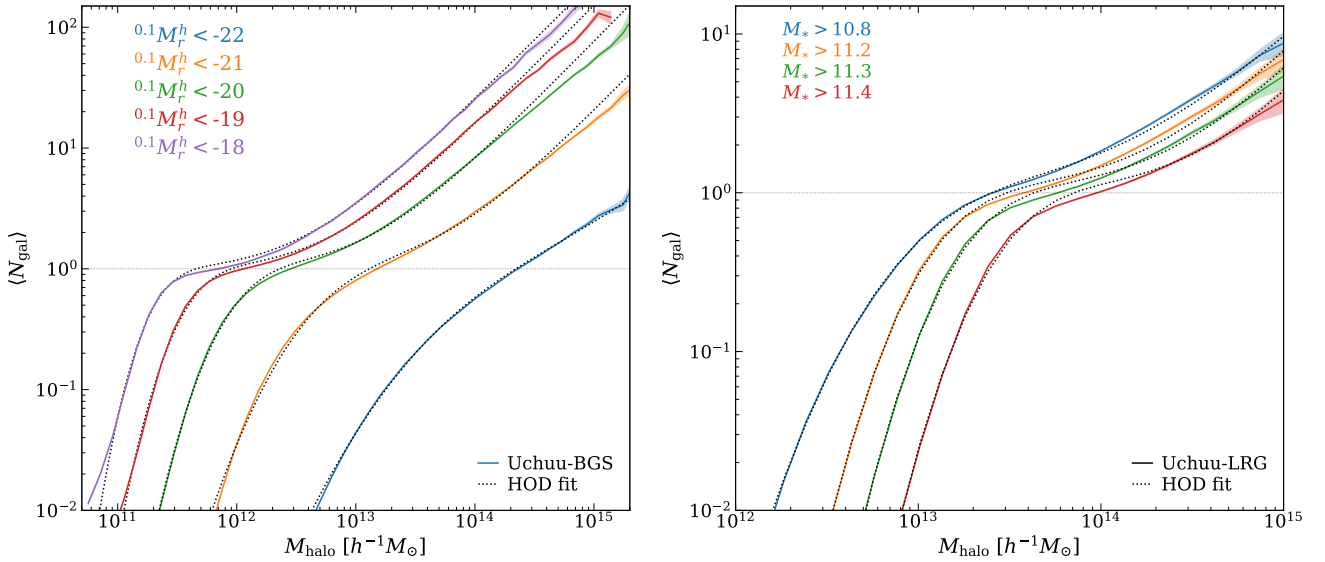


Figure 13. The same as Figure 12 but showing the HODs for several BGS BRIGHT luminosity-threshold (left panel) and LRG stellar mass-threshold samples (right panel), selected from our UCHUU-DESI lightcones. The coloured curves show the HODs measured from the full-sky mock, where the sample is indicated in the legend, and the shaded area indicates the jackknife error, using 100 jackknife regions. The best-fitting 5-parameter HOD model for each sample is shown by the black dotted curves. HOD model parameters are provided in Table 4 and Table 5 for the BGS and LRG samples, respectively.

parametrisation (Equation 6) and the absolute magnitude threshold by adopting the same functional form proposed by Zehavi et al. (2011). This is given by

$$M_r = M_r^* + A - 2.5 \log_{10} \left[\left(\frac{x}{M_t} \right)^{\alpha_M} \exp \left(1 - \frac{M_t}{x} \right) \right], \quad (7)$$

where $x \in \{M_{\text{min}}, M_1, M_0\}$. The normalisation A represents the median luminosity of central galaxies (in units of magnitude, relative to $M_r^* = -20.44$, Blanton et al. 2003) in halos of the transition mass, M_t (in units of $h^{-1} M_{\odot}$). α_M is the power-law index. The solid lines in the bottom panel of Figure 14 correspond to the fits with the best-fitting parameters. For M_{min} , $\{A, M_t, \alpha_M\} = \{1.450, 3.658 \times 10^{11} h^{-1} M_{\odot}, 0.320\}$. For the parameter M_1 , $\{A, M_t, \alpha_M\} = \{1.168, 7.612 \times 10^{12} h^{-1} M_{\odot}, 0.366\}$. For M_0 , $\{A, M_t, \alpha_M\} = \{1.880, 3.951 \times 10^{11} h^{-1} M_{\odot}, 1.0\}$.

The scatter in the relationship between halo mass and galaxy luminosity, denoted by $\sigma_{\log M}$, can be expressed through the equation

$$\sigma_{\log M} = a + \frac{b - a}{1 + \exp(M_r - M_r^* + c)}. \quad (8)$$

We also find that the same function form provides a good fit to the satellite fraction, $f_{\text{sat}}^{\text{Uchuu}}$, obtained from the UCHUU lightcones. The solid lines in the top panel of Figure 14 correspond to the fits. The best-fitting parameters for $\sigma_{\log M}$ are $\{a, b, c\} = \{0.265, 1.612, 1.769\}$ and for $f_{\text{sat}}^{\text{Uchuu}}$, we obtain $\{a, b, c\} = \{0.261, 0.199, -0.742\}$. The satellite power-law slope α is assumed to be 1, as expected.

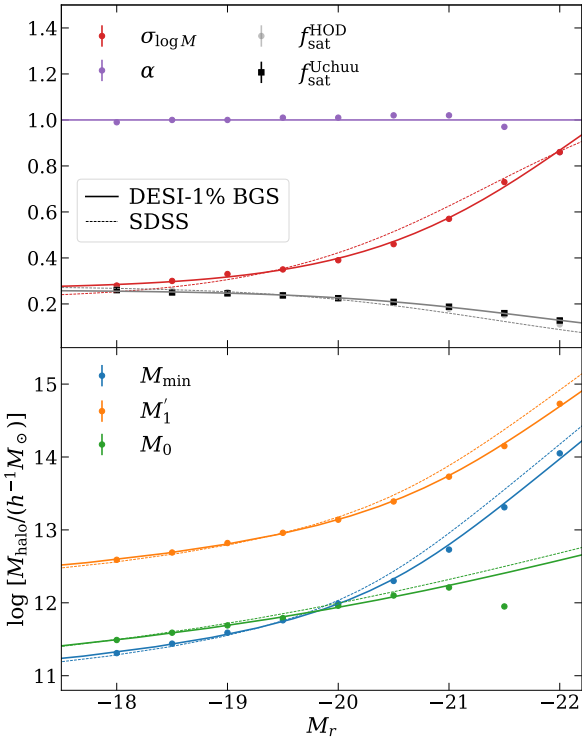


Figure 14. Best-fitting BGS HOD parameters and satellite fractions (points), as a function of magnitude threshold. The top panel shows the $\sigma_{\log M}$ (red) and α (purple) HOD parameters, plus the satellite fractions from our HODs (light grey) and Uchuu (dark grey). The mass parameters M_{\min} (blue), M_1 (orange) and M_0 (green) are shown in the lower panel. The dashed lines indicate the SDSS results obtained from Dong-Páez et al. (2022), while the solid lines correspond to our approximations given by the equations included in the text. For the $M_r < -22$ sample, the M_0 parameter is completely unconstrained.

4.2.2 LRG HOD: stellar mass dependency

The HODs predicted by UCHUU for LRG samples with different stellar mass cuts are shown in the right panel of Figure 13. For clarity, we show only four out of the five different samples. The stellar mass thresholds defining these samples are provided in Table 5. Similar to the BGS sample, the HOD of the total LRG sample (shown in the top-left panel of Figure 12) and the stellar mass threshold samples have very similar shapes. However, the HODs are shifted towards higher halo masses for higher stellar mass samples, as more massive galaxies tend to inhabit in more massive halos.

To assess the dependence of the HOD on the stellar mass threshold, we used the 5-parameter HOD of Equation 6 to fit the mean HOD obtained from the four UCHUU-LRG boxes with the SMF incompleteness already taken into account. As we did for the BGS sample, we performed separate fits for the central and satellite galaxies using the non-linear least squares method. For LRGs, we estimated the uncertainty in the mean HOD by assuming a Poisson distribution for the number of galaxies and calculating the associated error as \sqrt{N} , where N is the number of galaxies within each host halo mass bin. We assumed that there were no systematic uncertainties or selection biases in the halo mass measurements or binning process. Table 5 shows the HOD parameters that provide the best-fitting HODs, which are shown as dashed black curves in the right-hand panel of Figure 13.

Our findings are in agreement with previous BOSS LRG studies

(e.g. Nuza et al. 2013; Tinker et al. 2017; Stoppacher et al. 2019), showing that all halo mass HOD parameters increase with the stellar mass threshold, given that more massive galaxies inhabit more massive haloes. We also find that the power law slope, α , increases with the stellar mass threshold, with a value of $\alpha \approx 1$ for the complete and lowest stellar mass threshold samples. On the other hand, the parameter $\sigma_{\log M}$ remains constant for the 11.4, 11.3 and 11.2 stellar mass samples. However, as the stellar mass threshold decreases, the effect of SMF incompleteness enhances (see Figure 4), and a flatter central curve is obtained, which results in an increase in the value of $\sigma_{\log M}$.

As depicted in Figure 13, the 5-parameter HOD approximation produces fits that agree well with the mean measurement from the boxes. Nevertheless, for host halo masses above $3 \times 10^{13} h^{-1} M_{\odot}$, the model fails to fully capture the shape predicted by UCHUU. Specifically, the satellite HOD exhibits the largest discrepancy between the model and data.

4.2.3 ELG & QSO HODs

Due to the substantial impact of the modified SHAM method on the resulting halo occupation distribution, and the adoption of the same procedure for selecting both ELGs and QSOs, we analyze and discuss them together.

The HOD analysis of the ELG mocks reveals two mostly distinct components. The component of the HOD from the centrals follows a Gaussian distribution which dominates where $M_{\text{halo}} < 1.25 \times 10^{12} h^{-1} M_{\odot}$, while the satellites exhibit a power-law distribution which dominates at $M_{\text{halo}} > 1.25 \times 10^{12} h^{-1} M_{\odot}$. The central halos reach a peak occupation of 0.17, observed at $M_{\text{halo}} = 4.7 \times 10^{11} h^{-1} M_{\odot}$.

Comparing the HOD results with those from Favole et al. (2017) is challenging due to differences in the definition of halo occupancy. Favole et al. (2017) determine halo occupancy based on a denominator that includes only halos with centrals in their mock, rather than considering all distinct halos in the simulation. For their most inclusive sample ($L[\text{OII}] > 1 \times 10^{39} \text{ erg s}^{-1}$), they observe a peak central occupancy of about ~ 0.01 over the mass range from $10^{12} M_{\odot}$ to $3.2 \times 10^{13} M_{\odot}$.

Similar to the ELG HOD, the QSO HOD also exhibits a Gaussian distribution for the centrals, characterized by $M_{\text{halo}} < 6.3 \times 10^{12} h^{-1} M_{\odot}$, and a power-law behavior for the satellites, with $M_{\text{halo}} > 1.6 \times 10^{12} h^{-1} M_{\odot}$. The mean halo mass for the central quasars is $M_{\text{halo}} = 2.1 \times 10^{12} h^{-1} M_{\odot}$. This slightly deviates from the reported mean halo mass values reported in Rodríguez-Torres et al. (2017) for eBOSS QSOs, ranging from $3.2 \times 10^{12} h^{-1} M_{\odot}$ to $6.6 \times 10^{12} h^{-1} M_{\odot}$. This is expected since the reported V_{mean} values in their study are higher compared to the values presented in this paper. However, despite these differences in numerical values, the shapes of the HOD in both DESI and eBOSS studies exhibit a similar pattern.

4.3 Large-scale bias of all four tracers

The large-scale bias, b , for each of the four DESI tracers was measured from the DESI One-Percent Survey and compared to their prediction obtained from the UCHUU lightcones in the Planck cosmology. The results are presented in Figure 15. We performed these measurements of the linear bias by fitting

$$\xi_0(s) = b^2 \left(1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2 \right) \xi_{\text{lin}}(s) \quad (9)$$

$\log M_\star$	N_{eff}	V_{eff}	$\log n_g^{\text{LRG}}$	$\log n_g^{\text{Uchuu}}$	$\log M_{\text{min}}$	$\sigma_{\log M}$	$\log M_0$	$\log M'_1$	α	$f_{\text{sat}}^{\text{HOD}}$	$f_{\text{sat}}^{\text{Uchuu}}$	b^{LRG}	b^{Uchuu}
all	67466	91.50	-3.286	-3.286±0.001	13.04	0.53	11.95	14.08	1.03	0.117	0.119	1.89±0.05	1.847±0.005
10.8	66079	90.89	-3.294	-3.295±0.001	13.03	0.51	12.19	14.09	1.04	0.113	0.117	1.91±0.05	1.857±0.005
11.0	58609	87.19	-3.344	-3.347±0.001	13.04	0.44	12.36	14.15	1.07	0.103	0.111	1.96±0.05	1.900±0.005
11.2	37516	71.77	-3.533	-3.541±0.002	13.14	0.37	12.47	14.29	1.17	0.085	0.095	2.06±0.06	2.032±0.006
11.3	22006	51.40	-3.784	-3.772±0.003	13.29	0.36	12.72	14.41	1.21	0.076	0.081	2.15±0.07	2.189±0.007
11.4	11069	27.49	-4.100	-4.071±0.004	13.51	0.36	12.75	14.59	1.30	0.062	0.066	2.35±0.08	2.429±0.008

Table 5. HOD parameters and bias factors of the LRG samples with different stellar mass thresholds. The first column show the stellar mass (in M_\odot units) threshold used in each sample. The remaining columns are the same as described in Table 4. We provide the HOD model parameters (and 1σ errors) fitted to its mean halo occupancy, shown in the right panel of Figure 13. The last two columns present the bias factors measured from DESI and UCHUU at the median redshift, $z = 0.65$, of the samples, as shown in Figure 15.

to our correlation function monopole measurements, $\xi_0(s)$, over a given range of separations. $\xi_{\text{lin}}(s)$ is from the linear power spectrum at the redshift of our galaxy sample, and $\beta = \Omega_m^{0.6}/b$ (see Kaiser 1987; Hamilton 1998). The details and description of results are provided below for each tracer.

The linear bias for the BGS magnitude threshold samples are measured by, at the median redshift of each volume-limited sample, over the separation range $8 < s < 20 h^{-1}\text{Mpc}$ for most samples, except for the three brightest thresholds, where we use $15 < s < 40 h^{-1}\text{Mpc}$ (blue symbols in the top-left panel of Figure 15). As expected, the brightest galaxies have the highest bias, since they live in the most massive haloes, which are more strongly clustered. The bias values measured from the DESI One-Percent data (orange symbols) tend to be smaller than the predictions from the UCHUU mock. However, this can be explained by cosmic variance, since the volume of the One-Percent Survey is small and the uncertainties are large. We also show the good agreement with bias factors measured by Dong-Páez et al. (2022) for the SDSS, who also used our UCHUU simulation (green symbols). Note that we are fitting a linear model to clustering measurements on relatively small quasi-linear scales. On very large scales where linear theory is valid, our One-Percent Survey clustering measurements are dominated by noise due to the small survey volume. To obtain precise bias values, we had to restrict our fits to small scales. We have checked that the ratio $\xi_0(s)/\xi_{\text{lin}}(s)$ is flat over the scales used when fitting the bias. For the brightest samples, this ratio deviates from being flat at larger scales than the faint samples, which is why we use a different fitting range. Even on these small scales, the clustering of the faint samples are affected by cosmic variance, which is reflected in the large bias errors. Using larger datasets in the future will allow us accurately measure the bias on truly linear scales.

Following Zehavi et al. (2011), the bias as a function of magnitude can be modelled as

$$b(< M_r) = B_0 + B_1 \times 10^{B_2(M_r^* - M_r)/2.5} \quad (10)$$

where $M_r^* = -20.44$. We fit this to the bias measurements from the UCHUU-BGS mock, and the One-Percent BGS data, taking into account the uncertainties shown in Figure 15. For the UCHUU-BGS mock, we measure $\{B_0, B_1, B_2\} = \{1.03 \pm 0.01, 0.24 \pm 0.01, 0.95 \pm 0.04\}$, while for the DESI BGS, our best-fitting values are $\{B_0, B_1, B_2\} = \{0.59 \pm 0.43, 0.62 \pm 0.45, 0.43 \pm 0.29\}$. Since the uncertainties in the BGS bias measurements are large, the uncertainties in these parameters are also large. For UCHUU-SDSS $\{B_0, B_1, B_2\} = \{0.97 \pm 0.03, 0.27 \pm 0.02, 0.91 \pm 0.08\}$. We find reasonable agreement between these fits, although for the One-Percent data, the parameter B_0 is smaller than is measured in the mock. We caution against a direct comparison to the bias measurements of Zehavi et al. (2011), since these are done at $z = 0$, and in a differ-

ent cosmology. However, the UCHUU-SDSS mock matches well the clustering from SDSS (Dong-Páez et al. 2022).

The top-right panel of Figure 15 shows the large-scale bias factors of the LRGs, measured between 15 and $35 h^{-1}\text{Mpc}$, for the different stellar mass threshold samples. The results are as expected: the higher the stellar mass threshold, the larger the bias, since more massive galaxies reside in more massive halos which are, as mentioned above for BGS galaxies, more strongly clustered. The model and data agree well within the uncertainties. The bias factors are similar to those measured for BOSS LRGs.

The bias of ELGs vs redshift is shown in the bottom-left panel of Figure 15. The bias was calculated for each box defined in Table 2 and for the data cut into the same redshift range covered by the mocks. As in Avila et al. (2020) we use a separation range of $20 h^{-1}\text{Mpc}$ to $55 h^{-1}\text{Mpc}$ to facilitate comparison with their results. We find good agreement between the bias measured from the data and the bias measured from the mocks. Additionally, we have overplotted the single bias measurement of Avila et al. (2020) at the median redshift of their eBOSS ELG sample as a comparison. Our bias measurements are consistent with the measurements of Avila et al. (2020).

Finally, the large-scale bias of the QSOs is shown in the bottom-right panel of Figure 15, as a function of redshift, with bias factor measured in the separation range $10 < s < 85 h^{-1}\text{Mpc}$. The increasing bias measurements with redshift are consistent with those obtained by Krolewski, A. et al. (2023) using the DESI two-month data. We compare our results to those obtained by the eBOSS QSO survey, as presented by the $b(z)$ parametrisation in Laurent et al. (2017). We adopted the same $b(z)$ form to fit our DESI bias estimates, i.e.,

$$b(z) = \alpha[(1+z)^2 - 6.565] + \beta, \quad (11)$$

where z is the median redshift value from each QSO sample and α and β are parametric constants. We obtained the following values from the DESI QSO $b(z)$ fit: $\alpha = 0.278 \pm 0.011$, and $\beta = 2.383 \pm 0.033$, including higher redshift bias estimates from Krolewski, A. et al. (2023). This DESI QSO bias parametrisation is shown as a solid line in Figure 15, which is different from the eBOSS results with $\alpha = 0.278 \pm 0.018$, and $\beta = 2.393 \pm 0.042$.

5 SUMMARY

The work presented in this paper provides a detailed overview of the process employed to generate high-fidelity simulated lightcones for the DESI One-Percent Survey. These lightcones are constructed within the framework of the flat- Λ CDM Planck cosmology model using UCHUU, a 2.1 trillion particle N -body simulation specifically

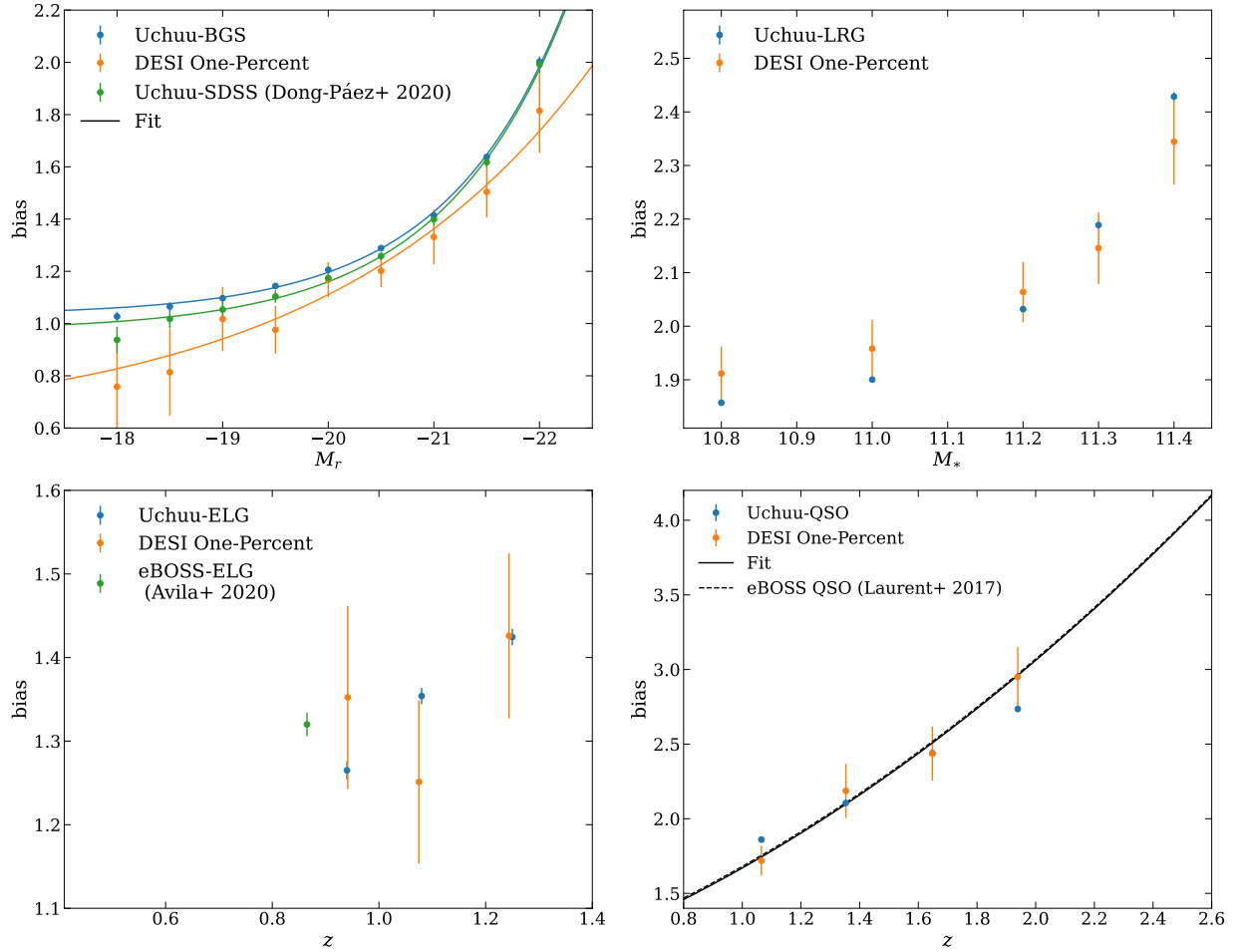


Figure 15. *Top left:* Bias of the BGS magnitude threshold volume-limited samples, at the median redshift of each sample. Blue points indicate the mean bias measured from the 102 UCHUU-BGS lightcones, where the small error bars are the error on the mean. Orange points show the bias measured from the BGS One-Percent Survey clustering measurements, where the errors are the 1σ scatter between the lightcones. The green points show bias measurements from the UCHUU mock, but cut to the SDSS volume limited samples, with redshift limits provided in Table 2 of Zehavi et al. (2011). The lines show our fits to these bias measurements as a function of magnitude using Equation 10. *Top right:* The same as the top left panel, but showing the bias measurements for the LRG stellar mass threshold samples. *Bottom left:* QSO bias measurements as a function of redshift. The black dashed lines show the parametric fit from Laurent et al. (2017), and the black solid line shows a similar fit to the DESI One Percent data.

designed for the DESI survey. UCHUU enables precise numerical resolution of dark matter haloes and subhaloes across a large volume, encompassing diverse scales ranging from galaxy clusters to dwarf galaxies. The UCHUU haloes are populated with DESI galaxies and quasars using the SHAM method. In this approach, the peak maximum circular velocity serves as a proxy for (sub)halo mass. The construction of BGS and LRG lightcones follows the conventional SHAM technique. However, for ELG and QSO tracers, a modified SHAM method is employed, incorporating additional parameters. This methodology takes into consideration the redshift evolution of the tracers and their clustering dependence on fundamental properties like luminosities and stellar masses. Moreover, the UCHUU lightcones provide covariance errors for the clustering measurements of all four tracer samples in the DESI One-Percent Survey. We carry out a thorough comparison of the measured clustering signals for each galaxy and quasar sample in the DESI One-Percent Survey with the corresponding predictions from UCHUU. Additionally, we determine the halo occupancy and large-scale bias factors for all four DESI targets.

Our main results are summarized as follows:

(i) We measure the redshift-space two-point correlation function monopole and quadrupole over the scales $0.1 h^{-1}\text{Mpc}$ to $100 h^{-1}\text{Mpc}$. Additionally, we measure the power spectrum monopole and quadrupole from $0.005 h\text{Mpc}^{-1} < k < 0.505 h\text{Mpc}^{-1}$. Overall, we find consistency between the One-Percent Survey measurements and the theoretical predictions based on the Planck cosmology using the UCHUU lightcones. We find some discrepancies, which can be attributed to cosmic variance (as observed for the BGS on large scales), incompleteness in the massive end of the stellar mass function (for the LRGs), and a simple model of the galaxy-halo connection (for ELGs and QSOs).

(ii) The clustering measurements for the entire BGS One-Percent sample show good agreement with UCHUU on scales below $30 h^{-1}\text{Mpc}$. The luminosity-dependent clustering for the BGS sample is also studied. A fair agreement is observed between UCHUU and BGS data for bright samples, but an offset is seen for fainter samples due to cosmic variance in the small volume of the One-Percent data, which may also explain the deviations above $30 h^{-1}\text{Mpc}$. It is worth noticing that the SHAM modeling should improve once we incorporate an intrinsic scatter dependency with galaxy luminosity.

(iii) For the LRG full sample, a good agreement between data and UCHUU is observed at scales larger than $5 h^{-1}\text{Mpc}$, but a systematically low prediction is found for UCHUU compared to DESI on smaller scales. This discrepancy is consistent with the incompleteness of the stellar mass function at the massive end, after studying the dependence of clustering on stellar mass and redshift.

(iv) For the ELGs, there is agreement between UCHUU and DESI above $2 h^{-1}\text{Mpc}$. However, UCHUU underpredicts clustering at the smallest scales, below $2 h^{-1}\text{Mpc}$.

(v) For QSOs, good agreement is found between UCHUU and the DESI One-Percent data in the respective redshift bins, although large errors are present on scales below $5 h^{-1}\text{Mpc}$ due to the low statistics of QSO pairs.

(vi) For the BGS and LRG galaxy samples where there is a monotonic relationship between halo mass and luminosity/stellar mass (with scatter), the HOD is reasonably described adopting the commonly used 5-parameter HOD form. A similar shape is seen in the HODs of BGS galaxies and LRGs. Since LRGs reside in more massive haloes, the halo occupancy of central halos is shifted towards higher masses compared to the BGS. We also study the HOD dependence with luminosity and stellar mass for the BGS and LRGs, respectively. For the former, we provide approximations of the measured HOD 5-parameters as a function of absolute magnitude, which agree perfectly well with those obtained from cutting the UCHUU mock to the same volume limited samples as the SDSS survey.

(vii) The ELG halo occupation consists of a Gaussian component for centrals with low halo masses ($M_{\text{halo}} < 1.25 \times 10^{12} h^{-1}M_{\odot}$) and a peak occupation of 0.17 at $M_{\text{halo}} = 4.7 \times 10^{11} h^{-1}M_{\odot}$, and a power law component for satellites with higher halo masses ($M_{\text{halo}} < 1.25 \times 10^{12} h^{-1}M_{\odot}$). The QSO HOD exhibits a similar form: a Gaussian component for central halos ($M_{\text{halo}} < 6.3 \times 10^{12} h^{-1}M_{\odot}$) with a peak occupation of 0.06 at $M_{\text{halo}} = 2.5 \times 10^{12} h^{-1}M_{\odot}$, and a power-law component for the satellites ($M_{\text{halo}} > 1.6 \times 10^{12} h^{-1}M_{\odot}$).

(viii) The linear bias factors were measured for all four tracers from the DESI One-Percent Survey and compared to predictions based on the UCHUU lightcones in the Planck cosmology. The bias values measured from the DESI One-Percent data tend to be smaller than the UCHUU predictions, possibly due to cosmic variance and the limited volume of the survey. Additionally, we measured the bias as a function of absolute magnitude threshold for the various BGS volume-limited samples, and a good agreement is observed with that obtained from the SDSS samples. The dependence of bias with stellar mass threshold is obtained for LRGs, which agrees with BOSS LRGs. For the ELG and QSO samples, the bias factors measured from the data and mocks show good agreement. The QSO bias measurements increase with redshift, and a parametrisation for this is provided. We compare the bias of the ELG and QSO samples to previous eBOSS results.

The findings presented in this study play a crucial role in refining and optimizing essential components of cosmology models. They provide valuable insights into improving the construction of simulated lightcones, enhancing the galaxy-halo connection schemes, and advancing our understanding of clustering signals. Through careful analysis and interpretation of the results from the One-Percent Survey, we can significantly enhance the accuracy and reliability of the final survey's cosmology interpretation. In conclusion, the lessons learned from the current size of DESI data are pivotal in ensuring the success of the final survey. As the next step, we encourage readers to explore forthcoming papers that will be based on the first year of DESI data and improved UCHUU lightcones.

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The authors are honored to be permitted to conduct scientific research on Iolkam Du'ag (Kitt Peak), a mountain with particular significance to the Tohono O'odham Nation.

DATA AVAILABILITY

The Uchuu-DESI lightcones are available at <https://data.desi.lbl.gov>.

The data points and Python scripts for reproducing all figures in this publication are available at <https://doi.org/10.5281/zenodo.8006825>.

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APPENDIX A: AUTHOR AFFILIATIONS

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