

# Constraining $M_\nu$ with the Bispectrum II: the Information Content of the Galaxy Bispectrum

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## ABSTRACT

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## 1. INTRODUCTION

- Neutrino mass background: condensed version of paper 1
- paragraph that transitions to why LSS neutrino mass measurement is important (condensed version of paper 1)
- and on why the bispectrum: condensed version of paper1
- transition to a paragraph on the summary of paper1 results
- paragraph on others including galaxy bias for  $M_\nu$  constraints, but they're all in the perturbation theory framework so none extend to nonlinear scales. In this paper we include galaxy bias in a simulation-based approach with emulation and LFI in mind. We use HODs, which are (a sentence on hods)

## 2. THE QUIJOTE SIMULATION SUITE

We use a subset of simulations from the QUIJOTE suite, a set of over 43,000  $N$ -body simulations that spans over 7000 cosmological models and contains, at a single redshift, over 8.5 trillion particles (Villaescusa-Navarro et al. 2019). The QUIJOTE suite was designed to quantify the information content of cosmological observables and also to train machine learning algorithms. Hence, the suite includes enough realizations to accurately estimate the covariance matrices of high-dimensional observables such as the bispectrum as well as the derivatives of these observables with respect to cosmological parameters. For the derivatives, the suite includes sets of simulations run at different cosmologies where only one parameter is varied from the fiducial cosmology:  $\Omega_m=0.3175$ ,  $\Omega_b=0.049$ ,  $h=0.6711$ ,  $n_s=0.9624$ ,  $\sigma_8=0.834$ , and  $M_\nu=0.0$  eV. Along  $\Omega_m$ ,  $\Omega_b$ ,  $h$ ,  $n_s$ , and  $\sigma_8$ , the fiducial cosmology is adjusted

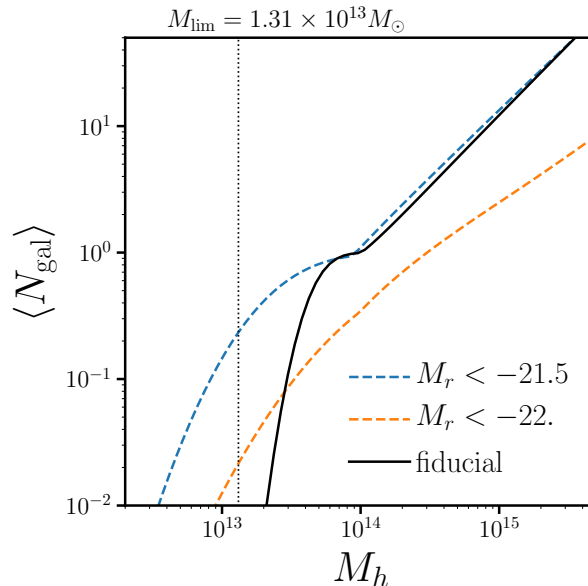
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**Table 1.** The QUIJOTE suite includes 15,000 standard  $N$ -body simulations at the fiducial cosmology to accurately estimate the covariance matrices. It also includes sets of 500 simulations at 13 other cosmologies, where only one parameter is varied from the fiducial value (underlined), to estimate derivatives of observables along the cosmological parameters.

Name	$M_\nu$	$\Omega_m$	$\Omega_b$	$h$	$n_s$	$\sigma_8$	ICs	realizations
Fiducial	0.0	0.3175	0.049	0.6711	0.9624	0.834	2LPT	15,000
Fiducial ZA	0.0	0.3175	0.049	0.6711	0.9624	0.834	Zel’dovich	500
$M_\nu^+$	<u>0.1</u> eV	0.3175	0.049	0.6711	0.9624	0.834	Zel’dovich	500
$M_\nu^{++}$	<u>0.2</u> eV	0.3175	0.049	0.6711	0.9624	0.834	Zel’dovich	500
$M_\nu^{+++}$	<u>0.4</u> eV	0.3175	0.049	0.6711	0.9624	0.834	Zel’dovich	500
$\Omega_m^+$	0.0	<u>0.3275</u>	0.049	0.6711	0.9624	0.834	2LPT	500
$\Omega_m^-$	0.0	<u>0.3075</u>	0.049	0.6711	0.9624	0.834	2LPT	500
$\Omega_b^+$	0.0	0.3175	<u>0.051</u>	0.6711	0.9624	0.834	2LPT	500
$\Omega_b^-$	0.0	0.3175	<u>0.047</u>	0.6711	0.9624	0.834	2LPT	500
$h^+$	0.0	0.3175	0.049	<u>0.6911</u>	0.9624	0.834	2LPT	500
$h^-$	0.0	0.3175	0.049	<u>0.6511</u>	0.9624	0.834	2LPT	500
$n_s^+$	0.0	0.3175	0.049	0.6711	<u>0.9824</u>	0.834	2LPT	500
$n_s^-$	0.0	0.3175	0.049	0.6711	<u>0.9424</u>	0.834	2LPT	500
$\sigma_8^+$	0.0	0.3175	0.049	0.6711	0.9624	<u>0.849</u>	2LPT	500
$\sigma_8^-$	0.0	0.3175	0.049	0.6711	0.9624	<u>0.819</u>	2LPT	500

by either a small step above or below the fiducial value:  $\{\Omega_m^+, \Omega_m^-, \Omega_b^+, \Omega_b^-, h^+, h^-, n_s^+, n_s^-, \sigma_8^+, \sigma_8^-\}$ . Along  $M_\nu$ , because  $M_\nu \geq 0.0$  eV and the derivative of certain observable with respect to  $M_\nu$  is noisy, QUIJOTE includes sets of simulations for  $\{M_\nu^+, M_\nu^{++}, M_\nu^{+++}\} = \{0.1, 0.2, 0.4\}$  eV. See Table 1 for a summary of the QUIJOTE simulations used in this work.

The initial conditions for all the simulations were generated at  $z = 127$  using second-order perturbation theory for simulations with massless neutrinos ( $M_\nu = 0.0$  eV) and the Zel’dovich approximation for massive neutrinos ( $M_\nu > 0.0$  eV). The initial conditions with massive neutrinos take their scale-dependent growth factors/rates into account using the Zennaro et al. (2017) method, while for the massless neutrino case we use the traditional scale-independent rescaling. From the initial conditions, the simulations follow the gravitational evolution of  $512^3$  dark matter particles, and  $512^3$  neutrino particles for massive neutrino models, to  $z = 0$  using GADGET-III TreePM+SPH code (Springel 2005). Simulations with massive neutrinos are run using the “particle method”, where neutrinos are described as a collisionless and pressureless fluid and therefore modeled as particles, same as CDM (Brandbyge et al. 2008; Viel et al. 2010). Halos are identified using the Friends-of-Friends algorithm (FoF; Davis et al. 1985) with linking length  $b = 0.2$  on the CDM + baryon distribution. We limit the halo catalogs to halos with masses above  $M_{\text{lim}} = 3.2 \times 10^{13} h^{-1} M_\odot$ . For the fiducial cosmology, the halo catalogs have  $\sim 156,000$  halos ( $\bar{n} \sim 1.56 \times 10^{-4} h^3 \text{Gpc}^{-3}$ ) with



**Figure 1.** The halo occupation our fiducial halo occupation (black) parameterized with the standard Zheng et al. (2007) HOD model. For the parameter values we modify the best-fit HOD parameters of the SDSS  $M_r < -21.5$  or  $< -22$ . sample best-fit parameters from Zheng et al. (2007). The halo mass limit of the QUIJOTE simulations,  $M_{\text{lim}} = 3.2 \times 10^{13} h^{-1} M_\odot$  (black dashed), prevent us from directly adopting the best-fit HOD parameters from Zheng et al. (2007). We include the halo occupation of the Zheng et al. (2007) best-fits of the  $M_r < -21.5$  (blue dashed) or  $< -22$ . sample (orange dashed) for reference.

$\bar{n}P_0(k = 0.1) \sim 3.23$ . We refer readers to Villaescusa-Navarro et al. (2019) and Hahn et al. (2019) for further details on the QUIJOTE simulations.

### 3. HALO OCCUPATION DISTRIBUTION

We are interested in quantifying the information content of the galaxy bispectrum. For a perturbation theory approach, this involves incorporating a bias model for galaxies (*e.g.* Sefusatti et al. 2006; Yankelevich & Porciani 2019; Chudaykin & Ivanov 2019). Perturbation theory approaches, however, break down on small scales and limit the constraining power from nonlinear regime. Instead, in our simulation based approach we use the halo occupation distribution (HOD) framework (*e.g.* Zheng et al. 2005; Leauthaud et al. 2012; Tinker et al. 2013; Zentner et al. 2016; Vakili & Hahn 2019). HOD models statistically populate galaxies in dark matter halos by specifying the probability of a given halo hosting a certain number of galaxies. This statistical prescription for connecting galaxies to halos has been remarkably successful in reproducing the observational statistics of galaxies (*e.g.* galaxy clustering) and, as a result, is the standard approach for constructing simulated galaxy mock catalogs in galaxy clustering analyses to estimate covariance matrices and test systematic effects (*e.g.* Rodríguez-Torres et al. 2016, 2017; Beutler et al. 2017). More importantly, HOD models in simulations for build galaxy clustering emulators (see the Aemulus project McClintock et al. 2018; Zhai et al. 2018). Emulation, as we mention above, is one of the most promising approaches for modeling small scale galaxy clustering and is what we’re trying to forecast in this work.

In the simplest HOD models, the probability of a given halo hosting  $N$  galaxies of a certain class is dictated by its halo mass —  $P(N|M_h)$ . We use the standard  $P(N|M_h)$  model from Zheng et al. (2007), which has been ubiquitously used in galaxy clustering analyses (*e.g.* Sinha et al. 2018, many more). The model specifies the mean number of galaxies in a halo as

$$\langle N_{\text{gal}} \rangle = \langle N_{\text{cen}} \rangle + \langle N_{\text{sat}} \rangle \quad (1)$$

with mean central galaxy occupation

$$\langle N_{\text{cen}} \rangle = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\log M_h - \log M_{\text{min}}}{\sigma_{\log M}} \right) \right] \quad (2)$$

and mean satellite galaxy occupation

$$\langle N_{\text{sat}} \rangle = \langle N_{\text{cen}} \rangle \left( \frac{M_h - M_0}{M_1} \right)^\alpha. \quad (3)$$

The mean number of centrals in a halo transitions smoothly from 0 to 1 for halos with mass  $M_h > M_{\text{min}}$ . The width of the transition is dictated by  $\sigma_{\log M}$ , which reflects the scatter between stellar mass/luminosity and halo mass (?). For  $M_h > M_{\text{min}}$ ,  $\langle N_{\text{sat}} \rangle$  follows a power law with slope  $\alpha$ .  $M_0$  is the halo mass cut-off for satellite occupation and  $M_h = M_0 + M_1$  is the typical mass scale for halos to host one satellite galaxy. The numbers of centrals and satellites for each halo are drawn from Bernoulli and Poisson distribution, respectively. Central galaxies are placed at the center of the halo while position and velocity of the satellite galaxies are sampled from a Navarro et al. (1997) (NFW) profile.

The halo occupation in the Zheng et al. (2007) model depends solely on  $M_h$ . Simulations, however, find evidence that secondary halo properties such as concentration or formation history correlate with spatial distribution of halos — a phenomenon referred to as “halo assembly bias” (Sheth & Tormen 2004; Gao et al. 2005; Harker et al. 2006; Wechsler et al. 2006). A model that only depends on  $M_h$ , does not account for this halo assembly bias and may not sufficiently describe the connection between galaxies and halos. Moreover, if unaccounted for in the HOD model, and thus not marginalized over, halo assembly bias may impact the cosmological parameter constraints. Zentner et al. (2016) and Vakili & Hahn (2019) recently examined evidence for assembly bias in the observed clustering measurements of the Sloan Digital Sky Survey (SDSS) DR 7 main galaxy sample. short description of the papers and how they compare with a model with assembly bias. However, they find little evidence for assembly bias in the galaxy clustering of the SDSS  $M_r < -21.5$  and  $-21$  samples. Therefore, in this work we use the standard Zheng et al. (2007) HOD model and assume it is sufficient for modeling the galaxy–halo connection.

For the fiducial parameter values of the HOD model we used values motivated by best-fit HOD parameters from the literature, namely the Zheng et al. (2007) fits to the SDSS  $M_r < -21.5$  and  $-22$  samples:

$$\{M_{\text{min}}, \sigma_{\log M}, \log M_0, \alpha \log M_1\} = \{13.65, 0.2, 14., 1.1, 14.\}. \quad (4)$$

**Table 2.** Marginalized Fisher parameter constraints from the redshift-space  $P_\ell$ ,  $B_0$ , and  $P_\ell + B_0$ . We list constraints for cosmological parameters  $M_\nu$ ,  $\Omega_m$ ,  $\Omega_b$ ,  $h$ ,  $n_s$ , and  $\sigma_8$  as well as HOD and nuisance parameters.

$P_\ell$ $B_0$ $P_\ell + B_0$
$M_\nu$
$\Omega_m$
$\Omega_b$
$h$
$n_s$
$\sigma_8$
$M_{\min}$
$\sigma_{\log M}$
$\log M_0$
$\alpha$
$\log M_1$

In Figure 1 we present the halo occupation of our fiducial HOD parameters (black). We include the best-fit halo occupations of the SDSS  $M_r < -21.5$  (blue) and  $-22$  (orange) samples from Zheng et al. (2007) for comparison. We also mark the halo mass limit,  $M_{\text{lim}}$ , of the QUIJOTE simulations (black dotted). At  $M_h \sim 10^{13} M_\odot$ , the best-fit halo occupations of the SDSS samples extend below  $M_{\text{lim}}$  — *i.e.* they have halos below  $M_{\text{lim}}$  that host galaxies. This prevents us from directly using the values from the literature and instead, we reduce  $\sigma_{\log M}$  to 0.2 dex. We confirm using QUIJOTE simulations with higher mass resolution ( $1024^3$  CDM particles) that  $M_{\text{lim}}$  does not impact the observables or their derivatives in our analysis for our fiducial HOD parameters.

As we mention above,  $\sigma_{\log M}$  reflects the scatter between stellar mass/luminosity and halo mass. The high  $\sigma_{\log M}$  in the  $M_r < -21.5$  and  $-22$  SDSS samples is caused by the turnover in this relation at high stellar mass/luminosity. Our fiducial halo occupation, with its lower  $\sigma_{\log M}$ , results in a galaxy sample with a tighter scatter than the samples selected based on  $M_r$  or  $M_*$  cuts, *e.g.* used in SDSS and BOSS. Hence, such a sample would require selecting based on observable galaxy properties that correlate more strong with  $M_h$  than luminosity or  $M_*$ . Alpaslan et al. in prep. find that  $L_{\text{sat}}$  is more correlated to  $M_h$  than luminosity or  $M_*$ ; however, it has yet to be used for galaxy sample selection. Regardless, in this work we are interested in quantifying the information content of the galaxy bispectrum and not analyzing an observed galaxy sample. We therefore opt for a more conservative set of HOD parameters with respect to  $M_{\text{lim}}$ .

#### 4. RESULTS

#### 5. SUMMARY

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TODO

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## APPENDIX

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