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Constraining M_ν with the Bispectrum II: the Information Content of the Galaxy Bispectrum

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ABSTRACT

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1. INTRODUCTION

intro goes here

2. THE QUIJOTE SIMULATION SUITE

We use a subset of simulations from the Quijote suite, a set of 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. in prep.). 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: $\Omega_{\rm m}$=0.3175, $\Omega_{\rm b}$=0.049, h=0.6711, n_s=0.9624, σ_8=0.834, and M_ν=0.0 eV. Along $\Omega_{\rm m}$, $\Omega_{\rm b}$, h, n_s, and σ_8, the fiducial cosmology is adjusted by either a small step above or below the fiducial value: $\{\Omega_{\rm m}^+, \Omega_{\rm m}^-, \Omega_{\rm b}^+, \Omega_{\rm b}^-, h^+, h^-, n_s^+, n_s^-, \sigma_8^+, \sigma_8^-\}$. Along M_ν, because $M_\nu \geq 0.0$ eV and the derivative of certain observable with respect to M_ν 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,

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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_ν	Ω_m	Ω_b	h	n_s	σ_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_ν^+	$\underline{0.1}$ eV	0.3175	0.049	0.6711	0.9624	0.834	Zel'dovich	500
M_ν^{++}	$\underline{0.2}$ eV	0.3175	0.049	0.6711	0.9624	0.834	Zel'dovich	500
M_ν^{+++}	$\underline{0.4}$ eV	0.3175	0.049	0.6711	0.9624	0.834	Zel'dovich	500
Ω_m^+	0.0	$\underline{0.3275}$	0.049	0.6711	0.9624	0.834	2LPT	500
Ω_m^-	0.0	$\underline{0.3075}$	0.049	0.6711	0.9624	0.834	2LPT	500
Ω_b^+	0.0	0.3175	$\underline{0.051}$	0.6711	0.9624	0.834	2LPT	500
Ω_b^-	0.0	0.3175	$\underline{0.047}$	0.6711	0.9624	0.834	2LPT	500
h^+	0.0	0.3175	0.049	$\underline{0.6911}$	0.9624	0.834	2LPT	500
h^-	0.0	0.3175	0.049	$\underline{0.6511}$	0.9624	0.834	2LPT	500
n_s^+	0.0	0.3175	0.049	0.6711	$\underline{0.9824}$	0.834	2LPT	500
n_s^-	0.0	0.3175	0.049	0.6711	$\underline{0.9424}$	0.834	2LPT	500
σ_8^+	0.0	0.3175	0.049	0.6711	0.9624	$\underline{0.849}$	2LPT	500
σ_8^-	0.0	0.3175	0.049	0.6711	0.9624	$\underline{0.819}$	2LPT	500

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 $M_{\rm lim} = 3.2 \times 10^{13} h^{-1} M_\odot$. For the fiducial cosmology, the halo catalogs have $\sim$156,000 halos ($\bar{n} \sim 1.56 \times 10^{-4}\ h^3{\rm Gpc}^{-3}$) with $\bar{n}P_0(k = 0.1) \sim 3.23$. We refer readers to Villaescusa-Navarro et al. (in preparation) 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

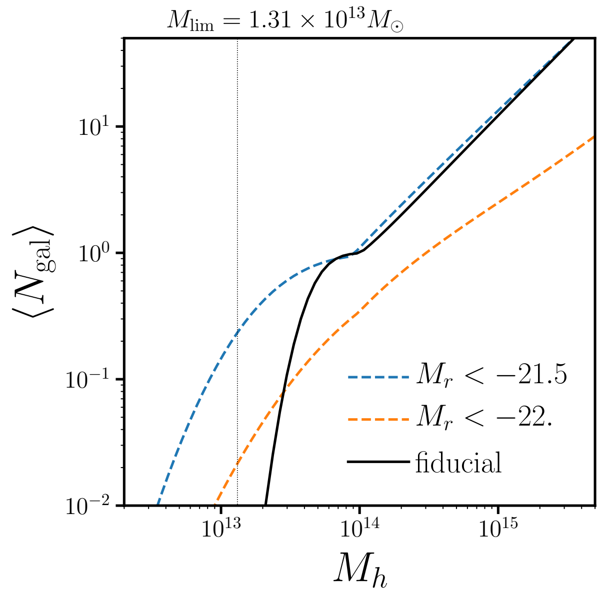

Figure 1. The halo occupation our fiducial halo occupation (black) parameterized with the standard Zheng et al. (2007) HOD model. The halo mass limit of the QUIJOTE simulations, $M_{\rm lim} = 3.2 \times 10^{13} h^{-1} M_\odot$ (black dashed), prevent us from adopting the best-fit HOD parameters of the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

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 TODO

$$\langle N_{\rm gal} \rangle = \langle N_{\rm cen} \rangle + \langle N_{\rm sat} \rangle \tag{1}$$

with mean central galaxy occupation

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

and mean satellite galaxy occupation

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

The mean number of centrals in a halo transitions smoothly from 0 to 1 for halos with mass $M_h > M_{\rm min}$. The width of the transition is dictated by $\sigma_{\log M}$, which reflects the scatter in the stellar-to-halo mass relation (SHMR **?**). For $M_h > M_{\rm min}$, $\langle N_{\rm sat}\rangle$ follows a power law with slope α. 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 soley 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 sufficient describe the connection between galaxies and halos. Moreover, if unaccounted for in the HOD model and not marginalized over, halo assembly bias may impact the cosmological parameter constraints. Zentner et al. (2016) and Vakili & Hahn (2019) 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 paper 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. TODO

- description of the halo mass constraints we're dealing with and how this prevents us from directly using best-fit HOD parameters from the literature. In fact, due to this constraint we modify the HOD parameters.
- plots showing how our HOD choice compares to HODs of the SDSS samples. Some handwavy arguments about how it shouldn't matter too much.

4. RESULTS

5. SUMMARY

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APPENDIX

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