The Imprint of Neutrinos on Clustering in Redshift Space

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Abstract

We investigate the signatures left by the cosmic neutrino background on the clustering of matter, CDM+baryons, and halos in redshift space using the HADES simulations. While on large scales the clustering of matter and CDM+baryons is very different in cosmologies with massive and massless neutrinos, we find that the effect of neutrinos on the clustering of CDM+baryons in redshift space on small scales is almost entirely due to the change in $\sigma_8$. We show that the effect of neutrinos on the clustering of halos is very different, on all scales, from the effects induced by varying $\sigma_8$. We find that the effects of neutrinos on the growth rate of CDM+baryons ranges from $0.3\%$ to $2\%$ on scales $k \in [0.01, 0.5] h \text{Mpc}^{-1}$ for neutrinos with masses $M_{\nu} \leq 0.15 \text{eV}$. We compute the bias between the momentum of halos and the momentum of CDM+baryons and find it to be $1$ on large scales for all models with massless and massive neutrinos considered. We show that, even on very large scales, nonlinear corrections are important to describe the clustering of halos in redshift space in cosmologies with massless and massive neutrinos at low redshift. We find that hydrodynamics and astrophysical processes, as implemented in our simulations, only distort the relative effect that neutrinos induce on the anisotropic clustering of matter, CDM+baryons, and halos in redshift space by less than $1\%$. Thus, the effect of neutrinos in the fully nonlinear regime can be written as a transfer function with very weak dependence on astrophysics that can be studied through $N$-body simulations.

Key words: cosmology: theory – large-scale structure of universe – neutrinos

1. Introduction

The Standard Model of particle physics describes neutrinos as fundamental massless particles. Neutrino oscillation experiments have shown, however, that at least two neutrino families have mass, with a lower limit on the sum of the neutrino masses (Forero et al. 2014; Gonzalez-Garcia et al. 2014; Esteban et al. 2017): $M_\nu = \sum m_{\nu_i} \geq 0.06 \text{eV}$. Unfortunately, oscillation measurements are not sensitive to the absolute mass scale of the neutrinos, requiring the use of alternative probes. Tritium beta decay experiments can be used to place upper limits on neutrino masses, with current constraints at the level of $M_\nu \lesssim 6.9 \text{eV}$ (Kraus et al. 2005).

Neutrinos are among the most abundant particles in the universe, with number densities only somewhat less than photons. Unlike photons, however, at least some neutrinos have rest mass, implying that relic neutrinos can produce significant effects on cosmological observables, in particular the low-redshift evolution of cosmological density perturbations. One key difference between neutrinos and other gravitating massive species, like baryons or cold dark matter (CDM), is that neutrinos have large thermal velocities, which can lead to distinctive signatures of neutrinos in many different cosmological observables. Those signatures have been used to place tight upper limits on the sum of the neutrino masses. The current tightest bounds have been obtained by combining different cosmological observables such as the anisotropies in the cosmic microwave background, galaxy clustering, and the Ly$\alpha$ forest: $M_\nu \lesssim 0.12 \text{eV}$ (Palanque-Delabrouille et al. 2015; Cuesta et al. 2016; Vagnozzi et al. 2017), significantly tighter than the bounds possible from terrestrial experiments for the foreseeable future.

These constraints, as impressive as they are, will only improve in the near future as additional cosmological surveys come online. In particular, surveys like EUCLID,⁷ DESI,⁸ WFIRST,⁹ and PFS¹⁰ will measure the 3D clustering of galaxies across a range of length scales and cosmic time. As is well known, 3D clustering represents one of the most important sources of cosmological information. Besides constraining neutrino masses, galaxy clustering also provides a wealth of information about many crucial cosmological questions, including the energy content of the universe, the initial conditions laid down during inflation, and the overall spatial geometry of the universe. However, multiple physical processes can impede both the measurement of matter clustering and its interpretation. First, at late times and on small scales, matter clustering becomes a highly nonlinear process and may be contaminated by poorly characterized astrophysical processes such as feedback from star formation, supernovae, and AGNs. Second, the dominant matter component, CDM, is not directly visible, meaning that the underlying clustering of matter typically must be indirectly inferred through biased tracers such as galaxies or neutral hydrogen. Third, peculiar velocities induce a shift in the redshifts we measure, distorting the clustering pattern

⁷ http://sci.esa.int/euclid/
⁸ http://desi.lbl.gov/
⁹ https://wfirst.gsfc.nasa.gov/
¹⁰ http://sumire.ipmu.jp/en/2652/
and breaking statistical isotropy of matter two-point clustering.

In spite of these difficulties, the cosmological surveys mentioned above will cover volumes so large that they will be able to either measure the neutrino masses or place extremely tight constraints on them (e.g., Audren et al. 2013; Font-Ribera et al. 2014; Allison et al. 2015; Villaescusa-Navarro et al. 2015; Petrarca et al. 2016; Sartoris et al. 2016). Given the statistical power of the upcoming generation of surveys, it is becoming increasingly crucial to have accurate theoretical predictions (Baldauf et al. 2016) that allow us to understand and to model accurately the impact of nonlinearities, galaxy bias, and redshift-space distortions in cosmologies with massive neutrinos. The impact of neutrino masses on the fully nonlinear clustering of matter in real space has been carefully studied in a number of different works (Brandbyge et al. 2008, 2010; Saito et al. 2008, 2009; Wong 2008; Viel et al. 2010, 2010; Agarwal & Feldman 2011; Bird et al. 2012; Wagner et al. 2012; Ali-Haïmoud & Bird 2013; Lesgourgues et al. 2013; Villaescusa-Navarro et al. 2013b, 2015; Blas et al. 2014; LoVerde 2014b; Rossi et al. 2014, 2014; Upadhye et al. 2014; Castorina et al. 2015; Führer & Wong 2015; Inman et al. 2015; Peloso et al. 2015; Banerjee & Dalal 2016; Emberson et al. 2016), and the halo model (Cooray & Sheth 2002) has been extended to cosmologies with massive neutrinos (Massara et al. 2014). In particular, halo bias in cosmologies with massive neutrinos has been recently studied in detail; it has been shown that neutrino masses induce a scale-dependent bias on large scales (Biagetti et al. 2014; Castorina et al. 2014, 2015; LoVerde 2014a; Villaescusa-Navarro et al. 2014). This happens because the transfer functions of neutrinos and CDM+baryons are different in shape and amplitude, even on large scales. Since halo properties are dictated by the statistics of an underlying density field of CDM+baryons, and not by the total matter field (which includes neutrinos; Ichiki & Takada 2012; Castorina et al. 2014; LoVerde 2014b), halo bias is sensitive to whether it is defined with respect to the CDM+baryon field or the total matter field. Not modeling properly this effect can lead to biases in the estimated values of the cosmological parameters and neutrino masses (Raccanelli et al. 2017). Banerjee & Dalal (2016) have pointed out that neutrinos have a larger effect on the clustering of cosmic voids than in halos; they induce a stronger scale-dependent bias on large scales. The reason behind this is that neutrinos affect more intensively voids than halos (Massara et al. 2015), since they barely cluster in the latter but cannot evacuate the former.

The purpose of this work is to investigate whether neutrinos imprint characteristic signatures on the clustering of matter, CDM+baryons, and halos, in redshift space. We note that previous works have studied redshift-space distortions in cosmologies with massive neutrinos (Marulli et al. 2011; Castorina et al. 2015; Upadhye et al. 2016). The goal of this work, in relation to previous investigations, is a more systematic study carried out using a much larger set of simulations covering large volumes. We also study for the first time the impact of neutrinos on the growth rate of cosmic structure and the extent of velocity or momentum bias generated by neutrinos. We also study the effect of baryons on the inference of neutrino properties. We notice that the impact of neutrinos on baryonic runs has been studied in several previous works (Viel et al. 2010; Bird et al. 2012; Villaescusa-Navarro et al. 2013b, 2015; Rossi et al. 2014; Harnois-Déraps et al. 2015; Mummery et al. 2017; Roncarelli et al. 2017).

We employ a set of more than 1000 state-of-the-art $N$-body and hydrodynamic simulations, with realistic neutrino masses, covering volumes larger than $100 (h^{-1}\,\text{Gpc})^3$. We try to answer key questions such as the information content on neutrino masses embedded into galaxy clustering in redshift space. An important limitation to that information content is the presence of degeneracies, among which the $M_{\nu} = \sigma_8$ is one of the most prominent.\footnote{It is well known that the $M_{\nu} = \sigma_8$ degeneracy can be broken by adding information from other sources, such as CMB data (e.g., Peloso et al. 2015). Notice, however, that the amplitude of the matter power spectrum on large scales cannot always be determined with absolute precision. For instance, in the case of the CMB observations the uncertainty in $\tau$ is the main limiting factor.}

We focus our analysis on the effect induced by neutrinos on the monopole, quadrupole, and fully 2D power spectrum of matter, CDM+baryon, and halo fields. We also estimate the amplitude and shape of the growth rate of the CDM+baryon field, an important ingredient to model the galaxy power spectrum in redshift space.

We compute the bias between the momentum of halos and the CDM+baryon fields and find that there is no detectable large-scale velocity bias between those fields generated by massive neutrinos. This implies that a bias between the momentum of halos and the total matter field will be present in models with massive neutrinos. Finally, we study the range of validity of linear theory to model the clustering of halos in redshift space in models with massive neutrinos.

We also study the impact of baryonic processes on redshift-space distortions in models with massive neutrinos. We investigate the impact of baryonic processes on both the absolute and relative amplitude and shape of the clustering pattern of the matter, CDM+baryons, and halo fields in redshift space.

This paper is organized as follows. In Section 2 we describe the simulation suite we have used in this paper. The relative differences induced by the neutrino masses considered in this paper are much smaller than the overall amplitude of the quantities we consider. Thus, in this paper we focus on relative differences, and we show absolute quantities in Section 3. In Section 4 we investigate the impact of neutrino masses on the matter and CDM+baryon density fields and estimate the growth rate of CDM+baryons in the fully nonlinear regime. We investigate the impact of neutrinos on the clustering of halos, the momentum bias, and the validity of linear theory shown in Section 5. In Section 6 we study the impact of baryonic effects on the distribution of matter, CDM+baryons, and halos in redshift space. We draw the main conclusions of this work in Section 7.

## 2. Numerical Simulations

We use a subset of the HADES\footnote{https://franciscovillaescusa.github.io/hades.html} simulations. We briefly describe the characteristics of this subset here and refer the reader to F. Villaescusa-Navarro et al. (2017, in preparation) for further details. The simulations have been run using the TreePM+SPH code GADGET-III (Springel 2005). All simulations are run in a periodic box size of $1 \, h^{-1}\,\text{Gpc}$, and all models share the value of the following cosmological parameters:

- $h = 0.677$
- $\Omega_{\text{m}} = 0.315$
- $\Omega_{\text{b}} = 0.048$
- $\Omega_{\nu} = 0.001$
- $\tau = 0.096$
- $n_s = 0.966$
- $\sigma_8 = 0.834$
- $\Omega_{\Lambda} = 0.685$
- $\Omega_{\nu} = 0.967$
While for low neutrino masses the hierarchy can have a rather large impact, we did not implement it, as our rescaling code exhibits some small differences with respect to linear theory that propagate to redshift 0 and can induce subpercent differences with respect to linear theory. We notice, however, that for the model with 0.06 eV the difference in the linear power spectrum between using the correct normal hierarchy and assuming degenerate masses is not larger than 0.5%. Thus, degenerate neutrino masses for the model with 0.06 eV neutrinos should just be considered as a good approximation to the correct underlying model.

### 2.1. N-body

In these simulations we follow the gravitational evolution of $N_{\text{cdm}}$ CDM plus $N_{\nu}$ neutrino particles (only in the case of massive neutrinos models) from $z = 99$ to $z = 0$. For each cosmological model we have two types of simulations with different resolutions. In one case we have $N_{\text{cdm}} = 512^3$ and $N_{\nu} = 512^3$ with 100 independent realizations for each model (low-resolution simulations), while in the other we have $N_{\text{cdm}} = 1024^3$ and $N_{\nu} = 1024^3$ and 13 realizations for each model (high-resolution simulations).

The initial conditions are generated at $z = 99$ using the rescaling method outlined in Zennaro et al. (2017) employing the Zel’dovich approximation. The matter power spectra, transfer functions, and growth rates required as input in reps are obtained through the Code for Anisotropies in the Microwave Background (CAMB; Lewis et al. 2000). The gravitational softening is set to 1/40 of the mean inter-particle distance for both CDM and neutrinos. The random seeds are the same for the same realization in different models and vary from realization to realization for the same model.

The simulations cover eight different cosmological models, which can be split into models with massive and massless neutrinos. We simulate three different models with degenerate

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**Table 1**

| Name   | $\sum_{\nu}$ (eV) | $10^3A_s$ | $\sigma_8^e$ | $\sigma_8^b$ | $N_{\text{cdm}}^{1/3}$ | $N_{\text{gas}}^{1/3}$ | $N_{\nu}^{1/3}$ | $m_{\text{cdm}}$ | $m_{\text{gas}}$ | $m_{\nu}$ | $\epsilon$ | Realizations |
|--------|------------------|-----------|--------------|--------------|------------------|------------------|--------------|-----------------|-----------------|-------------|-------------|--------------|
| L0 (fid) | 0.00             | 2.13      | 0.833        |              | 512              | 0                | 0            | 65.66           | 0               | 0           | 50          | 100          |
|        |                  |           |              |              | 512              | 0                | 0            | 55.52           | 10.13           | 0           | 50          | 100          |
|        |                  |           |              |              | 1024             | 0                | 0            | 8.21            | 0               | 0           | 25          | 13           |
| L0-1   | 0.00             | 2.074     | 0.822        |              | 512              | 0                | 0            | 65.66           | 0               | 0           | 50          | 100          |
|        |                  |           |              |              | 512              | 0                | 0            | 55.52           | 10.13           | 0           | 50          | 100          |
|        |                  |           |              |              | 1024             | 0                | 0            | 8.21            | 0               | 0           | 25          | 13           |
| L0-2   | 0.00             | 2.053     | 0.818        |              | 512              | 0                | 0            | 65.66           | 0               | 0           | 50          | 100          |
|        |                  |           |              |              | 512              | 0                | 0            | 55.52           | 10.13           | 0           | 50          | 100          |
|        |                  |           |              |              | 1024             | 0                | 0            | 8.21            | 0               | 0           | 25          | 13           |
| L0-3   | 0.00             | 2.00      | 0.807        |              | 512              | 0                | 0            | 65.66           | 0               | 0           | 50          | 100          |
|        |                  |           |              |              | 512              | 0                | 0            | 55.52           | 10.13           | 0           | 50          | 100          |
|        |                  |           |              |              | 1024             | 0                | 0            | 8.21            | 0               | 0           | 25          | 13           |
| L0-4   | 0.00             | 1.954     | 0.798        |              | 512              | 0                | 0            | 65.66           | 0               | 0           | 50          | 100          |
|        |                  |           |              |              | 512              | 0                | 0            | 55.52           | 10.13           | 0           | 50          | 100          |
|        |                  |           |              |              | 1024             | 0                | 0            | 8.21            | 0               | 0           | 25          | 13           |
| L6     | 0.06             | 2.13      | 0.819        | 0.822        | 512              | 0                | 0            | 65.36           | 0               | 29.57       | 50          | 100          |
| L10    | 0.10             | 2.13      | 0.809        | 0.815        | 512              | 0                | 0            | 65.16           | 0               | 49.28       | 50          | 100          |
|        |                  |           |              |              | 1024             | 0                | 0            | 8.15            | 0               | 6.16        | 25          | 13           |
| L15    | 0.15             | 2.13      | 0.798        | 0.806        | 512              | 0                | 0            | 64.92           | 0               | 73.95       | 50          | 100          |
|        |                  |           |              |              | 512              | 0                | 0            | 54.78           | 10.13           | 73.95       | 50          | 100          |
|        |                  |           |              |              | 1024             | 0                | 0            | 8.12            | 0               | 9.24        | 25          | 13           |

**Note.** All simulations share the values of the following cosmological parameters: $\Omega_m = 0.3175$, $\Omega_b = 0.049$, $\Omega_\Lambda = 0.6825$, $n_s = 0.9624$, $h = 0.6711$. The values of $M_*, A_s$, and $\sigma_8$ for each model are given in Columns (2)–(5). The value of the pivot scalar is $0.05 h$ Mpc$^{-1}$. The simulations follow the evolution of $N_{\text{cdm}}$, CDM particles, $N_{\text{gas}}$, gas particles, and $N_{\nu}$, neutrino particles, with masses $m_{\text{cdm}}$, $m_{\text{gas}}$, and $m_{\nu}$, within a box size of $1 h^{-1}$ Gpc. Neutrino masses are assumed to be degenerate. The softening length for both CDM and neutrinos is given by $\epsilon$, while for gas it is set to the smoothed particle hydrodynamics (SPH) radius.

The number of realizations for each model is shown in the last column. Simulations without gas particles are N-body, while those with gas particles are hydrodynamic.

The underlying model.

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13 While for low neutrino masses the hierarchy can have a rather large impact, we did not implement it, as our rescaling code exhibits some small differences with respect to linear theory that propagate to redshift 0 and can induce subpercent differences with respect to linear theory. We notice, however, that for the model with 0.06 eV the difference in the linear power spectrum between using the correct normal hierarchy and assuming degenerate masses is not larger than 0.5%. Thus, degenerate neutrino masses for the model with 0.06 eV neutrinos should just be considered as a good approximation to the correct underlying model.

14 https://github.com/matteozennaro/reps
massive neutrinos with different masses: \( M_\nu = 0.06 \, \text{eV}, M_\nu = 0.10 \, \text{eV}, \) and \( M_\nu = 0.15 \, \text{eV}. \) Those simulations are run employing the so-called particle method (Brandbyge et al. 2008; Viel et al. 2010), where neutrinos are described as a collisionless and pressureless fluid and therefore modeled as particles in the same fashion as CDM. In our simulations the tree is always on to compute forces on small scales for neutrinos.

The different models with massless neutrinos only differ in the value of \( \sigma_8. \) We use those simulations to study the \( M_\nu-\sigma_8 \) degeneracy, i.e., to understand whether the difference between the models is driven by neutrino masses of \( \sigma_8. \) In cosmologies with massive neutrinos \( \sigma_8 \) can be computed with respect to total matter, \( \sigma_8^m, \) or with respect to CDM+baryons, \( \sigma_8^b. \) It has been shown in several works (see, e.g., Ichiki & Takada 2012; Castorina et al. 2014; LoVerde 2014b; Villaescusa-Navarro et al. 2014) that in models with massive neutrinos, halos closely trace the CDM+baryon field, as opposed to the total matter (CDM+baryon+\( \nu \)) field. The values of \( \sigma_8 \) in our simulations with massless neutrino simulations were chosen to match either \( \sigma_8^b \) or \( \sigma_8^m \) of the massive neutrino cosmologies. In Figure 1 we show the amplitude and shapes of the linear power spectra of the different models normalized by the linear power spectrum of the fiducial cosmology.

For each realization of each model we save snapshots at \( z = 0, z = 0.5, z = 1, \) and \( z = 3. \) Dark matter halos are identified by employing the Friends-of-Friends algorithm (FoF; Davis et al. 1985) by setting the linking length parameter \( b = 0.2. \) The group finder is run only on top of the CDM+baryon distribution, as the contribution of neutrinos to the masses of halos has been shown to be negligible (Brandbyge et al. 2010; Villaescusa-Navarro et al. 2011; Ichiki & Takada 2012; Villaescusa-Navarro et al. 2013a; Castorina et al. 2014; LoVerde 2014b). Only halos that contain more than 20 particles are identified, although for the main analysis we only consider halos with masses above \( 3 \times 10^{12} \, h^{-1} M_\odot \) for the low- and high-resolution simulations, respectively.

Since cosmic variance decreases with volume and is not affected by resolution, and given the fact that the effects induced by the neutrino masses considered in this paper are very small, we use for most of the analysis in this paper the lower-resolution 512^3 simulations, and we employ the higher-resolution (1024^3) simulations to compute the momentum bias for low-mass halos not resolved by the coarser simulations.

2.2. Hydrodynamic

Besides the \( N \)-body simulations, we also run hydrodynamic simulations for the fiducial and 0.15 eV models. In those simulations we follow the evolution of 512^3 CDM + 512^3 gas particles, plus 512^3 neutrino particles for the 0.15 eV model, in a box of \( 1 \, h^{-1} \, \text{Gpc} \) from \( z = 99 \) to \( z = 0. \) As with \( N \)-body, we assume degenerate neutrino masses. The physical processes incorporated in those simulations are radiative cooling by hydrogen and helium, uniform UV heating, star formation, and supernova feedback following Springel & Hernquist (2003). Supernova feedback is implemented as kinetic feedback with particles ejected at a velocity of \( \approx 350 \, \text{km s}^{-1}. \) Our simulations do not account for AGN feedback.

Initial conditions are also generated at \( z = 99 \) using the Zel’'dovich approximation. A different power spectrum and growth rate are computed for each species, CDM, gas, and neutrinos, using the \textit{reps} rescaling code (Zennaro et al. 2017). For the gas particles we employ a softening length that is equal to the SPH gas radius. We do this to avoid the artificial coupling of CDM and gas at high redshifts (Angulo et al. 2013). Thus, our simulations are able to reproduce the large-scale clustering of each individual component separately from linear theory (see Appendix C for a discussion on the impact of the gas smoothing lengths on the clustering of matter and halos in real and redshift space).

We save snapshots at redshifts 0, 0.5, 1, 2, and 3 and identify halos through FoF. Halos are identified using both CDM and baryons. For the analysis we only take halos with masses larger than \( 3.2 \times 10^{13} \, h^{-1} M_\odot. \)

We use these simulations to investigate the impact of baryons and astrophysical effects on our results.

3. General Features

In this work we are interested in investigating the impact of neutrino masses on several quantities, such as the clustering of matter, CDM+baryons and halos in redshift space, or the growth rate. We will focus our analysis on scales \( k \approx [10^{-2}, 0.5] \, h \, \text{Mpc}^{-1} \) and redshifts \( z \in [0, 2]. \) While the amplitudes of the monopoles, quadrupoles, and the fully 2D power spectra vary several orders of magnitude in that redshift range, the relative differences among the models we study here are limited to a few percent. What this means in practice is that if we plot, let’s say, the monopoles at a given redshift for all the different models, we will see one line on top of another. Similar arguments apply to the case of the growth rate.

For this reason, in this paper we focus our analysis on relative differences instead of absolute differences. In this section we show the monopoles, quadrupoles, and fully 2D power spectra of the fiducial model, together with the growth rate of the model with 0.15 eV neutrinos.
3.1. Clustering

For each of the 100 realizations of the fiducial cosmology we have computed the monopoles, quadrupoles, and fully 2D power spectra of both the matter and halos at redshifts 0, 0.5, 1, and 2, and what we show here is the mean from all realizations. We have subtracted the shot noise of the halo field when computing the monopoles and 2D power spectra for each realization and redshift.

In the left panels of Figure 2 we show the monopoles and quadrupoles of the matter and halo distributions in redshift space at redshifts 0, 0.5, 1, and 2. For the matter distribution the amplitude of the monopoles increases with redshift, due to the nonlinear growth of the matter perturbations. For halos the trend is inverted owing to the fact that we are consider halos with the same minimum mass in all cases, $3.2 \times 10^{13} h^{-1} M_{\odot}$: the halo bias increases with redshift more rapidly than perturbation growth (see Appendix B).

We find a cutoff in the quadrupole of the matter distribution on small scales induced by the fingers of God (FoG), an effect whose amplitude increases with decreasing redshift. At high redshifts and on large scales the amplitude of the quadrupoles and monopoles of the matter distribution agrees very well. This is a consequence of the linear growth rate being close to 1 (see Figure 3), i.e., $1 + 2f/3 + f^2/5 \approx 4f/3 + 4f^2/7$, where $f$ is the growth rate.

The halo quadrupoles do not exhibit instead a cutoff on small scales, reflecting the almost absence of FoG in the halo field. The amplitude of the halo quadrupoles on large scales shows a nonmonotonic relation with redshift, which can be explained by taking into account the different time evolution of the growth factor, growth rate, and halo bias. In the linear regime, the amplitude of the quadrupole goes as $D^2 b^2 (4\beta/3 + 4\beta^2/7)$, where $D$ is the growth factor, $b$ is the halo bias, and $\beta = f/b$. While both $b$ and $f$ increase with redshift, $D$ shrinks with it.

In the right panels of Figure 2 we show the 2D power spectra of matter and halo fields in redshift space at redshifts 0, 0.5, 1, and 2. The power spectrum of the matter field shows the increase of power with decreasing redshift displayed in the left panels of Figure 2. From the structure of the 2D matter power spectrum it is also clear that the magnitude of the FoG decreases with redshift.

Figure 2. Effects induced by the neutrino masses considered in this work are very small in all the quantities investigated. We thus focus our analysis on relative differences instead of absolute differences. As a reference, we show in this plot the absolute scale of the matter and halo power spectra for the fiducial model with massless neutrinos. Left: monopoles (solid lines) and quadrupoles (dashed lines) for matter (top panel) and halos (bottom panel) at $z = 0$ (black), $z = 0.5$ (blue), $z = 1$ (green), and $z = 2$ (red). Right: 2D power spectra of matter (left column) and halos (right column) at $z = 0$ (first row), $z = 0.5$ (second row), $z = 1$ (third row), and $z = 2$ (fourth row). Black lines show isopower contours. We only consider halos with masses larger than $3.2 \times 10^{13} h^{-1} M_{\odot}$.
where $i \in \{c, b, \nu\}$ and $P_i = (\nabla \cdot J_i) = \nabla \cdot [(1 + \delta) \nu]$, is the divergence of the momentum of the field $i$. $P_b(k)$ and $P_\nu(k)$ are the divergence of the momentum and density power spectrum, respectively. On linear scales, the above growth factor reduces to the standard linear growth rate, while on small scales it measures an angle-average growth rate as we show below.\(^{15}\)

We can express the overdensity of the species $i$ at any time as $\delta_i(k, a) = D_i(k, a)/D_i(k, a_0)\delta_i(k, a_0)$, and using the continuity equation, we get

$$aHf_i(k, a)\delta_i(k, a) = P_i(k, a),$$

where $f_i(k, a) = d \log D_i(k, a)/d \log a$. The relation between the growth rate we estimate from Equation (1) and $f_i(k, a)$ is then given by

$$P_\delta(k, a)f_i^2(k, a) = P_{\delta f}(k, a),$$

with the right-hand side representing the power spectrum of the product of $\delta$ and $f_i$.

We have computed the growth rate of the CDM+baryon and neutrino fields for each realization (100 in total) of the model with 0.15 eV neutrinos, and in Figure 3 we show the average and standard deviation at different redshifts. We show the results for this model and not for the fiducial model because in terms of the growth rate of the CDM+baryon field results are very similar, but we can also show the results for the neutrino field.

We find that linear theory is able to reproduce very well the results of the simulations on large scales for both CDM+baryons and neutrinos at all redshifts. We notice that even at linear order the growth of both CDM+baryons and neutrinos is scale dependent, in contrast with the growth of matter for a massless neutrino cosmology.\(^{16}\) From Figure 3 this effect is clear for neutrinos, but it is so small for CDM+baryons that it cannot be properly seen in the plot. This effect can, however, be visualized clearly in Figure 5.

On smaller scales the growth rate measured in simulations departs, as expected, from linear theory. There are several reasons for this: (1) the growth rate becomes nonlinear,\(^{17}\) (2) the quantity that we measure in simulations on small scales is not exactly the growth rate, but a convolution of density perturbations and growth rate, and (3) in the case of neutrinos there is a non-negligible contribution coming from the neutrino shot noise that increases with redshift. The last point explains why the agreement with linear theory improves on smaller scales for higher redshift for CDM+baryons but gets worse for neutrinos. Results for other models, and the comparison with linear theory, are as good for the other models as for the model with 0.15 eV.

### 3.2. Growth Rate

We estimate the growth rate of both the CDM+baryons and neutrino fluids as

$$f_i(k, a) = \frac{1}{aH} \left( \frac{P_{\delta f}(k)}{P_{\delta f}(k)} \right),$$

where $i \in \{c, b, \nu\}$ and $P_i = (\nabla \cdot J_i) = \nabla \cdot [(1 + \delta) \nu]$, is the divergence of the momentum of the field $i$. $P_b(k)$ and $P_\nu(k)$ are the divergence of the momentum and density power spectrum, respectively. On linear scales, the above growth factor reduces

15 Notice that on small scales the growth rate depends on both scale and direction. In other words, the rate at which perturbations grow depends on their density, on whether they are inside an overdensity/underdensity, and also on environment.
16 Notice that this is only true on scales below the horizon.
17 We expect that this takes place on scales where the power spectrum deviates from linear theory.
18 We do not show these results here, as they have been extensively studied in other works.
Figure 4. Impact of neutrino masses and $\sigma_8$ on the clustering of matter in redshift space. Top: monopoles (upper row) and quadrupoles (bottom row) for the different models, normalized by the results of the fiducial cosmology, at $z = 0.0$ (left), $z = 0.5$ (middle left), $z = 1.0$ (middle right), and $z = 2.0$ (right). The dotted black lines show the results for the models with massless neutrinos and lower values of $\sigma_8$ than the fiducial model (see Figure 1). The red, green, and blue lines display the results for the models with 0.06, 0.10, and 0.15 eV neutrinos, respectively. Solid and dashed lines represent the results for the matter and CDM+baryon fields, correspondingly.

Bottom: 2D power spectrum of the different models, normalized by the results of the fiducial model at $z = 0.0$. The top part of each panel shows the model for which the results are displayed. For models with massive neutrinos we show both the 2D power spectrum of CDM+baryons (top row) and total matter (bottom row). Panels in the same column have similar values of $\sigma_8$. The solid black lines show isopower contours. While the effect of neutrinos is very different from the one of $\sigma_8$ on large scales, on small scales there is an almost perfect degeneracy between these parameters for the CDM+baryon field. In the matter field that degeneracy is less prominent and the quadrupole can be used to break it.
In the top panels of Figure 4 we show the monopoles and quadrupoles in redshift space, normalized by the results of the fiducial cosmology, for matter and CDM+baryons, for the different models. The effect of massive neutrinos on the matter or CDM+baryons monopole in redshift space exhibits the same features as in real space: a suppression on power from large to small scales that increases with increasing redshift. This effect is also seen in the quadrupole ratio goes to in redshift space, normalized by the results of the fiducial model. The scale at which this happens depend on the nonlinearity level, i.e., on $\sigma_8$. In our case, the models with neutrinos have lower value of $\sigma_8$; thus, their quadrupole will go to zero on smaller scales than the fiducial model, giving rise to that shape in the quadrupole ratio.

In the bottom part of Figure 4 we show the fully 2D power spectrum for the different models, normalized to the 2D power spectrum of the fiducial model, in redshift space at $z = 0$. As can be seen, both $\sigma_8$ and $M_\text{f}$, change the structure of the 2D power spectrum in a complicated way. As we have seen from the monopole and quadrupole results, the effect of $M_\text{f}$ on large scales is different from the one of $\sigma_8$; the reduction of power on large scales from massive neutrinos is smaller than the one induced by decreasing $\sigma_8$, as can be seen from the bottom left part of the panels, showing results for models with massive neutrinos. In agreement with our previous results for monopoles and quadrupoles, we find a strong degeneracy between $M_\text{f}$ and $\sigma_8$ on small scales, which it is more prominent for CDM+baryons than for total matter.

In order to further check the intrinsic degeneracy between $M_\text{f}$ and $\sigma_8$, we have also computed the variance of the field

$$\sigma_2^2(k) = \int_0^1 P^2(k, \mu) d\mu - \left( \int_0^1 P(k, \mu) d\mu \right)^2$$

for the different models. The reason to do this is to verify that the degeneracy in monopoles and quadrupoles is not just a coincidence but that the fully 2D power spectra are very similar. For instance, two models with different structure of the 2D power spectrum can be tuned to give similar results for their monopoles and quadrupoles. By looking at the variance of the field, differences in the 2D structures of the field can be enhanced; thus, if results also show a degeneracy, it represents an additional and quantitative probe on the underlying degeneracy. We find a very strong degeneracy also when employing this quantity, confirming quantitatively our visual impression from Figure 4.

### 4.1. Growth Rate

As we shall see below, an important quantity to describe the clustering properties of halos or galaxies is the growth rate of the CDM+baryon fluid. We, for the first time, measure this quantity in cosmologies with massive neutrinos and investigate the impact of neutrino masses and $\sigma_8$ on its amplitude and shape in the fully nonlinear regime.

In Figure 5 we show the growth rate for the different cosmological models, normalized by the growth rate of the fiducial model, at redshifts 0, 0.5, 1, and 2. Results represent the mean over the 100 realizations of each model. We find that the growth rate of the CDM+baryon fluid is, on all scales and redshifts probed by our simulations, smaller than the fiducial model with massless neutrinos. The growth becomes slower as the sum of the neutrino masses increases, in agreement with the expectations of linear theory. For the neutrino masses considered here, the difference in the growth rate with respect to the fiducial model is never larger than $\sim 2\%$ down to $k = 0.5 \ Mpc^{-1}$. We have compared our results with linear theory, and, on large scales, we find a very good agreement. The dotted lines in Figure 5 show the results for the models with massless neutrinos and different values of $\sigma_8$. As expected from linear theory, on large scales the growth rate does not exhibit any dependence with $\sigma_8$, while on small scales the nonlinear gravitational evolution induces a scale dependence that is different with respect to the fiducial model. We find a degeneracy, on small scales, between the growth rate of models with massless neutrinos sharing the same value of $\sigma_8$ and the models with massive neutrinos.

### 5. Halo Distribution

We now investigate the impact of massive neutrinos and $\sigma_8$ on the clustering properties of dark matter halos in redshift space. We have computed, for each realization of each model, the halo monopoles, quadrupoles, and 2D power spectrum in redshift space, subtracting the contribution from shot noise. The results we show here represent the average over all realizations for each model. We only consider the simulations with low resolution and therefore focus our analysis on halos with masses above $3.2 \times 10^{13} \ h^{-1} M_\odot$.

In the upper part of Figure 6 we show the ratios between the monopoles and quadrupoles of the different models to the fiducial model, at redshifts 0, 0.5, 1, and 2 in redshift space. In contrast to the results of matter and CDM+baryons, the amplitude of the halo monopole is larger, on all the scales considered here, than that of the fiducial model. The reason for this is that we are considering halos of fixed mass, so the lower value of $\sigma_8$ in the models with massive neutrinos translates into a larger halo bias (see Appendix B) that boosts the overall amplitude of the monopole. The same reason also explains why the amplitude of the monopoles increases with decreasing $\sigma_8$ for models with massless neutrinos. On large scales, the effect of massive neutrinos on the halo monopole is not degenerate with the effect induced by $\sigma_8$, similarly to what happens in the matter...
and CDM+baryon fields. We find, however, a degeneracy between $M_\nu$ and $\sigma_8$ on small scales, although it is less strong than the one present for matter and CDM+baryons.

We find that the effect of massive neutrinos on the halo quadrupole on large scales is also pretty different from the one induced by $\sigma_8$, in agreement with our results for the matter and CDM+baryon fields. Our results point out that a degeneracy between $\sigma_8$ and $M_\nu$ is present on small scales, which is weaker for models with larger neutrino masses. Notice that the sample variance errors associated with this measurement are unfortunately too large to prevent a clear distinction of the differences between models. Thus, we cannot claim statistical differences for the quadrupole with the volumes our simulations probe.

In the bottom part of Figure 6 we display the ratio between the 2D power spectrum of halos and the results of the fiducial model in redshift space, for the different models, at $z = 0$. As in the case of matter and CDM+baryons, we find that both massive neutrinos and $\sigma_8$ induce a nontrivial effect on the structure of the 2D power spectrum. On large scales, the modifications to the structure of the 2D power spectrum induced by $M_\nu$ and $\sigma_8$ are different, as expected from our previous results. On small scales both effects are, however, very degenerate. We find that the degeneracy is much stronger when the value of $\sigma_8$ of the model with massless neutrinos matches the value of $\sigma_8^\text{C}$ of the cosmology with massive neutrinos, in agreement with previous works (Castorina et al. 2014, 2015; Villaescusa-Navarro et al. 2014).

It is interesting to notice that massive neutrinos induce a feature on the 2D power spectrum on large scales that is not reproduced by the models with massless neutrinos and different $\sigma_8$; the 2D power spectrum exhibits a larger variance as a function of $\mu$ for models with massive neutrinos than for massless models. This can be seen in the bottom part of Figure 6 as an excess of power in the perpendicular direction with respect to the line of sight. That feature can, however, be reproduced by linear theory. For instance, as we shall see in Section 5.2, we can write the halo power spectrum in redshift space as $P_{\text{hh}}(k, \mu) = (b + f_{\text{ch}}(\mu)^2) P_{\text{b}}(k)$. If we take that expression, with the value of the corresponding value of the halo bias for each model, and compute the ratio of Figure 6, we will find that feature. We thus conclude that its origin is due to (1) the differences between the CDM+baryon power spectrum of the models with massive and massless neutrinos on large scales and (2) the differences on the growth rate, although the former is more important.

5.1. Momentum Bias

In this subsection we try to answer the question whether, in cosmologies with massive neutrinos, the peculiar velocities of dark matter halos follow that of the underlying CDM+baryon fluid—in other words, whether there is a velocity bias between the halos and CDM+baryons. The root of this question resides in the fact that, in models with massive neutrinos, there are two different fields with different clustering properties: the total matter field and the CDM+baryon field. In Villaescusa-Navarro et al. (2014) and Castorina et al. (2014) it was shown for the first time that the clustering properties of halos are dictated by the properties of the underlying CDM+baryon field rather than by the total matter field. The theory template used to extract a neutrino mass from velocity/momentum observations, such as kSZ surveys or galaxy clustering, would be biased by
inaccurate assumptions about neutrino momentum bias at 0.5σ–1σ (Raccanelli et al. 2017). As $M_\nu = 0.06$ eV, the smallest allowed neutrino mass, will only be detected at 3σ–4σ using a combination of data from several observations, it is necessary to avoid any such bias. This is especially important for surveys sensitive to kSZ, such as ACT, SPT, the Simons Observatory, or CMB S4.

Employing similar arguments to those described in Castorina et al. (2014), it seems natural to expect that the statistical properties of the halo velocity field on large scales should
resemble those of the underlying CDM+baryon field. The purpose of this section is to investigate whether the velocity bias between halos and CDM+baryons differs from 1 on large scales.

The velocity bias can be defined as

$$ b^2_v(k) = \frac{P_{\delta\delta}(k)}{P_{\theta\theta}(k)} $$

where \( \theta = - \nabla \cdot \mathbf{v} \). We have tried to measure this quantity directly from our simulations by estimating the velocity field either by assigning velocities from particles/halos to a grid using the cloud-in-cell (CIC) or the piecewise-cubic-spline (PCS) interpolation schemes (see, e.g., Sefusatti et al. 2016) or by using the Delaunay tessellation field interpolation (DTFE) method (Cautun & van de Weygaert 2011). While for the CDM+baryon field the usage of the two different methods yields similar results, for halos the situation is very different. We find that in order to avoid having empty cells where the velocity is not well defined, a very coarse grid needs to be employed with either CIC or PCS (Pueblas & Scoccimarro 2009). That coarseness avoids a reliable estimation of the halo velocity power spectrum even on large scales, due to effects such as aliasing. On the other hand, by employing the DTFE method, where the halo velocity field is well defined everywhere, we find a very strong sampling bias that depends on the number density of the tracers, in agreement with previous works (see, e.g., Jennings et al. 2015; Zheng et al. 2015).

In order to avoid these problems, we employ the momentum, \( J = (1 + \beta)\mathbf{v} \), instead of the velocity field, since that is a quantity that is well defined everywhere. We then define the momentum bias either as

$$ b^2_J(k) = \frac{P_{\delta\delta}(k)}{P_{\theta\theta}(k)} $$

or as

$$ b_J(k) = \frac{P_{\delta\delta}(k)}{P_{\theta\theta}(k)} $$

where \( P_{\delta\delta}(k) \) and \( P_{\theta\theta}(k) \) are the auto-power spectra of the halos and CDM+baryon momentum and \( P_{\delta\delta}(k) \) is the cross-power spectrum between the momentum of halos and the momentum of CDM+baryons. We believe that on large scales, where the halos and CDM+baryon overdensities are small, the momentum bias should resemble the velocity bias.

In Figure 7 we plot the momentum bias at different redshifts using the above two different definitions and for halos with masses above \( 3.2 \times 10^{13} h^{-1} M_\odot \) and \( 3 \times 10^{12} h^{-1} M_\odot \) for different models with massive and massless neutrinos. For the halos with masses above \( 3.2 \times 10^{13} h^{-1} M_\odot \) we use the 100 realizations of the low-resolution simulations, while for the halos with \( M > 3 \times 10^{12} h^{-1} M_\odot \) we use the 13 high-resolution realizations.

We find that the momentum bias on large scales, for all halo masses, redshifts, and neutrino masses shown in Figure 7, tends to 1. The bottom part of each panel shows the relative difference between the momentum bias of each model and the results of the fiducial model. Our results point out that relative differences on large scales are completely negligible (below 0.5%) for all models.

We thus conclude that we do not find evidence for a bias between the momentum of halos and the momentum of CDM+baryons. While the momentum receives contributions from the density even on large scales, the fact that the momentum bias is equal to 1 for halos of different mass, at different redshifts, and for different cosmologies tends to indicate the lack of velocity bias between halos and CDM+baryons on large scales. If that were not true, a very precise cancellation between the contributions from density and velocity would be required to produce such a trend. The lack of momentum/velocity bias is in tension with the claim of Okoli et al. (2017), who predicted a velocity bias between CDM+baryons and halos on large scales due to the dynamical friction induced on halos by the cosmic neutrino background.

We remark that since the statistical properties of the velocity field of CDM+baryons will be different from the ones of the matter field for models with massive neutrinos, there will be a velocity/momentum bias between the halos and the underlying total matter field. It is important to account for this when extracting information from velocity/momentum observations, such as kSZ surveys, in order to avoid biases in the values of the derived parameters.

### 5.2. Comparison with Linear Theory

We now investigate the scales where linear theory is able to describe the clustering properties of halos in redshift space. Following the results of this paper and previous works such as Castorina et al. (2015), we can write the halo power spectrum in redshift space, \( P_{\text{hal}}(k, \mu) \), as

$$ P_{\text{hal}}(k, \mu) = (b + f_c b^2) P_{b}(k) $$

where \( b \) is the halo bias and \( f_c \) and \( P_{b}(k) \) are the growth rate and power spectrum of CDM+baryons, respectively.

The justification of the above expression is as follows: the halo clustering resembles the clustering of the CDM+baryon field, instead of the total matter field (Castorina et al. 2014; Villaescusa-Navarro et al. 2014), and therefore the last term on the right-hand side of the above equation should be the CDM+baryon power spectrum. Our results suggest that halo velocities follow the velocities of the CDM+baryon field on large scales, so no velocity bias should be added to the above equation. Finally, given the fact that halo properties are controlled by the CDM+baryon field, it is expected that the growth rate in the above equation will be the one of CDM+baryons instead of total matter (see Castorina et al. 2015, for a similar justification).

We show the ratio between the halo monopole in redshift and real space at different redshifts in the top panels of Figure 8. The amplitude of that ratio, on large scales, is given by \( b + 2/\beta \beta/3 + \beta^2/5 \) in linear theory, with \( \beta = f_{b\delta} / b \), which we show in that figure with dashed lines. The error bars on the ratios represent the standard deviation of the mean from the 100 realizations, and therefore the expected error for a volume of \( (h^{-1} \text{Gpc})^3 \). The halo linear bias is estimated by fitting the ratio between the halo-CDM cross-power spectrum and the CDM auto-power spectrum to a constant line over the scales \( k \leq 0.05 h^{-1} \text{Mpc} \). The linear growth rate is obtained from CAMB.

We find that, given the error bars of our measurements, linear theory is not particularly good at describing the amplitude of our results on large scales. As expected, the agreement with linear theory increases with redshift. At \( z = 0 \),
Bias between the momentum of halos and the CDM+baryon fields. The momentum bias is estimated using the square root of the ratio between the auto-power spectra of the halo momentum and the CDM+baryon momentum (left column) and the ratio between the cross-power spectrum of the halo and CDM+baryon momenta and the CDM+baryon momentum auto-power spectrum (right column). The first two rows show the results for halos with masses above $3.2 \times 10^{13} h^{-1} M_\odot$ at $z = 0$ (first row) and $z = 0.5$ (second row). The third and fourth rows display the results for halos with masses above $3 \times 10^{12} h^{-1} M_\odot$ at $z = 0$ (third row) and $z = 1$ (fourth row). Results are shown for models with massless neutrinos, fiducial models (solid black), and models with lower $\sigma_8$ (dotted black; see Figure 1), while models with 0.06, 0.10, and 0.15 eV are shown in red, green, and blue, respectively. This implies that in cosmologies with massive neutrinos the halo momentum does not trace the momentum of the underlying matter field. It is important to account for this in order to extract unbiased neutrino information from velocity/momentum observables, such as kSZ surveys.
even on the largest scales we probe in our simulations, we find a scale dependence in the monopole ratio that cannot be described by linear theory. Notice, however, that we find an overall amplitude offset between our results and predictions by linear theory at $z = 0.5$, although it is not significant: $\sim 1\sigma \sim 1.5\sigma$. This can be due to an underestimation of the value of the linear bias from our fits.

We show the monopole ratios, normalized by the results of the fiducial model, in the lower part of the top panels of Figure 8. We see that the effect of massive neutrinos with masses of $0.15 \text{ eV}$ is limited to $1\%$. We find that models with massive neutrinos change the monopole ratio in a scale-dependent way, with the amplitude on large scales more suppressed than on small scales, with respect to the fiducial model. This effect is mainly driven by $\sigma_8$, as we find from the dotted lines, showing the results for models with massless neutrinos and lower values of $\sigma_8$. This points out that it is the change in the bias, mainly controlled by $\sigma_8$, and not in the growth rate, that drives the differences.

The bottom panels of Figure 8 show the ratio between the halo quadrupole and monopole in redshift space. As expected, nonlinearities’ growth with time and linear theory validity shift to larger scales as redshift decreases. Linear theory is not accurate enough to reproduce our monopole results at $z \leq 0.5$, even on the largest scales we probe. On the other hand, it reproduces the quadrupole results better, mainly due to the associated larger errors.
however, larger than those from the monopole ratio, since cosmic variance affects more strongly the quadrupole than the monopole.

In the lower part of those panels we display the results normalized by the output of the fiducial model. As in the case of the monopole ratio, we find that massive neutrinos induce an amplitude reduction that is scale dependent. That effect is, however, mainly driven by $\sigma_8$, since we find a strong degeneracy between the results of the massive neutrinos and the models with massless neutrinos and lower $\sigma_8$ (dotted lines).

We conclude that measuring neutrino masses through the quadrupole/monopole ratio on large scales is challenging, even with volumes as large as 100 $(h^{-3}\text{Gpc})^3$. This is because the quadrupole-to-monopole ratio is sensitive to both the halo bias and the linear growth rate. While the halo bias is completely degenerate with $\sigma_8$, neutrinos induce a very weak scale dependence on the growth rate. Unfortunately, the error bars, even with such gigantic volume, are not small enough to discriminate among models.

### 6. Baryonic Effects

Here we investigate, for the first time, the impact of baryonic effects on redshift-space distortions in cosmologies with massive neutrinos.

It is well known that baryonic effects imprint their signature on the spatial distribution of matter (e.g., van Daalen et al. 2011), affecting both the shape and amplitude of the matter power spectrum. This represents a major complication for cosmology, as the physics and the efficiency involved in those astrophysical processes are not fully understood. We will, however, show that the relative effect induced by massive neutrinos can be, to a very good approximation (1% down to $k = 0.5 \text{ h Mpc}^{-1}$), factored out. This means that neutrino effects can be written as a transfer function that can be calibrated using $N$-body instead of fully hydrodynamic simulations. We notice that Mummery et al. (2017) carried out a similar analysis in real space, reaching similar conclusions to ours. We notice that our hydrodynamical simulations do not include AGN feedback; thus, our analysis lacks one of the most important processes that can change the clustering gas and matter on large scales. We therefore warn the reader to take our results as an intermediate step between those of Mummery et al. (2017). Our goal in this section is to show that under the premise of not having simulated the most energetic astrophysical processes, the effect of baryons and neutrinos can be described separately even in redshift space.

In Figure 9 we show the effect of baryons on the absolute amplitude and shape of the power spectrum of matter and halos in real and redshift space (monopoles) at redshifts $z = 0$ and $z = 1$. In our simulations we find that the effects of baryons on the matter power spectrum in real space are limited to 1%–2% at those redshifts, in agreement with previous works (e.g., Rudd et al. 2008). We notice, however, that this is also caused by the way we set the smoothing lengths of the gas particles (see Appendix C for a detailed analysis). On the other hand, in redshift space, baryonic effects can be as large as 6% at $z = 0$. We notice that previous works (Hellwing et al. 2016) have found the magnitude this effect to be slightly lower than our findings. We have verified that our results are robust against the way we set the smoothing lengths of the gas particles (see Appendix C). It is important to emphasize that the changes induced by baryons on the CDM+baryon field are as large as those caused by neutrinos with 0.15 eV masses (see Figure 4).

The effect of hydrodynamics and astrophysical processes on the clustering of halos has a magnitude of 1%–3%, with a very mild dependence on scale down to $0.5 \text{ h Mpc}^{-1}$ that correlates with redshift.

We study the relative differences in the monopoles, quadrupoles, and fully 2D power spectrum of the matter, CDM+baryon, and halo fields induced by massive neutrinos when employing $N$-body and hydrodynamic simulations. Given the fact that hydrodynamic simulations are much more computationally expensive than $N$-body simulations, we focus our analysis on just one model with 0.15 eV massive neutrinos.

**Figure 9.** Impact of baryons on the clustering of matter (left) and halos (right) in real (red) and redshift space (blue) at $z = 0$ (solid) and $z = 1$ (dashed). The plot shows the ratio between the power spectrum from the $N$-body simulations and the hydrodynamics simulations. Baryons affect the shape and amplitude of the matter power spectrum in redshift space by up to 5% at $k = 0.5 \text{ h Mpc}^{-1}$, while for halos the effect is mainly an overall amplitude suppression of $\approx 1.5\%$. 

![Figure 9](image-url)
We show in the first column of the top part of Figure 10 the monopoles of CDM + baryons and matter for the 0.15 eV model in redshift space at $z = 0$ and $z = 1$, normalized by the results of the fiducial model, when using $N$-body and hydrodynamic simulations. As can be seen, for CDM+baryons, the relative difference is barely affected by hydrodynamics (well below 1%) down to $k = 0.5 \, h \, \text{Mpc}^{-1}$ at both redshifts. We find that baryons induce slightly larger differences in the matter field, but still below 1%. The second column of the top part displays the results for the quadrupole of the CDM+baryon and matter fields.
fields. Also in this case we find that hydrodynamics and astrophysical effects only change the relative difference caused by neutrinos by less than 1%.

The third and fourth columns of the top part of Figure 10 show the results for the halo monopole and quadrupole in redshift space, respectively. As for the matter and CDM+baryon fields, we find that baryons do not change appreciably the relative effect induced by neutrino masses. Given the error bars arising from cosmic variance, we conclude that the results from N-body and hydrodynamic simulations are in very good agreement.

Finally, we investigate whether baryons affect the morphology of the relative difference induced by massive neutrinos on the CDM+baryon and halo fields. We show the results in the bottom part of Figure 10 for the CDM+baryon field (left panels) and the halo field (right panels) at redshifts z = 0 (upper row) and z = 1 (bottom row). We find that the angle dependence of the relative effect of massive neutrinos is not much affected by baryons, at both redshifts and for both halos and CDM+baryons. Our results point out that while the relative difference in the 2D power spectrum of CDM+baryons is almost unaffected by baryons for modes with low $k_{||}$ (independently of $k_{\perp}$), we observe a larger effect for modes with large $k_{||}$, although differences are below 1%. This effect is, however, averaged out when estimating the relative difference in the monopole, as can be seen in the upper part of Figure 10. This happens because only a relatively small fraction of modes are affected by this effect.

We reach similar conclusions by looking at the halo field, where baryons barely affect the 2D structure of the relative difference between 0.15 eV and massless neutrinos. Unfortunately, cosmic variance is still large enough so that we cannot quantify any baryonic effect on the amplitude or angle dependence of the ratio. We have verified that our results are robust against the way we set the smoothing lengths of the gas particles (see Appendix C).

We thus conclude that even though baryons can largely affect the absolute amplitude and shape of the clustering pattern of matter, CDM+baryons, and halos in redshift space, massive neutrino effects can be factored out, and relative differences are robust to hydrodynamics and astrophysical processes within 1%, for the observables we have considered in this paper down to $k = 0.5 h \, \text{Mpc}^{-1}$. We emphasize that a study like the one presented here, where the fully 2D power spectrum in redshift space is compared by varying cosmological models and baryon effects, can only be carried out given the very large volumes we have accessible through our numerical simulations. We highlight once again the fact that our simulations do not include AGN feedback, one of the most energetic astrophysical processes. Thus, these conclusions should be revisited with new simulations that incorporate AGN feedback.

7. Conclusions

Measuring the sum of the neutrino masses is one of the most important challenges in modern cosmology. Upcoming large-scale structure surveys are expected to have enough statistical power to be able to detect the minimum sum of the neutrino mass allowed by neutrino oscillation experiments.

Unfortunately, our ability to extract cosmological information from galaxy clustering measurements is limited by several physical processes: (1) the density field becomes nonlinear on small scales and/or low redshifts owing to gravitational evolution; (2) we do not observe the density field directly, but only tracers of it such as galaxies or cosmic neutral hydrogen; (3) the redshifts of the tracers we measure are affected by their peculiar velocities; and (4) astrophysical processes such as feedback may potentially affect the distribution of matter and peculiar velocities in a nontrivial way.

Precise theory predictions are required to measure the sum of the neutrino masses robustly from redshift surveys. Since the effect of neutrino masses is so small, any inaccuracy on the theory side can give rise to biases in both the sum of the neutrino masses and the value of the other cosmological observables. For neutrinos, these biases can incorrectly lead to major consequences. For instance, a cosmological detection of neutrino masses below $\approx 0.06 \, \text{eV}$ at $3\sigma$ will have major implications for both cosmology and particle physics.

It is thus timely to understand and model as accurately as possible the impact of nonlinearities, halo/galaxy bias, redshift-space distortions, and baryonic effects on cosmologies with massive neutrinos. While the first three complications above have been carefully studied in cosmologies with massless neutrinos (and only partially the fourth), only the first and the second have been systematically studied for models with massive neutrinos.

In this work we have analyzed in detail the following aspects: (1) the impact of neutrinos and $\sigma_8$ on the clustering of matter, CDM+baryons, and halos in redshift space in the fully nonlinear regime; (2) the impact of neutrinos on the nonlinear growth rate; (3) the bias between the momentum of halos and the CDM+baryon field; (4) the scales where linear theory is able to describe the clustering properties of halos in models with massive neutrinos; and (5) the impact of baryons on redshift-space distortions in cosmologies with massive and massless neutrinos.

We investigate the above points using a very large set containing more than 1000 N-body and hydrodynamical simulations with realistic neutrino masses. For each model we have 100 low-resolution N-body realizations, where we resolve halos with masses above $\approx 3 \times 10^{13} h^{-1} \, \text{M}_\odot$ in a box of $1 \, h^{-1} \, \text{Gpc}$, and 13 high-resolution N-body realizations, resolving halos with masses above $\approx 3 \times 10^{12} h^{-1} \, \text{M}_\odot$ in a box of $1 \, h^{-1} \, \text{Gpc}$. We simulate three different cosmologies with 0.06, 0.10, and 0.15 eV degenerate massive neutrinos. We also have five different cosmologies with massless neutrinos and different values of $\sigma_8$ that more or less match the value of either $\sigma_8^\nu$ or $\sigma_8^m$ from the models with massive neutrinos. For the fiducial and $M_{\nu} = 0.15 \, \text{eV}$ models we also have 100 low-resolution hydrodynamic simulations.

We now summarize the main conclusions of this work:

1. We find that massive neutrinos and $\sigma_8$ produce very different effects on the clustering of matter, CDM+baryons, and halos in redshift space on large scales. On the other hand, they produce almost identical effects on the clustering of CDM+baryons on small scales. That degeneracy is also present in the matter field but can be partially broken through the quadrupole. The magnitude of this degeneracy is smaller for the clustering of halos, although both parameters produce, within a few percent, almost the same effect.

In the near future, theory predictions for galaxy clustering in redshift space may arise by combining the output of N-body simulations with halo occupation
distribution (HOD) models. Given the degeneracy between $M_*$ and $\sigma_8$ on small scales, the neutrino signal may be partially mimicked by assembly bias, since both assembly bias and massive neutrinos can change the amplitude of the clustering on large scales, keeping fixed the small-scale clustering.

2. The amplitude of the growth rate of the CDM+baryon field in cosmologies with massive neutrinos is lower, on scales $k \approx 10^{-1} - 0.5 \ h \ Mpc^{-1}$, than the one of the corresponding massless neutrino cosmology. That suppression is, however, very small: less than 2% for 0.15 eV neutrinos at $k = 0.5 \ h \ Mpc^{-1}$. On small scales, $\sigma_8$ and $M_*$ produce very similar effects.

3. We find no bias between the momentum of halos and CDM+baryons on large scales. Since in cosmologies with massive neutrinos the properties of the CDM+baryons and matter fields are different, this implies that there is a momentum bias between halos and matter. It is important to account for this when extracting neutrino information from velocity/momentum observations such as kSZ surveys.

4. Our results indicate that, at linear order and in cosmologies with massive neutrinos, the galaxy power spectrum in redshift space, $P^i_{gg}(k)$, can be written as

$$P^i_{gg}(k) = (b + f_{cb}(k)\mu^2)P_{cb}(k),$$

where $b$ is the galaxy bias and $f_{cb}$ and $P_{cb}(k)$ are the growth rate and power spectrum of the CDM+baryon field, respectively. We find that the above expression can reproduce the clustering properties of dark matter halos down to $k = 0.07$, 0.08, and 0.09 $h \ Mpc$ at $z = 0$, 0.5, and 1, respectively.

5. We show that baryonic effects can affect the shape and amplitude of the CDM+baryon and matter power spectrum by as much as $\approx 5\%$ at $k = 0.5 \ h \ Mpc^{-1}$ at $z = 0$. The effect on halos is smaller: $\approx 1\%$, and it has a weak dependence with scale. We show that the relative effect that neutrinos induce on the clustering of matter, CDM+baryons, and halos, i.e., $P_M(k, \mu)/P_{M=0}(k, \mu)$, is affected by baryons by less than 1% down to $k = 0.5 \ h \ Mpc^{-1}$. This means that the neutrino effects (at least to $k = 0.5 \ h \ Mpc^{-1}$) can be written as a transfer function that, to a very good approximation, does not depend on baryons. That transfer function can be calibrated using $N$-body instead of hydrodynamical simulations. We, however, warn the reader that our hydrodynamic simulations do not incorporate AGN feedback; thus, we limit our claims to the baryonic effects that we simulate.

This work represents a step forward into a careful and systematic description of neutrino effects on cosmological observables in the mildly nonlinear regime.

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Appendix A

Convergence Tests

Here we present convergence tests for the matter and halo power spectrum, in real and redshift space, at $z = 0$ for the model with 0.15 eV neutrinos. Results for the other models are very similar to this one, so we omit them here for clarity. We choose to show results at $z = 0$, as this is the most nonlinear epoch proven by our simulations, i.e., results are expected to be better at higher redshifts.

We work with two different simulation sets. On one hand, we use the 100 L15 simulations with 512$^3$ CDM and 512$^3$ NU particles. We refer to this set as the low-resolution set. On the other hand, we take the 13 L15 simulations with 1024$^3$ CDM and 1024$^3$ NU particles, which we coin the high-resolution test. Our halo catalogs contain halos with masses above $3.2 \times 10^{13} h^{-1} M_\odot$.

In Figure 11 we show the matter (left) and halo (right) power spectrum for the low- and high-resolution simulation sets. From the top panels we can see that agreement between both sets is very good. In the bottom panels we quantify that agreement by showing the ratio between the results of both simulation sets. It can be seen how our results for matter in real space are converged at 2% down to $k = 0.7 \ h \ Mpc^{-1}$. Notice that the high-resolution simulation exhibits more power on small scales than the low-resolution simulations, as expected. On large scales, the differences between the two data sets can be as large as 4%. This is due to cosmic variance. In order to understand whether that difference is significant, we show in the bottom panels a blue region displaying the 1$\sigma$ error on the mean from the high-resolution simulations. It can be seen how on large scales the scatter from the low-resolution simulations is within the expected error, confirming our hypothesis of cosmic variance. We emphasize that the agreement between the results from two sets is not expected to be smaller than the intrinsic scatter of one of them.

We find larger differences for the halo power spectrum in real space. In this case, we find that the mean power spectra from the two sets differ by $\approx 10\%$ at $k = 0.4 \ h \ Mpc^{-1}$. This behavior is somehow expected, as the smallest halos we are considering in this work are made up of only $\approx 50$ particles, i.e., it is not unreasonable to think that as we increase the mass and spatial resolution, the positions and masses of those small halos will be slightly affected. This will be reflected in the halo power spectrum. As with the matter power spectrum, on large scales we also observe rather large differences arising from cosmic variance.

We show in Figure 12 the results for matter and halos in redshift space. We focus our attention on the monopoles and quadrupoles. From the top panels we can see that the agreement between the results of both simulation sets is very good. The middle and bottom panels show the monopole and quadrupole ratios, respectively. We find that the matter monopoles are converged at 2% down to $k = 0.7 \ h \ Mpc^{-1}$. Notice that in this case there is more power in the monopole of the low-resolution simulations than in the high-resolution simulations on small scales. This is expected since by increasing the mass resolution we are enhancing the amplitude of the FoG.

Cosmic variance is much larger for the matter quadrupole, where we can only say that the measurements from both sets are compatible until $k \approx 0.25 \ h \ Mpc^{-1}$, where the quadrupoles go to 0. On smaller scales, $k \sim 0.4-0.7 \ h \ Mpc^{-1}$, where the amplitude of the quadrupole is negative but not close to 0, we
find that relative differences are around 4%. This small discrepancy is also expected, as in the higher-resolution simulations we are able to resolve smallest halos, whose internal velocity dispersions will enhance the magnitude of the FoG.

Our results for the halo monopole are similar to those of the halo power spectrum in real space. However, in redshift space our results are slightly better: 10% converged at $k \approx 0.5 \, h \, \text{Mpc}^{-1}$. This happens because the two competing effects, (1) differences in clustering in real space and (2) the
amplitude of the FoG, go in opposite directions, so they slightly cancel. Our results for the halo quadrupoles are, on the other hand, pretty good, since the measurements from the two sets are compatible at $2\sigma$ on all scales down to $k=0.7\, h\, \text{Mpc}^{-1}$. We notice that the reason for this is because the error bars on the quadrupoles are still very large on all scales.

From the above results, we conclude that our absolute results are not converged at 1% down to the smallest scales we prove in this paper, $k=0.5\, h\, \text{Mpc}^{-1}$. We notice that this statement applies not only to our neutrino simulations but also to standard massless neutrino cosmologies and is expected from the considerations of the halo model. We will now try to prove that even if the absolute results are not converged at 1%, our relative results are very well converged down to $k=0.5\, h\, \text{Mpc}^{-1}$.

We focus on the halo monopoles and quadrupoles, which show large differences (much larger in the monopole) on small scales owing to mass and spatial resolution. In Figure 13 we show the halo monopole ratios and halo quadrupole ratios between the 0.15 eV model and the fiducial 0.0 eV model. The red lines show the results for the low-resolution simulations, while the blue lines are for the high-resolution simulations. The error bars represent the error on the mean. We find a very good agreement between the results of both sets. In the bottom panels we observe that both results are in agreement at 1σ down to $k=0.7\, h\, \text{Mpc}^{-1}$. Notice also that the absolute difference between the two sets is around 1%. We obtain similar results for other quantities like the matter power spectrum in real and redshift space.

We thus conclude that while the low-resolution simulations cannot be used to make absolute predictions at 1% down to $k=0.5\, h\, \text{Mpc}^{-1}$, they can be used to study the relative effect of neutrinos very precisely. For the matter and halo power spectra in real and redshift space, our results are converged at $\simeq 1\%$ down to $k=0.7\, h\, \text{Mpc}^{-1}$.

### Table 2
Values of Linear Halo Bias, for Halos with Masses above $3.2\times 10^{13}\, h^{-1} M_{\odot}$, for the Different Models at Redshifts 0, 0.5, 1, and 2

| Name     | $M_{\nu}$ | $\sigma^m_k$ | $\sigma^q_k$ | $\xi=0$ | $\xi=0.5$ | $\xi=1$ | $\xi=2$ |
|----------|-----------|--------------|--------------|---------|-----------|---------|---------|
| L0 (fid) | 0.00      | 0.833        | 1.739        | 2.524   | 3.633     | 6.839   |
| L0-1     | 0.00      | 0.822        | 1.770        | 2.573   | 3.712     | 7.000   |
| L0-2     | 0.00      | 0.818        | 1.782        | 2.594   | 3.742     | 7.082   |
| L0-3     | 0.00      | 0.807        | 1.814        | 2.643   | 3.821     | 7.255   |
| L0-4     | 0.00      | 0.798        | 1.842        | 2.689   | 3.895     | 7.394   |
| L6       | 0.06      | 0.819        | 0.822        | 1.766   | 2.566     | 3.690   | 6.942   |
| L10      | 0.10      | 0.809        | 0.815        | 1.797   | 2.614     | 3.770   | 7.110   |
| L15      | 0.15      | 0.798        | 0.806        | 1.828   | 2.660     | 3.840   | 7.258   |

### Appendix B
Halo Bias

Here we show the value of the halo linear bias we measure from our simulations. We measure the halo bias as

$$b_h(k) = \frac{P_{ch}(k)}{P_{cb}(k)}$$

where $P_{ch}(k)$ is the CDM+baryon-halos cross-power spectrum and $P_{cb}(k)$ is the CDM+baryon auto-power spectrum, both in real space. For each model, we measure the halo bias using the above equation for each of the 100 realizations available. We then compute the mean and standard deviation and extract the value of the linear bias by fitting the results to a constant, $b_1$, over the range of the scales $k \leq 5 \times 10^{-2}\, h\, \text{Mpc}^{-1}$. 

![Figure 13](image-url) Halo monopole ratio (left) and quadrupole ratio (right) for the low- and high-resolution sets. Even if individual quantities are not well converged, the ratios are converged at 2% down to $k=0.5\, h\, \text{Mpc}^{-1}$. In other words, relative differences induced by neutrinos are much more robust to resolution than absolute quantities.
In Table 2 we show the values of $b_1$, for halos with masses above $3.2 \times 10^{13} h^{-1} M_\odot$, for the different cosmologies explored in this work at several redshifts.

### Appendix C

**Effects from Gas Smoothing Length**

The hydrodynamic simulations employed in this work have been run by setting the smoothing length of the gas particles equal to their SPH radii. The reason is to avoid the short-scale forces that produce an undesired coupling between CDM and gas (Angulo et al. 2013). That coupling induces a significant deviation of the gas power spectrum on all scales, which translates into a shift with respect to linear theory on large scales.

Unfortunately, some side effects arise by doing that, such as gas losing power with respect to linear theory at high redshift on small scales. In order to test the robustness of our results against these effects, we have run an equivalent set of hydrodynamical simulations to those in Table 1 by setting the smoothing length of the gas particles to 1/40 of their mean interparticle distance, i.e., the same as for CDM. We have then repeated the analysis of Section 6.

The effect of baryons on the matter and halo power spectrum in real and redshift space is shown in Figure 14. We find that baryonic effects in real space are now below the percent level at both $z = 0$ and $z = 1$, in agreement with Hellwing et al. (2016) and Springel et al. (2017). This is due to the fact that the gas in our standard runs loses power at high redshift, inducing a transient that still persists at low redshift. We notice that a way to, at least partially, avoid this is simply to increase the resolution of our standard runs. In our case, given the volumes we are interested in, this is computationally unfeasible.

In redshift space the matter clustering seems to be less sensitive to the way gas smoothing lengths are set. As with our standard runs, we find that baryons increase the amplitude of the monopole on small scales with respect to the $N$-body simulations. Our results are in tension with those of Hellwing et al. (2016), who found a much smaller effect. Unfortunately, we cannot discern whether this discrepancy is due to the way we generate the initial conditions or is just an artifact of the relatively poor resolution of our hydrodynamic runs.

The effect of the gas smoothing length on the halo clustering is mostly attributed to an overall change in the amplitude. The reason is that in our standard runs we have a deficit of power on small scales due to gas losing power on small scales at high redshift. This manifests in a lower abundance of halos in those hydrodynamic runs than those in $N$-body simulations or hydrodynamic simulations with standard smoothing lengths. That lower abundance induces a higher amplitude of the halo clustering in our standard runs. By using the standard smoothing lengths for the gas particles, we find that the effect of baryons on halo clustering is below 1% down to $k = 0.5 h \text{ Mpc}^{-1}$.

We finally check the impact of the gas smoothing lengths on our claim that neutrino effects can be factored out and studied using $N$-body simulations. In Figure 15 we show the equivalent of Figure 10 when the smoothing lengths of the gas particles are set to 1/40 of their mean interparticle distance. We find that baryons imprint a larger modification on the relative difference that neutrinos induce, with respect to our fiducial runs, for both CDM+baryons and halos. The effect is, however, of the order of 1%, and most of the differences take place on small scales.

We thus conclude that by setting the smoothing lengths of the gas particles to be equal to their SPH radii, the power spectrum of gas follows linear theory on large scales. On the other hand, gas loses power at high redshift on small scales owing to the relatively large smoothing lengths. That produces a suppression of power on small scales with respect to $N$-body simulations, which is also translated into a lower abundance of halos. While the problem of the lack of gas power on small scales can be alleviated by setting the smoothing lengths of the gas particles to their standard value, this procedure induces that the gas will not follow linear theory on large scales owing to its numerical gravitational coupling with CDM on small scales.

Although both implementations have their pros and cons, our results indicate that the relative neutrino effects are not largely affected ($\sim 1\%$) by baryons down to $k = 0.5 h \text{ Mpc}^{-1}$.

![Figure 14](image-url). Same as Figure 9, but when the smoothing lengths of the gas particles are set to 1/40 of their mean interparticle distance. In our standard hydrodynamic simulations we set the smoothing lengths of the gas particles to be equal to their SPH radii.
Therefore, we confirm that neutrino effects can be factored out and its magnitude can be determined through N-body simulations as long as calculations do not require subpercent accuracy.

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Figure 15. Same as Figure 10, but when the smoothing lengths of the gas particles are set to 1/40 of their mean interparticle distance. In our standard hydrodynamic simulations we set the smoothing lengths of the gas particles to be equal to their SPH radii.

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