Effects of Massive Neutrinos on the Large-Scale Structure of the Universe

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Overview

- Cosmological neutrinos strongly affect the evolution of the largest structures in the Universe (see e.g. Doroshkevich et al. 1981; Hu et al. 1998; Abazajian et al. 2005; Kiakotou et al. 2008; Brandbyge et al. 2010; Viel et al. 2010, and reference therein)
- N-body simulations $\Longrightarrow$ halo mass function, two-point correlation function and redshift-space distortions $\Longrightarrow$ errors on the linear distortion parameter β introduced if cosmological neutrinos are assumed to be massless
- If not taken correctly into account and depending on the total neutrino mass M_ν, these effects could lead to a potentially fake signature of modified gravity
- Future all-sky spectroscopic galaxy surveys will be able to constrain M_ν using β measurements alone and independently of the value of the matter power spectrum normalisation σ_8

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Introduction

- Neutrinos are massive particles. This is considered as definite evidence for new physics beyond the Standard Model

- The matter distribution in the Universe is sensitive to the free-streaming of cosmological neutrinos $\Longrightarrow$ astrophysical constraints are therefore a very competitive alternative method to measure/constrain the masses of neutrinos

- Neutrinos in the mass range 0.05 eV $\leq \Sigma m_\nu \leq$ 1.5 eV become non-relativistic in the redshift range $3000 \geq z \geq 100$. In the mass range of degenerate neutrino masses the thermal velocities can be approximated as

$$v_{\rm th} \sim 150\,(1+z)\,\left[\frac{1\,{\rm eV}}{\Sigma m_\nu}\right]{\rm km/s}\,.$$

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Introduction

- The neutrino contribution in terms of energy density can be expressed as:

$$f_\nu = \Omega_{0\nu}/\Omega_{0\mathrm{m}}\,, \qquad \Omega_{0\nu} = \frac{\sum m_\nu}{93.8\, h^2 \mathrm{eV}}$$

- When neutrinos become non relativistic in the matter dominated era, there is a minimum wavenumber

$$k_{\mathrm{nr}} \sim 0.018\,\Omega_{0\mathrm{m}}^{1/2} \left[\frac{\sum m_\nu}{1\,\mathrm{eV}}\right]^{1/2} h/\mathrm{Mpc}\,,$$

above which the physical effect produced by neutrino free-streaming damps small-scale neutrino density fluctuations, while modes with $k < k_{\mathrm{nr}}$ evolve according to linear theory

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Constraints on neutrino masses

The neutrino oscillation experiments provide a lower limit for the sum of the neutrino masses of 0.05-0.1 eV. Current upper bounds range from a factor of 4-10 above the lower limit.
Cosmological probes of neutrino masses:

Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)
CMB Primordial	1.3	0.6
Lensing of CMB	∞	$0.2 - 0.05$
Galaxy Distribution	0.6	0.1
Lensing of Galaxies	0.6	0.07
Lyman α	0.2	0.1
21 cm	∞	$0.1 - 0.006$
Galaxy Clusters	0.3	0.1
Core-Collapse Supernovae	∞	$\theta_{13} > 0.001^*$

(Abazajian et al. 2011)

see Carbone et al. 2011 for updated forecasts on neutrino mass constraints using future galaxy redshift surveys, in combination with CMB priors

Model dependence

Abazajian et al. 2011

Measurementes of the neutrino mass from cosmological observations are inherently model-dependent. However, they can be considered robust with respect to reasonable modifications of the ΛCDM model.

- Extra relativistic species (e.g. sterile neutrinos and axions):
  these scenarios generically predict modifications to the outcome of big bang nucleosynthesis and thus can be independently constrained by observations of the primordial light elemental abundances
- Warm dark matter:
  the effects of replacing CDM with WDM are generally limited to the very small scales, and are not degenerate with light neutrino masses
- Inflation physics:
  primordial gravitational wave background and isocurvature modes affect only the CMB anisotropies at low multipoles and are not directly degenerate with neutrino masses. A running spectral index can in principle mimic the suppression in the matter power spectrum caused by free-streaming massive neutrinos. However, it can be tightly constrained by the CMB anisotropies.
- Dynamical dark energy:
  the dark energy equation of state parameter exhibits considerable degeneracy with the neutrino mass. However, a combination of distance probes (e.g., BAO and Supernova Ia) can very effectively remove this degeneracy
- Modified gravity and non-flat spatial geometry:
  phenomenologically they share some similarities with the dynamical dark energy scenarios

Hydrodynamical simulation with massive neutrinos

Viel et al. 2010

Hydrodynamical TreePM-SPH code: GADGET III (Springel et al. 2005) + massive neutrinos

"Grid based implementation": neutrinos are treated as a fluid. The linear growth of the perturbations in the neutrino component is followed by interfacing the hydrodynamical code with the code CAMB

- side of the box: 512 h^{-1} Mpc
- number of particles: $1448^3 \sim 3 \cdot 10^9$
- particle mass: $1.4 \cdot 10^{10} M_\odot/h$ and $6.9 \cdot 10^{10} M_\odot/h$ for gas and dark matter, respectively
- cosmological parameters: $n_s = 1$, $\Omega_m = 0.3$, $\Omega_b = 0.05$, $\Omega_\Lambda = 0.7$ and $h = 0.7$, plus a cosmological massive neutrino component $\Omega_\nu \equiv M_\nu/(h^2 93.8\mathrm{eV})$
- total neutrino mass: $M_\nu = 0, 0.3, 0.6$ eV

* Virialized DM haloes $\Longleftrightarrow$ standard friends-of-friends (FOF) group-finder algorithm
* DM substructures $\Longleftrightarrow$ SUBFIND algorithm (Springel et al. 2001)

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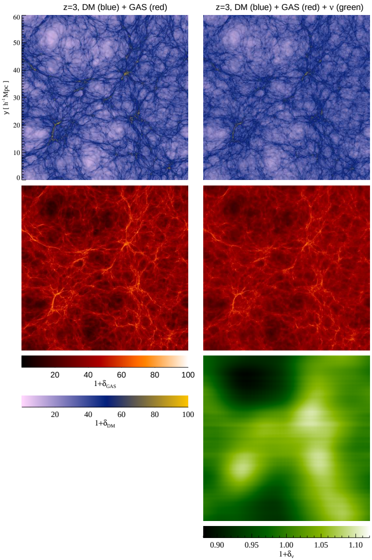


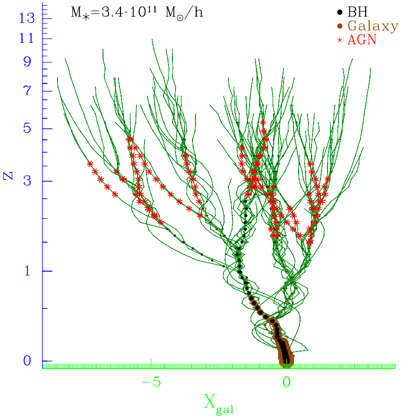
Density slices of thickness 6 h^{-1} comoving Mpc at z=3 extracted from two 60 h^{-1} Mpc hydrodynamical simulations. The right column shows a simulation that includes neutrinos with Σm_ν=1.2 eV. The presence of neutrinos (bottom panel, green) clearly affects both the gas (red) and the dark matter (blue) distribution

* Other numerical studies: Bond, Efstathiou and Silk 1980, Klypin et al. 1993, Ma & Bertschinger 1994, J. Brandbyge et al. 2008, Brandbyge & Hannestad 2009, 2010

* Analytical estimates:
- renormalization group time-flow approach: Lesgourgues et al. 2009, Saito, Takada and Taruya 2009
- perturbation theory: Wong 2008, Saito, Takada and Taruya 2008
- halo model: Hannestad et al. 2005, Abazajian et al. 2005

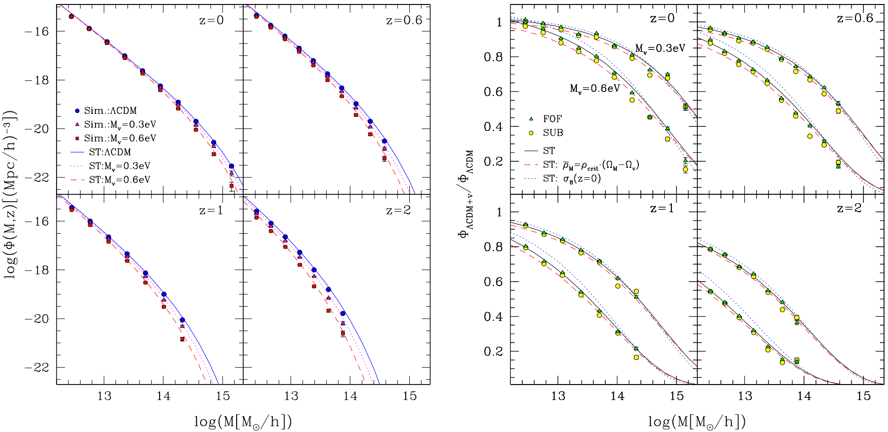
Galaxy merger tree

Marulli et al. 2009



A typical galaxy merger tree. The variable on the horizontal axis represents the displacement between the parent galaxy and its progenitor, defined as $X_{\rm gal} = \sum_{i=1}^{3}(x^i_{\rm gal} - x^i_{\rm par})$, where $x^i_{\rm gal}$ and $x^i_{\rm par}$ represent the three Cartesian, comoving components of the progenitor and the parent galaxy, respectively, in unit of $\mathrm{M}_\odot$.

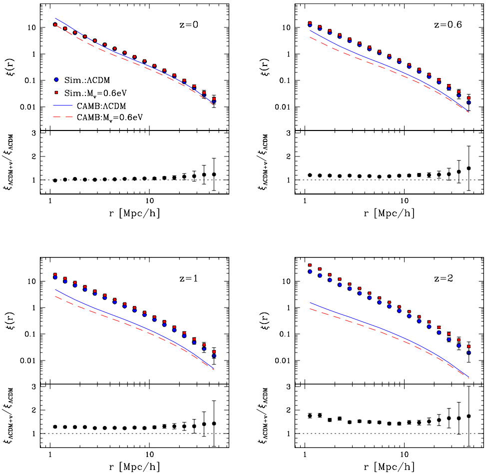
The halo mass function



There is a significant suppression in the average number density of massive structures. As an example, the number density of haloes with mass $10^{14} M_{\odot}/h$ at $z = 0$ decreases by $\sim 15\%$ for $M_\nu = 0.3$ eV and by $\sim 30\%$ for $M_\nu = 0.6$ eV, and, at $z = 1$, by$\sim 40\%$ and $\sim 70\%$, respectively.

The difference between the MFs with and without neutrinos does not reduce merely to a σ_8 renormalization of the background cosmology.

The halo clustering



Two-point correlation function :

$$dP_{12} = n^2[1 + \xi(r)]dV_1 dV_2$$

where dP_{12} is the probability of finding a pair with one object in the volume dV_1 and the other in the volume dV_2, separated by a comoving distance r.

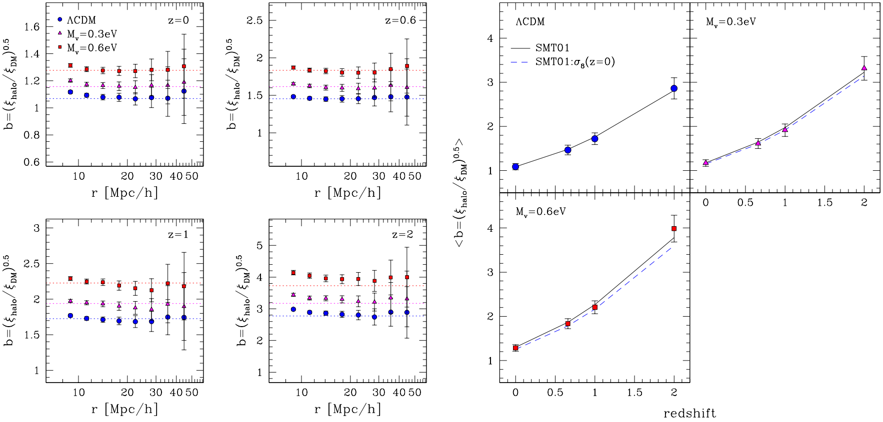
Landy & Szalay (1993) estimator:

$$\xi(r) = \frac{HH(r) - 2RH(r) + RR(r)}{HH(r)}$$

$HH(r)$, $RH(r)$ and $HH(r)$ are the fraction of halo–halo, halo–random and random–random pairs, with spatial separation r, in the range $[r - \delta r/2, r + \delta r/2]$.

While the total matter correlation function decreases with respect to the ΛCDM case, the halo correlation function undergoes the opposite trend.

The halo bias



The analytical predictions have been obtained using the Sheth et al. 2001 bias, weighted with the ST MF:

$$b(z) = \frac{\int_{M_{\rm min}}^{M_{\rm max}} n(M,z) b_{\rm SMT}(M,z) dM}{\int_{M_{\rm min}}^{M_{\rm max}} n(M,z) dM}$$

Clustering anisotropies

dynamic distortions - redshift space

We cannot measure comoving distances directly, we need redshifts.
An observed galaxy redshift is composed by two terms:

$$z_{\rm obs} = z_{\rm c} + \frac{v_{\|}}{c}(1+z_{\rm c})$$

$z_{\rm c}$ is the *cosmological* redshift due to the Hubble flow, $v_{\|}$ is the component of the galaxy peculiar velocity parallel to the line-of-sight.
The *real* comoving distance of a galaxy is:

$$r_{\|} = \frac{c}{H_0}\int_0^{z_{\rm c}} \frac{dz'_{\rm c}}{\sqrt{\Omega_\Lambda + \Omega_{\rm M}(1+z'_{\rm c})^3}}$$

assuming $\Omega_\Lambda + \Omega_{\rm M} = 1$

Clustering anisotropies

geometic distortions - Alcock&Paczynski test

An object which is spherical in comoving real space will appear spherical also in redshift space only if the correct cosmology is assumed.

The relation between the separations $r_\perp$ and $r_\parallel$ in two different cosmologies (referred to by the subscripts 1 and 2) reads (Ballinger et al. 1996):

$$r_{\perp 1} = \frac{B_1}{B_2} r_{\perp 2}$$

$$r_{\parallel 1} = \frac{A_1}{A_2} r_{\parallel 2}$$

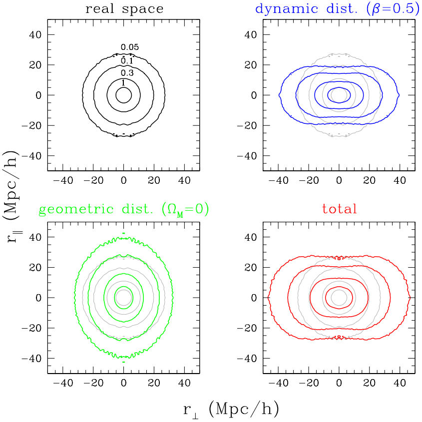
where the parameters A and B for a spatially flat cosmology are:

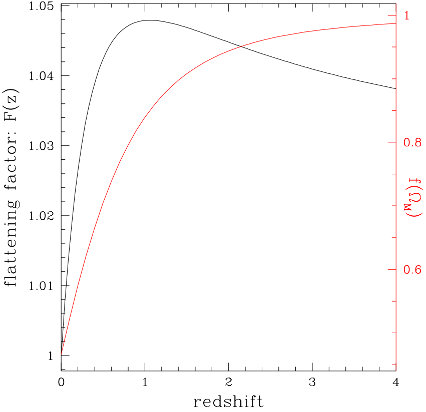
$$A = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_\Lambda + \Omega_{\mathrm{M}}(1+z)^3}}$$

$$B = \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_\Lambda + \Omega_{\mathrm{M}}(1+z')^3}}$$

Clustering anisotropies

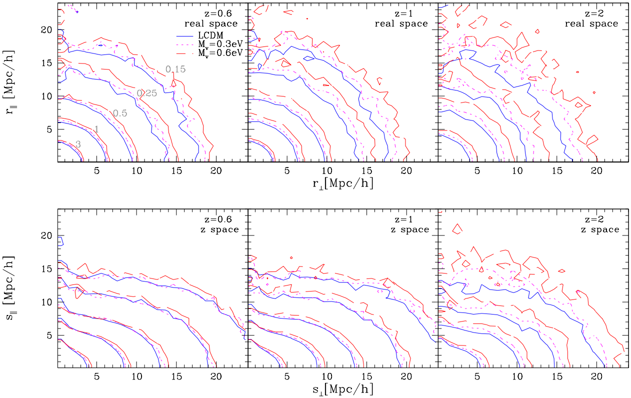
their characterists and redshift dependences





$$\beta = \frac{f(\Omega_{\rm M})}{b} = \Omega_{\rm M}(z)^{0.55}; \quad F(z) = \frac{A_1}{A_2}\frac{B_2}{B_1}, \text{ where } \Omega_{\rm M,1} = 0.25 \text{ and } \Omega_{\rm M,2} = 1 \text{ (and } \Omega_\Lambda + \Omega_{\rm M} = 1)$$

Clustering anisotropies



In the case of massive neutrinos, the clustering is less enhanced in redshift-space than in real-space on large scales, while on small scales FoG get decreased.
This might induce a bias in the inferred growth rate from data analysis, and therefore a potentially false signature of modified gravity. Moreover, estimates of β and σ_{12}, yield an indirect neutrino mass measurement.

Modelling the dynamical distortions

linear theory

At large scales and in the plane-parallel approximation:

$$\xi(r_\perp, r_\parallel)_{\rm lin} = \xi_0(s)P_0(s) + \xi_2(s)P_2(s) + \xi_4(s)P_4(s)$$

where P_l are the Legendre polynomials and $\beta = \frac{f(\Omega_{\rm M})}{b}$ (Kaiser 1987, Hamilton 1992). The multipoles of $\xi(r_\perp, r_\parallel)$ can be written as follows:

$$\xi_0(s) = \left(1 + \frac{2\beta}{3} + \frac{\beta^2}{5}\right)\xi(r)$$

$$\xi_2(s) = \left(\frac{4\beta}{3} + \frac{4\beta^2}{7}\right)[\xi(r) - \overline{\xi}(r)]$$

$$\xi_4(s) = \frac{8\beta^2}{35}\left[\xi(r) + \frac{5}{2}\overline{\xi}(r) - \frac{7}{2}\overline{\overline{\xi}}(r)\right]$$

where:

$$\overline{\xi}(r) = \frac{3}{r^3}\int_0^r dr'\xi(r')r'^2$$

$$\overline{\overline{\xi}}(r) = \frac{5}{r^5}\int_0^r dr'\xi(r')r'^4$$

Modelling the dynamical distortions

non-linear corrections

To include in the model also the small scales, we can use the following equation:

$$\xi(r_\perp, r_\parallel) = \int_{-\infty}^{\infty} dv f(v) \xi(r_\perp, r_\parallel - v/H(z)/a(z))_{\rm lin}$$

where $f(v)$ is the distribution function of random pairwise velocities that are measured in physical (not comoving) coordinates (but see e.g. Scoccimarro 2004; Matsubara 2004). On large scales the ratio between redshift-space and real-space correlation functions can be approximated as follows:

$$\frac{\xi(s)}{\xi(r)} = 1 + \frac{2\beta}{3} + \frac{\beta^2}{5}$$

For this work, we test two different forms for $f(v)$:

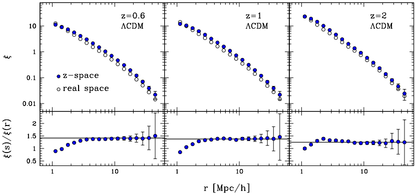
$$f_{\rm exp}(v) = \frac{1}{\sigma_{12}\sqrt{2}} \exp\left(-\frac{\sqrt{2}|v|}{\sigma_{12}}\right)$$

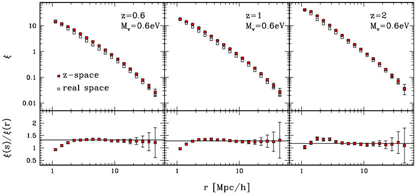
and

$$f_{\rm gauss}(v) = \frac{1}{\sigma_{12}\sqrt{\pi}} \exp\left(-\frac{v^2}{\sigma_{12}^2}\right)$$

where σ_{12} is the dispersion in the pairwise peculiar velocities.

Redshift-space distortions

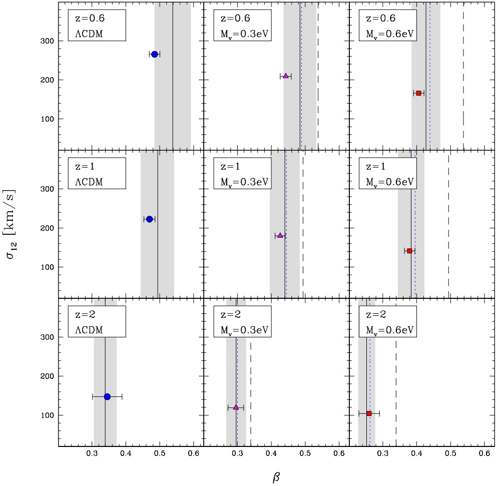




The redshift-space halo correlation function slightly suppressed in a ΛCDM+ν cosmology. In the bottom panels we show the ratios $\xi(s)/\xi(r)$ compared to the theoretical value:

$$\frac{\xi(s)}{\xi(r)} = 1 + \frac{2\beta}{3} + \frac{\beta^2}{5}.$$

Best-fit parameters

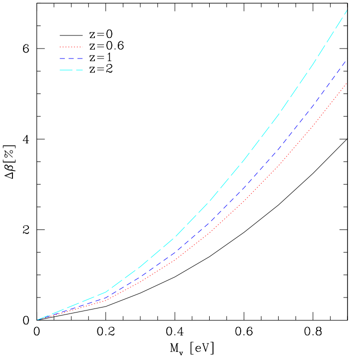


Neutrinos free-streaming suppresses β and σ_{12} by an amount which increases with M_ν and z.

As an example, at $z = 0.6$ the β best-fit values decrease by $\sim$ 10% for $M_\nu = 0.3$ eV, and by $\sim$ 25% for $M_\nu = 0.6$ eV. Likewise, the σ_{12} best-fit values decrease by $\sim$ 25% for $M_\nu = 0.3$ eV, and by $\sim$ 45% for $M_\nu = 0.6$.

If an error of $\sim$ 10% is assumed on bias measurements, we are not able to distinguish the effect of massive neutrinos on β when the two cosmological models with and without ν are normalised to the same σ_8.

Degeneracy with σ_8



The relative difference between the theoretical β values calculated in the ΛCDM+ν and ΛCDM cosmologies, normalised to the same σ_8. At $z = 1$ and for $M_\nu > 0.6$ eV, the relative difference with respect to the $M_\nu = 0$ case is $\Delta\beta/\beta \lesssim 3\%$.

Future spectroscopic galaxy surveys, as EUCLID, JEDI and WFIRST, should be able to measure the linear redshift-space distortion parameter with errors $\leq 3\%$ at $z \leq 1$, per redshift bin.

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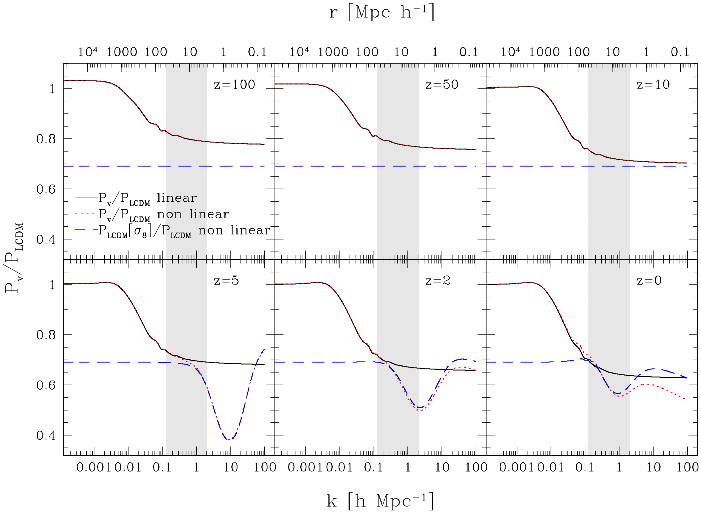

Conclusions

- Massive neutrinos suppress the comoving number density of DM haloes by an amount that increases with the total neutrino mass M_ν. The suppression affects mainly haloes of mass $10^{14} M_\odot/h < M < 10^{15} M_\odot/h$, depending slightly on the redshift z.
- The trend of the halo correlation function $\xi(r)$ is opposite to the dark matter one, since the halo bias results to be significantly enhanced.
- The rise of the spatial halo clustering due to massive neutrinos is less enhanced in the redshift-space than in the real-space. On small scales, also FoG get decreased in the presence of massive neutrinos, so that the best-fit values of β and σ_{12} reduce by an amount which increases with M_ν and z.
- If not taken correctly into account, these effects could lead to a potentially fake signature of modified gravity. Moreover, estimates of β and σ_{12} can be used to extract measurements of the total neutrino mass and may help breaking degeneracies with the other cosmological parameters.

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- At $z = 1$ and for $M_\nu > 0.6$ eV, the relative difference with respect to the $M_\nu = 0$ case is $\Delta\beta/\beta \gtrsim 3\%$. This results is interesting, since future all-sky spectroscopic galaxy surveys, like EUCLID, JEDI and WFIRST, should be able to measure the linear redshift-space distortion parameter with errors $\lesssim 3\%$ at $z \leq 1$, per redshift bin.

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