Massive neutrinos and the Large Scale Structure of the Universe

Emanuele Castorina
SISSA

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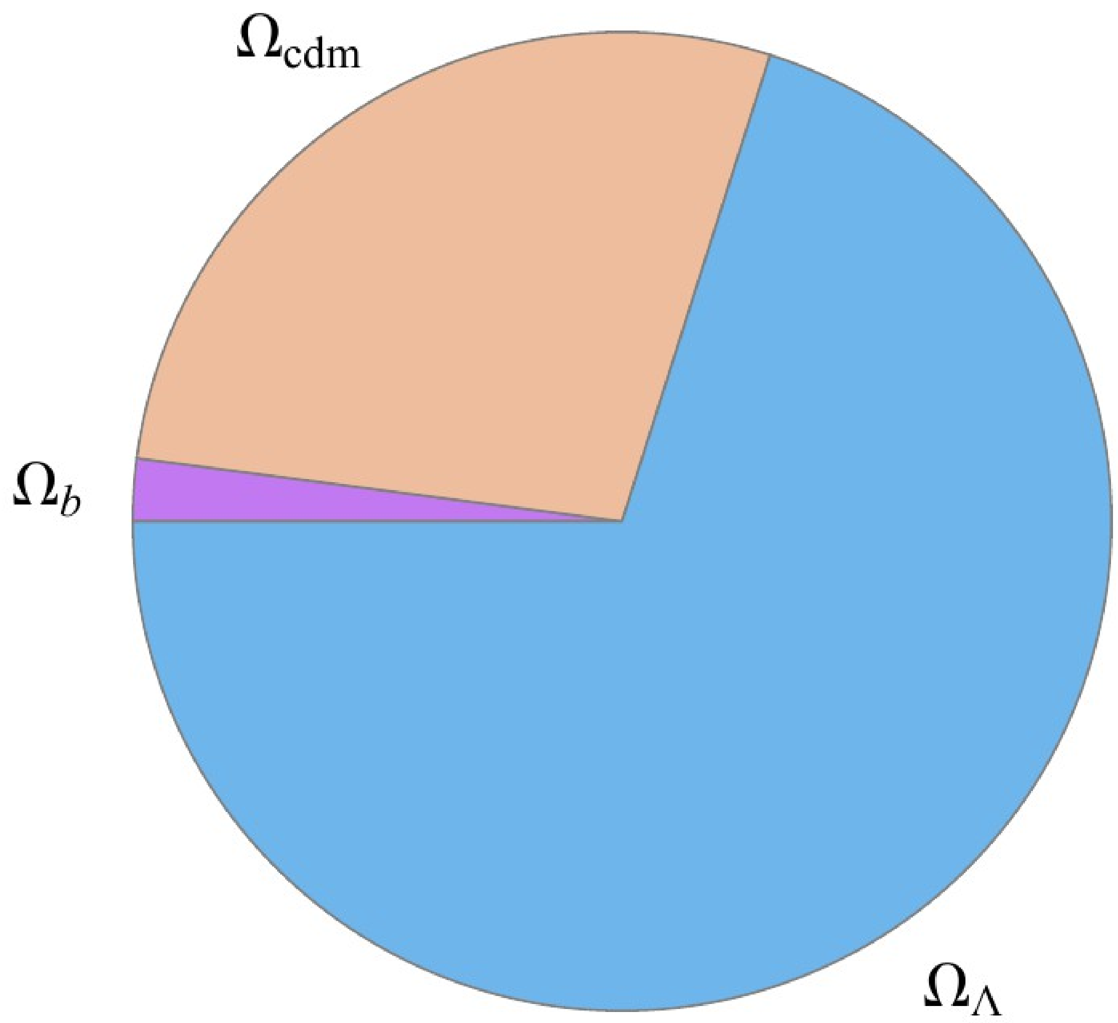
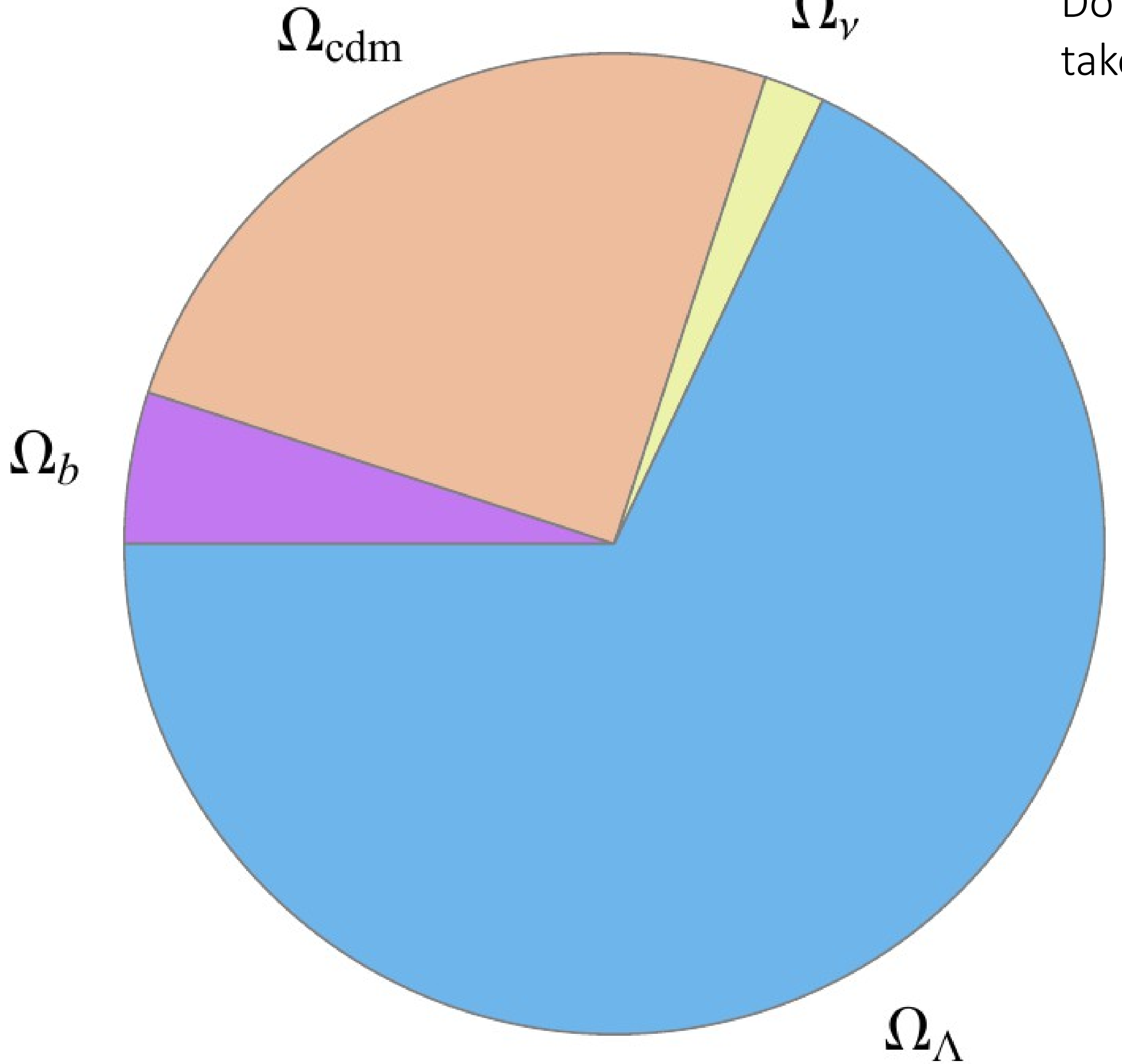
w/ Sheth, Sefusatti, Viel, Villaescusa-Navarro, Carbone, Bel, Borgani, Costanzi

The pizza nobody asked for



Planck 2015

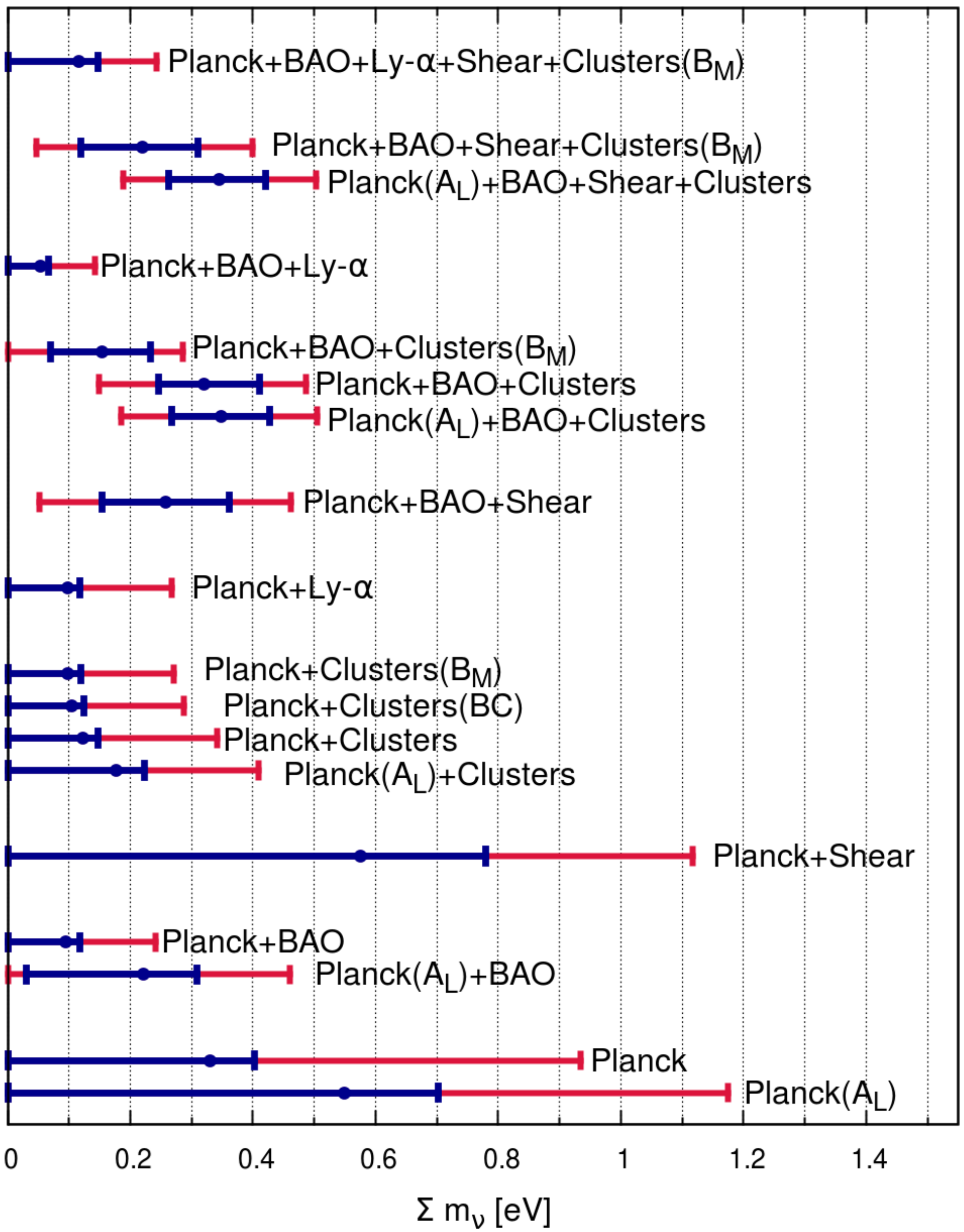
The real picture



Do we really have to take them seriously ?

Relevant for precision cosmology, % level accuracy, and interplay with particle physics.

Neutrino mass madness



Costanzi+14

Galaxy clustering in k-space in the BOSS CMASS sample suggests non-zero neutrino masses, Beutler+13

$$\sum m_\nu = 0.35 \pm 0.10 \ \text{eV}$$

Clustering wedges in real space of the same sample + LOWZ yields, Sanchez+13

$$\sum m_\nu < 0.24 \ \text{eV}$$

BAO+CMB+Ly-alpha, Palanque-Delabrouille+15

$$\sum m_\nu < 0.12 \ \text{eV}$$

Planck15+SN+BAO+H0

$$\sum m_\nu < 0.23 \ \text{eV}$$

The goal : clustering in massive neutrino cosmologies

Massive neutrinos induce peculiar features in cosmological observables. However these effects are small.

We are primarily interested in the clustering of dark matter halos and galaxies in the *non linear* regime.

- a prediction for the evolution of the *underlying matter density field* w/ Perturbation Theory or fitting formulae (HALOFIT) ;

- a relation between the matter distribution and discrete objects, such as halos and galaxies, i.e. *halo/galaxy bias* ;

- a description of *redshift space distortions* (RSD) ;

- extension to higher order correlation functions ;

Check w/ simulations the validity of the analytic model for two- and three- point statistics, the *power spectrum* and the *bispectrum.*

Non relativisitc transition

Neutrinos become non-rel when the temperature of the universe drops below their mass

$$z_{nr} \simeq 1900 \left(\frac{m_\nu}{1 \text{ eV}}\right)$$

$$\Omega_{dm} = \Omega_{cdm} + \Omega_\nu$$

$$f_\nu \equiv \frac{1}{\Omega_m} \frac{\sum m_\nu}{93.14 h^2 \text{ eV}}$$

However neutrinos are Hot Dark Matter, with very high free streaming velocities

$$\sigma_\nu \simeq 180 \frac{1+z}{m_\nu/eV} \;\; km/s$$

Linear theory facts in neutrinos cosmologies (I)

After non-relativistic transition

$$\delta_m \equiv (1 - f_\nu)\, \delta_{cdm} + f_\nu\, \delta_\nu\,, \qquad f_\nu \equiv \Omega_\nu / \Omega_m.$$

Growth of neutrino perturbation is suppressed by free streaming,

$$\lambda_{fs}(m_\nu, z) = a \left(\frac{2\pi}{k_{fs}} \right) \simeq 7.7 \frac{1+z}{(\Omega_\Lambda + \Omega_m (1+z)^3)^{1/2}} \left(\frac{1\, eV}{m_\nu} \right) \; h^{-1}\, \mathrm{Mpc}$$

It has a maximum at the redshift of the non-rel transition

$$k_{nr} = k_{fs}(z_{nr}) \simeq 0.018 \Omega_m^{1/2} \left(\frac{m_\nu}{1\, eV} \right) \; h\, \mathrm{Mpc}^{-1}$$

Linear theory facts in neutrinos cosmologies (II)

$$P_{mm}(k) = (1 - f_\nu)^2 \, P_{cc}(k) + f_\nu^2 P_{\nu\nu}(k) + 2 f_\nu (1 - f_\nu) P_{\nu c}(k)$$

Below the free-streaming scale neutrino perturbations are washed out

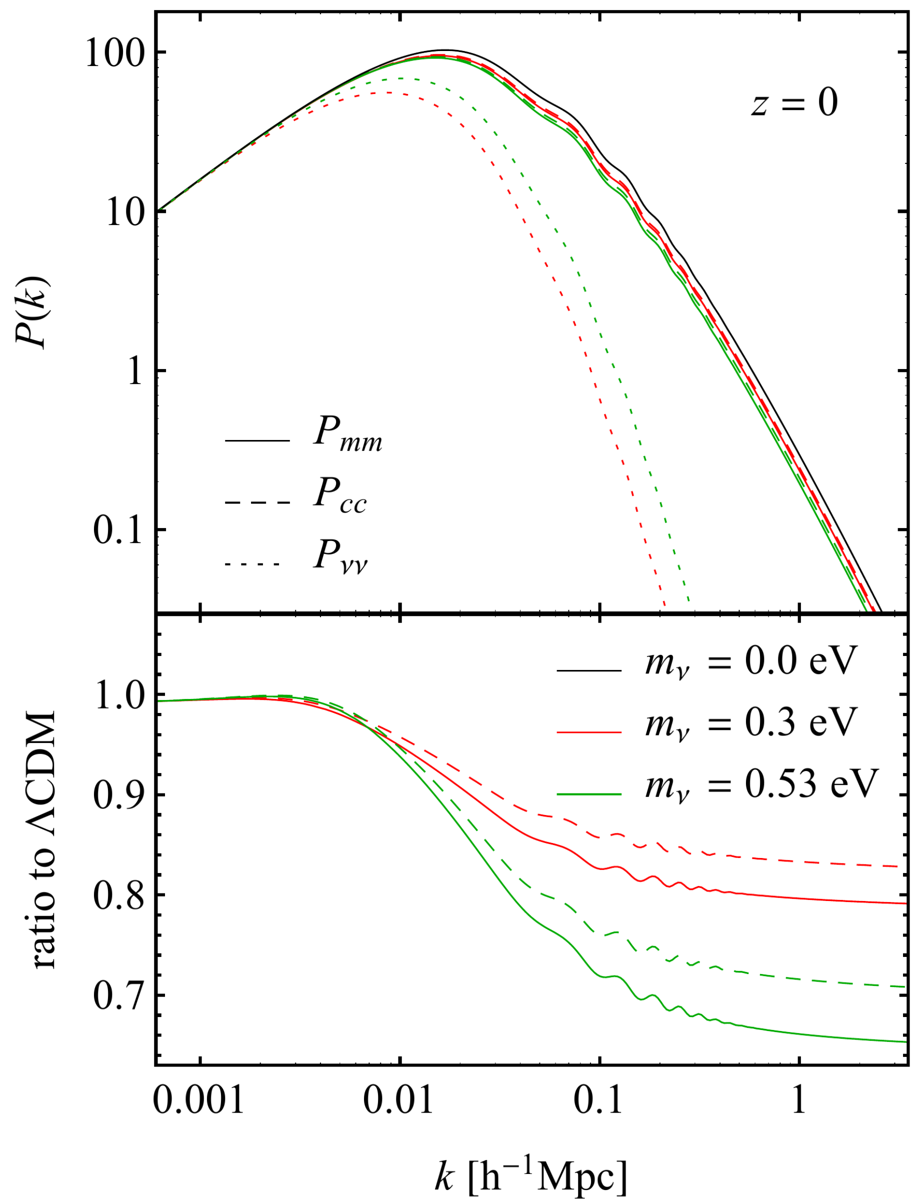
$$P_{mm}(k) = \begin{cases} P_{cc}(k) & \text{if } k < k_{nr} \\ (1 - f_\nu)^2 \, P_{cc}(k) & \text{if } k \gg k_{nr} \, . \end{cases}$$

Back-reaction on CDM

$$\delta_c \propto a^{1-3/5 f_\nu}$$

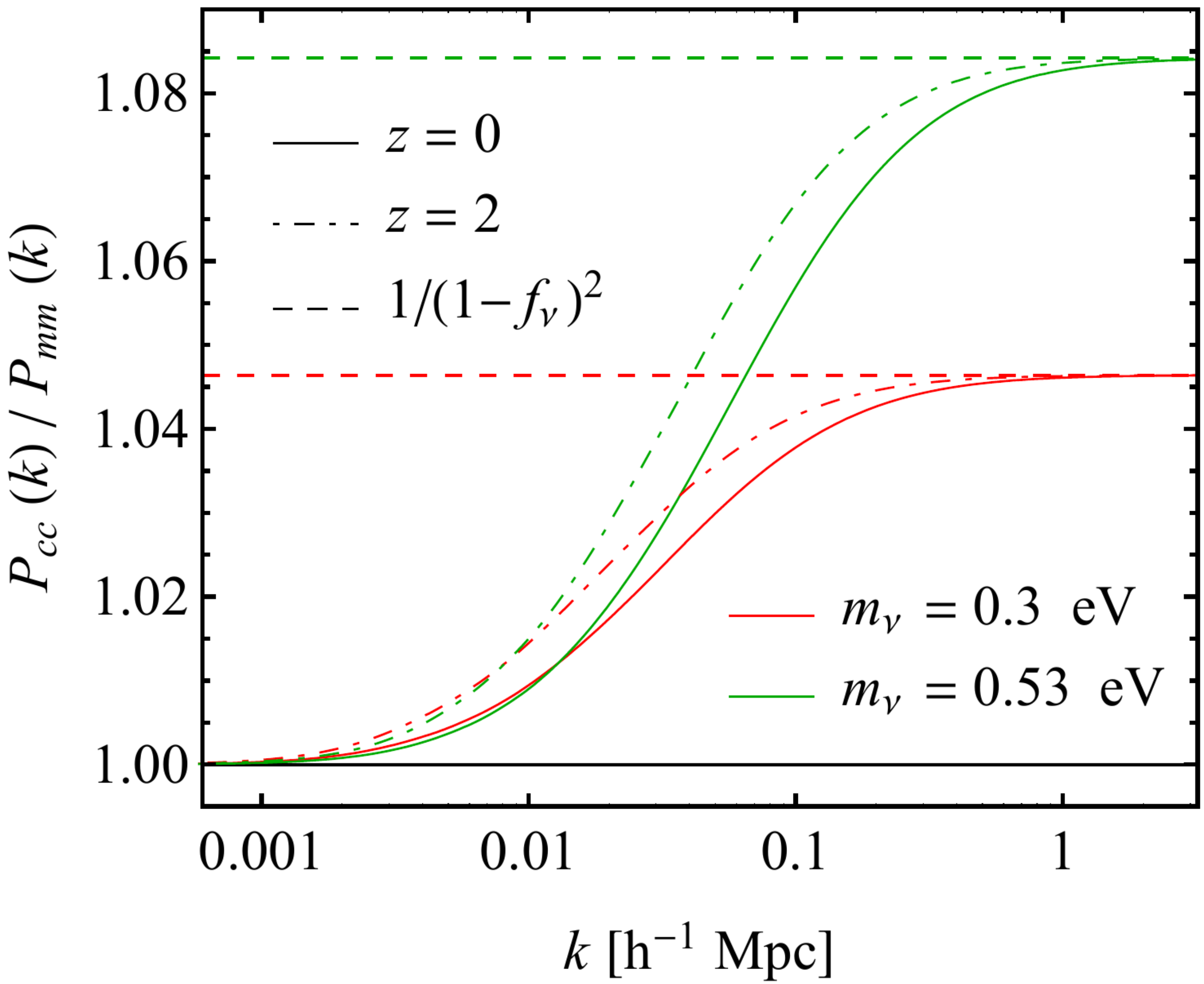
leads to a suppression of power in the CDM component wrt a massless neutrino universe. The net result for the DM power spectrum is

$$\frac{P_{mm}(k; f_\nu)}{P_{mm}(k; f_\nu = 0)} \simeq 1 - 8 f_\nu$$



Linear theory facts in neutrino cosmologies (III)

In massive neutrino cosmologies the total matter power spectrum and the CDM power Spectrum are not the same.



The simulations

The goal is to study the clustering of matter and halos in massive neutrino comologies.

- Four cosmlogies ;

- Box size 2 Gpc/h ;

- 2048^3 CDM particles, 2048^3 neutrino particles ;

- Neutrinos are treated as CDM particles, with large thermal velocities (free streaming) ;

	$\sum m_\nu[\mathrm{eV}]$	Ω_{cdm}	f_ν	$\sigma_{8,dm}$	$\sigma_{8,cdm}$	$m_p^c[h^{-1}M_\odot]$	$m_p^\nu[h^{-1}M_\odot]$
P00	0.0	0.270	0.000	0.841	0.841	8.27×10^{10}	–
P17	0.17	0.266	0.012	0.796	0.806	8.16×10^{10}	1.05×10^{9}
P30	0.30	0.263	0.022	0.763	0.778	8.08×10^{10}	1.85×10^{9}
P53	0.53	0.2576	0.039	0.708	0.731	7.94×10^{10}	3.27×10^{9}

$$\sigma_{8,X}^2 = \int d^3k\, P_X(k,z) W^2(kR_8)$$

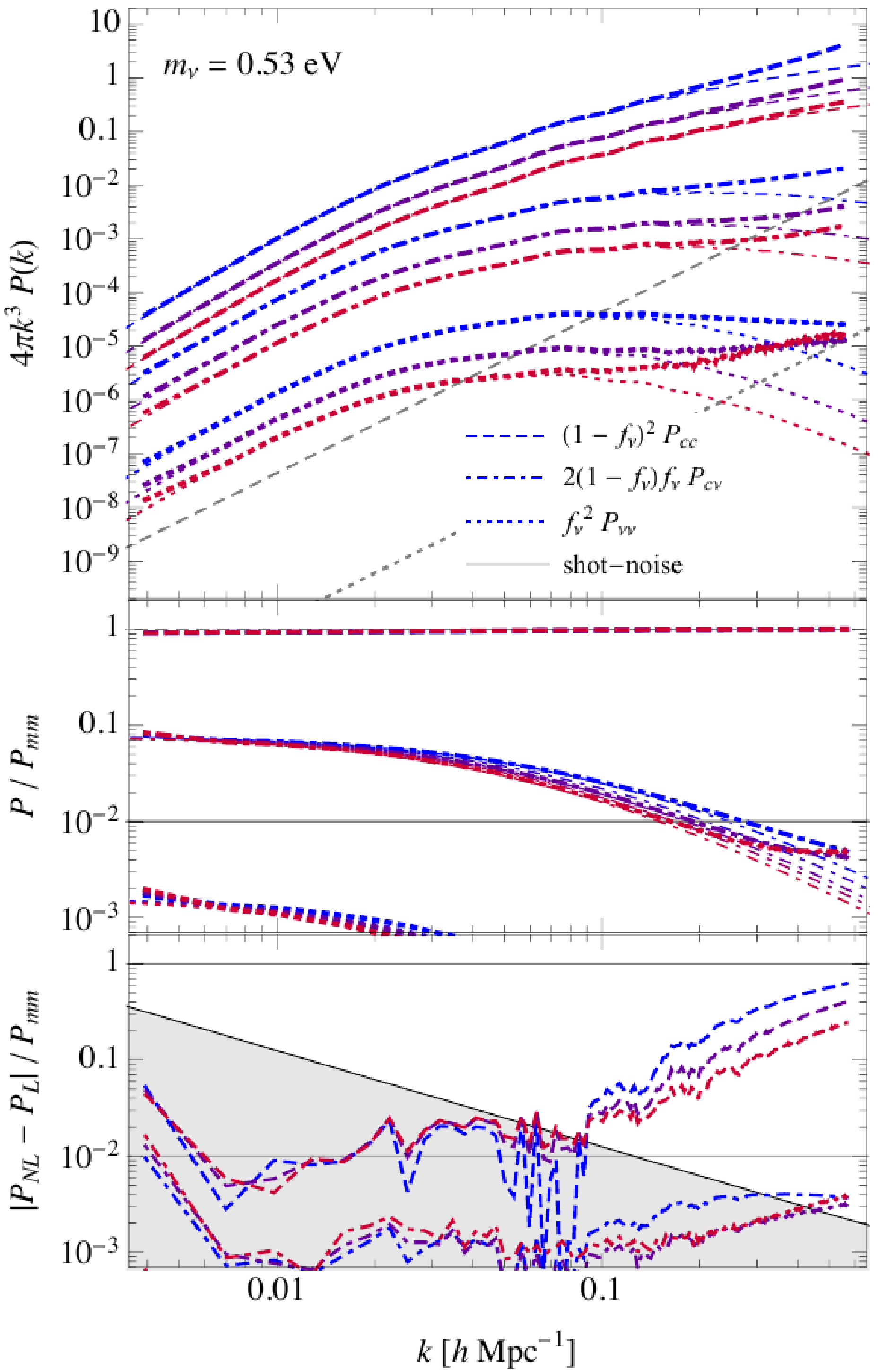
Non linear power spectra

$$4\pi k^3 P_{mm}(k) \equiv \Delta_{mm}(k) =$$
$$(1-f_\nu)^2\Delta_{cc}(k) + 2f_\nu(1-f_\nu)\Delta_{c\nu}(k) + f_\nu^2\Delta_{\nu\nu}(k)$$

Non linear effects in the cross and the neutrino auto power spectrum are negligible.

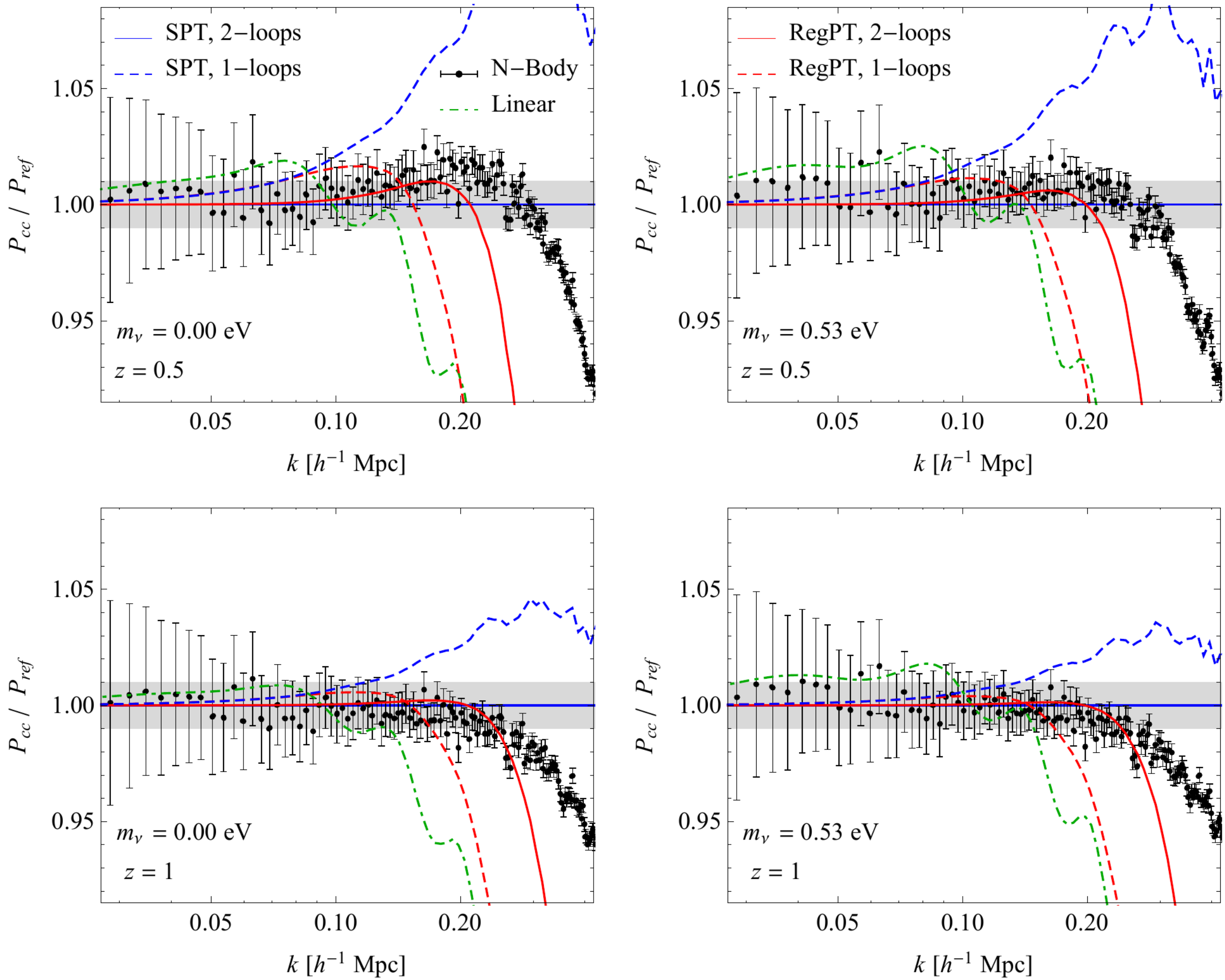
Suppressed by powers of fnu.

Relevant for perturbation theory/EFTofLSS



PT results (I) for CDM

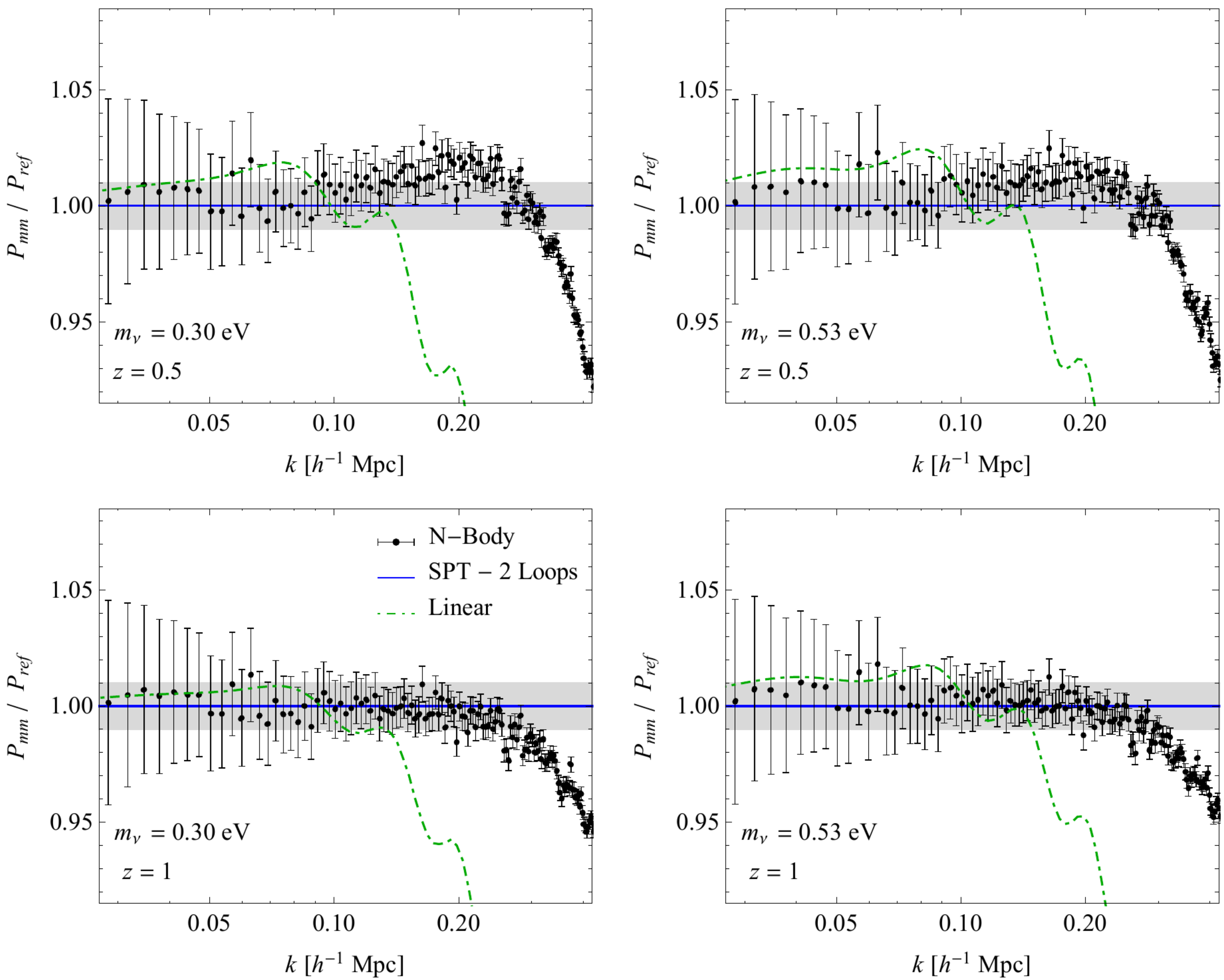
% error bar around BAO wiggles for the 1st time.



PT results (II) for DM

$$P_{mm}^{PT}(k) = (1-f_\nu)^2\, P_{cc}^{PT}(k) + f_\nu^2 P_{\nu\nu}(k) + 2 f_\nu (1-f_\nu) P_{\nu c}(k)$$

Same accuracy as CDM.
Useful for HALOFIT.



The halo mass function (I)

$$n(M) = \frac{\rho}{M} f(\sigma, z) \frac{d \ln \sigma^{-1}}{dM}, \qquad f(\sigma, z) = A(z) \left[\sigma^{-a(z)} + b\right] e^{-c(z)/\sigma^2}$$

$$\sigma^2(M, z) = \int d^3k \, P(k, z) \, W_R^2(k)$$

A universal mass function does not explicitly depend on redshift.

The abundance of massive clusters can be predicted using only linear theory quantities.
Halo mass is defined by

$$M \equiv \rho \int d^3x \, W(x, R) = \frac{4\pi}{3} \rho_{cdm} R^3$$

Brandbyge et al. (2010), Villaescusa-Navarro et. al (2012) : neutrino contribution to halo masses is negligible, i.e. f_ν is small . Halo finders can be safely runned over the CDM particles only.

$$\sigma_{cc}^2 = \int d^3k \; P_{cc}(k) \; W^2$$

$$\sigma_{mm}^2 = \int d^3k \; P_{mm}(k) \; W^2$$

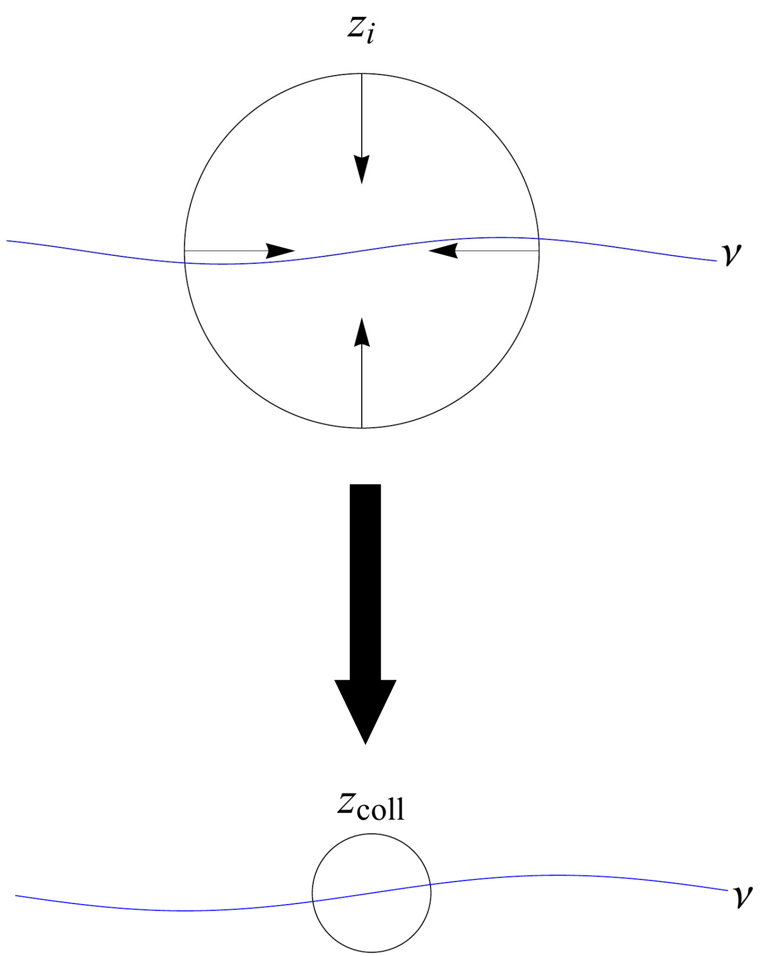
Note that

$$\boxed{P_{cdm}(k, z) \geq P_m(k, z)}$$

The halo mass function (II)

The physical picture: $\delta_{cdm} > \delta_{crit} + a\,\delta_{\nu}$

the free streaming length is much larger than <u>Lagrangian</u> size of halos, neutrino perturbations do not play any role in the collapse.



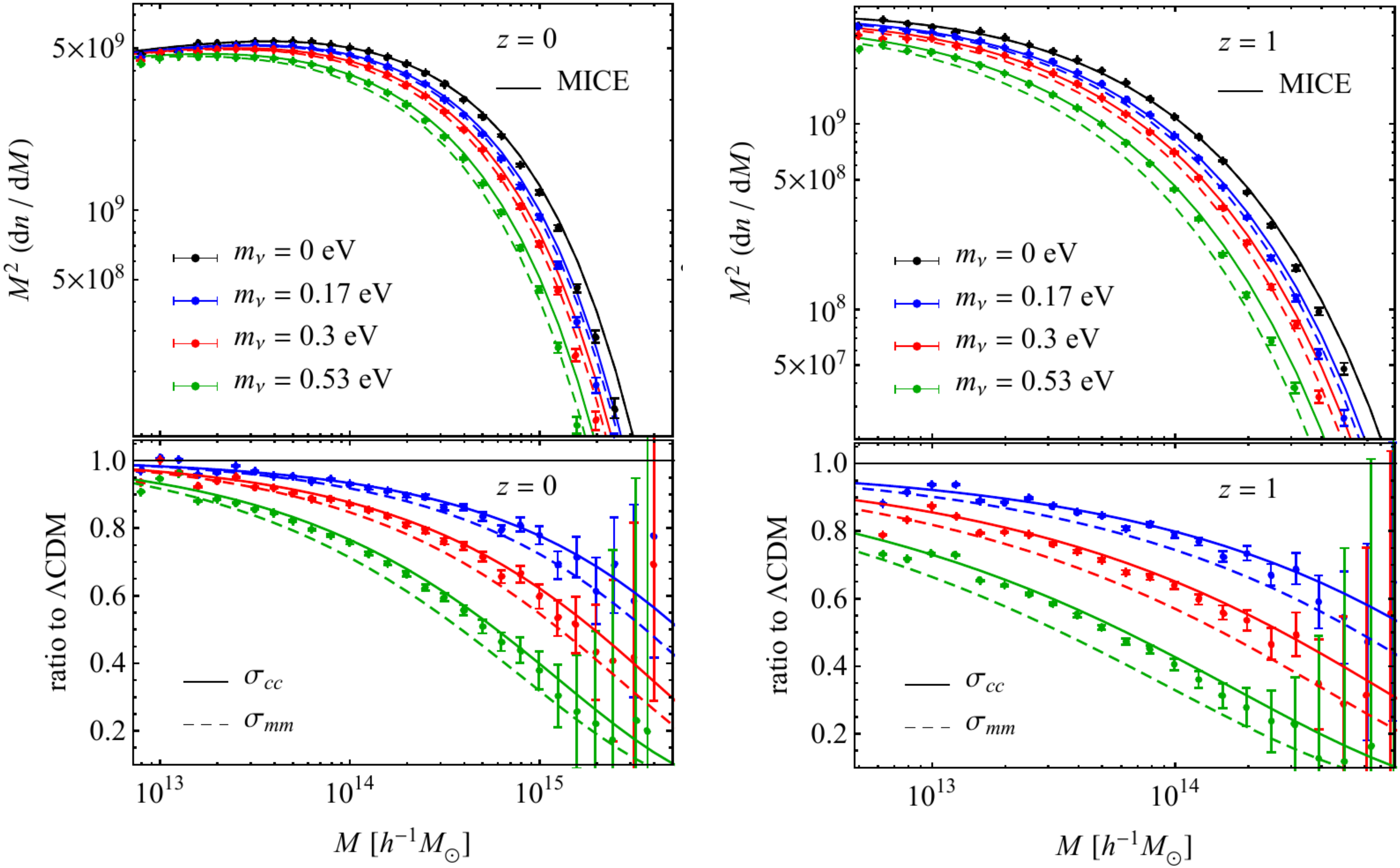
Ichiki&Takada(2012) studied the spherical collapse with massive neturinos, finding sub % effect on the collapse threshold.

They can be treaded as a background cosmology effect, like a Cosmological Constant, and we can and should use the CDM power spectrum.

Not obvious a priori, think of a WDM particle, Axions or a Clustering Quintessence.

The halo mass function (III)

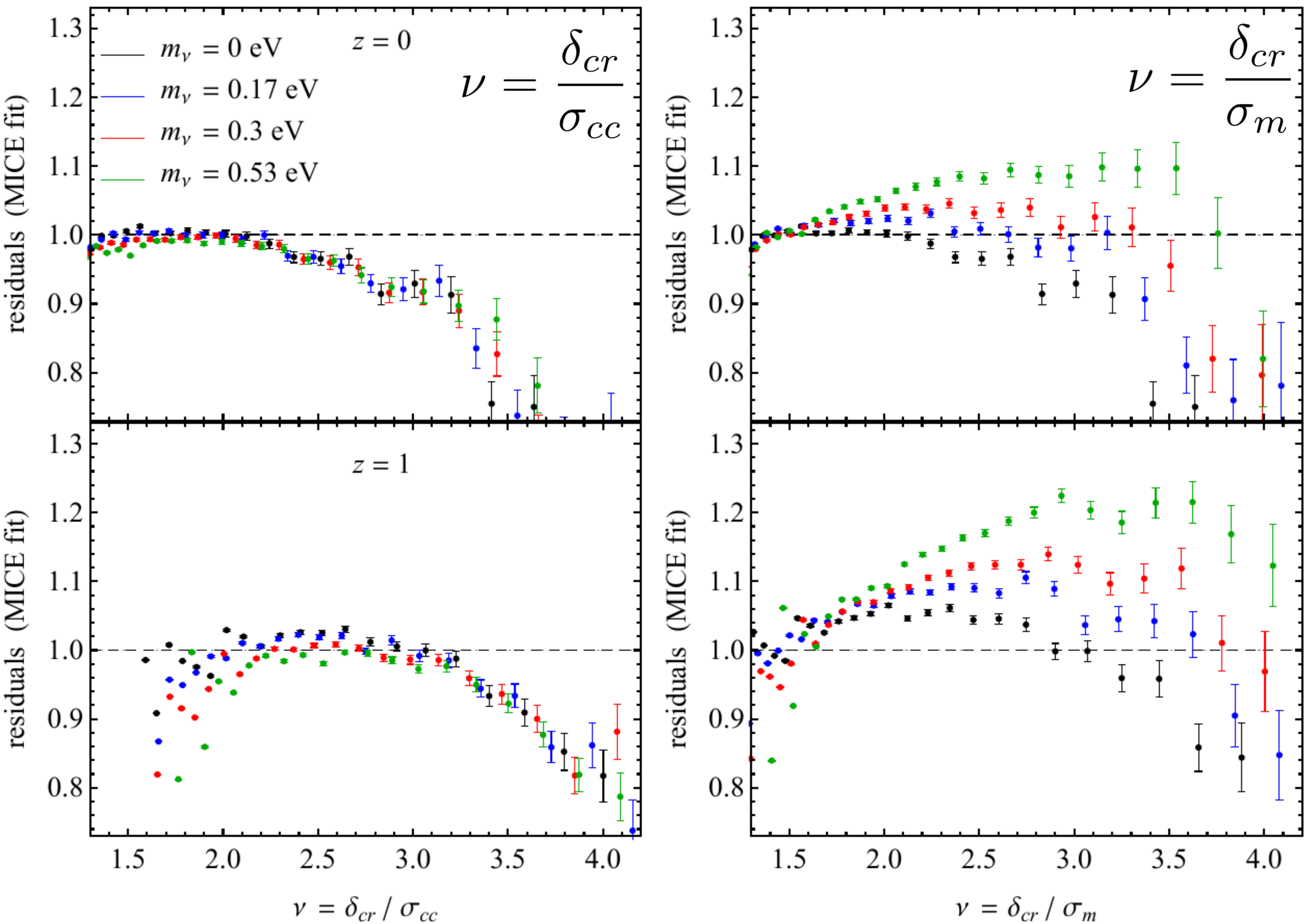
Prediction from MICE. Obtained for LCDM models, it keeps working if CDM is used.



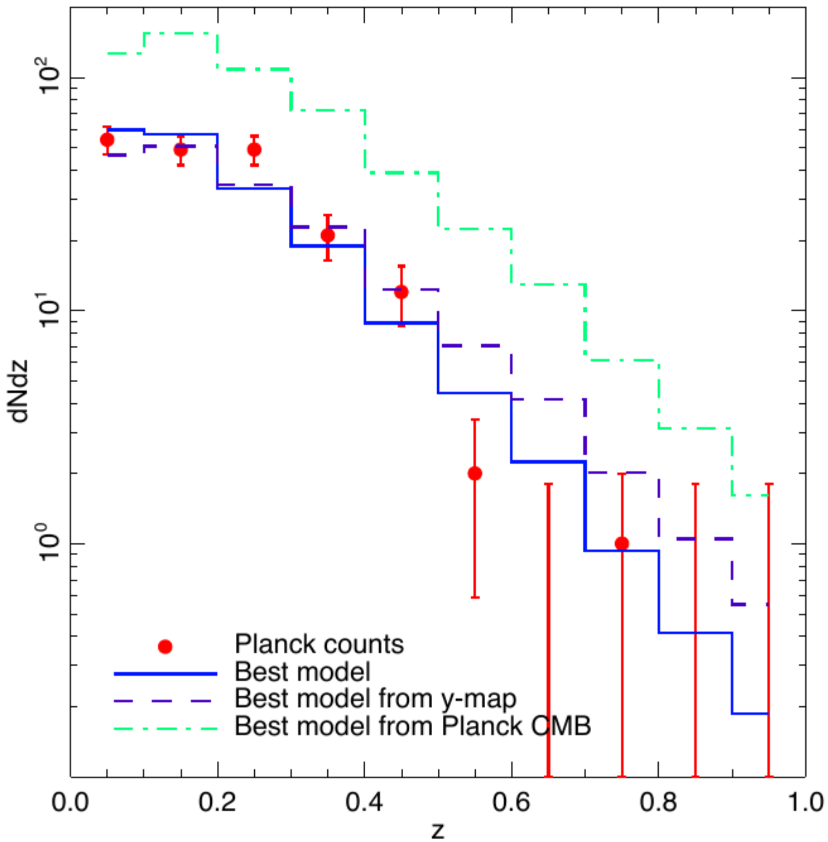
The halo mass function (IV)

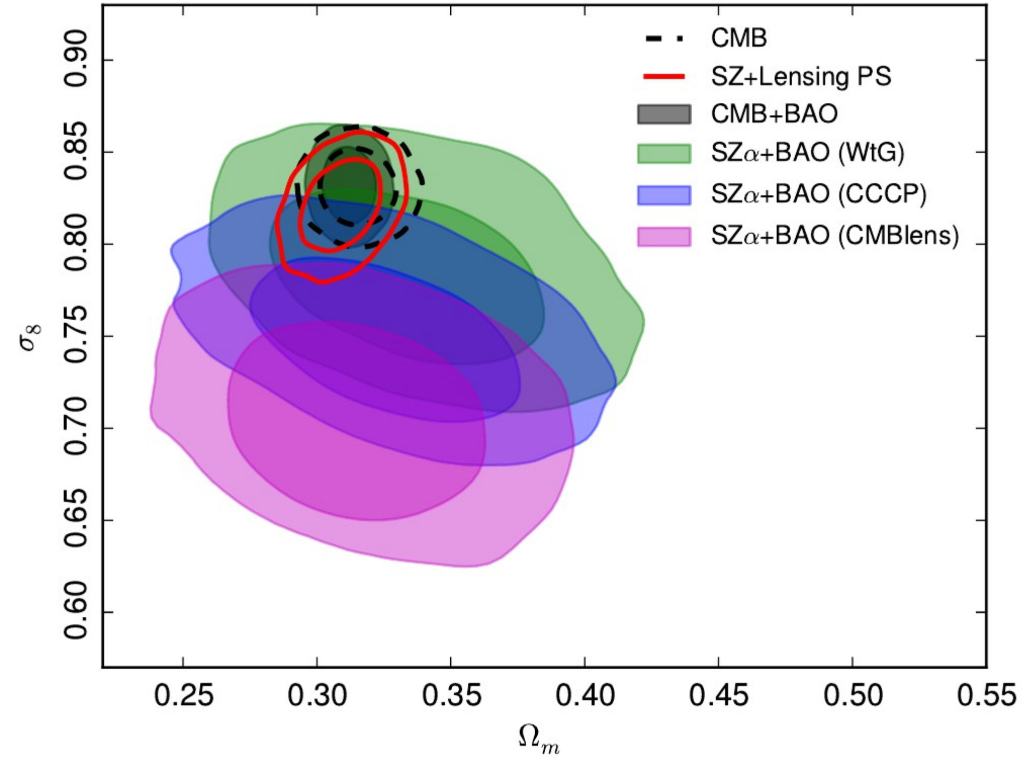
Crucial for cosmological parameter estimation.

$$\nu f(\nu) \equiv \frac{M^2}{\rho}\, n(M)\, \frac{d\ln M}{d\ln \nu}$$



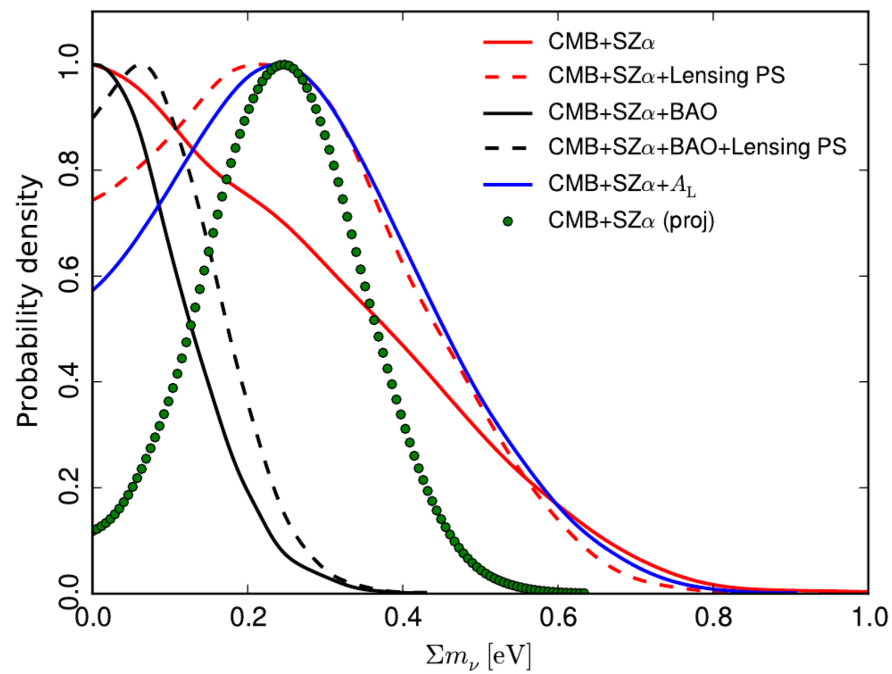
The Planck SZ – Planck CMB tension, Planck Results XX





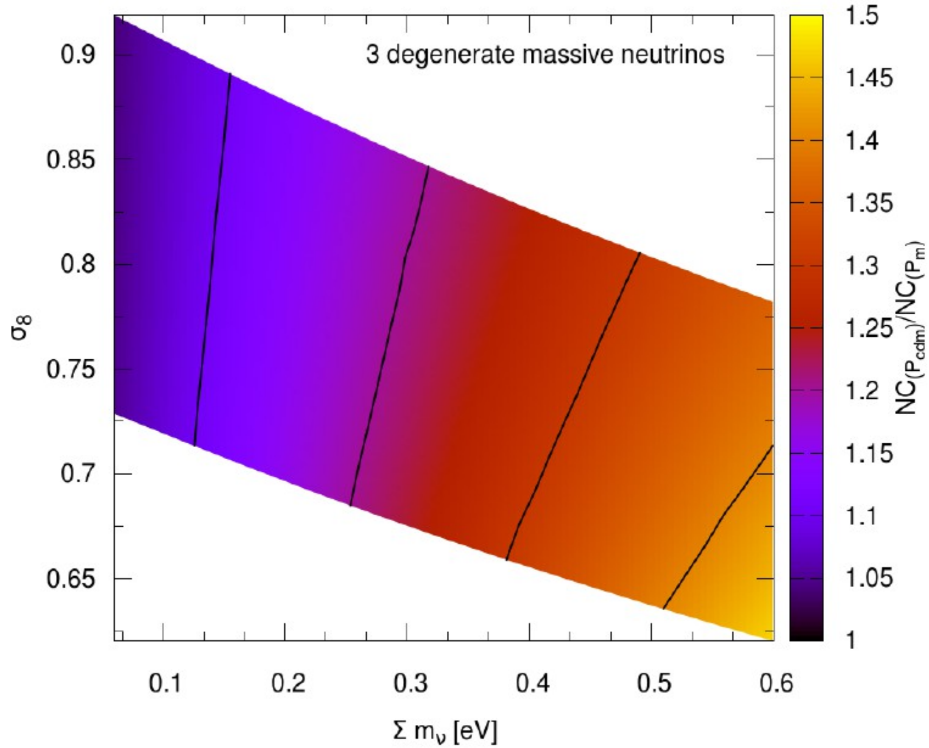
The Planck TT best fit model predicts more clusters than actually measured with SZ.

Massive neutrinos could help to reduce the tension ?



The halo mass function, implications for cluster counts

$NC(P_{cdm})/NC(P_m)$



$$N_i = \int_{z_i}^{z_{i+1}} \mathrm{d}z \int_{\Delta\Omega} \mathrm{d}\Omega \frac{\mathrm{d}V}{\mathrm{d}z\mathrm{d}\Omega} \int_0^\infty dM \, X(M,z,\mathbf{\Omega}) \, n(M,z)$$

For reasonable values of σ_8 and Ω_m
the difference in the predicted number counts can reach the 10-20 %.

$$0.0 < z < 1.0$$

$$\Delta\Omega = 27.000 \deg^2$$

$M_{\rm lim}(z)$ from Planck SZ

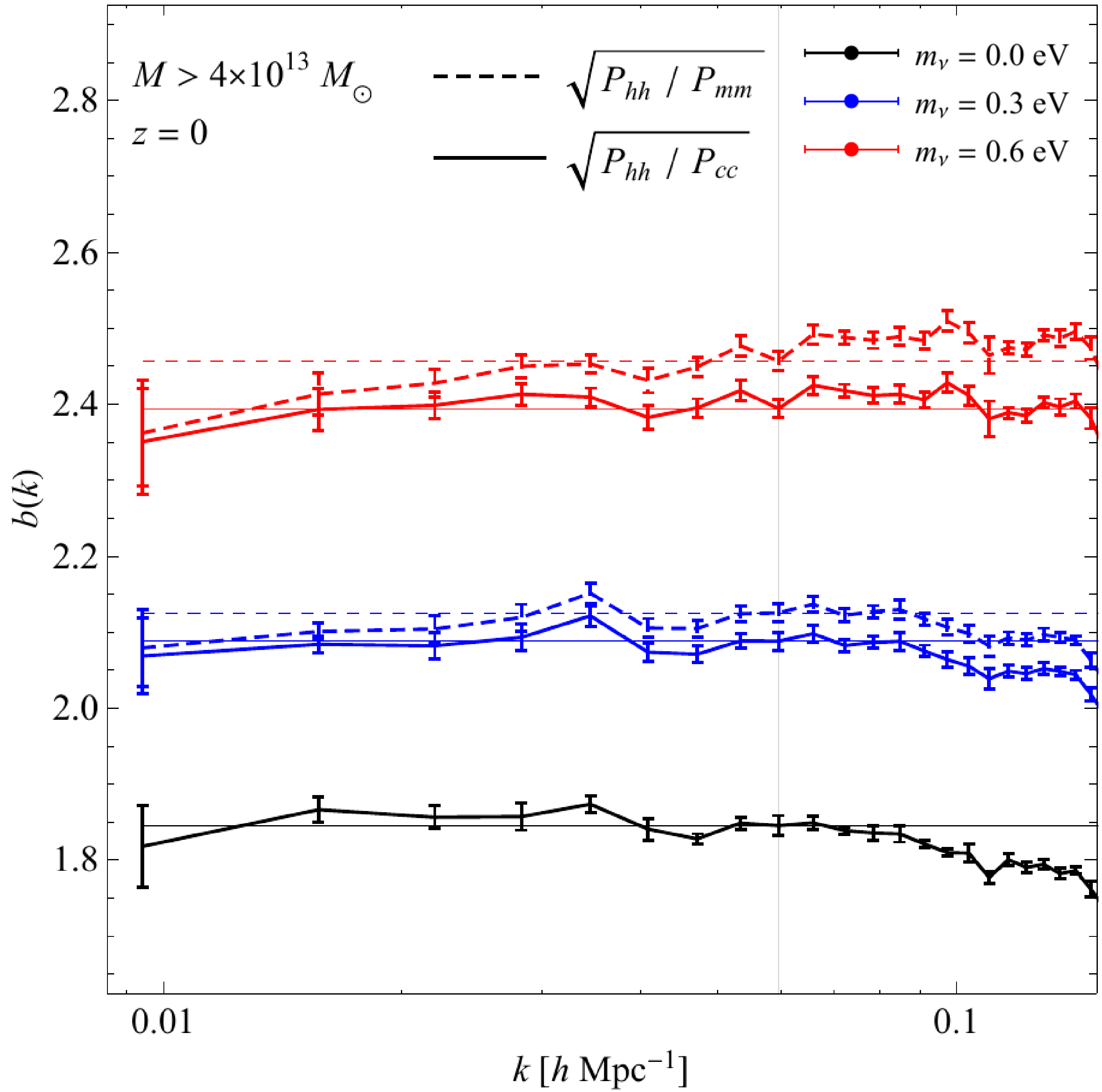
Halo bias (II)

Halos and galaxies are biased tracers of the underlying mass distribution

$$\delta_h(x) = b\,\delta_m(x)$$

Linear bias is expected to be scale-independent on large scales.
Potential systematic error in galaxy clustering measurements.

See Biagetti+14 for beyond linear bias.



$$b_c^{(hh)} \equiv \sqrt{\frac{P_{hh}(k)}{P_{cc}(k)}}$$

or

$$b_m^{(hh)} \equiv \sqrt{\frac{P_{hh}}{P_{mm}}} = b_c^{(hh)}\sqrt{\frac{P_{cc}}{P_{mm}}}$$

Take home message(s)

Do everything with CDM quantities:

- Dark matter clustering in the non linear regime is very well captured by CDM only, relevant for galaxy P(k) and WL ;

- The halo mass function of massive neutrino cosmologies is correctly described in terms of the CDM field only.
  Universality wrt to cosmology not recovered if P_m is used. Important for cluster counts ;

- Linear bias factors are scale independent and universal if CDM perturbations are used. Relevant for galaxy P(k)

- Incorrect assumptions for halo bias lead to systematic effects in RSD analysis ;

- Description of the bispectrum consistent with power spectrum

Redshift Space Distorsions, Kaiser limit (I)

To go in RS we need two more ingredients :

- peculiar velocities ;

- predictions for the growth rate ;

In the linear regime, w/o velocity bias the Kaiser formula holds

$$\delta_m^{(s)} = (1 + f\mu^2)\delta_m \qquad f(a) = \frac{\mathrm{d}\log D(a)}{\mathrm{d}\log a}$$

that for bias tracers means

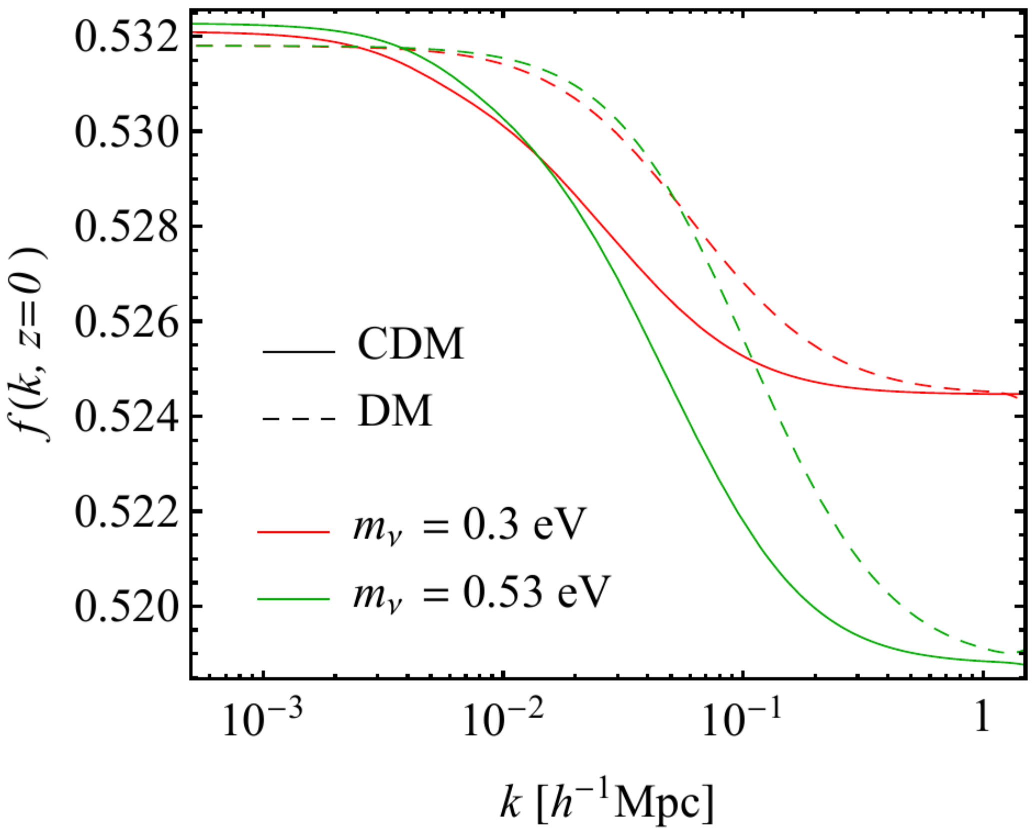
$$\delta_{hh}^{(s)} = (1 + \beta\mu^2)\delta_{hh} \qquad \beta \equiv \frac{f}{b}$$

$$P_{hh}(k)^{(s)} = (1 + \beta\mu^2)^2 P_{hh}(k) = \sum_{l=0,2,4} P_{hh,\ell}\, L_\ell(\mu)$$

Linear theory facts (V)

In massive neutrino cosmologies the growth rate f depend scale dependent

$$\frac{f_c(k)}{f_{\Lambda\mathrm{CDM}}} \xrightarrow{k \gg k_{\mathrm{FS}}} \frac{1}{4}\left(5 - \sqrt{25 - 24\, f_\nu}\right) \simeq 1 - \frac{3}{5}\, f_\nu$$



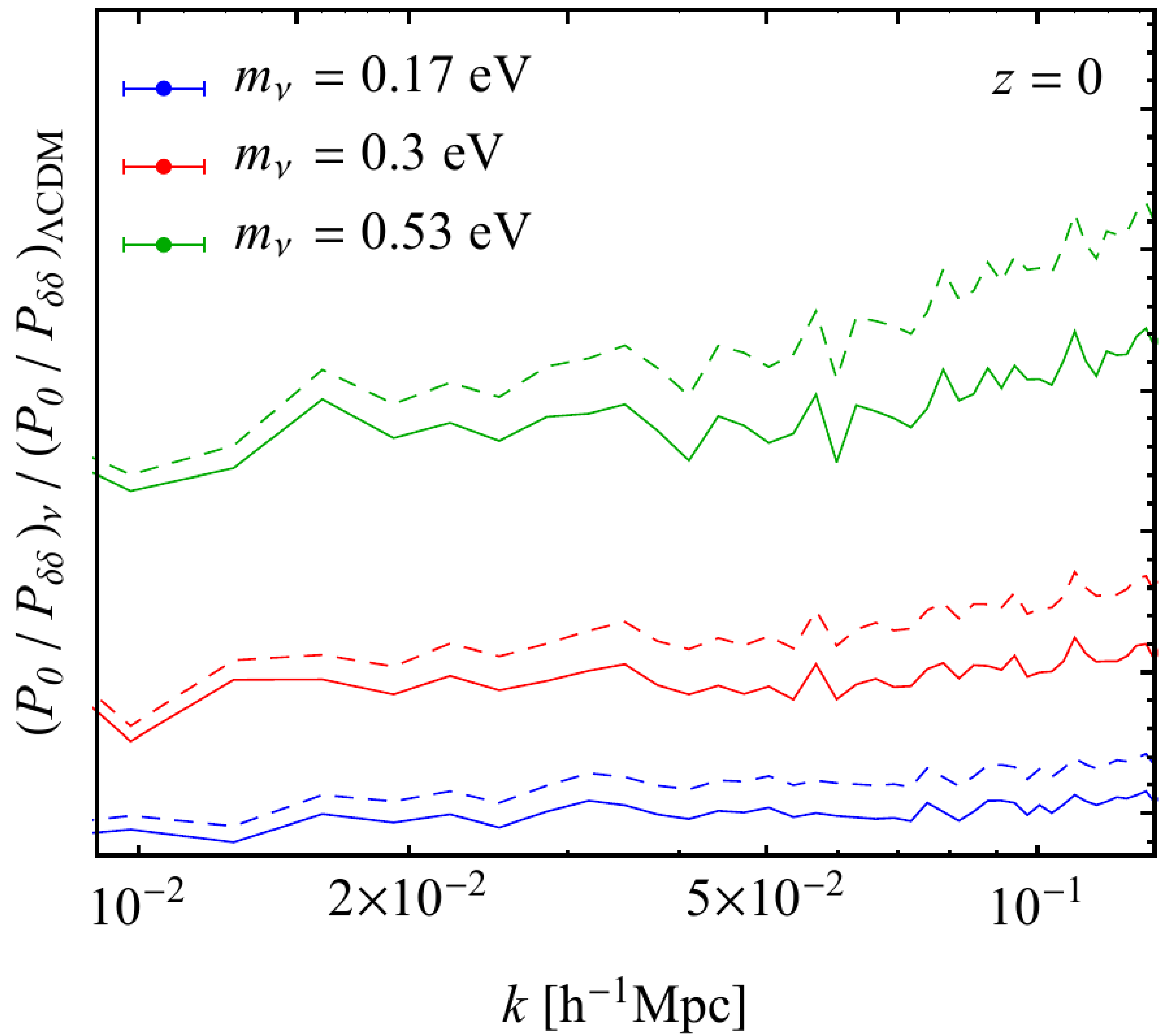
Here the difference between CDM and DM is negligible.

! Most of the difference in the monopoles and quadrupoles comes from the bias !

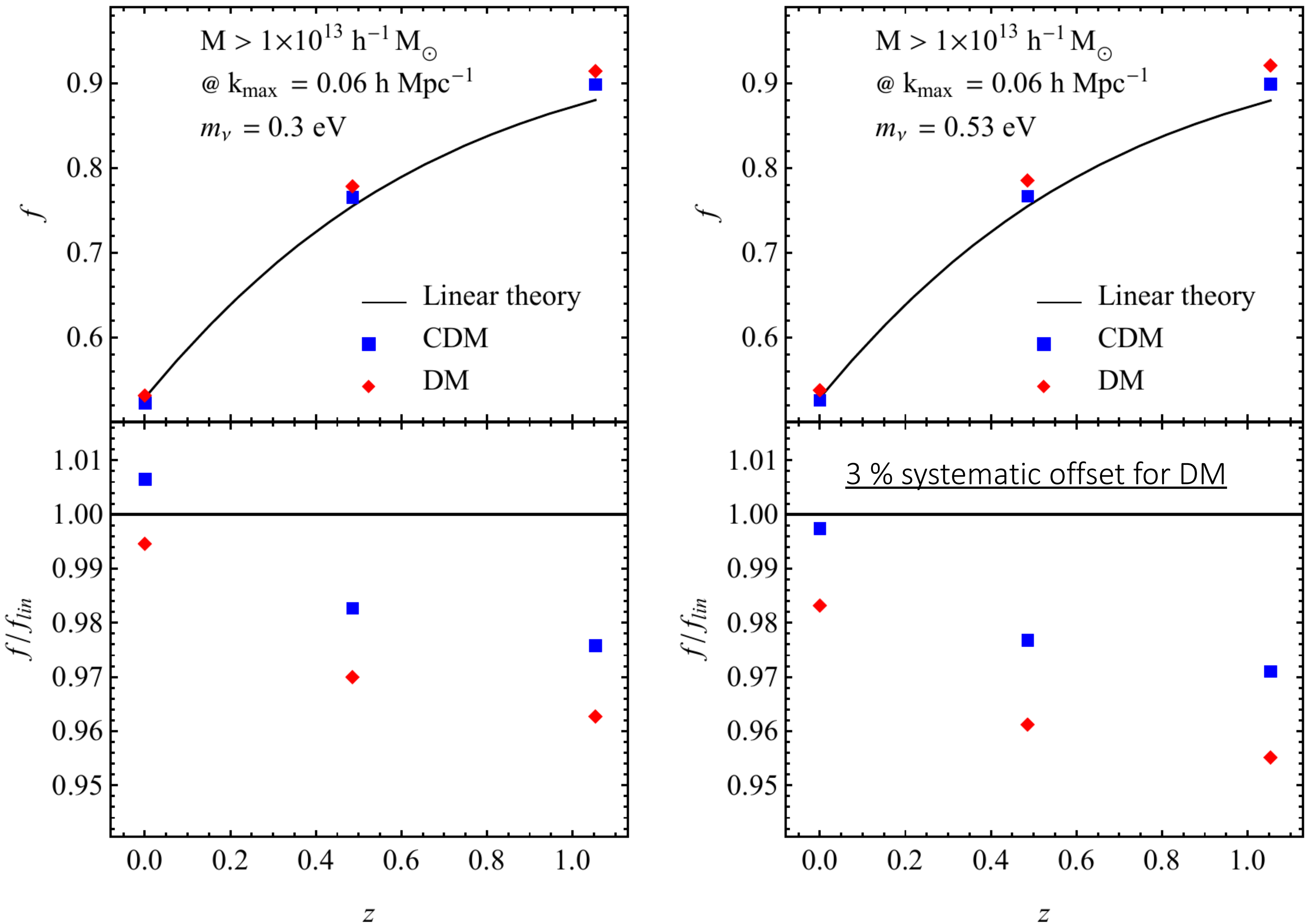
RSD (II)

$$\frac{P^0_{hh}}{P_m} = b^2 + \frac{2}{3} f b + \frac{1}{5} f^2$$

Larger scale dependence for DM defined multipoles



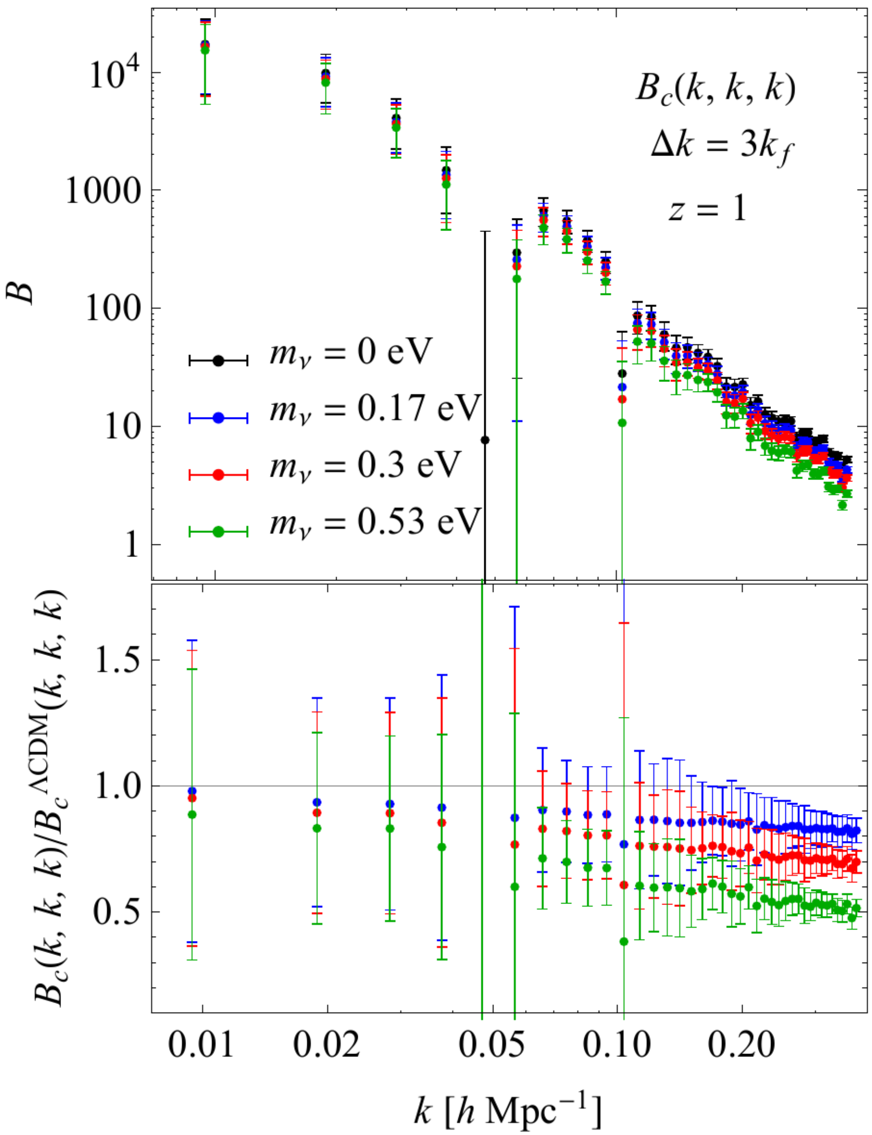
RSD (III)

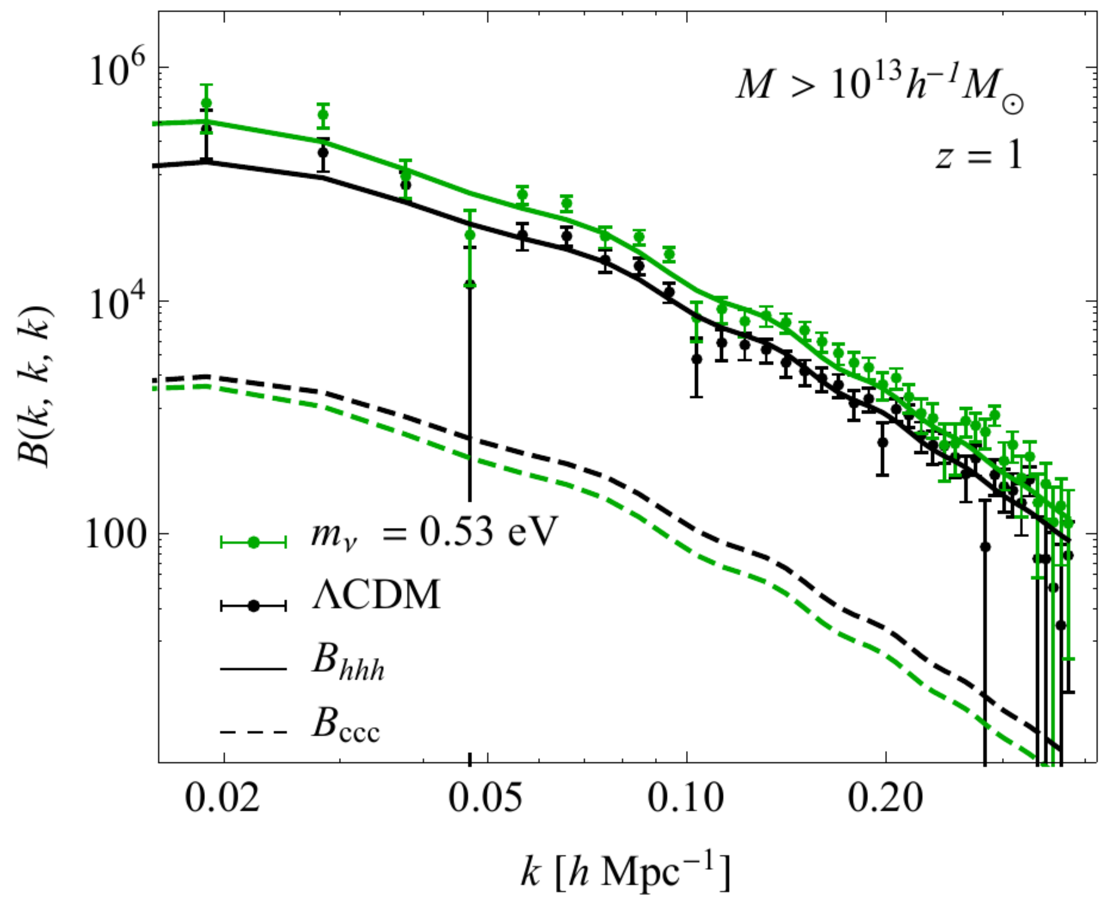


$M > 1\times10^{13}\ h^{-1}\ M_\odot$
@ $k_{max} = 0.06\ h\ Mpc^{-1}$
$m_\nu = 0.3$ eV
Linear theory
CDM
DM
f
f/f_{lin}
z
$M > 1\times10^{13}\ h^{-1}\ M_\odot$
@ $k_{max} = 0.06\ h\ Mpc^{-1}$
$m_\nu = 0.53$ eV
Linear theory
CDM
DM
3 % systematic offset for DM
f
f/f_{lin}
z

The Bispectrum, for the aficionados

CDM Bispectrum and its relation to the halo Bispectrum





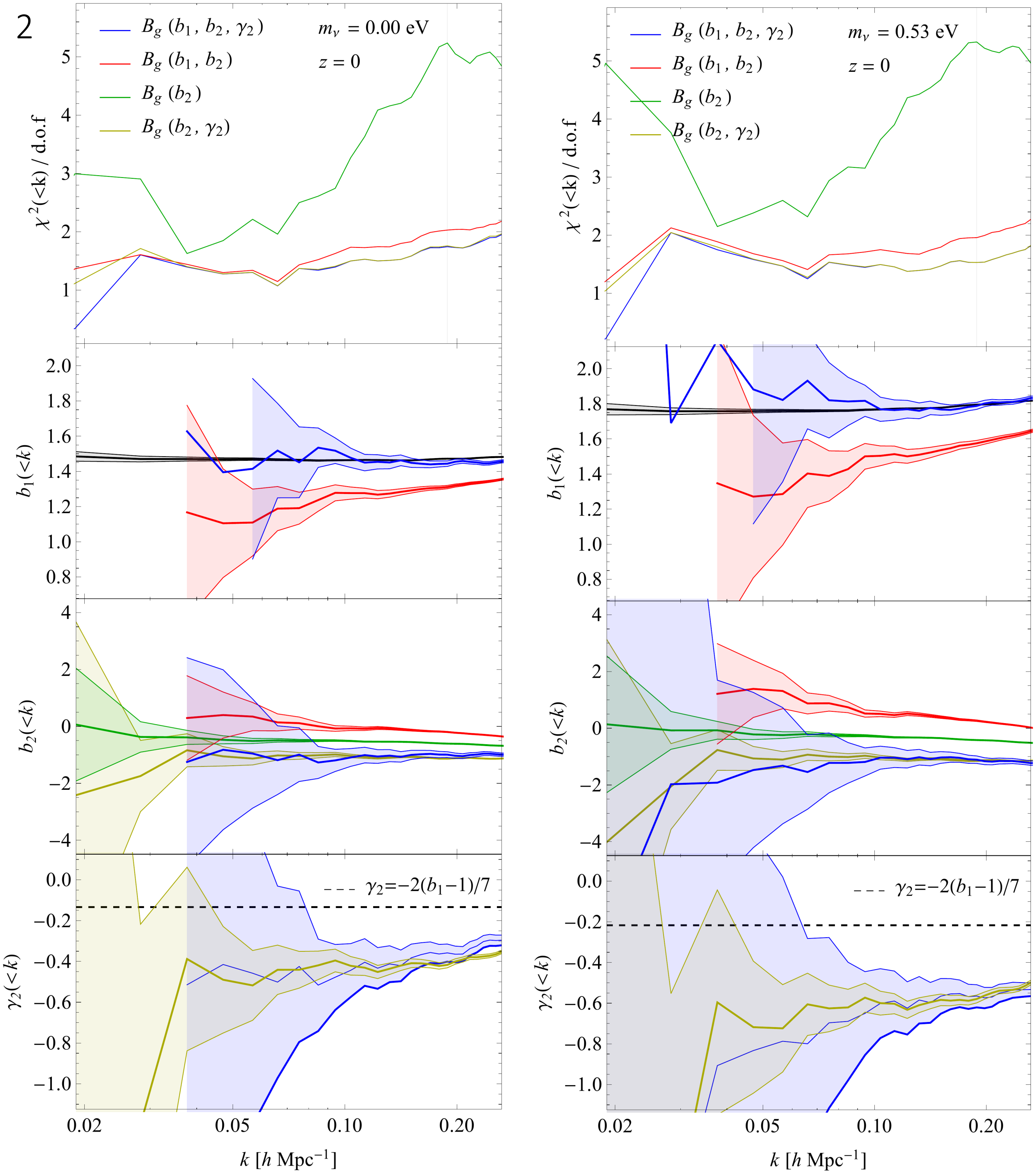
Predicted Bhhh given the PT Bccc, and fitting a non local bias model.

The Bispectrum (II)

In a non local bias model

$$B_{hhh}(k_1, k_2, k_3) = b_1^3 B_{123} + b_1^2 b_2 (P_1 P_2 + cyc.) + 2 b_1^2 \gamma_2 [(\mu_{12}^2 - 1) P_{12} + cyc.]$$

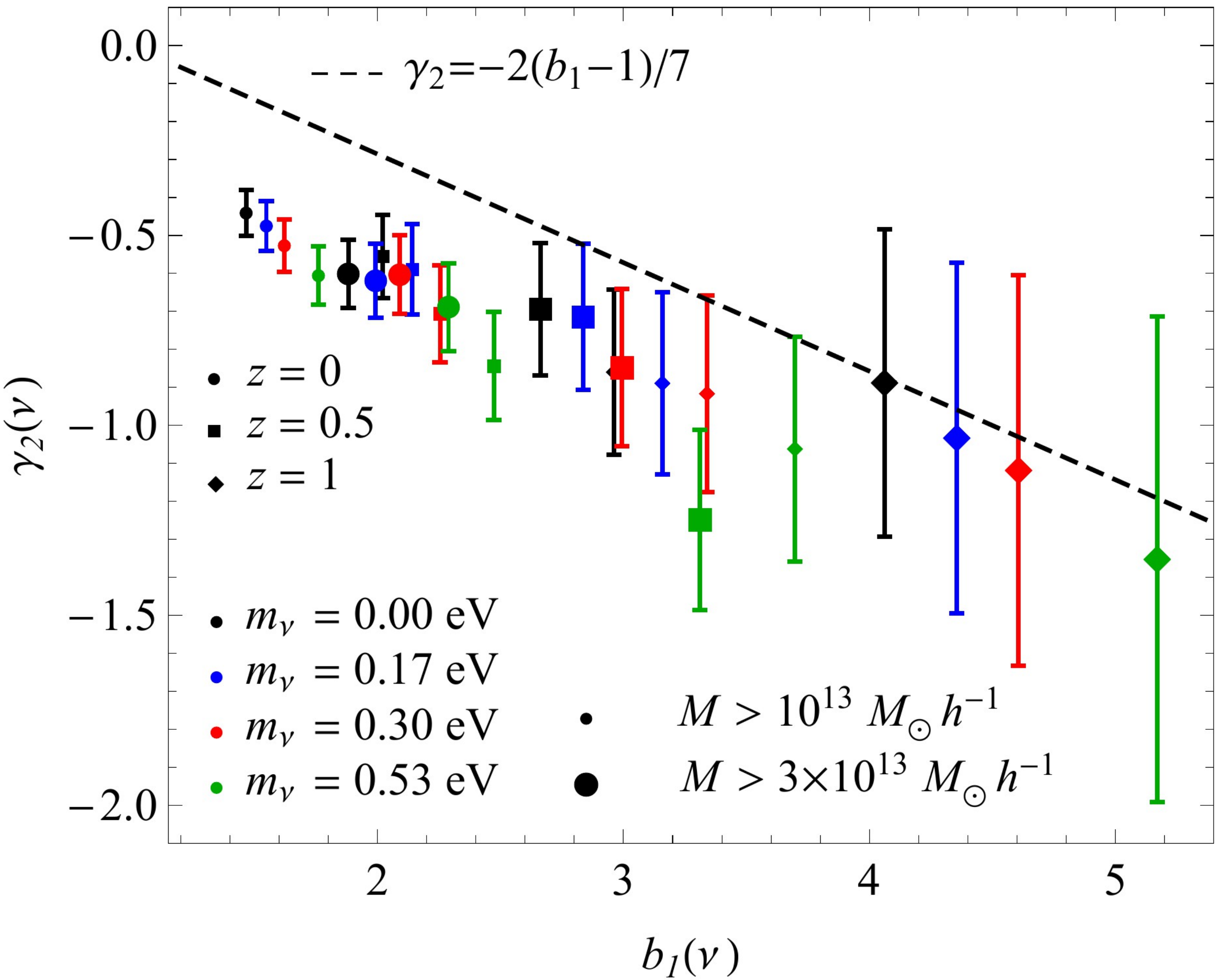
Chan+12
Baldauf+12



The Bispectrum, for the aficionados (III)

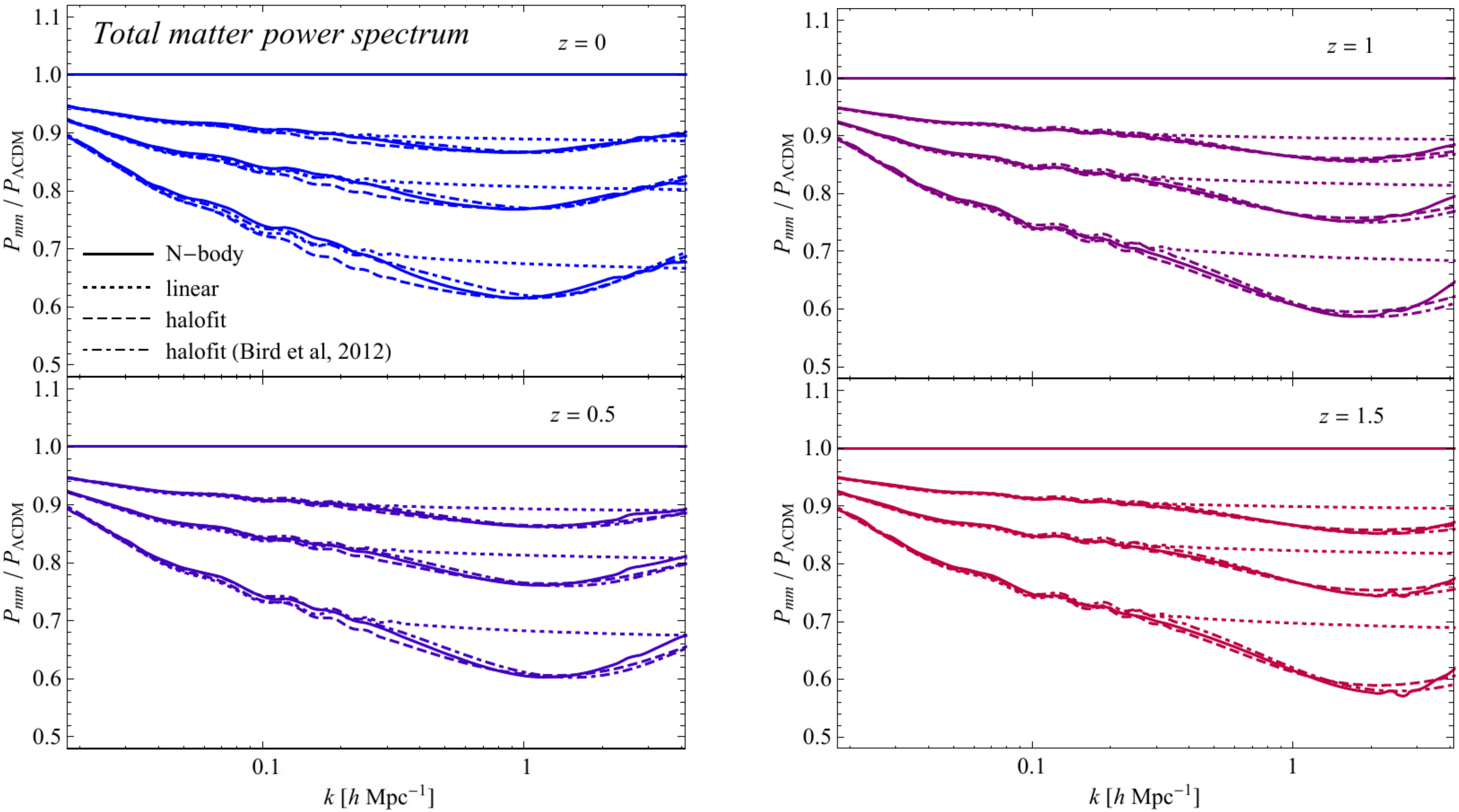
If the lagrangian non-local term is zero, PT predicts

$$\gamma_2 = 2(b_1 - 1)/7$$

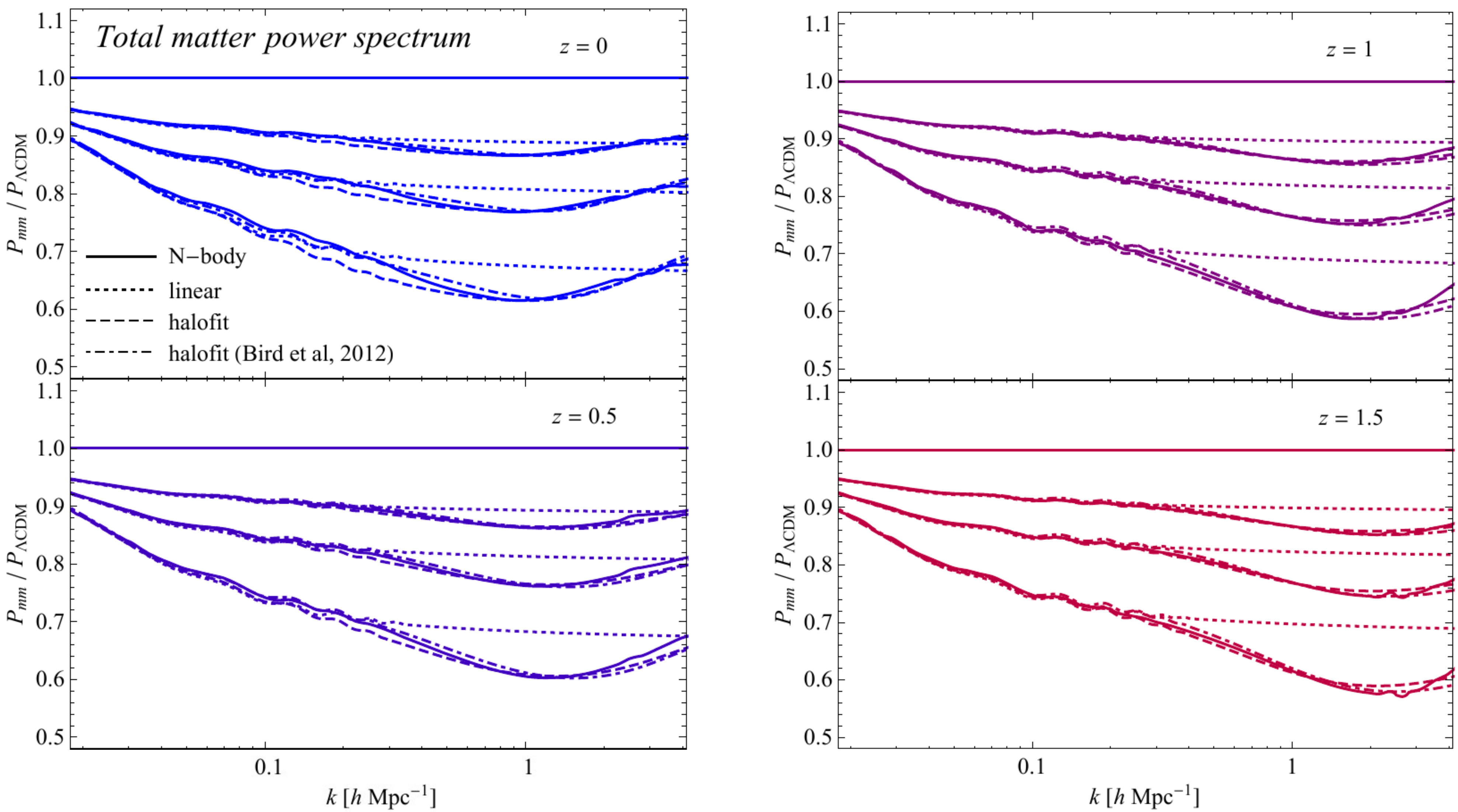


Thank you !

Halofit


Total matter power spectrum
z = 0
z = 0.5
z = 1
z = 1.5
N−body
linear
halofit
halofit (Bird et al, 2012)
P_mm / P_ΛCDM
k [h Mpc⁻¹]
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.1
1

Halofit



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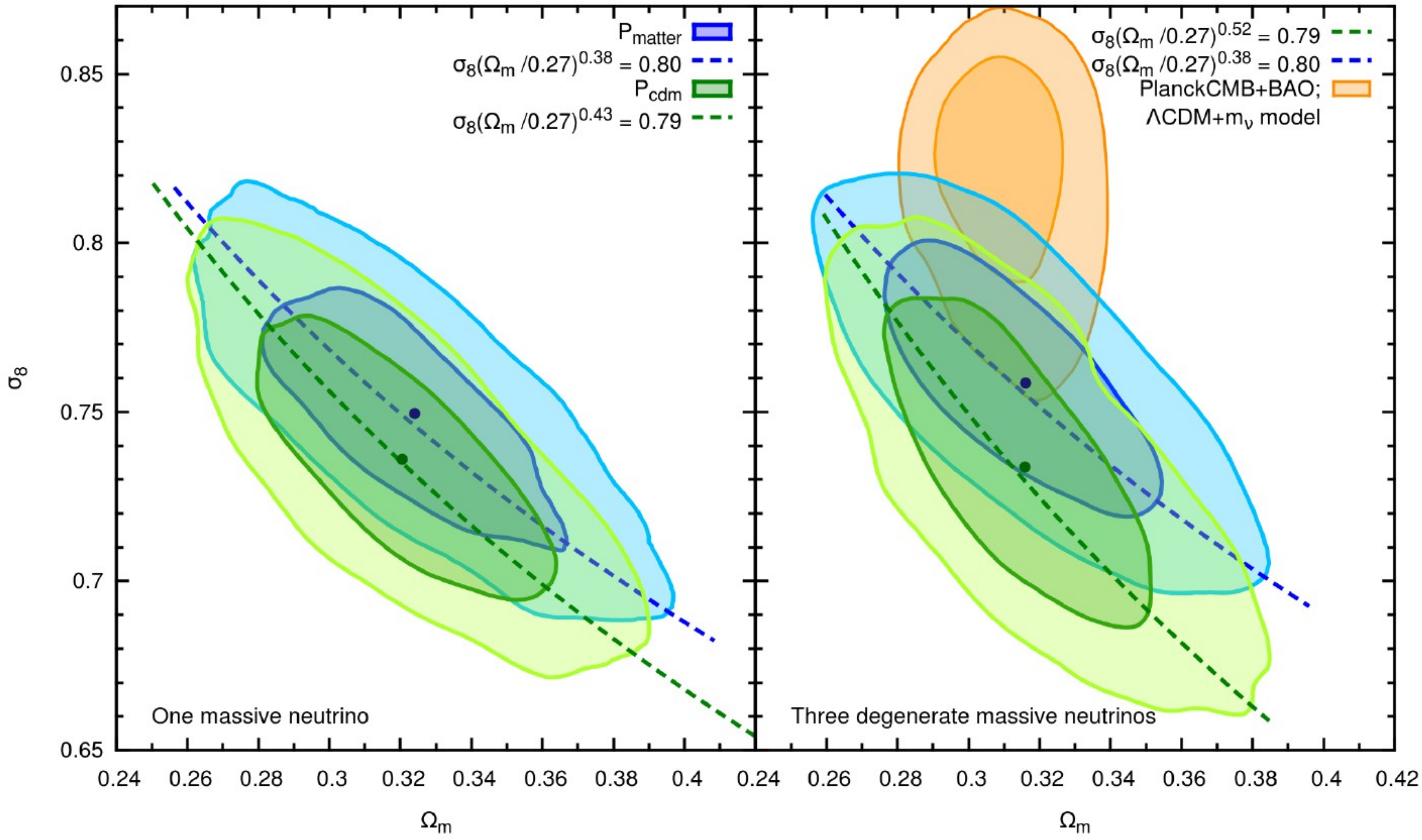
halofit (Bird et al, 2012)
P_{mm} / $P_{\Lambda\mathrm{CDM}}$
k [h Mpc^{-1}]
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.1
1

The halo mass function, implications for cluster counts



A higher value of neutrino masses is required to reduce the tension with CMB data at fixed Ω_m.

Take a wavepacket of size

$$\delta_x = c\Delta t_{coll}$$

At decoupling

$$\Delta t_{coll} \simeq H^{-1} \simeq M_P T_D^2$$

Consider now a superposition of 2 waves of different velocities,

$$\Delta v \simeq \Delta m^2/p^2 \simeq \Delta m^2/T^2$$

Condition for loss of coherence reads

$$\Delta m^2 \gg T^3/T_D$$

Unitarity of PMNS matrix ensures energy conservation, and at equilibrium,

$$f_{\nu_i} = \sum_{\alpha} |U_{\alpha i}|^2 f_{\nu_\alpha} = f_{\nu_\alpha}$$