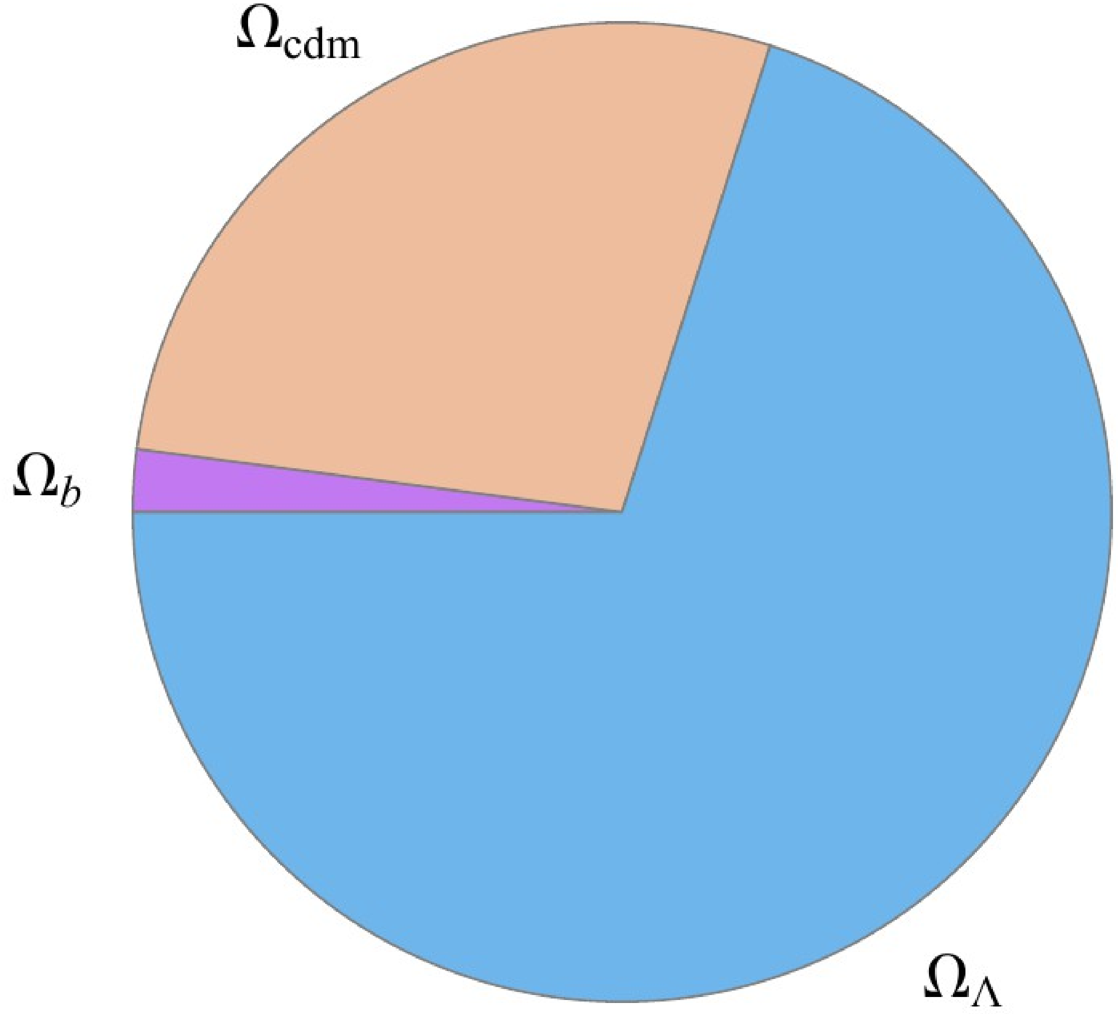
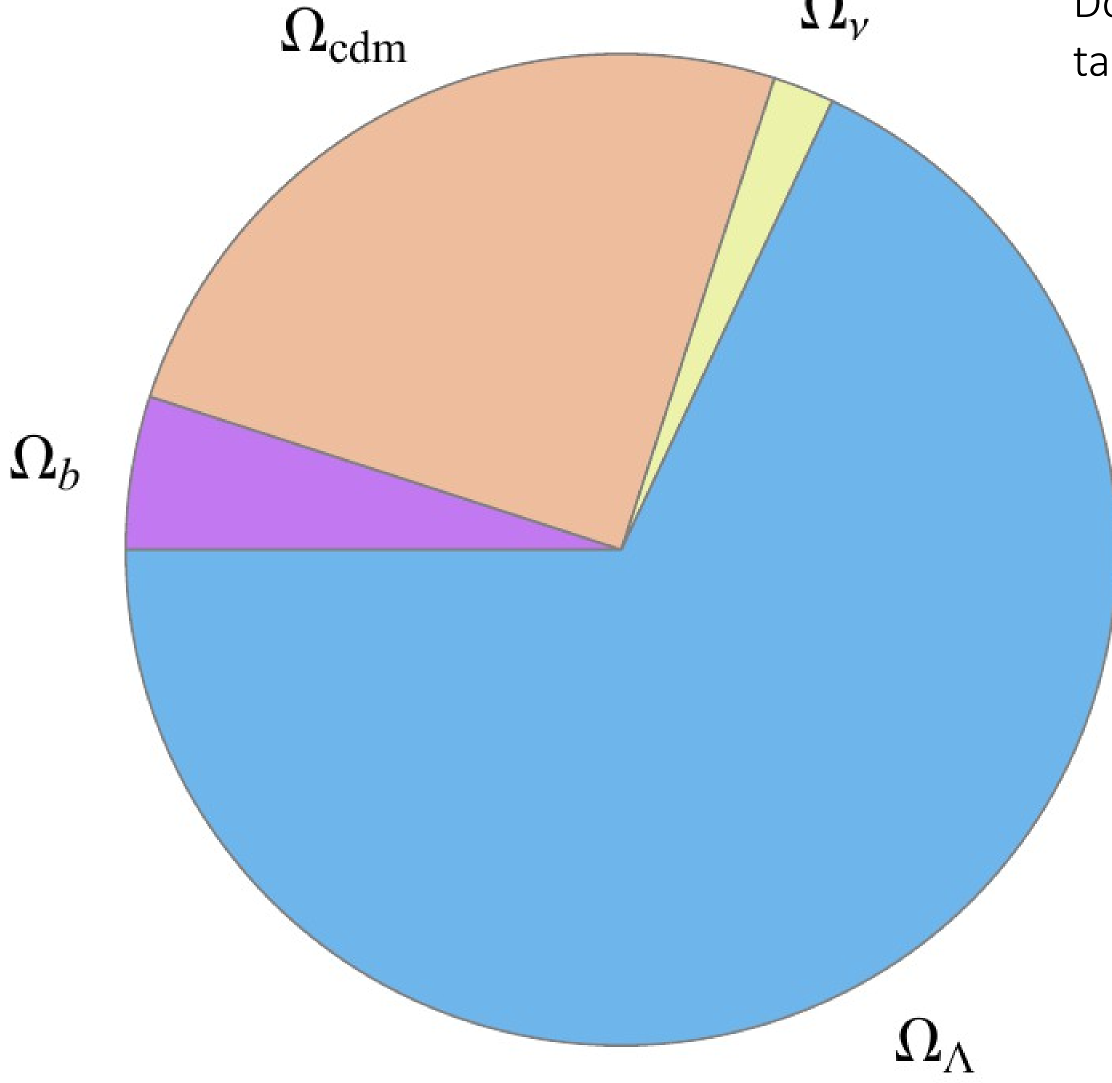
The pizza nobody asked for



Planck 2013

The real picture



Do we really have to take them seriously ?

I'd say yes for a number of reasons :

1) Precision cosmology, i.e. sub % errors on cosmological parameters, requires accurate knowledge of all physical effects that could bias parameters estimation.
An example is the degeneracy between massive neutrinos and modified gravity ;

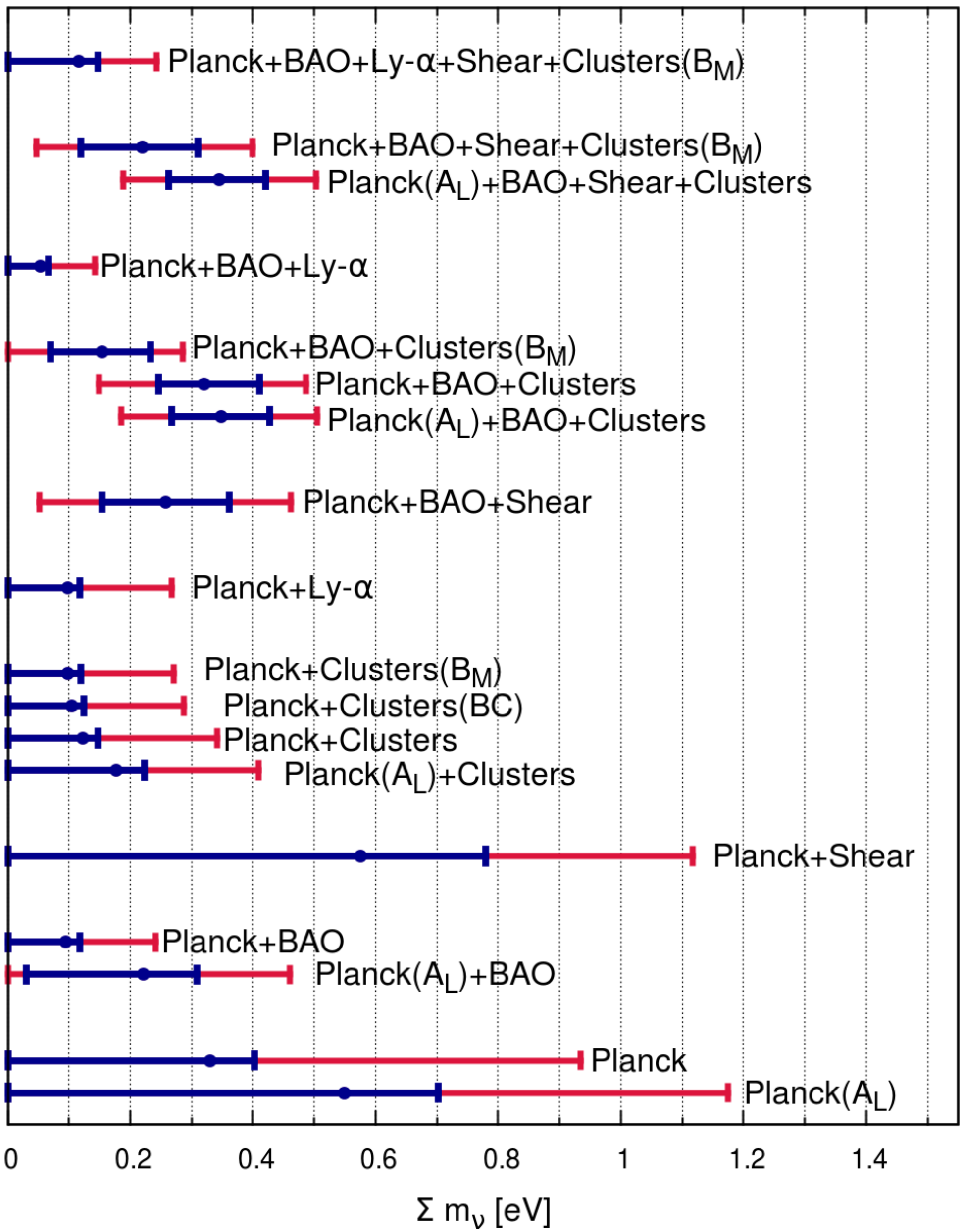
2) Late time cosmology shows some tension between different probes, that might be alleviated by the introduction of massive neutrinos ;

3) Interplay with particle physics ;

...
...

A systematic study of the effects of neutrino masses on cosmological observables is needed.

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+14

$$\sum m_\nu < 0.14 \text{ eV}$$

An incomplete list of quantities affected by neutrino masses :

- The dark matter power spectrum ;

- The halo (or galaxy) power spectrum, i.e. bias ;

- The halo mass function ;

- Redshift space distorsions ;

- High order correlation function, e.g. the Bispectrum of matter and halos ;

- BAO ;

…

Non relativisitc transition

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

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

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

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

But neutrinos are Hot Dark Matter, 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

$$\delta_{dm} = (1 - f_\nu)\delta_{cdm} + f_\nu \delta_\nu$$

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)

Below the free-streaming scale neutrino perturbations are washed out

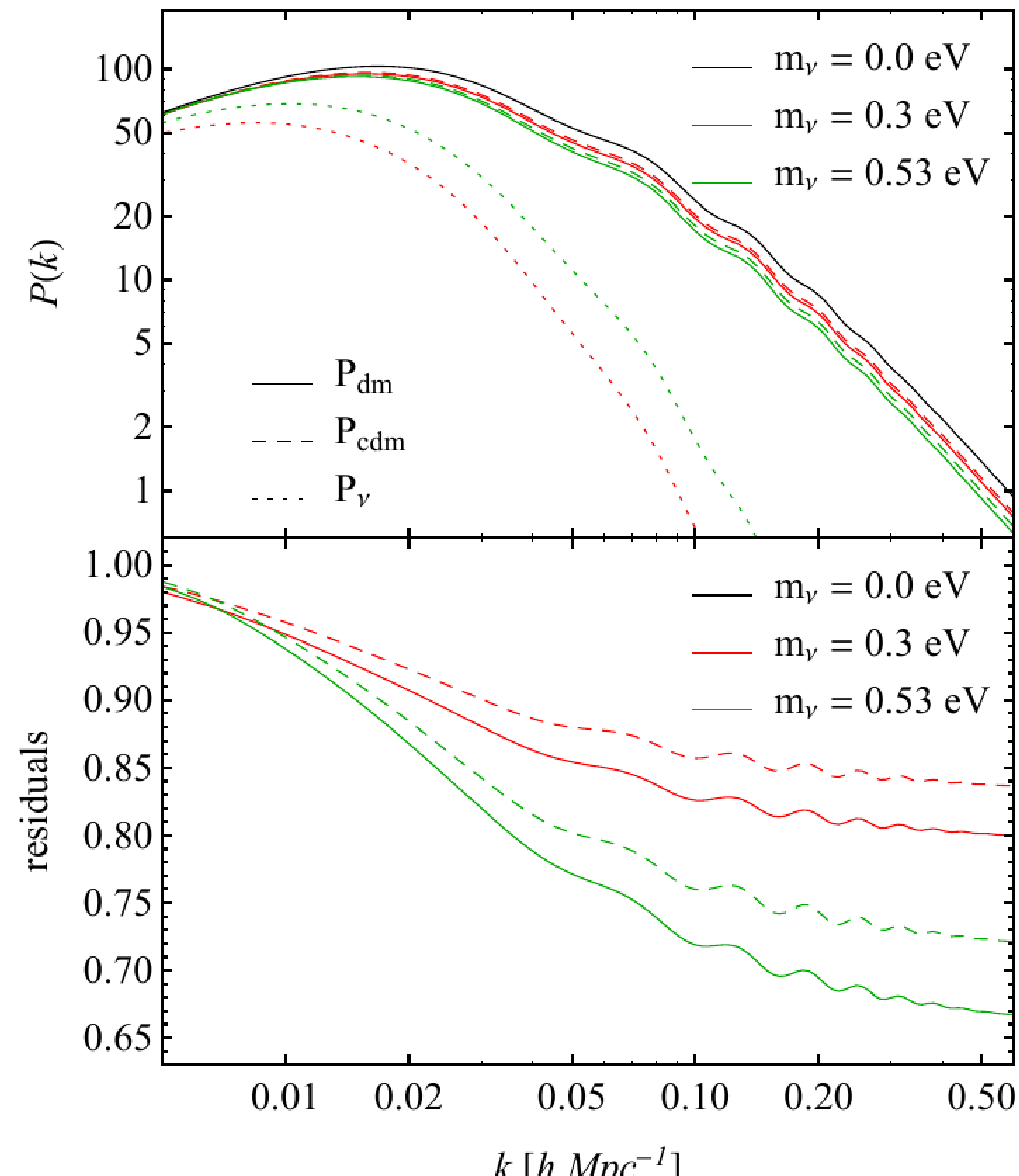
$$P_{dm}(k) = \begin{cases} P_{cdm}(k) & \text{if } k \leq k_{nr} \\ (1-f_\nu)^2 P_{cdm}(k) & \text{if } k \gg k_{nr} \end{cases}$$

Back-reaction on CDM

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

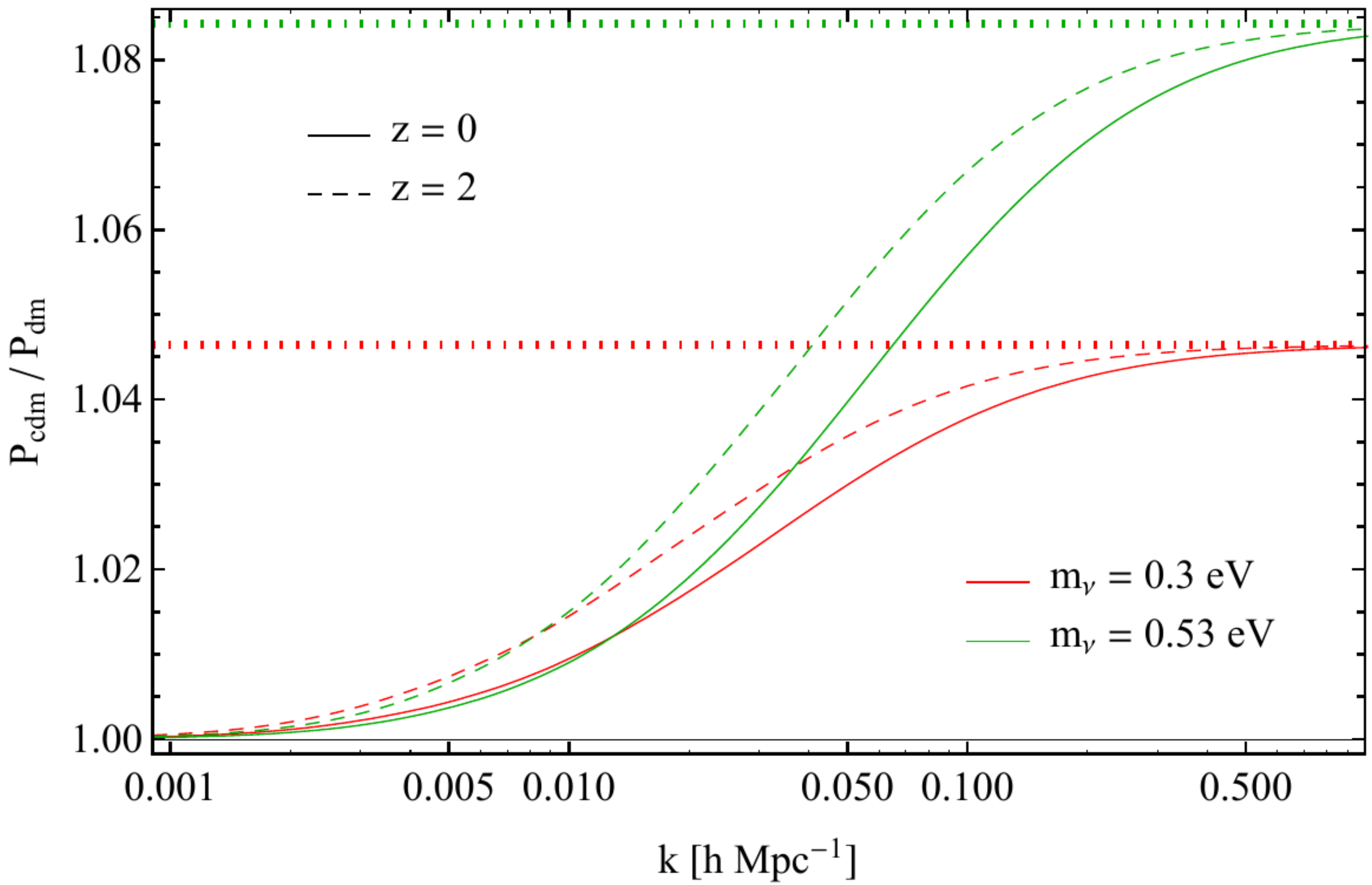
leads to a suppression of power in the CDM component wrt a massless neutrino universe. The net result for the DM power spectrum is

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



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) ;

	$\sum m_\nu$[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

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

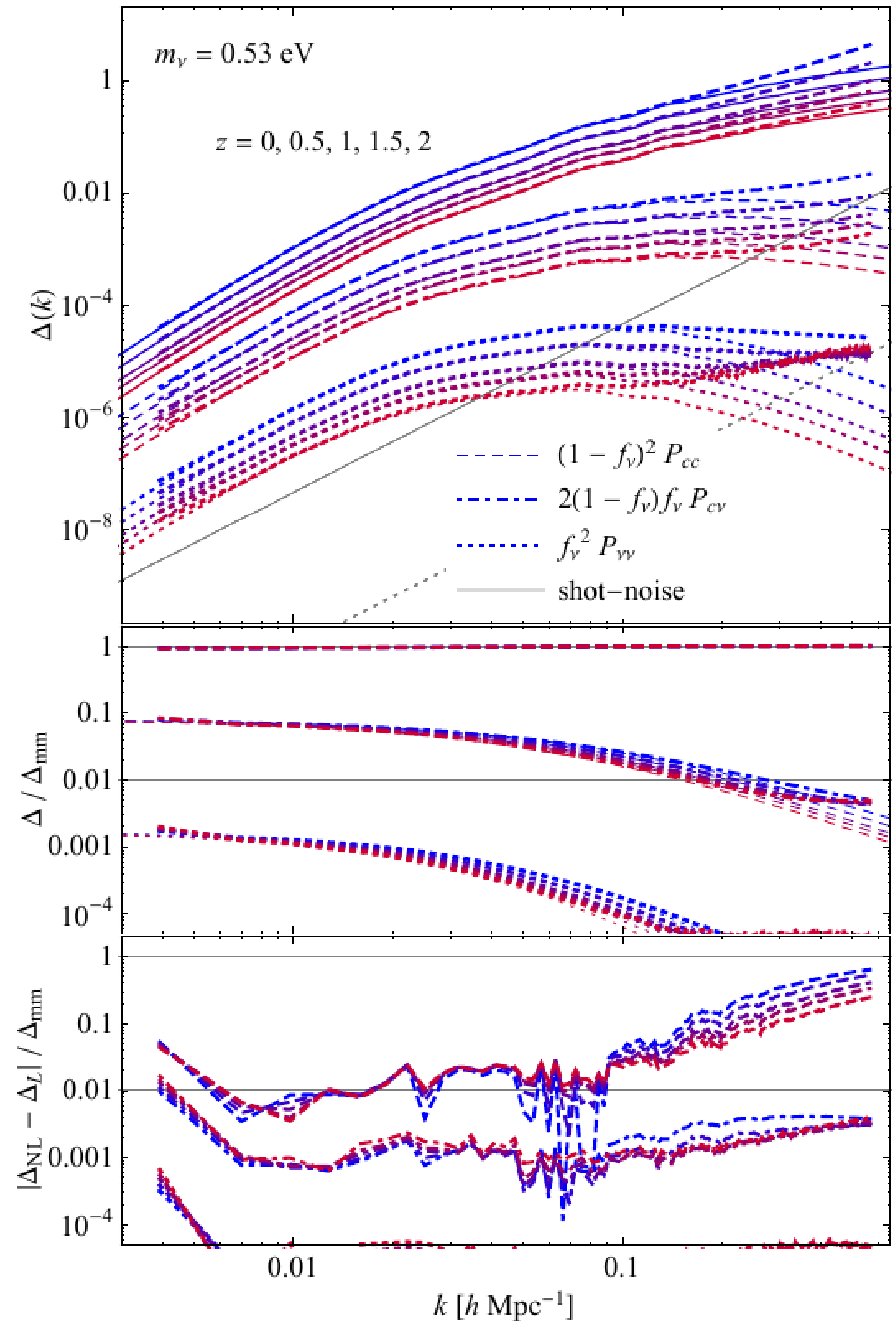
Non linear power spectra

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

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

Suppressed by powers of fnu.

Relvant for perturbation theory/EFTofLSS, it simplifies calculations a lot.



PT results (I)

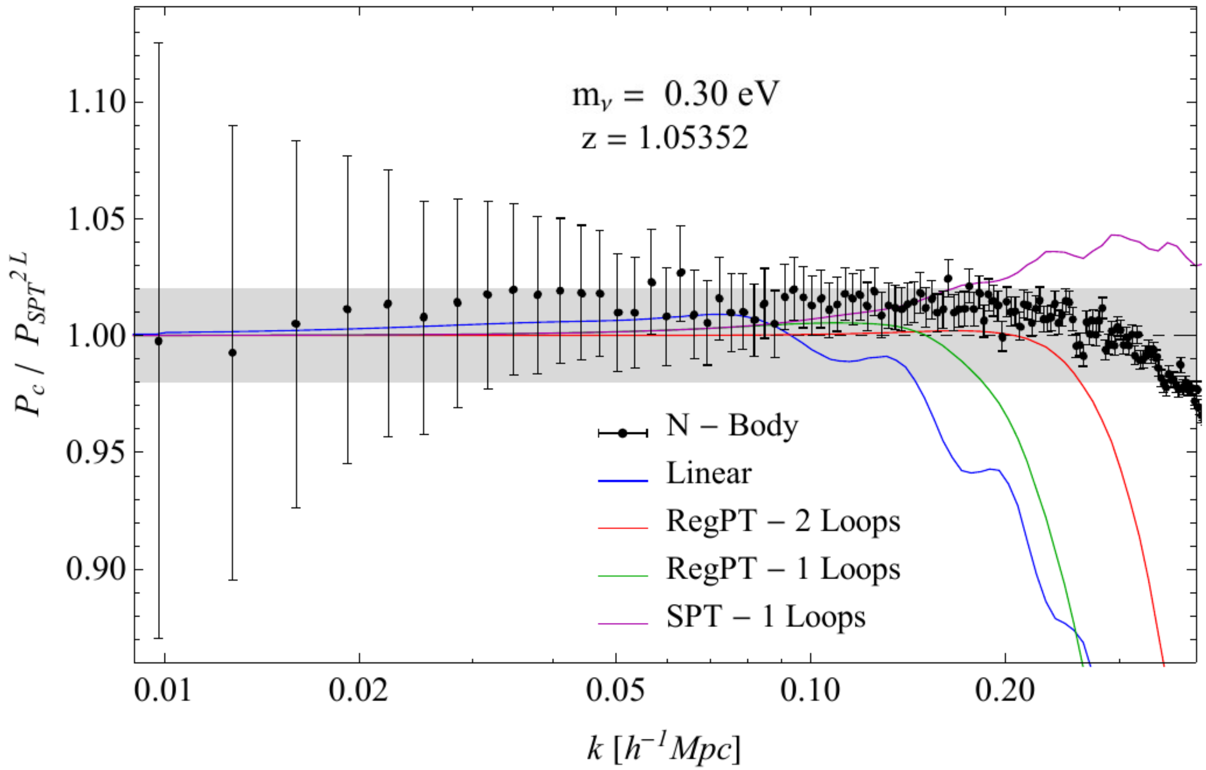
Non linear just in the CDM component.

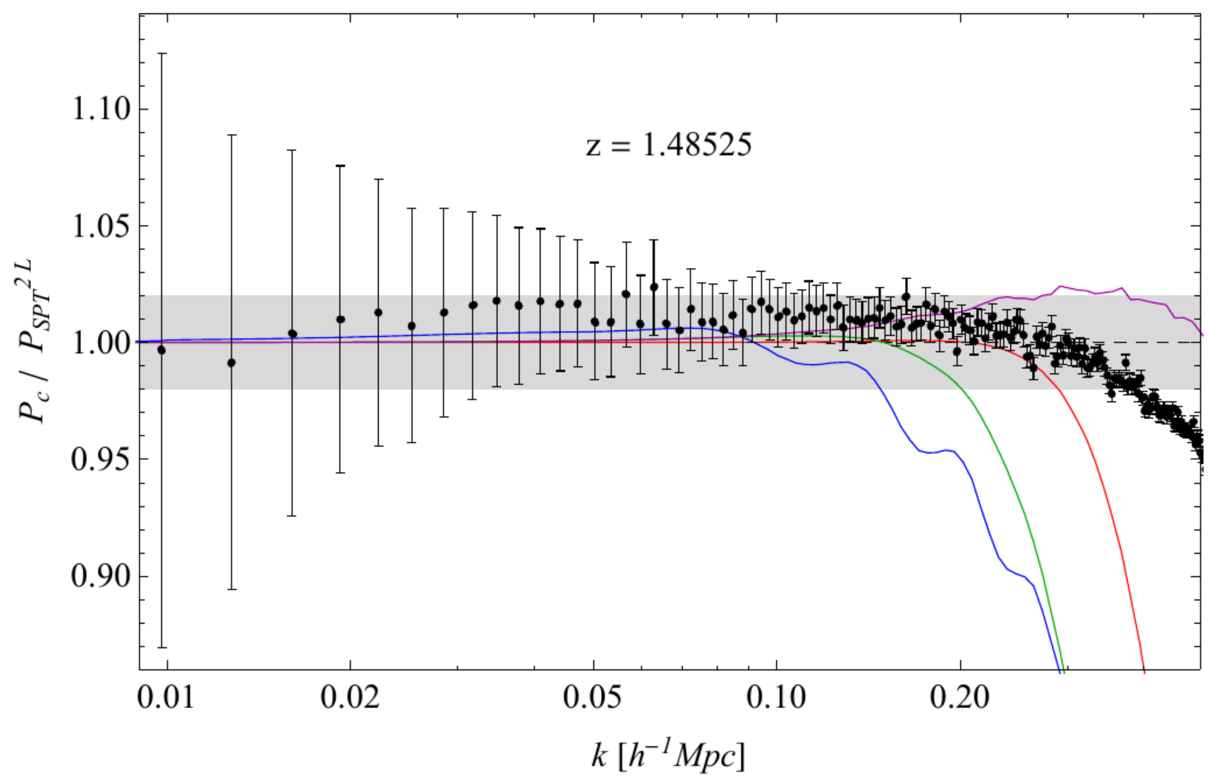
Neglect scale dependent growth factor, see Blas+14

PT works at mildly non linear scales as in LCDM cosmology

At z=1.5 PT is accurate at a few % level up to kmax = 0.4 h/Mpc

What about Pmm?





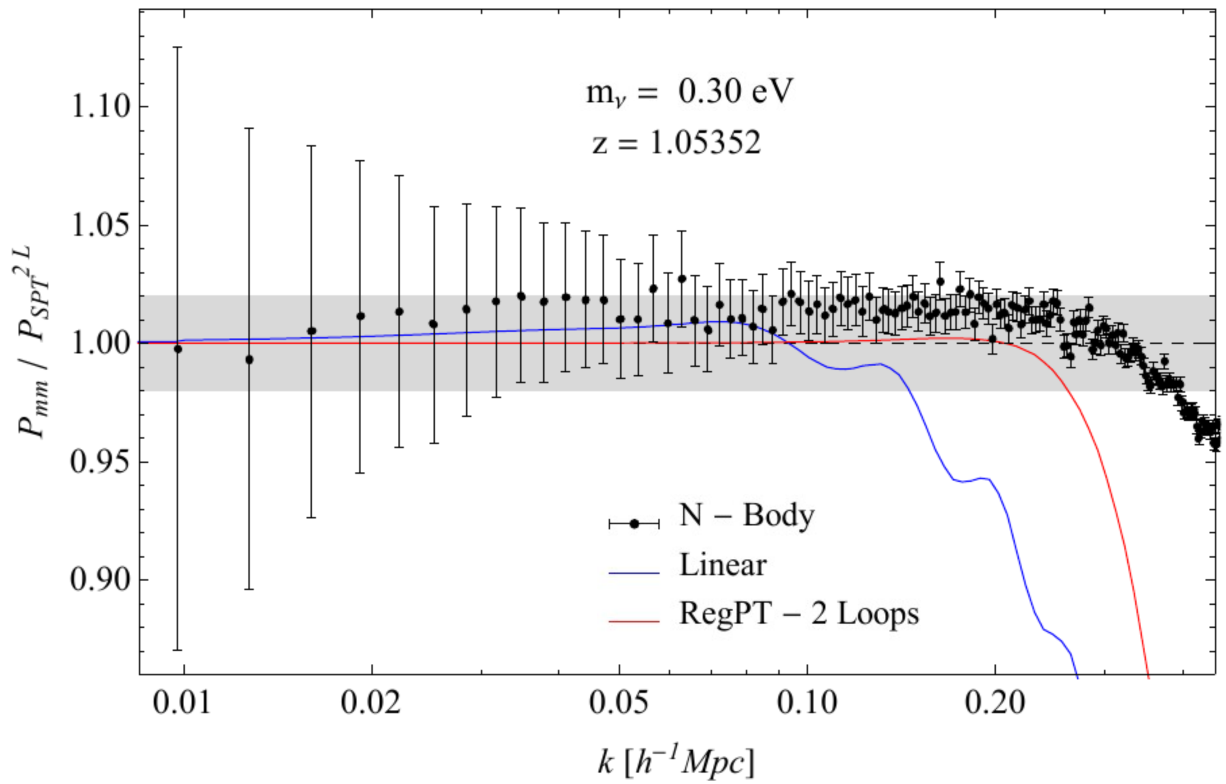
PT results (II)

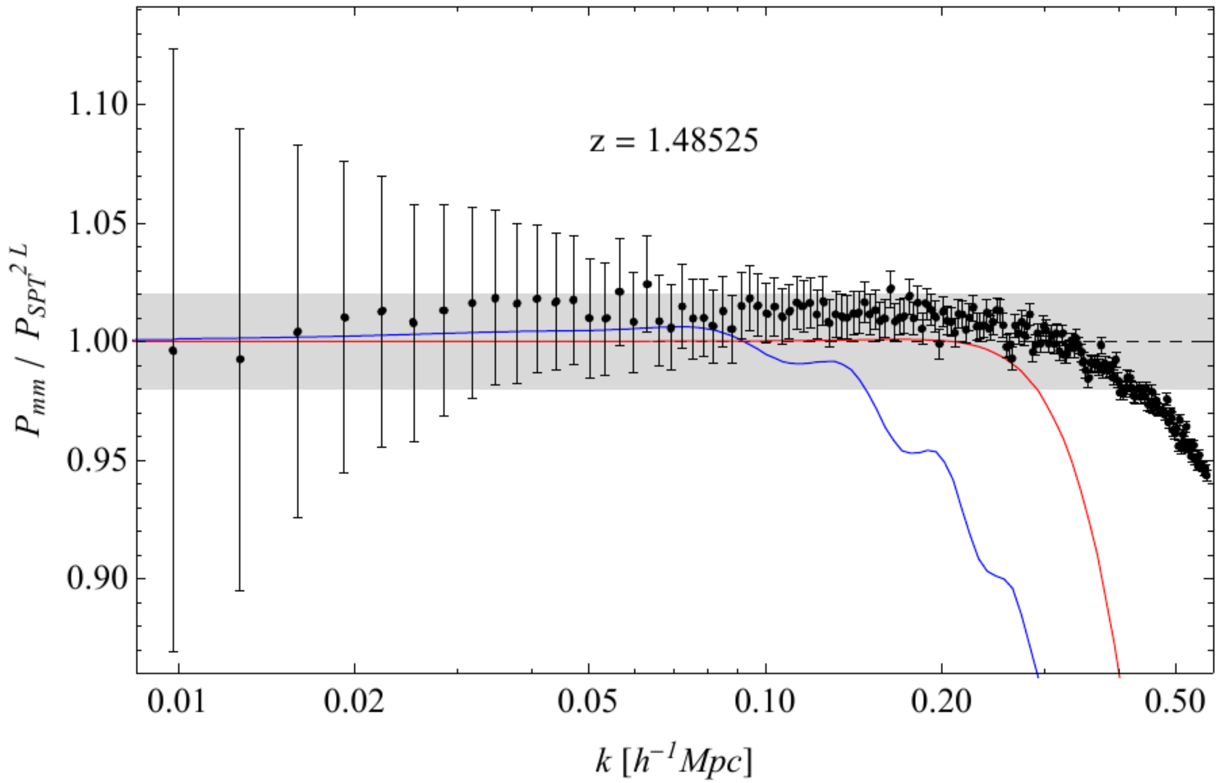
Keep Pcn and Pnn linear in the evaluation of the PT total matter power spectrum. See Blas+14 for general case.

Non linearities in the neutrinos are very small.

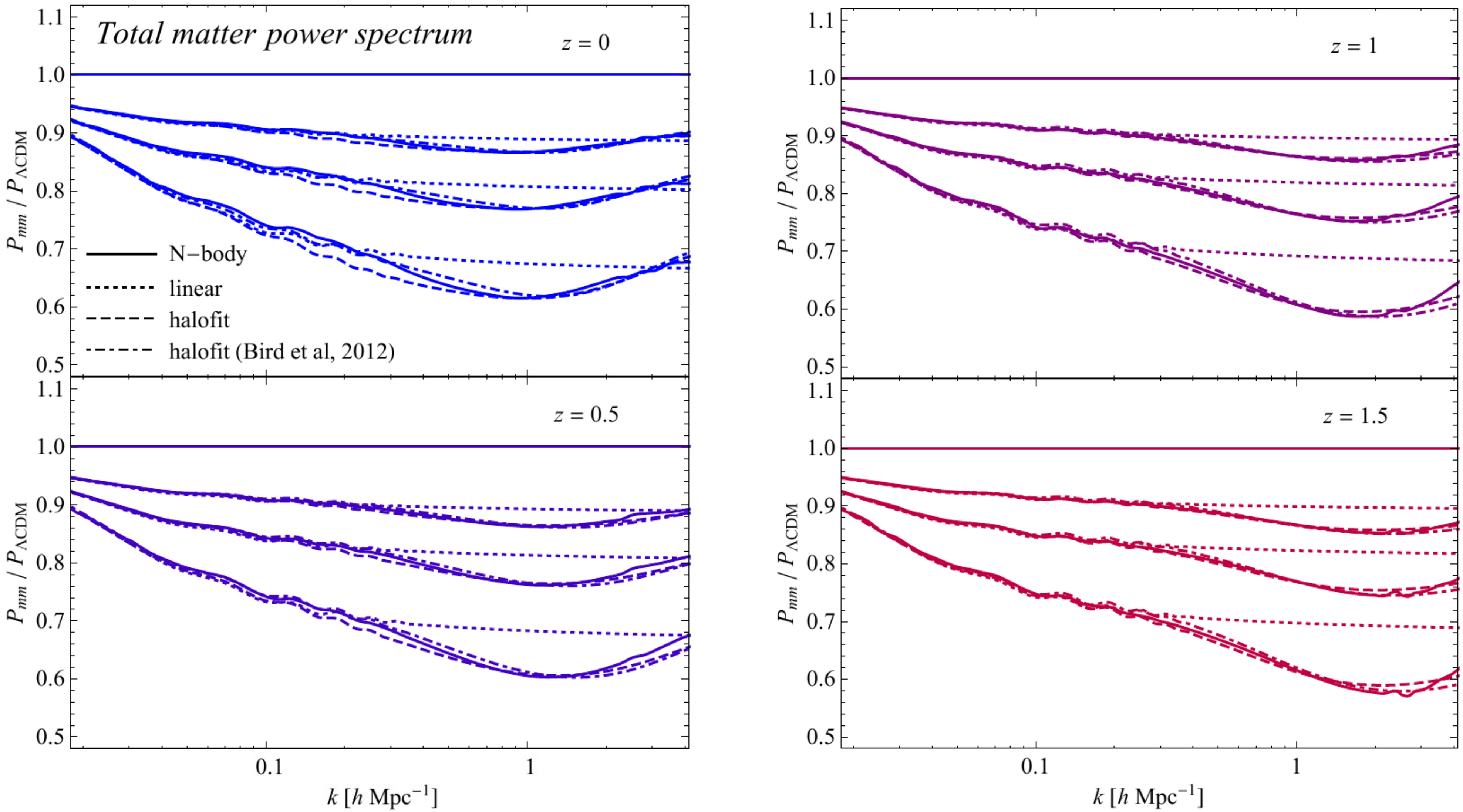
BOSS didn't use this method, computed PT power spectra using the total linear Pmm. Few % different at k> 0.4 h/Mpc

Same argument applies to full non linear regime. In HALOFIT no need to add other parameters to describe neutrinos



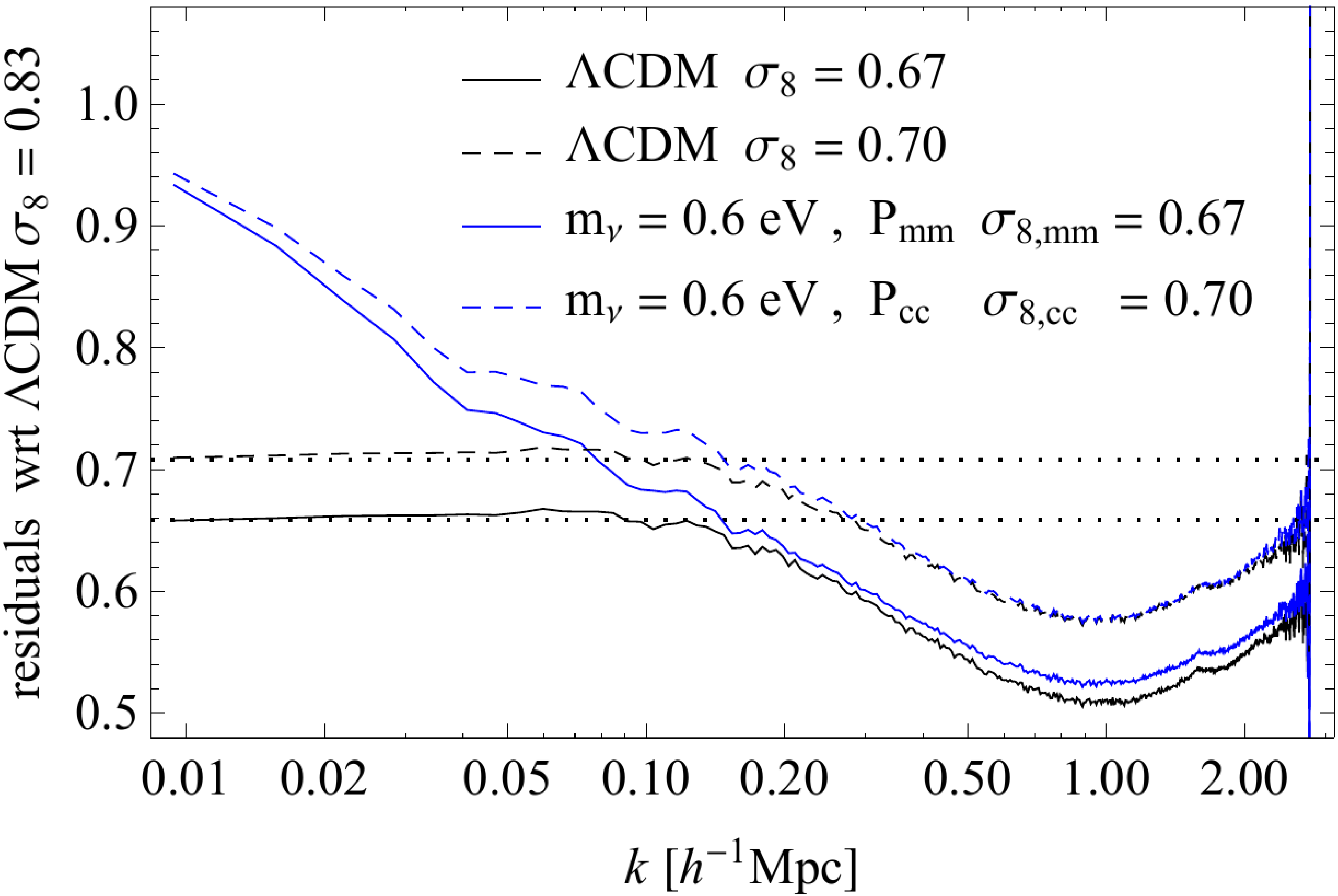


Halofit



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} / $P_{\Lambda CDM}$
k [h Mpc^{-1}]

Neutrino mass degeneracies



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.

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

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

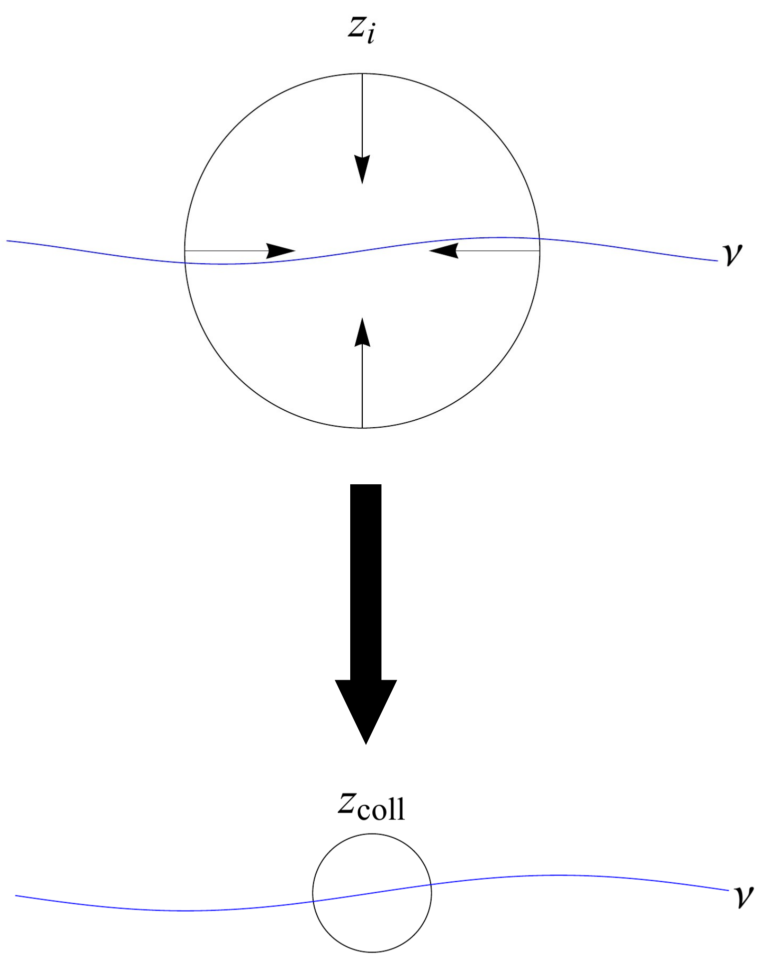
Note that

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

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.

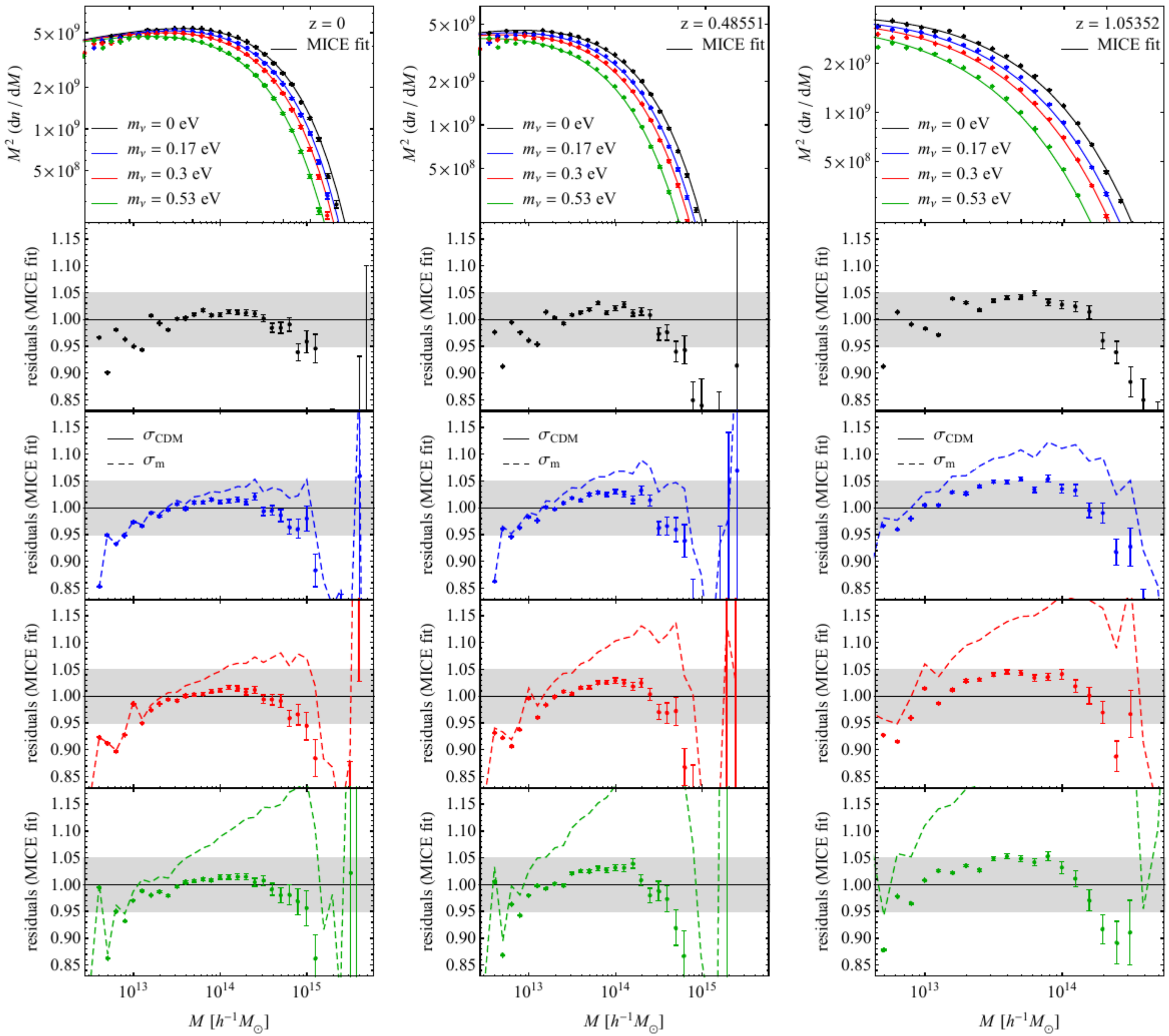
The halo mass function (III)

The MICE fit is *not* universal in redshift.

The discrepancy is the same for all cosmologies if we use the CDM P(k).

Non-universality in redshift similar to MICE.

The DM prescription is off by ~20% at clusters mass.



The halo mass function (IV)

Crucial for cosmological parameter estimation.

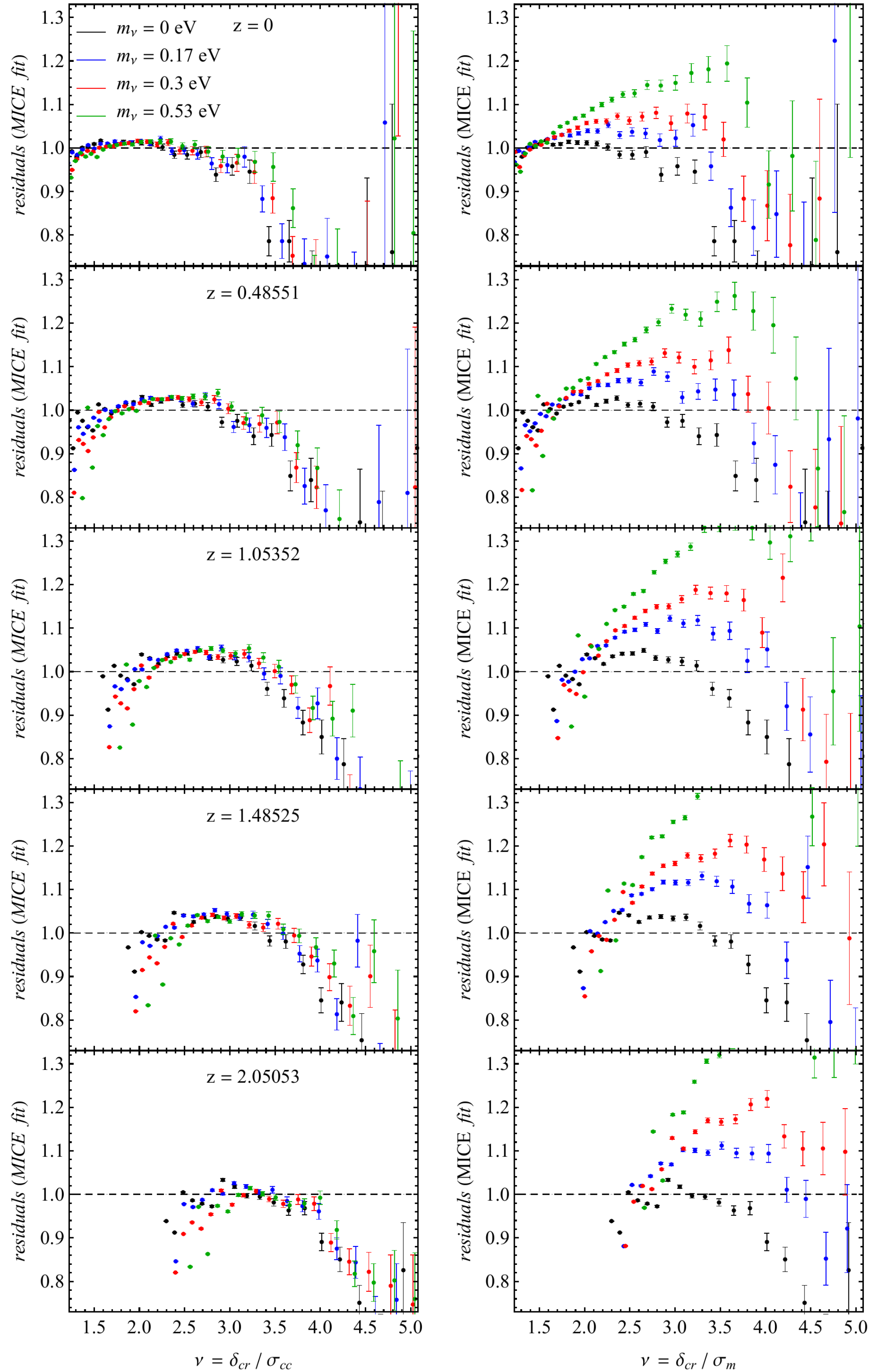
$$\nu\, f(\nu) \equiv \frac{M^2}{\rho}\, n(M)\, \frac{d\ln M}{d\ln \nu}$$

$$\nu = \delta_{cr}/\sigma_{cc}$$

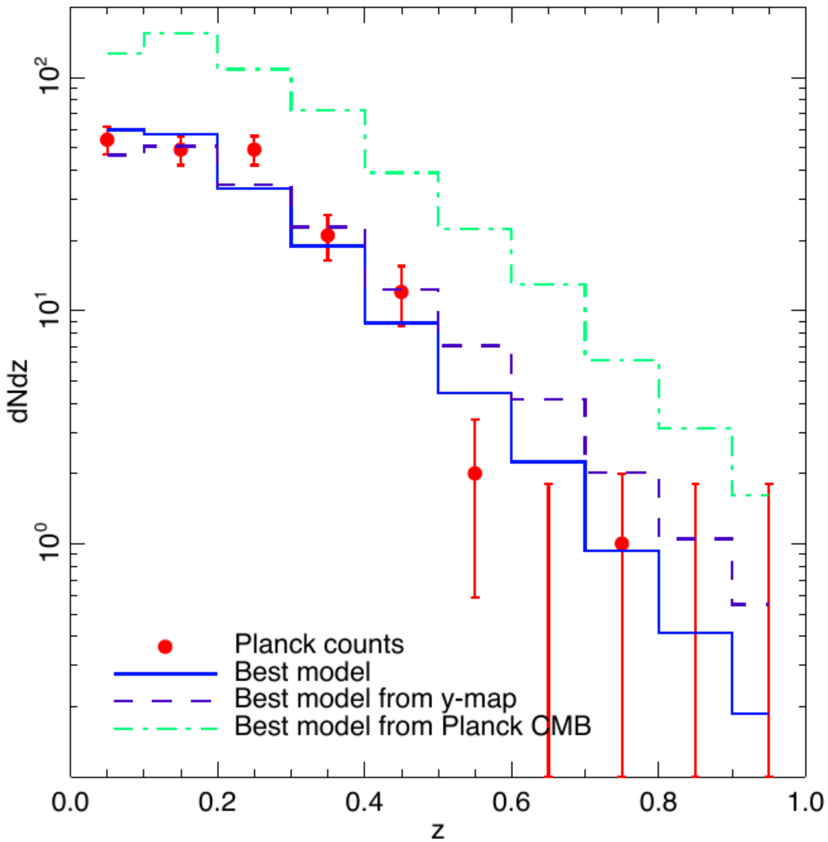
or

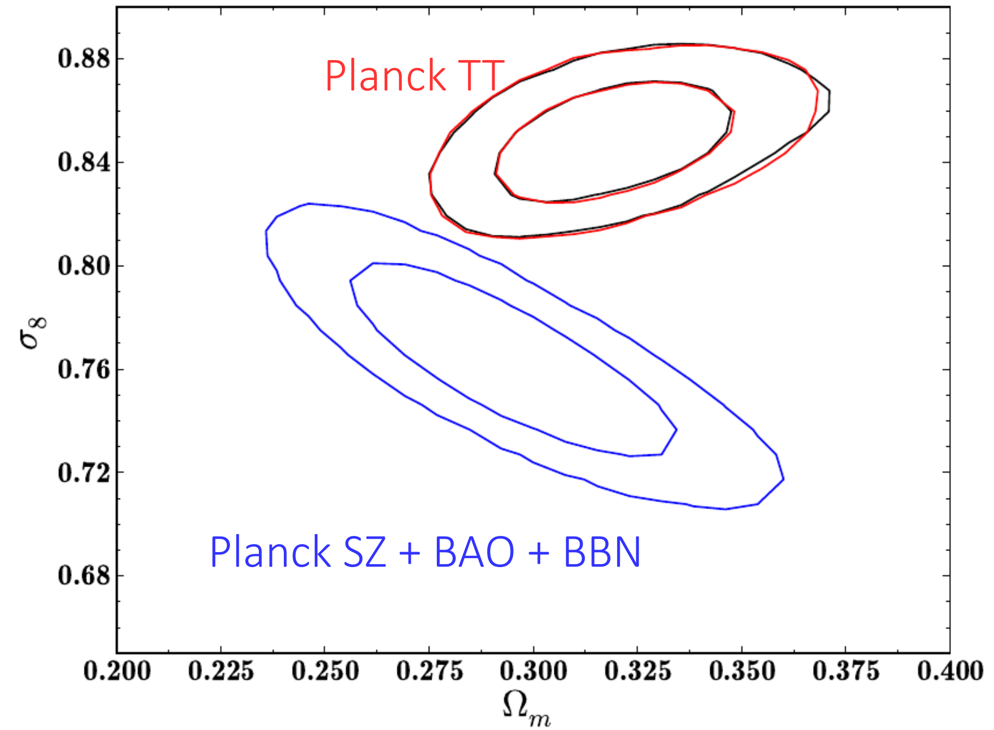
$$\nu = \delta_{cr}/\sigma_{mm}$$

Universality wrt neutrino masses achieved using the CDM power spectrum



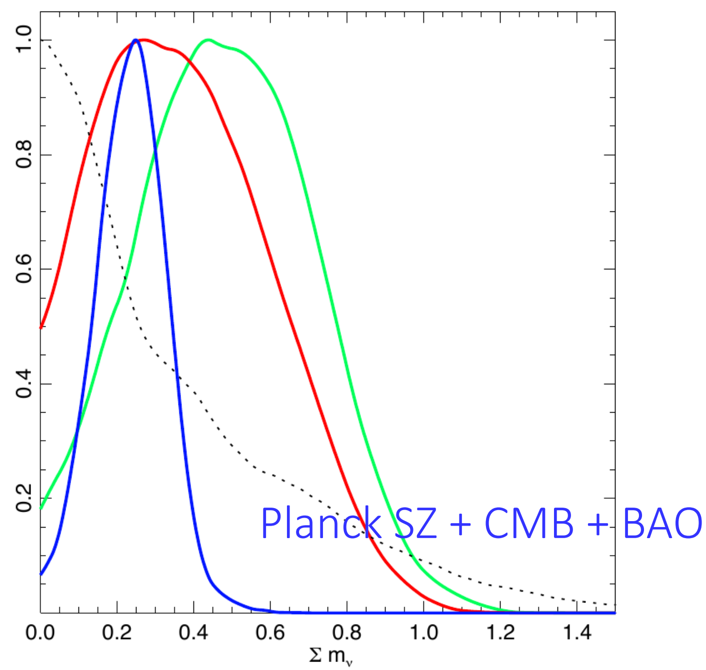
The Planck SZ – Planck CMB tension, Planck Results XX





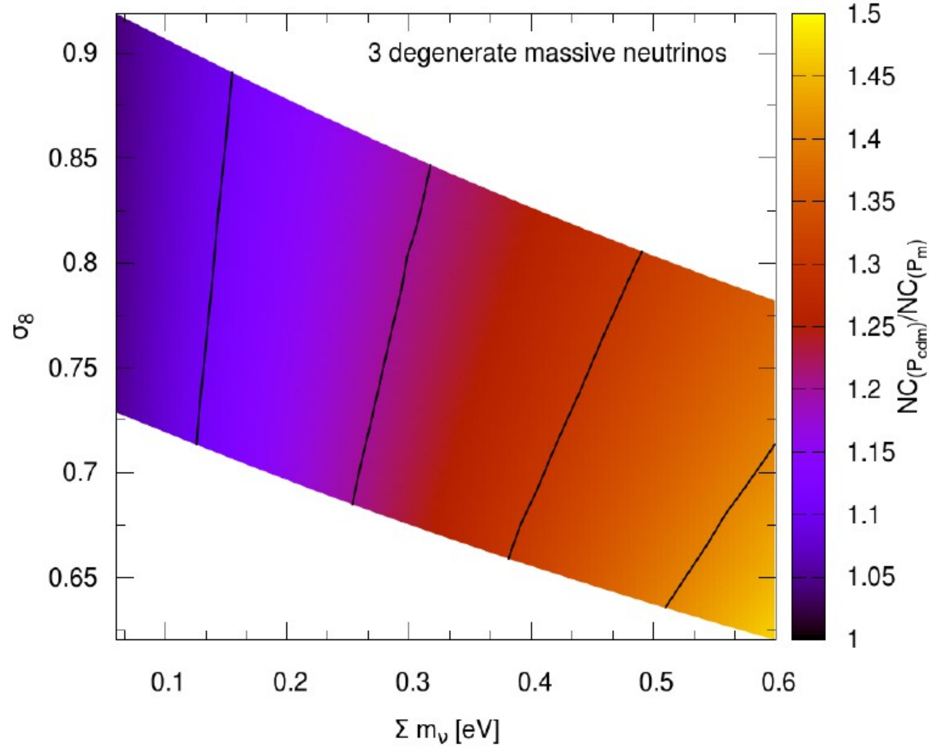
The Planck TT best fit model predicts more clusters than actually measured with SZ.
Massive neutrinos could help to reduce the tension ?

$$\sum m_\nu = (0.22 \pm 0.09)\,\mathrm{eV}$$



The halo mass function, implications for cluster counts

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



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

$$0.0 < z < 1.0$$

$$\Delta\Omega = 27.000 \text{ deg}^2$$

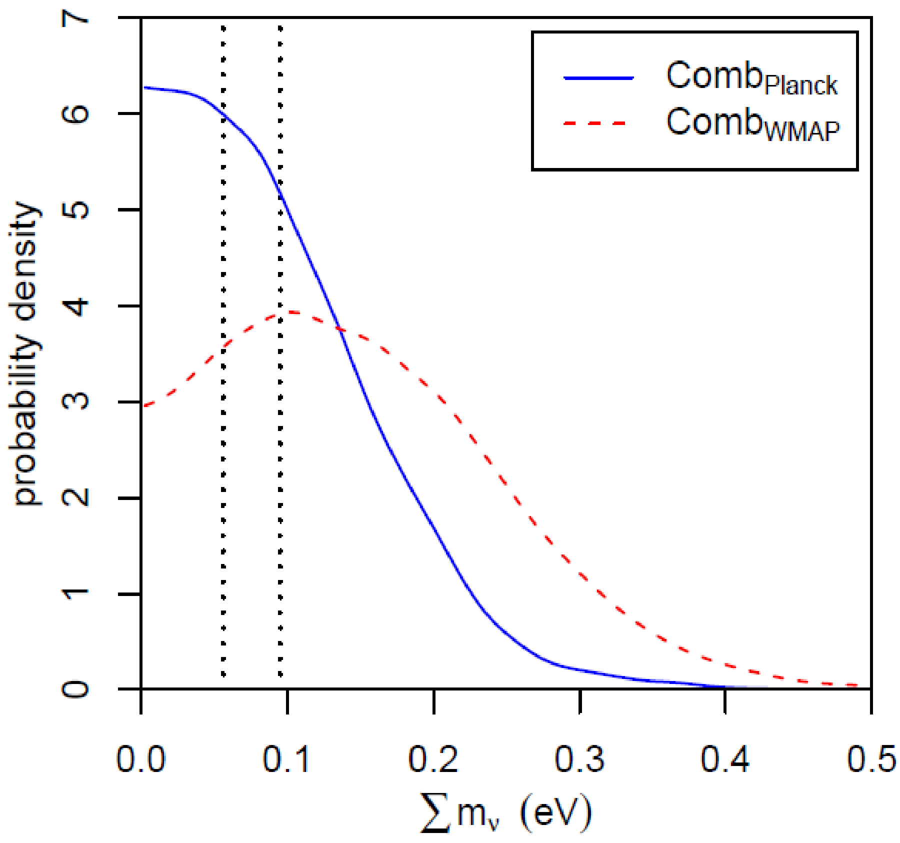
For reasonable values of σ_8 and Ω_m
the difference in the predicted number counts can reach the 10-20 %.

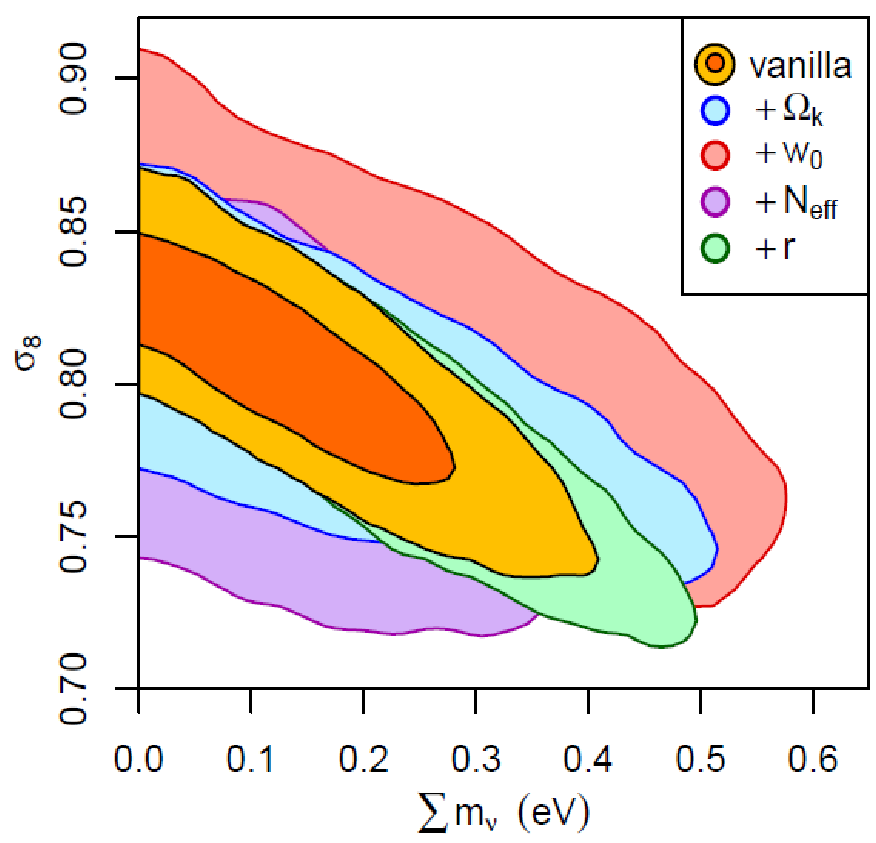
$M_{\mathrm{lim}}(z)$ from Planck SZ

The halo mass function, weighing the giants IV

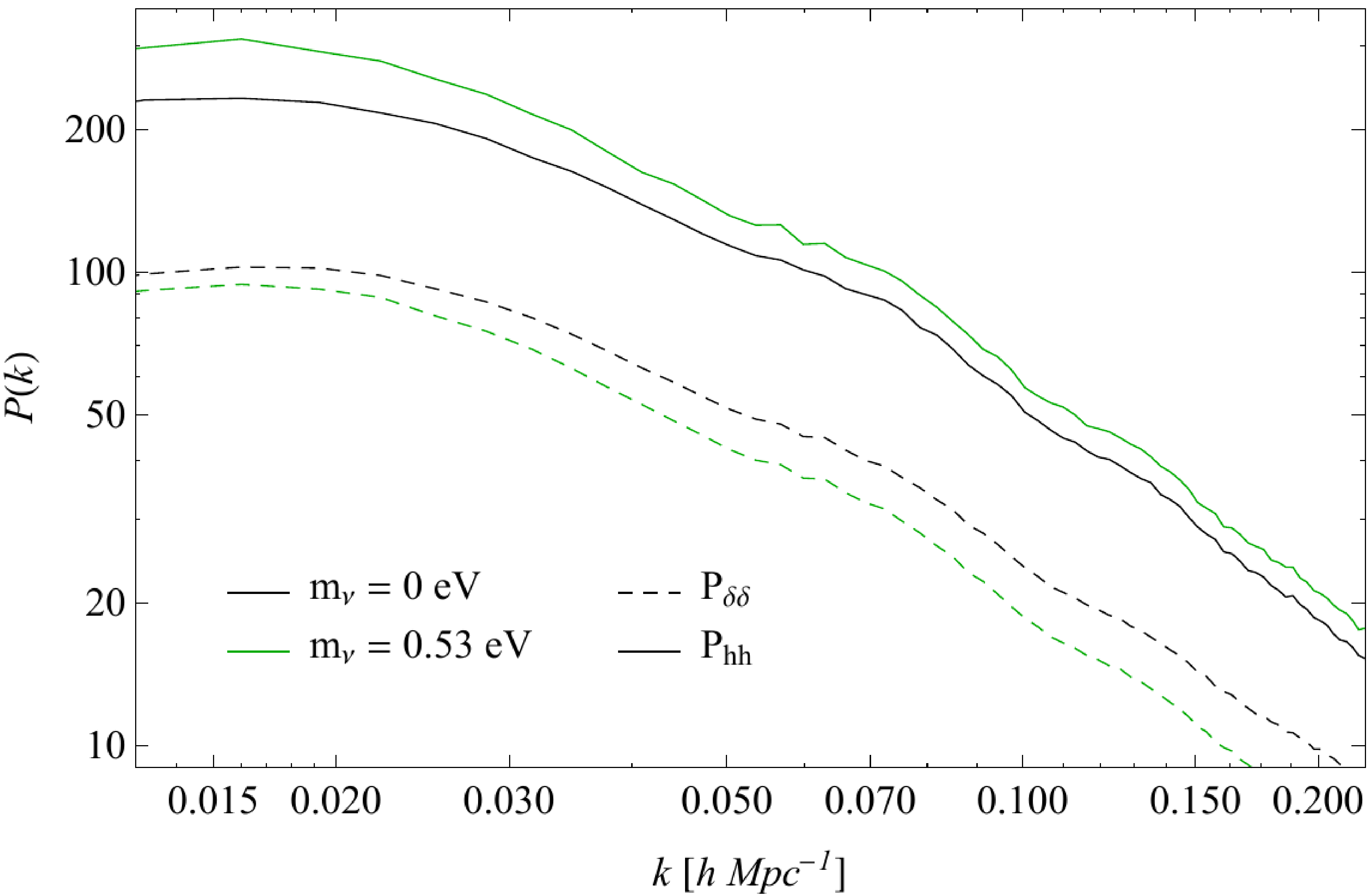
From Mantz+14, 1st analysis using CDM only

Consistent with minimum value even if CDM predicts more objects than DM.





Halo bias



P(k)
200
100
50
20
10
0.015
0.020
0.030
0.050
0.070
0.100
0.150
0.200
k [h Mpc^-1]
m_ν = 0 eV
m_ν = 0.53 eV
$P_{\delta\delta}$
P_{hh}

Halo Bias (I)

Do halos and galaxies trace the CDM or DM distribution?

The Peak Background Split argument : If you know the mass function you know the bias.
(Kaiser84, Fry&Gaztanaga93, Sheth&Tormen99)

$$1 + \delta_h^L = \frac{\mathcal{N}(M|\delta, R)}{(\mathrm{dn}/\mathrm{dM})\mathrm{V}_0} \simeq 1 + b_1^L \delta \quad \longrightarrow \quad b_1^L = -\frac{1}{\delta_c} \frac{\mathrm{d}\log \nu\, \mathrm{f}(\nu)}{\mathrm{d}\log \nu}$$

Linear bias factors are scale independent.
Universality in both redshift and cosmology.

CDM is the way to go

Halo bias (II)

Halos and galaxies are biased tracers of the underlying mass distribution

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

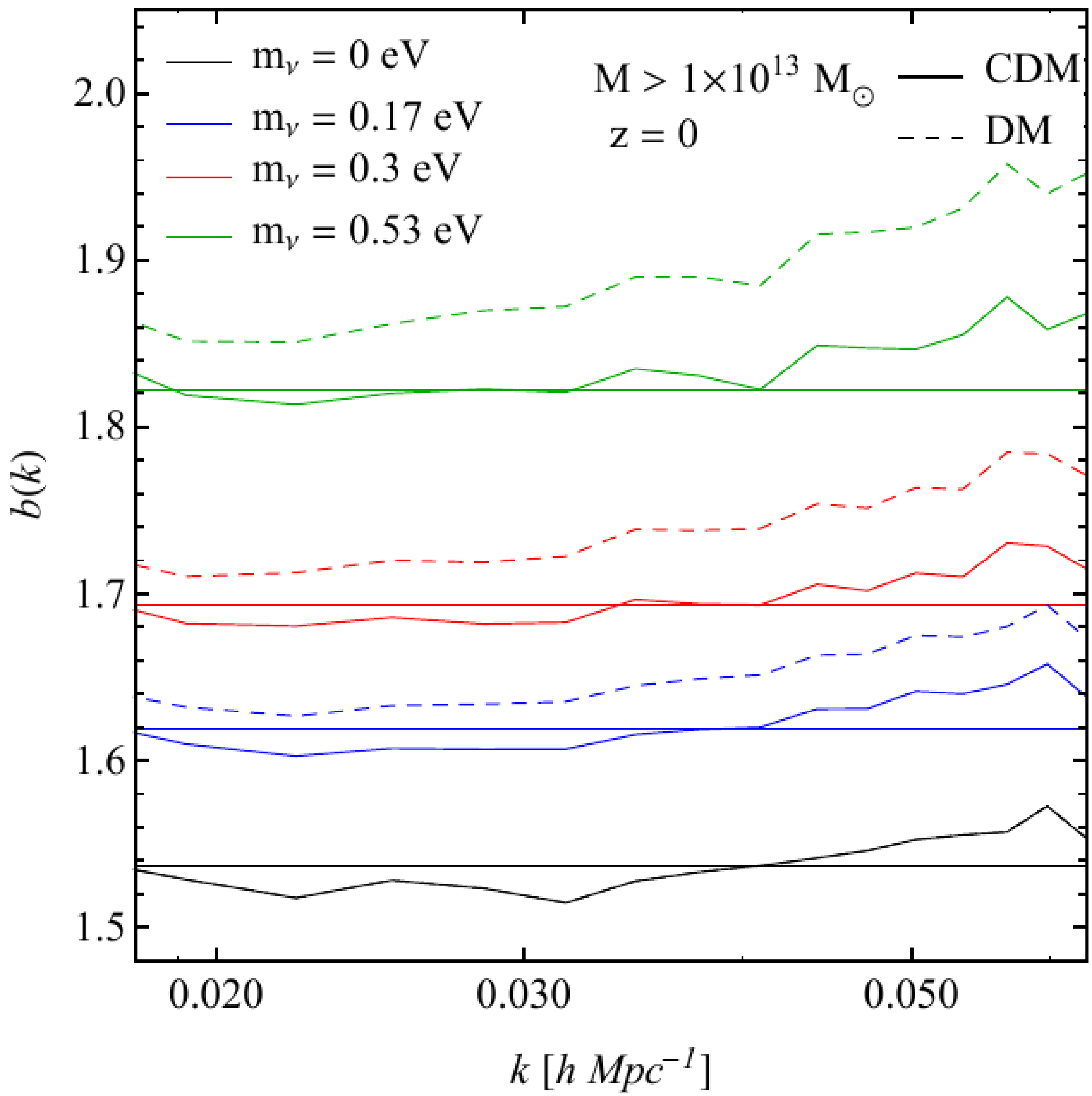
Linear bias is expected to be scale-independent on large scales.

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

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

Potential systematic error in galaxy clustering measurements.

See Biagetti+14 for beyond linear bias.



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

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

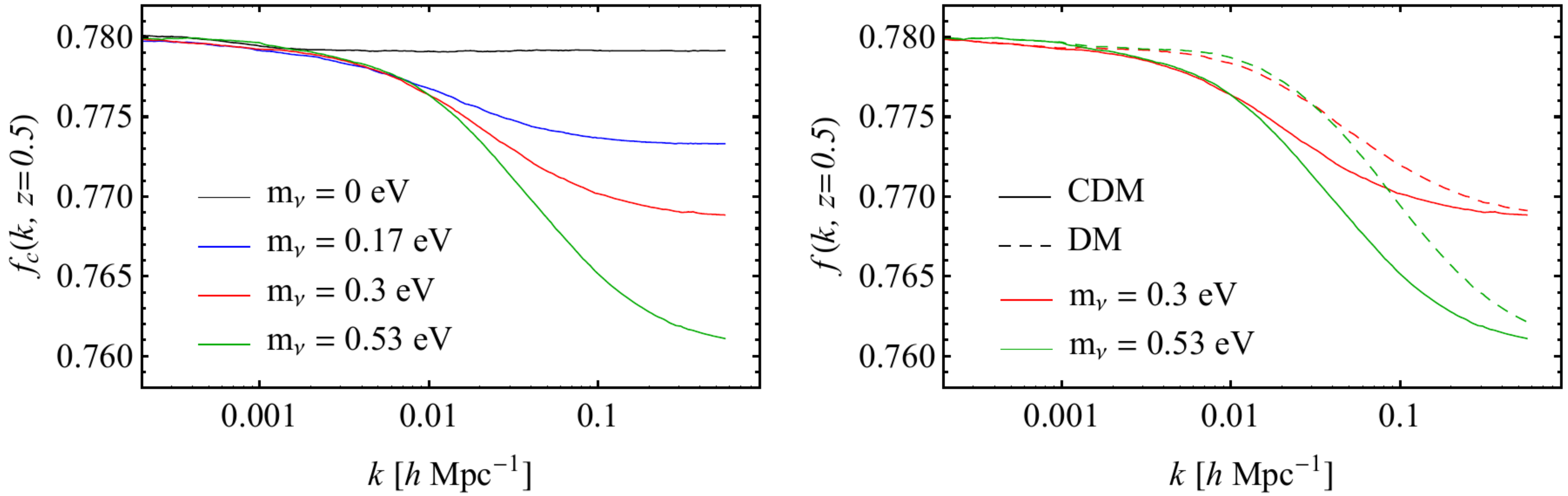
that for bias tracers means

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

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

Linear theory facts (V)

In massive neutrino cosmologies the growth rate f depend scale dependent



Here the difference between CDM and DM is negligible.

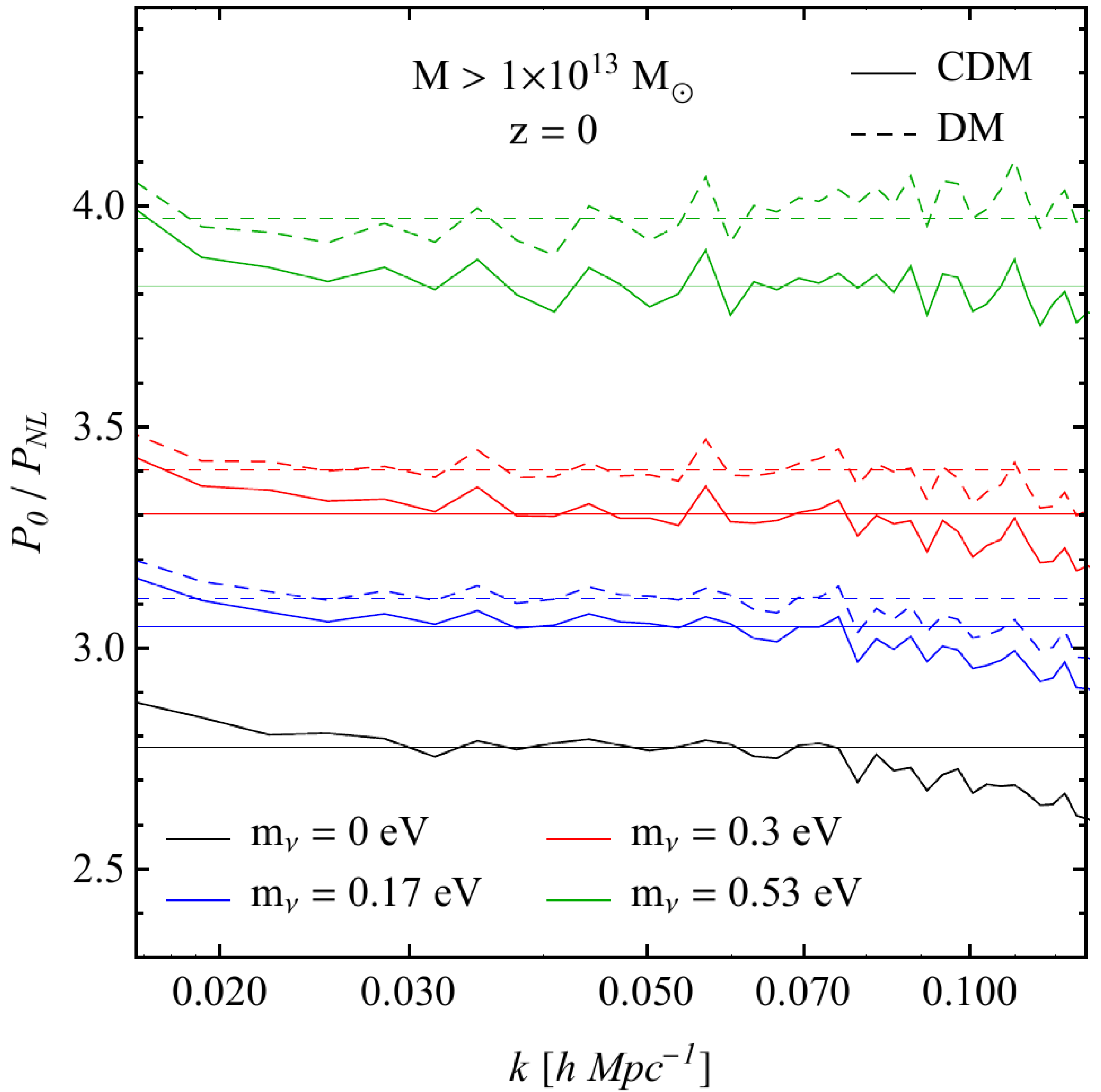
! Most of the difference in the monopoles and quadrupoles comes from the bias !

RSD (II)

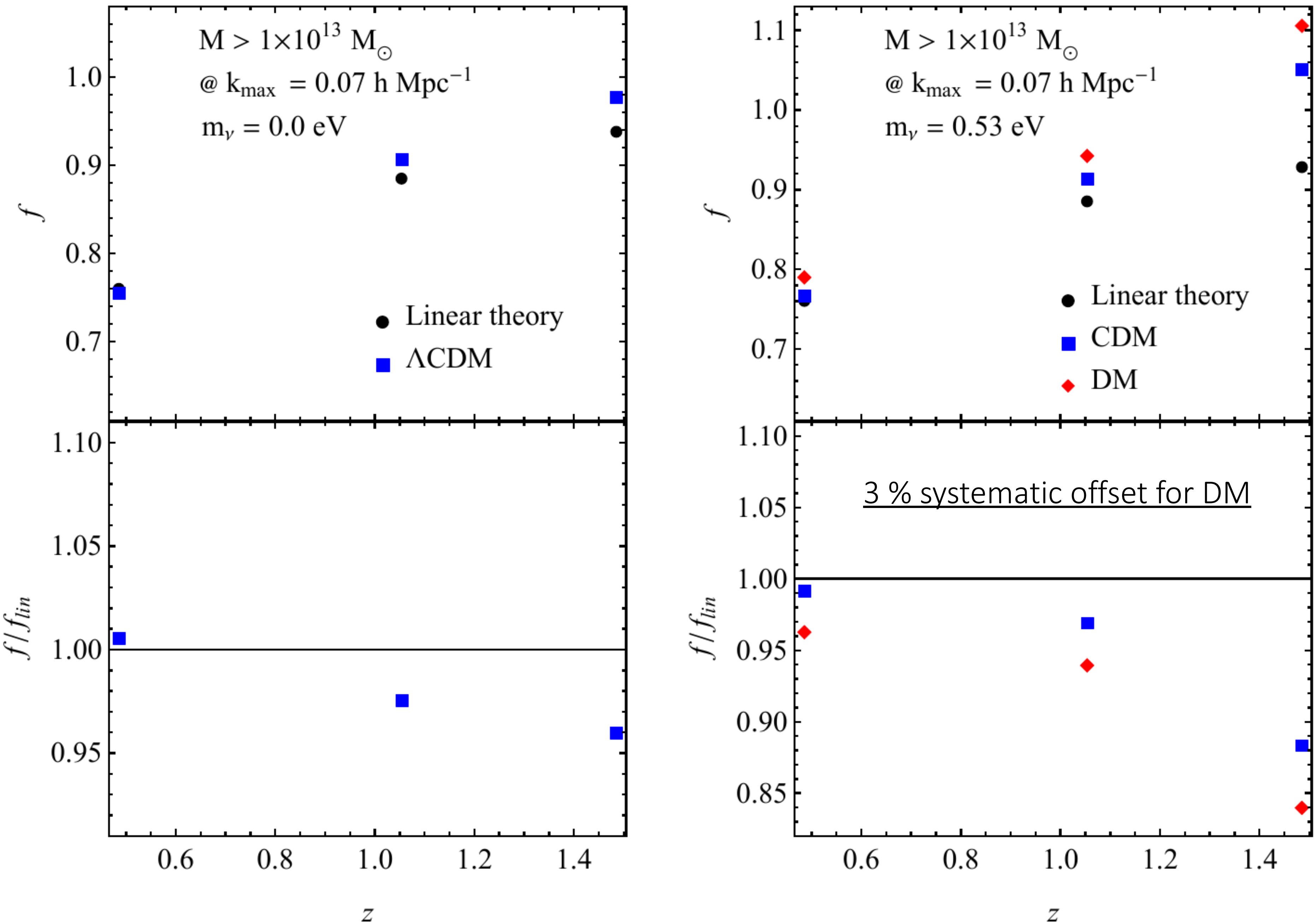
$$\frac{P_{hh}^0}{P_m} = b^2 + \frac{2}{3}fb + \frac{1}{5}f^2$$

At low redshift scale dependent growth + bias make the Kaiser formula working up to smaller scales than LCDM.

For DM scale dependence alleviated by growth competing with the bias.



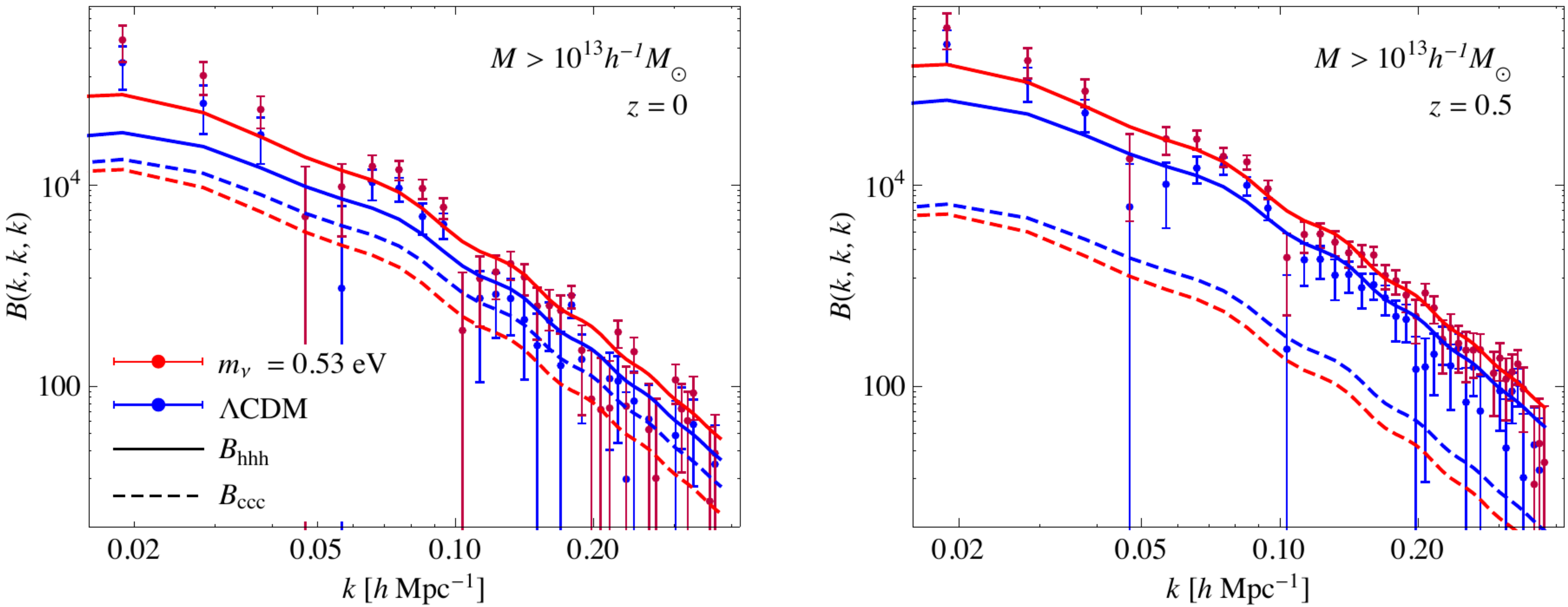
RSD (III)



M > 1×10^13 M⊙
@ k_max = 0.07 h Mpc^−1
m_ν = 0.0 eV
Linear theory
ΛCDM
f
f / f_lin
z
0.6
0.8
1.0
1.2
1.4
M > 1×10^13 M⊙
@ k_max = 0.07 h Mpc^−1
m_ν = 0.53 eV
Linear theory
CDM
DM
3 % systematic offset for DM

The Bispectrum, for the aficionados

CDM Bispectrum and its relation to the halo Bispectrum

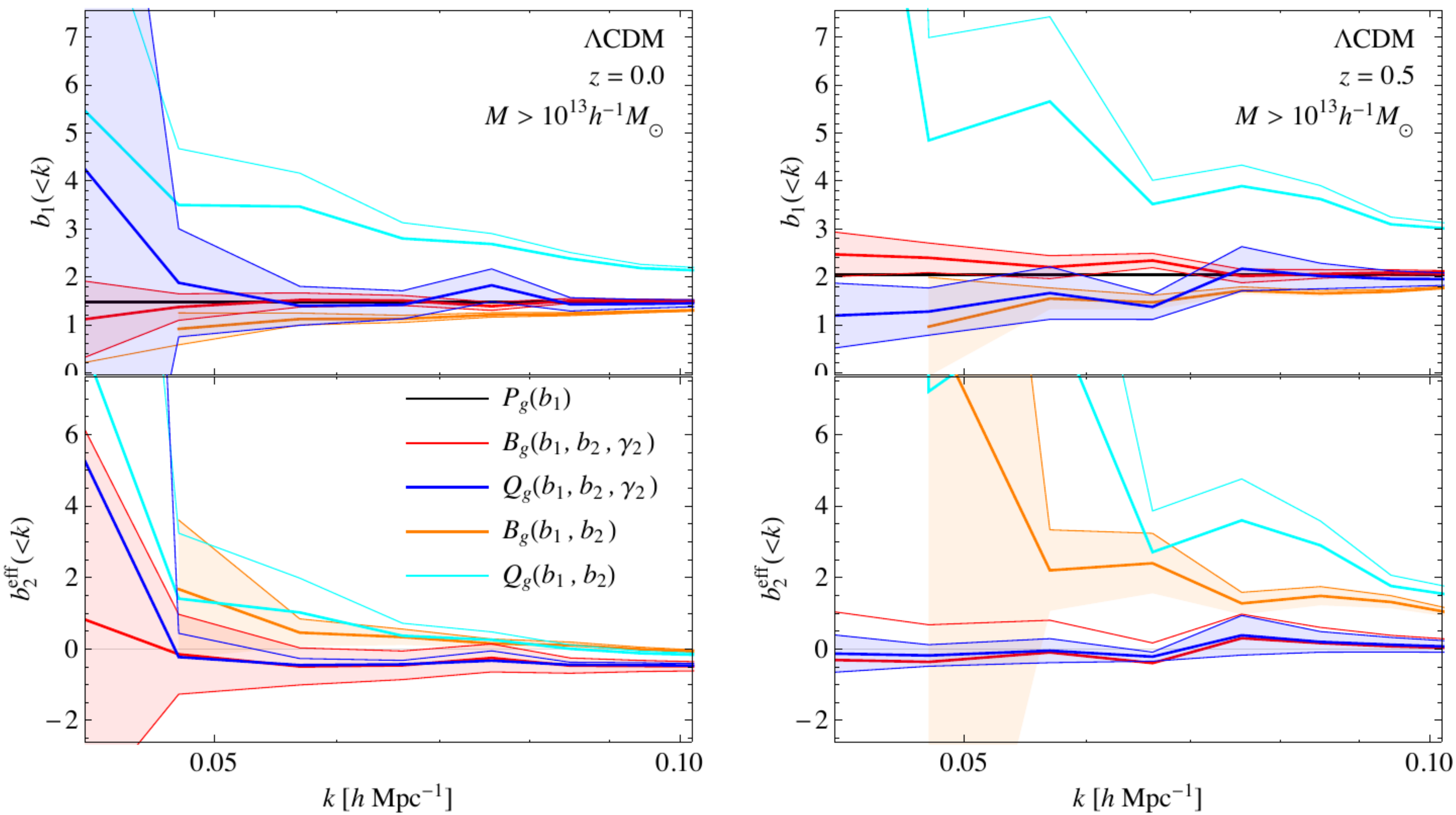


Predicted Bhhh given the tree-level Bccc, and fitting a non local bias model. What's that ???

The Bispectrum, for the aficionados (II)

In a local bias model

$$B_{hhh}(k_1, k_2, k_3) = b_1^3 B_{123} + b_1^2 b_2 (P_1 P_2 + cyc.)$$

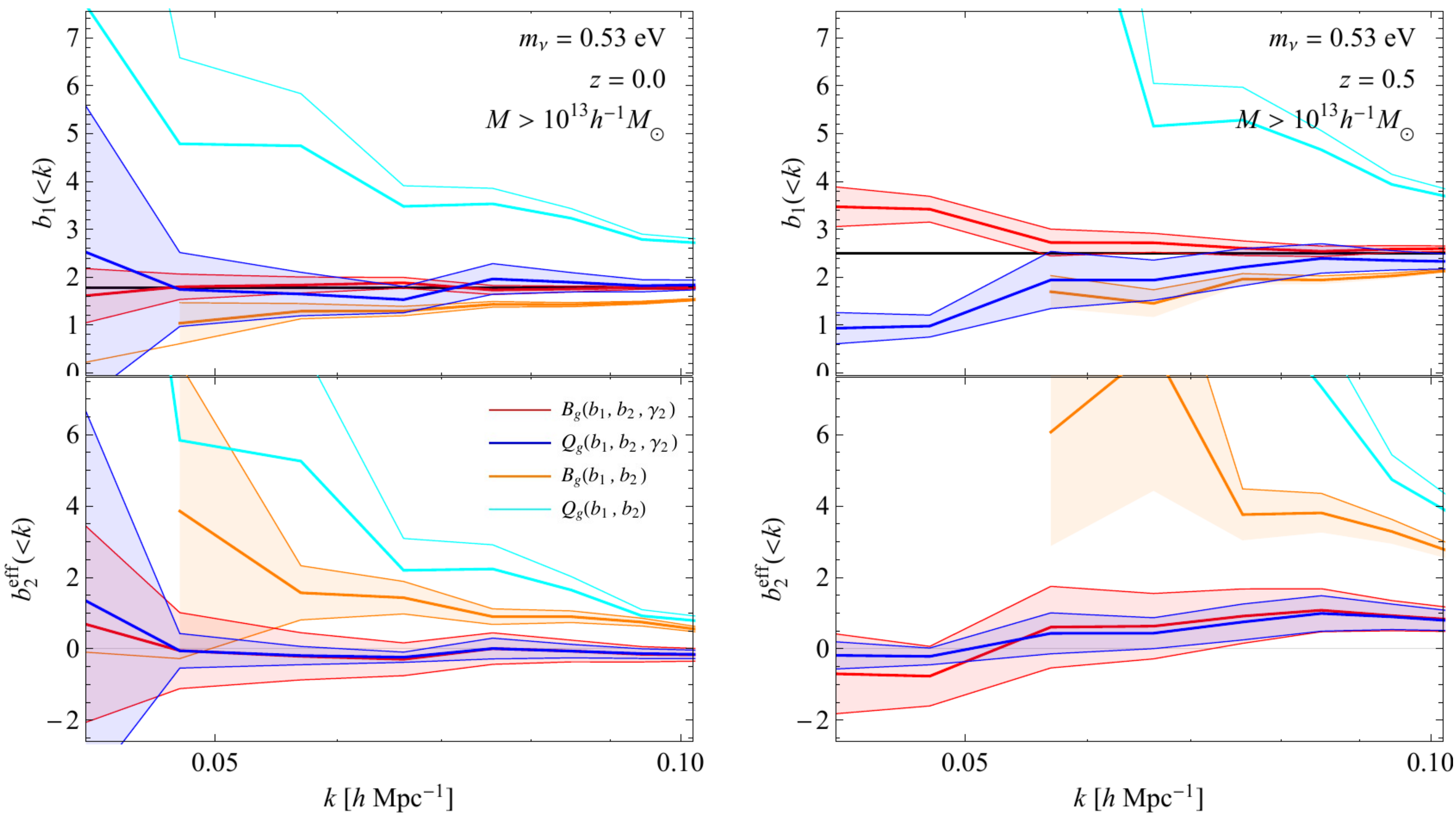


The Bispectrum, for the aficionados (III)

Chan+12
Baldauf+12

In a non local bias model

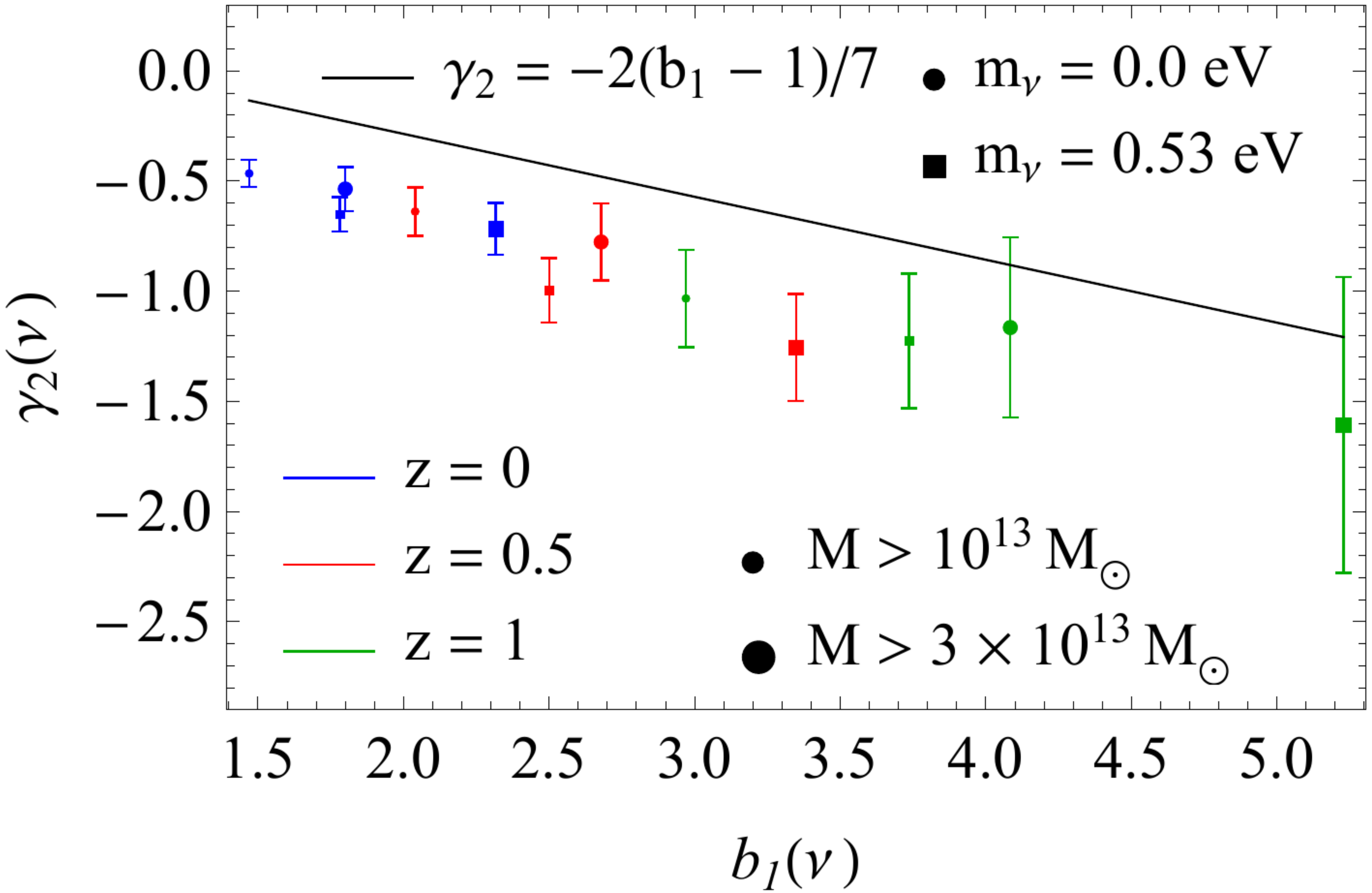
$$B_{hhh}(k_1,k_2,k_3) = b_1^3 B_{123} + b_1^2 b_2 (P_1 P_2 + cyc.) + 2 b_1^2 \gamma_2 [(\mu_{12}^2 - 1) P_{12} + cyc.]$$



The Bispectrum, for the aficionados (IV)

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

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



Conclusions and perspectives

We have studied several effects of massive neutrinos on the LSS of the Universe :

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

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

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

- Incorrect assumptions in the bias lead to <u>systematic</u> effects in <u>RSD analysis</u> ;

- The non local bias model for the Bispectrum work in neutrino cosmologies as well.
  Further evidence for <u>non local lagrangian bias ;</u>

Next:

- Correlation function and the BAO peak;

- Angular 2D clustering (DES) and weak lensing ;

- Voids !

Thank you !