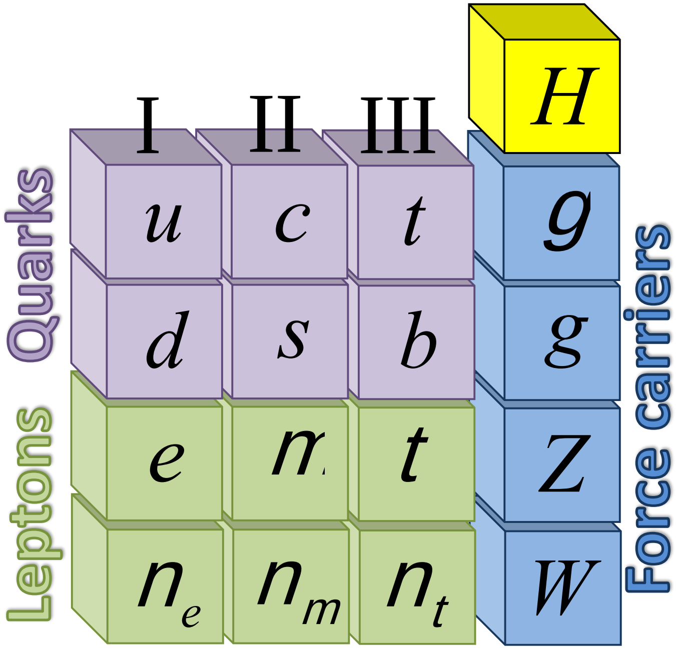
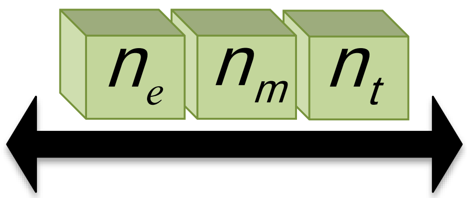
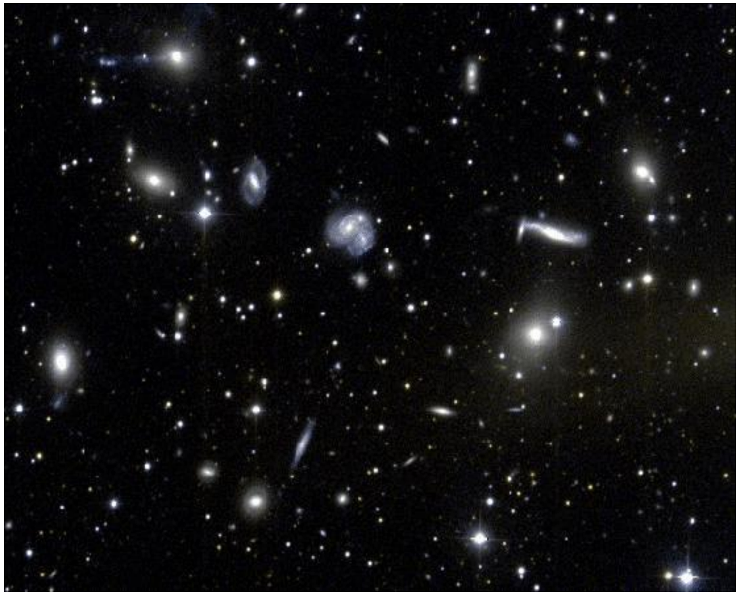
Massive neutrinos and their effect on the large scale structure of the Universe

Francisco Villaescusa-Navarro
OATS/INAF/INFN, Trieste, Italy

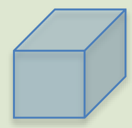
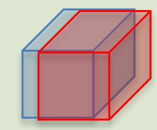






Geneva || 28th Texas Symposium on Relativistic Astrophysics || December 15

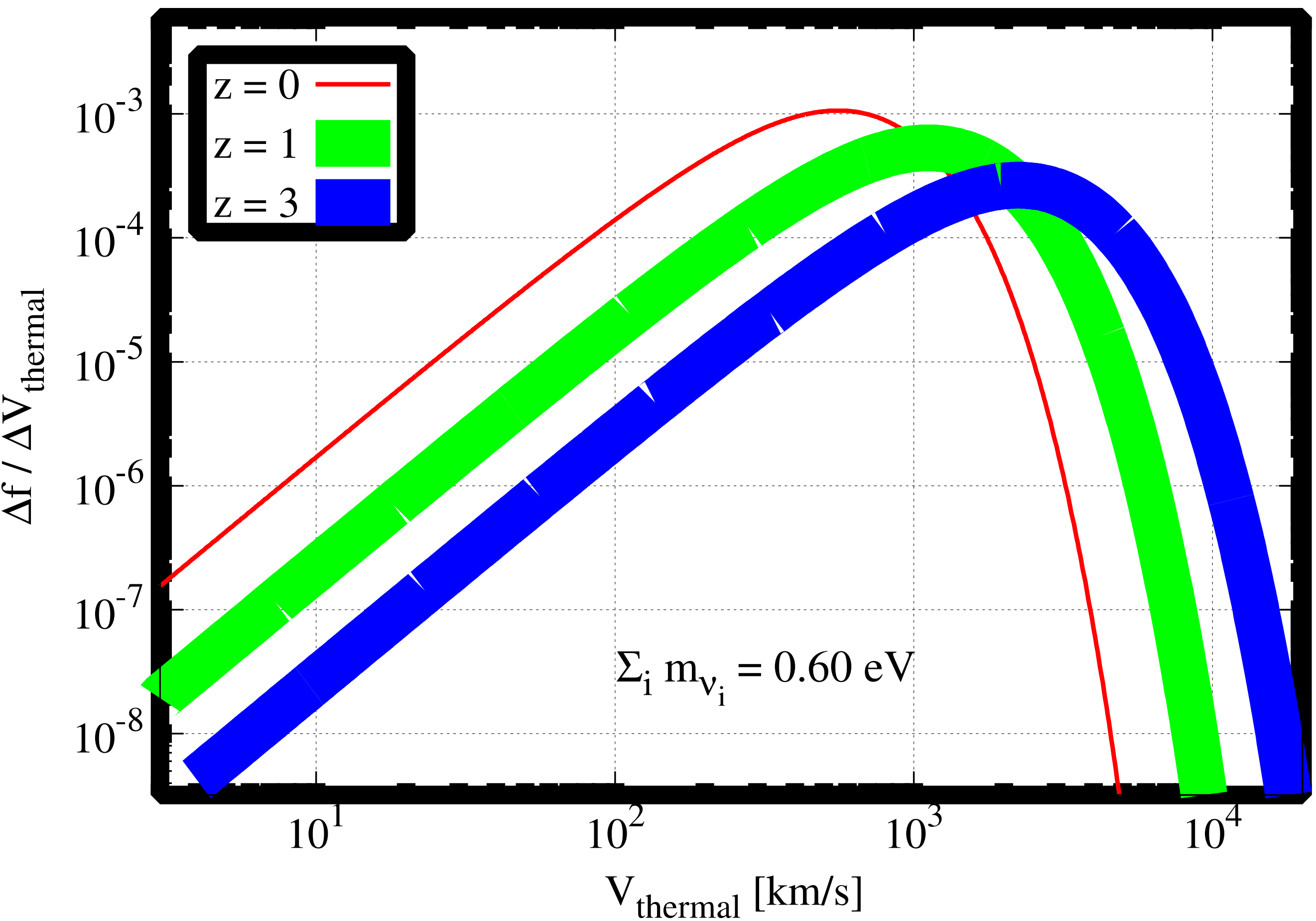
N-body simulations with neutrinos

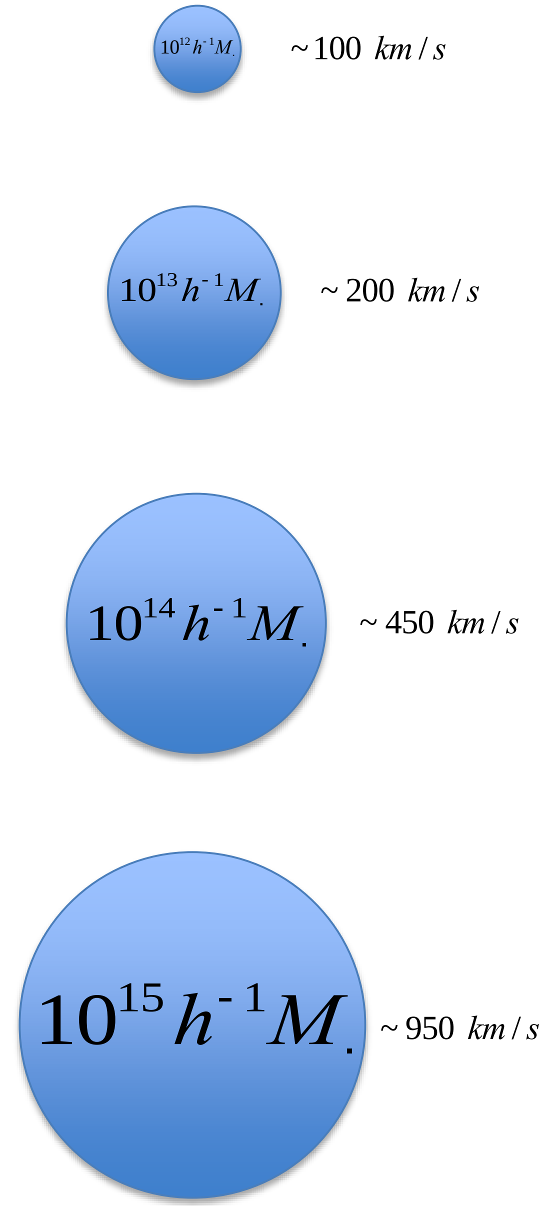
	CDM	CDM + ν
Power spectrum	$P_m(k)$ 	$P_{cb}(k)$ $P_n(k)$ 
Growth factor	Scale independent	Scale dependent
Growth rate	Scale independent	Scale dependent
Velocities	Peculiar	Peculiar Peculiar + thermal
Radiation	-	May be important

Neutrino clustering

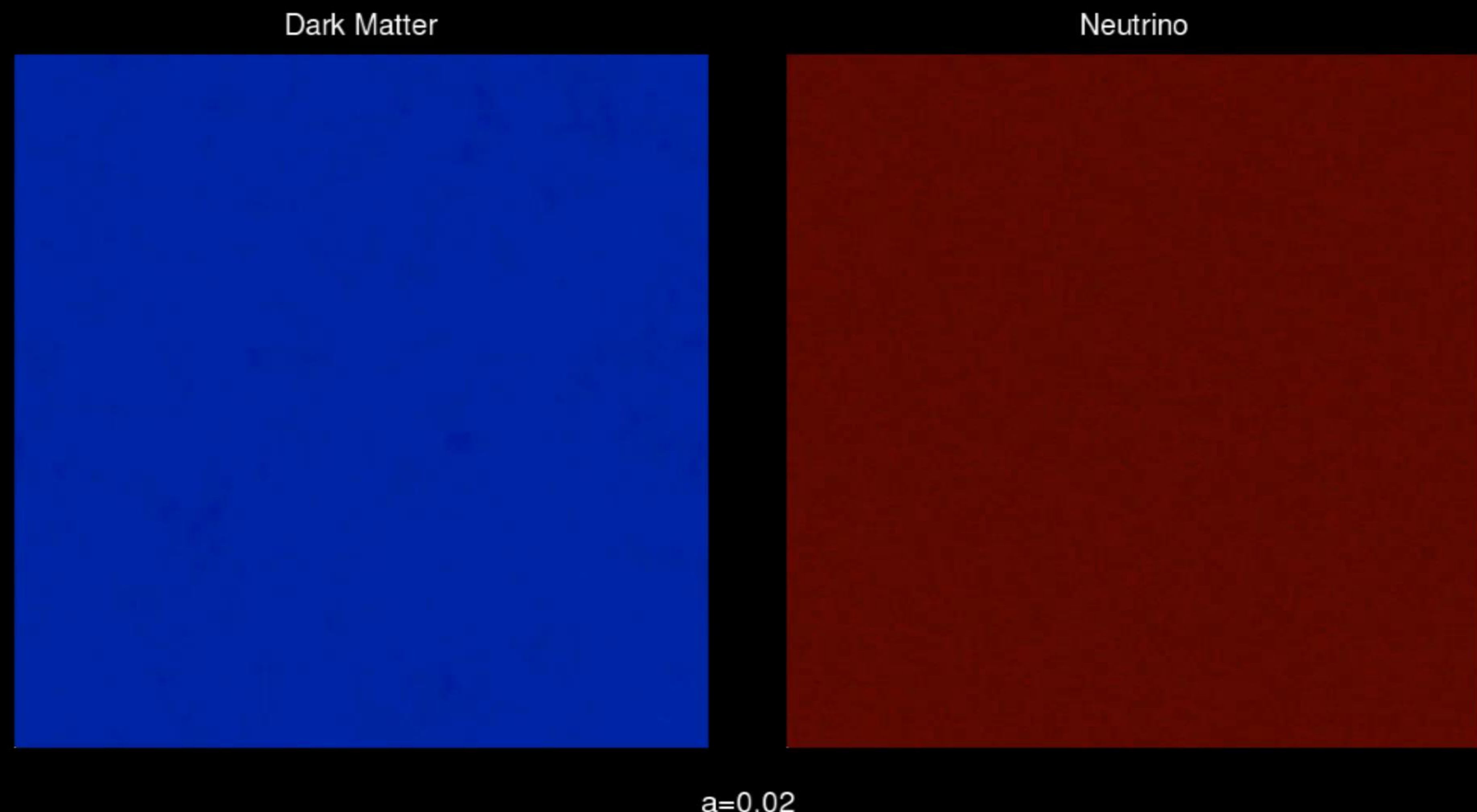
$$n_\nu(p,z)dp \cong \frac{4\pi g_\nu}{(2\pi\hbar c)^3}\left(\frac{p^2 dp}{e^{(p/k_B T_\nu(z))}+1}\right)$$

$$T_n(z) = 1.95(1+z)\ K$$

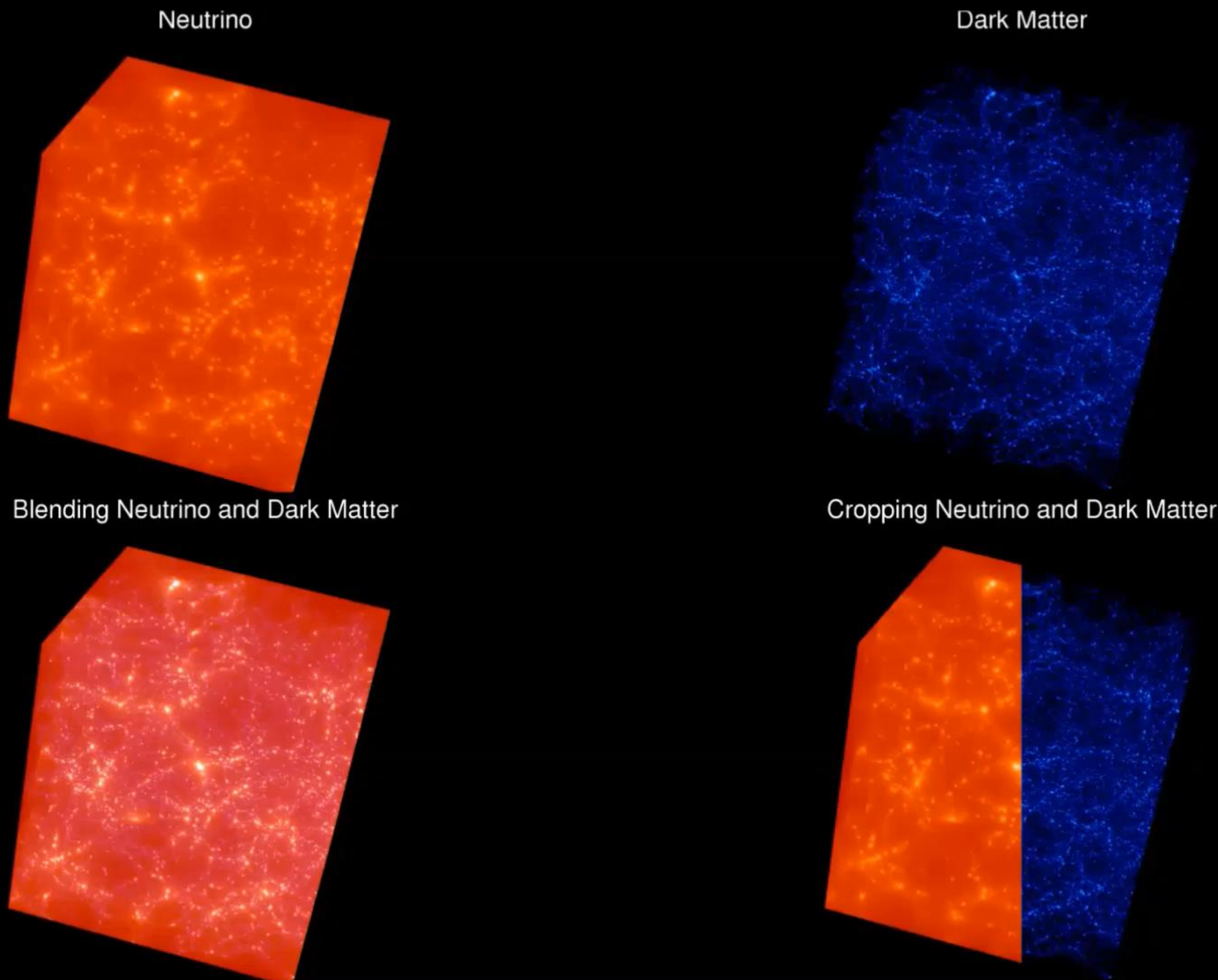




Neutrino clustering



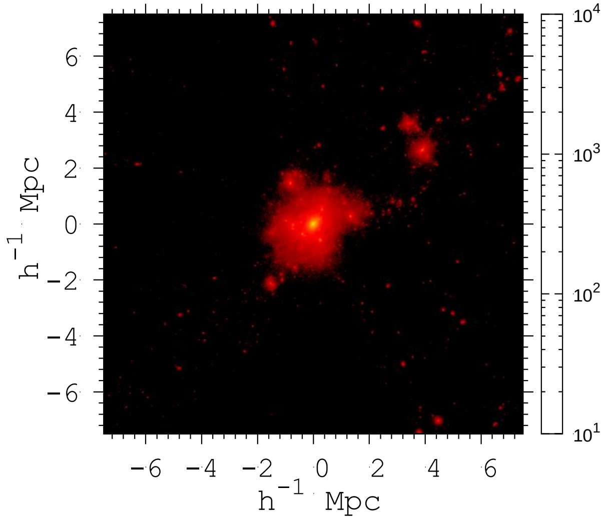
Neutrino clustering

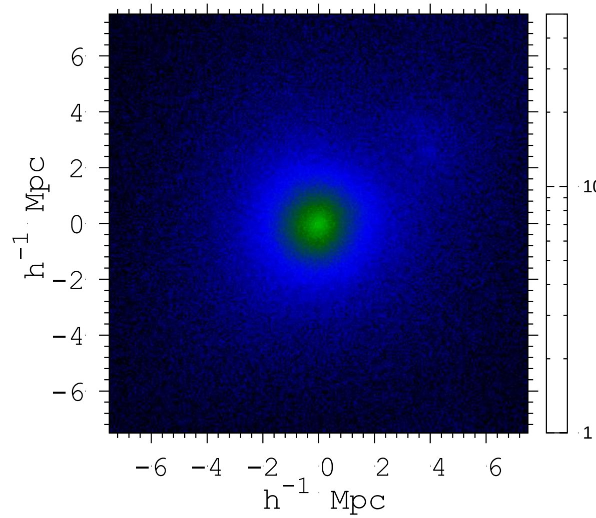


Clustering of relic neutrinos

FVN, Bird, Peña-Garay, Viel, 2013
FVN, Miralda-Escude, Peña-Garay, Quilis, 2011

$M_{CDM} = 4x10^{14} M_{.} / h$



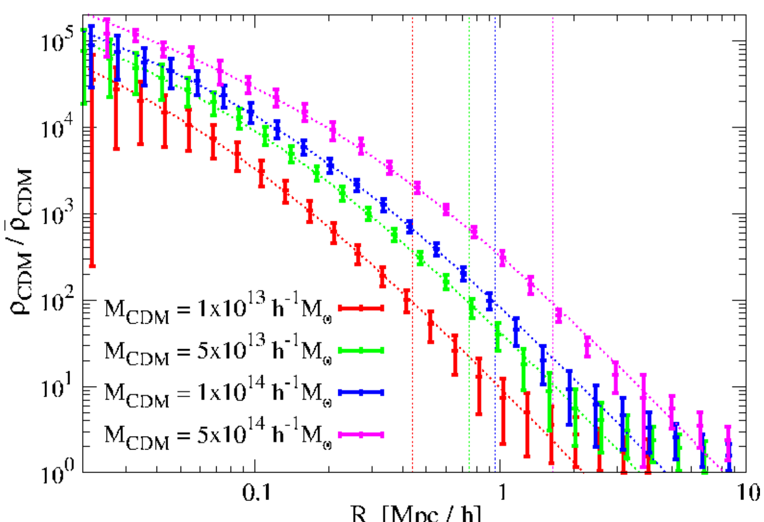


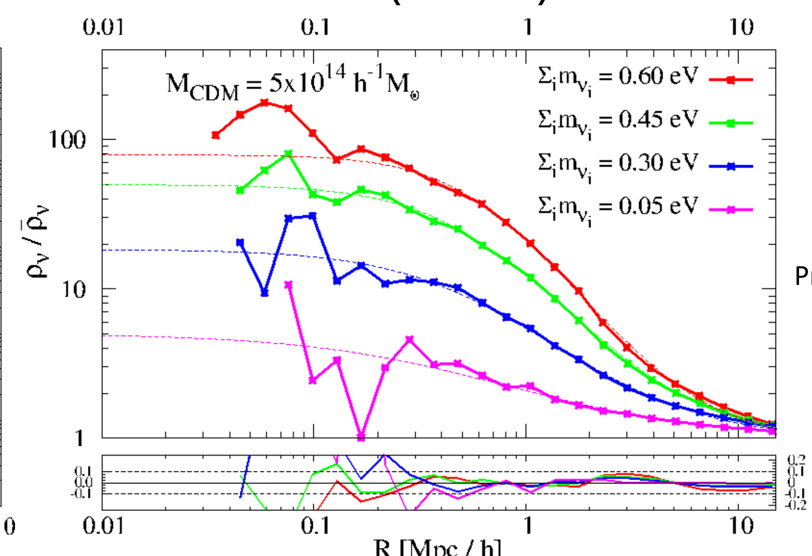
$$c = \frac{r_v}{r_s}$$

$$r_{CDM}(r) = \frac{r_s}{(r/r_s)(1+r/r_s)^2}$$

$$d_n(r) = \frac{r_c}{(1+r/r_c)^a}$$

$$F_h = \begin{cases} 9.5\times10^{-4} \rightarrow 0.3 \text{ eV} \\ 2.6\times10^{-3} \rightarrow 0.6 \text{ eV} \end{cases}$$





PTOLEMY

Princeton Tritium Observatory
for Light, Early-Universe,
Massive-Neutrino Yield

Halo mass function

Castorina, Sefussati, Sheth, FVN, Viel 2013

$$\frac{dn(M,z)}{dM} = \nu f(\nu)\frac{\rho_m}{M^2}\frac{d\ln\nu}{d\ln M}$$

Universal

$$\begin{cases} \nu \equiv \dfrac{\delta_c}{\sigma(M,z)} & \delta_c = 1.686 \\ \sigma^2(M,z) = \dfrac{1}{2\pi^2}\displaystyle\int_0^\infty k^2 P_m(k) W^2(k,R)\,dk \\ M = \dfrac{4\pi}{3}\rho_m R^3 \end{cases}$$

What about massive neutrino cosmologies?

- ~~No prescription~~ — Brandbyge et al. 2010 — ~~$\rho_m \rightarrow \rho_m \quad P_m(k)$~~ $\rightarrow P_m(k)$
- Matter prescription — Brandbyge et al. 2010, Marulli et al. 2011, Villaescusa-Navarro et al. 2013 — $\rho_m \rightarrow \rho_{cdm} \quad P_m(k) \rightarrow P_m(k)$
- Cold dark matter prescription — Ichiki & Takada 2011, Castorina et al. 2013, Costanzi et al. 2013 — $\rho_m \rightarrow \rho_{cdm} \quad P_m(k) \rightarrow P_{cdm}(k)$

Halo mass function

Castorina, Sefussati, Sheth, FVN, Viel 2013

FoF halos : b=0.2

$$\frac{dn(M,z)}{dM} = nf(n)\frac{r_m}{M^2}\frac{d\ln n}{d\ln M}$$

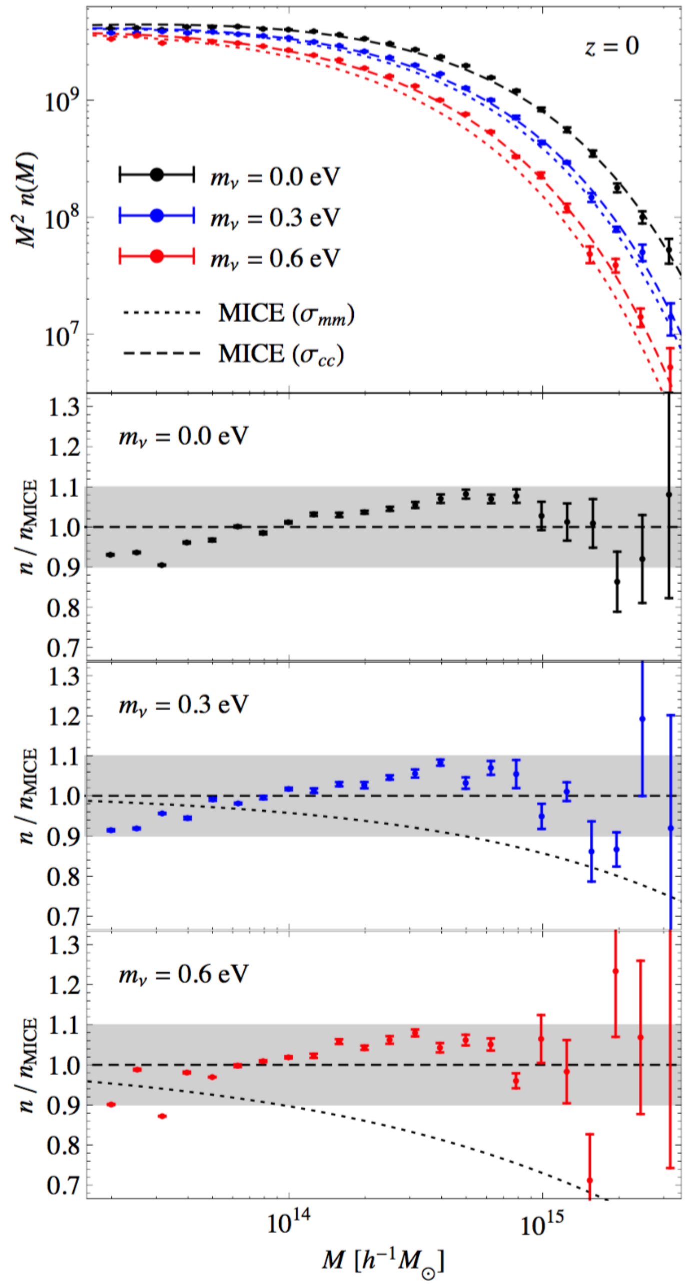
Crocce et al. 2010

Matter prescription

$r_m \to r_{cdm} \quad P_m(k) \to P_m(k)$

Cold dark matter prescription

$r_m \to r_{cdm} \quad P_m(k) \to P_{cdm}(k)$



Halo mass function

Castorina, Sefussati, Sheth, FVN, Viel 2013

FoF halos : b=0.2

$$\frac{dn(M,z)}{dM} = nf(n)\frac{r_m}{M^2}\frac{d\ln n}{d\ln M}$$

Universal?

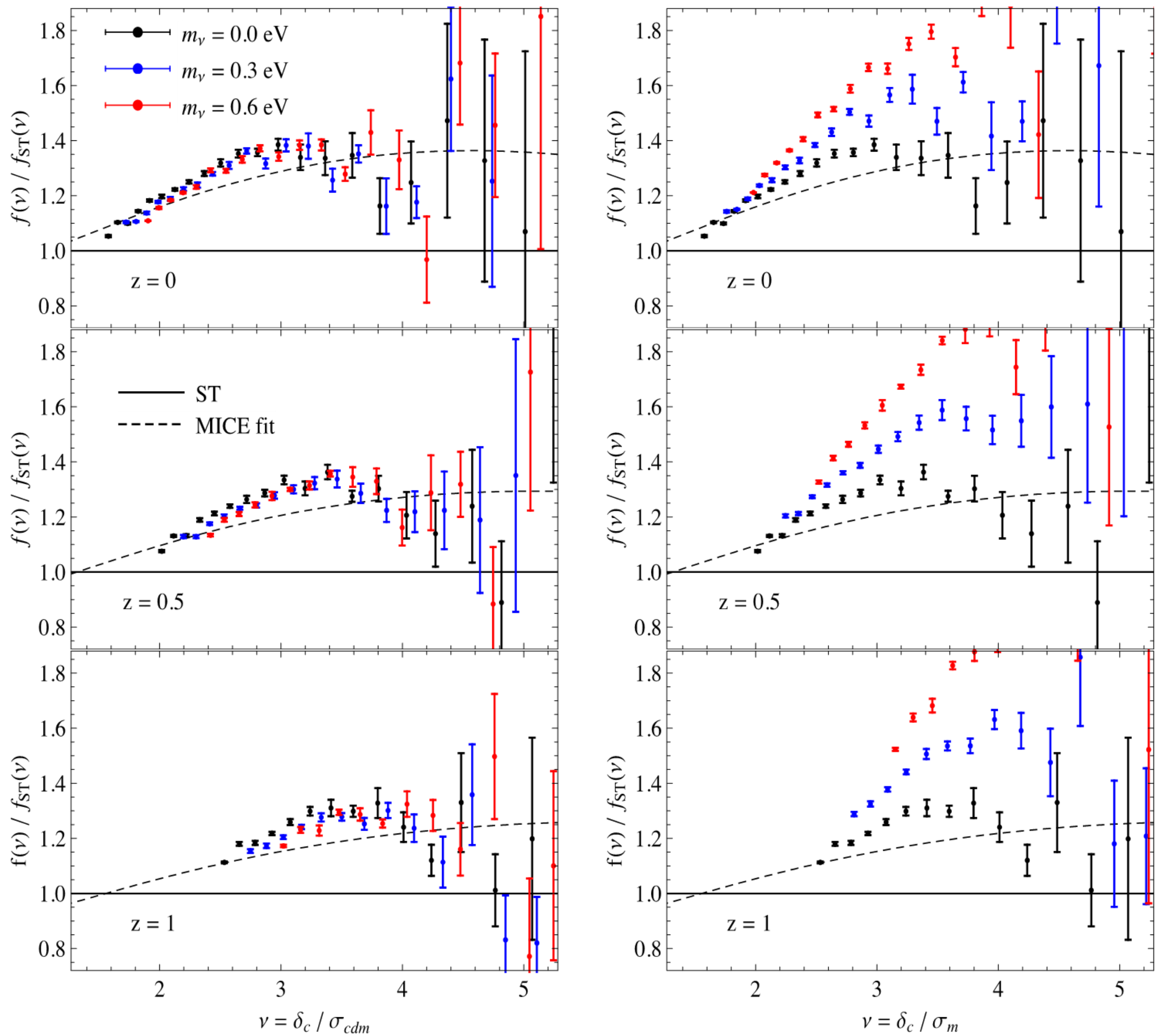
$$f(n) = \frac{M^2}{r}\frac{1}{n}\frac{d\ln M}{d\ln n}\frac{dn(M,z)}{dM}$$

~~Matter prescription~~

$r_m \to r_{cdm}$ $\quad P_m(k) \to P_m(k)$

Cold dark matter prescription ✓

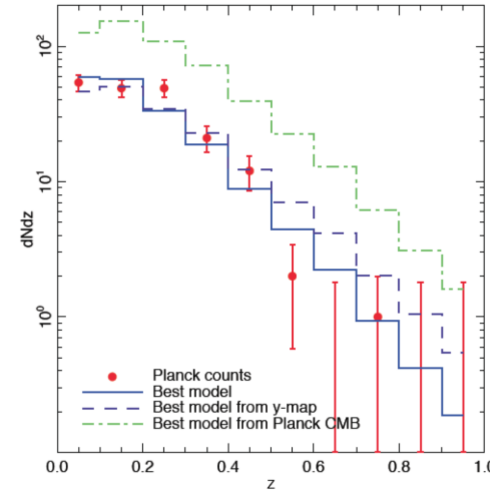
$r_m \to r_{cdm}$ $\quad P_m(k) \to P_{cdm}(k)$

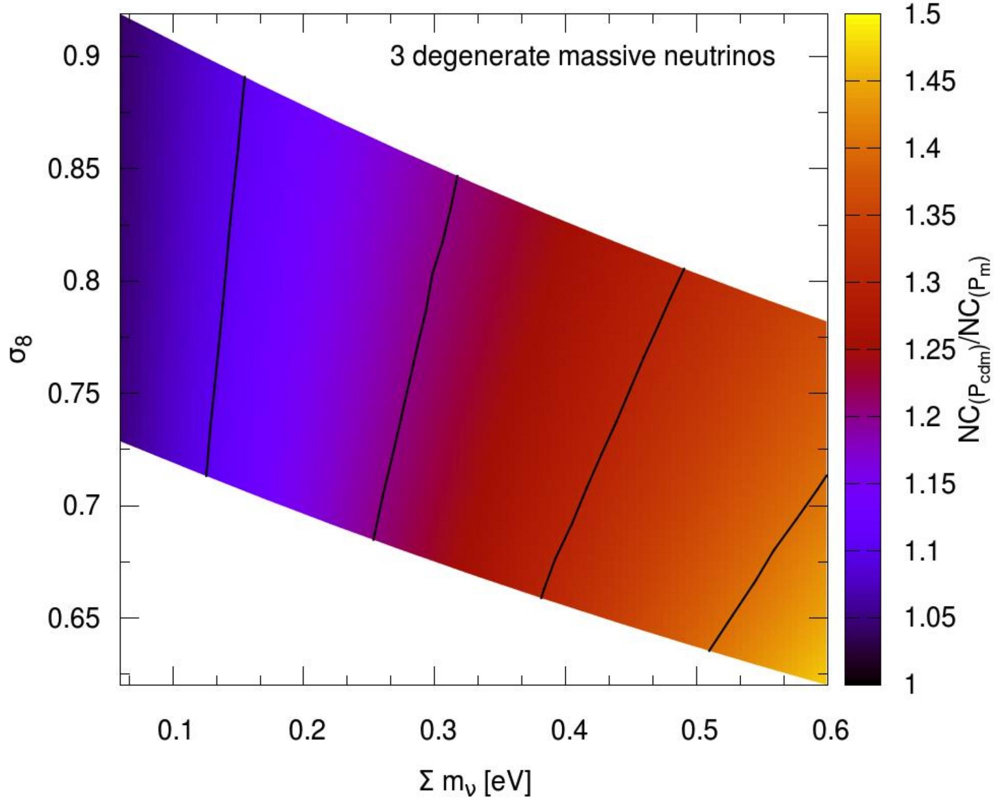


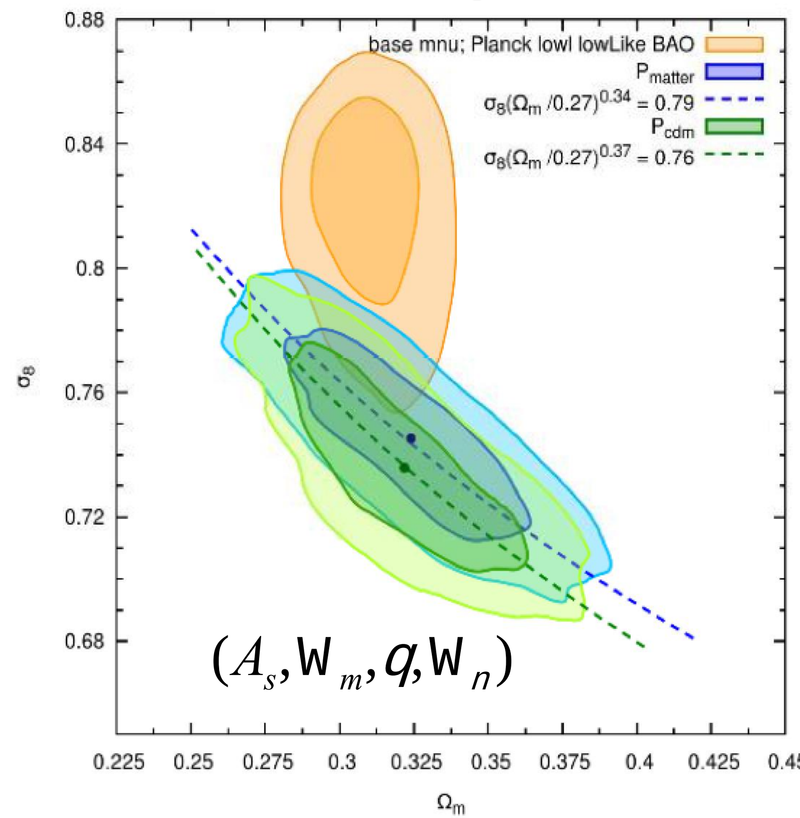
Halo mass function: consequences

Costanzi, FVN, Viel, Xia, Borgani, Castorina, Sefusatti 2013

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





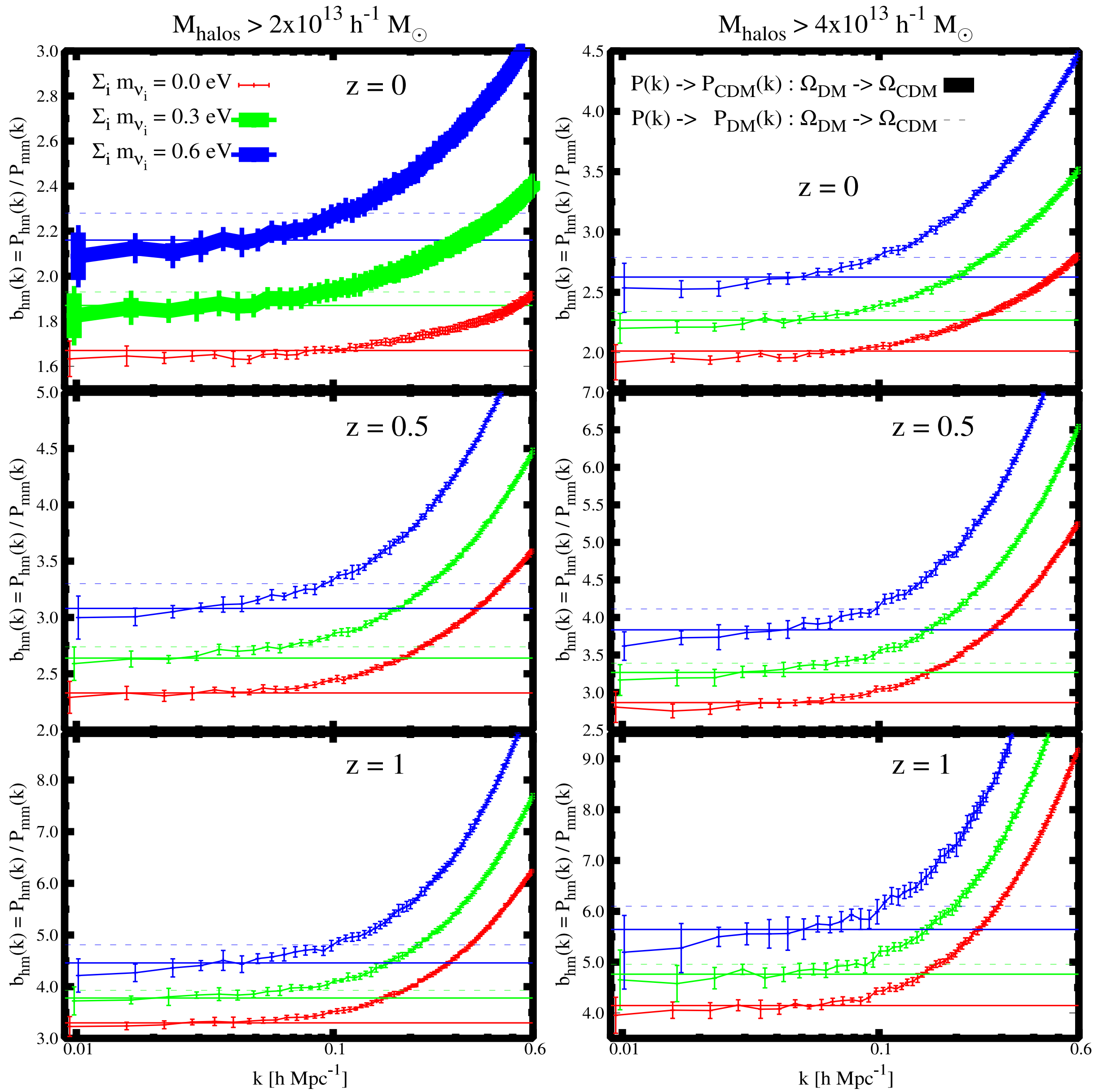


Clustering of dark matter halos

FVN, Marulli, Viel, Branchini, Castorina, Sefusatti, Saito 2013
Castorina, Sefusatti, Sheth, FVN, Viel 2013

$$b_{hm}(k) = \frac{P_{hm}(k)}{P_{mm}(k)}$$

0.0 eV ⟶ 8 realizations
0.3 eV ⟶ 8 realizations
0.6 eV ⟶ 8 realizations

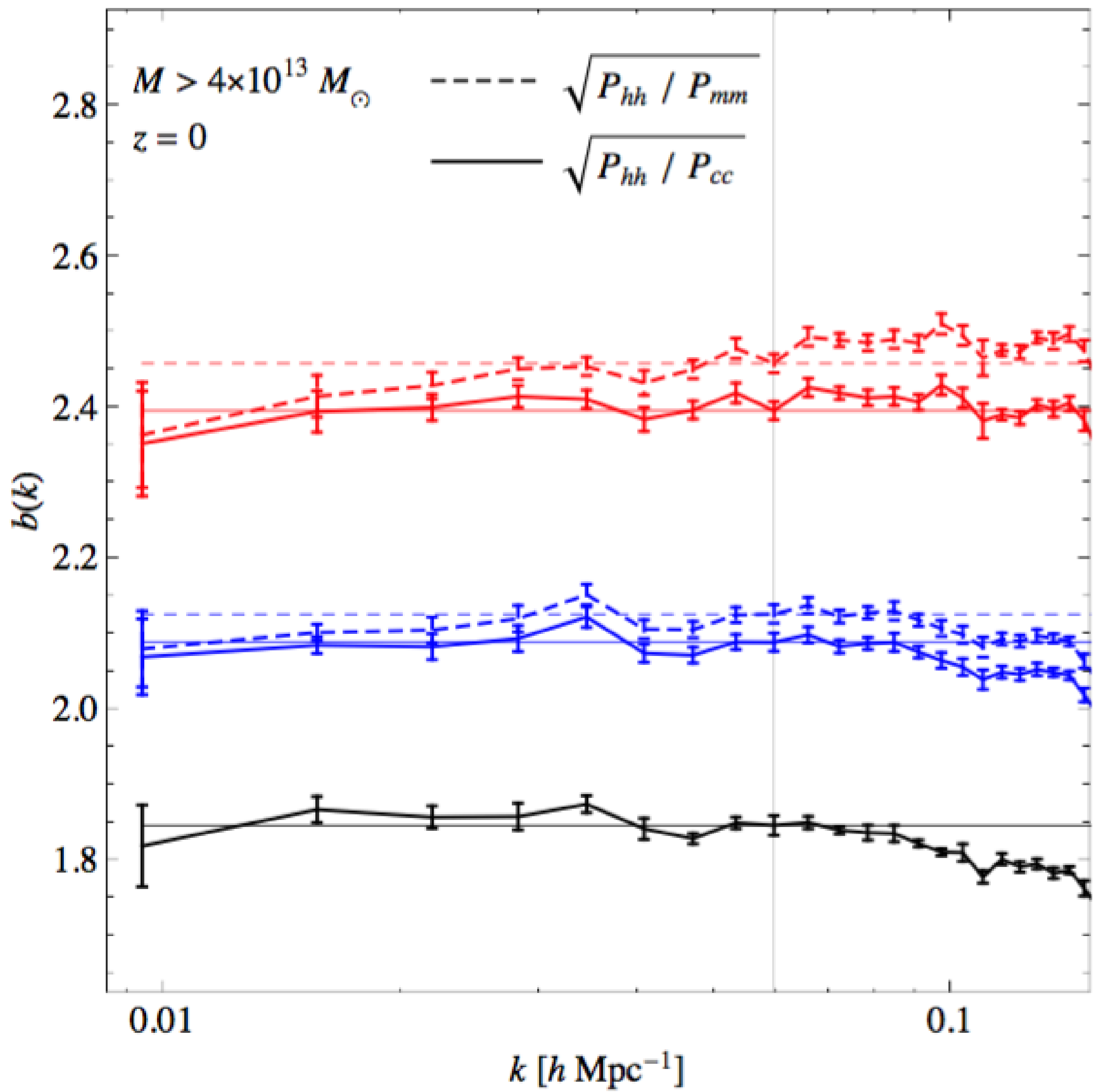


Clustering of dark matter halos

Castorina, Sefusatti, Sheth, FVN, Viel 2013
FVN, Marulli, Viel, Branchini, Castorina, Sefusatti, Saito 2013

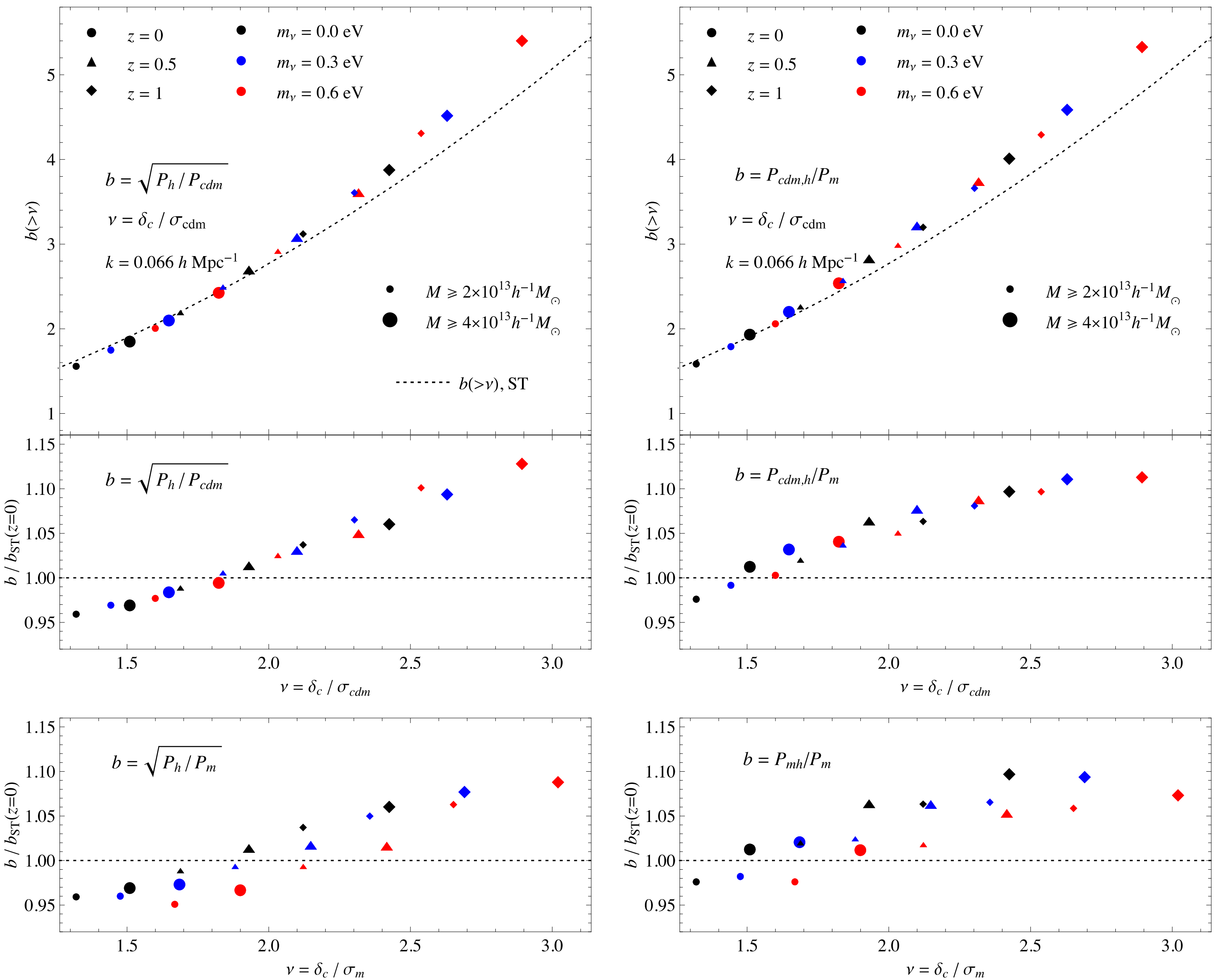
$$b_{hm}(k) = \frac{P_{hm}(k)}{P_{mm}(k)}$$

$$b_{hc}(k) = \frac{P_{hc}(k)}{P_{cc}(k)}$$



Clustering of dark matter halos

Castorina, Sefusatti, Sheth, FVN, Viel 2013



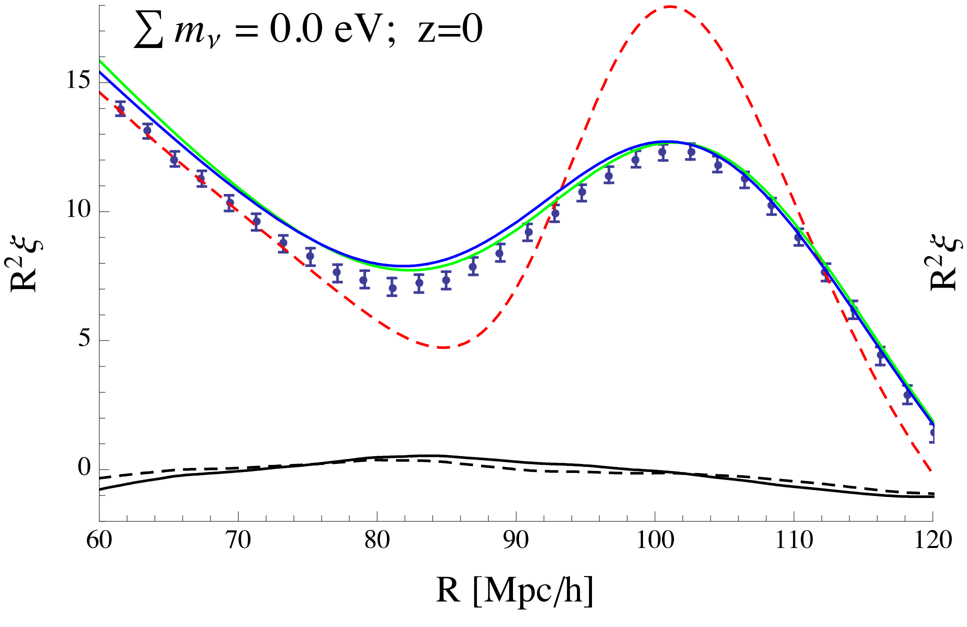
Neutrino effects on BAO

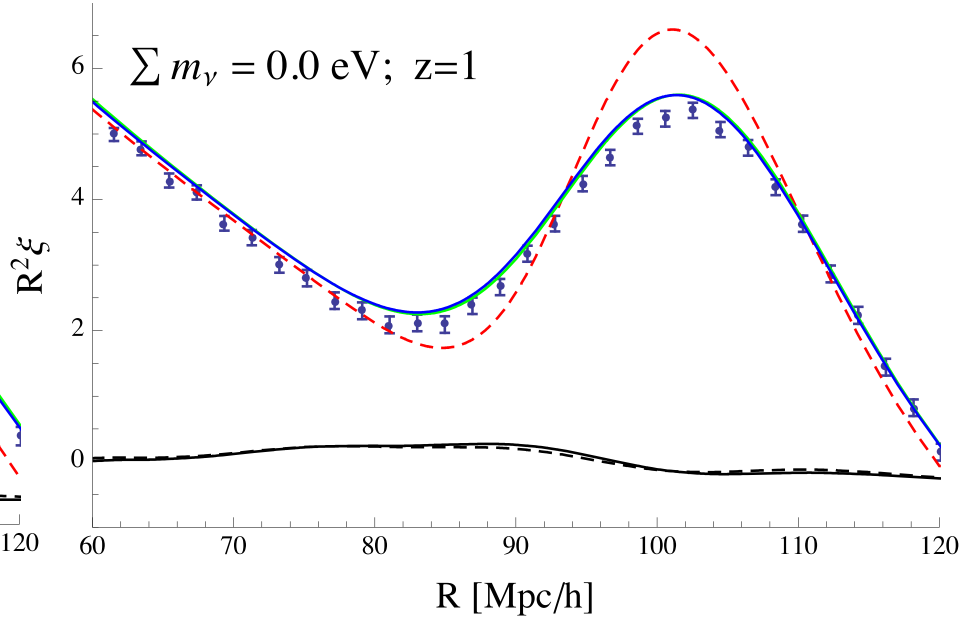
Peloso, Pietroni, Viel, FVN, 2015

100 N-body simulations
z_i=99; 1000 Mpc/h
256^3 CDM + 256^3 Neutrinos
0.0 eV, 0.15 eV, 0.3 eV, 0.6 eV

$$P^{(1)}(k,z) = e^{-k^2\sigma_v^2(z)} P^{lin}(k,z)\,,$$

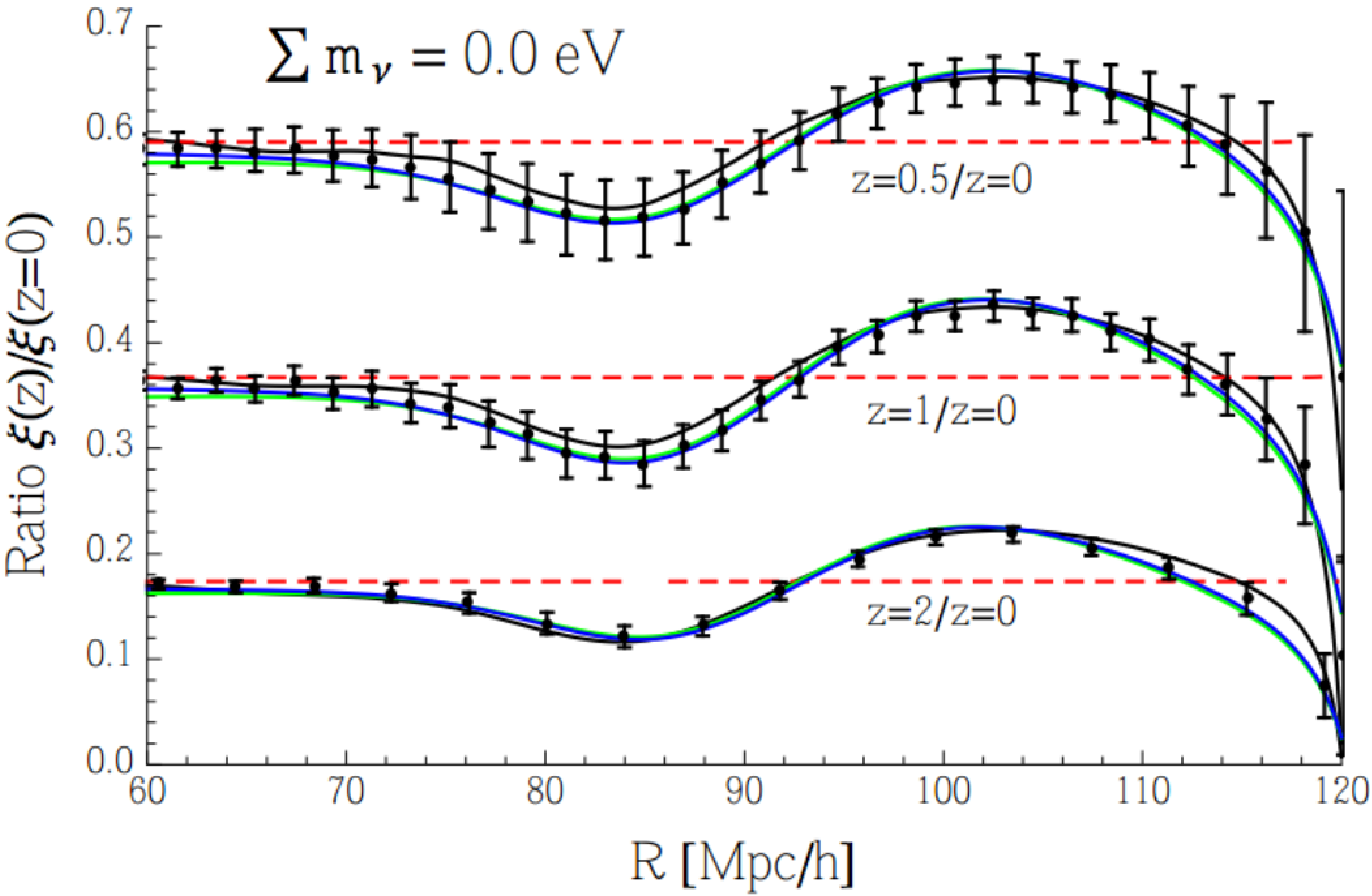
$$\sigma_v^2(z) = \frac{1}{3}\int \frac{d^3q}{(2\pi)^3}\,\frac{P^{lin}(q,z)}{q^2}\,.$$





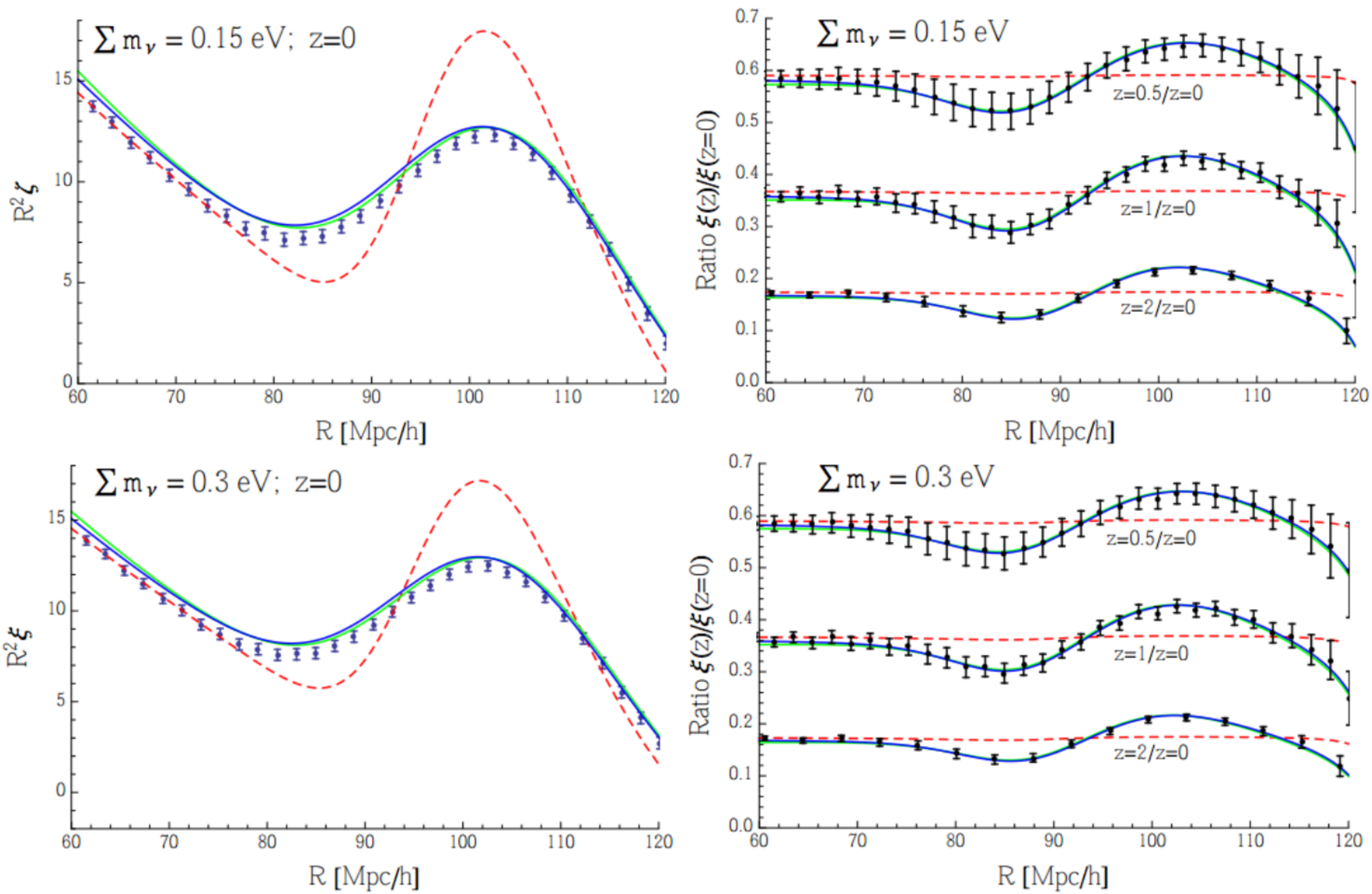
Neutrino effects on BAO

Peloso, Pietroni, Viel, FVN, 2015



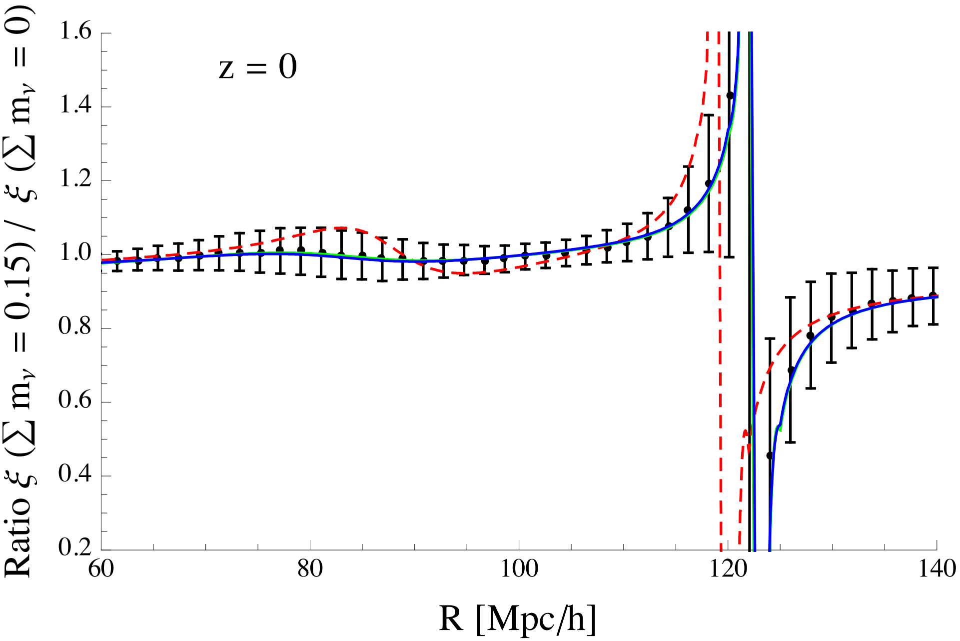
Neutrino effects on BAO

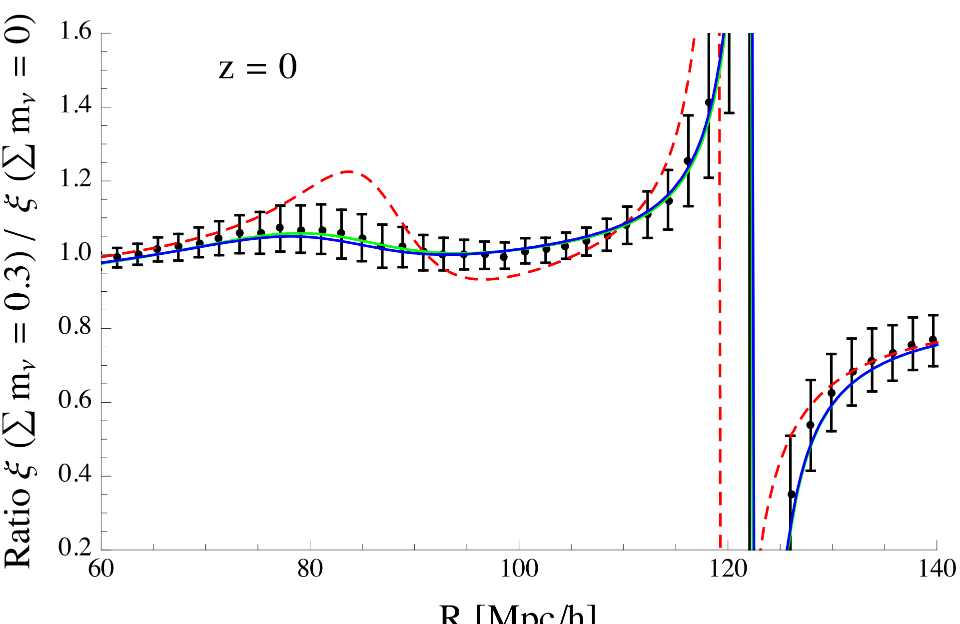
Peloso, Pietroni, Viel, FVN 2015

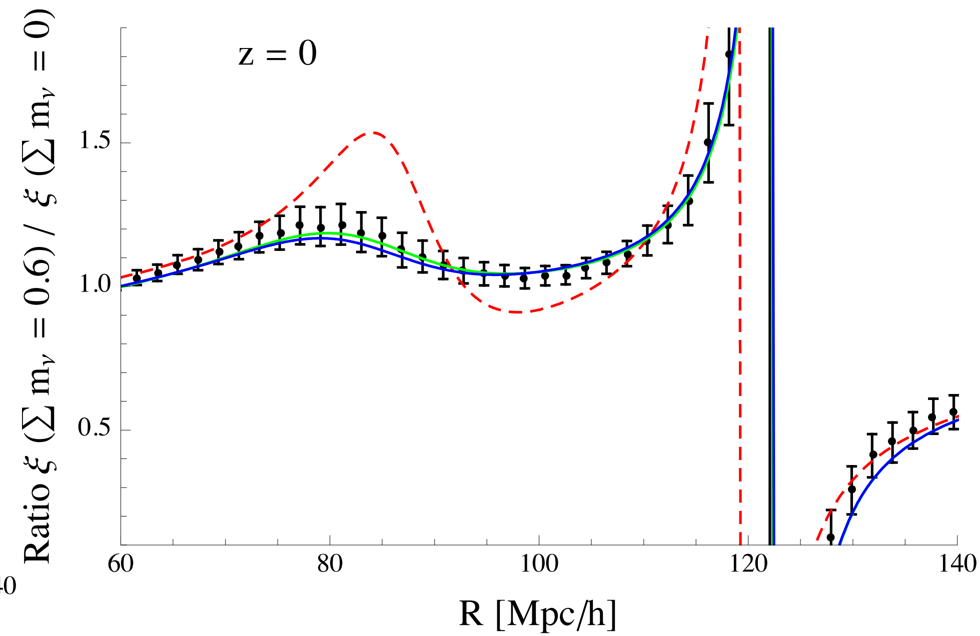


Neutrino effects on BAO

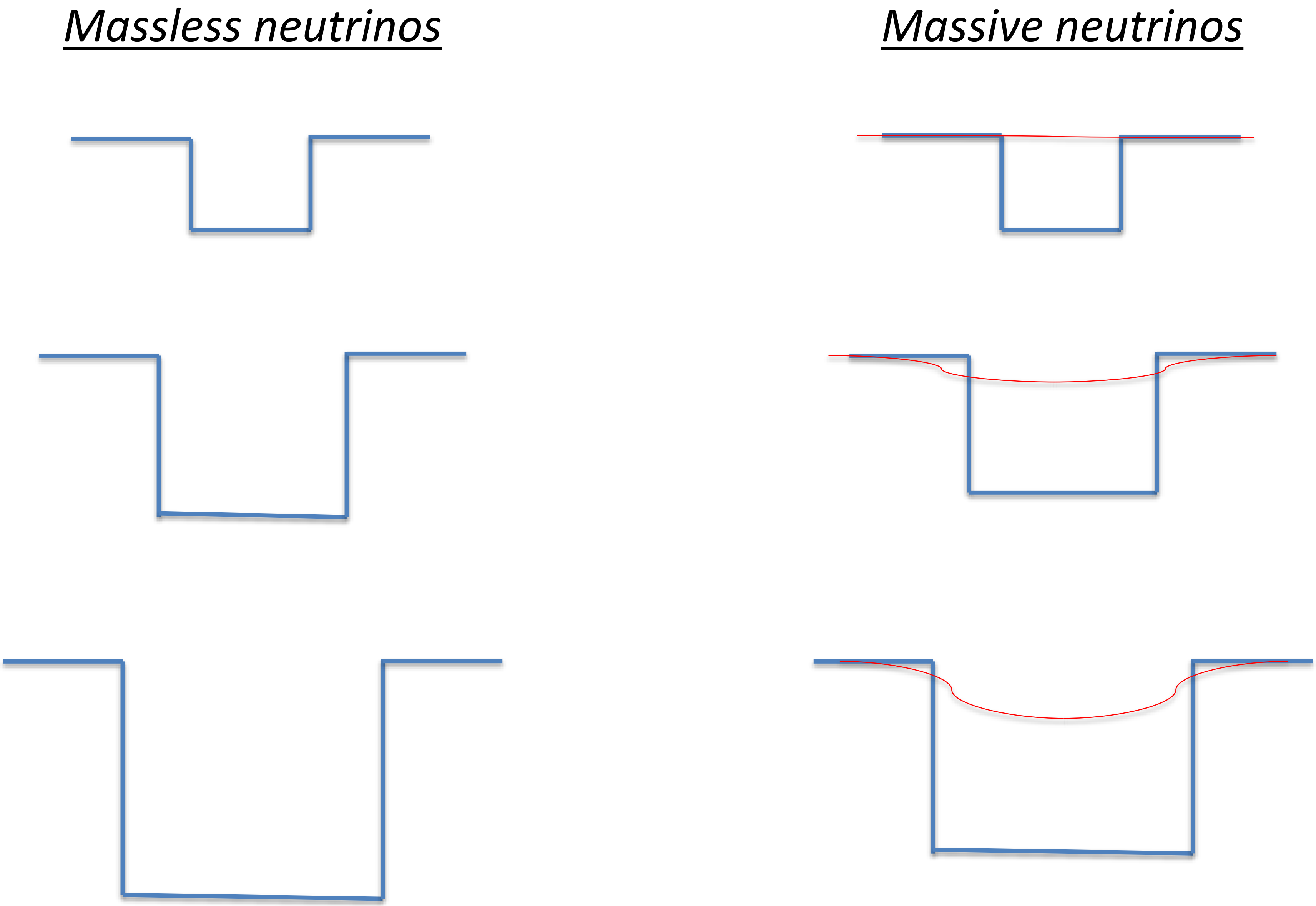
Peloso, Pietroni, Viel, FVN 2015







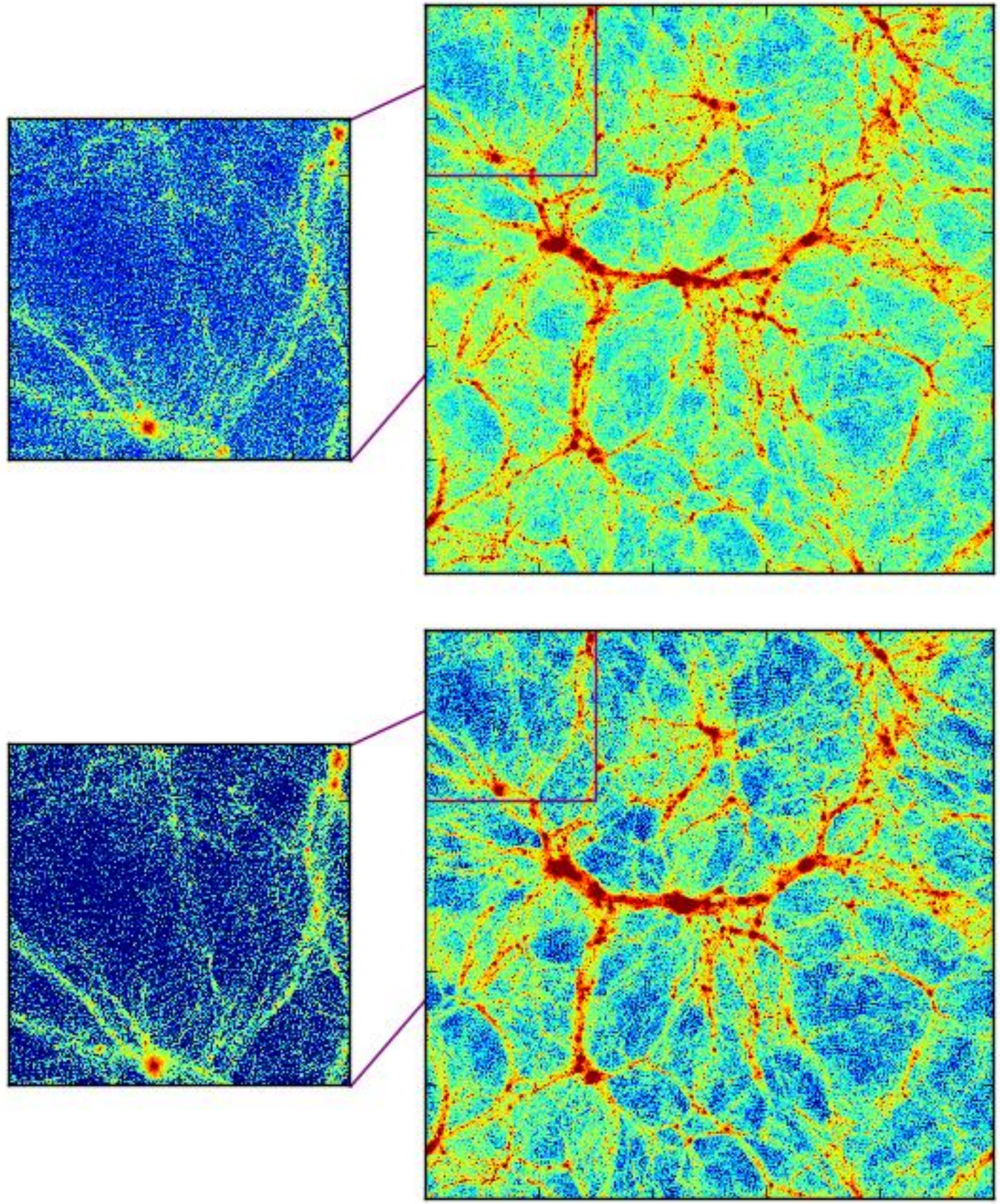
Neutrino effects on voids



0.6 eV

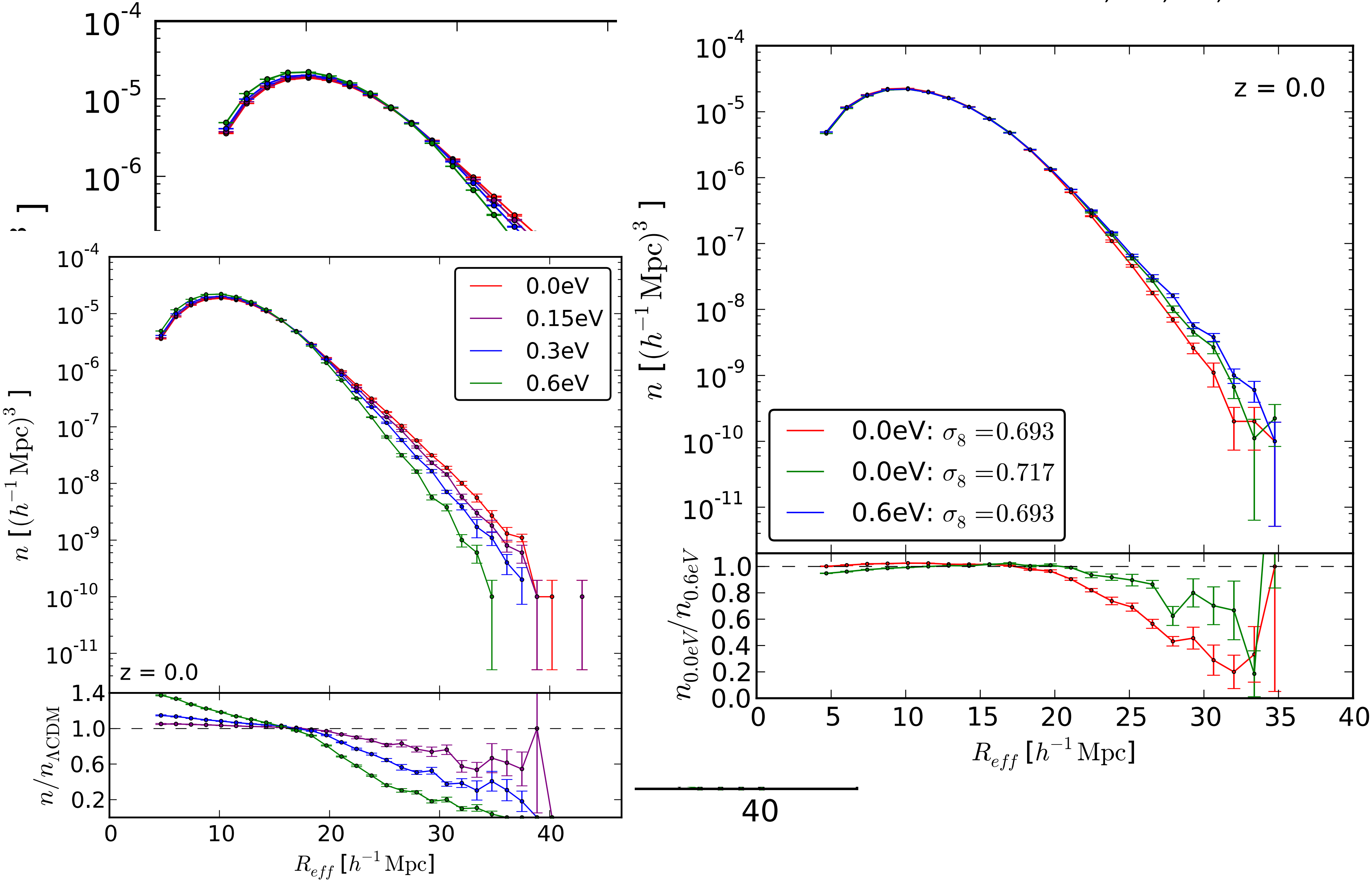
The impact of massive neutrinos on cosmic voids

0.0 eV



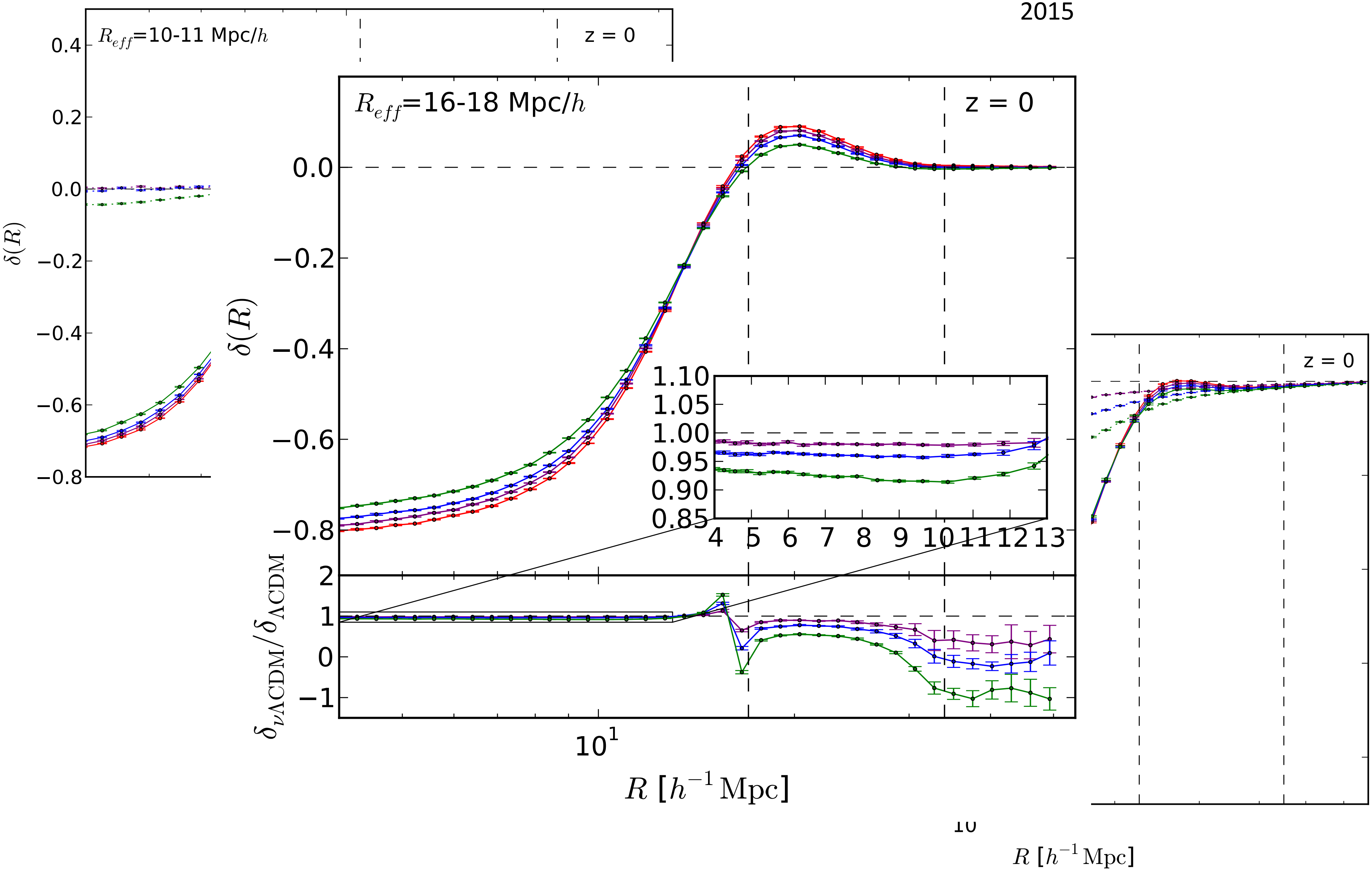
Neutrino effects on voids

Massara, FVN, Viel, Sutter 2015



Neutrino effects on voids

Massara, FVN, Viel, Sutter
2015

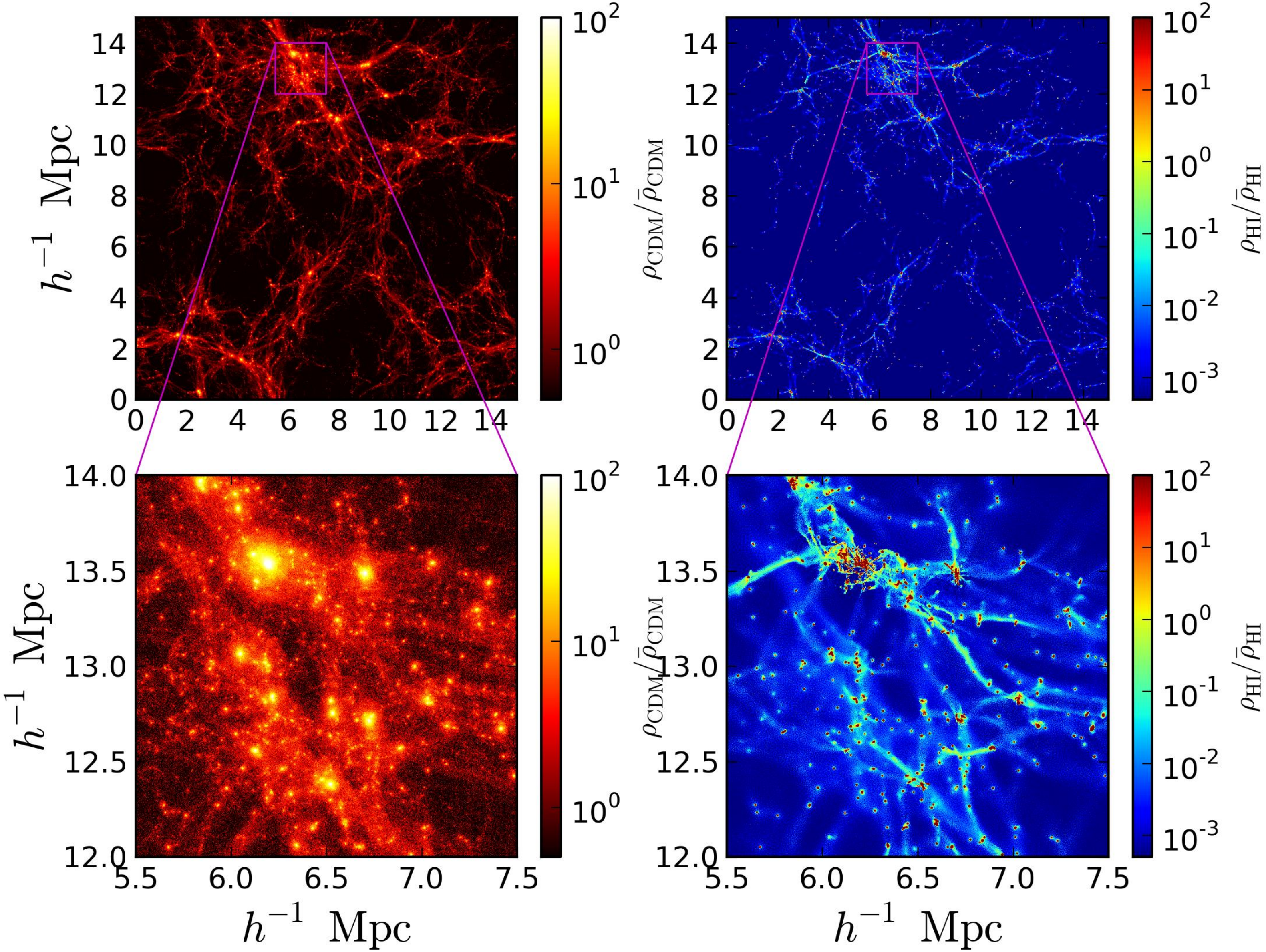


Future constraints from cosmology

Particle physics	Cosmology
$m(\bar{\nu}_e) \le 2.3\ \text{eV}\ (95\%\ \text{C.L.})$ Kraus et al. 2005	$\sum_i m_{\nu_i} < 0.12\ \text{eV}\ (95\%\ \text{C.L.})$ Palanque-Delabrouille et al. 2015
Tritium beta decay	CMB + BAO + Lya forest
$m(\bar{\nu}_e) \le 0.2\ \text{eV}\ (90\%\ \text{C.L.})$ KATRIN	?
Tritium beta decay	21cm CMB+21cm

Weighing neutrinos with cosmic neutral hydrogen

Post-reionization era



Weighing neutrinos with cosmic neutral hydrogen

1. Forecast the sensitivity of SKA to the sum of the neutrino masses.

↕

1. Study the properties of HI in cosmologies with massive neutrinos using hydrodynamic simulations.

Neutrino effects on 21cm

Hydrodynamical simulations

HI self-shielding

Presence of H_2

- Radiative cooling by H and He
- Heating by uniform UV background
- Star formation
- Feedback (galactic winds)
- CDM + baryons + neutrinos

Name	Box (h^{-1}Mpc)	Ω_{cdm}	Ω_b	Ω_ν	Ω_Λ	Ω_k	h	n_s	$10^9 A_s$	σ_8 ($z=0$)
$\mathcal{F}$	50	0.2685	0.049	0.0	0.6825	0	0.67	0.9624	2.13	0.834
ν^+	50	0.2685	0.049	0.007075	0.675425	0	0.67	0.9624	2.13	0.778
ν_m^+	50	0.261425	0.049	0.007075	0.6825	0	0.67	0.9624	2.13	0.764
ν_m^{++}	50	0.25435	0.049	0.01415	0.6825	0	0.67	0.9624	2.13	0.693
$\mathcal{C}^+$	50	0.287	0.049	0.0	0.664	0	0.67	0.9624	2.13	0.868
$\mathcal{C}^-$	50	0.25	0.049	0.0	0.701	0	0.67	0.9624	2.13	0.797
$\mathcal{B}^+$	50	0.2685	0.055	0.0	0.6765	0	0.67	0.9624	2.13	0.816
$\mathcal{B}^-$	50	0.2685	0.043	0.0	0.6885	0	0.67	0.9624	2.13	0.853
$\mathcal{H}^+$	50	0.2685	0.049	0.0	0.6825	0	0.71	0.9624	2.13	0.886
$\mathcal{H}^-$	50	0.2685	0.049	0.0	0.6825	0	0.63	0.9624	2.13	0.777
$\mathcal{N}^+$	50	0.2685	0.049	0.0	0.6825	0	0.67	1.0009	2.13	0.846
$\mathcal{N}^-$	50	0.2685	0.049	0.0	0.6825	0	0.67	0.9239	2.13	0.822
$\mathcal{A}^+$	50	0.2685	0.049	0.0	0.6825	0	0.67	0.9624	2.45	0.894
$\mathcal{A}^-$	50	0.2685	0.049	0.0	0.6825	0	0.67	0.9624	1.81	0.769

Ingredients for 21cm IM

$$M_{HI}(M,z)$$

$$b_{HI}(z) = \frac{\int_0^\infty n(M,z)\,b(M,z)\,M_{HI}(M,z)\,dM}{\int_0^\infty n(M,z)\,M_{HI}(M,z)\,dM}$$

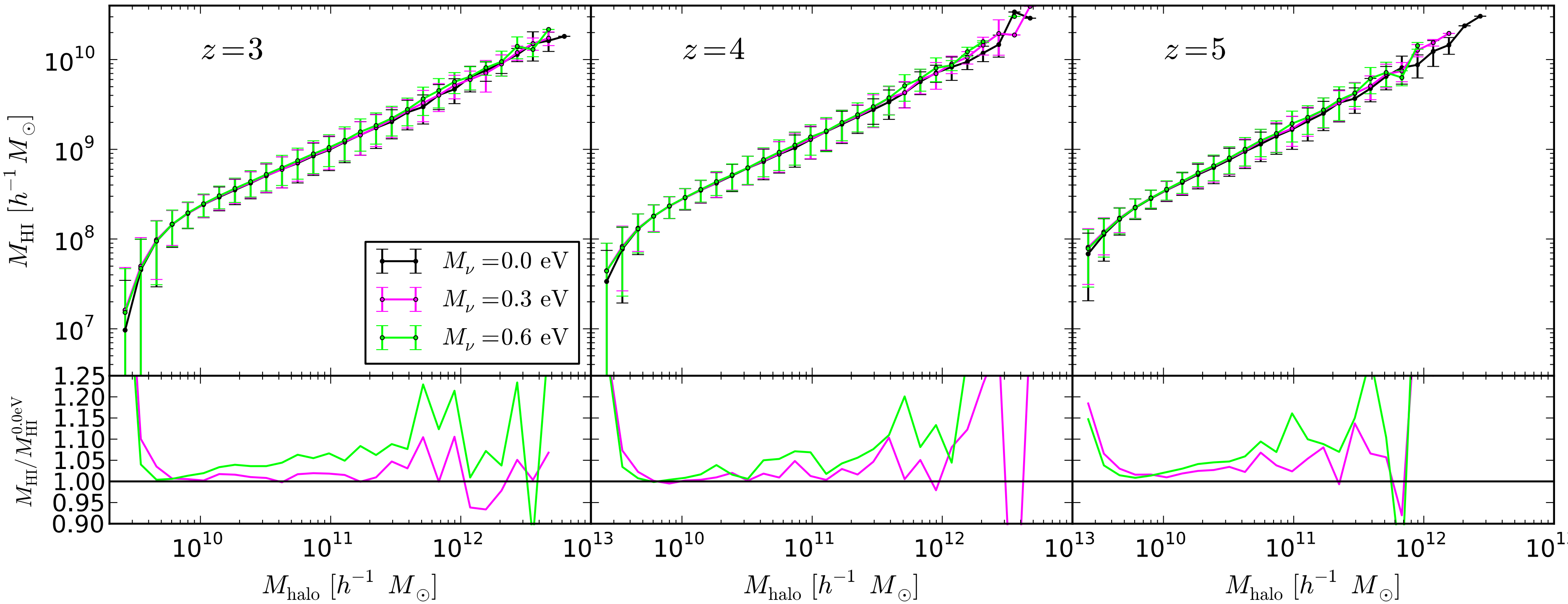
$$\Omega_{HI}(z) = \frac{1}{\rho_c^0}\int_0^\infty n(M,z)\,M_{HI}(M,z)\,dM$$

$$\overline{\delta T_b}(z) = 189\left(\frac{H_0(1+z)^2}{H(z)}\right)\Omega_{HI}(z)\,h\ \ mK$$

$$P_{21cm}(k,z) = \overline{\delta T_b^2}(z)\,b_{HI}^2(z)\left(1+\frac{2}{3}b(z)+\frac{1}{5}b^2(z)\right)P_m(k,z)$$

Neutrino effects on 21cm

FVN, Bull, Viel 2015



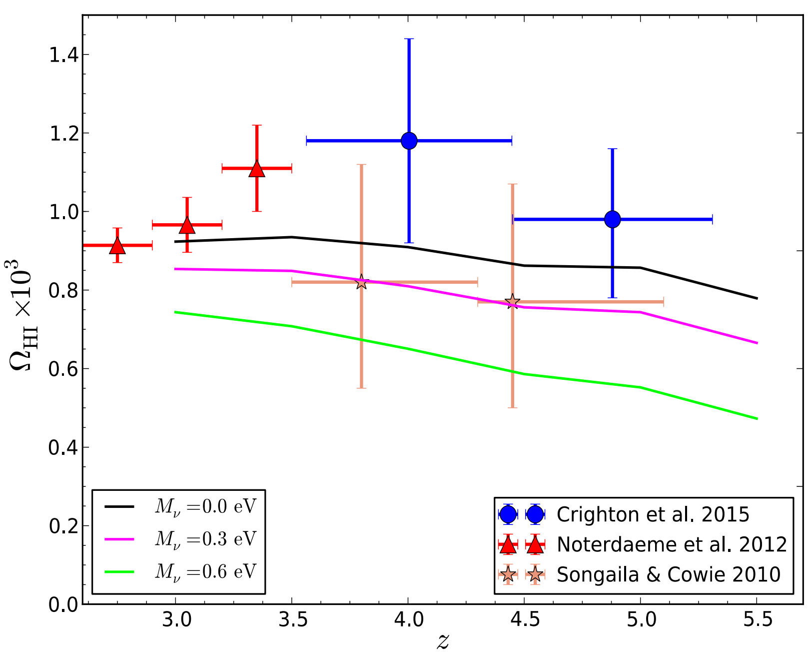
Halos with low masses do not host HI.

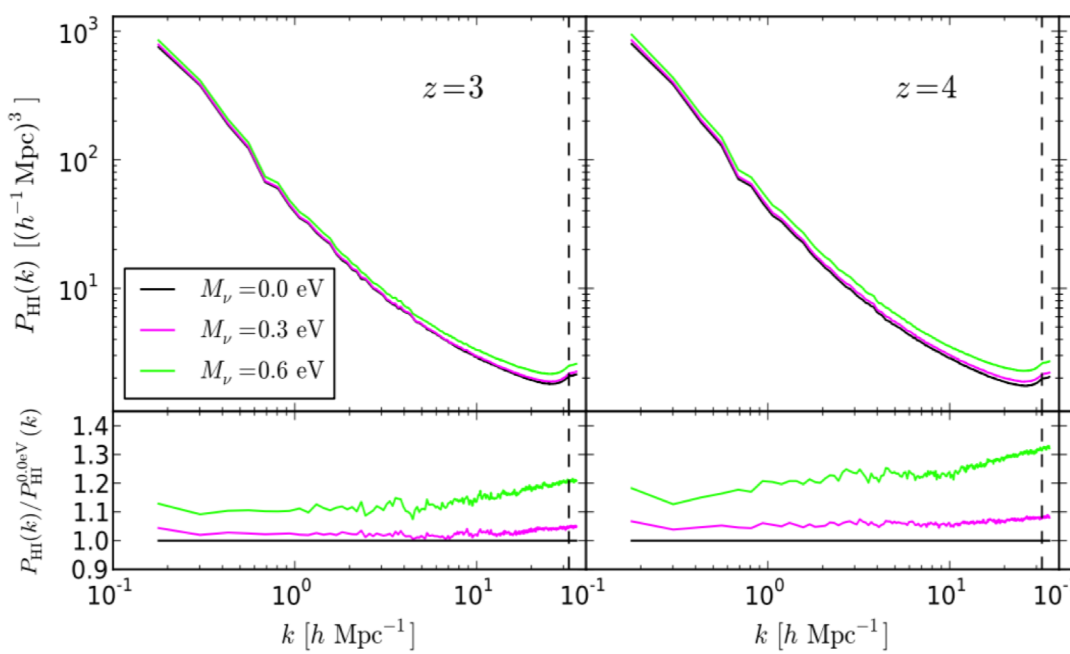
$M_{HI}(M,z)$ will exhibit a cut-off at low masses

Neutrino effects on 21cm

FVN, Bull, Viel 2015

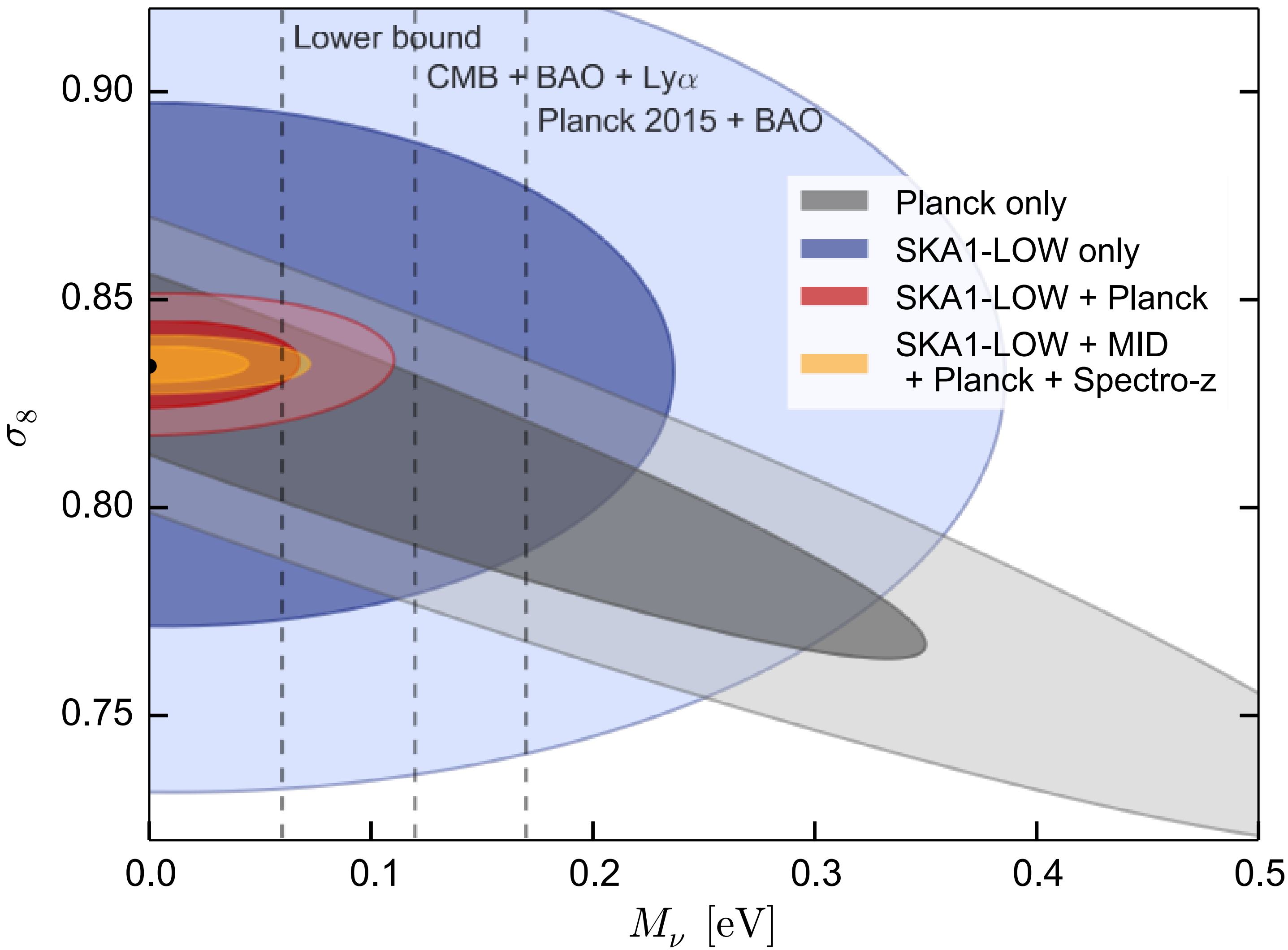
Cosmology	$M_{HI}(M,z)$		Ω_{HI}	f_{HI} (DLAs)	$P_{HI}(k)$	$P_{21cm}(k)$
$M_n = 0$	REF		REF	REF	REF	REF
$M_n{}^{1}\ 0$	=		↓	↓	↑	↓





Forecasts for SKA

FVN, Bull, Viel 2015



Only 21cm monopole

SKA1-MID
- 0<z<3
- Single dish
- 10000 hours
- 25000 deg^2
- 200 dishes; 15m

SKA1-LOW
- 3<z<6
- interferometry
- 10000 hours
- 20 deg^2

LOW+MID+CMB

$\sigma(M_\nu)=0.034$ eV

LOW+MID+CMB+spectro-z

$\sigma(M_\nu)=0.029$ eV

CMB+BAO+Lya

$M_\nu<0.120$ eV

Conclusions

- Neutrinos have mass!!!
  Major consequences for particle physics and cosmology

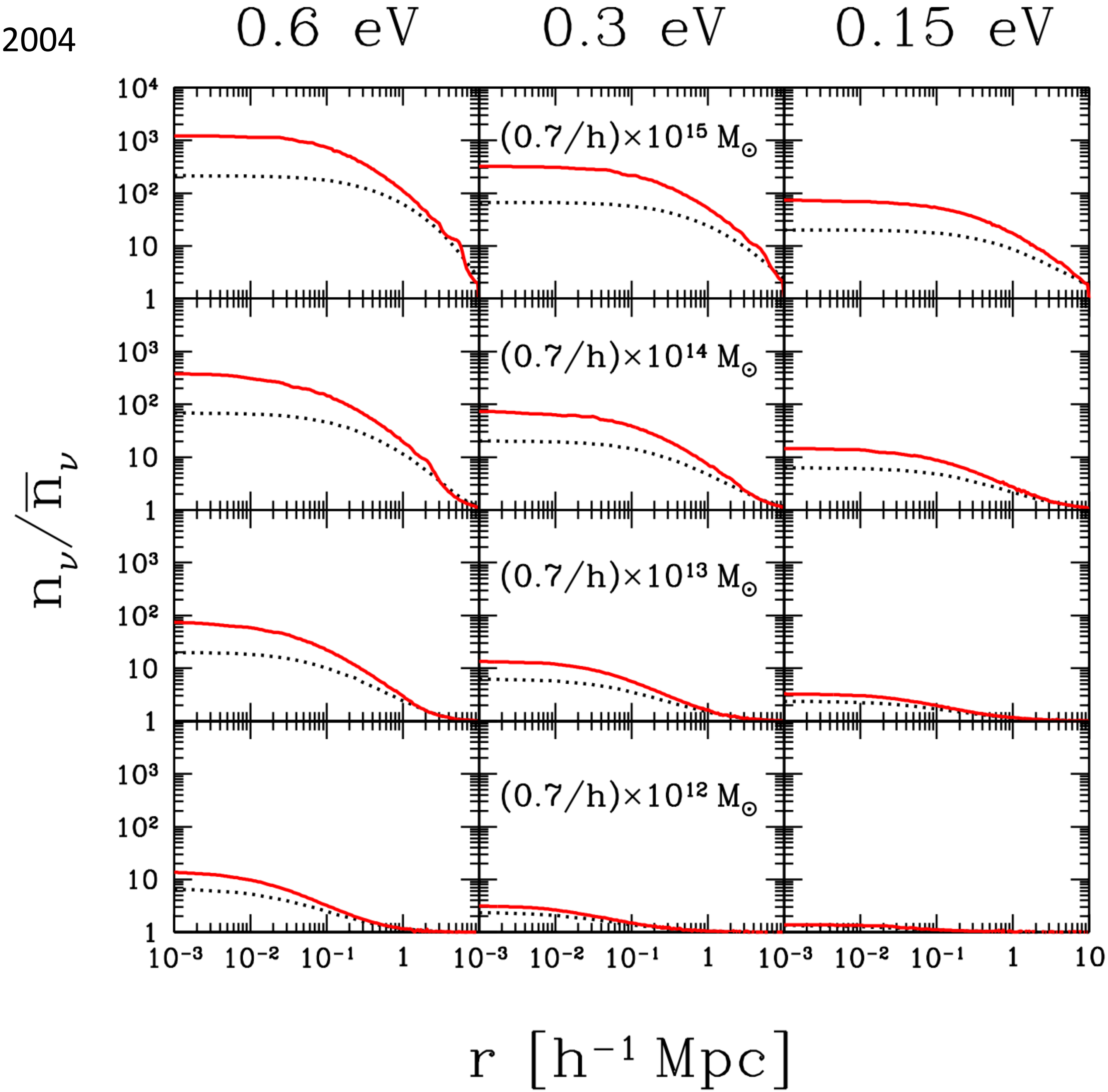
- Big Bang theory predicts the existence of the CνB

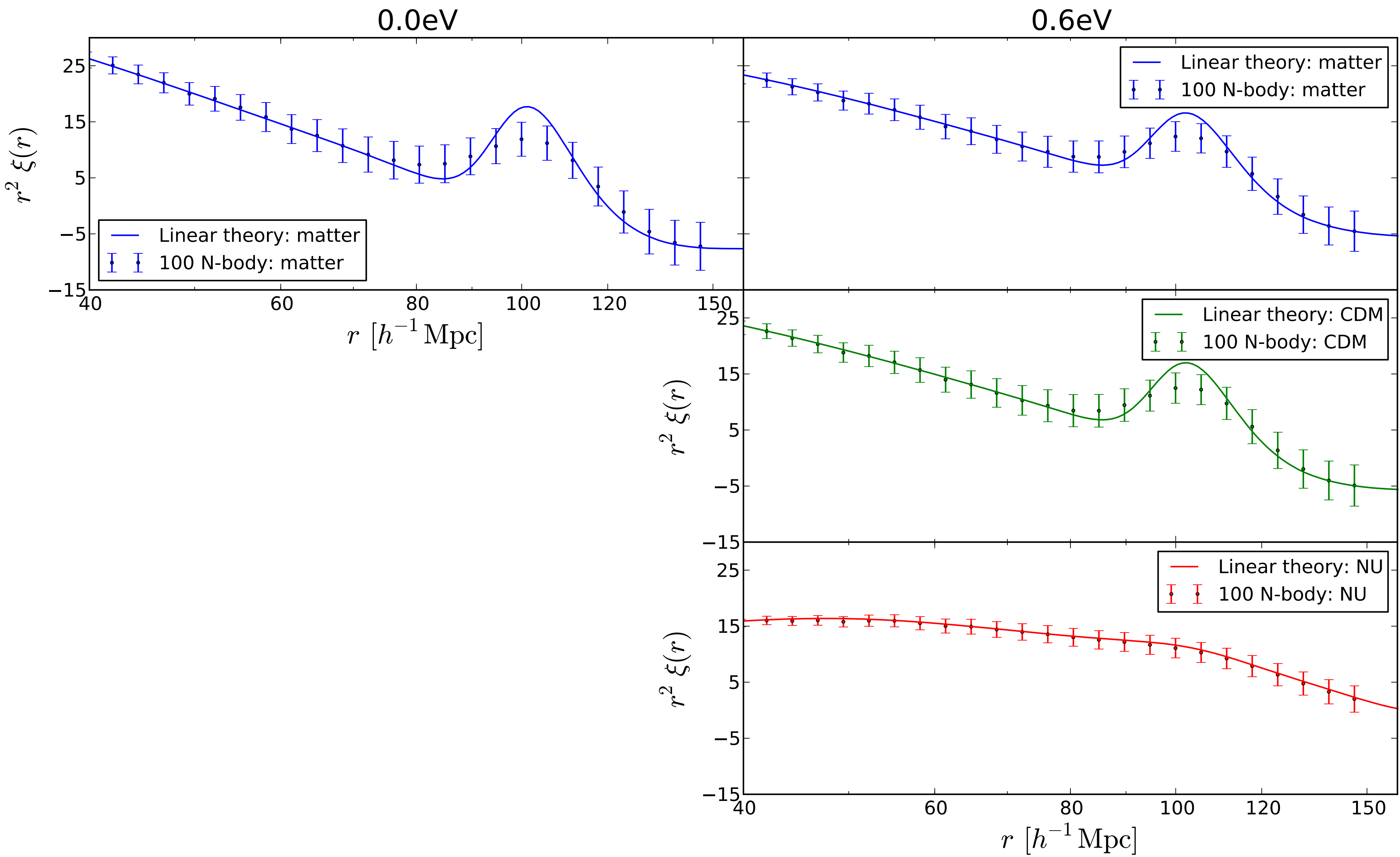
- Massive neutrino effects well understood at linear order

- Many effects at fully non-linear level
  - Neutrino clustering
  - Halo properties
  - Halo mass function
  - Bias
  - BAO
  - Voids
  - HI abundance and clustering

- SKA IM survey+CMB will set $\sigma(M_\nu)$=0.034 eV (M_ν<0.120 eV eV)

Ringwald & Wong 2004
Singh & Ma 2002





0.0eV
0.6eV
Linear theory: matter
100 N-body: matter
Linear theory: matter
100 N-body: matter
Linear theory: CDM
100 N-body: CDM
Linear theory: NU
100 N-body: NU
$r^2\,\xi(r)$
$r\ [h^{-1}\,\mathrm{Mpc}]$

Massive neutrinos
2 fluid approximation

We numerically solve the coupled equations:

$$\begin{cases} \ddot{\delta}_c + 2H\dot{\delta}_c - \frac{3}{2}H^2\Omega_m\left\{[1-f_\nu]\delta_c + f_\nu\delta_\nu\right\} = 0 \\ \ddot{\delta}_\nu + 2H\dot{\delta}_\nu - \frac{3}{2}H^2\Omega_m\left\{[1-f_\nu]\delta_c + [f_\nu - (k/k_{fs})^2]\delta_\nu\right\} = 0 \end{cases}$$

where we defined: $k_{fs} = \sqrt{\frac{4\pi G\rho_{tot}}{c_s^2(1+z)^2}}$

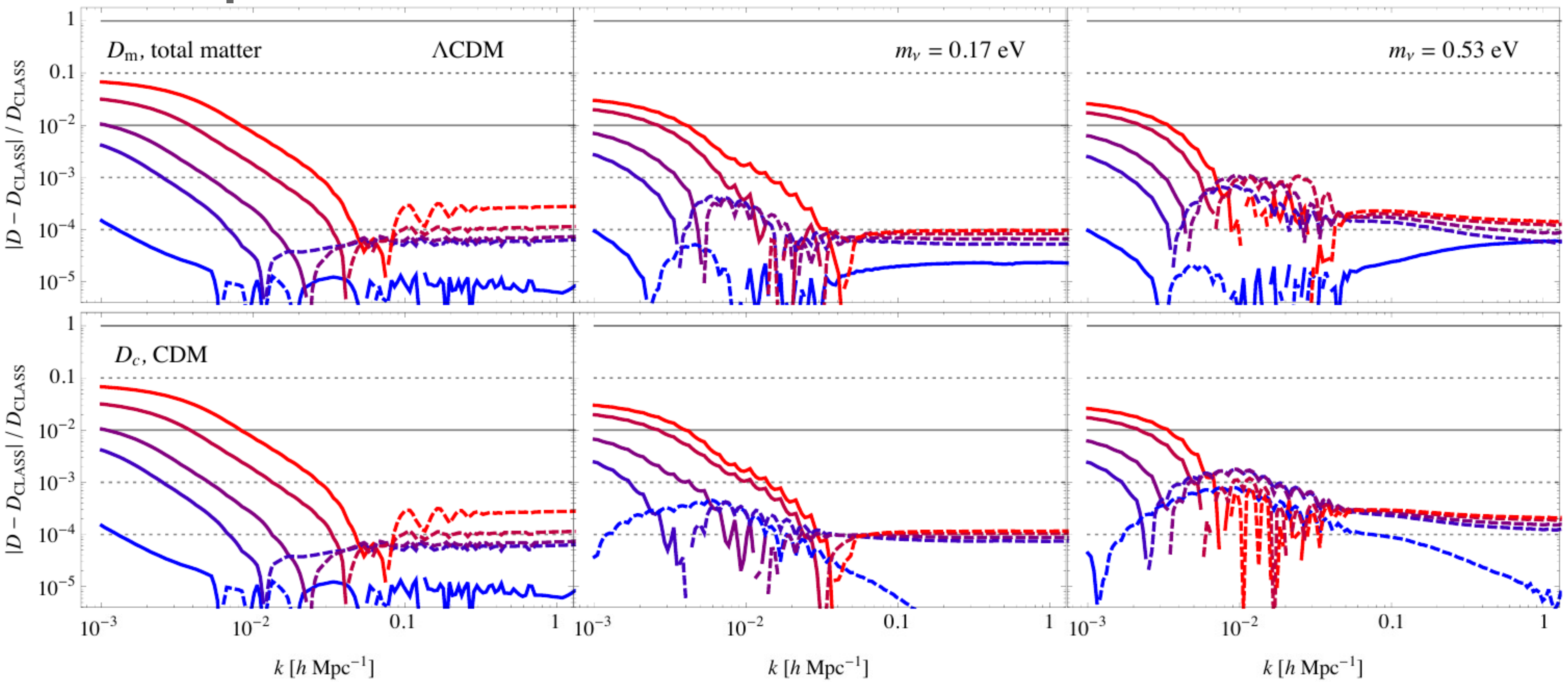
collapse induced by gravity

effective pressure support

scale of dissipation of neutrino density perturbations (free streaming scale)

To set the ICs of a simulation, we use these equations to rescale a z=0 power spectrum to initial redshift z_{in}, using the same physics of the simulation itself

2 fluid approximation
Comparison with Boltzmann codes

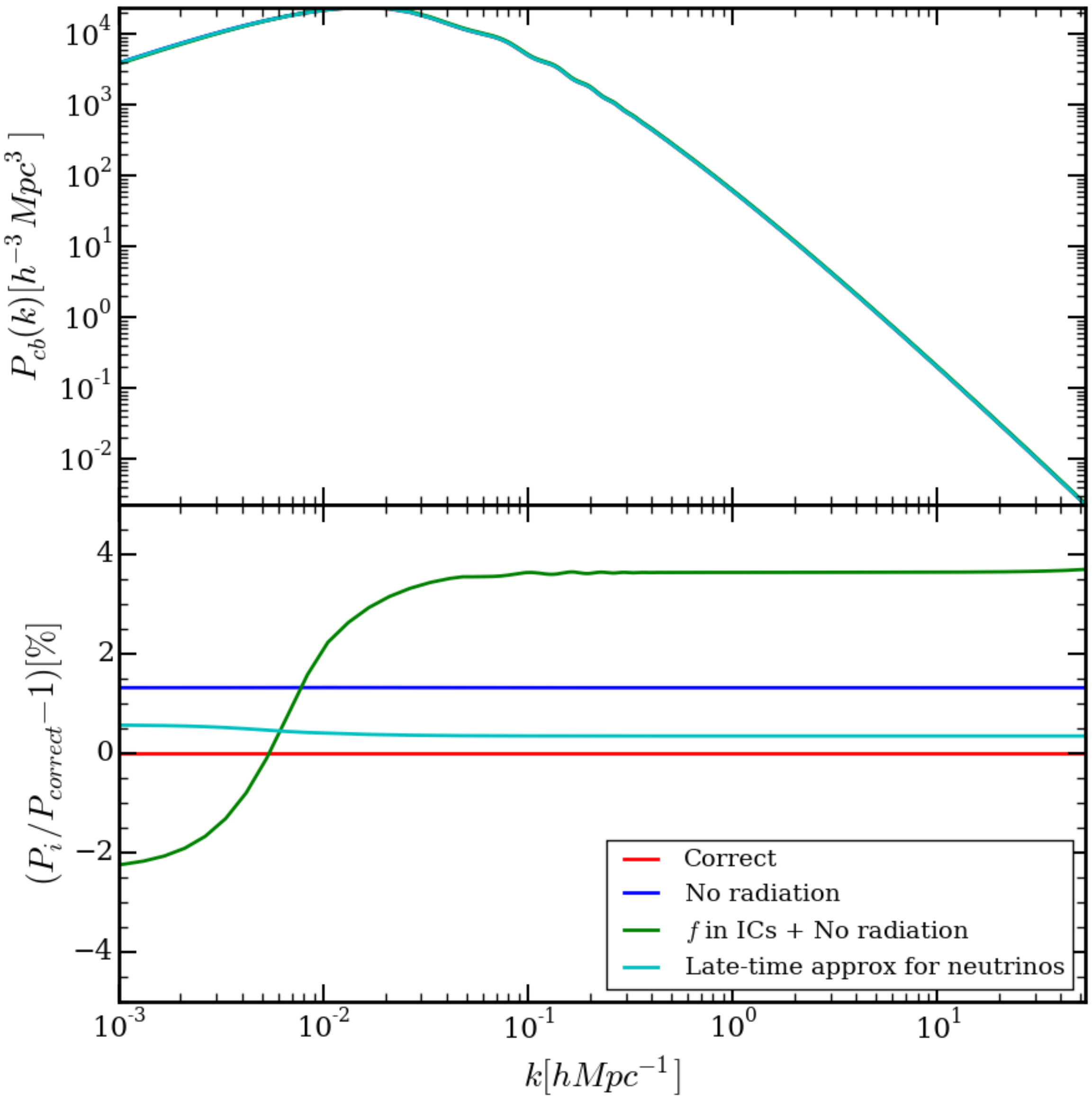


Our solutions agree with those coming from Boltzamann codes...
...but we can do what simulations do, we can switch on/off:

→ radiation in evolution,
→ horizon crossing in ICs,
→ relativistic behavior of neutrinos

Massive neutrinos

Problems in many simulations



Take-home message:
We use this method to:

1) Set ICs correctly (by rescaling a z=0 PS using the same physics that drives evolution in the simulation)

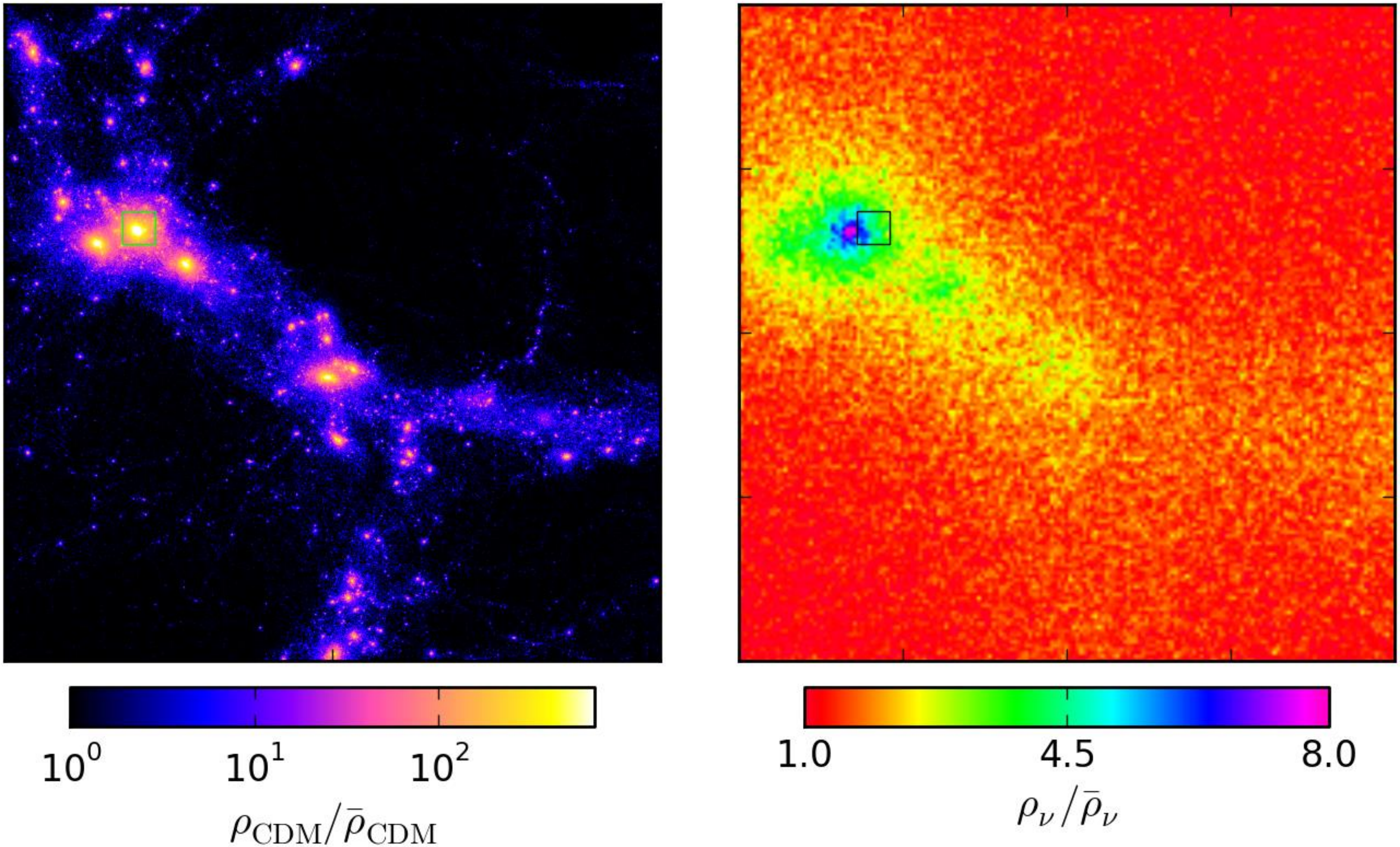
2) Predict theoretical PS for simulations run:

→ with no radiation in the evolution

→ where *f* in ICs doesn't account for horizon crossing

→ with neglected relativistic behavior of neutrinos

Neutrino wake



Relic Neutrino Detection

- Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in 1962 [*Phys. Rev*. 128:3, 1457]
  - Look for relic neutrino capture on tritium by measuring electrons at or above the endpoint spectrum of tritium beta-decay

$$\nu_e + A_Z \rightarrow e^- + A^*_{Z+1}$$

$$T_e = T_\nu + 2m_\nu + Q$$

What do we know?

Gap constrained to <0.6eV by WMAP

(some electron flavor expected above 0.05eV)

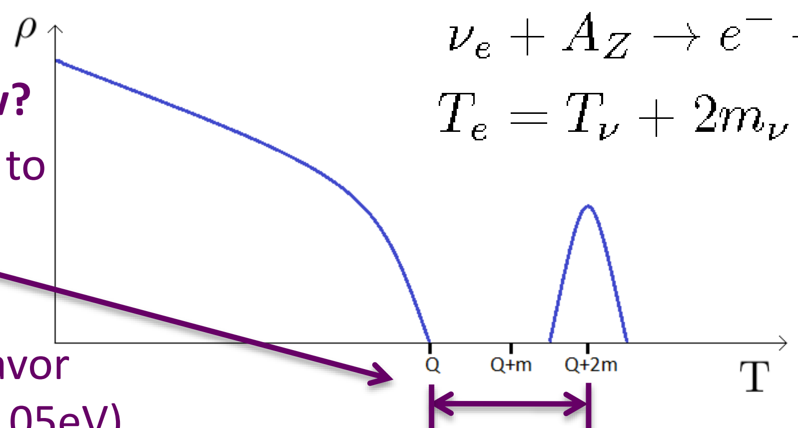


Figure 1: Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

From Chris Tully