Massive neutrino signatures on the large-scale structure of the Universe

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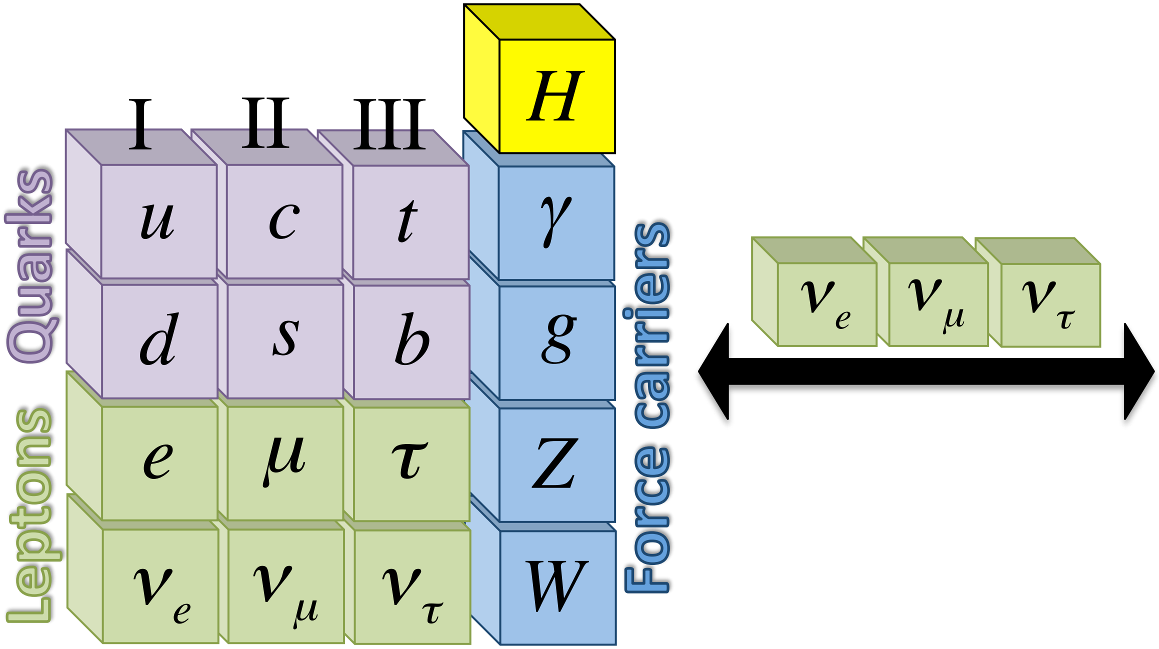
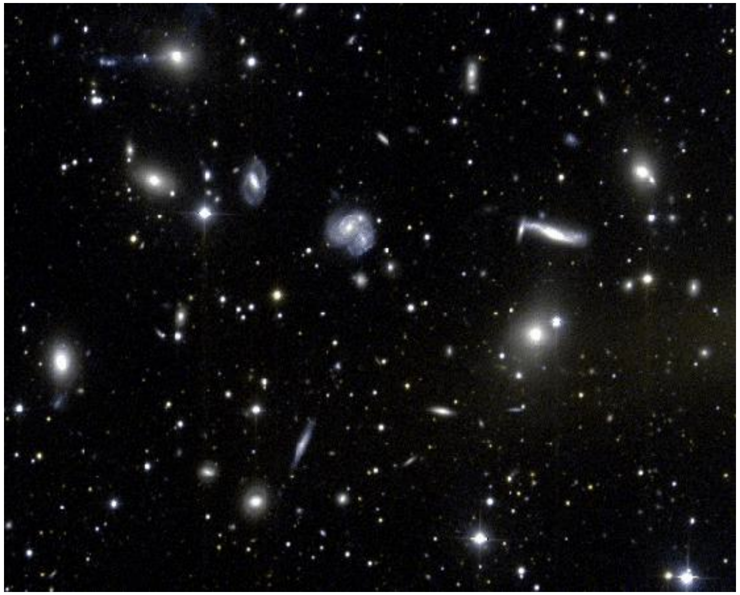




November 6 / Berkeley

Outline

1. Introduction

2. Cosmic neutrino background
   - Effects at linear order
   - Effects at non-linear order

3. Conclusions

Neutrinos

Pauli 1930

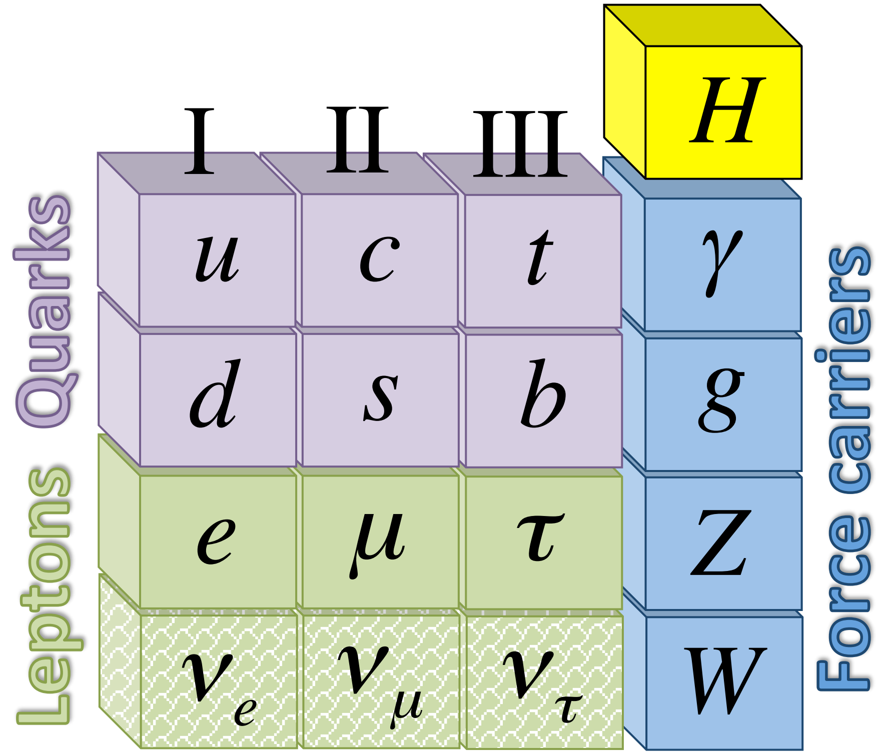
$$n \rightarrow p^{+} + e^{-}$$

Violation of Energy
Violation of Momentum
Violation of Spin

$$n \rightarrow p^{+} + e^{-} + \bar{\nu}_e$$

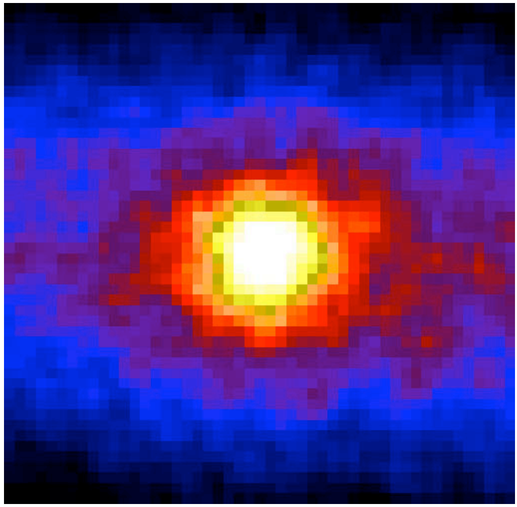
Cowan & Reines 1956

- Fundamental particles
- Neutral leptons: ½ spin fermions
  only sensitive to electroweak force and *gravity*
- N_ν=3 from Z boson decay
- Very weak cross section
  a neutrino could pass through a light year of lead and not be stopped by any of the lead atoms!
- **Massless** in the SM



Neutrinos

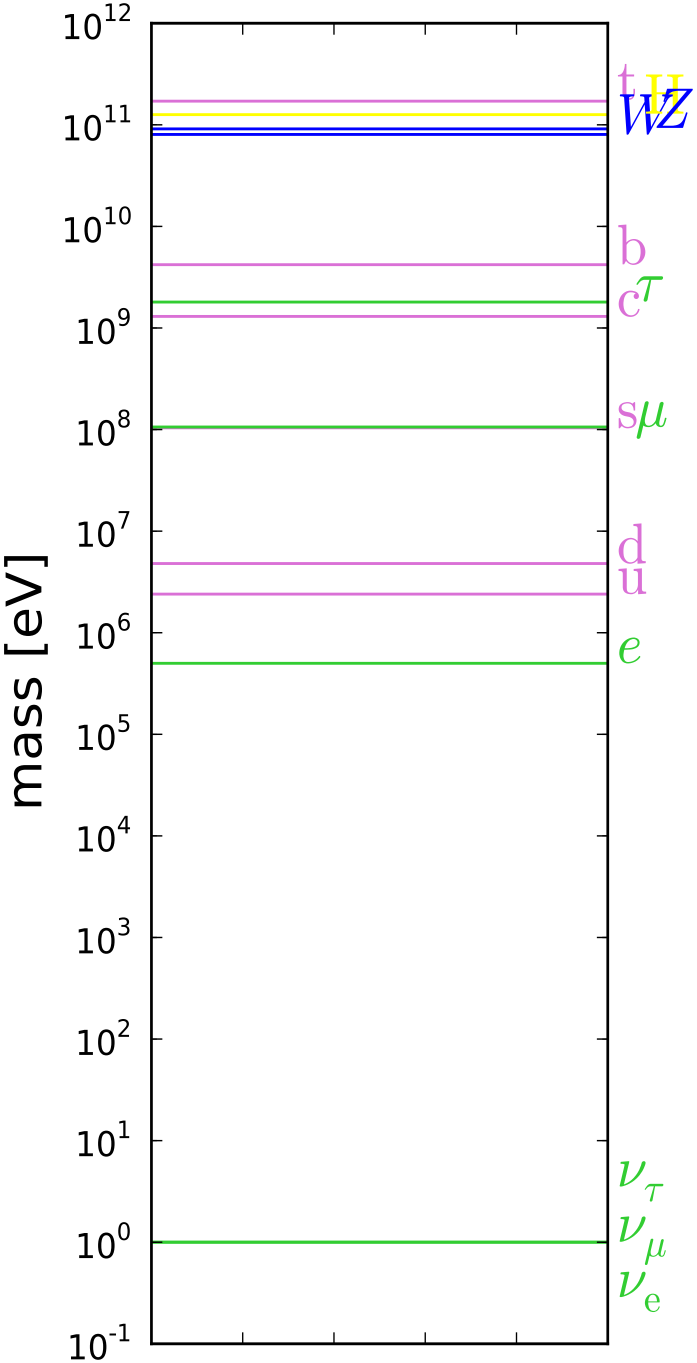
Implications



- Physics beyond the standard model
- Cosmology
  (neutrinos are the second most abundance particle in the Universe)
- Neutrino astronomy
  (account for neutrino oscillations to estimate expected fluxes)

Open questions

- What is the neutrino mass hierarchy?
- What is the absolute neutrino mass scale?
- What is the neutrino nature? Dirac or Majorana?

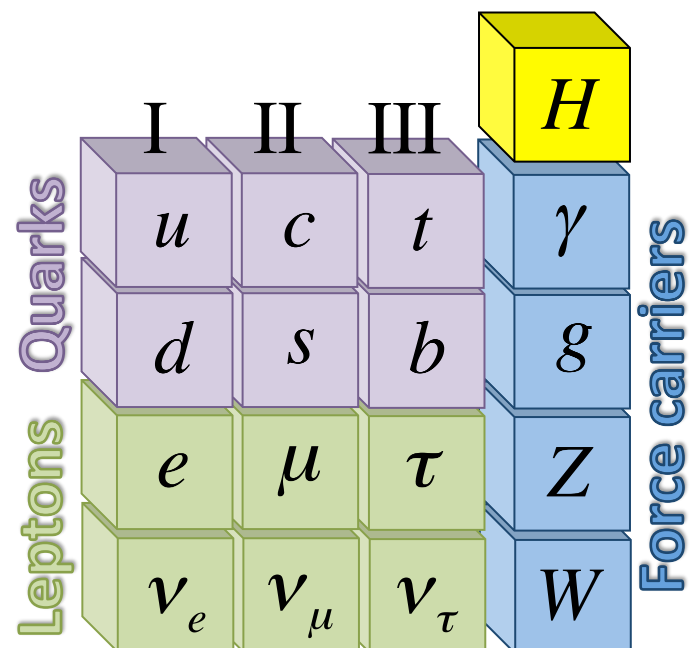


Neutrinos

- **Neutrinos have mass**
- **What are the neutrino masses?**

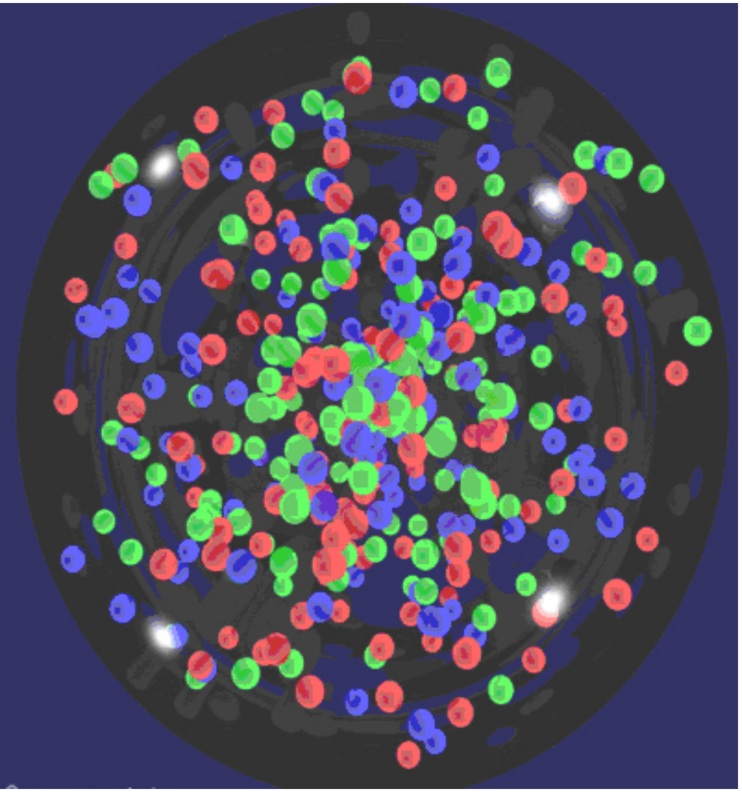
$$\sum m_\nu \geq 0.06 \text{ eV} \qquad m(\bar{\nu}_e) \leq 2.3 \text{ eV}$$

1. *Impact on cosmology*
2. *Weigh neutrinos with cosmology*



Cosmic neutrino background

$$T \approx 10^{10}\ \text{K} \approx 1\ \text{MeV}$$



- Photons
- Electrons & Positrons
- Neutrinos & Antineutrinos

$$\nu + e^- \Leftrightarrow \nu + e^- \qquad e^- + e^+ \Leftrightarrow \nu + \bar{\nu}$$

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

$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma,0} \approx 1.95\ \text{K} \qquad T_\nu(z) = T_{\nu,0}(1+z)$$

S. Weinberg, Cosmology, Oxford University Press, 2008

Cosmic neutrino background

Properties

$$\bar{n}_\nu(z) = \int_0^\infty n_\nu(p,z)\,dp \cong 113\ (1+z)^3 \frac{\nu}{cm^3}$$

$$\bar{V}_\nu(z) = \frac{1}{\bar{n}_\nu(z)} \frac{1}{m_\nu} \int_0^\infty n_\nu(p,z)\,p\,dp \cong 160(1+z)\left(\frac{\mathrm{eV}}{m_\nu}\right)\ \mathrm{km/s}$$

$$\rho_\nu = \int_0^\infty n_\nu(p,z)\,dp\sqrt{p^2+m_\nu^2} \qquad P_\nu = \int_0^\infty n_\nu(p,z)\,dp\frac{p^2}{3\sqrt{p^2+m_\nu^2}}$$

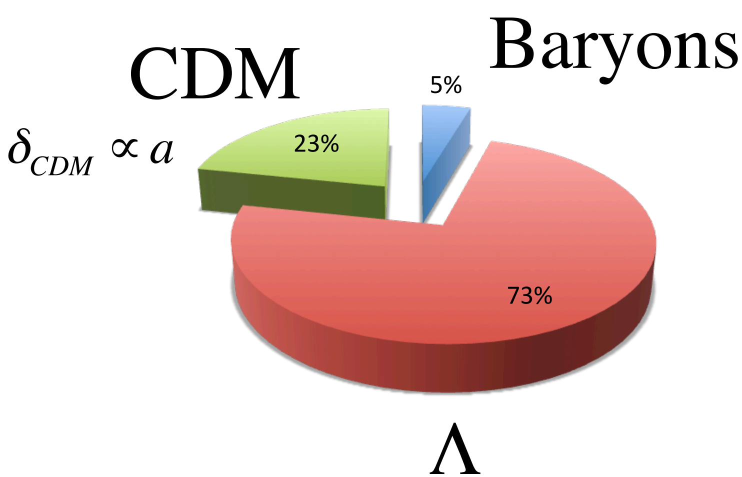
At high redshift $\begin{cases} p >> m_\nu \\ P_\nu \approx \dfrac{\rho_\nu}{3} \end{cases}$

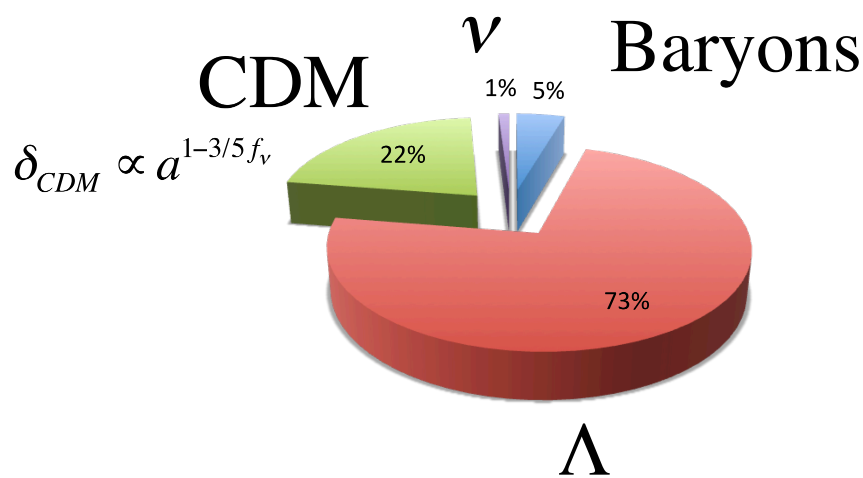
At low redshift $\begin{cases} p << m_\nu \\ P_\nu \approx 0 \end{cases}$

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{93.3eV}$$

Effects at linear order

1. Modification of the Matter-Radiation equality time
2. Slow down the growth of matter perturbations

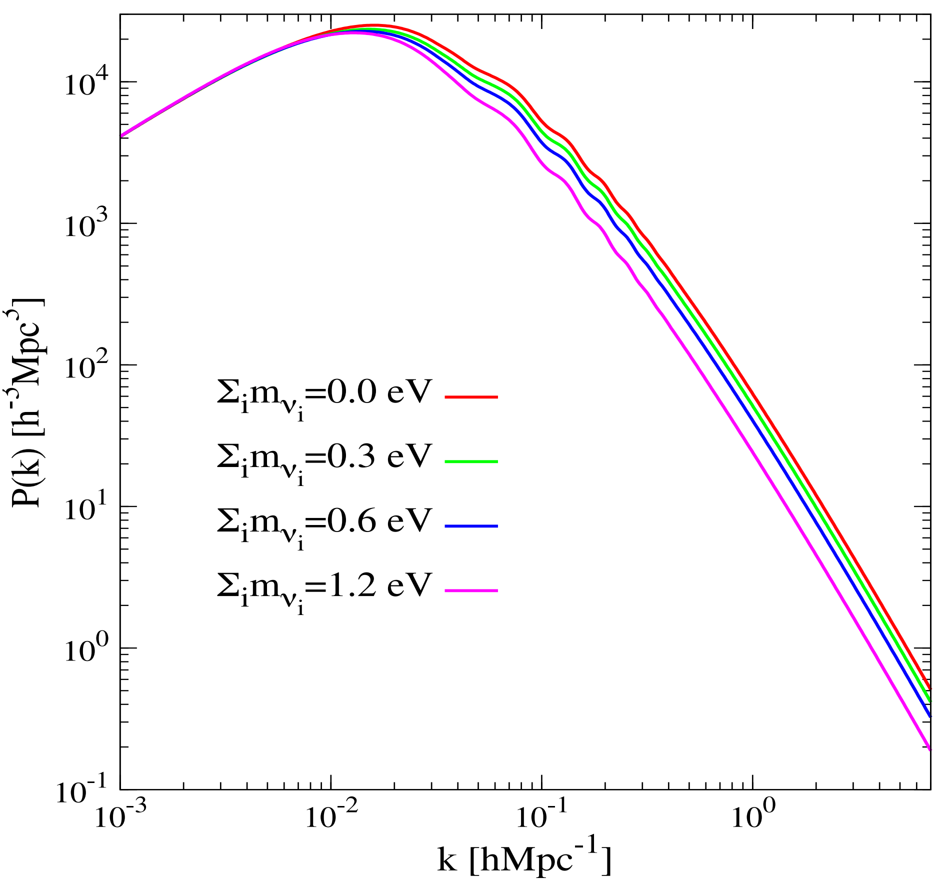


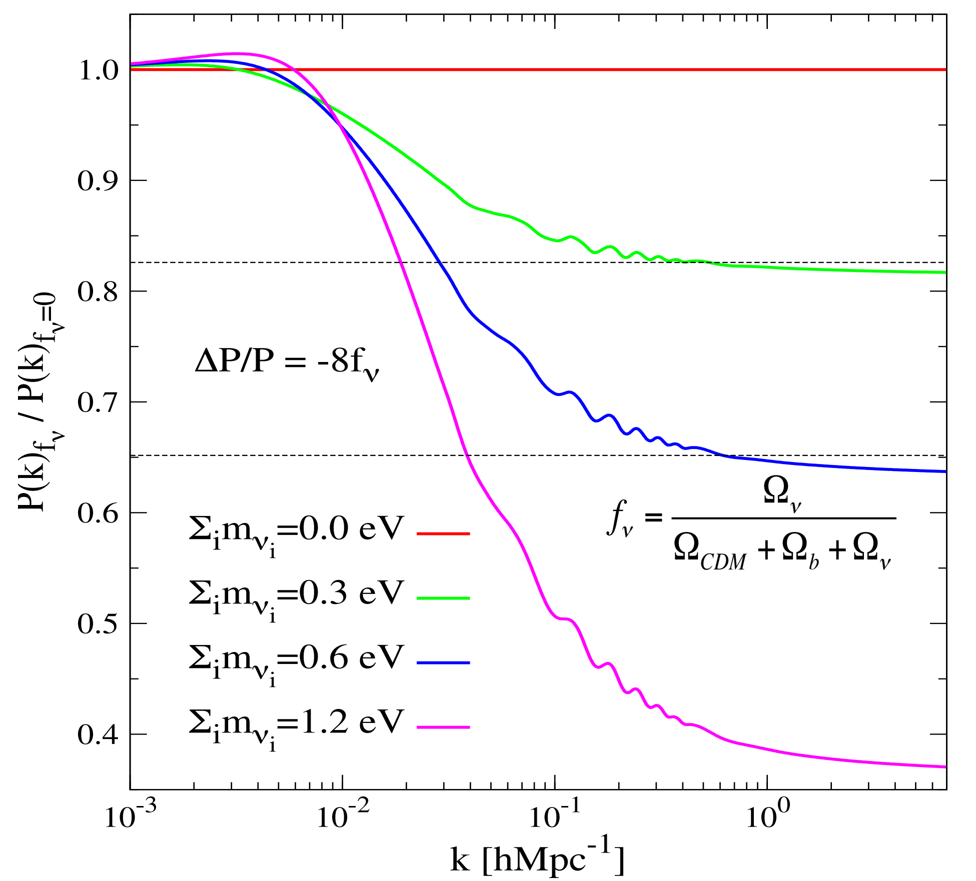


$$\Omega_{\mathrm{DM}} = \Omega_{\mathrm{CDM}} + \Omega_\nu = \text{fixed}$$

Lesgourgues & Pastor, Physics Reports, 429, 6, 2006

Effects at linear order





1. Modification of the Matter-Radiation equality time

2. Slow down the growth of matter perturbations

$$\Omega_{DM} = \Omega_{CDM} + \Omega_\nu = \text{fixed}$$

Lesgourgues & Pastor, Physics Reports, 429, 6, 2006

Effects on the non-linear regime

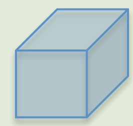
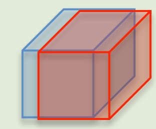
Why?

- Important on small scales
- Important at low redshift
- Lots of modes in the middle—non-linear regime

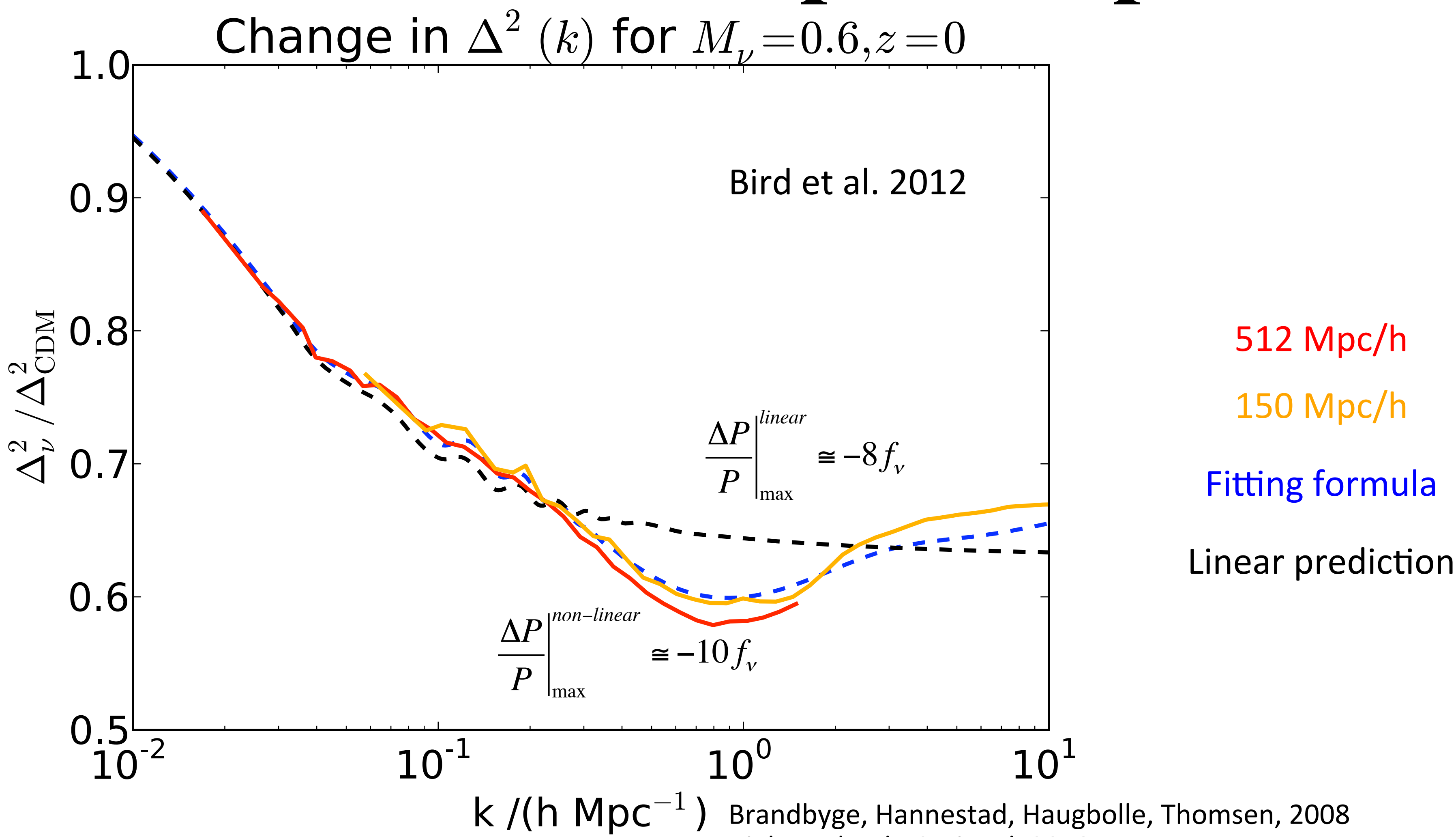
How?

- Semi-analytic methods
  N-1-body, Ringwald & Wong, 2004
  (see also Singh & Ma, 2003)
- Perturbation theory
  Blas, Garny, Konstandin, Lesgourgues, 2014
- N-body simulations

N-body simulations with neutrinos

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

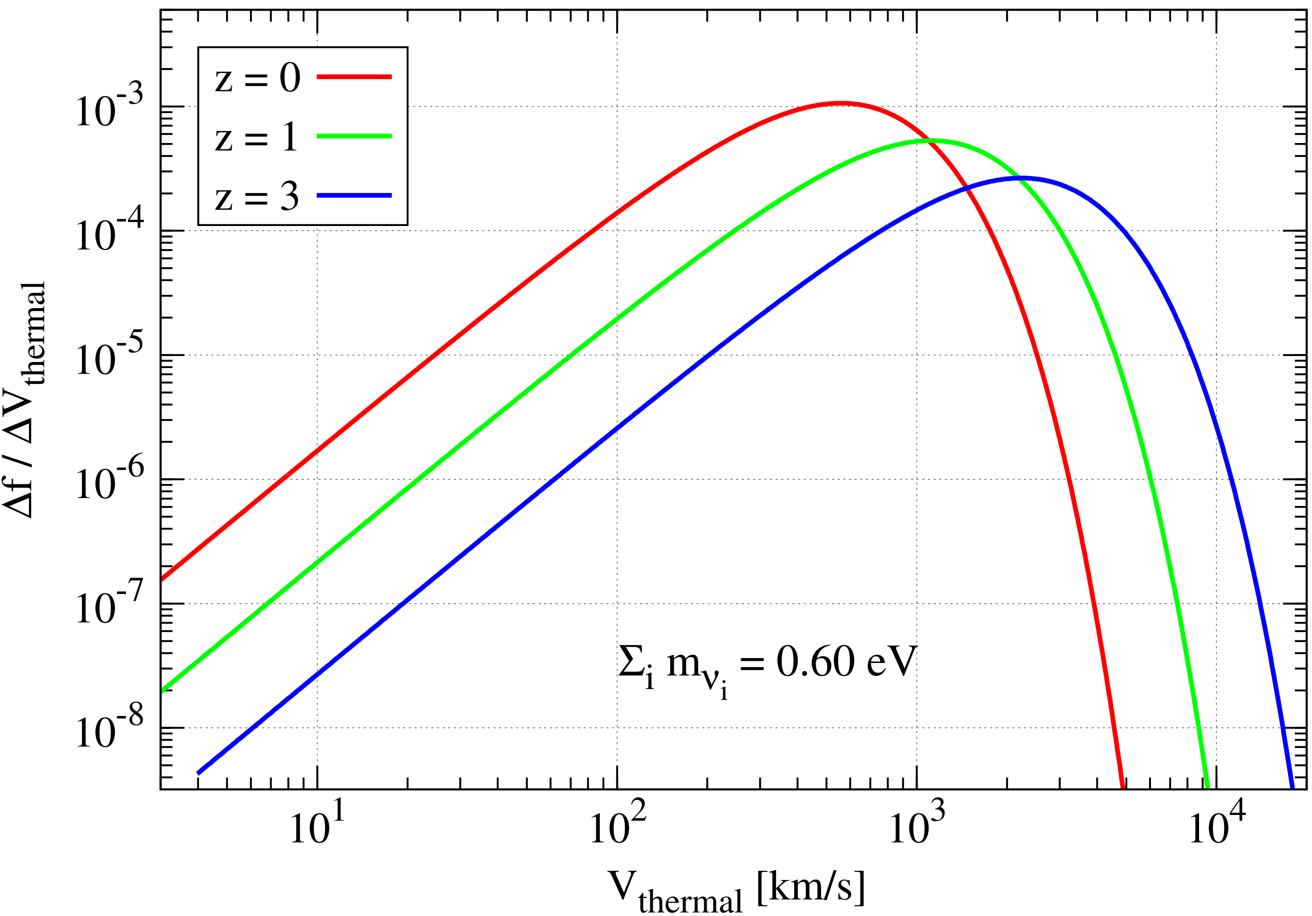
Effects on matter power spectrum

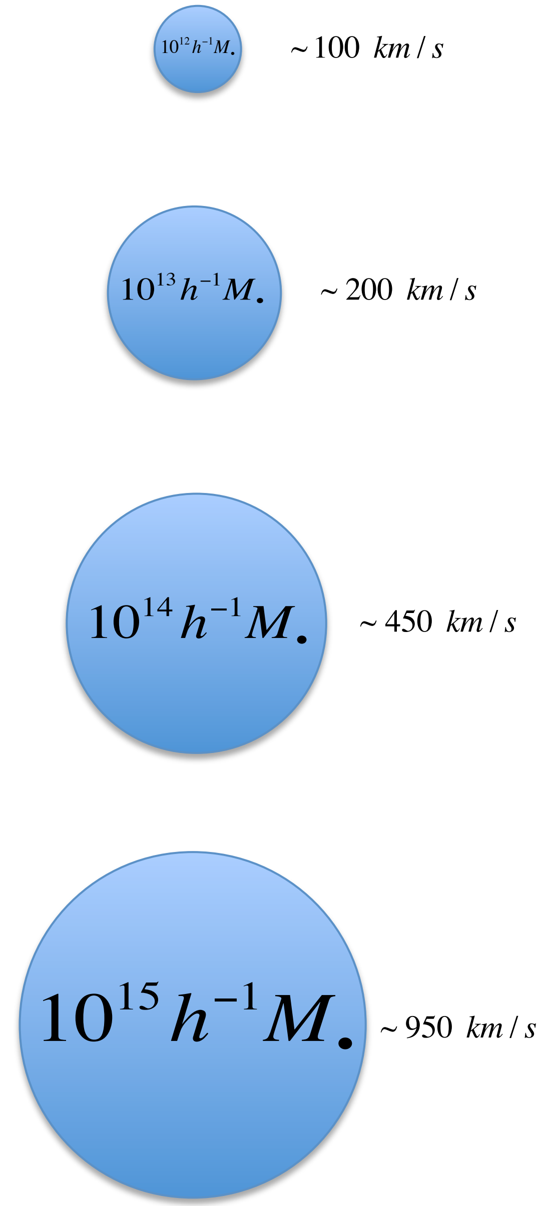


Brandbyge, Hannestad, Haugbolle, Thomsen, 2008
Viel, Haehnelt, Springel, 2010
Bird, Viel, Haehnelt, 2012
Wagner, Verde, Jimenez, 2012
Agarwal, Feldman, 2011
Massara, FVN, Viel, 2014
Upadhye, Biswas, Pope, Heitmann, Habib, Finkel, Frontiere, 2014
Inman, Emberson, Pen, Farchi, Yu, Harnois-Deraps, 2015

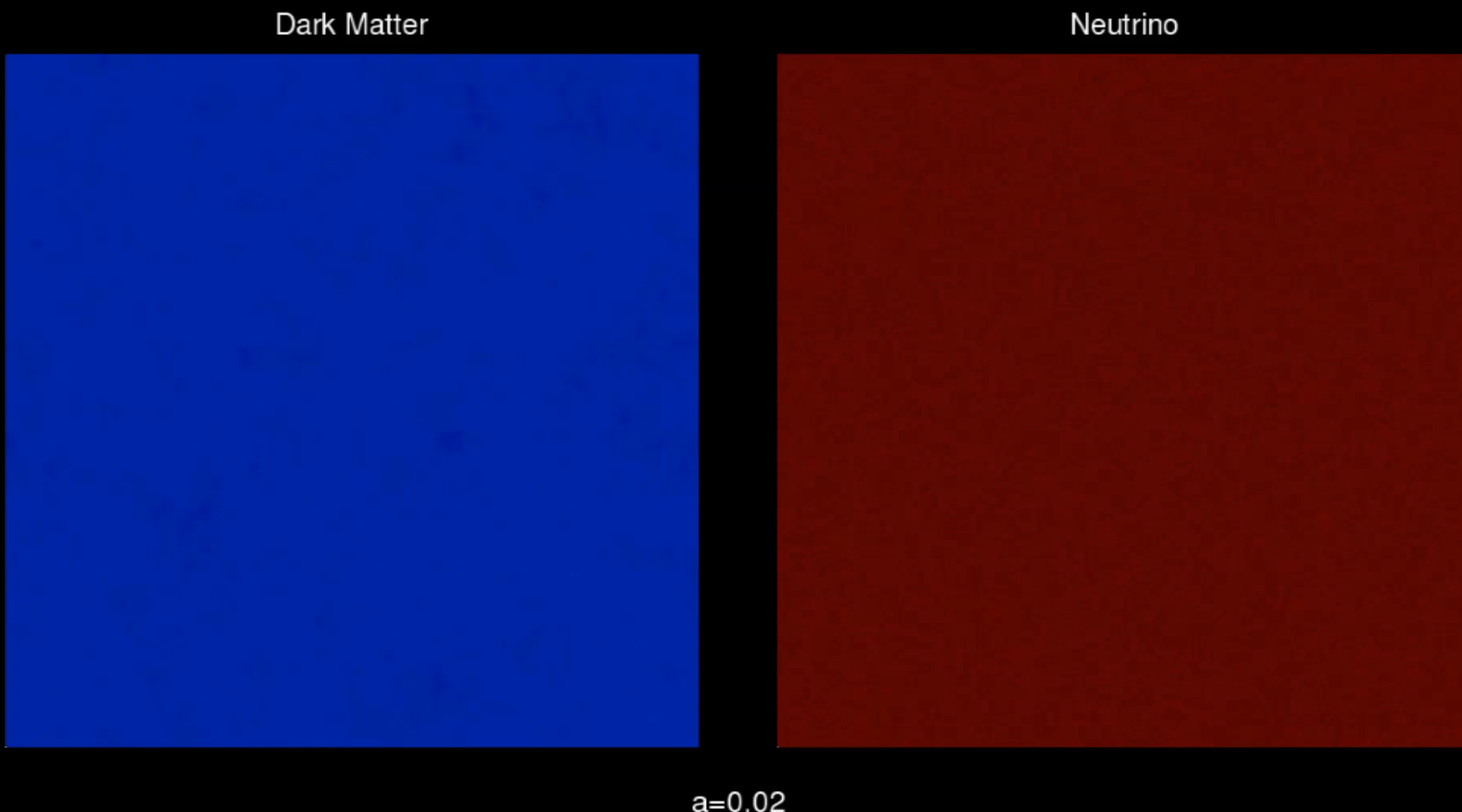
Neutrino clustering

$$n_\nu(p,z)dp \cong \frac{4\pi g_\nu}{(2\pi\hbar c)^3}\left(\frac{p^2 dp}{e^{(p/k_B T_\nu(z))}+1}\right) \qquad T_\nu(z) = 1.95(1+z)\ K$$

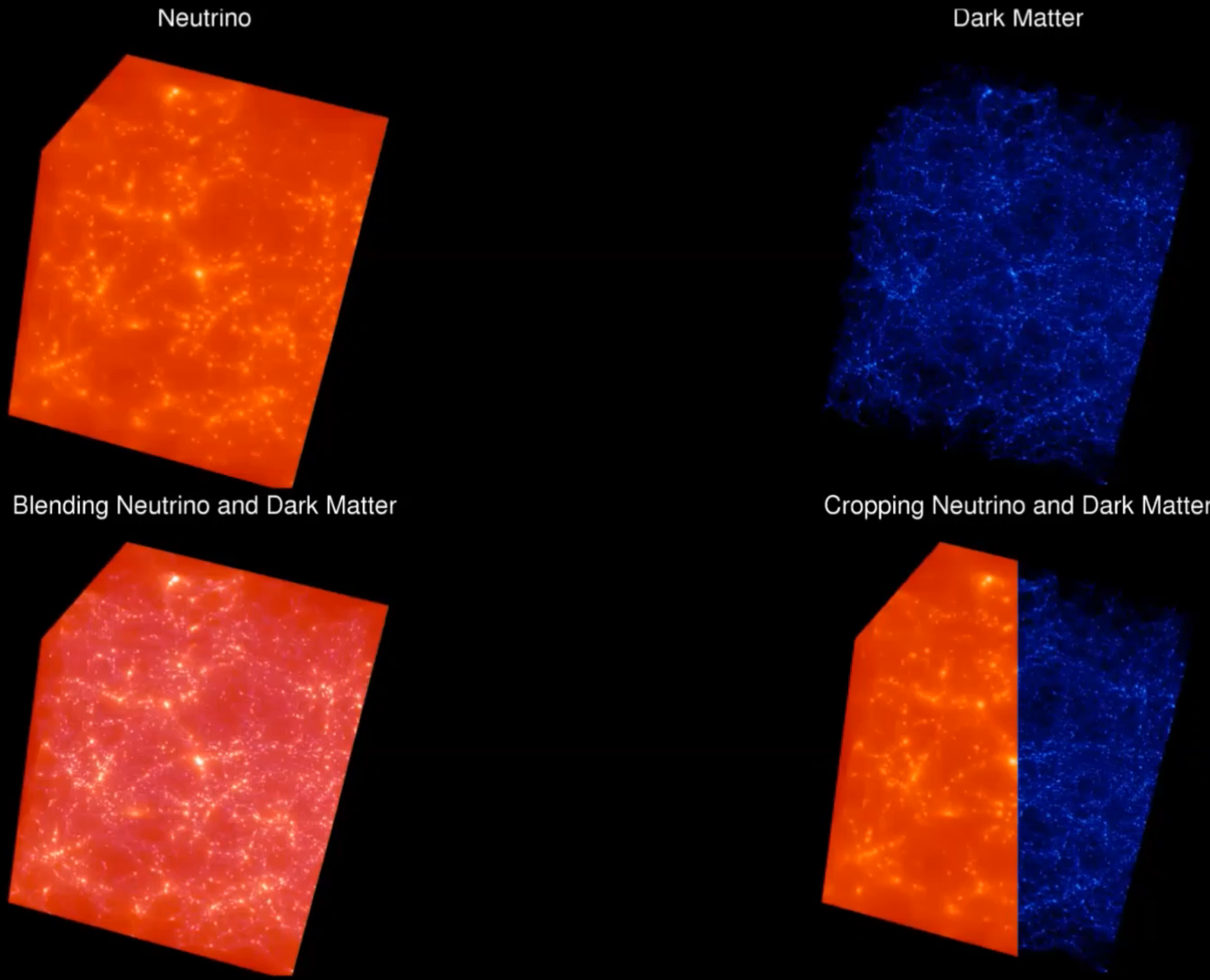




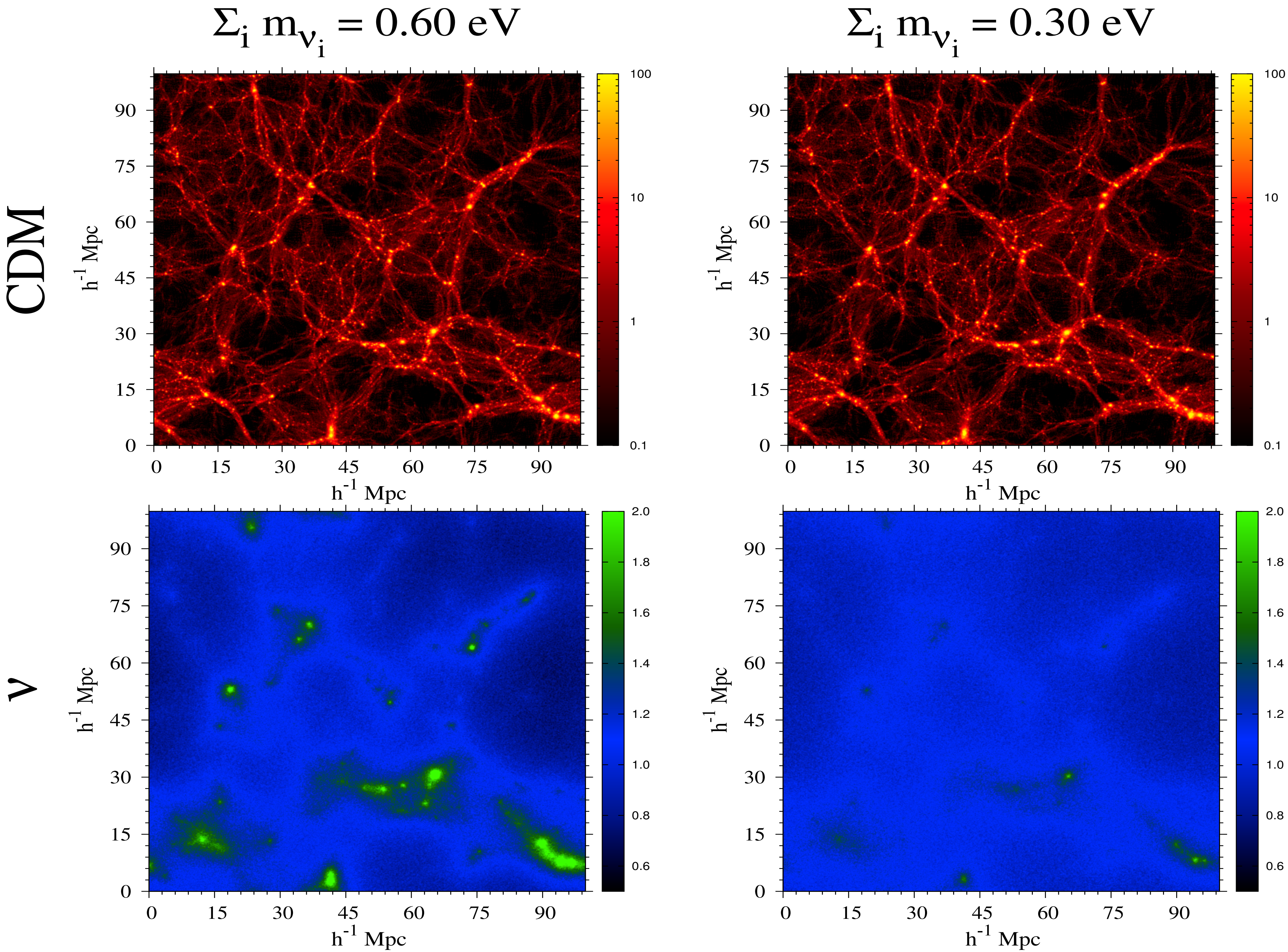
Neutrino clustering



http://som.ific.uv.es/movies



https://www.youtube.com/watch?v=_-Q3dO1Iq4g&list=PLBc4nJxpIePXY0wdpHfKZi7jHJUjRTaAz

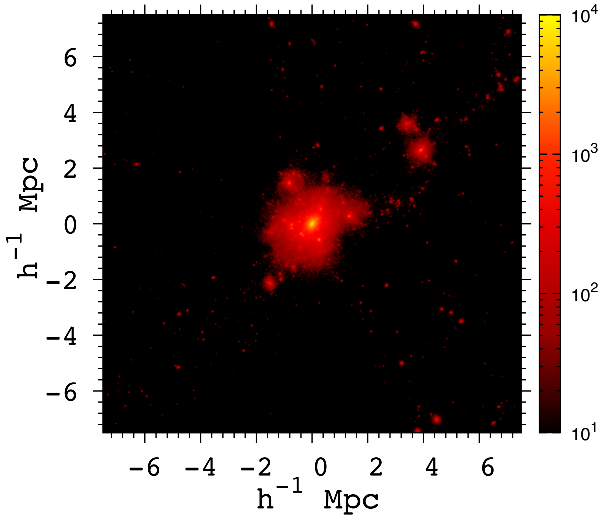


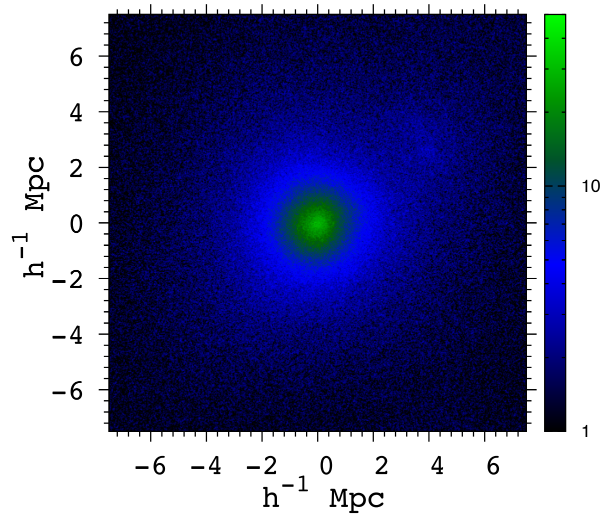
$\Sigma_i m_{\nu_i} = 0.60$ eV
$\Sigma_i m_{\nu_i} = 0.30$ eV
CDM
ν
h^{-1} Mpc
0
15
30
45
60
75
90
100
10
1
0.1
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6

Clustering of relic neutrinos

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

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



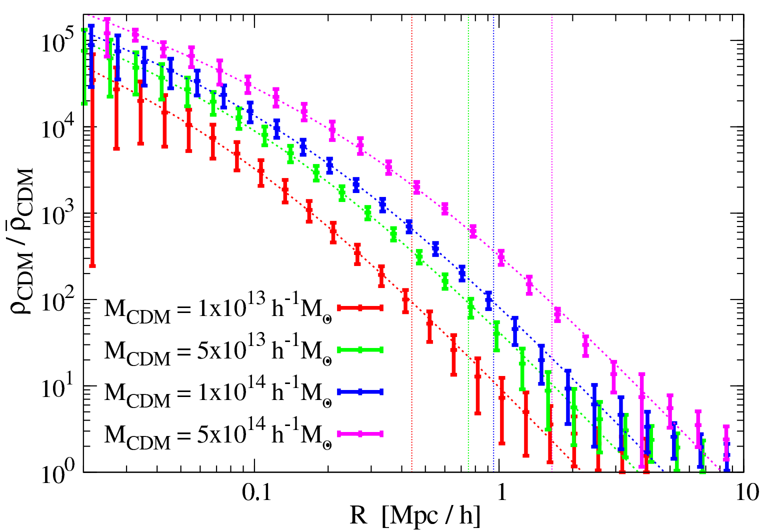


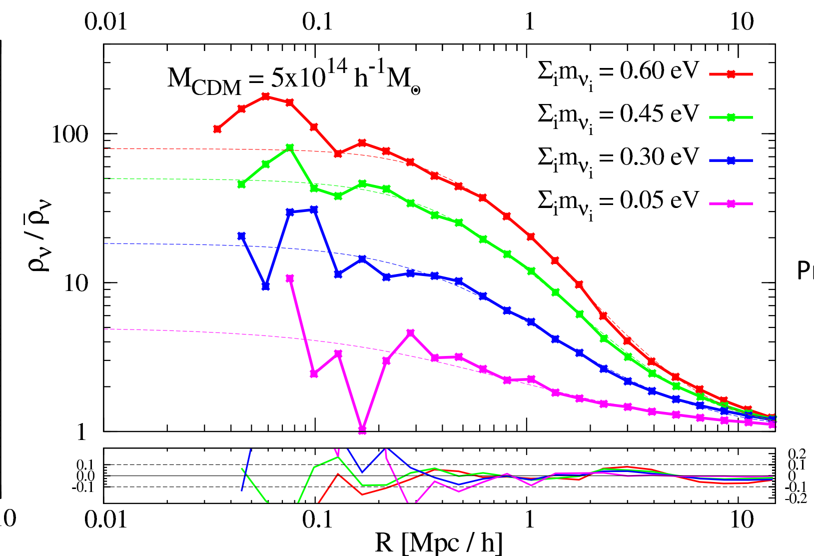
$$c = \frac{r_v}{r_s}$$

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

$$\delta_\nu(r) = \frac{\rho_c}{(1+r/r_c)^\alpha}$$

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





PTOLEMY

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

Halo mass function

Castorina, Sefussati, Sheth, FVN, Viel 2013

$$\frac{dn(M,z)}{dM} = \nu f(\nu)\frac{\rho_m}{M^2}\frac{d\ln\nu}{d\ln M} \quad \begin{cases} \nu \equiv \dfrac{\delta_c}{\sigma(M,z)} \qquad \delta_c = 1.686 \\ \sigma^2(M,z) = \dfrac{1}{2\pi^2}\displaystyle\int_0^\infty k^2 P_m(k) W^2(k,R)\,dk \\ M = \dfrac{4\pi}{3}\rho_m R^3 \end{cases}$$

Universal

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

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

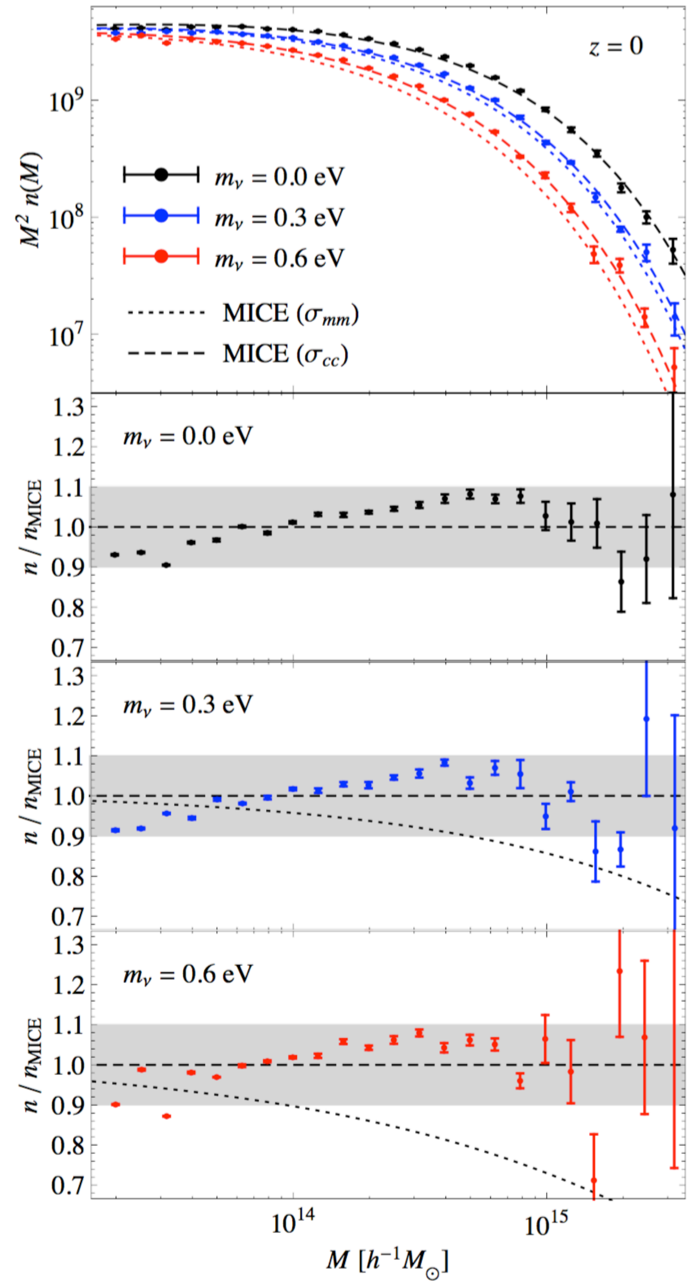
Crocce et al. 2010

Matter prescription

$\rho_m \rightarrow \rho_{cdm} \quad P_m(k) \rightarrow P_m(k)$

Cold dark matter prescription

$\rho_m \rightarrow \rho_{cdm} \quad P_m(k) \rightarrow P_{cdm}(k)$



Halo mass function

Castorina, Sefussati, Sheth, FVN, Viel 2013

FoF halos : b=0.2

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

Universal?

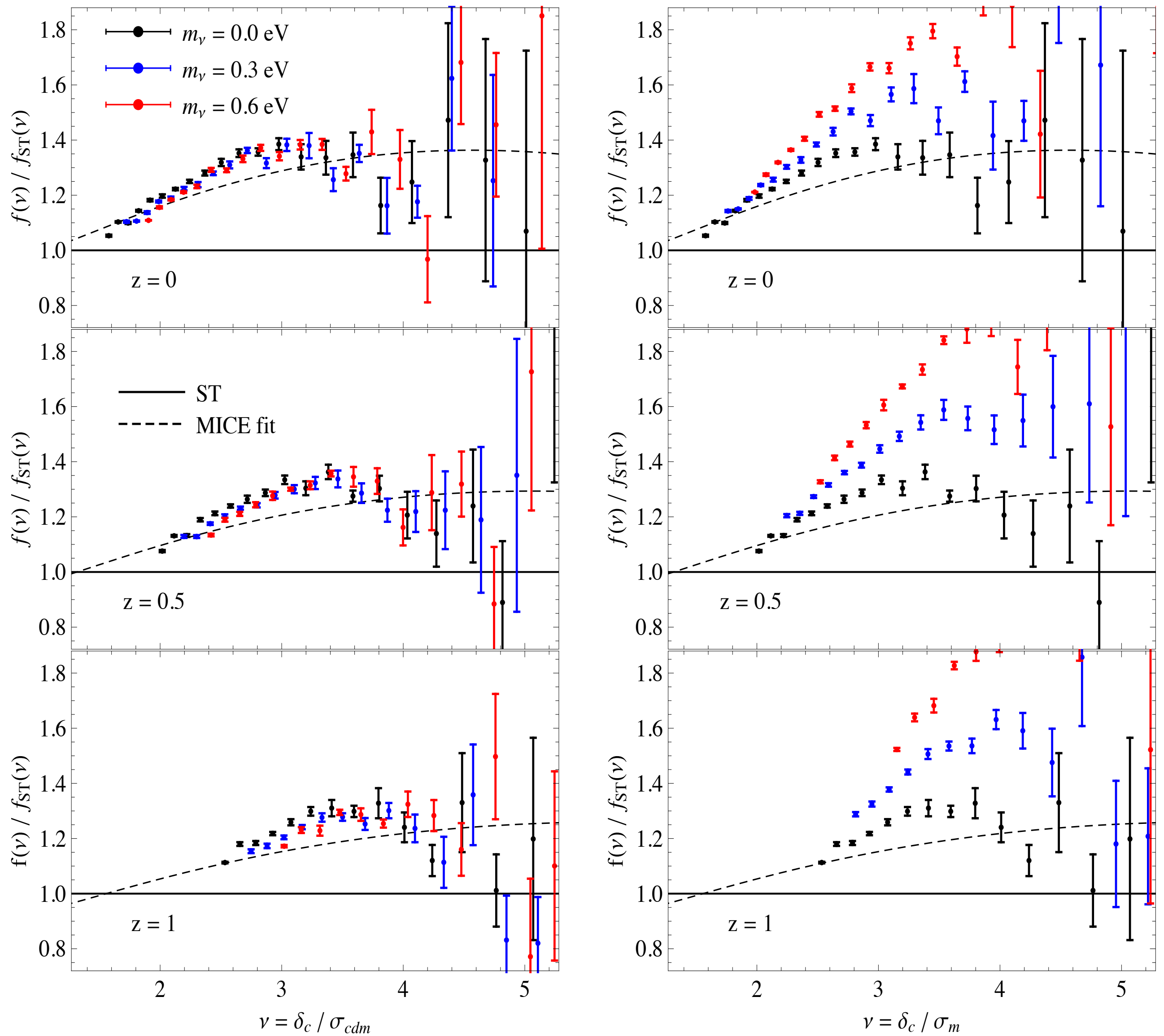
$$f(\nu) = \frac{M^2}{\rho} \frac{1}{\nu} \frac{d\ln M}{d\ln\nu} \frac{dn(M,z)}{dM}$$

~~Matter prescription~~

~~$\rho_m \rightarrow \rho_{cdm} \quad P_m(k) \rightarrow P_m(k)$~~

Cold dark matter prescription ✓

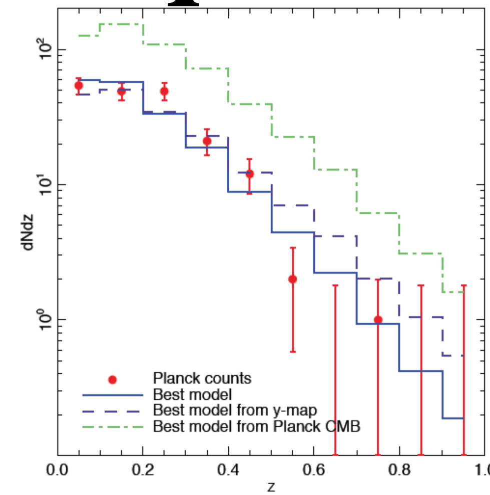
$\rho_m \rightarrow \rho_{cdm} \quad P_m(k) \rightarrow P_{cdm}(k)$

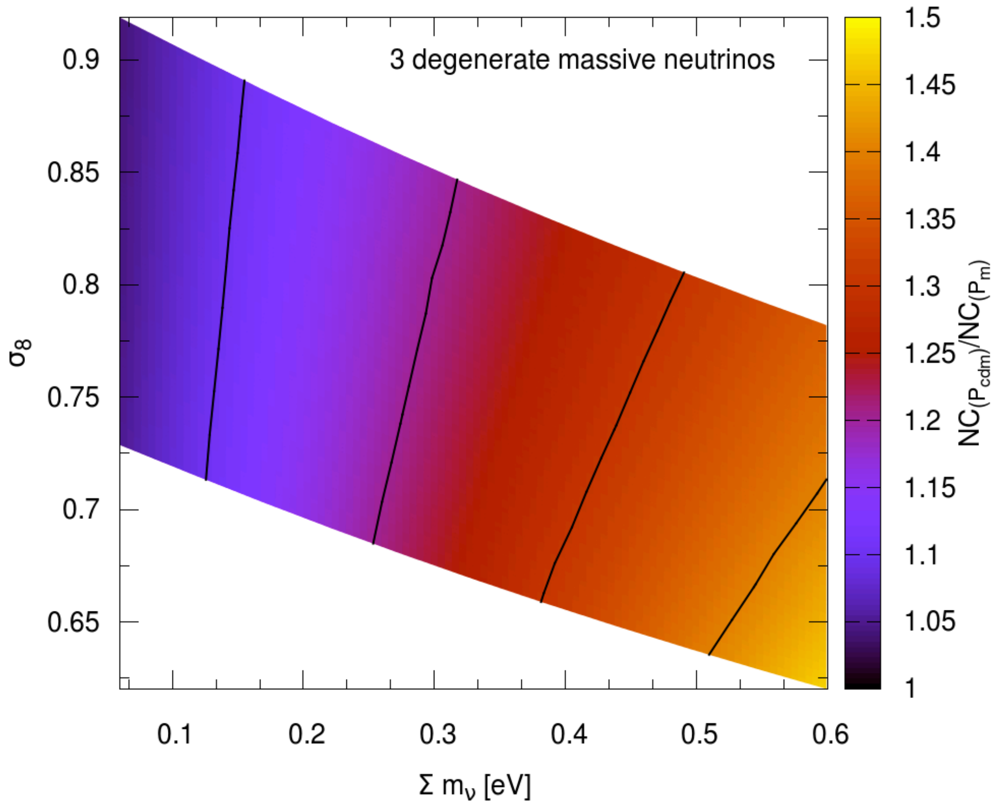


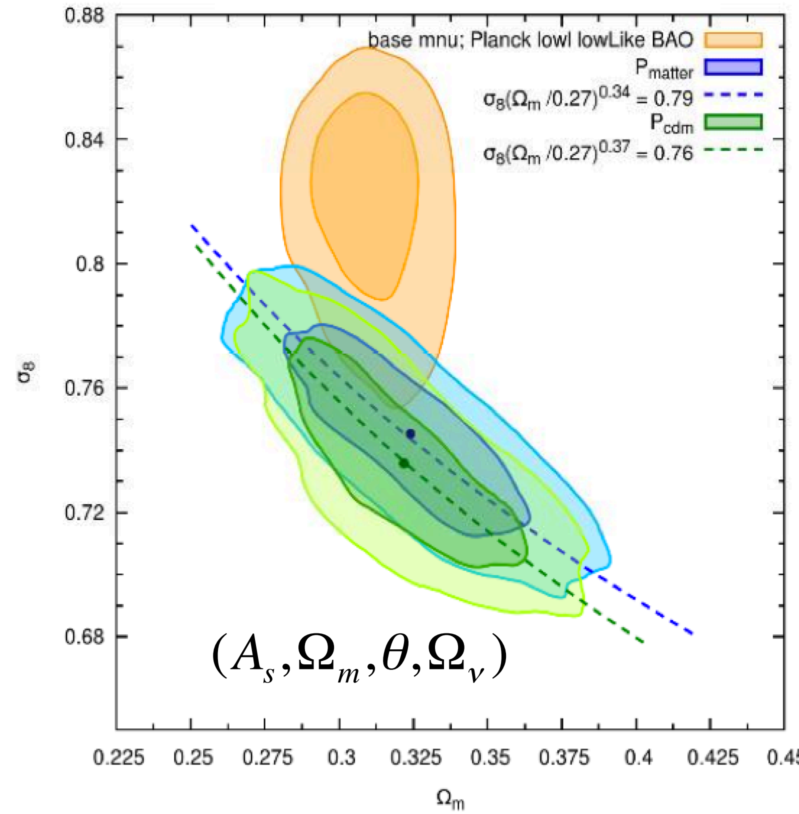
Halo mass function: consequences

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

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







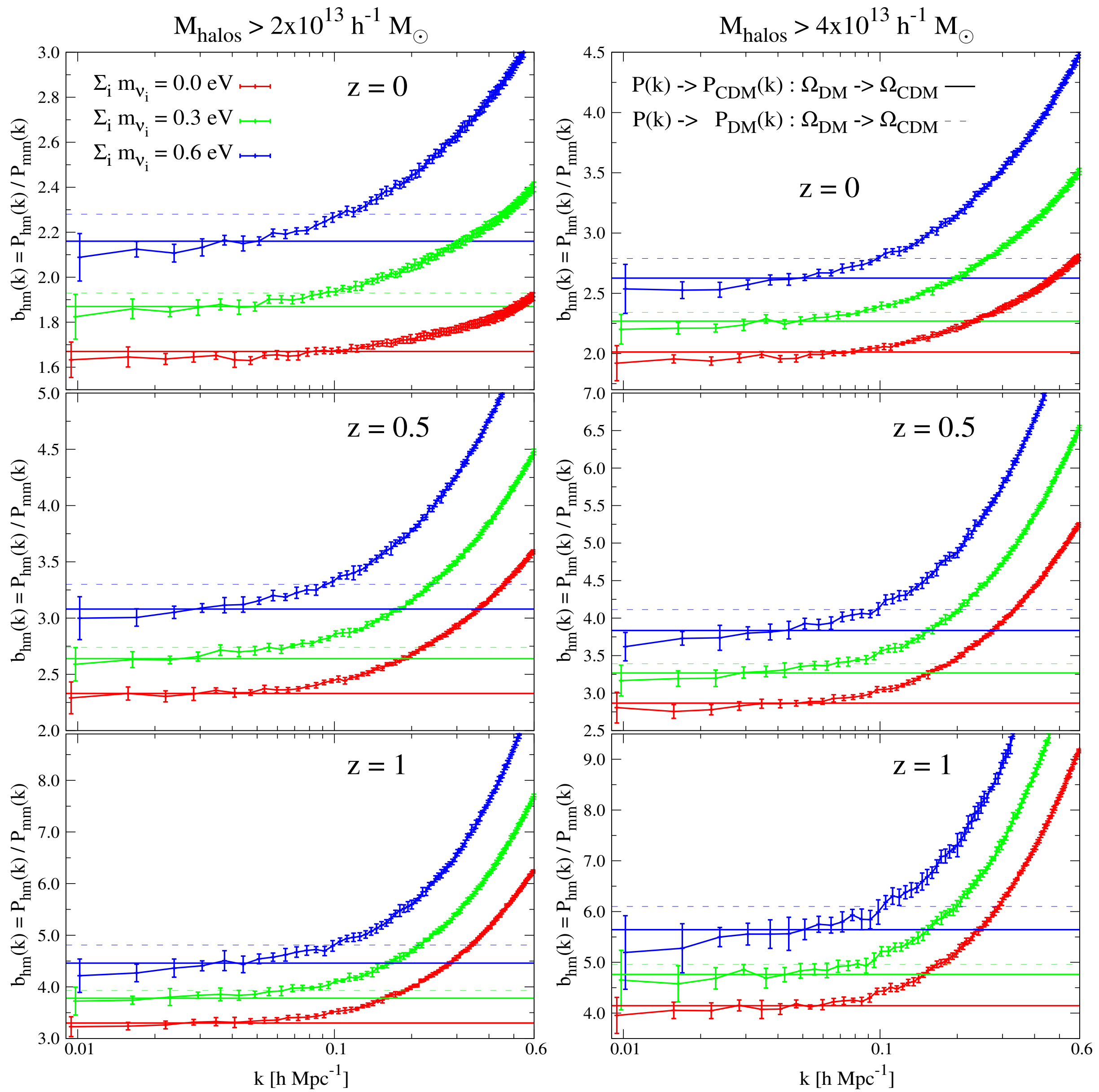
$(A_s, \Omega_m, \theta, \Omega_\nu)$

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

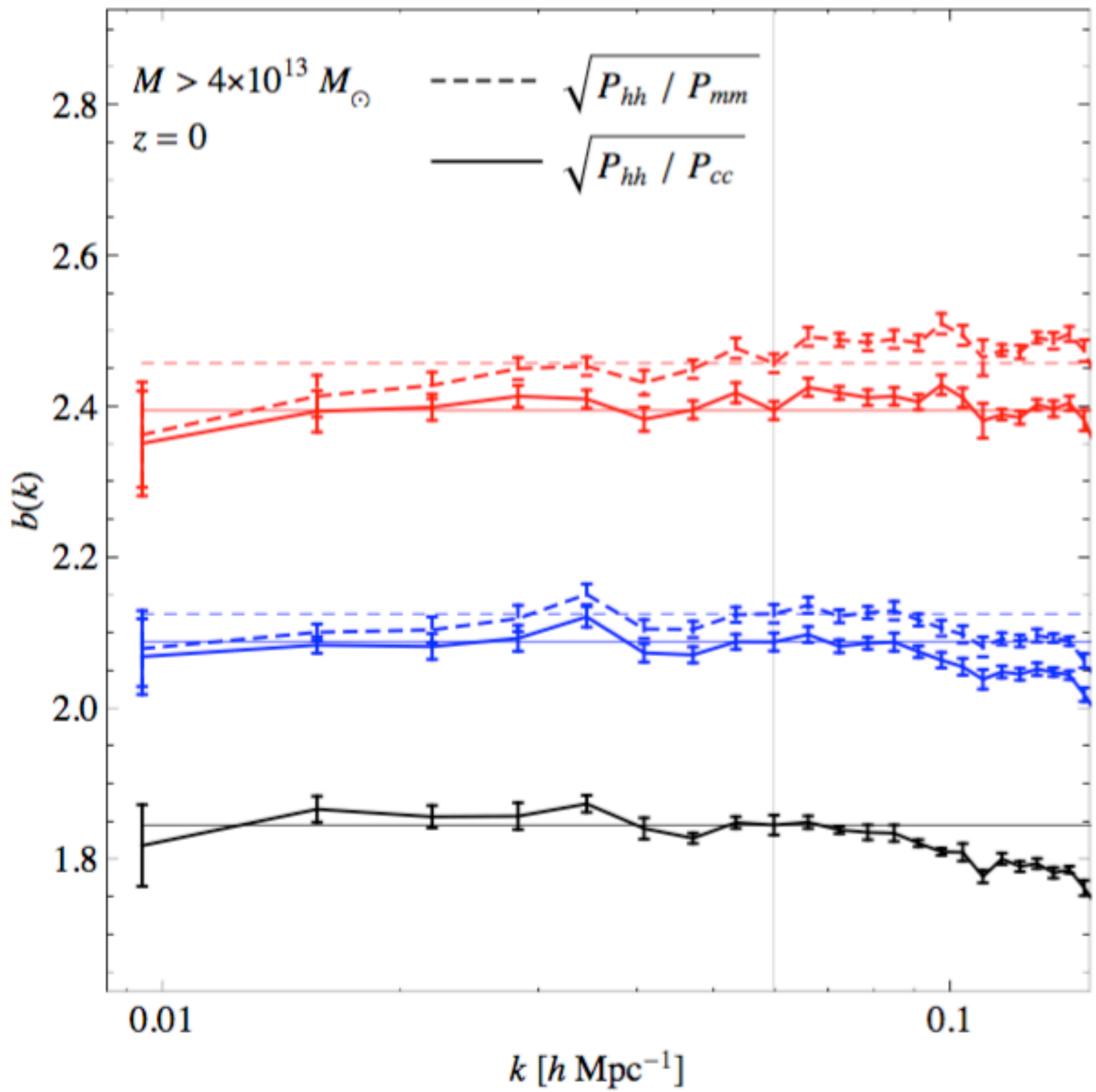


Clustering of dark matter halos

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

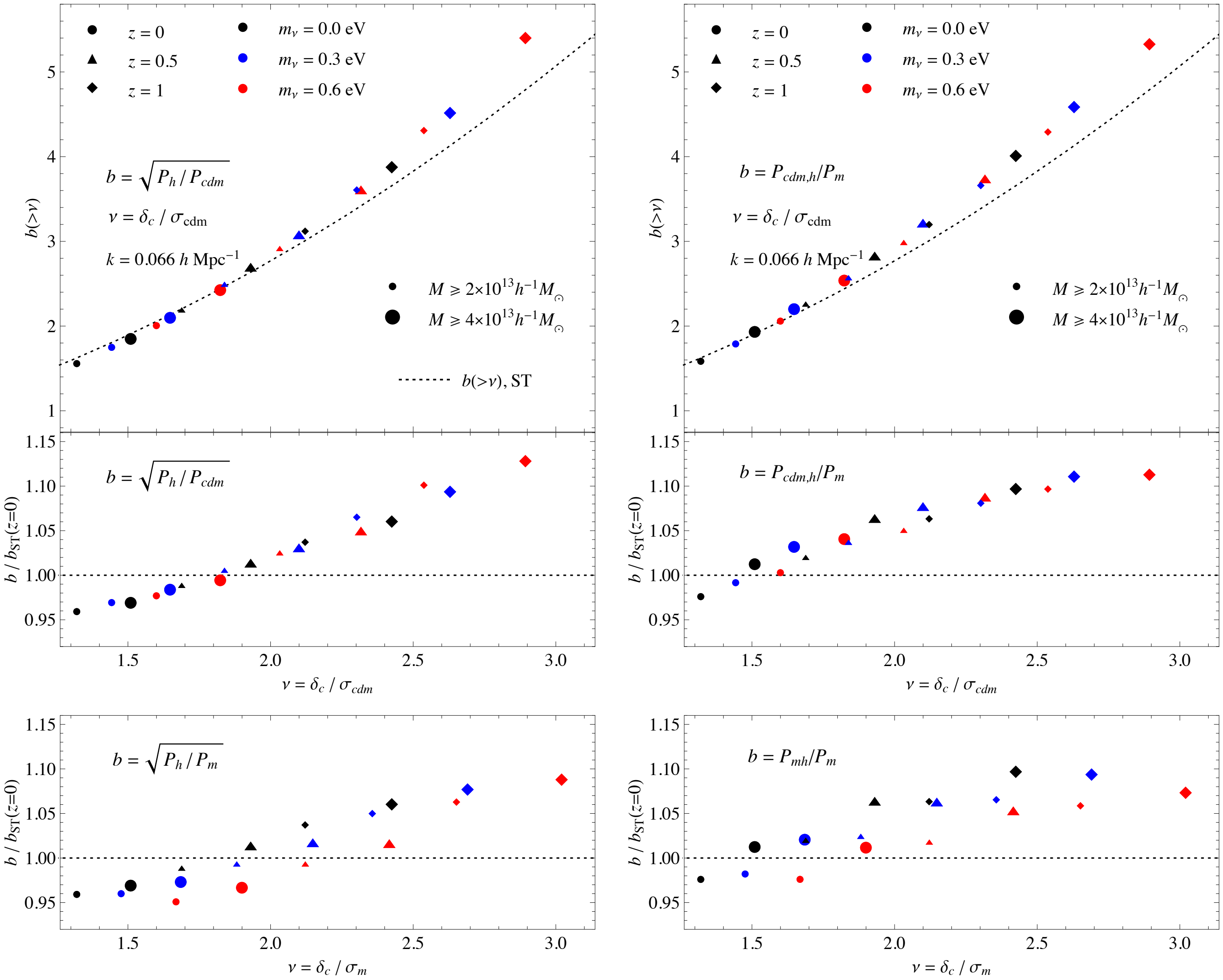
$$b_{hm}(k) = \frac{P_{hm}(k)}{P_{mm}(k)}$$

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



Clustering of dark matter halos

Castorina, Sefusatti, Sheth, FVN, Viel 2013



Halo model

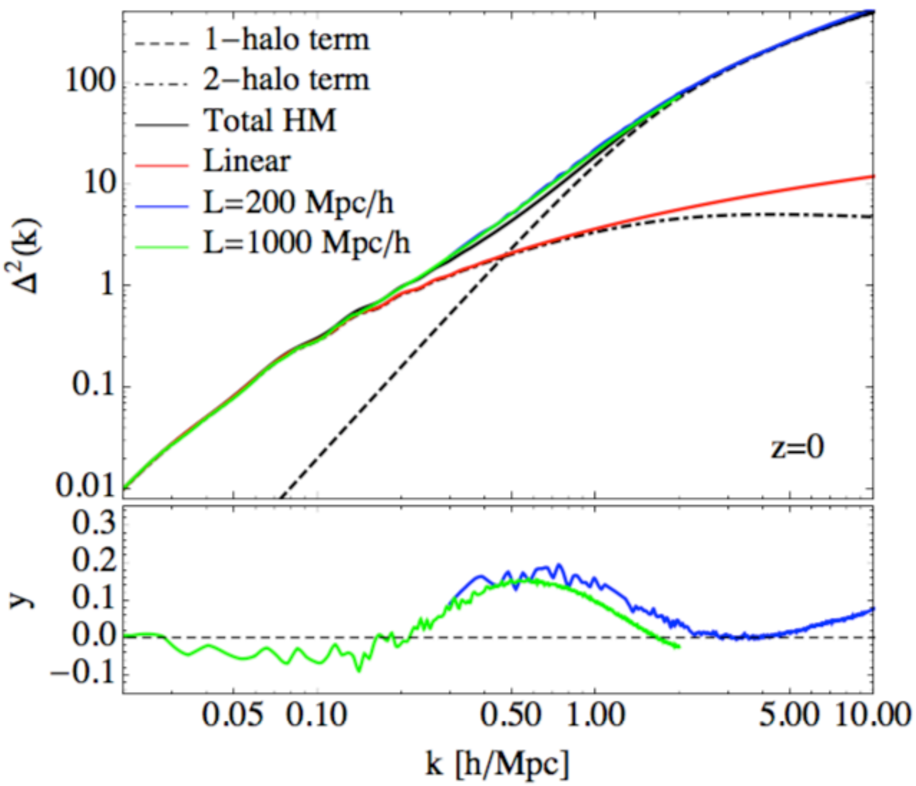
Seljak 2000; Ma & Fry 2000
Peacok & Smith 2000; Cooray & Sheth 2002

Assumptions →

- All matter in halos

Ingredients →

- Linear matter power spectrum
- Halo mass function
- Halo bias
- Density profile



$$P(k) = P_{1h}(k) + P_{2h}(k)$$

$$P_{1h}(k) = \int_0^\infty f(\nu)\frac{M}{\bar{\rho}}\left|u(k|\nu)\right|^2 d\nu$$

$$P_{2h}(k) = \left[\int_0^\infty b(\nu) f(\nu) u(k|\nu)\, d\nu\right]^2 P_L(k)$$

Halo model

Massara, FVN, Viel 2014

$$\rho_m = \rho_{cb} + \rho_\nu$$

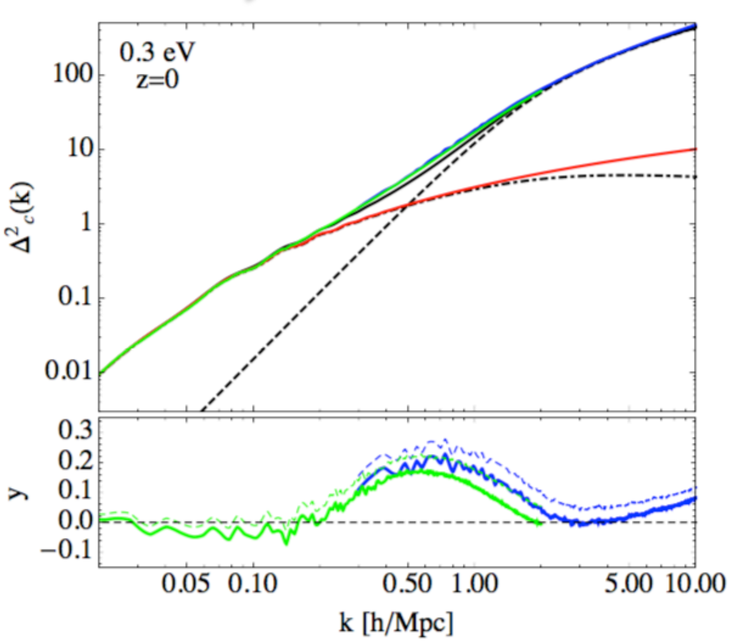
$$P_m(k) = \left(\frac{\Omega_{cb}}{\Omega_m}\right)^2 P_{cb}(k) + 2\left(\frac{\Omega_{cb}\Omega_\nu}{\Omega_m}\right) P_{cb\nu}(k) + \left(\frac{\Omega_\nu}{\Omega_m}\right)^2 P_\nu(k)$$

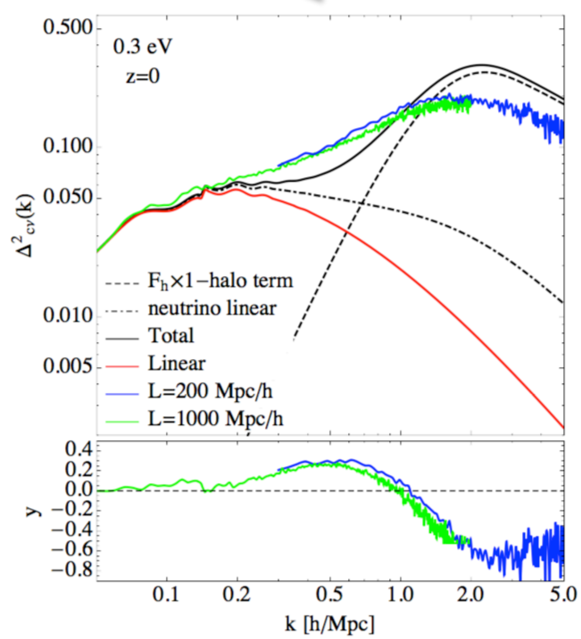
- ~~All matter in halos~~
- ~~HMF and halo bias as a function of matter field~~

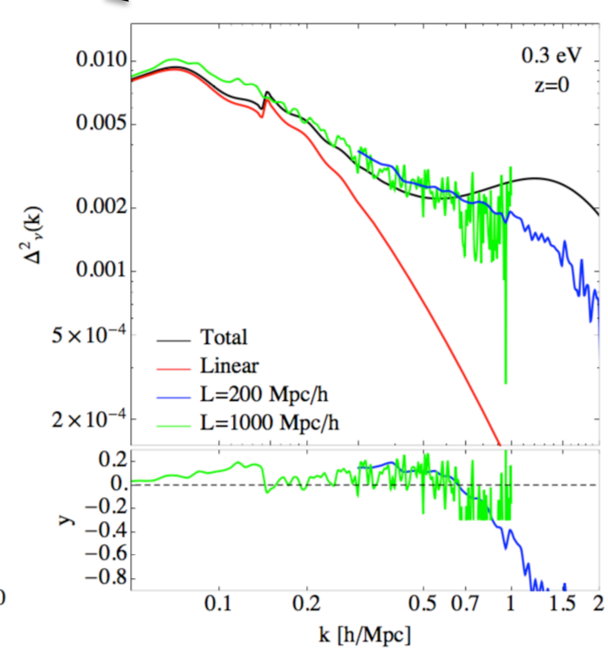
- All CDM in halos
- HMF and halo bias as a function of CDMB field
- Concentration in halos
- Only a fraction of ν in halos

$$\delta_\nu = F_h \delta_\nu^h + (1 - F_h)\delta_\nu^h$$

$$\delta_\nu(r) = \frac{\rho_c}{(1 + r/r_c)^\alpha}$$

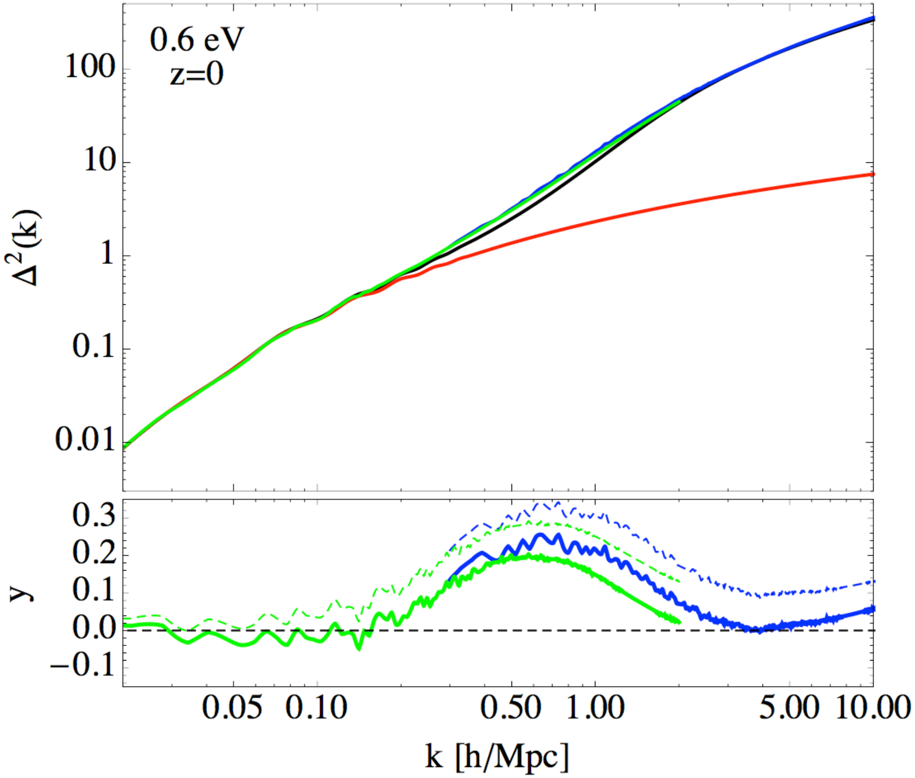


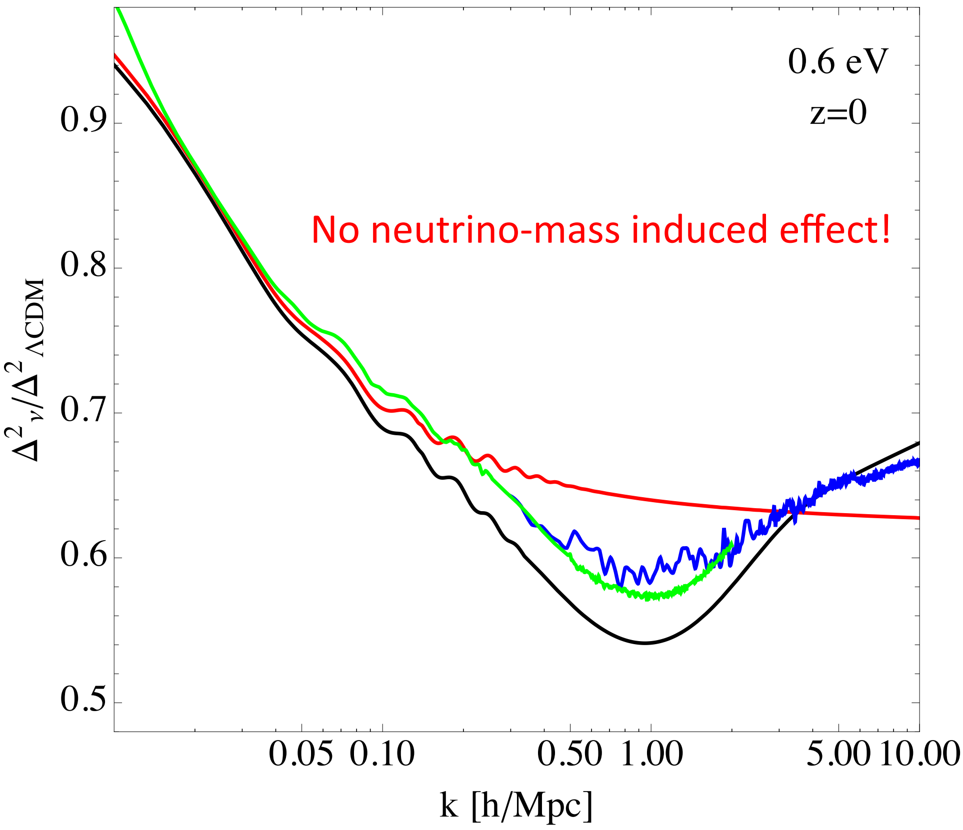




Halo model

Massara, FVN, Viel 2014





$$\frac{P_{\nu\Lambda CDM}(k)}{P_{\Lambda CDM}(k)} \begin{cases} M_\nu = 0.15 \text{ eV} \rightarrow 2\% \\ M_\nu = 0.30 \text{ eV} \rightarrow 5\% \\ M_\nu = 0.60 \text{ eV} \rightarrow 10\% \end{cases}$$

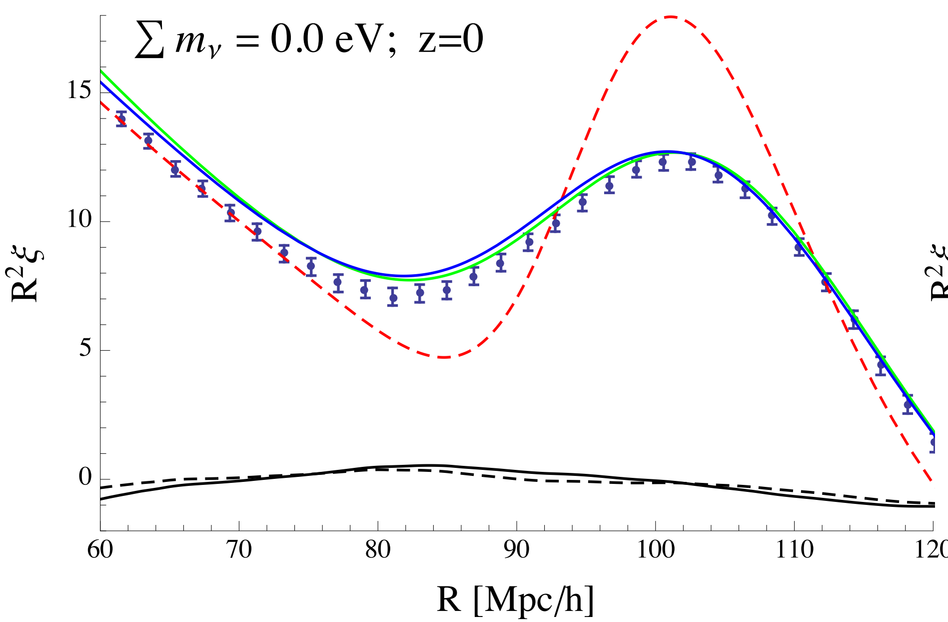
Neutrino effects on BAO

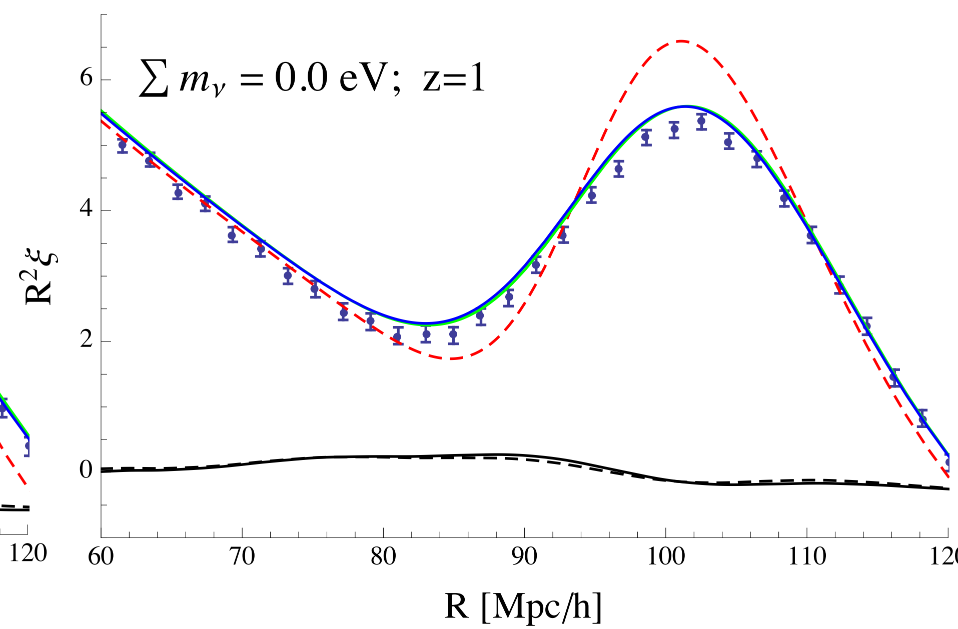
Peloso, Pietroni, Viel, FVN, 2015

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

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

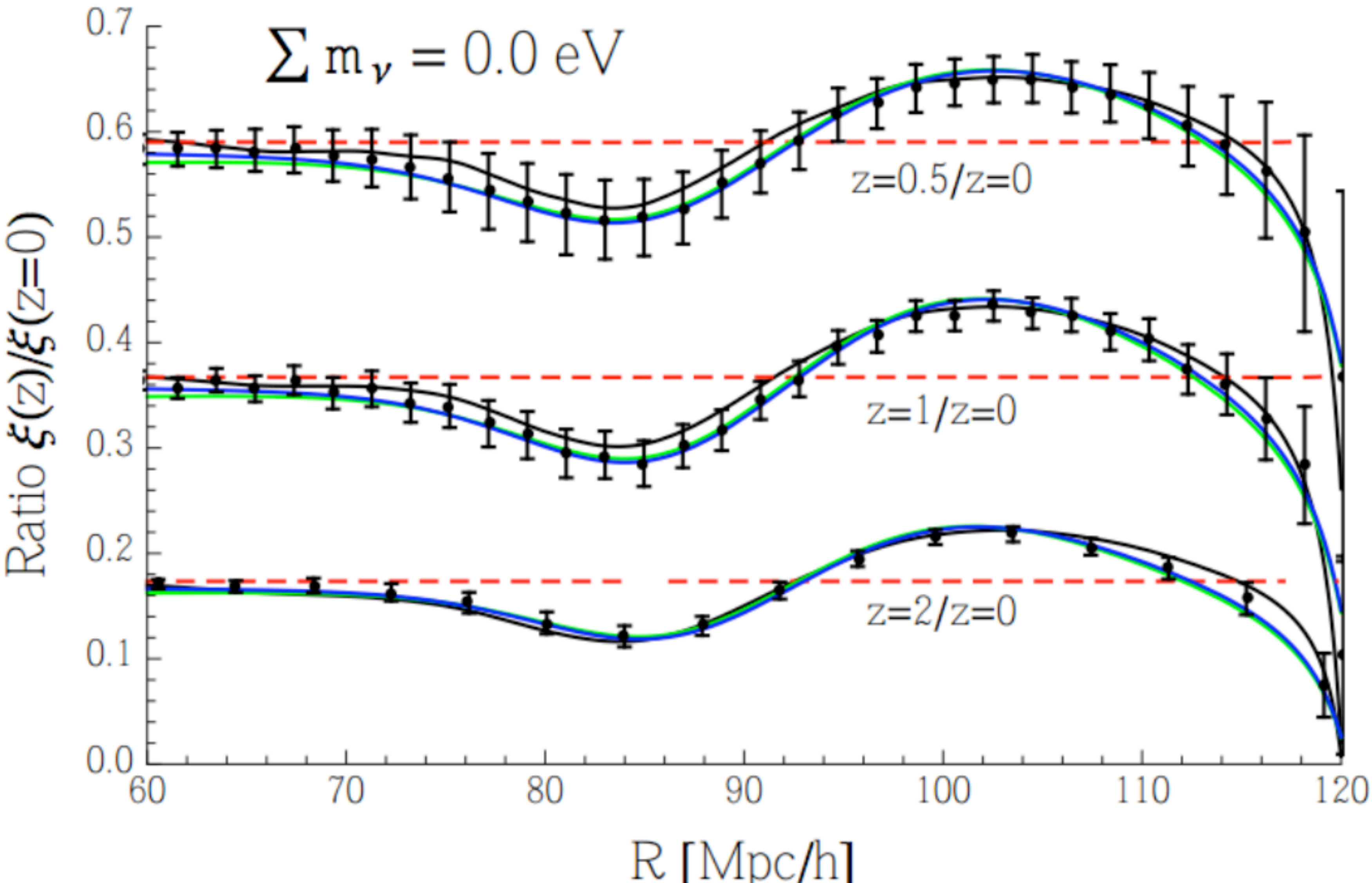
$$\sigma_v^2(z) = \frac{1}{3}\int \frac{d^3q}{(2\pi)^3}\,\frac{P^{lin}(q,z)}{q^2}\,.$$





Neutrino effects on BAO

Peloso, Pietroni, Viel, FVN, 2015



Neutrino effects on BAO

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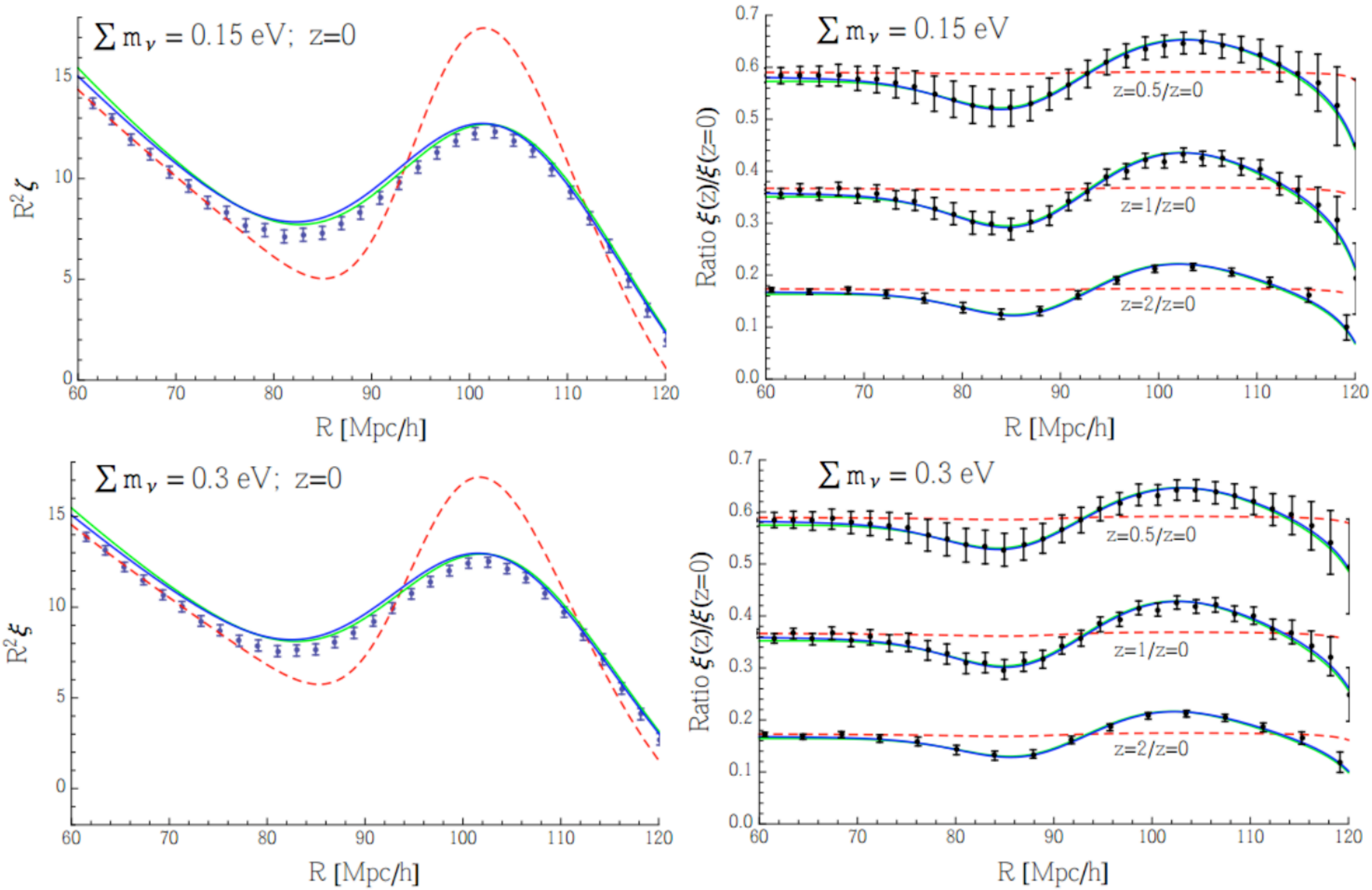
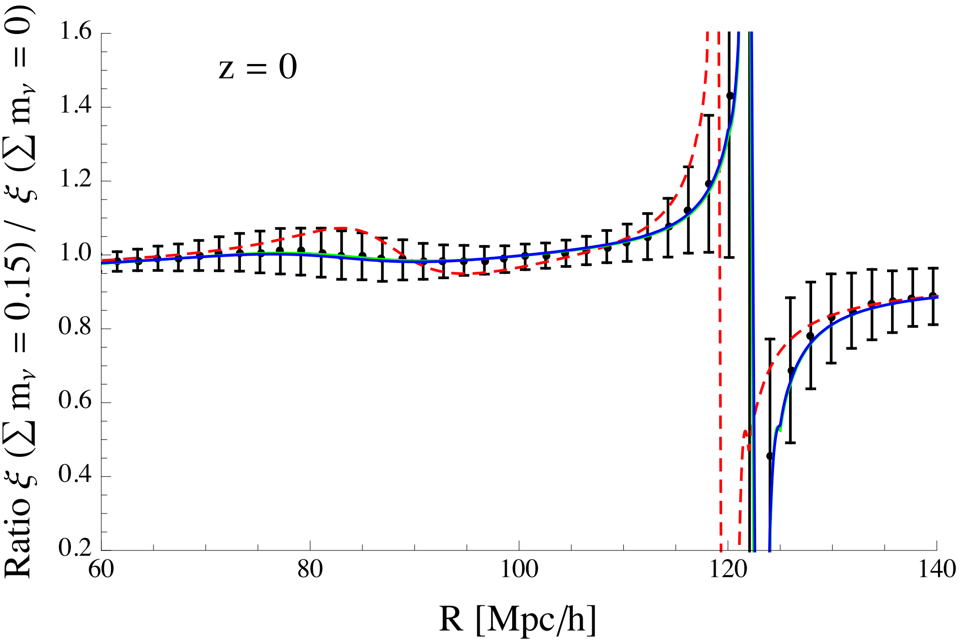
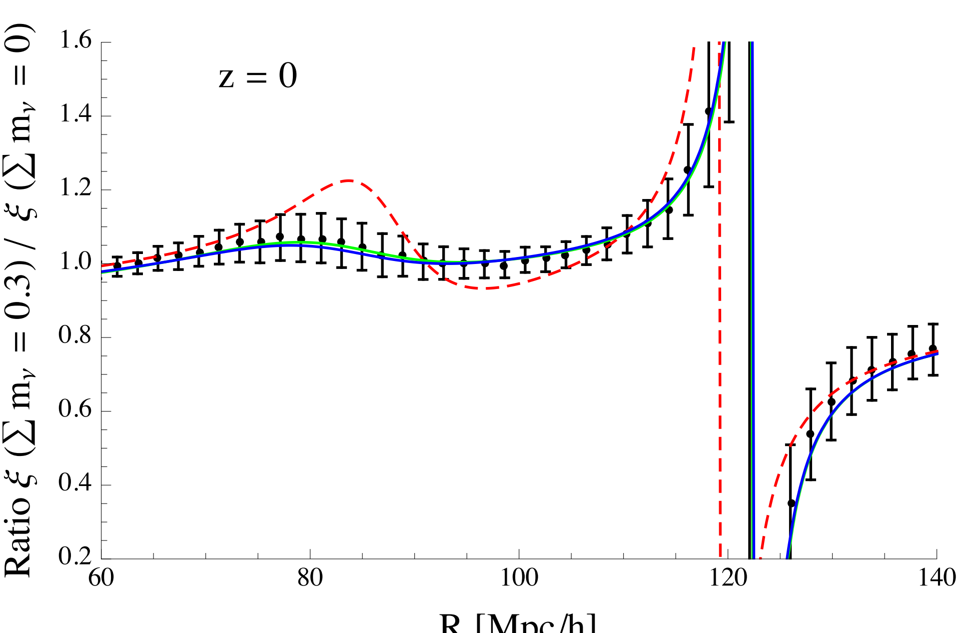
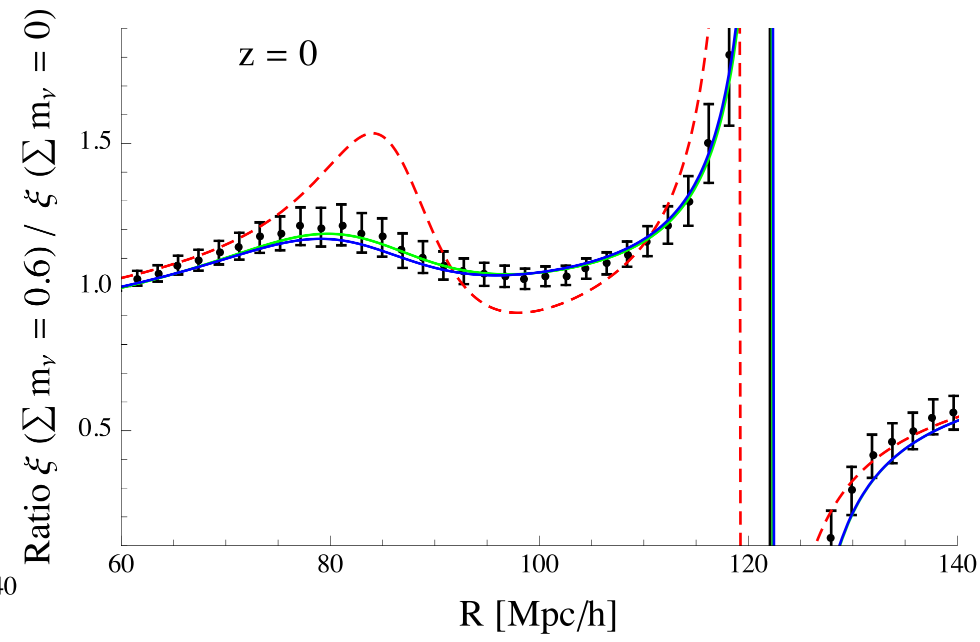


Neutrino effects on BAO

Peloso, Pietroni, Viel, FVN 2015

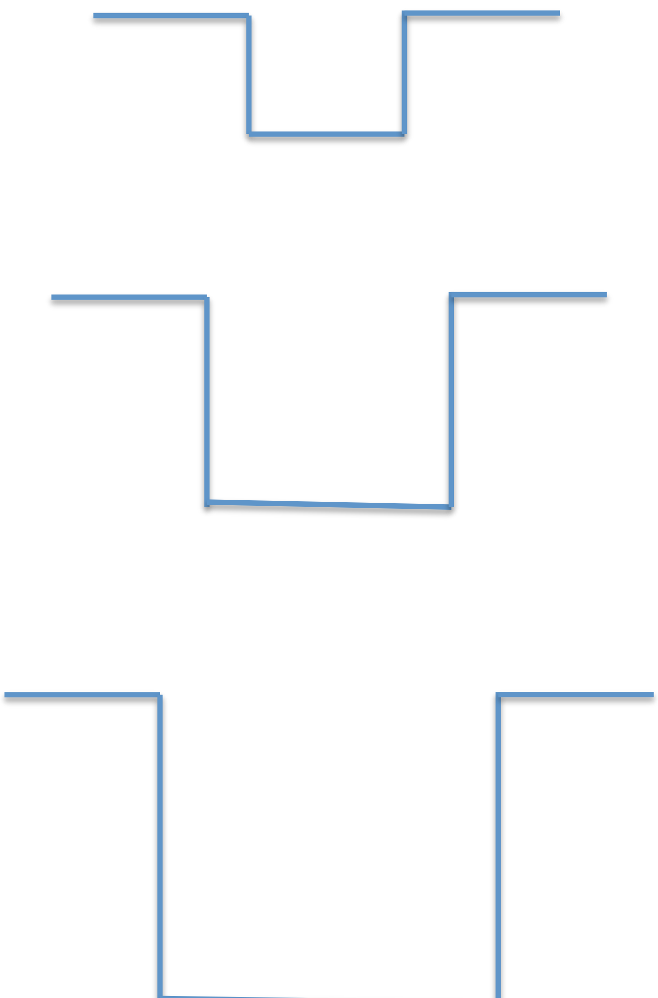




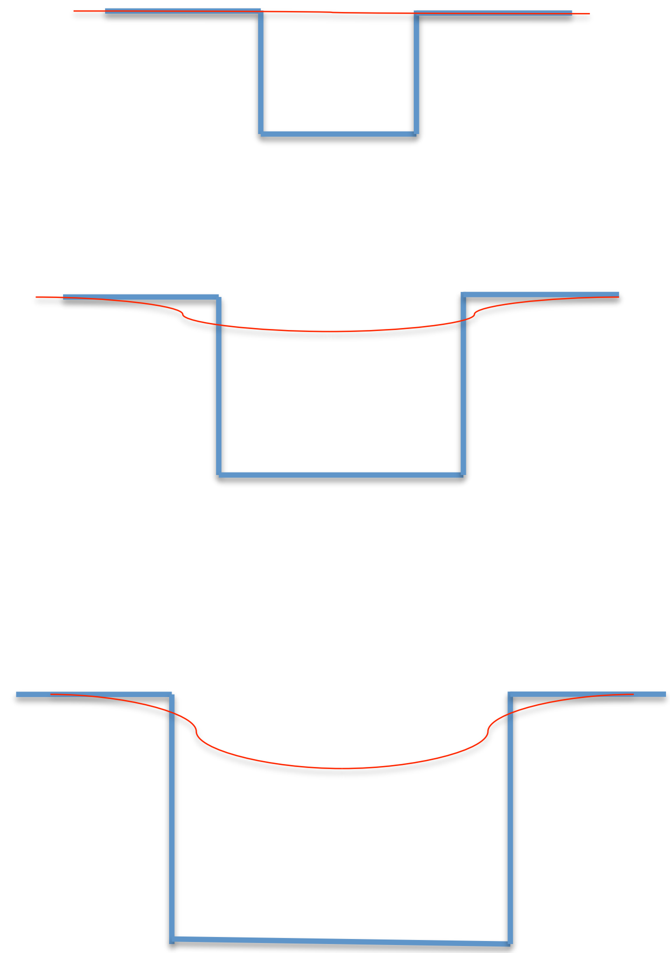


Neutrino effects on voids

Massless neutrinos



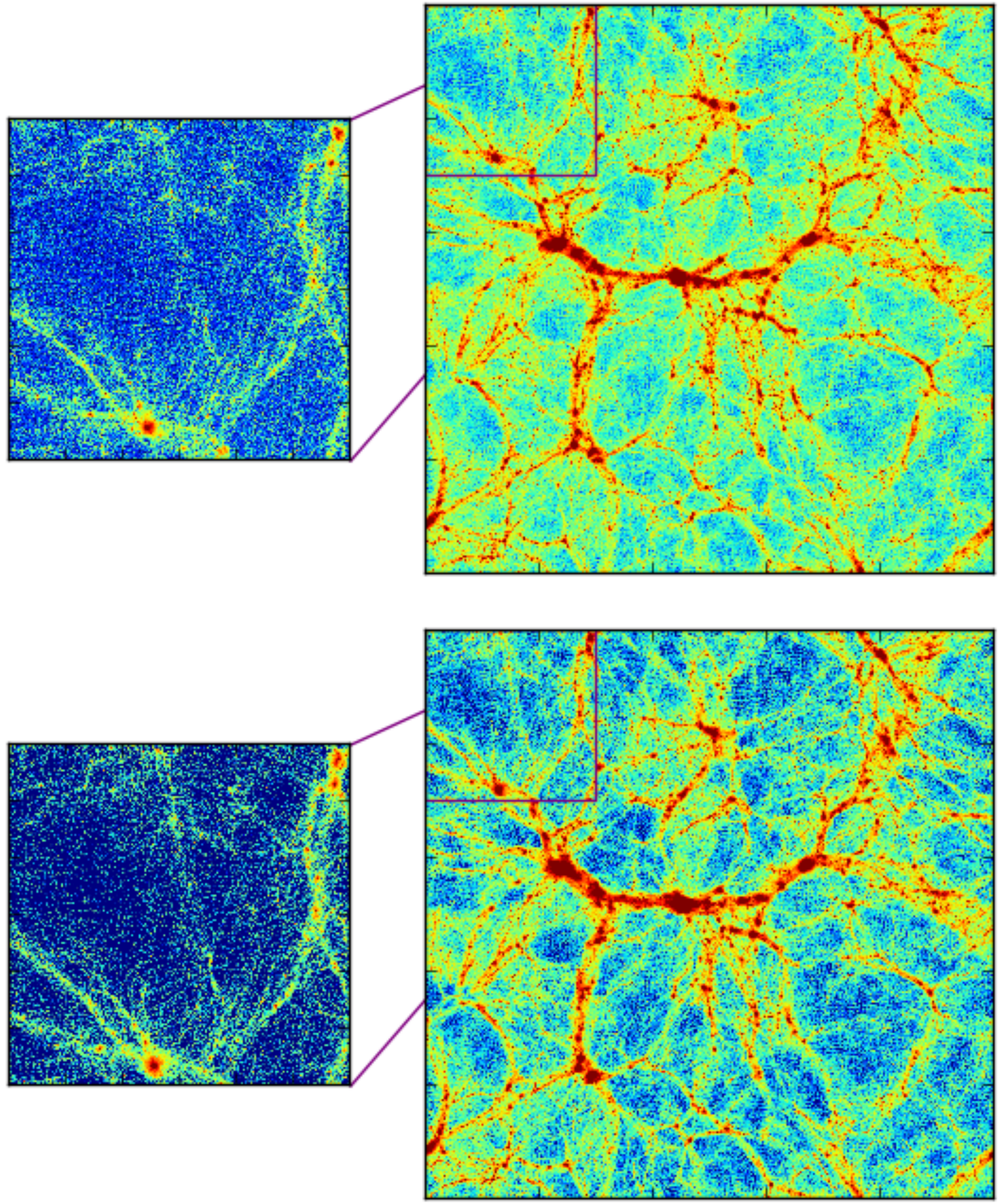
Massive neutrinos



0.6 eV →

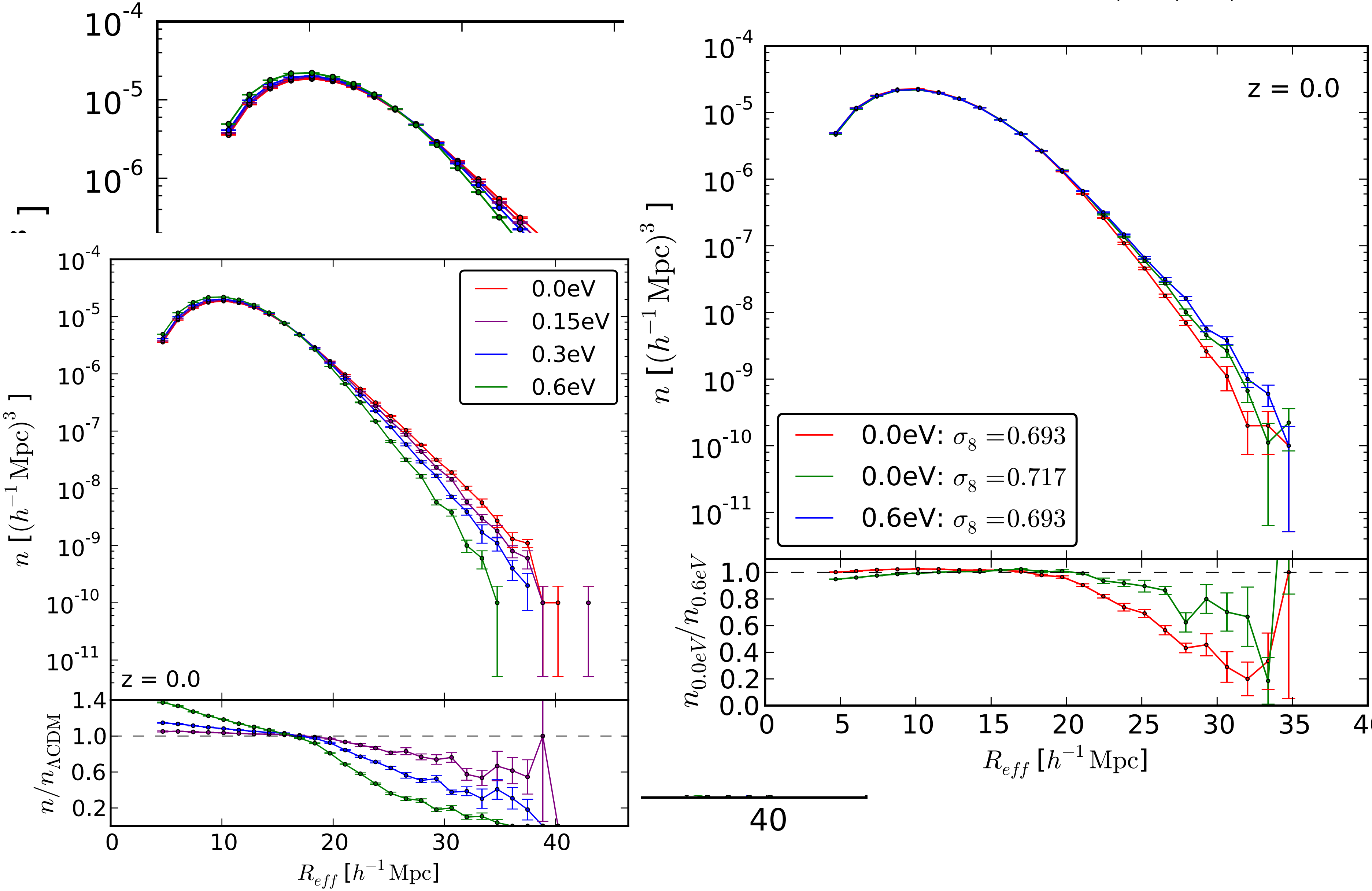
The impact of massive neutrinos on cosmic voids

0.0 eV →



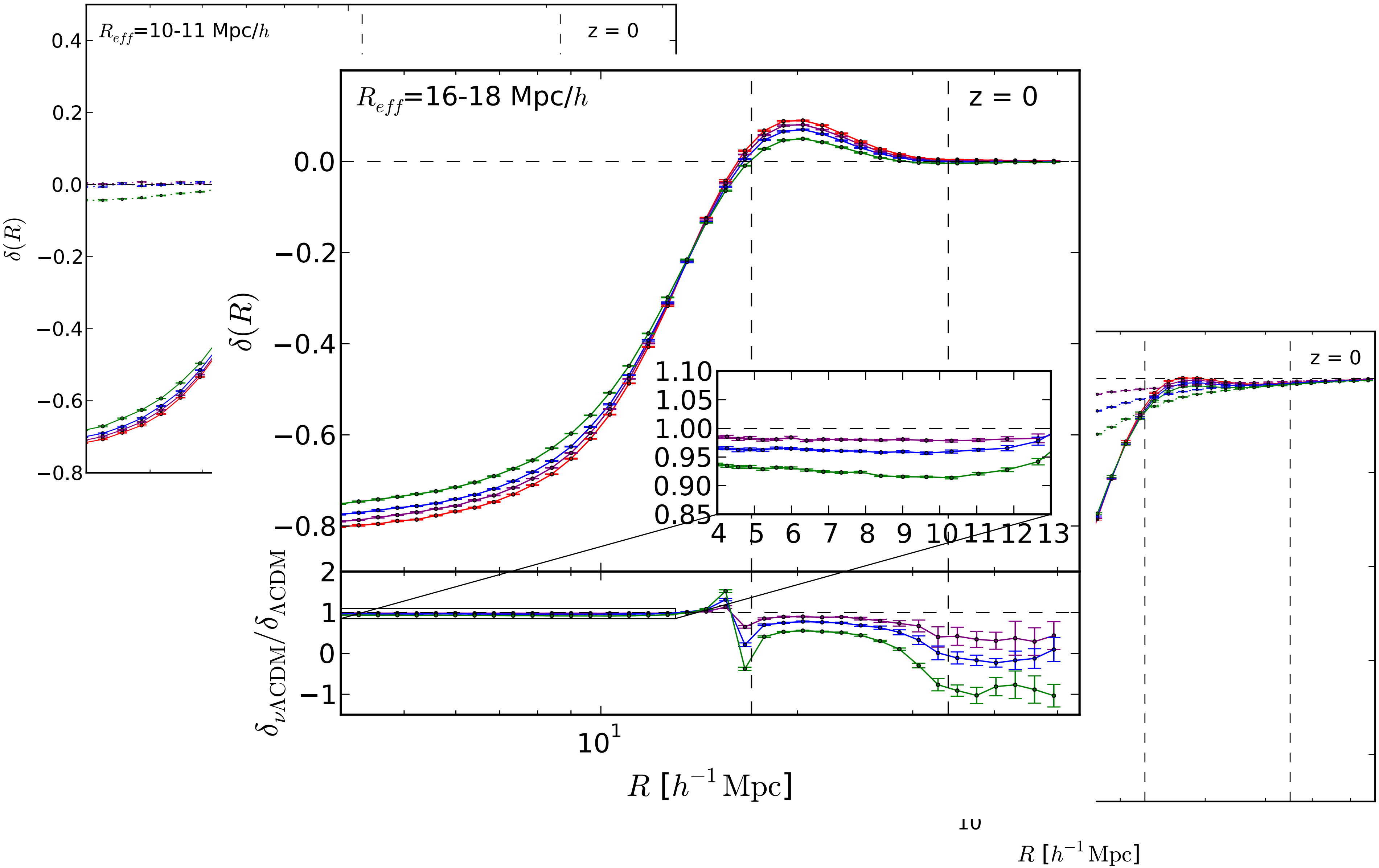
Neutrino effects on voids

Massara, FVN, Viel, Sutter 2015



Neutrino effects on voids

Massara, FVN, Viel, Sutter 2015

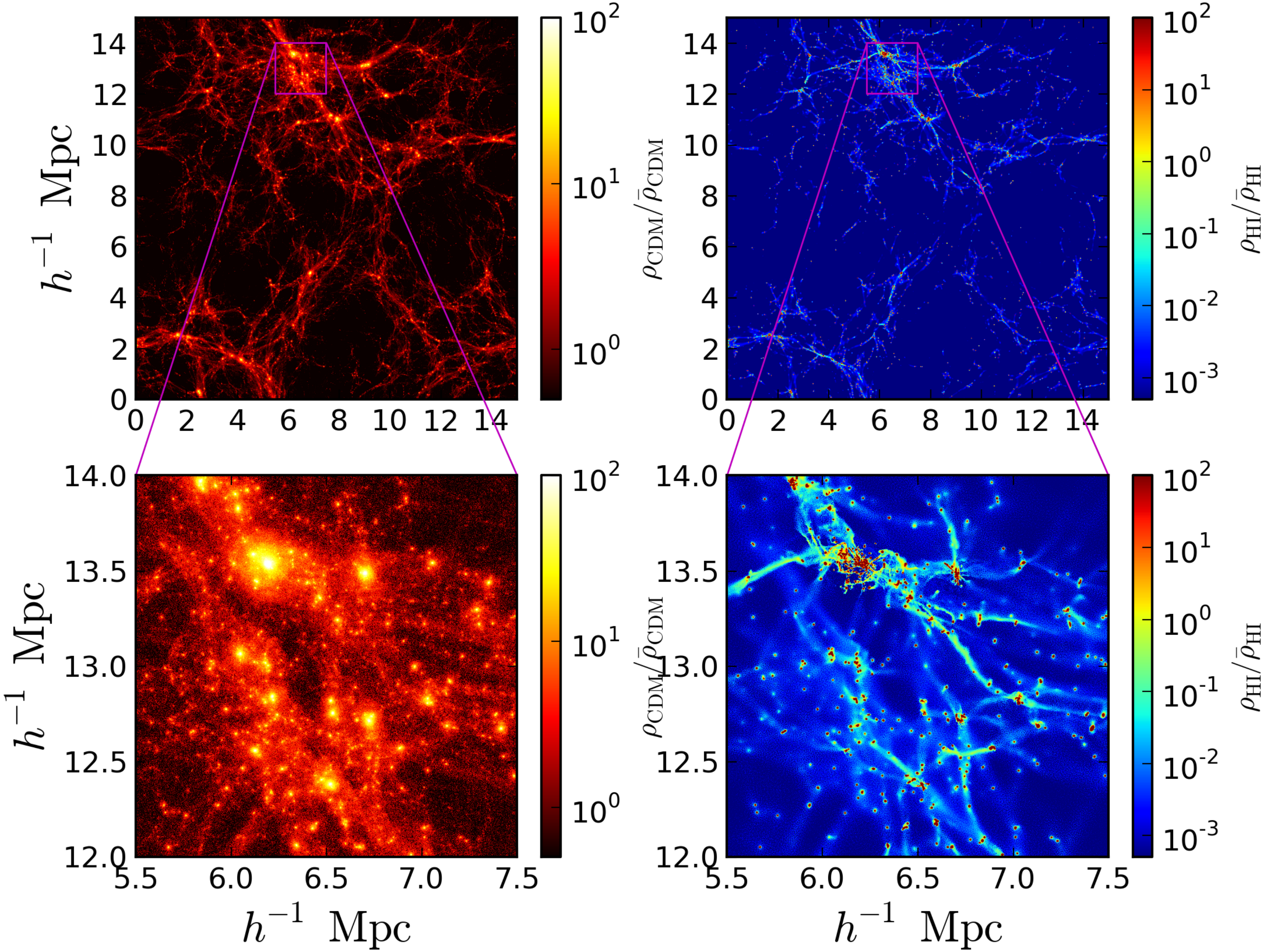


Future constraints from cosmology

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

Weighing neutrinos with cosmic neutral hydrogen

Post-reionization era



Weighing neutrinos with cosmic neutral hydrogen

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

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

Neutrino effects on 21cm

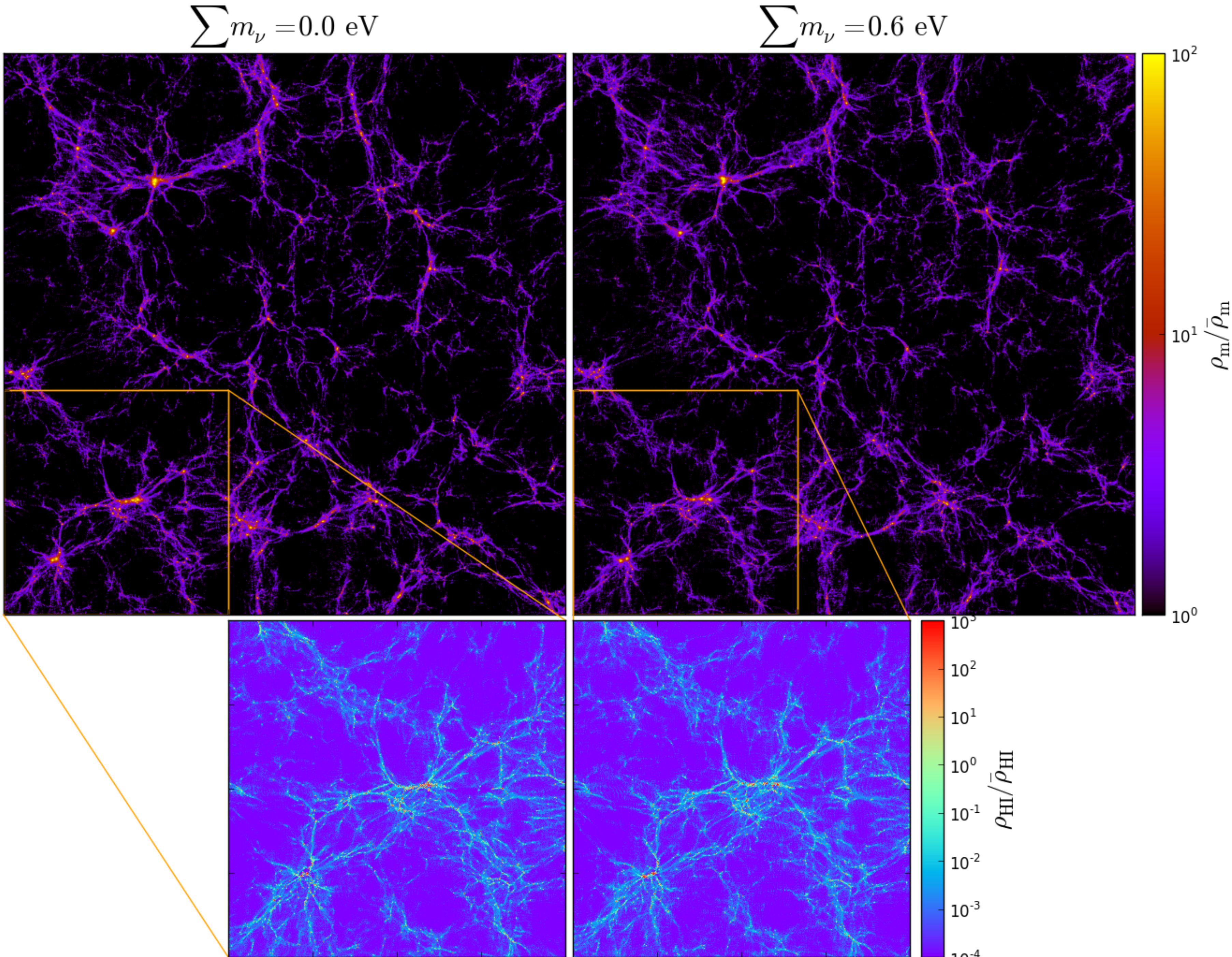
Hydrodynamical simulations

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

HI self-shielding

Presence of H_2

Name	Box (h^{-1}Mpc)	$\Omega_{\rm cdm}$	$\Omega_{\rm b}$	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
$\nu_{\rm m}^+$	50	0.261425	0.049	0.007075	0.6825	0	0.67	0.9624	2.13	0.764
$\nu_{\rm m}^{++}$	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



$\sum m_\nu = 0.0$ eV
$\sum m_\nu = 0.6$ eV
10^2
10^1
10^0
$\rho_{\rm m}/\bar{\rho}_{\rm m}$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\rho_{\rm HI}/\bar{\rho}_{\rm HI}$

Ingredients for 21cm IM

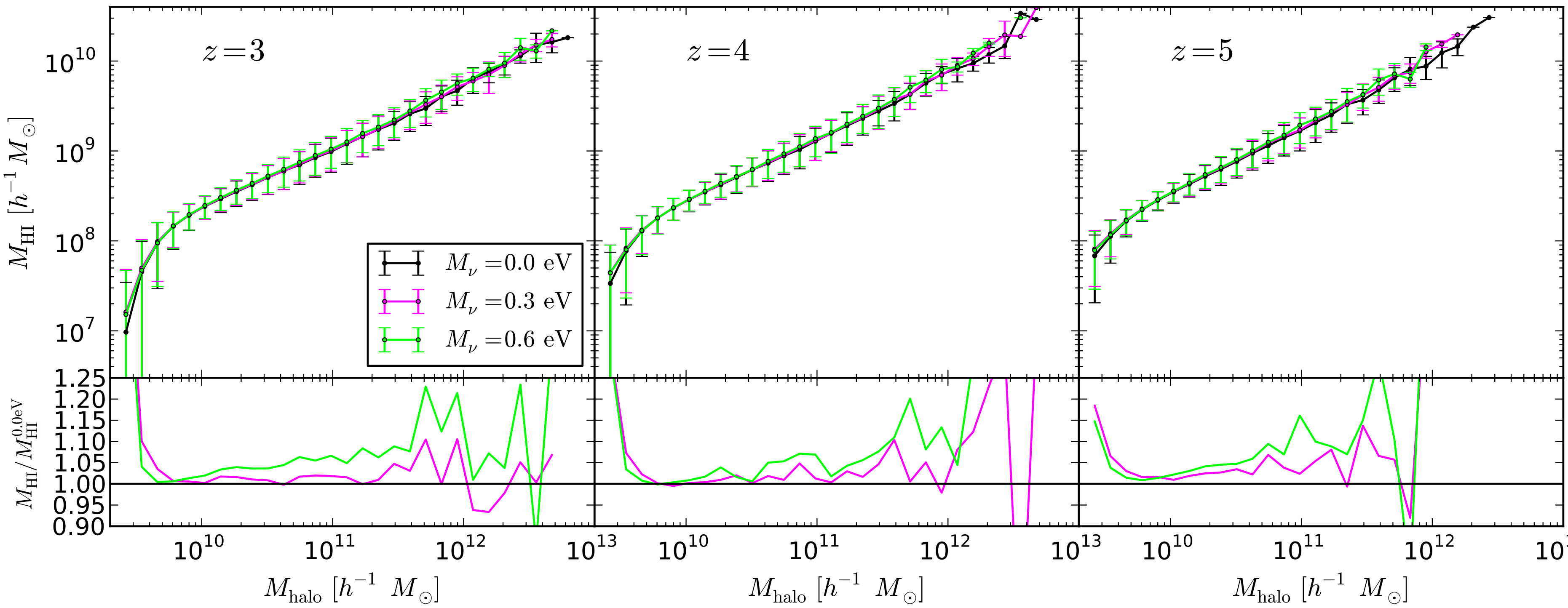
$$M_{HI}(M,z) \left\{ \begin{array}{l} b_{HI}(z) = \dfrac{\int_0^\infty n(M,z)b(M,z)M_{HI}(M,z)\,dM}{\int_0^\infty n(M,z)M_{HI}(M,z)\,dM} \\ \\ \Omega_{HI}(z) = \dfrac{1}{\rho_c^0}\int_0^\infty n(M,z)M_{HI}(M,z)\,dM \end{array} \right.$$

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

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

Neutrino effects on 21cm

FVN, Bull, Viel 2015



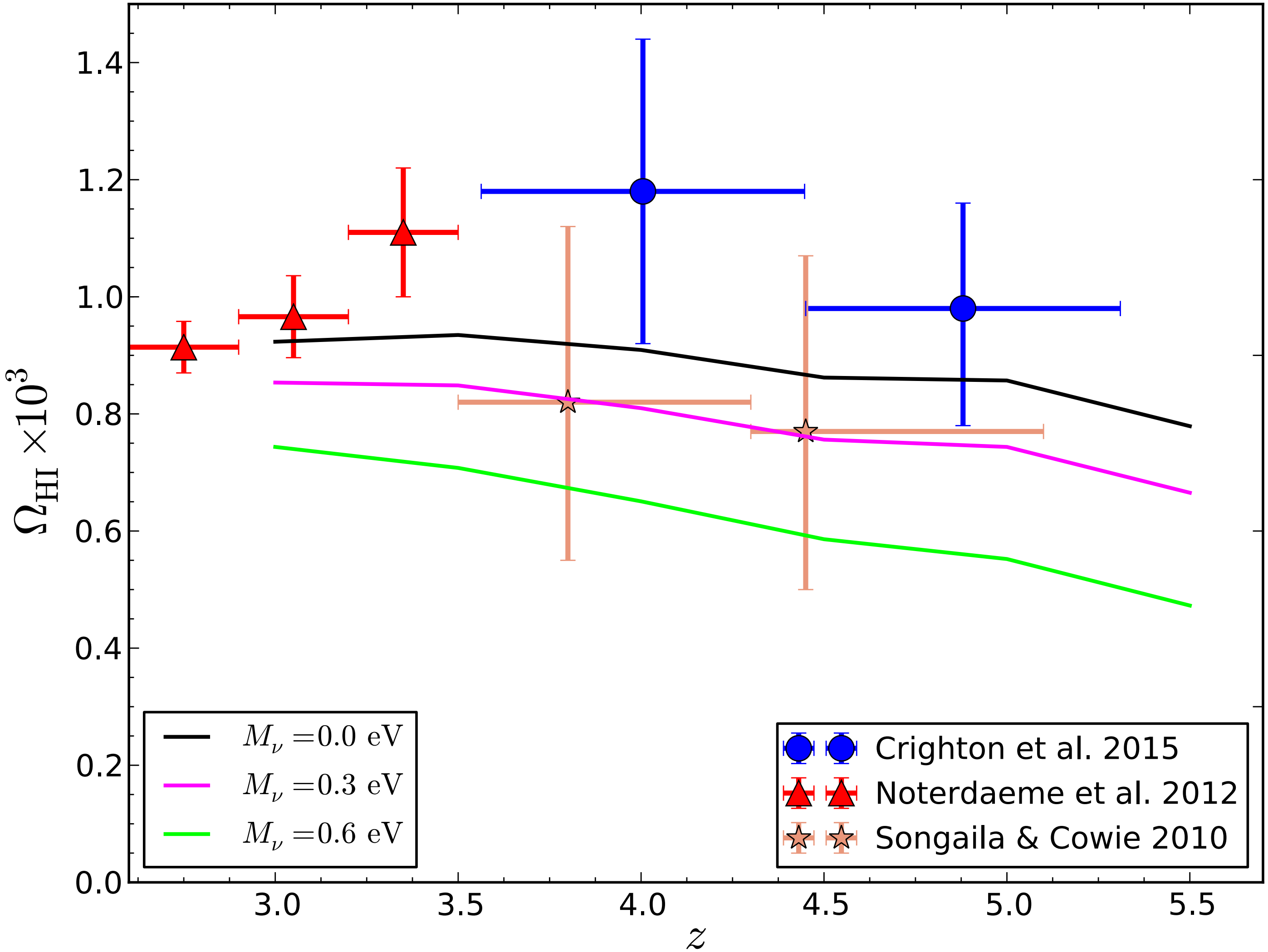
<u>Halos with low masses do not host HI.</u>

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

Neutrino effects on 21cm

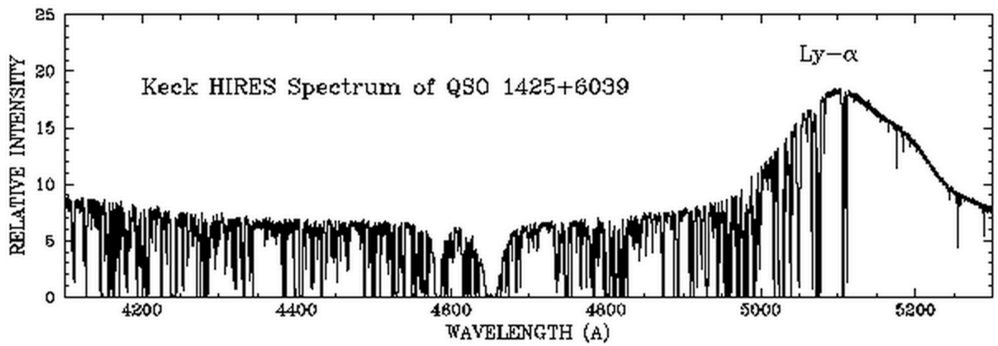
$$\Omega_{HI}(z) = \frac{1}{\rho_c^0}\int_0^\infty n(M,z)M_{HI}(M,z)\,dM$$

FVN, Bull, Viel 2015

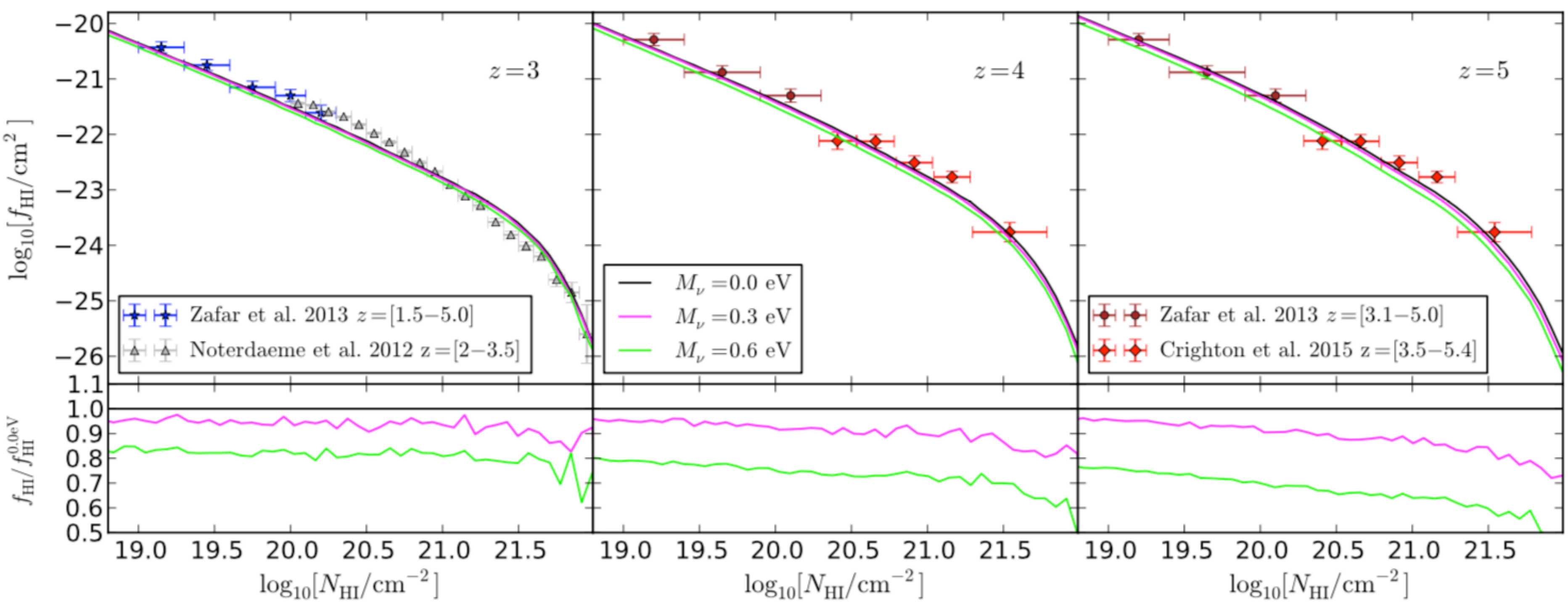


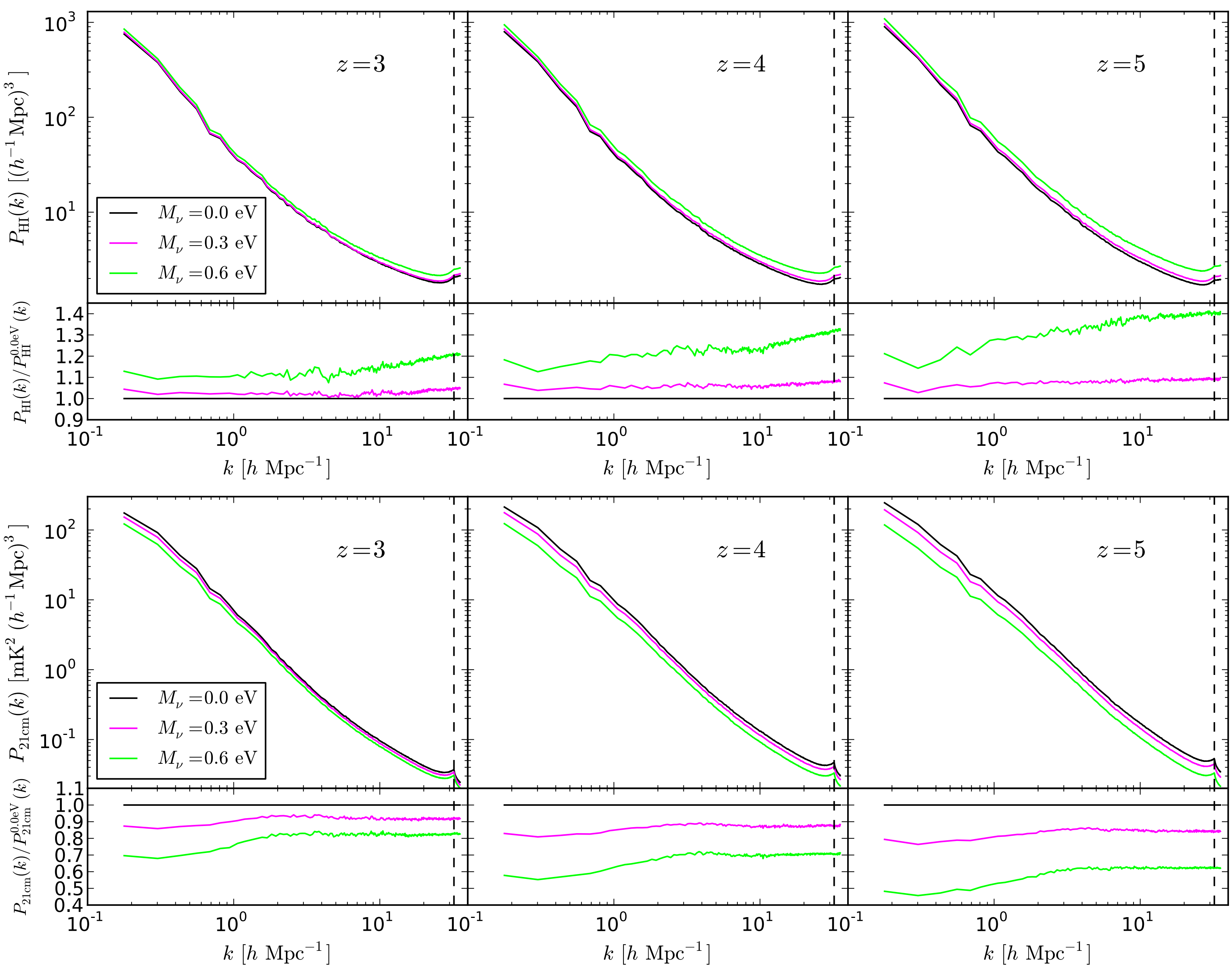
Neutrino effects on 21cm

FVN, Bull, Viel 2015



$$f_{HI}(N_{HI}) = \frac{d^2 n}{dN_{HI} dX}$$



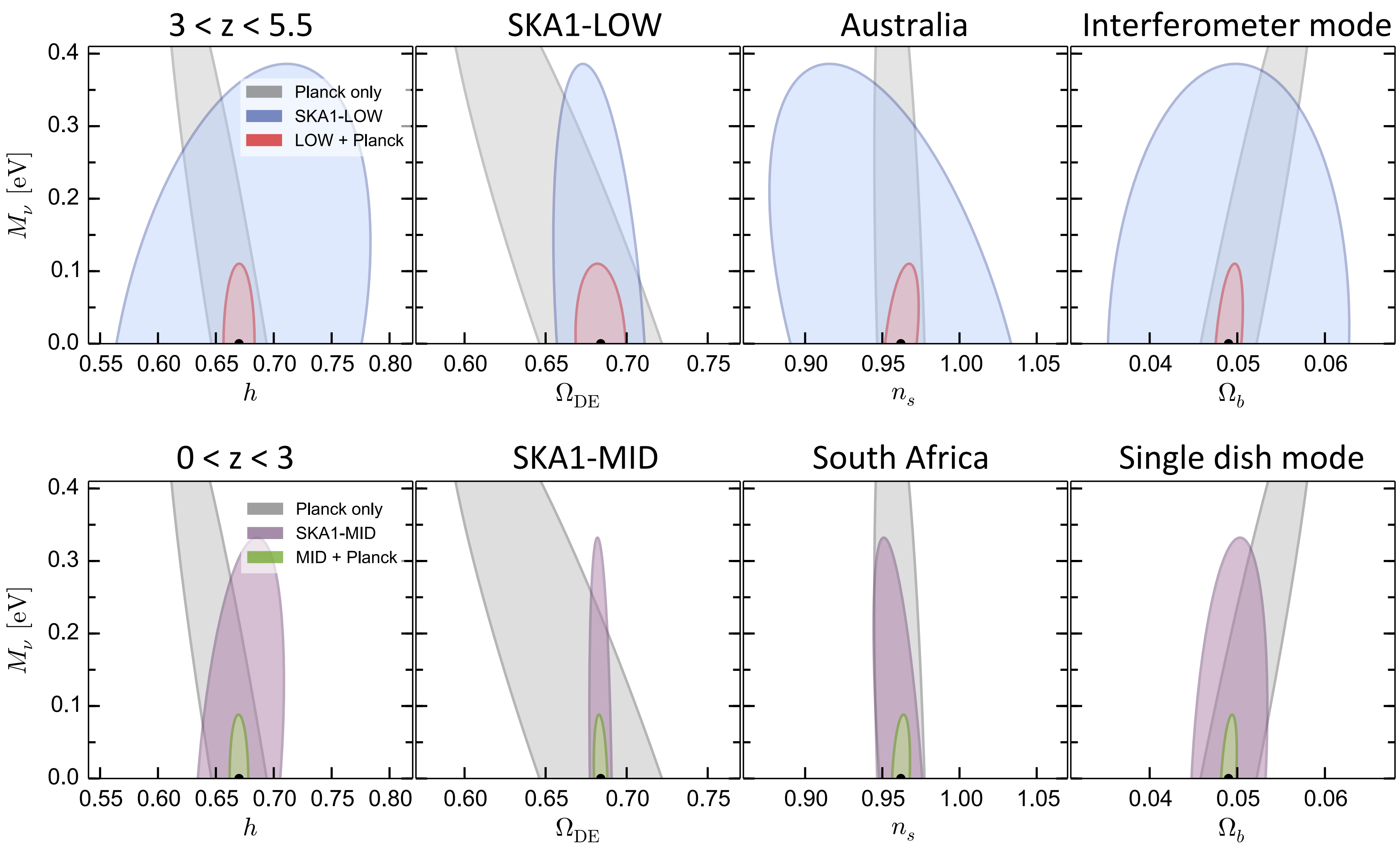


FVN, Bull, Viel 2015

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

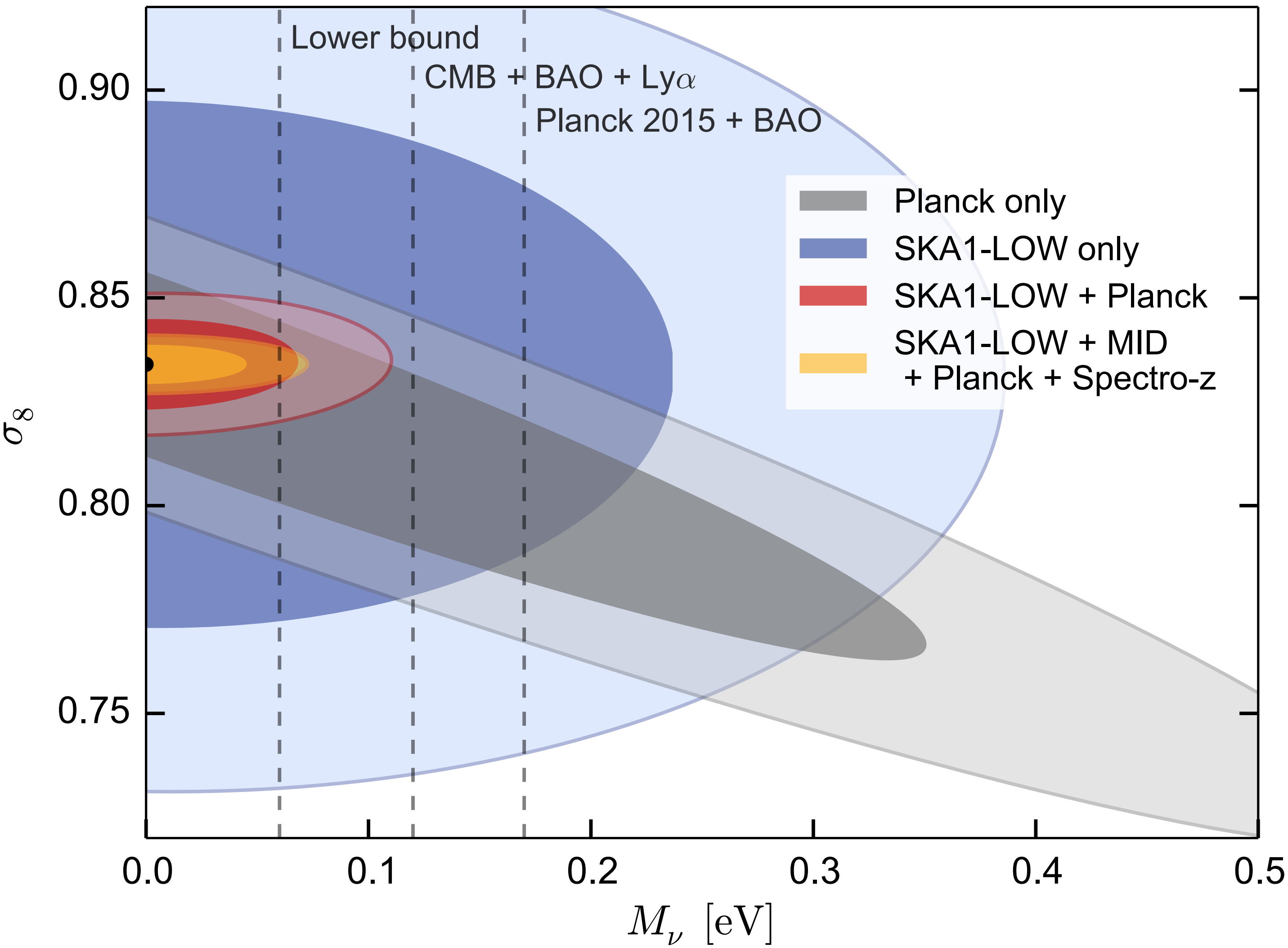
Forecasts for SKA

FVN, Bull, Viel 2015



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_ν<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)