Cosmological Neutrinos

Matteo Viel – SISSA - viel@sissa.it

Multi messenger School - Asiago *17th January 2020*

CONCLUSIONS

QUESTIONS TO BE ADDRESSED

1) Can they be probed by looking at their energy density contribution?

YES, mainly by CMB experiments

2) Can they be probed by looking at their perturbations?

Not yet in the LSS but yes in the CMB

3) Have we detected departures from the standard/expected Cosmic Neutrino Background (CNB)?

Not convincingly

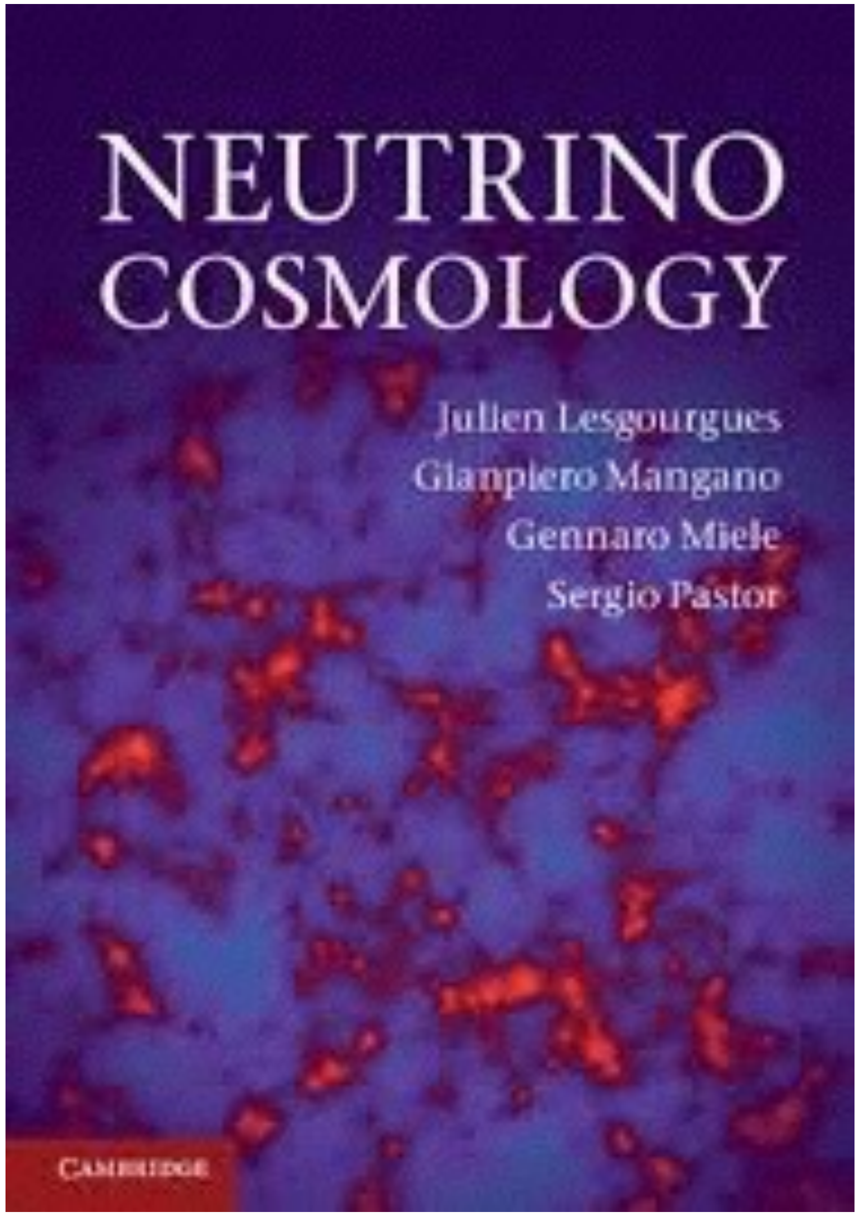
4) Are these findings robust?

Subject to model assumptions and known systematics (marginalized over)

5) Are there perspectives of discoveries in the next few years?

Bright, multi-probe future ahead with sensitivities from 15 to 30 meV

Almost everything you want to know….



COSMIC NEUTRINO BACKGROUND

The cosmological neutrino background

Predicted in 1953 with correct temperature ($T_\nu = (4/11)^{4/3}\, T_\gamma$) by *Alpher, Follin & Herman*:

PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Physical Conditions in the Initial Stages of the Expanding Universe*·†

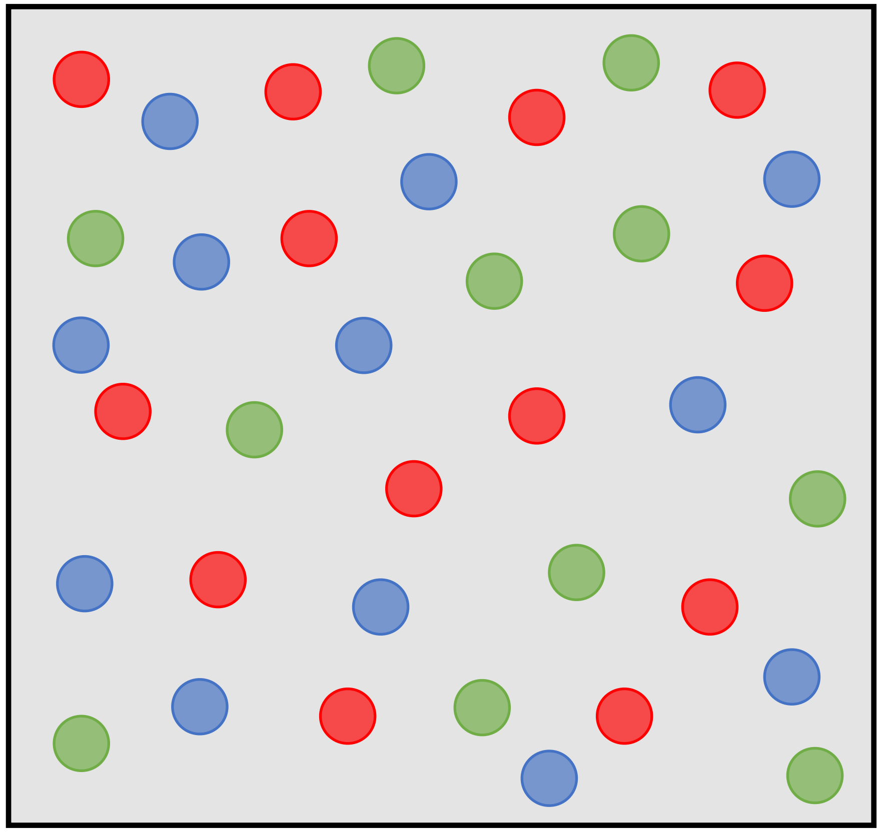
RALPH A. ALPHER, JAMES W. FOLLIN, JR., AND ROBERT C. HERMAN
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
(Received September 10, 1953)

How can we probe this?
studying energy density?
studying perturbations?

…is there more to be probed?

Neutrino decoupling from SM

$T > 10^{10}\,\mathrm{K} \sim 1\ \mathrm{MeV}$

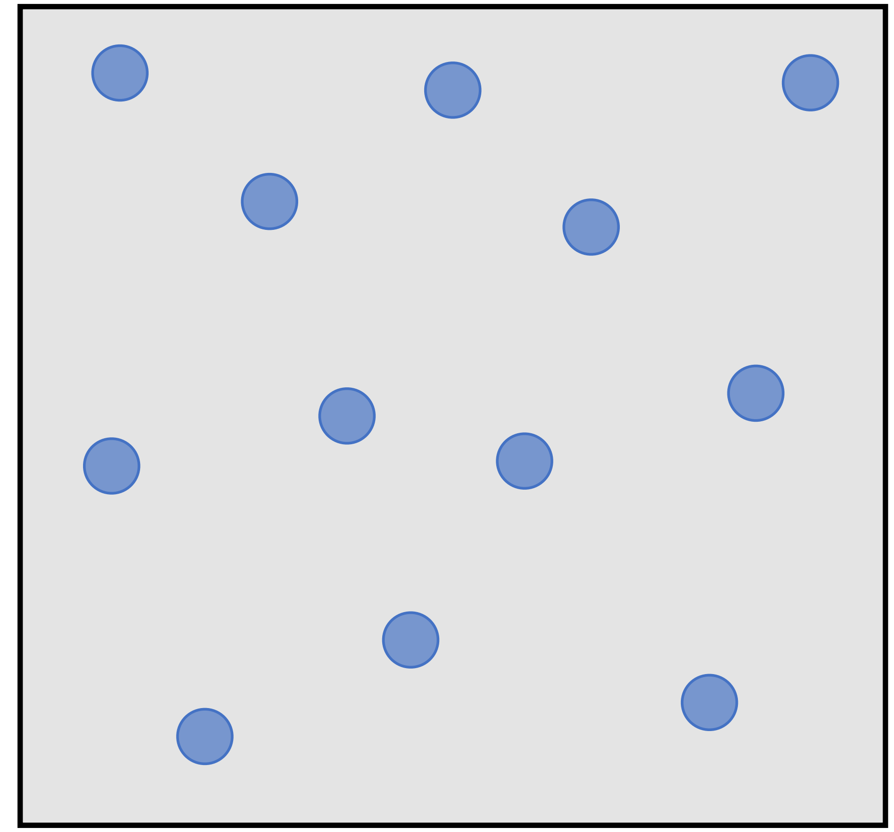


- Neutrinos
- Antineutrinos

- Photons

- Electrons
- Positrons

$T < 10^{10}\,\mathrm{K} \sim 1\ \mathrm{MeV}$



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

$$n_\nu(p,T)dp = \frac{4\pi g_\nu}{(2\pi\hbar c)^3}\left(\frac{p^2 dp}{e^{\left(\sqrt{p^2+m_\nu^2}/k_B T\right)}+1}\right)$$

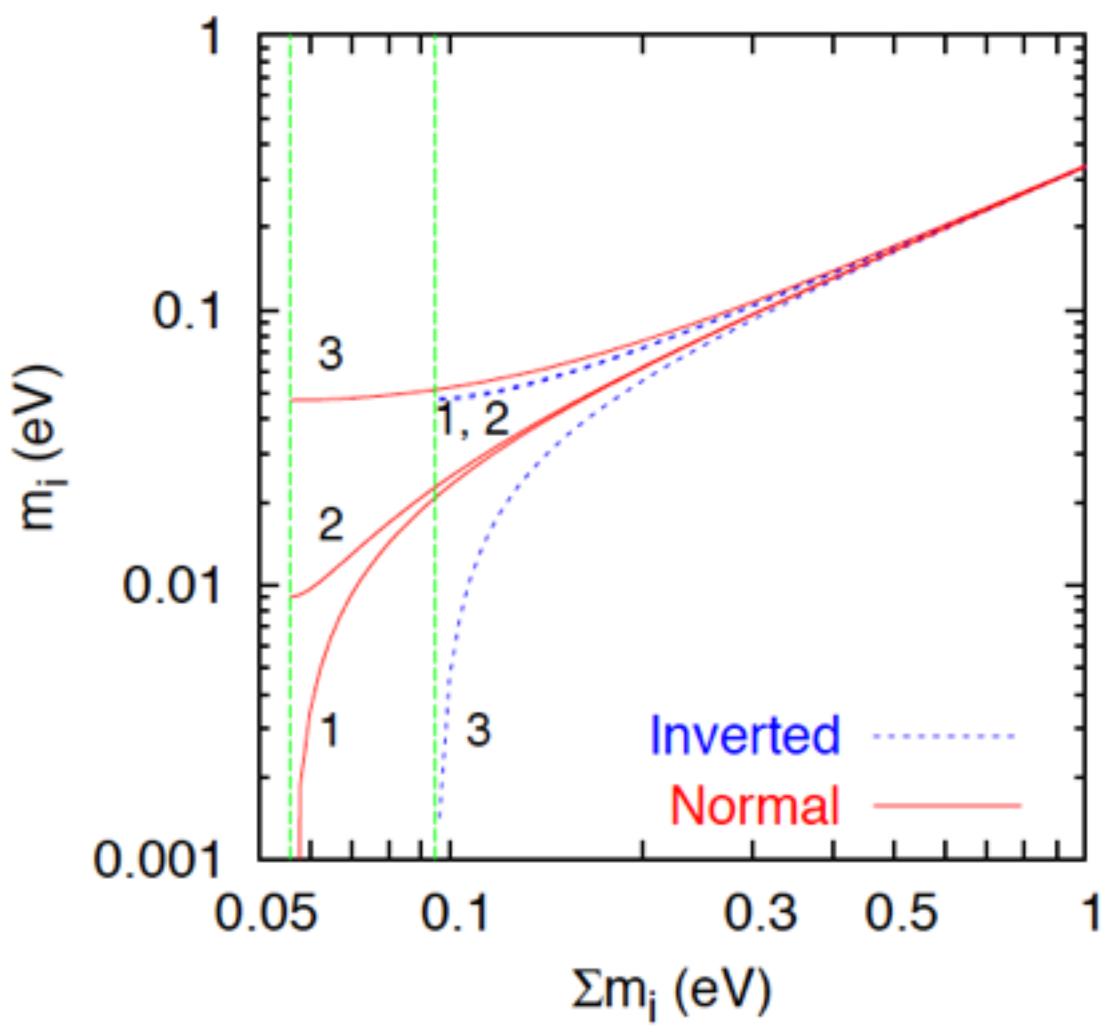
$$n_\nu(p,z)dp \cong \frac{4\pi g_\nu}{(2\pi\hbar c)^3}\left(\frac{p^2 dp}{e^{\left(p/k_B T_\nu(z)\right)}+1}\right)$$

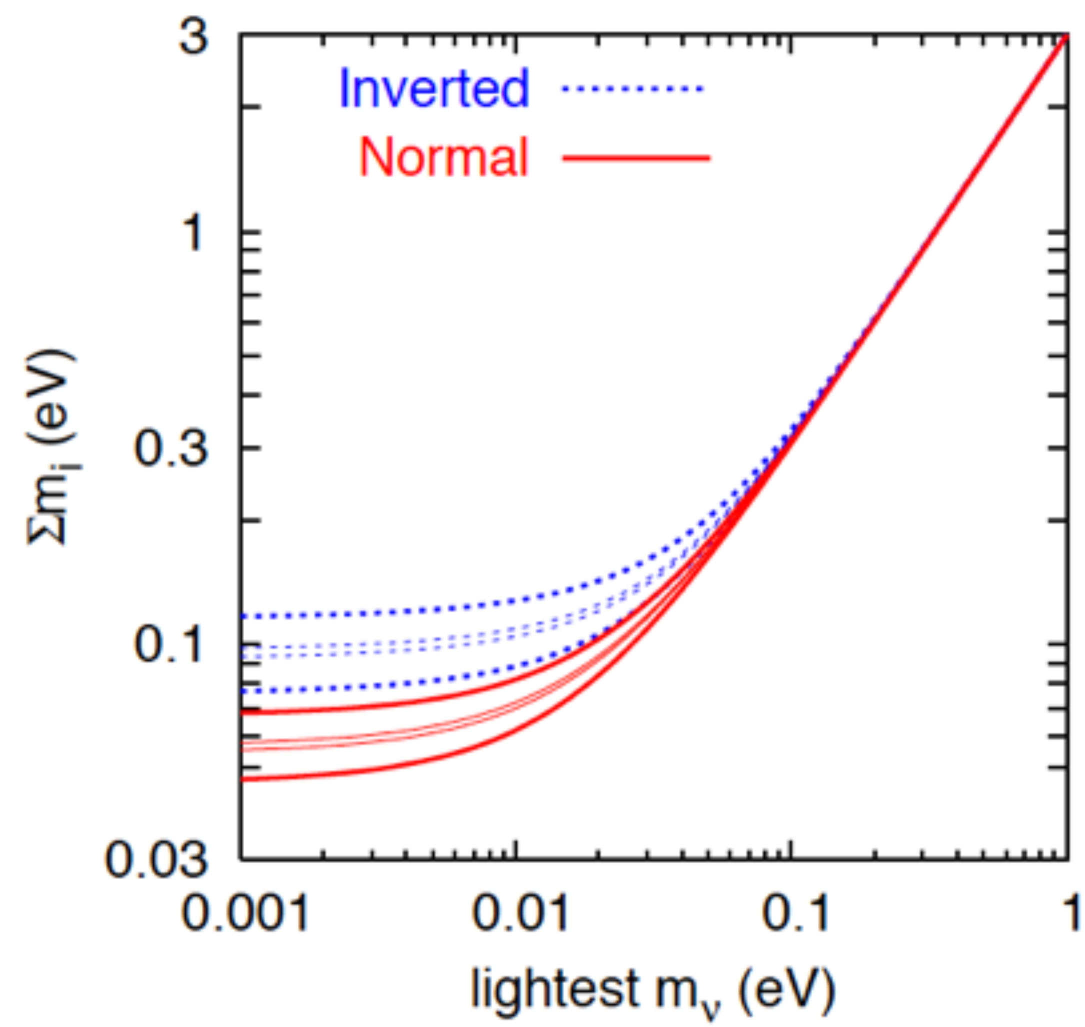
The present Universe is filled by a relic neutrino background with T = 1.9 K and n = 113 part/cm³ per species but… see later!

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

Particle Physics Starting Point

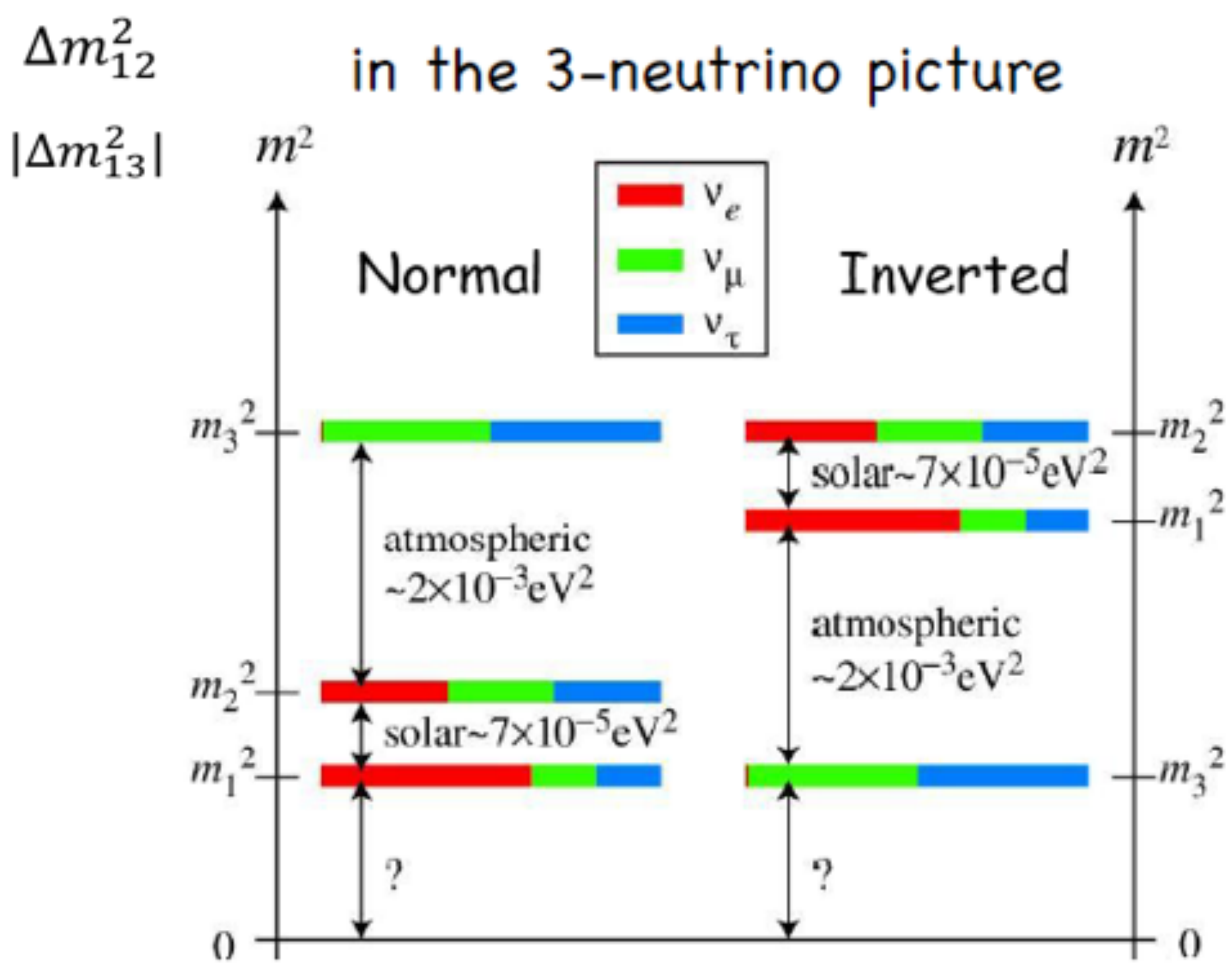
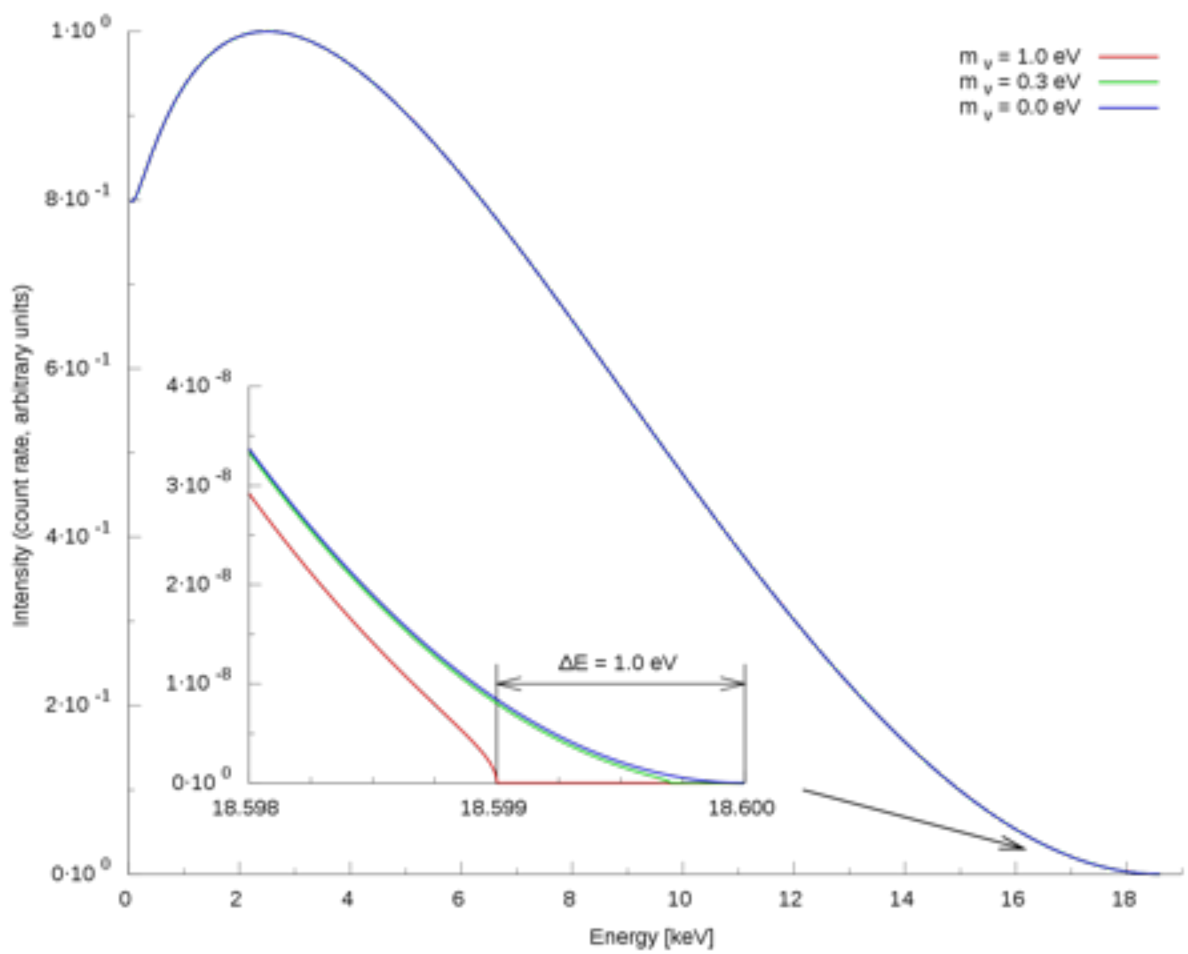
Lesgourges&Pastor 2005





$$0.056\,(0.095)\ \mathrm{eV} \lesssim \sum_i m_i \lesssim 6\ \mathrm{eV}$$

Particle Physics Starting Point - II

Neutrino oscillations	Tritium beta decay experiments
	
$\sum m_\nu > 0.06$ eV $\quad$ $\sum m_\nu > 0.10$ eV	$m(\bar{\nu}_e) \leq 2.3$ eV (95% C.L.)

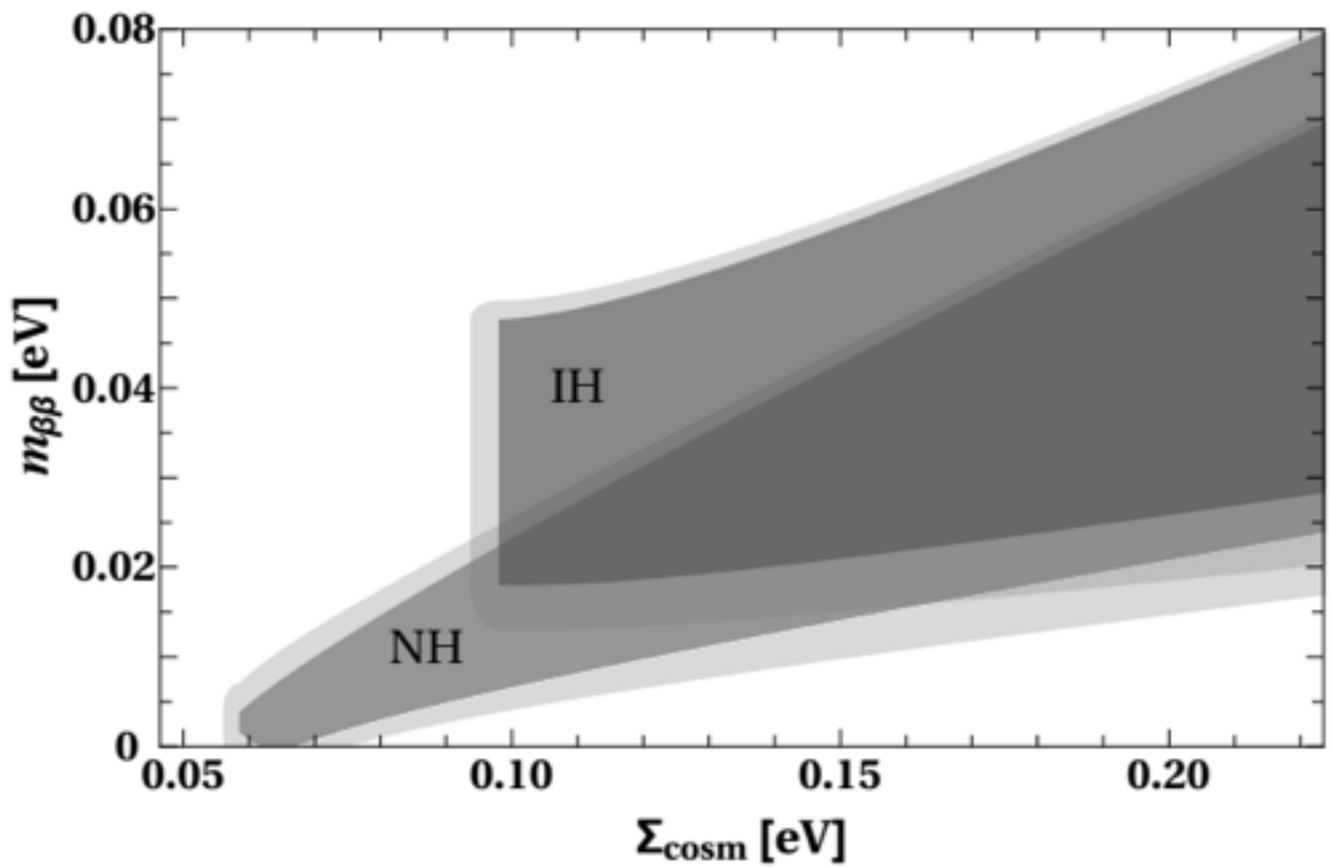
$$0.06 \text{ eV} < \sum m_\nu < 6.9 \text{ eV}$$

see Katrin experiment

Particle Physics Starting Point - III

Or neutrinoless double beta decay

$$(A, Z) \to (A, Z+2) + 2e^-.$$



Dell'Oro, Marcocci, MV, Vissani 2016 Review
arXiv: 1601.07512

Matter or Radiation?

Neutrinos are non relativistic today

$$\rho_\nu = m_\nu n_\nu = m_\nu g_\nu \int f(p) d^3p \propto m_\nu g_\nu T_\nu^3$$

$$\Omega_\nu = \sum_\nu \frac{\rho_\nu}{\rho_c} = \frac{\sum_\nu m_\nu}{93.14 h^2 \text{ eV}}$$

But were relativistic at decoupling

$$\rho_\nu = g_\nu \int p f(p) d^3p \propto g_\nu T_\nu^4$$

$$\rho_{\text{rad}} = \rho_\nu + \rho_\gamma = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\nu\right] \rho_\gamma$$

Energy densities

Alpher et al.'s prediction with refined neutrino decoupling at ~ 1 MeV, and update to 3 ν□s, leads to :

$$\omega_R = \omega_\gamma \, (1 + N_{eff} \times 7/8 \, (4/11)^{4/3}) \quad \text{with } N_{eff} = 3.046$$

in relativistic regime, and contribution to matter density for $T_\nu < m_\nu$:

$$\omega_M = \omega_b + \omega_{CDM} + (\Sigma \, m_\nu) \, / \, 93.14 \text{ eV}$$

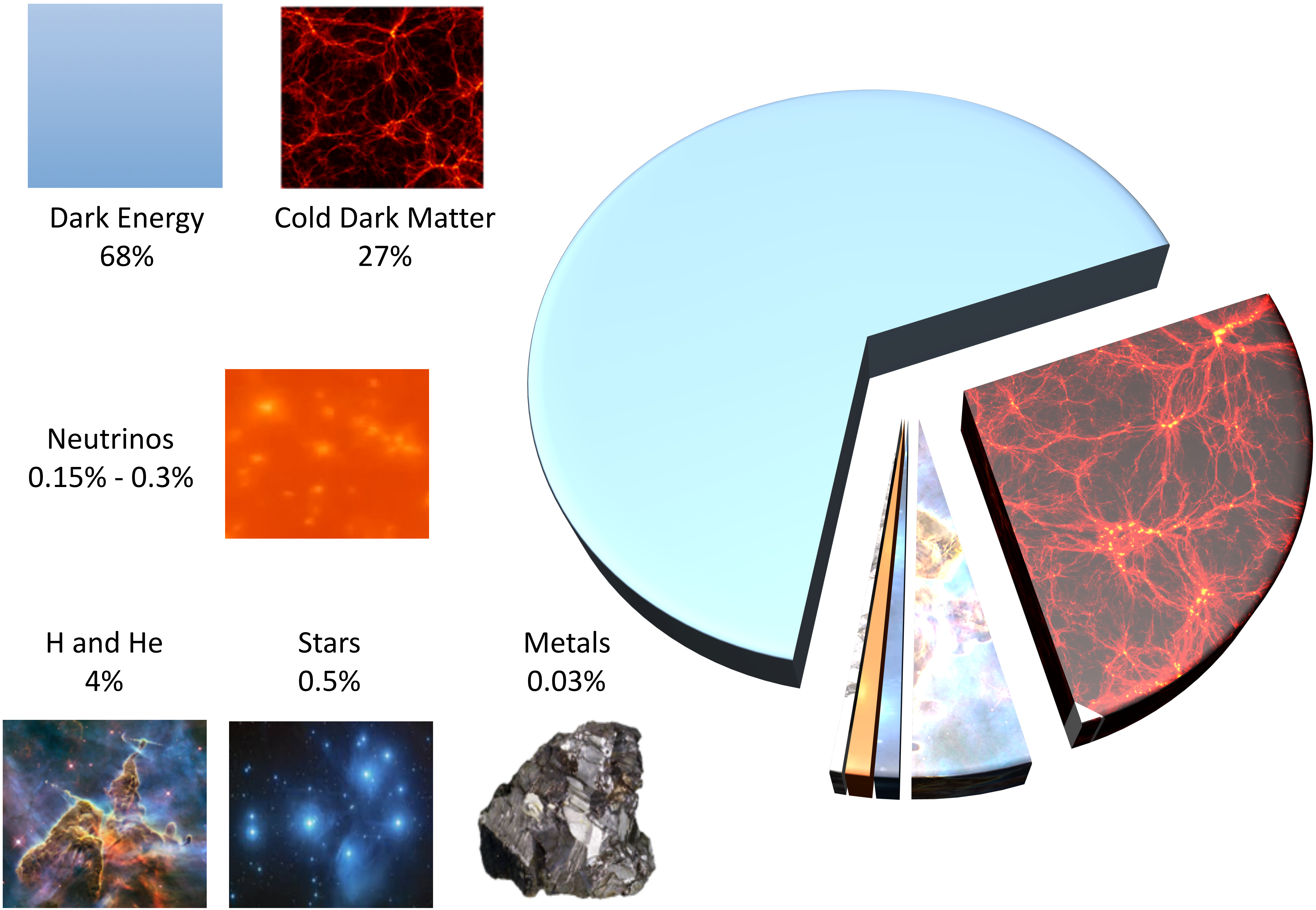
$\downarrow$

Impact on d_{Arec}, θ_s can be compensated by decreasing H_0

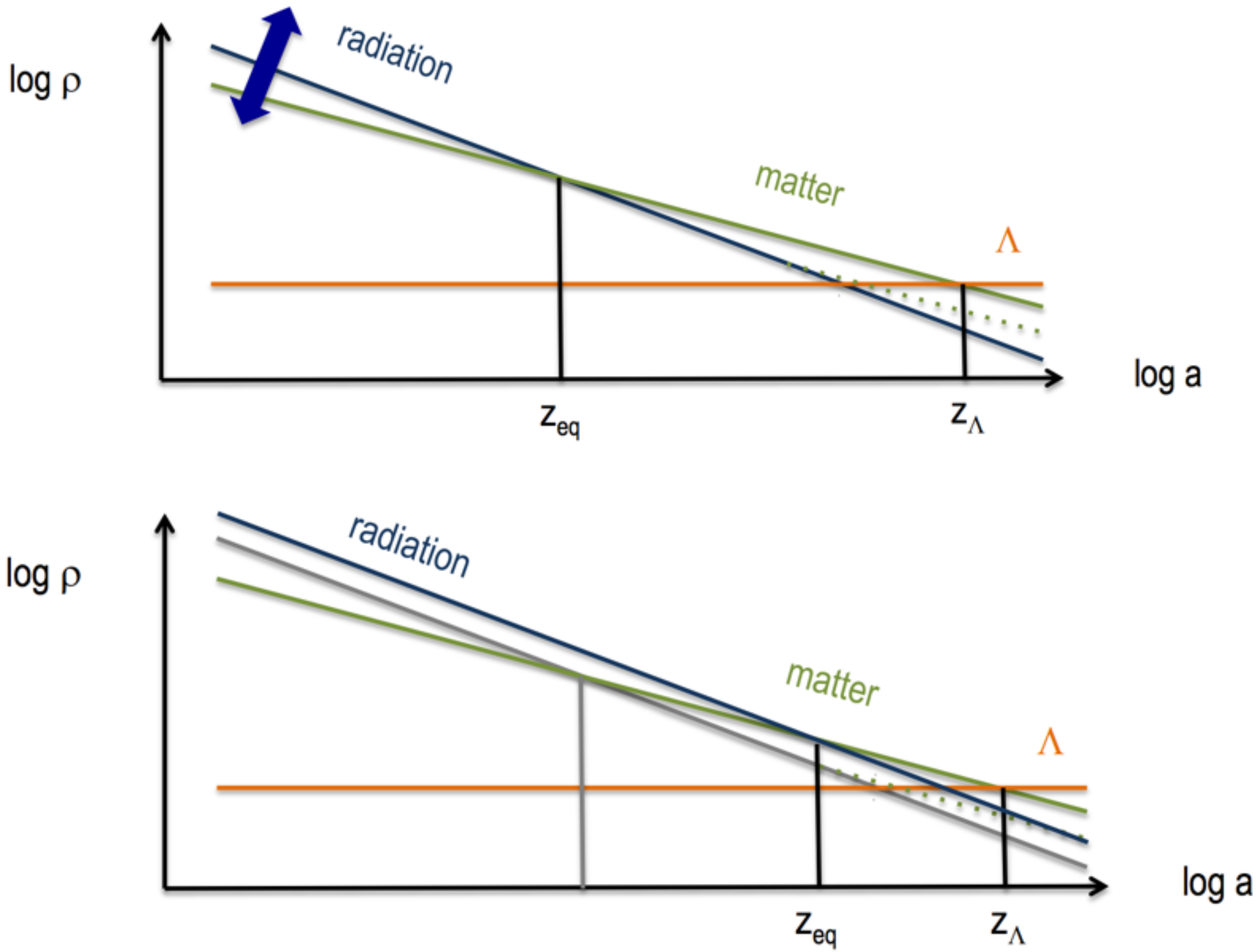
Impact on Late ISW below cosmic variance

… very difficult to detect before Planck CMB

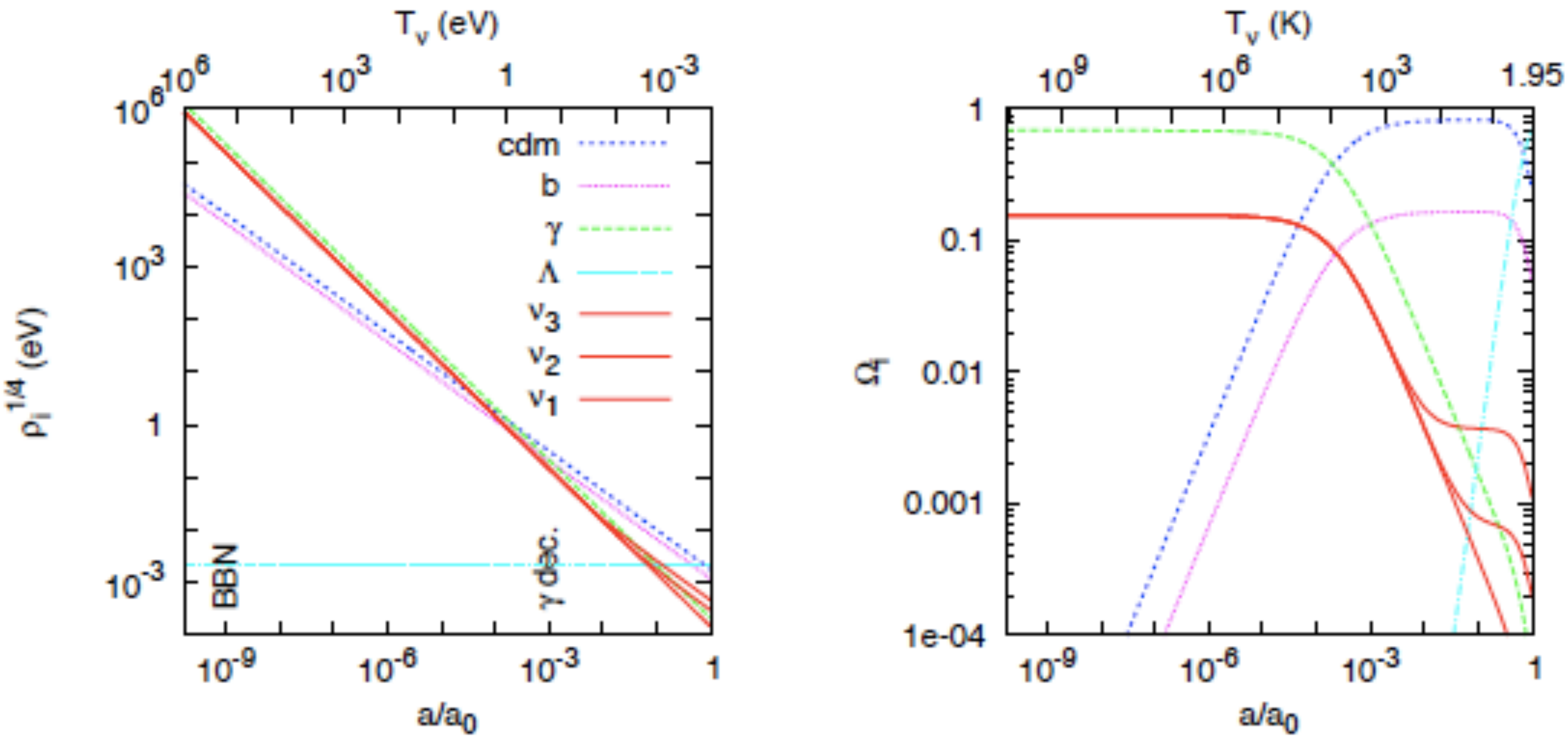
Cosmic energy budget



….and its cosmological evolution



…and its cosmological evolution (more precise)



$$H(a) = H_0 \left[\frac{\Omega_m}{a^3} + \frac{\Omega_r}{a^4} + \frac{\Omega_k}{a^2} + \frac{\Omega_\Lambda}{a^{3(1+w_{\rm eff}(a))}} \right]^{1/2}$$

$$\Omega_r = \Omega_\gamma \, (1 + 0.2271 N_{\rm eff})$$

Note that the equation above is not exact
but it is a good approximation (e.g. Komatsu et al 11)

COSMIC MICROWAVE BACKGROUND

The effect on the primary CMB spectrum comes from the fact that they contribute to the ***radiation density*** at the time of **equality**, and to ***non-relativistic matter density*** **today**.

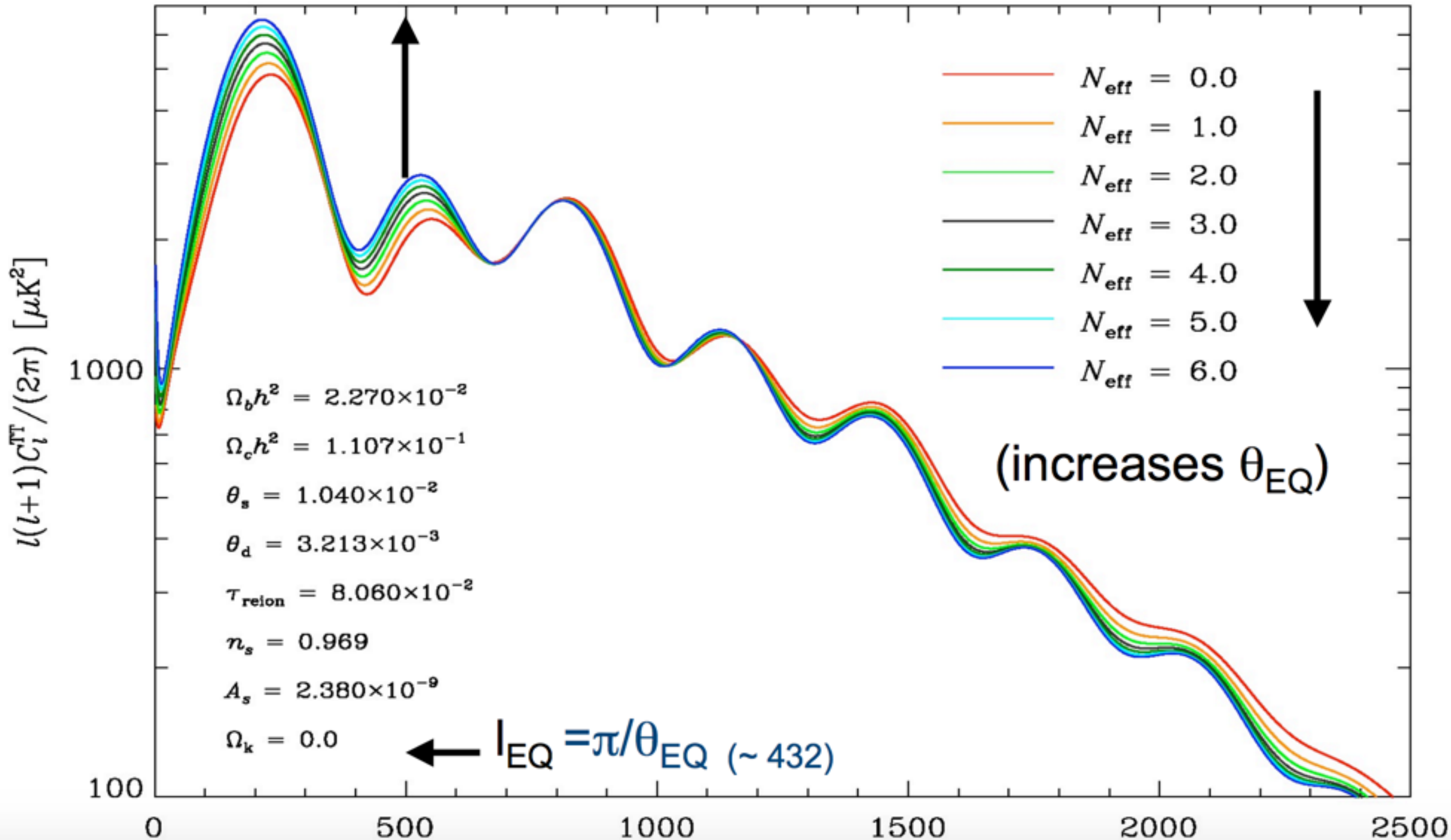
This induces an in integrated Sachs-Wolfe effect (both at early and late times) and/or a change in the angular diameter distance to the last scattering surface.

Before Planck, these were the dominant effects in constraining the neutrino mass from CMB data.

Planck hits a new regime where the dominant effect is **gravitational lensing**.

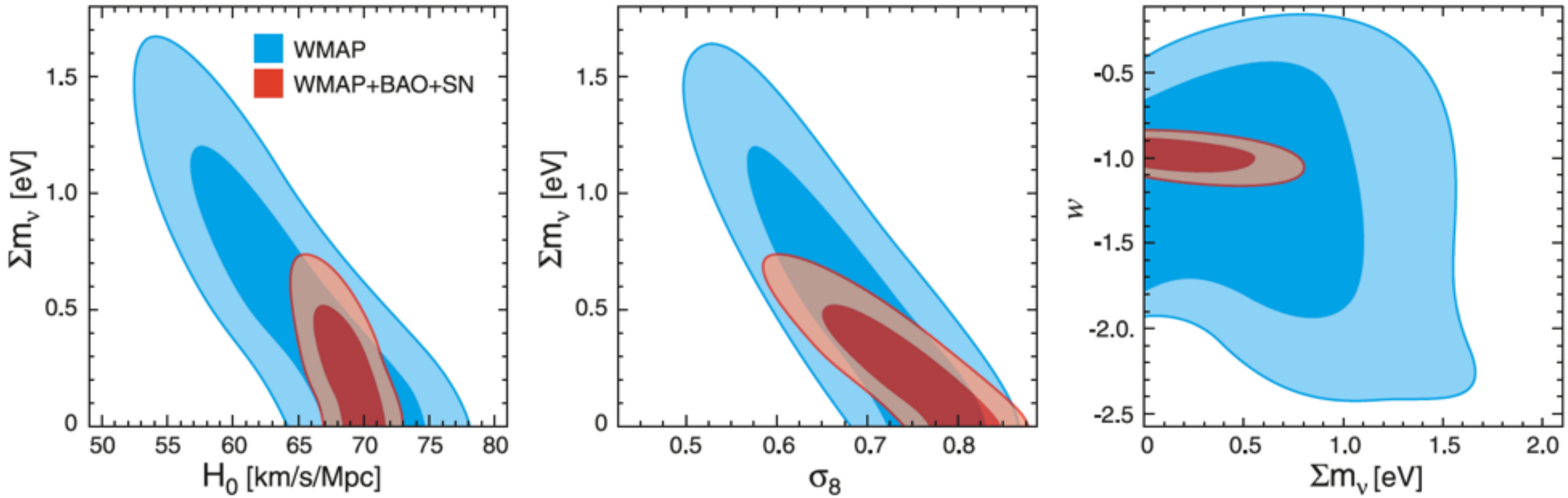
Increasing the neutrino mass suppresses clustering on scales smaller than the size of the horizon at the time of the NR transition, thereby suppressing the lensing potential.

N_{eff} and the CMB damping tail



Pre-Planck era and the power of BAO

WMAP5 Komatsu+2008

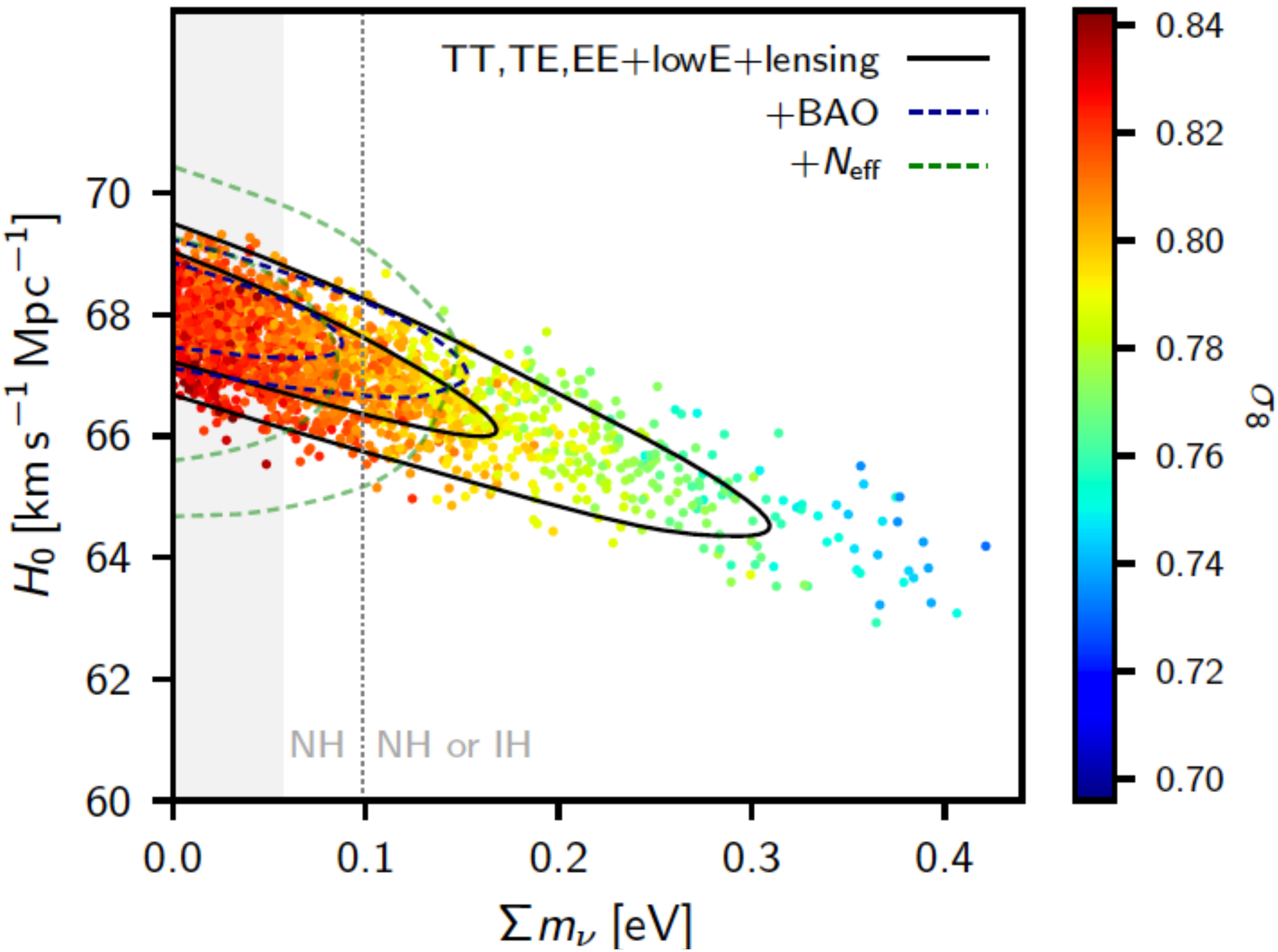


As the matter-to-radiation ratio was smaller than one would naively expect, **it would accelerate the decay of gravitational potential around the decoupling epoch.** This leads to an enhancement in the so-called early integrated Sachs-Wolfe (ISW) eff ect. The larger M_nu is, the larger early ISW becomes. *The large ISW causes the first peak position to shift to lower multipoles by adding power at l ~ 200; however, this shift can be absorbed by a reduction in the value of H0.*

NOTE: degeneracies - NOTE: BAO

M_nu vs H_0 and $sigma_8$

Planck18

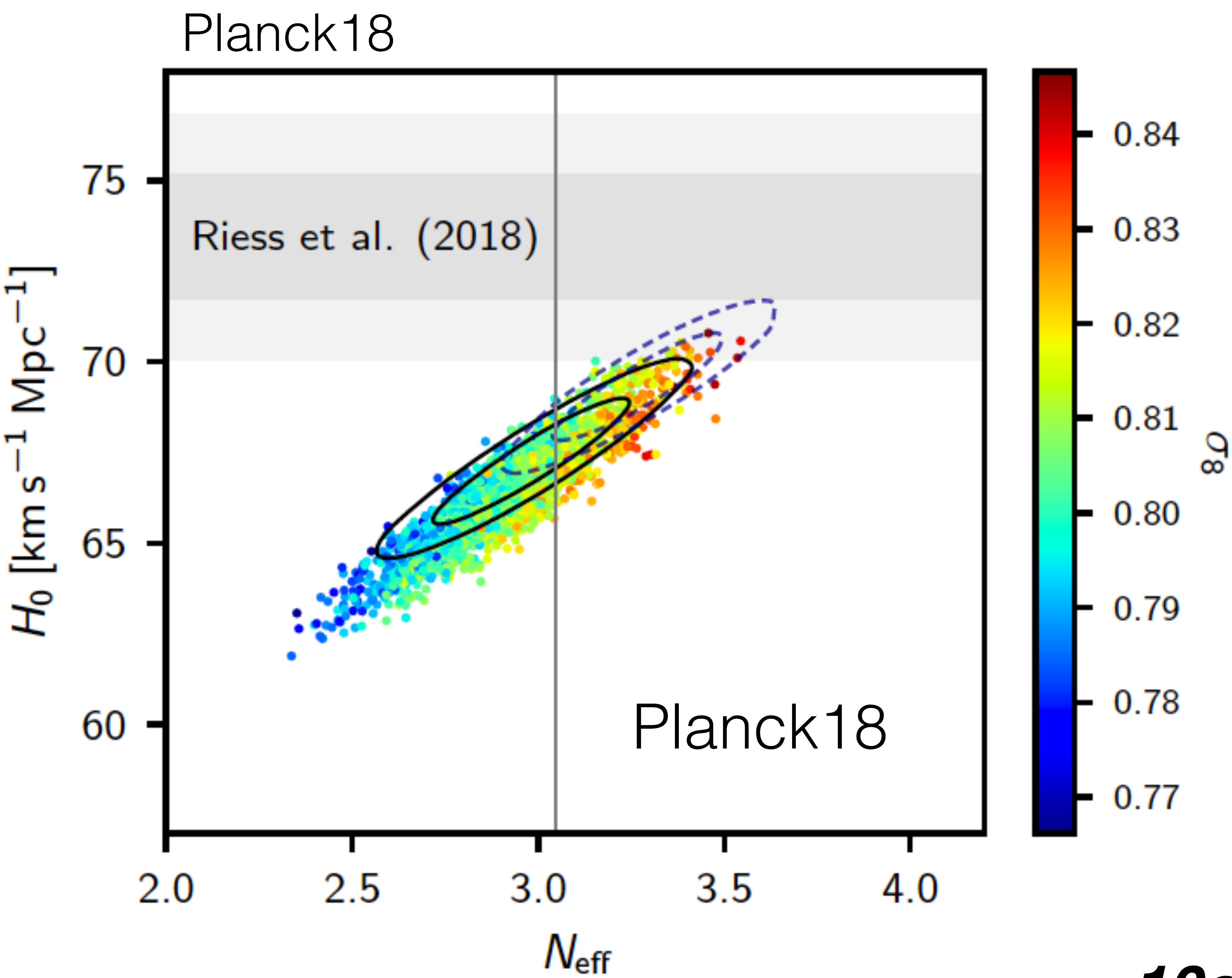


$$\sum m_\nu < 0.13 \text{ eV} \quad (95\,\%, \textit{Planck} \text{ TT+lowE+lensing +BAO}),$$

$$\sum m_\nu < 0.12 \text{ eV} \quad (95\,\%, \textit{Planck} \text{ TT,TE,EE+lowE +lensing+BAO}).$$

ROBUST UPPER LIMIT

N_{eff} vs H_0 and $sigma_8$



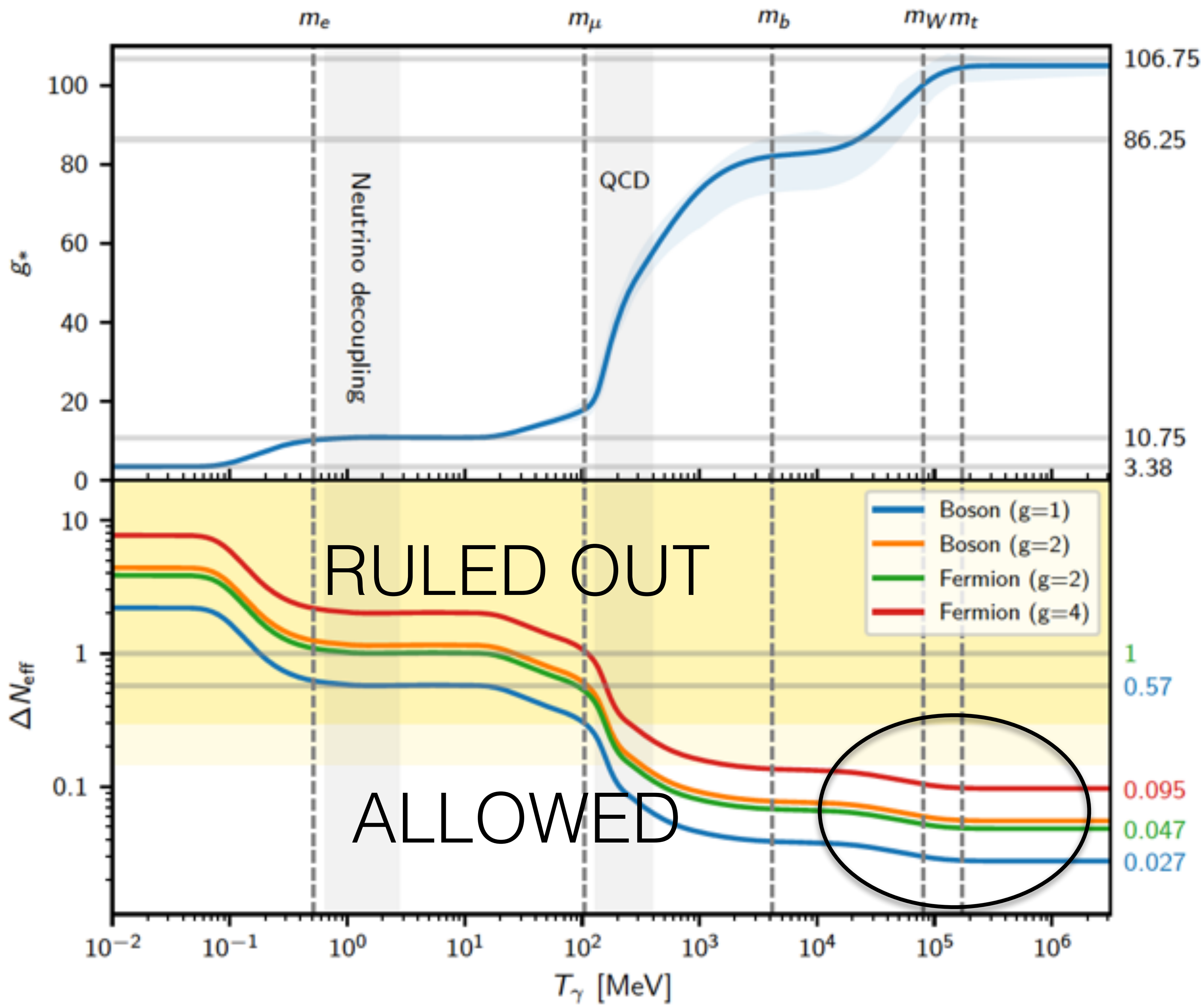
10sigma detection!

$$N_{\rm eff} = 3.11^{+0.44}_{-0.43} \quad (95\,\%, \text{ TT+lowE+lensing+BAO});$$

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad (95\,\%, \text{ TT,TE,EE+lowE+lensing +BAO}).$$

Constraints on extra relativistic particles

Planck18



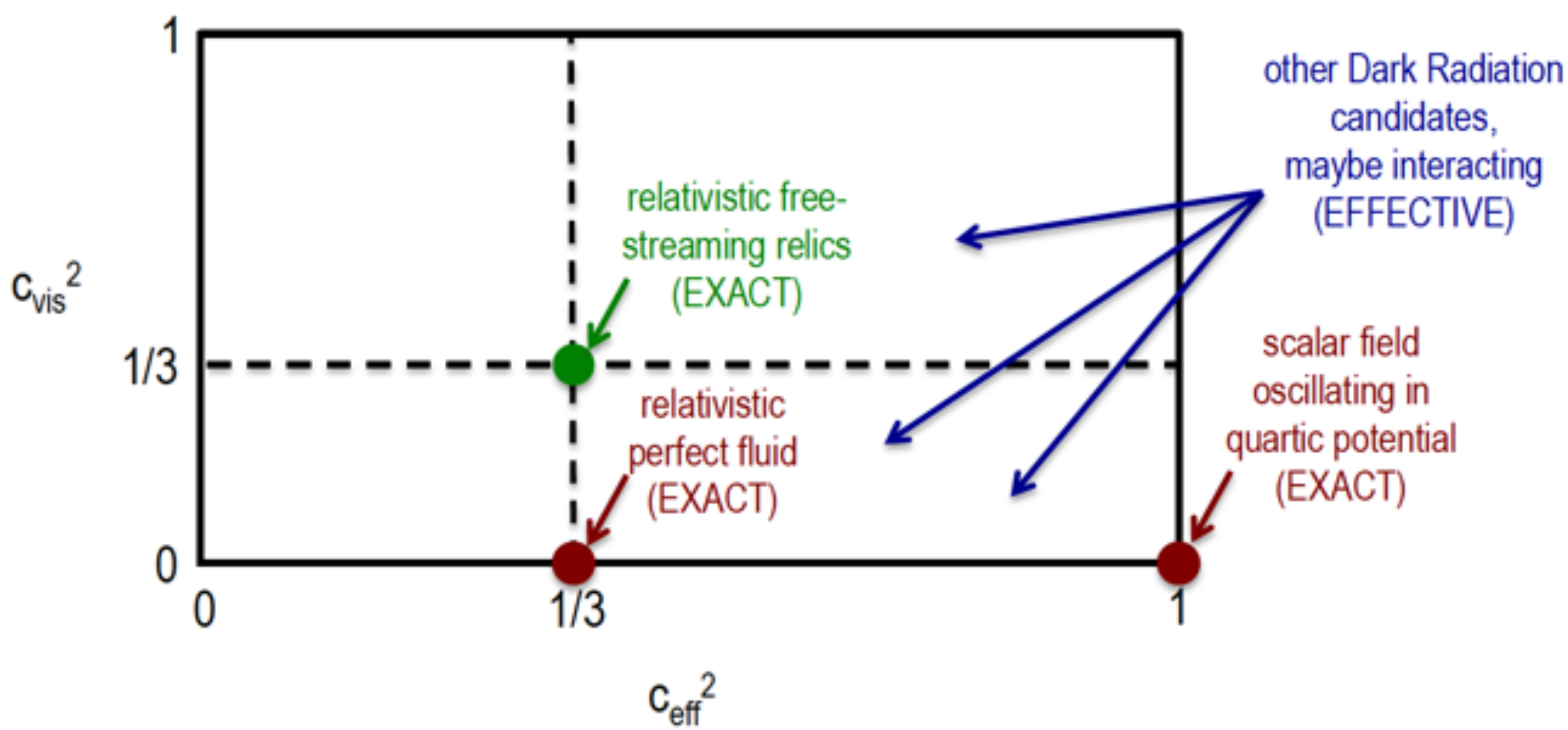
Theory: effective degrees of freedom from SM

Neff today

Constraints on additional relativistic particles. Evolution of the effective degrees of freedom for SM particle density, g , as a function of photon temperature in the early Universe. Vertical bands show the approximate temperature of neutrino decoupling and the QCD phase transition, and dashed vertical lines denote some mass scales at which corresponding particles annihilate with their antiparticles, reducing g . The solid line shows the fit of Borsanyi et al. (2016) plus standard evolution at T < 1 MeV, and the pale blue bands the estimated 1 error region from Saikawa & Shirai (2018). Numbers on the right indicate specific values of g expected from simple degrees of freedom counting. **Bottom** : Expected Neff today for species decoupling from thermal equilibrium as a function of the decoupling temperature, where lines show the prediction from the Borsanyi et al. (2016) fit assuming a single scalar boson (g = 1, blue), bosons with g = 2 (e.g., a massless gauge vector boson, orange), a Weyl fermion with g = 2 (green), or fermions with g = 4 (red). One-tailed 68% and 95% regions excluded by Planck TT,TE,EE + lowE+ lensing+ BAO are shown in gold; this rules out at 95% significance light thermal relics decoupling after the QCD phase transition (where the theoretical uncertainty on g is negligible), including specific values indicated on the right axis of Ne =0: 57 and 1 for particles decoupling between muon and positron annihilation. At temperatures well above the top quark mass and electroweak phase transition, g remains somewhat below the naive 106.75 value expected for all the particles in the Standard Model, giving interesting targets for Ne that may be detectable in future CMB experiments (see e.g. Baumann et al. 2017).

Imprint of neutrino perturbations on CMB anisotropies

- Until photon decoupling *neutrino perturbations* governed by Vlasov equation, like any decoupled (*free-streaming*) relativistic relic.
- Their density/pressure perturbations, energy flux and anisotropic pressure/shear act as sources in Einstein equations: *gravitational interactions with photons, baryons*.
- Affects the amount of gravitational boost of CMB acoustic oscillations just after Hubble crossing.
- Controls amplitude and phase of CMB acoustic oscillations.

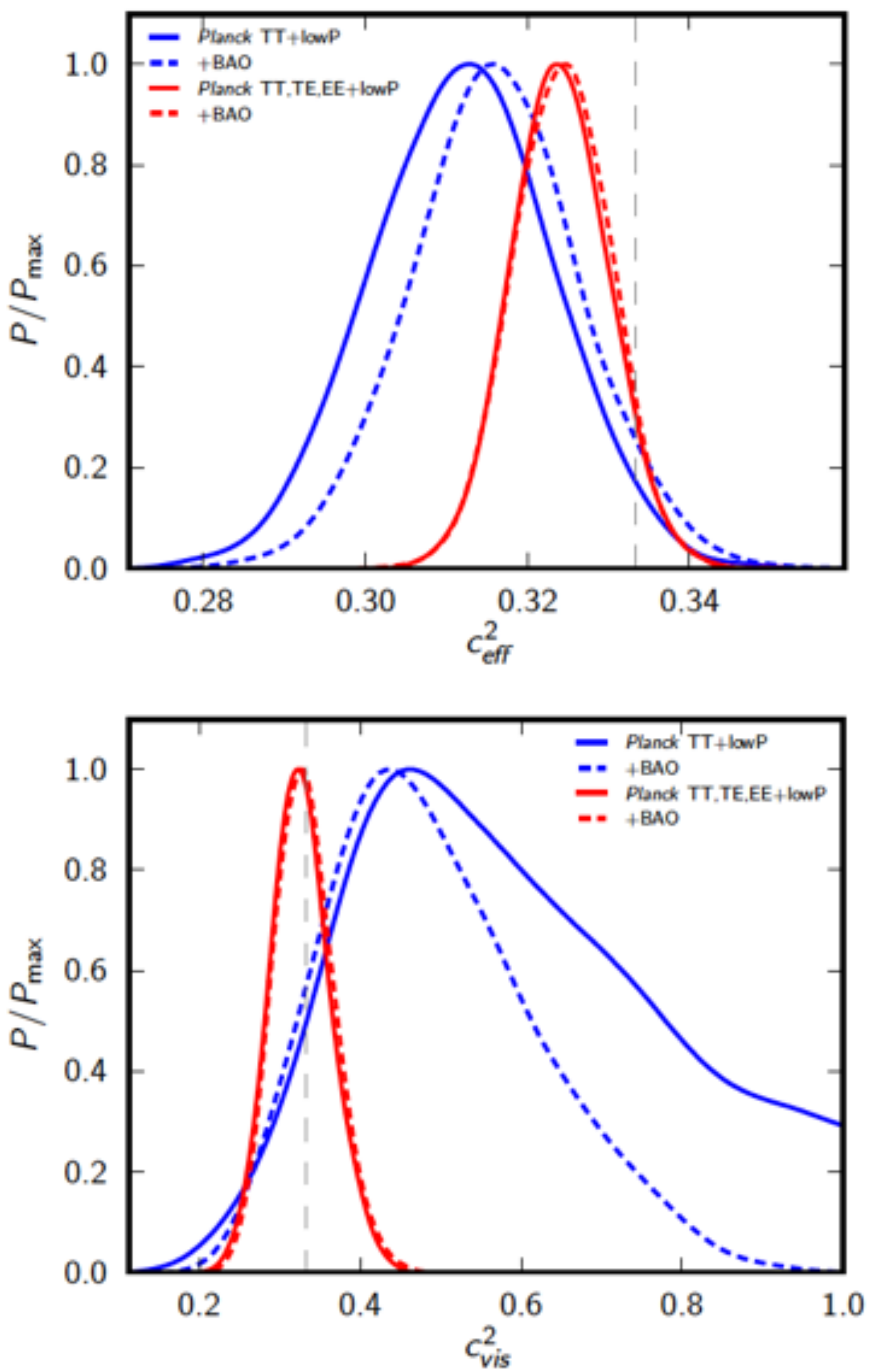


1) Effective *sound speed* : $\delta p = c_{eff}^2 \delta\rho$

2) Effective *viscosity speed* c_{vis} controlling the amount of anisotropic pressure / shear

Constraining the properties of the fluid

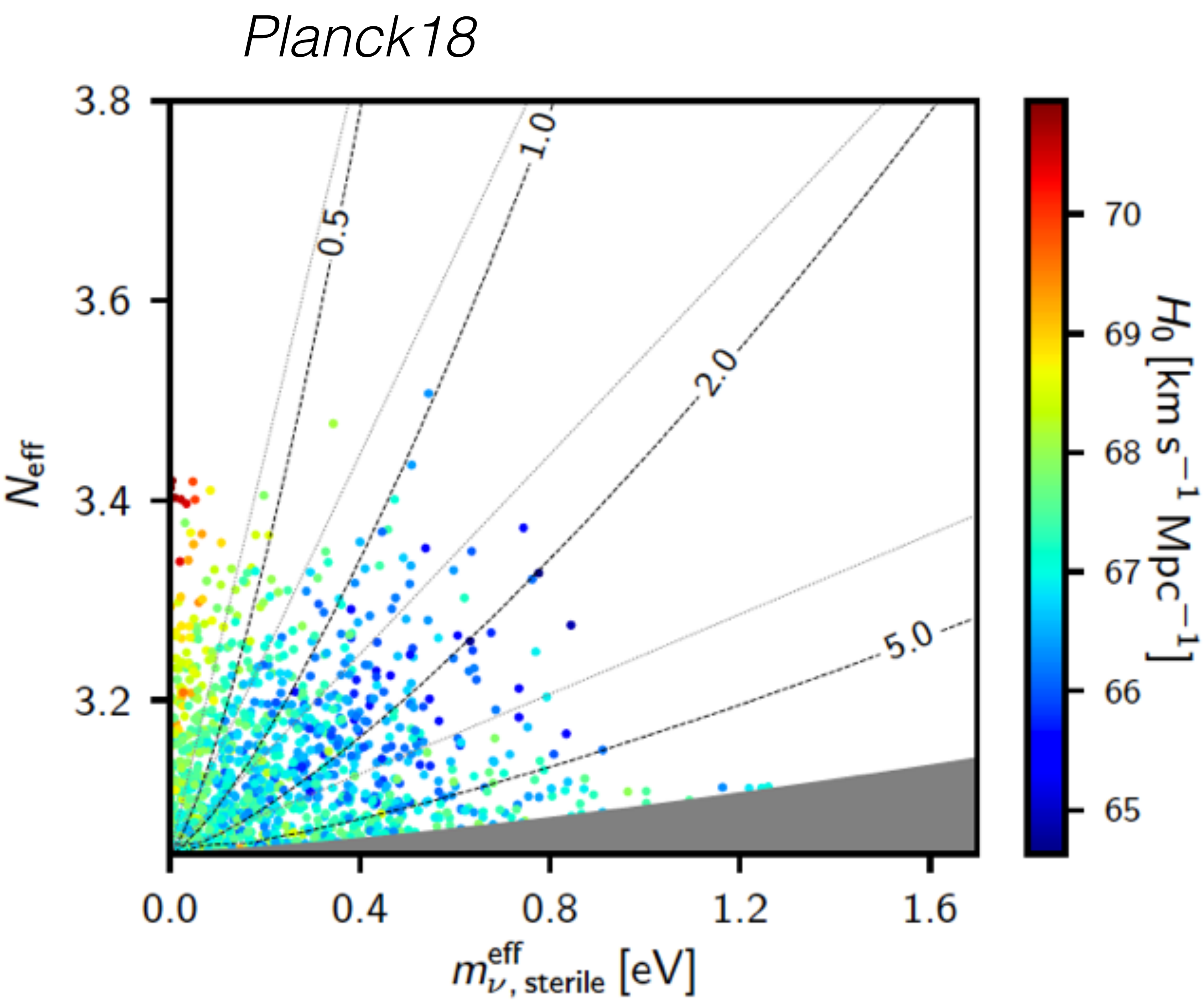
Planck18



Properties of this neutrino fluid constrained, to be pretty “normal”.
So far nothing exotic going on.

Importance of polarization data, especially for viscosity: neutrino anisotropies induce a phase shift which is more visible in polarization since peaks are narrower.

Need for sterile neutrinos?



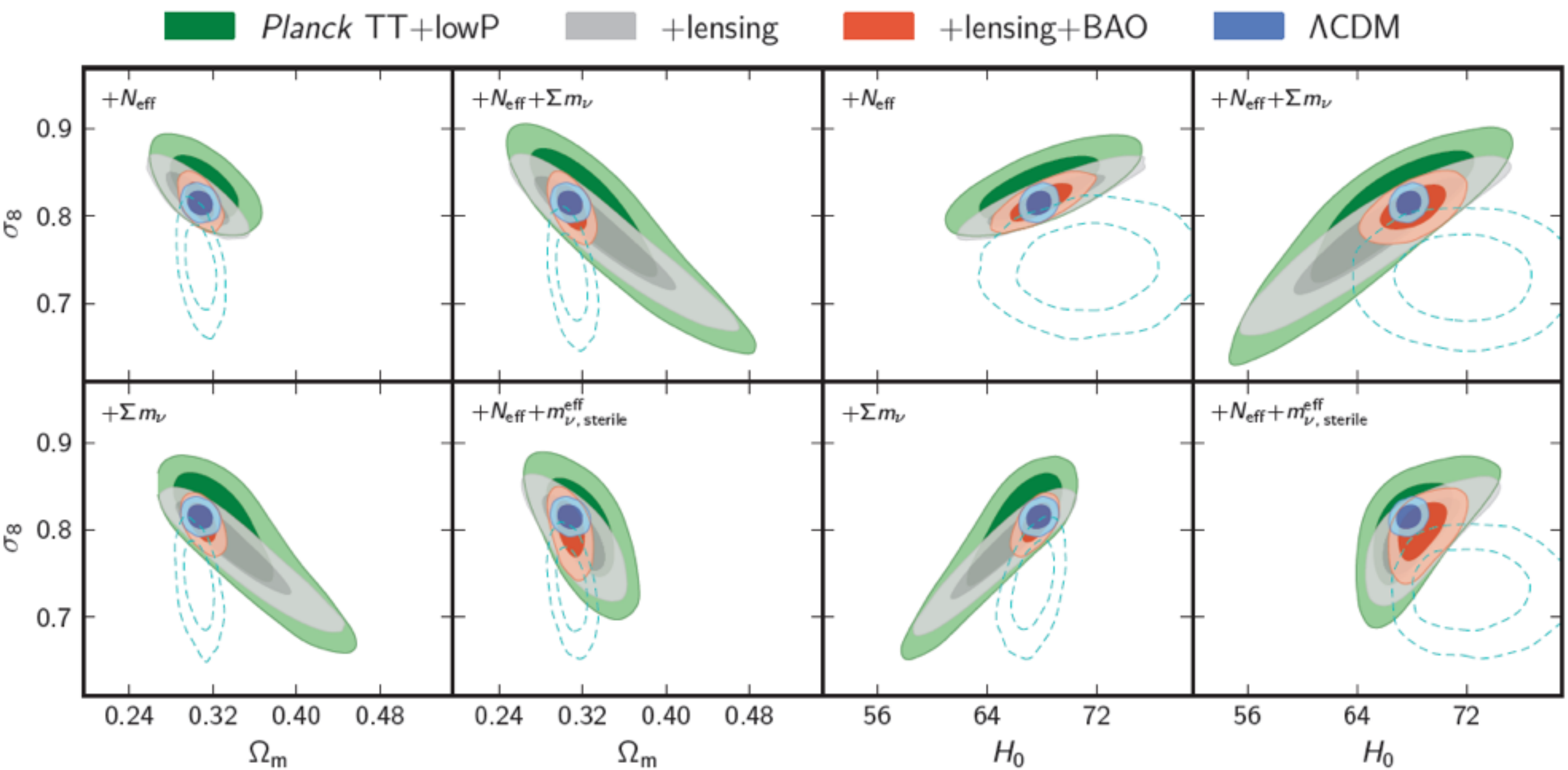
Scenario: minimal-mass active neutrinos and one additional sterile neutrino.

Mass for thermally-produced sterile neutrinos, is constant along the grey lines (mass in eV); the equivalent resultfor sterile neutrinos produced via the Dodelson-Widrow mechanism (Dodelson & Widrow 1994) is shown by thinner lines.

The dark grey shaded region shows the part of parameter space excluded by our default prior mthermal sterile < 10 eV, where the sterile neutrinos would behave like dark matter for CMB constraints.

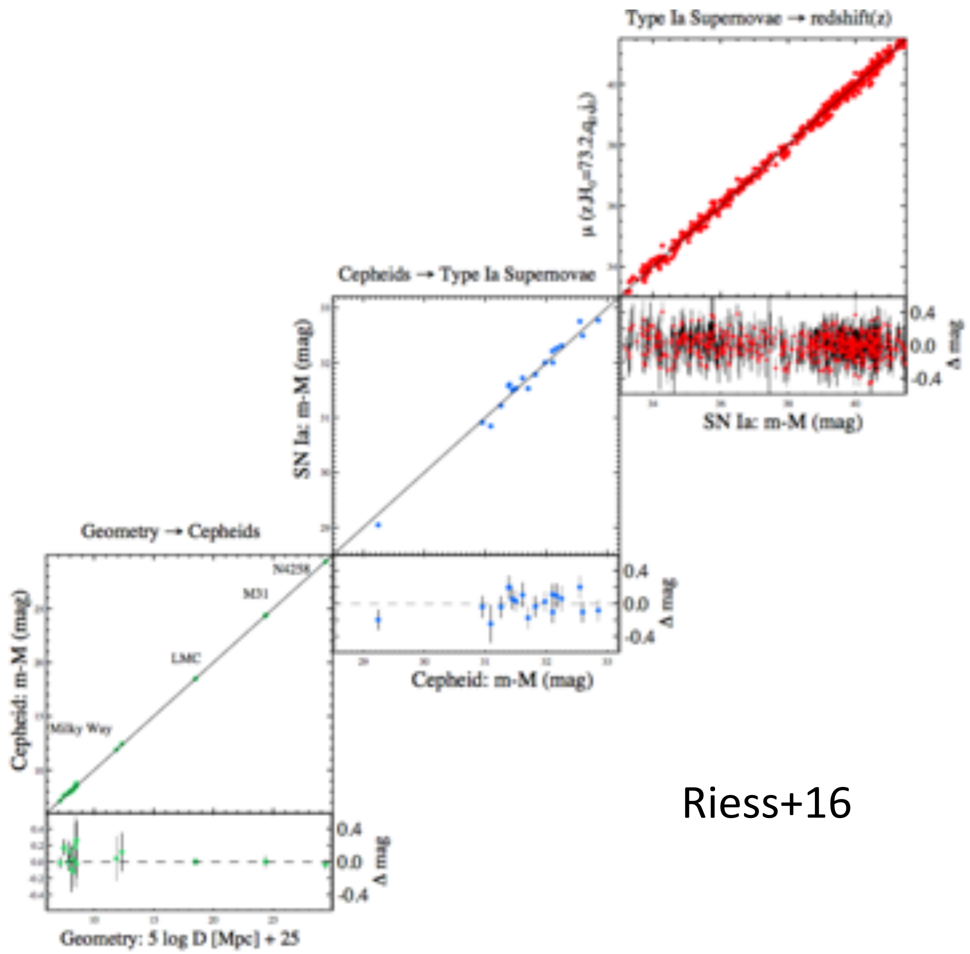
Beyond LCDM with neutrinos?

Planck15



The standard ΛCDM model and beyond: tensions

Geometry: H_0 from distance ladder



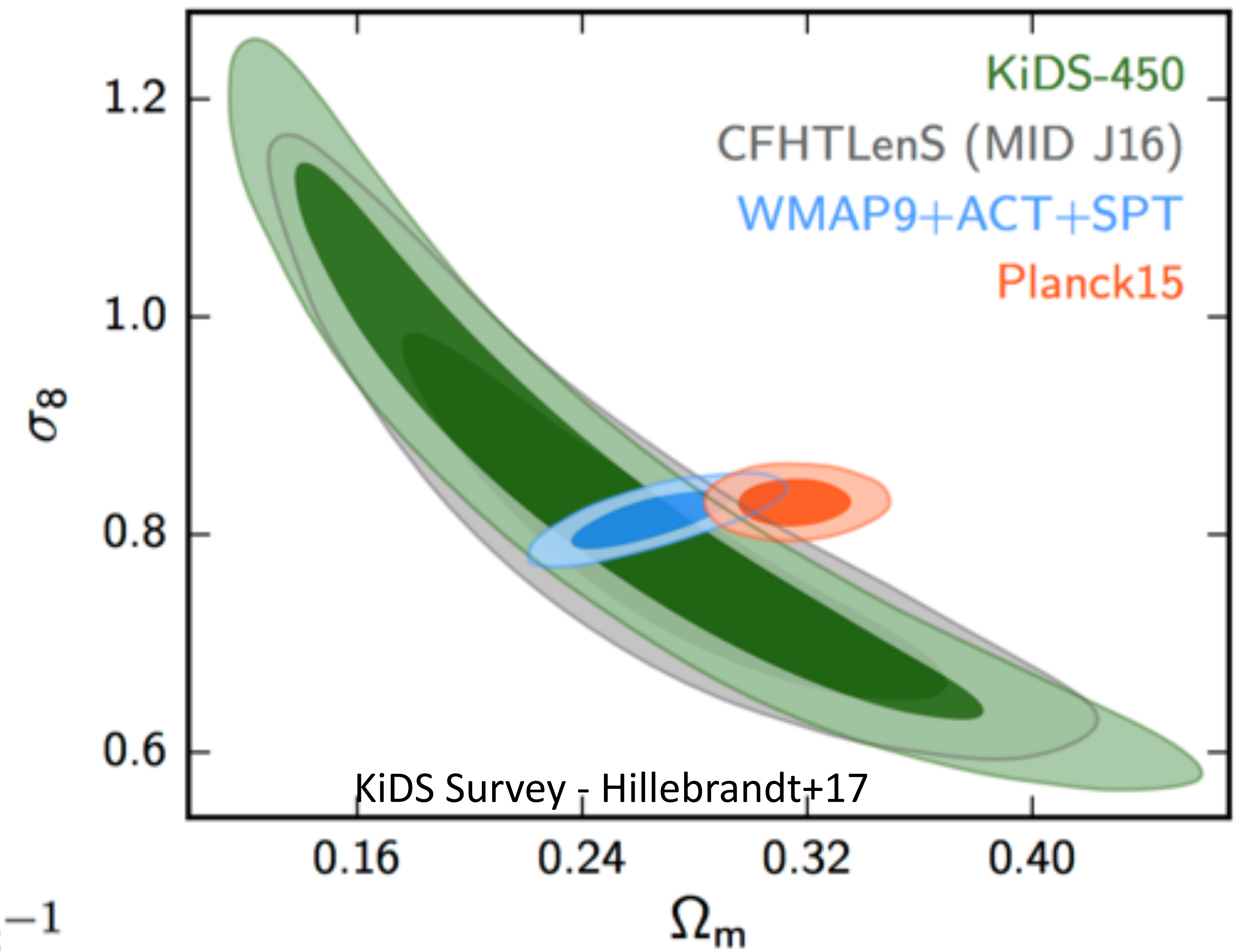
Riess+16

Supernovae $H_0 = 73.24 \pm 1.74 \text{ km s}^{-1} \text{ Mpc}^{-1}$

Planck $H_0 = 66.93 \pm 0.62 \text{ km s}^{-1} \text{ Mpc}^{-1}$

Tension at a level **> 3**σ
Systematics involved:
Calibrations

Dynamics: Weak gravitational lensing



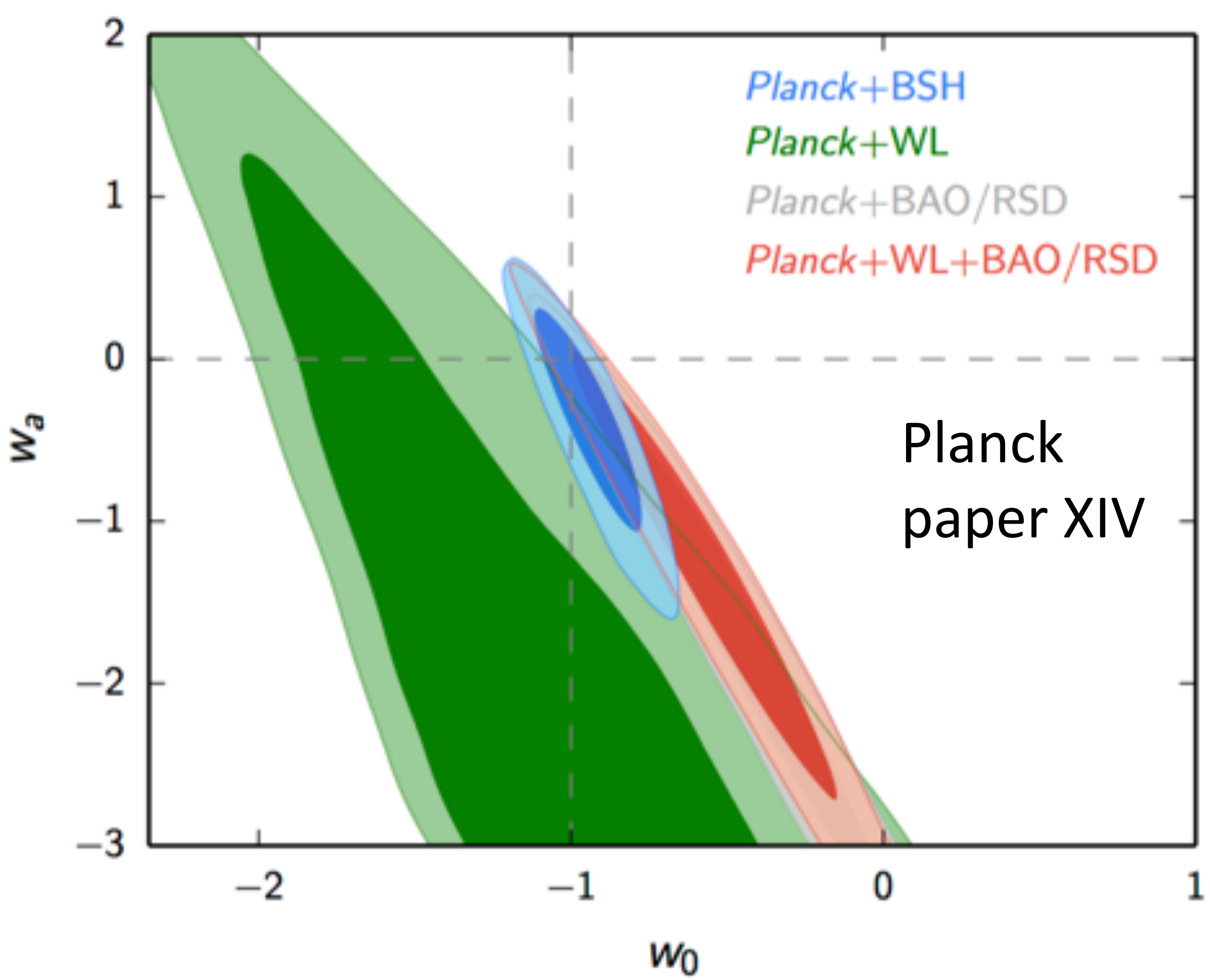
Tension at a level **> 2.3**σ
Systematics involved:
Baryonic corrections
Intrinsic alignments of galaxies
Non-linear modelling
Point spread function of the telescope

The standard ΛCDM model and beyond: solutions?

1) Solution nr. 1 to alleviate tensions with weak lensing and cluster number counts: add **massive active neutrinos** with total masses 0.3 eV (sterile neutrinos < 1 eV could also help).

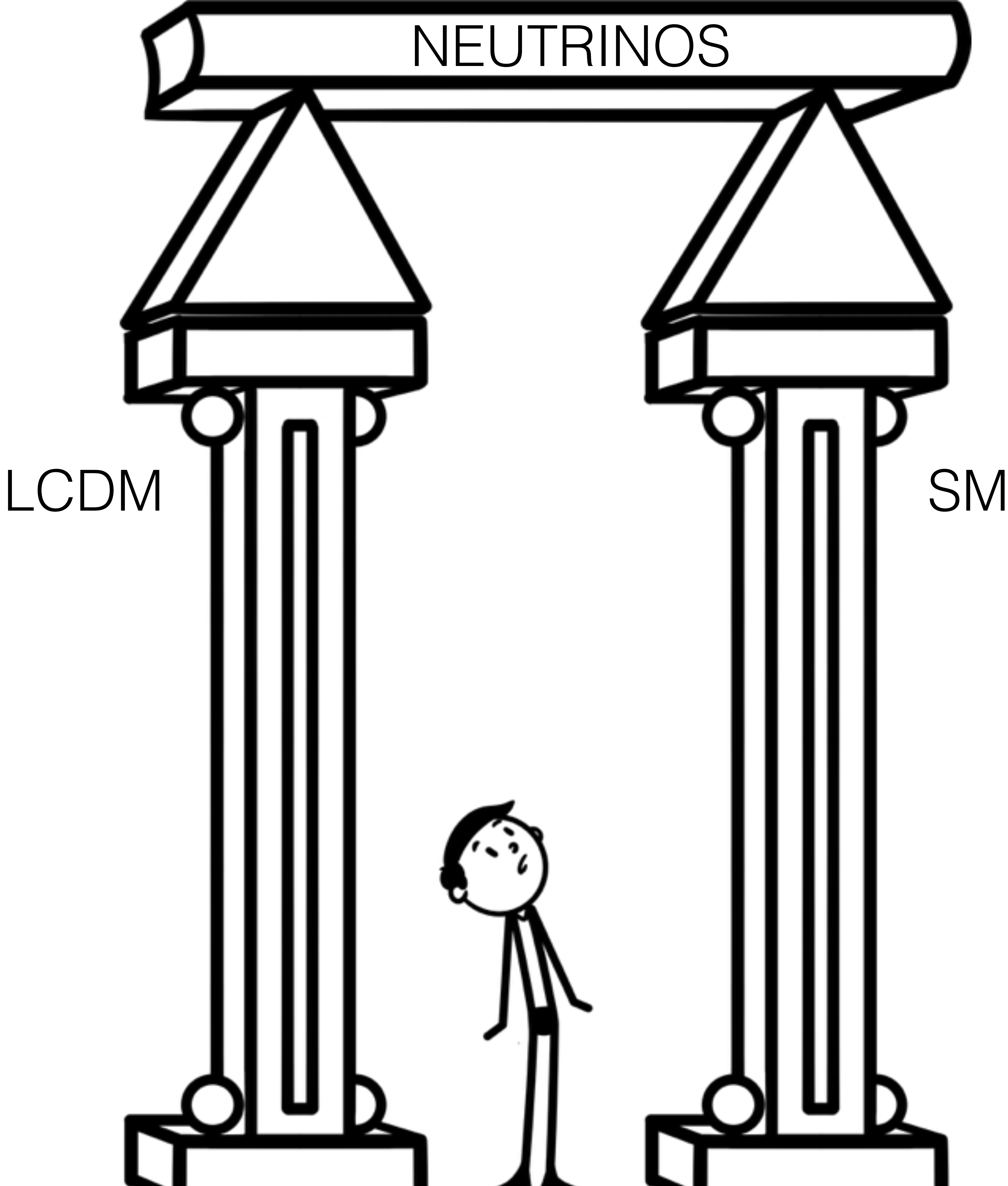
2) Solution nr. 2 to solve/alleviate tensions with H_0: add relativistic degrees of freedom $\Delta N_{eff}=1$, this is **radiation.**

3) Solution nr. 3 to solve/alleviate tensions with H_0 make $w<-1$. **Phantom dark energy** (negative kinetic term in the scalar field Lagrangian).



Solutions 1,2,3 ***do break internal agreement of CMB (Planck) data.***

New physics?
Wrong model?
Systematics?


NEUTRINOS
LCDM
SM

COSMIC NEUTRINO BACKGROUND

IN THE STRUCTURE FORMATION ERA

COSMOLOGICAL NEUTRINOS-I: FREE-STREAMING SCALE

Neutrino thermal velocity

$$v_{\rm th} \equiv \frac{\langle p\rangle}{m} \simeq \frac{3T_\nu}{m} = \frac{3T_\nu^0}{m}\left(\frac{a_0}{a}\right) \simeq 150(1+z)\left(\frac{1\,{\rm eV}}{m}\right){\rm km\,s^{-1}}$$

Neutrino free-streaming scale

$$k_{FS}(t) = \left(\frac{4\pi G\bar{\rho}(t)a^2(t)}{v_{\rm th}^2(t)}\right)^{1/2}$$

Scale of non-relativistic transition

$$k_{\rm nr} \simeq 0.018\ \Omega_{\rm m}^{1/2}\left(\frac{m}{1\,{\rm eV}}\right)^{1/2} h\,{\rm Mpc}^{-1}$$

THREE COSMIC EPOCHS	RADIATION ERA z>3400
	MATTER RADIATION z<3400
	NON-RELATIVISTIC TRANSITION z ~ 500

Below k_{nr} there is suppression in power at scales that are cosmologically important:
suppression due to 1) absence of perturbations in the neutrino fluid
2) slower growth of CDM/baryons

COSMOLOGICAL NEUTRINOS-II: FREE-STREAMING SCALE is cosmologically relevant

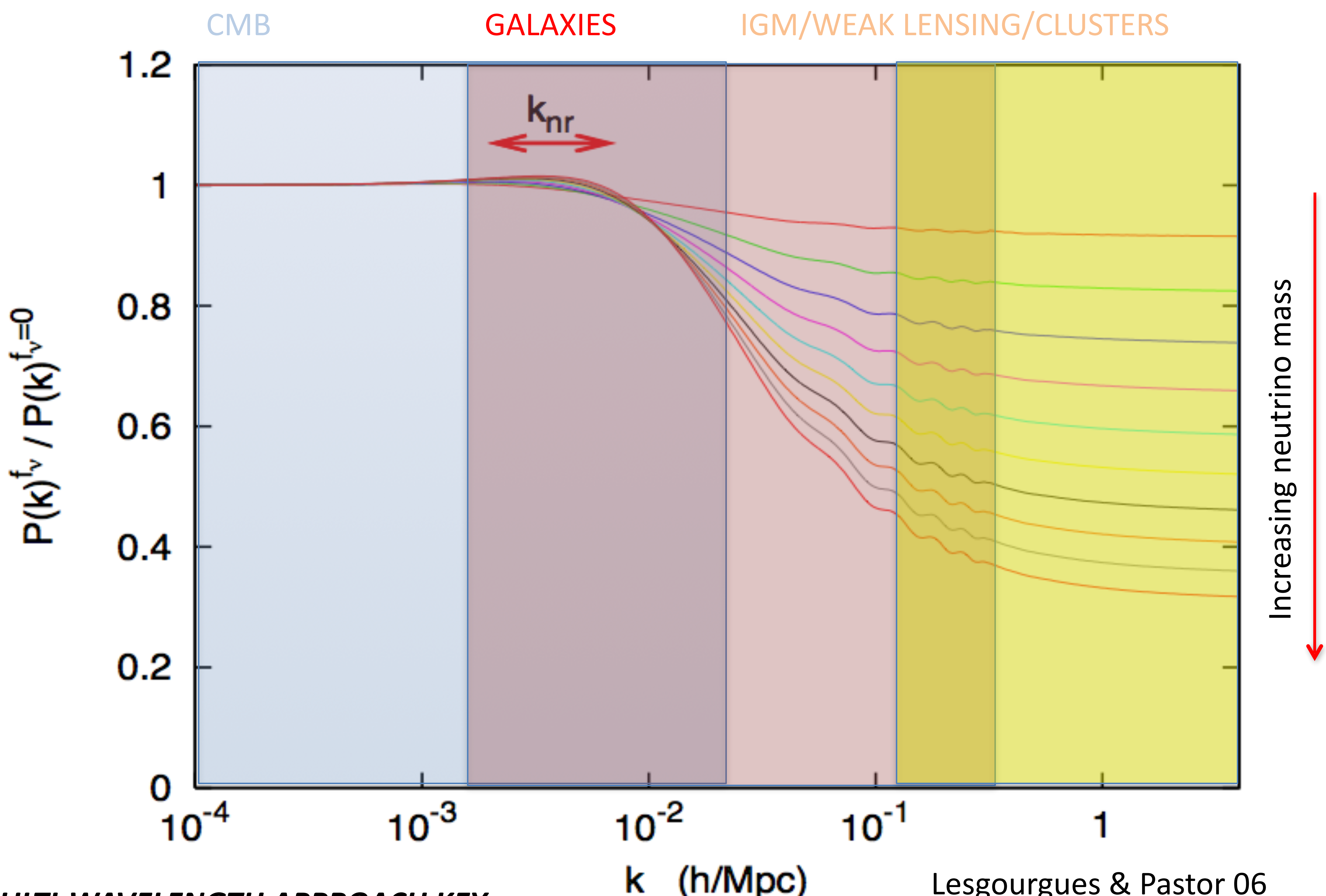
$$\lambda_{FS}(t) = 7.7 \frac{1+z}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}} \left(\frac{1\,\mathrm{eV}}{m}\right) h^{-1}\mathrm{Mpc}\ ,$$

$$k_{FS}(t) = 0.82 \frac{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}{(1+z)^2} \left(\frac{m}{1\,\mathrm{eV}}\right) h\,\mathrm{Mpc}^{-1},$$

after non-relativistic transition and during matter domination, the free-streaming length continues to increase, but only like $(aH)^{-1} \propto t^{1/3}$, i.e. more slowly than the scale factor $a \propto t^{2/3}$. Therefore, thecomoving free-streaming length λ_{FS}/a actually decreases like $(a^2H)^{-1} \propto t^{-1/3}$.

As a consequence, for neutrinos becoming non-relativistic during matter domination, **the comoving free-streaming wavenumber passes through a minimum k_{nr} at the time of the transition**, i.e. when $m = \langle p \rangle = 3T_\nu$ and $a_0/a = (1+z) = 2.0\times10^3 (m/1\ \mathrm{eV})$.

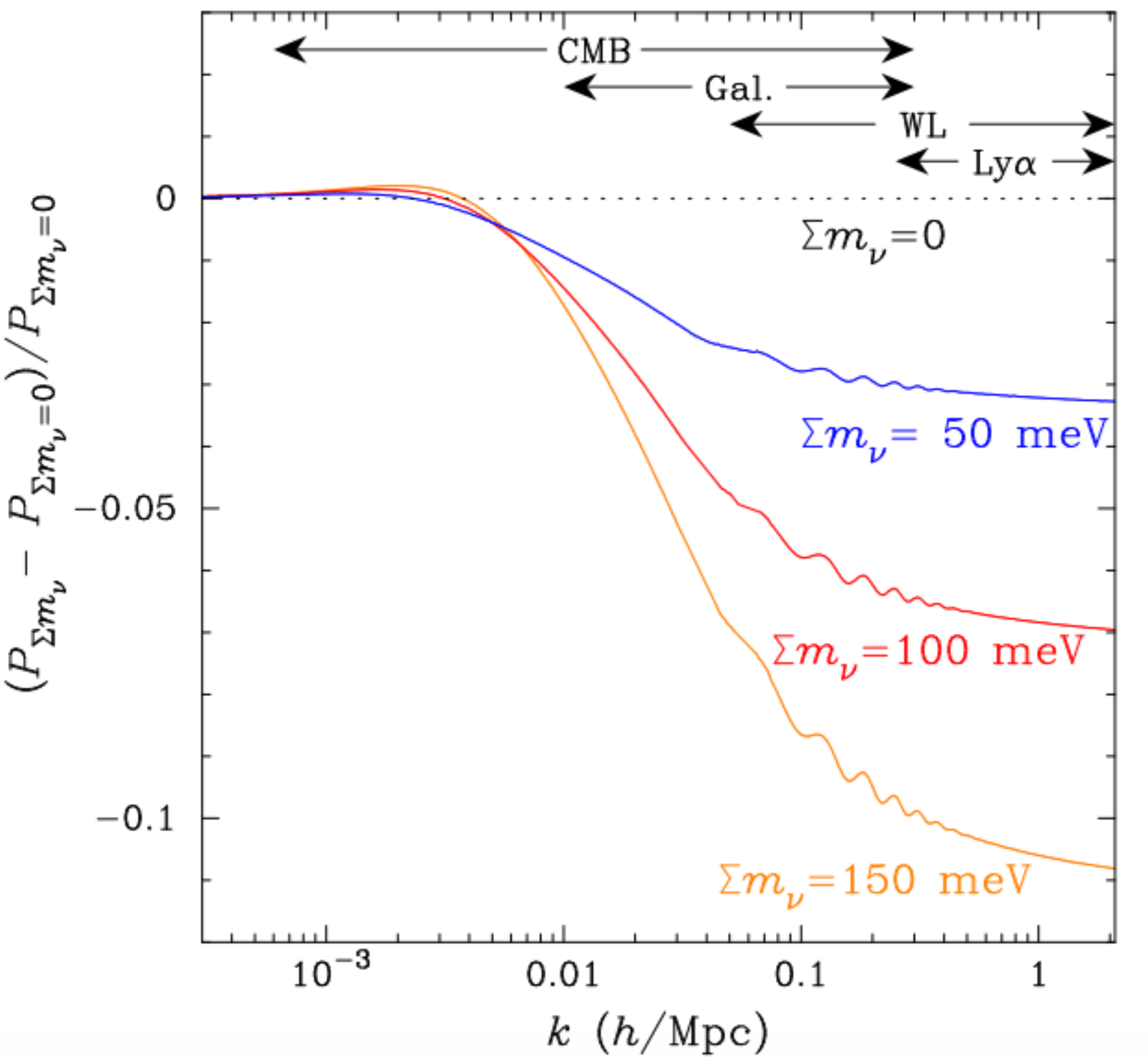
COSMOLOGICAL NEUTRINOS-III: LINEAR MATTER POWER



Lesgourgues & Pastor 06

MULTI-WAVELENGTH APPROACH KEY ISSUE TO MEASURE NEUTRINOS IN THE SKY

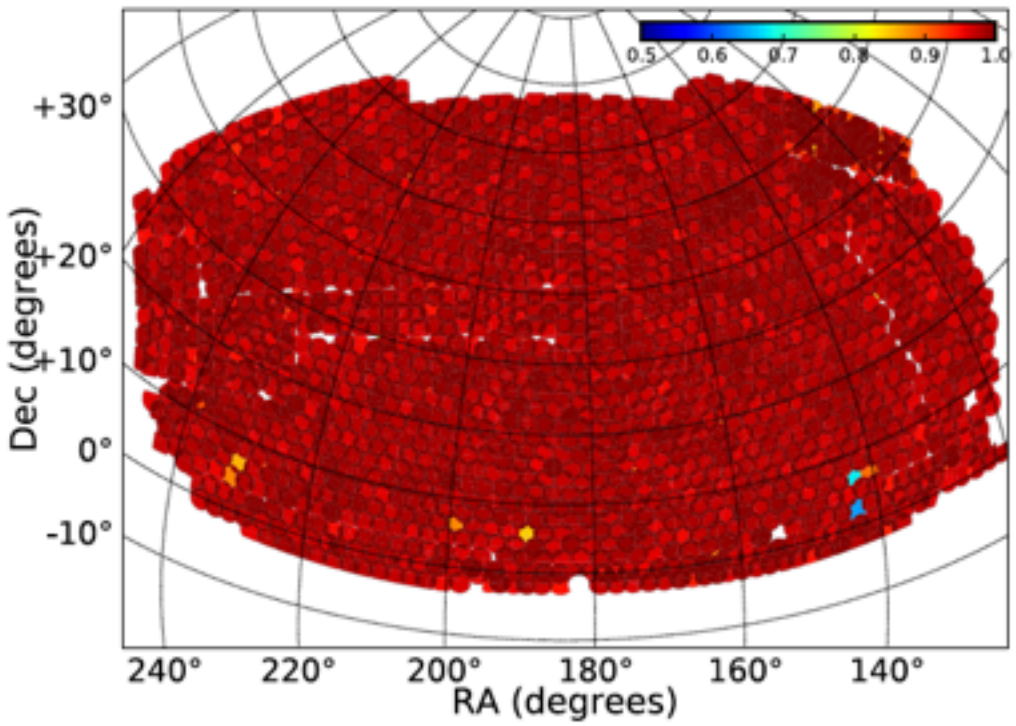
COSMOLOGICAL NEUTRINOS-IV: LINEAR MATTER POWER

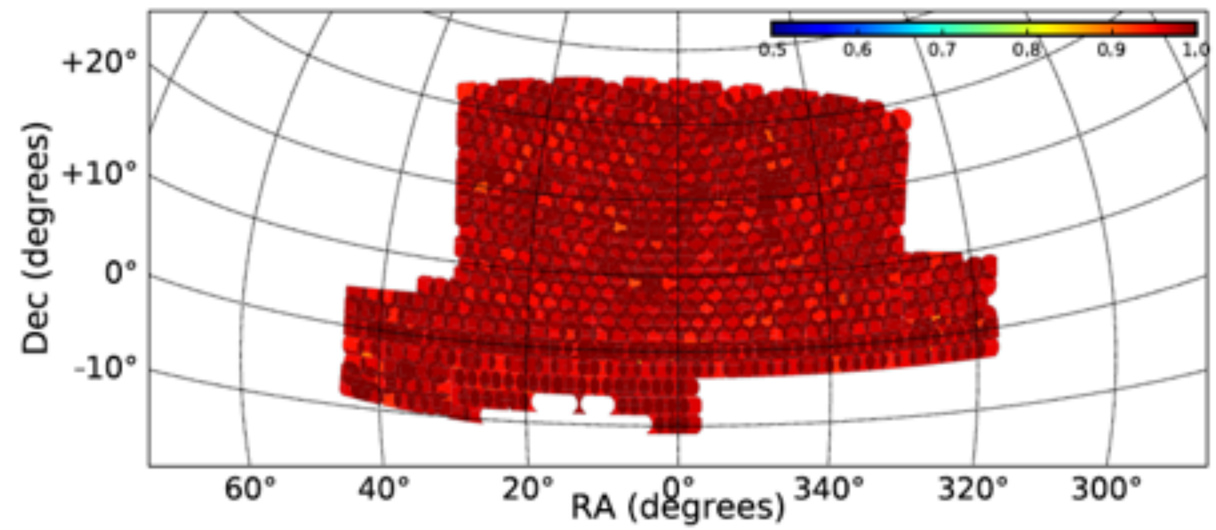


- Relatively large O(5%) differences
- Different probes with different systematics/astro/redshfit ranges
- Strategy! measure probe by probe and combine to constrain the unique prediction (shape and amplitude)

NEUTRINOS FROM GALAXY CLUSTERING

Galaxy clustering: data set





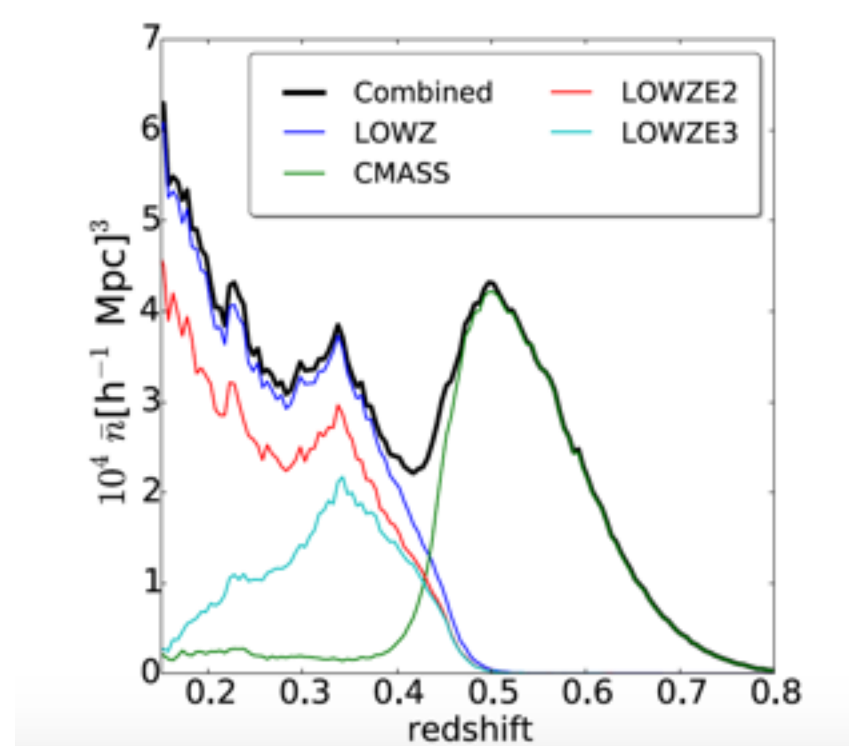
10,000 sq. deg. & 1.2 million galaxies in V=20 Gpc^3

medium-resolution spectra
(R ≈ 1500–2600) in the wavelength range from 3600 to 10000 Å
through 2 arcsec fibres

LOWZ was designed
to target luminous red galaxies up to z ≈ 0.4, while CMASS
was designed to target massive galaxies from 0.4 < z < 0.7

Seven data analyses performed with different methodologies (tested on mocks)

		N_{gals}	V_{eff} (Gpc^3)	V (Gpc^3)
$0.2 < z < 0.5$	NGC	429 182	2.7	4.7
	SGC	174 819	1.0	1.7
	Total	604 001	3.7	6.4
$0.4 < z < 0.6$	NGC	500 872	3.1	5.3
	SGC	185498	1.1	2.0
	Total	686 370	4.2	7.3
$0.5 < z < 0.75$	NGC	435 741	3.0	9.0
	SGC	158 262	1.1	3.3
	Total	594 003	4.1	12.3



Galaxy Clustering - I: Theoretical Framework

Analysis of **anisotropic correlation function** focussed on the BAO signal

Two sources of anisotropies: Redshift Space Distortion (RSD)
Geometrical induced anisotropy (AP)

$$\xi(r,\mu) = \frac{\mathrm{DD}(r,\mu) - 2\mathrm{DR}(r,\mu) + \mathrm{RR}(r,\mu)}{\mathrm{RR}(r,\mu)}, \qquad \xi_\ell(r) = \frac{2\ell+1}{2}\int_{-1}^{+1} \mathrm{d}\mu\, \xi(r,\mu)\, L_\ell(\mu)$$

Non-linear modelling of correlation function

$$P(k,\mu) = (1+\beta\mu^2)^2 F(k,\mu,\Sigma_s) P_{\rm NL}(k,\mu).$$

$$F(k,\mu,\Sigma_s) = \frac{1}{(1+k^2\mu^2\Sigma_s^2)}$$

$$P_{\rm dw}(k,\mu) = [P_{\rm lin}(k) - P_{\rm nw}(k)] \times \exp\left[-\frac{k^2\mu^2\Sigma_{\parallel}^2 + k^2(1-\mu^2)\Sigma_{\perp}^2}{2}\right] + P_{\rm nw}$$

$$P_{\rm l,t}(k) = \frac{2l+1}{2}\int_{-1}^{1} P_t(k,\mu) L_{\rm l}(\mu)\mathrm{d}\mu$$

$$\xi_{\rm l,t}(r) = i^l \int \frac{k^3\,\mathrm{d}\log(k)}{2\pi^2} P_{\rm l,t}\, j_{\rm l}(kr).$$

$$\xi_0(r) = B_0^2 \xi_{0,t}(r) + A_0(r),$$
$$\xi_2(r) = \xi_{2,t}(r) + A_2(r),$$

where

$$A_\ell(r) = \frac{a_{\ell,1}}{r^2} + \frac{a_{\ell,2}}{r} + a_{\ell,3};\ \ell = 0, 2, \perp, \parallel$$

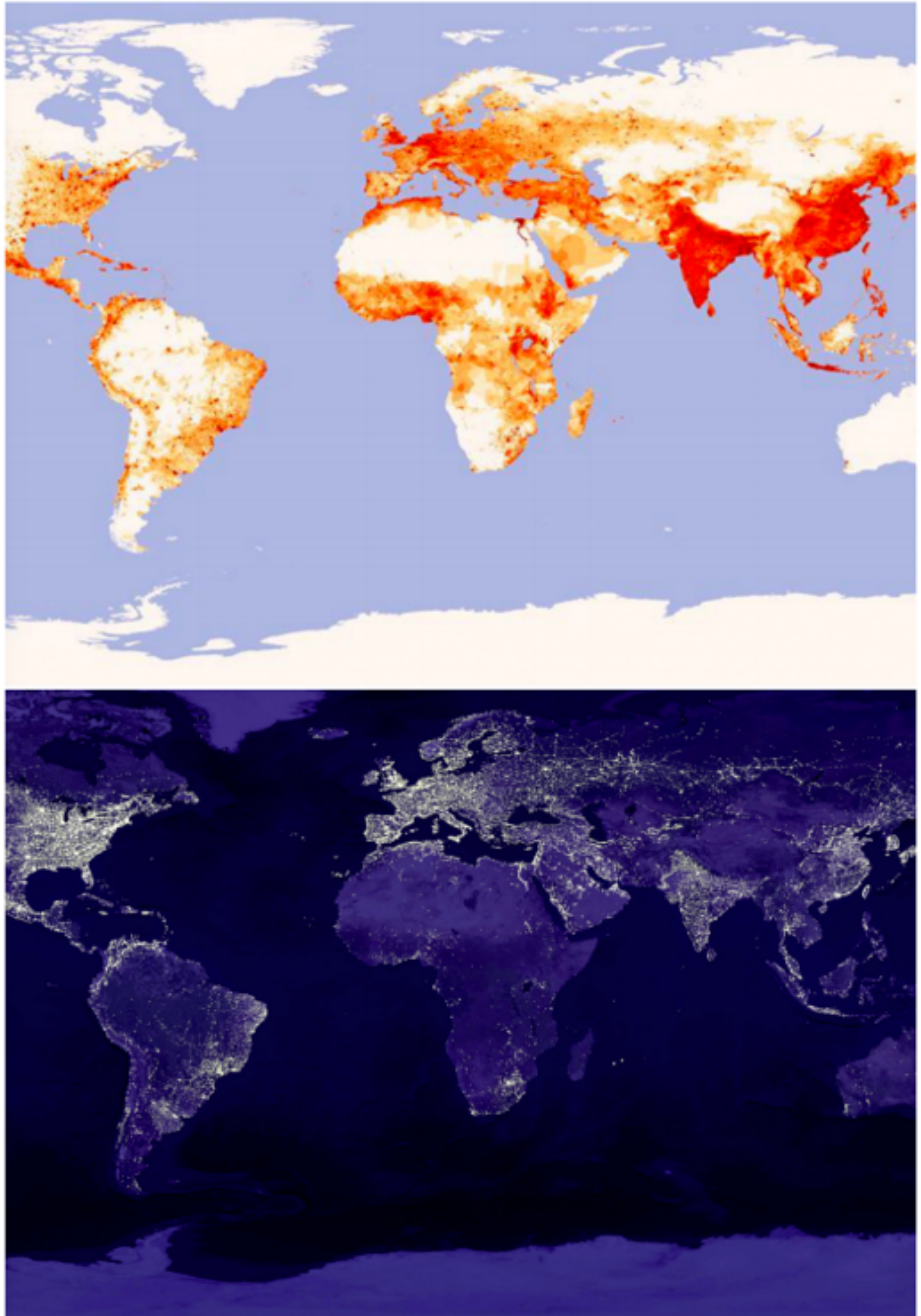
Galaxy Clustering - II: Theoretical Framework

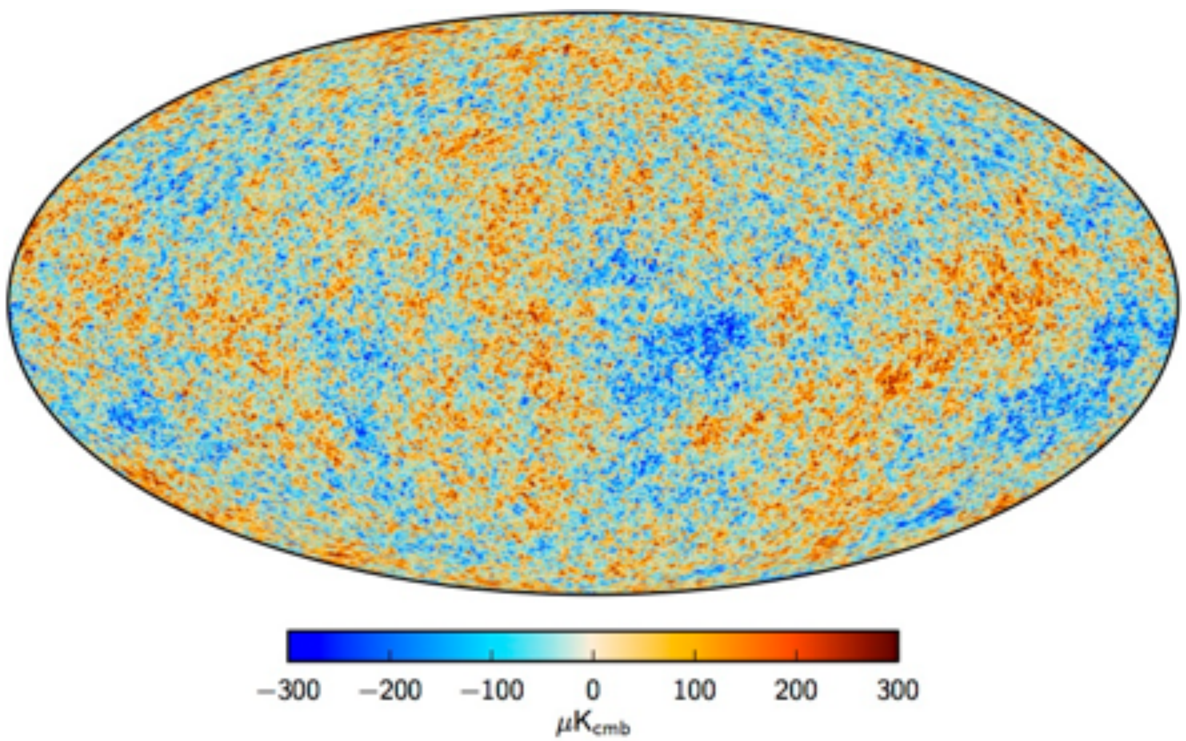
…or in Fourier space

$$\delta_g(\mathbf{k}) = (b_\delta + b_\eta f \mu^2)\delta_m(\mathbf{k}) + \epsilon$$

but…..can we trust this?
maybe yes! as long as:
1) galaxy formation is a local process
2) field to be modelled is matter or cdm/baryons

Perturbative approaches
N-body
HOD/SHAM modelling
hydro sims.

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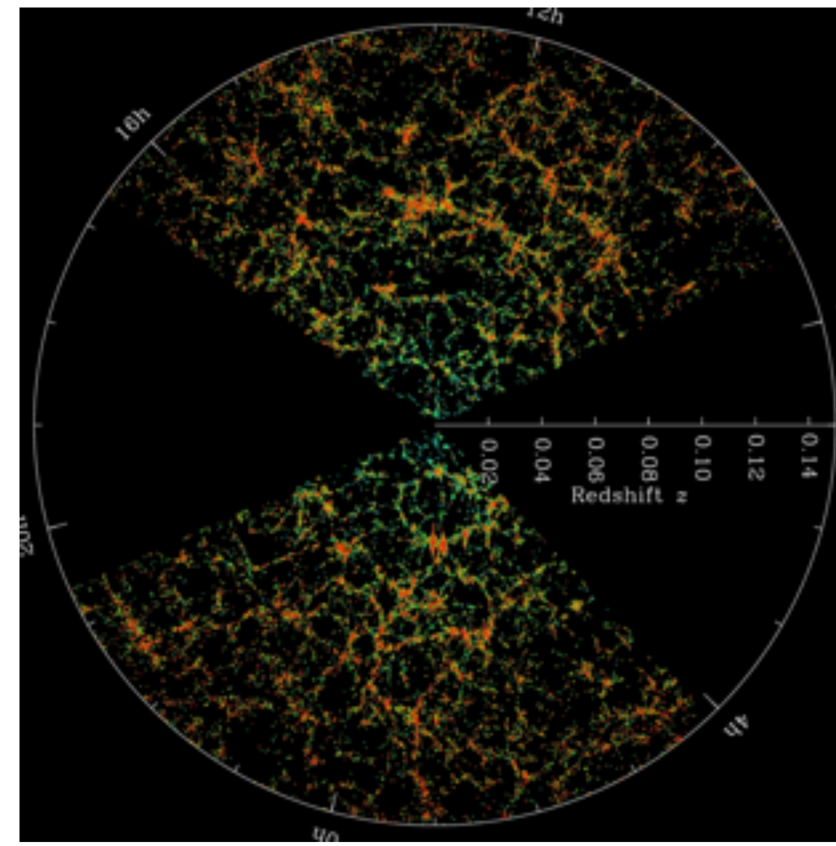
μK_cmb


12h
16h
8h
20h
4h
0h
0.02 0.04 0.06 0.08 0.10 0.12 0.14
Redshift z

THE ASTROPHYSICAL JOURNAL, **263**:L1–L5, 1982 December 1

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

P. J. E. PEEBLES
Joseph Henry Laboratories, Physics Department, Princeton University
Received 1982 July 2; accepted 1982 August 13

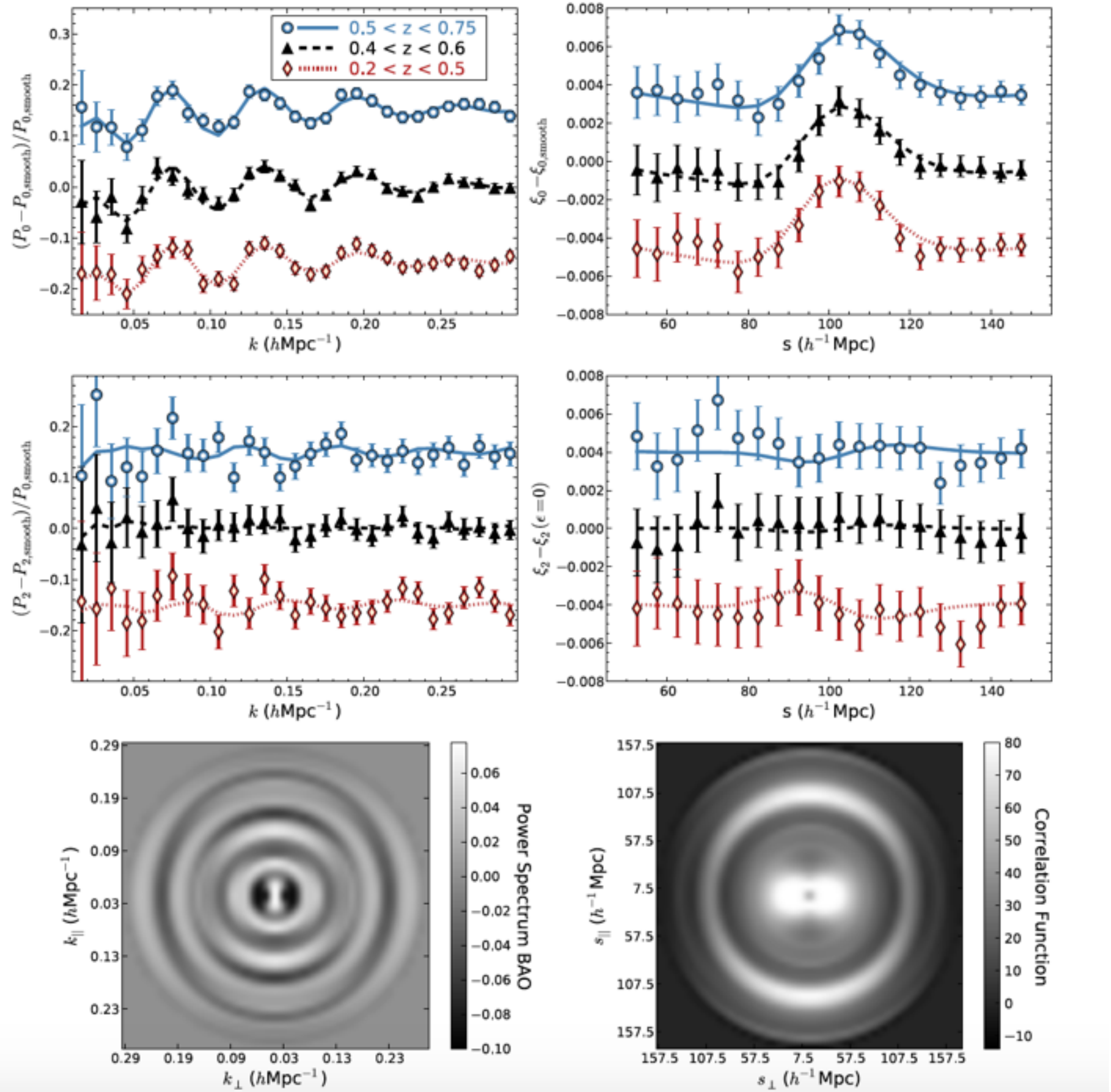
ABSTRACT

The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum $P \propto$ wavenumber. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, m_x, if $m_x \gtrsim 1$ keV. The expected background temperature fluctuations are well below present observational limits.

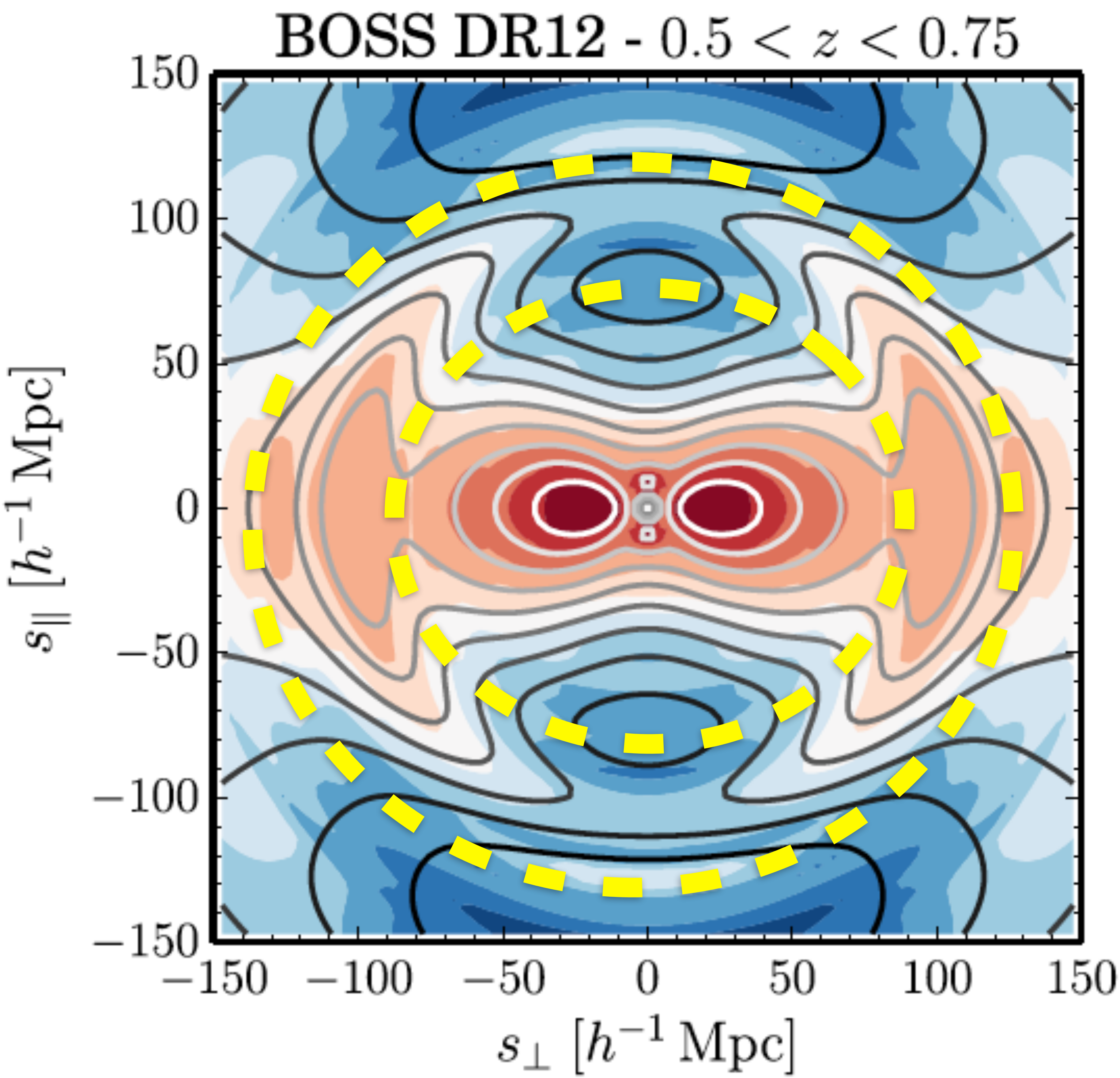
Subject headings: cosmic background radiation — cosmology — galaxies: formation

Galaxy clustering: the signal

Analysis performed in configuration and Fourier space and gives consistent results



The information in galaxy clustering



What is galaxy clustering adding (if anything) to what we already know from the CMB results?

Galaxy Clustering: BAO position

$$\alpha = \alpha_{\perp}^{2/3}\alpha_{||}^{1/3},$$
$$1+\epsilon = \left(\frac{\alpha_{||}}{\alpha_{\perp}}\right)^{1/3}$$

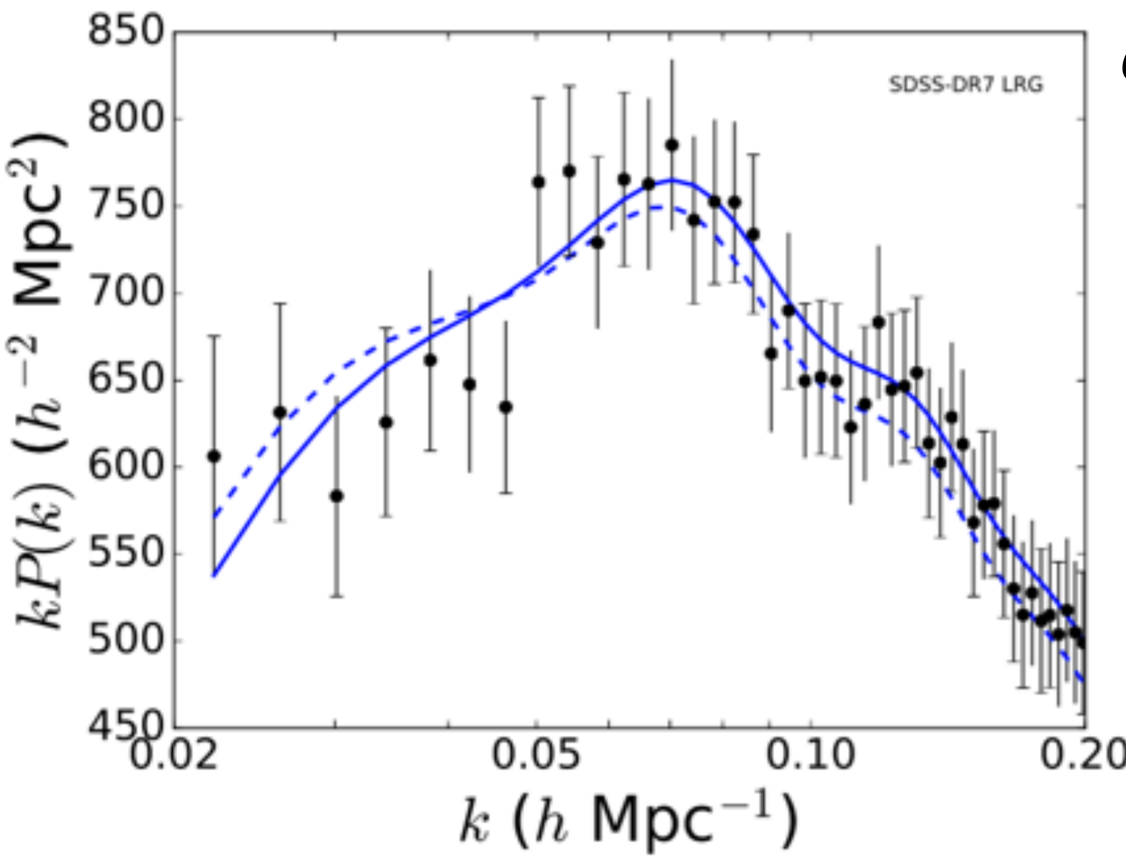
$$\alpha_{\perp} = \frac{D_{\mathrm{A}}(z)r_{\mathrm{s}}^{\mathrm{fid}}}{D_{\mathrm{A}}^{\mathrm{fid}}r_{\mathrm{s}}},$$

$$\alpha_{||} = \frac{H^{\mathrm{fid}}(z)r_{\mathrm{s}}^{\mathrm{fid}}}{H(z)r_{\mathrm{s}}}$$

α, ε usually appear when referring to systematics/mocks while distances and F_{AP} when quoting final cosmologically relevant numbers

$$D_V(z) = \left(D_M^2(z)\frac{cz}{H(z)}\right)^{1/3}$$
$$F_{\mathrm{AP}}(z) = D_M(z)H(z)/c.$$

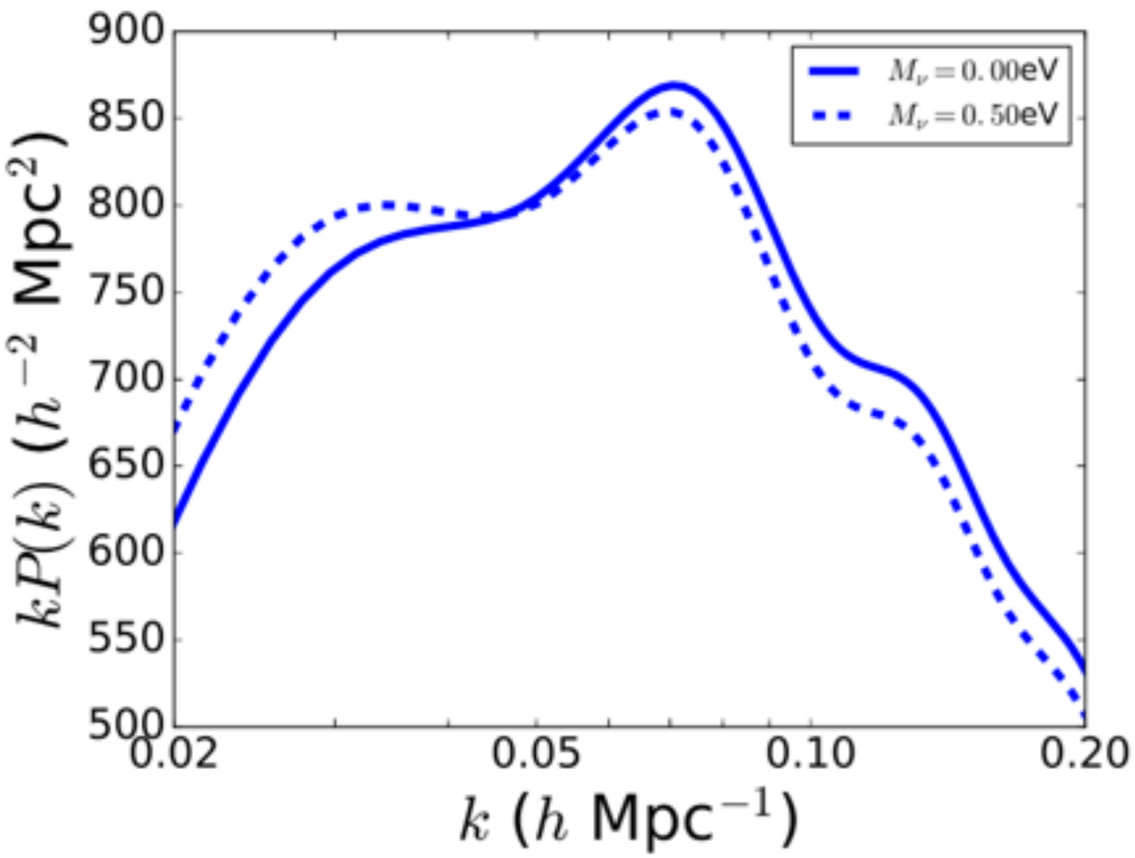
Constraints from galaxy clustering



Cuesta+16

•Galaxy clustering offers independent constraints that mainly exploit the shape

•Notice: galaxy bias Pgal=b^2 x Pmatter marginalized over but some assumptions
on the bias b(k,z) model must be made



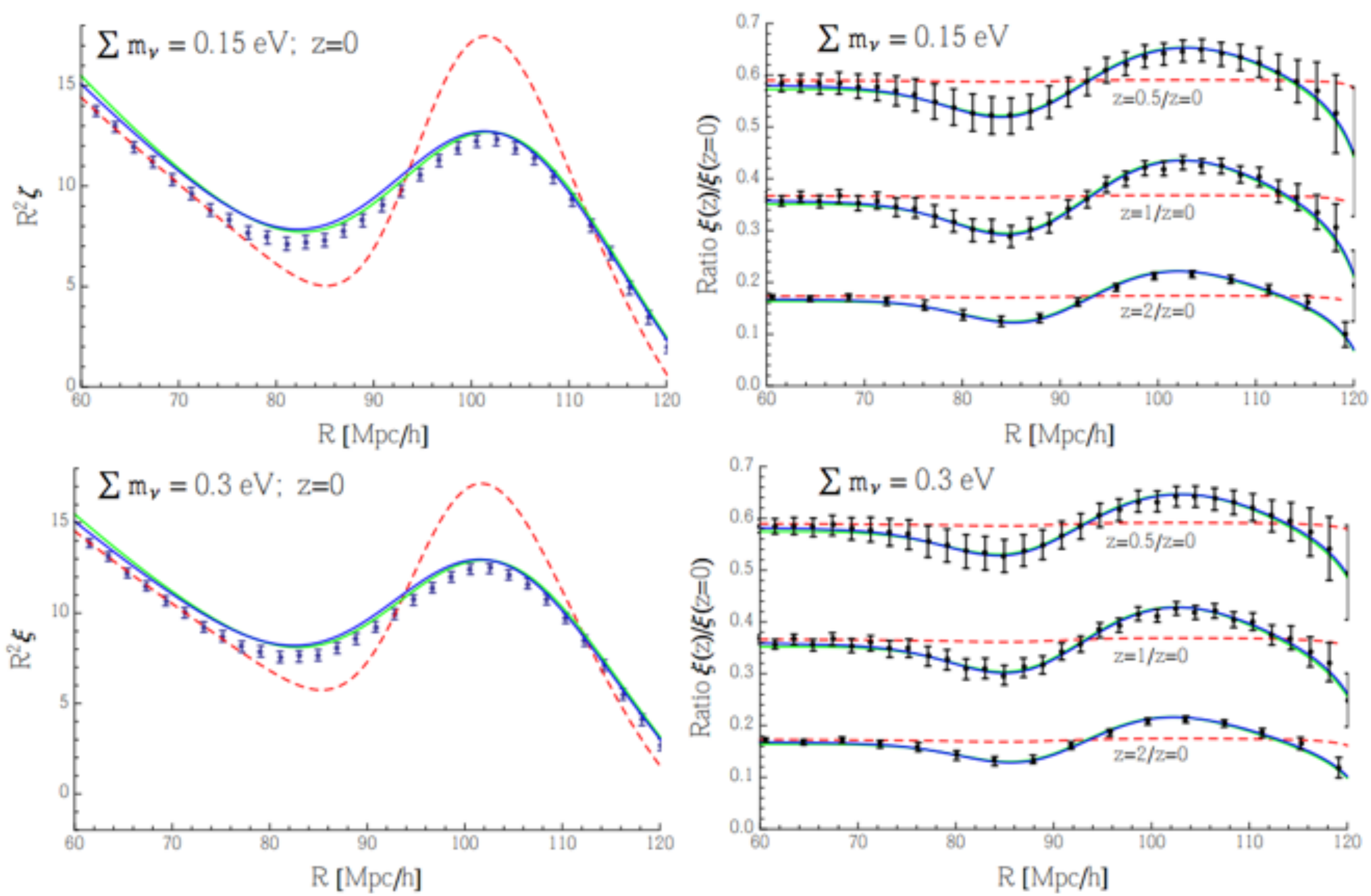
Parameter	CMB15+LRG+BAO
$100\ \omega_b$	$2.236^{+0.014}_{-0.014}$
$\omega_{\rm cdm}$	$0.1183^{+0.0012}_{-0.0011}$
n_s	$0.9677^{+0.0042}_{-0.0045}$
$\tau_{\rm reio}$	$0.083^{+0.016}_{-0.017}$
$ln(10^{10}A_s)$	$3.097^{+0.031}_{-0.034}$
H_0	$68.06^{+0.55}_{-0.55}$
σ_8	$0.831^{+0.016}_{-0.015}$
M_ν [eV]	< 0.13

Non-linearities at the BAO scales

The effect of massive neutrinos on the BAO peak

Marco Peloso[1], Massimo Pietroni[2,3], Matteo Viel[4,5], Francisco Villaescusa-Navarro[4,5]

The effect of massive neutrinos on the BAO peak



RESULTS: the peak decreases by ~ 0.6 % for Pmν = 0.15 eV and increases by ~ 1.2% for Pmν = 0.3 eV, with respect to a massless neutrino cosmology with equal value of the other cosmological parameters.

Galaxy clustering challenges - ca 2020

Measurement of galaxy clustering hampered by **systematics** and **statistical** errors.

Estimating the window function and selection function is not trivial.

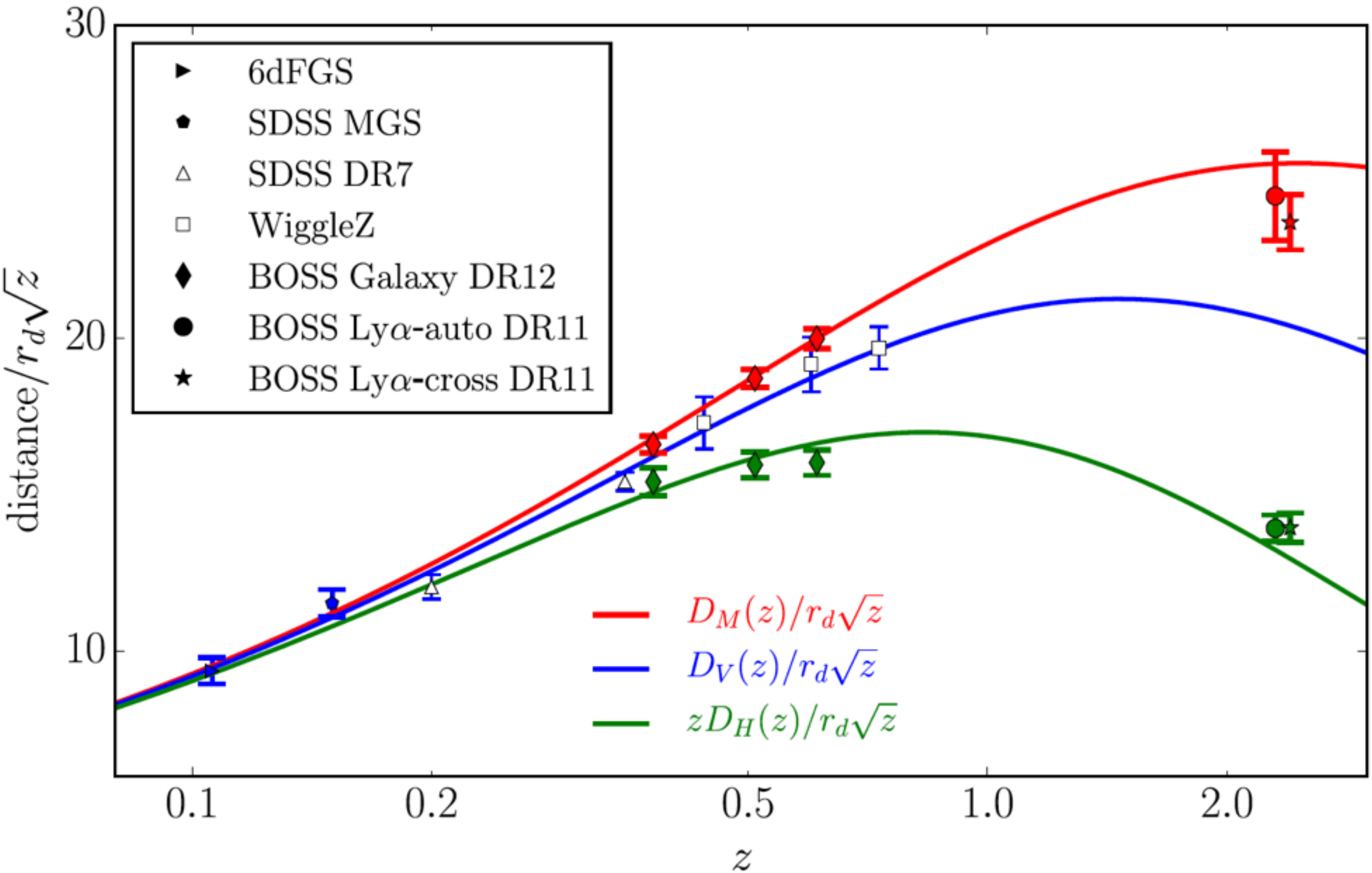
Focus on:

1) optimization of codes to handle large number of objects
2) getting reliable mocks
3) quantifying systematic effects
4) covariance matrix estimation
5) improving **reconstruction techniques**

State-of-the-art provided by BOSS survey (e.g. Alam+18, Vargas-Magana+18)

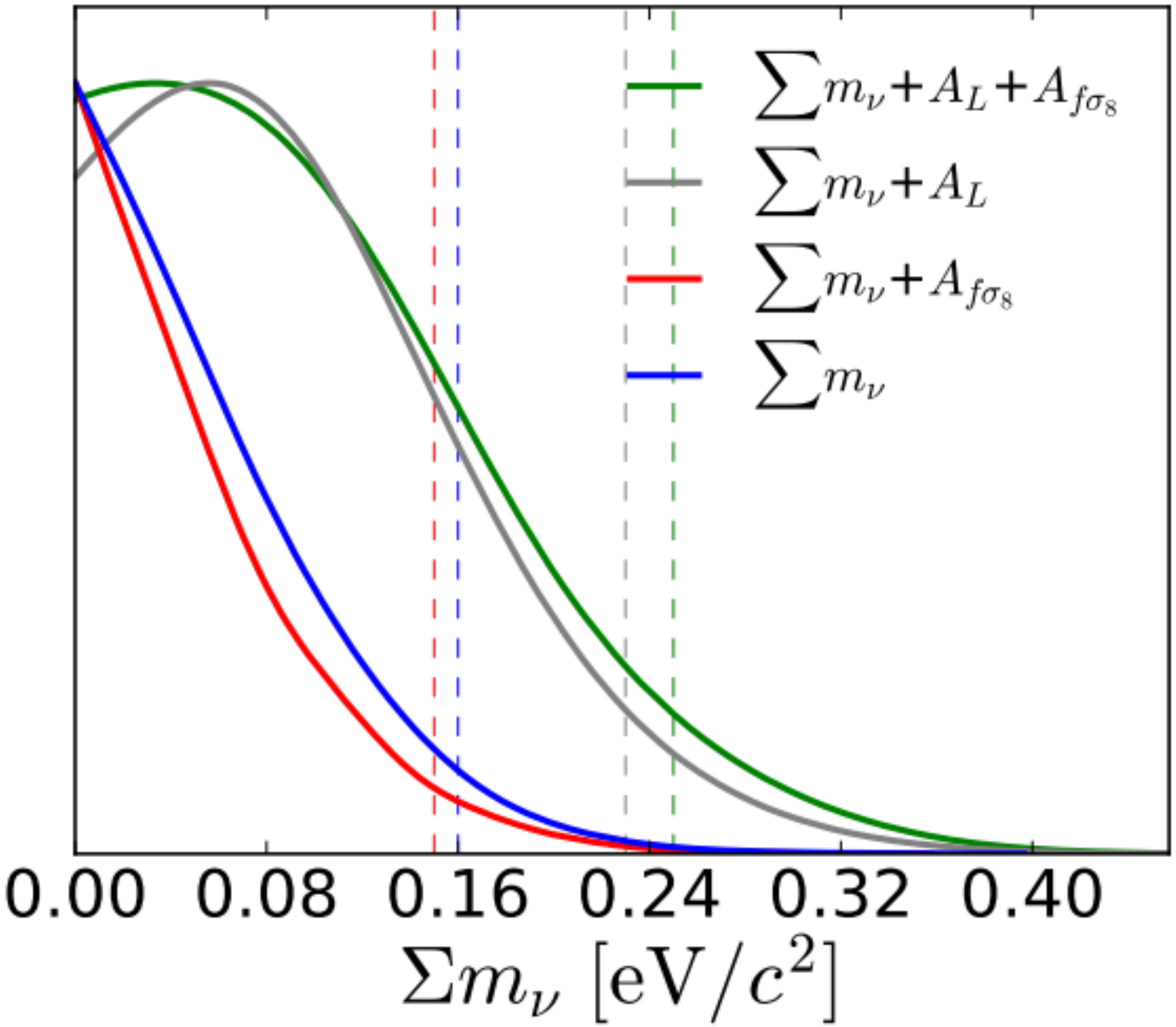
1) Systematics are estimated and appear as weights in the selection function
2) Mock generation using several different methods - based on Perturbation theory or N-body simulations
3) Estimation of the 2D correlation function using Landy-Szalay estimator
4) Analysis focused on BAO peak and in second instance on sub-BAO **shape** info
5) Different pipelines tested with estimation of systematic errors introduced in each step
6) Main conclusions: unlike naively expected latest BOSS results **are dominated by statistical errors**

BAO Hubble Diagram



Neutrinos from galaxy clustering

Alam+ 2017 DR12 BOSS



The 95 per cent upper limit is **0.16 eV**; this can be compared to the minimum of 0.06 eV. Removing any growth of structure information (i.e., fσ8 information from data set and CMB lensing information from Planck), we find the upper limit increases to **0.25 eV**, with the information coming primarily from the effect of the neutrino mass on the expansion history

BOSS: main conclusions

1) ~1% constraints on H(z) and DA(z) from BAO

2) amplitude of pec. vel. measured at ~10% level

3) No evidence for physics beyond LCDM

4) Agreement with Planck low values for H0, with limits remarkably stable also for owCDM or ow0waCDM models with 1sigma error bar of 1km/s/Mpc

5) Limits on neutrino mass are 0.16 eV, which become 0.25 when removing RSD and ~0.3 when opening the w parameter space

6) No support for Neff>3

OVERALL the stage is set and future seems promising for the next experimentslike eBO SS, DESI, WFIRST, Euclid etc.
it is expected that statistical errors will improve and a new level of systematics will be hit (sub-percent precision constraints)

IMPORTANT:

We have seen the effect of neutrinos on the energy densities and anisotropies on the CMB and galaxy clustering

Have we probed the neutrino free streaming in the structure formation era?

No: 1) so far mainly upper limits
2) clustering data used mainly to probe geometry
3) power spectrum (i.e. dynamical growth of structure not playing a big role in terms of constraints so far)

STRUCTURE FORMATION
(NON-LINEAR REGIME)

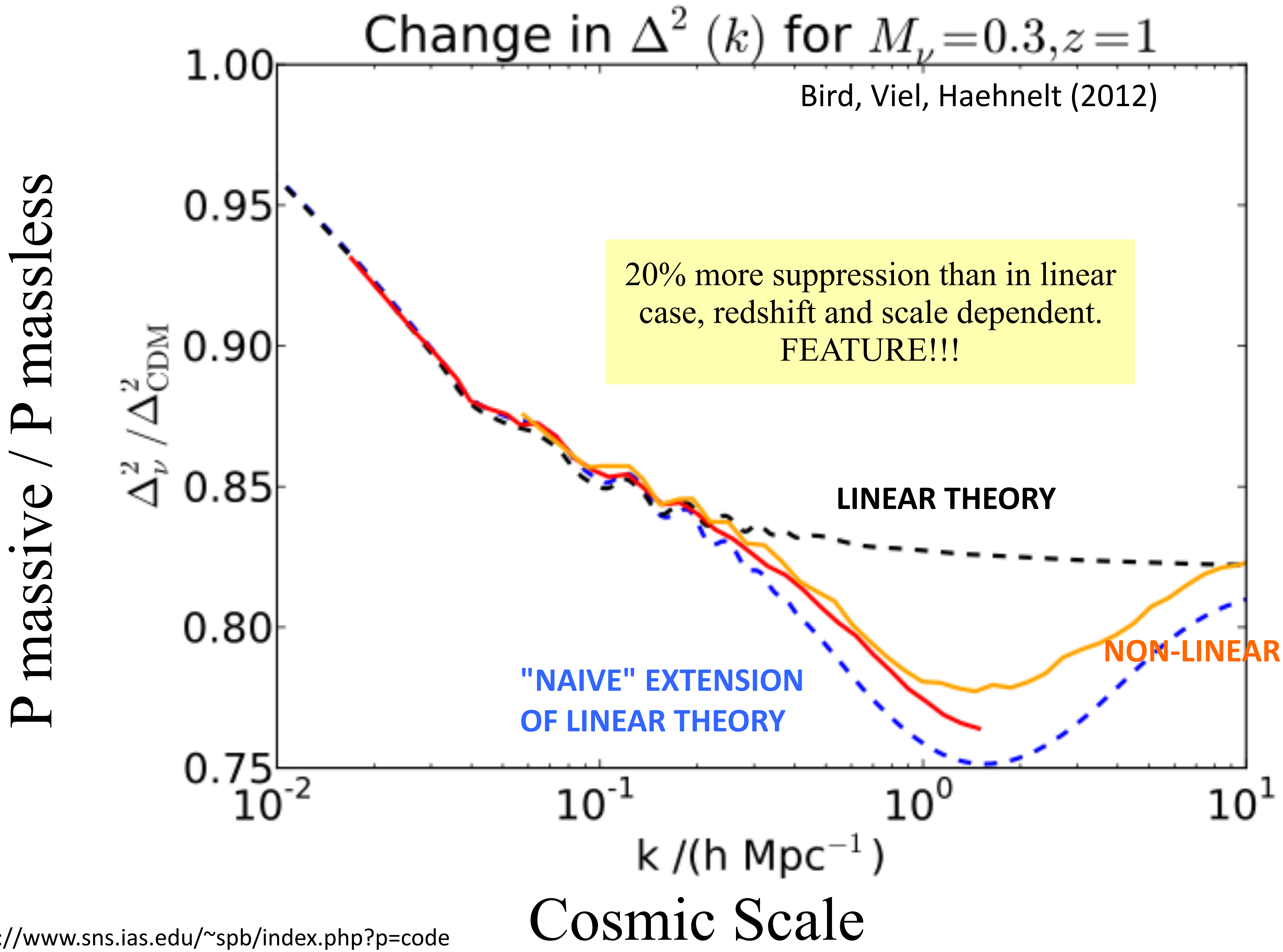
Neutrino implementations

- ☑ Particle Mesh (PM) Grid: fast *Brandbyge, Hannestad 08,09 - Brandbyge+08*
- ☑ Particles: shot noise - *Brandbyge, Hannestad 09 - Viel, Haehnelt, Springel 10 - Bird, Viel, Haehnelt 12*
- ☑ Hybrid methods (grid then at low z particles): non trivial how to convert *Brandbyge & Hannestad 10*
- ☑ Linear (and non-linear) response: fast but approximated *Ali-Hamoud & Bird 13, Liu+17*
- ☑ Cosmological neutrinos from Boltzmann solver + N-body - *Dakin+18 (nuCONCEPT code)*
- ☑ Particles: to reduce shot noise, better momentum sampling in ICs - *Banerjee+18*
- ☑ Hybrid: to reduce shot-noise hybrid with momentum space sampling - *Brandbyge+19*
- ☑ Paired neutrino sims to reduce CV - *Villaescusa-Navarro+19*

IMPORTANT NOTE:

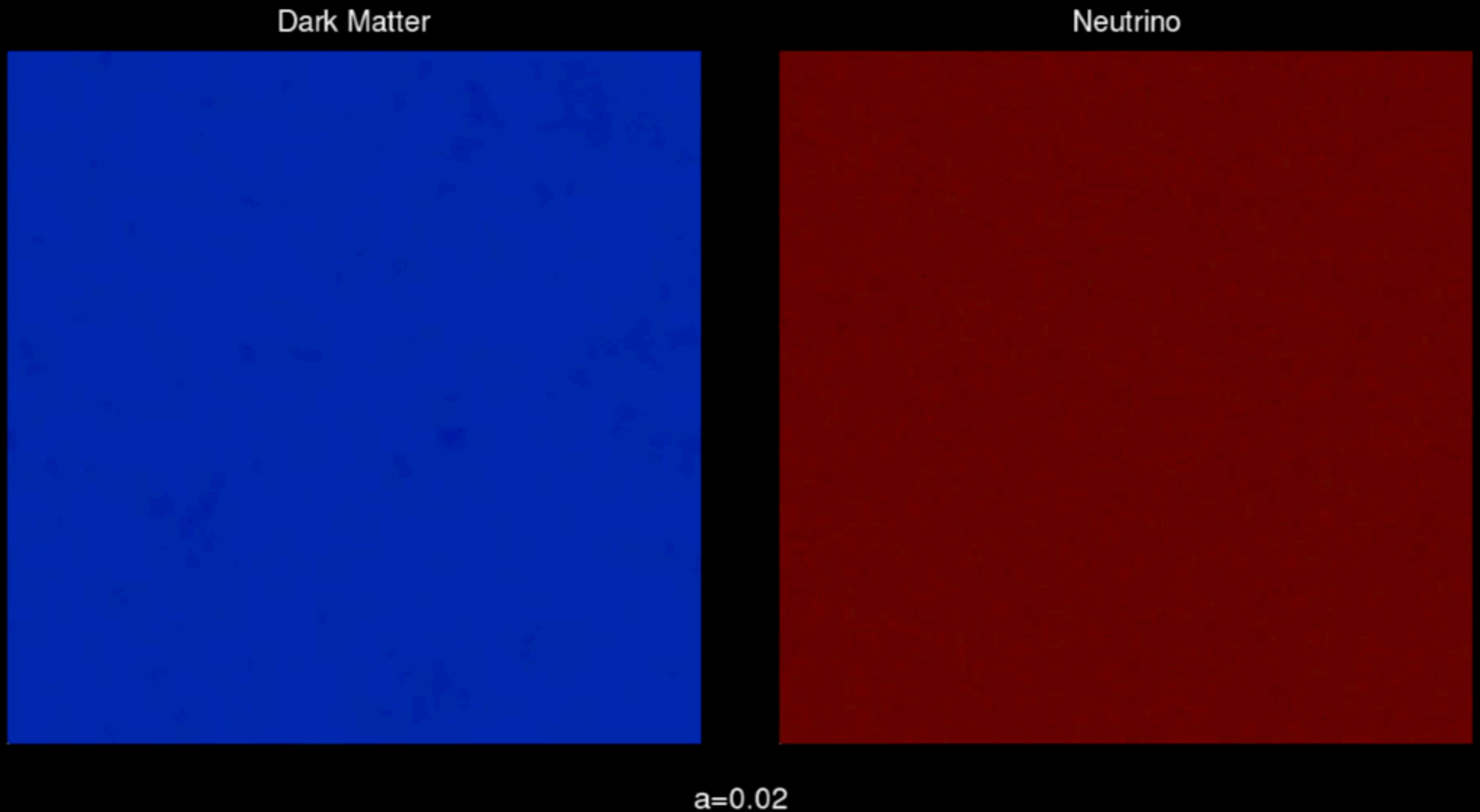
The idea of a best neutrino simulation is misleading, the best neutrino simulation is determined by the particular physical observable to be addressed.

COSMOLOGICAL NEUTRINOS: NON-LINEAR MATTER POWER

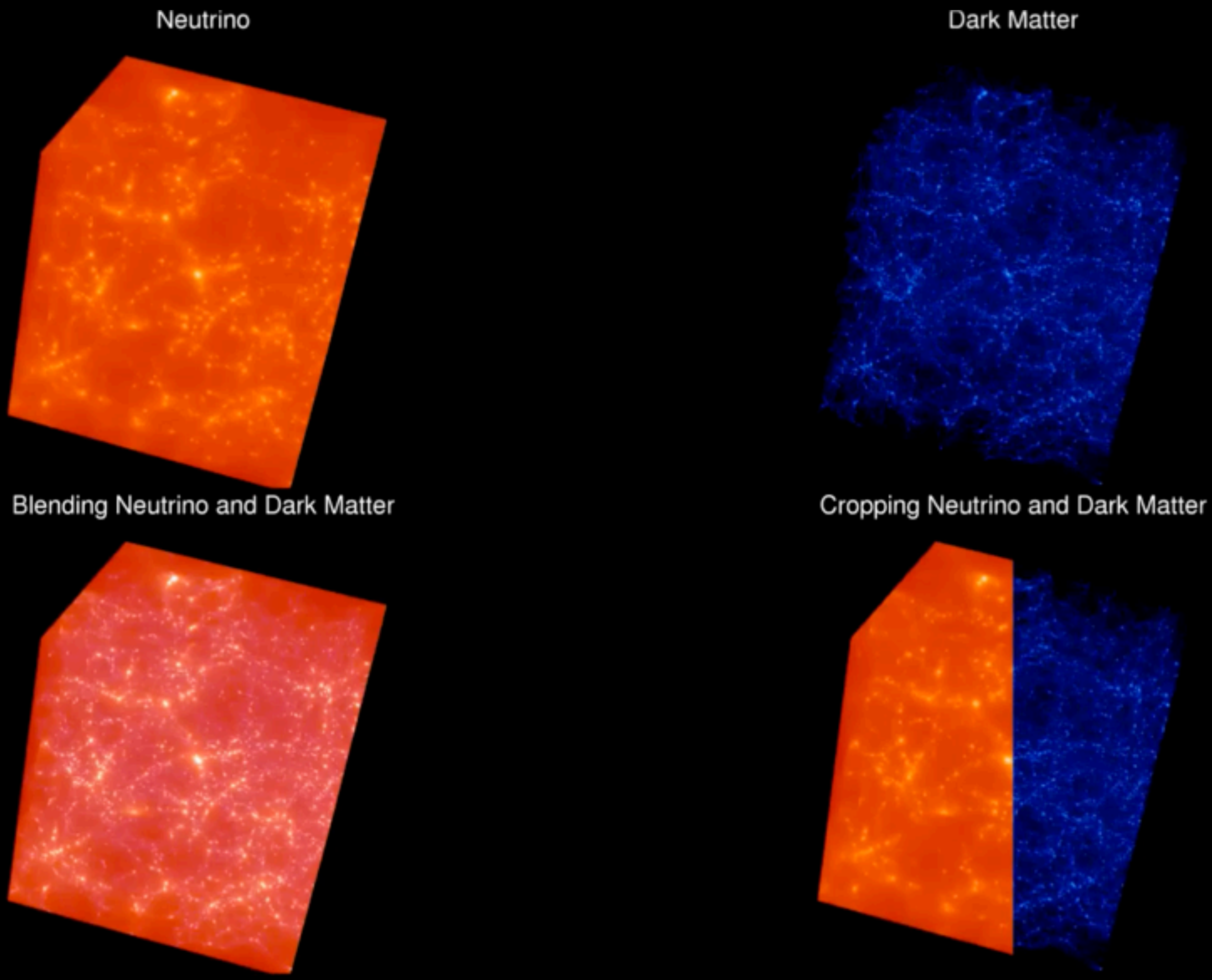


http://www.sns.ias.edu/~spb/index.php?p=code

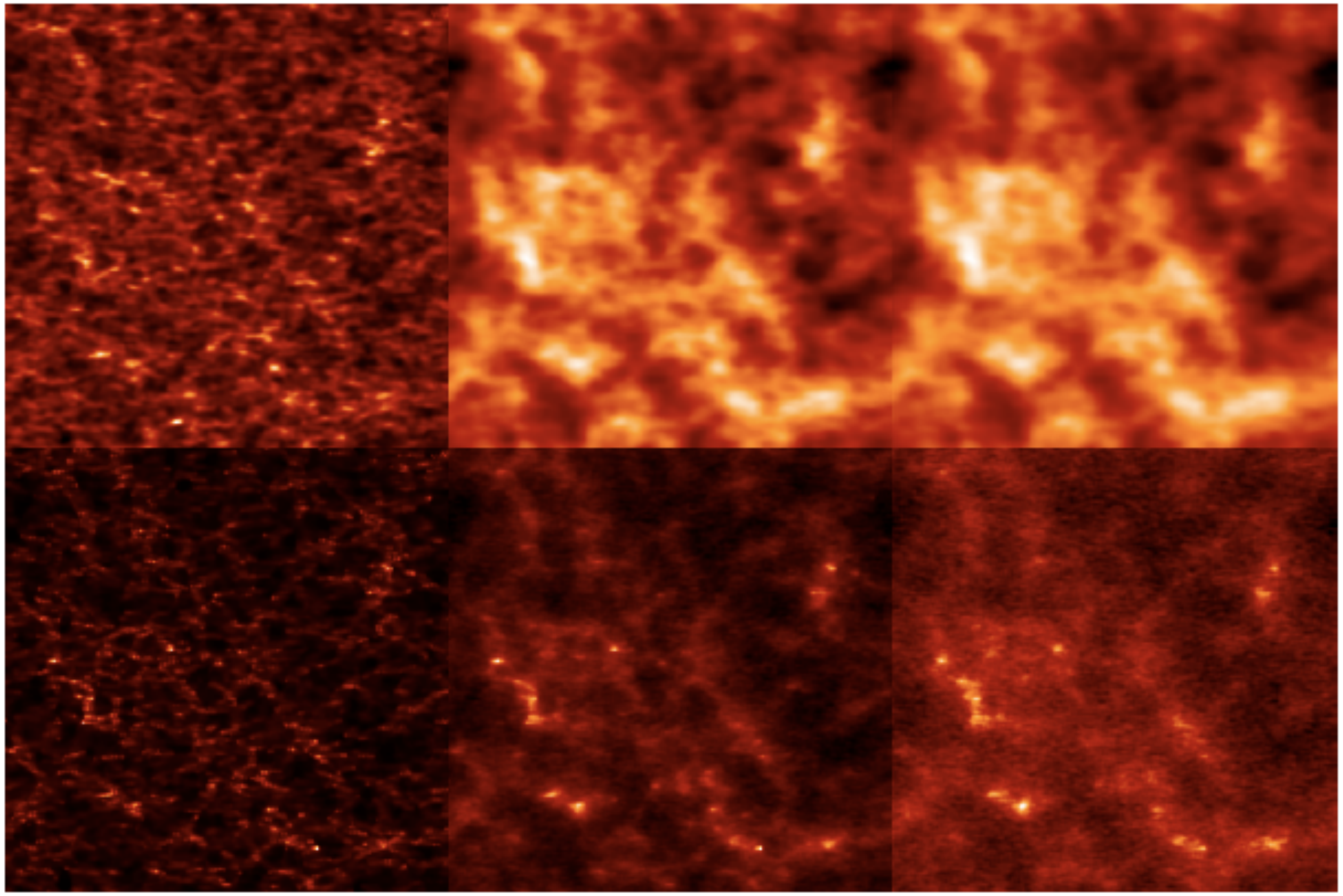
Neutrino clustering



Neutrino clustering



N-body simulations – I: particles

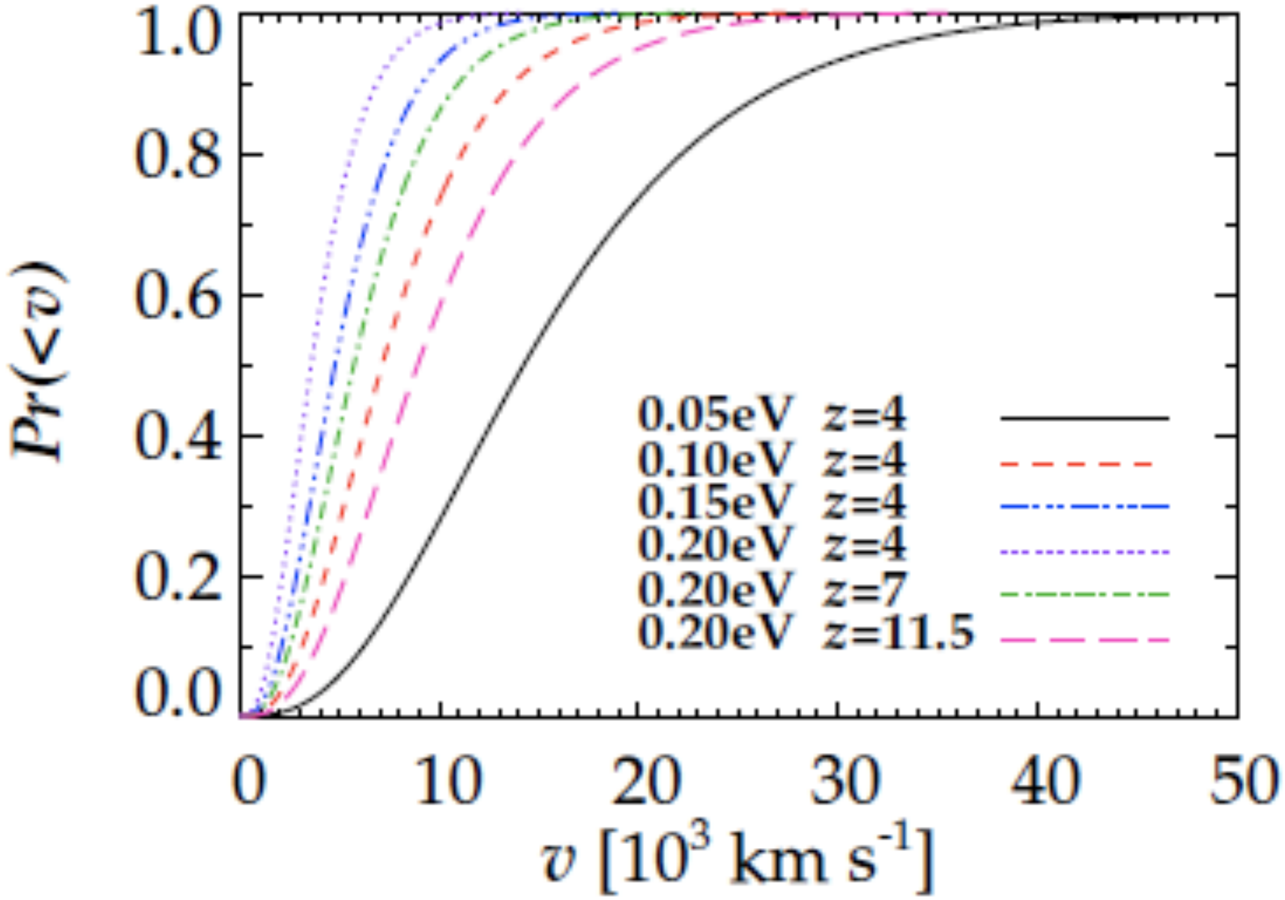


COLD DM NEUTRINOS 0.6 eV NEUTRINOS 0.3 eV

Brandbyge, Hannestad, Haugbolle, Thomsen 08

Simulation of neutrinos as an independent set of particles that interact gravitationally

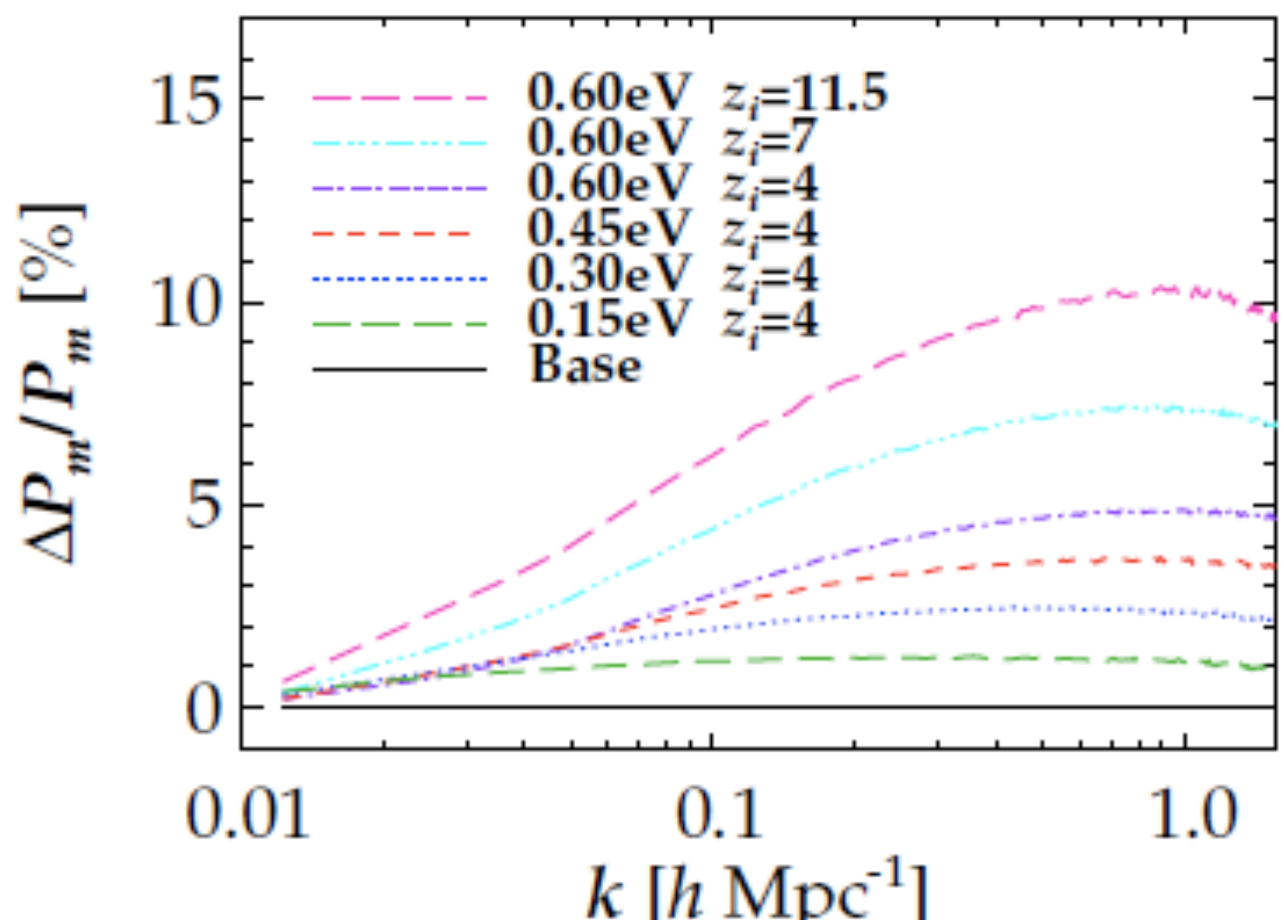
N-body simulations – II: neutrino velocities matter



$$T_\nu \simeq T_\gamma (4/11)^{1/3}$$

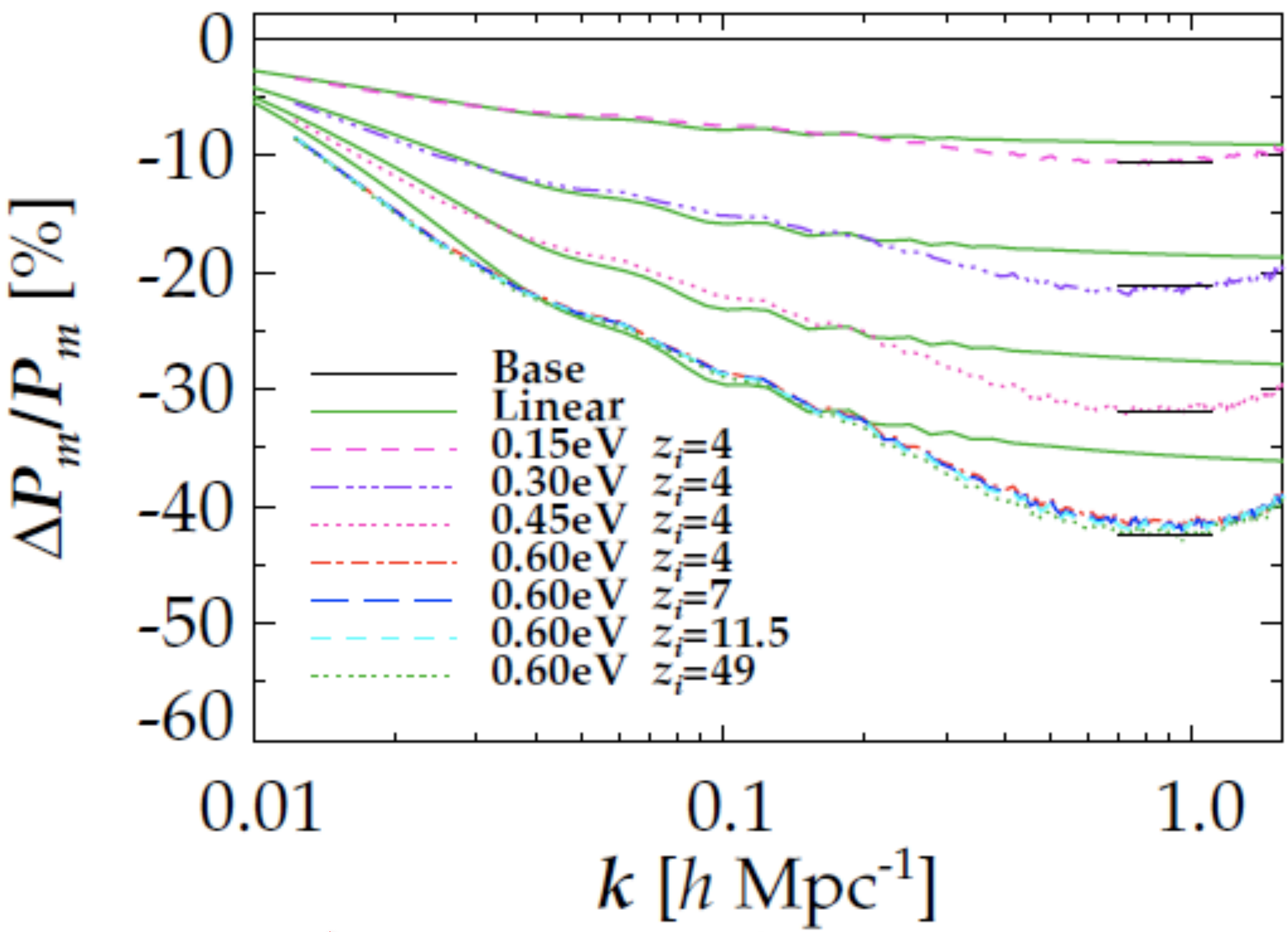
$$Pr(<p) = N \int_0^p \frac{p'^2}{e^{p'c/k_b T_\nu} + 1} dp'$$

Draw velocity from Fermi-Dirac distribution



Brandbyge et al 08

N-body simulations - III: effects in terms of non-linear power



Brandbyge et al 08

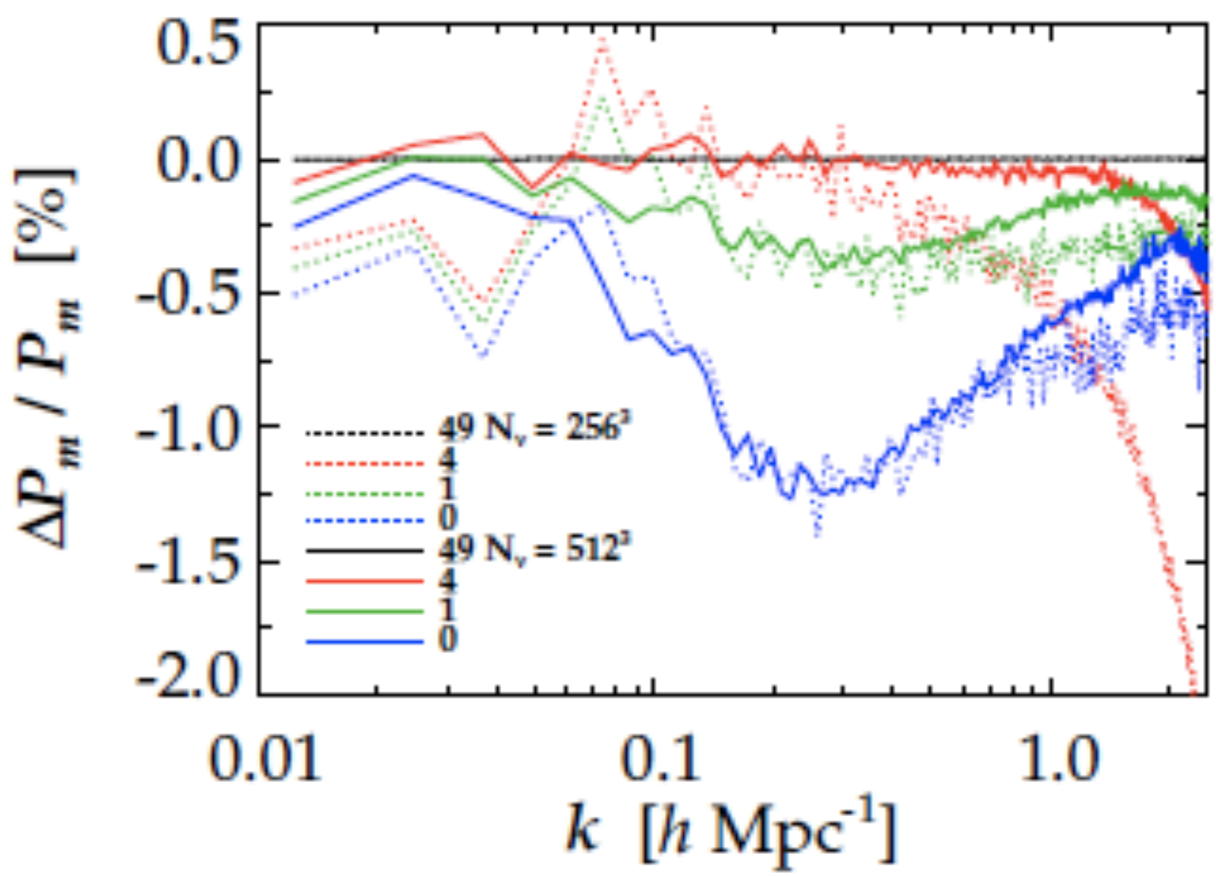
$$\cancel{\left.\frac{\Delta P}{P}\right|_{\max} \approx -8\frac{\Omega_\nu}{\Omega_m}} \longrightarrow \left.\frac{\Delta P}{P}\right|_{\max} \sim -9.8\frac{\Omega_\nu}{\Omega_m}$$

N-body simulations – IV: mesh method

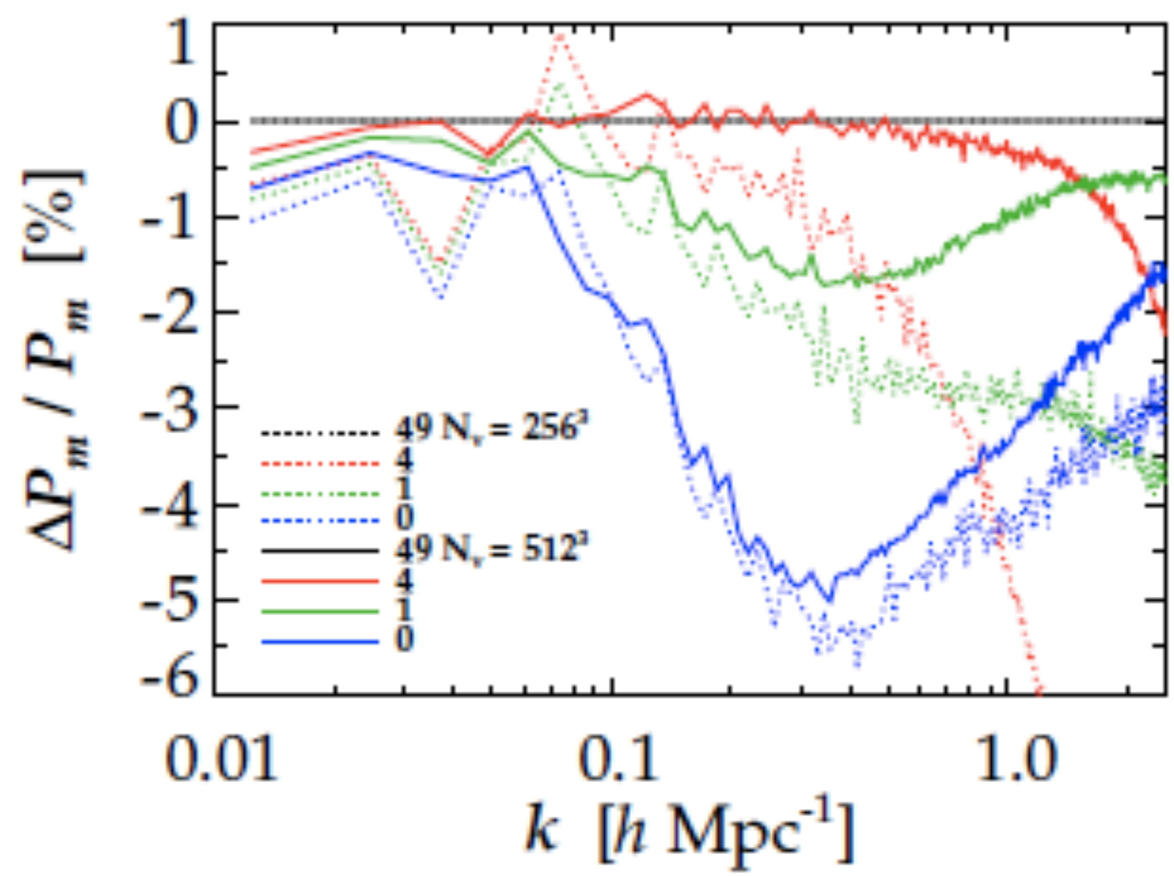
Computing the neutrino gravitational potential on the PM grid and summing up its contribution to the total matter gravitational potential – this is much faster!

COMPARISON GRID VS PARTICLES

M_ν =0.6 eV



M_ν = 1.2 eV



Brandbyge et al 08b

N-body simulations – V: a hybrid approach

$$f = f_0 + \frac{\partial f_0}{\partial T}\delta T = f_0(1+\Psi) \qquad f_0(q) = \frac{1}{e^{q/T}+1}$$

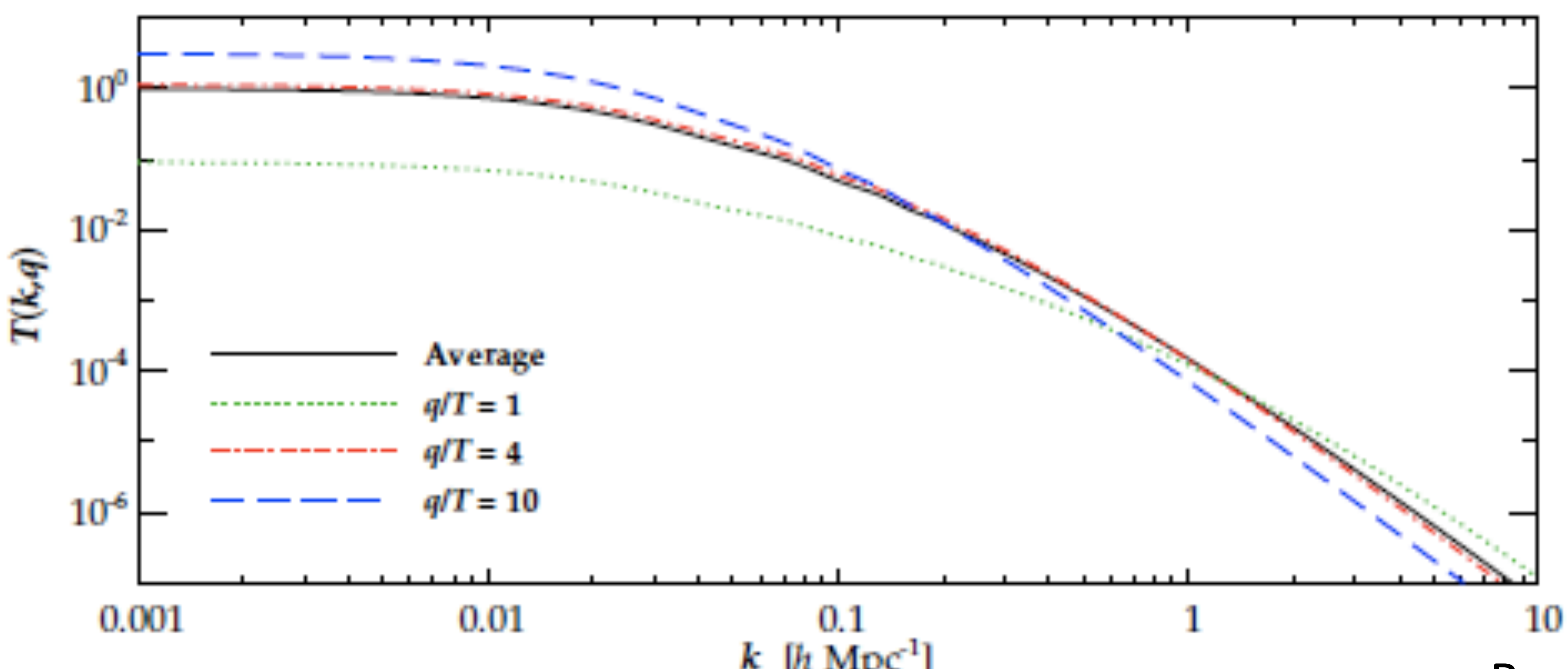
After neutrino decoupling CBE

$$\frac{df}{d\tau} = \frac{\partial f}{\partial \tau} + \frac{dx^i}{d\tau}\frac{\partial f}{\partial x^i} + \frac{dq}{d\tau}\frac{\partial f}{\partial q} + \frac{dn_i}{d\tau}\frac{\partial f}{\partial n_i} = 0$$

$$\delta\rho_\nu(k) = 4\pi a^{-4}\int q^2 dq \epsilon f_0 \Psi_0 \qquad \epsilon = (q^2 + a^2 m^2)^{1/2}$$

Expansion of ψ in Legendre series

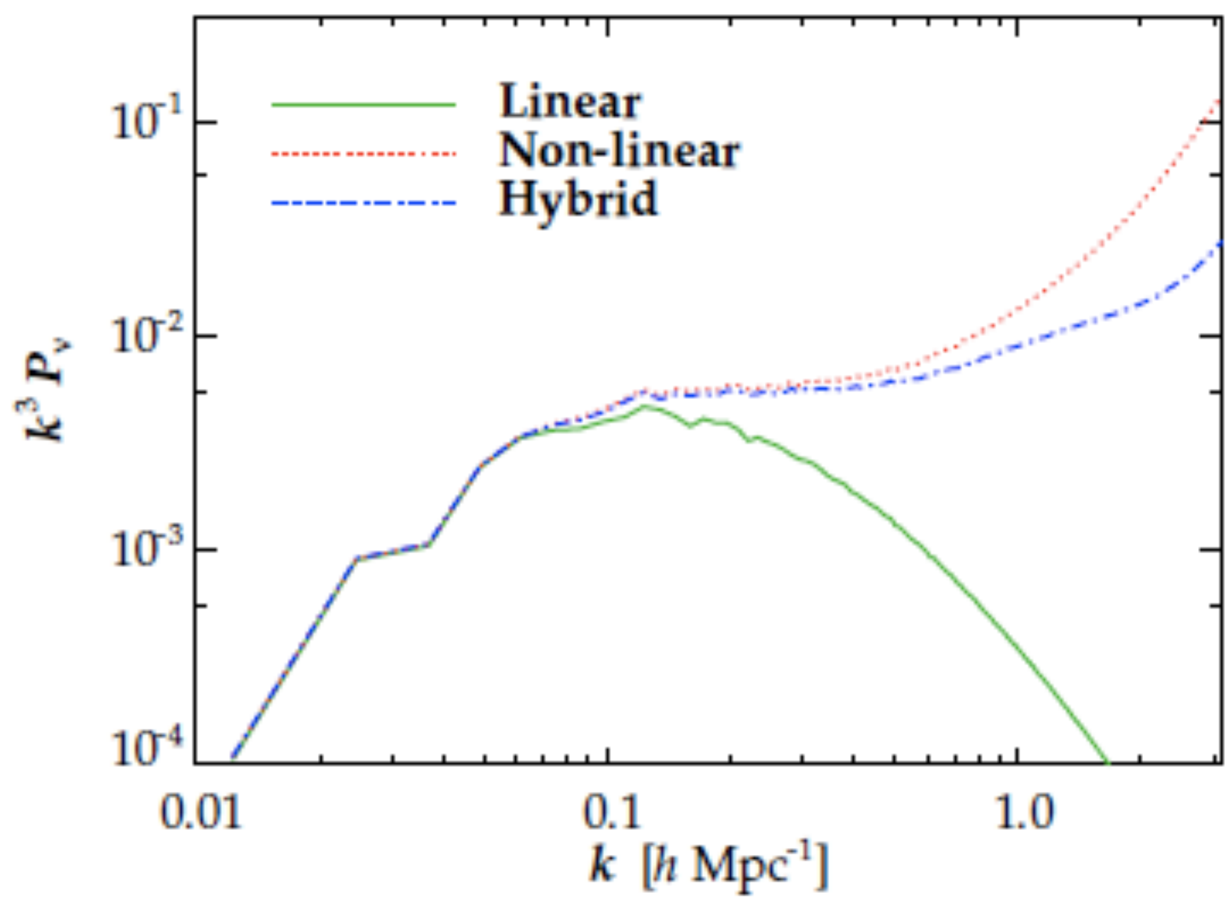
$$\dot\Psi_0 = -\frac{qk}{3\epsilon}\Psi_1 - \dot\phi\frac{d\ln f_0}{d\ln q},$$
$$\dot\Psi_1 = \frac{qk}{\epsilon}\left(\Psi_0 - \frac{2}{5}\Psi_2\right) - \frac{\epsilon k}{q}\psi\frac{d\ln f_0}{d\ln q},$$
$$\dot\Psi_l = \frac{qk}{\epsilon}\left(\frac{l}{2l-1}\Psi_{l-1} - \frac{l+1}{2l+3}\Psi_{l+1}\right),\ l \geq 2$$



$$\Psi_0(k,q,z) = T(k,q,z)\Psi_0^I(k,q)$$

Brandbyge & Hannestad 09

N-body simulations – VI: comparison



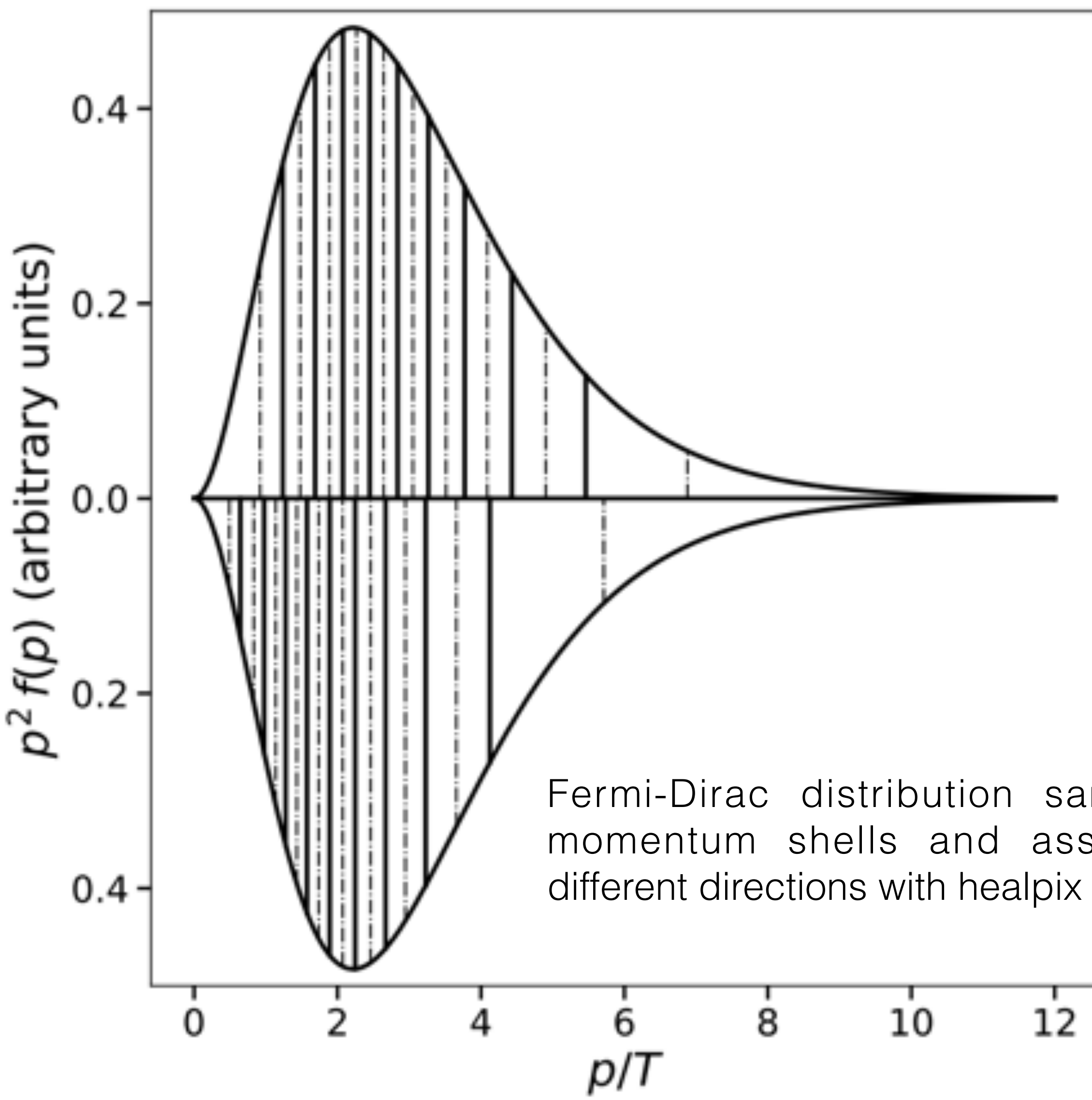
PARTICLES: accurate non-linear sampling but prone to shot-noise errors

GRID: fast and accurate but no phase mixing (i.e. non-linear regime suppression maybe it is less than it should be)

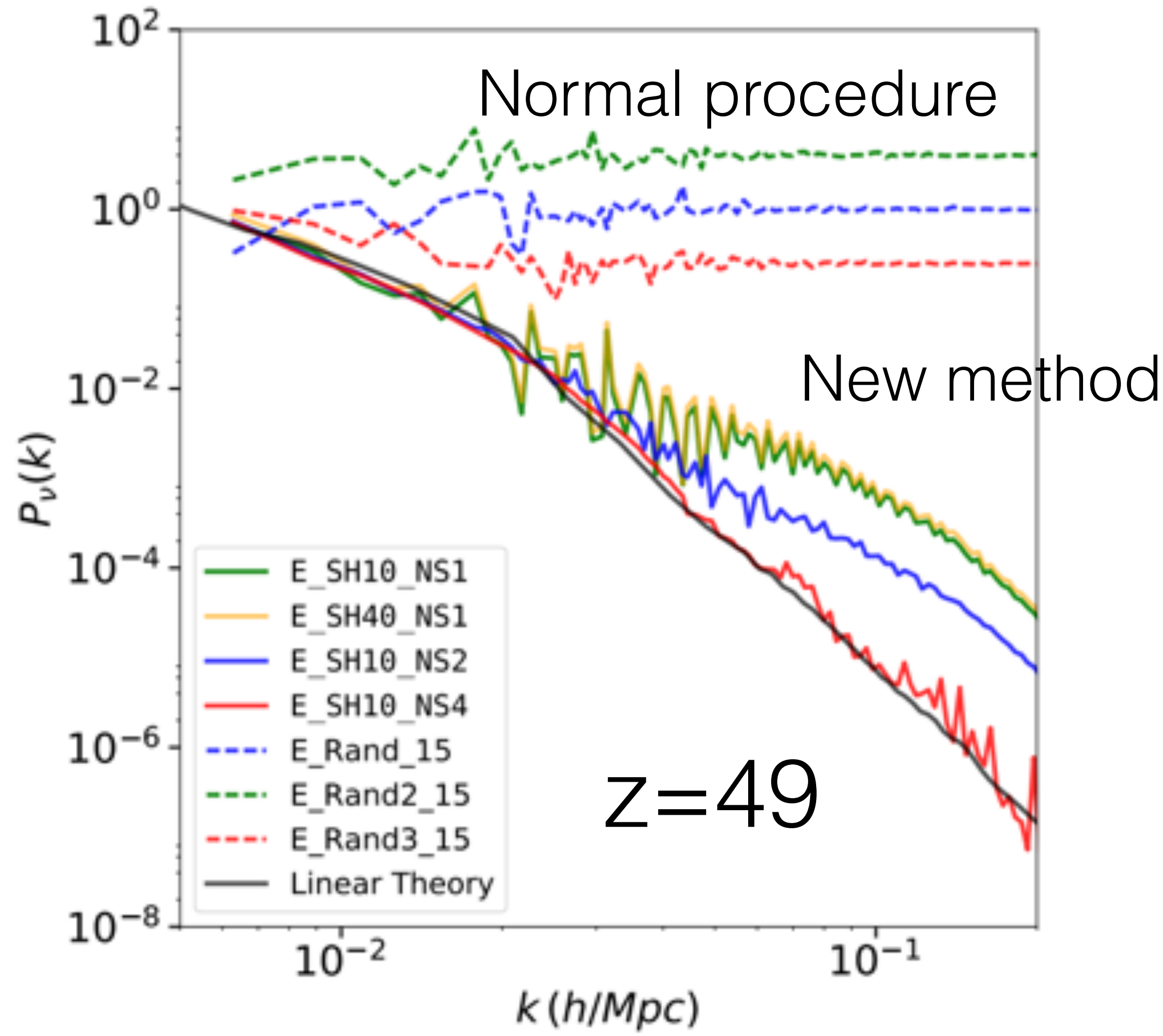
HYBRID: ideal for non-linear objects but memory demanding and prone to convergence issues

SAMPLING NEUTRINOS IN MOMENTUM SPACE

Banerjee+19

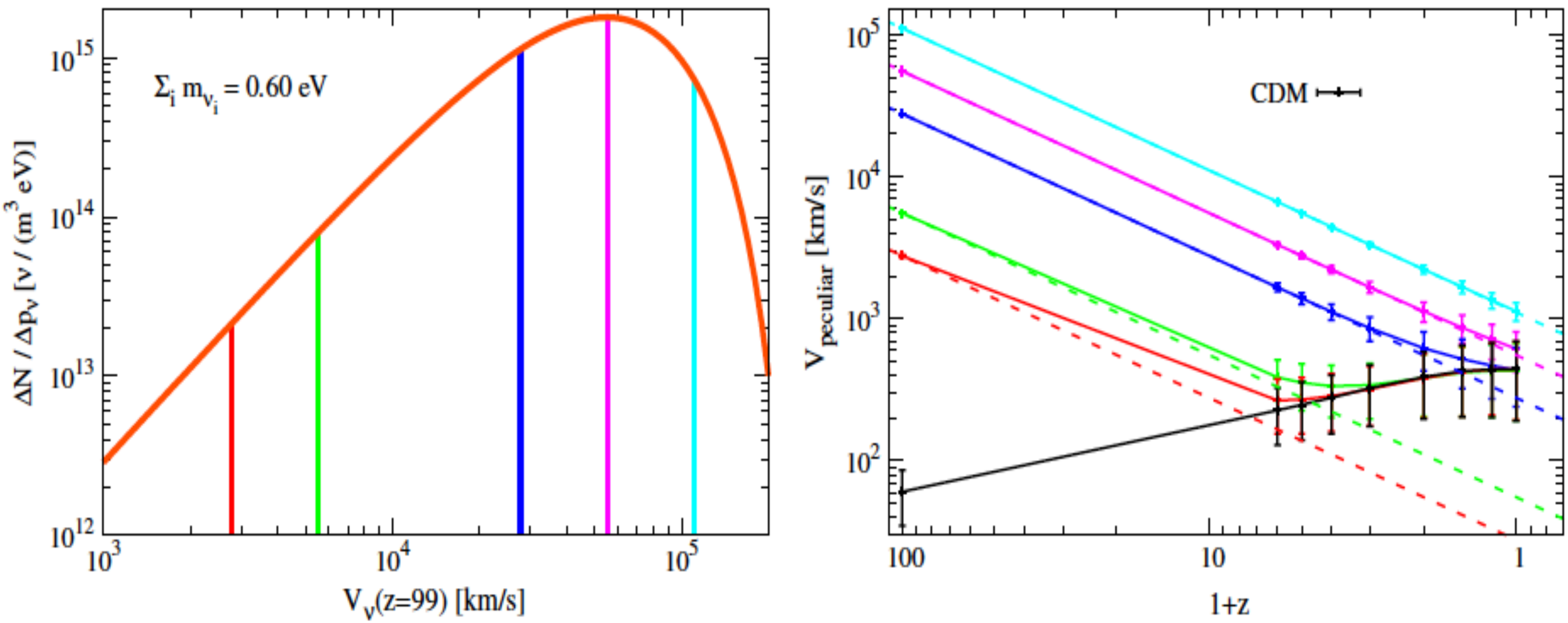


Fermi-Dirac distribution sampled in momentum shells and assigned in different directions with healpix



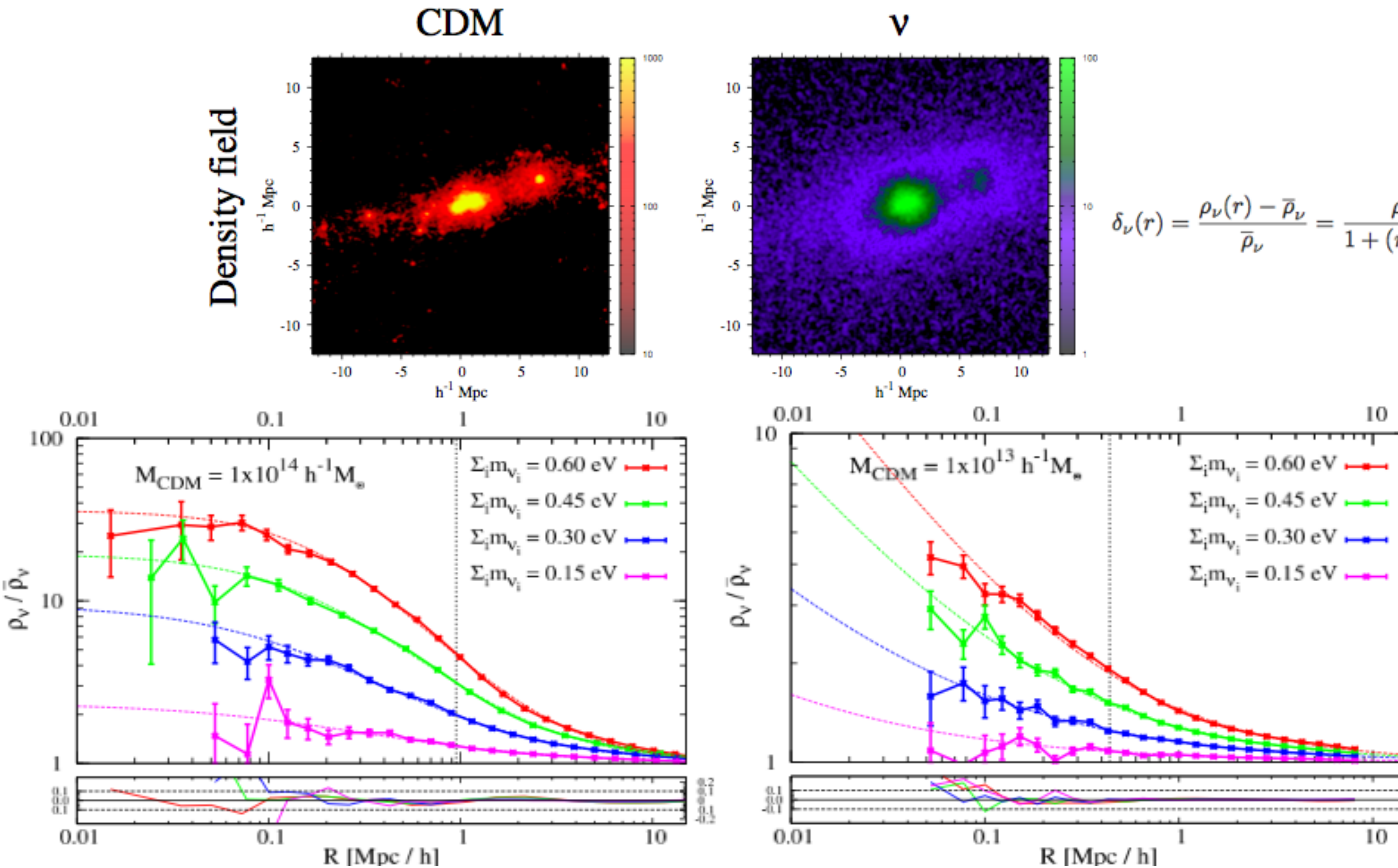
Brandbyge+19 uses this method in the hybrid code and finds somewhat spurious power at small redshift

VELOCITY DISTRIBUTION IN A COSMOLOGICAL VOLUME



Villaescusa-Navarro, Bird, Garay, Viel, 2013, JCAP, 03, 019

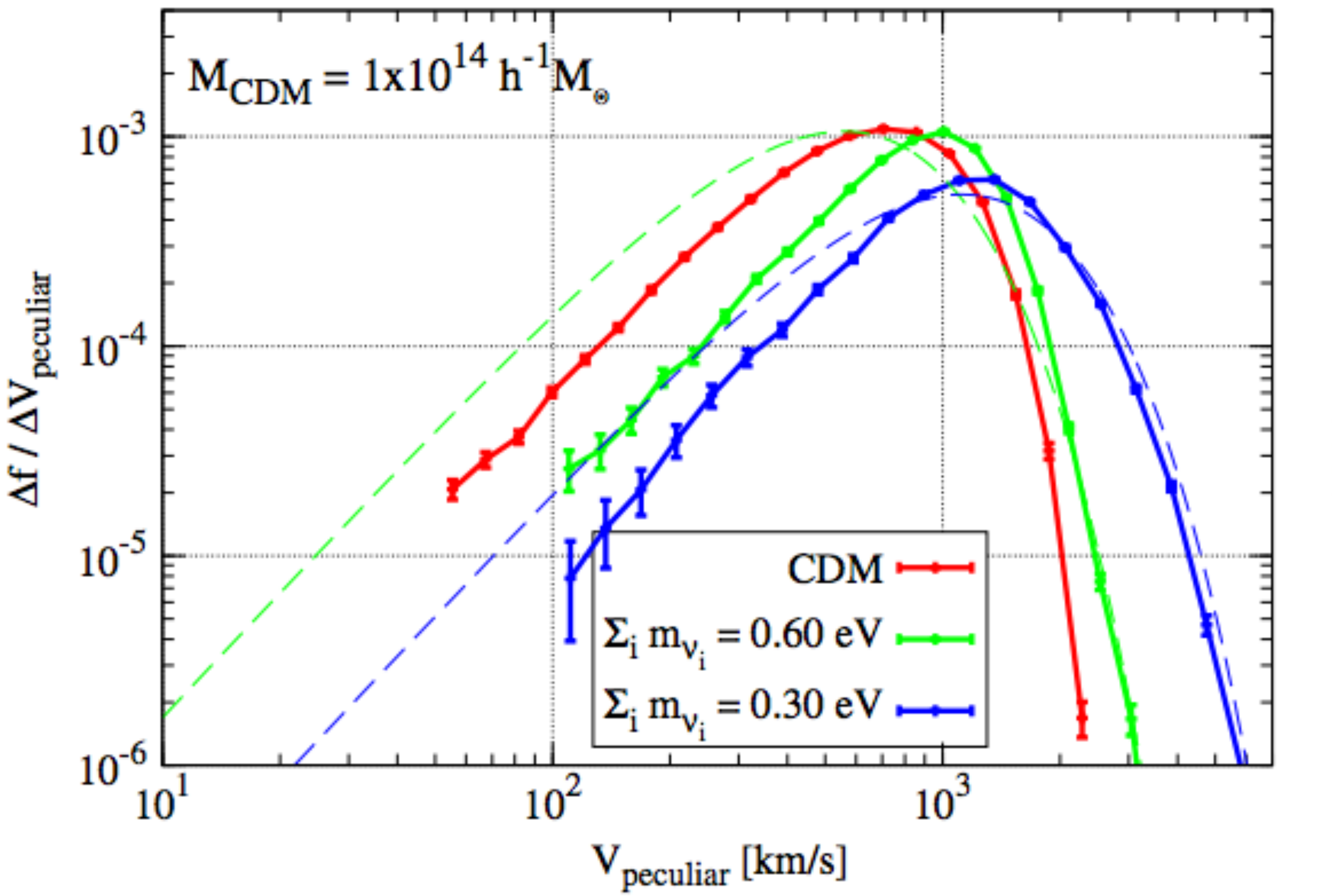
THE NEUTRINO HALO



$$\delta_\nu(r) = \frac{\rho_\nu(r) - \bar{\rho}_\nu}{\bar{\rho}_\nu} = \frac{\rho_c}{1 + (r/r_c)^\alpha}$$

Villaescusa-Navarro, Bird, Garay, MV, 2013, JCAP, 03, 019
Marulli, Carbone, MV 2011, MNRAS, 418, 346

VELOCITY DISTRIBUTION AROUND A HALO



MODELLING NEUTRINOS NON-LINEARLY WITHOUT N-BODY SIMS

$$P(k) = \left(\frac{\bar{\rho}_c}{\bar{\rho}}\right)^2 P_c(k) + 2\,\frac{\bar{\rho}_c\bar{\rho}_\nu}{\bar{\rho}^2}\,P_{c\nu}(k) + \left(\frac{\bar{\rho}_\nu}{\bar{\rho}}\right)^2 P_\nu(k)$$

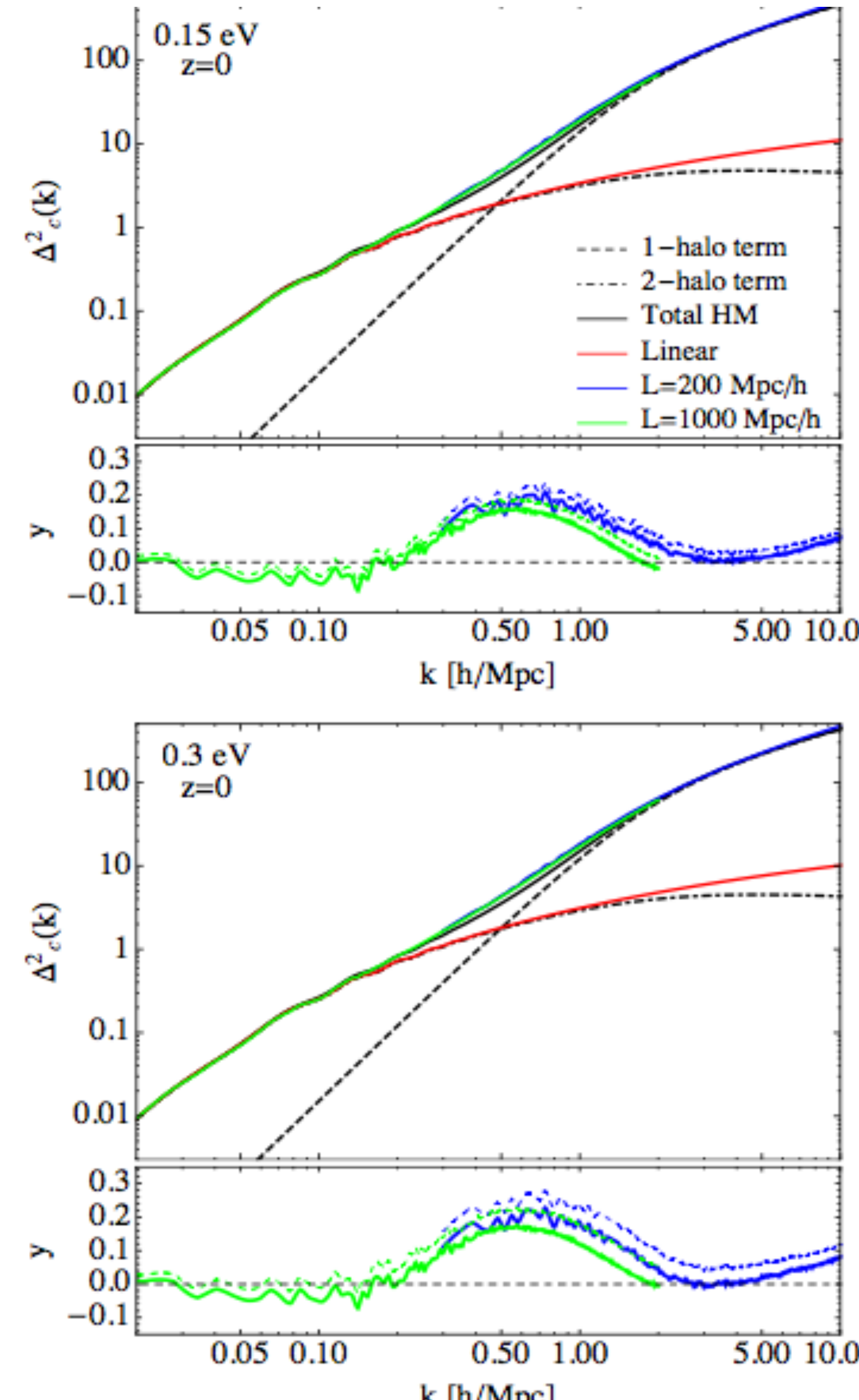
- Assumption: all matter within haloes 1h and 2h terms

- Simple modelling of non-linear power spectra (including cross-spectra)

- When used to predict ratios w.r.t. massless case it is as good as hydro/N-body to 2% level

- When used to compute actual power it suffers from limitation and it is good at the 20% level

NON LINEAR POWER SPECTRA



Massara, Villaescusa, MV (2014) – Castorina+ (2014) for bias and mass functions

HALO MASS FUNCTION: UNIVERSALITY IN A MASSIVE NEUTRINO COSMOLOGY

Castorina, Sefusatti, Sheth, Villaescusa-Navarro, Viel 2013

FoF halos : b=0.2

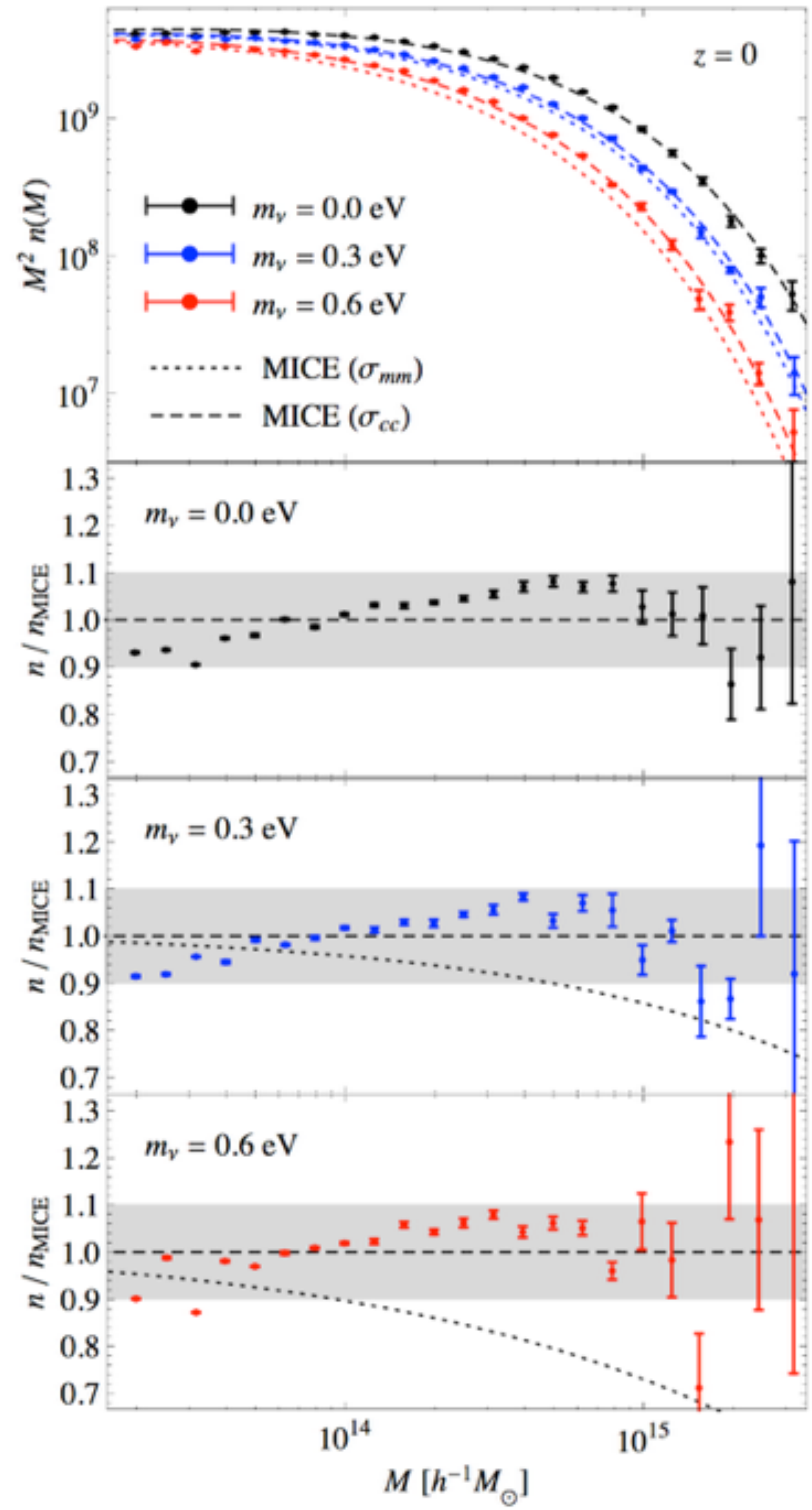
$$\frac{dn(M,z)}{dM} = \underbrace{\nu f(\nu) \frac{\rho_m}{M^2} \frac{d\ln\nu}{d\ln M}}$$

Matter prescription

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

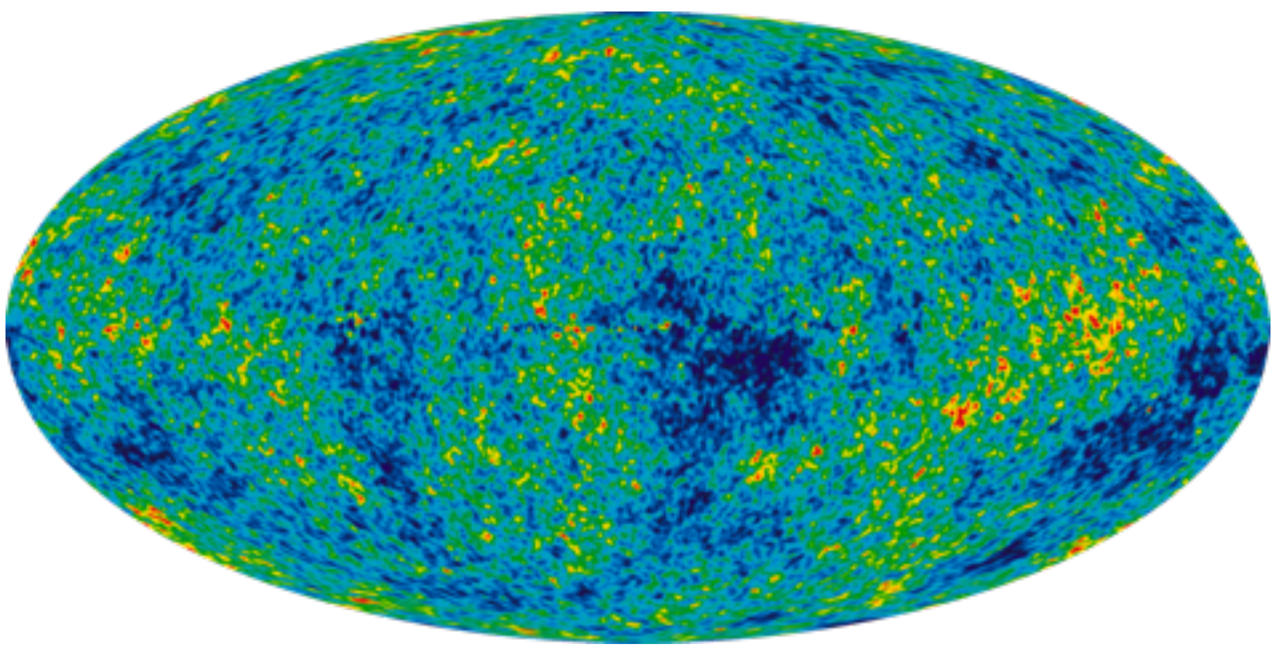
Cold dark matter prescription

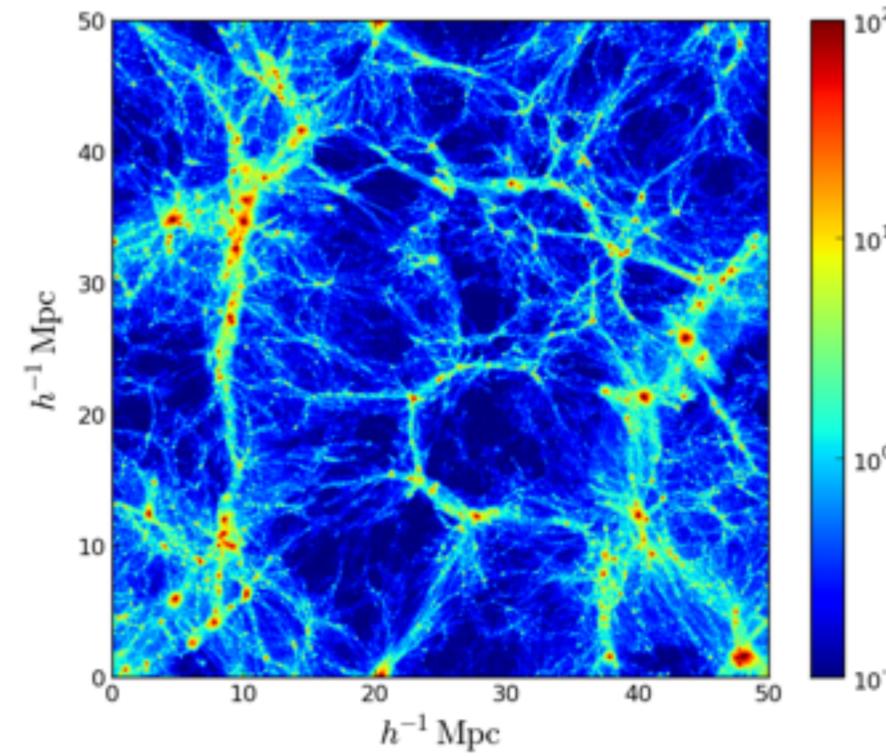
$\rho_m \rightarrow \rho_{cdm} \quad P_m(k) \rightarrow P_{cdm}(k)$



Non-linear neutrino effects

To get a robust (5σ?) constraint on the sum of the neutrino masses we need to go into the non-linear regime





Neutrino clustering

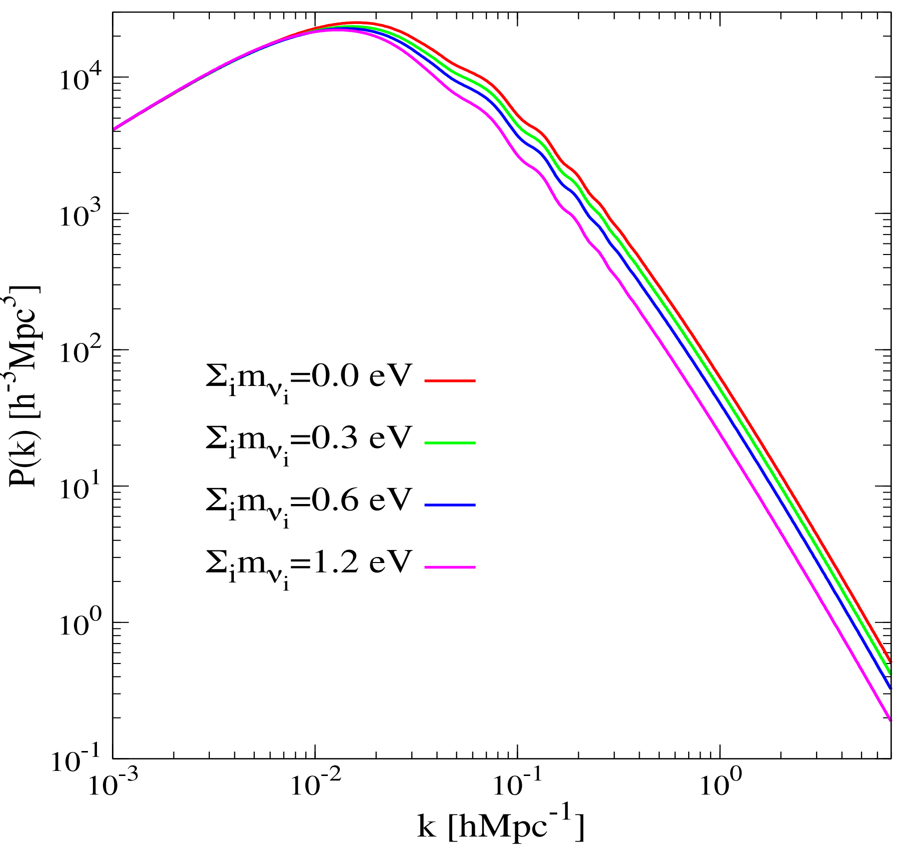
Neutrino effects

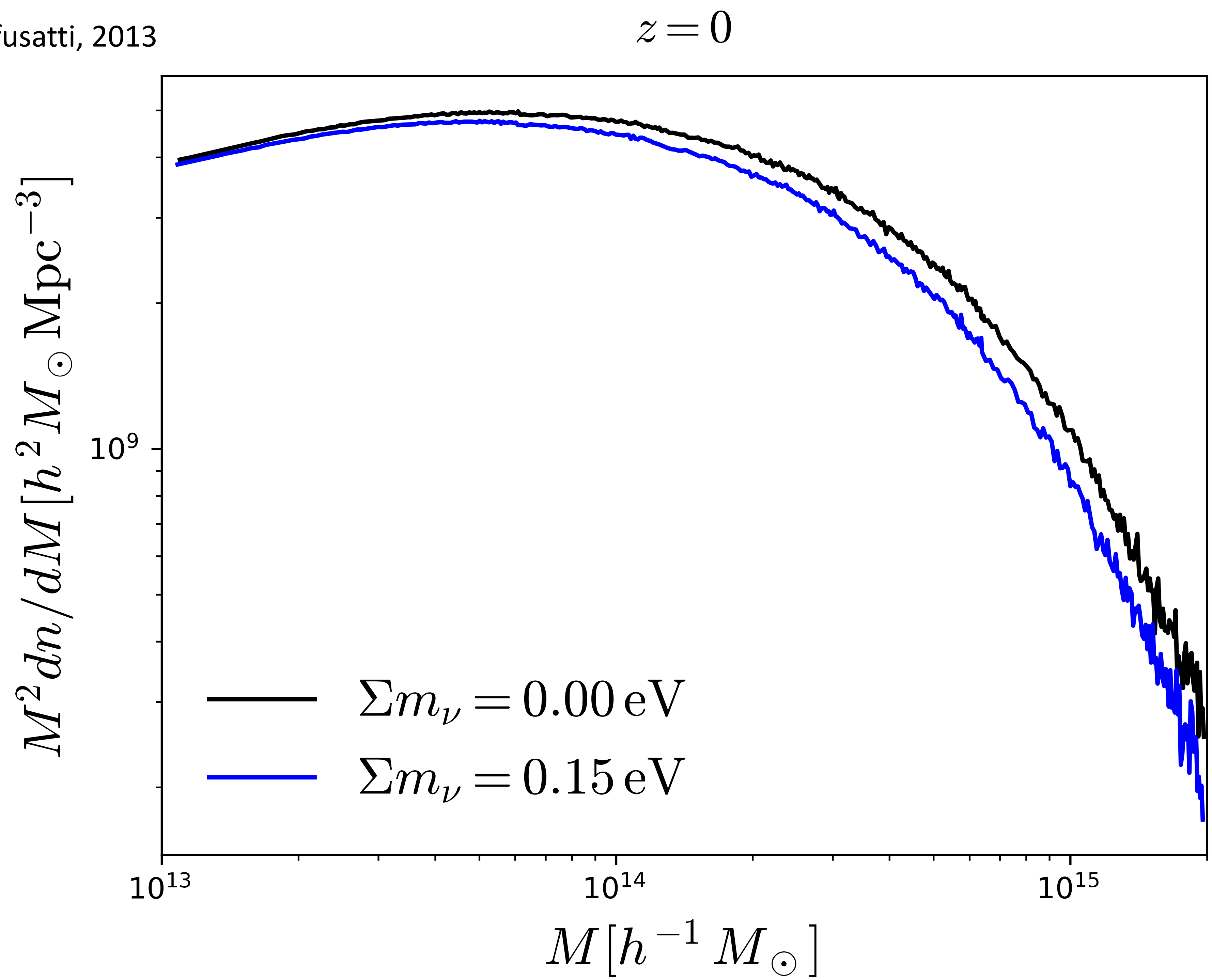
- Halo mass function
- Halo/galaxy clustering
- Voids

Neutrino effects I: halo mass function

Neutrino effects I: halo mass function

Ichiki & Takada 2011
Castorina, Sefussati, Sheth, **FVN**, Viel 2013
Costanzi, **FVN**, Viel, Xia, Borgani, Castorina, Sefusatti, 2013





$$\frac{dn(M,z)}{dM} = g(M, \rho_m(z), P_m(k,z))$$

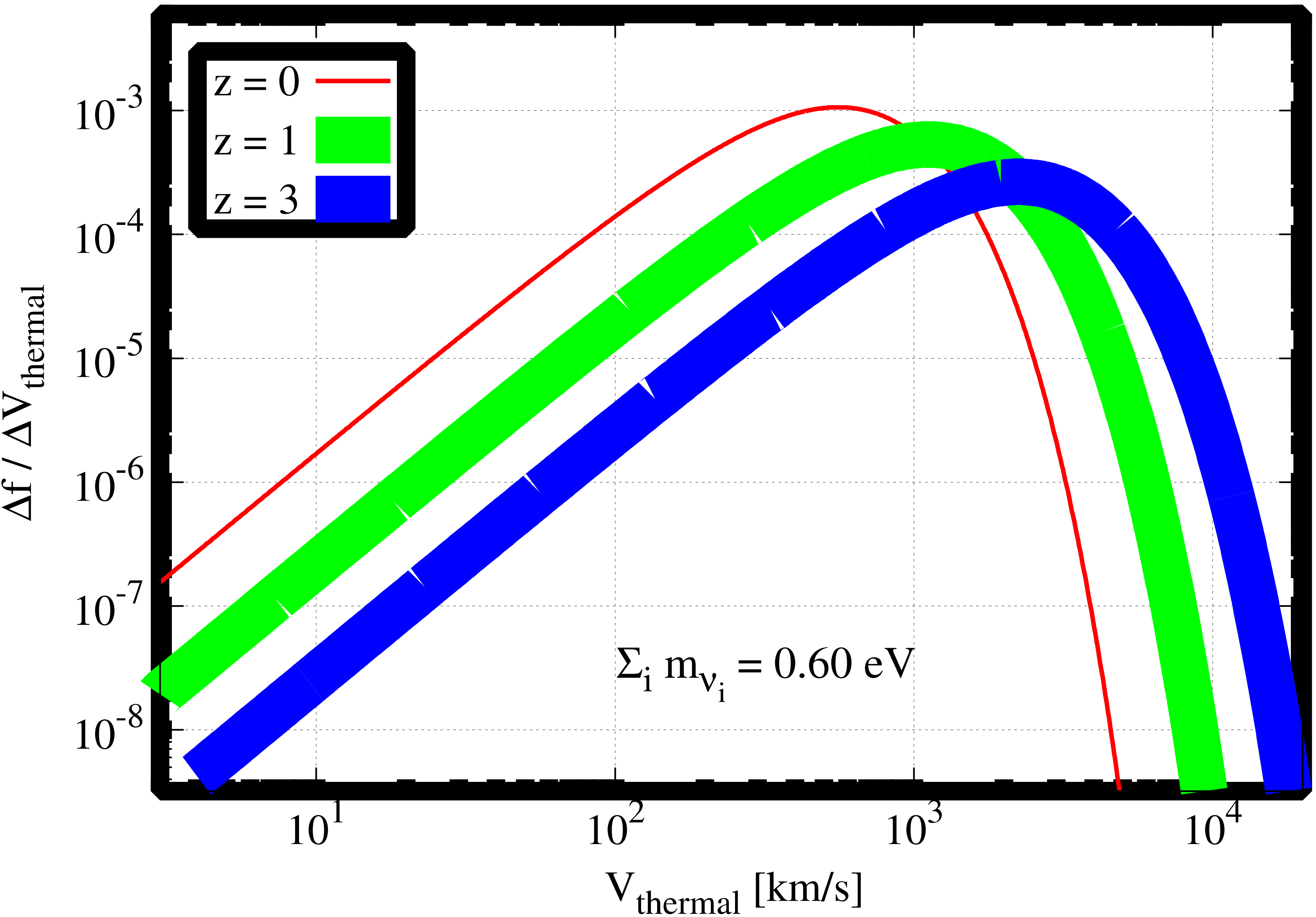
g is an universal function

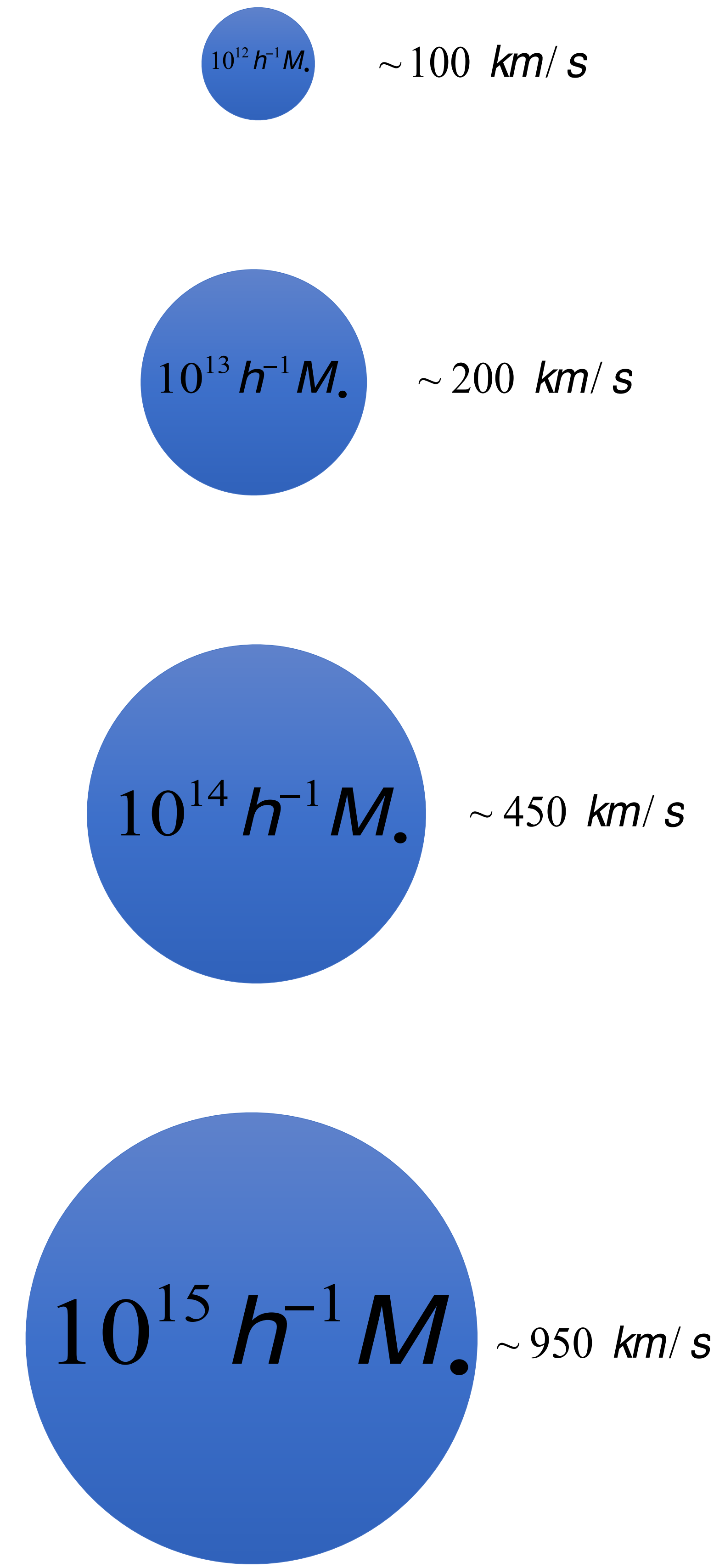
$$\rho_\mathrm{m} \to \rho_\mathrm{cb}$$

$$P_\mathrm{m}(k) \to P_\mathrm{cb}(k)$$

Neutrino clustering

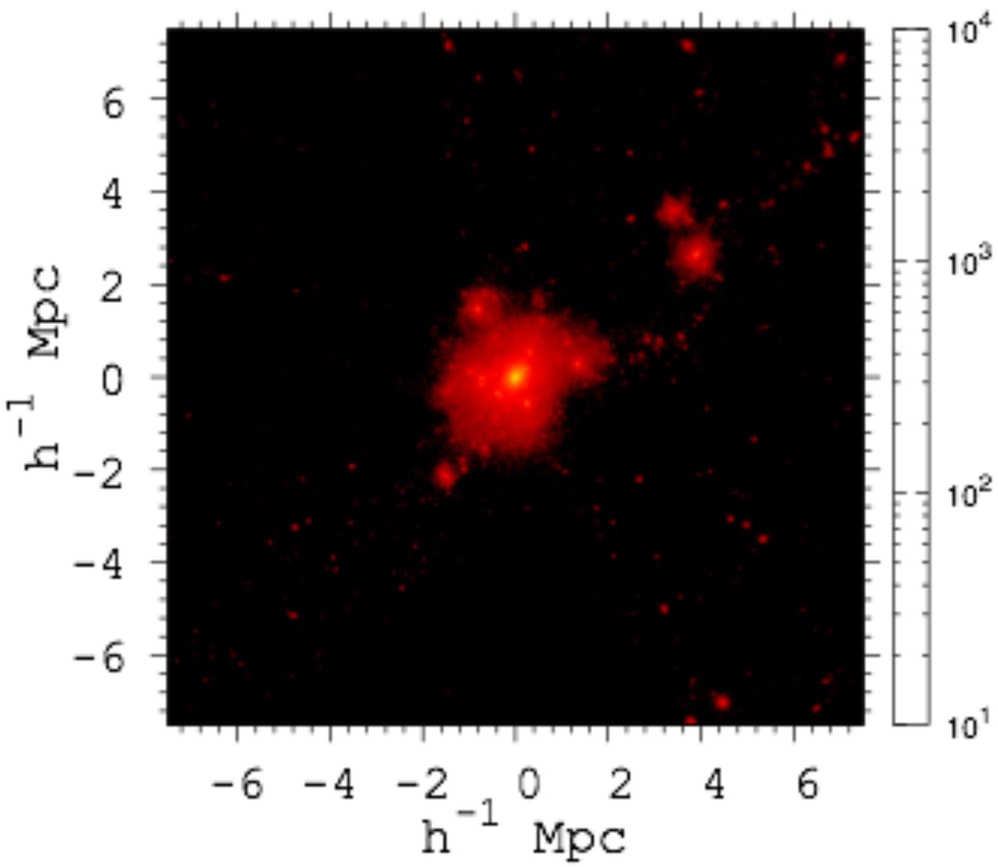
$$n_\nu(p,z)dp \cong \frac{4\pi g_\nu}{(2\pi\hbar c)^3}\left(\frac{p^2 dp}{e^{(p/k_B T_\nu(z))}+1}\right)$$

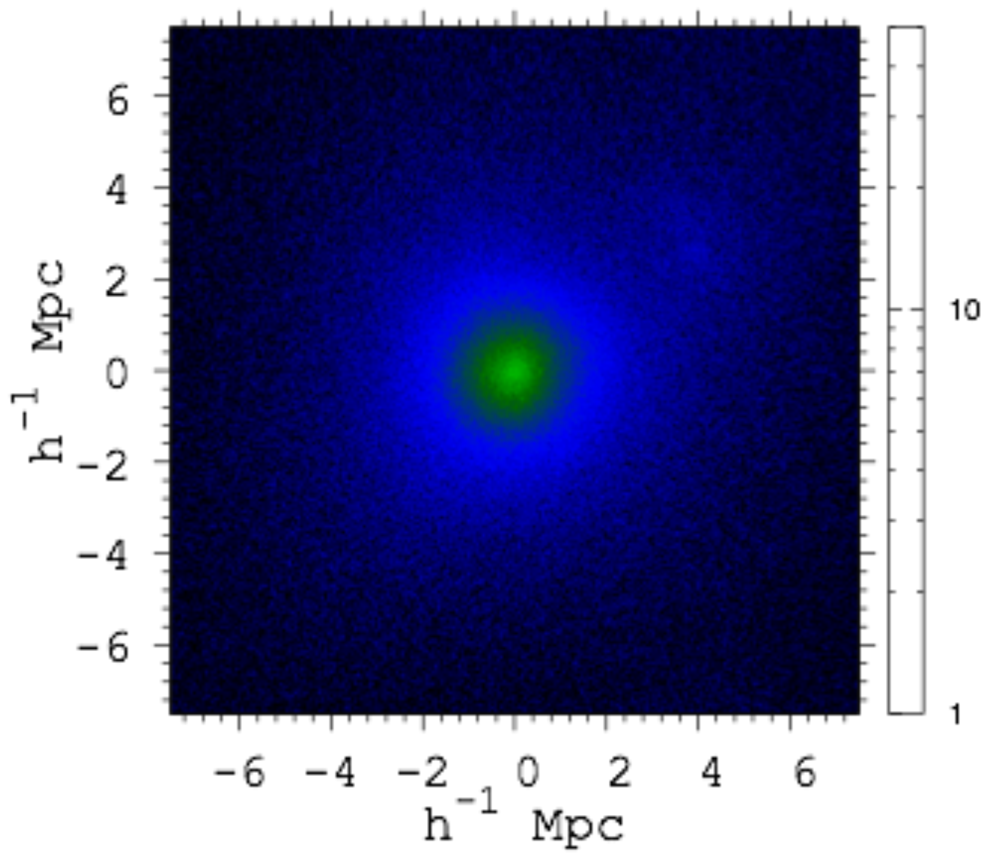




Neutrino clustering

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





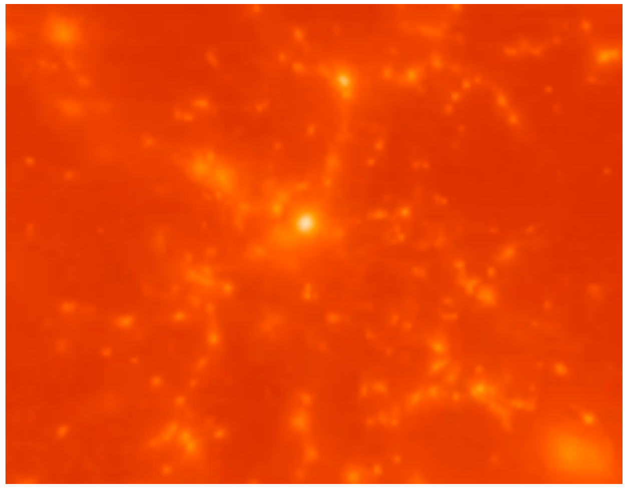
$$F_h \sim 10^{-3} \longrightarrow 0.3\ \mathrm{eV}$$

$$M_h = M_{\mathrm{CDM}} + M_{\mathrm{b}} + \cancel{M_\nu}$$

Non-linear neutrino effects

To get a robust 5σ constraint on the sum of the neutrino masses we need to go into the non-linear regime

Neutrino clustering



Neutrino effects

- Halo mass function
- Halo/galaxy clustering
- Voids

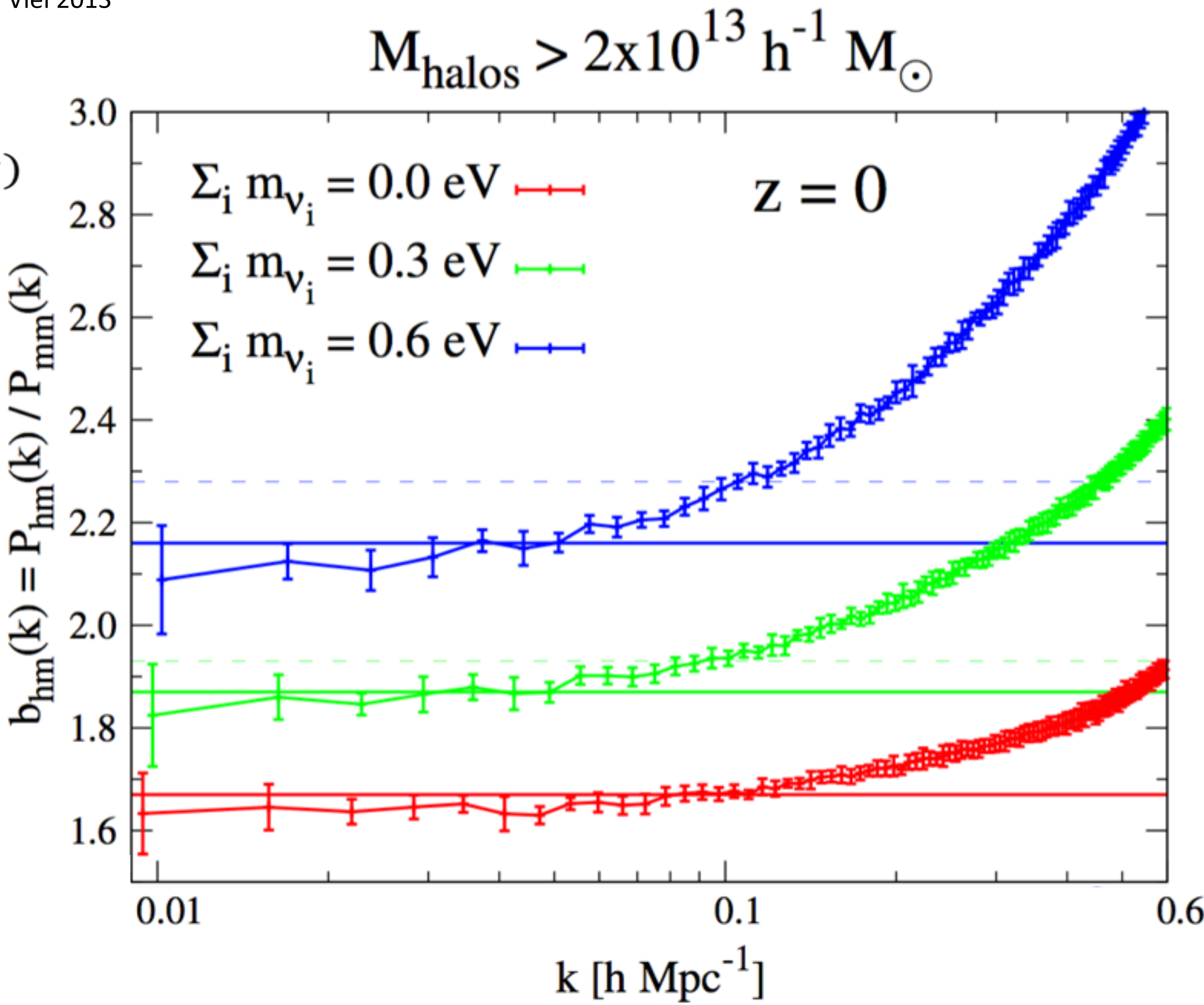
Neutrino effects II: halo clustering

$$P_g(k) = b^2(k)P_m(k)$$

Neutrino effects II: halo clustering

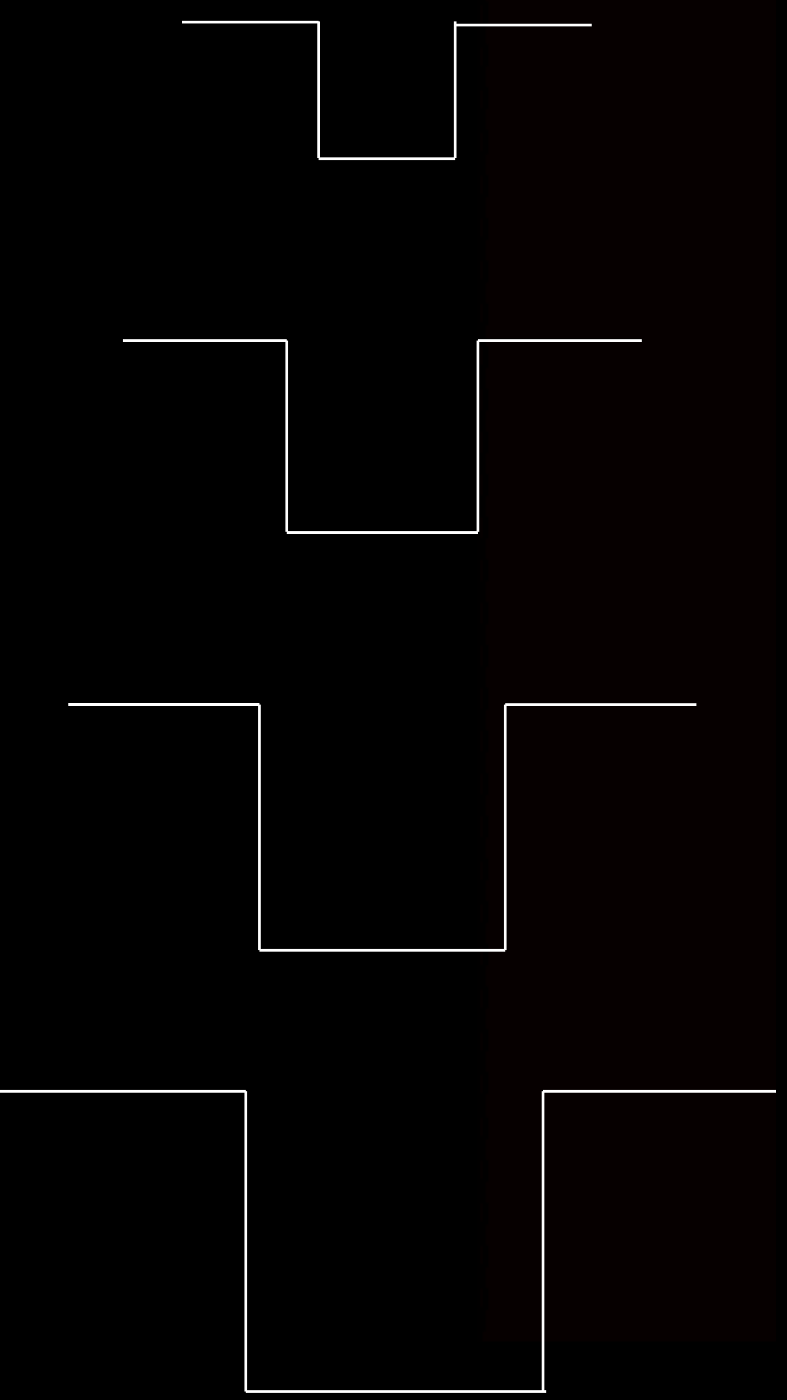
FVN, Marulli, Viel, Branchini, Castorina, Sefusatti, Saito 2013
Castorina, Sefusatti, Sheth, **FVN**, Viel 2013
Chiang, Hu, Li, LoVerde 2018
Chiang, LoVerde, **FVN**, 2018

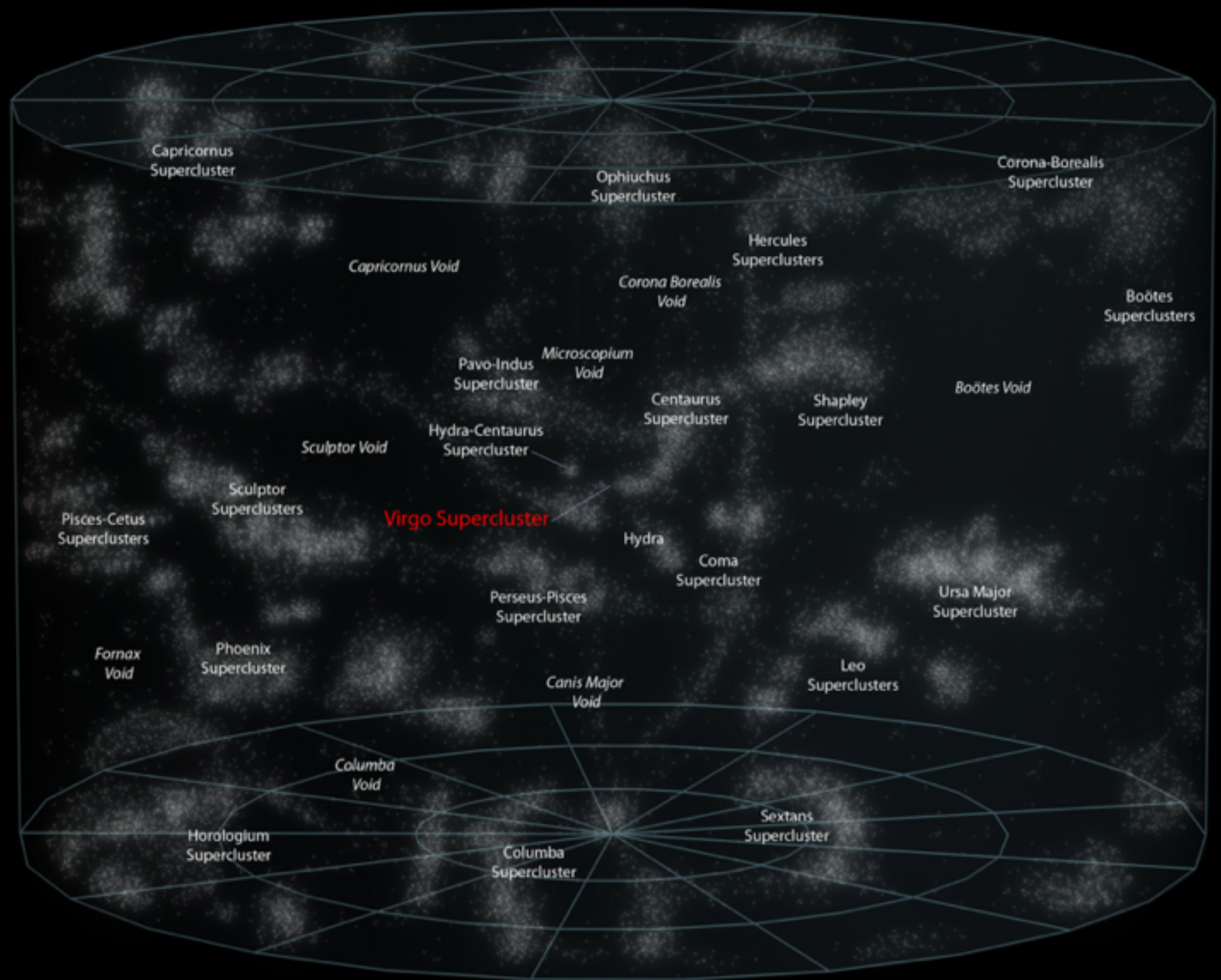
$$P_h(k) = b^2 P_m(k)$$



Neutrino effects III: voids

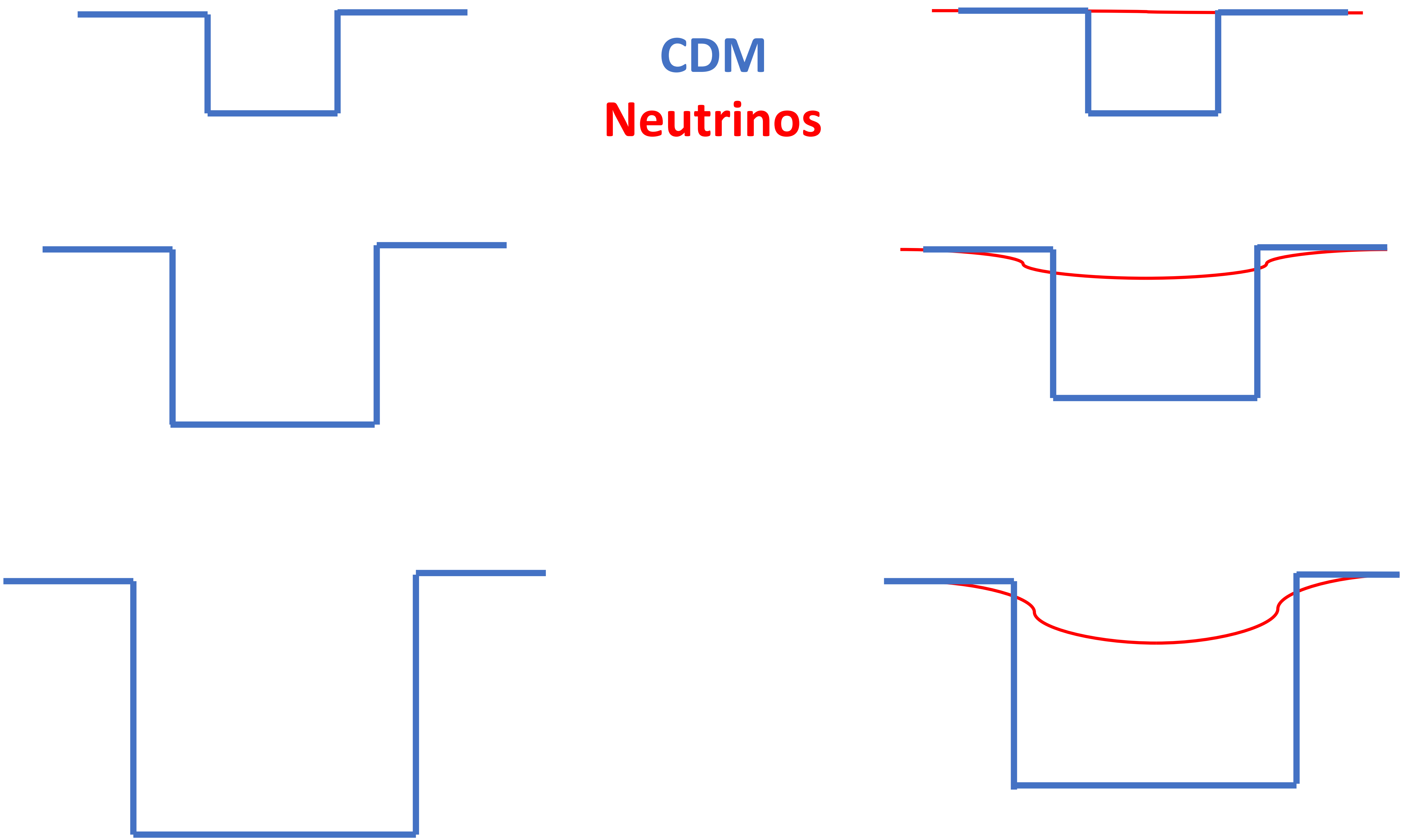
<u>*Massless neutrinos*</u>





Neutrino effects III: voids

Massless neutrinos | ***Massive neutrinos***

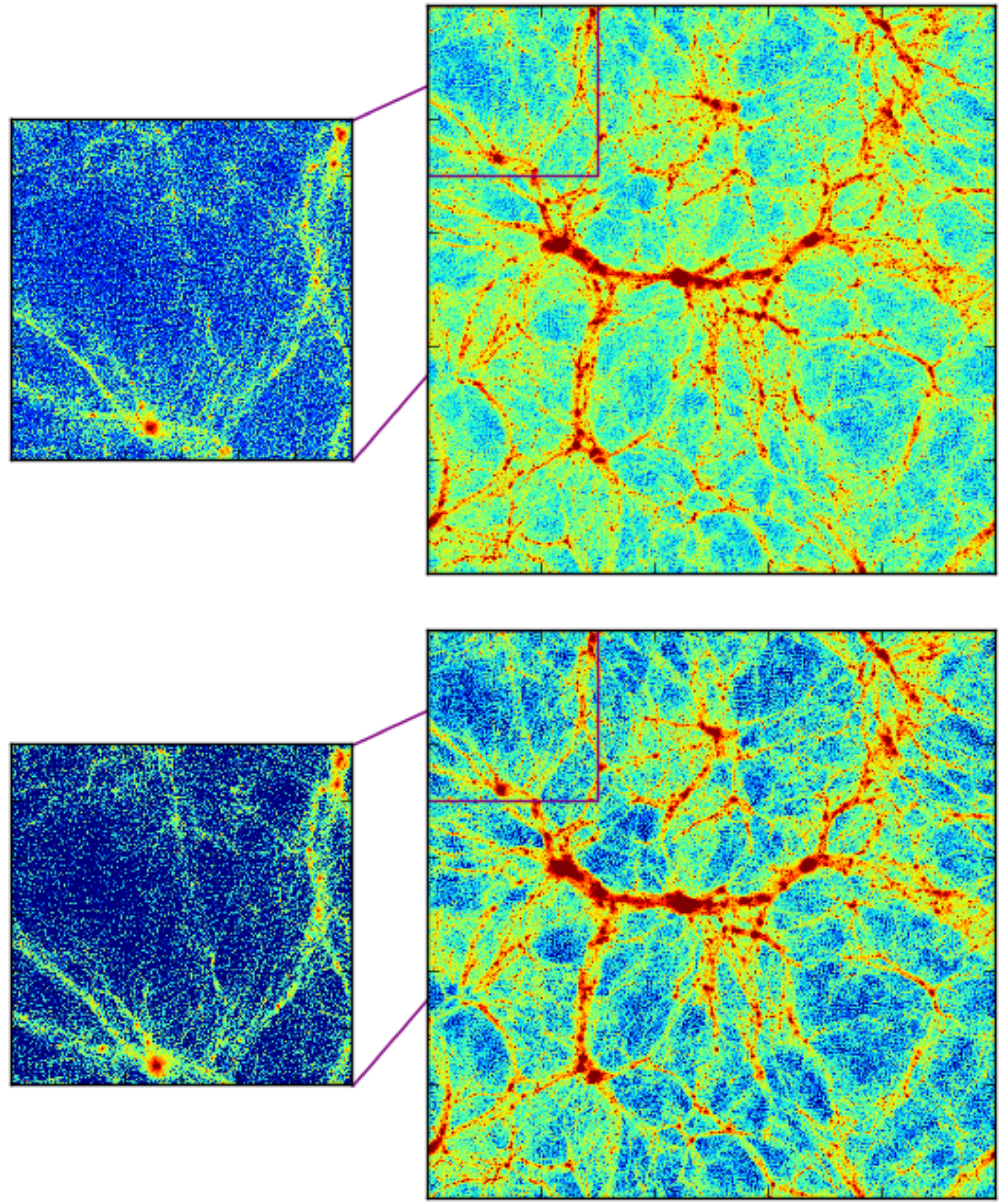


Neutrino effects III: voids

FVN, Vogelsberger, Loeb, Viel, 2012
Massara, **FVN**, Viel, Sutter 2015

Massive neutrinos →

Massless neutrinos →



• Starting point	Neutrinos have mass! We want to know the neutrino masses, hierarchy, nature and properties to learn about fundamental physics
• Cosmic neutrino background	$\Omega_\nu \sim 0.3\%$ $\langle V_\nu \rangle \sim 3000\ \mathrm{km/s}$
• Linear effects	Neutrino masses leave signatures on cosmological observables Standard probes: 3σ - 4σ 1. Very accurate theory predictions: avoid biases 2. New and unique observables: robust 5σ detection
• Non-linear effects	• Halos/galaxies $\rho_m = \rho_c + \rho_b \cancel{+ \rho_\nu}$ • Voids $\rho_m = \rho_c + \rho_b + \rho_\nu$

Villaescusa-Navarro+19

THE QUIJOTE SIMULATIONS

ABSTRACT

The QUIJOTE simulations are a set of 43100 full N-body simulations spanning more than 7000 cosmological models in the $\{\Omega_\mathrm{m}, \Omega_\mathrm{b}, h, n_s, \sigma_8, M_\nu, w\}$ hyperplane. At a single redshift the simulations contain more than 8.5 trillions of particles over a combined volume of 43100 $(h^{-1}\mathrm{Gpc})^3$. Billions of dark matter halos and cosmic voids have been identified in the simulations, whose runs required more than 35 million core hours. The QUIJOTE simulations have been designed for two main purposes: 1) to quantify the information content on cosmological observables, and 2) to provide enough data to train machine learning algorithms. In this paper we describe the simulations and show a few of their applications. We also release the Petabyte of data generated, comprising hundreds of thousands of simulation snapshots at multiple redshifts, halo and void catalogs, together with millions of summary statistics such as power spectra, bispectra, correlation functions, marked power spectra, and estimated probability density functions.

Name	Ω_m	Ω_b	h	n_s	σ_8	M_ν(eV)	w	realizations	simulations	ICs	$N_c^{1/3}$	$N_\nu^{1/3}$
Fid	0.3175	0.049	0.6711	0.9624	0.834	0	-1	15000 500 500 1000 100	standard standard paired fixed standard standard	2LPT Zeldovich 2LPT 2LPT 2LPT	512 512 512 256 1024	0 0 0 0 0
Ω_m^+	0.3275	0.049	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
Ω_m^-	0.3075	0.049	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
Ω_b^{++}	0.3175	0.051	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
Ω_b^+	0.3175	0.050	0.6711	0.9624	0.834	0	-1	500	paired fixed	2LPT	512	0
Ω_b^-	0.3175	0.048	0.6711	0.9624	0.834	0	-1	500	paired fixed	2LPT	512	0
Ω_b^{--}	0.3175	0.047	0.6711	0.9624	0.834	0	-1	500 500	standard paired fixed	2LPT	512	0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	500	standard	[illegible]	[illegible]	[illegible]

The Quijote simulations

FVN, Massara, Spergel, Wandelt, Ho, Verde,MV+19

$$\mathrm{F}_{\alpha\beta} = \frac{1}{2}\left[\frac{\partial \vec{d}}{\partial \theta_\alpha} C^{-1} \frac{\partial \vec{d}}{\partial \theta_\beta} + \frac{\partial \vec{d}}{\partial \theta_\beta} C^{-1} \frac{\partial \vec{d}}{\partial \theta_\alpha}\right] + \frac{1}{2}\mathrm{Tr}\left[C^{-1} \frac{\partial \vec{d}}{\partial \theta_\alpha} C^{-1} \frac{\partial \vec{d}}{\partial \theta_\beta}\right]$$

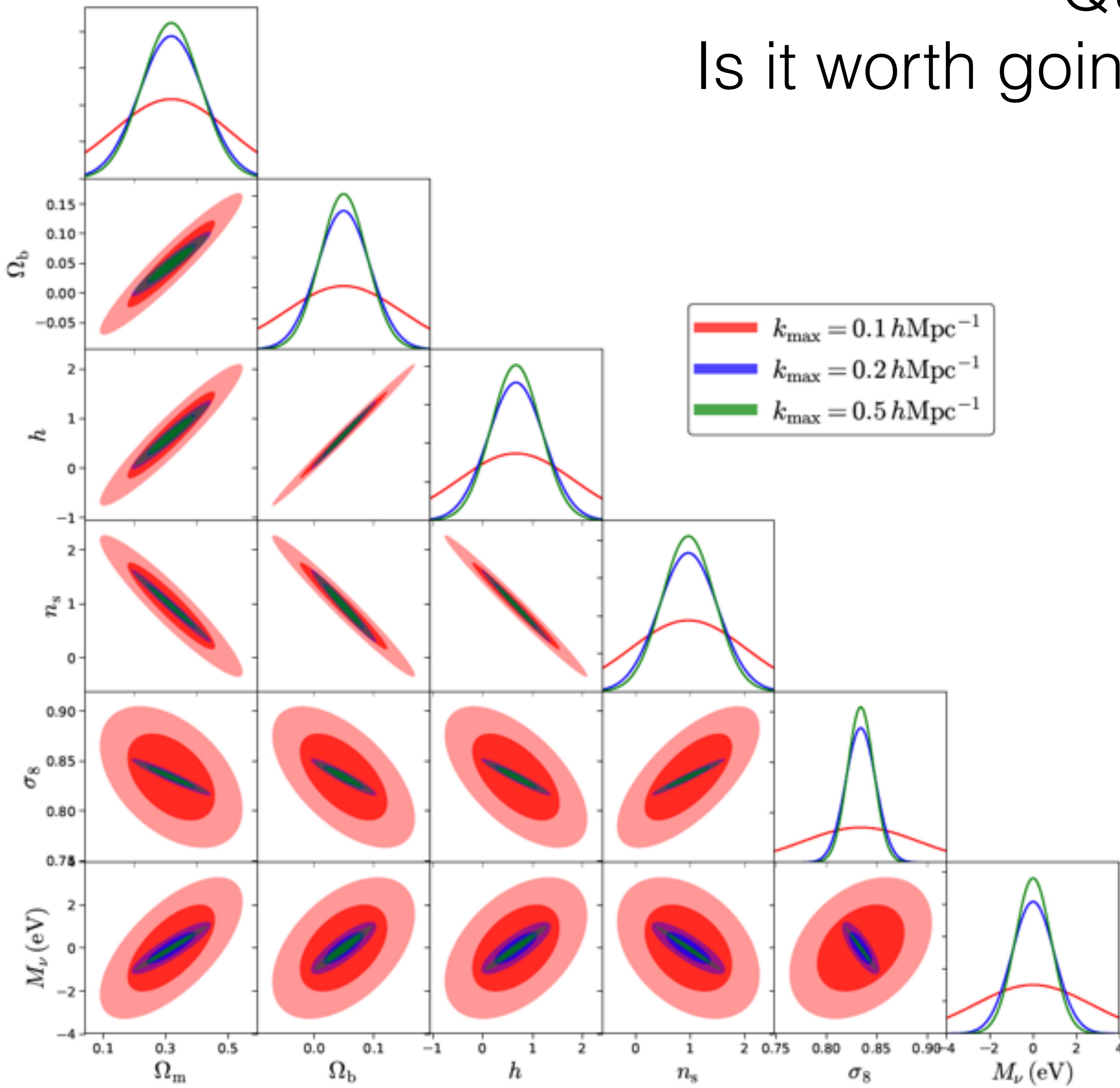
1000 simulations/parameter
$\{\Omega_m, \Omega_b, h, n_s, \sigma_8, \sum m_\nu\}$

15000 simulations

- A set of 25000 **publicly available** N-body simulations
- 1000 Mpc/h $\quad$ 512^3 DM particles (+ 512^3 ν particles) $\quad$ z = {0, 0.5, 1, 2, 3}
- More than 3.6 trillion particles at a single redshift
- 500 Tb, 13M cpu hours

The power spectrum

Question:
Is it worth going to smaller scales?

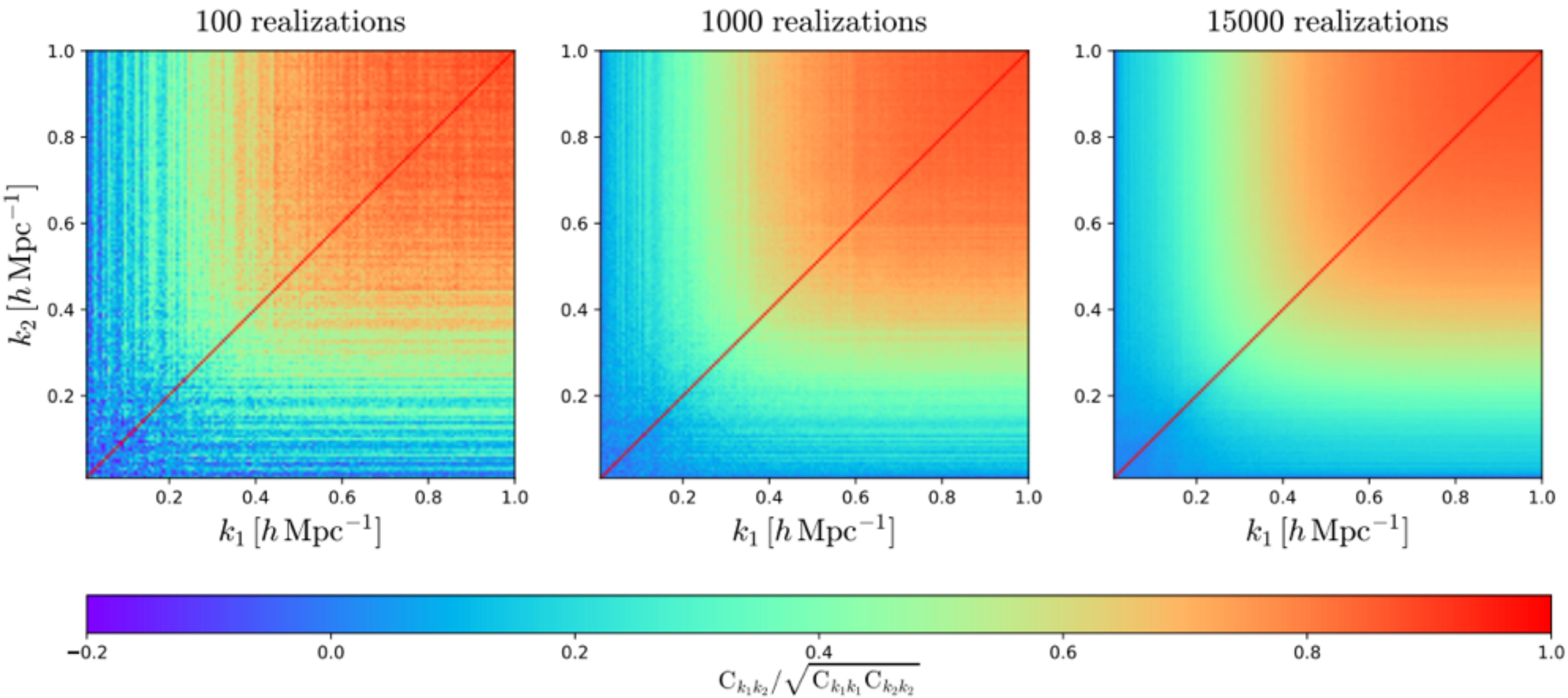


The gain with scale does not scale proportional to kmax , as naively expected just by counting number of modes. There are two main reasons for this:

1) the **covariance** becomes non-diagonal on small scales; modes become correlated and therefore the number of independent modes do not scale as kmax

2) **degeneracies** among parameters limit the amount of information that can be extracted.

Covariance matrix

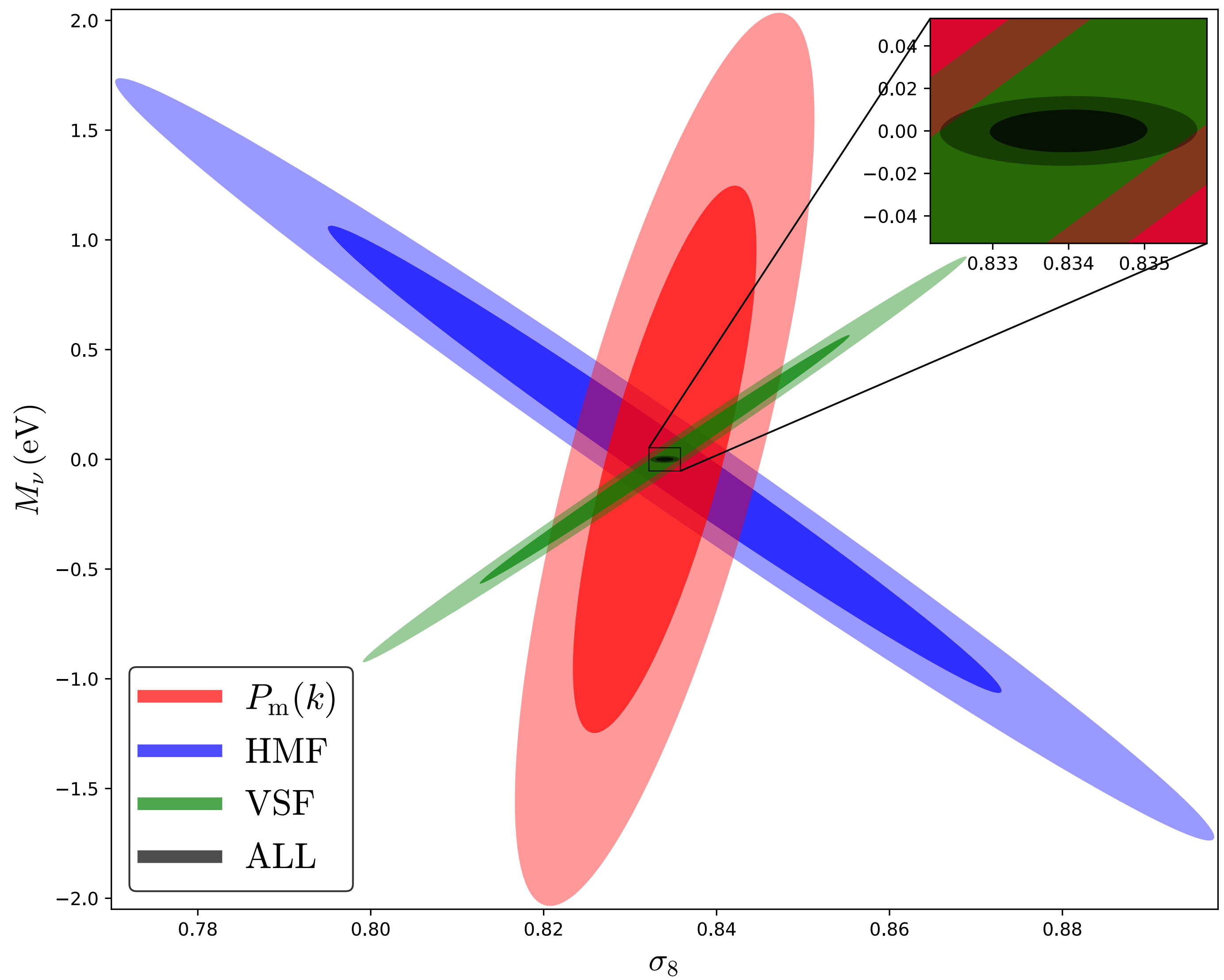


Villaescusa-Navarro+19

Ambitious plan for neutrino masses

• Introduction	Neutrinos have mass! We want to know the neutrino masses, hierarchy, nature and properties to learn about fundamental physics
• Cosmic neutrino background	$\Omega_\nu \sim 0.3\%$ $\quad\quad \langle V_\nu \rangle \sim 3000\ \mathrm{km/s}$
• Linear effects	Neutrino masses leave signatures on cosmological observables Standard probes: 3σ - 4σ 1. Very accurate theory predictions: avoid biases 2. New and unique observables: robust 5σ detection
• Non-linear effects	• Halos/galaxies $\quad \rho_m = \rho_c + \rho_b \cancel{+ \rho_\nu}$ • Voids $\quad \rho_m = \rho_c + \rho_b + \rho_\nu$
• Forecasts	Power spectrum + Halo mass function + Void size function $\longrightarrow$ 5σ with 1 $(\mathrm{Gpc}/h)^3$

Going multiprobe to achieve > 4 sigma

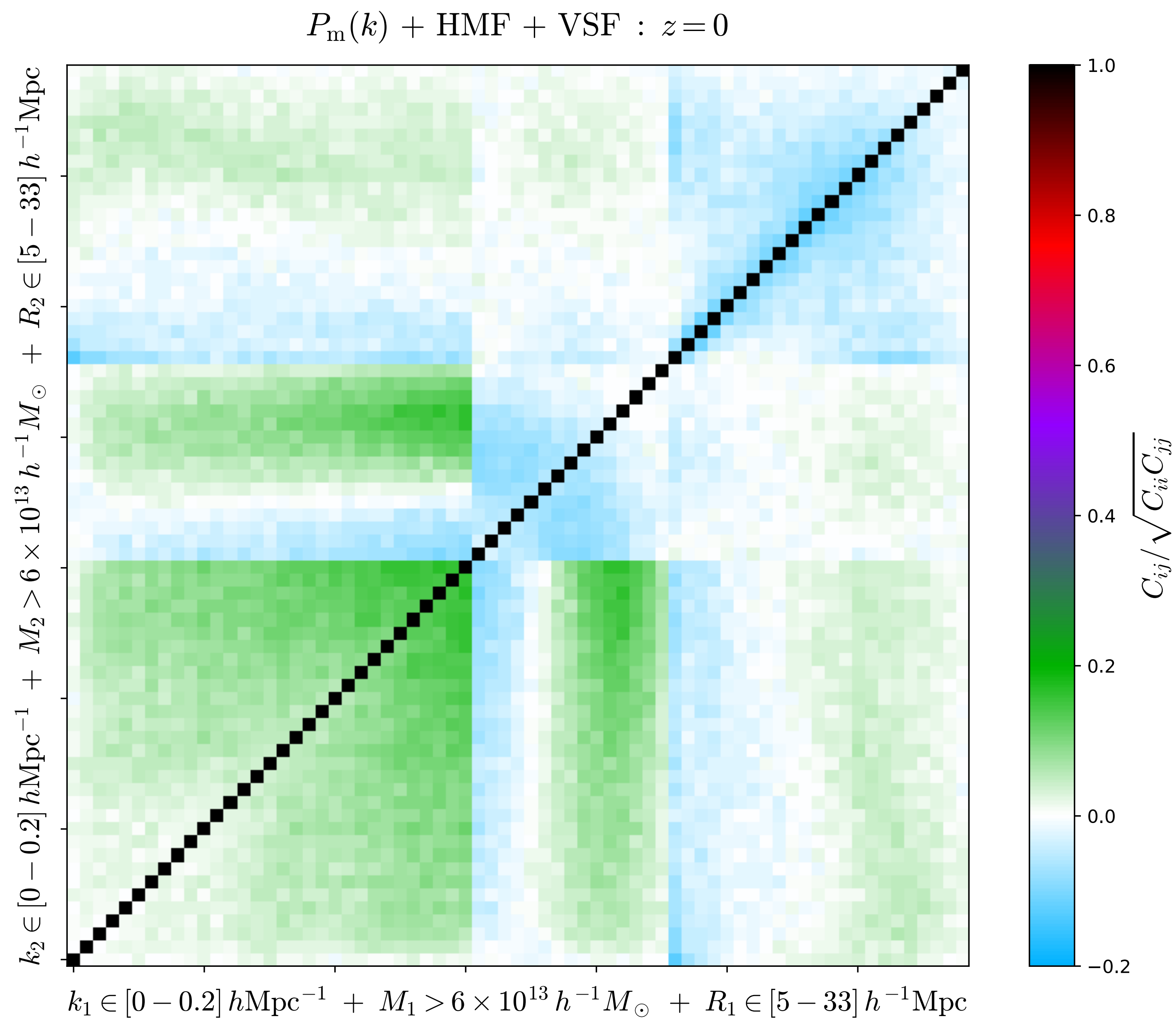


We are somehow probing the neutrino density field directly.

Very tight constraints can be achieved through it.

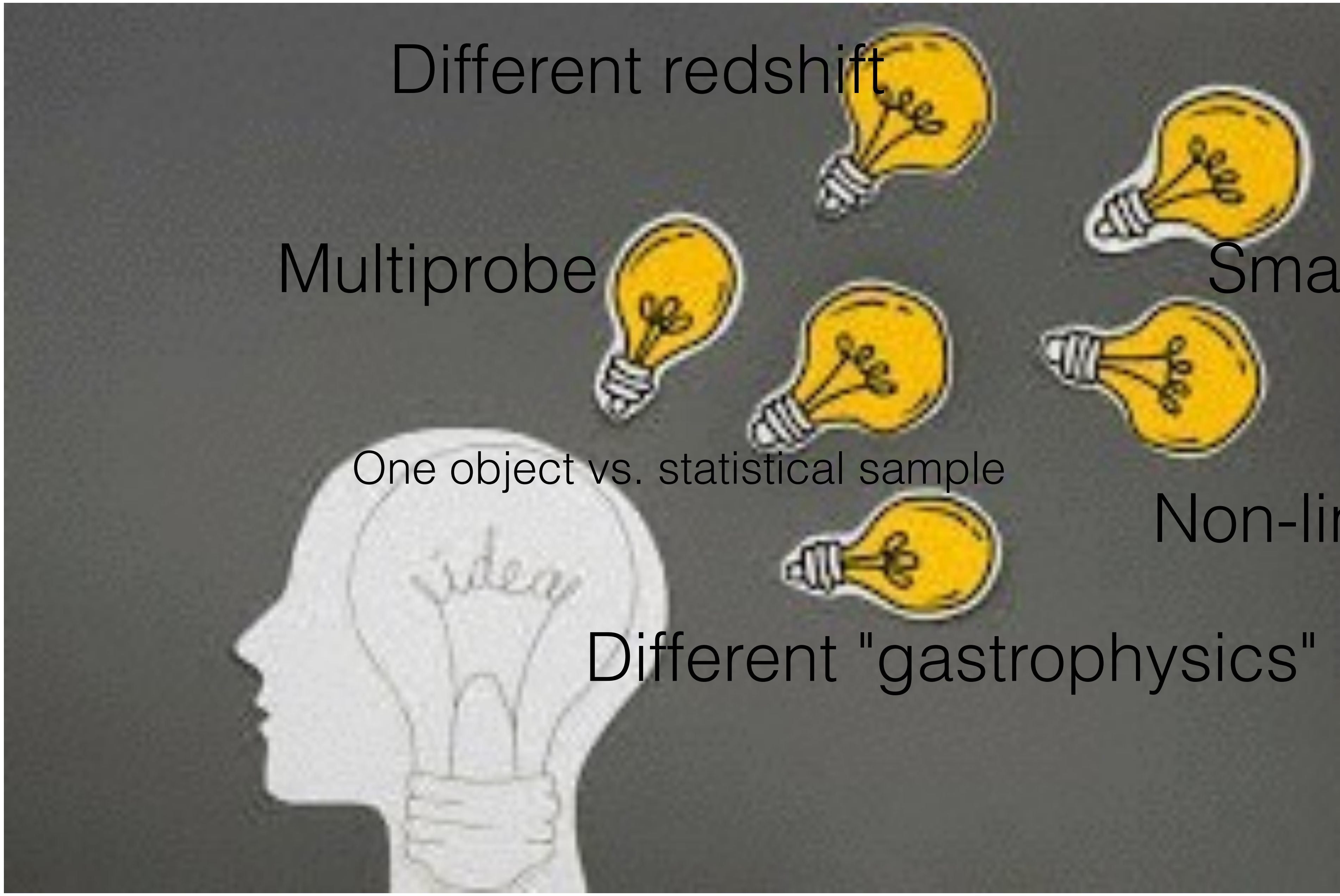
Villaescusa-Navarro+19, in prep.

COVARIANCE BETWEEN PROBES



Villaescusa-Navarro+19, in prep.

Neutrino searches



Different redshift

Multiprobe

Small scales

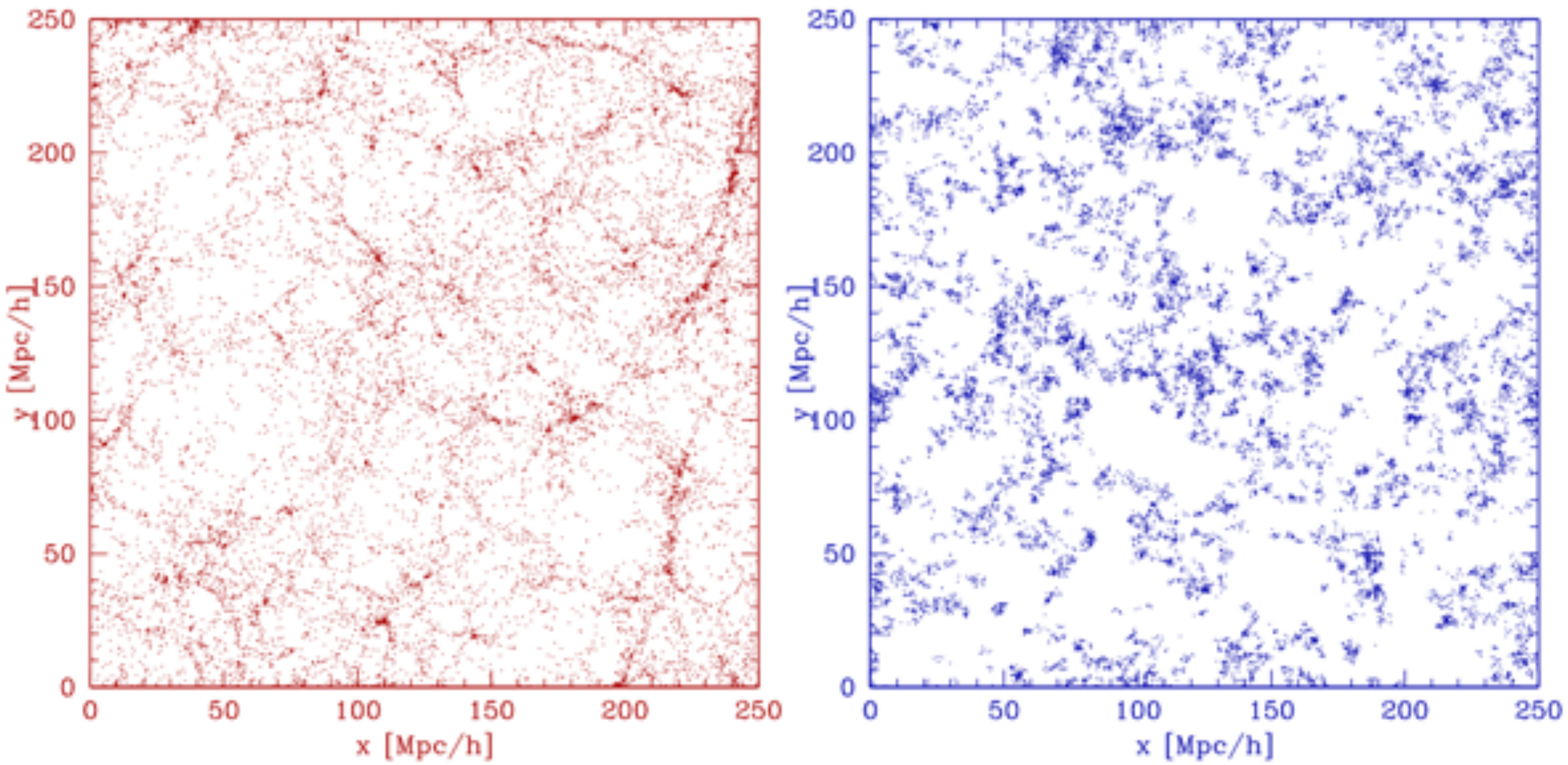
One object vs. statistical sample

Non-linear

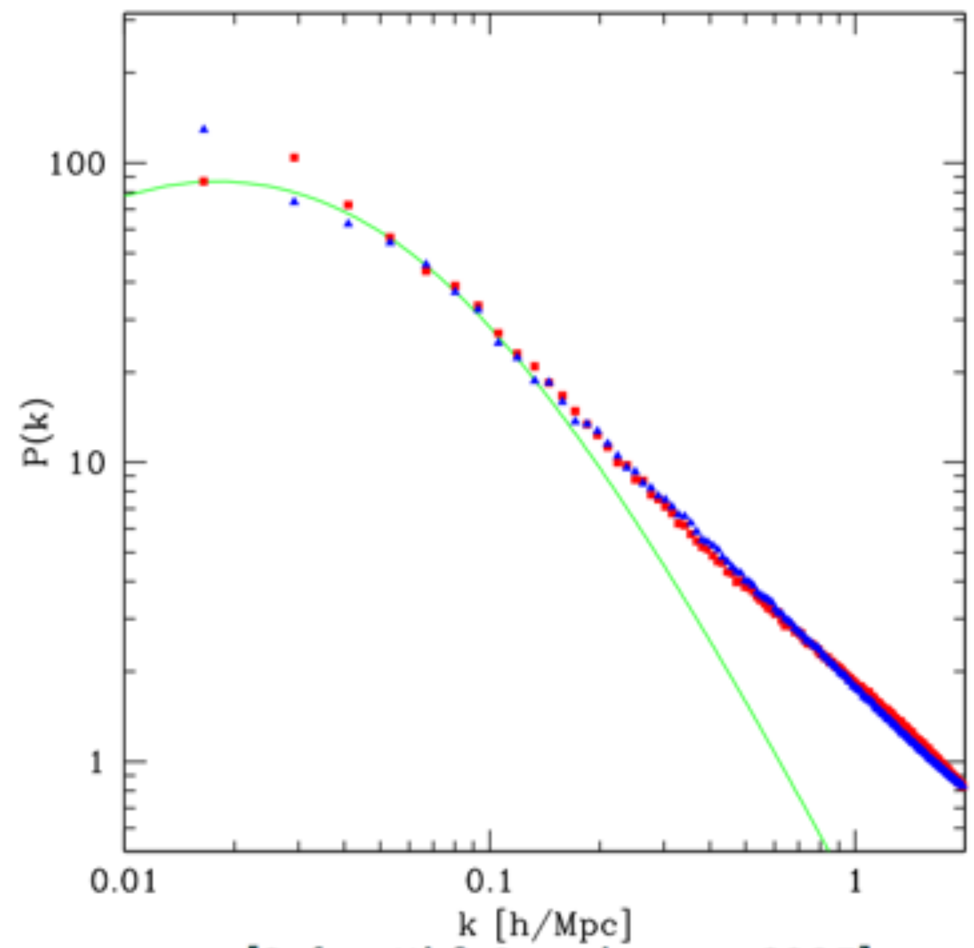
Different "gastrophysics"

….more ideas?

Going higher order - I



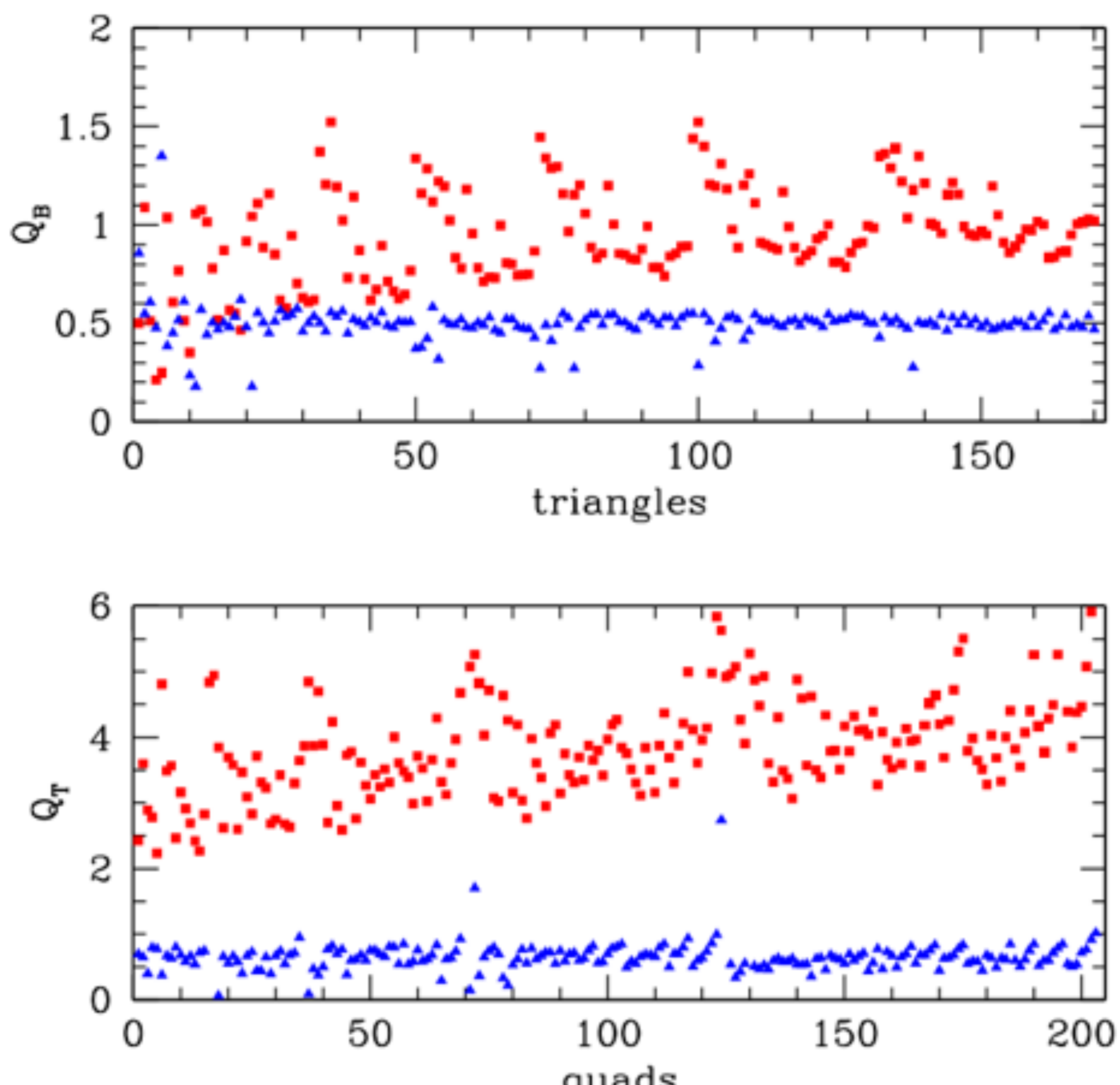
N-body vs Levy flight



[Sefusatti & Scoccimarro, 2005]

Going higher order - II

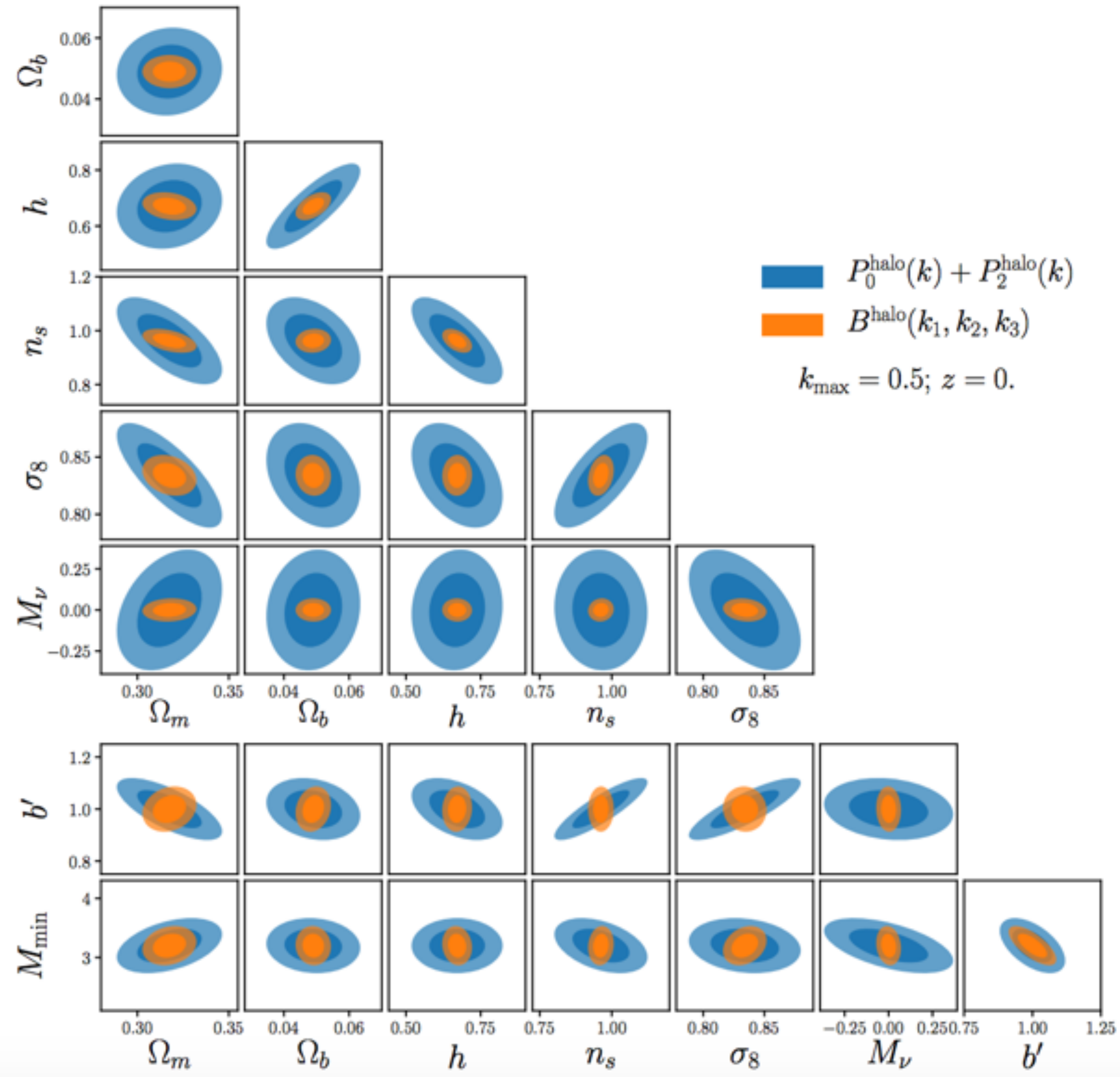
$$Q(k_1, k_2, k_3) = \frac{B(k_1, k_2, k_3)}{P(k_1)\,P(k_2) + P(k_2)\,P(k_3) + P(k_3)\,P(k_1)}.$$



[Sefusatti & Scoccimarro, 2005]

...with neutrinos

Fisher matrix for matter redshift space power spectrum



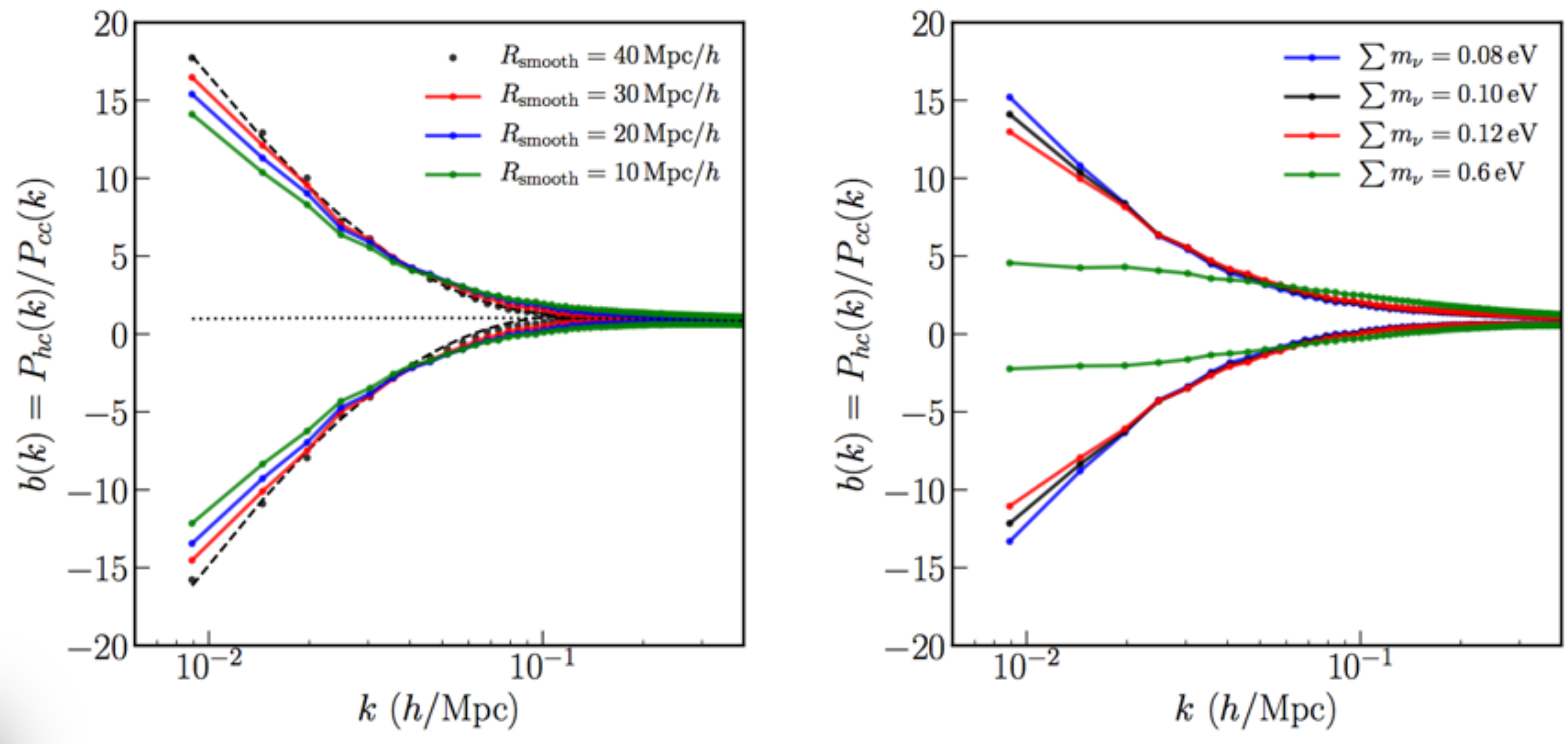
The bispectrum substantially improves constraints on all of the cosmological parameters over the power spectrum. Constraints on Ωm, Ωb, h, ns, and σ8 improve by factors of 1.9, 2.6, 3.1, 3.6, and 2.6, respectively. For Mν, the bispectrum improves $\sigma_{M\nu}$ from 0.2968 to 0.0572 eV — over **a factor of ~5 improvement over the power spectrum.**

Hahn+19

…Or invent new observables

Weighing neutrinos with the halo environment

Arka Banerjee,[a,b,c,1] Emanuele Castorina,[d,e] Francisco Villaescusa-Navarro,[f] Travis Court,[g,h] Matteo Viel[i,j,k,l]



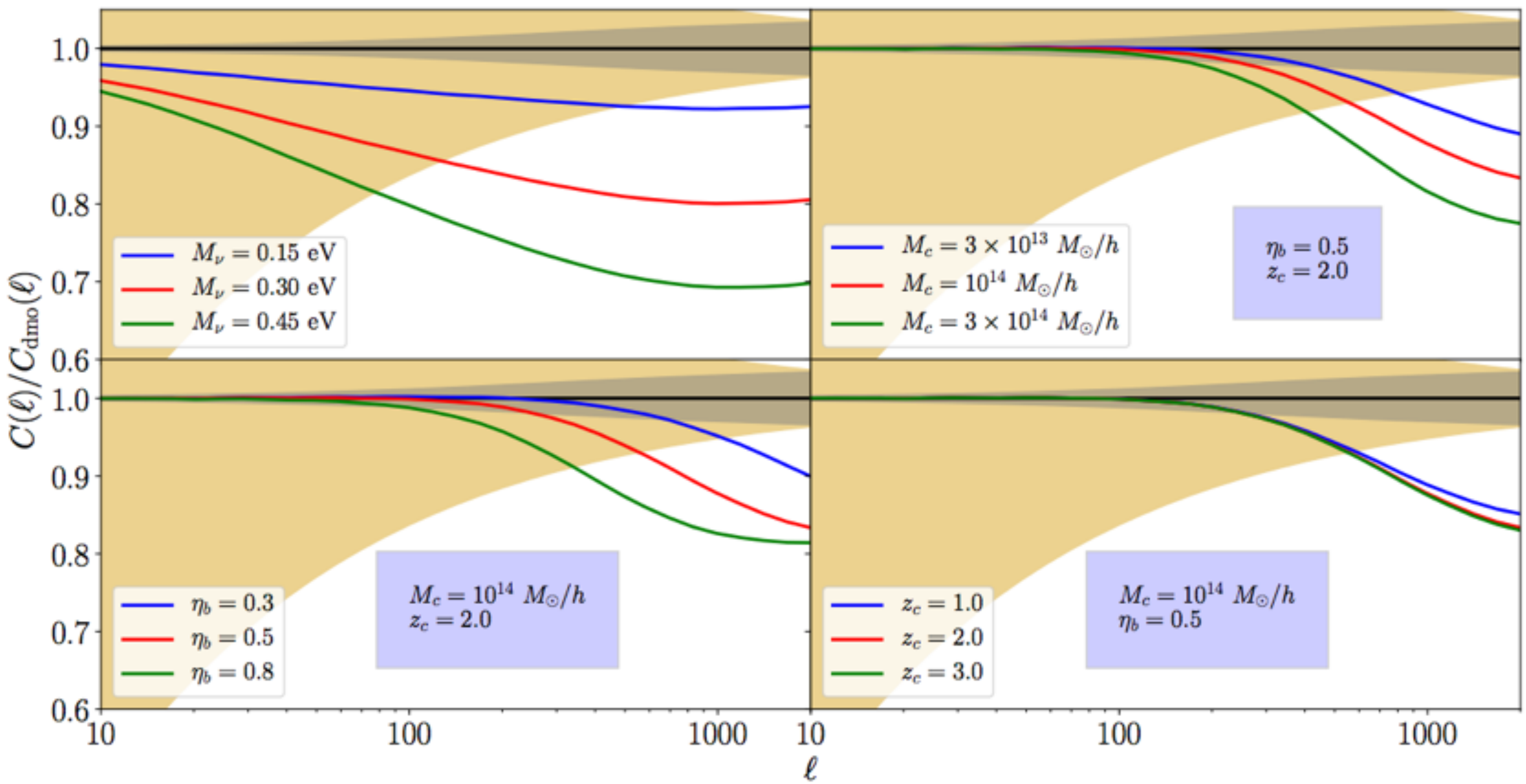
Left panel: Bias of the two halo populations when split on the overdensity in the neutrino field at scale Rsmooth for Mν = 0.10 eV, at z = 0. The dotted black line indicates the bias of the full halo sample. Right panel: Bias of the two halo populations when split on the overdensity in the neutrino field at scale Rsmooth = 10 Mpc/h for different sum of neutrino masses.

What have we learnt so far?
Importance of linear scales
But information also on non-linear scales
Some probes sensitive to CDM
Some probes sensitive to total matter

What about if GAS (i.e. baryons) modify small scales?

BARYON CORRECTION - I

MCMC analysis for GC and WL   Parimbelli, MV, Sefusatti 19



Template fitting

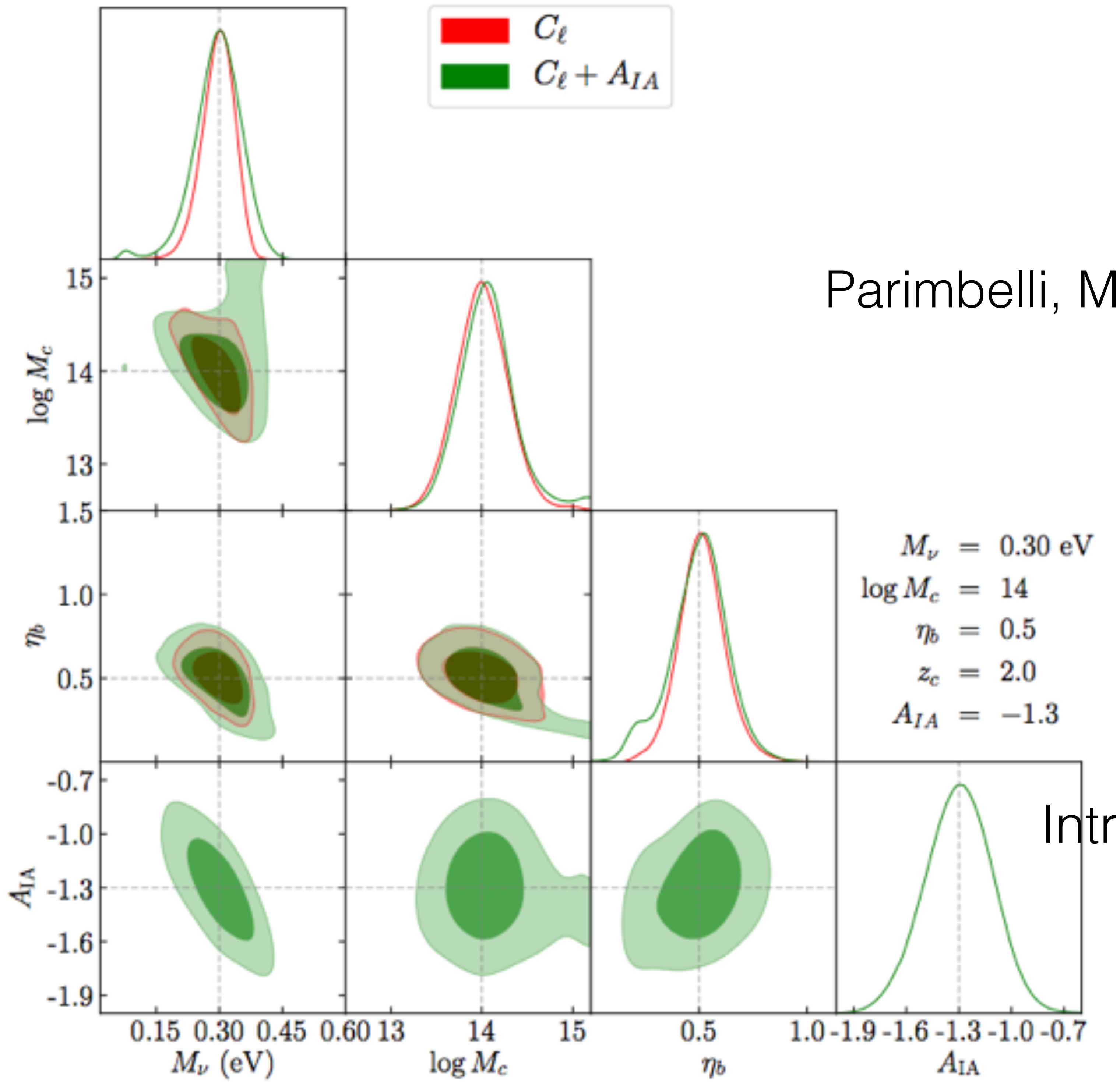
M_c, z_c, eta_b

Stellar feedb.

$$F_{\rm bf}(k,z|M_c,\eta_{\rm b},z_{\rm c}) \equiv \frac{P_{\rm feed}(k)}{P_{\rm dmo}(k)} = \left\{\frac{B(z)}{1+(k/k_g)^3} + [1-B(z)]\right\} S(k),$$

BARYON CORRECTION - II

Parimbelli, MV, Sefusatti 19

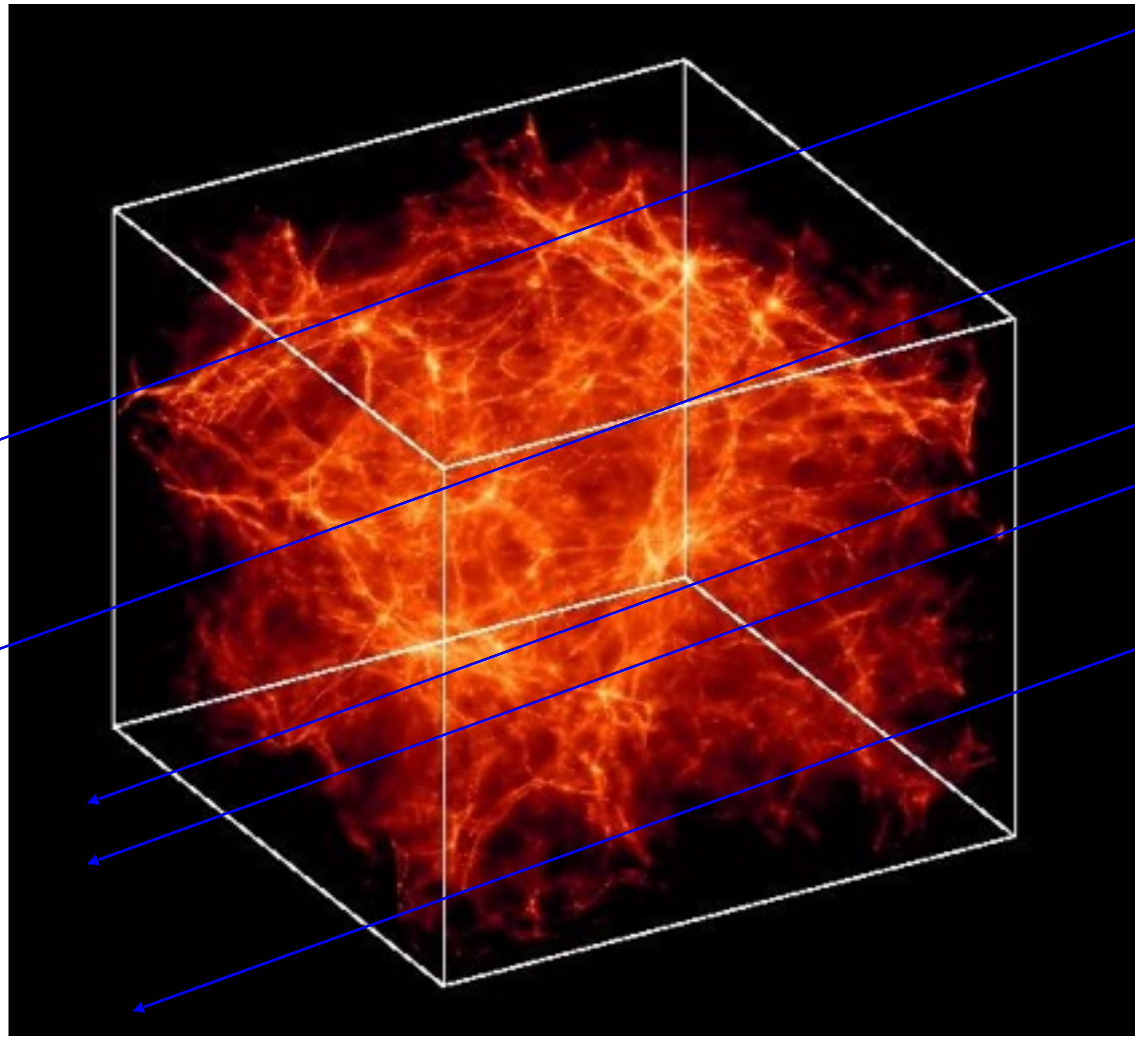


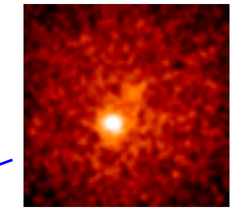
Intrinsic Alignment

Impact on structure formation:

IGM

The Intergalactic Medium: Theory vs. Observations





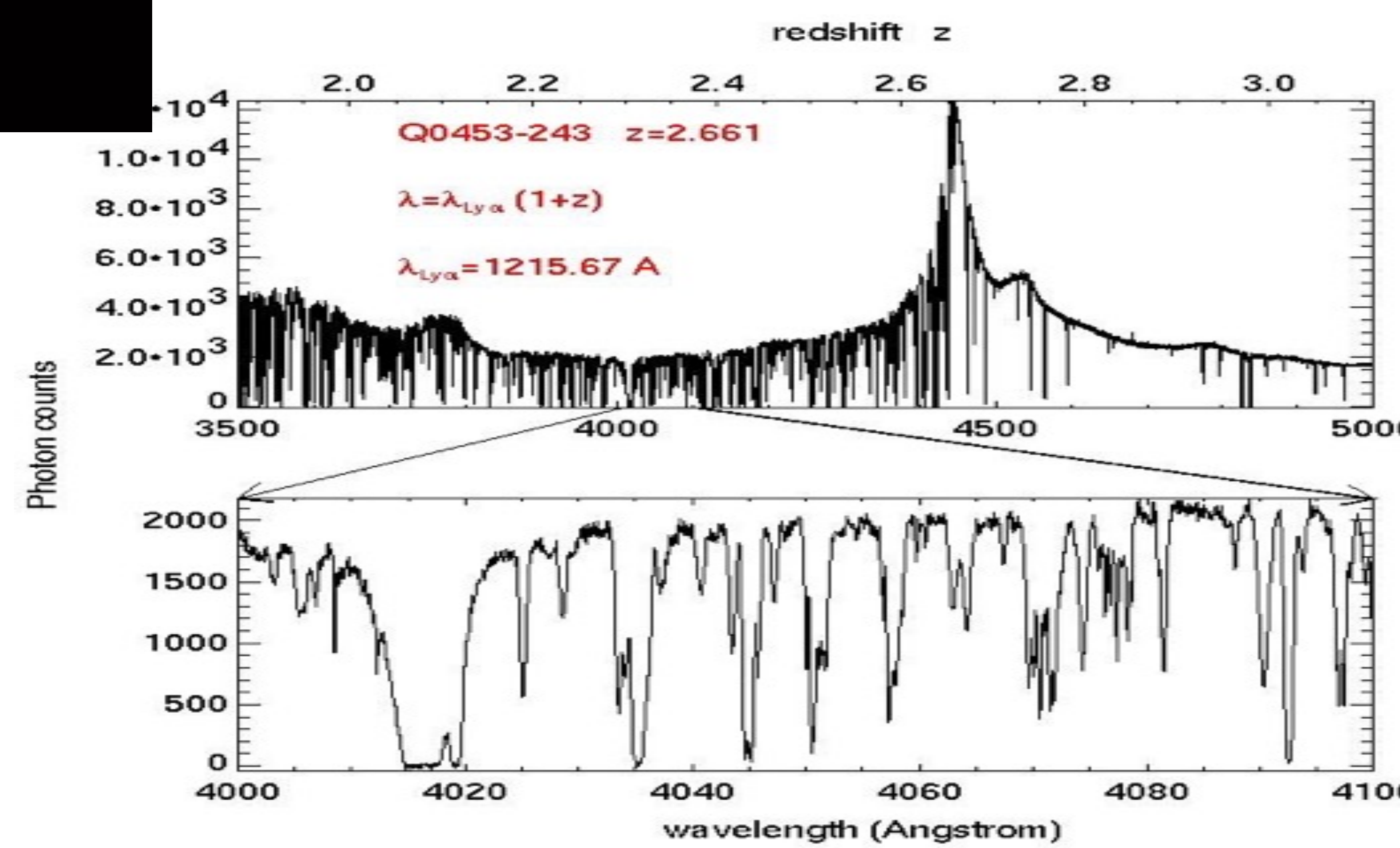
80% of the baryons at z=3 are in the **Lyman-α forest**

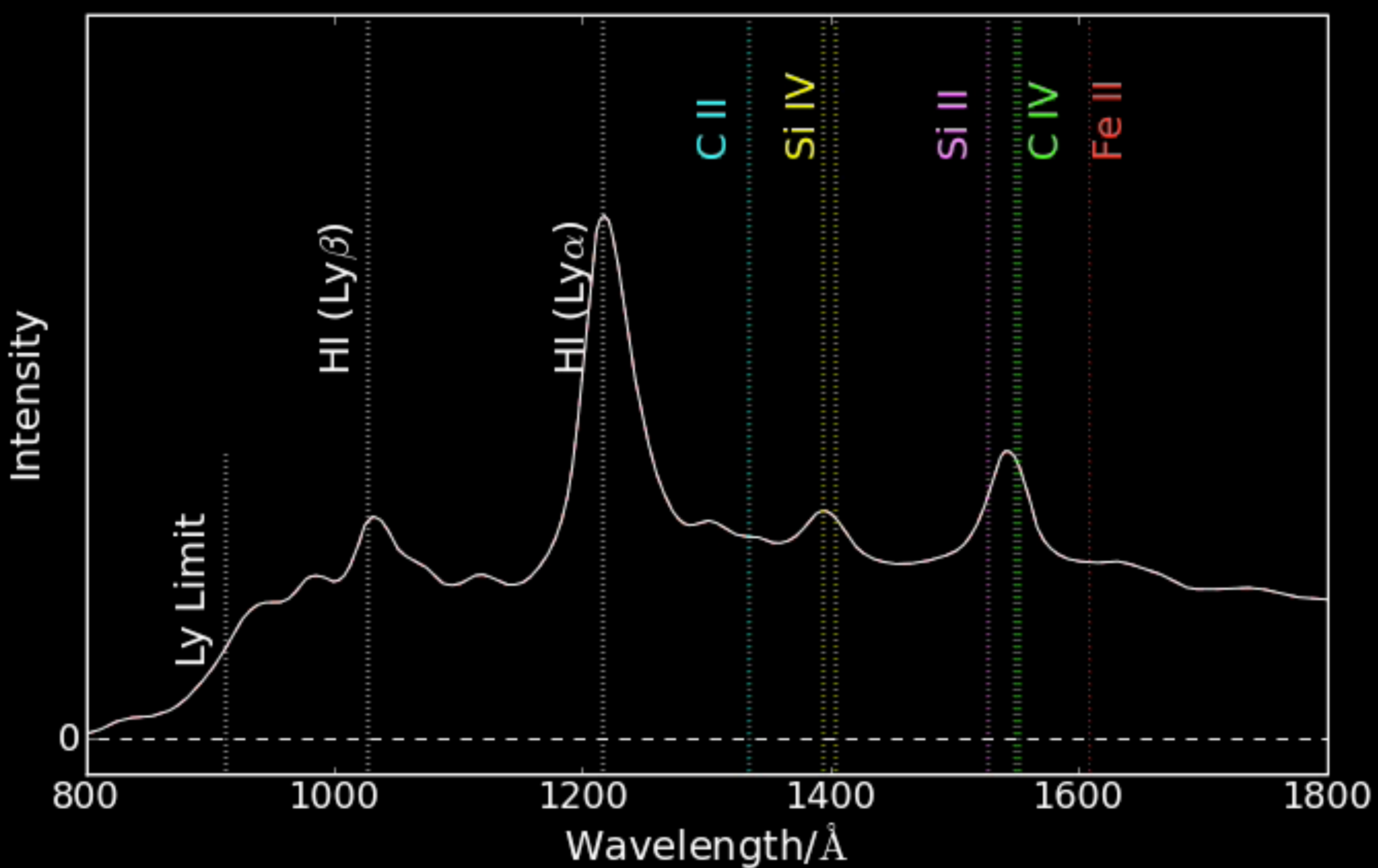
Bi & Davidsen (1997), Rauch (1998)
Review by Meiksin (2009)

baryons as tracer of the dark matter density field

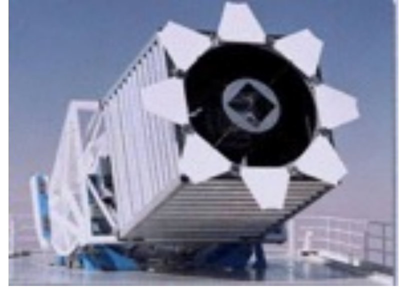
$\delta_{IGM} \sim \delta_{DM}$

Croft+ 99,02
MV+ 04
McDonald+ 01,03



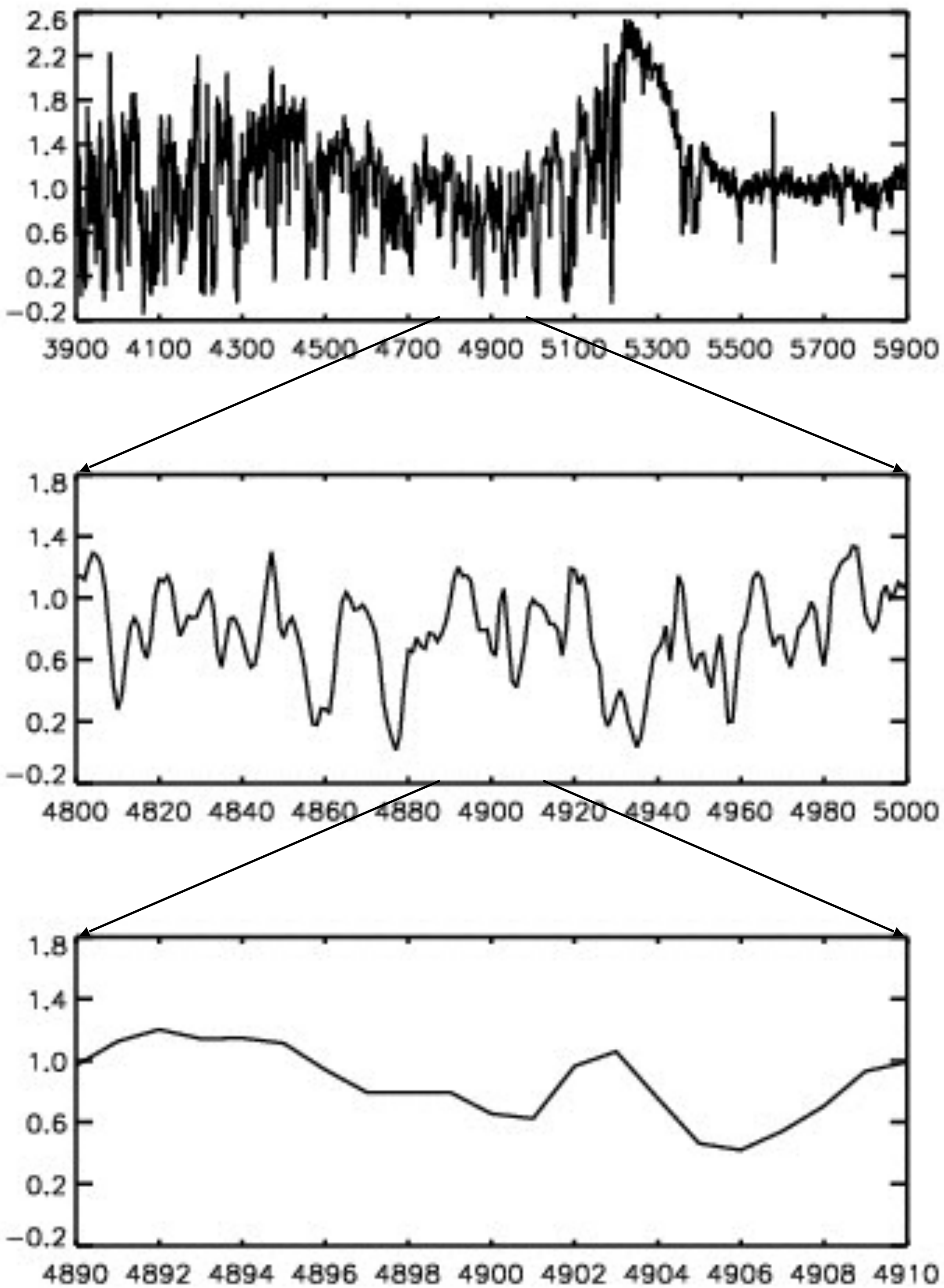

Intensity
Ly Limit
HI (Lyβ)
HI (Lyα)
C II
Si IV
Si II
C IV
Fe II
0
800
1000
1200
1400
1600
1800
Wavelength/Å

The data sets

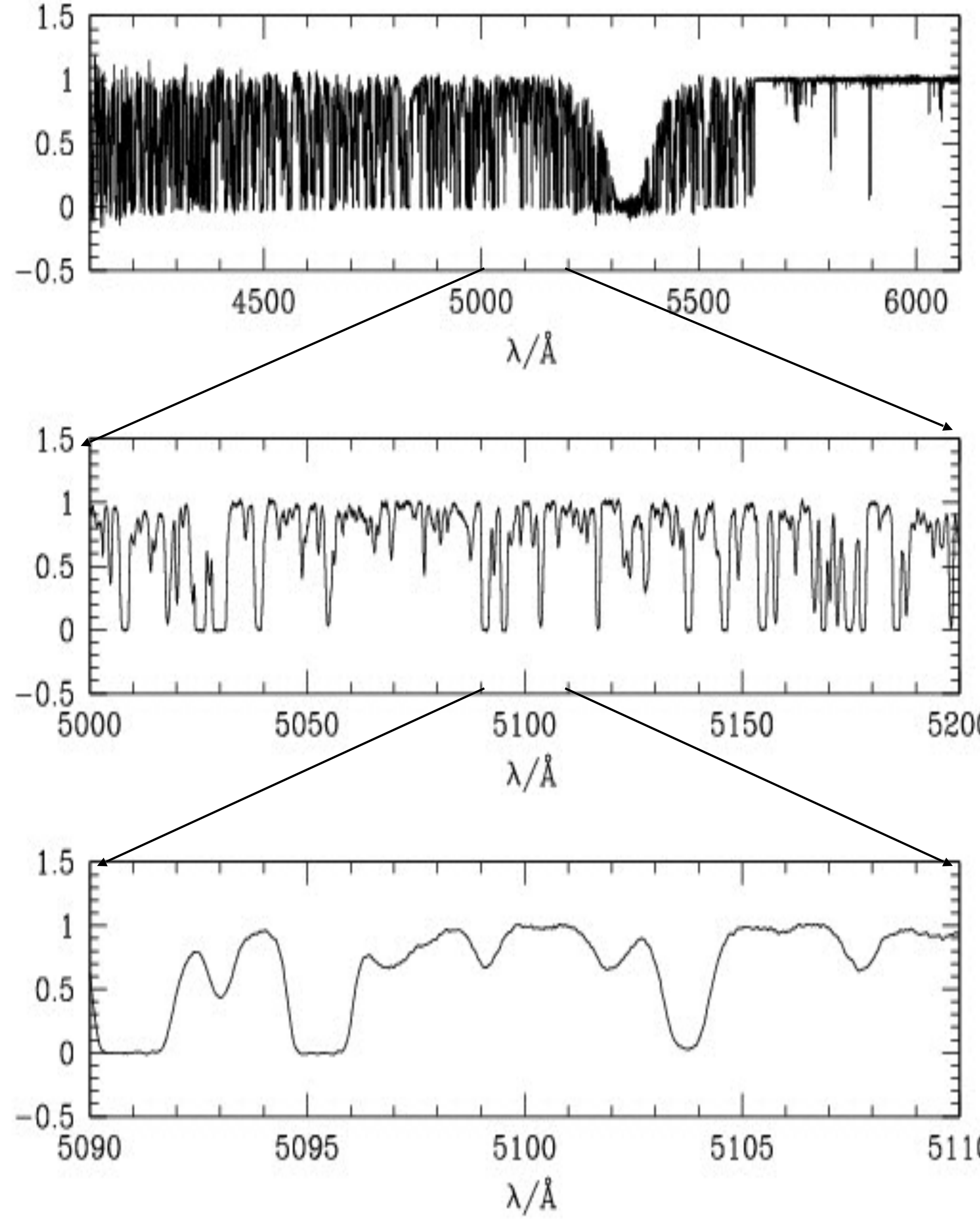


SDSS vs UVES

McDonald et al. 2005



Kim, MV+ 2004



SDSS

~10^4 LOW RESOLUTION LOW S/N vs

UVES/KECK etc.

~10^2 HIGH RESOLUTION HIGH S/N

Key aspects

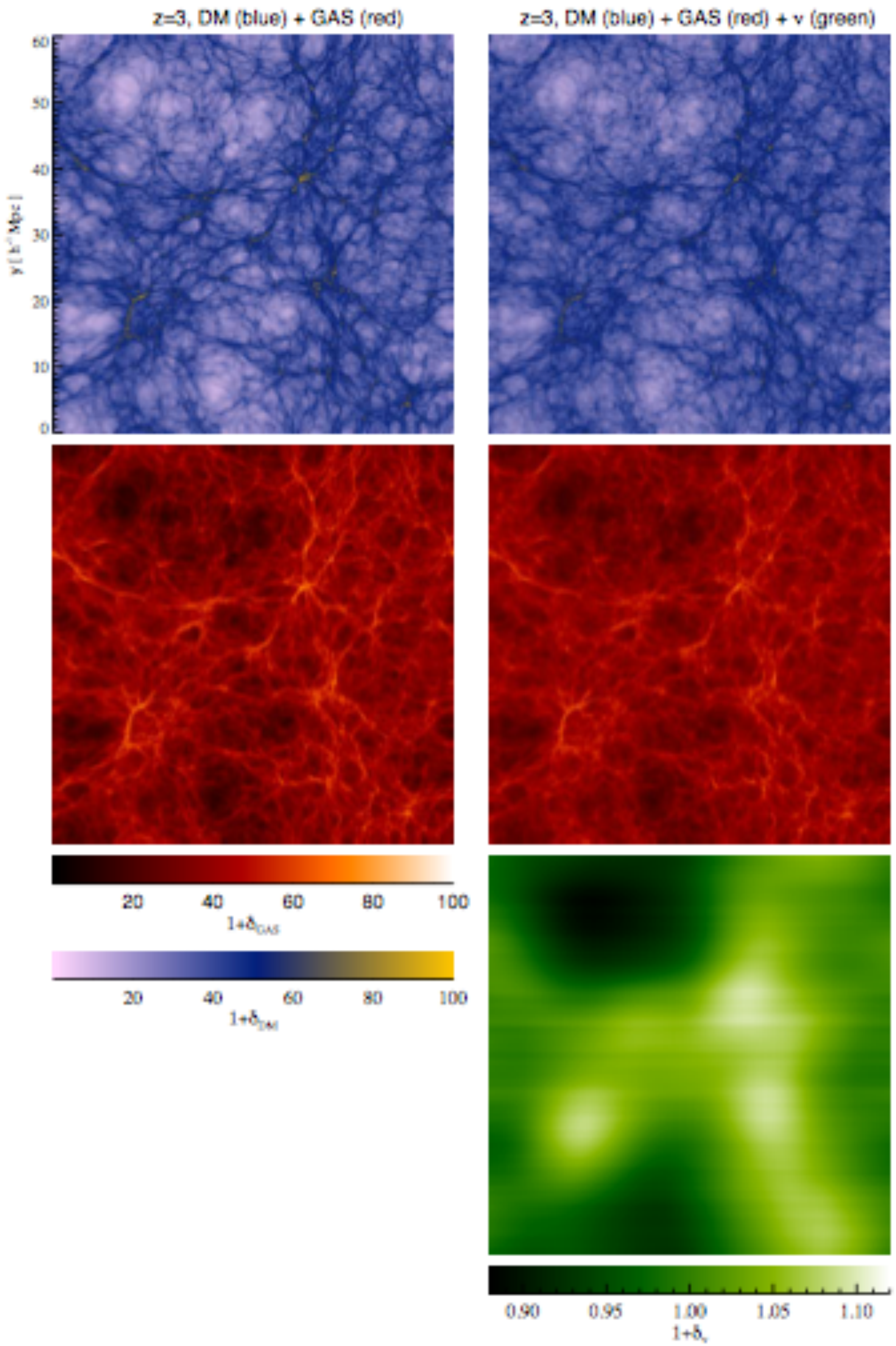
- High redshift (and small scales):
  possibly closer to linear behaviour

- 1D power:

$$P_{1D}(k) = \frac{1}{2\pi}\int_k^\infty P_{3D}(x)x\,dx$$

- Matter probed at around the mean density

NEUTRINOS IN THE IGM



FROM IGM ONLY:

$\Sigma m_{\nu} < 0.9$ eV(2σ)

Viel, Haehnelt, Springel 2010
Rossi+ 14, Villaescusa-Navarro+14

METHOD

DATA: thousands of low-res. Spectra for neutrino constraints. Few tens for cold dark matter coldness

SIMULATIONS: Gadget-III runs: 20 and 60 Mpc/h and (512^3,786^3,896^3)

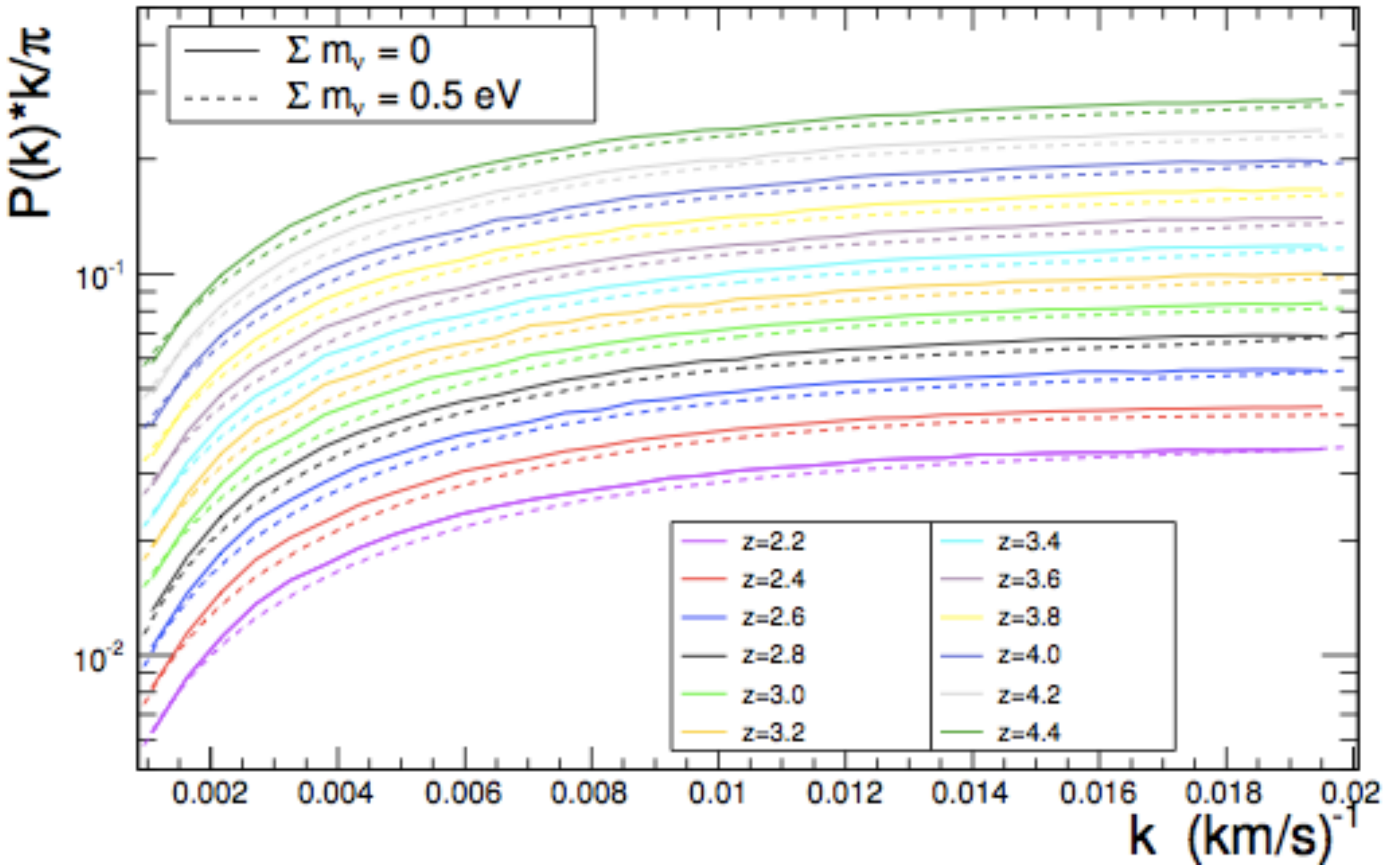
Cosmology parameters: σ_8, n_s, Ω_m, H_0, $m_{WDM,}$+ neutrino mass
Astrophysical parameters: z_{reio}, UV fluctuations, T_0, γ, <F>
Nuisance: resolution, S/N, metals

METHOD: Monte Carlo Markov Chains likelihood estimator
+ **very conservative assumptions** for the continuum fitting and error bars on the data

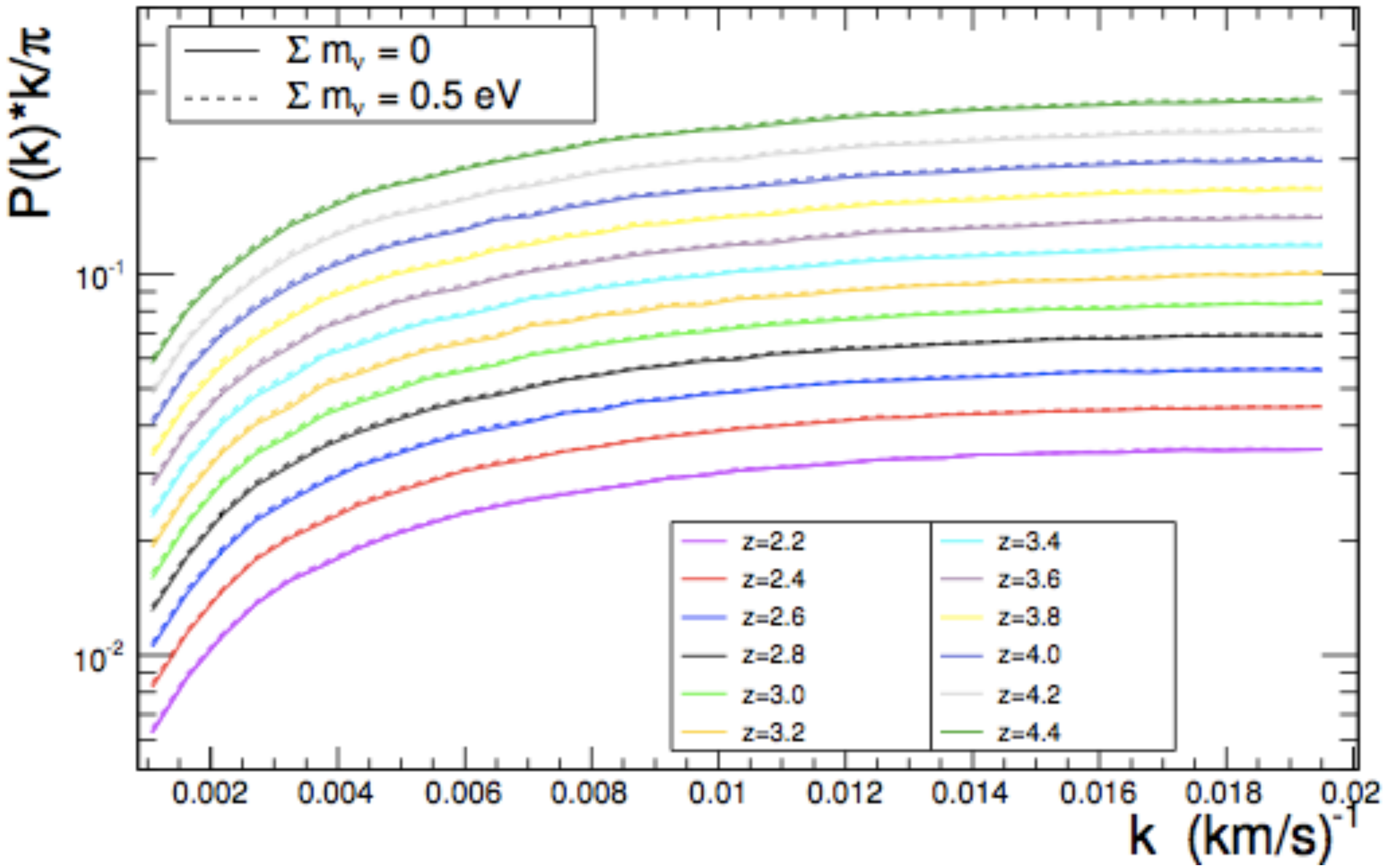
Parameter space: second order Taylor expansion of the flux power

$$P_F(k,z;\mathbf{p}) = P_F(k,z;\mathbf{p}^0) + \sum_i^N \left.\frac{\partial P_F(k,z;p_i)}{\partial p_i}\right|_{\mathbf{p}=\mathbf{p}^0} (p_i - p_i^0)$$ + second order

NEUTRINO IMPACT - I



NEUTRINO IMPACT - II

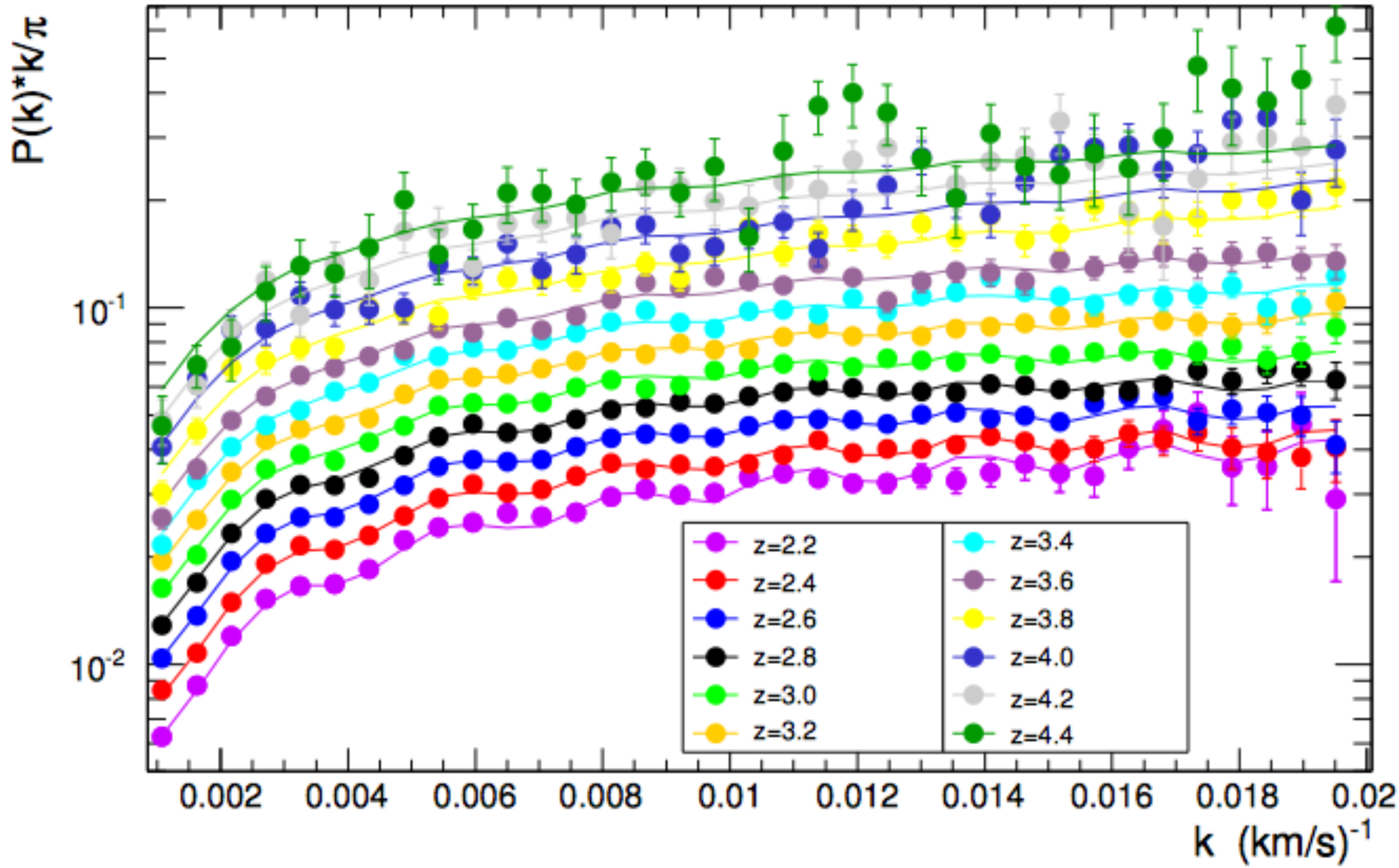


GROWTH OF STRUCTURES AT HIGH REDSHIFT

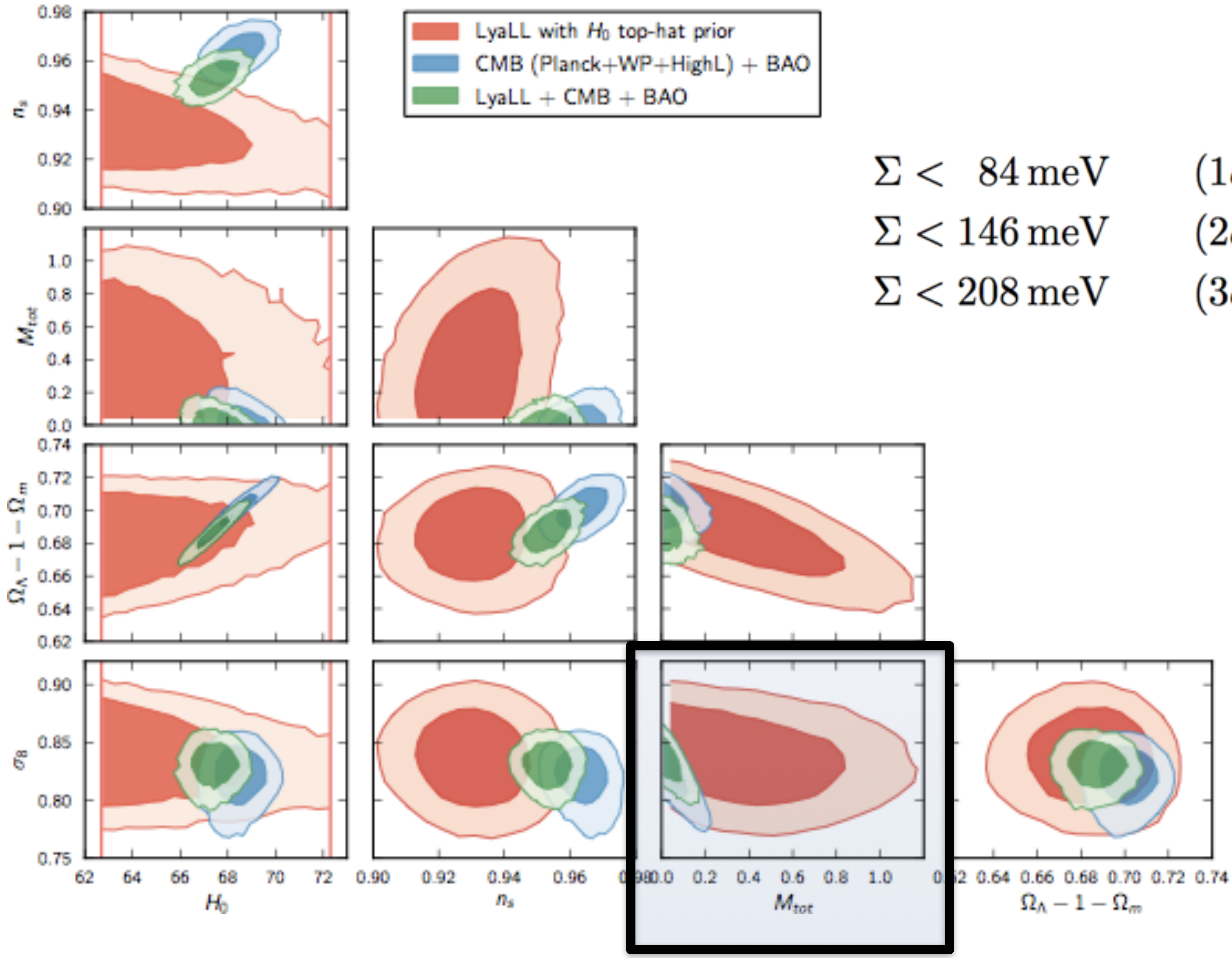
Constraint on neutrino masses from SDSS-III/BOSS Lyα forest and other cosmological probes

Nathalie Palanque-Delabrouille,[a,b] Christophe Yèche,[a] Julien Lesgourgues,[c,d,e] Graziano Rossi,[a,f] Arnaud Borde,[a] Matteo Viel,[g,h] Eric Aubourg,[i] David Kirkby,[j] Jean-Marc LeGoff,[a] James Rich,[a] Natalie Roe,[b] Nicholas P. Ross,[k] Donald P. Schneider,[l,m] David Weinberg[n]

1D Flux power spectrum evolution



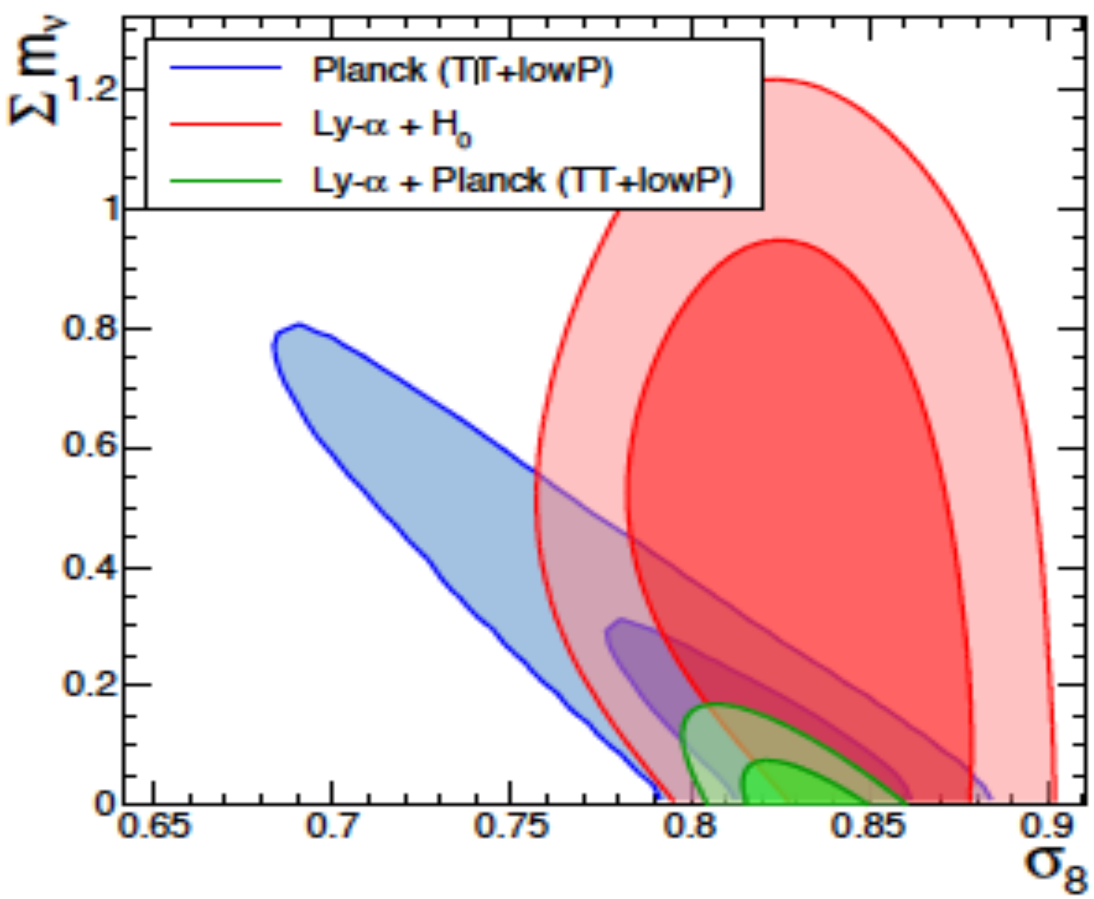
BAYESIAN ANALYSIS



$$\Sigma < 84\,\mathrm{meV} \quad (1\sigma\,\mathrm{C.L.})$$
$$\Sigma < 146\,\mathrm{meV} \quad (2\sigma\,\mathrm{C.L.})$$
$$\Sigma < 208\,\mathrm{meV} \quad (3\sigma\,\mathrm{C.L.})$$

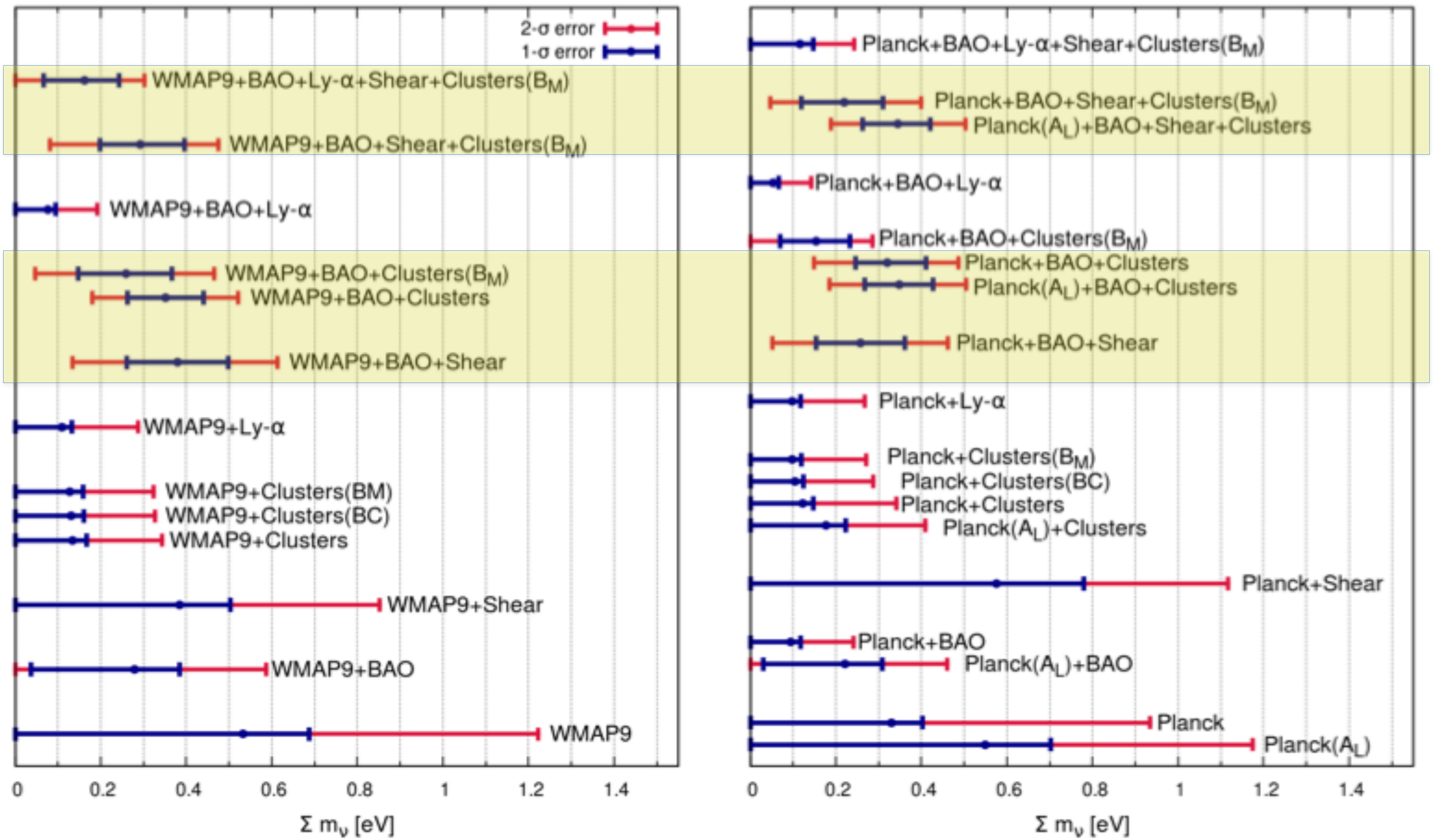
Palanque-Delabrouille+ 2015

Parameter	(1) Lyα + H_0^{Gaussian} ($H_0 = 67.3 \pm 1.0$)	(2) Lyα + Planck TT+lowP	(3) Lyα + Planck TT+lowP + BAO	(4) Lyα + Planck TT+TE+EE+lowP + BAO
σ_8	0.831 ± 0.031	0.833 ± 0.011	0.845 ± 0.010	0.842 ± 0.014
n_s	0.938 ± 0.010	0.960 ± 0.005	0.959 ± 0.004	0.960 ± 0.004
Ω_m	0.293 ± 0.014	0.302 ± 0.014	0.311 ± 0.014	0.311 ± 0.007
H_0 (km s^{-1} Mpc^{-1})	67.3 ± 1.0	68.1 ± 0.9	67.7 ± 1.1	67.7 ± 0.6
$\sum m_\nu$ (eV)	< 1.1 (95% CL)	< 0.12 (95% CL)	< 0.13 (95% CL)	< 0.12 (95% CL)
Reduced χ^2	0.99	1.04	1.05	1.05



Limits are close to the SDSS-II data release (Seljak, McDonald, Slosar 2005-2006) using different data and theory

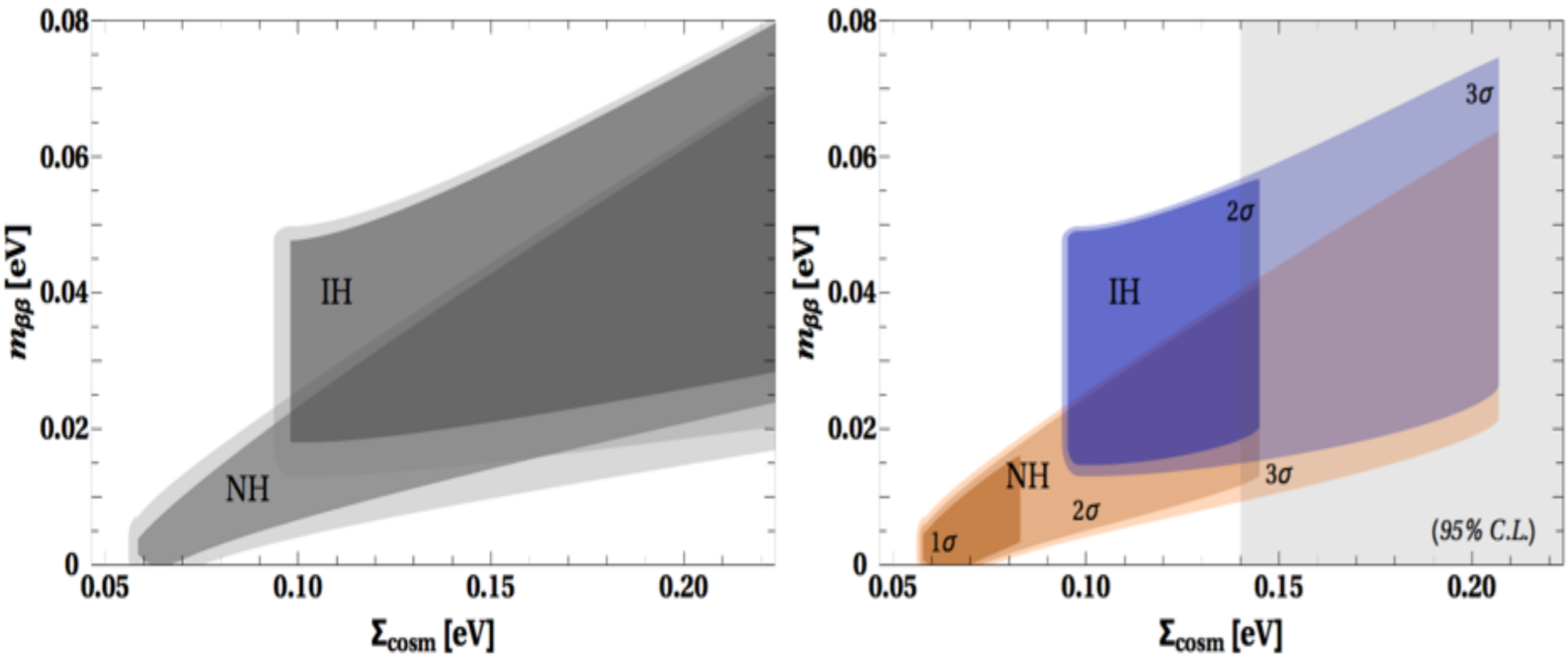
in that case < 0.14 eV



2-σ error
1-σ error
WMAP9+BAO+Ly-α+Shear+Clusters(B_M)
WMAP9+BAO+Shear+Clusters(B_M)
WMAP9+BAO+Ly-α
WMAP9+BAO+Clusters(B_M)
WMAP9+BAO+Clusters
WMAP9+BAO+Shear
WMAP9+Ly-α
WMAP9+Clusters(BM)
WMAP9+Clusters(BC)
WMAP9+Clusters
WMAP9+Shear
WMAP9+BAO
WMAP9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Σ m_ν [eV]
Planck+BAO+Ly-α+Shear+Clusters(B_M)
Planck+BAO+Shear+Clusters(B_M)
Planck(A_L)+BAO+Shear+Clusters
Planck+BAO+Ly-α
Planck+BAO+Clusters(B_M)
Planck+BAO+Clusters
Planck(A_L)+BAO+Clusters
Planck+BAO+Shear
Planck+Ly-α
Planck+Clusters(B_M)
Planck+Clusters(BC)
Planck+Clusters
Planck(A_L)+Clusters
Planck+Shear
Planck+BAO
Planck(A_L)+BAO
Planck
Planck(A_L)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Σ m_ν [eV]

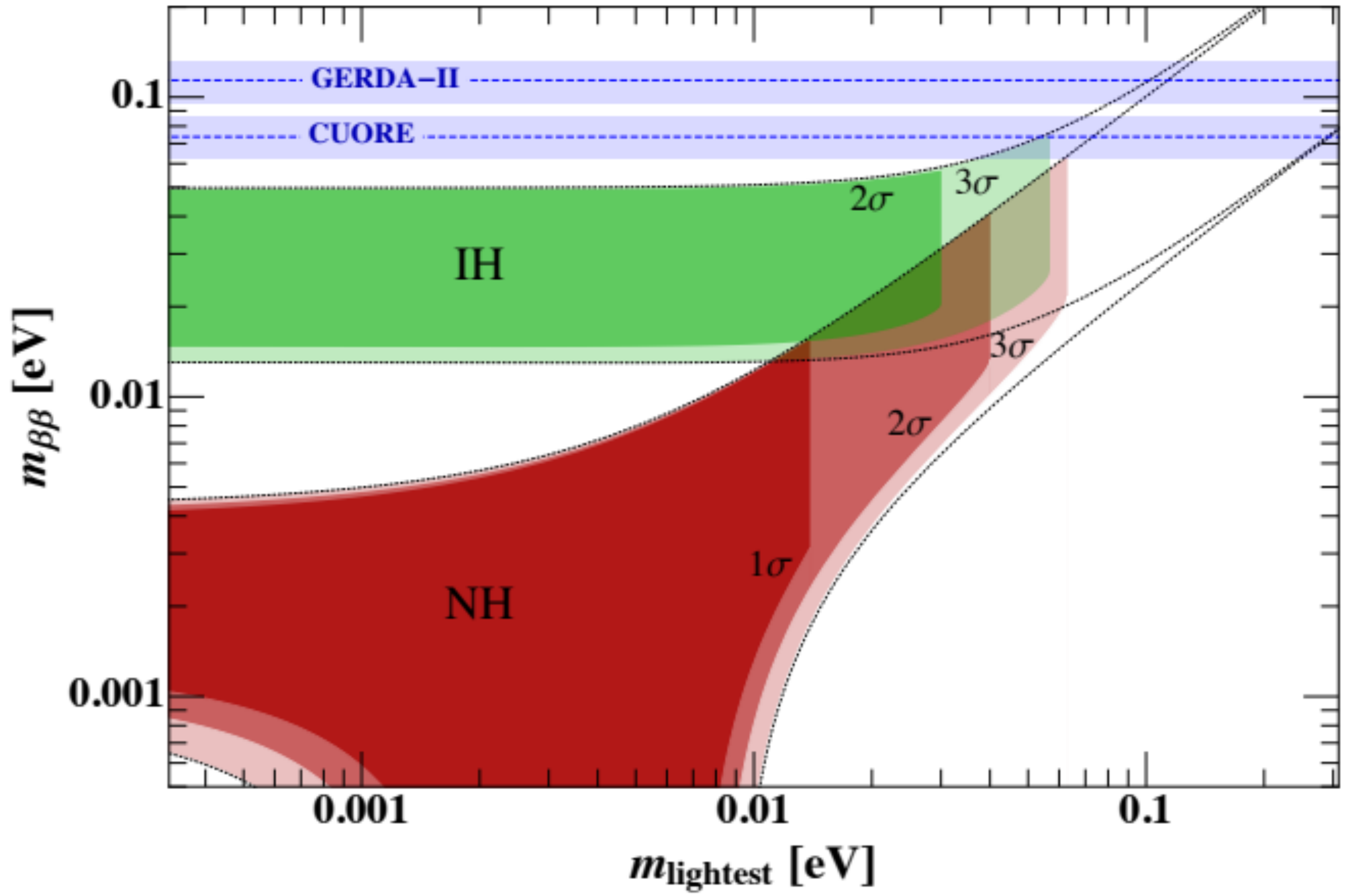
Implications for neutrinoless double beta decay - I

Dell'Oro, Marcocci, Viel, Vissani 15,16



Mass spectrum	$m_{\beta\beta}$ max [meV] (C.L. on Σ)		
	1σ	2σ	3σ
$\mathcal{NH}$	16	41	64
$\mathcal{IH}$	-	57	75

Implications for neutrinoless double beta decay - II

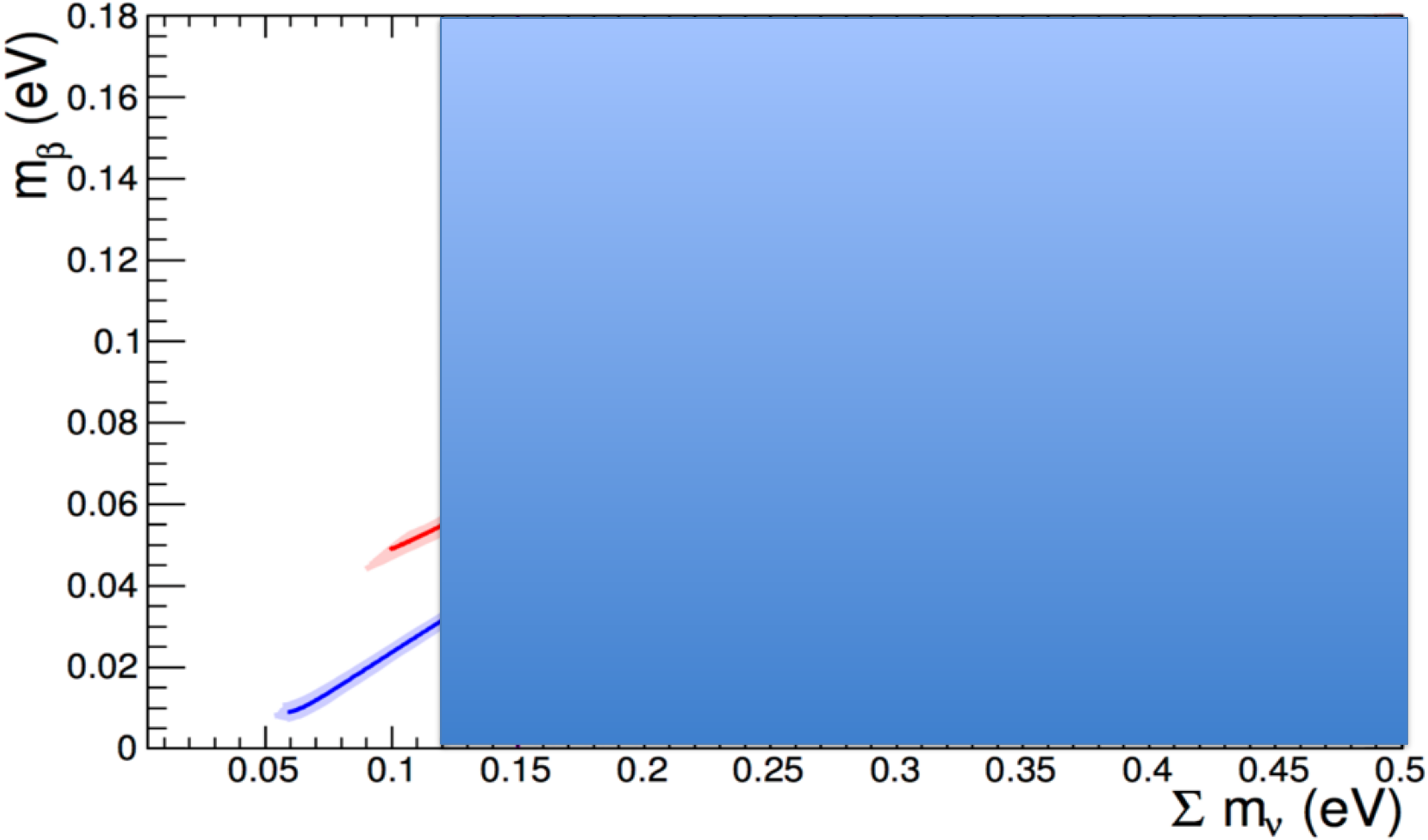


Dell'Oro, Marcocci, Viel, Vissani 15,16

Strong (negative) implications for experiments!!!!

Implications for Tritium beta decay

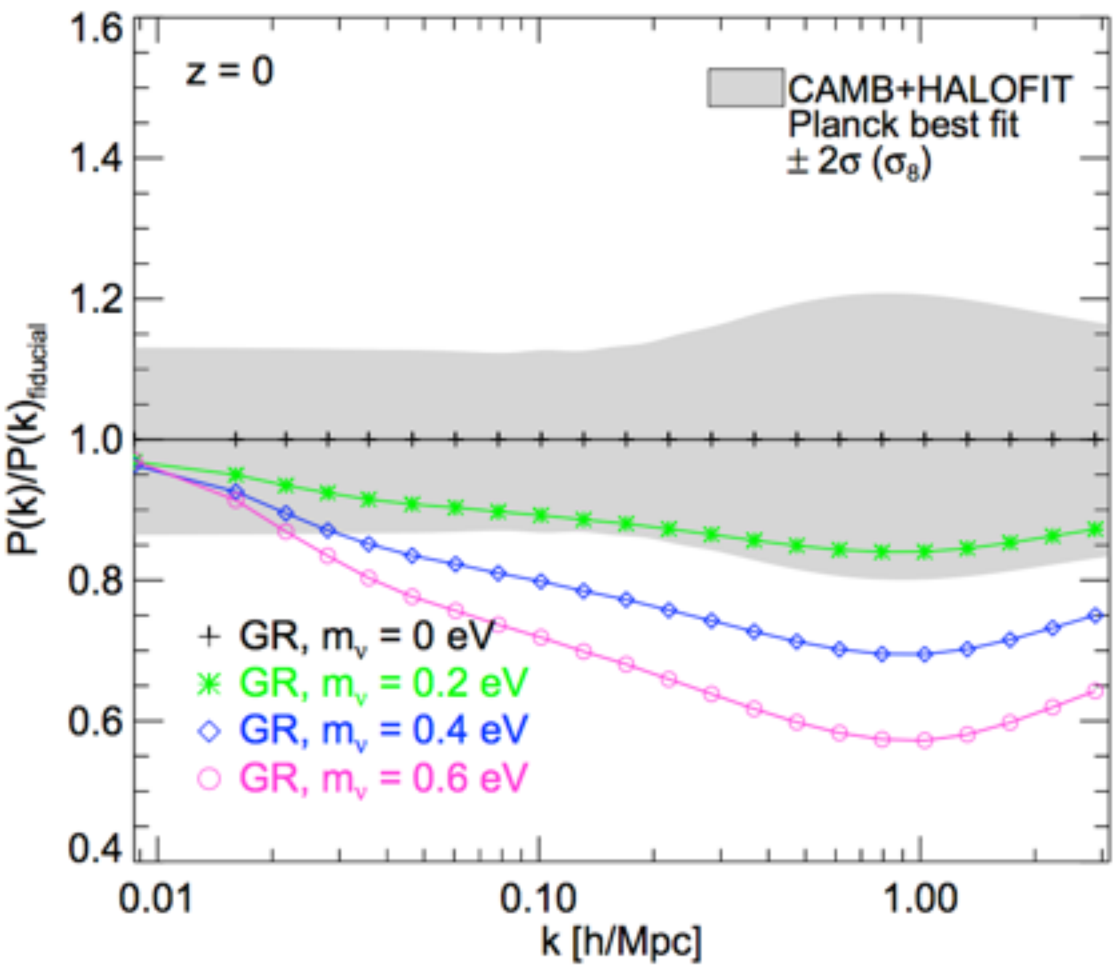
$$m_\beta = \left(\sum_i |U_{ei}|^2 m_i^2\right)^{\frac{1}{2}} = \left(c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right)^{\frac{1}{2}}$$



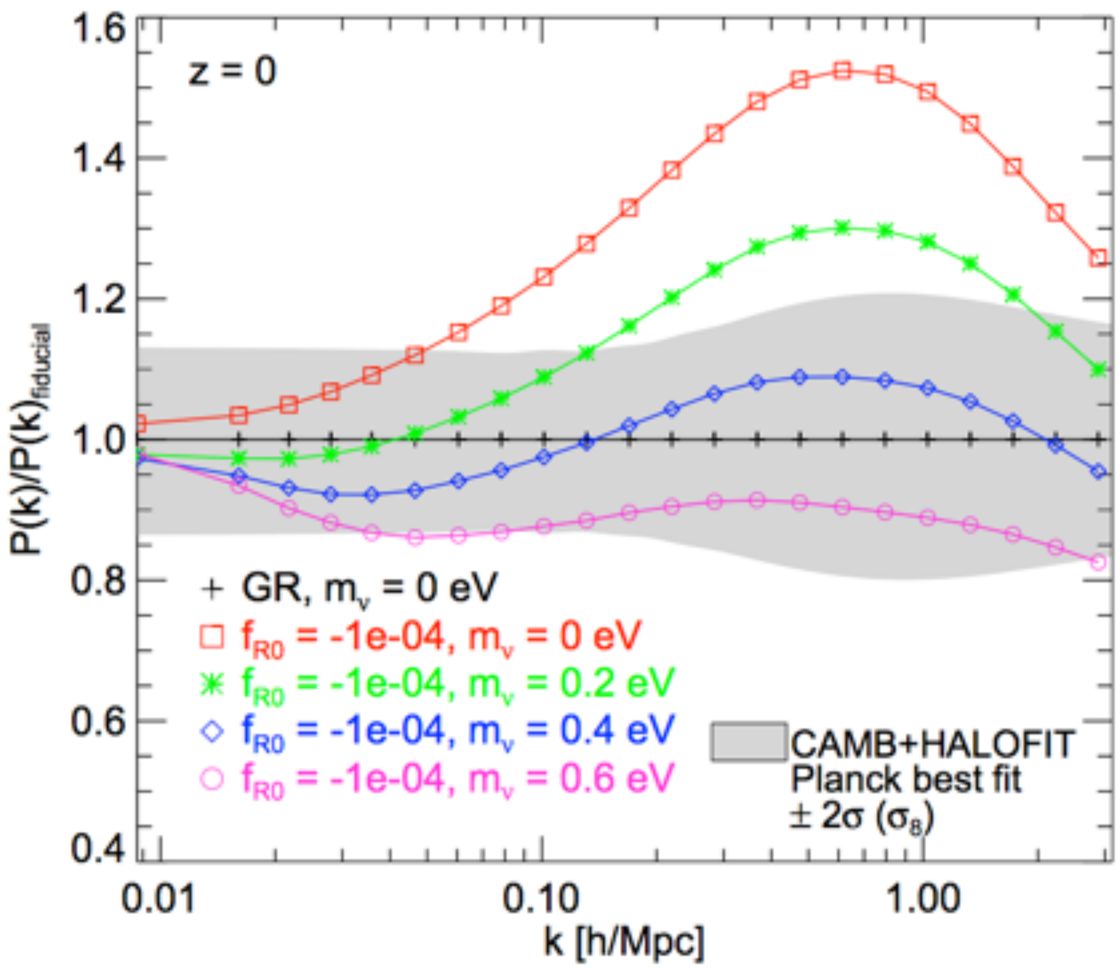
What if … large non-zero neutrino mass found?

Baldi, Villaescusa-Navarro, Viel, Puchwein, Springel, Moscardini, 2014

General Relativity + massive neutrinos

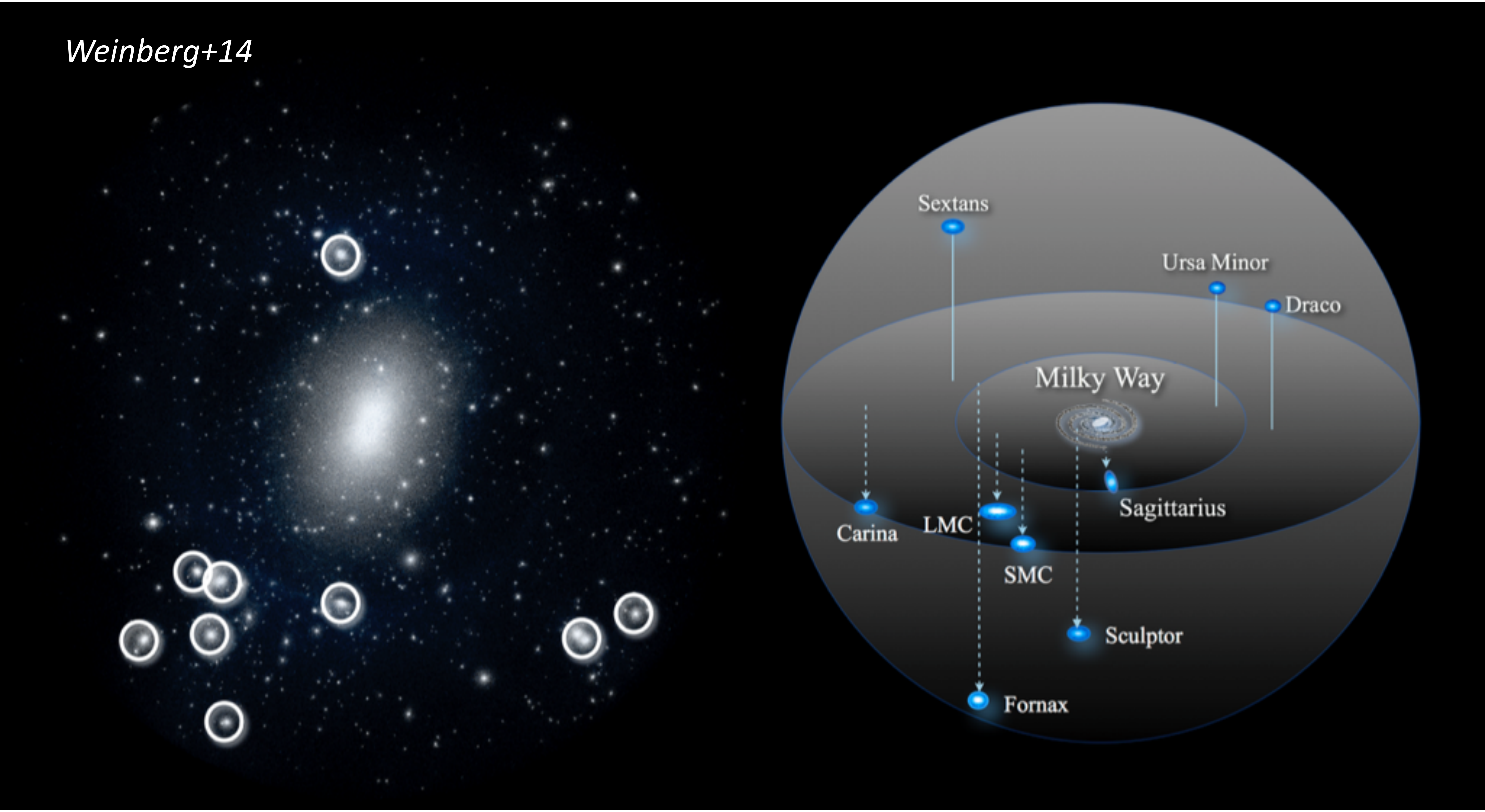


Modified gravity + massive neutrinos



STERILE NEUTRINOS as DM

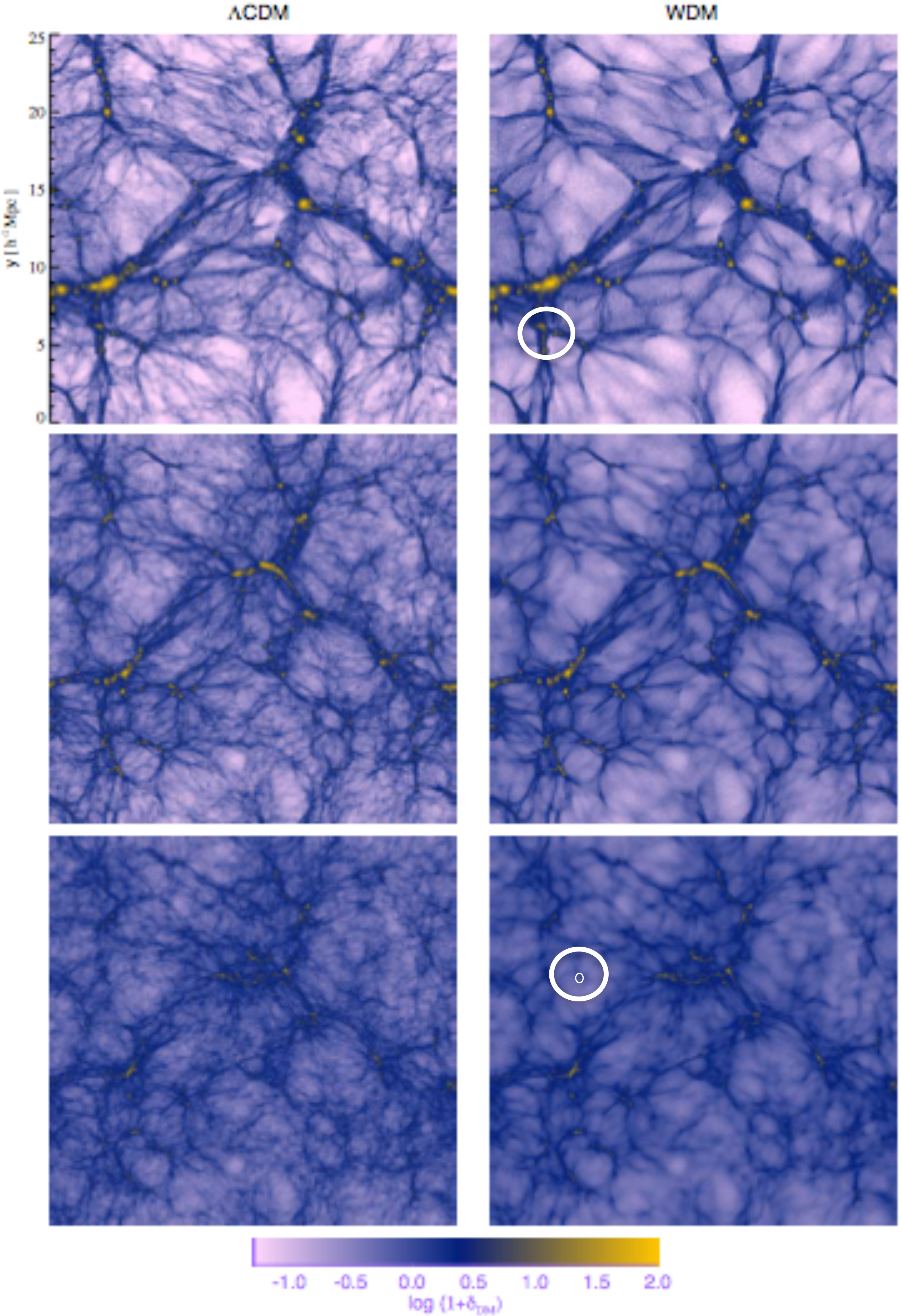
ΛCDM model: other small scales problems?



1) Too big to fail problem
2) Missing satellite problem
3) Cusp-core problem

Note that baryonic physics (e.g. galactic feedback) could also solve the tension. Contrived to have DM perfectly mimicking baryons (different z-evolution?)

The cosmic web in cold and warm dark matter



z=0

$$\frac{T_x}{T_\nu} = \left(\frac{10.75}{g_*(T_D)}\right)^{1/3} < 1$$

$$k_{\rm FS} = \frac{2\pi}{\lambda_{\rm FS}} \sim 5\,{\rm Mpc}^{-1}\left(\frac{m_x}{1\,{\rm keV}}\right)\left(\frac{T_\nu}{T_x}\right)$$

$$\omega_x = \Omega_x h^2 = \beta\left(\frac{m_x}{94\,{\rm eV}}\right)$$

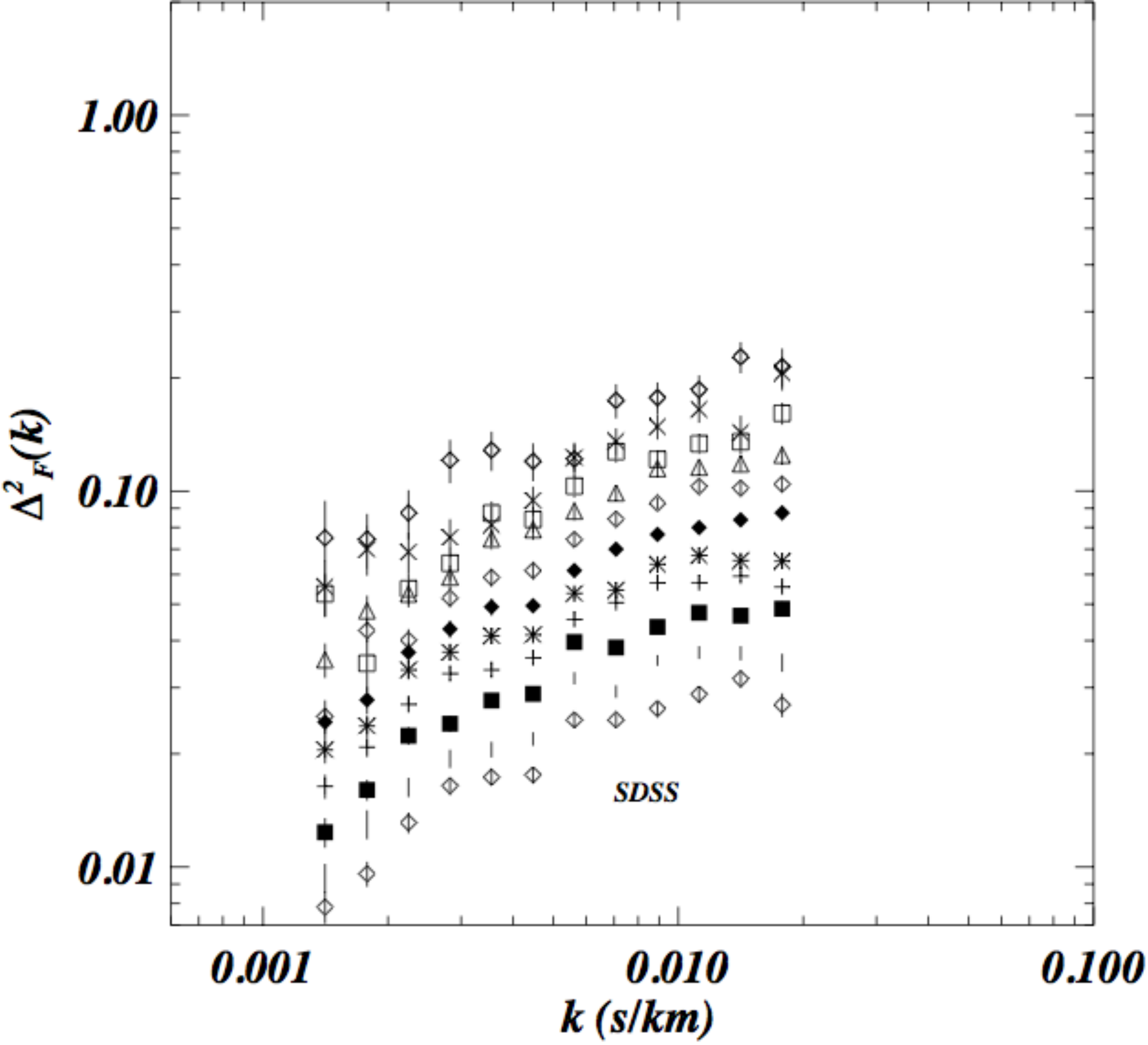
$$\beta = (T_x/T_\nu)^3$$

z=2

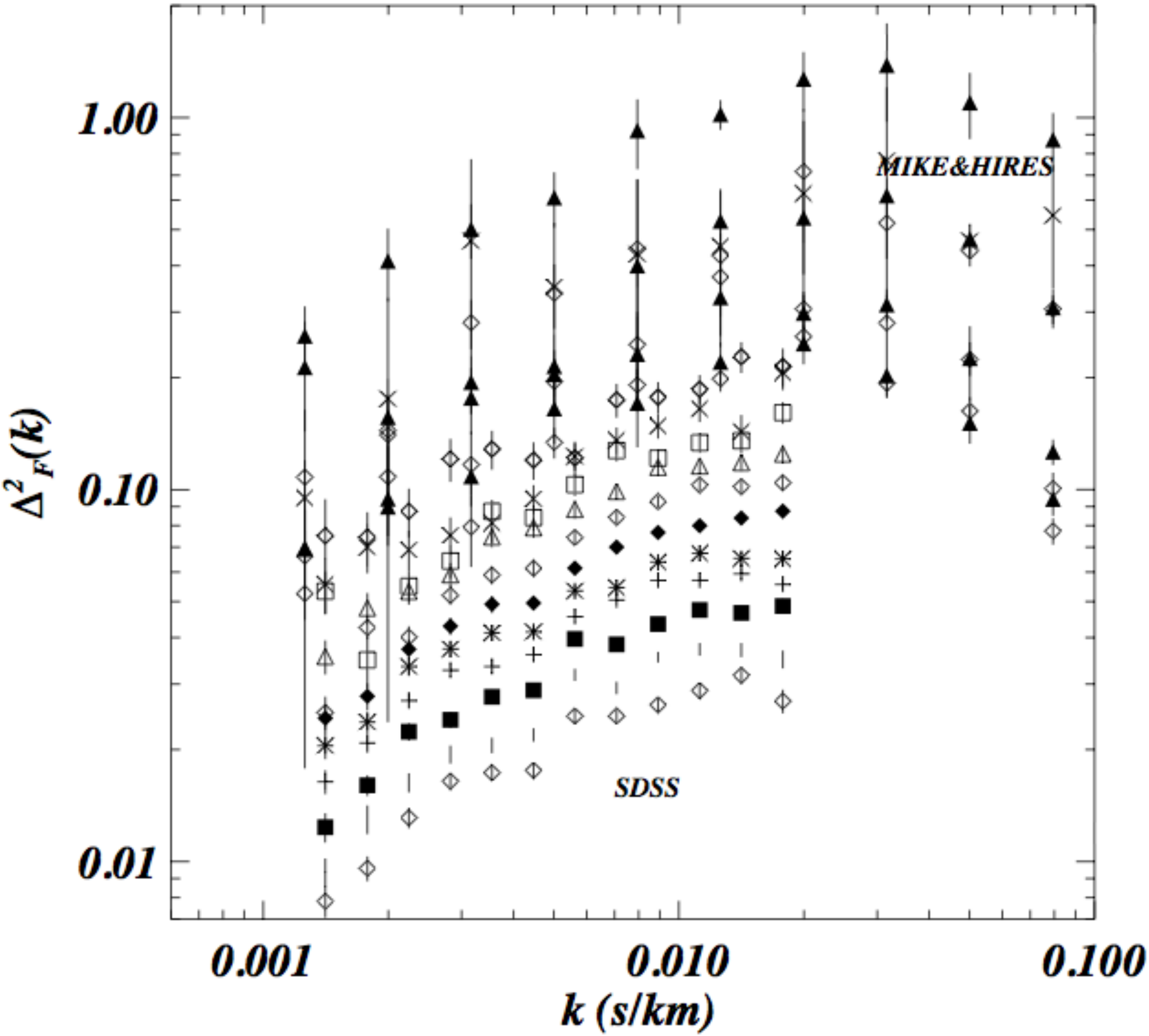
$$k_{\rm FS} \sim 15.6\frac{h}{\rm Mpc}\left(\frac{m_{\rm WDM}}{1{\rm keV}}\right)^{4/3}\left(\frac{0.12}{\Omega_{\rm DM}h^2}\right)^{1/3}$$

z=5

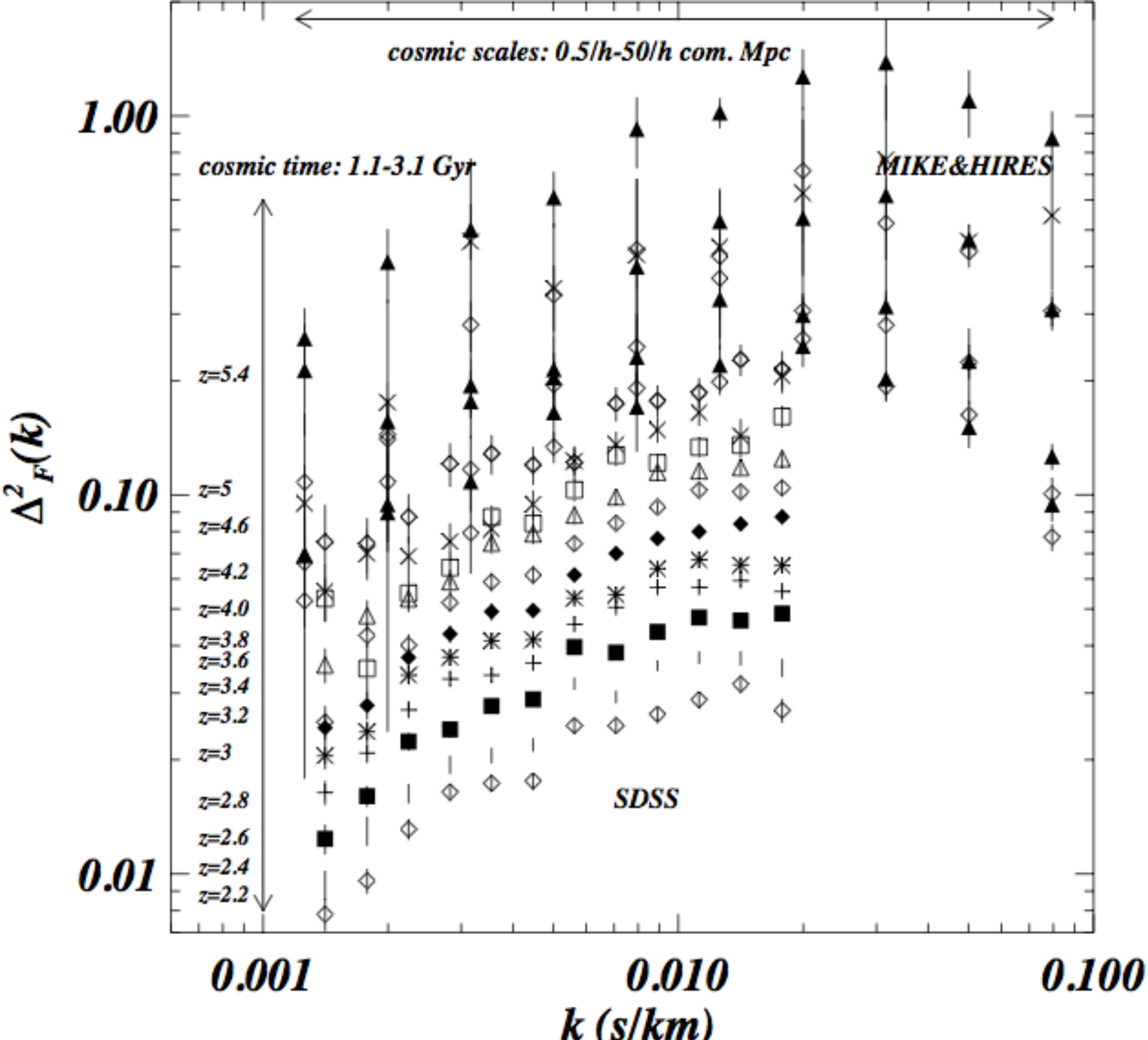
MV, Markovic, Baldi & Weller 2013
Markovic & MV, 2014



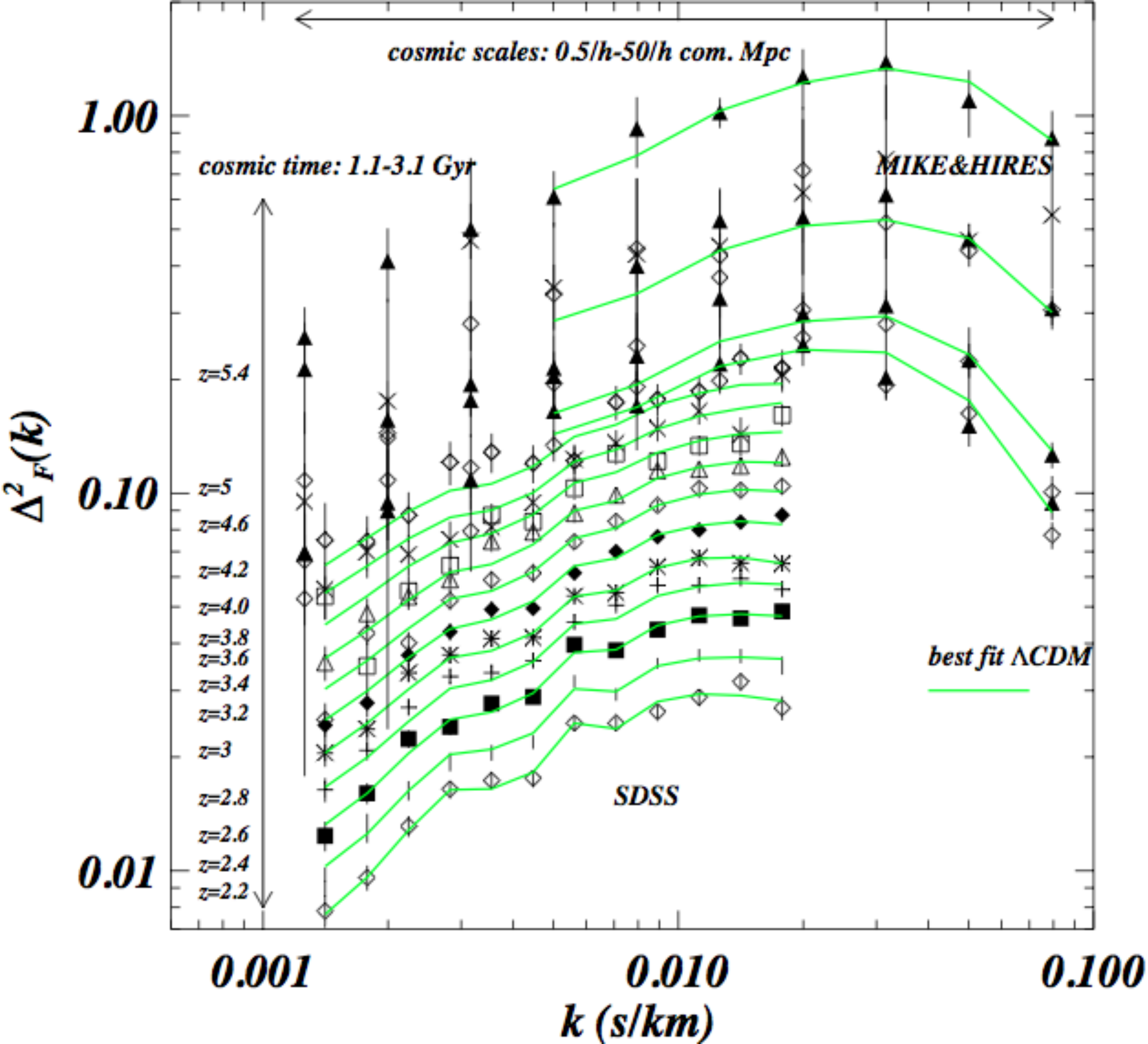
1.00
0.10
0.01
$\Delta^2_F(k)$
SDSS
0.001
0.010
0.100
k (s/km)



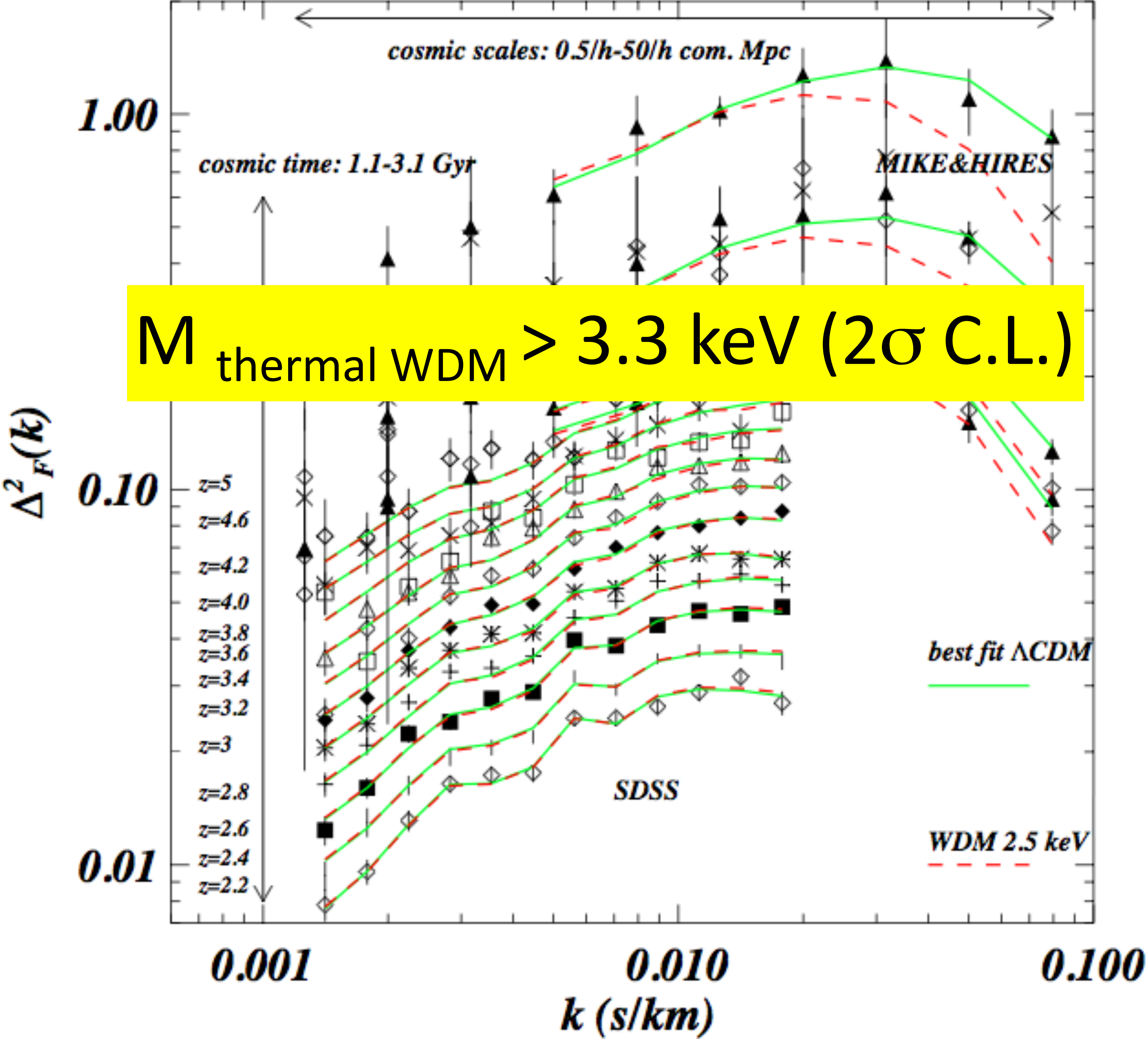
1.00
0.10
0.01
$\Delta^2_F(k)$
MIKE&HIRES
SDSS
0.001
0.010
0.100
k (s/km)



cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
SDSS
z=5.4
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
1.00
0.10
0.01
0.001
0.010
0.100
$\Delta^2_F(k)$
k (s/km)



cosmic scales: 0.5/h-50/h com. Mpc
cosmic time: 1.1-3.1 Gyr
MIKE&HIRES
best fit ΛCDM
SDSS
z=5.4
z=5
z=4.6
z=4.2
z=4.0
z=3.8
z=3.6
z=3.4
z=3.2
z=3
z=2.8
z=2.6
z=2.4
z=2.2
1.00
0.10
0.01
0.001
0.010
0.100
$\Delta^2_F(k)$
k (s/km)



M $_{\text{thermal WDM}}$ > 3.3 keV (2σ C.L.)

CONCLUSIONS

- Neutrino induced non-linearities in the matter or cold dark matter distributions are useful and distinctive, however this regime is tricky especially for baryonic effects **BUT** lots of data

- Numerical methods are converging and giving consistent results in this regime

- Present neutrino indirect constraints are obtained by comparing growth at different scales: limits < 0.12-0.15 eV at 2sigma C.L.

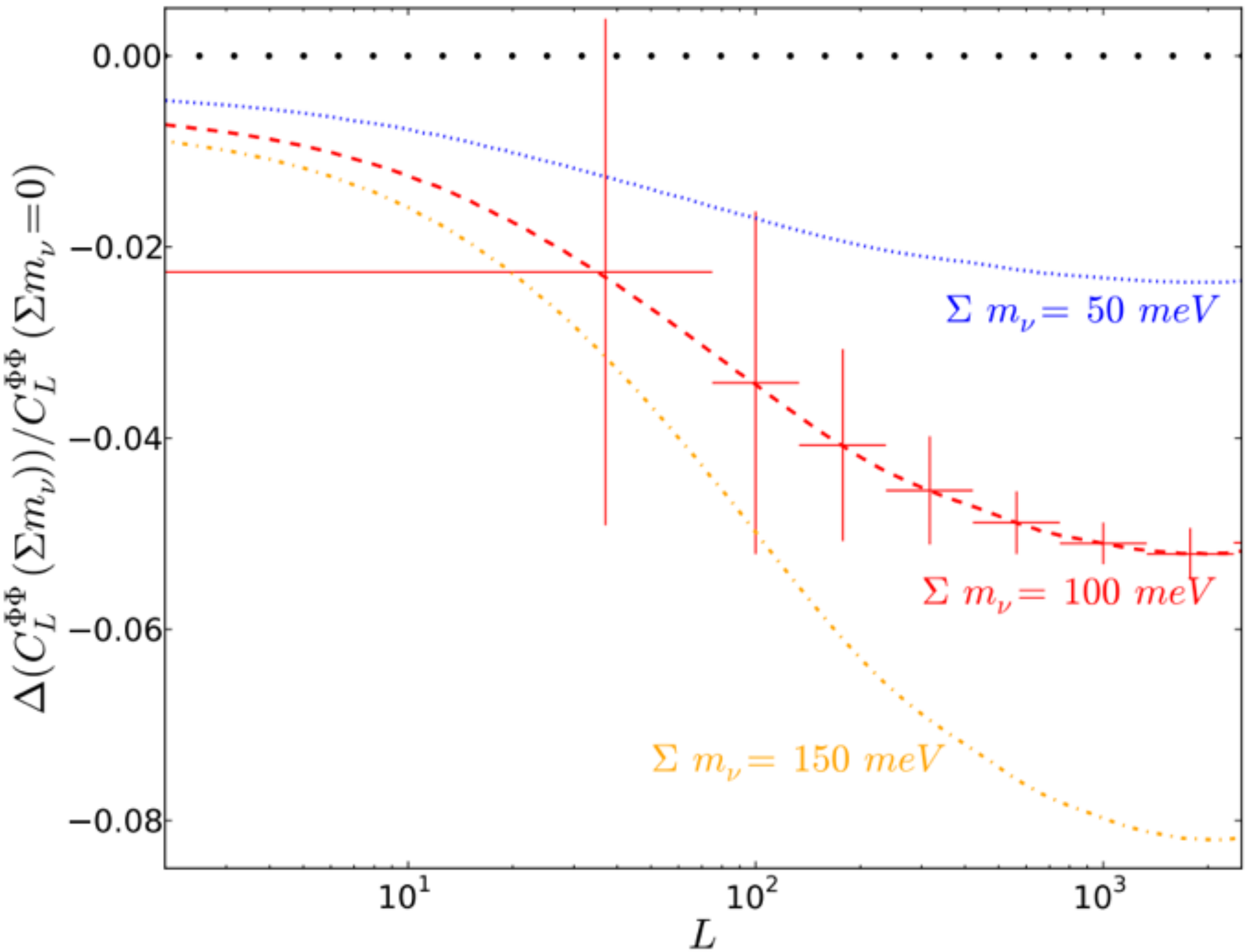
- Warm dark matter is also tightly constraints by small scale IGM data to a level at which it behaves like Cold Dark Matter (>3.3 keV thermal relic)

- Above numbers are obtained by marginalizing over nuisances, however they are model dependent and subjected to some prior assumptions

FUTURE SEEMS BRIGHT…

Stage-IV CMB: lensing

Abazajian+2013: arXiv: 1309.5383



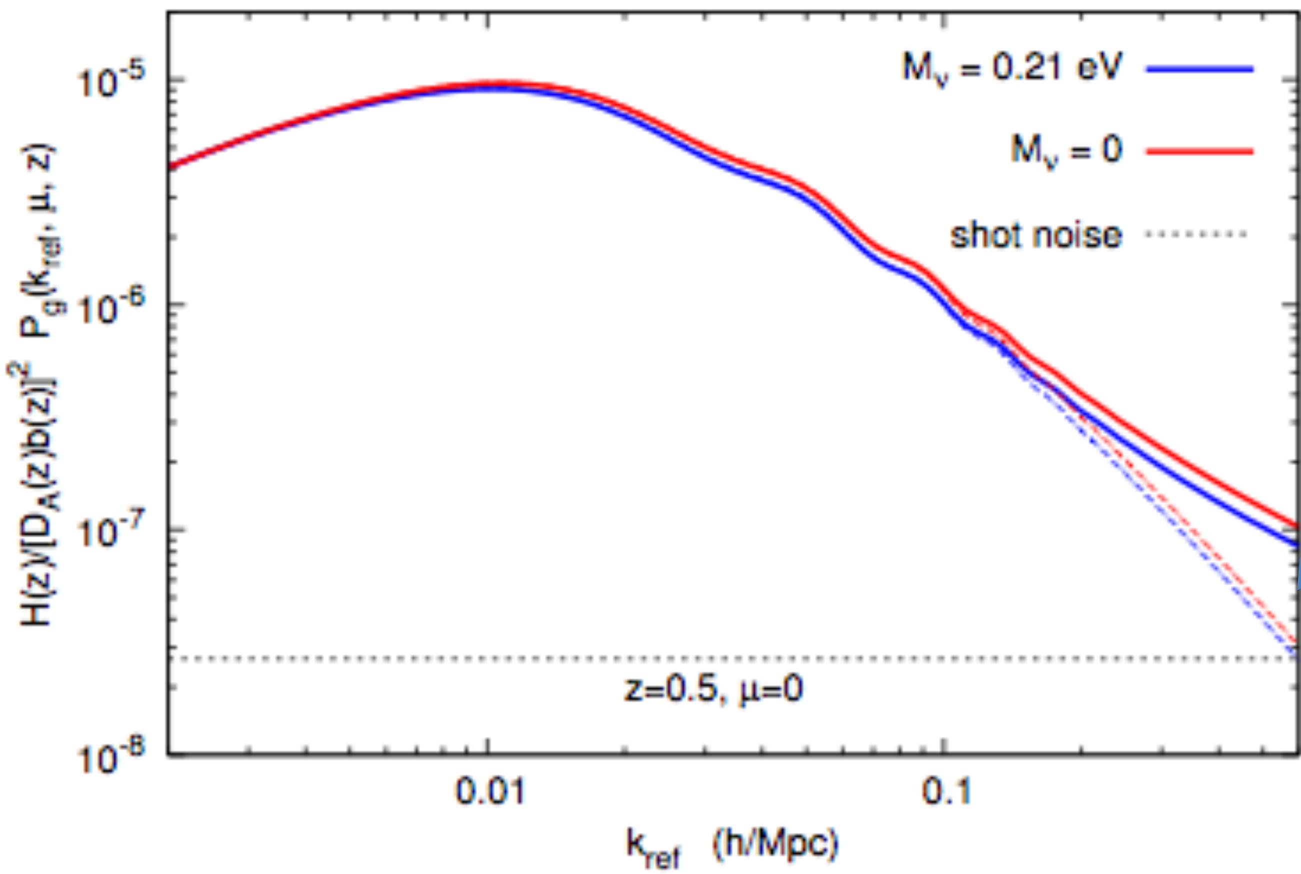
The effect of massive neutrinos on the CMB lensing potential power spectrum. The fractional change for a given value of Pmν is shown relative to the case for zero neutrino mass.

Projected constraints for a Stage-IV CMB experiment are shown for Pmν = 100 meV. Here we have approximated all of the neutrino mass to be in one mass eigenstate and fixed the total matter density

The 1σ constraint for Pmν is approximately 45 meV for lensing alone and drops to **16 meV** when combined with other probes.

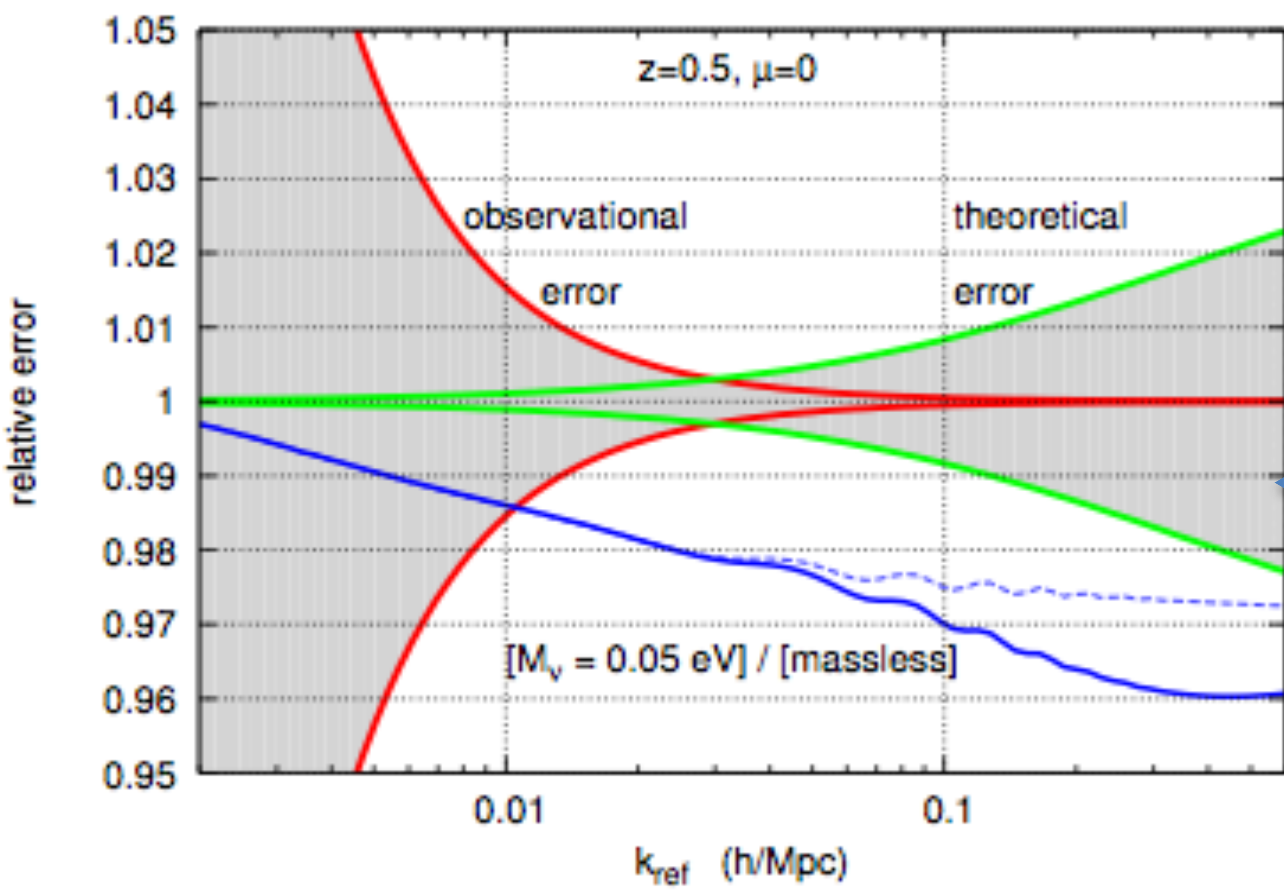
Forecasts for Euclid

Audren, Lesgourgues, Bird, Haehnelt, MV 2013



Non-linearities

- $\sigma(M_\nu)$=18 meV → 5 meV when going from 0.1 to 0.6 h/Mpc
- with conservative errors the improvement is modest
- with realistic error could be 20%



Need to be modelled accurately

See also Costanzi et al. 2013 for clusters

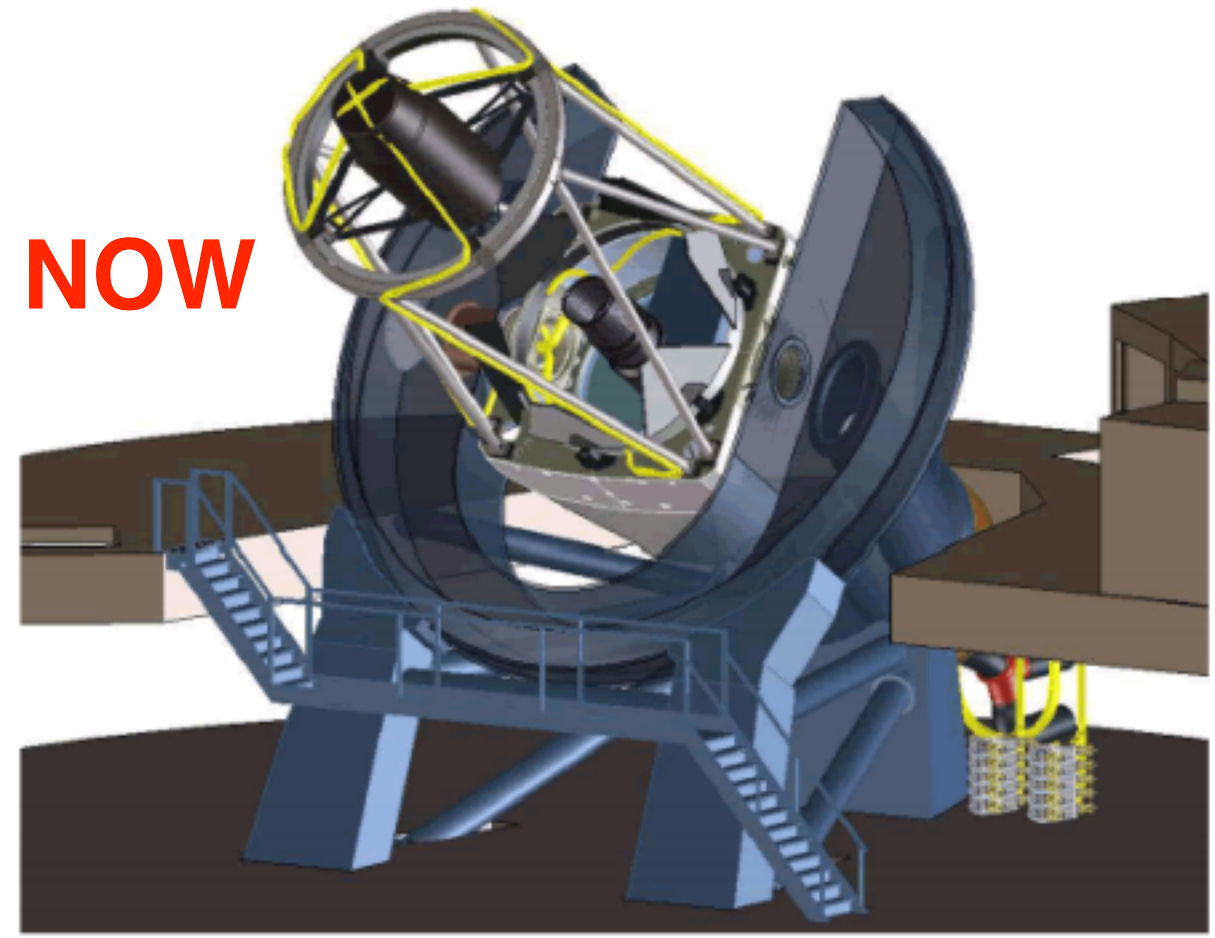
Forecasts for Euclid

Audren, Lesgourgues, Bird, Haehnelt, MV 2013

$k_{\max}$ (h/Mpc)	un. err.	co. err.	$10^4\omega_b$	$10^4\omega_c$	$10^3 n_s$	$10^{11}A_s$	$10^3 h$	$z_{\rm reio}$	$3m_\nu = M_\nu$ (meV)
0.1	–	–	1.2	6.2	2.8	3.0	4.1	0.38	18
0.1	1/10	–	1.2	6.9	2.8	3.1	4.5	0.39	18
0.1	1/2	–	1.3	9.5	3.2	3.5	6.1	0.39	23
0.1	•	–	1.3	11	3.4	3.6	6.7	0.40	25
0.1	•	•	1.3	11	3.4	3.6	6.7	0.40	25
0.6	–	–	0.86	2.1	0.37	1.2	0.40	0.23	5.9
0.6	1/10	–	1.1	4.8	2.5	2.7	3.0	0.37	14
0.6	1/2	–	1.2	8.6	3.2	3.4	5.7	0.39	22
0.6	•	–	1.3	10	3.4	3.6	6.7	0.39	25
0.6	•	•	1.3	10	3.4	3.6	6.7	0.39	25

Going non-linear, surely worth… but….

Stage-IV CMB: galaxy clustering and galaxy weak lensing



LSST:

- Photometric experiment: takes pictures of the sky
- 5 bands can give an estimate of a redshift
- Passed CD3 in August 2015

DESI:

- Spectroscopic experiment: takes spectra
- Spectra give redshifts - real 3D experiment
- Passed CD3 in May 2016

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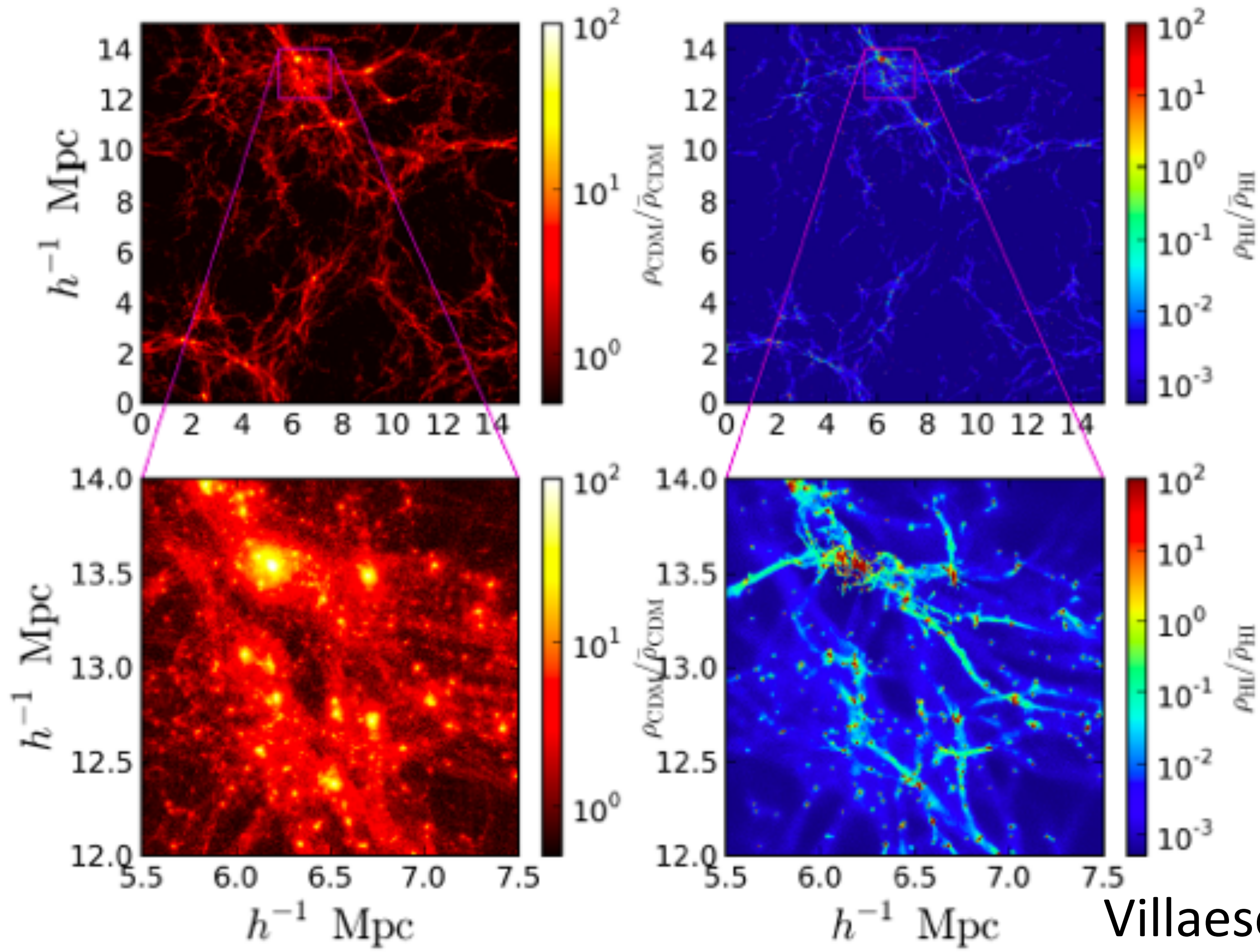
Abbreviation	Data Set
P	Planck CMB (and a 5% constraint on H_0 that only matters in severely under-constrained cases).
BgB	BOSS galaxy BAO.
BlB	BOSS Lyα forest and high-z quasar BAO.
$BgAk_{\max,\mathrm{eff}}$	BOSS galaxy broadband to $k < k_{\max,\mathrm{eff}}$ hMpc^{-1} (plus BAO beyond that).
DES	DES lensing and galaxy clustering.
hdB	HETDEX BAO
$hdAk_{\max,\mathrm{eff}}$	HETDEX broadband to $k < k_{\max,\mathrm{eff}}$ hMpc^{-1} (plus BAO beyond that).
$ebgAk_{\max,\mathrm{eff}}$	eBOSS galaxy broadband to $k < k_{\max,\mathrm{eff}}$ hMpc^{-1} (plus BAO beyond that).
$BBgB$	DESI galaxy BAO.
$BBlB$	DESI Lyα forest and high-z quasar BAO.
$BBAk_{\max,\mathrm{eff}}$	DESI galaxy broadband to $k < k_{\max,\mathrm{eff}}$ hMpc^{-1} (plus BAO beyond that).
euB	Euclid BAO (for 50 million galaxies).
$euAk_{\max,\mathrm{eff}}$	Euclid galaxy broadband to $k < k_{\max,\mathrm{eff}}$ hMpc^{-1} (plus BAO beyond that).
$LSST$	LSST lensing and galaxy clustering.
BlA	BOSS Lyα forest broadband (including relatively small, ~1D scales).
$l1D$	~ 100 high resolution Lyα forest spectra.
$BBlA$	DESI Lyα forest broadband (including relatively small, ~1D scales).
$BB24$	24 is appended to BB to indicate 24000 sq. deg. DESI instead of the baseline 14000 sq. deg.
wfB	WFIRST BAO.
$wfAk_{\max,\mathrm{eff}}$	WFIRST galaxy broadband to $k < k_{\max,\mathrm{eff}}$ hMpc^{-1} (plus BAO beyond that).

	ω_m	ω_b	θ_s	Σm_ν	$\log_{10}(A)$	n_s
value	0.141	0.0221	0.597	0.0600	−8.66	0.961
P	0.0037	0.00015	0.00035	0.35	0.0039	0.0038
$P + BgB + BlB$	0.00074	0.00015	0.00014	0.10	0.0038	0.0038
$P + BgA0.1 + BlB$	0.00070	0.00013	0.00014	0.068	0.0037	0.0031
$P + BgA0.2 + BlB$	0.00071	0.00012	0.00015	0.046	0.0037	0.0028
$P + DES$	0.0013	0.00013	0.00017	0.041	0.0036	0.0032
$P + BBgA0.1 + BBlB$	0.00044	0.00011	0.00014	0.024	0.0036	0.0024
$P + BBgA0.2 + BBlB$	0.00042	0.00010	0.00014	0.017	0.0035	0.0022
$P + LSST$	0.00080	0.00011	0.00015	0.020	0.0030	0.0029
$P + BBgA0.1 + BBlB + LSST$	0.00042	0.00010	0.00013	0.015	0.0028	0.0021
$P + BBgA0.2 + BBlB + LSST$	0.00041	0.00010	0.00013	0.014	0.0026	0.0020
$P + BB24gA0.2 + BB24lA + l1D + euA0.2 + LSST$	0.00032	$9.5e-05$	0.00013	0.011	0.0024	0.0014

- We should clearly see something by mid 2020s, using three independent(ish) techniques:
  - Planck + redshift-space distortions (DESI)
  - Planck + weak gravitational lensing (LSST)
  - Planck + CMB S4 + BAO

From absorption to emission

HI halo model	
Linear matter power spectrum	$P_m(k,z)$
Halo mass function	$n(M,z)$
Halo bias	$b(M,z)$
HI mass in halos	$M_{HI}(M,z)$
HI density profile in halos	$\rho_{HI}(r\,\vert\,M,z)$

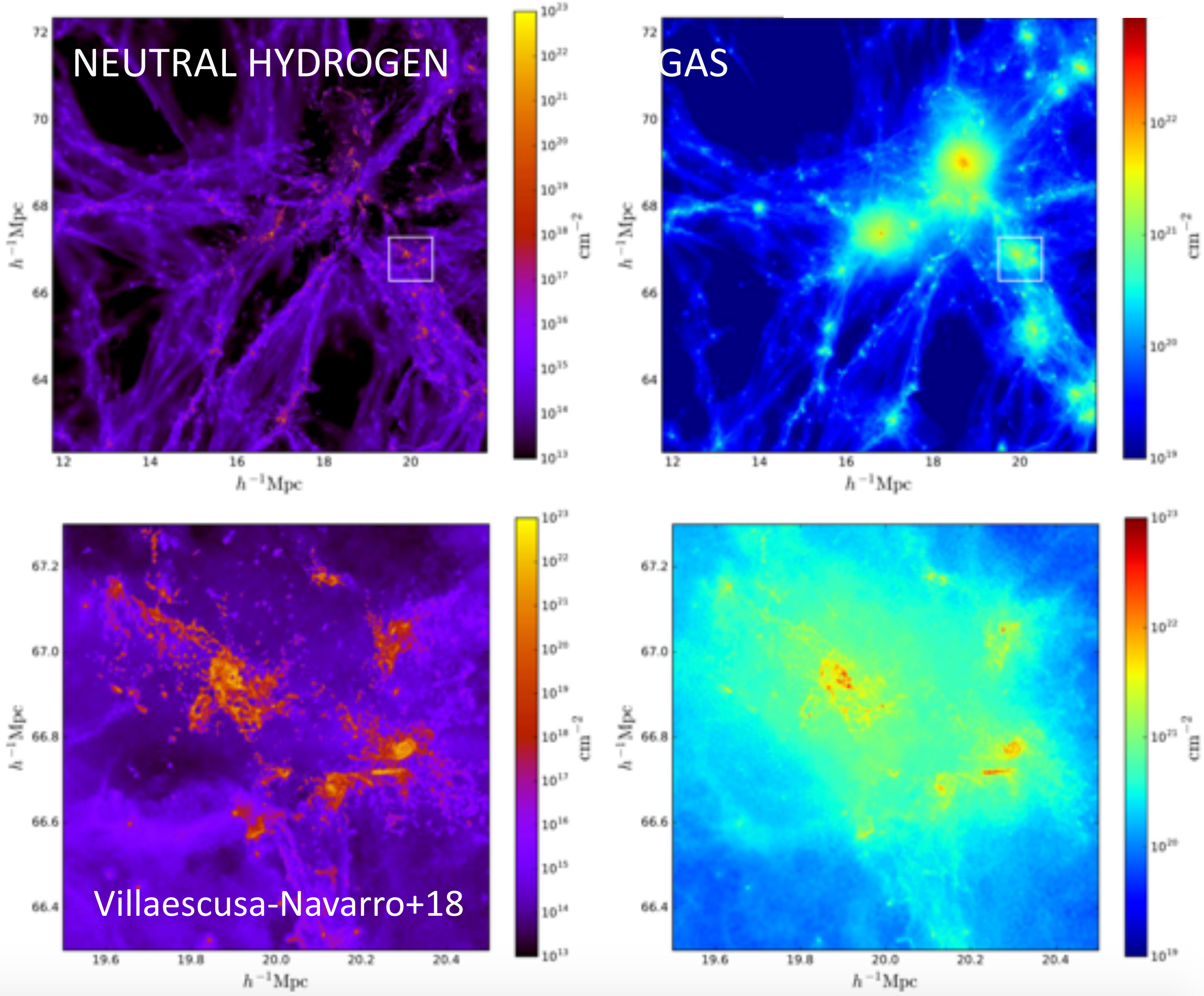


Villaescusa-Navarro, MV+ 2014

Intensity mapping

Linear theory model:

$$P_{21\,\mathrm{cm}}(k,\mu,z) = \bar{T}_b(z)^2[(b_{\mathrm{H\,I}}(z) + f(z)\mu^2)^2 P_{\mathrm{m}}(k,z) + P_{\mathrm{SN}}(z)],$$



$$\bar{T}_b(z) = 189h\left(\frac{H_0(1+z)^2}{H(z)}\right)\Omega_{\mathrm{H\,I}}(z)\ \mathrm{mK},$$

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

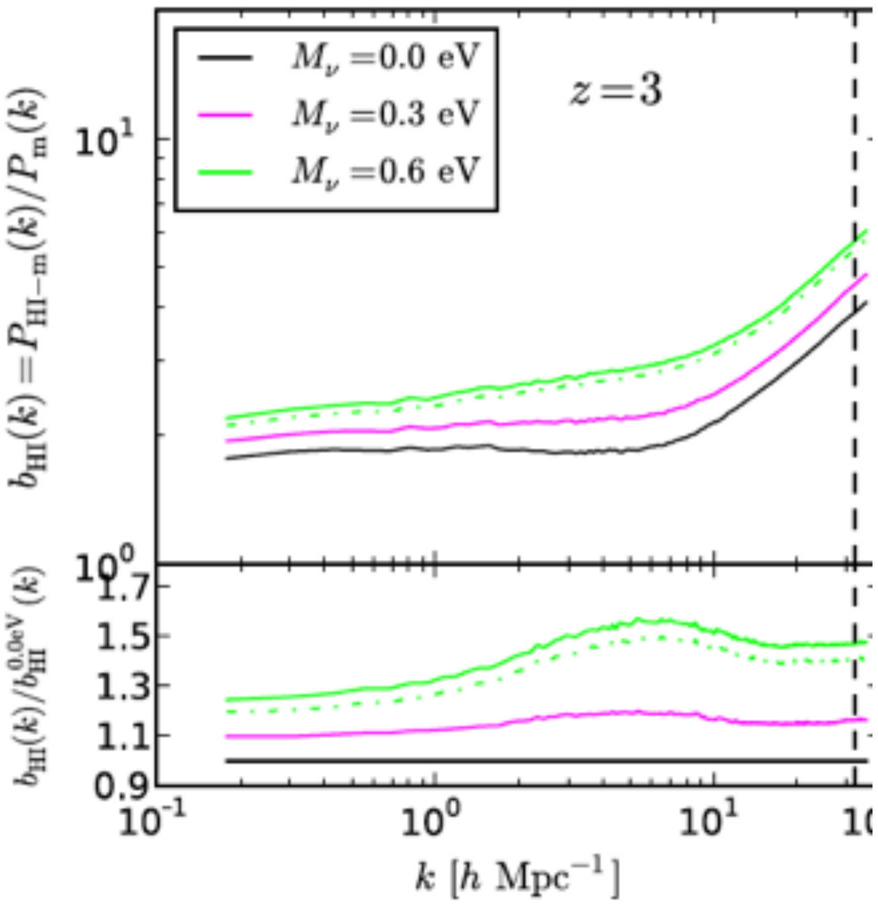
$$b_{\mathrm{H\,I}}(z) = \frac{1}{\rho_c^0\Omega_{\mathrm{H\,I}}(z)}\int_0^\infty n(M,z)b(M,z)M_{\mathrm{H\,I}}(M,z)dM,$$

$$P_{\mathrm{SN}}(z) = \frac{1}{(\rho_c^0\Omega_{\mathrm{H\,I}}(z))^2}\int_0^\infty n(M,z)M_{\mathrm{H\,I}}^2(M,z)dM,$$

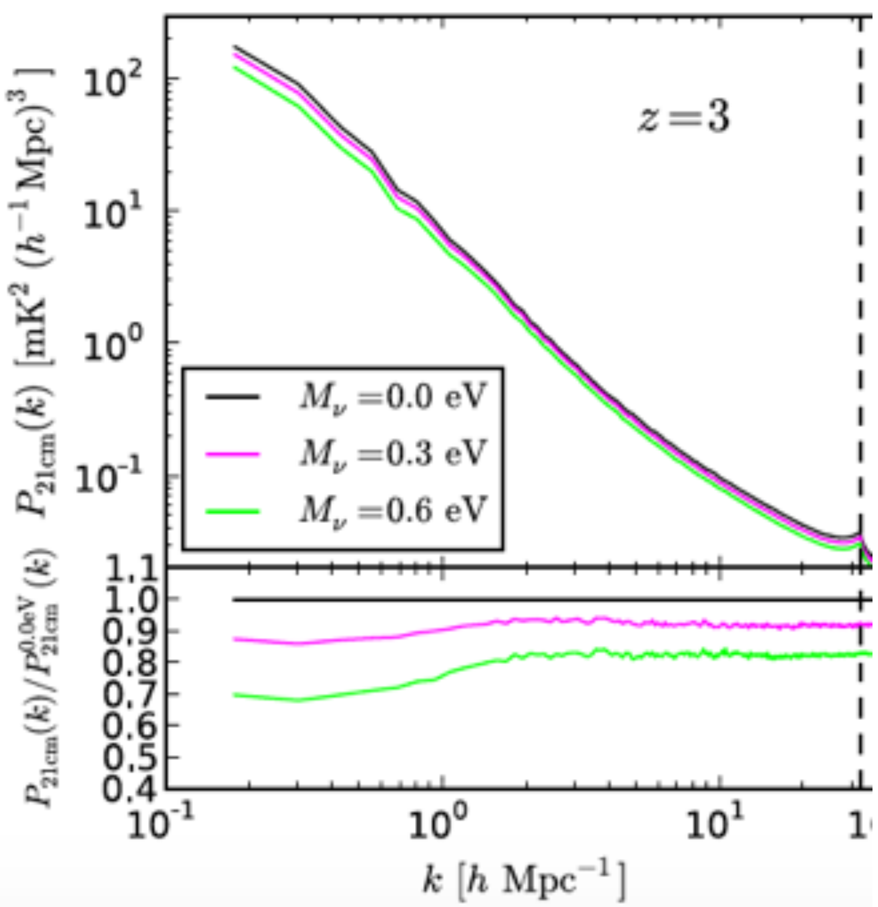
$$\boxed{M_{\mathrm{H\,I}}(M,z) = M_0\left(\frac{M}{M_{\mathrm{min}}}\right)^\alpha \exp(-(M_{\mathrm{min}}/M)^{0.35}).}$$

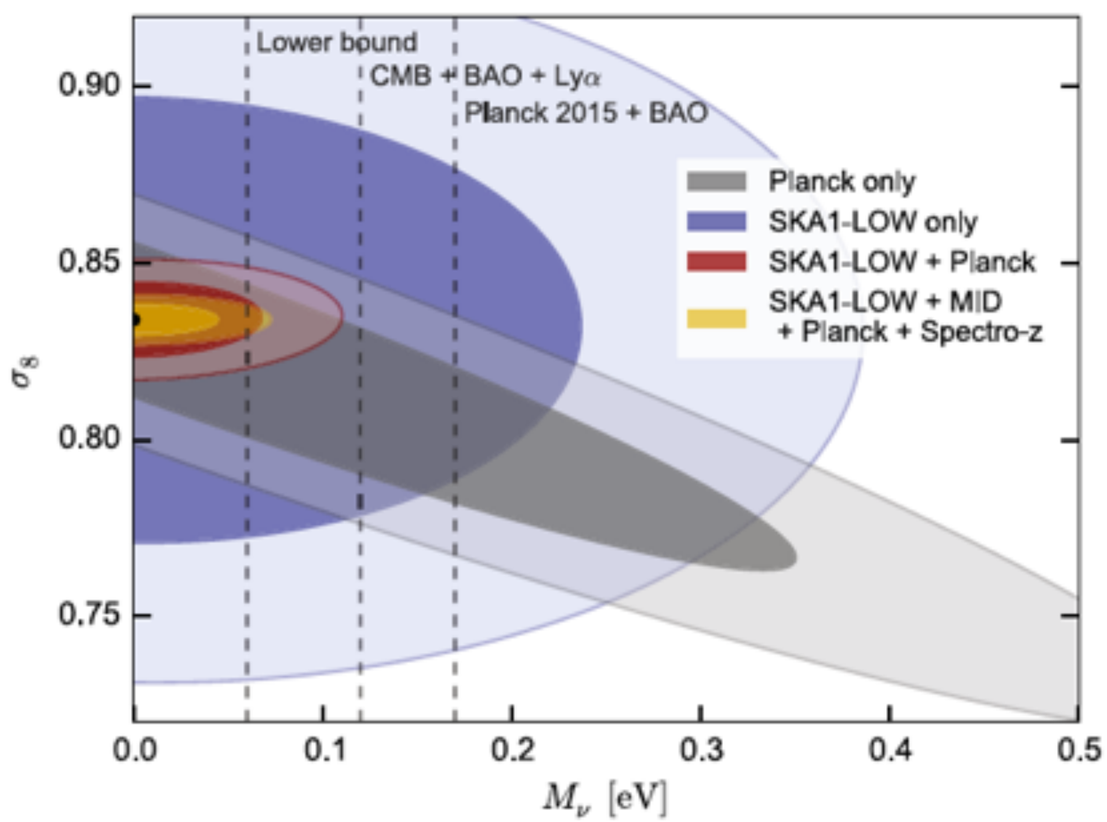
M_{min} decreases with redshift
alpha increases with redshift

Simulating intensity mapping signal: large scales



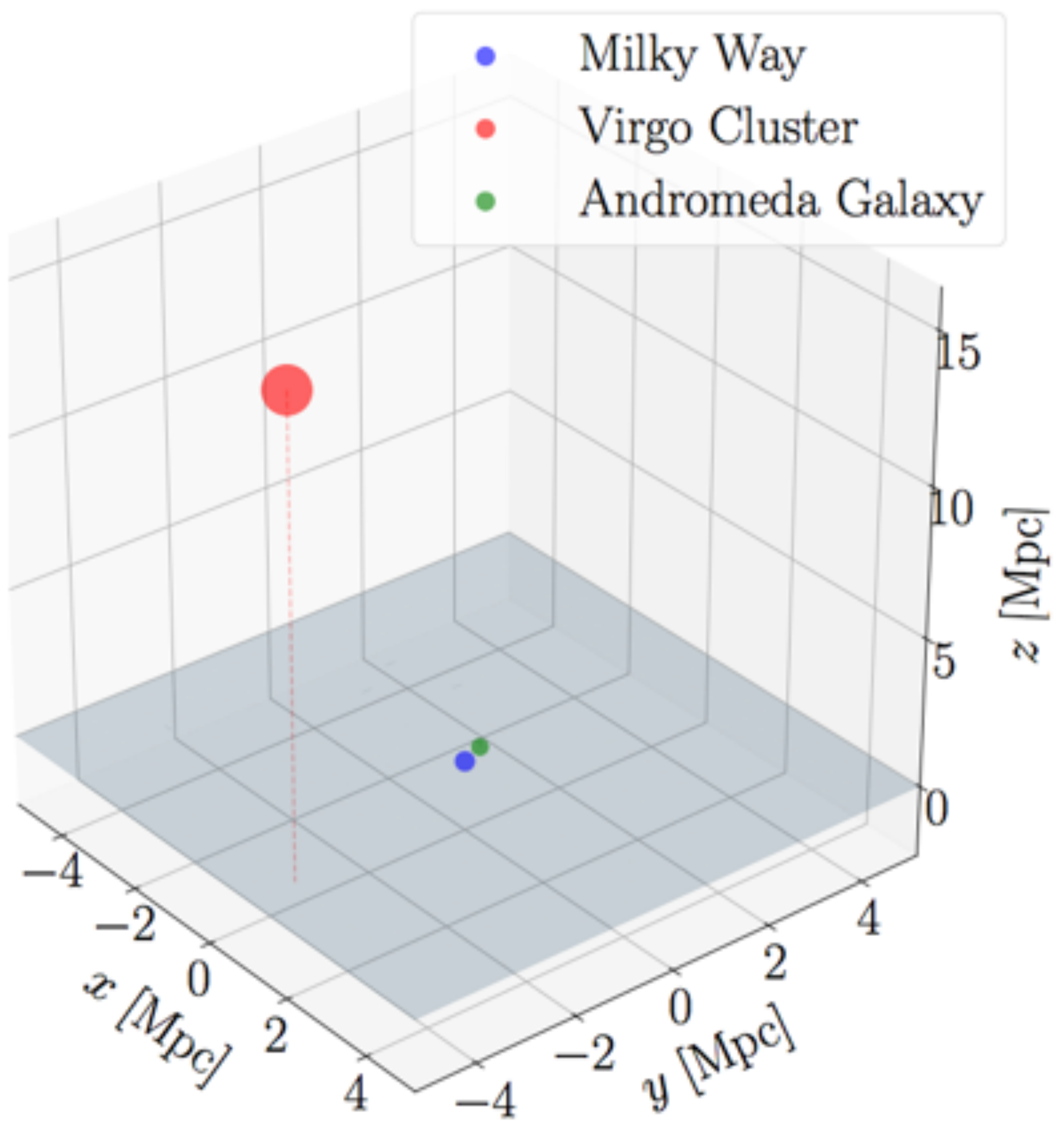
- Scale dependence bias also present in massive neutrino cosmologies.
- M_{HI}(M) not affected by the presence of neutrinos.
- HI is more clustered in massive neutrino sims. (but $Omega_{HI}$ lower) - because small mass haloes are suppressed i.e. impact on n_{HALO}(M).
- IM alone would provide constraint of about sigma(M_nu) = 30 meV (not very constraining compared to other probes).
- Radiative transfer postprocessing important but does not impact much the limit above

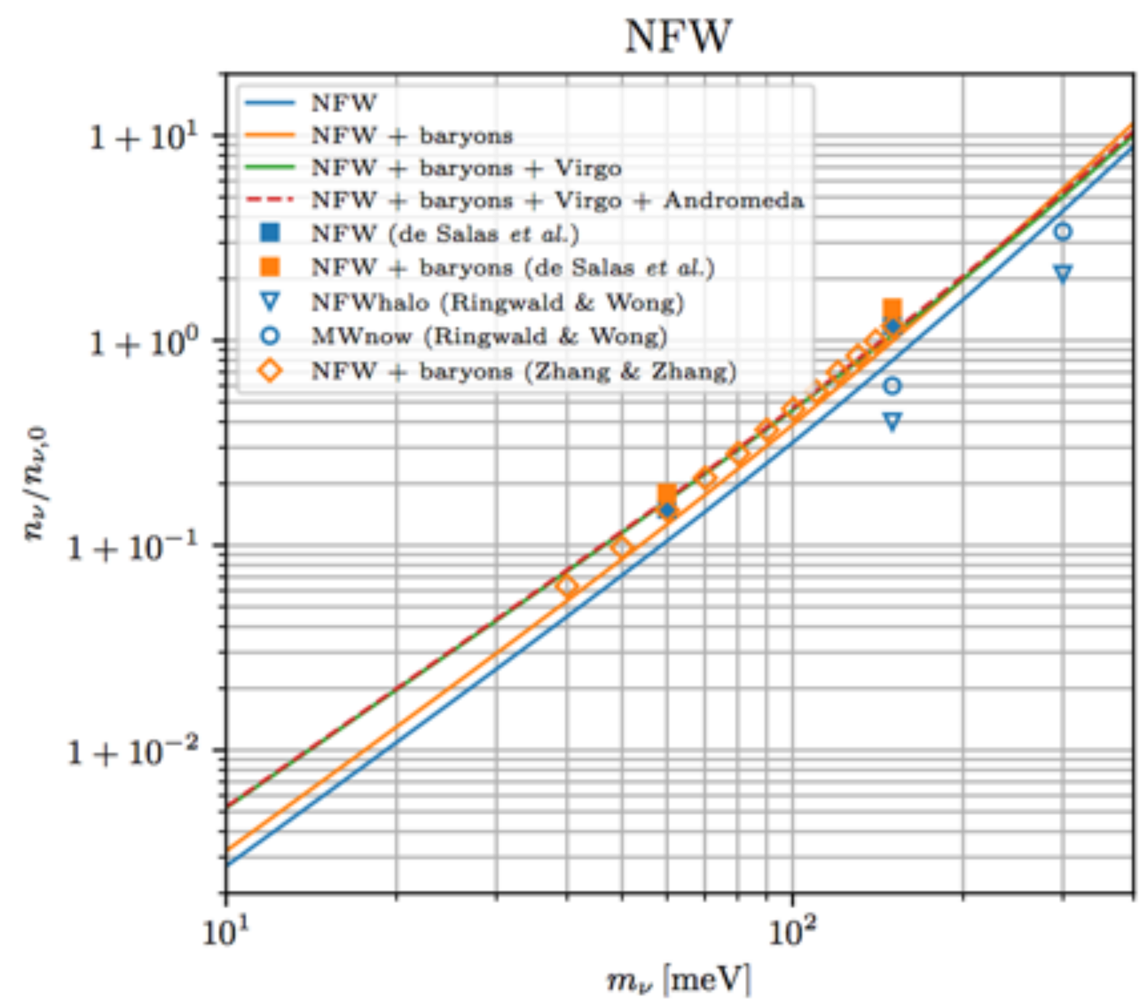




Villaescusa-Navarro, MV, Bull, 2015

Neutrino at Earth's position





Neutrino clustering in the Milky Way and beyond

P. Mertsch,[a] G. Parimbelli,[b,c,d] P.F. de Salas,[e] S. Gariazzo,[f] J. Lesgourgues[a] and S. Pastor[f]

Neutrino at Earth's position

$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$

Neutrino physics with the PTOLEMY project: active neutrino properties and the light sterile case

M.G. Betti,[a,b] M. Biasotti,[c] A. Boscá,[d] F. Calle,[d] N. Canci,[e]
G. Cavoto,[a,b] C. Chang,[f,g] A.G. Cocco,[h] A.P. Colijn,[i,j]
J. Conrad,[k] N. D'Ambrosio,[e] N. De Groot,[i,l] P.F. de Salas,[m]
M. Faverzani,[n] A. Ferella,[k] E. Ferri,[n] P. Garcia-Abia,[o]
I. García-Cortés,[p] G. Garcia Gomez-Tejedor,[q] S. Gariazzo,[r]

2026: scenario nr. 1

So we can come back in 2026 with a mass detection M_ν=0.078 ± 0.019 eV from DESI, Euclid, Lyman-alpha

then what?

Well…

1) measured fundamental property of the Universe
2) triggered laboratory searches in a more motivated regime (provided particle physicists will believe)
3) triggered theoretical models to explain that value

2026: scenario nr. 2

So we can come back in 2026 with a mass detection $M_\nu = 0.6 \pm 0.2$ eV particle physics experiments like Katrin then what?

Well…

1) cosmology wrong?
2) evidence for new physics beyond LCDM

2026: scenario nr.3

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So we can come back in 2026 with some crack in the pillars of SM or LCDM before the measurement of neutrino mass. Suppose H0 tension will survive or evidence of small scale crisis persist or new particles discovered at LHCs

Well…

1) theoretical models/LSS simulationswill have to say whether these extensions could impact on neutrino mass constraints
2) possibly hint for a non-standard neutrino sector (interactions, cross-section, decay..etc.)