Carnegie Mellon University

Neutrino mass bounds from Cosmic Microwave Background and galaxy surveys

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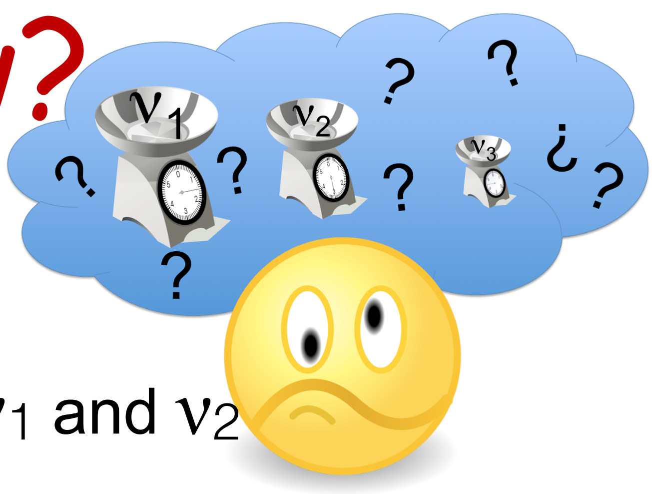
Workshop on CMB polarization, Large-Scale Structure, and 21 cm surveys
Madrid 2016

Outline

- Introduction
- Cosmic neutrino background
- Impact of massive neutrinos on cosmological observables
- Constraints on massive neutrino from cosmology
- Conclusions

Neutrino mass: what do we know?



Oscillation experiments involving solar, atmospheric, reactor and accelerator neutrinos provide information on the squared mass differences:

$$\Delta m^2_{12} = m^2_2 - m^2_1 \simeq 7.5 \times 10^{-5} \mathrm{eV}^2 \longrightarrow$$ splitting between ν_1 and ν_2

$$| \Delta m^2_{3i} | = m^2_3 - \frac{m^2_1 + m^2_2}{2} \simeq 2.45 \times 10^{-3} \mathrm{eV}^2 \xrightarrow[i \,=\, 1\ (2)]{}$$ distance between ν_3 and the mid-point of ν_1 and ν_2 masses

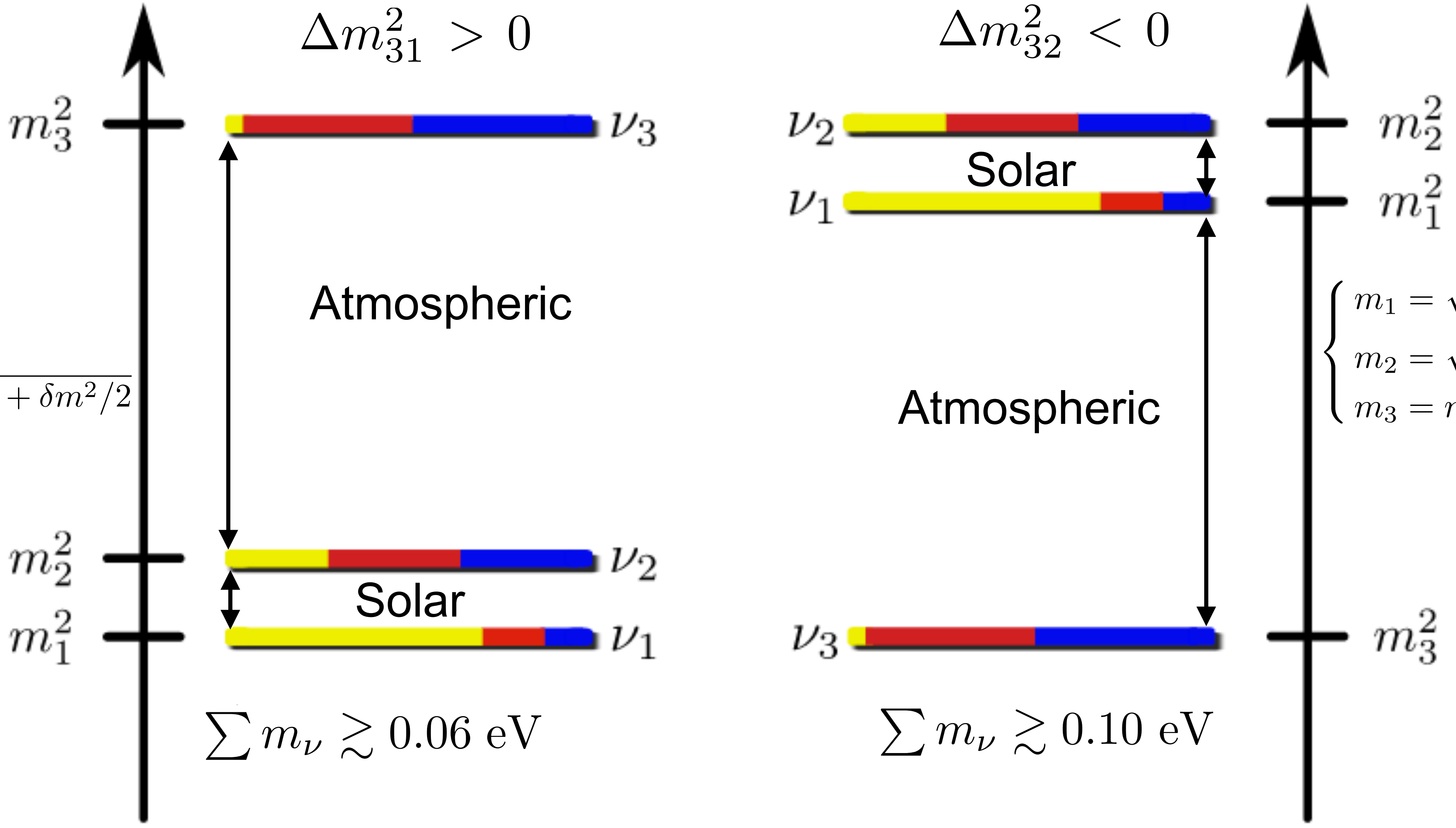
Gonzales-Garcia et al., JHEP 2014

Normal Hierarchy

$$\Delta m^2_{31} > 0$$

Inverted Hierarchy

$$\Delta m^2_{32} < 0$$



$$\begin{cases} m_1 = m \\ m_2 = \sqrt{m^2 + \delta m^2} \\ m_3 = \sqrt{m^2 + \Delta m^2 + \delta m^2/2} \end{cases}$$

$$\begin{cases} m_1 = \sqrt{m^2 + \Delta m^2 - \delta m^2/2} \\ m_2 = \sqrt{m^2 + \Delta m^2 + \delta m^2/2} \\ m_3 = m. \end{cases}$$

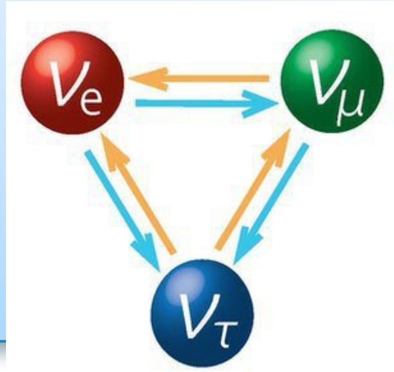
$$\sum m_\nu \gtrsim 0.06 \text{ eV}$$

$$\sum m_\nu \gtrsim 0.10 \text{ eV}$$

Neutrino Mass Measurements

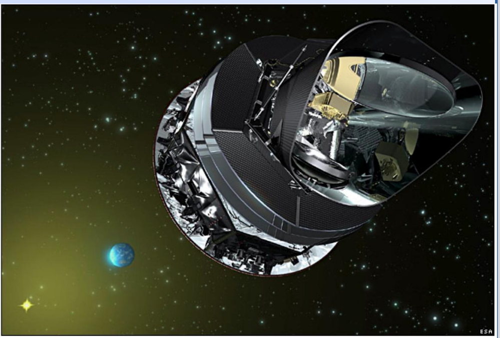
Neutrino Oscillations

- Sensitive to the mass differences
- Uses quantum mechanical effects
- Sources: Solar, atmospheric reactor



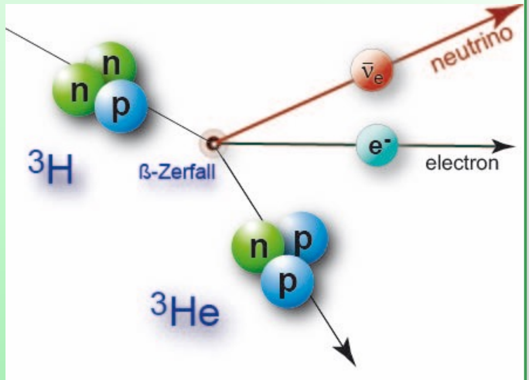
Cosmology

- Sensitive to the total neutrino mass
- Uses General Relativity
- Measured by satellites and ground-based observatories



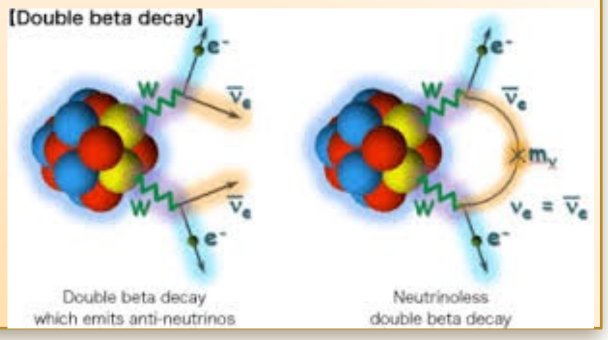
Single Beta Decay

- Sensitive to the absolute neutrino mass scale
- Uses conservation of energy
- Model independent

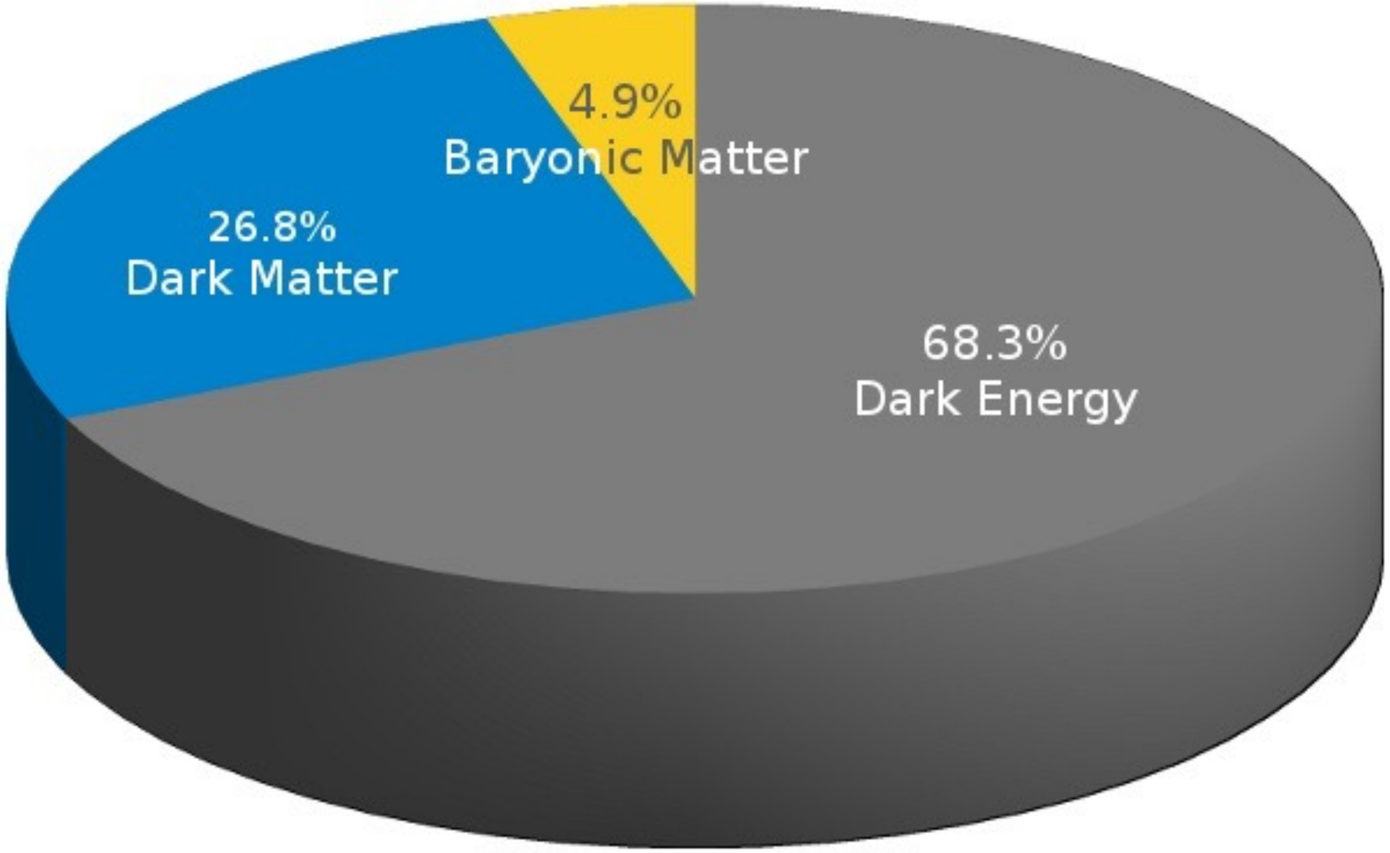


0ν Double Beta Decay

- Sensitive to the Majorana masses
- Uses decay
- Probes the nature of neutrinos



Cosmic Pies



Planck 2015

"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T SEE THEM."

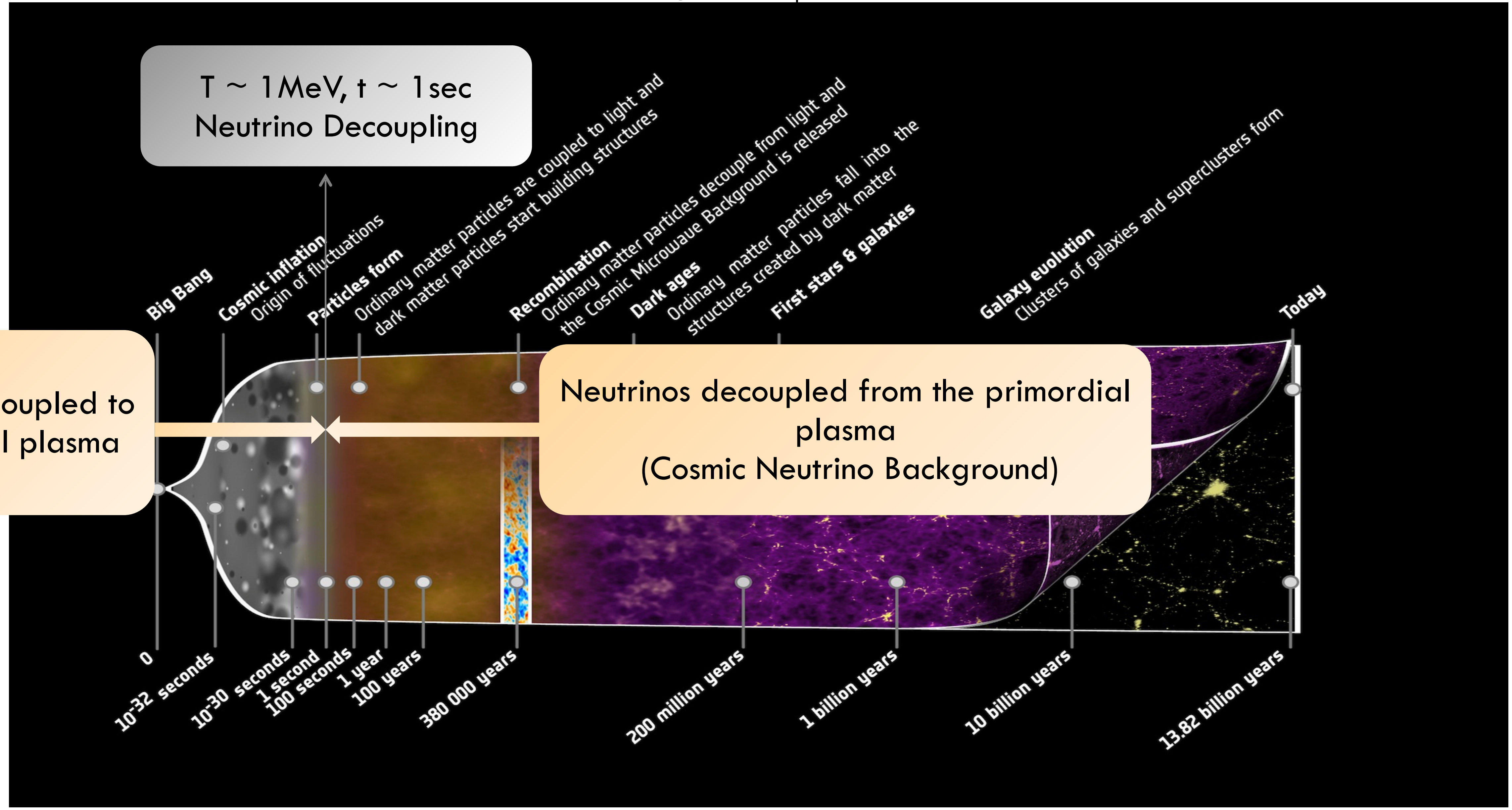
DARK MATTER → HDM + CDM

Neutrinos

Cosmic Neutrinos

- In the standard cosmological model, cosmic neutrinos are produced at high temperature in the early Universe by frequent weak interactions and they are maintained in thermal equilibrium with the e.m. plasma.
- Neutrinos decouple at T ~ 1MeV ($n_\nu \sigma_\nu v \approx H$), keeping a Fermi-Dirac Distribution:

$$f_\nu(p) = \frac{1}{e^{p/T} + 1}$$



T ~ 1MeV, t ~ 1sec
Neutrino Decoupling

Neutrinos coupled to primordial plasma

Neutrinos decoupled from the primordial plasma
(Cosmic Neutrino Background)

Cosmic Neutrinos

- $T_\gamma \sim m_e$, $e^+ e^-$ annihilation heats the photons but not the decoupled neutrinos:

Temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \to \; T_{\nu,0} = 1.945\mathrm{K} \sim 1.676 \times 10^{-4}\mathrm{eV}$$

Number density:

$$n_\nu = \left(\frac{3}{11}\right) n_\gamma \to \; n_{\nu,0} \approx 113\mathrm{cm}^{-3}$$

Energy density:

$$\rho_\nu = \begin{cases} \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_\gamma^3 \\ m_\nu n_\nu \end{cases}$$

Relativistic $m_\nu << T_\nu$

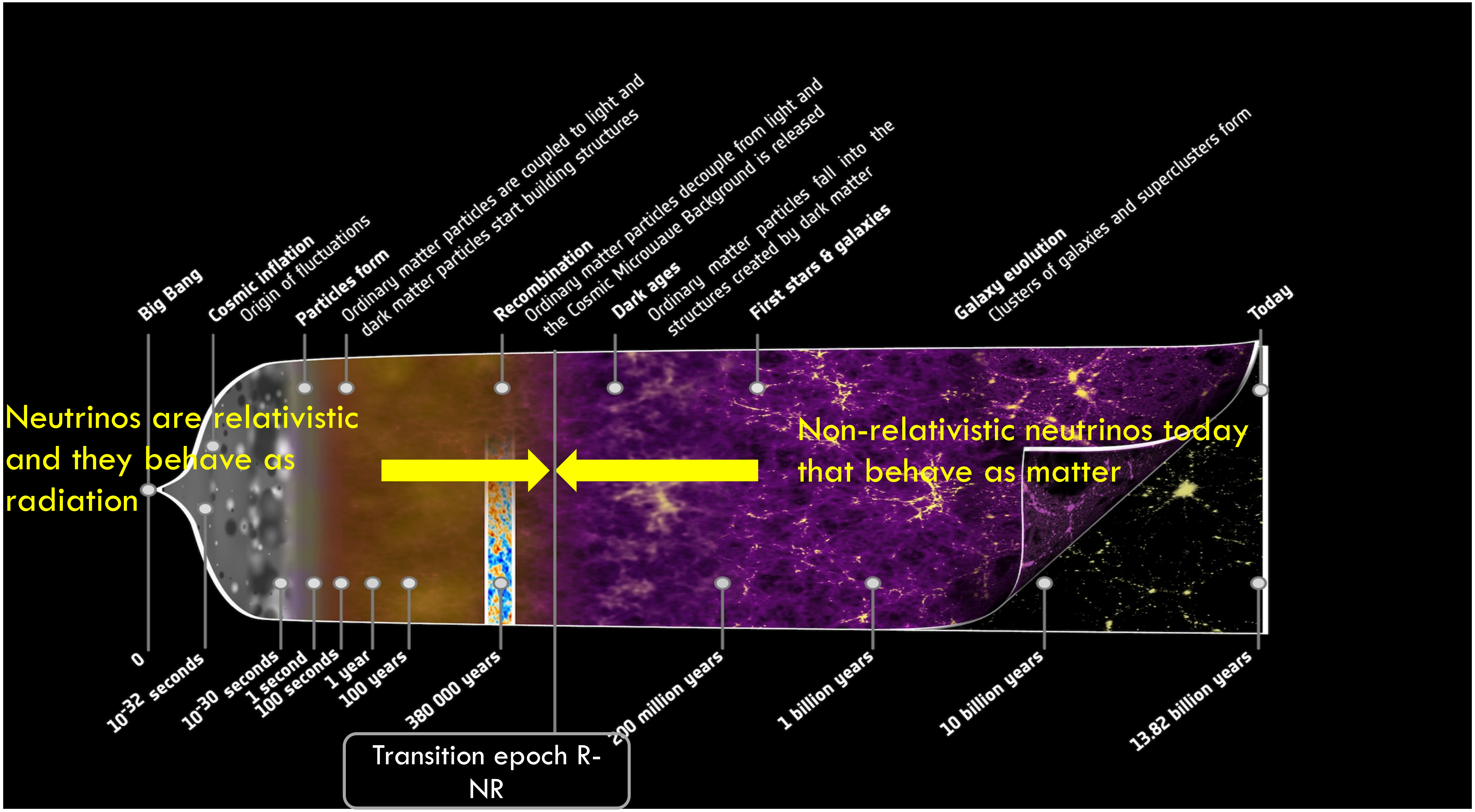
Non-relativistic $m_\nu >> T_\nu$

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

Neutrino energy density parameter

Cosmic Neutrinos

- Neutrinos behave as radiation at early times and as matter at late times.



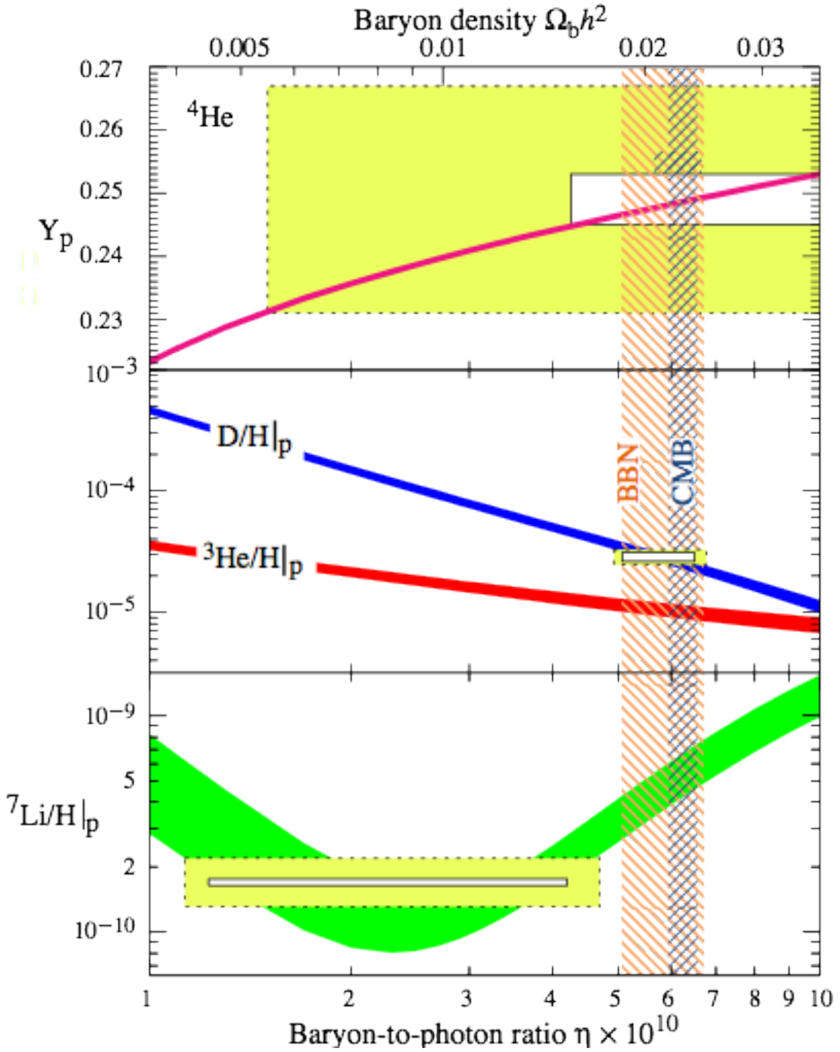
Neutrinos are relativistic and they behave as radiation

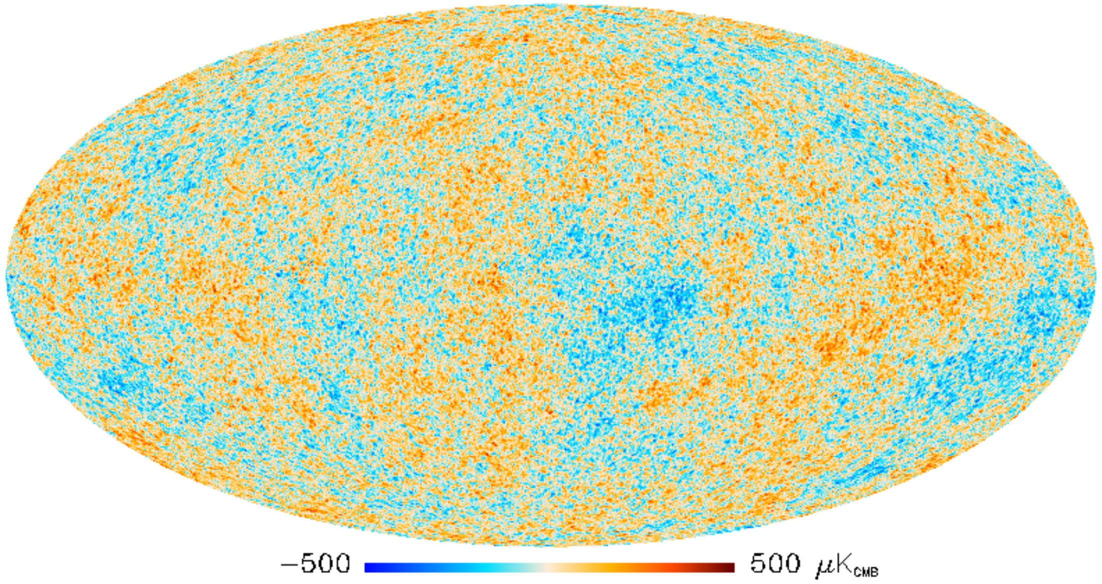
Non-relativistic neutrinos today that behave as matter

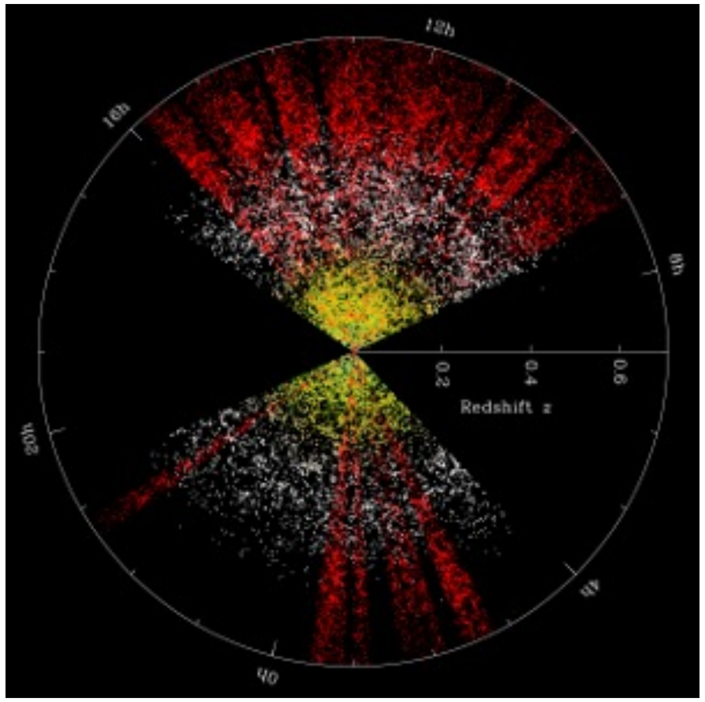
Transition epoch R-NR

Cosmological Observations

Relic neutrinos are very abundant and they influence several cosmological observables.







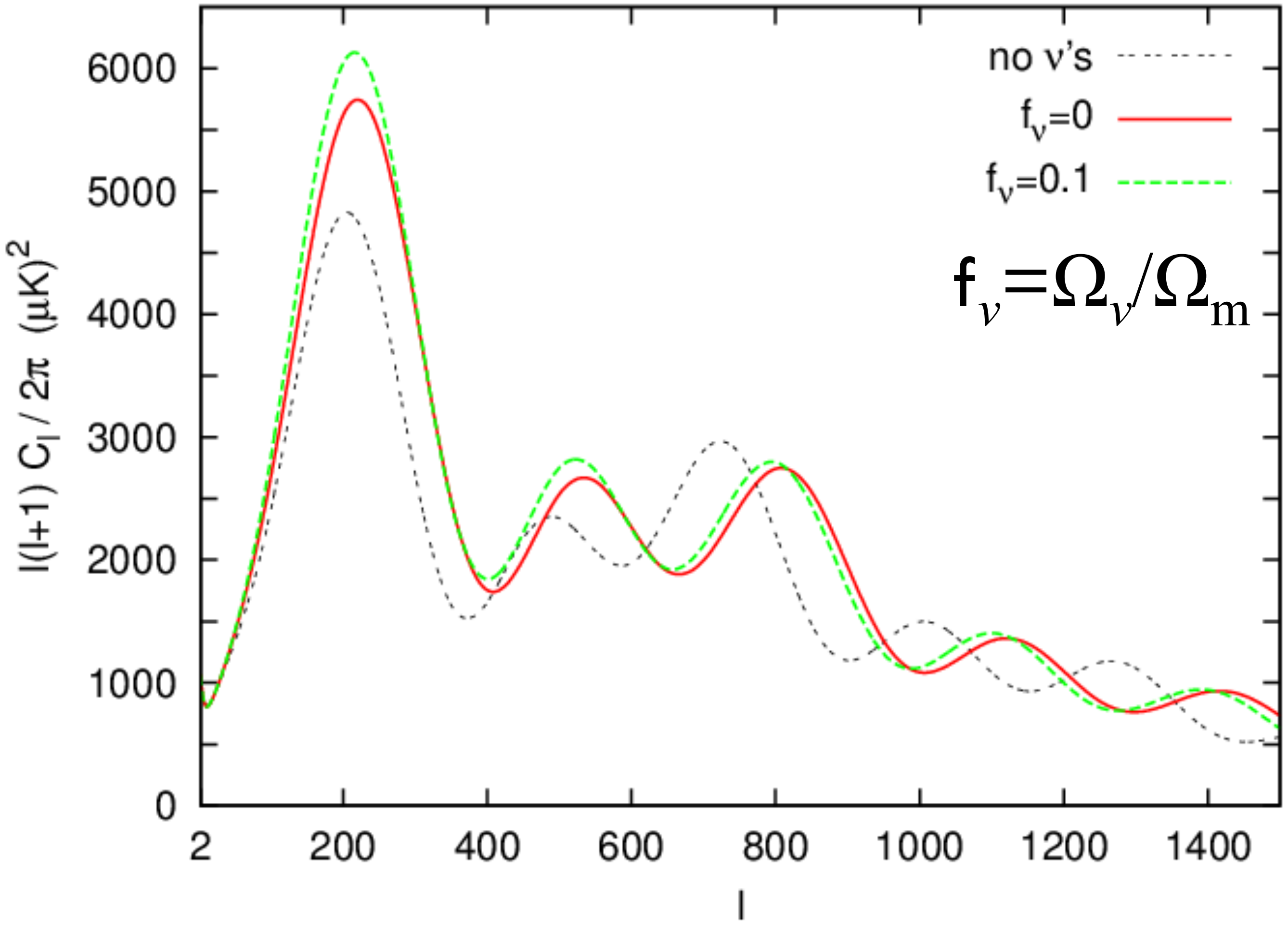
Big Bang Nucleosynthesis (BBN)

Cosmic Microwave Background (CMB)

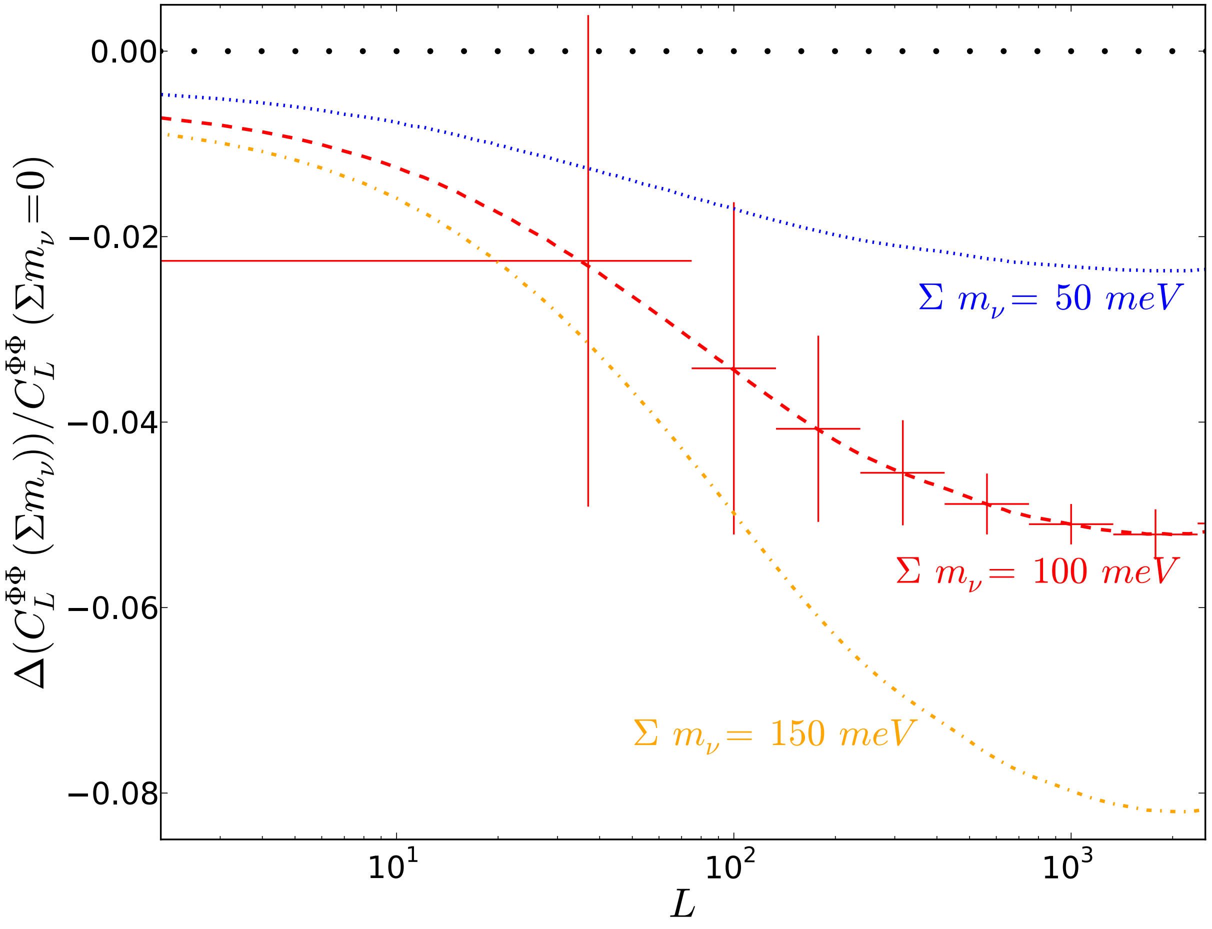
Large Scale Structure (LSS)

Sub-eV massive neutrinos cosmological signatures

- CMB: a) *Early Integrated Sachs Wolfe effect.* The transition from the relativistic to the non relativistic neutrino regime affect the decay of the gravitational potentials at decoupling period (especially near the first acoustic peak).
  b) Suppression of lensing potential. An increase of the neutrino mass suppresses clustering on scales smaller than the size of the horizon at the time of the non-relativistic transition, suppressing the lensing potential.



Lesgourgues, Pastor, Phys.Rept.,2006

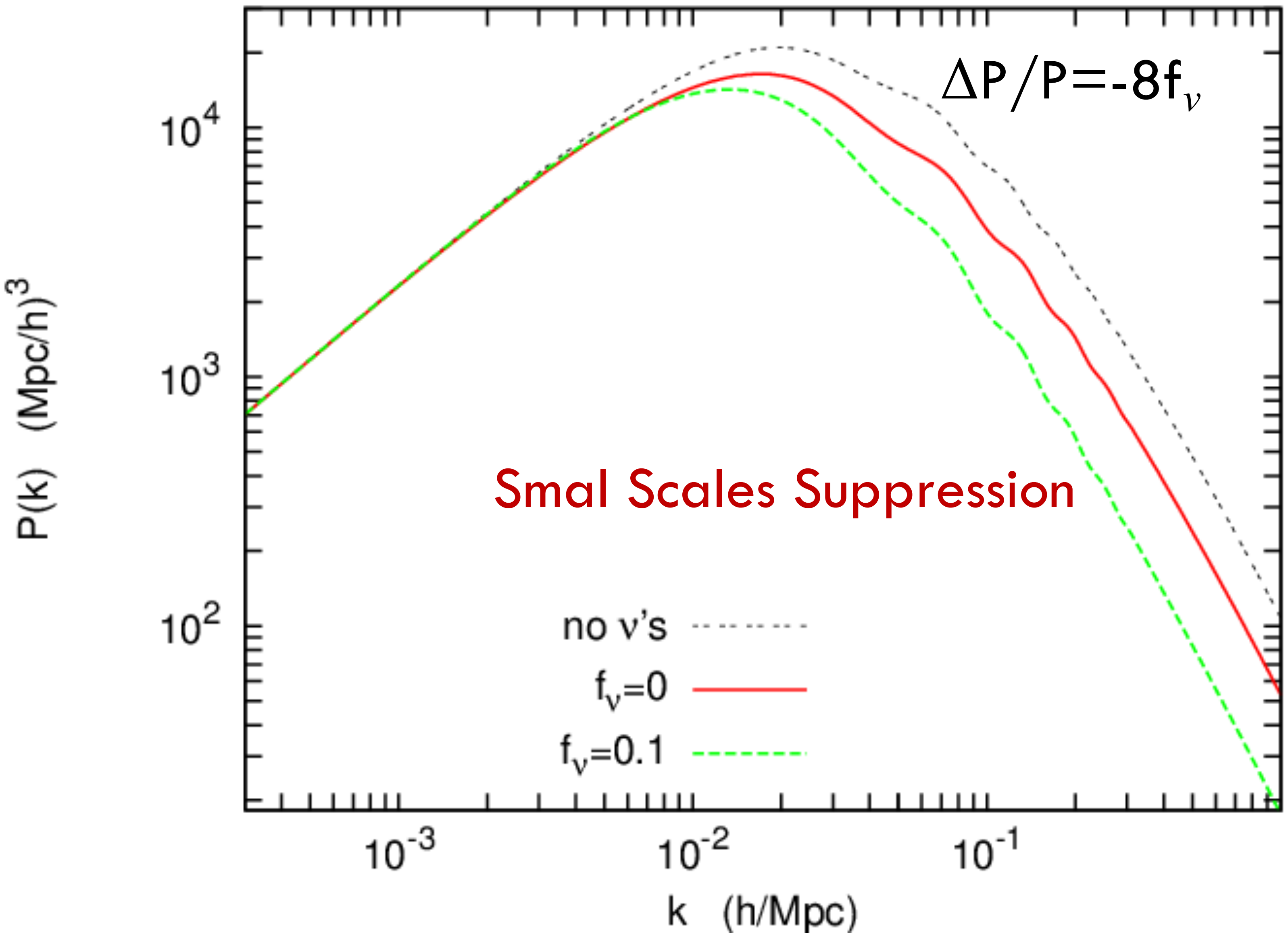


Abazajian et al., Astropart. Phys.,2015

Sub-eV massive neutrinos cosmological signatures

- LSS: Suppression of structure formation on scales smaller than the free streaming scale when neutrinos turn non relativistic, affecting also the Baryon acoustic oscillation (BAO) scale which are the imprint on the matter distribution of the pressure-gravity competition in the baryon-photon fluid.

$$k_{fs,\nu}(z) \simeq 0.7 \left(\frac{m_\nu}{1eV}\right) \sqrt{\frac{\Omega_M}{1+z}} \ \mathbf{h\ Mpc}^{-1}$$



$\Delta P/P=-8f_\nu$

Smal Scales Suppression

- Large scales ($k<k_{fs}$)

Neutrinos cluster and behave as cold dark matter:

$$\delta_\nu = \delta\rho/\rho = \delta_{cdm} \approx a$$

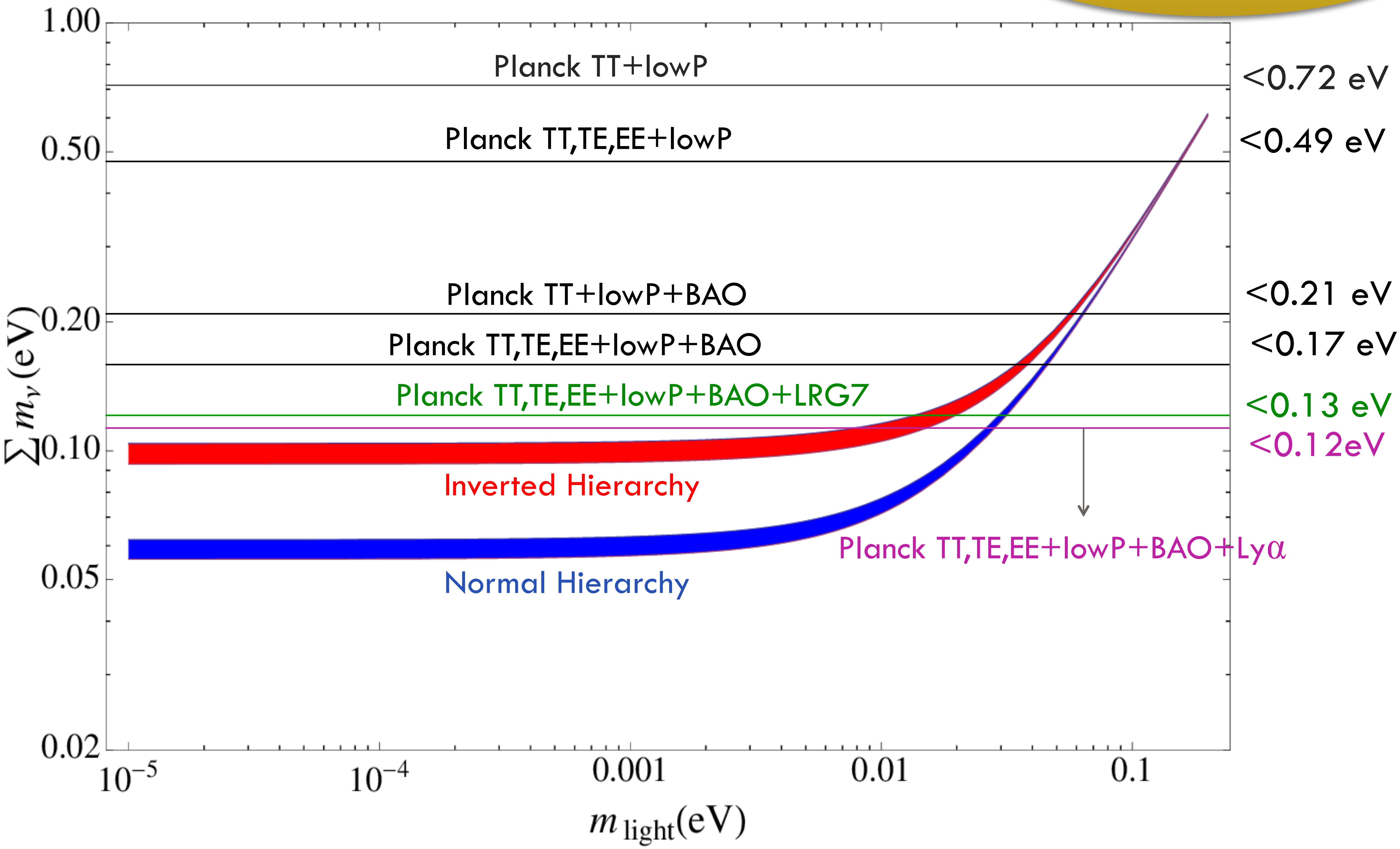
- Small scales ($k>k_{fs}$)

Perturbations can not grow due to the large neutrino velocity dispersion. Matter power spectrum is suppressed.

Lesgourgues, Pastor, Phys.Rept.'06

2016 state on neutrino mass 95% CL bounds

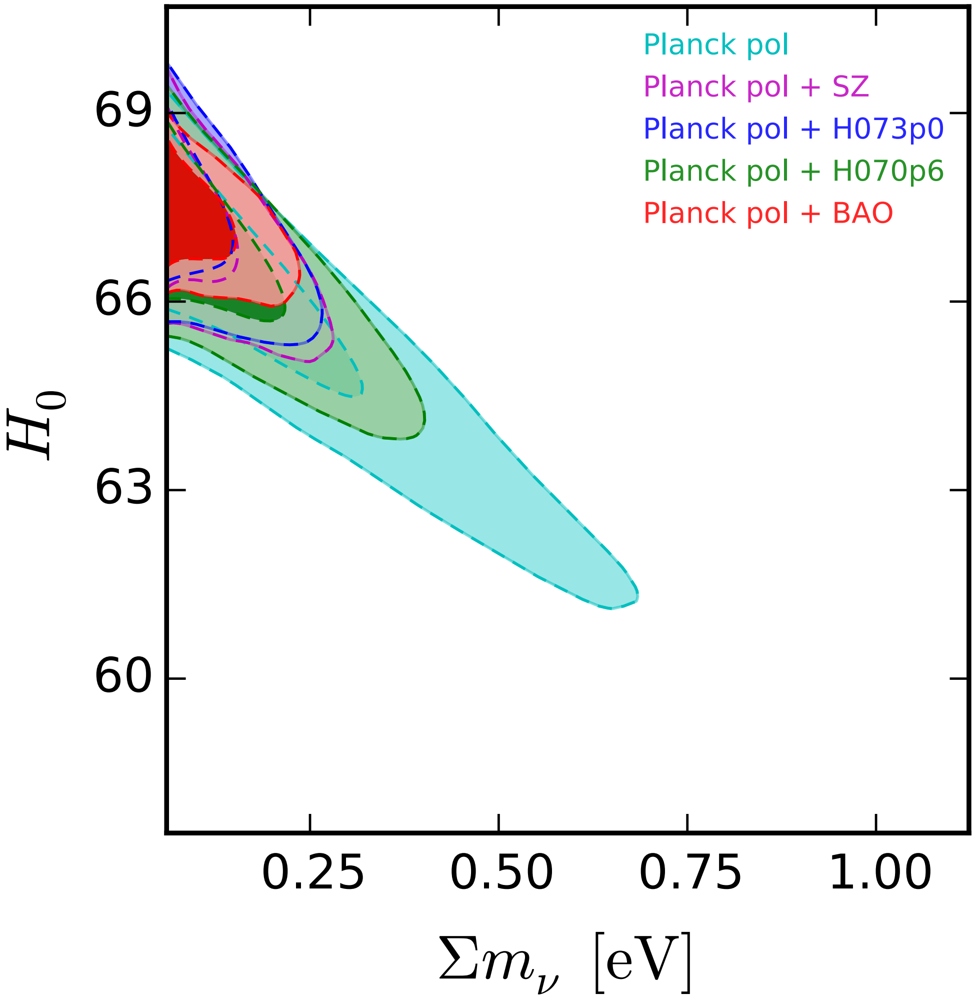
three degenerate massive neutrinos



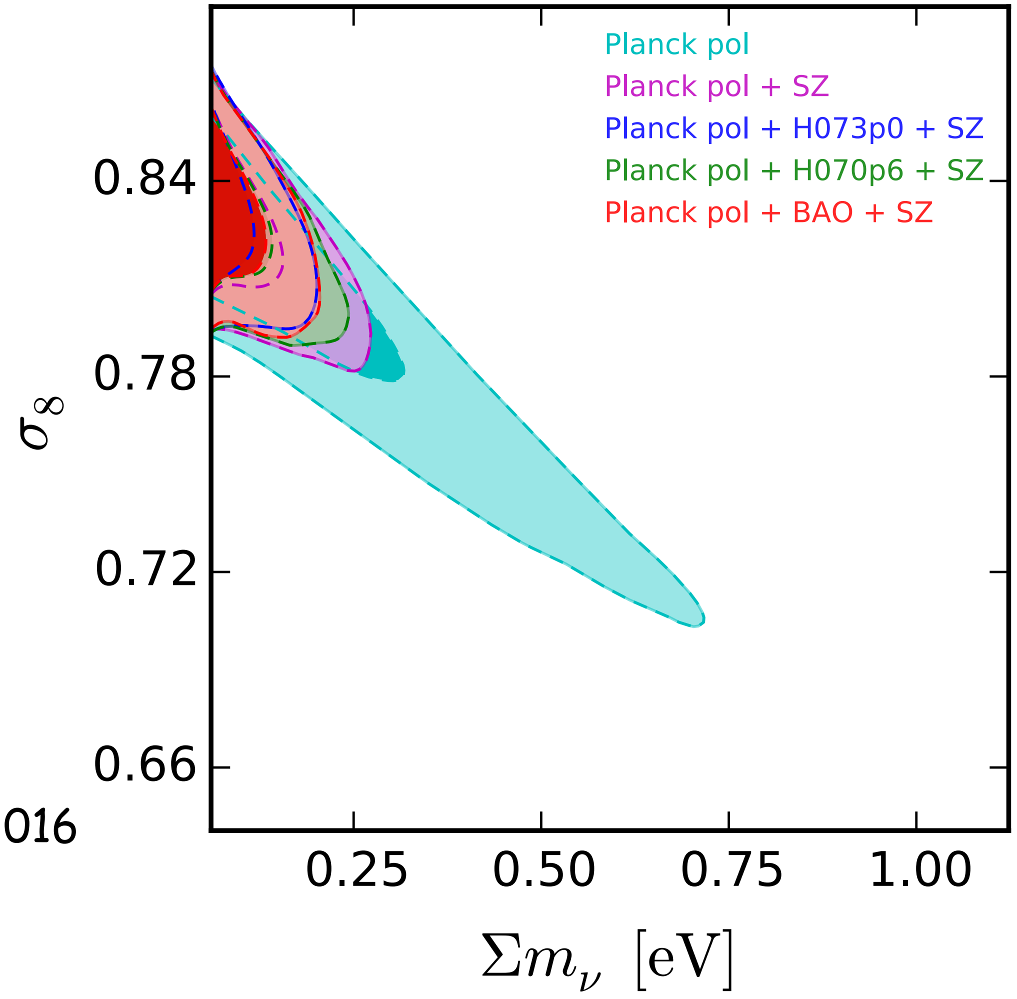
Planck Collaboration 2015, arXiv:1502.01582 A. J. Cuesta et al., Phys. Dark. Univ., 2016 Palanque-Delabrouille et al, JCAP 2015

2016 state on neutrino mass 95% CL bounds

Implications of a low-redshift priors for massive neutrinos



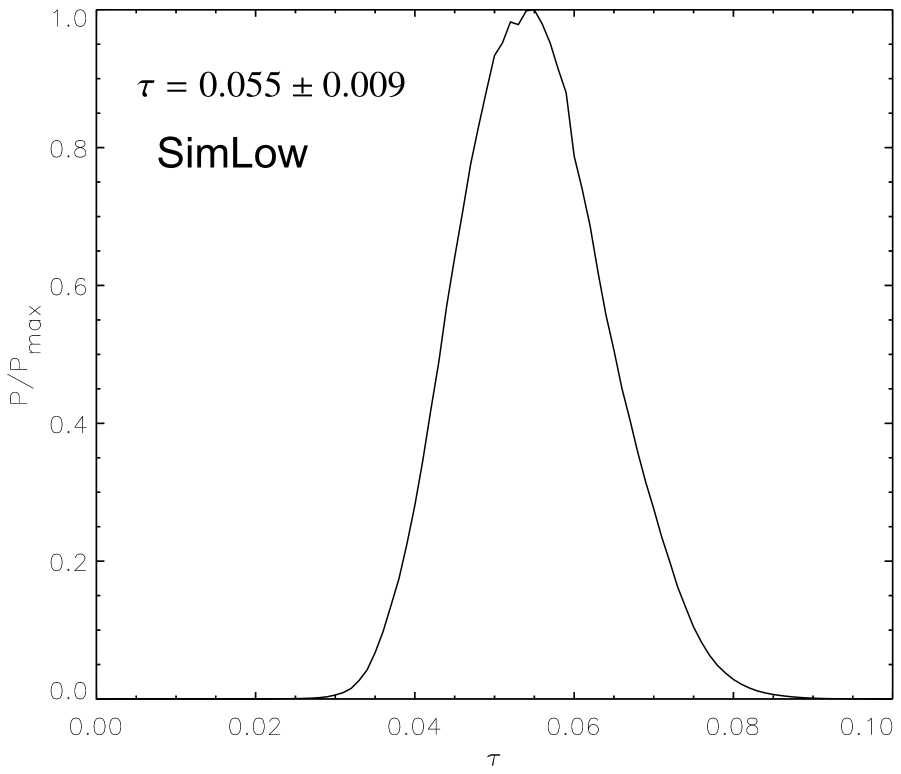
	Planckpol+ H70p6	Planck pol+ H73p0	Planck pol+ BAO+SZ	Planck pol+ BAO+SZ+H73p0
$\sum m_\nu[eV]$	< 0.291	< 0.180	< 0.147	< 0.126



Di Valentino, EG, et al., Phys. Rev. D, 2016

2016 state on neutrino mass 95% CL bounds

Implications of a lower value of τ for massive neutrinos



Planck Collaboration 2016, arXiv:1605.02985

$\Sigma m_\nu < 0.59$ eV PlanckTT+SimLow
$\Sigma m_\nu < 0.34$ eV PlanckTT,TE,EE+SimLow
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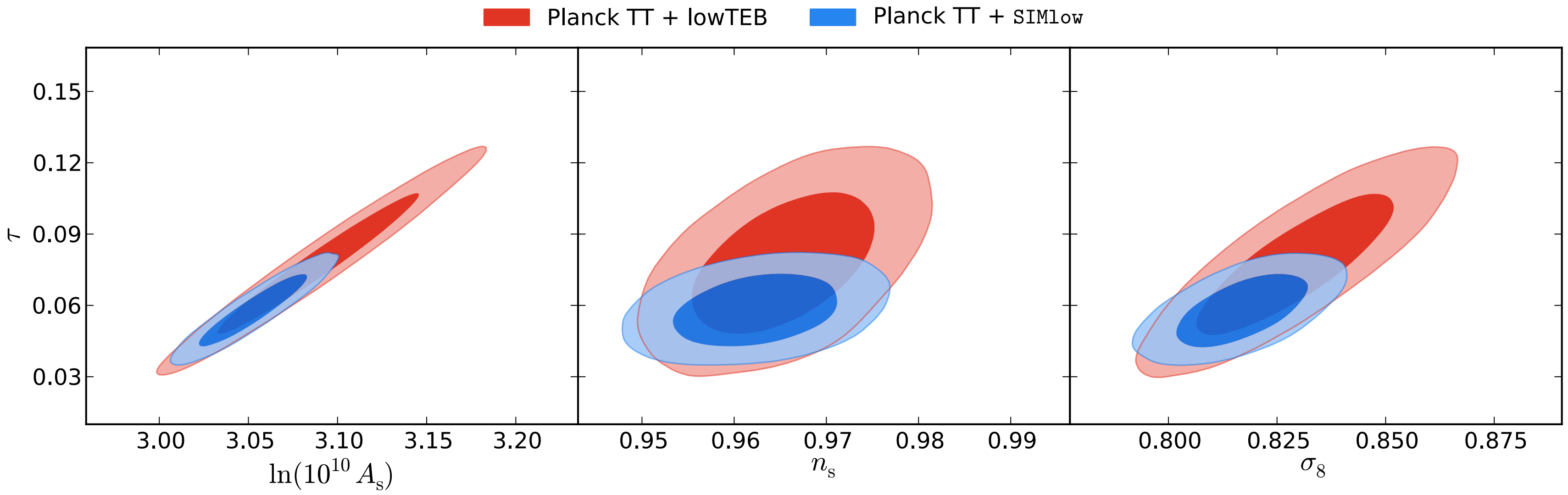

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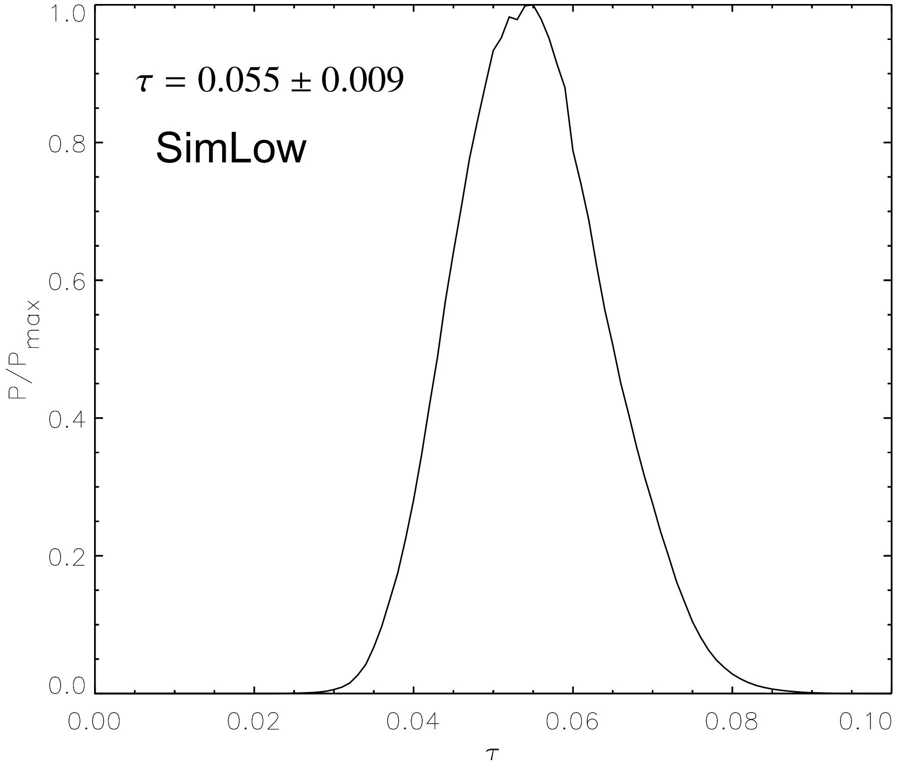

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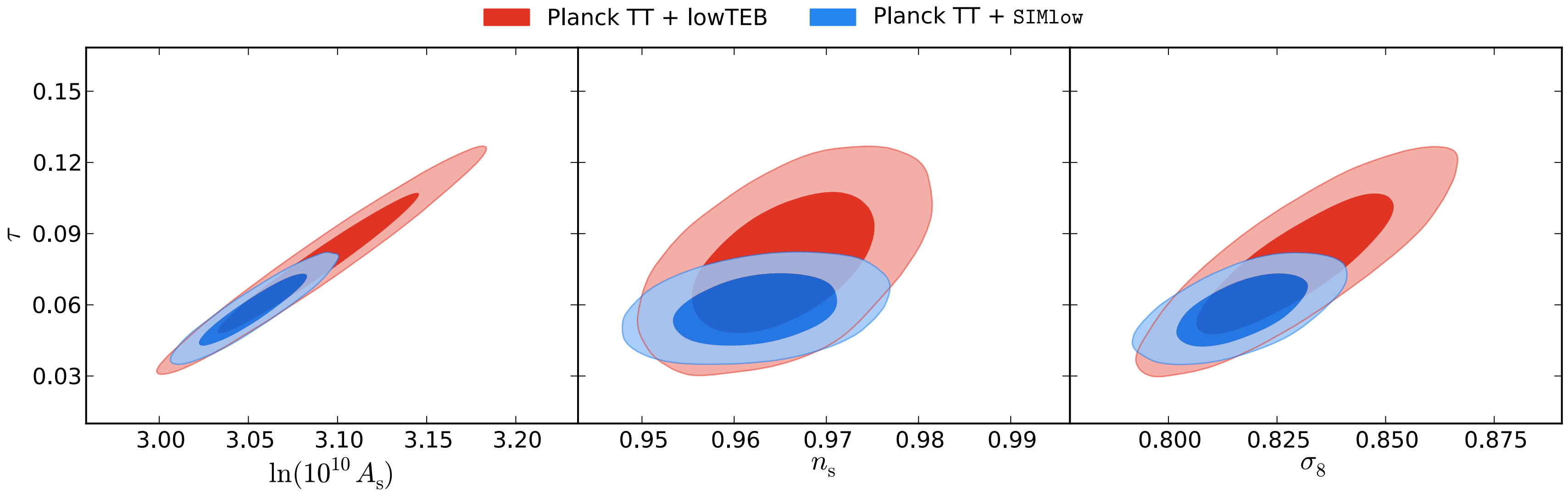
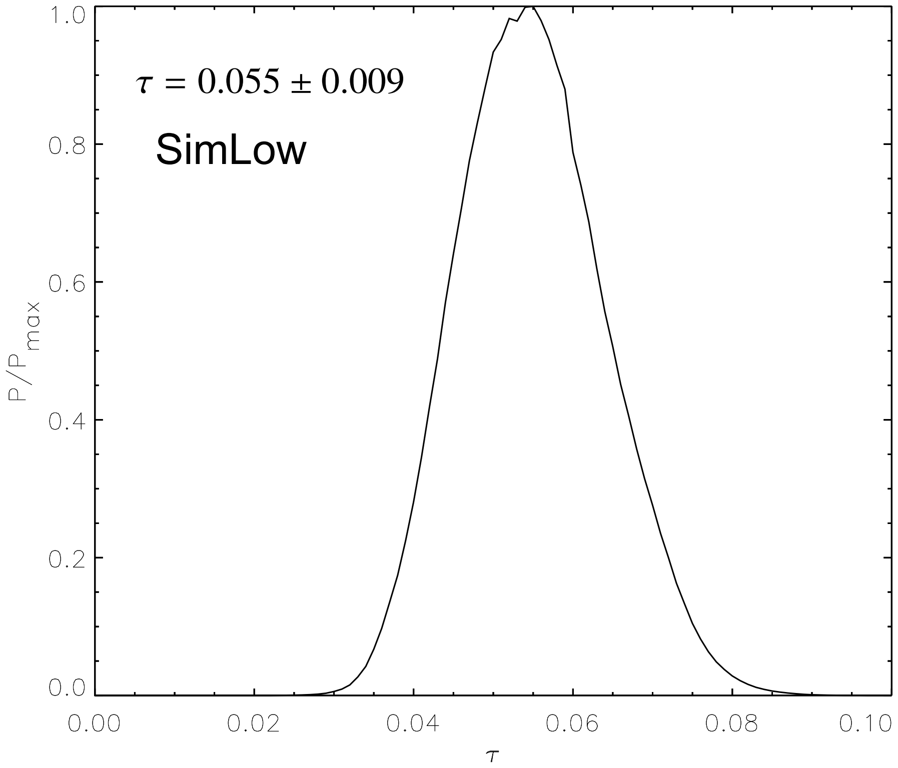


All these bounds are obtained considering three massive degenerate state!

2016 state on neutrino mass 95% CL bounds

Implications of a lower value of τ for massive neutrinos



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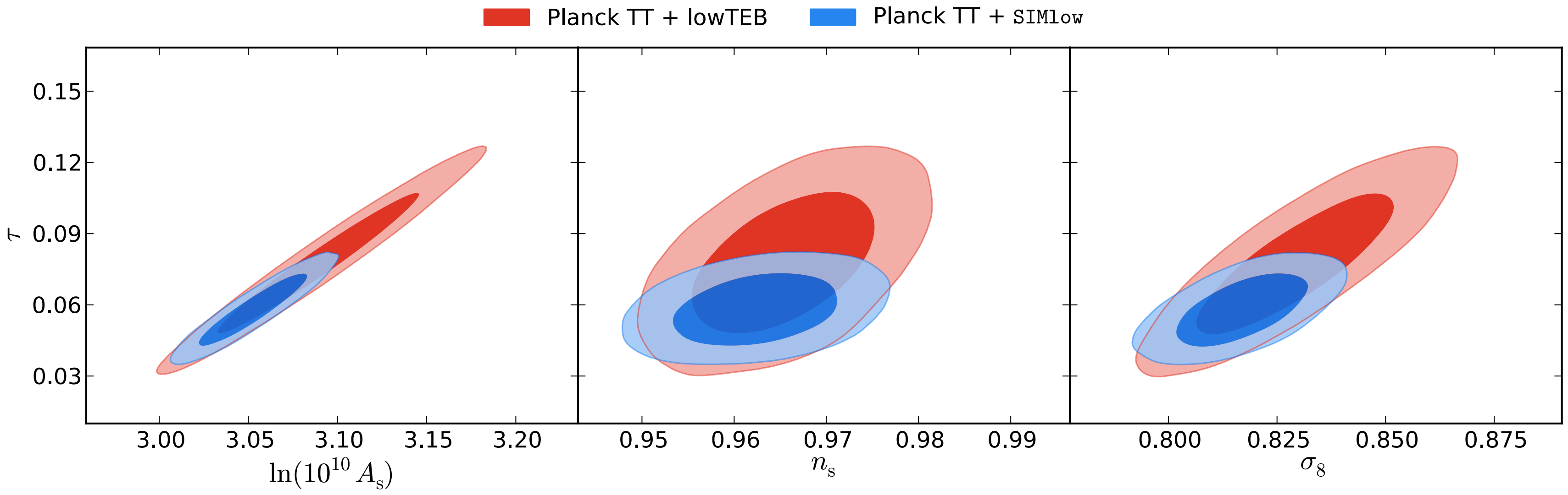

All these bounds are obtained considering three massive degenerate state!

How cosmological data are sensitive to the neutrino mass distribution? How the total mass is distributed among the massive eigenstates?

Cosmological datasets

✓ CMB:

- Planck 2015 temperature and polarization measurements. We combine the large angular scale temperature and polarization measured by Planck LFI experiment with the small-scale TT temperature spectrum measured by Planck HFI (here denoted as *Planck TT*).
- We also add to this combination the small-scale TE and EE polarization spectra measured by Planck HFI (denoted as *Planck pol*).

Planck Collaboration 2015, arXiv:1502.01582

✓ BOSS (Baryon Oscillation Spectroscopic Survey, SDSS III)

- Data Release 9 (3D galaxy power spectrum shape).

Ahn et al., APJ 2012 [SDSS Collaboration]

Cosmological datasets

✓ Hubble constant measurements:

- ○ Observations of Cepheids variable from the Hubble Space Telescope, H_0=73.02 ± 1.79 km/s/Mpc, (denoted as *H073p02*).

  Riess et al., arXiv:1604.01424

- ○ Recent reanalysis of Efstathiou consisting of a lower estimate H_0=70.6± 3.3 km/s/Mpc, and a higher estimate, H_0=72.5± 2.5 km/s/Mpc,(denoted as *H070p6* and *H072p5*). Efstathiou, Mon. Not. Roy. Astron. Soc. 2014

✓ BAO geometrical information:

- ○ WiggleZ Dark Energy Survey, at z=0.44, 0.60 and 0.73.

  Blake et al., Mon. Not. Roy. Astron. Soc. 2011

- ○ 6-degree Field Galaxy Survey, at z=0.106.

  Beutler et al., Mon. Not. Roy. Astron. Soc. 2011

- ○ BOSS Data Release 11 LowZ sample, at z=0.32.

  Anderson et al. [BOSS Collaboration], Mon. Not. Roy. Astron. Soc. 2014

Clustering modelling

DR9 CMASS sample of galaxy with redshift $0.43 < z < 0.7$ with a mean redshift of 0.57:

- We consider an extra free parameter S to take account of systematic effects that affect the measured power spectrum, $P_{\rm meas}(k)$:

$$P_{\rm meas}(k) \; = \; P_{\rm meas,w}(k) - S[P_{\rm meas,nw}(k) - P_{\rm meas,w}(k)]$$

measured power spectrum after account for systematic uncertainties

the measured power spectrum without systematic effects

Clustering modelling

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measured power spectrum after account for systematic uncertainties

the measured power spectrum without systematic effects

- Theoretical model for galaxy power spectrum:

$$P^{g}_{\rm th}(k,z) = b^2_{\rm HF} P^{\rm m}_{{\rm HF}\nu}(k;z) + P^{\rm s}_{\rm HF},$$

scale independent bias

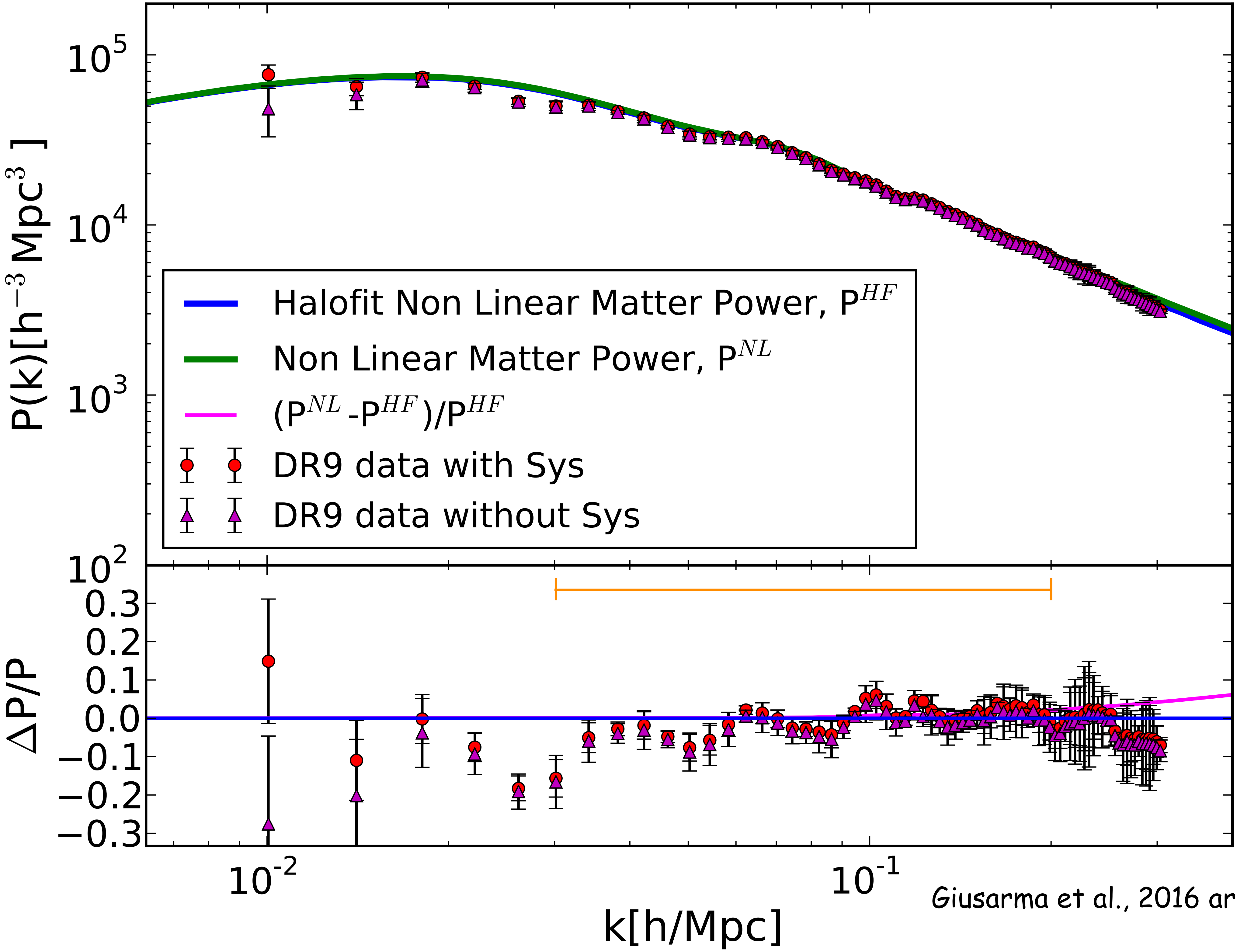
model matter power spectrum computed using the Halofit prescription in presence of massive neutrinos

shot noise

S. Bird et al., Mon. Not. Roy. Astron. Soc. 2012

Clustering modelling

0.03<k<0.2 h/Mpc



Giusarma et al., 2016 arXiv:1605.04320

Analysis Method

ΛCDM model described by six parameters, plus the sum of neutrino masses, $\{\Omega_b, \Omega_c, \theta, \tau, A_S, n_s, \Sigma m_\nu\}$. We consider three different scenarios:

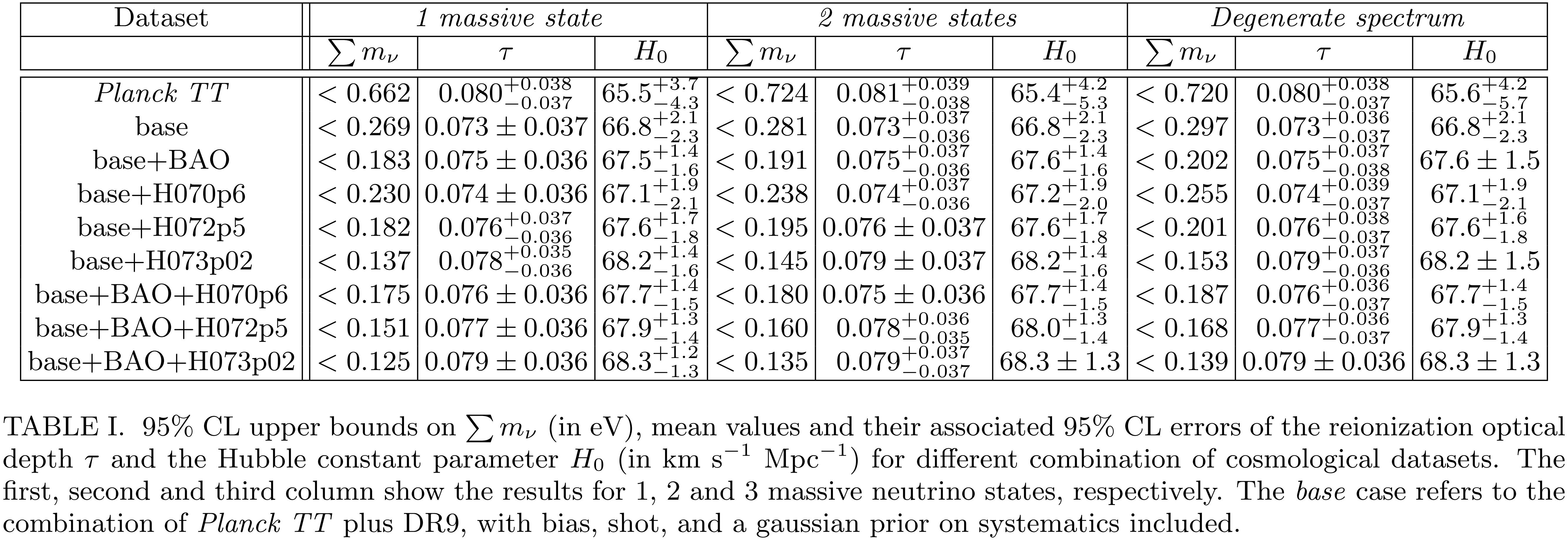
- ✓ 1 massive + 2 massless neutrino states,
- ✓ 2 massive + 1 massless neutrino states,
- ✓ 3 degenerate massive neutrino states.

Our *Base* dataset is the combination of *Planck TT+DR9* data.
We refer to the combination of *Planck pol*+DR9 as *Basepol.*

We derive our cosmological constraints using the Monte Carlo Markov Chain package, **COSMOMC**.

Results

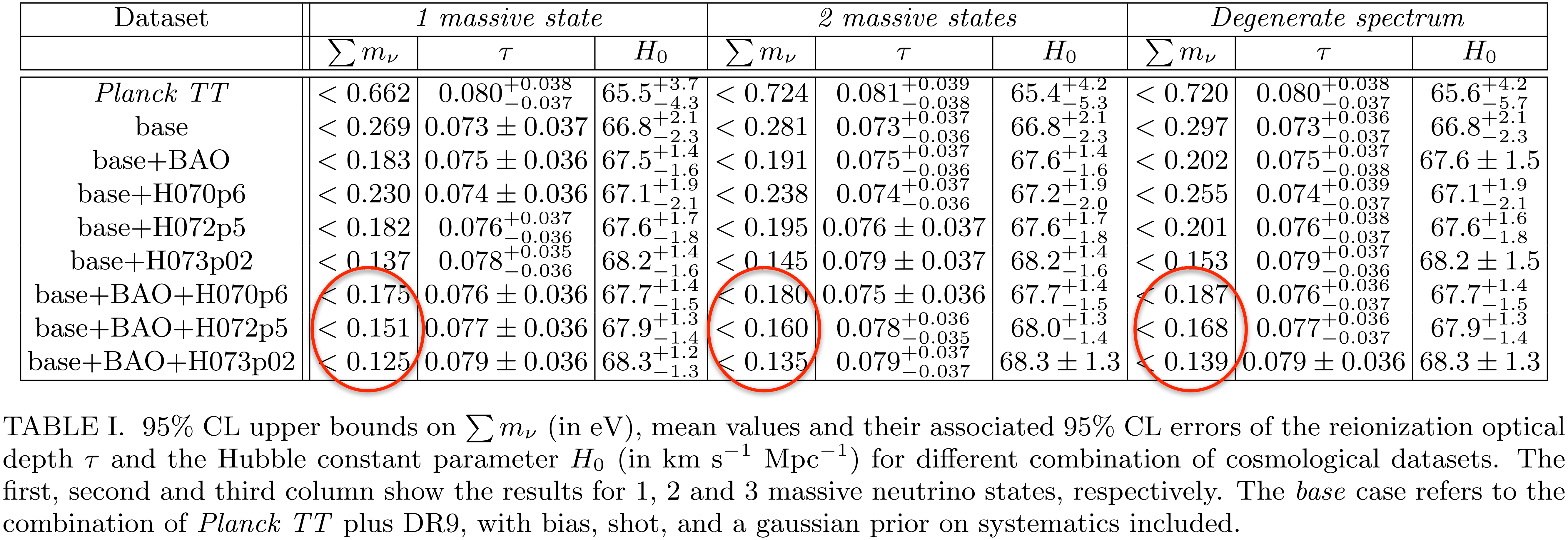
Giusarma et al., 2016 arXiv:1605.04320



Dataset	*1 massive state*			*2 massive states*			*Degenerate spectrum*		
	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0
Planck TT	< 0.662	$0.080^{+0.038}_{-0.037}$	$65.5^{+3.7}_{-4.3}$	< 0.724	$0.081^{+0.039}_{-0.038}$	$65.4^{+4.2}_{-5.3}$	< 0.720	$0.080^{+0.038}_{-0.037}$	$65.6^{+4.2}_{-5.7}$
base	< 0.269	0.073 ± 0.037	$66.8^{+2.1}_{-2.3}$	< 0.281	$0.073^{+0.037}_{-0.036}$	$66.8^{+2.1}_{-2.3}$	< 0.297	$0.073^{+0.036}_{-0.037}$	$66.8^{+2.1}_{-2.3}$
base+BAO	< 0.183	0.075 ± 0.036	$67.5^{+1.4}_{-1.6}$	< 0.191	$0.075^{+0.037}_{-0.036}$	$67.6^{+1.4}_{-1.6}$	< 0.202	$0.075^{+0.037}_{-0.038}$	67.6 ± 1.5
base+H070p6	< 0.230	0.074 ± 0.036	$67.1^{+1.9}_{-2.1}$	< 0.238	$0.074^{+0.037}_{-0.036}$	$67.2^{+1.9}_{-2.0}$	< 0.255	$0.074^{+0.039}_{-0.037}$	$67.1^{+1.9}_{-2.1}$
base+H072p5	< 0.182	$0.076^{+0.037}_{-0.036}$	$67.6^{+1.7}_{-1.8}$	< 0.195	0.076 ± 0.037	$67.6^{+1.7}_{-1.8}$	< 0.201	$0.076^{+0.038}_{-0.037}$	$67.6^{+1.6}_{-1.8}$
base+H073p02	< 0.137	$0.078^{+0.035}_{-0.036}$	$68.2^{+1.4}_{-1.6}$	< 0.145	0.079 ± 0.037	$68.2^{+1.4}_{-1.6}$	< 0.153	$0.079^{+0.037}_{-0.036}$	68.2 ± 1.5
base+BAO+H070p6	< 0.175	0.076 ± 0.036	$67.7^{+1.4}_{-1.5}$	< 0.180	0.075 ± 0.036	$67.7^{+1.4}_{-1.5}$	< 0.187	$0.076^{+0.036}_{-0.037}$	$67.7^{+1.4}_{-1.5}$
base+BAO+H072p5	< 0.151	0.077 ± 0.036	$67.9^{+1.3}_{-1.4}$	< 0.160	$0.078^{+0.036}_{-0.035}$	$68.0^{+1.3}_{-1.4}$	< 0.168	$0.077^{+0.036}_{-0.037}$	$67.9^{+1.3}_{-1.4}$
base+BAO+H073p02	< 0.125	0.079 ± 0.036	$68.3^{+1.2}_{-1.3}$	< 0.135	$0.079^{+0.037}_{-0.037}$	68.3 ± 1.3	< 0.139	0.079 ± 0.036	68.3 ± 1.3

TABLE I. 95% CL upper bounds on $\sum m_\nu$ (in eV), mean values and their associated 95% CL errors of the reionization optical depth τ and the Hubble constant parameter H_0 (in km s^{-1} Mpc^{-1}) for different combination of cosmological datasets. The first, second and third column show the results for 1, 2 and 3 massive neutrino states, respectively. The *base* case refers to the combination of *Planck TT* plus DR9, with bias, shot, and a gaussian prior on systematics included.

Results



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base+BAO+H072p5	< 0.151	0.077 ± 0.036	$67.9^{+1.3}_{-1.4}$	< 0.160	$0.078^{+0.036}_{-0.035}$	$68.0^{+1.3}_{-1.4}$	< 0.168	$0.077^{+0.036}_{-0.037}$	$67.9^{+1.3}_{-1.4}$
base+BAO+H073p02	< 0.125	0.079 ± 0.036	$68.3^{+1.2}_{-1.3}$	< 0.135	$0.079^{+0.037}_{-0.037}$	68.3 ± 1.3	< 0.139	0.079 ± 0.036	68.3 ± 1.3

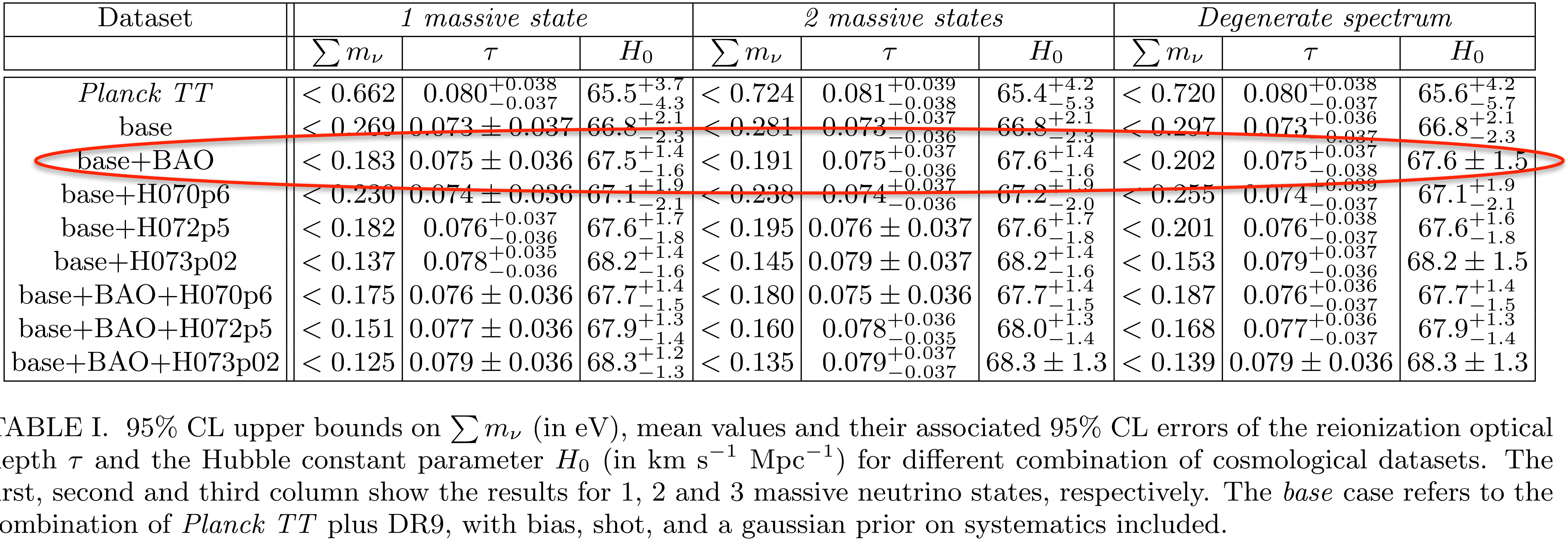
TABLE I. 95% CL upper bounds on $\sum m_\nu$ (in eV), mean values and their associated 95% CL errors of the reionization optical depth τ and the Hubble constant parameter H_0 (in km s^{-1} Mpc^{-1}) for different combination of cosmological datasets. The first, second and third column show the results for 1, 2 and 3 massive neutrino states, respectively. The *base* case refers to the combination of *Planck TT* plus DR9, with bias, shot, and a gaussian prior on systematics included.

Among the strongest bounds in the literature derived using Planck TT data only!!

BUT

Less conservative, because of the tension between the Hubble prior used here and the Planck 2015 estimates of H_0.

Results



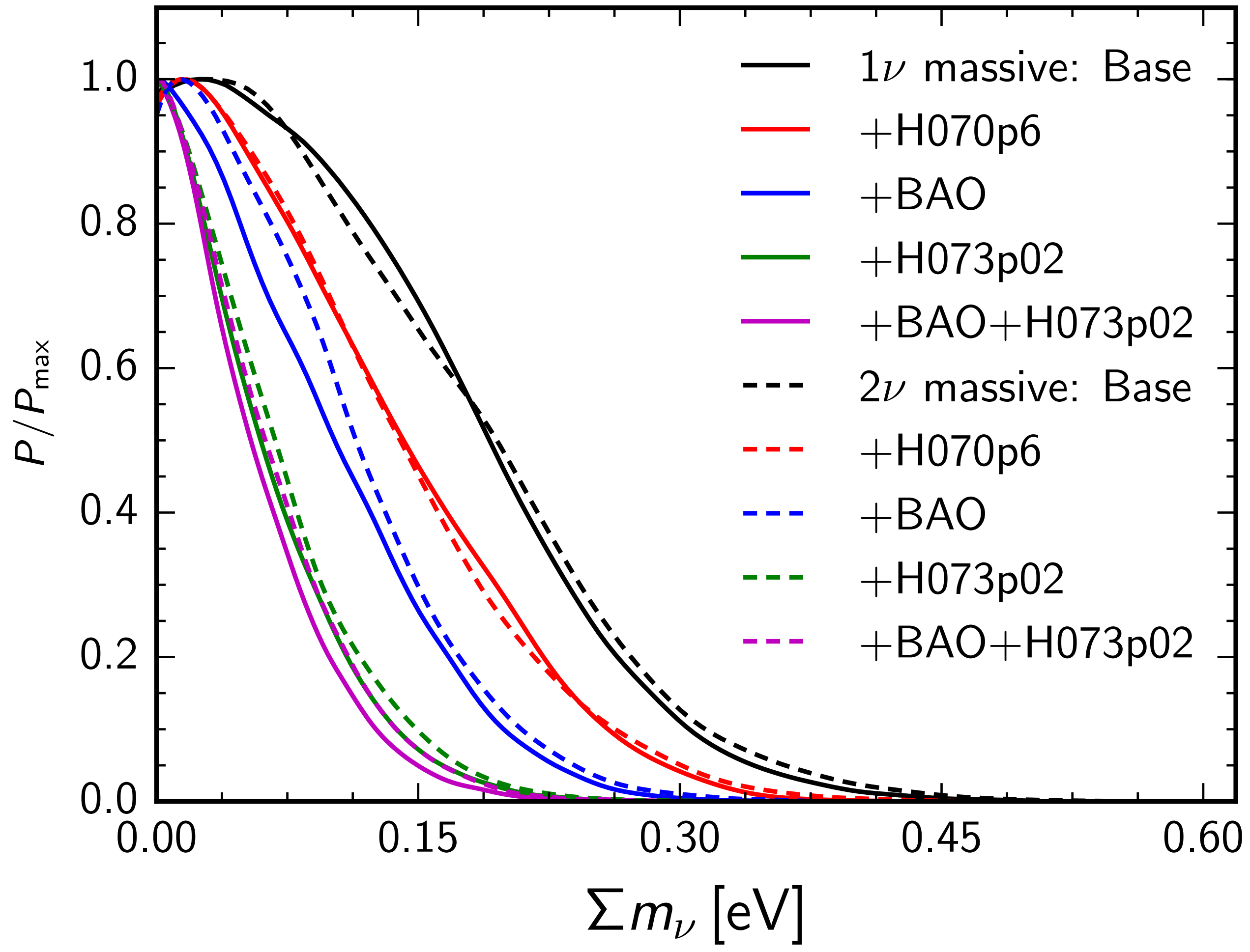
Dataset	*1 massive state*			*2 massive states*			*Degenerate spectrum*		
	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0
Planck TT	< 0.662	$0.080^{+0.038}_{-0.037}$	$65.5^{+3.7}_{-4.3}$	< 0.724	$0.081^{+0.039}_{-0.038}$	$65.4^{+4.2}_{-5.3}$	< 0.720	$0.080^{+0.038}_{-0.037}$	$65.6^{+4.2}_{-5.7}$
base	< 0.269	0.073 ± 0.037	$66.8^{+2.1}_{-2.3}$	< 0.281	$0.073^{+0.037}_{-0.036}$	$66.8^{+2.1}_{-2.3}$	< 0.297	$0.073^{+0.036}_{-0.037}$	$66.8^{+2.1}_{-2.3}$
base+BAO	< 0.183	0.075 ± 0.036	$67.5^{+1.4}_{-1.6}$	< 0.191	$0.075^{+0.037}_{-0.036}$	$67.6^{+1.4}_{-1.6}$	< 0.202	$0.075^{+0.037}_{-0.038}$	67.6 ± 1.5
base+H070p6	< 0.230	0.074 ± 0.036	$67.1^{+1.9}_{-2.1}$	< 0.238	$0.074^{+0.037}_{-0.036}$	$67.2^{+1.9}_{-2.0}$	< 0.255	$0.074^{+0.039}_{-0.037}$	$67.1^{+1.9}_{-2.1}$
base+H072p5	< 0.182	$0.076^{+0.037}_{-0.036}$	$67.6^{+1.7}_{-1.8}$	< 0.195	0.076 ± 0.037	$67.6^{+1.7}_{-1.8}$	< 0.201	$0.076^{+0.038}_{-0.037}$	$67.6^{+1.6}_{-1.8}$
base+H073p02	< 0.137	$0.078^{+0.035}_{-0.036}$	$68.2^{+1.4}_{-1.6}$	< 0.145	0.079 ± 0.037	$68.2^{+1.4}_{-1.6}$	< 0.153	$0.079^{+0.037}_{-0.036}$	68.2 ± 1.5
base+BAO+H070p6	< 0.175	0.076 ± 0.036	$67.7^{+1.4}_{-1.5}$	< 0.180	0.075 ± 0.036	$67.7^{+1.4}_{-1.5}$	< 0.187	$0.076^{+0.036}_{-0.037}$	$67.7^{+1.4}_{-1.5}$
base+BAO+H072p5	< 0.151	0.077 ± 0.036	$67.9^{+1.3}_{-1.4}$	< 0.160	$0.078^{+0.036}_{-0.035}$	$68.0^{+1.3}_{-1.4}$	< 0.168	$0.077^{+0.036}_{-0.037}$	$67.9^{+1.3}_{-1.4}$
base+BAO+H073p02	< 0.125	0.079 ± 0.036	$68.3^{+1.2}_{-1.3}$	< 0.135	$0.079^{+0.037}_{-0.037}$	68.3 ± 1.3	< 0.139	0.079 ± 0.036	68.3 ± 1.3

TABLE I. 95% CL upper bounds on $\sum m_\nu$ (in eV), mean values and their associated 95% CL errors of the reionization optical depth τ and the Hubble constant parameter H_0 (in km s^{-1} Mpc^{-1}) for different combination of cosmological datasets. The first, second and third column show the results for 1, 2 and 3 massive neutrino states, respectively. The *base* case refers to the combination of *Planck TT* plus DR9, with bias, shot, and a gaussian prior on systematics included.

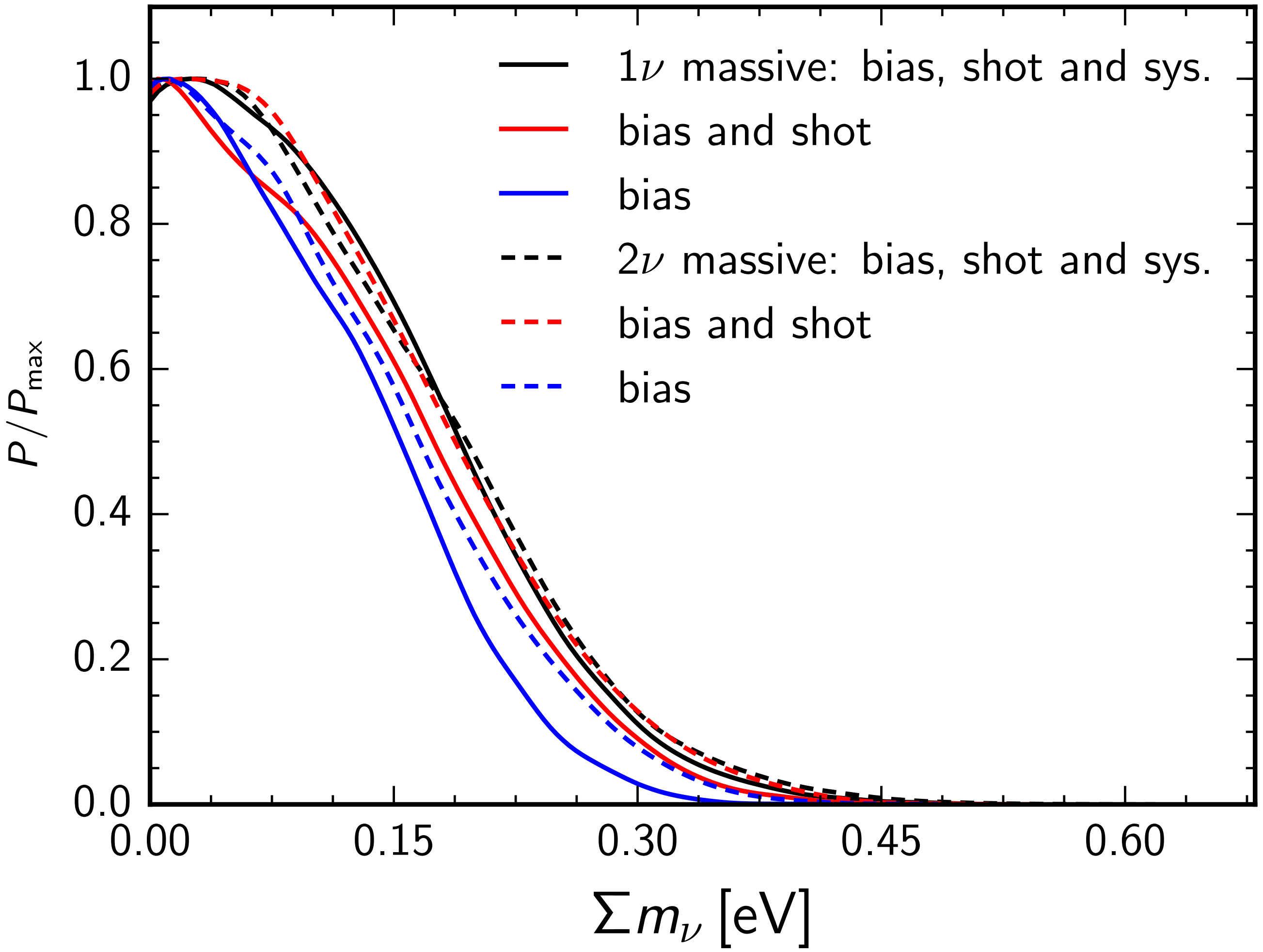
Current cosmological measurements are sensitive to the number of neutrino eigenstates!

Results

Giusarma et al., 2016 arXiv:1605.04320



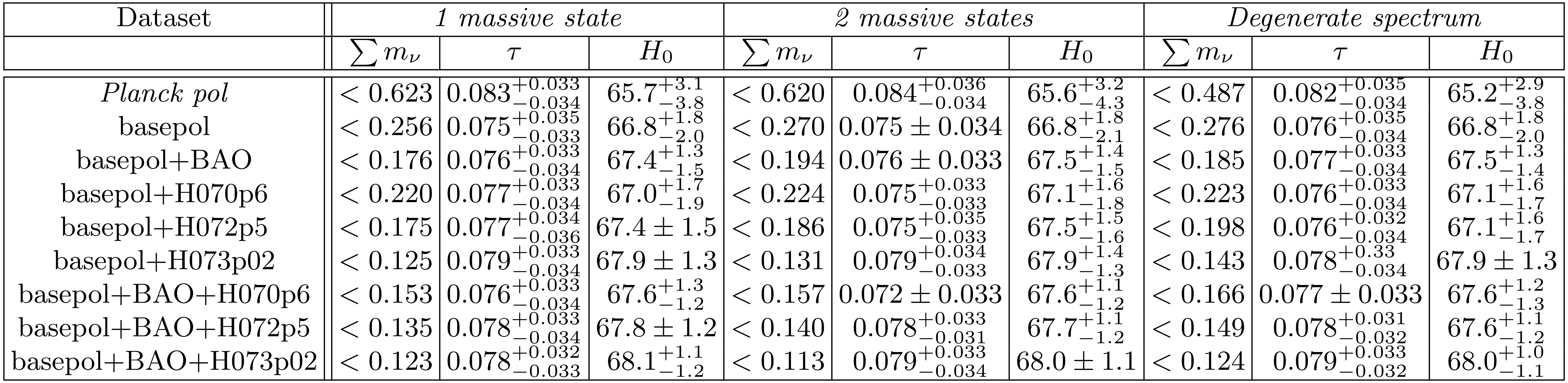
One-dimensional posterior probability for the sum of massive neutrinos.



Impact of marginalizing over bias, shot noise and systematics.

Results

For the sake of comparison with previous results in the literature, we also present the constraints obtained when high-multipole polarization data are also included in the analysis!



Dataset	*1 massive state*			*2 massive states*			*Degenerate spectrum*		
	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0
Planck pol	< 0.623	$0.083^{+0.033}_{-0.034}$	$65.7^{+3.1}_{-3.8}$	< 0.620	$0.084^{+0.036}_{-0.034}$	$65.6^{+3.2}_{-4.3}$	< 0.487	$0.082^{+0.035}_{-0.034}$	$65.2^{+2.9}_{-3.8}$
basepol	< 0.256	$0.075^{+0.035}_{-0.033}$	$66.8^{+1.8}_{-2.0}$	< 0.270	0.075 ± 0.034	$66.8^{+1.8}_{-2.1}$	< 0.276	$0.076^{+0.035}_{-0.034}$	$66.8^{+1.8}_{-2.0}$
basepol+BAO	< 0.176	$0.076^{+0.033}_{-0.034}$	$67.4^{+1.3}_{-1.5}$	< 0.194	0.076 ± 0.033	$67.5^{+1.4}_{-1.5}$	< 0.185	$0.077^{+0.033}_{-0.034}$	$67.5^{+1.3}_{-1.4}$
basepol+H070p6	< 0.220	$0.077^{+0.033}_{-0.034}$	$67.0^{+1.7}_{-1.9}$	< 0.224	$0.075^{+0.033}_{-0.033}$	$67.1^{+1.6}_{-1.8}$	< 0.223	$0.076^{+0.033}_{-0.034}$	$67.1^{+1.6}_{-1.7}$
basepol+H072p5	< 0.175	$0.077^{+0.034}_{-0.036}$	67.4 ± 1.5	< 0.186	$0.075^{+0.035}_{-0.033}$	$67.5^{+1.5}_{-1.6}$	< 0.198	$0.076^{+0.032}_{-0.034}$	$67.1^{+1.6}_{-1.7}$
basepol+H073p02	< 0.125	$0.079^{+0.033}_{-0.034}$	67.9 ± 1.3	< 0.131	$0.079^{+0.034}_{-0.033}$	$67.9^{+1.4}_{-1.3}$	< 0.143	$0.078^{+0.33}_{-0.034}$	67.9 ± 1.3
basepol+BAO+H070p6	< 0.153	$0.076^{+0.033}_{-0.034}$	$67.6^{+1.3}_{-1.2}$	< 0.157	0.072 ± 0.033	$67.6^{+1.1}_{-1.2}$	< 0.166	0.077 ± 0.033	$67.6^{+1.2}_{-1.3}$
basepol+BAO+H072p5	< 0.135	$0.078^{+0.033}_{-0.034}$	67.8 ± 1.2	< 0.140	$0.078^{+0.033}_{-0.031}$	$67.7^{+1.1}_{-1.2}$	< 0.149	$0.078^{+0.031}_{-0.032}$	$67.6^{+1.1}_{-1.2}$
basepol+BAO+H073p02	< 0.123	$0.078^{+0.032}_{-0.033}$	$68.1^{+1.1}_{-1.2}$	< 0.113	$0.079^{+0.033}_{-0.034}$	68.0 ± 1.1	< 0.124	$0.079^{+0.033}_{-0.032}$	$68.0^{+1.0}_{-1.1}$

TABLE II. As Tab. I but for the *basepol* case, which refers to the combination of *Planck pol* plus DR9, with bias, shot, and a gaussian prior on systematics included, see text for details.

Effect of a scale dependent bias

We consider two different parameterizations:

- The Power low bias model:

$$b(z,k) = b_0(z) + b_1(z)\left(\frac{k}{k_1}\right)^n$$

with n=2 and k_1=1h/Mpc

Fry and Gaztanaga, Ap. J., 1993

Flat priors on b_0 and b_1: [0.1,10] for b_0, [-10,10] for b_1.

- The Q model:

$$b(z,k) = b_0(z)\left[\frac{1+Q(z)(k/k_1)^2}{1+A(z)(k/k_1)}\right]^{1/2}$$

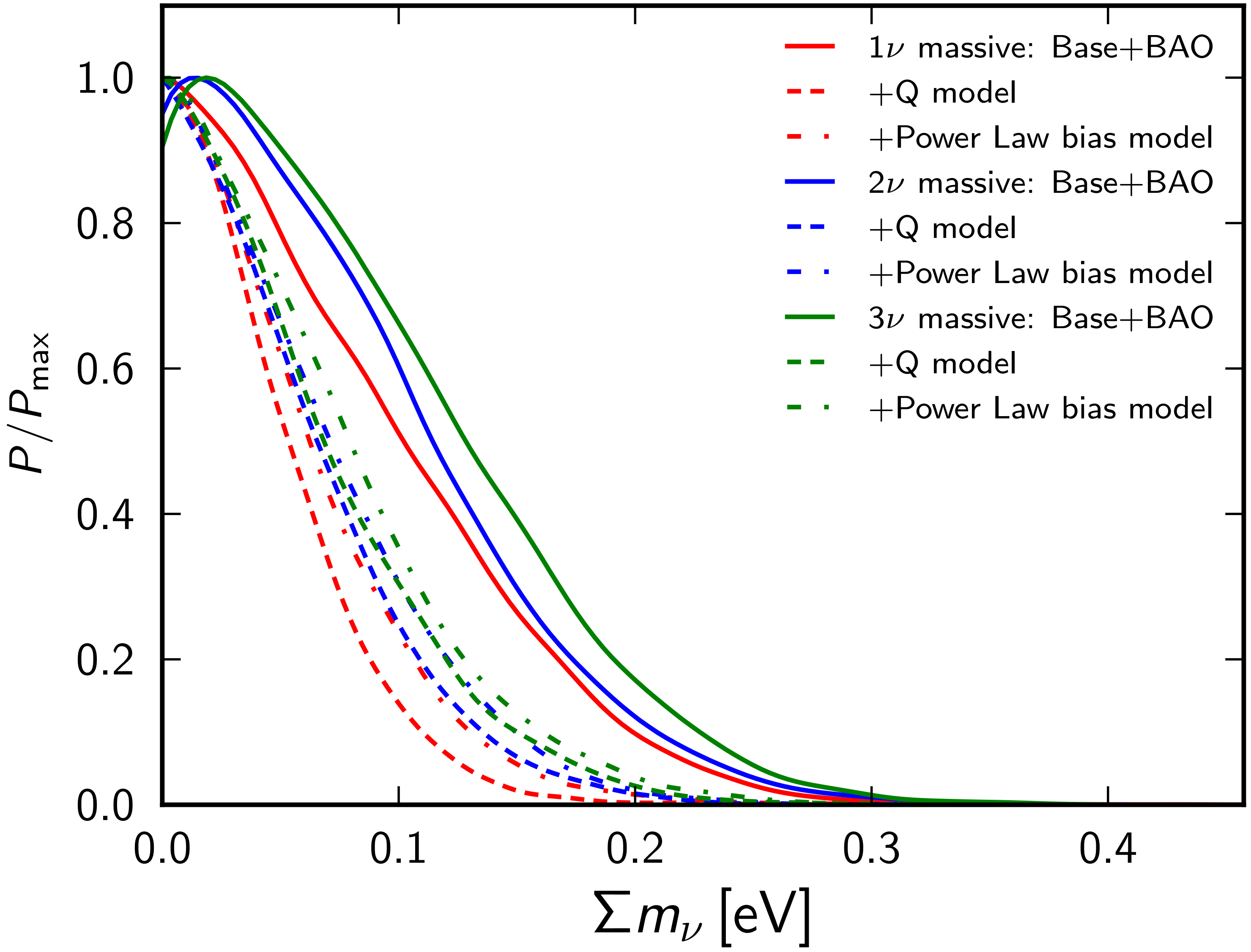
Cole at al (2dFGRS Collaboration), MNRAS 2005

The parameter Q describes the scale dependence of the bias and A=1.4 in the redshift space.

Flat priors on b_0 and Q: [0.,10] for b_0, [0.1,100] for Q.

In the above cases, we marginalize over two parameters for the matter power spectrum analysis, in addition to the systematic correction.

Results



The bounds on neutrino masses are tighter!!

Power low bias model

Dataset	*1 massive state*	*2 massive states*	*Degenerate spectrum*
	$\sum m_\nu$	$\sum m_\nu$	$\sum m_\nu$
base+BAO	< 0.128	< 0.141	< 0.155

Q model

Dataset	*1 massive state*	*2 massive states*	*Degenerate spectrum*
	$\sum m_\nu$	$\sum m_\nu$	$\sum m_\nu$
base+BAO	< 0.106	< 0.131	< 0.146

Conclusions

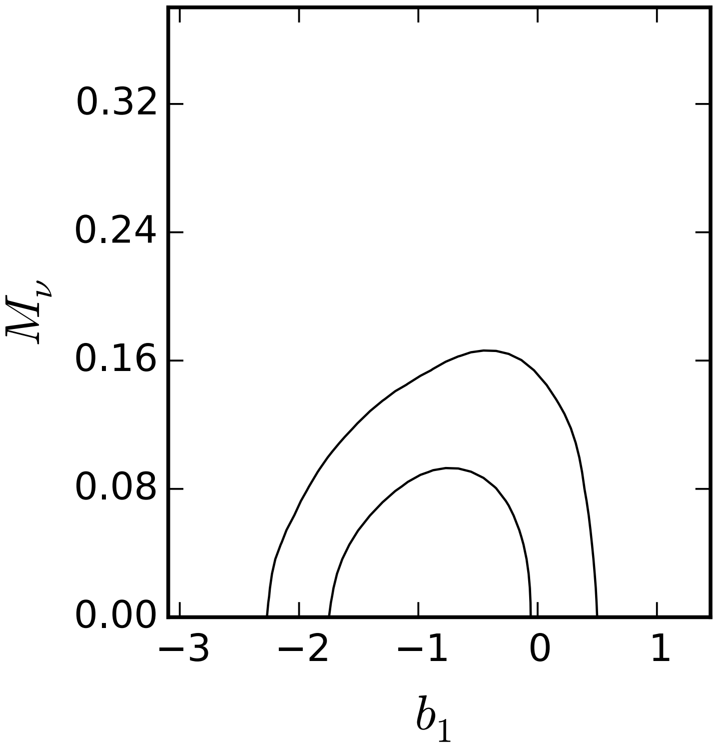
- Cosmological probes are currently the most powerful in constraining the absolute scale of neutrino masses.
- From oscillation experiments, the minimum value of Σm_ν in inverted hierarchy is 0.1eV. This value could be reached improving the sensitivity of future cosmological data.
- The limit found here for the total neutrino mass, $\Sigma m_\nu < 0.183$ eV at 95% CL , is among the tightest ones in the literature, and it goes in the same direction than other existing bounds in the literature.
- Current cosmological data are sensitive to the distribution of hot dark matter.
- A scale dependent bias could modify the bounds on neutrino masses.

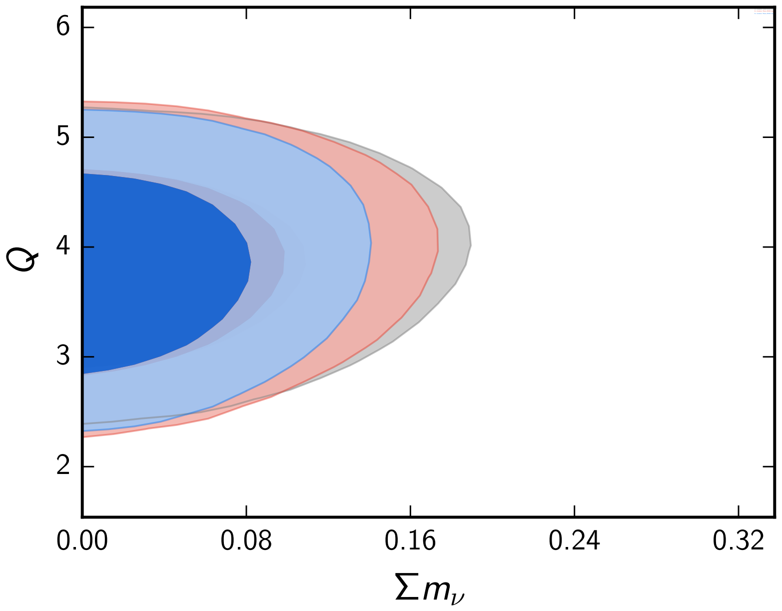
Thank You

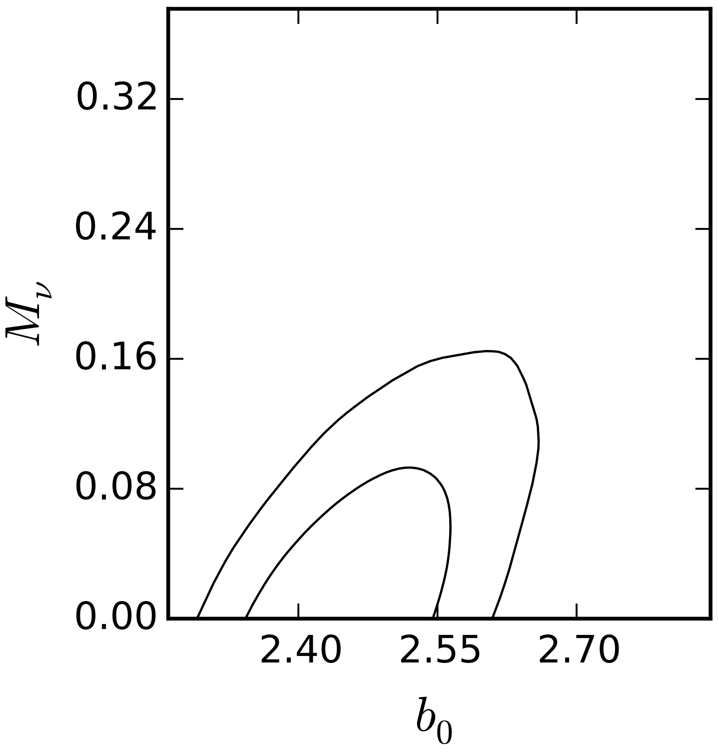
Backup

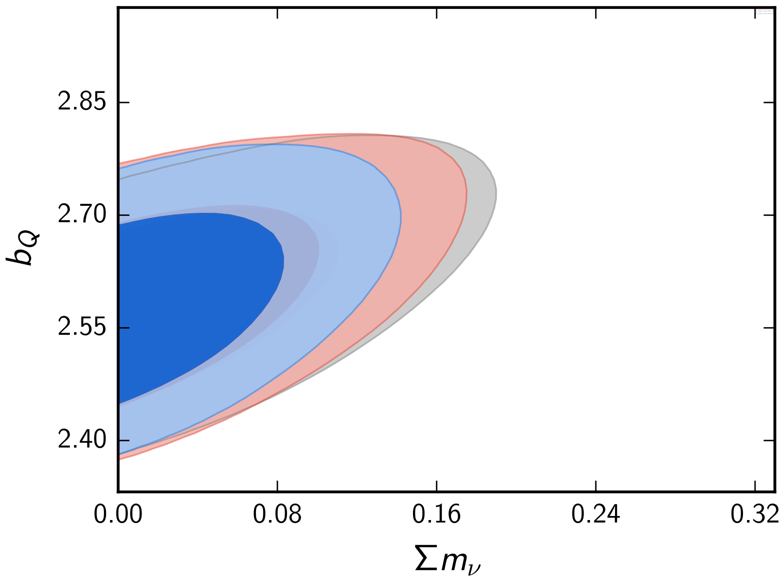
Power low bias model

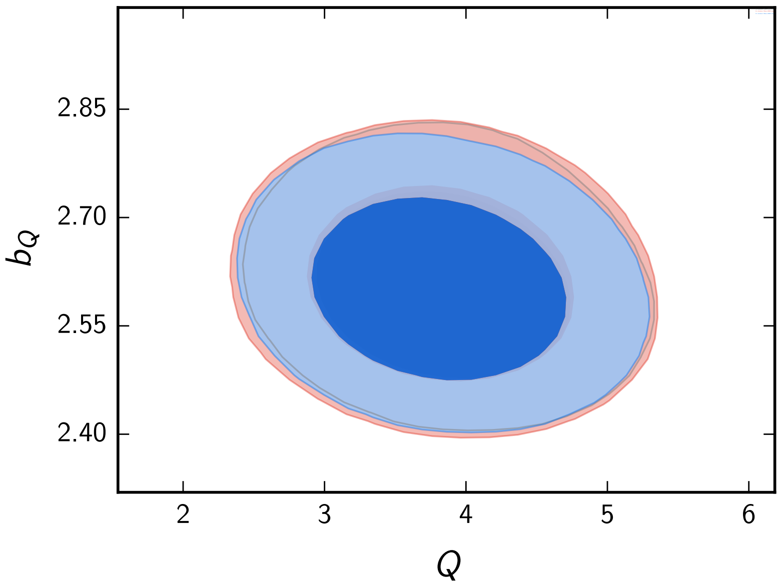
Q model





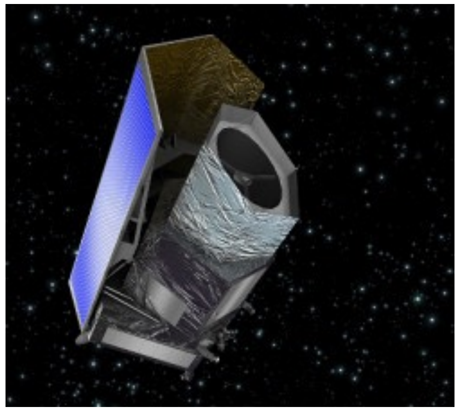


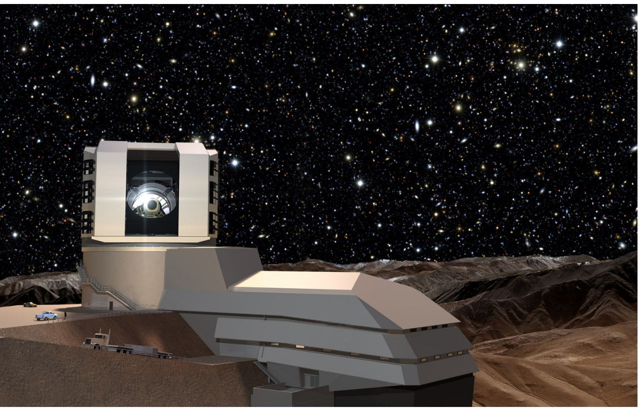


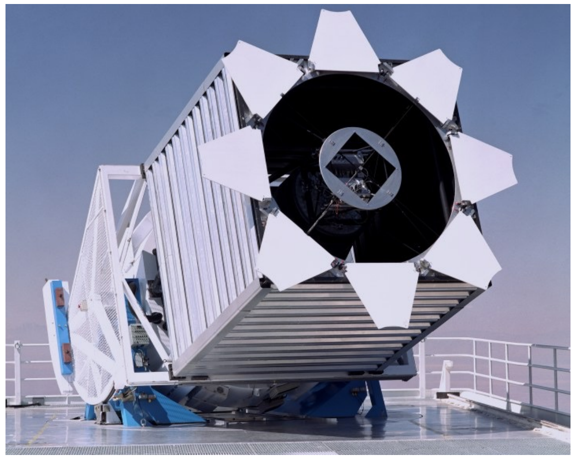


Future cosmological data

- CMB Experiments
- CMB Lensing
- Galaxy cluster survey
- Galaxy weak lensing (cosmic shear)
- Lyman α
- 21-cm H line survey

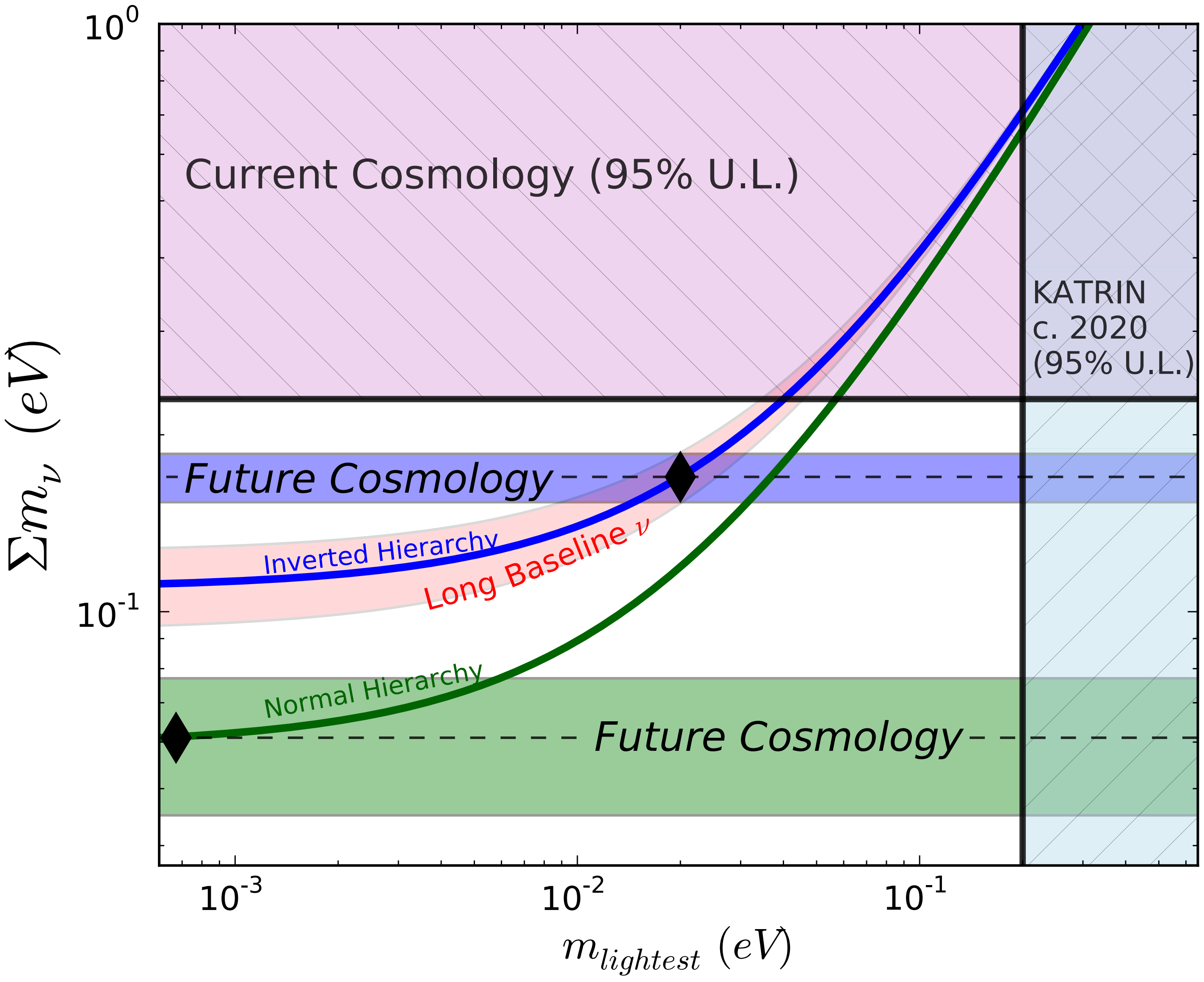






Future cosmological data

Current constraints and forecast sensitivity of cosmology to the neutrino mass in relation to the neutrino mass hierarchy



	$\sigma\left(\sum m_\nu\right)$ [meV]
CMB Lensing (current galaxy clustering):	
Stage-IV CMB	45
Stage-IV CMB + BOSS BAO	**25**
CMB Lensing + Galaxy clustering:	
Stage-IV CMB + eBOSS BAO	23
Stage-IV CMB + DESI BAO	**16**
Stage-IV CMB no lensing + DESI galaxy clustering	15/20
Galaxy Weak Lensing:	
Planck + LSST [51]	23
Planck + Euclid [48]	25

Abazajian et al., Astropart.Phys 2015

Forecasts seems indicate 20 meV sensitivities to Σm_ν are possible!