Cosmology and Neutrino Hierarchy (NH)

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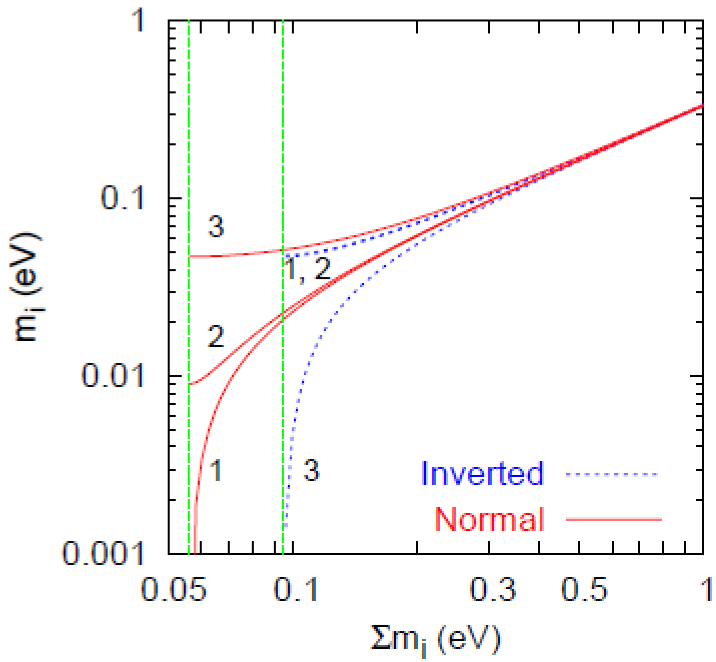
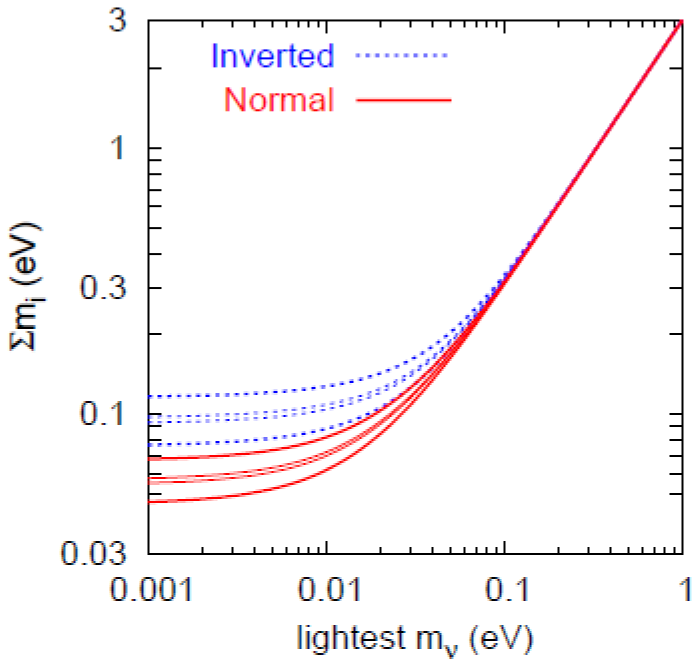
- **Constraints on NH from Cosmology**
- **Impact of NH determination on Cosmology**

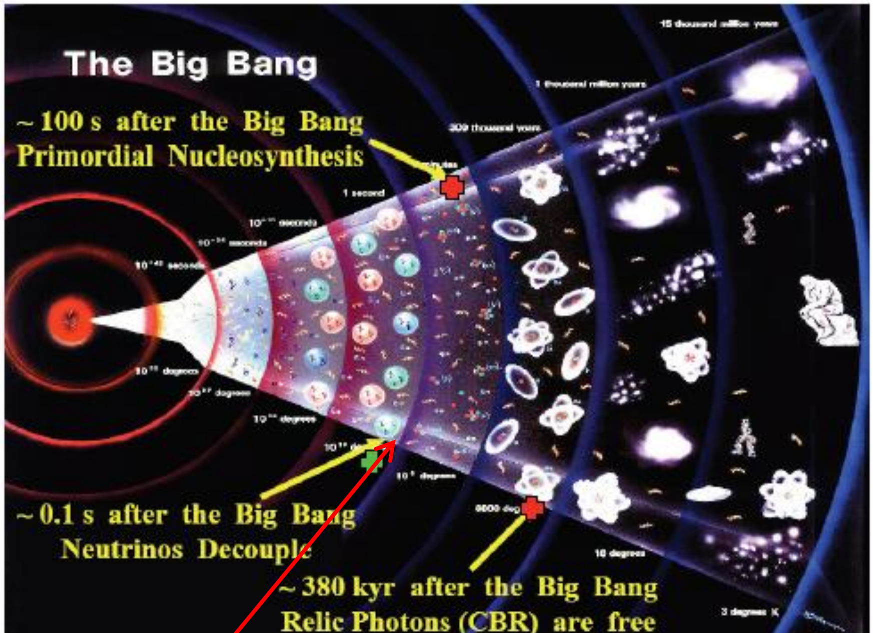
Expected values of the neutrino masses according to neutrino oscillation measurements (3σ)





Lesgourgues (2010)

Where to find the signature of CNB ?



$$f_\nu(p,T) = \frac{1}{e^{E_\nu/T_\nu \pm \xi_\nu} + 1} \qquad \xi_\nu \equiv \frac{\mu_\nu}{T_\nu}$$

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

Effective number of relativistic neutrino species

Non-instantaneous decoupling + QED corrections: $N_{eff} \approx 3.046$ for standard 3 neutrino flavors

Mangano et al. (2005)

$$\Delta N_{eff}(\xi_\nu) = 3\left[\frac{30}{7}\left(\frac{\xi_\nu}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi_\nu}{\pi}\right)^4\right]$$

1. The Big Bang Nucleosynthesis (@ ~ 100 sec.):

• increase N_{eff} ⟹ radiation energy density goes up
expansion rate goes up ⟹ neutrino freeze out earlier
with direct effect on n-p reactions: $\nu_e + n \longleftrightarrow p + e^-$ $e^+ + n \longleftrightarrow p + \bar{\nu}_e$
⟹ Y_p goes up

Y_p sensitive to the expansion rate

• for $\xi_\nu = \mu_\nu / kT > 0$ ⟹ more ν_e than anti-ν_e ⟹
n/p goes down ⟹ Y_p goes down

Y_p sensitive to the lepton asymmetry

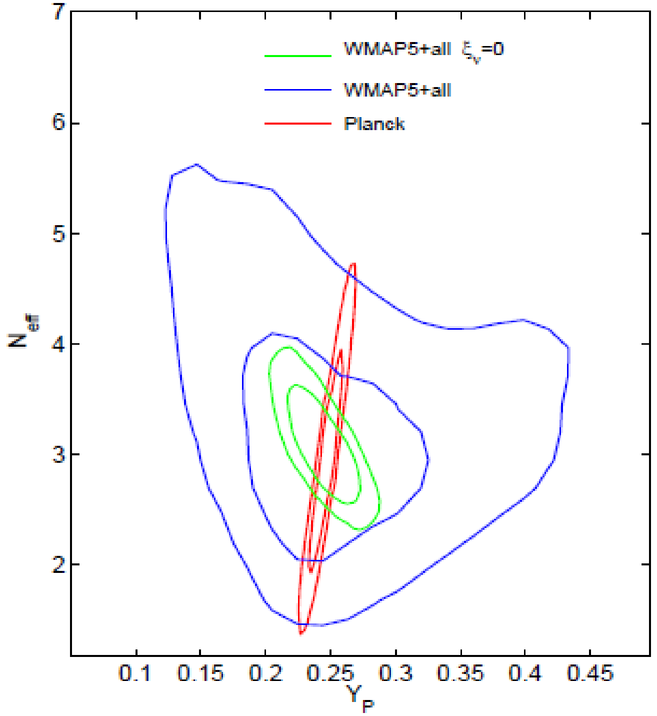
BBN
$N_{eff} = 3.1 \ \ +1.4 / -1.2 \ \ (2\sigma)$

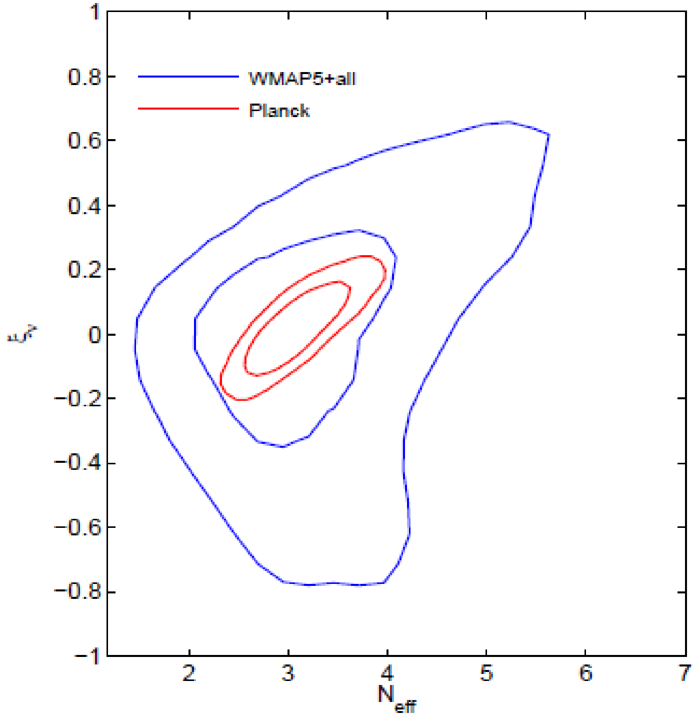
$\xi_\nu = 0.0245 \ \ +/- \ \ 0.018$

In SM: $L_\nu \approx B \sim 10^{-10}$

2. Epoch of matter-radiation equality (@ ~ 400 kyr):

increase N_{eff} ⟶ more relativistic particles ⟶ structure formation starts later





$$L_\nu \approx (4.5 \pm 1.3) 10^{-4}$$

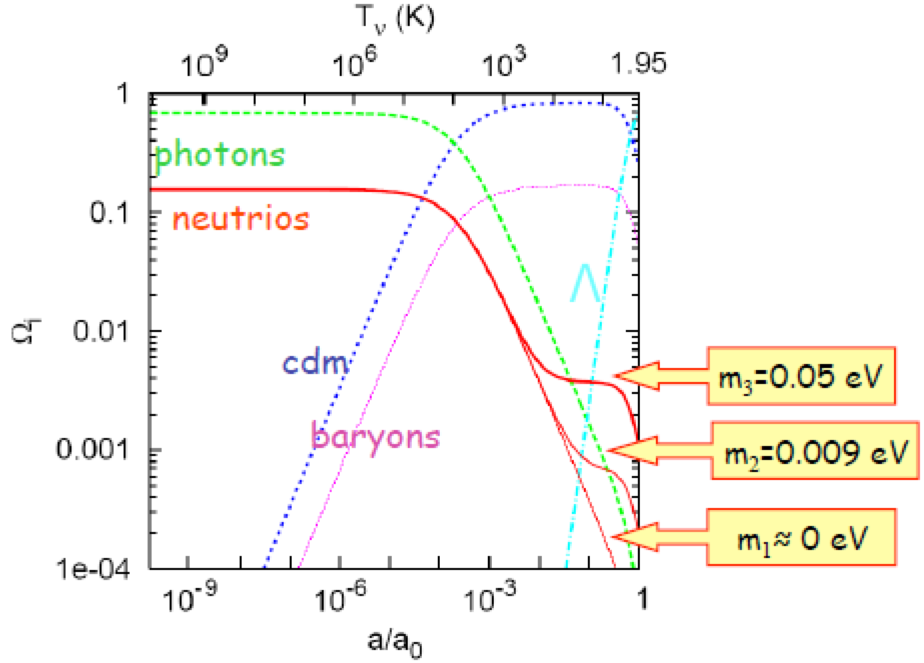
Popa & Vasile (2009)

Contribution to the energy density of the Universe

$$\Omega_\nu h^2 = 1.7 \times 10^{-5}$$ Massless

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2\ eV}$$ Massive $m_\nu \gg T$

Modify the background evolution: change in spatial curvature or other Ω_i



Effect of Neutrinos mass:

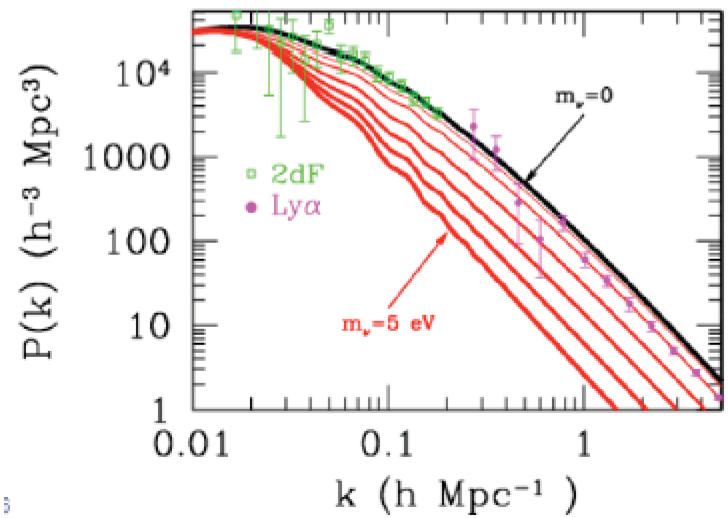
$\lambda = \int v\, dt$ neutrino diffusion length

For scales $(2\pi/k) < \lambda$ free-streaming supresses growth of structures

The small-scale suppression is given by

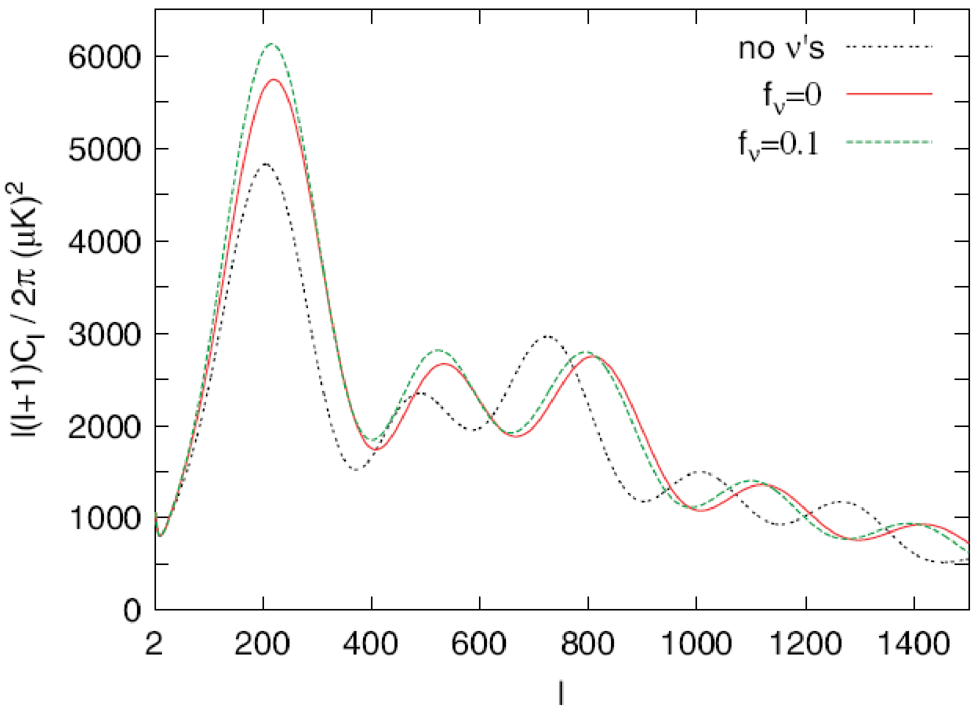
$$\left(\frac{\Delta P}{P}\right) \approx -8\frac{\Omega_\nu}{\Omega_m} \approx -0.8\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\left(\frac{0.1N}{\Omega_m h^2}\right)$$

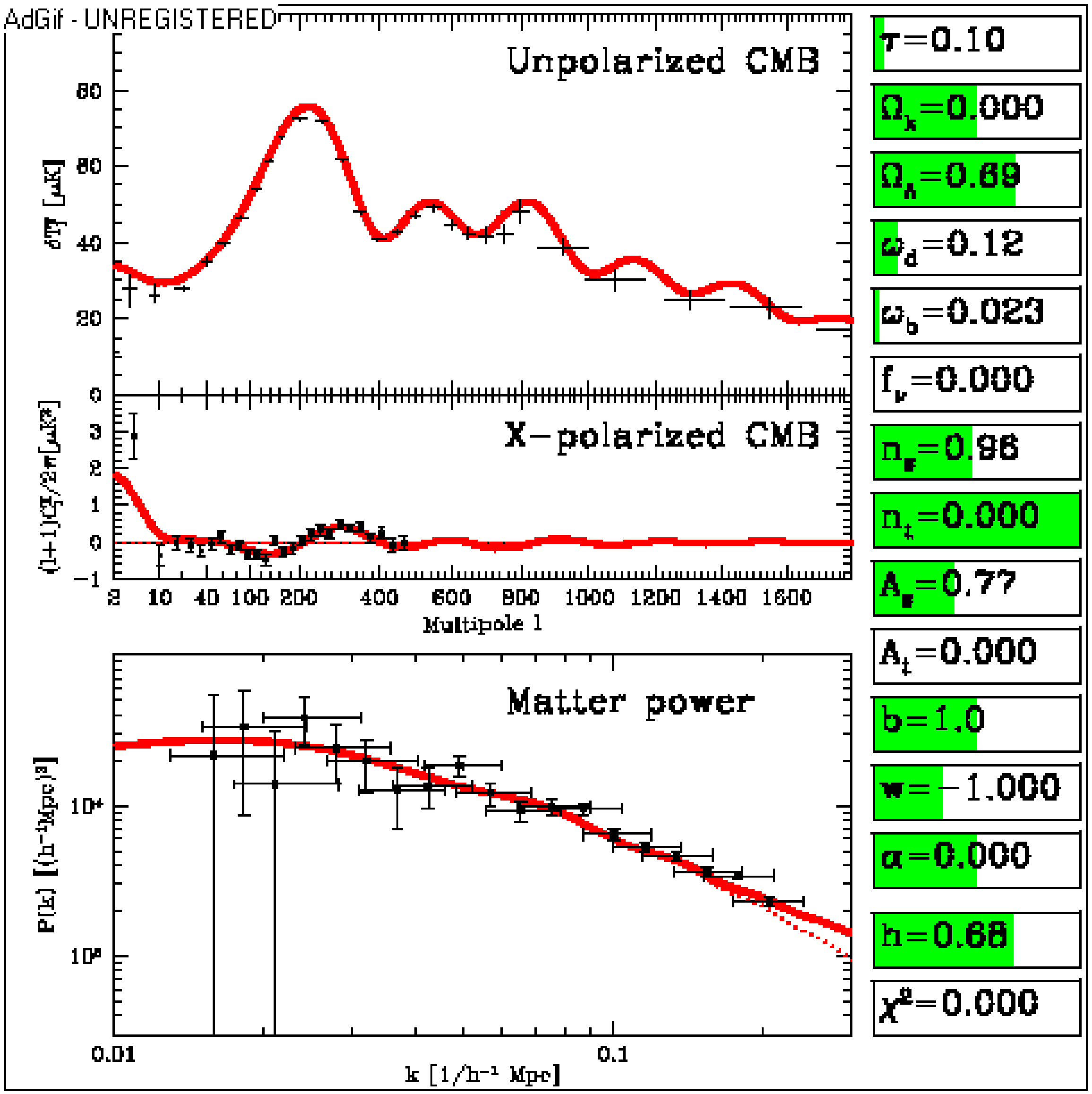
Limits on m_ν from Structure Formation



causal horizon

$$R_{fs} = \frac{1}{k_{fs}} = \frac{\eta(a)}{\sqrt{1+(a/a_{nr})^2}}, \quad \eta(a) = \int_0^a \frac{da}{a^2 H},$$

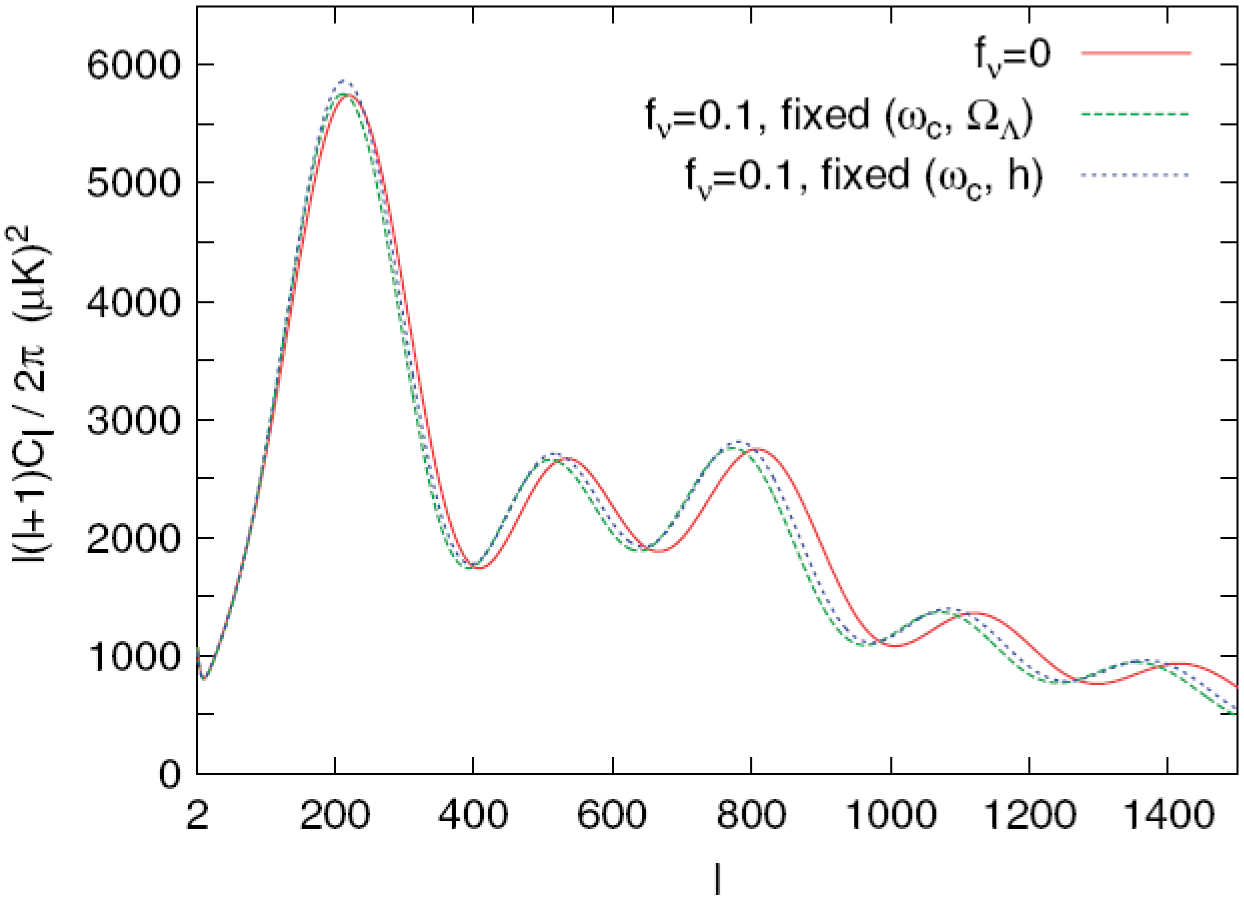




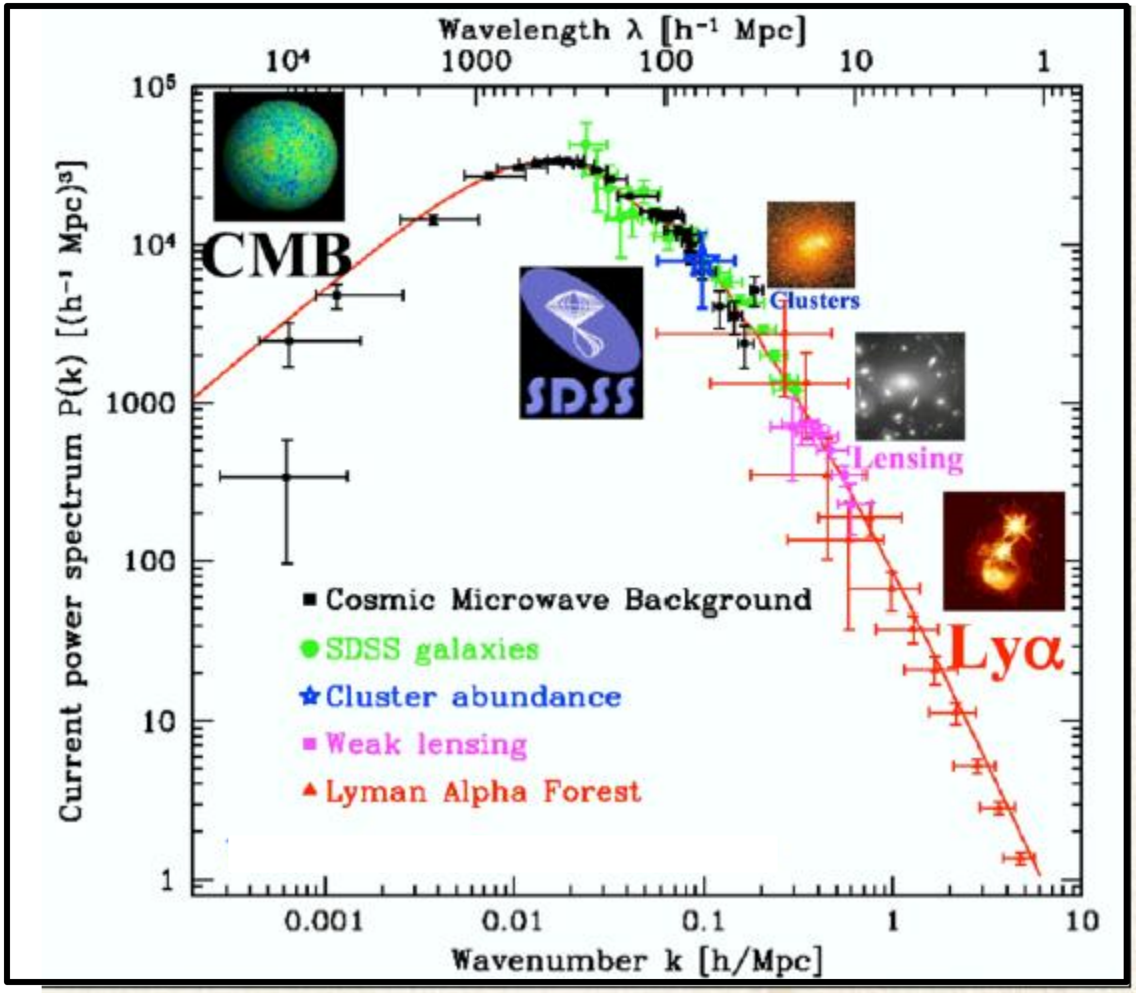
Parameter	Meaning
τ	Reionization optical depth
ω_b	Baryon density
ω_d	Dark matter density
f_ν	Dark matter neutrino fraction
Ω_Λ	Dark energy density
w	Dark energy equation of state
Ω_k	Spatial curvature
A_s	Scalar fluctuation amplitude
n_s	Scalar spectral index
α	Running of spectral index
r	Tensor-to-scalar ratio
n_t	Tensor spectral index
b	Galaxy bias factor

Courtesy Max Tegmark

Parameter degeneracy: change in other cosmological parameters can mimic the effect of neutrino masses



Power Spectrum of Density fluctuations



Tegmark & Zaldarriaga (2009)

An unique cosmological bound on neutrino mass DOES NOT exists

Recent cosmological neutrino mass limits at 95% C.L. (statistical).

Dependence on data sets

Authors	Ref.	Upper limit $\sum m_\nu$ [eV]	Used data
Ichikawa, Fukugita, Kawasaki	[9]	2.0	WMAP
Tegmark *et al.* (SDSS Collab.)	[10]	1.8	WMAP, SDSS
Spergel *et al.* (WMAP Collab.)	[11]	0.69	WMAP, CMB, 2dF, HST, Bias
Barger, Marfatia, Tregre	[12]	0.75	WMAP, CMB, 2dF, SDSS, HST
Crotty, Lesgourgues, Pastor	[13]	1.0	WMAP, CMB, 2dF, SDSS
		0.6	+ HST, SNe Ia
Hannestad	[14]	0.65	WMAP, SDSS, SNe Ia (gold sample)
			Ly-α (Keck sample)
Seljak *et al.*	[15]	0.42	WMAP, SDSS, Bias, Ly-α (SDSS sample)

Cosmological bounds on neutrino mass: dependence on physical assumptions

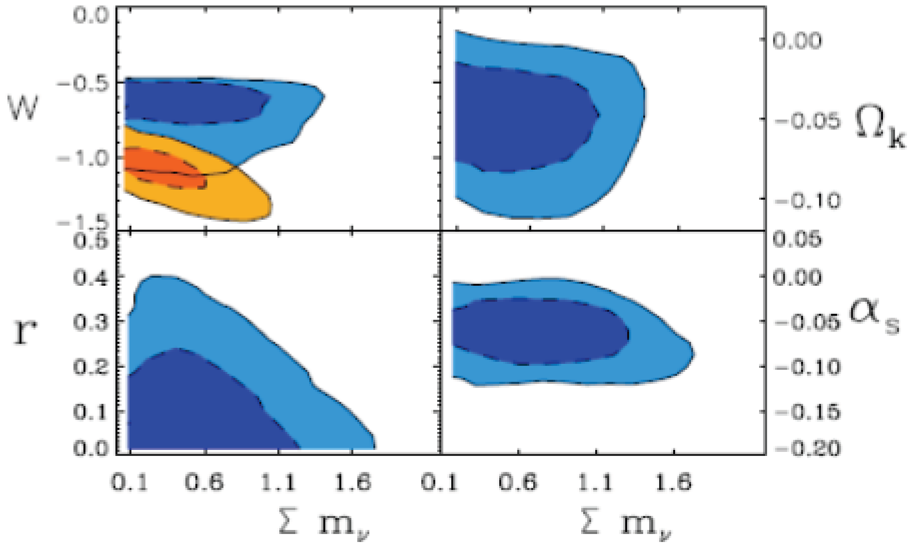
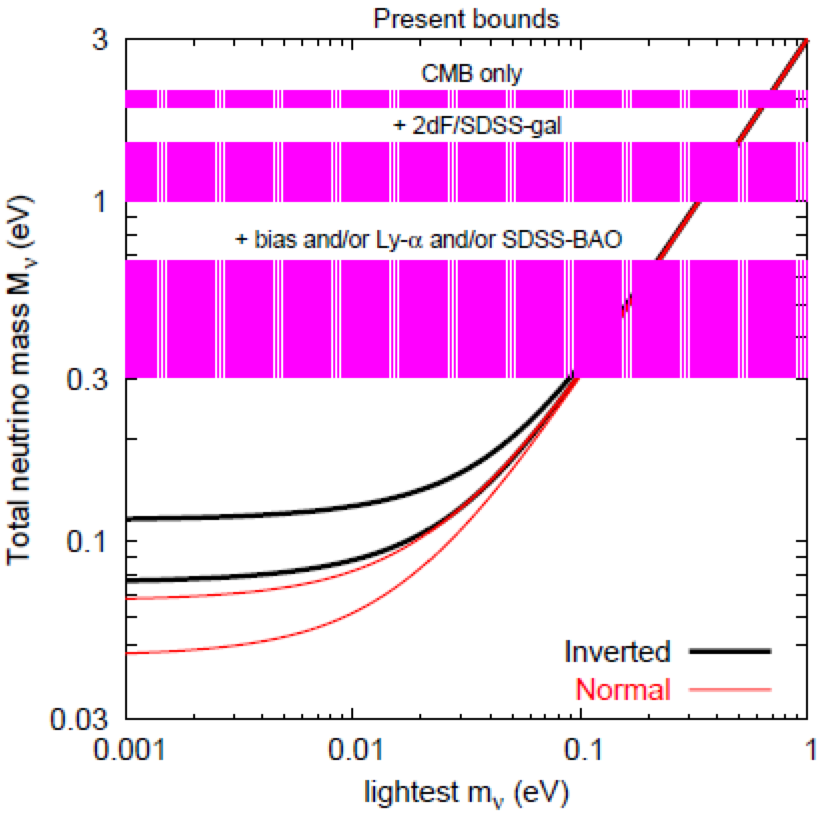


Table 2. Constraints on neutrino mass for different extensions to parameter space for the fiducial CMB + LSS dataset.

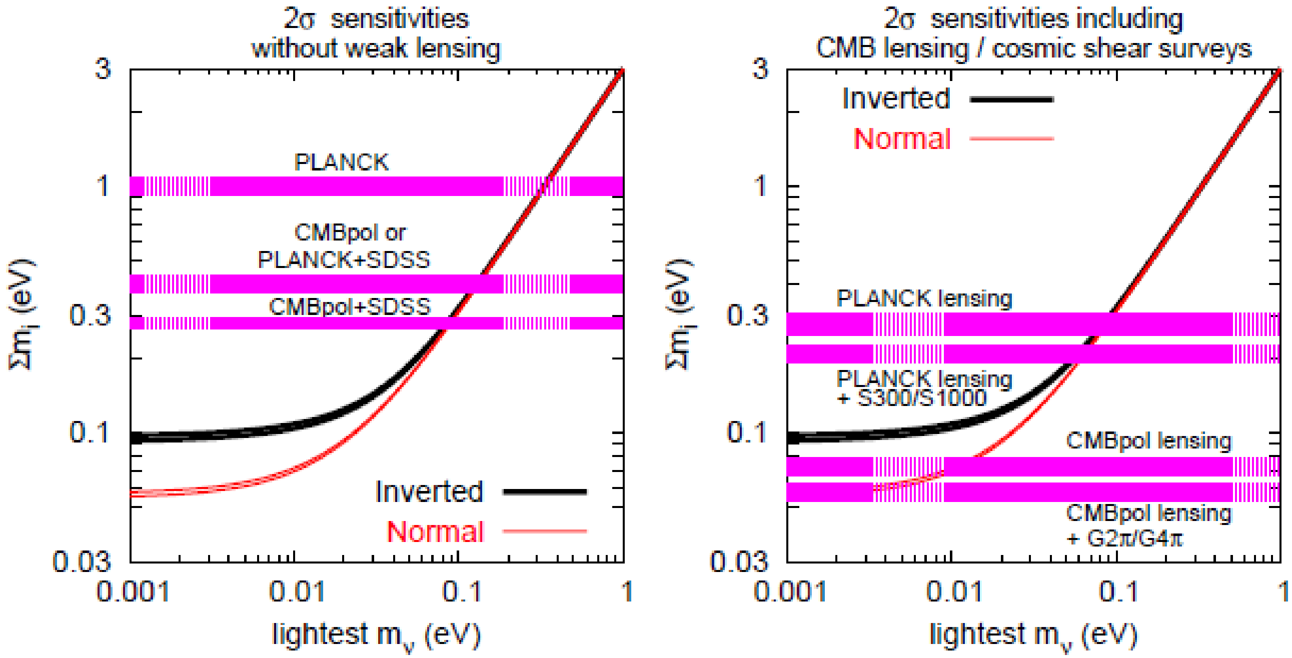
Additional parameters	$\sum m_\nu$ for $N_\nu = 3.04$ 95% CL
Spatial curvature, Ω_k	1.17 eV
Dark energy (w = constant)	1.18 eV
Tensors, r	1.38 eV
Running spectral index, α_s	1.66 eV
Isocurvature (all modes)	2.2 eV

Zunckel & Ferreira (2007)


Present bounds
CMB only
+ 2dF/SDSS-gal
+ bias and/or Ly-α and/or SDSS-BAO
Inverted
Normal
3
1
0.3
0.1
0.03
0.001
0.01
0.1
1
Total neutrino mass Mν (eV)
lightest mν (eV)

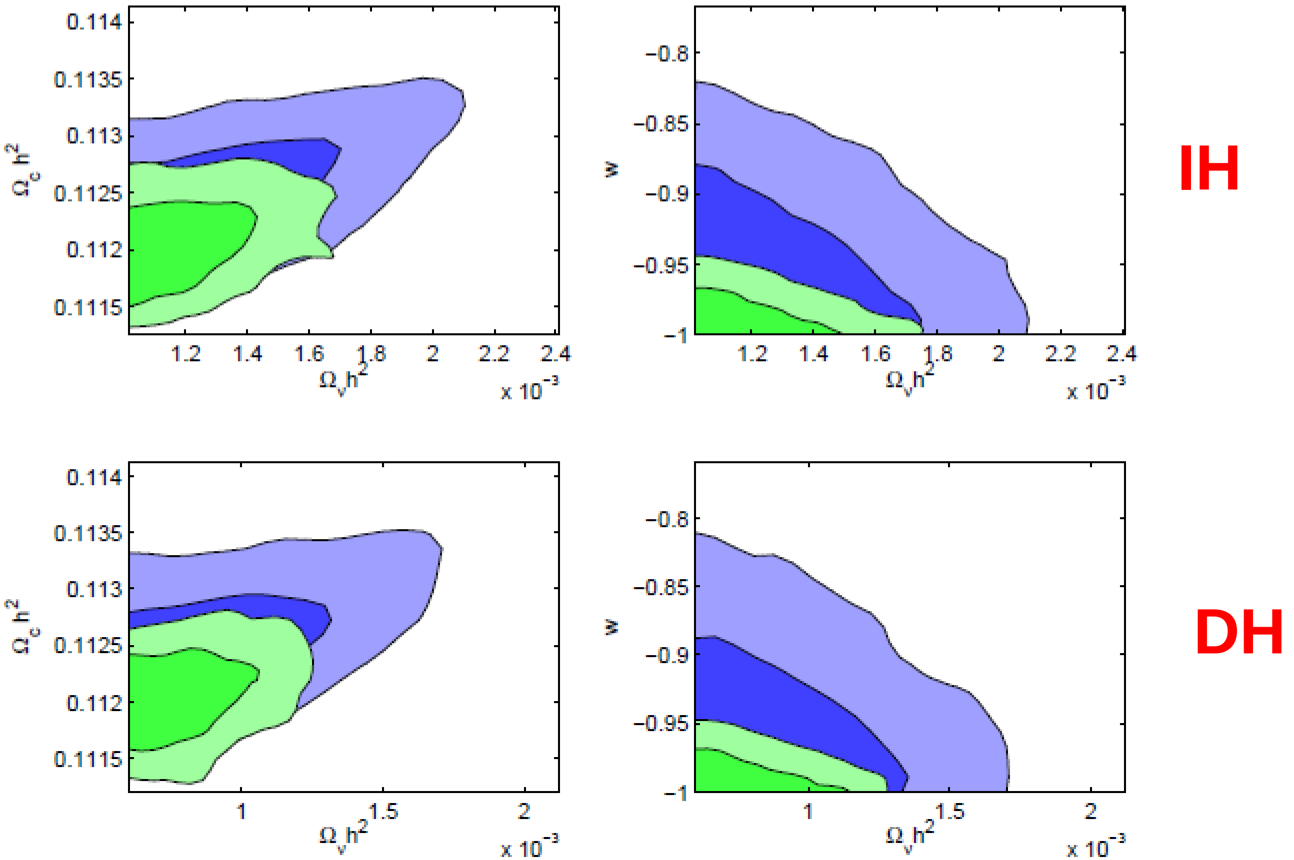
Cosmological sensitivity forecasts for detecting non-vanishing neutrino masses.

Authors	Ref.	Future surveys	$\sum m_\nu$ [eV] sensitivity
Hannestad	[17]	Planck & SDSS	0.12
Lesgourgues, Pastor, Perotto	[18]	Planck & SDSS	0.21
		Ideal CMB & $40 \times$ SDSS	0.13
Abazajian, Dodelson	[19]	4000 deg^2 weak lensing survey	0.1
Kaplinghat, Knox, Song	[20]	CMB lensing	0.15 (Planck)
			0.044 (CMBpol)
Wang, Haiman, Hu, Khoury, May	[21]	Weak-lensing selected	
		sample of $> 10^5$ clusters	0.03



2σ sensitivities
without weak lensing
PLANCK
CMBpol or
PLANCK+SDSS
CMBpol+SDSS
Inverted
Normal
Σm_i (eV)
lightest m_ν (eV)
3
1
0.3
0.1
0.03
0.001
0.01
0.1
1
2σ sensitivities including
CMB lensing / cosmic shear surveys
Inverted
Normal
PLANCK lensing
PLANCK lensing
+ S300/S1000
CMBpol lensing
CMBpol lensing
+ G2π/G4π

Impact of NH determination on Cosmology



Hall & Challinor (2012)

Conclusions

• Cosmological observables can be used to bound the neutrino properties, in particular the sum of neutrino masses:
still affected by parameters degeneracy and the choice of priors

• With present bounds on neutrino mass cosmological measurements can not distinguish between NH and IH: sub-eV bounds are expected from CMB and LSS lensing measurements

• Knowing NH would help to better constrain fundamental cosmological parameters (e.g. DE equation of state)