Neutrino properties constrained by WMAP

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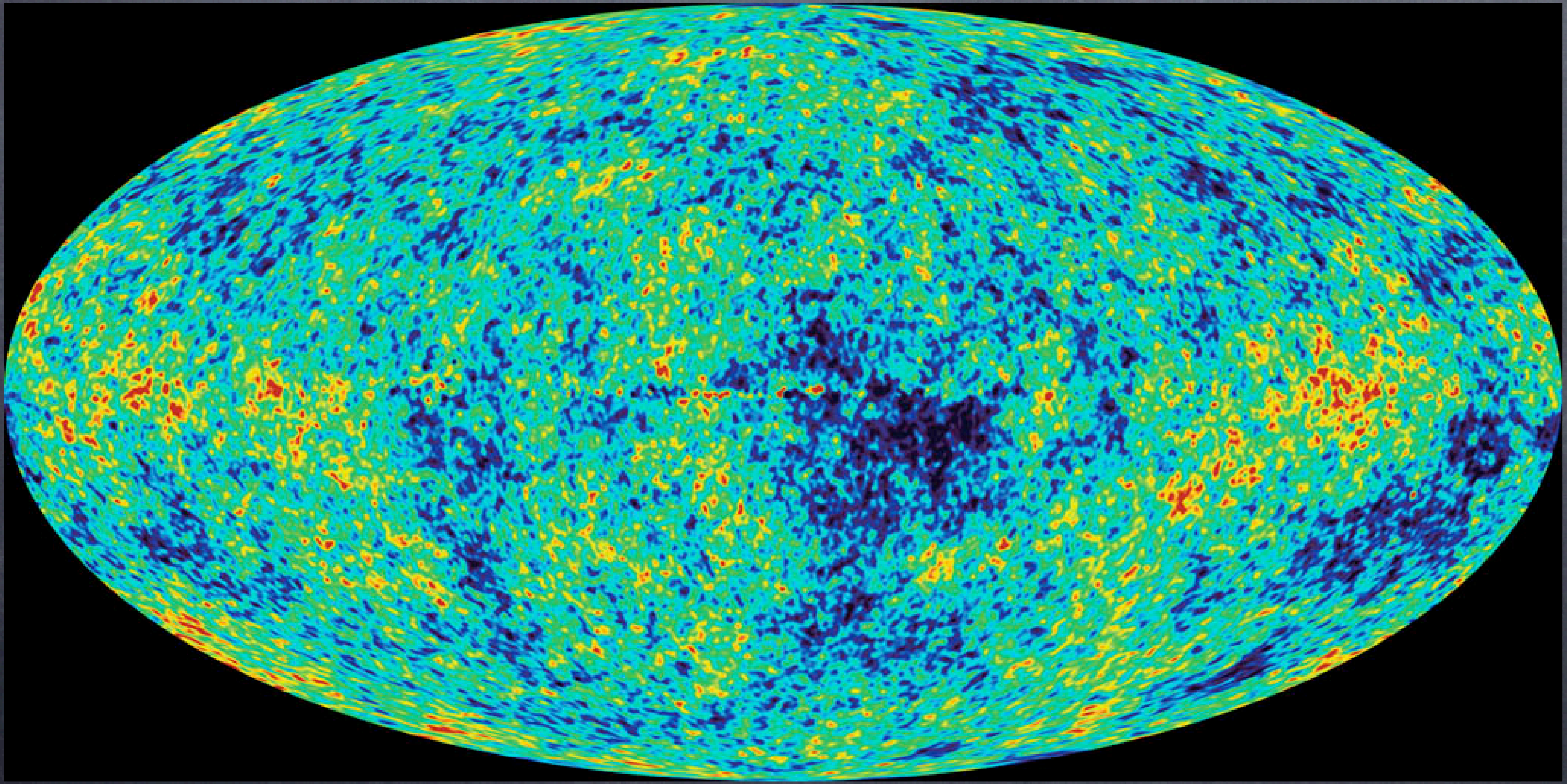
Introduction

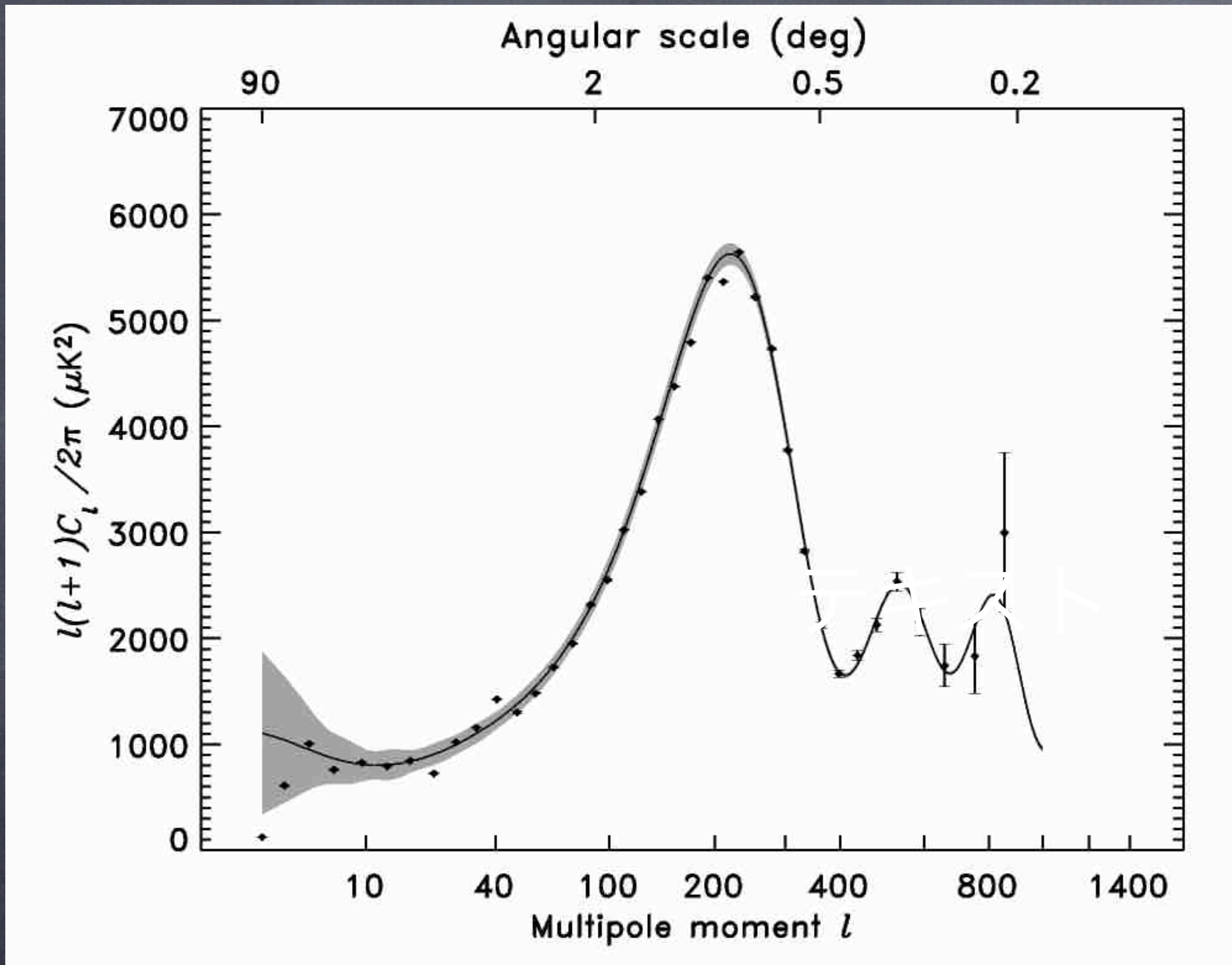
WMAP (Wilkinson Microwave Anisotropy Probe)

First detailed full-sky map of the oldest light in the universe



http://map.gsfc.nasa.gov/

Angular Power spectrum



$$\Delta T(\vec{n}) = \sum_{\ell} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\vec{n})$$

$$\langle a_{\ell m} a^{*}_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_{\ell}$$

Bennett et al (2003)

Cosmological Parameters are determined with accuracy <10%

Cosmological Parameters

WMAP only, assuming a flat universe

1. Baryon $\omega_b \equiv \Omega_b h^2 = 0.024 \pm 0.001$
2. Matter $\omega_m \equiv \Omega_m h^2 = 0.14 \pm 0.02$
3. Hubble $h = 0.72 \pm 0.05$
4. Spectral Index $n_s = 0.99 \pm 0.04$
5. Optical Depth $\tau = 0.166^{+0.076}_{-0.071}$

Spergel et al (2003)

WMAP and Neutrino

CMB Fluctuation (Angular Power Spectrum) is also sensitive to Cosmic Background Neutrinos

→ WMAP provides useful constraints on properties of Cosmic Neutrinos

- Neutrino Mass
- Number of Neutrino Species
- . . . .

Plan of Talk

1. Introduction
2. WMAP Constraint on Neutrino Mass
3. Limit on Number of Neutrino Species
4. Conclusion

Masses of Neutrinos

- Oscillation Experiments (SK, K2K, SNO, Kamland)

$$\delta m_{12} = \left| m_2^2 - m_1^2 \right| \simeq 7 \times 10^{-5} \mathrm{eV}^2$$

$$\delta m_{23} = \left| m_3^2 - m_2^2 \right| \simeq 3 \times 10^{-3} \mathrm{eV}^2$$

- Tritium Beta Decay

$$m_{\nu_e} < 3 \text{ eV} \quad \text{(PDG2005)}$$

- Dobble Beta Decay

$$\langle m_\nu \rangle = \left| \sum U_{1j}^2 m_{\nu_j} \right| \lesssim 1 \text{ eV}$$

- Cosmological Constraint

Effect of Neutrino Mass on CMB

assuming $m_{\nu_1} = m_{\nu_2} = m_{\nu_3}$

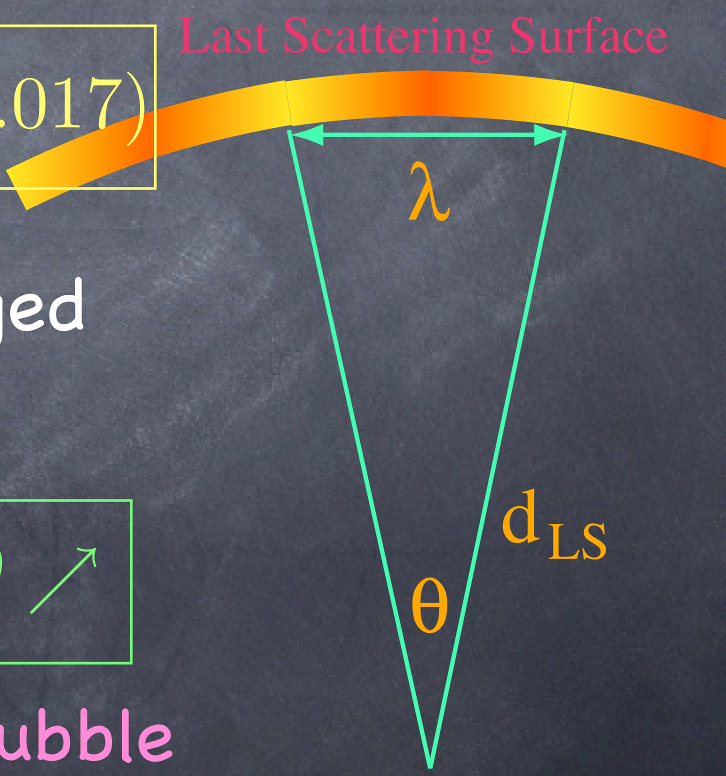
Neutrino becomes non-relativistic at

$$1 + z_{\rm nr} \simeq 6.2 \times 10^4 \Omega_\nu h^2$$

⟺ recombination $z_{\rm rec} \simeq 1088$

⇓

$$z_{\rm nr} > z_{\rm rec} \; (m_{\nu,tot} > 1.6 \text{ eV}, \; \Omega_\nu h^2 > 0.017)$$



I. Position of acoustic peaks are changed

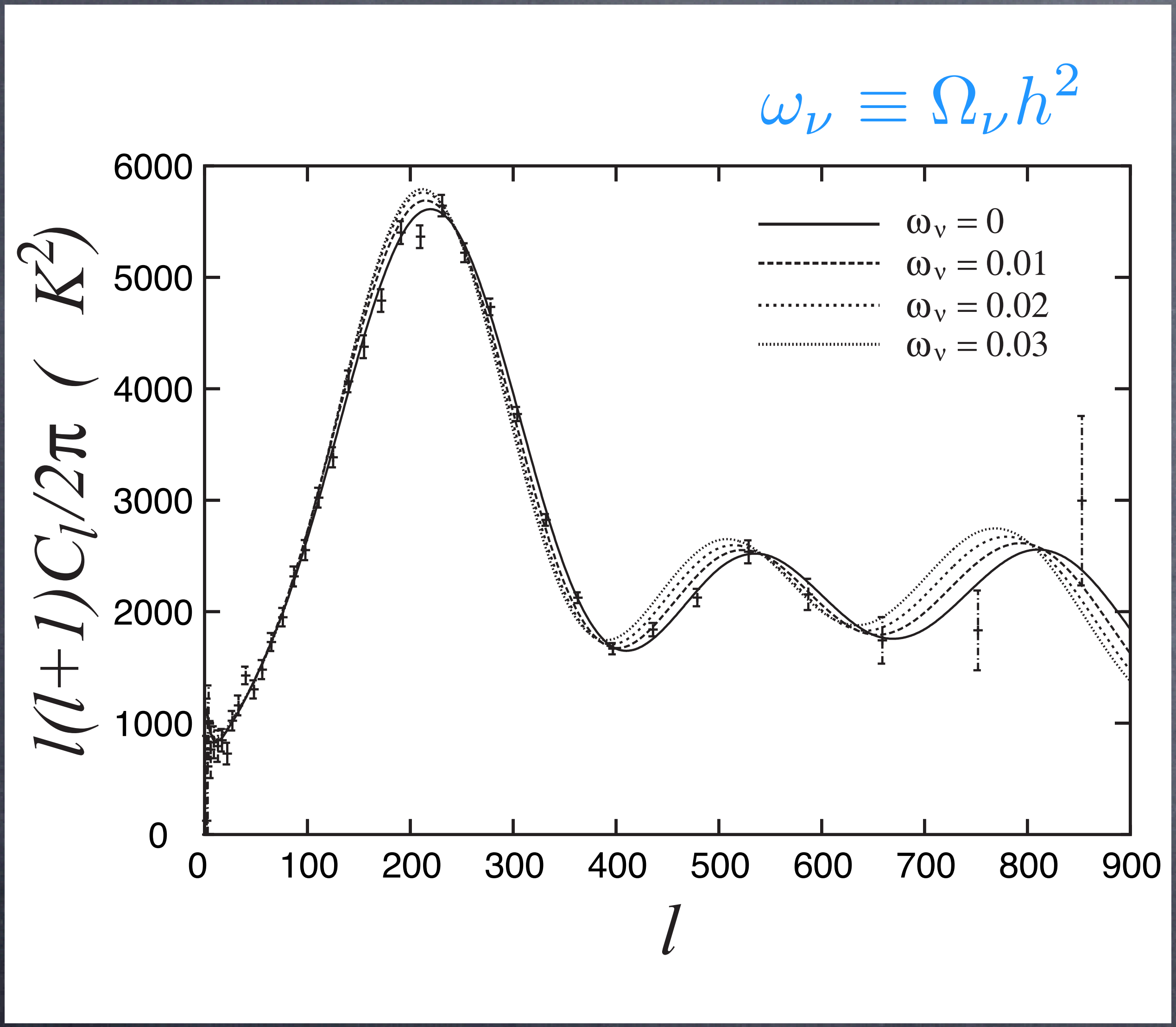
$$z_{\rm nr} < z_{\rm rec}$$

$$\Omega_\nu \nearrow \; \Rightarrow \; \Omega_\Lambda \searrow \; \Rightarrow \; d_{\rm LS} \searrow \; \Rightarrow \; \theta \nearrow$$

compensated by decrease of Hubble

II. Acoustic peaks are enhanced

$z_{\mathrm{nr}} > z_{\mathrm{rec}}$



neutrino: relativistic → non-relativistic

⇓

Faster Decay of Gravitational Potential

⇓

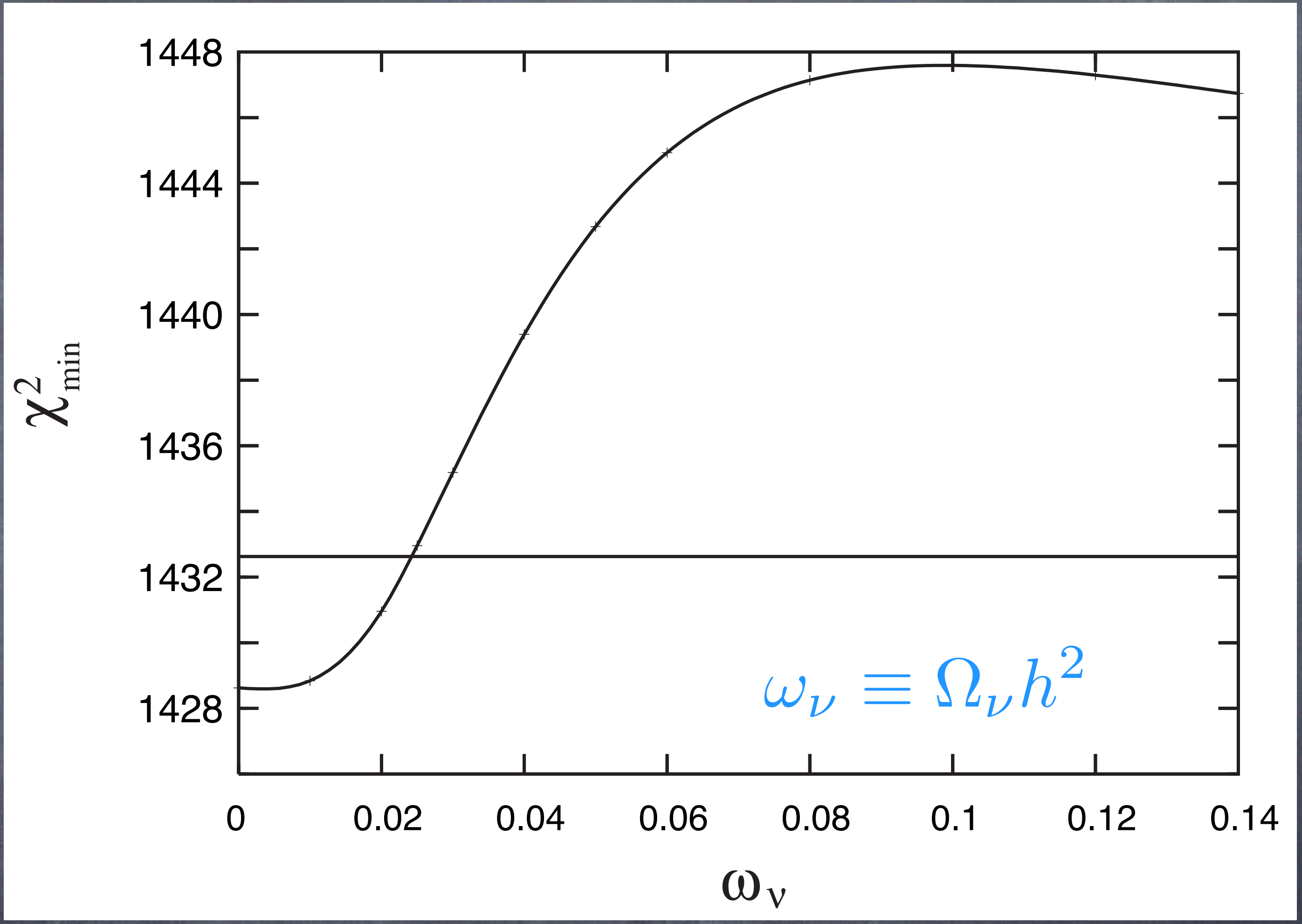
More forcing of acoustic oscillation

WMAP Constraint on Neutrino Mass

WMAP only

minimizing chi2 with 6 cosmological parameters

[Ichikawa, Fukugita, MK (2004)]



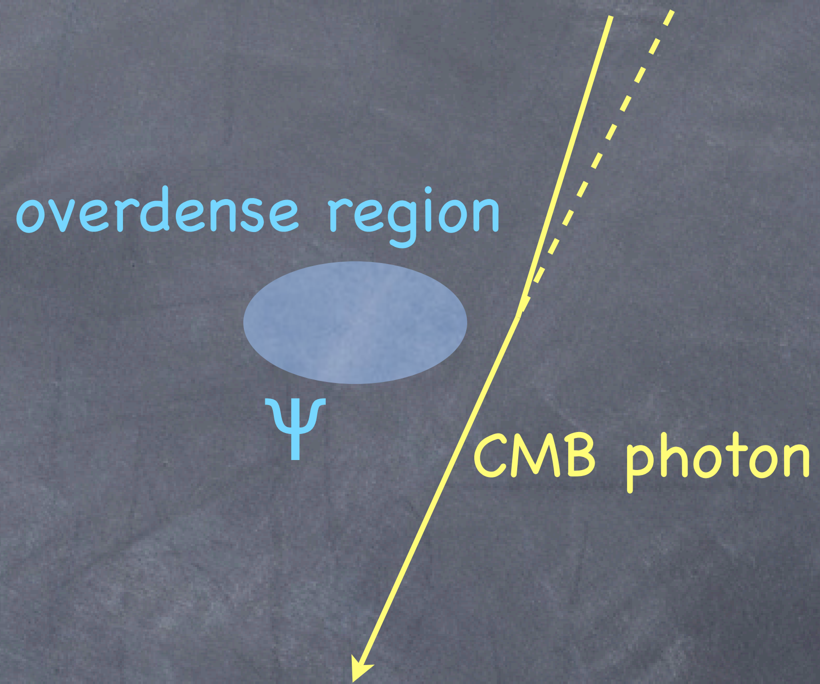
→ $\sum m_\nu < 2.0$ eV $\quad (\Omega_\nu h^2 < 0.021)$

$m_\nu < 0.66$ eV (→ In future $m_\nu < 0.5$ eV)

$z_{\rm nr} > z_{\rm rec}$

III. Gravitational Lensing

Gravitational field distorts the paths traveled by CMB photons



High resolution maps of CMB temperature and polarization anisotropies

↓

Deflection angle (d) power spectrum

$$d = \nabla\phi$$

$$\phi = -2\int dr\Psi(r\hat{n}, r)(r - r_s)/(rr_s)$$

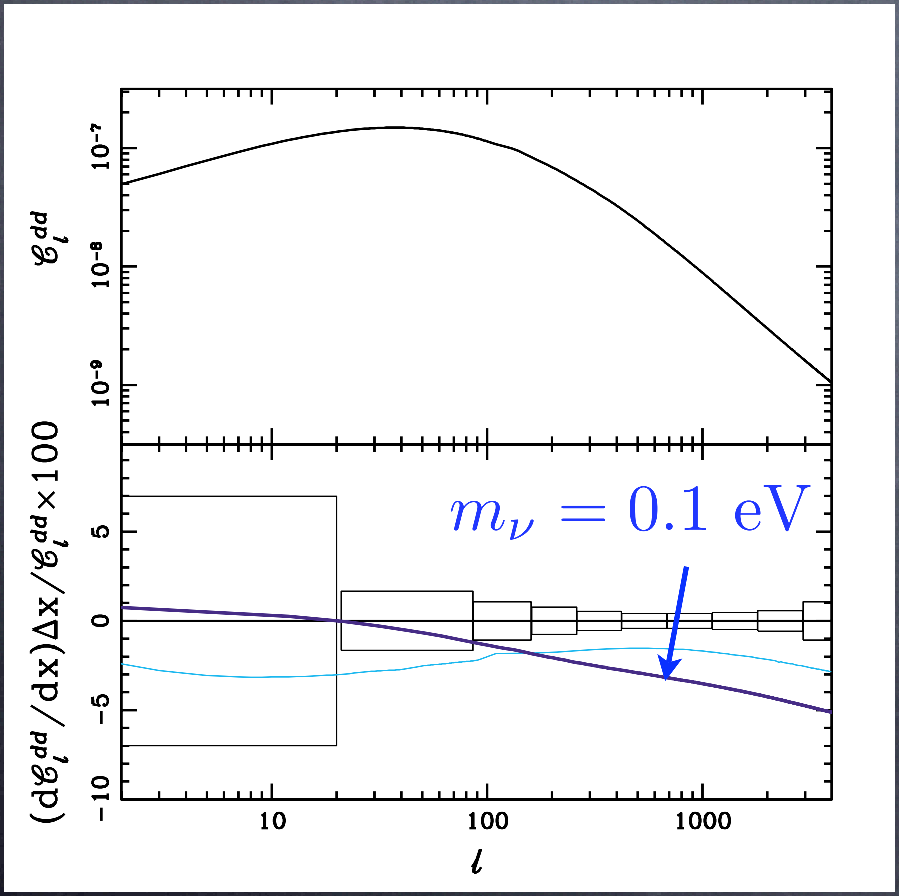
↑

Line-of-sight projection of the gravitational potential ϕ

Massive Neutrino

$$z_{\rm nr} < z_{\rm rec}$$

- Changes gravitational potential after recombination
- Changes deflection angle power spectrum



Planck has a sensitivity down to 0.15 eV

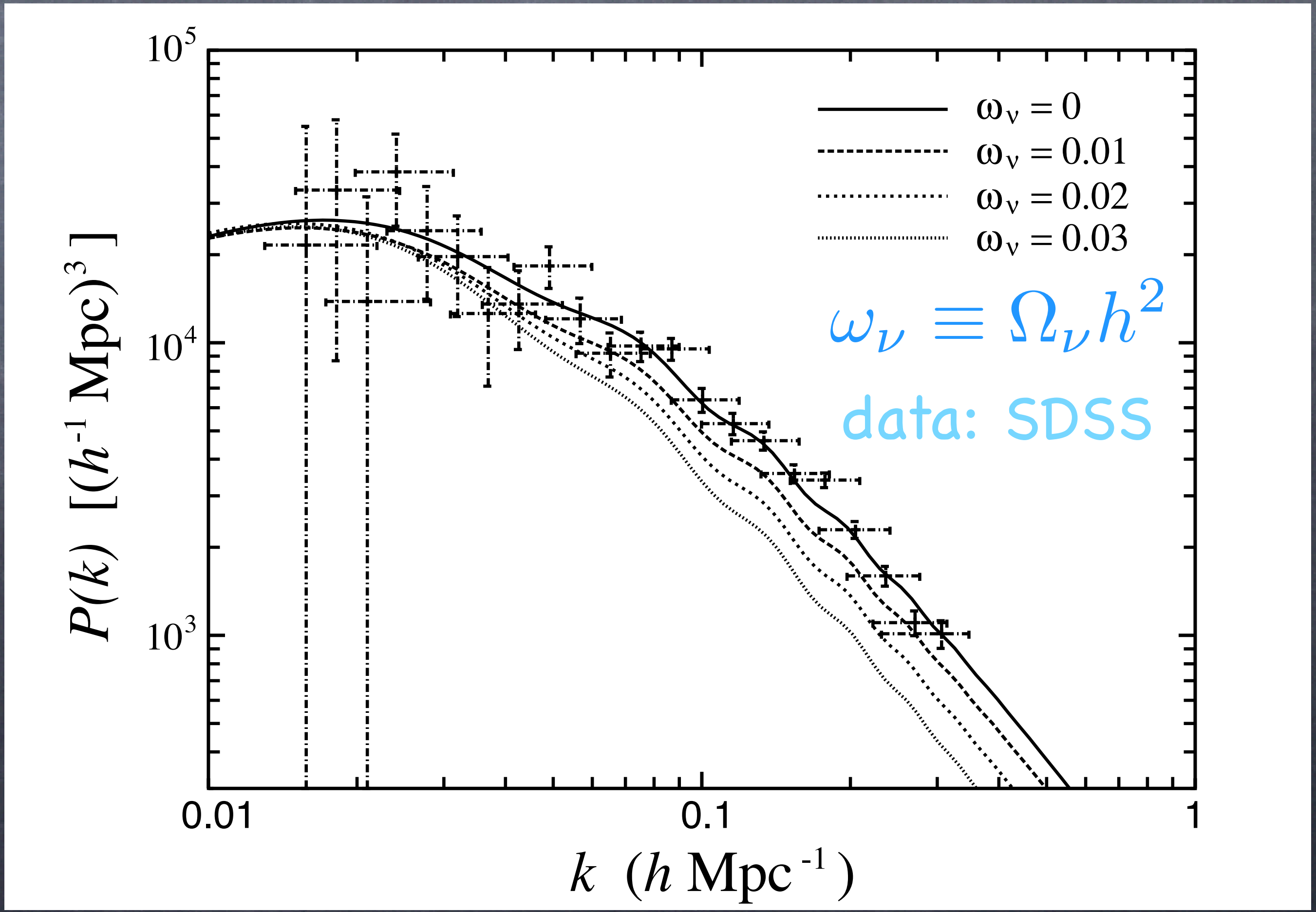
[Kaplinghat (2003)]

Other Cosmological Effects of m_ν

Neutrino Free Streaming

⇨ Erases density perturbations on small scales

⇨ Changes Spectrum of Matter Fluctuations



Constraints from CMB and LSS

CMB	LSS	Other data	Limit (eV)	Ref.
WMAP+CBI+ACBAR	2dFGRS	Lyα	0.71	Spergel et al (2003)
WMAP+CBI+ACBAR	2dFGRS	HST,SNIa	1.01	Hannestad (2003)
WMAP+Wang comp.	2dFGRS	X-ray	$0.56^{+0.30}_{-0.26}$	Allen et al (2003)
WMAP	SDSS	–	1.7	Tegmark et al (2003)
WMAP	2dFGRS +SDSS	–	0.75	Barger et al (2003)
WMAP+ACBAR	2dFGRS +SDSS	–	1.0	Crotty et al (2004)
WMAP	SDSS	Bias	0.54	Sejlak et al (2004)
WMAP	–	–	2.0	Ichikawa et al (2004)

Problem in using LSS data

Spectrum of Matter Fluctuations

⇧

Galaxy Survey (2dFGRS, SDSS)

However, $\delta_m \neq \delta_{galaxy}$

uncertain

$$P(k)_{galaxy} = b^2 P(k)_m$$

b: bias

Without information on bias
stringent constraint cannot be derived

For example

Tegmark et al $m_{\nu,tot} < 1.7\ \mathrm{eV}$ [only use shape of P(k)]

Spergel et al $m_{\nu,tot} < 0.71\ \mathrm{eV}$ [shape & amplitude of P(k)]

Number of Neutrino Species N_ν

Why is N_ν important?

$$N_\nu = \frac{\rho_\nu}{\rho_{\nu,eq}}$$

- Sterile Neutrino or New Particles may exist

$$N_\nu \nearrow$$

- Hot Universe may begin at MeV scale

$$N_\nu \searrow$$

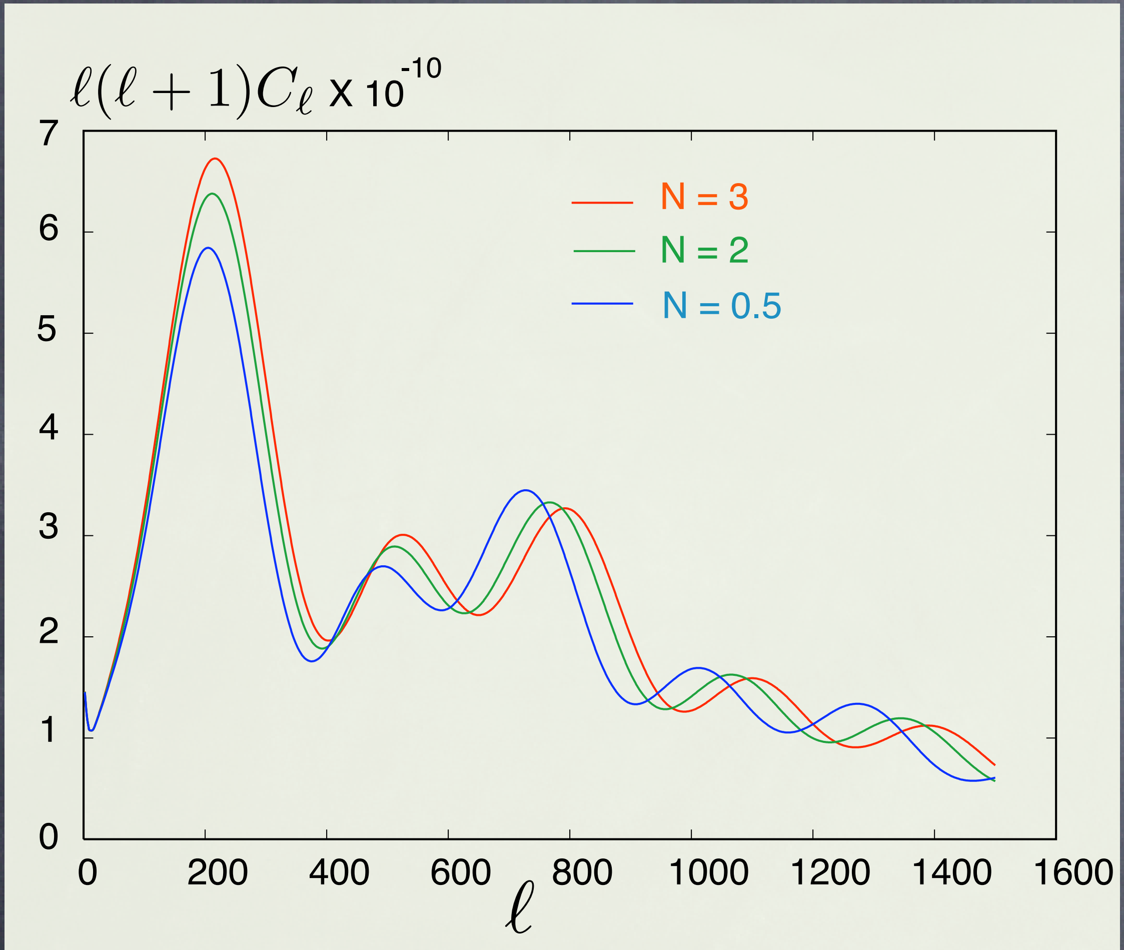
- Dark Radiation from Extra-Dimension

$$H^2 = \frac{8\pi G}{3}\rho + \rho_{dark}$$

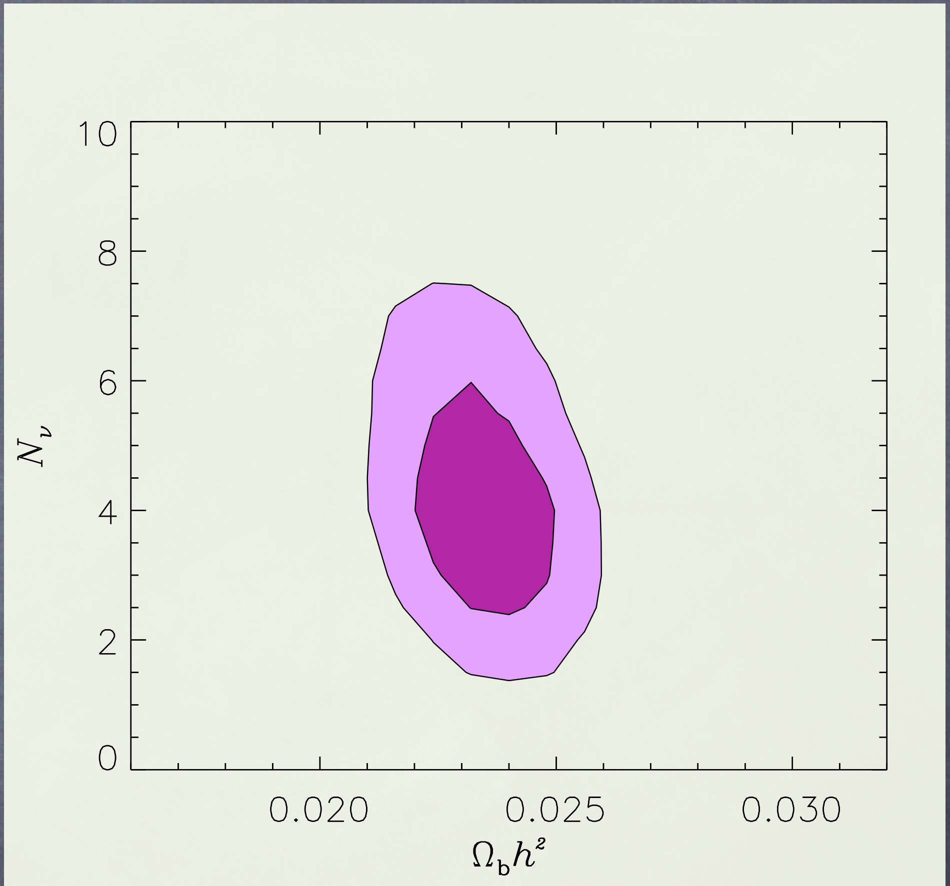
$$N_\nu \searrow \text{ or } \nearrow$$

e.g. Rundall & Sundrum Model (1999),
Shiromizu, Maeda, Sasaki (1999)

CBR Constraint on N_ν



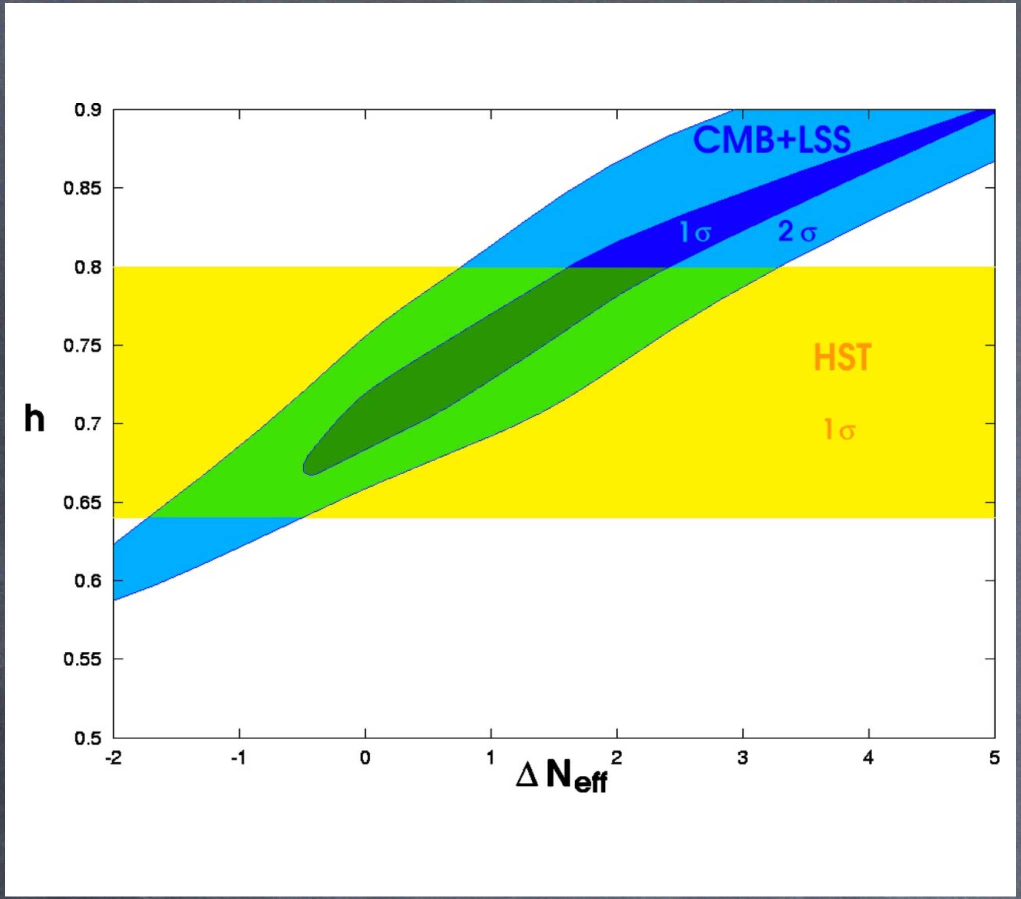
Hannestad (2003)

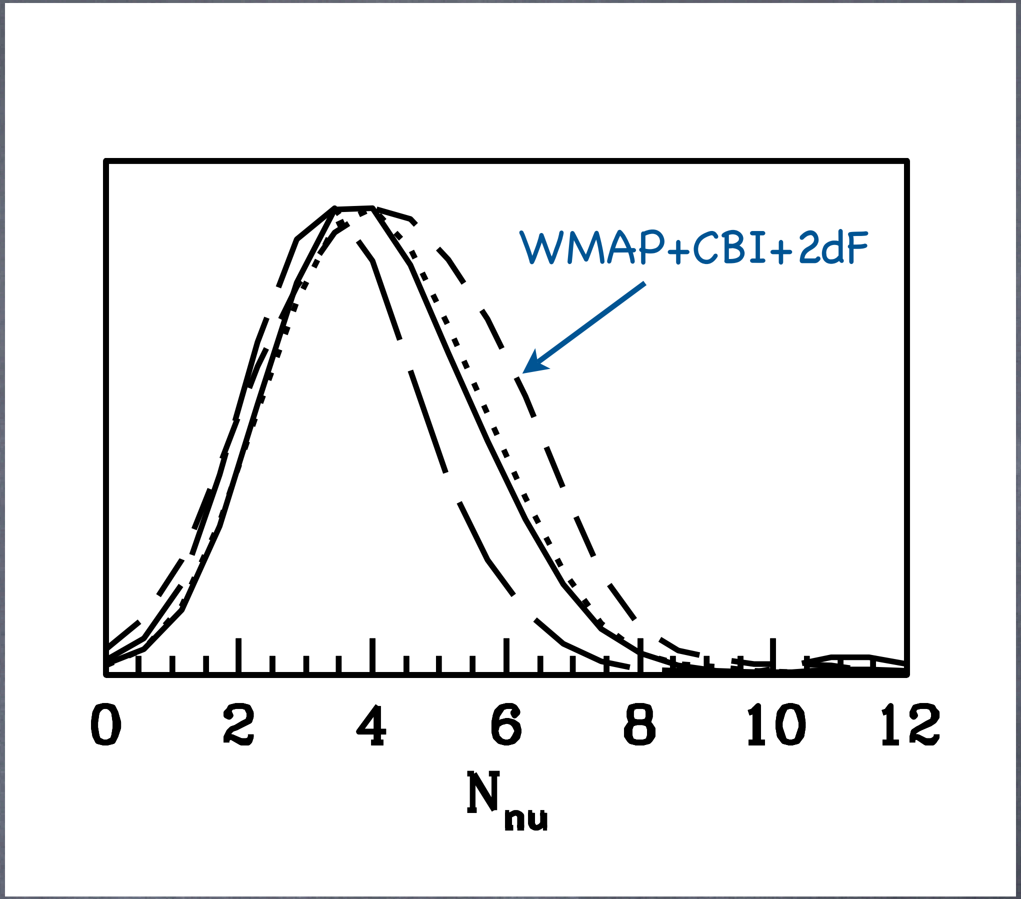


Hannestad (2003)

WMAP only $N_\nu = 2.1^{+6.7}_{-2.2}$ (95%CL)

WMAP + 2dF $N_\nu = 3.1^{+3.9}_{-2.8}$





Crotty, Lesgourgues, Pastor (2003)

WMAP + Wang comp.+2dF

$$N_\nu = 3.5^{+3.3}_{-2.1}$$

Pierpaoli(2003)

WMAP + CBI.+2dF

$$N_\nu = 4.3^{+2.8}_{-1.7}$$

CBR+BBN

BBN can impose a stringent limit on N ν

$$N_\nu \nearrow \quad \Rightarrow \quad Y_p \nearrow$$

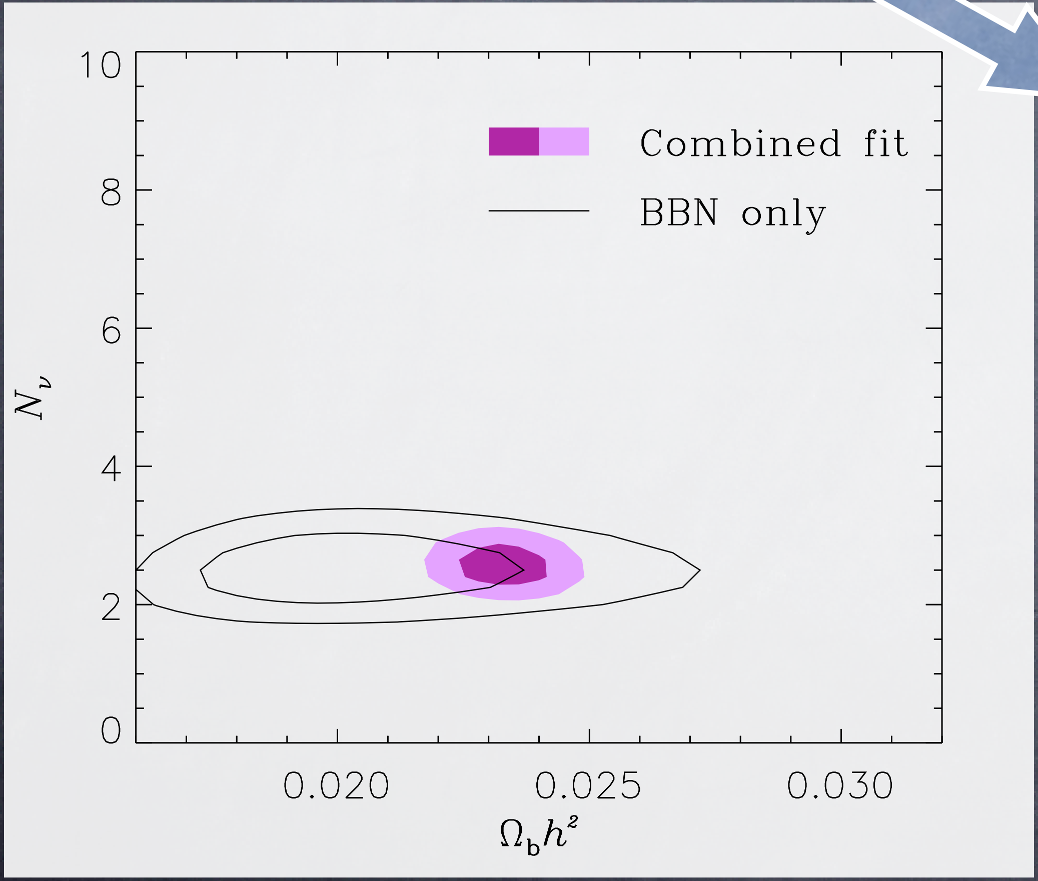
Fields, Olive (1998)

$$Y_p = 0.238 \pm 0.005$$

More systematic errors?

Olive, Skillman (2004)

$$Y_p = 0.249 \pm 0.009$$

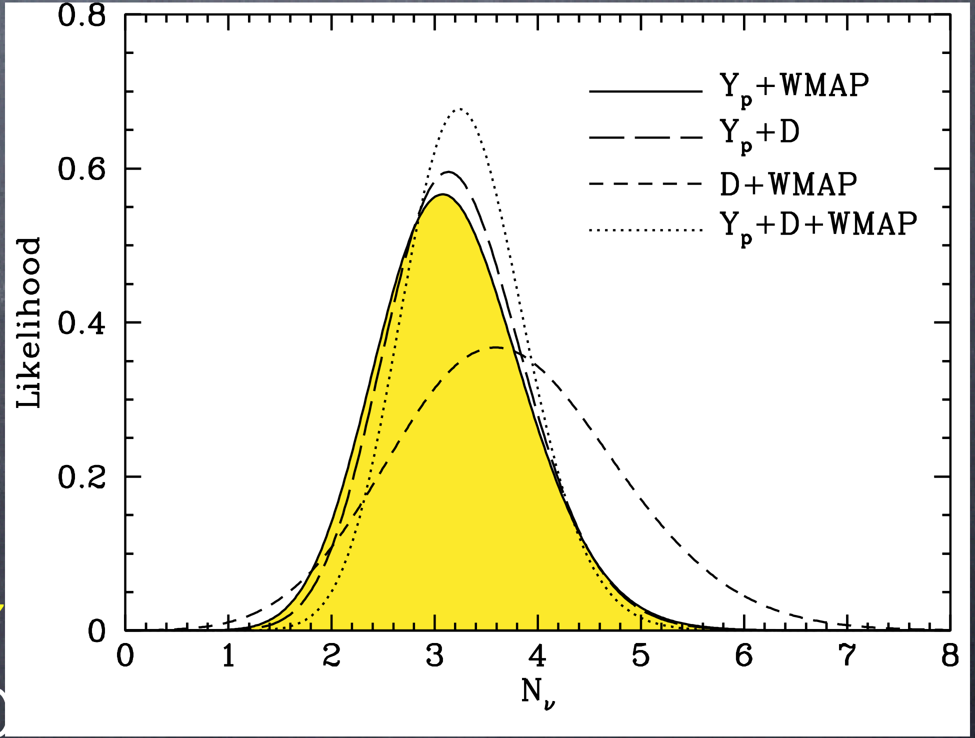


Hannestad (2003)

$$N_\nu = 2.6^{+0.4}_{-0.3}$$

$$N_\nu = 3.1 \pm 0.7$$

Cyburt et al (2005)

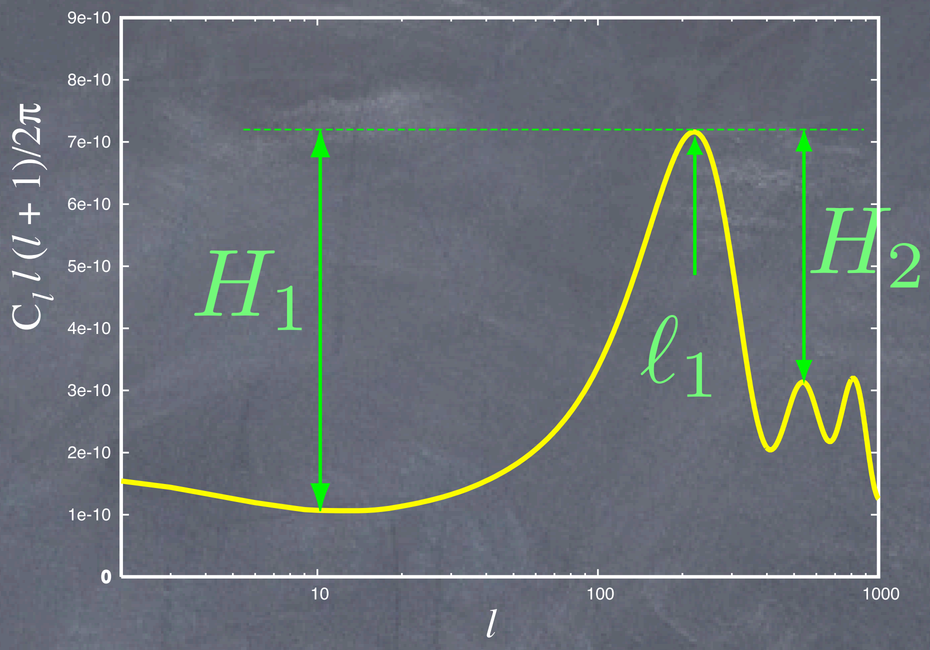


Summary

* WMAP provides a more stringent limit on neutrino mass than laboratory experiments
* Together with large scale structure data improve the limit
* WMAP also give a constraint on the number of neutrino specie

h and ω_ν degeneracy

$$\omega_\nu \equiv \Omega_\nu h^2$$



$$\Delta\ell_1 = 17\frac{\Delta\omega_b}{\omega_b} - 26\frac{\Delta\omega_m}{\omega_m} \boxed{-44\frac{\Delta h}{h}} + 36\frac{\Delta n_s}{n_s} \boxed{-532\Delta\omega_\nu}$$

$$\Delta H_1 = 3.3\frac{\Delta\omega_b}{\omega_b} - 3.1\frac{\Delta\omega_m}{\omega_m} - 2.5\frac{\Delta h}{h} + 18\frac{\Delta n_s}{n_s} - 1.6\frac{\Delta\tau}{\tau} + 9.8\Delta\omega_\nu$$

$$\Delta H_2 = -0.31\frac{\Delta\omega_b}{\omega_b} - 0.0093\frac{\Delta\omega_m}{\omega_m} + 0.42\frac{\Delta n_s}{n_s} - 0.19\Delta\omega_\nu$$

Ichikawa, Fukugita, MK (2004)