Neutrino mass constraint from CMB and its degeneracy with the Hubble constant

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CMB alone limit (95% C.L.)

We assume 3 species of neutrinos with degenerate mass hierarchy.

$$\sum m_\nu = 3m_\nu$$

WMAP1:

$m_\nu < 0.66\,\mathrm{eV}$ *KI, Fukugita & Kawasaki, 2005*

$m_\nu < 0.70\,\mathrm{eV}$ *Hannestad, 2006*

$m_\nu < 0.63\,\mathrm{eV}$ *Lesgourgues & Pastor, 2006*

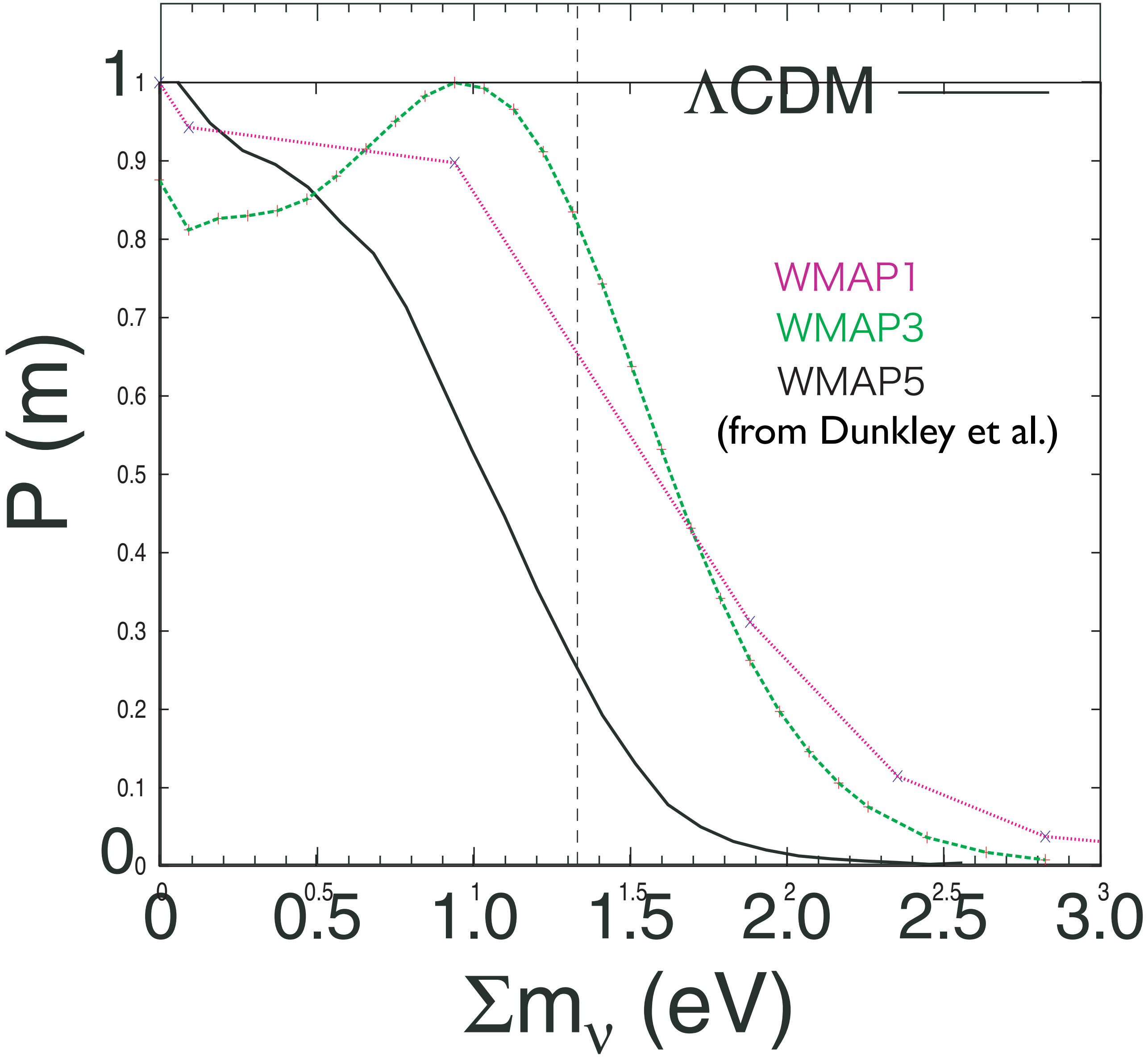
WMAP3:

$m_\nu < 0.60\,\mathrm{eV}$ *Spergel et al., 2007*

$m_\nu < 0.60\,\mathrm{eV}$ *Fukugita, KI, Kawasaki, Lahav, 2006*

WMAP5:

$m_\nu < 0.43\,\mathrm{eV}$ *Komatsu et al., 2008*



Limits for mass sum:

2.0 eV

1.8 eV

1.3 eV

Massive neutrinos become nonrelativistic before the epoch of recombination if $m_\nu \gtrsim 0.6\ \mathrm{eV}$

The epoch of recombination z_{rec} ~ 1088

Tnu,now ~ 1.9 K ~ 2 x 10^{-4} eV
Tnu,rec ~ 2 x 10^{-1} eV

<p> ~ 3 T [average over Fermi distribution with temperature T]

Neutrinos on average become nonrelativistic when <p> ~ m

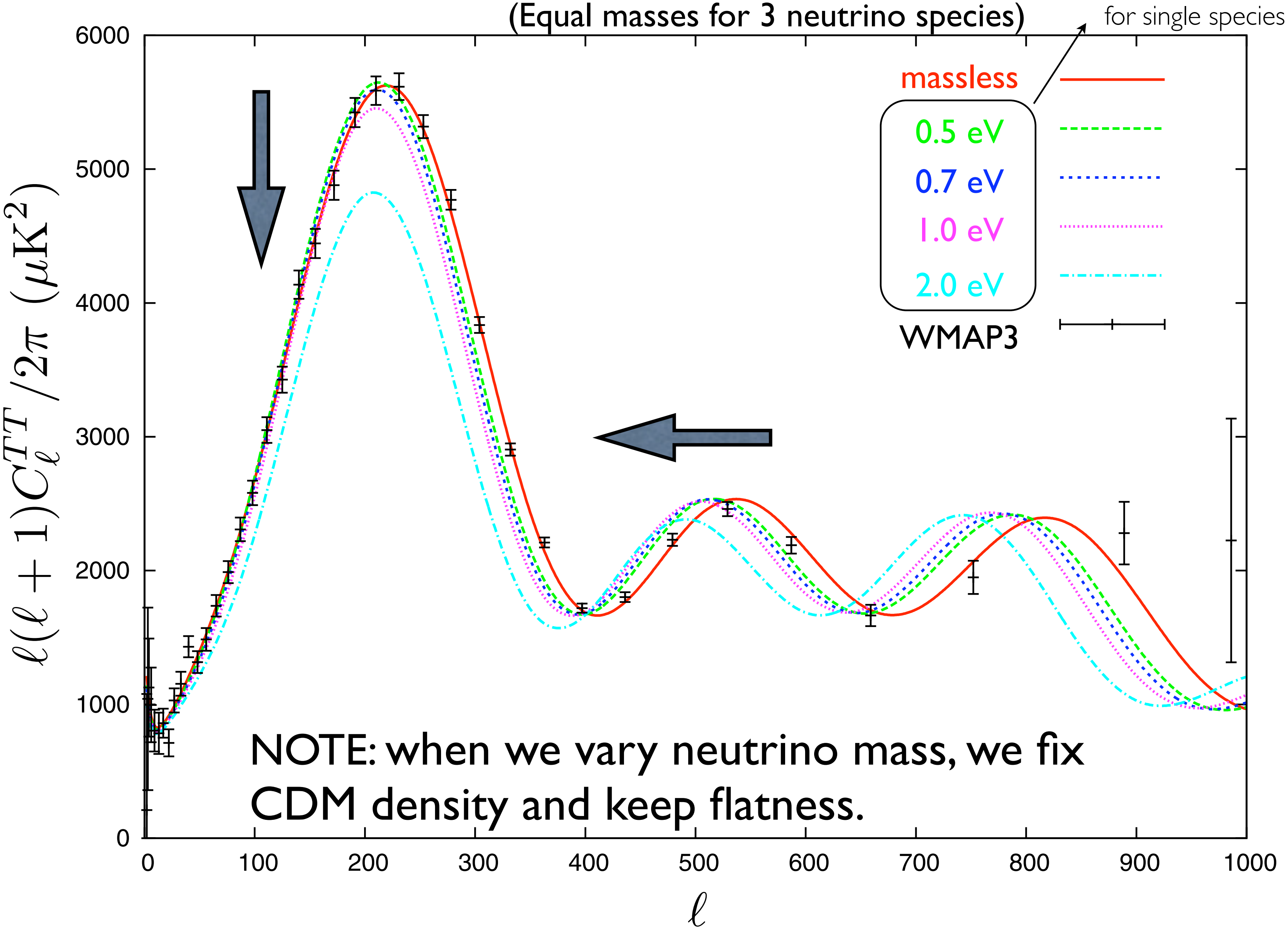
m ~ 3 Tnu,rec ~ 0.6 eV

⇒ Characteristic signals imprinted in acoustic peaks.

⇒ Can be constrained by CMB.

Effect of neutrino masses on CMB power spectrum

(Equal masses for 3 neutrino species)



NOTE: when we vary neutrino mass, we fix CDM density and keep flatness.

1. Horizontal shift (to smaller multipoles)

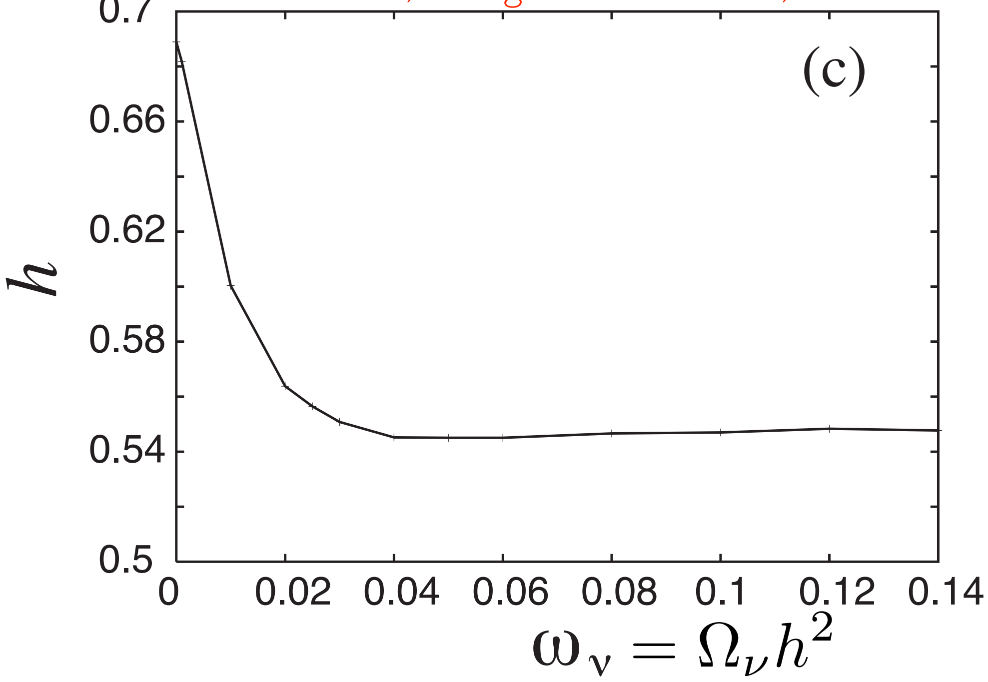
$m_\nu \uparrow$ makes the distance to the last scattering surface smaller.

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94.1\ \mathrm{eV}} \Longrightarrow$$

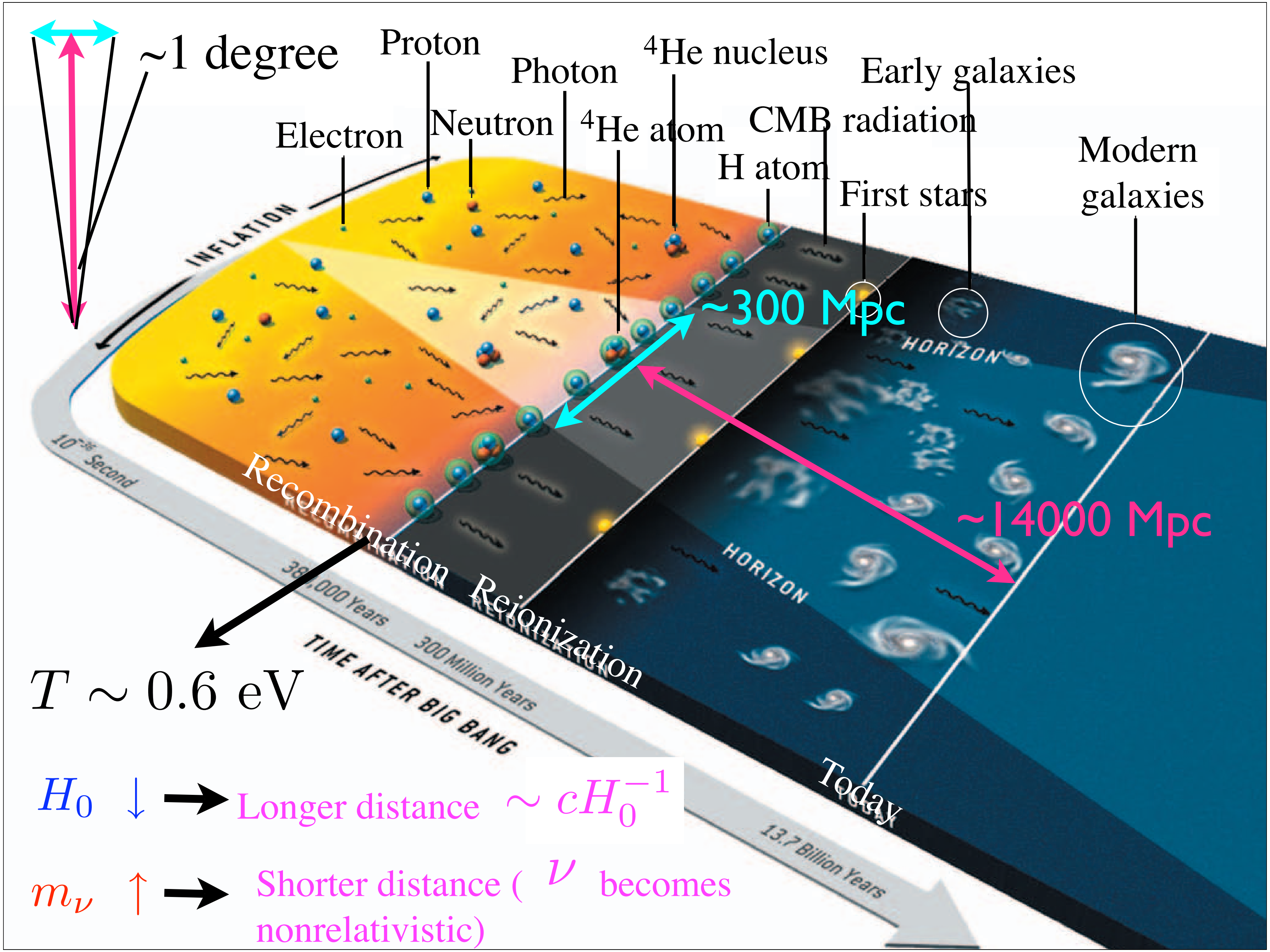
1eV corresponds to $\Omega_\nu h^2 \sim 0.03$

But this effect is absorbed by decreasing the Hubble constant.

KI, Fukugita & Kawasaki, 2005



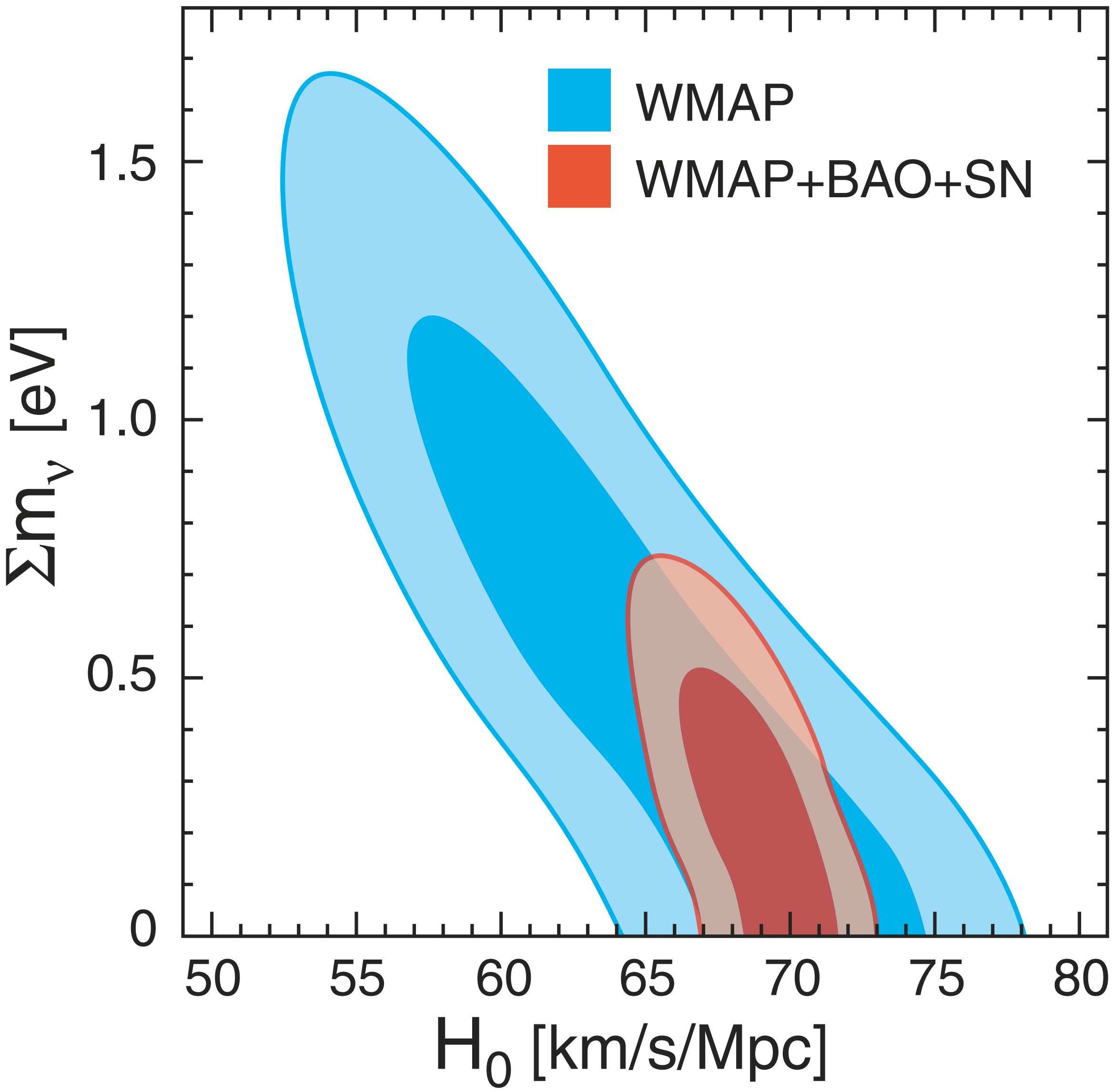
Hubble parameter which gives best fit for each mnu. (WMAP1)



$T \sim 0.6$ eV

H_0 ↓ → Longer distance $\sim cH_0^{-1}$

m_ν ↑ → Shorter distance (ν becomes nonrelativistic)



Komatsu et al., 2008

$m_\nu - H_0$ degeneracy

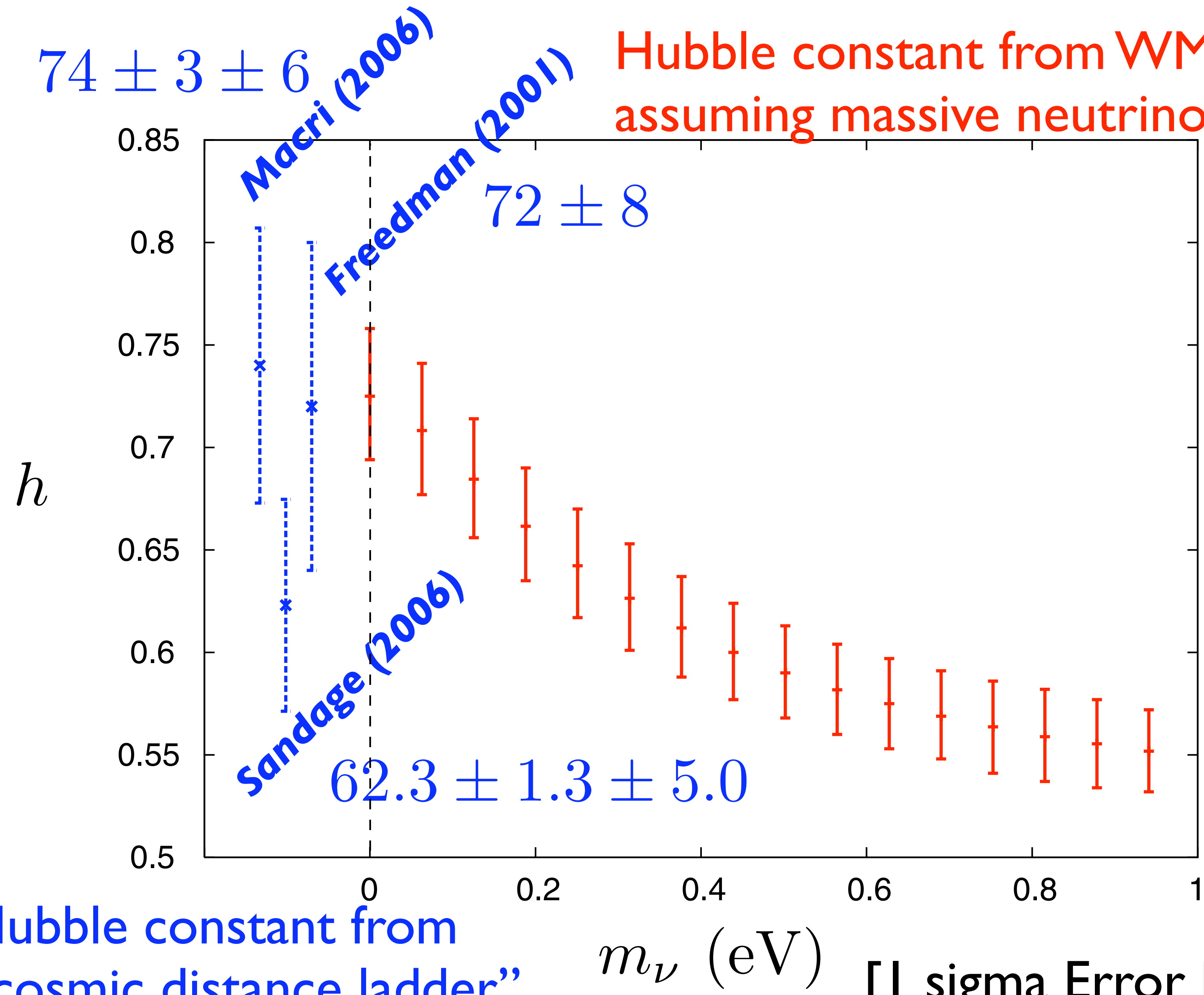
1. Use this to push down the mnu limit.
   If H0 is bounded from below externally (e.g. by distance ladder, BAO, SN etc), more stringent limit could be obtained.

or

2. We thought H0 is determined very precisely (71.9 +/- 2.6) by WMAP but this assumes massless neutrinos.

   Uncertainty of m_ν is one of the largest systematic errors for estimating cosmological parameters from CMB.
   If neutrino mass is detected to be m_ν > 0.3 eV, it would be more consistent with the people claiming a small Hubble constant < 65.

Hubble constant from WMAP3
assuming massive neutrinos

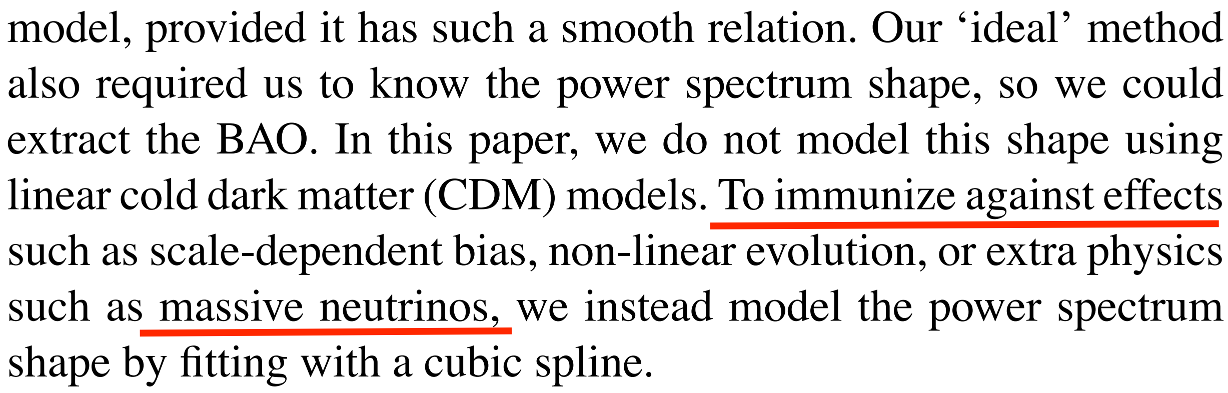


Hubble constant from
“cosmic distance ladder”

[1 sigma Error bars]

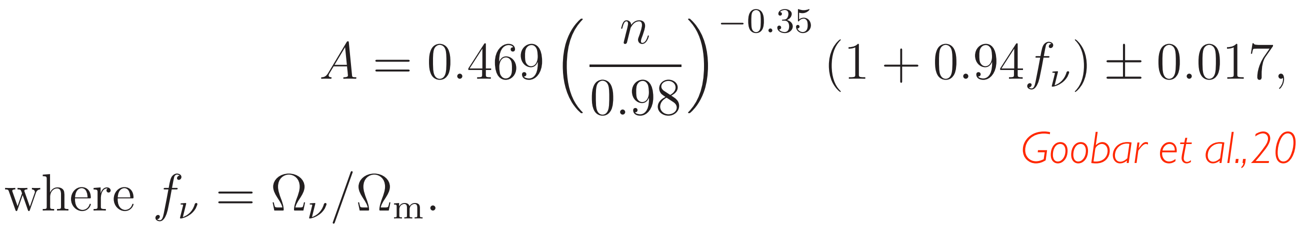
BAO

Percival et al.,2007



model, provided it has such a smooth relation. Our ‘ideal’ method also required us to know the power spectrum shape, so we could extract the BAO. In this paper, we do not model this shape using linear cold dark matter (CDM) models. To immunize against effects such as scale-dependent bias, non-linear evolution, or extra physics such as massive neutrinos, we instead model the power spectrum shape by fitting with a cubic spline.

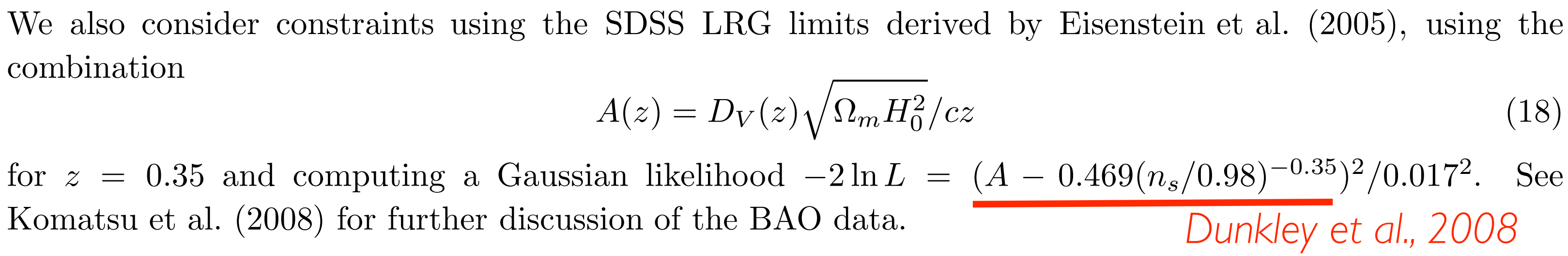
seems to be more robust than the BAO peak measured from correlation function (Eisenstein et al. 2005)



$$A = 0.469\left(\frac{n}{0.98}\right)^{-0.35}(1 + 0.94 f_\nu) \pm 0.017,$$

where $f_\nu = \Omega_\nu/\Omega_{\rm m}$.

Goobar et al.,2006



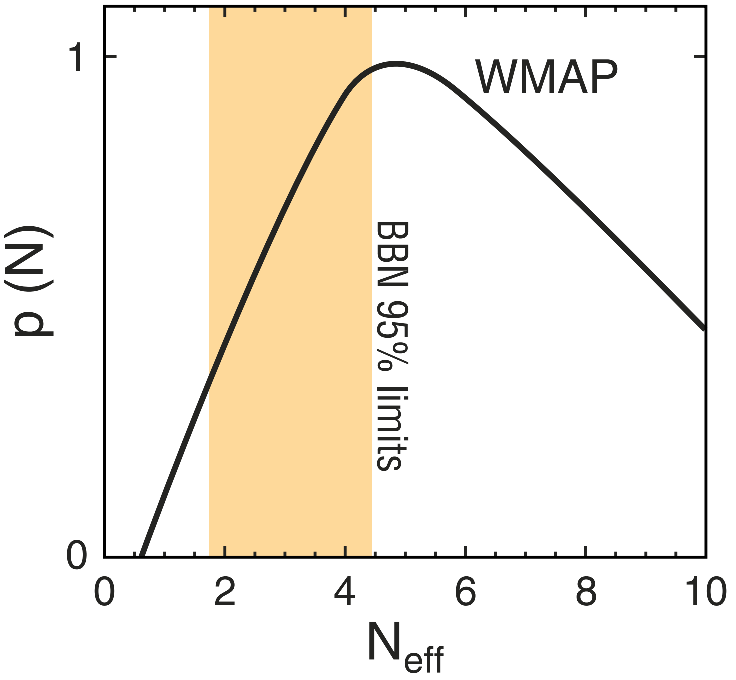
We also consider constraints using the SDSS LRG limits derived by Eisenstein et al. (2005), using the combination

$$A(z) = D_V(z)\sqrt{\Omega_m H_0^2}/cz \qquad (18)$$

for $z = 0.35$ and computing a Gaussian likelihood $-2\ln L = (A - 0.469(n_s/0.98)^{-0.35})^2/0.017^2$. See Komatsu et al. (2008) for further discussion of the BAO data.

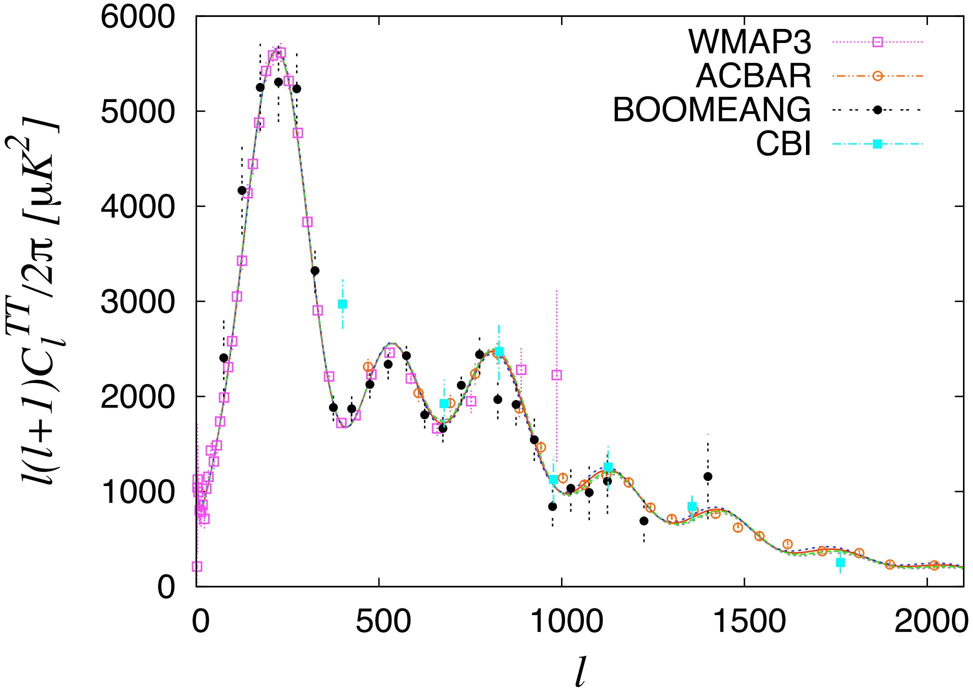
Dunkley et al., 2008

Nnu

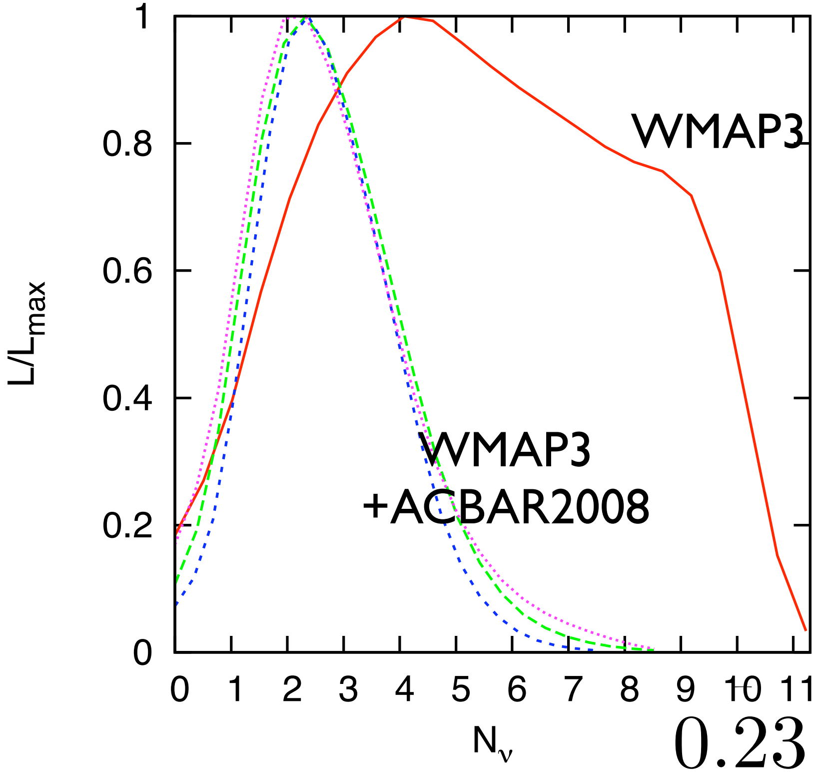


Dunkley et al., 2008

$$N_{\rm eff} > 2.3 \ (95\% \ {\rm CL}).$$



KI, Sekiguchi, T.Takahashi, arXiv:0803.0889



CMB alone limit

$$0.23 < N_\nu < 5.54 \text{ at } 95\,\%\,\text{C.L.}$$

Implication of the lower limit on N for low (MeV-scale) reheating temperature scenario

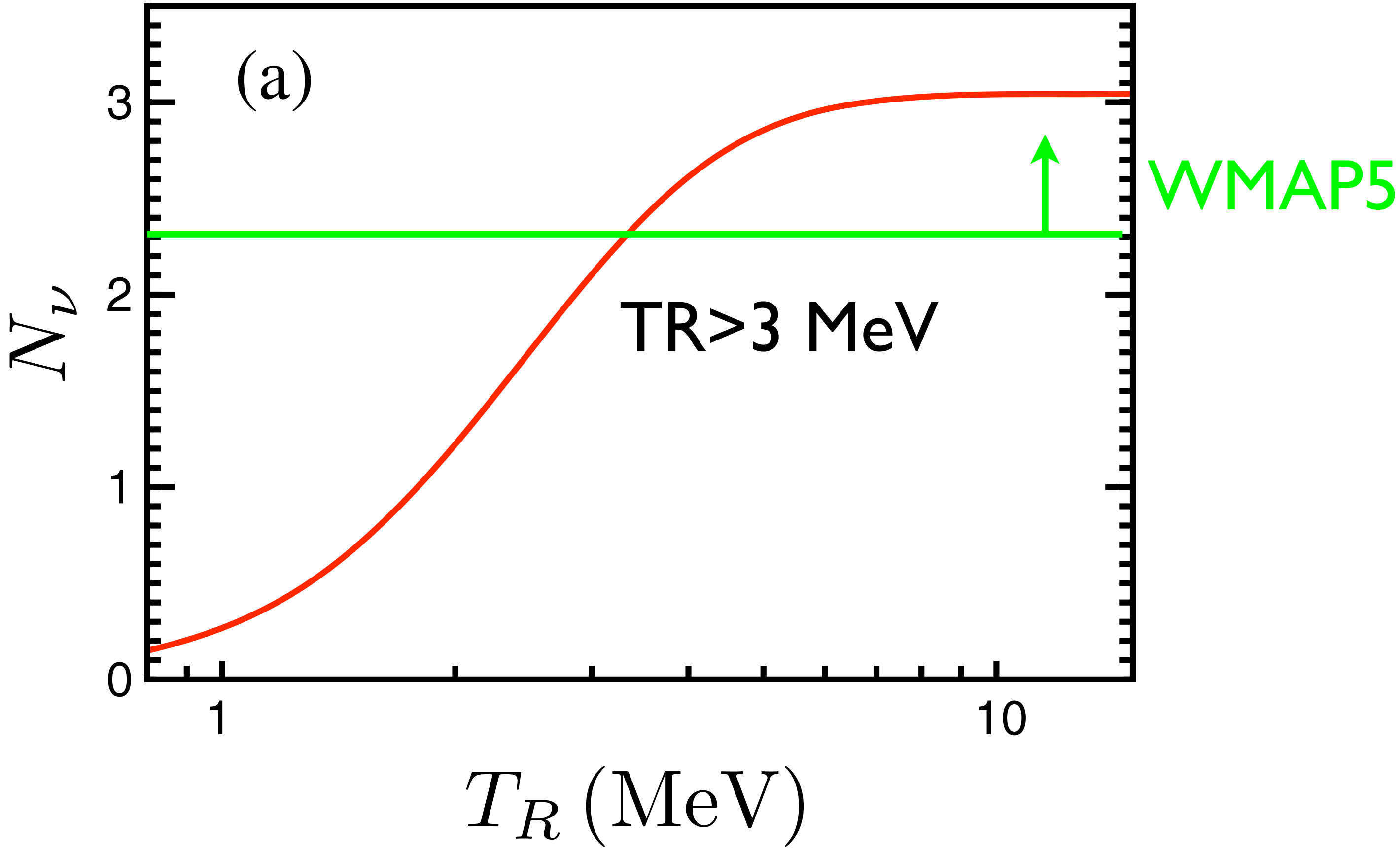
The universe was not very hot.
Neutrinos are not fully thermalized
(do not obey a Fermi distribution)

$$N_\nu = \frac{\rho_{\rm rel} - \rho_\gamma}{\rho_{\nu,\rm thm}} \qquad \rho_{\nu,\rm thm} = \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T^4$$

Fermi distribution

Implication of the lower limit on N for low (MeV-scale) reheating temperature scenario

KI, Kawasaki, F.Takahashi, PRD72,043522 (2005)



The universe needs to be heated at least to 3 MeV.