Constraints on neutrinos from the measurement of cosmic microwave background

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Two angular scales

- **Sound horizon scale**
  Very precisely measured by the locations of acoustic peaks (0.06% from Planck in LCDM)

- **Photon diffusion damping scale**
  0.2% precision from Planck in LCDM
Two angular scales

\[ \theta_s \]

\[ \theta_d \]

\[ N_{\text{eff}} = 3.0 \]
Two angular scales fixing $\Omega_b h^2$, $z_{eq}$, $\theta_s$
Two angular scales

\[ \theta_s, \theta_d \]

\[ N_{\text{eff}} = 0.2 \]
Two angular scales

\[ \theta_s, \theta_d \]

\[ N_{\text{eff}} = 10 \]
fixing $\Omega_b h^2$, $z_{eq}$, $\theta_s$

$N_{eff} = 1$

$N_{eff} = 5$

Hou et al., arXiv:1104.2333
fixing $\Omega_b h^2$, $z_{eq}$, $\theta_s$, $\theta_d$
fixing $\Omega_b h^2$, $z_{eq}$, $\theta_s$, $\theta_d$
Phase shift

$\Lambda$CDM + $N_{\text{eff}} + Y_p$

Hou et al., 2012
Planck 2013, XVI

WMAP7+SPT
Planck+WP+ highL

$Y_p$

$N_{\text{eff}}$

BBN

Hou et al., 2012
Planck 2013, XVI

$10^{s/\theta}$ $10^{s/\theta}$
\[ \Lambda CDM + N_{\text{eff}} + Y_p \]

- **Hou et al., 2012**
- **WMAP7 + SPT**
- **Planck + WP + highL**

- **Bashinsky & Seljak, 2004**
- **Hou et al., 2012**
- **Planck 2013, XVI**

**Phase shift**
Neutrino mass imprint on CMB by ISW

fixing $\Omega_b h^2$, $\Omega_c h^2$, $\theta_s$

Increased by early-time ISW

Decreased by late-time ISW

Decreased by early-time ISW

$C_\ell (\Sigma m_\nu = 0.5 \text{ eV})$

$C_\ell (\Sigma m_\nu = 1.0 \text{ eV})$

Hou et al., 2012
Expansion rate with neutrino mass

fixing $\Omega_b h^2$, $\Omega_c h^2$, $\theta_s$
BAO, H0 and neutrino mass

$10^2 r_s (z_{drag})/D_V(0.57)$

$\Lambda$CDM+$\Sigma m_\nu$

WMAP7+SPT

$\Lambda$CDM+$\Sigma m_\nu$

Planck+WP+highL

Hou et al., 2012

$H_0 [\text{km s}^{-1}\text{Mpc}^{-1}]$

$\Sigma m_\nu [\text{eV}]$
CMB lensing and neutrino mass

\[ P/P_{\text{max}} \]

\[ \Sigma m_{\nu} \ [\text{eV}] \]

Planck 2013, XVI

Planck + WP + highL
Planck + WP + highL(A_L)
CMB lensing and neutrino mass

$f_{\phi} = \frac{1}{C_L} \frac{10^7 \Lambda L (L+1)^2}{(2\pi)}$

fixing $\Omega_b h^2$, $\Omega_c h^2$, $\theta_s$
Summary

- The ratio between $\theta_d$ and $\theta_s$ dominates the constraint on $N_{\text{eff}}$ from CMB temperature power spectrum measurement. The phase shift by neutrino perturbation contributes to further constraint on $N_{\text{eff}}$.

- Important contribution from early ISW effect to neutrino masses constraint.

- Given CMB data, the shape variation of the expansion rate by the neutrino mass – additional sensitivity from BAO, H0 measurement.

- CMB lensing is also important for neutrino masses.