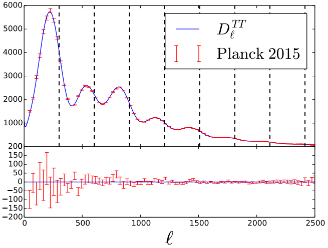
Signatures of Cosmic Neutrinos on Cosmic Microwave Background

Zhen Pan
University of California, Davis

Dec 16, 2015 @ ACFI, Umass

Outline

- Background Information
  I. brief history of the universe
  II. temperature power spectrum:
  acoustic oscillation, diffusion damping
- Signatures of Neutrinos (number)
  I. on background: diffusion damping
  II. on perturbation: phase shift
- Signatures of Neutrinos (mass)
  I. on background: expansion history
  II. on perturbation: large scale structure



Background Information: a brief introduction

Recombination $z \simeq 1100$

Before Recombination: $\gamma + e^- \to \gamma + e^-$

$z \simeq 1100$ Recombination: $e^- + p \to H$

After Recombination: $\gamma \to \gamma$

Background Information: a brief introduction

Recombination $z \simeq 1100$

Before Recombination: $\gamma + e^- \to \gamma + e^-$

$z \simeq 1100$ Recombination: $e^- + p \to H$

After Recombination: $\gamma \to \gamma$

Projection

$\Theta \equiv \delta T / T$

$$\Theta(\hat{\gamma})|_{\vec{x}=0,\eta=\eta_0} \simeq \Theta_0|_{\hat{\gamma}(\eta_0-\eta_\star)}$$

Recombination $z \simeq 1100$

Before Recombination: $\gamma + e^- \to \gamma + e^-$

$z \simeq 1100$ Recombination: $e^- + p \to H$

After Recombination: $\gamma \to \gamma$

Projection

$$\Theta \equiv \delta T / T$$

$$\Theta(\hat{\gamma})|_{\vec{x}=0,\eta=\eta_0} \simeq \Theta_0|_{\hat{\gamma}(\eta_0-\eta_\star)}$$

$$\Theta(\hat{\gamma})|_{\vec{x}=0,\eta=\eta_0} = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{m=\ell} a_{\ell m} Y_{\ell m}(\hat{\gamma})$$

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

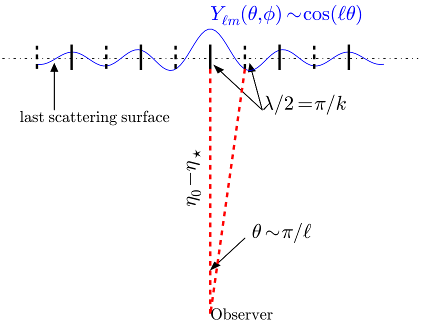


Figure : $\Theta_0^2(k, \eta_\star) \simeq C^{TT}_{\ell \simeq k(\eta_0-\eta_\star)}$

acoustic oscillation + diffusion damping

Tight Coupling Approximation (TCA): $r_{mfp} \ll \lambda$

$$\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = -\, k^2 \Phi_+$$

Inflation inspired initial conditions: $\Theta_0(\eta = 0) = ..., \dot{\Theta}_0(\eta = 0) = 0.$

$$\Theta_0 \sim cos(k \int c_s d\eta) = cos(kr_s(\eta))$$

Taking diffusion into account: $r_d \propto \sqrt{\eta} \sim \sqrt{1/H}$ Hou et.al. (2011)

$$\Theta_0 \sim cos(kr_s) e^{-(kr_d)^2}$$

acoustic oscillation + diffusion damping

Tight Coupling Approximation (TCA): $r_{mfp} \ll \lambda$

$$\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = -k^2 \Phi_+$$

Inflation inspired initial conditions: $\Theta_0(\eta = 0) = ..., \dot{\Theta}_0(\eta = 0) = 0.$

$$\Theta_0 \sim cos(k \int c_s d\eta) = cos(kr_s(\eta))$$

Taking diffusion into account: $r_d \propto \sqrt{\eta} \sim \sqrt{1/H}$ Hou et.al. (2011)

$$\Theta_0 \sim cos(kr_s)e^{-(kr_d)^2}$$

$$N_\nu \to H \to r_d \to e^{-(kr_d)^2}$$

phase shift

Forced Oscillator: $\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = -k^2 \Phi_+$

phase shift

Forced Oscillator: $\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = -k^2 \Phi_+$

$$\Theta_0(kr_s) = \Theta_0(0)\cos(kr_s) - \int_0^{kr_s} d(kr_s')\Phi_+(kr_s')\sin(kr_s - kr_s'),$$

$$\Theta_0 \sim \cos(kr_s + \theta)$$

phase shift

Forced Oscillator: $\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = -k^2\Phi_+$

$$\Theta_0(kr_s) = \Theta_0(0)\cos(kr_s) - \int_0^{kr_s} d(kr_s')\Phi_+(kr_s')\sin(kr_s - kr_s'),$$

$$\Theta_0 \sim \cos(kr_s + \theta)$$

Neglecting Neutrinos: $k^2\Phi_+ \propto \rho_\gamma\delta_\gamma, v_p(\gamma) = c_s$

$$\theta(\eta \to \infty) = 0$$

phase shift

Forced Oscillator: $\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = -k^2 \Phi_+$

$$\Theta_0(kr_s) = \Theta_0(0)\cos(kr_s) - \int_0^{kr_s} d(kr_s')\Phi_+(kr_s')\sin(kr_s - kr_s'),$$

$$\Theta_0 \sim \cos(kr_s + \theta)$$

Neglecting Neutrinos: $k^2\Phi_+ \propto \rho_\gamma \delta_\gamma, v_p(\gamma) = c_s$

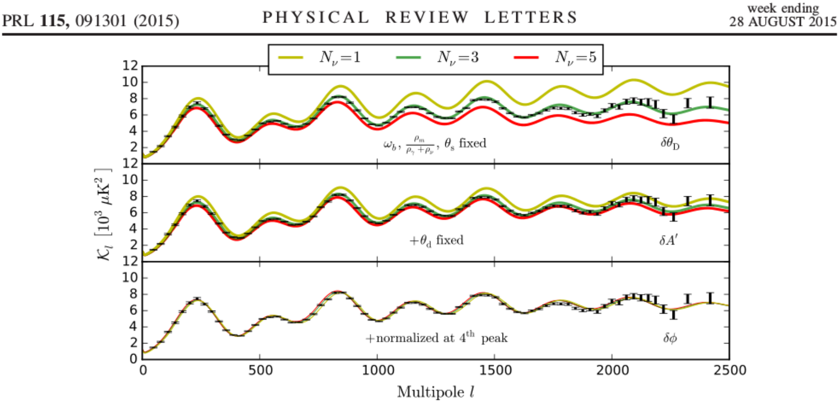
$$\theta(\eta \to \infty) = 0$$

Including Neutrinos: $k^2\Phi_+ \propto (\rho_\gamma \delta_\gamma + \rho_\nu \delta_\nu), v_p(\nu) = c > c_s$

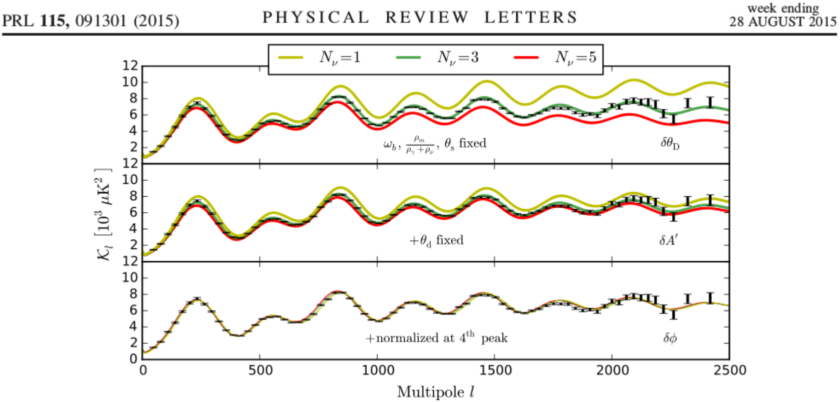
$$\theta(\eta \to \infty) = 0.19\pi R_\nu + O(R_\nu^2)$$

Bashinsky (2004,2007), Baumann et.al. (2015)

Signatures of neutrinos (number)



Signatures of neutrinos (number)

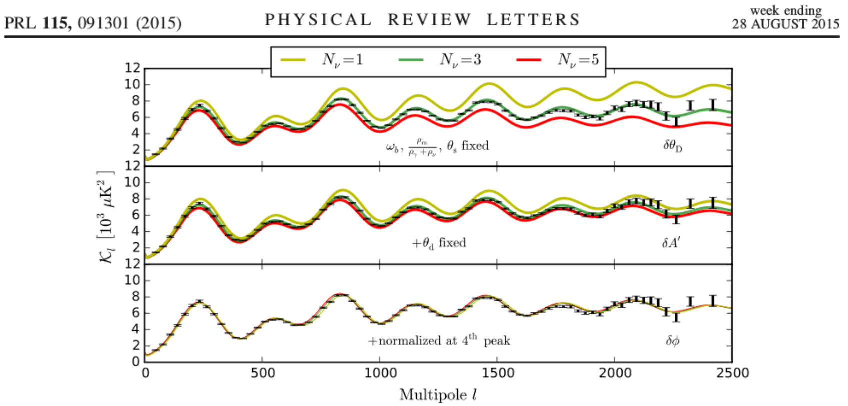


Planck13 TT

Follin ,..., Pan (2015) $N_\nu^{\delta\phi} = 3.50 \pm 0.65$

Planck XVI (2013) $N_\nu^{\delta\phi+\delta\theta_D} = 3.36 \pm 0.33$

Signatures of neutrinos (number)



Planck13 TT

Follin ,..., Pan (2015) $N_\nu^{\delta\phi} = 3.50 \pm 0.65$

Planck XVI (2013) $N_\nu^{\delta\phi+\delta\theta_D} = 3.36 \pm 0.33$

Planck15 TT, EE,TE

Baumann et.al. (2015) $N_\nu^{\delta\phi} = 2.99 \pm 0.30$

Planck III (2015) $N_\nu^{\delta\phi+\delta\theta_D} = 2.99 \pm 0.20$

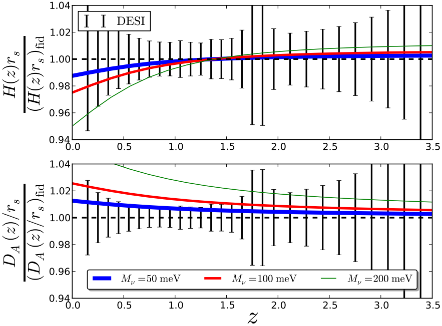
Signatures of neutrinos (mass)

Expansion History:

$\theta_{s,\star} \equiv \frac{r_{s,\star}}{D_{A,\star}} = (1.04096 \pm 0.00032) \times 10^{-2}$ (Planck 2015)

$$D_{A,\star} = \int_0^{z_\star} \frac{dz}{H(z)}$$

$$(M_\nu \uparrow + \Omega_\Lambda \downarrow) \Rightarrow Fixing\ \theta_{s,\star}$$



Pan and Knox (2015)

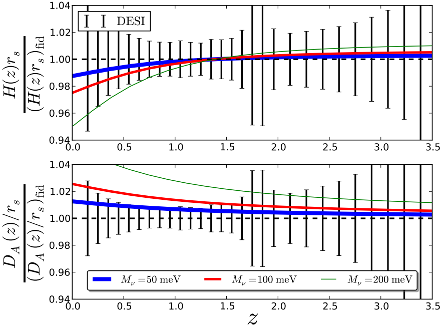
Signatures of neutrinos (mass)

Expansion History:

$\theta_{s,\star} \equiv \frac{r_{s,\star}}{D_{A,\star}} = (1.04096 \pm 0.00032) \times 10^{-2}$ (Planck 2015)

$$D_{A,\star} = \int_0^{z_\star} \frac{dz}{H(z)}$$

$$(M_\nu \uparrow + \Omega_\Lambda \downarrow) \Rightarrow \textit{Fixing } \theta_{s,\star}$$



Pan and Knox (2015)

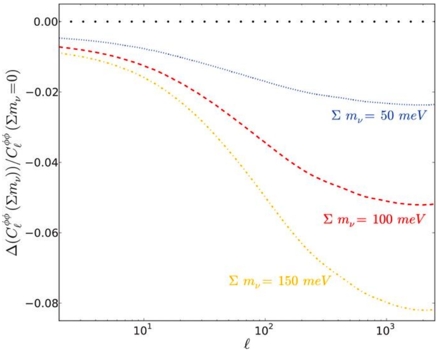
ω_m and M_ν are negatively correlated from BAO.

Signatures of neutrinos (mass)

Structure Growth:

$$r_{fs} \sim vt \sim \frac{T_\nu(z)}{M_\nu}\frac{1}{H(z)}$$

$> r_{fs}$ neutrinos cluster
$< r_{fs}$ neutrinos freely stream



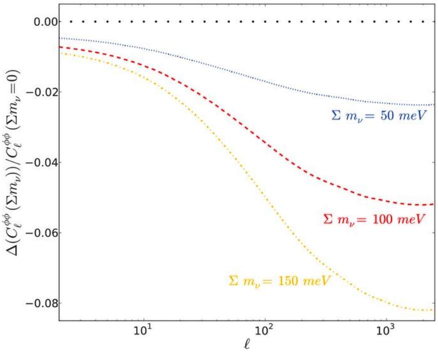
Wu et.al (2014)

Signatures of neutrinos (mass)

Structure Growth:

$$r_{fs} \sim vt \sim \frac{T_\nu(z)}{M_\nu}\frac{1}{H(z)}$$

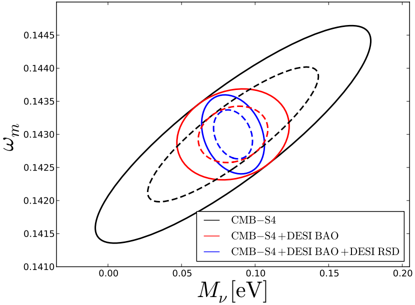
$> r_{fs}$ neutrinos cluster
$< r_{fs}$ neutrinos freely stream



Wu et.al (2014)

ω_m and M_ν are positively correlated from lensing.

Contraints on M_ν



Pan and Knox (2015)

$\sigma(M_\nu) = 38$ meV — CMB-S4

$\sigma(M_\nu) = 15$ meV — + DESI BAO

$\sigma(M_\nu) = 9$ meV — + DESI RSD

Summary

$\sum m_i$

$$\sigma\left(\sum m_i\right)_{CMB-S4+DESI\ BAO} = 15meV$$

$$+\left(\Delta m_{ij}^2\right)_{neutrino\ oscillation\ experiments} \to m_i$$

Model dependent (flat ΛCDM model).
Degeneracy with Ω_k, w broken by external datasets ?

$N_\nu(\delta\theta_D, \delta\phi)$

$$N_\nu^{\delta\phi} = 2.99 \pm 0.30|_{Planck\ 2015\ TT,TE,EE}$$

`Implications`: consistent with 3.046 neutrinos, no sign of $\nu\bar{\nu}$ interaction

$$\sigma(N_\nu^{\delta\phi})_{cosmic\ variance\ limit} \approx 0.05$$