The neutrino phase shift in the CMB

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A First Detection of the Acoustic Oscillation Phase Shift Expected from the Cosmic Neutrino Background

Brent Follin, Lloyd Knox, Marius Millea, Zhen Pan
http://arxiv.org/abs/1503.07863
10.1103/PhysRevLett.115.091301

abstract:
The unimpeded relativistic propagation of cosmological neutrinos prior to recombination of the baryon-photon plasma alters gravitational potentials and therefore the details of the time-dependent gravitational driving of acoustic oscillations. We report here a first detection of the resulting shifts in the temporal phase of the oscillations, which we infer from their signature in the Cosmic Microwave Background (CMB) temperature power spectrum.

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Easy to understand:

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  $\Rightarrow$ decreases Δt for a given ΔT
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For point 3, subtle difference in C_ℓ between neutrinos (free-streaming radiation) and photons (acoustic radiation)

Depend on $f_\nu = \rho_\nu/(\rho_\gamma + \rho_\nu)$

Must first understand dominanant radiation effects of $f_{rad} = (\rho_\gamma + \rho_\nu)/\rho_M$.

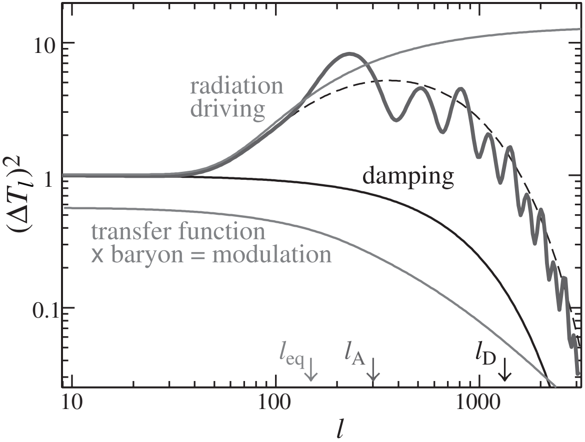
T modes superimposed on potential modes

$$\phi_k(t) \sim \frac{G\Delta M_k}{\lambda_k} \sim \frac{G\Delta\rho_k\lambda_k^3}{\lambda_k} \sim G\bar{\rho}(t)\,\frac{\Delta\rho_k}{\bar{\rho}}\lambda_k^2$$

$$\textit{matter epoch}: \quad \bar{\rho}\,(\Delta\rho_k/\bar{\rho}) \propto a(t)^{-3}\,a(t) \quad \Rightarrow \phi_k(t) \sim \textit{const}.$$

$$\textit{radiation epoch}: \quad \bar{\rho}\,(\Delta\rho_k/\bar{\rho}) \propto a(t)^{-4}\,a(t)^0 \quad \Rightarrow \phi_k(t) \propto a^{-2}$$

The modes: $cos(\vec{k} \cdot \vec{r}) \to Y_{\ell m}(\theta, \phi)$ on sky



$\ell \sim \pi D(z_{rec}) k$

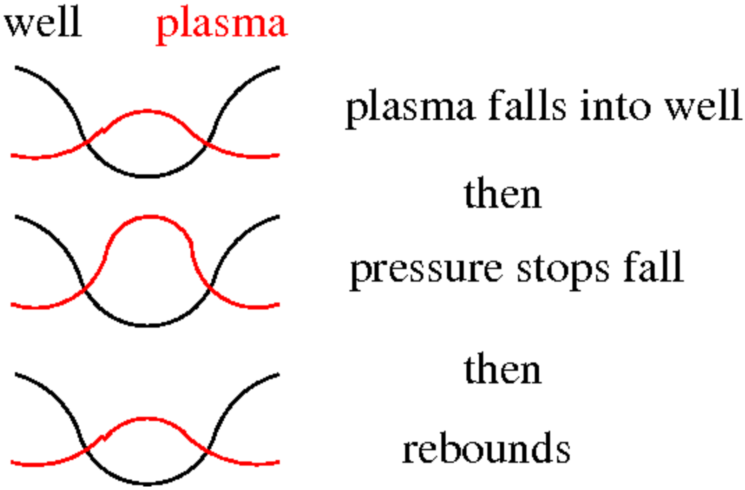
Three angular scales:

ℓ_{eq} (modes inside horizon during radiation epoch);

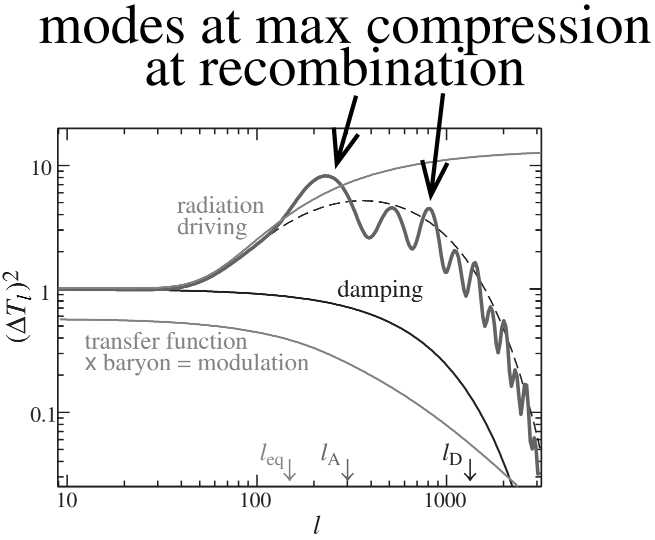
$\ell_A = D_{rec}/r_s$ (acoustic peaks); ℓ_D (dampled by photon diffusion)

Hu et al, (2001) ApJ 549,669

Baryon oscillations in constant CDM wells ($t < t_{rec}$)



Modes at extrema at recombination



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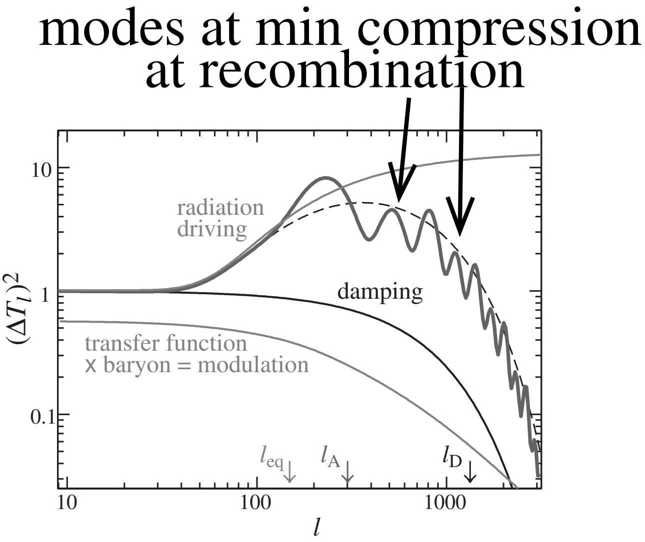
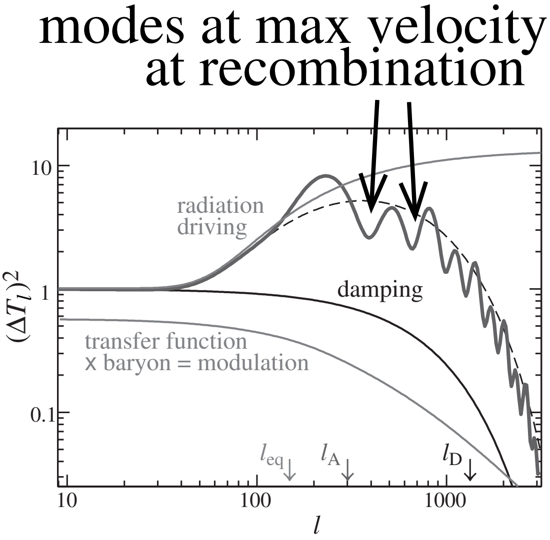
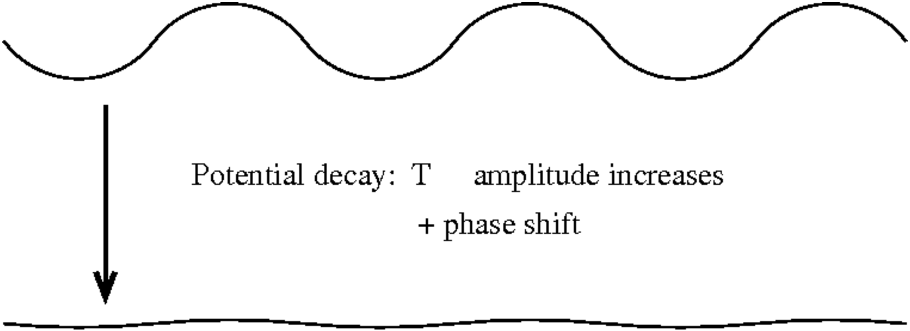


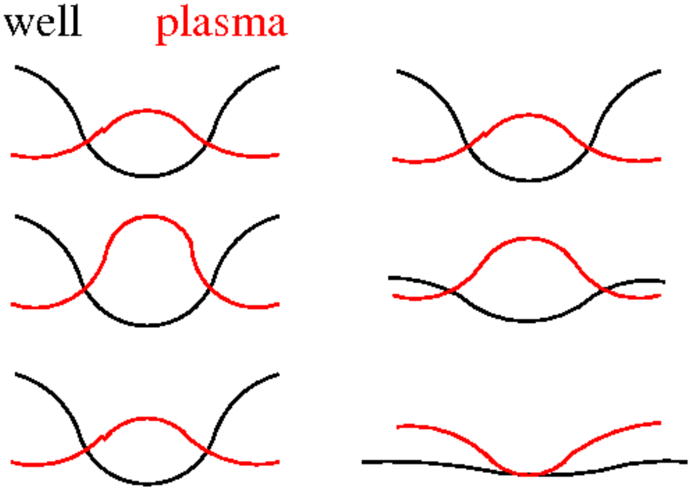
Doppler effect suppresed by baryon mass



Potential decay drives sub-Hubble temperature oscillations

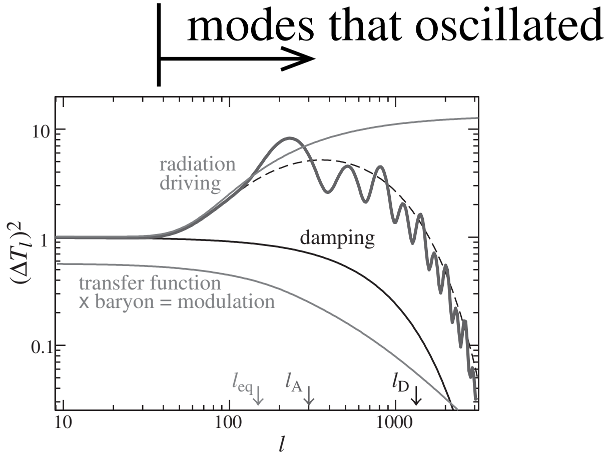


Baryon oscillations in wells vs. decaying wells



Potential-less oscillations: just normal everyday sound waves

Large $\ell \Rightarrow$ Potential decay $\Rightarrow$ increase in C_ℓ



$C_{first\ peak}/C_{30}$ determines $(\rho_\gamma + \rho_\nu)/\rho_M$)

$\Rightarrow$ Assuming $N_\nu = 3$ determines ρ_M $\Rightarrow \Omega_{\mathrm{M}} h^2$.

note: $C_{first\ peak}/C_{second\ peak}$ determines (ρ_b/ρ_M)

Large $\ell \Rightarrow$ Potential decay $\Rightarrow$ phase shift

For $\ell \sim 200$ near recombination, modes are oscillating as

$$A_k \sim cos(kr_s(t) + 0.267\pi) \qquad r_s(t) \sim \int_0^t c_s(t)dt$$

Modes at a maxima at recombination satisfy

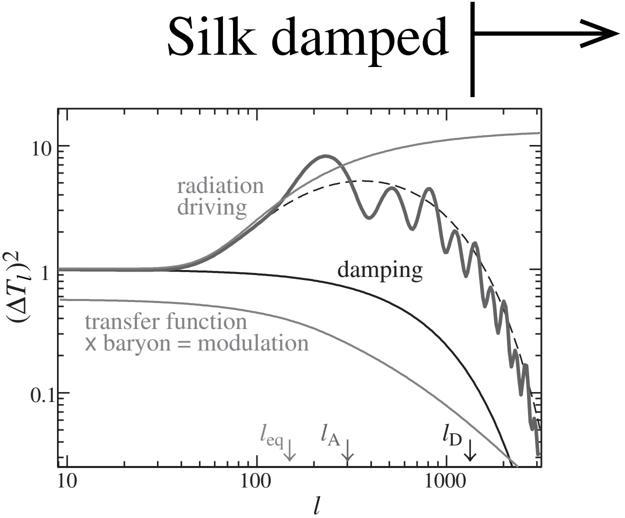
$$kr_s(t_{rec}) + 0.267\pi = n\pi \qquad k \sim \frac{\ell}{\pi D_{rec}}$$

For $D_{rec} = 13891 Mpc$ and $r_s(t_{rec}) = 147 Mpc$:

$$n = 1 \qquad \Rightarrow \ell \sim 0.73 \frac{\pi \times 13891 Mpc}{147 Mpc} \sim 220$$

Both the amplification and phase shift depend slightly on whether the potential decay is due to acoustic oscillations or to free streaming.

High-ℓ modes damped by photon random walk during one Hubble time at recombination



Damping from photon random walk at t_{rec}

$r^2_{damp} \sim$ (time to walk)$\times$(photon mean free path)

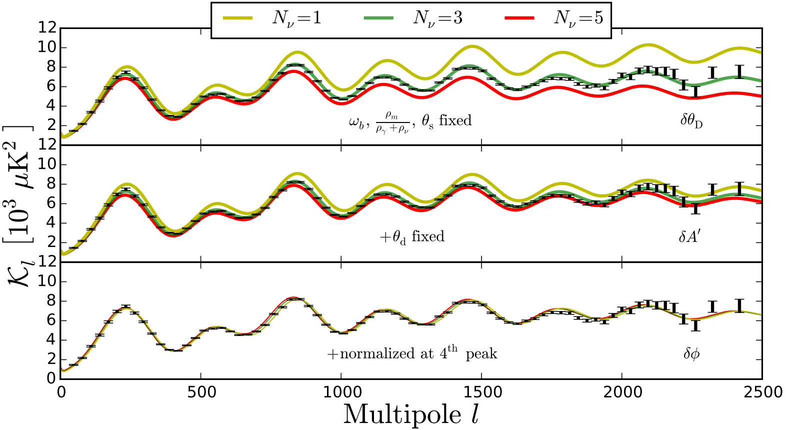
$$r^2_{damp} \sim H^{-1}_{rec} \times \frac{1}{n_e \sigma_T} \;\sim\; \frac{1}{\sqrt{G\rho_{rec}}} \times \frac{1}{n_b \times n_e/n_b \times \sigma_T}$$

On the other hand, $r_s \sim 1/H_{rec}$, so

$$\frac{r^2_{damp}}{r^2_s} \sim \frac{\sqrt{G\rho_{rec}}}{n_b \times n_e/n_b \times \sigma_T}$$

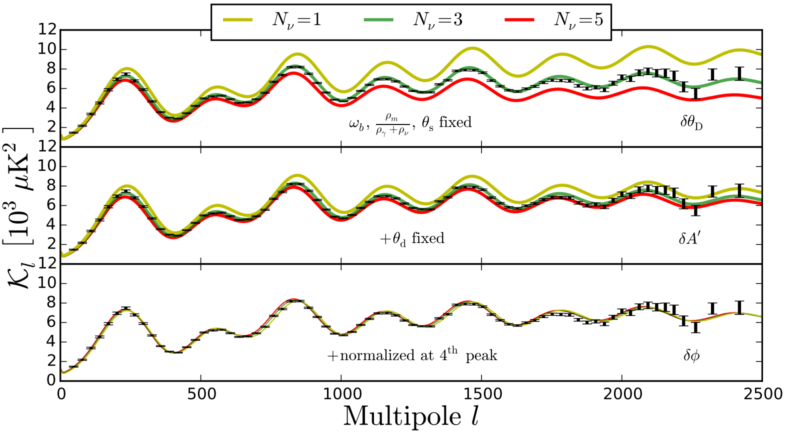
$r^2_{damp}/r^2_s \Rightarrow (\rho_M + \rho_\gamma + \rho_\nu)$
$C_{220}/C_{30} \Rightarrow \rho_M/(\rho_\gamma + \rho_\nu)$
$T_{CMB} \Rightarrow \rho_\gamma$
$\Rightarrow N_\nu$ (r_{damp}/r_s, peak heights, T_γ, and Helium abundance)

Cummulative effects of N_ν



Frame 1: D_{rec} adjusted so that first peak at $\ell = 220$. $\rho_\gamma + \rho_\nu / \rho_M$ fixed to fiducial to approximately fix amplitude of first peak. Damping depends on N_ν.

Cummulative effects of N_ν



Frame 2: He/H adjusted so that r_s/r_{damp} = fiducial. Amplitude depends on ρ_ν/ρ_γ.

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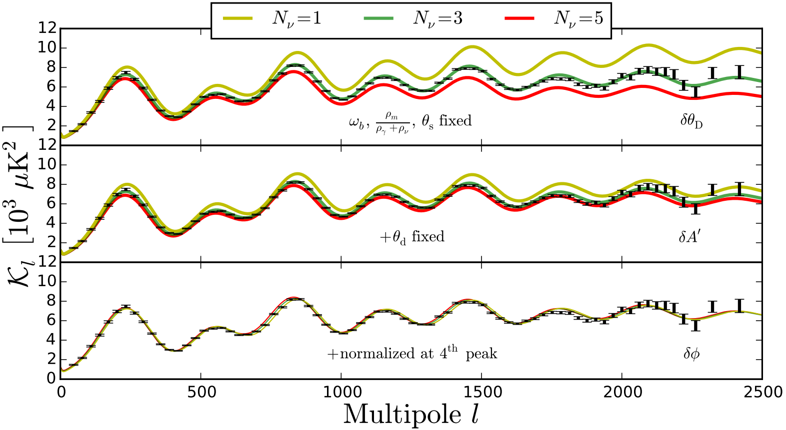
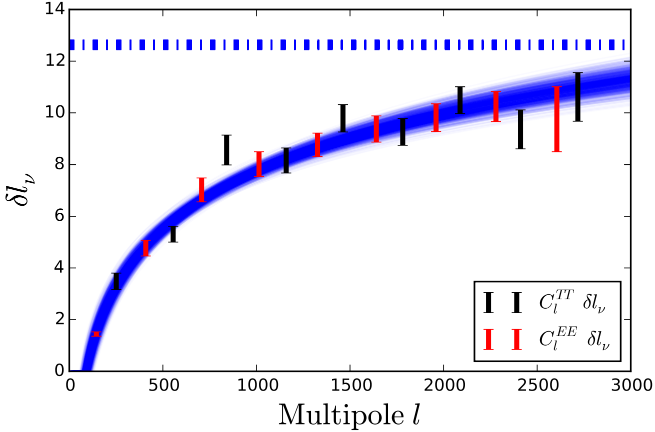


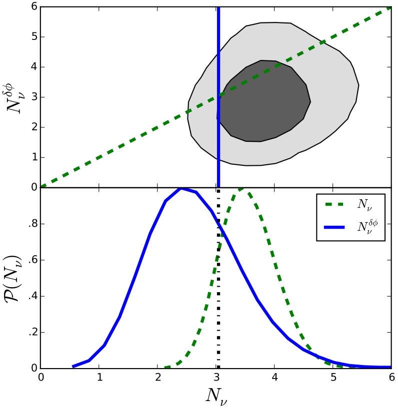
Frame 3: Amplitude renormalized to show phase shift due to neutrinos.

Calculated neutrino phase shift for $\Delta N_\nu = 2$

(The part of the phase shift that depends on ρ_ν/ρ_γ for fixed $(\rho_\nu + \rho_\gamma)/\rho_M$)



Constraints on $(N_\nu, N_\nu^{\delta\phi})$



$N_\nu = 3.3^{+0.7}_{-0.2}$
determined by damping tail

$N_\nu^{\delta\phi} = 2.3^{+1.1}_{-0.4}$
determined by positions of the extrema of C_ℓ
(well-defined feature not degererate with other parameters)

How the simultaneous fit is done in a physically consistent manner is not entirely clear to me.
One consistent way would add anomolous neutrino-neutrino scattering to prevent free-streaming.