Free-Streaming Neutrinos in the Early Universe

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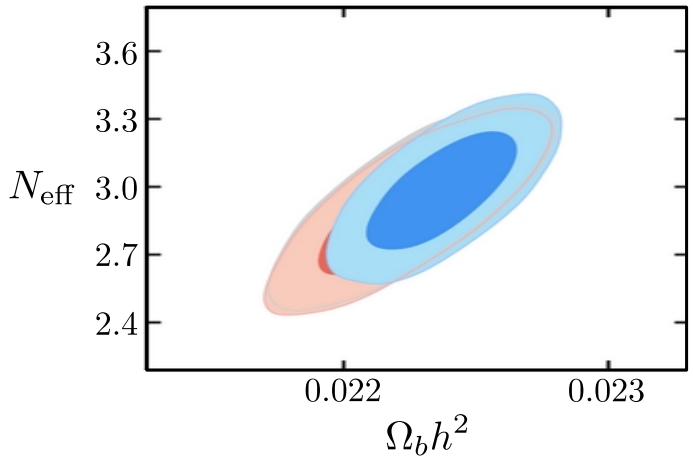
Based on work in preparation with Katherine Freese & Gabriele Montefalcone

CMB-S4 Spring Collaboration Meeting, March 2024

Status: Cosmological Radiation Constraints

5-10% constraint on effective number of relativistic degrees of freedom:

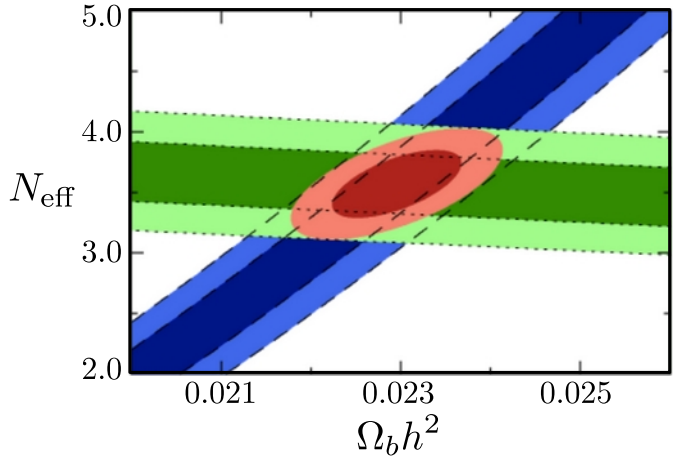
$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$



CMB: anisotropy measurements

$$N_{\rm eff}^{\rm CMB} = 2.99 \pm 0.17$$

Planck 2018



BBN: primordial abundances

$$N_{\rm eff}^{\rm BBN} = 3.28 \pm 0.28$$

Cooke et al.

BUT: Are we actually detecting neutrinos (via gravity)?

Cosmic Neutrinos

Gravitationally important properties of neutrinos:

- (Radiation) energy density $\bar{\rho}_\nu$.

  ⟶ Measurements consistent with expected $N_{\mathrm{eff}}^{\mathrm{SM}} = 3.044$.

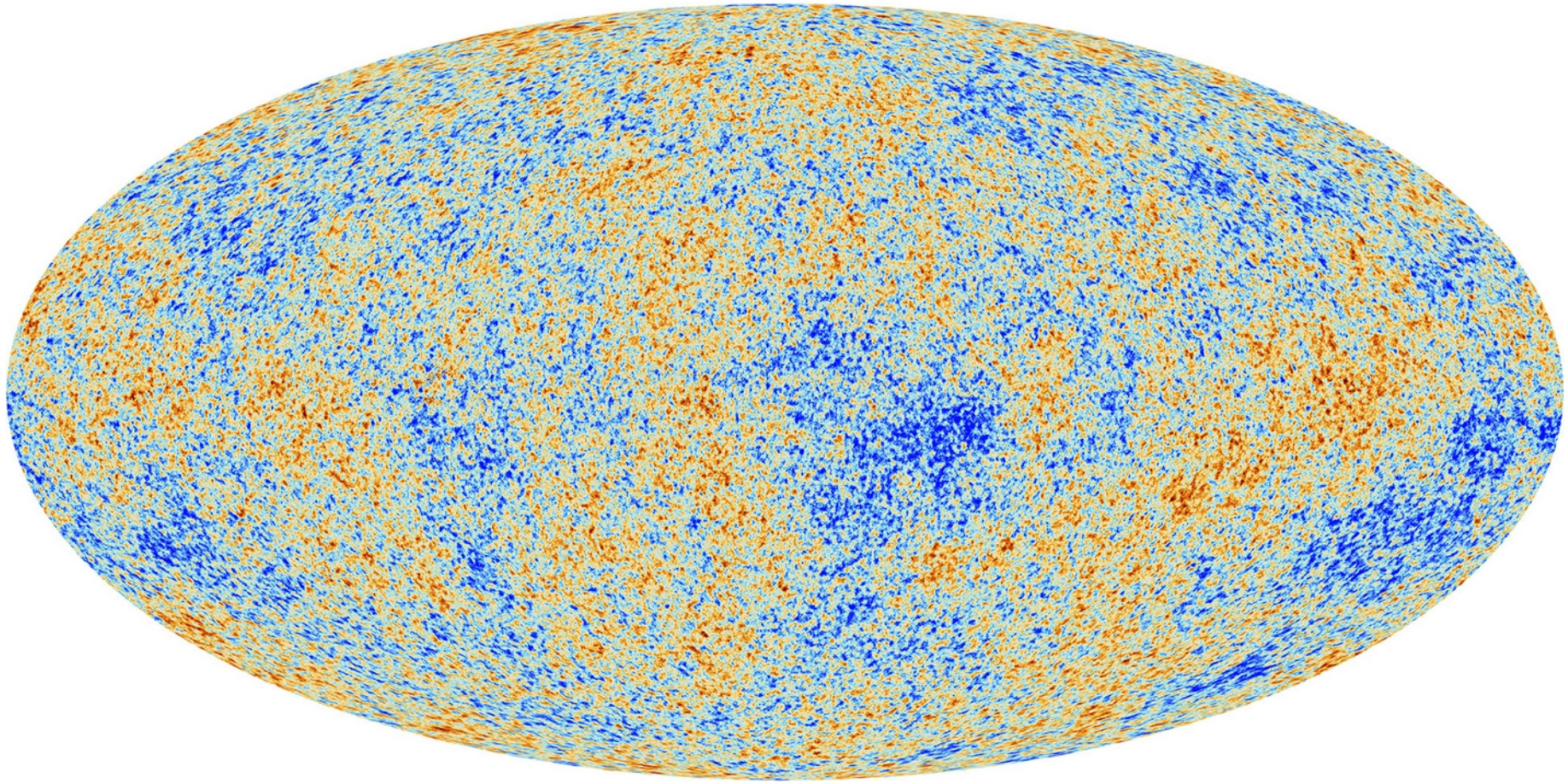
- Neutrino masses m_ν.

  ⟶ No detection, but unimportant in the early universe.

- Free-streaming after their decoupling around $t \sim 1\,\mathrm{s}$.

  ⟶ Can we detect this?

Cosmic Microwave Background Anisotropies



1 in 10,000

Planck Collaboration

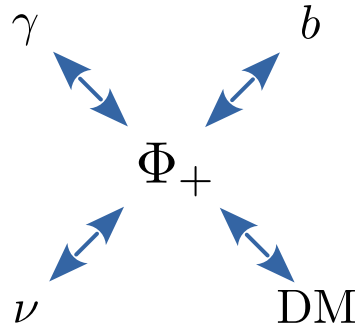
Cosmic Sound Waves

In the early universe, photons and baryons were strongly coupled.

Perturbations excited sound waves in the photon-baryon fluid:

$$\ddot{\delta}_\gamma - c_\gamma^2 \nabla^2 \delta_\gamma = \nabla^2 \Phi_+$$

sound waves — pressure — gravity

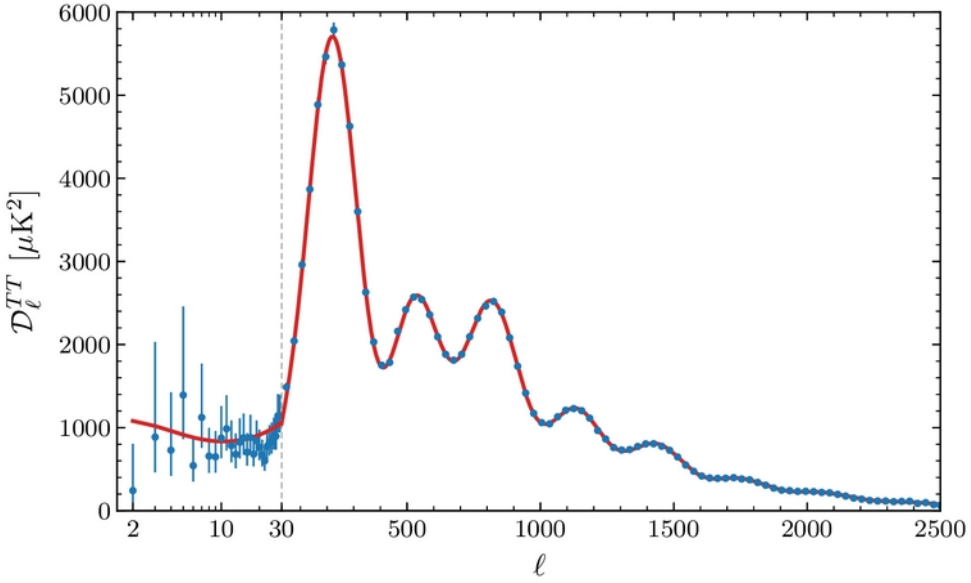


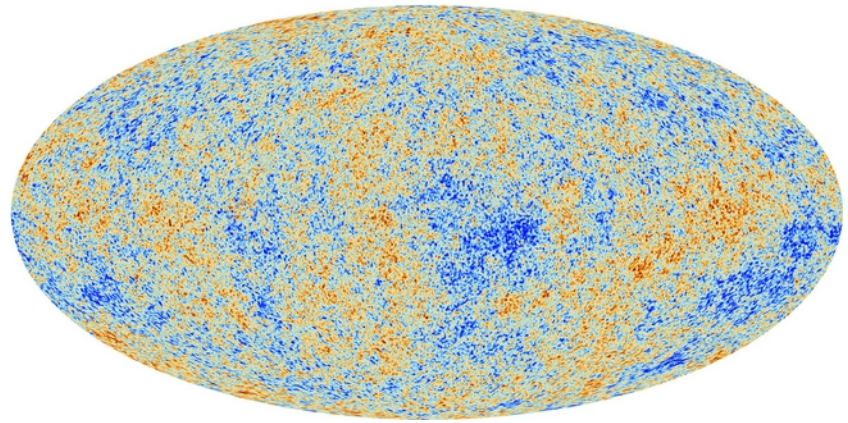
These acoustic oscillations are what we observe in the CMB power spectra:

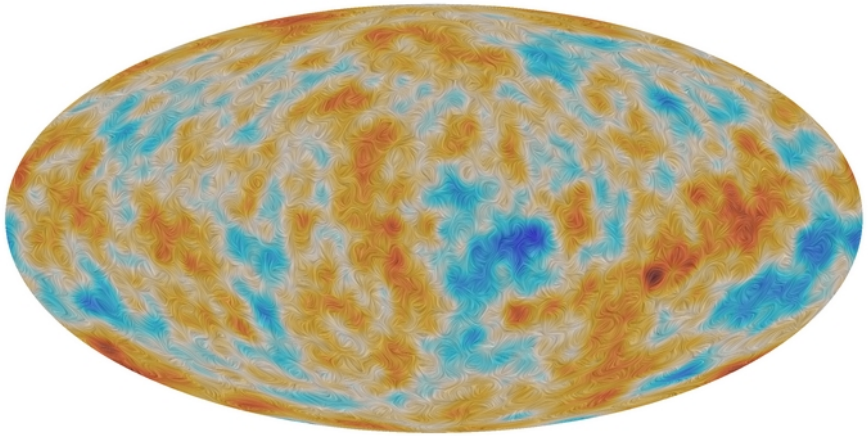
$$\delta_\gamma \sim A_{\vec{k}} \cos(c_s k \tau)\,, \qquad c_s^2 \sim \frac{c^2}{3(1+R_b)}$$

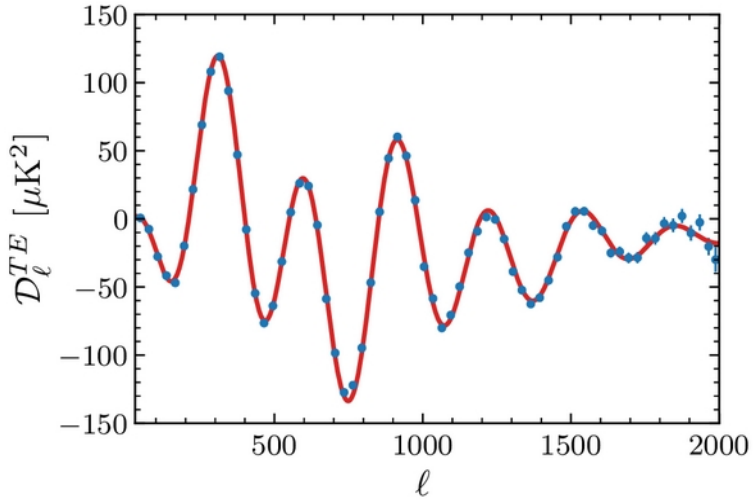
inflation/initial conditions — sound waves

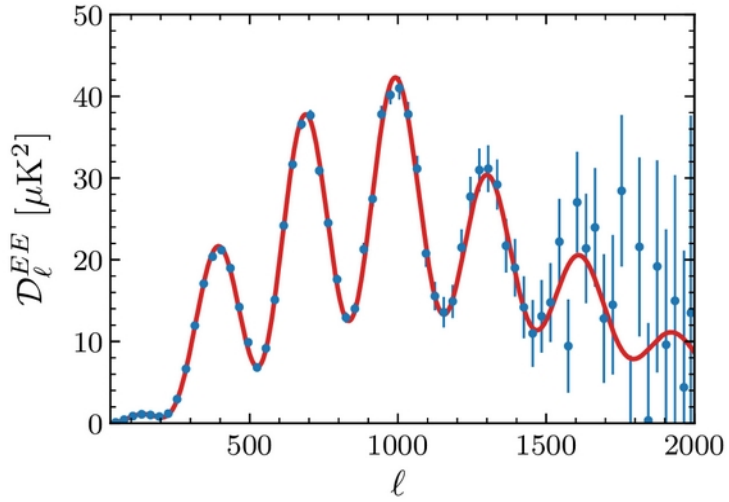
CMB Power Spectra











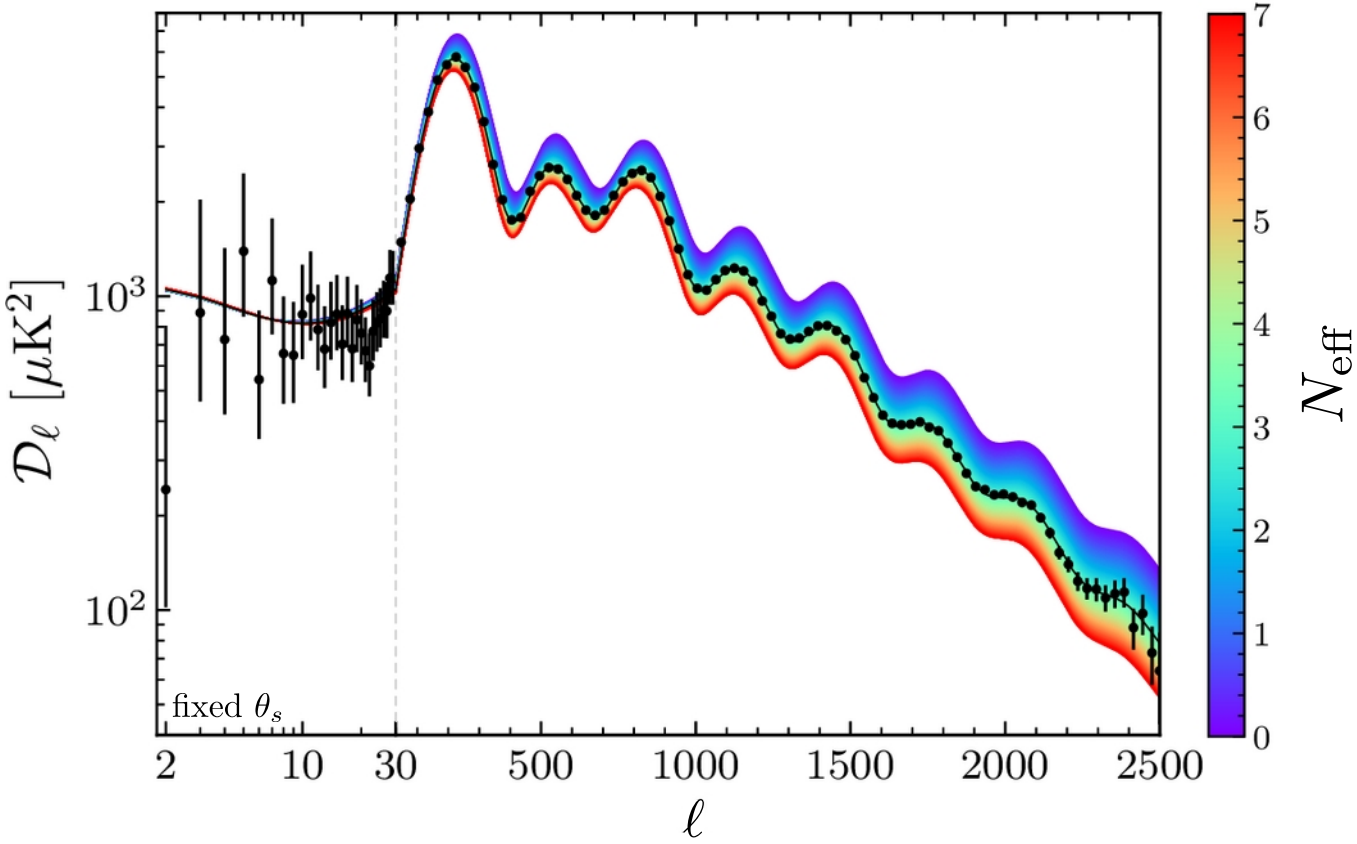
Planck Collaboration

Cosmic Neutrinos

- 41% of the radiation density in the universe:
  - → Leave gravitational imprint,
  - → Can detect their energy density.

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

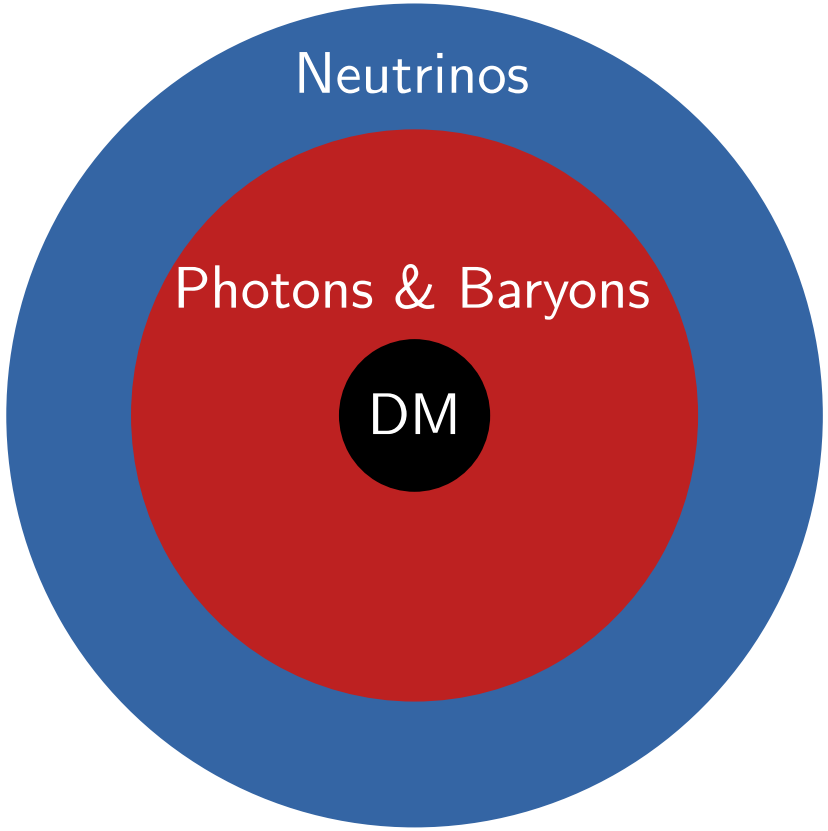
$$N_{\rm eff}^{\rm SM} = 3.044$$



Free-Streaming Neutrinos

What distinguishes free-streaming and non-free-streaming neutrinos observationally?

Free-streaming neutrinos overtake the photons and baryons and pull them ahead of the sound horizon:



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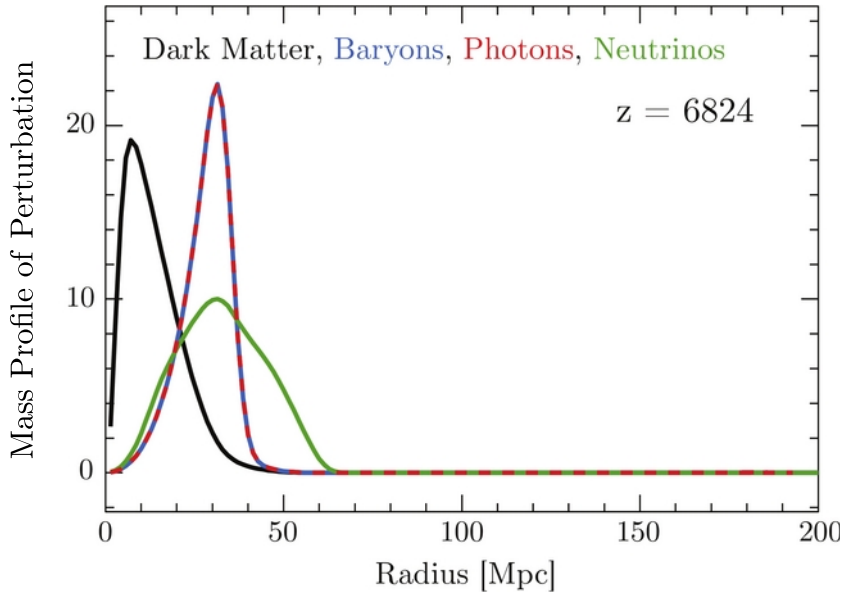
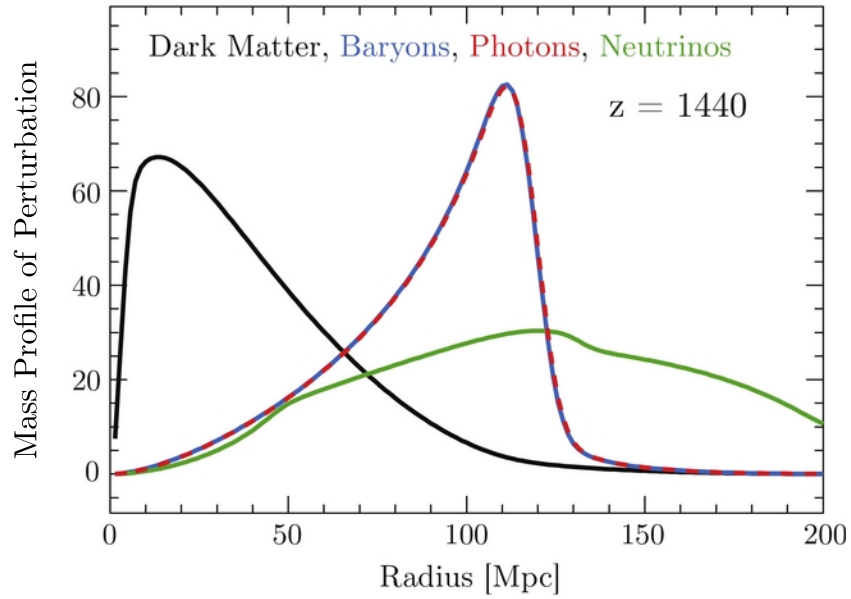


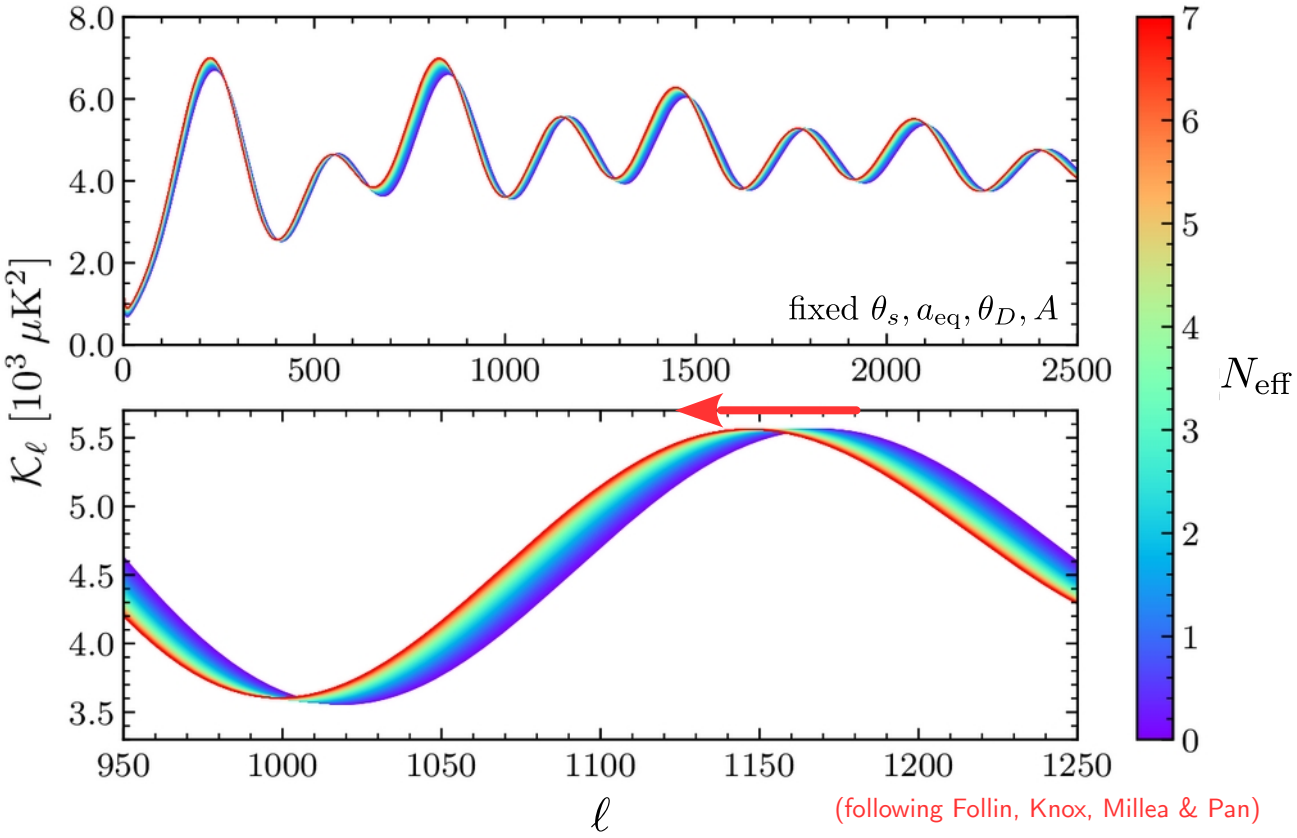


Eisenstein, Seo and White (2007)

Phase Shift in the CMB Spectrum

This corresponds to an amplitude and especially phase shift in the CMB power spectra:

Bashinsky & Seljak



undamped temperature power spectrum

(following Follin, Knox, Millea & Pan)

$$\delta_\gamma(\vec{k}) \approx A(\vec{k})\,\cos(kr_s + \phi)$$

Detected in Planck 2013 TT data!

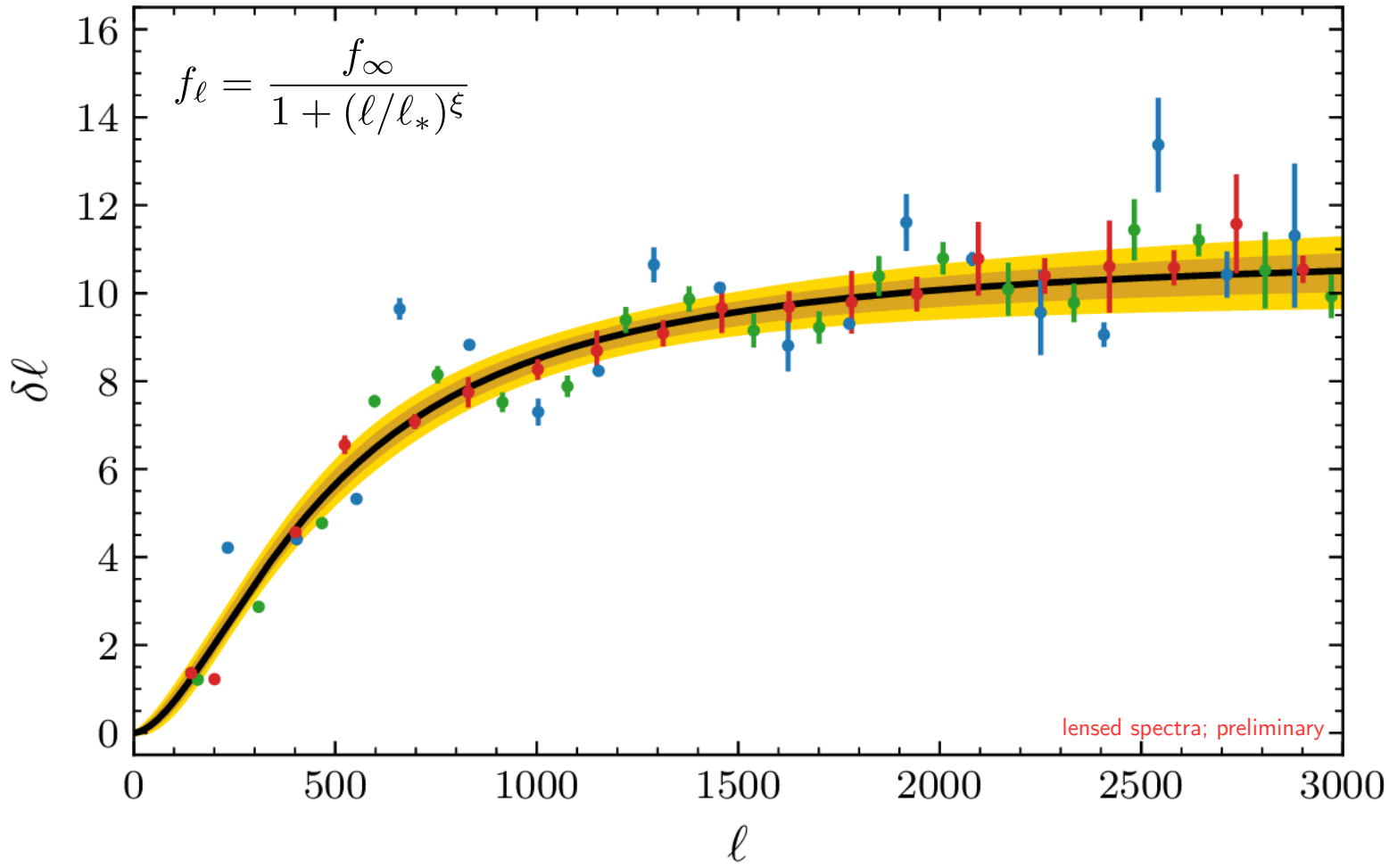
Follin, Knox, Millea & Pan

Free-streaming neutrinos are a causal way to produce such a coherent shift.

Baumann, Green, Meyers & BW

Phase Shift in the CMB Spectrum

$$\delta\ell = A(N_{\rm eff})f_\ell$$



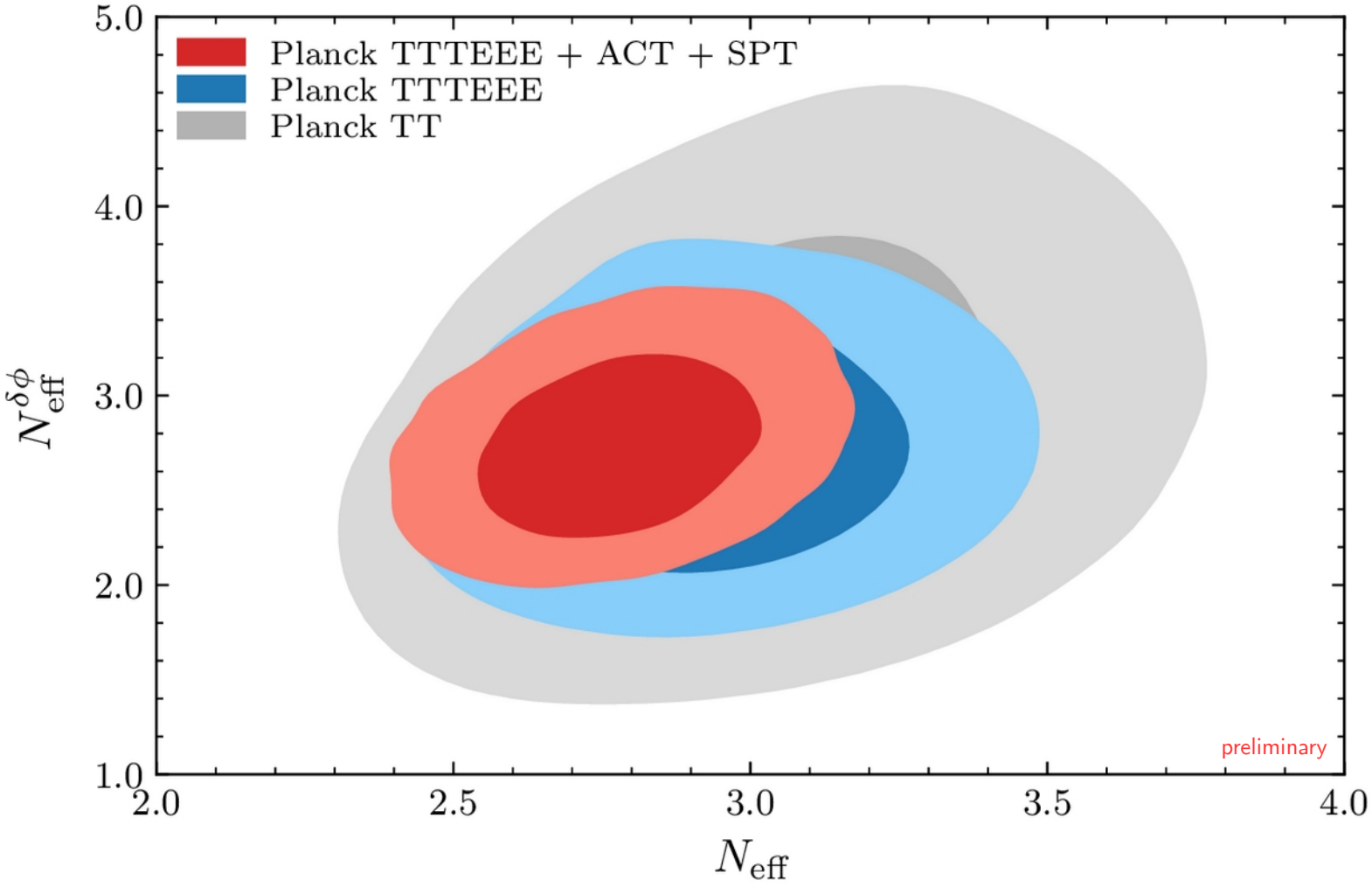
TT peaks/troughs

EE peaks/troughs

TE peaks/troughs

Freese, Montefalcone & BW (in prep.)

Phase Shift Constraints



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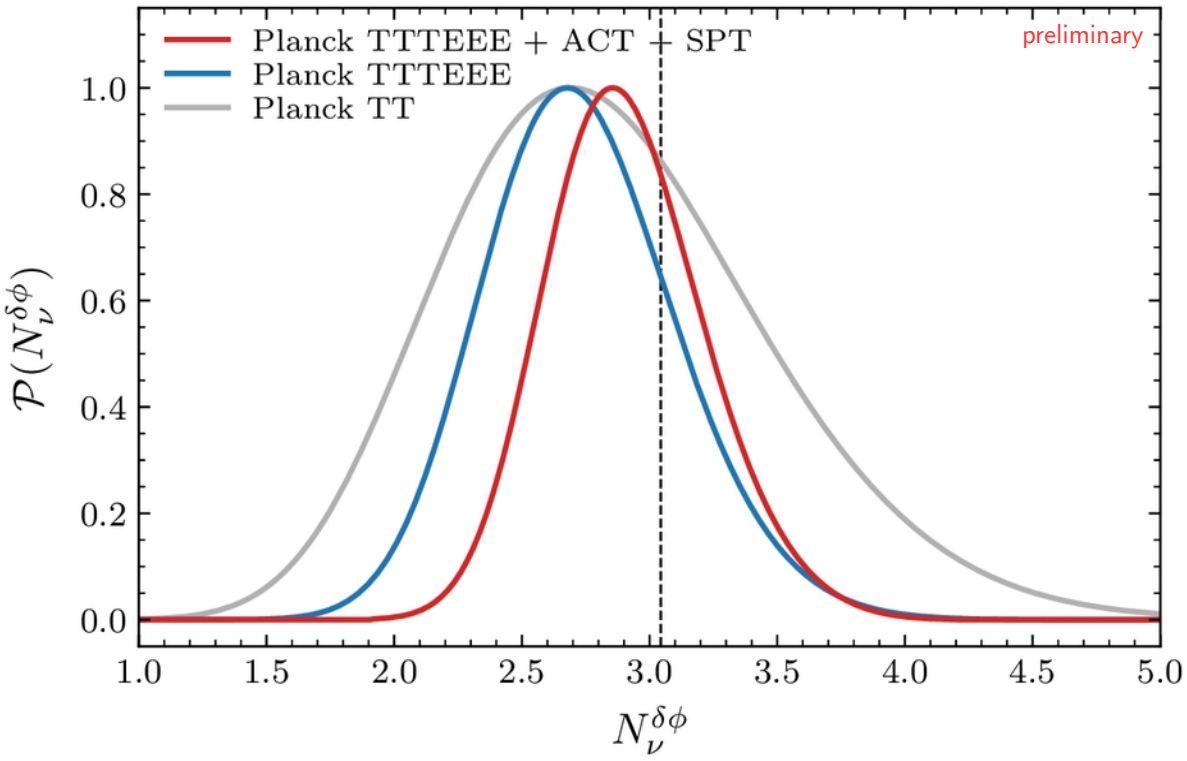


Based on Planck 2013 temperature data:

$$N_\nu^{\delta\phi} = 2.3^{+1.1}_{-0.4}$$

$$(N_{\rm eff} = N_\nu = 3.044)$$

Follin et al.

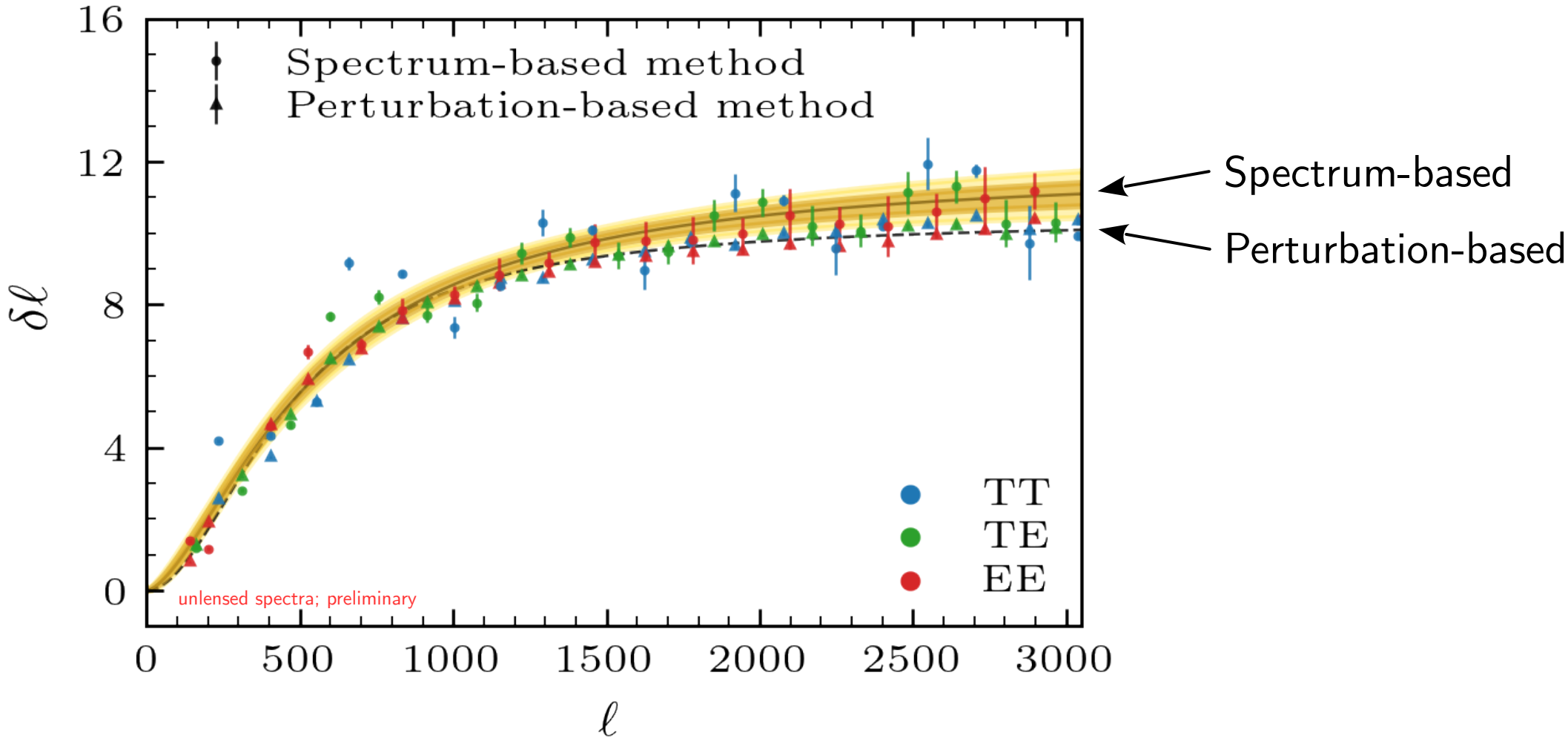
Work in progress (preliminary):

- Current data, including polarization:
  - Planck 2018: $N_\nu^{\delta\phi} = 2.7^{+0.5}_{-0.4}$
  - + ACT + SPT: $N_\nu^{\delta\phi} = 2.9^{+0.3}_{-0.3}$
- Forecasts:
  - SO: $\sigma(N_\nu^{\delta\phi}) \sim 0.2$
  - CMB-S4: $\sigma(N_\nu^{\delta\phi}) \sim 0.1$

Freese, Montefalcone & BW (in prep.)

Perturbation-Based Method

Extract the phase shift at the level of the perturbations $\delta_\gamma(\vec{k})$ instead of spectra.



Freese, Montefalcone & BW (in prep.)

Summary

Theoretical insights into and observational control of CMB and LSS power spectra analyses allow for extraction of additional physical information.

Example here (but much more possible):

Neutrinos are free-streaming particles in the early universe!

– Phase shift is a robust signature of free-streaming neutrinos.

– We can constrain this property of neutrinos in current CMB (and LSS) surveys.

– Interesting improvements in sensitivity are forthcoming, especially CMB-S4.

Thank you!

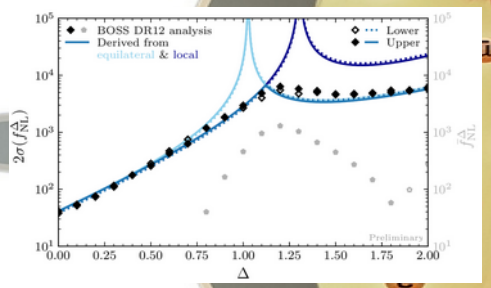
Beyond

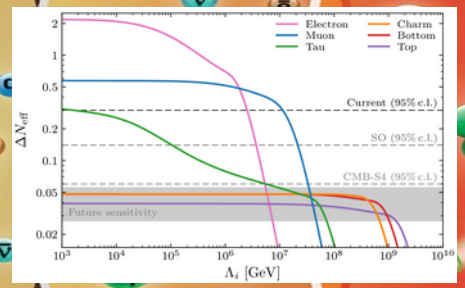
Dark Matter

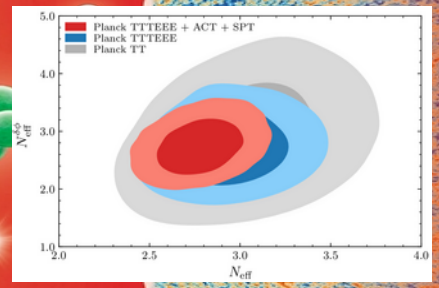
Neutrinos

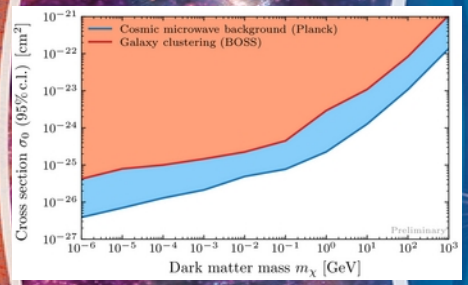
Light Relics

PNG & Features









Inflation?

Standard Evolution?

Cosmic Microwave Background

Large-Scale Structure

Early Universe

Observable Universe

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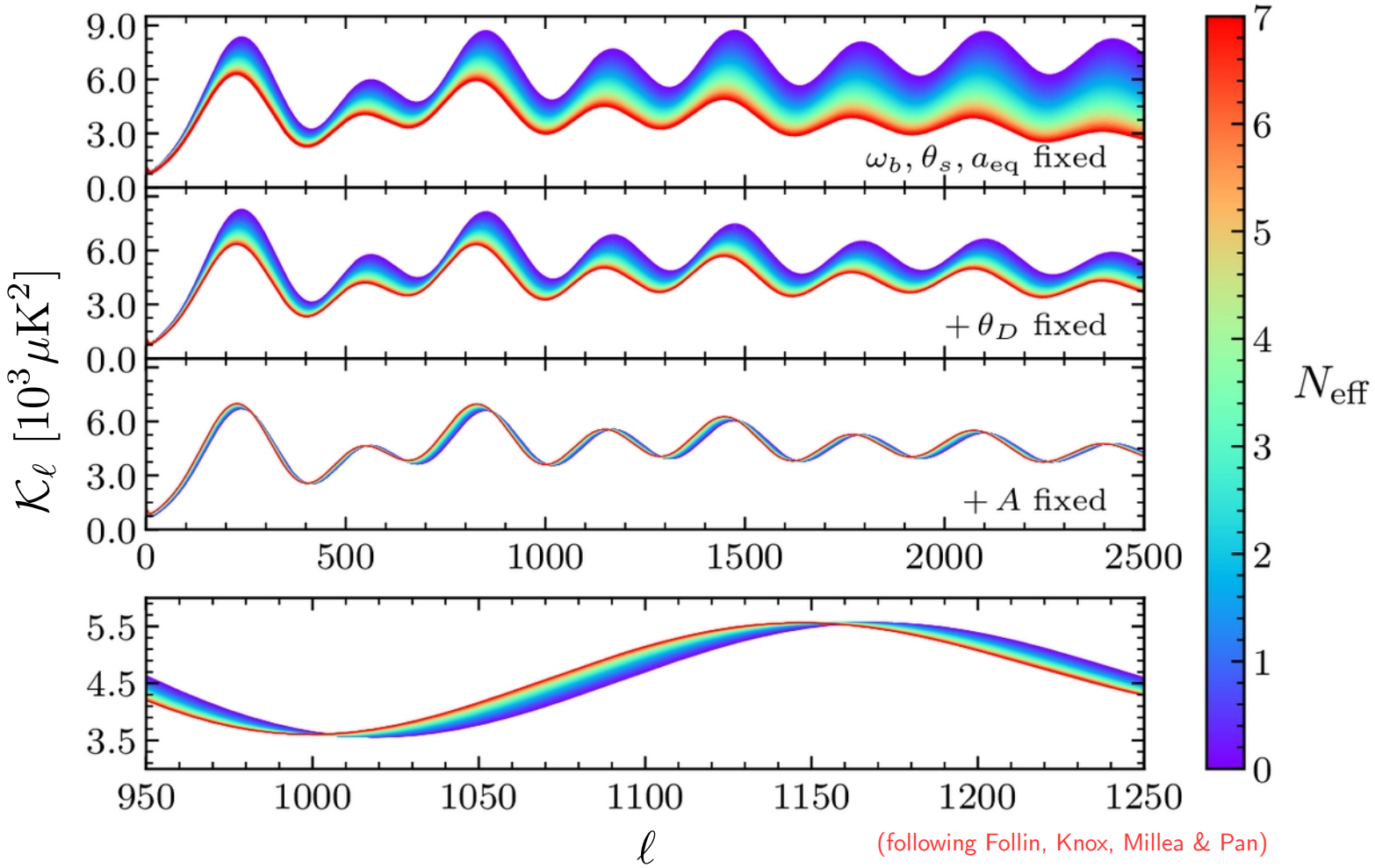
Backup Slides

Phase Shift in the CMB



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