Free-Streaming Neutrinos in the Early Universe

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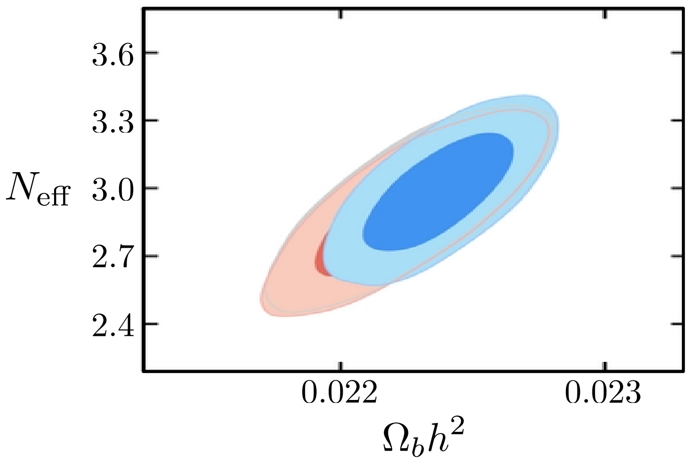
Status: Cosmological Radiation Constraints

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

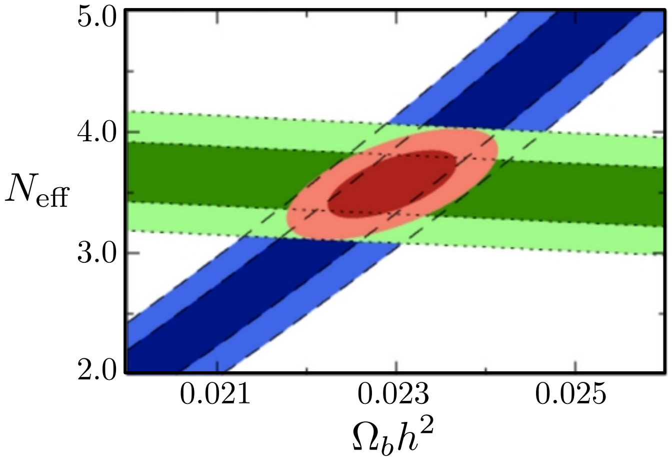
$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$



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 $N_{\mathrm{eff}}^{\mathrm{SM}} = 3.044$.

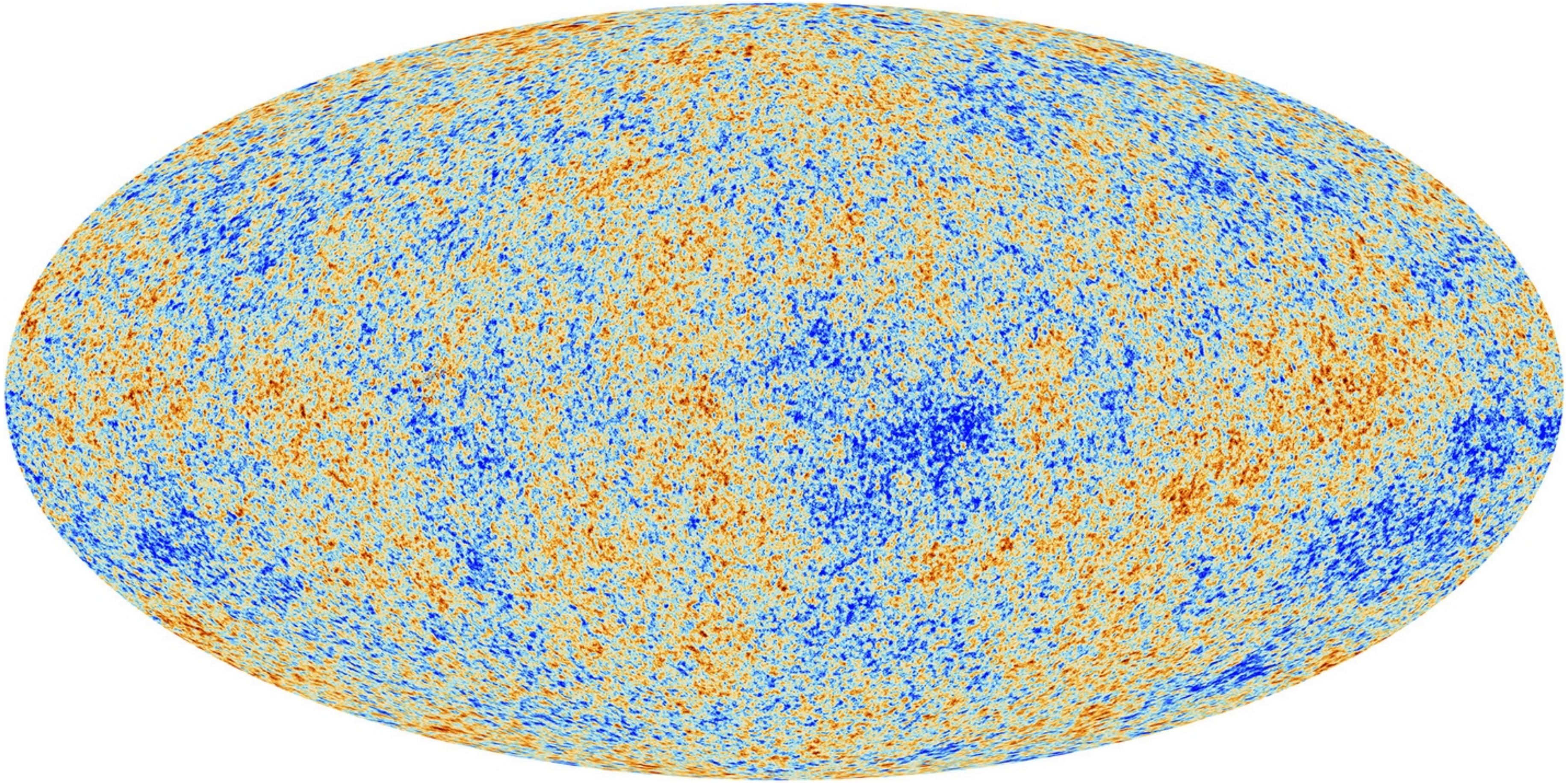
- Neutrino masses m_ν.

  ⟶ No detection, but unimportant in the early universe.

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

  ⟶ Can we detect this?

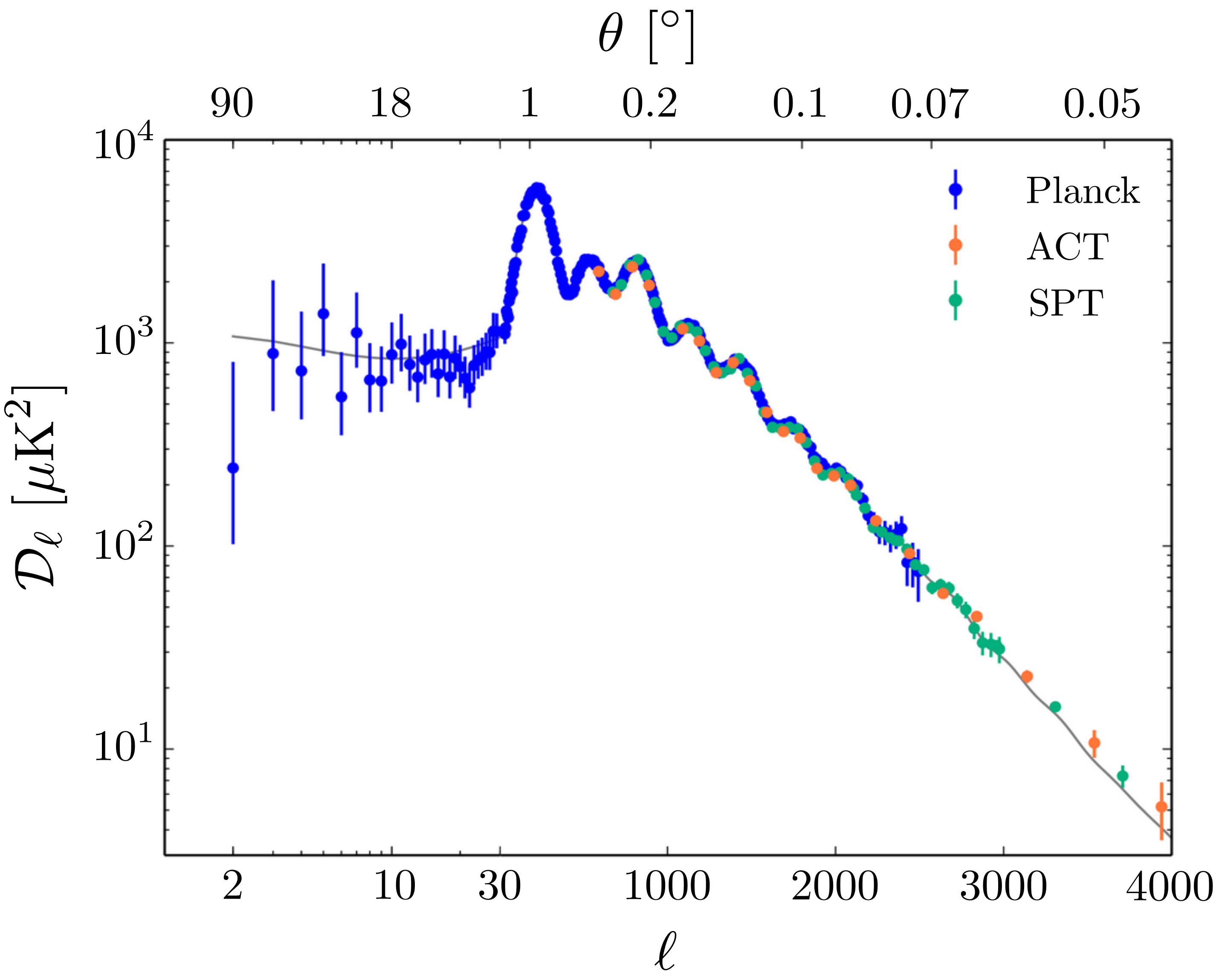
Cosmic Microwave Background Anisotropies



1 in 10,000

Planck Collaboration

Cosmic Microwave Background Anisotropies



Planck, ACT & SPT Collaborations

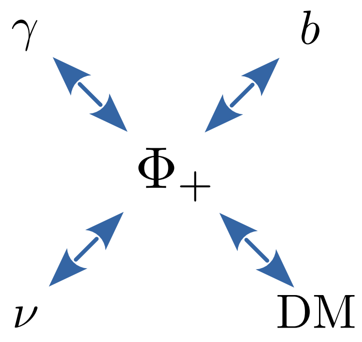
Cosmic Sound Waves

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

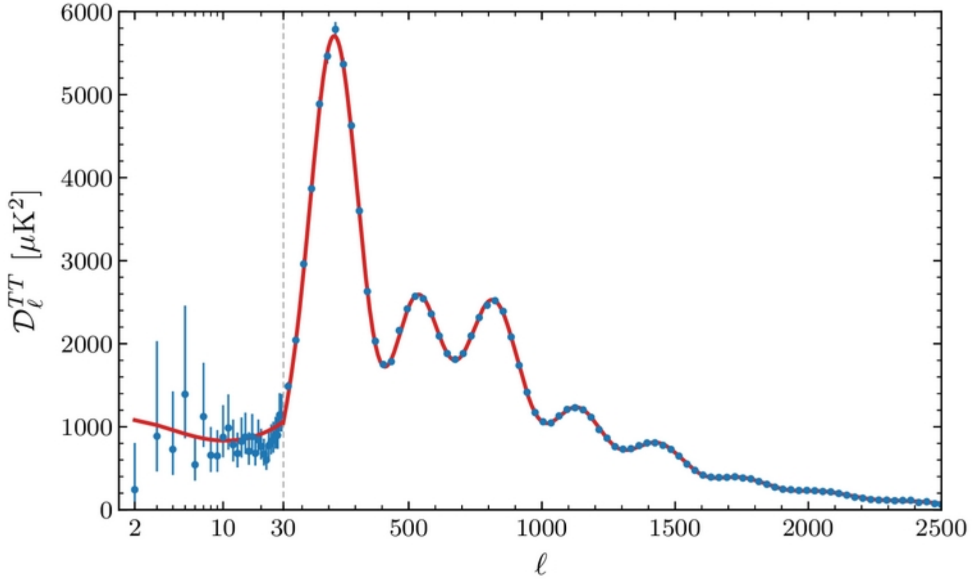


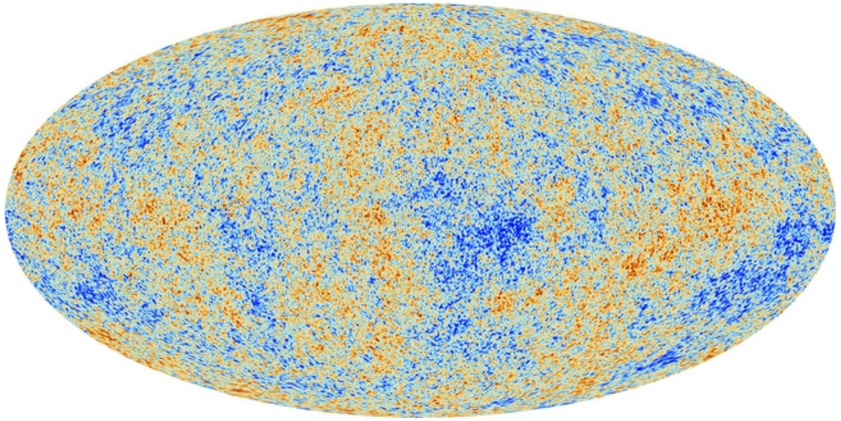
These acoustic oscillations are what we observe in the CMB power spectra:

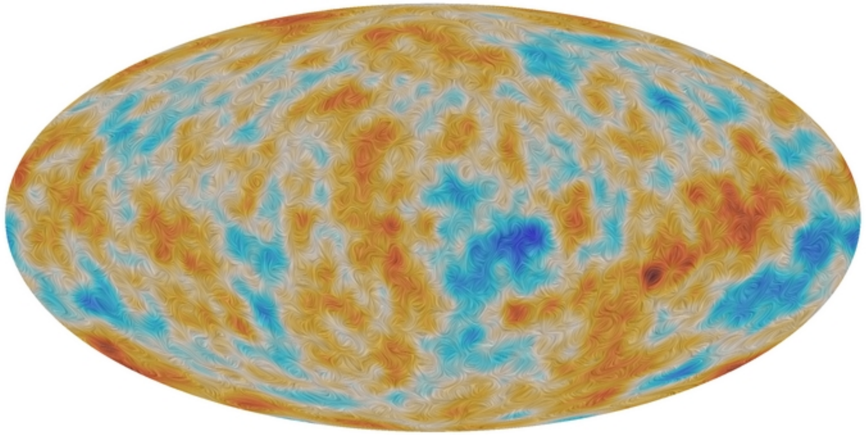
$$\delta_\gamma \sim A_{\vec{k}} \cos(c_s k \tau)\,, \qquad c_s^2 \sim \frac{c^2}{3(1+R_b)}$$

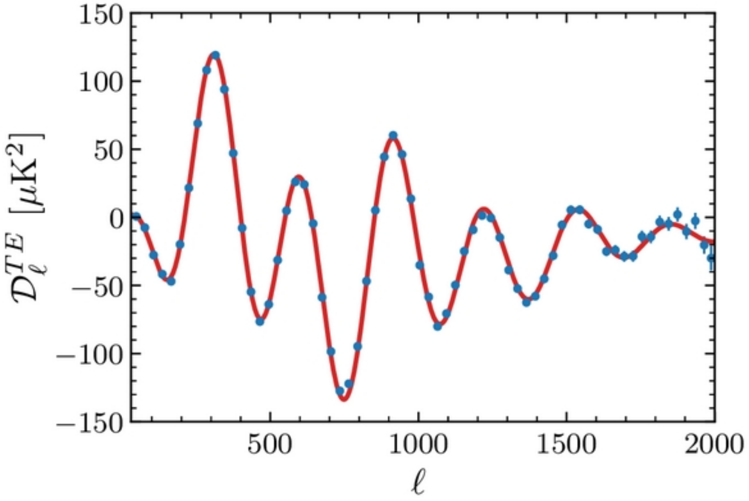
inflation/initial conditions　sound waves

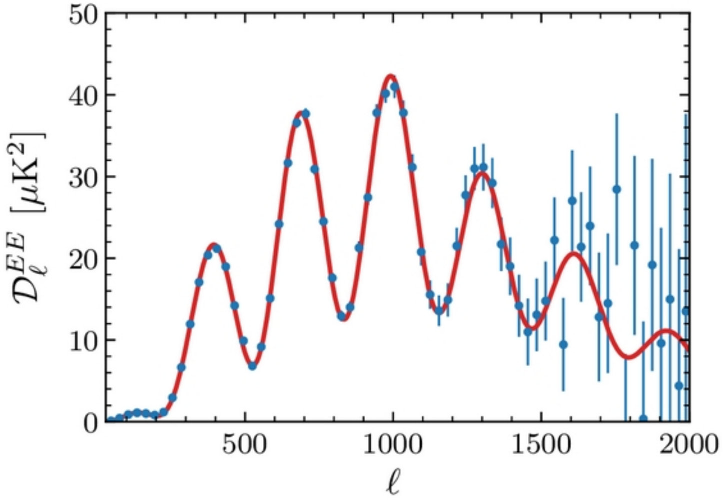
CMB Power Spectra











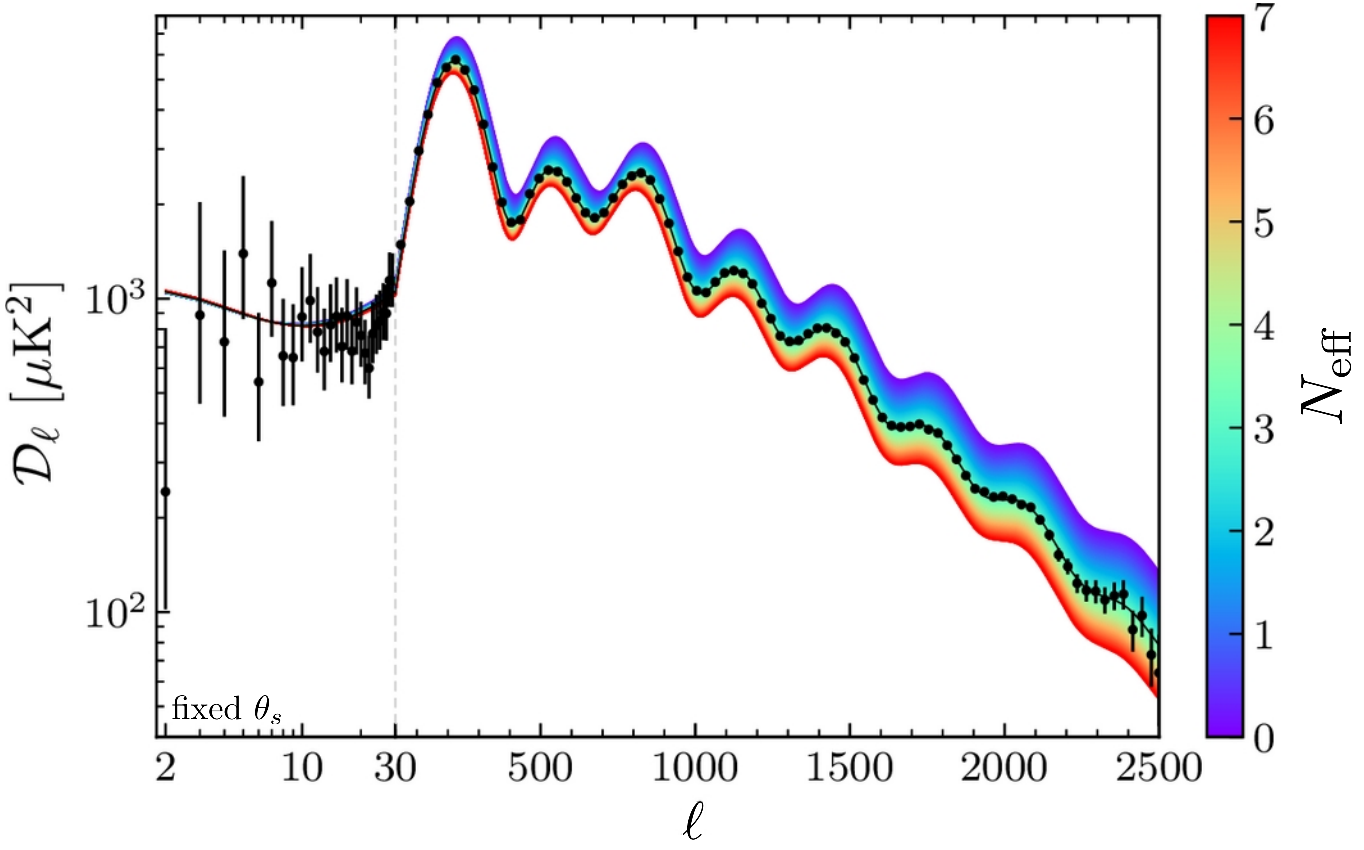
Planck Collaboration

Cosmic Neutrinos

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

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

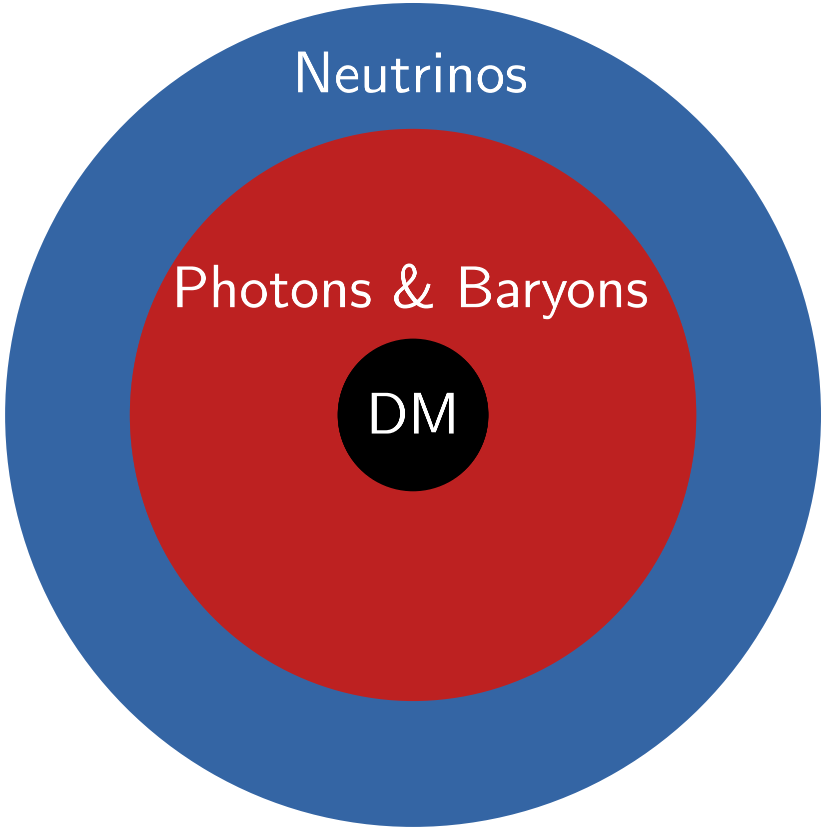
$$N_{\mathrm{eff}}^{\mathrm{SM}} = 3.044$$



Free-Streaming Neutrinos

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

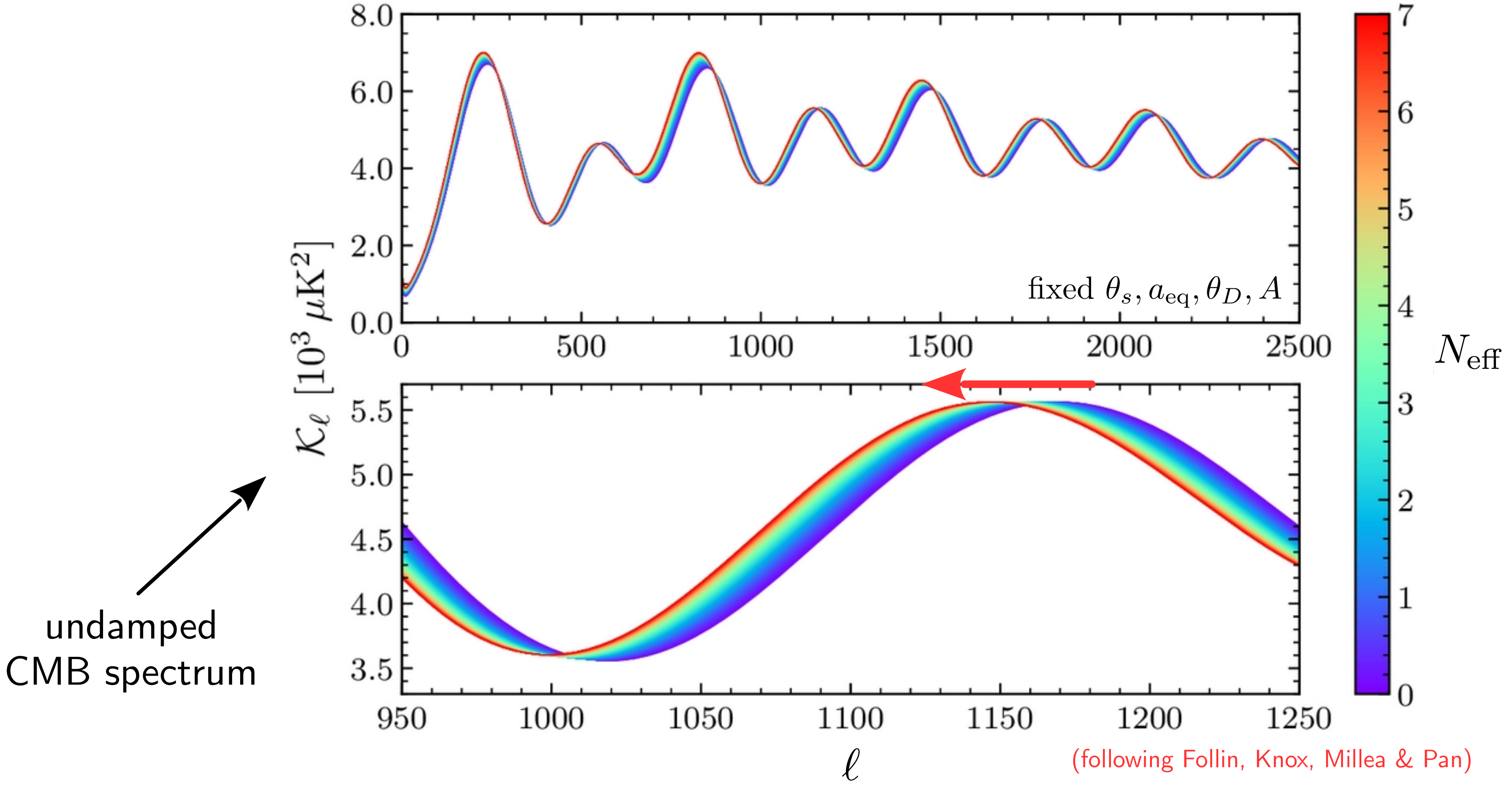
Free-streaming neutrinos overtake the photons and baryons and pull them ahead of the sound horizon:



Phase Shift in the CMB Spectrum

This corresponds to a frequency, amplitude and especially phase shift in the CMB power spectrum:

Bashinsky & Seljak



(following Follin, Knox, Millea & Pan)

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

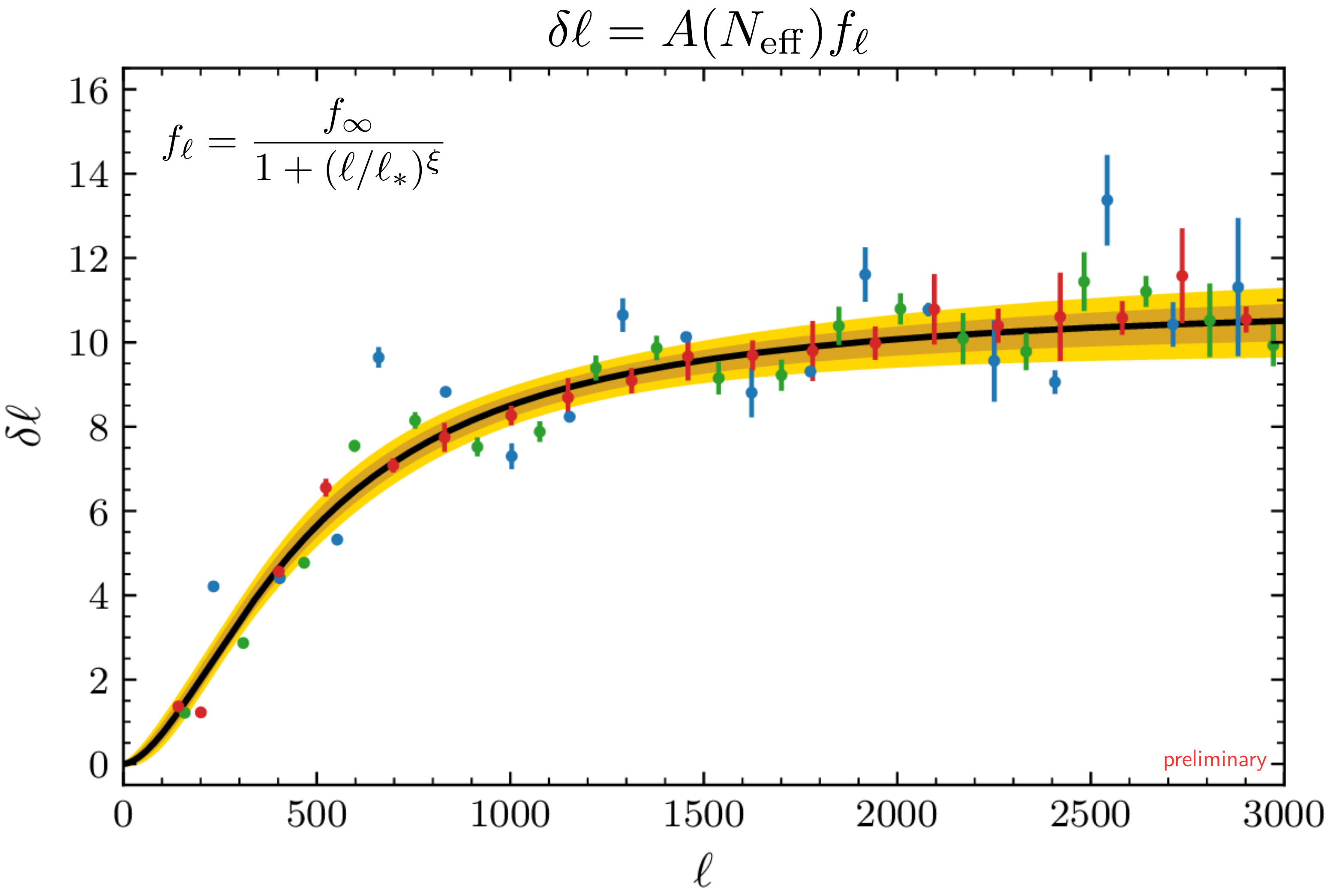
Detected in Planck 2013 TT data!

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



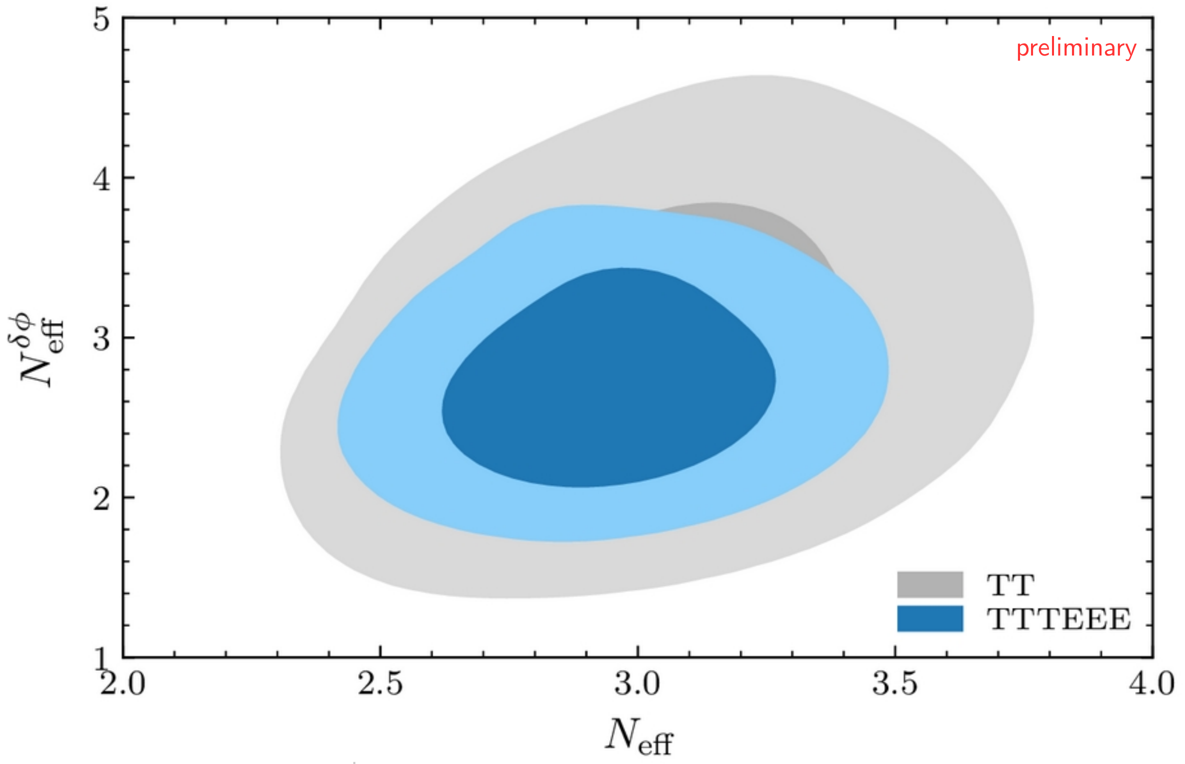
TT peaks/troughs

EE peaks/troughs

TE peaks/troughs

Freese, Montefalcone & BW (in prep.)

Phase Shift in the CMB Spectrum



Based on Planck 2013 temperature data:

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

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

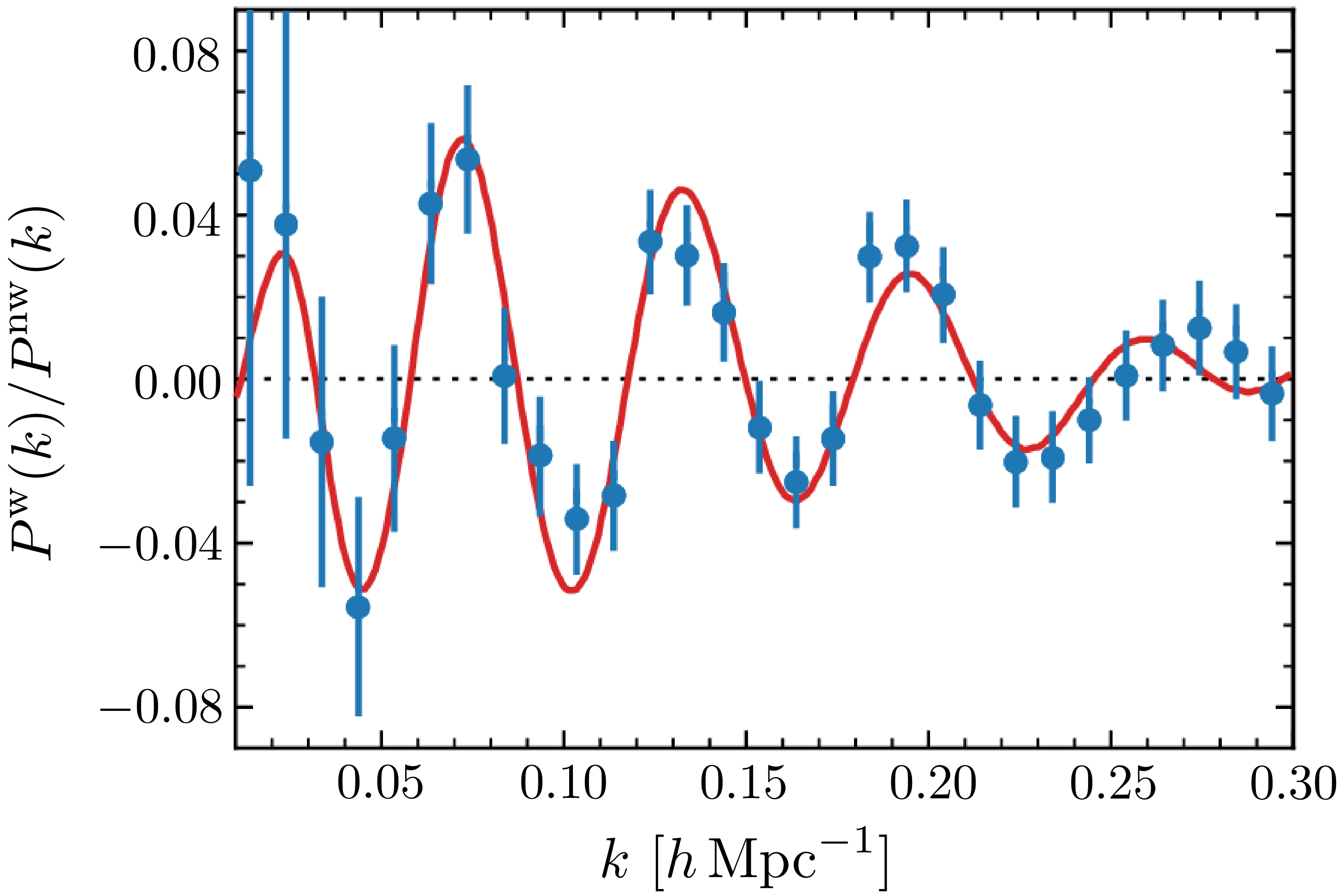
Follin et al.

Work in progress (preliminary):

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

Freese, Montefalcone & BW (in prep.)

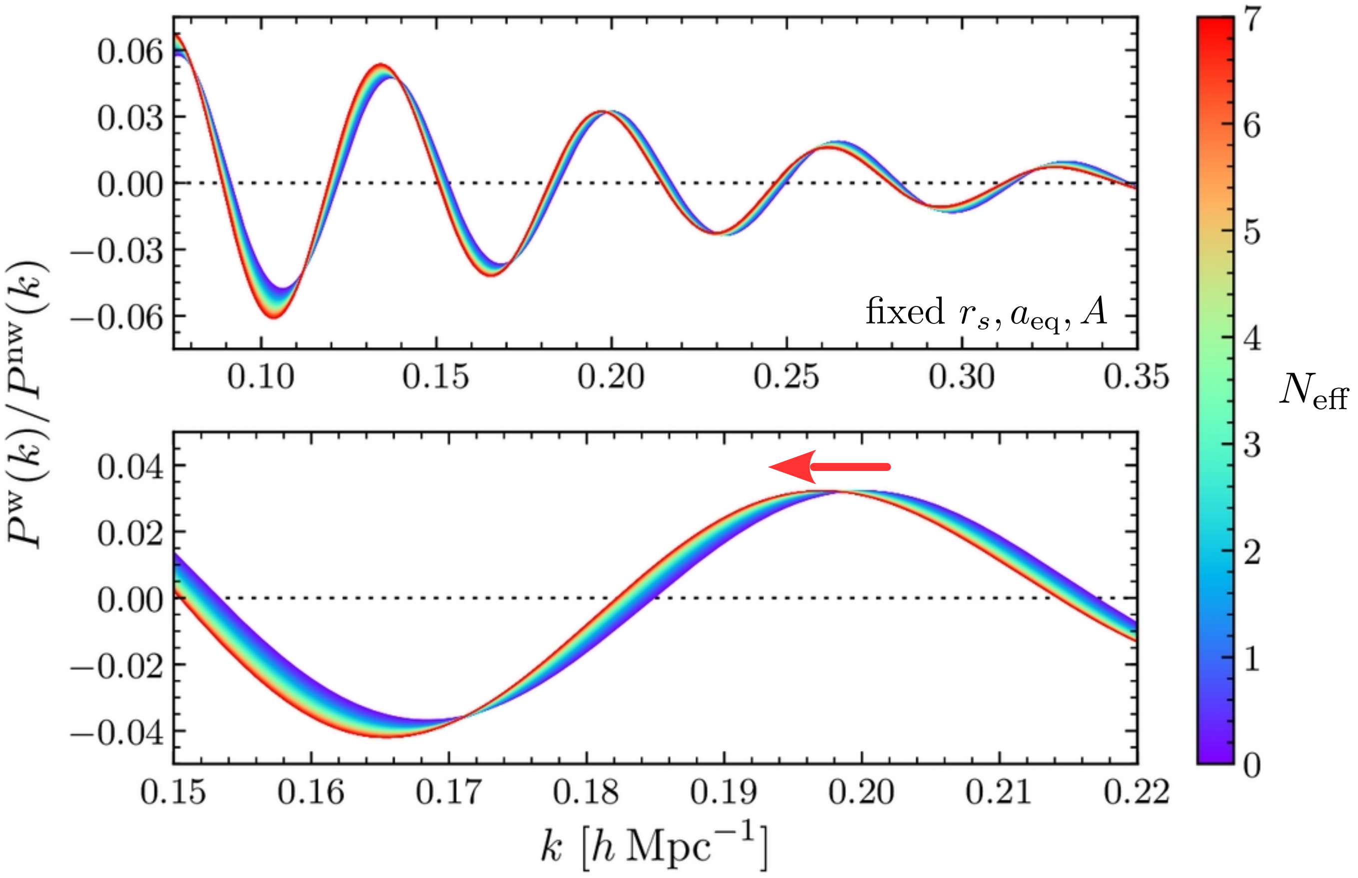
Baryon Acoustic Oscillations in Large-Scale Structure



Beutler et al. (BOSS)

Phase Shift in the BAO Spectrum

The same coherent shift can be seen in the BAO spectrum:



Baumann, Green & BW

The phase is immune to the effects of nonlinear gravitational evolution.

Baumann, Green & Zaldarriaga

Generalized BAO Analysis

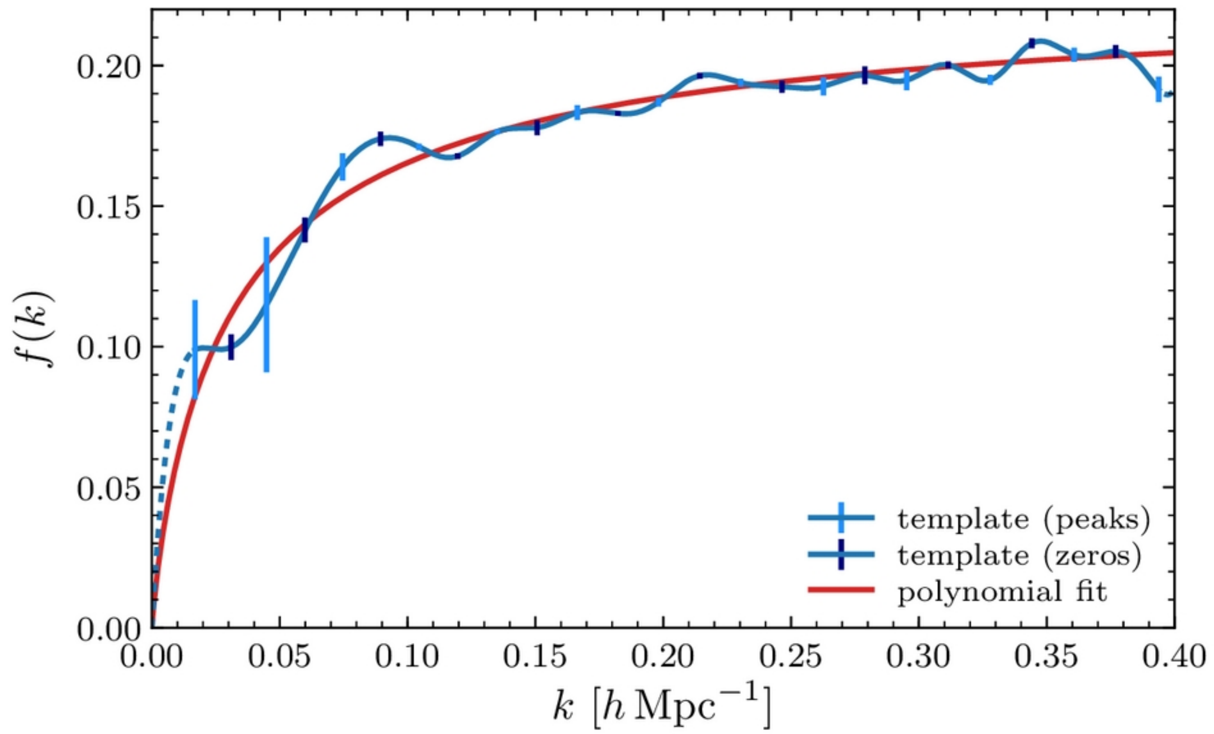
Proposal to adapt the standard BAO analysis:

template

$$P^w(k) \sim A(k)\,\sin(kr_s/\alpha + \beta f(k))$$

standard BAO parameter

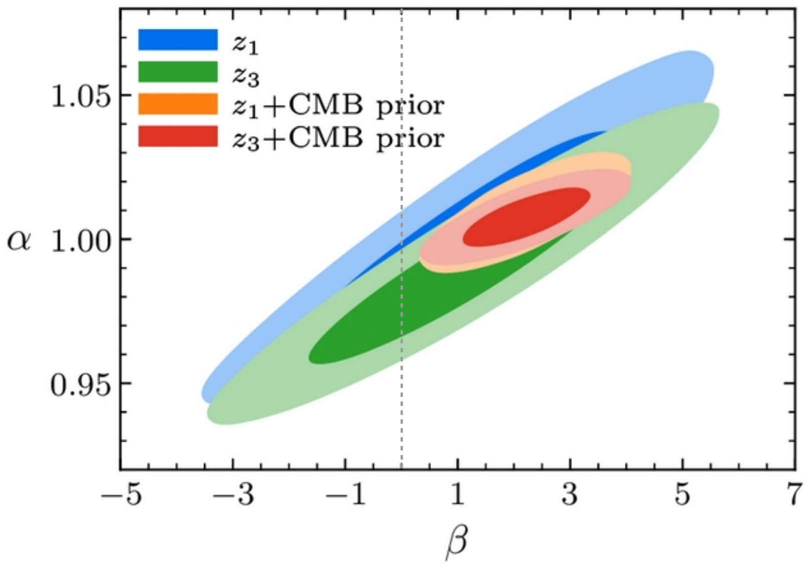
phase shift amplitude

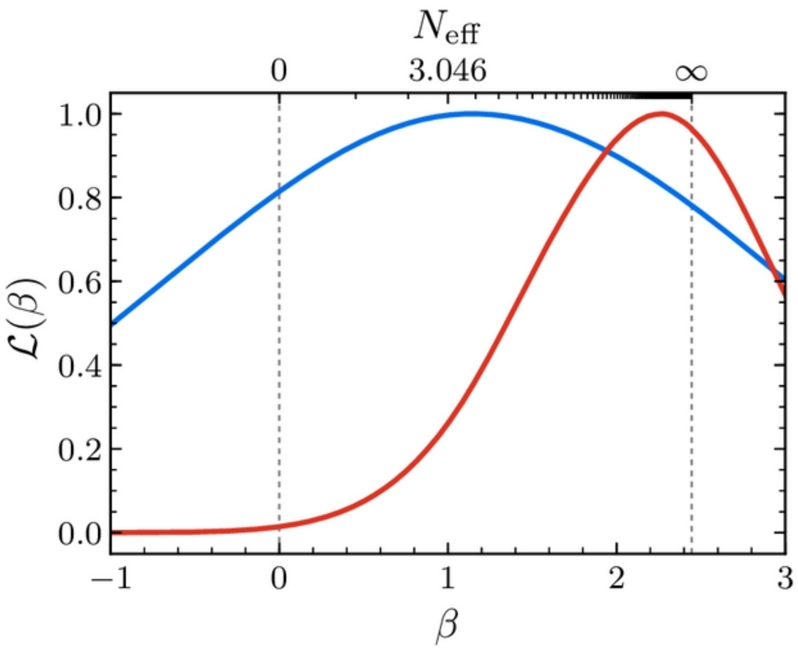


Baumann, Green & BW

First Constraint

The neutrino-induced phase shift can be measured in the BOSS DR12 dataset:





$$\beta = 2.22 \pm 0.75$$

$$\beta > 0 \text{ at } > 99\% \text{ c.l.}$$

(CMB prior from Planck 2018)

This is a proof of principle for directly extracting information on neutrinos (and other light relics) from galaxy clustering data.

Future observations will greatly improve on this first measurement.

Baumann, Beutler, ..., BW, ...

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):

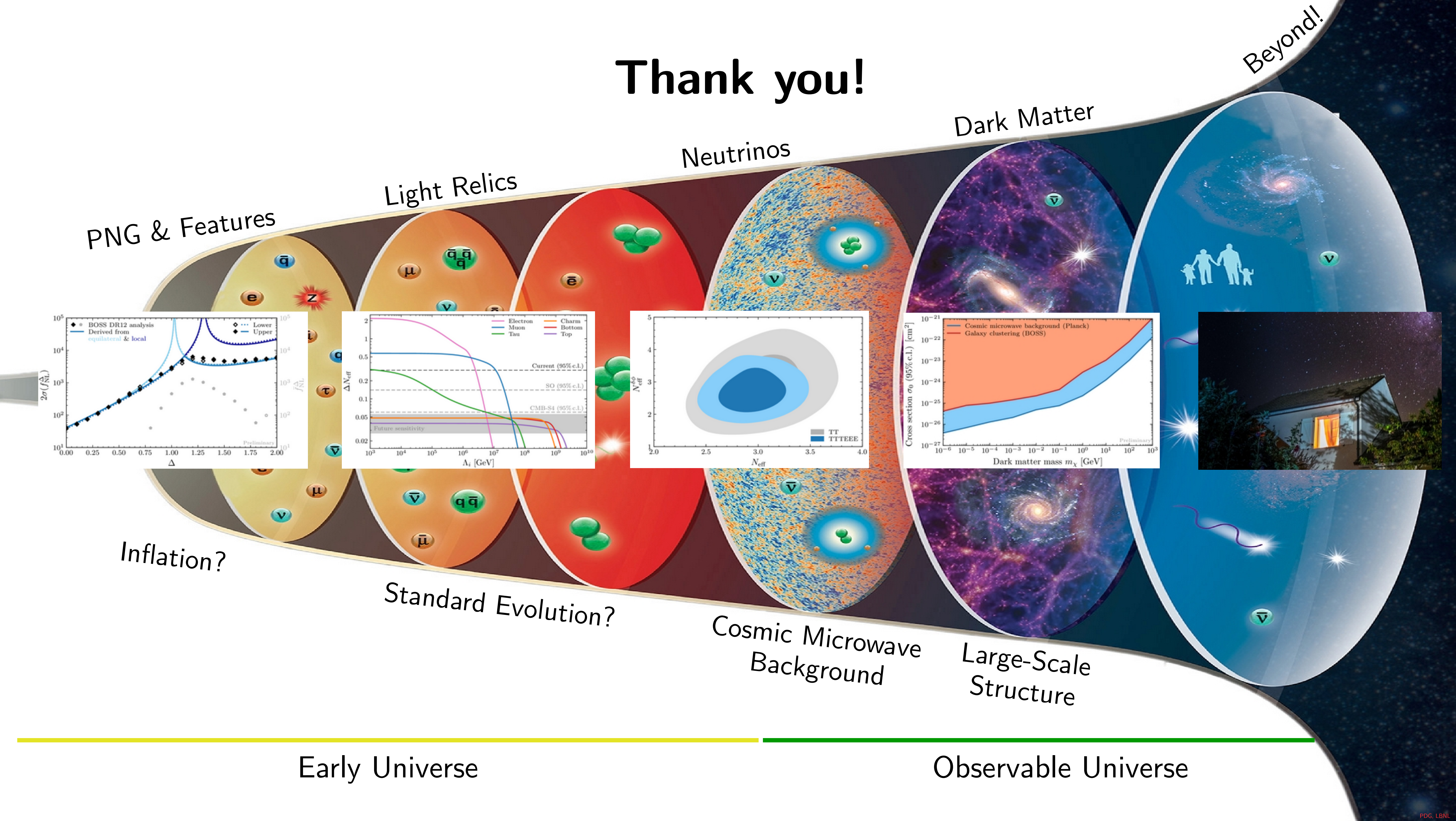
Neutrinos are free-streaming particles in the early universe!

– 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.

Thank you!



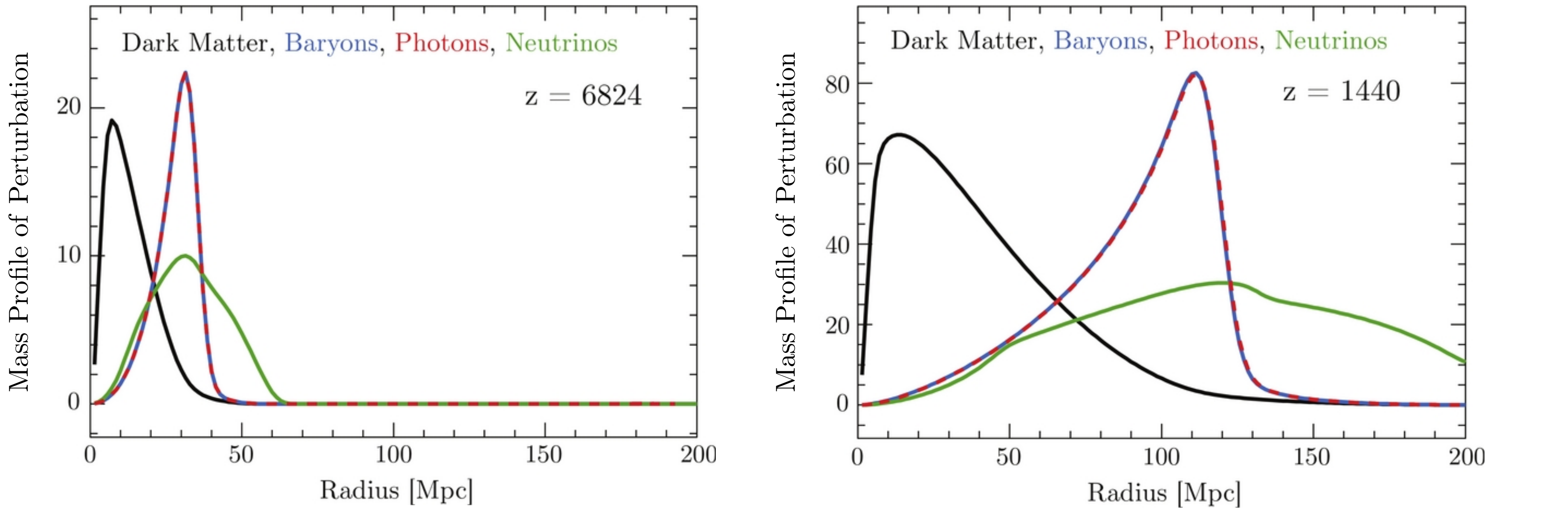
PNG & Features
Light Relics
Neutrinos
Dark Matter
Beyond!
BOSS DR12 analysis
Derived from
equilateral & local
Lower
Upper
Δ
Preliminary
Electron
Muon
Tau
Charm
Bottom
Top
Current (95% c.l.)
SO (95% c.l.)
CMB-S4 (95% c.l.)
Future sensitivity
$\Delta N_{\rm eff}$
Λ_i [GeV]
TT
TTTEEE
$N_{\rm eff}$
Cosmic microwave background (Planck)
Galaxy clustering (BOSS)
Cross section σ_0 (95% c.l.) [cm^2]
Dark matter mass m_χ [GeV]
Preliminary
Inflation?
Standard Evolution?
Cosmic Microwave
Background
Large-Scale
Structure
Early Universe
Observable Universe

Backup Slides

Free-Streaming Neutrinos

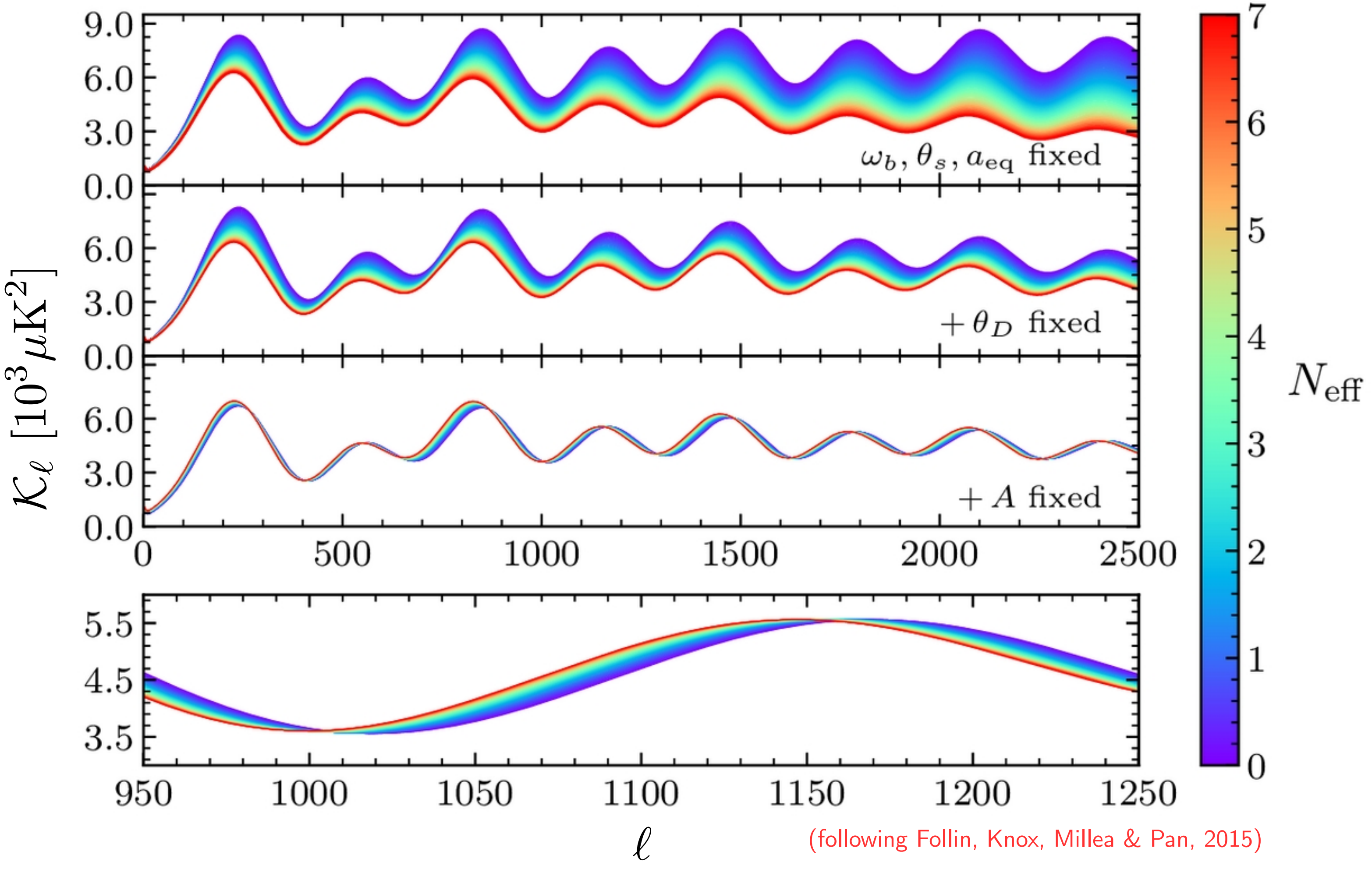
What distinguishes free-streaming and non-free-streaming radiation observationally?

Free-streaming neutrinos overtake the photons and induce metric fluctuations ahead of the sound horizon:



Eisenstein, Seo and White (2007)

Phase shift in the CMB

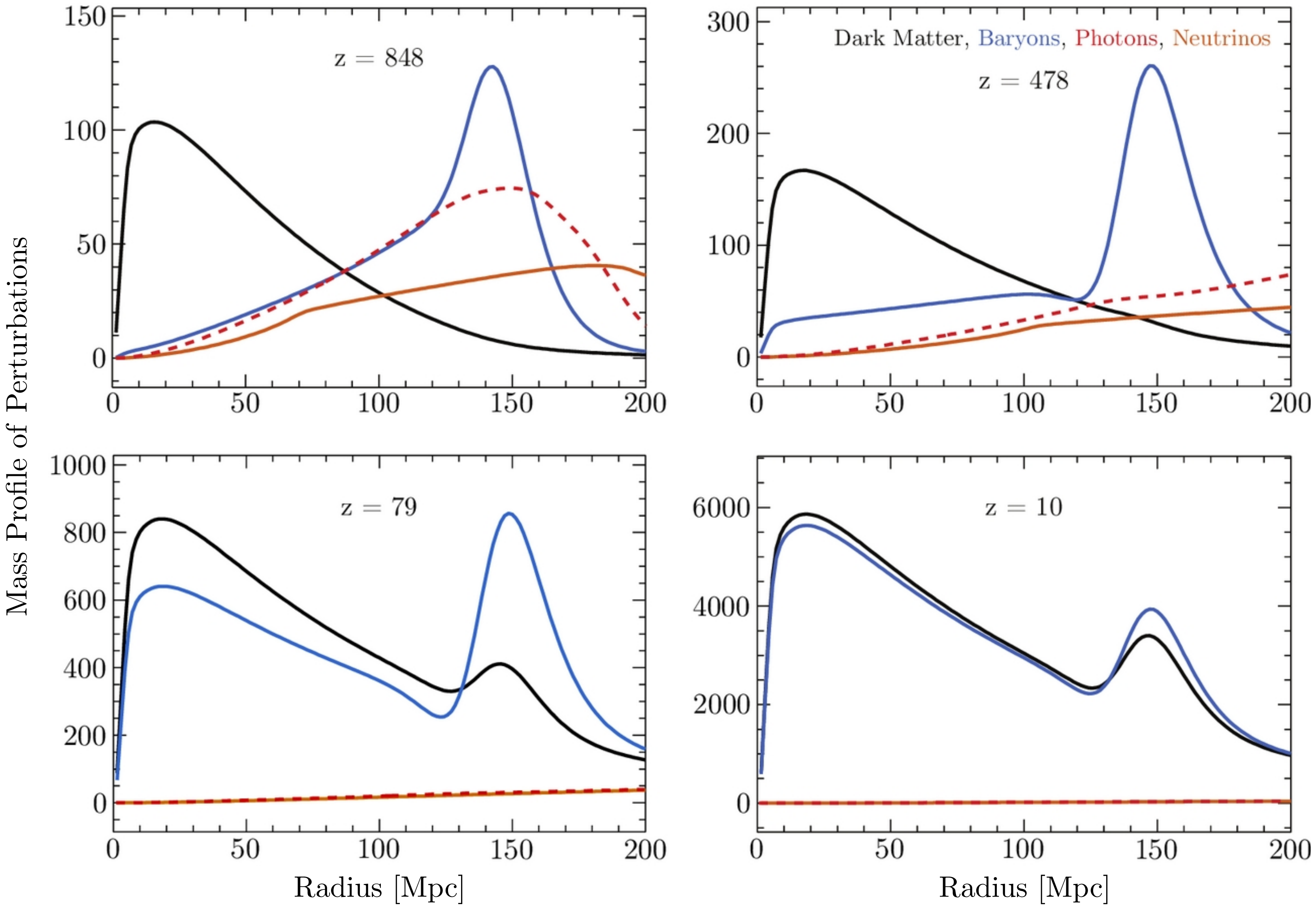


Undamped
CMB spectrum

(following Follin, Knox, Millea & Pan, 2015)

Baumann, Green & BW

Baryon Acoustic Oscillations

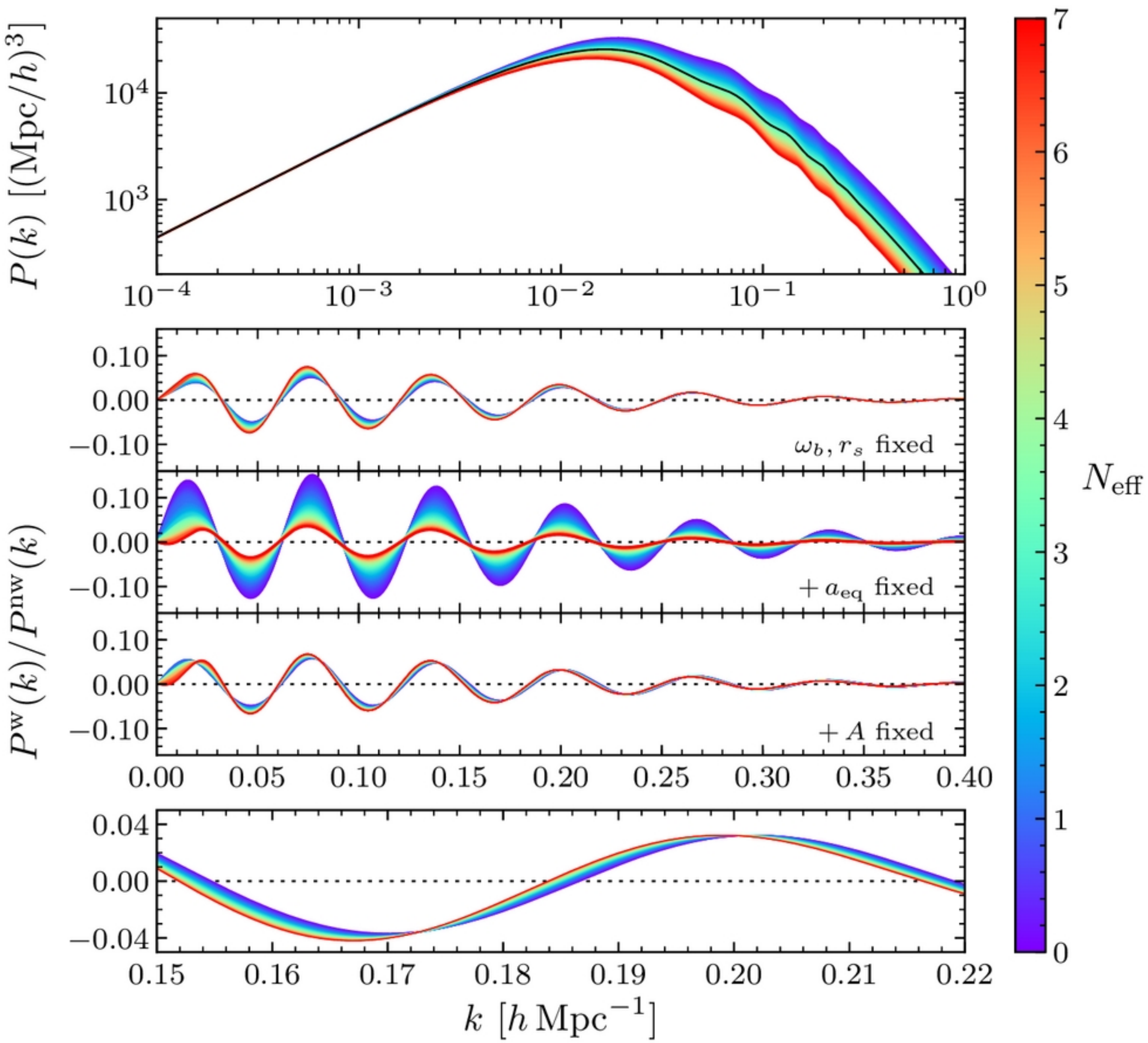


Eisenstein, Seo and White

Phase shift in LSS

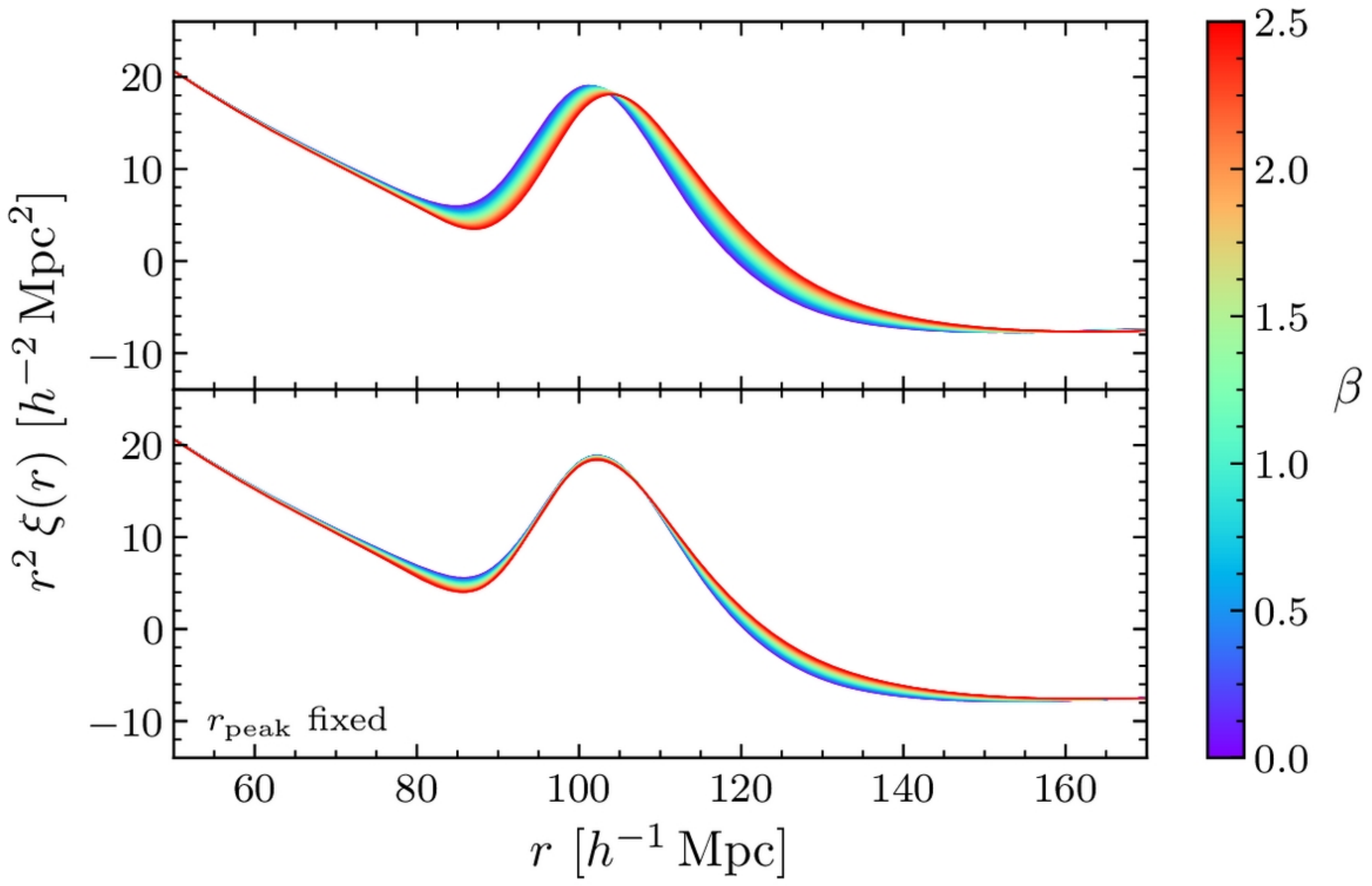
$$P(k) \equiv P^{\rm w}(k) + P^{\rm nw}(k)$$
$$\equiv P^{\rm nw}(k)\,[1 + O(k)]$$

BAO spectrum $O(k)$



Baumann, Green & BW

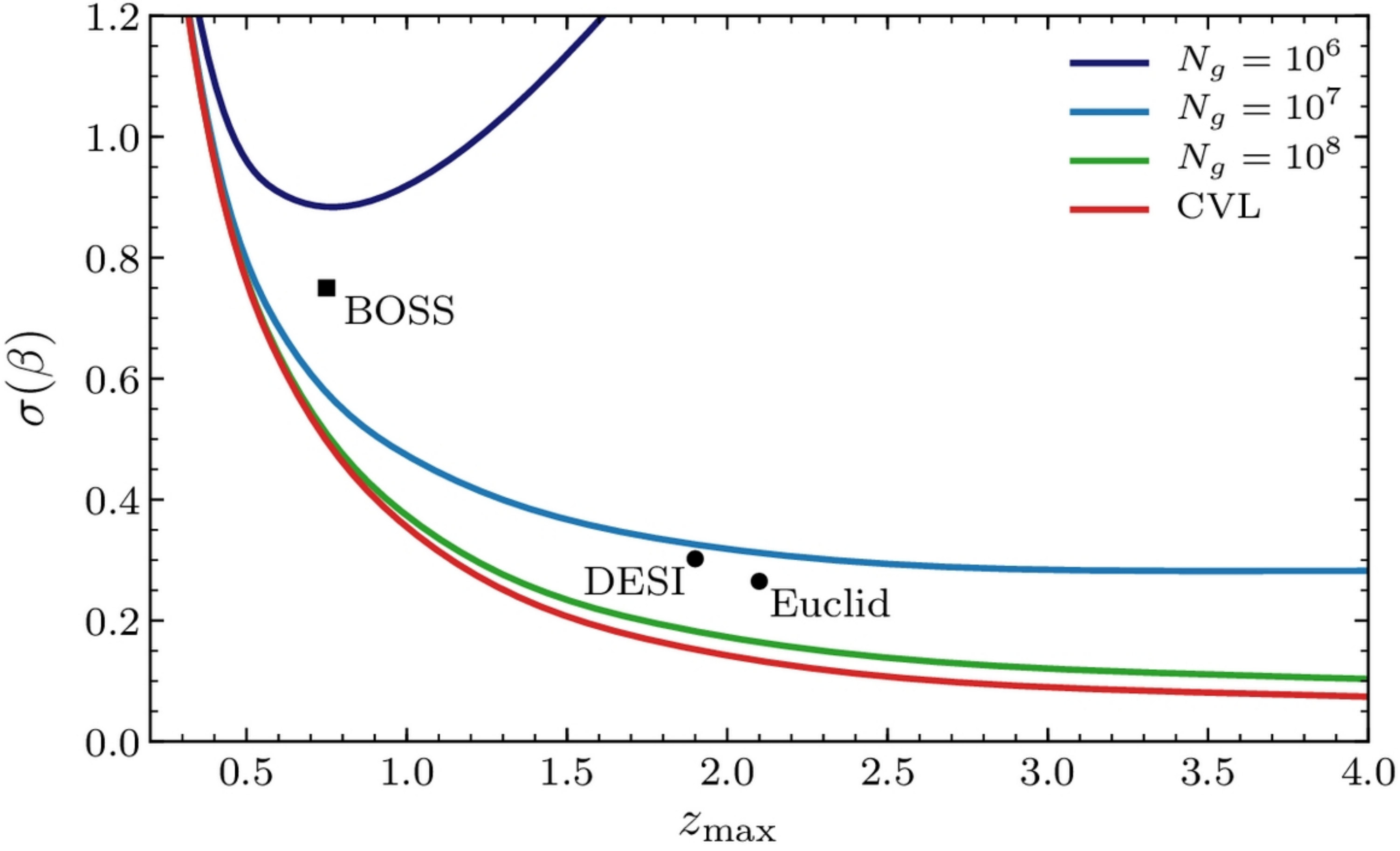
Phase Shift in Configuration Space



Baumann, Beutler, ..., BW, ...

Future Prospects

Future observations will greatly improve on this first measurement of the phase:



Baumann, Green & BW; Baumann, Beutler, ..., BW, ...