Free-Streaming Neutrinos in the CMB and LSS

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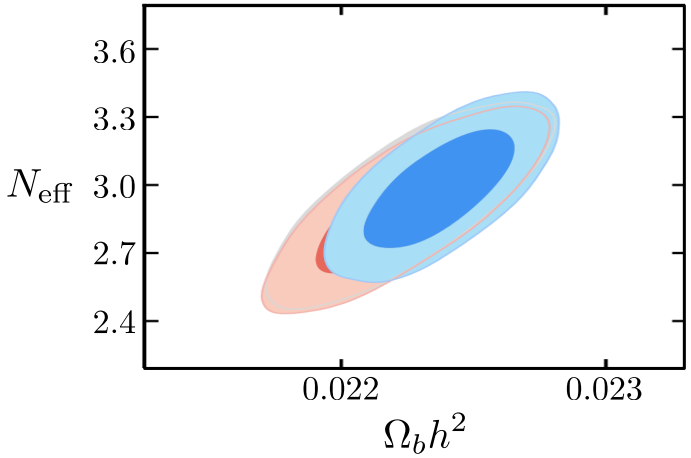
Based on work with:
Daniel Baumann, Daniel Green; Joel Meyers;
Florian Beutler, Raphael Flauger, Anže Slosar,
Mariana Vargas-Magaña, Christophe Yèche

Topics in Cosmic Neutrino Physics, Fermilab, October 2019

Status: Cosmological Radiation Constraints

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

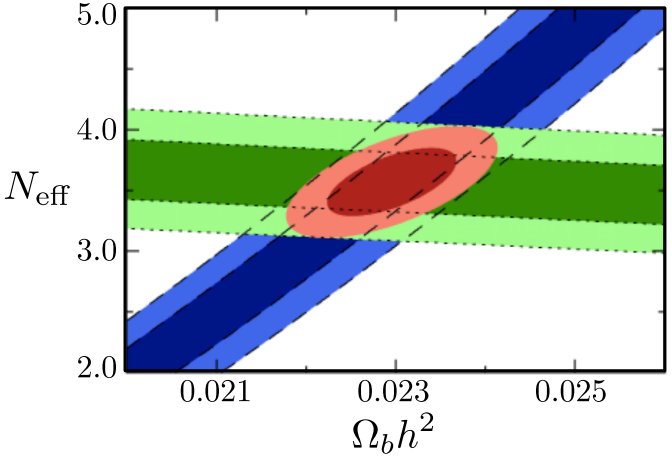
$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$



CMB: anisotropy measurements

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

Planck (2018)

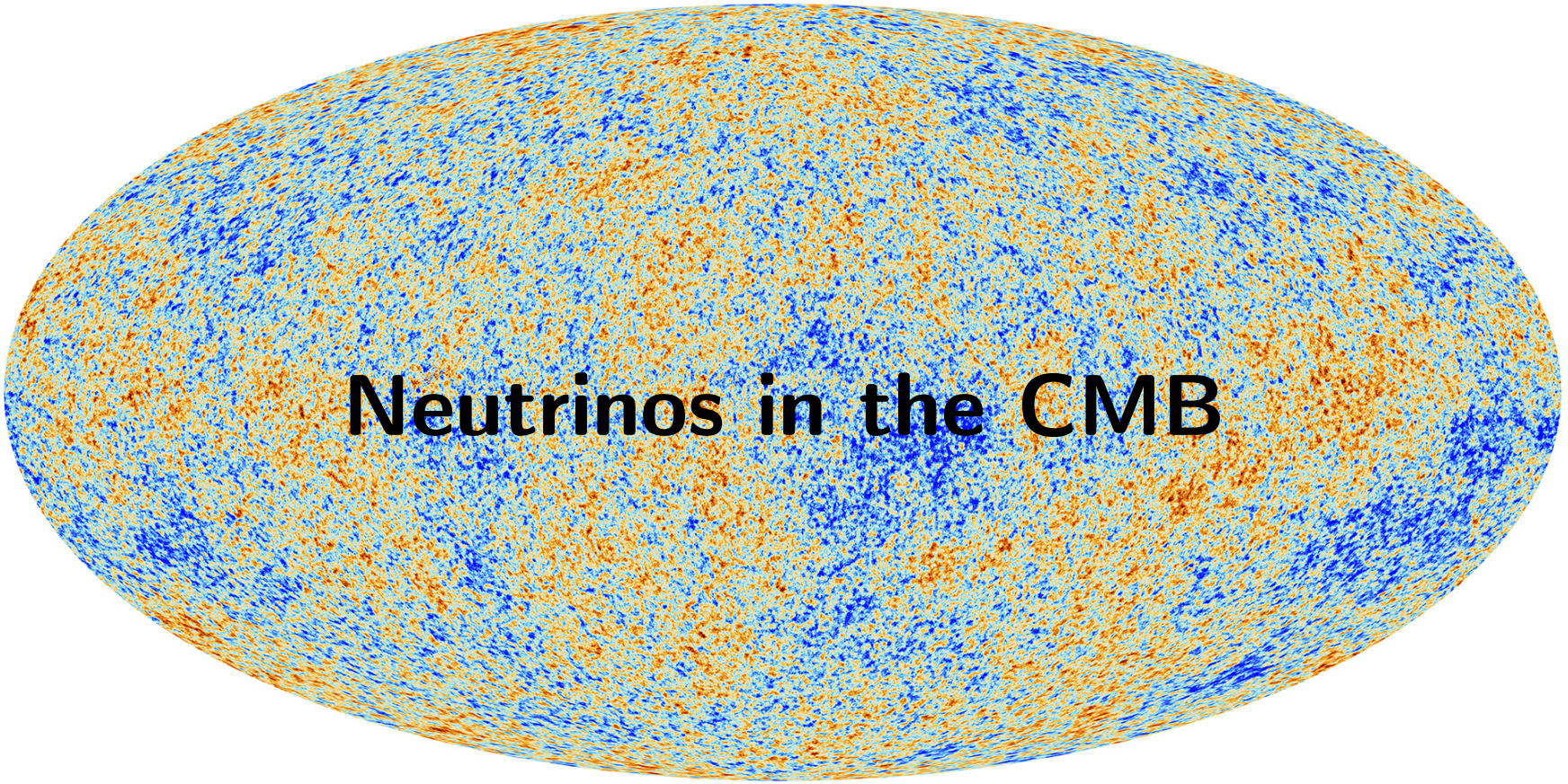


BBN: primordial abundances

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

Cooke et al. (2015)

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



Neutrinos in the CMB

D. Baumann, D. Green, J. Meyers and BW
arXiv:1508.06342 (JCAP 2016)

Planck (2015)

Cosmic Neutrinos

Gravitationally important properties of neutrinos:

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

  ⟶ Measurements consistent with expected $N_{\rm eff}^{\rm SM} = 3.046$.

- 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 Neutrinos

Gravitationally important properties of Standard Model neutrinos:

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

  ⟶ Measurements consistent with expected $N_{\rm eff}^{\rm SM} = 3.046$.

- 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?

  ⟶ Introduce parametrization:

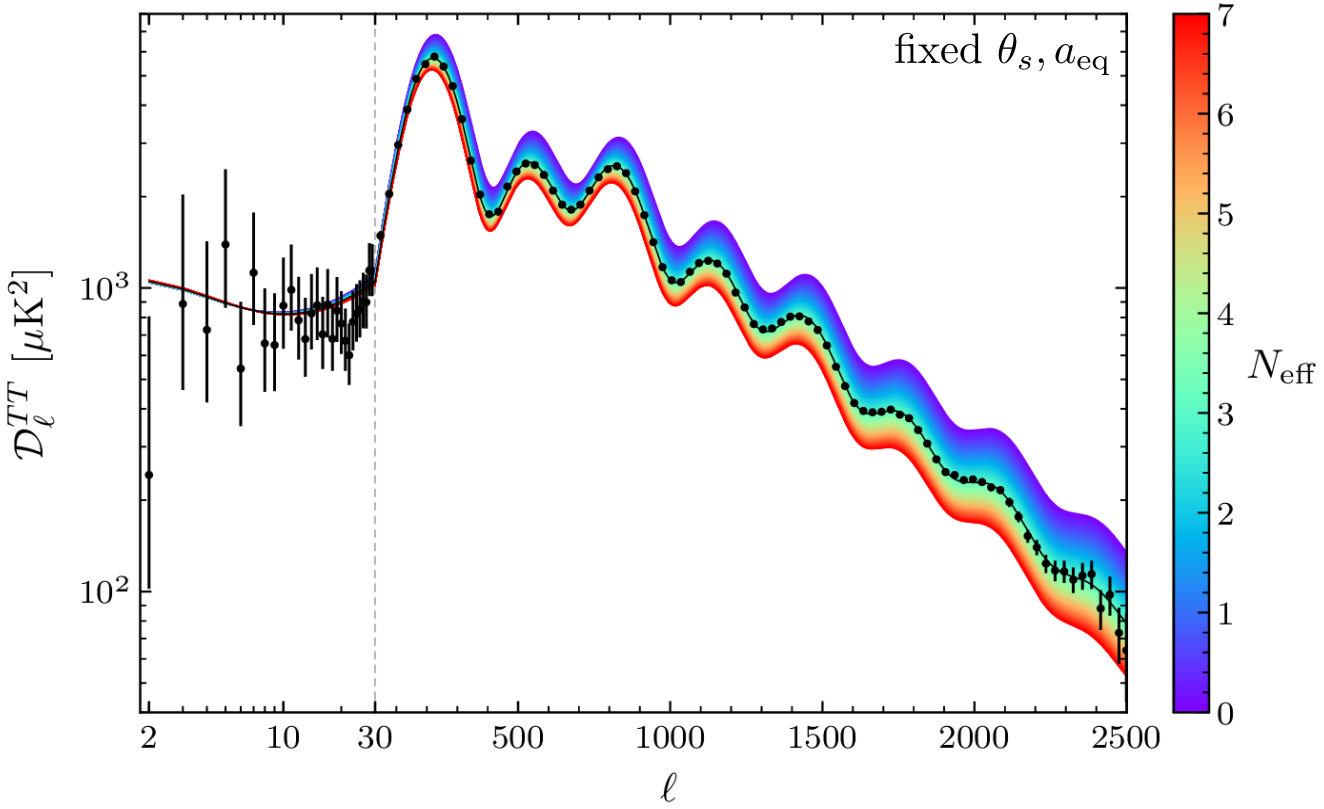
cf. Bell et al. (2005), Friedland et al. (2007), Chacko et al. (2015)

$N_{\rm eff}$ ↓ free-streaming radiation density

$N_{\rm fluid}$ ↓ non-free-streaming radiation density

Cosmic Neutrinos

Main effect of radiation is on the CMB damping tail:

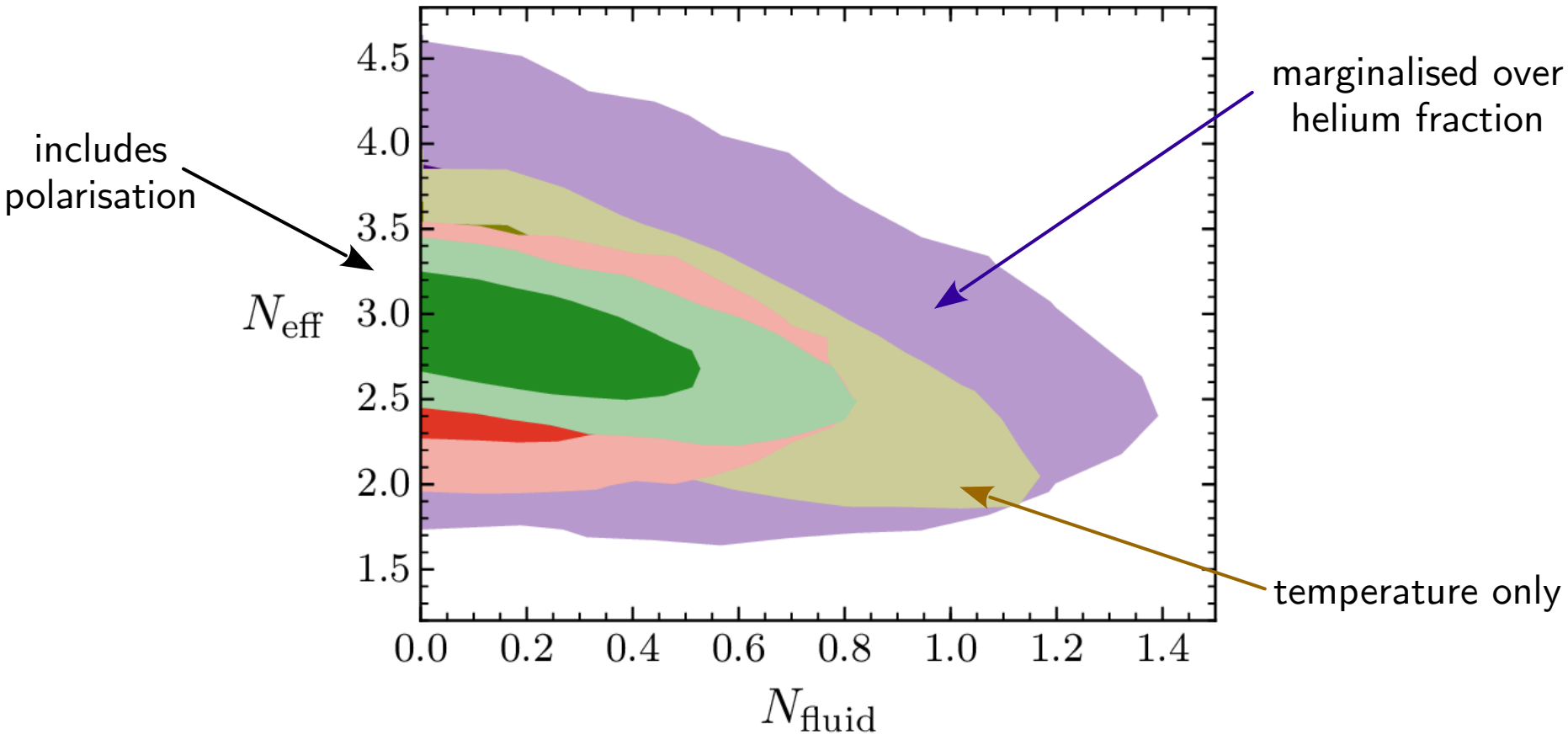


Degenerate with change in the primordial helium fraction Y_p.

Only sensitive to background energy density: $N_{\rm eff} + N_{\rm fluid}$.

Planck (2015)

Planck Constraints

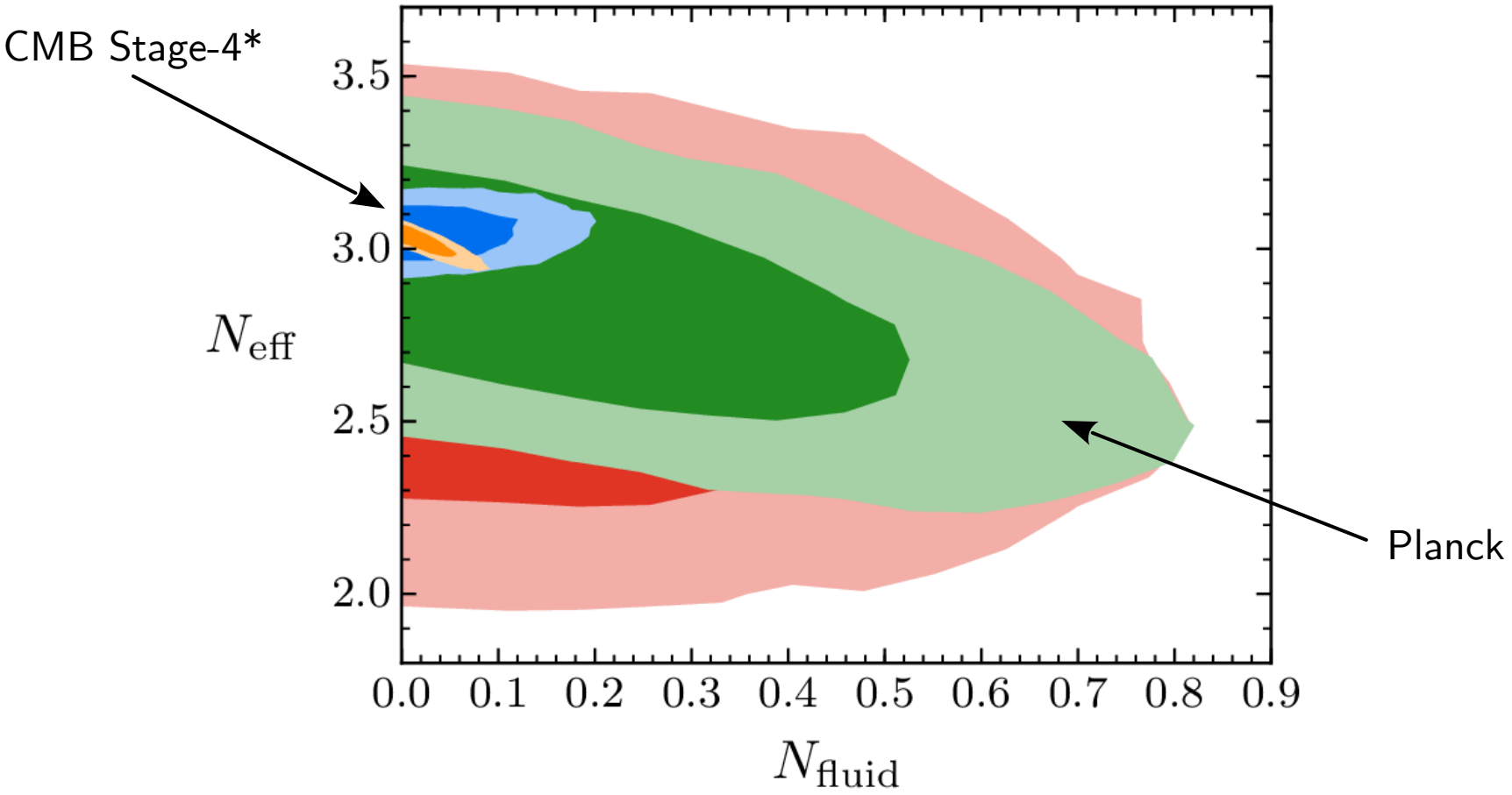


$$N_{\rm eff} = 2.80 \pm 0.24 \qquad N_{\rm fluid} < 0.67 \ (95\% \ \text{c.l.})$$

$\rightarrow$ Standard Model neutrinos are free-streaming!

Baumann, Green, Meyers & BW (2016)

CMB Stage-4 Forecast



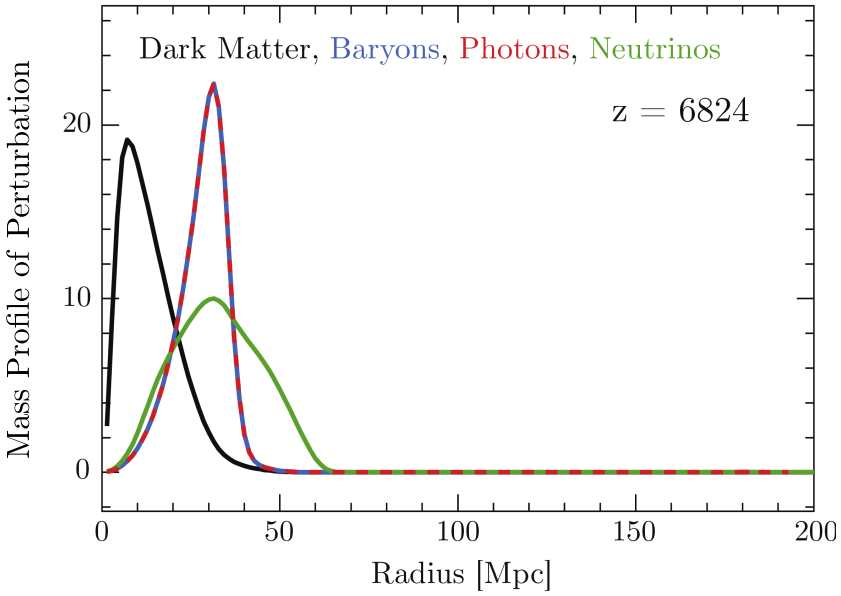
*Assumed specifications more optimistic than current CMB-S4 configuration.

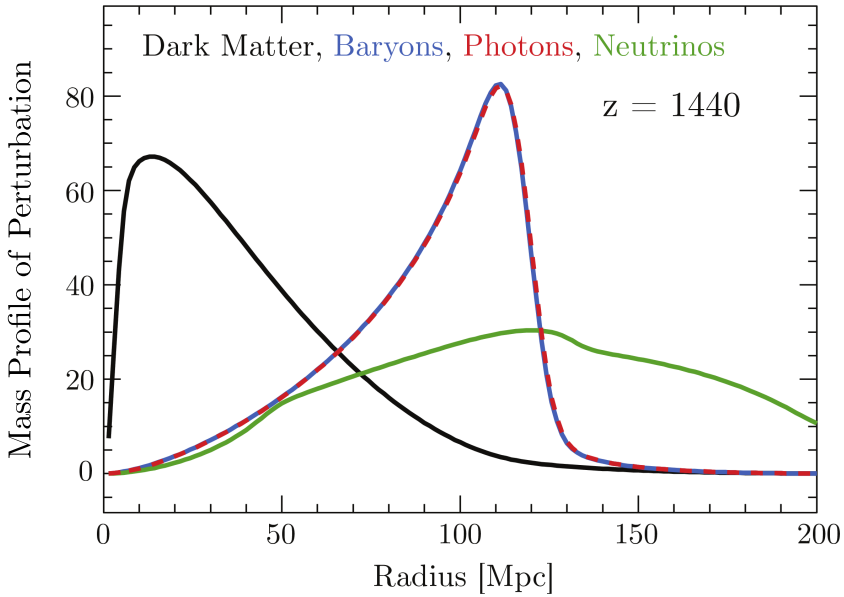
Baumann, Green, Meyers & BW (2016)

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:





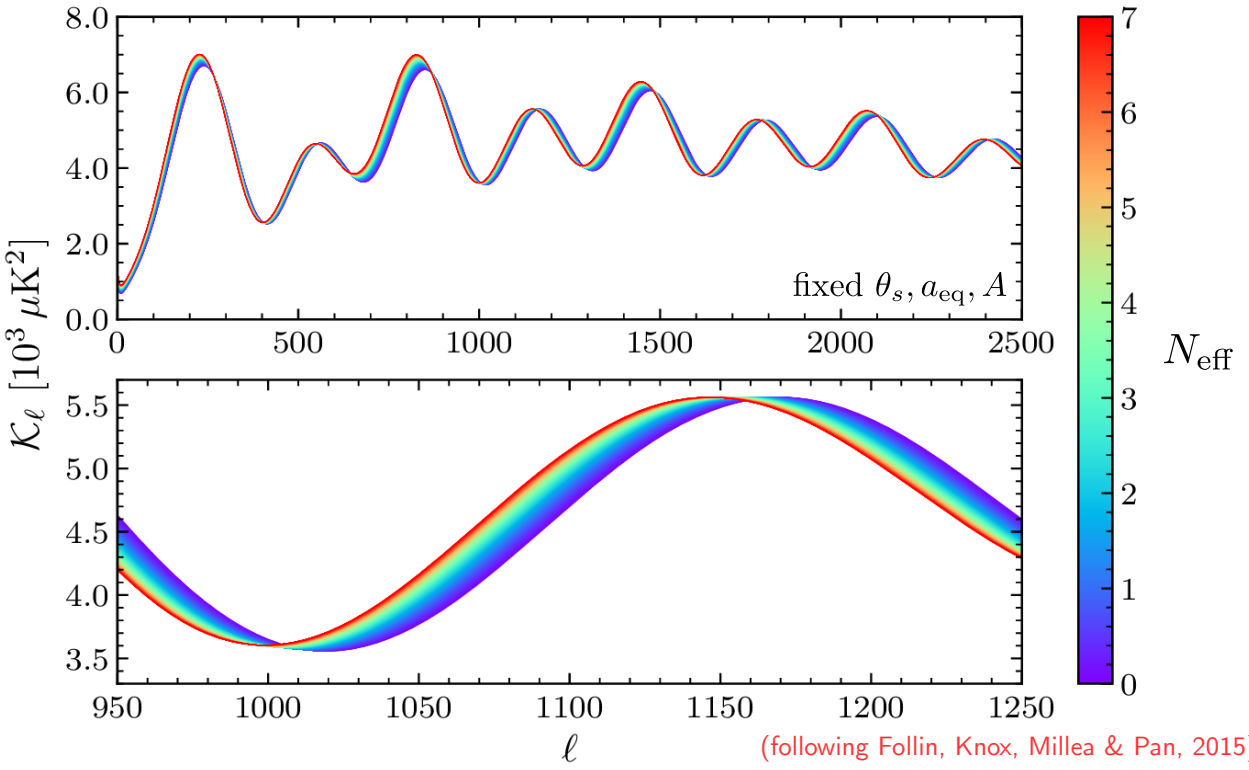
Eisenstein, Seo and White (2007)

Phase Shift

This corresponds to a phase shift in the CMB power spectrum:

Bashinsky & Seljak (2003)

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



undamped CMB spectrum

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

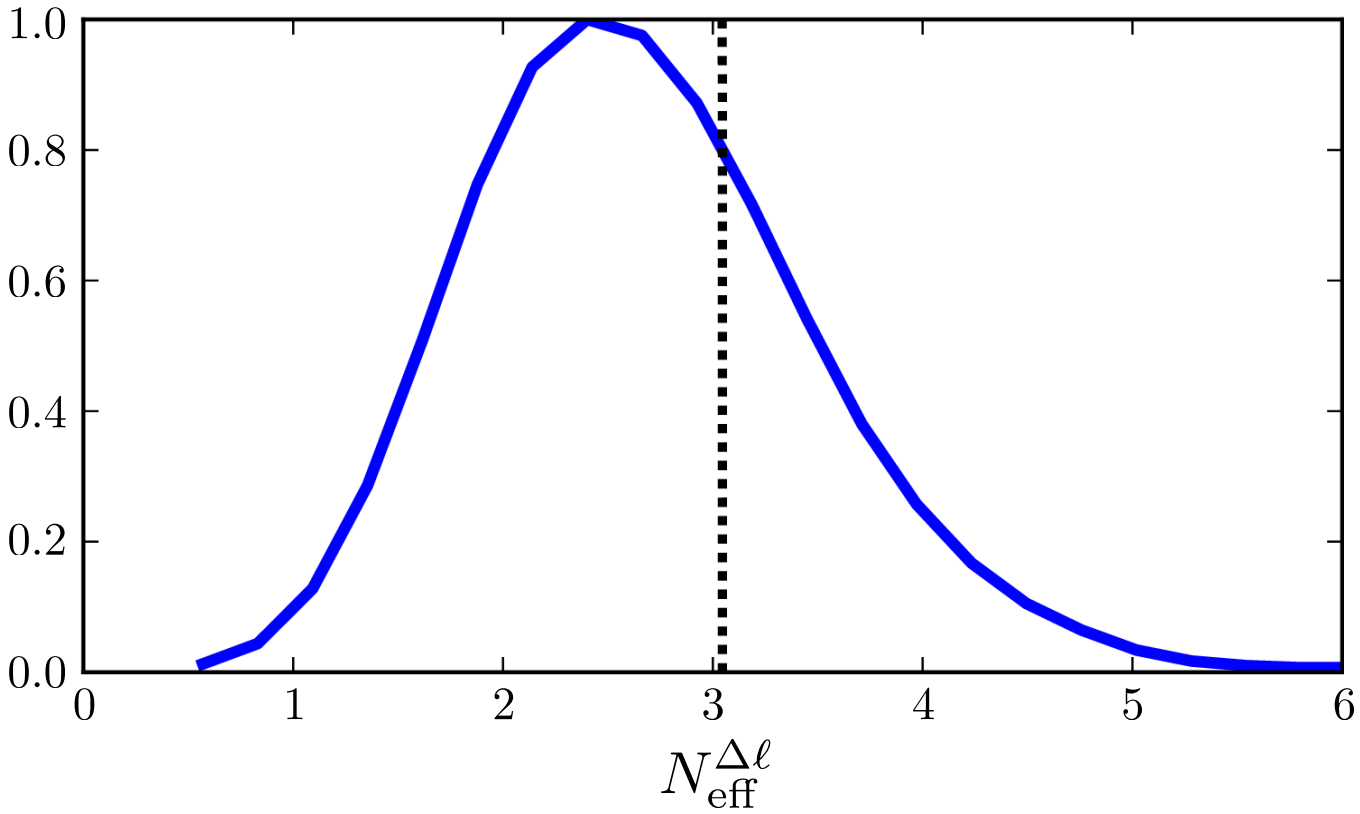
Free-streaming neutrinos are a causal way to produce such a shift.

Baumann, Green, Meyers & BW (2016)

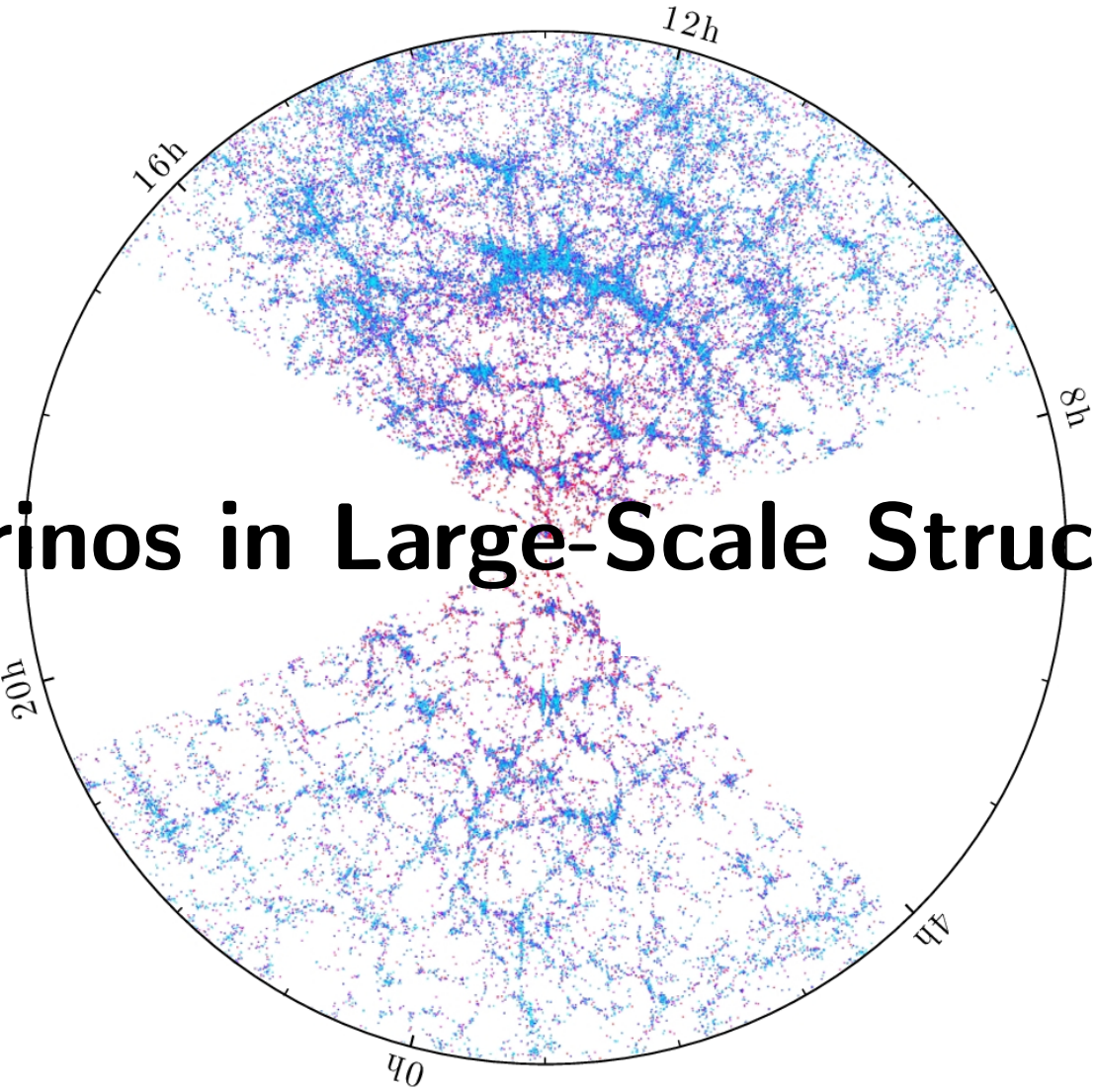
Phase Shift

Small effect: $\Delta\ell \approx 5.0 \times \Delta N_{\rm eff}$.

But neutrino imprint in phase shift has been detected in Planck data:



Follin, Knox, Millea & Pan (2015); cf. Baumann, Green, Meyers & BW (2016)



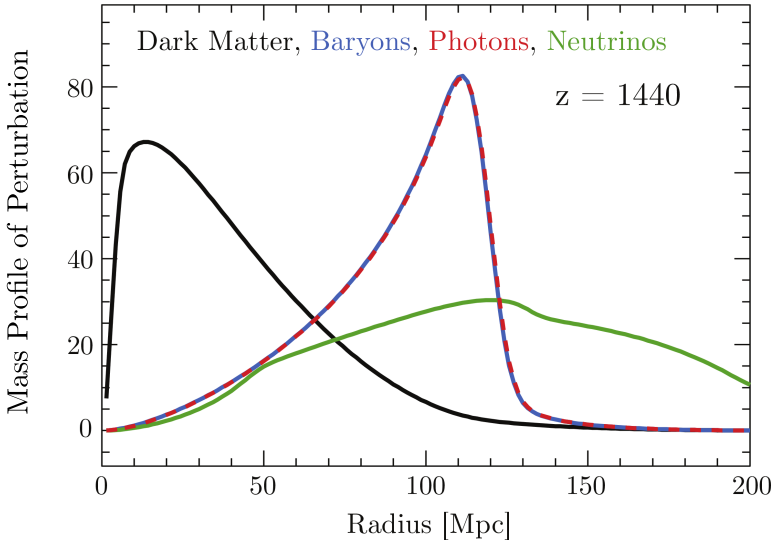
Neutrinos in Large-Scale Structure

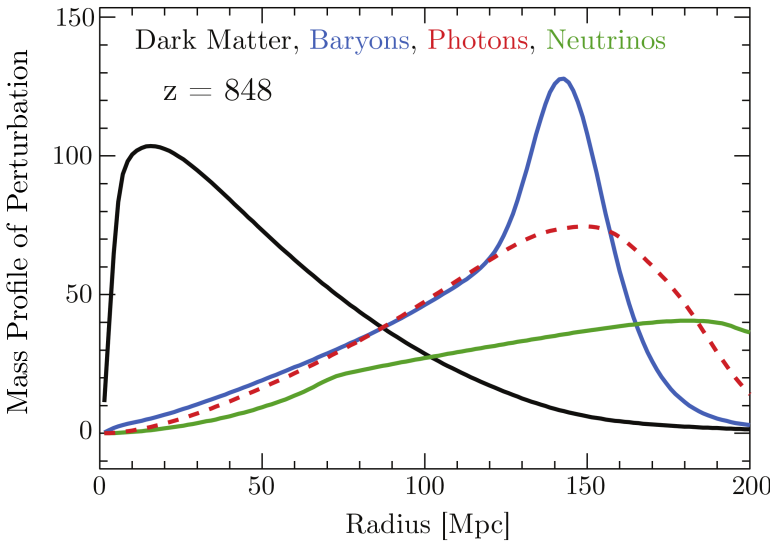
D. Baumann, D. Green and BW,
arXiv:1712.08067 (JCAP 2018)

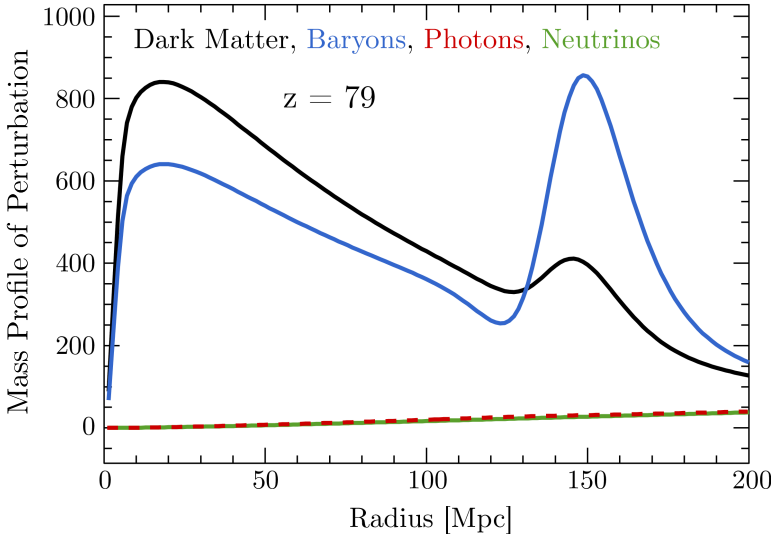
D. Baumann, F. Beutler, R. Flauger, D. Green, A. Slosar, M. Vargas-Magaña, BW and C. Yèche,
arXiv:1803.10741 (Nat. Phys. 2019)

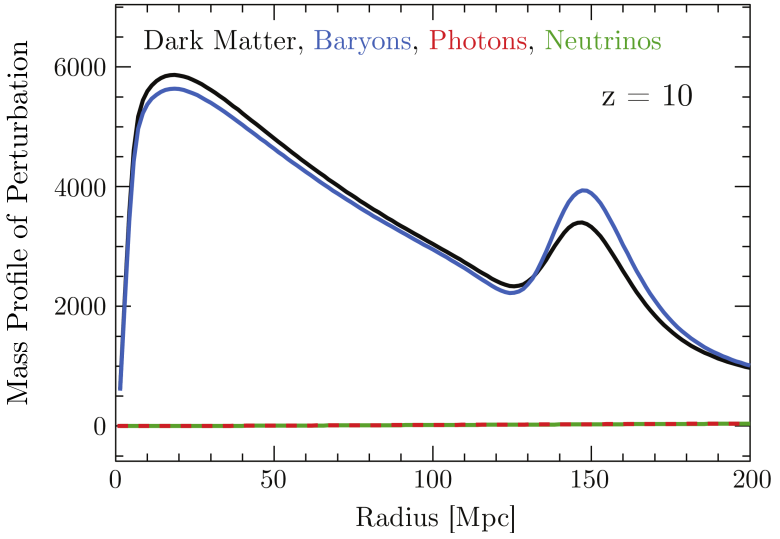
SDSS

Baryon Acoustic Oscillations





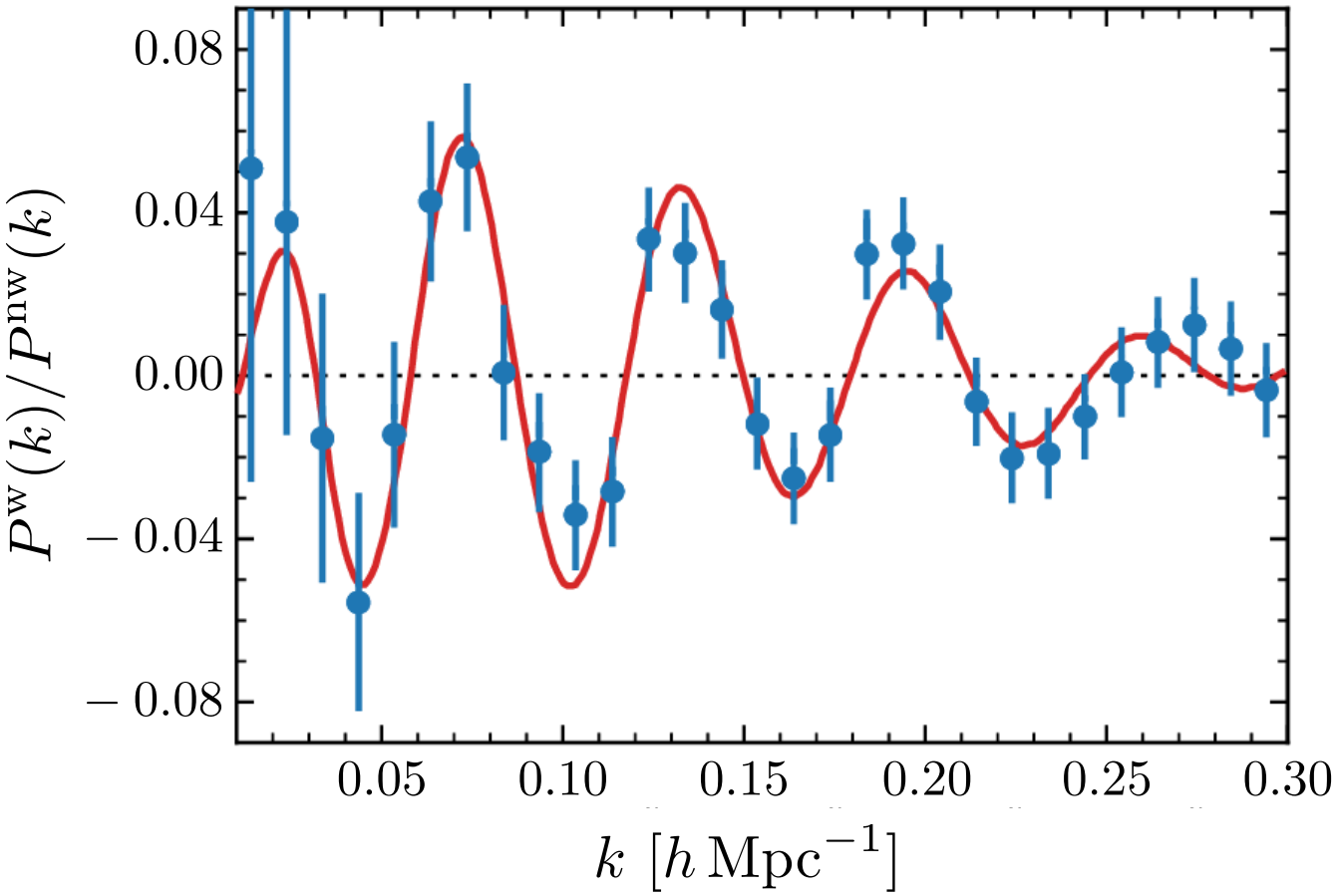




Eisenstein, Seo and White (2007)

Baryon Acoustic Oscillations

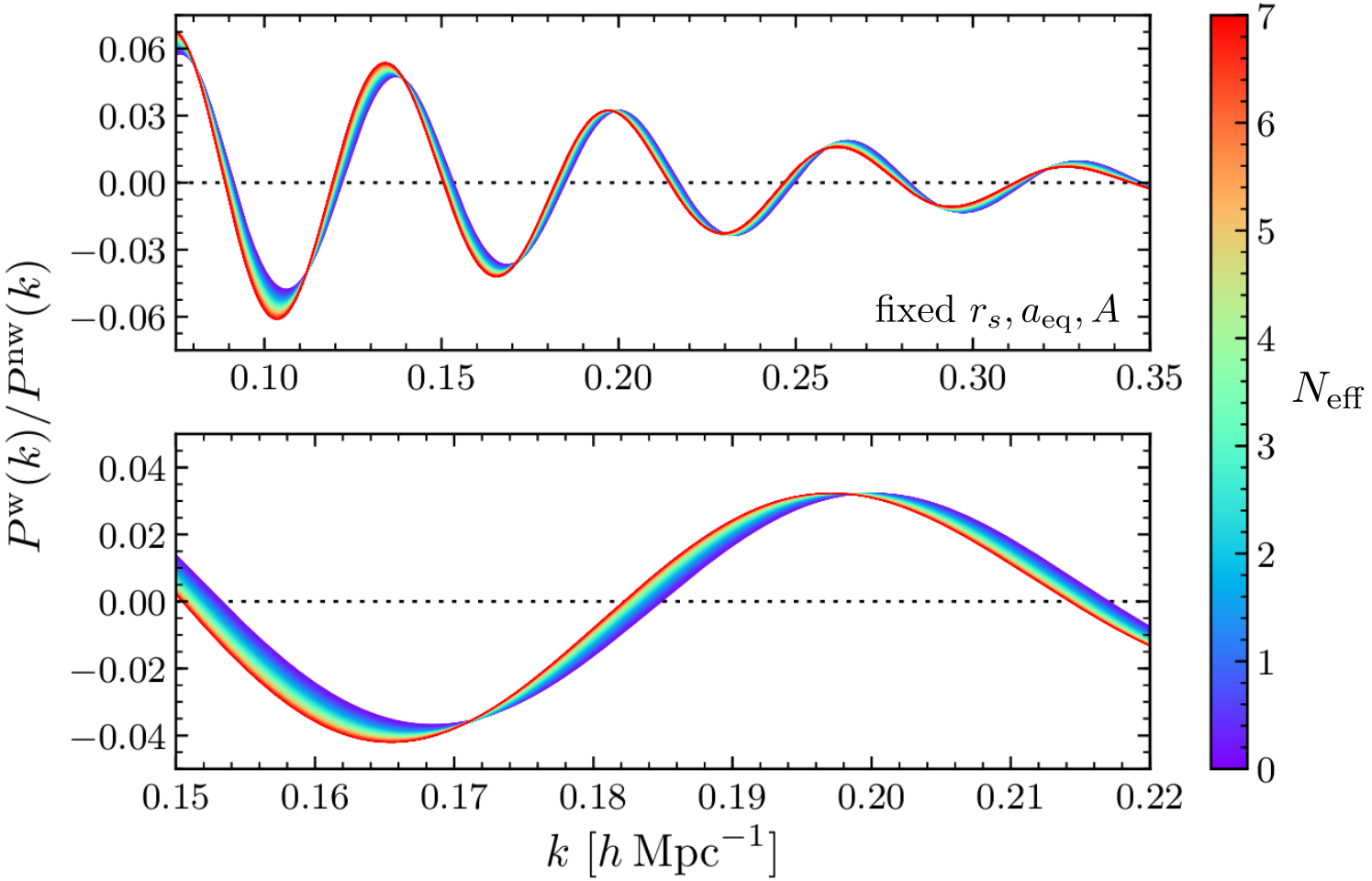
In Fourier space, this corresponds to the BAO spectrum, e.g. of the distribution of galaxies:



Beutler et al. (BOSS, 2016)

Phase Shift in the BAO Spectrum

Free-streaming neutrinos lead to the same phase shift as in the CMB:



Baumann, Green & BW (2018)

Phase Shift in the BAO Spectrum

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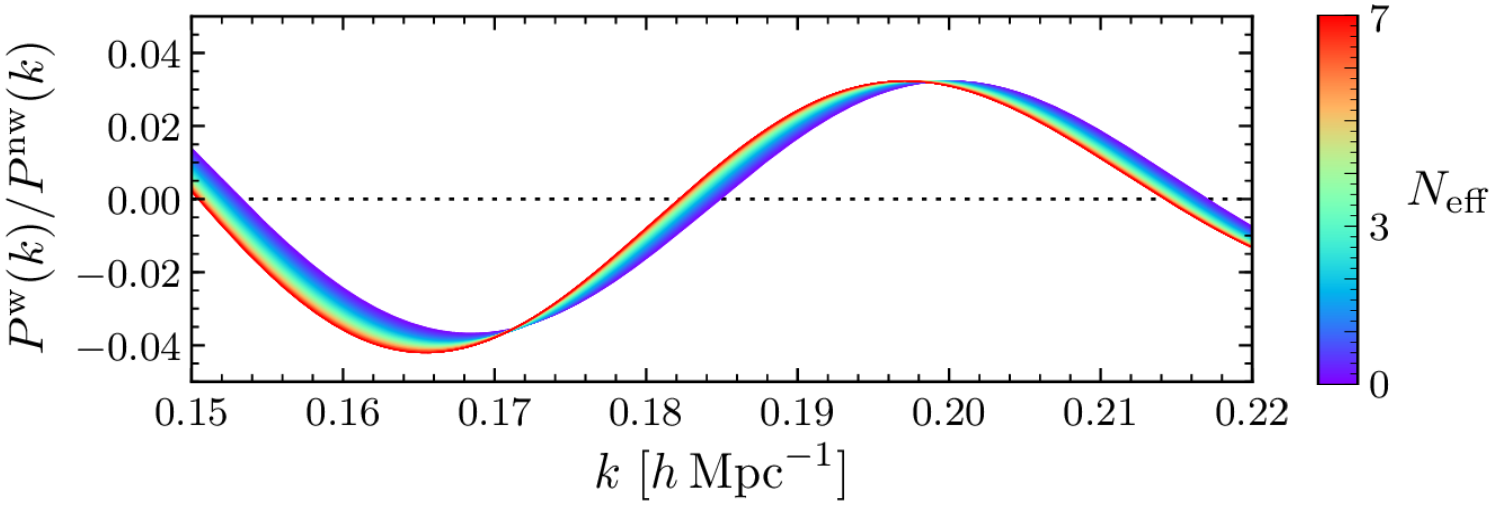


Phase is immune to the effects of nonlinear gravitational evolution.

Baumann, Green & Zaldarriaga (2017)

Certain information encoded in the peak locations is robust to uncertainties in the broadband spectrum.

Baumann, Green & BW (2018)

Generalized BAO Analysis

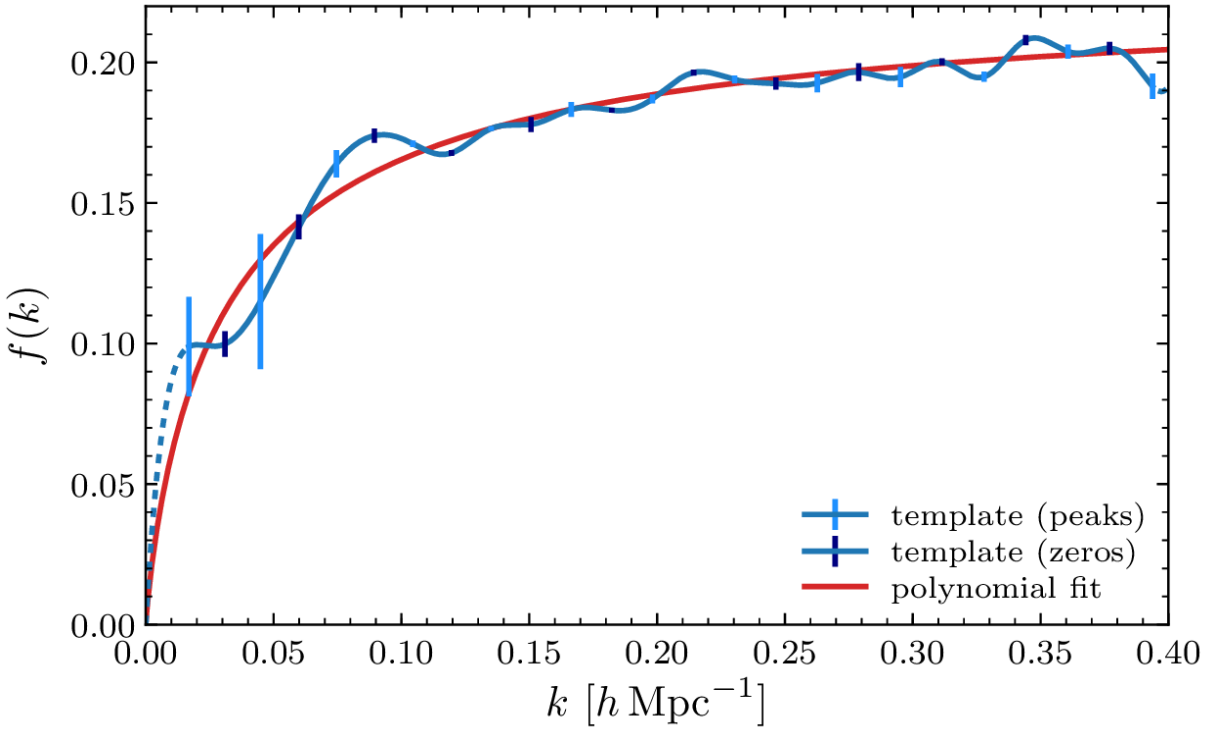
Proposal to adapt the standard BAO analysis:

template

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

standard BAO parameter

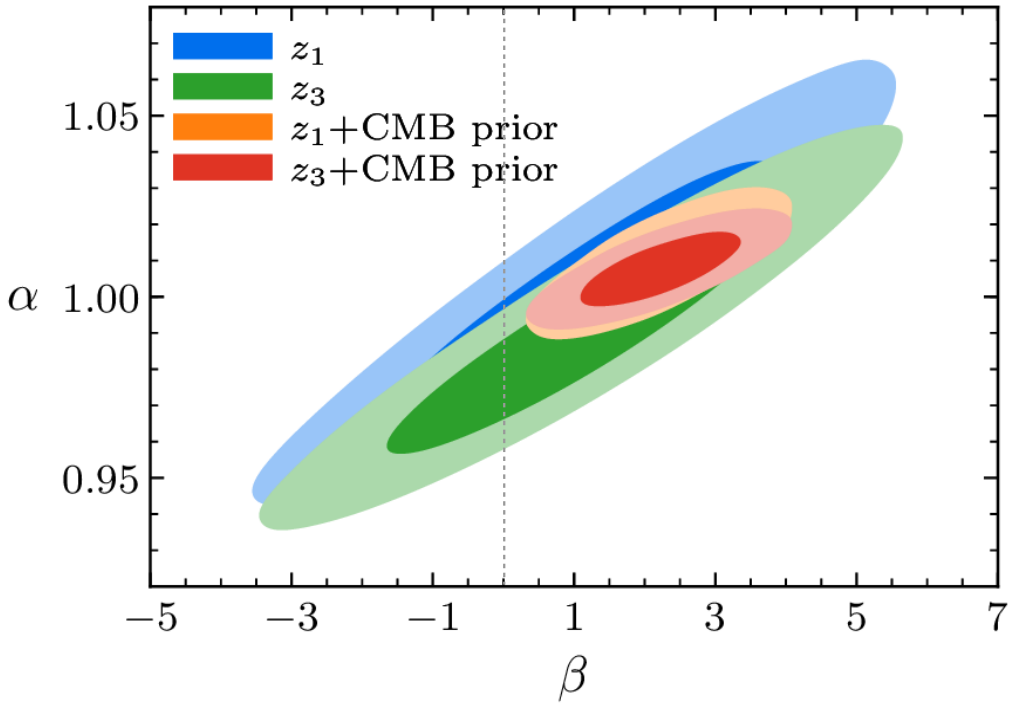
phase shift amplitude



Baumann, Green & BW (2018)

First Constraint from BOSS DR12 Data

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



$\beta > 0$ at $> 99\%$ c.l.

(CMB prior from Planck 2018)

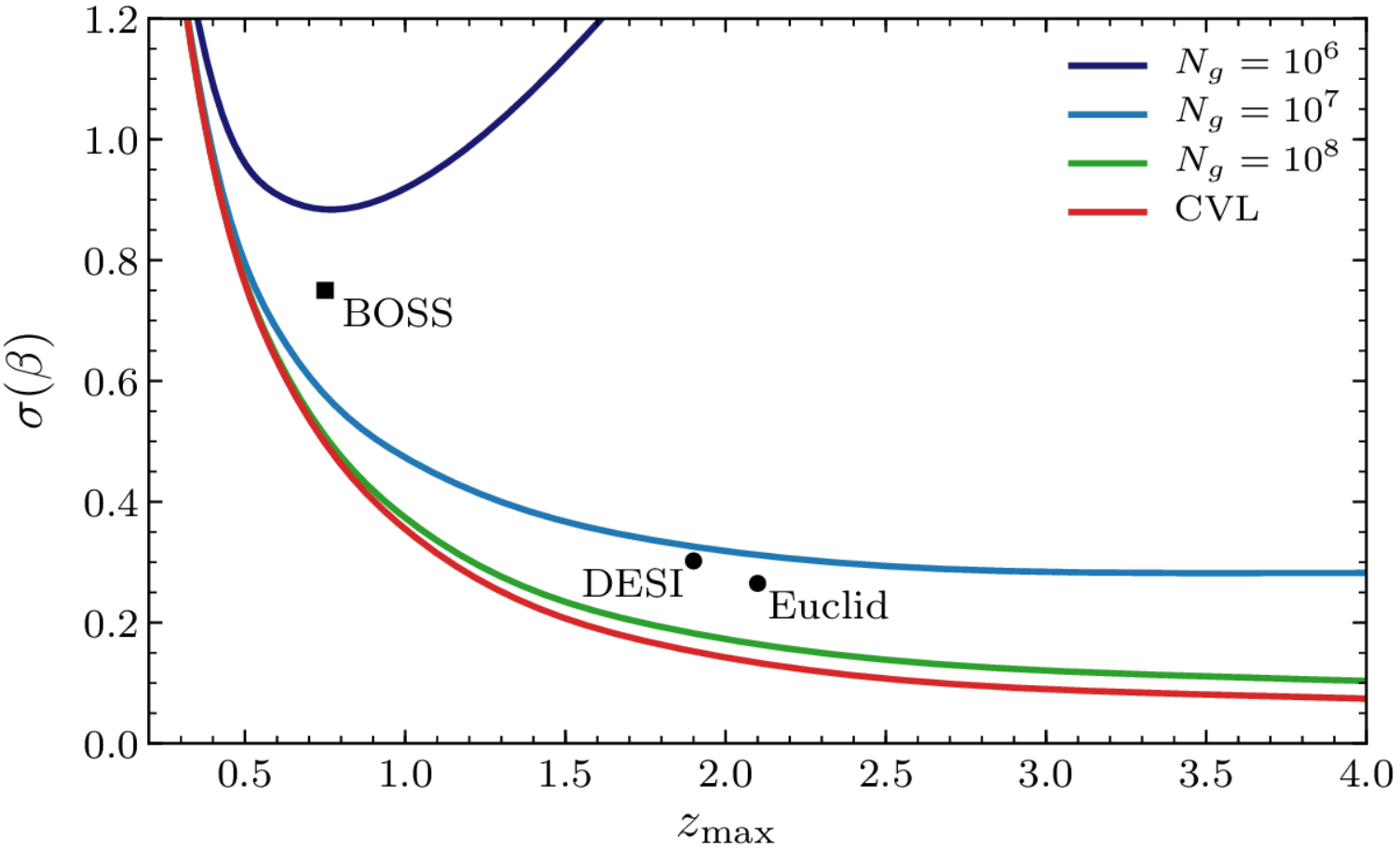
→ Free-streaming!

This is a proof of principle for directly extracting information on neutrinos and their free-streaming nature from galaxy clustering data.

Baumann, Beutler, ..., BW, ... (2019)

Future Prospects

Future observations will greatly improve on this first measurement:



Baumann, Green & BW (2018); Baumann, Beutler, ..., BW, ... (2019)

Conclusions

(1) Phase shift is a robust signature of free-streaming neutrinos.

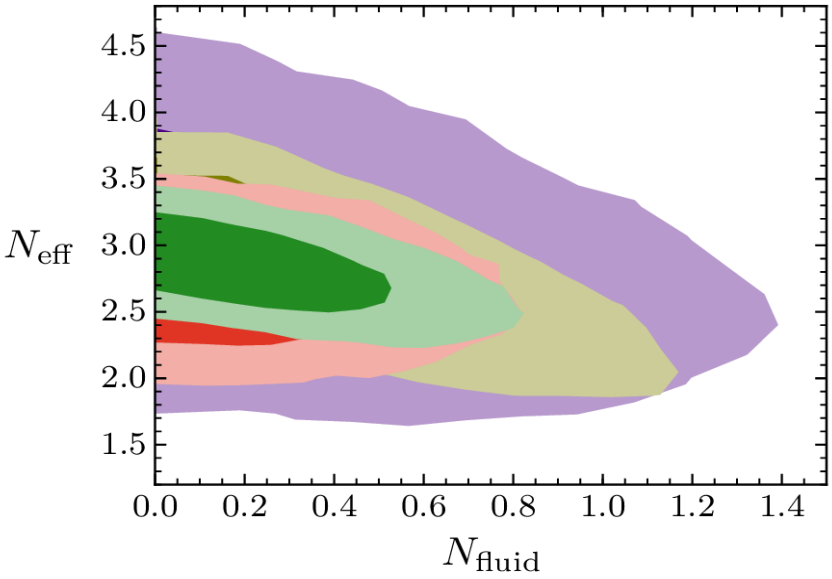
(2) Sensitivity to the phase shift breaks degeneracies.

(3) We can distinguish free-streaming from non-free-streaming neutrinos in both Planck and BOSS data.

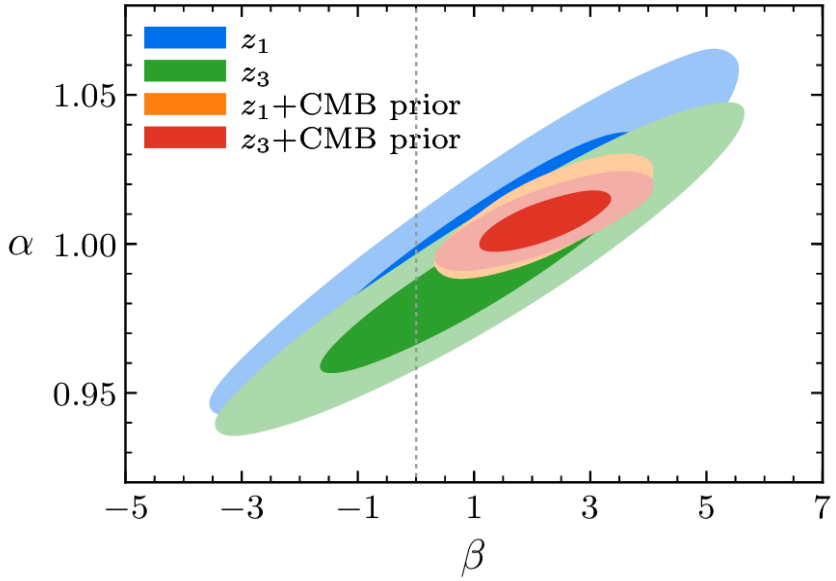
(4) In the future, the constraints on the phase shift will improve in both the CMB and LSS.

Thank you!

Free-streaming neutrinos in the CMB



Free-streaming neutrinos in LSS



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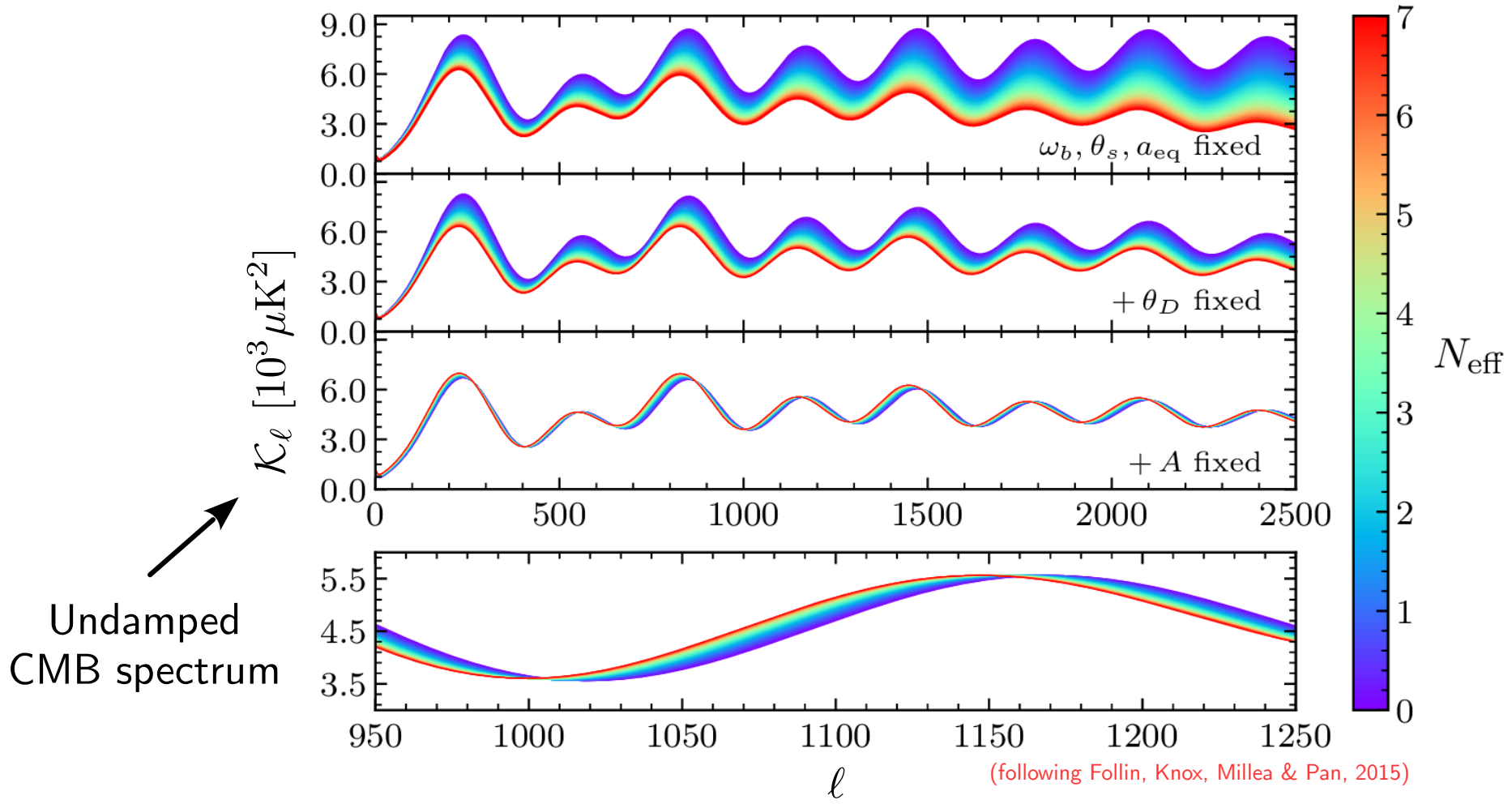
(cf. arXiv:1810.02800)

Backup Slides

Phase Shift in the CMB

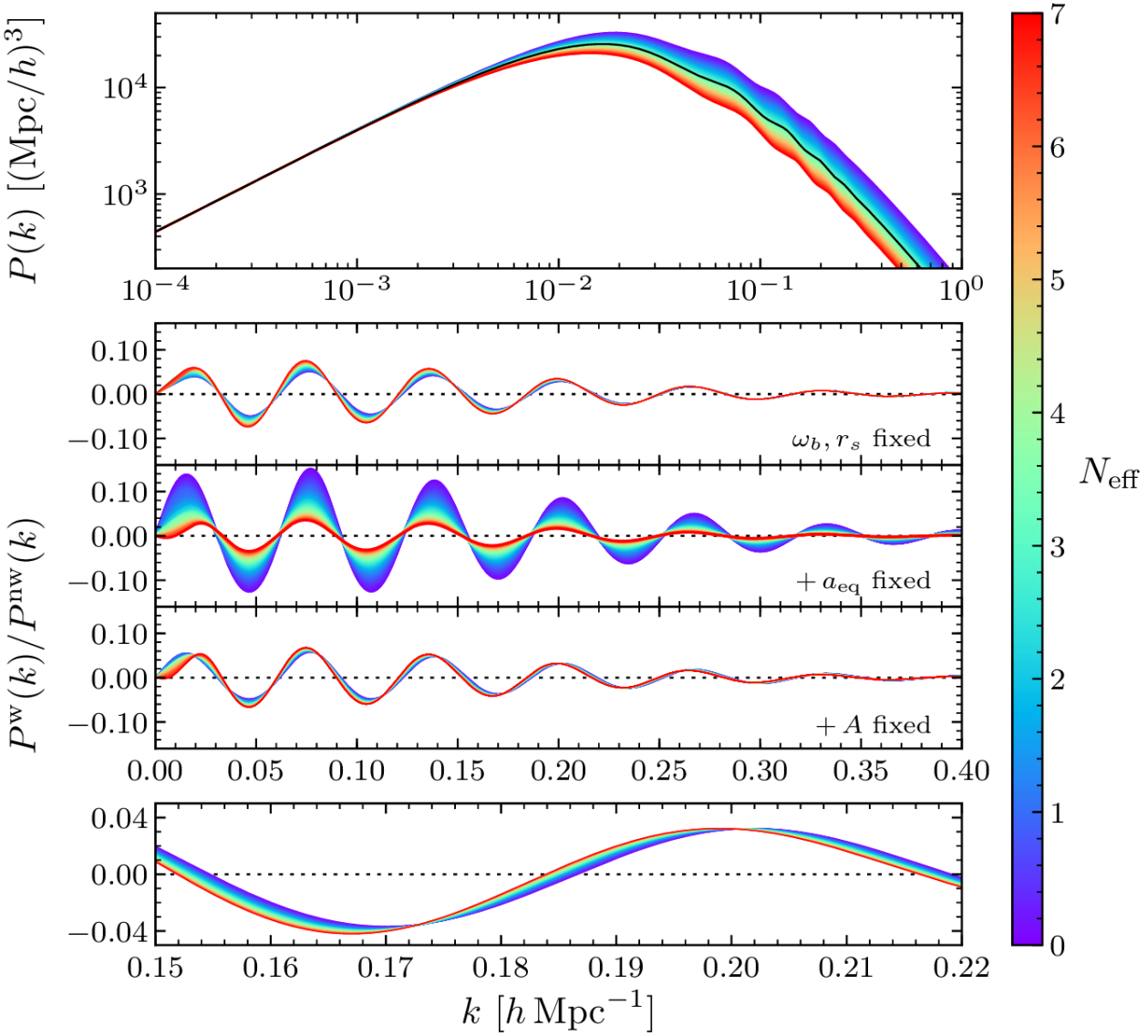


Baumann, Green & BW (2018)

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 (2018)

Analysis of BOSS DR12 Data

- Likelihood-based forecasts:
  - Estimate of sensitivity,
  - Several checks to establish analysis,
  - Cross-check of mock and data analyses.

- Validation of method on 999 MultiDark-Patchy mock catalogs.

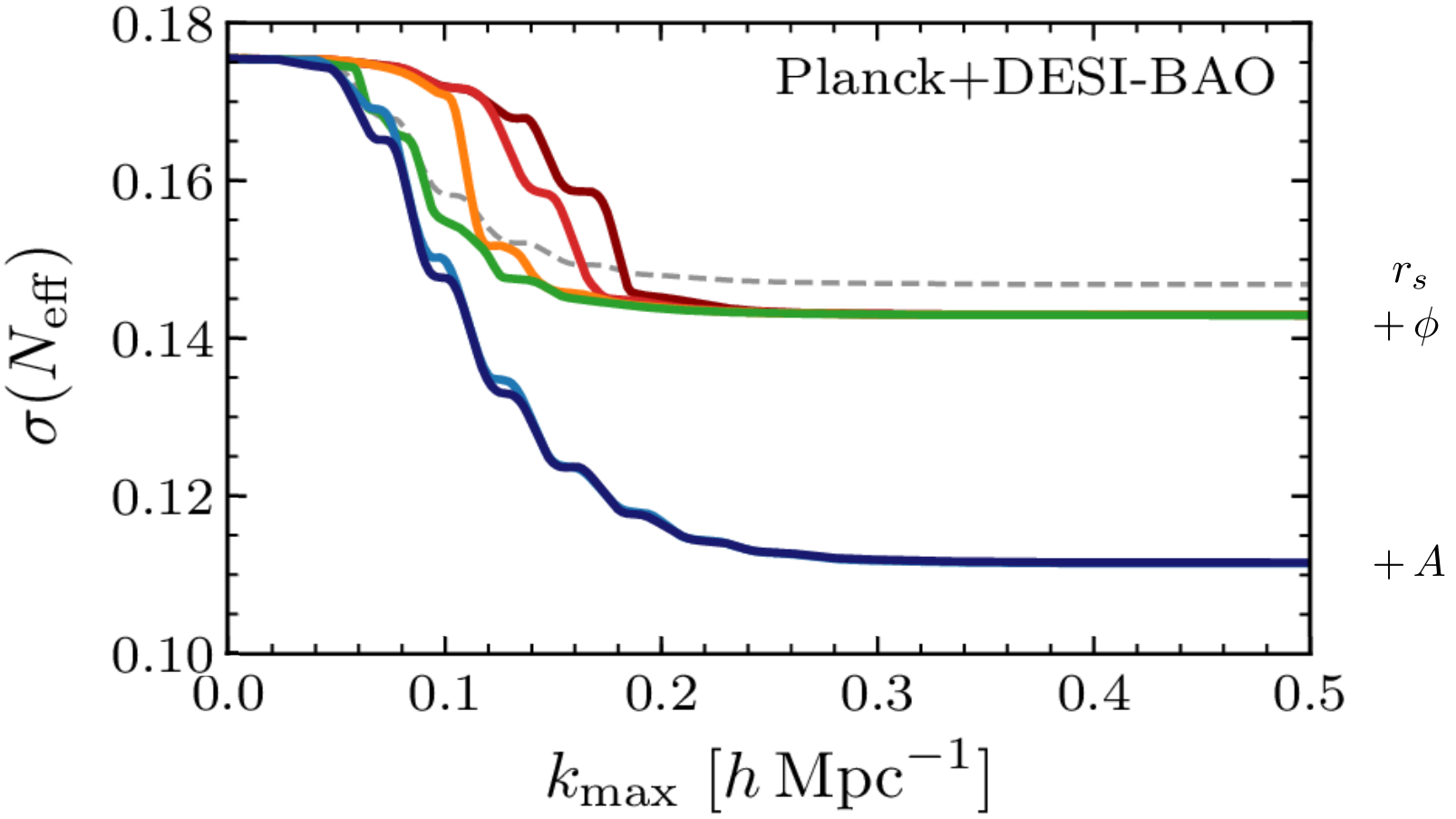
- Data based on spectra of 1.2 million galaxies over 10 252 deg^2.

- Two redshift bins in $0.2 < z < 0.75$.

- Total parameters: α_{z_1}, α_{z_3}, β & 18 nuisance parameters (bias, broadband and damping scale).

Frequency, Amplitude and Phase Shift

$$O(k) \sim A \sin(k r_s + \phi)$$



Baumann, Green & BW (2018)