October 18th 2023

Cosmology-Astro Seminar
Leinweber Center for Theoretical Physics, University of Michigan

The Imprint of cosmic neutrinos & other light-relics in the CMB

Gabriele Montefalcone
Weinberg Institute for Theoretical Physics, University of Texas at Austin

Based on ongoing work with Benjamin Wallisch and Katherine Freese

UNIVERSITY OF MICHIGAN

TEXAS
The University of Texas at Austin

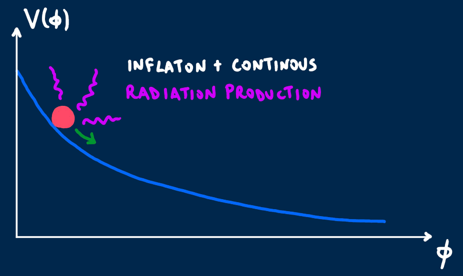
A bit about myself

MY RESEARCH INTERESTS:

primordial cosmology - cosmological probes to constrain fundamental physics - the dark sector

Recent Developments in Warm Inflation

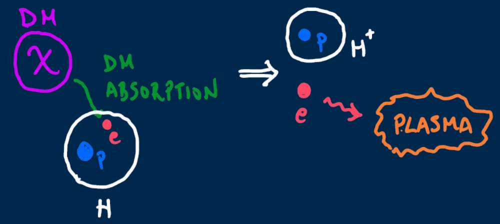
[Phys.Rev.D 107 (2023), *JCAP03* (2023)002, arXiv:2306.16190, more in prep.]



with K. Freese, V. Aragam, R.O. Ramos, B. Shams Es Haghi, G. S. Vicente, L. Visinelli

For the rest of the week, You can find me in 3477A, Randall Lab!

Constraining dark matter-baryon interactions with the CMB [in prep.]



with K. Buddy, N. Bellomo, S. Molstner

Inprint of free streaming radiation in the CMB [in prep.]

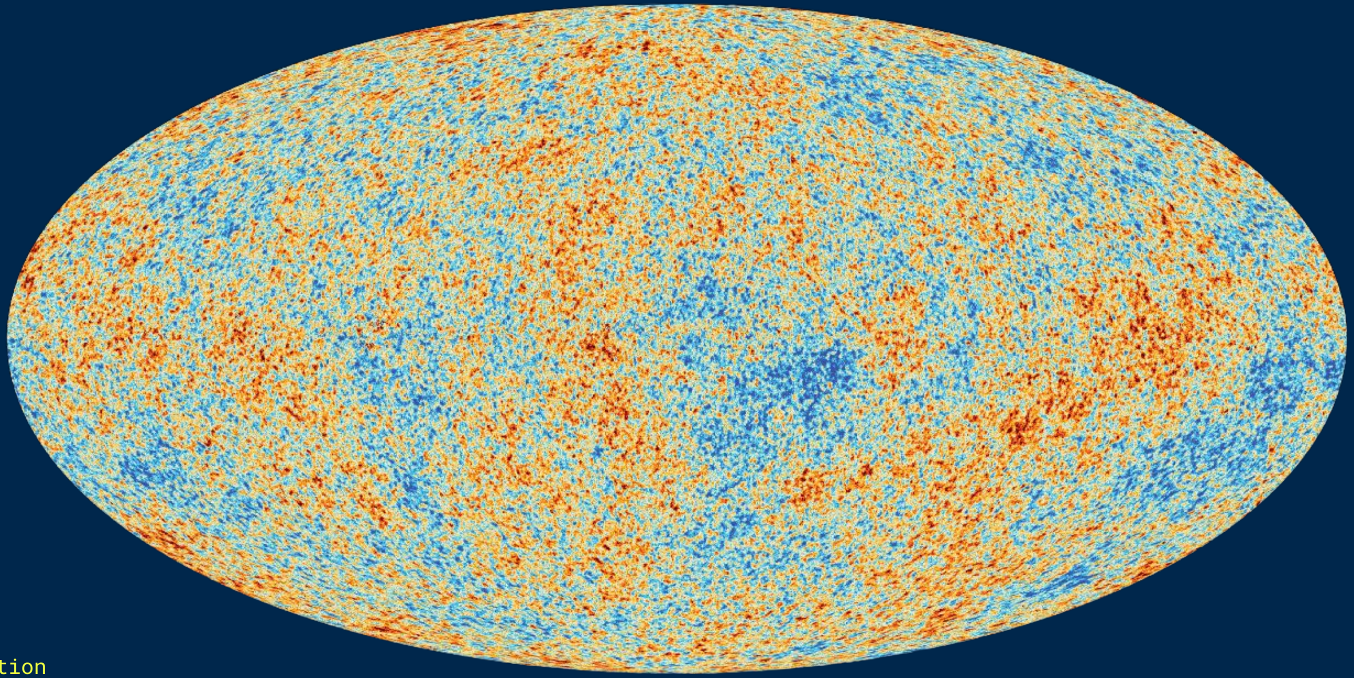
with K. Freese, B. Wallisch

Outline of the Talk

- Cosmic Microwave Background (CMB) Anisotropies
- Cosmic Neutrinos and other Light Relics
- Measuring free-streaming radiation in the CMB
- Conclusions

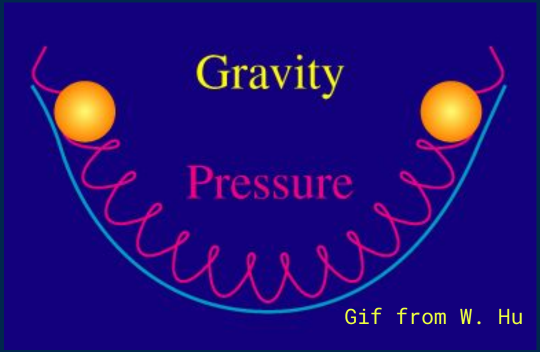
The Cosmic Microwave Background Anisotropies

- An almost perfect black-body spectrum at a single temperature of $T_0 = 2.7255$ K today
- Temperature anisotropies in the order of 10^{-5}



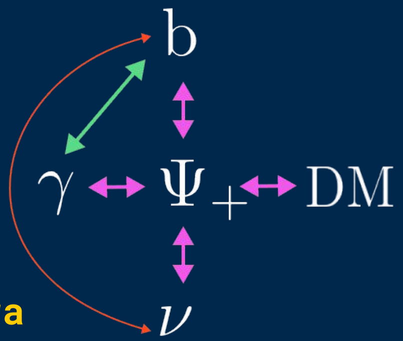
Planck Collaboration

Cosmic sound waves in the CMB



- Photons and baryons are strongly coupled
- Initial fluctuations excited sound waves in the primordial plasma
- Gravity sources the fluctuations in the photon-baryon fluid

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



We observe these acoustic oscillations in the CMB power spectra

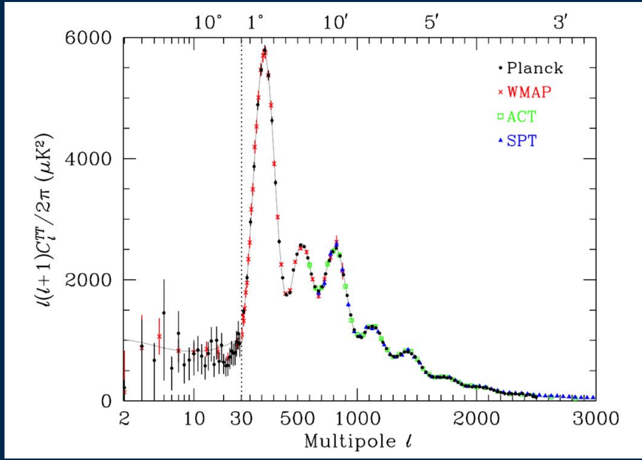
$$\delta_\gamma \sim \underbrace{A_{\vec{k}}}_{\text{Initial condition (inflation)}} \cos\left(c_s k \tau\right),$$

$$c_s^2 \sim \frac{c}{3\left(1 + \underbrace{R_b)}_{R_b \equiv 3\bar{\rho}_b / \left(4\bar{\rho}_\gamma\right)}}$$

Baryons add inertia to the fluid

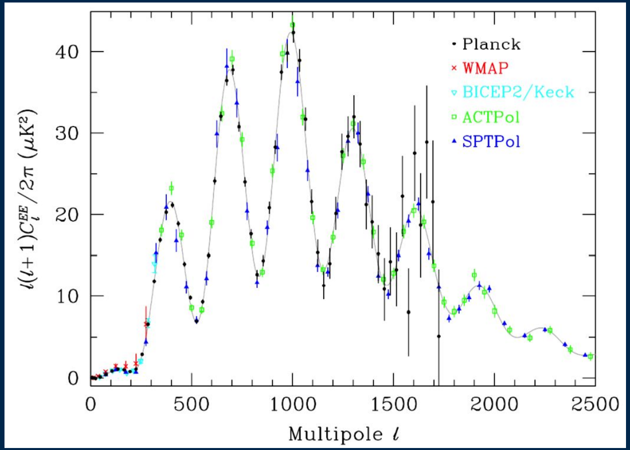
CMB Power Spectra

Temperature spectrum traces **density** perturbations, roughly the gravitational potential



$$\mathcal{D}_\ell^{\mathrm{TT}} \propto \cos^2(\ell\theta_s)$$

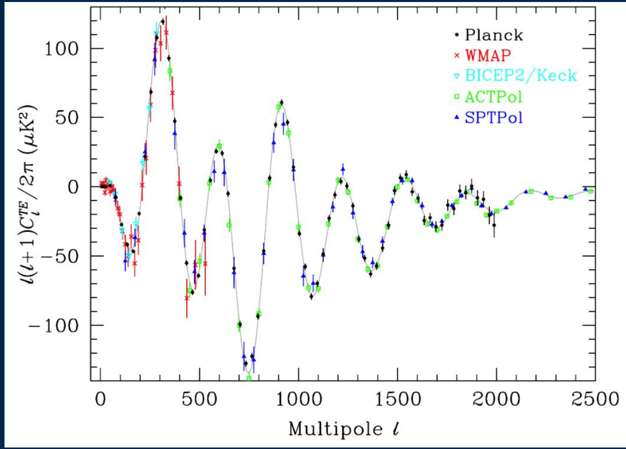
Polarization spectrum traces **velocity** perturbations



$$\mathcal{D}_\ell^{\mathrm{EE}} \propto \sin^2(\ell\theta_s)$$

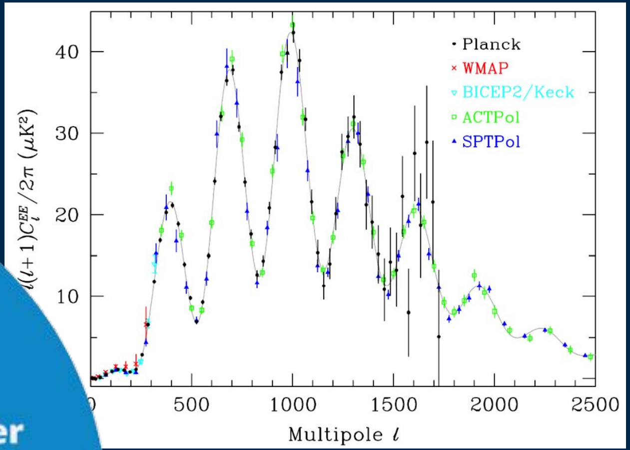
TE spectrum roughly tells us how the plasma is moving into the gravitational potential wells

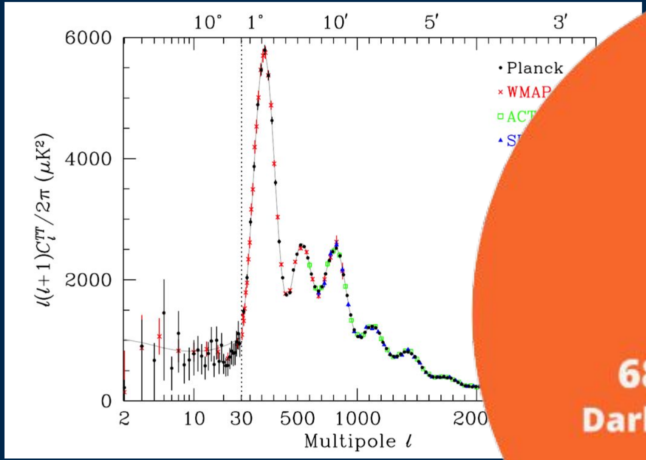
$$\mathcal{D}_\ell^{\mathrm{TE}} \propto \sin(\ell\theta_s)\cos(\ell\theta_s)$$

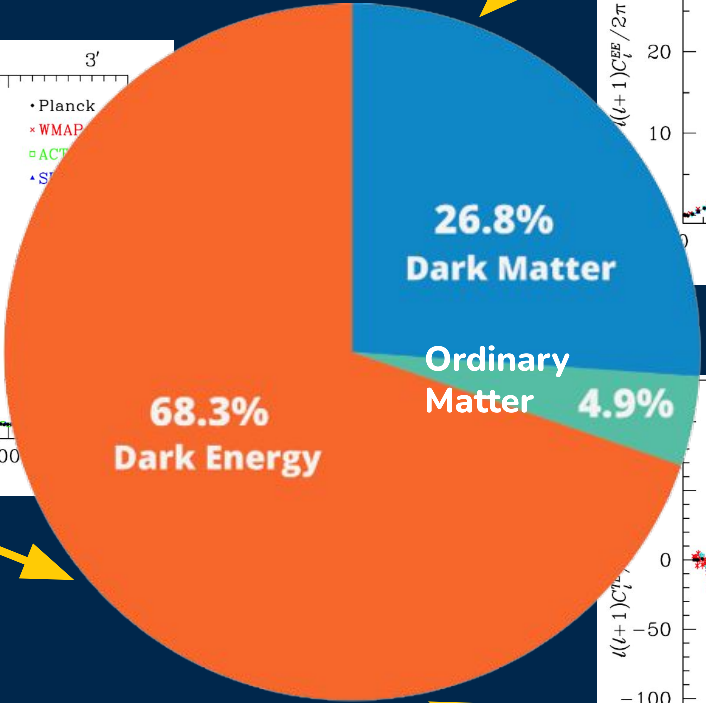


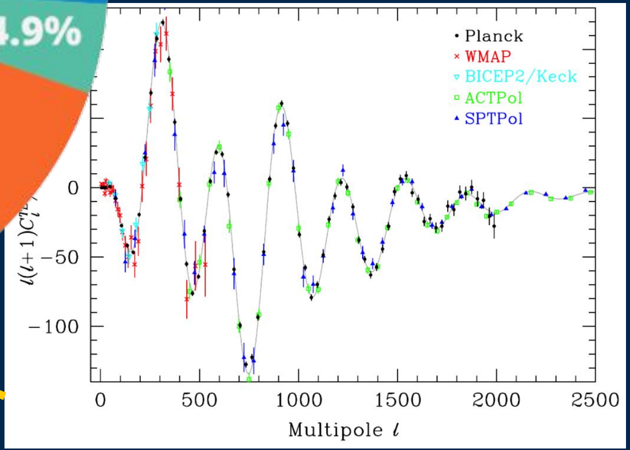
Planck, WMAP, ACT & SPT Collaborations
Figures from PDG

CMB Power Spectra





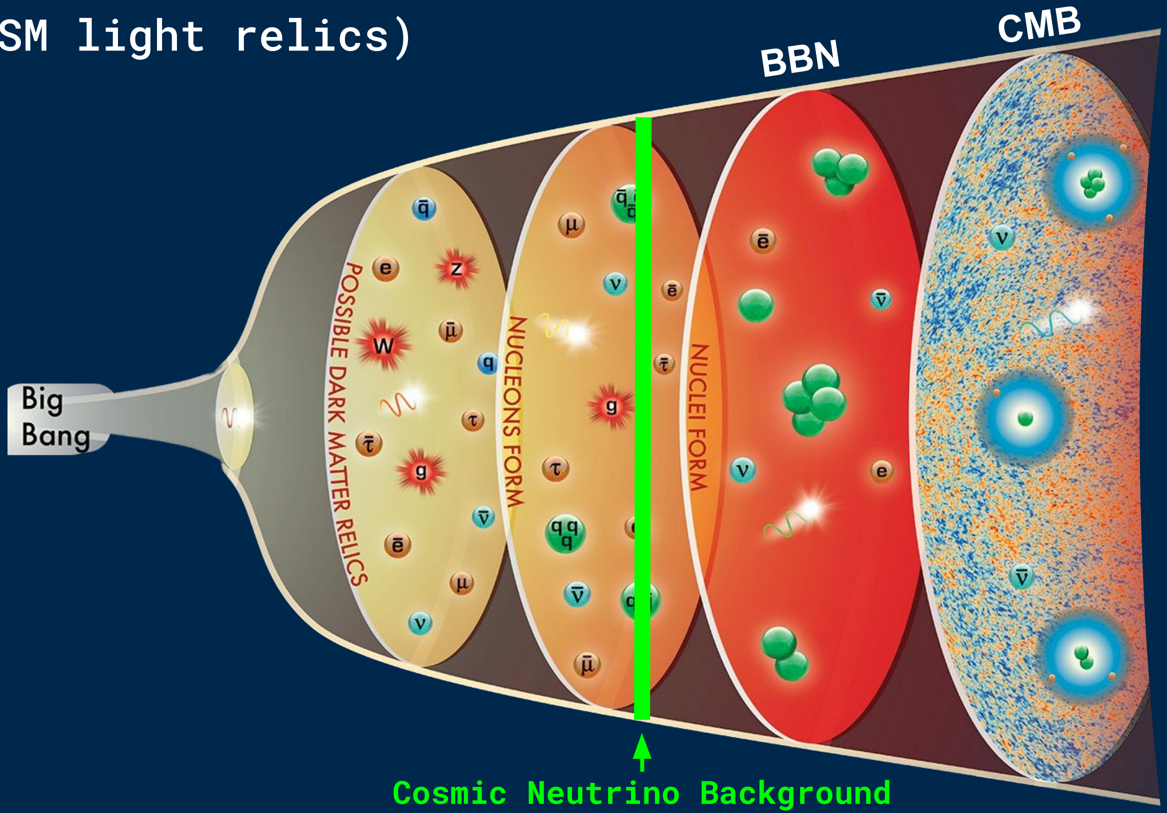




Concordance with Flat ΛCDM

Planck, WMAP, ACT & SPT Collaborations
Figures from PDG and Ligo Collaboration

Cosmic Neutrinos
(SM light relics)



Free-streaming since their decoupling at **T~ 1 MeV**

Cosmic Neutrinos
(SM light relics)

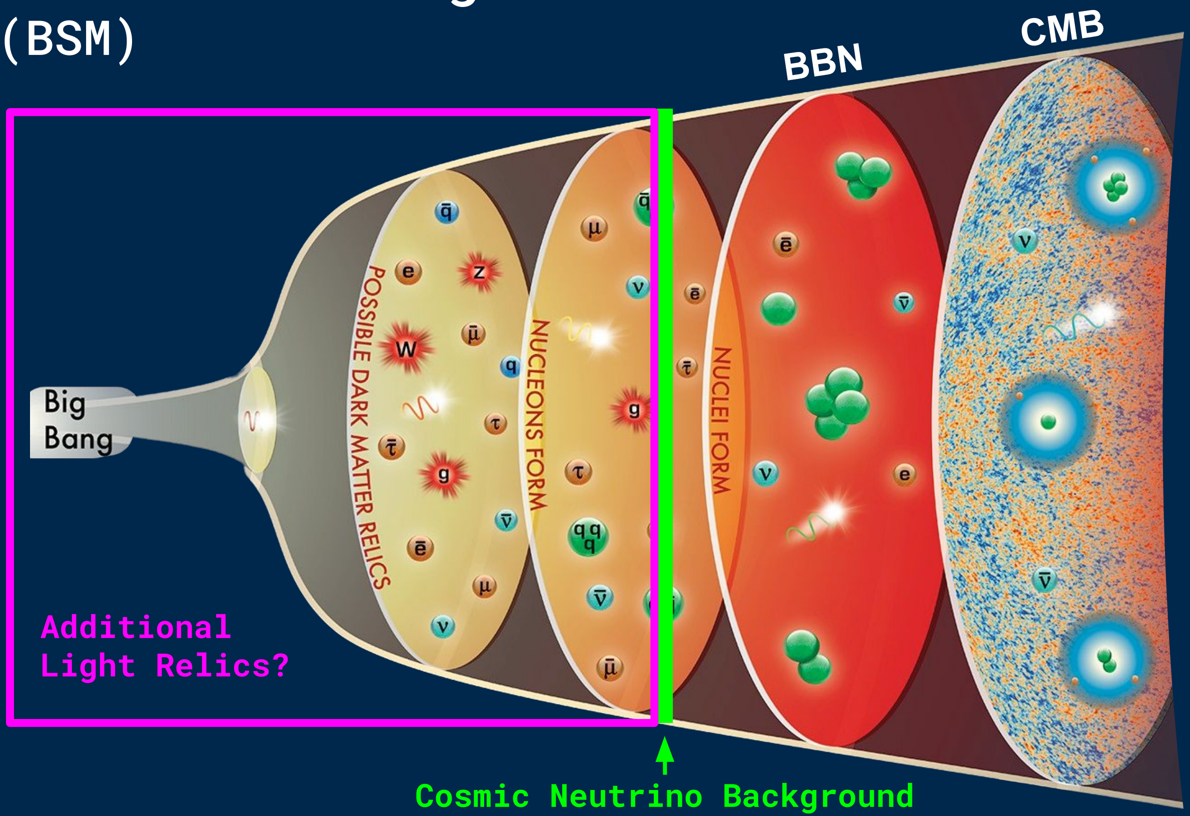
$$p_r = \rho_\gamma \left(1 + \underbrace{\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}}_{\text{Neutrino contribution}}\right)$$

- 41% of the radiation density in the universe

$$a_\nu \left[\equiv \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}\right]^{-1} \simeq 4.40$$

- They are parametrized by the observable N_{eff} "the effective number of neutrinos"
  - In the SM: **N_{eff} = 3.044** Akita1, Yamaguchi 2020
- Cosmology is sensitive to their gravitational effects
  - Both through their energy density and perturbations
  - Planck 2018: $\boxed{N_{\rm eff}^{\rm CMB} = 2.92 \pm 0.19}$

Additional Light thermal relics
(BSM)



By light I mean particles which were relativistic at recombination, i.e. **m < 1 eV**

Figure from PDG

Additional Light thermal relics (BSM)

$$p_r = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\text{eff}}\right)$$

$$\boxed{N_{\text{eff}} = N_{\text{eff}}^{\text{SM}} + \Delta N_{\text{eff}}}$$

- Light and weakly interacting particles arise in many BSM models
  - e.g. axions, dark photons, sterile neutrinos

$$\mathcal{L} \subset \frac{\mathcal{O}_X \mathcal{O}_{\text{SM}}}{\Lambda^\Delta} \rightarrow \Gamma\left(\Lambda, T_{\text{dec}}\right) \approx H\left(T_{\text{dec}}\right) \rightarrow \rho_X(\Lambda)$$

coupling to SM — decoupling — relic density

$$\Delta N_{\text{eff}}\left(T_{\text{dec}}\right) = \frac{\rho_X}{\rho_{\nu_i}} = 0.027 g_{*,X} \left(\underbrace{\frac{g_{*,\text{SM}}}{g_*\left(T_{\text{dec}}\right)}}_{\text{(the effective number of relativistic degrees of freedom)}}\right)^{4/3}$$

$g_{*,X} = 1, \frac{4}{7}, 2, \ldots$ for spin- $0, \frac{1}{2}, 1, \ldots$

$g_{*,\text{SM}} = 106.75$

Additional Light thermal relics
(BSM)

$$N_{\text{eff}} = N_{\text{eff}}^{\text{SM}} + \Delta N_{\text{eff}}$$

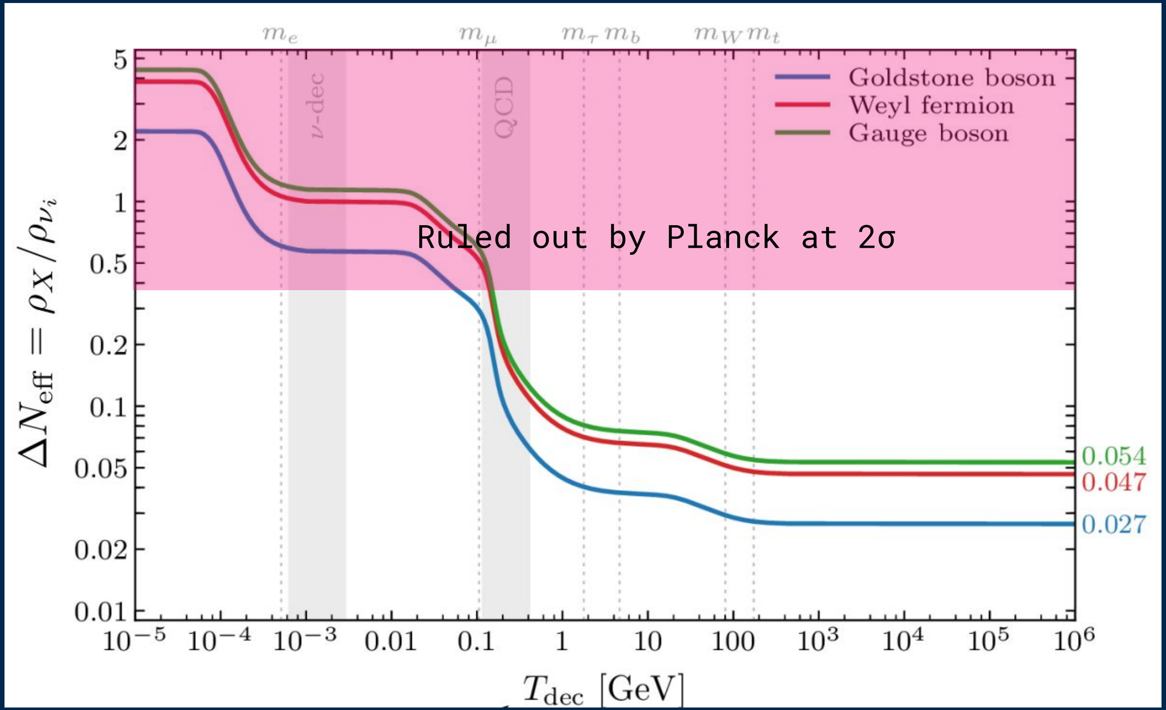


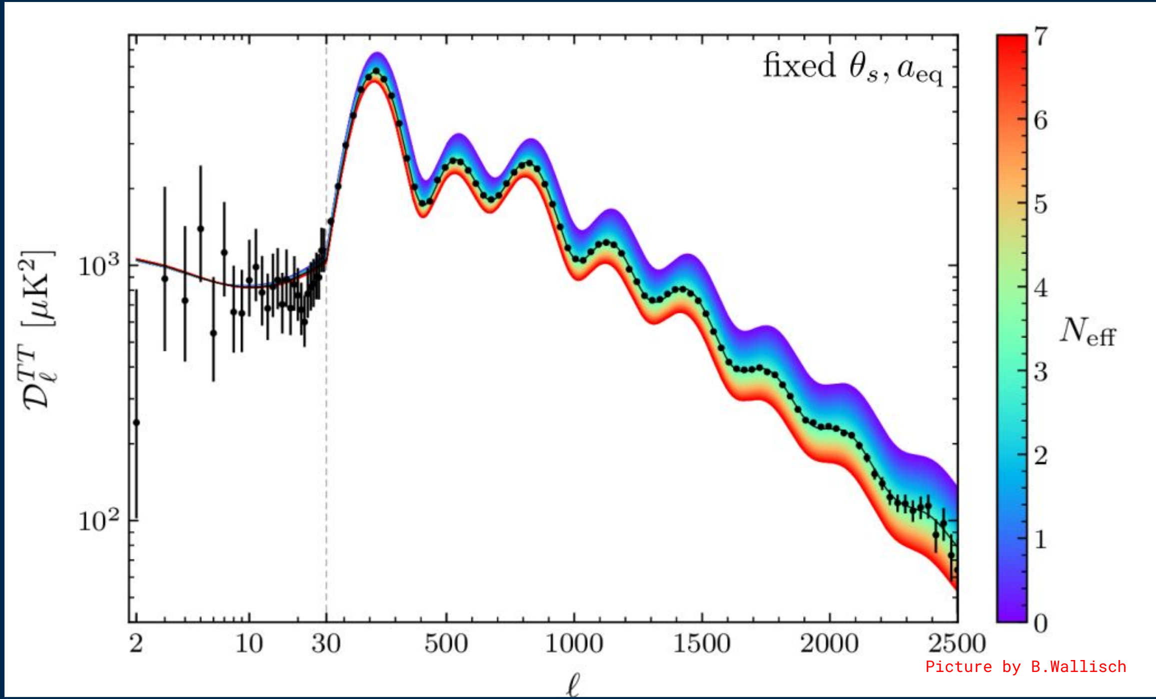
Figure from B. Wallisch

Light relics in the CMB

- Main effect in the damping tail of the CMB TT power spectrum, via their effect on the expansion rate

$$\theta_d \propto (H/n_e)^{1/2}\theta_s$$

  - For fixed $\mathbf{a_{eq}}$ and $\boldsymbol{\theta_s}$, **larger $\mathbf{N_{eff}}$ means more damping**
  - Degeneracy with primordial Helium fraction $\mathbf{Y_{He}}$ via $\mathbf{n_e}$

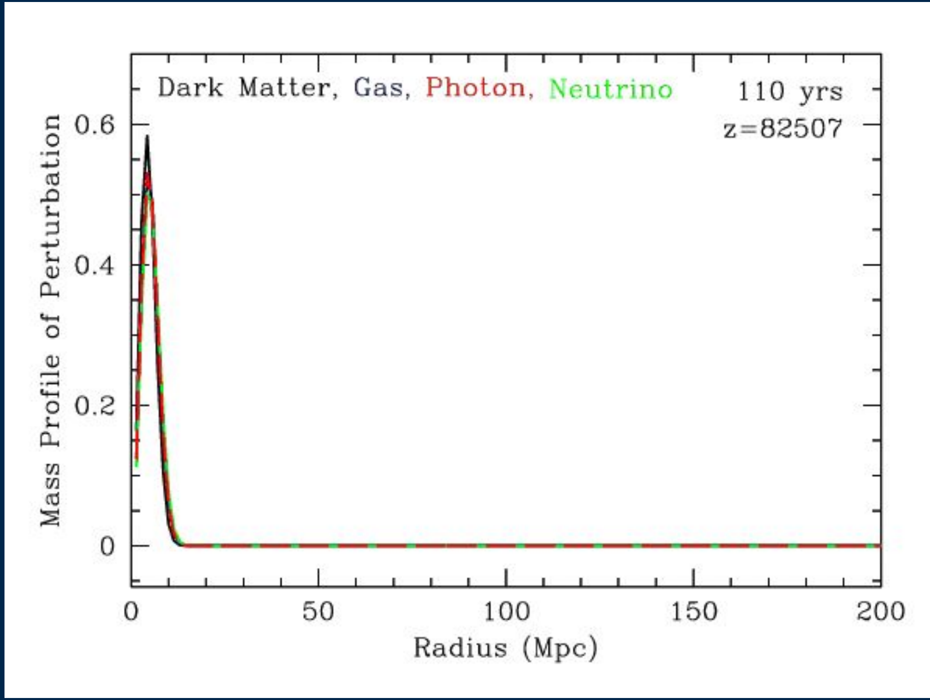


Picture by B.Wallisch

Light relics in the CMB

- Perturbations from free-streaming radiation induce **metric perturbations ahead of the sound horizon**

- The photon-baryon fluid is **pulled** by such perturbations, shifting their perturbations peaks to larger radii.



Eisenstein, Seo and White

Light relics in the CMB

- This results in a **shift in the phase of the acoustic peaks of the CMB**
  - Larger radii → smaller multipoles

Bashinsky & Seljak

- Small effect:
$\Delta\ell \approx 5 \cdot \Delta N_{\mathrm{eff}}$

Undamped power spectrum

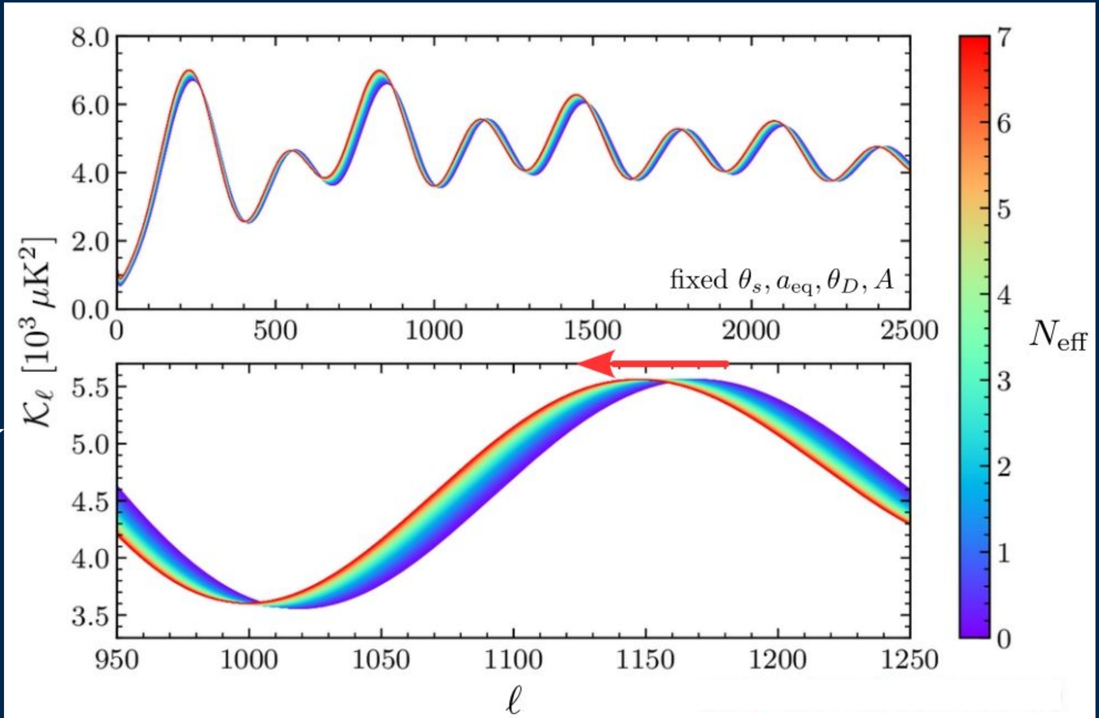
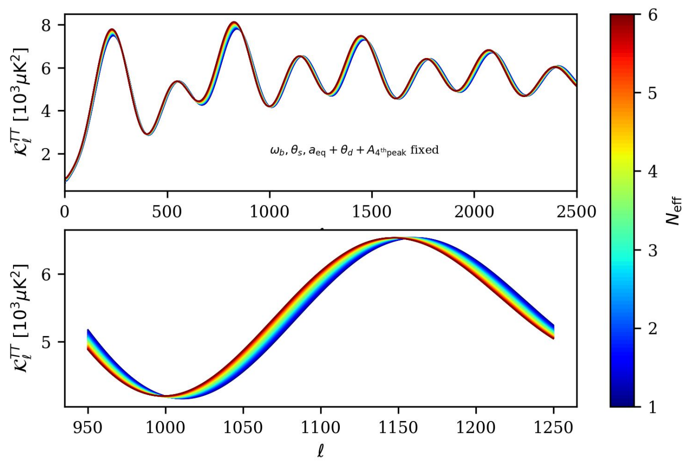


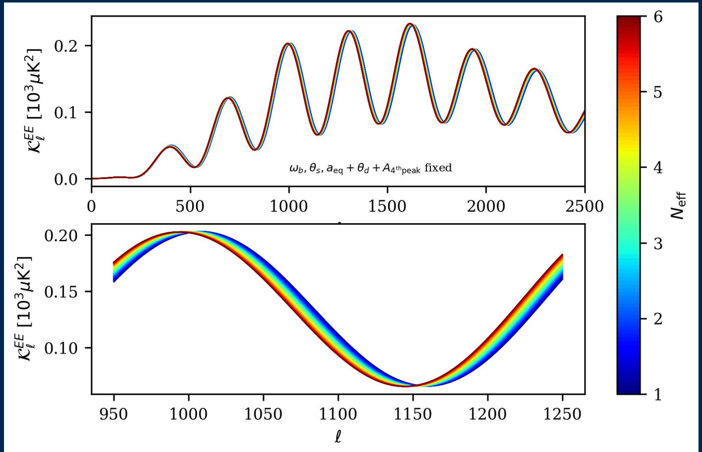
Figure from B. Wallisch

The special role of the Phase shift

- Difficult to reproduce in the absence of **free-streaming**
    - Either free-streaming or non-adiabatic fluctuations
      Baumann, Green, Meyers & Wallisch
- Same shift both in temperature and polarization spectrum
- **Detected in Planck 2013 TT data!**

Follin, Knox, Millea & Pan



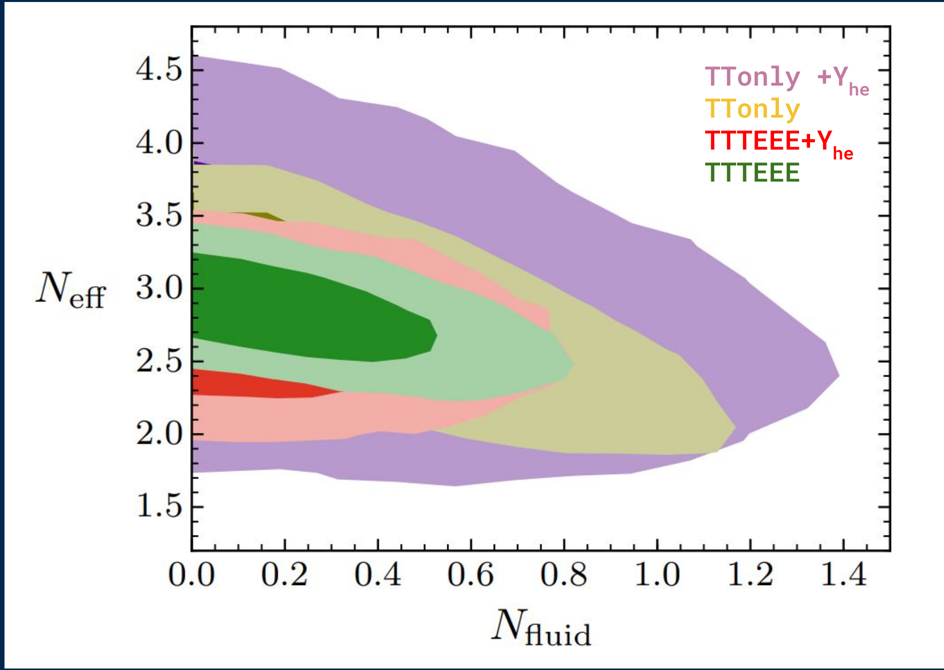


Constraints from Planck 2015 data via N_{fluid}

- Allow for a contribution from non-free-streaming radiation **Y**, capture by the following parameter

$$N_{\rm fluid} \equiv a_\nu \frac{\rho_Y}{\rho_\gamma}$$

- $\mathbf{N_{fluid}}$ will only affect the damping tail of the CMB power spectra
    - No induced phase shift



Baumann, Green, Meyers & Wallisch

Results are consistent with absence of non-free streaming neutrinos

The Phase shift in the CMB spectrum

Following Follin, Knox, Millea & Pan

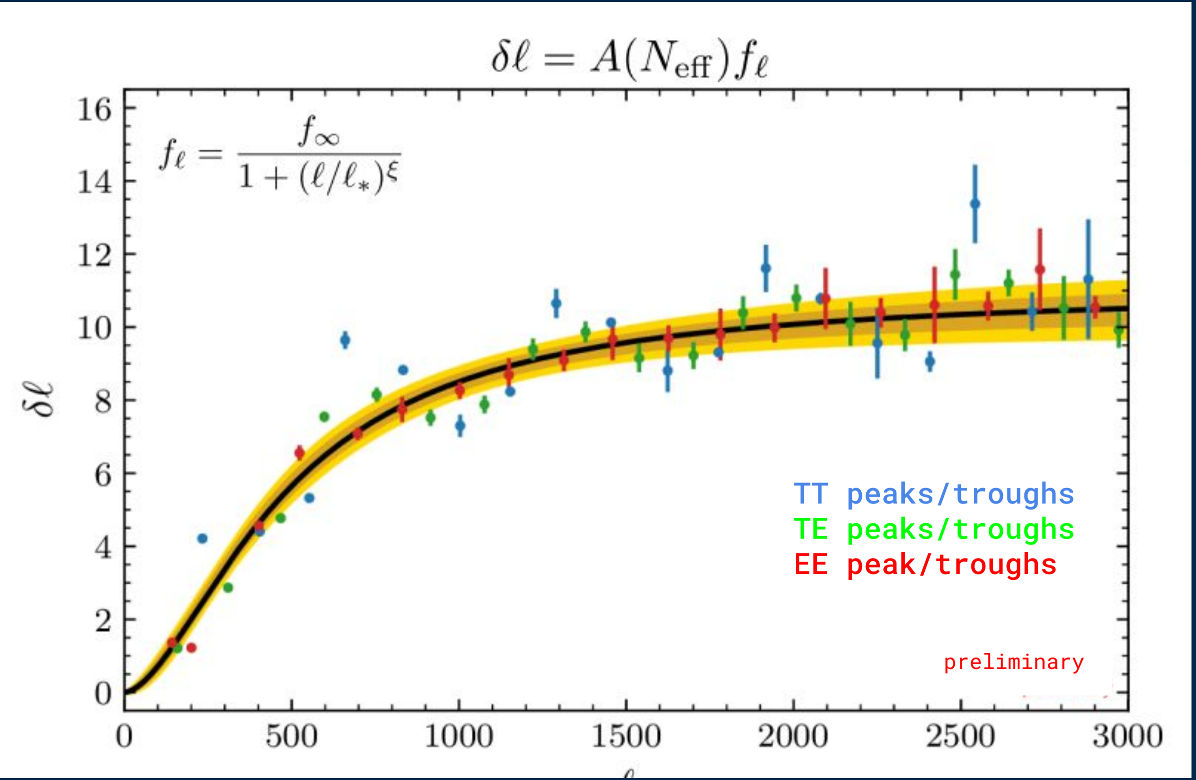
- A new parameter to control the shift

$$N_{\rm eff}^{\delta\phi}$$

$$C_\ell \to \mathcal{K}_\ell \to \mathcal{K}_{\ell+\delta\ell_\nu} \to \mathcal{C}_{\ell+\delta\ell_\nu}$$

$$\delta\ell_\nu = A\left(N_{\rm eff}^{\delta\phi}, N_{\rm eff}\right) f(\ell)$$

- A new analytic form of the template
- Test this with both temperature and polarization data



Constraints on the phase shift from Planck 2018

- Based on Planck 2013 TT:

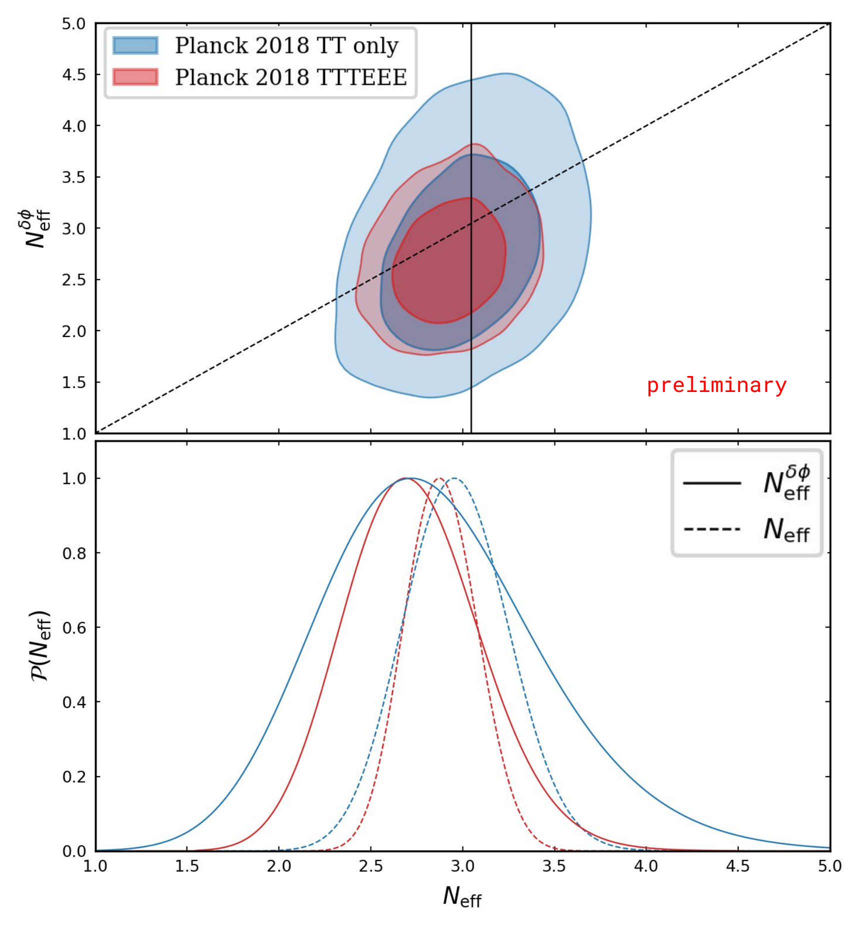
$$N_{\rm eff}^{\delta\phi} = 2.3^{+1.1}_{-0.4}$$ Follin et al.

- Planck 2018 (preliminary):

$$N_\nu = 2.96^{+0.29}_{-0.30}$$
$$N_{\delta\phi} = 2.84^{+0.60}_{-0.69}$$

$$N_\nu = 2.91^{+0.19}_{-0.18}$$
$$N_{\delta\phi} = 2.73^{+0.38}_{-0.41}$$

  - Strong evidence of **free-streaming** nature of **neutrinos!**
  - Planck 2018 is still compatible with **SM**
  - **1st template-based measurement** of the phase shift using **Polarization data**

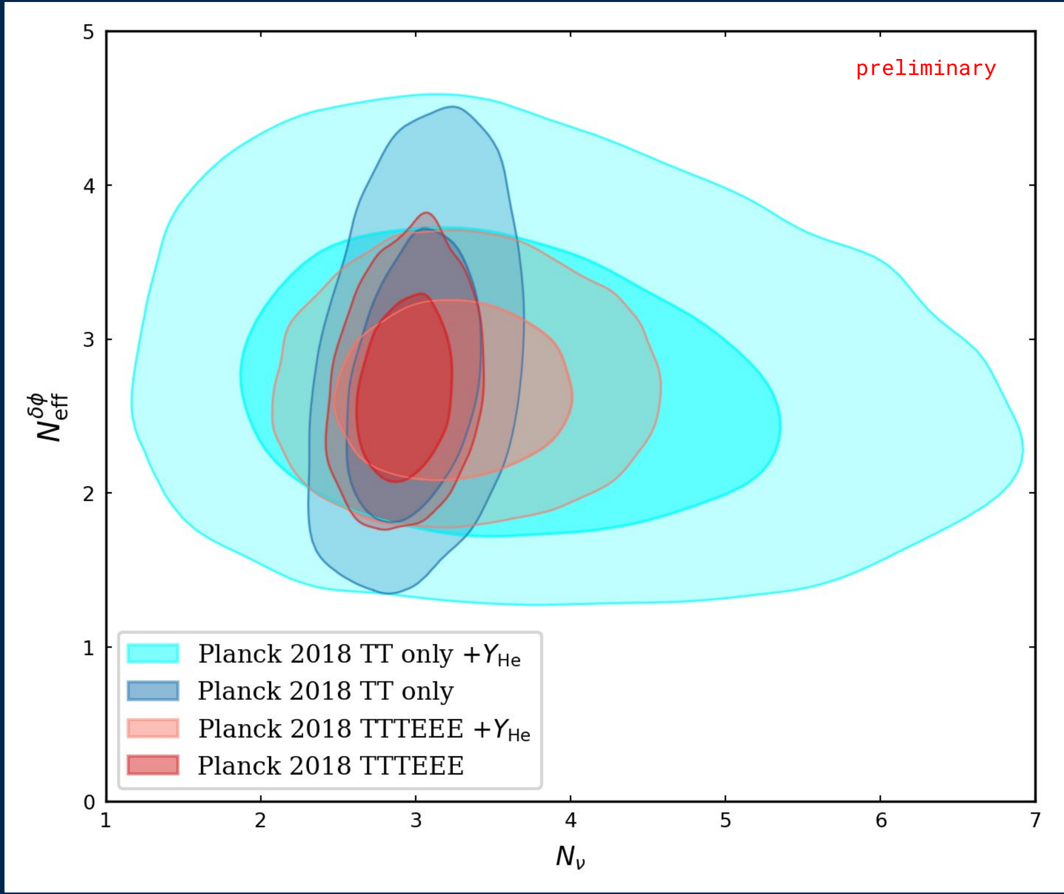


Freese, Wallisch & GM (in prep.)

Constraints on the phase shift from Planck 2018

- The phase shift is a robust probe of free-streaming radiation

- No degeneracy with the Helium fraction $\mathbf{Y_{He}}$



Freese, Wallisch & GM (in prep.)

Can we do better?
Analysis of current and future CMB data

- PLanck 2018 + ACT + SPT **(work in progress)** $\sigma(N_{\text{eff}}^{\delta\phi}) \sim 0.3$
  - Expect improvements, particularly from higher sensitivity of ground-based experiments to larger multipoles
- Forecasts: **(future work)**
  - SO
  - CMB-S4

Freese, Wallisch & GM (in prep.)

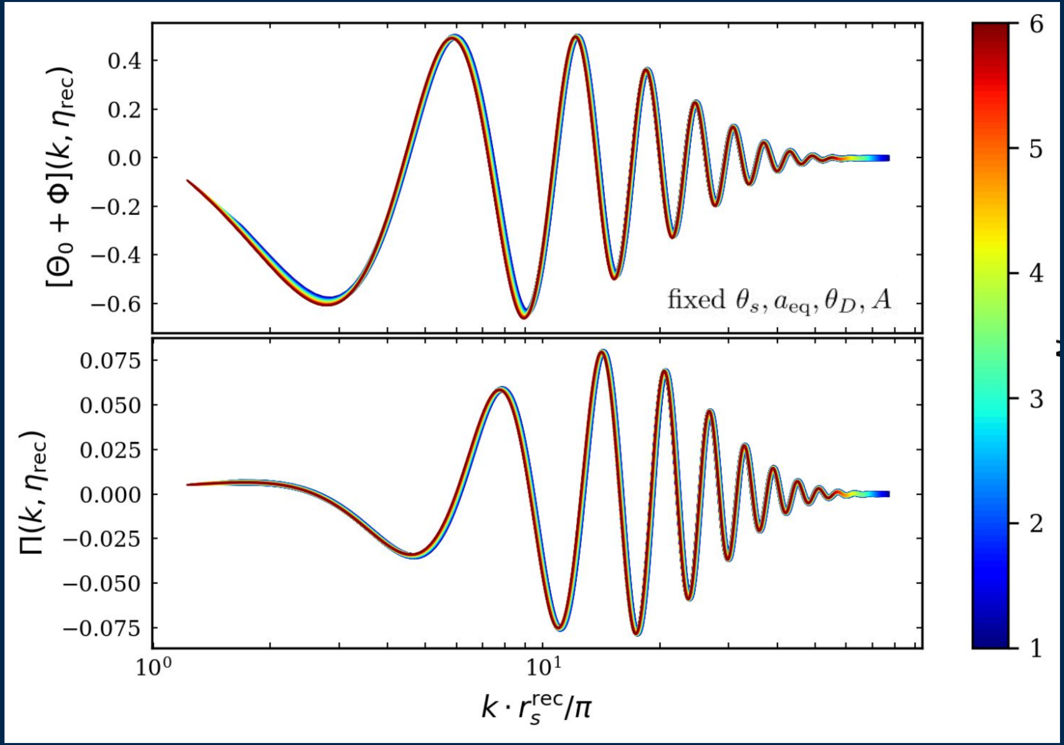
Can we do better?
A perturbation-based template

- The phase shift is imprinted at the perturbations level
- A perturbation-based template avoids projection and smearing effects

$$\Delta_{X\ell}(k) = \int_0^{\tau_0} \mathrm{d}\tau \underbrace{S_X(k,\tau)}_{\text{Sources}} \underbrace{P_{X\ell}\left(k\left[\tau_0 - \tau\right]\right)}_{\text{Projection}}$$

$$\downarrow$$

$$C_\ell^{XY} = \frac{2}{\pi} \int k^2 \, \mathrm{d}k \underbrace{P(k)}_{\text{Inflation}} \underbrace{\Delta_{X\ell}(k)\Delta_{Y\ell}(k)}_{\text{Anisotropies}}$$

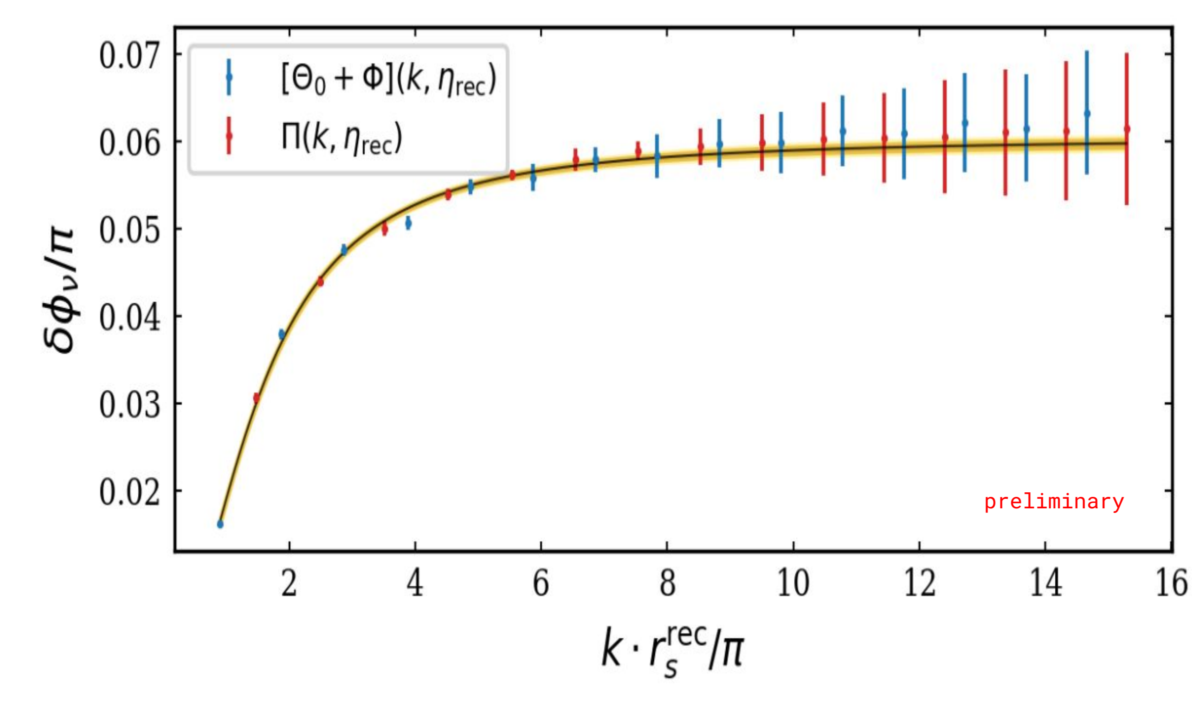


Freese, Wallisch & GM (in prep.)

Can we do better?
A perturbation-based template

$$\delta\phi_\nu = A(N_{\rm eff}) f_{\delta\phi_\nu}(kr_s)$$

$$f_{\delta\phi_\nu}(kr_s) \equiv \frac{f_\infty}{1+\left[\frac{kr_s}{(kr_s)_*}\right]^\xi}$$



- Less scatter in the obtained template
- Complex implementation (Work in progress)

Freese, Wallisch & GM (in prep.)

Summary

- The characteristic **phase shift** that arises from **free-streaming radiation** is a robust probe of physics beyond the standard model
  - It break degeneracies with cosmological parameters
  - Allows to distinguish between different forms of radiation

- Planck 2018 data provide strong evidence of the **free-streaming** nature of **neutrinos**, and is still compatible with **SM**
  - We provide the **1st template-based measurement** of the phase shift using **Polarization data**

Grazie per l’attenzione

Gabriele Montefalcone
Weinberg Institute for Theoretical Physics, University of Texas at Austin

Based on ongoing work with Benjamin Wallisch and Katherine Freese