February 20th 2025

Weinberg Institute Brown bag Seminar
Austin, TX

Free-streaming neutrinos in the CMB power spectra

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

Based on **2501.13788** with Benjamin Wallisch and Katherine Freese

TEXAS
The University of Texas at Austin

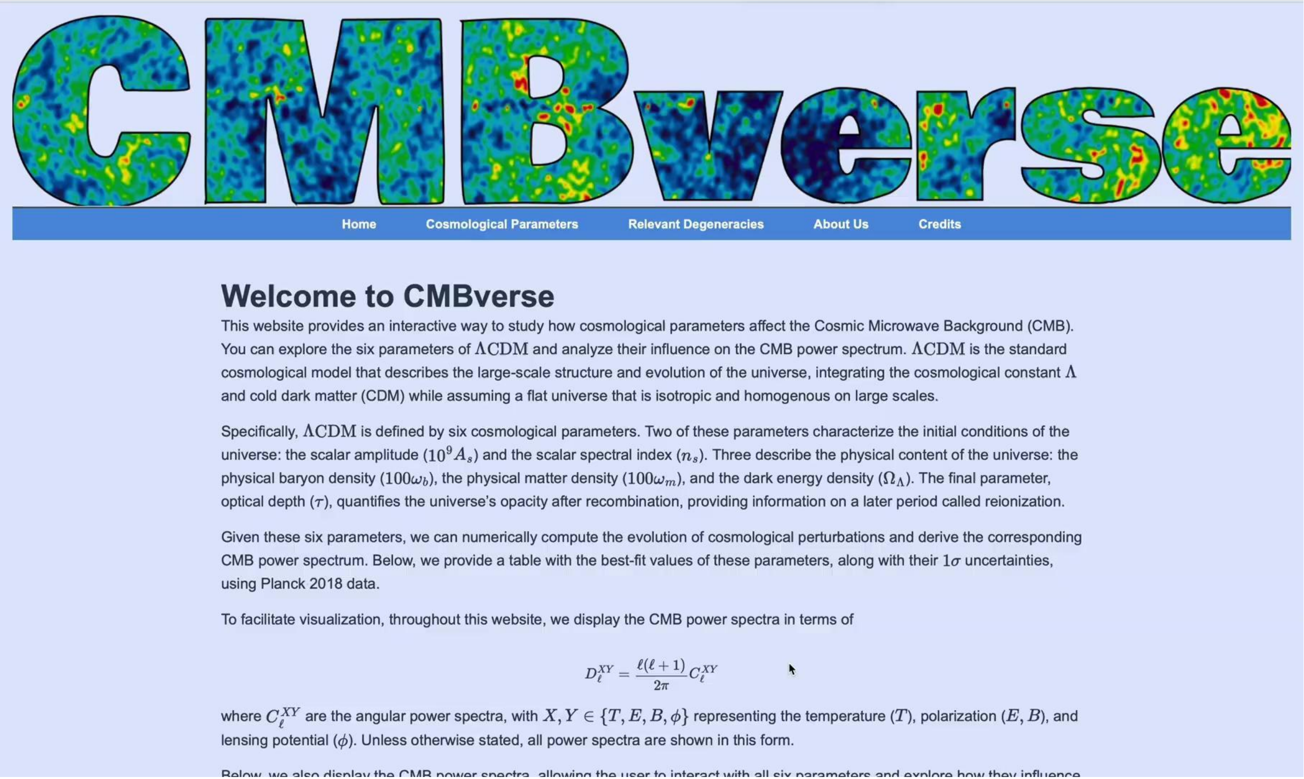
An Aside: A New Website to Learn about the CMB

Jack

Sofia

Chase

www.gabrielemontefalcone/CMBverse



CMBverse

Home | Cosmological Parameters | Relevant Degeneracies | About Us | Credits

Welcome to CMBverse

This website provides an interactive way to study how cosmological parameters affect the Cosmic Microwave Background (CMB). You can explore the six parameters of $\Lambda\mathrm{CDM}$ and analyze their influence on the CMB power spectrum. $\Lambda\mathrm{CDM}$ is the standard cosmological model that describes the large-scale structure and evolution of the universe, integrating the cosmological constant Λ and cold dark matter (CDM) while assuming a flat universe that is isotropic and homogenous on large scales.

Specifically, $\Lambda\mathrm{CDM}$ is defined by six cosmological parameters. Two of these parameters characterize the initial conditions of the universe: the scalar amplitude ($10^9 A_s$) and the scalar spectral index (n_s). Three describe the physical content of the universe: the physical baryon density ($100\omega_b$), the physical matter density ($100\omega_m$), and the dark energy density (Ω_Λ). The final parameter, optical depth (τ), quantifies the universe's opacity after recombination, providing information on a later period called reionization.

Given these six parameters, we can numerically compute the evolution of cosmological perturbations and derive the corresponding CMB power spectrum. Below, we provide a table with the best-fit values of these parameters, along with their 1σ uncertainties, using Planck 2018 data.

To facilitate visualization, throughout this website, we display the CMB power spectra in terms of

$$D_\ell^{XY} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{XY}$$

where C_ℓ^{XY} are the angular power spectra, with $X, Y \in \{T, E, B, \phi\}$ representing the temperature (T), polarization (E, B), and lensing potential (ϕ). Unless otherwise stated, all power spectra are shown in this form.

Below, we also display the CMB power spectra, allowing the user to interact with all six parameters and explore how they influence

SCAN ME

An Aside: A New Website to Learn about the CMB

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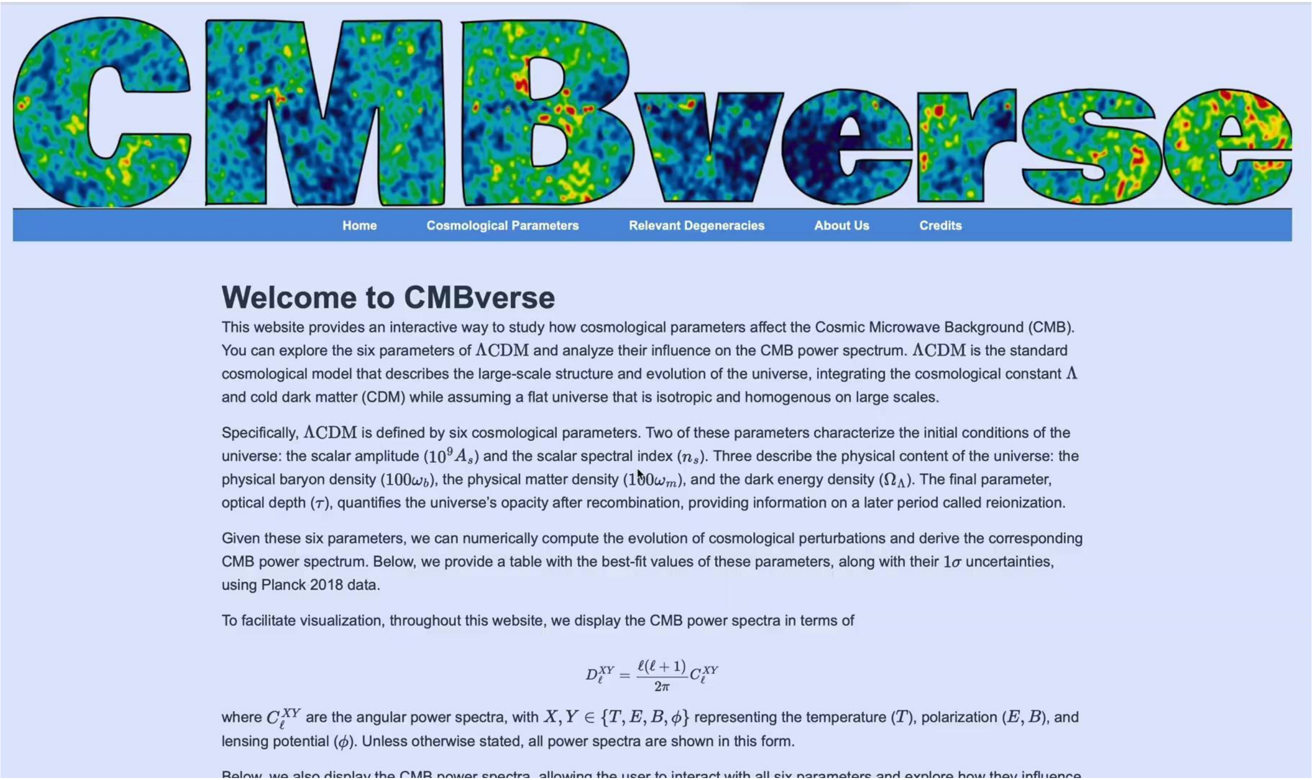

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This website provides an interactive way to study how cosmological parameters affect the Cosmic Microwave Background (CMB). You can explore the six parameters of ΛCDM and analyze their influence on the CMB power spectrum. ΛCDM is the standard cosmological model that describes the large-scale structure and evolution of the universe, integrating the cosmological constant Λ and cold dark matter (CDM) while assuming a flat universe that is isotropic and homogenous on large scales.

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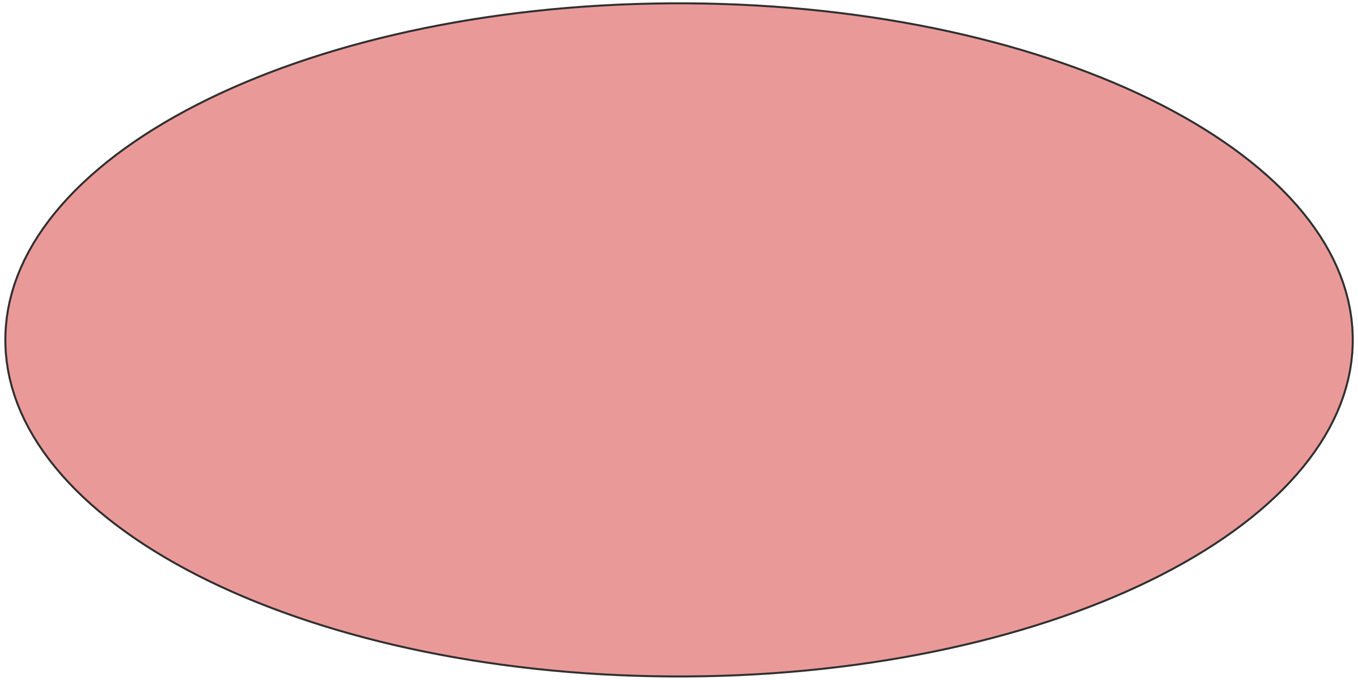
The Cosmic Microwave Background

The background radiation associated with the **decoupling** of photons from the primordial plasma

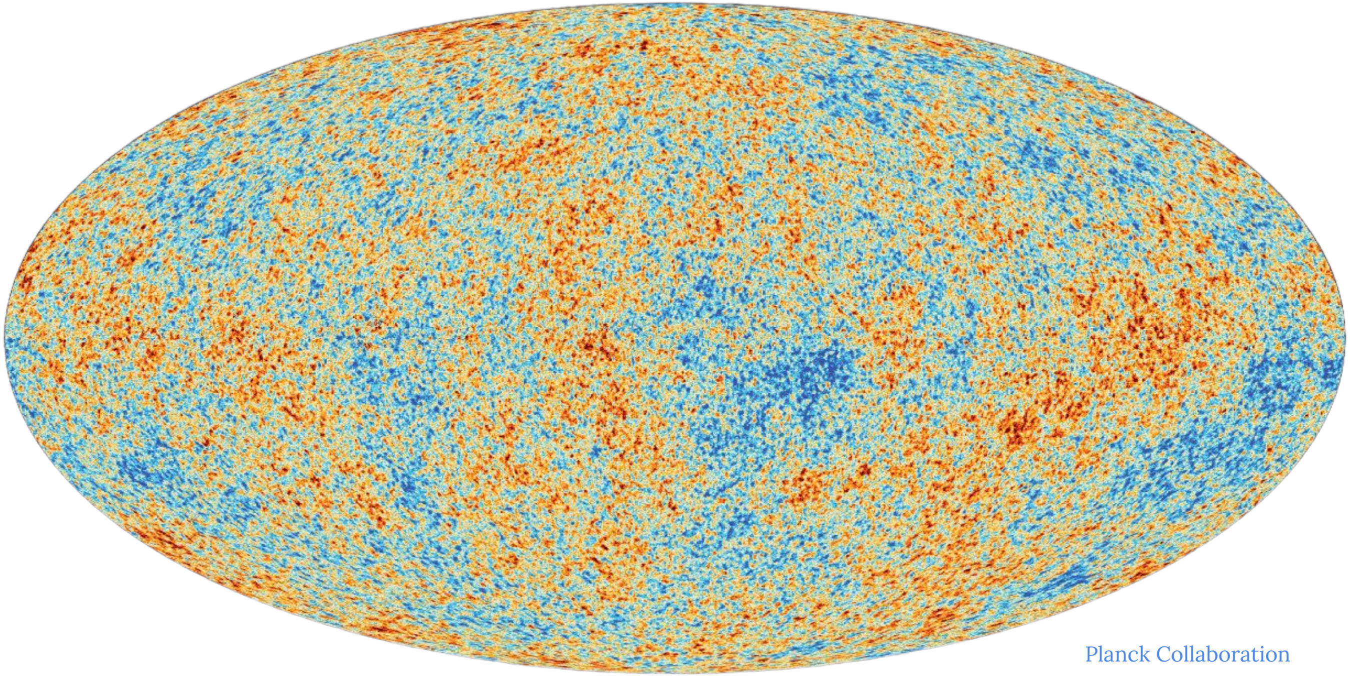
T = 2.7255 K



The Cosmic Microwave Background

The background radiation associated with the **decoupling** of photons from the primordial plasma

$\Delta T/T \sim 10^{-4}$



Planck Collaboration

Neutrinos & the CMB

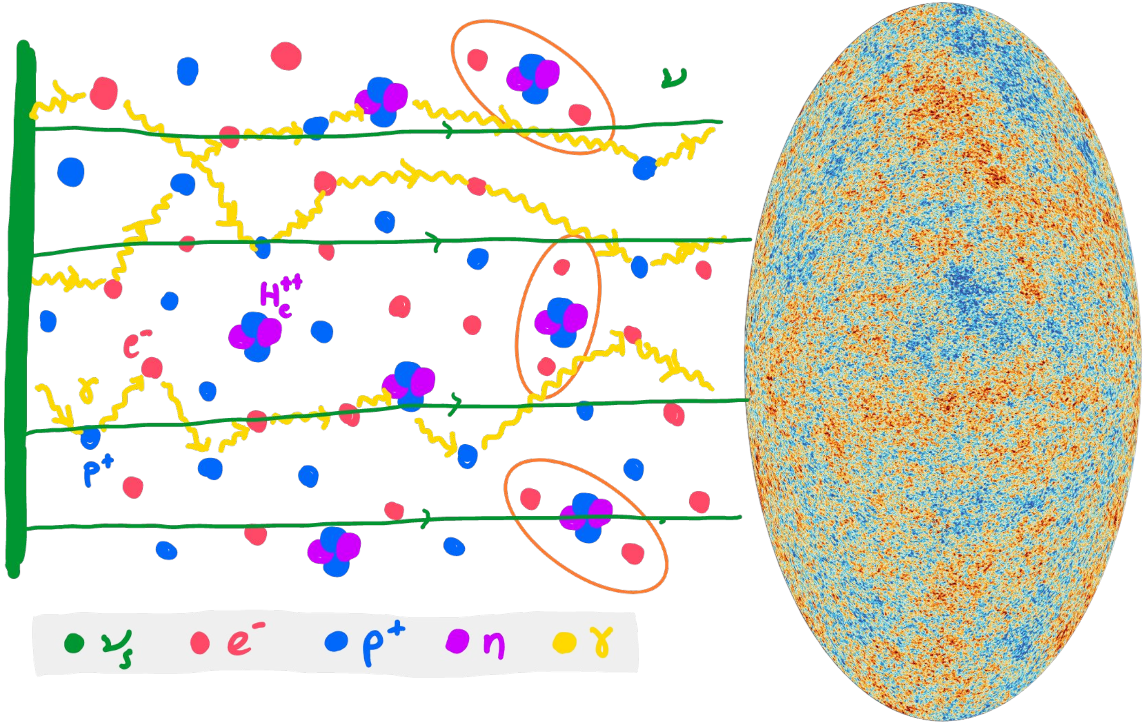
The background radiation associated with the **decoupling** of photons from the primordial plasma

Cosmic Neutrino Background

$\Delta T/T \sim 10^{-4}$

- Significant fraction of **energy density** in neutrinos

- **Free-streaming** since their decoupling at **t~1 s**



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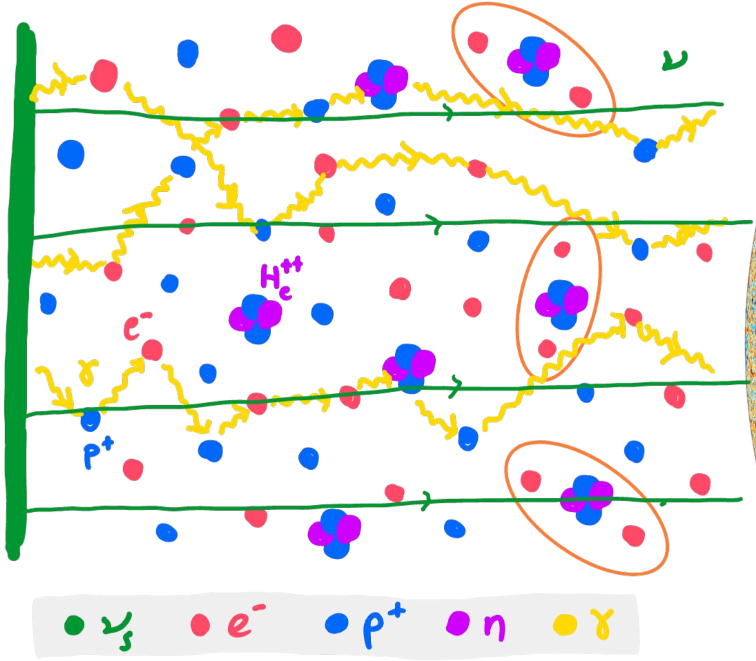
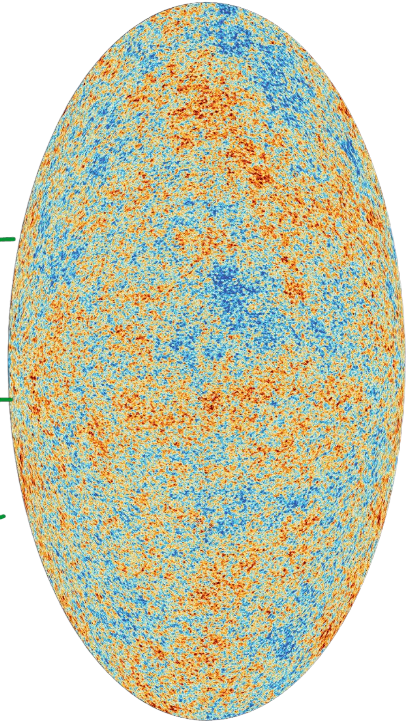
Can we detect this?





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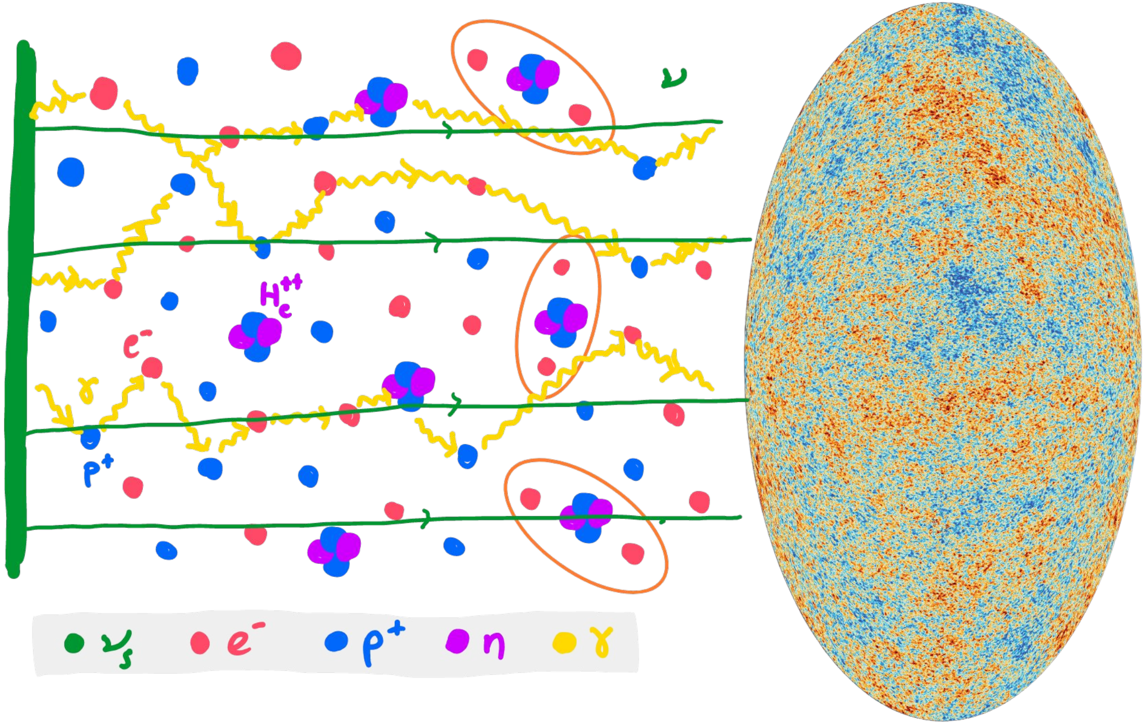


- Significant fraction of **energy density** in neutrinos
- **Free-streaming** since their decoupling at **t~1 s**

Can we detect this?

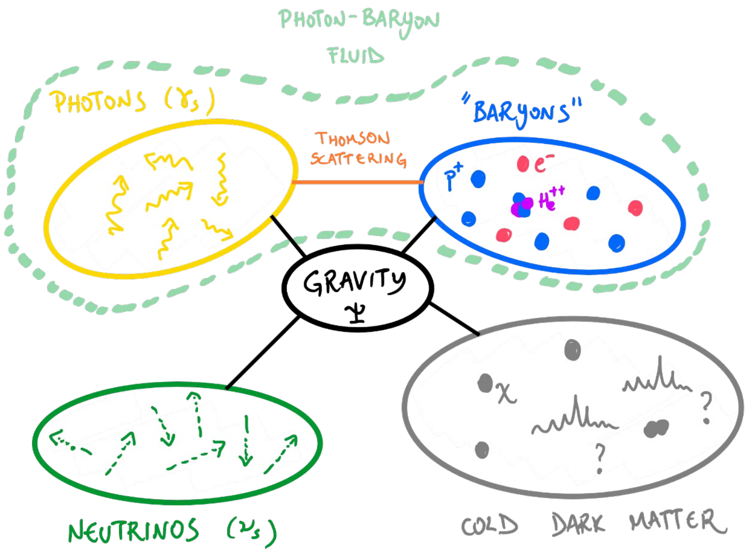
- Neutrino masses $\mathbf{m_\nu}$?
  no detection but **unimportant** in the early universe

Outline

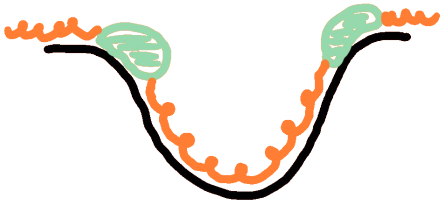
1. CMB Physics in a Nutshell
2. Neutrinos in the CMB
3. The Multipole Shift in the CMB Spectra
4. The Phase Shift in the Perturbations
5. Validation of Analysis Pipeline with Mock Data
6. Current CMB Data Analysis and Forecasts
7. Summary & Future Directions

Cosmic Sound Waves

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



$$\ddot{\delta}_\gamma - \underbrace{c_\gamma^2 \nabla^2 \delta_\gamma}_{\textbf{Photon Pressure}} = \underbrace{\nabla^2 \Psi_+}_{\textbf{Gravity}}$$



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

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

Baryons add inertia to the fluid

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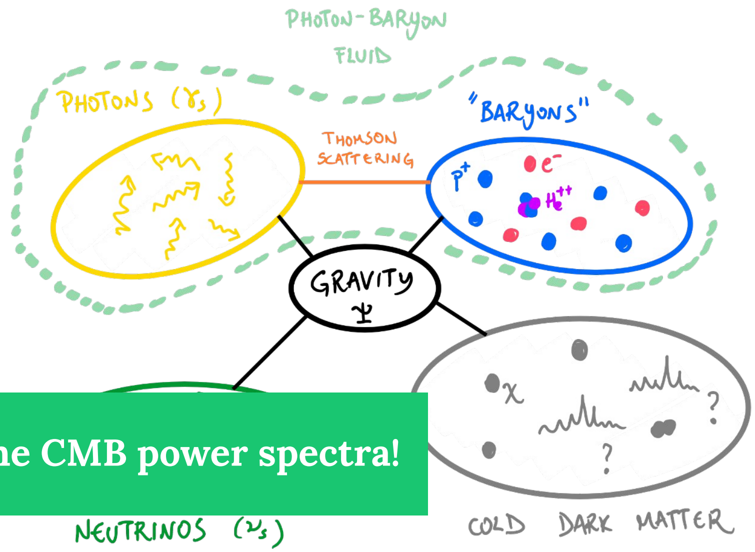
- **Gravity** photon-

We observe these acoustic oscillations in the CMB power spectra!



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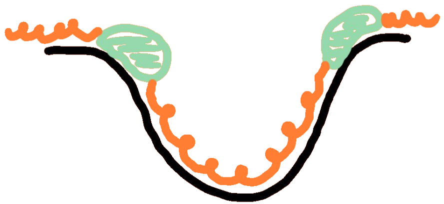

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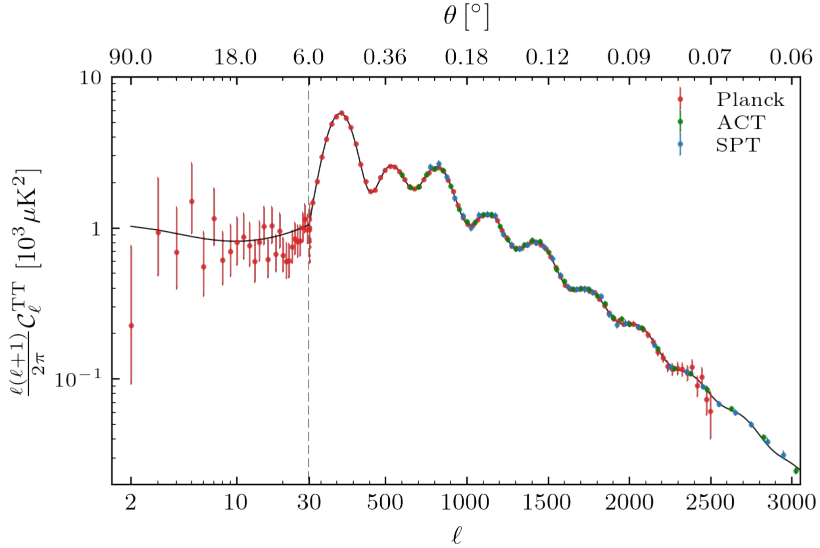
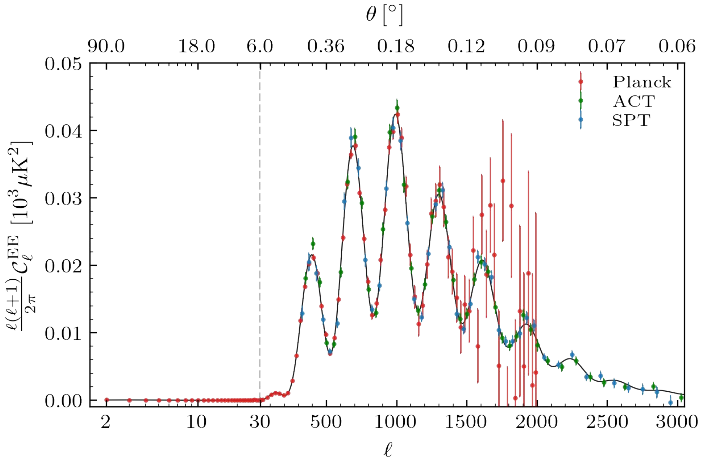
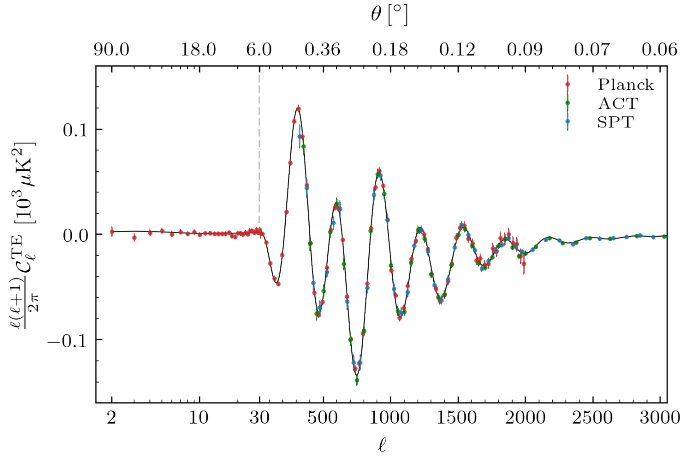
The CMB Power Spectra







We observe these acoustic oscillations in the CMB power spectra!

Cosmic Neutrinos

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

- 41% of the radiation density in the universe
- Parametrized by the observable $\mathbf{N_{eff}}$, known as *the effective number of relativistic species*
  - In the SM, $N_{eff} = 3.044$ Akita1, Yamaguchi (2020)
- Cosmology is sensitive to their gravitational effects

$\Rightarrow$ CMB measurements are **consistent with SM value** of N_{eff}

$$\boxed{N_{\text{eff}} = 2.92 \pm 0.18}$$

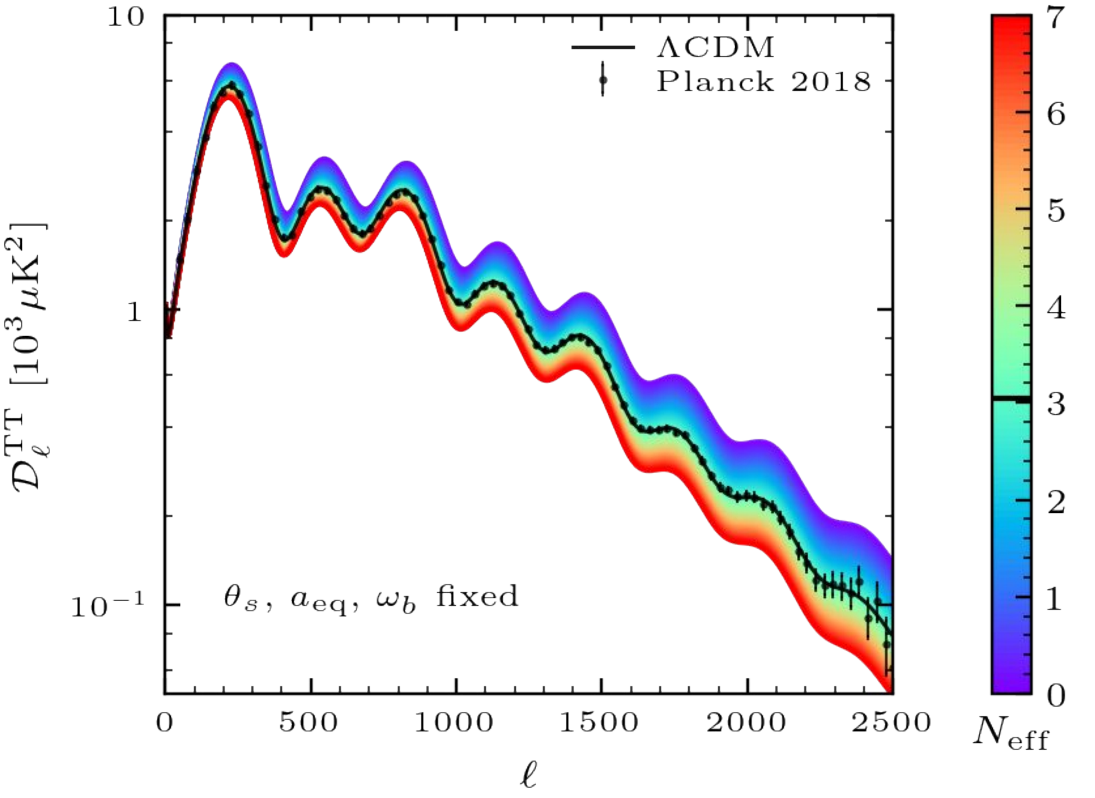
Planck 2018

Cosmic Neutrinos in the CMB
Energy Density

- 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 a_{eq} and θ_s, **larger N_{eff} means more damping**

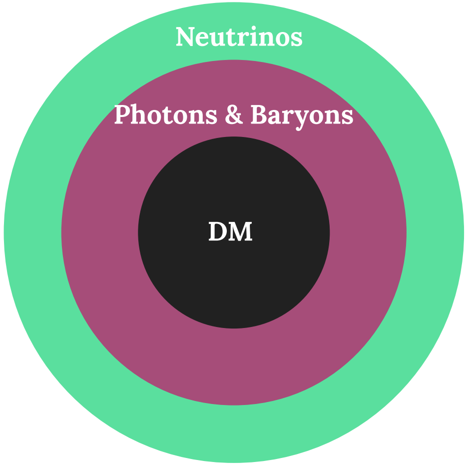


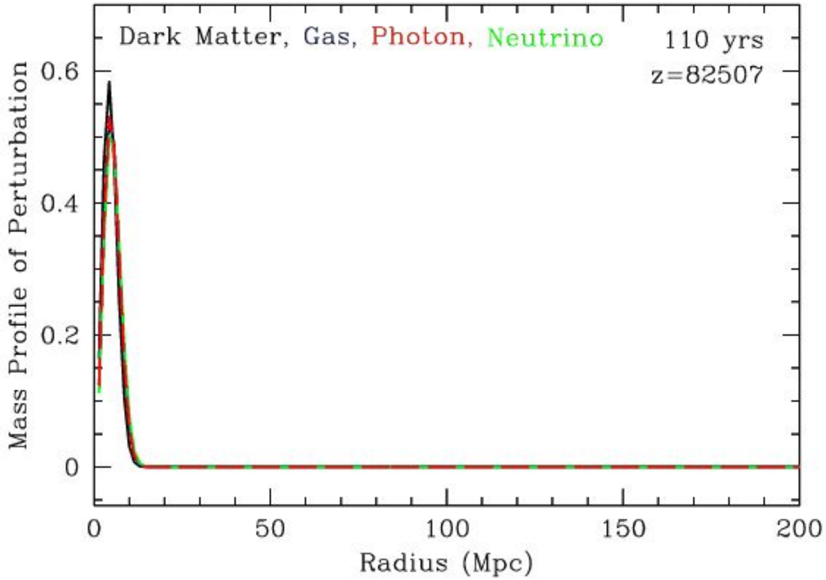
$$\mathcal{D}_\ell^{XY} \equiv \frac{\ell(\ell+1)}{2\pi}\mathcal{C}_\ell^{XY}$$

Cosmic Neutrinos in the CMB
Free-Streaming Nature

- Perturbations from free-streaming neutrinos 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

Cosmic Neutrinos in the CMB
Free-Streaming Nature

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

- This results in a **phase shift in the acoustic peaks of the CMB**

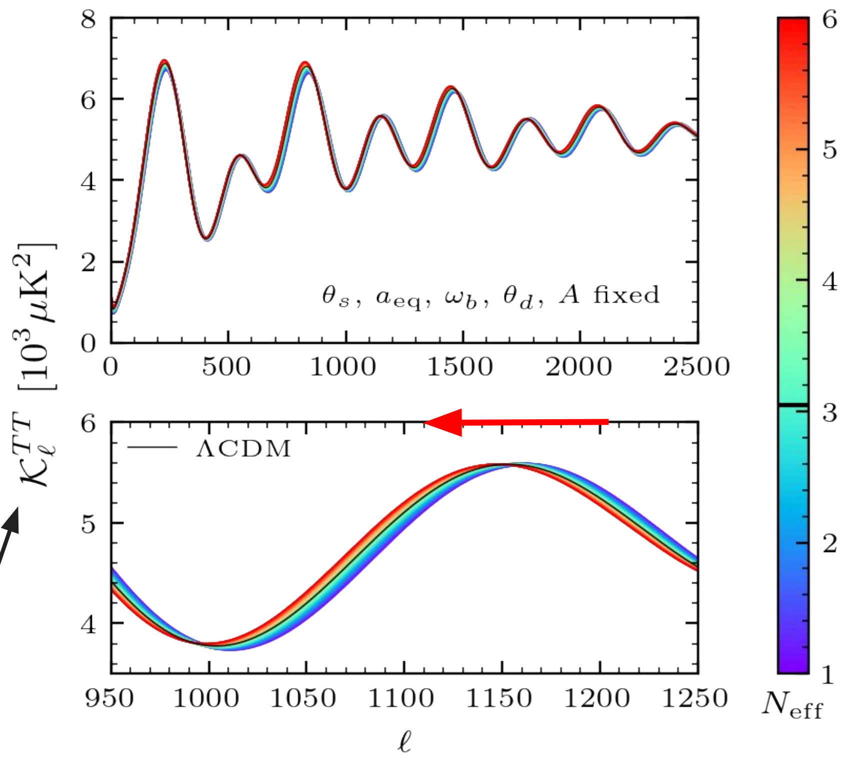
  Bashinsky & Seljak (2003)

  - Larger radii → smaller multipoles
  - Small effect, prop. to: $\epsilon_\nu \equiv \rho_\nu / \rho_r$

- Difficult to reproduce in the absence of **free-streaming**
  - Either free-streaming or non-adiabatic fluctuations   Baumann, Green, Meyers & Wallisch (2015)

$$\mathcal{K}_\ell^{XY} \equiv \frac{\ell(\ell+1)}{2\pi} \mathcal{C}_\ell^{XY} \exp\{a(\ell\theta_d)^\kappa\}$$

Undamped temperature power spectrum



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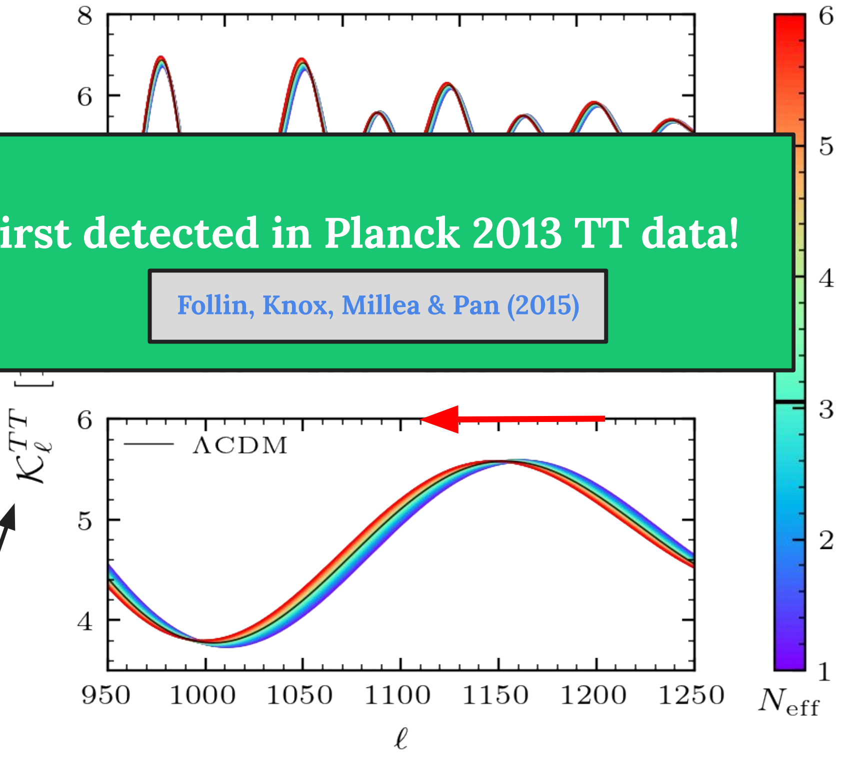


First detected in Planck 2013 TT data!

Follin, Knox, Millea & Pan (2015)

Cosmic Neutrinos in the CMB

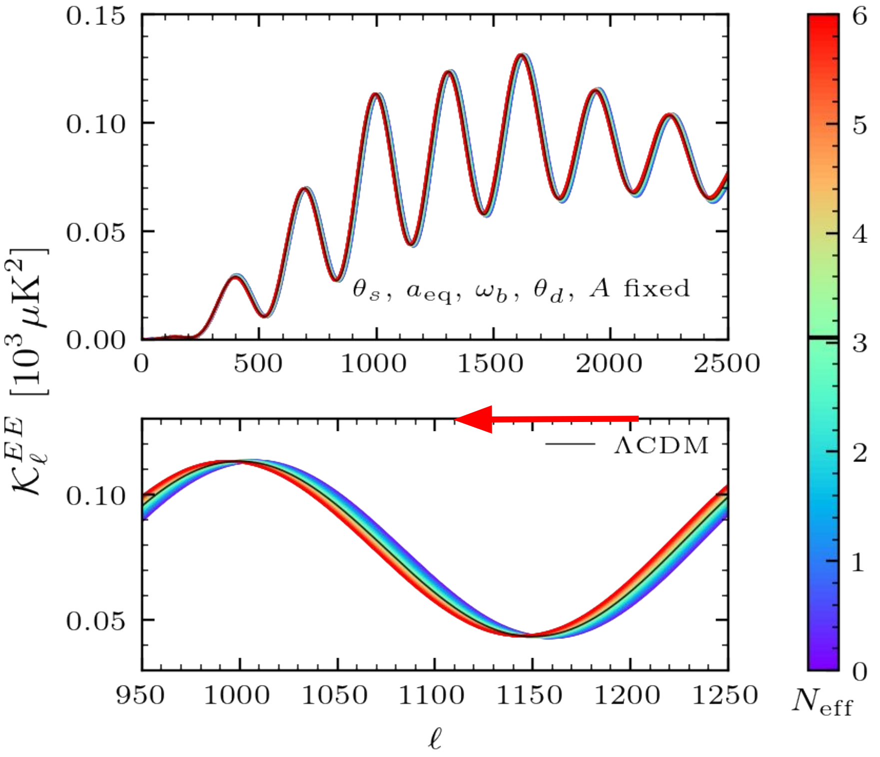
Free-Streaming Nature

- Same shift both in temperature and polarization spectrum

$$\Pi(k,\eta) \sim \frac{d}{d\eta}\delta_\gamma(k,\eta)$$

  - polarization provides cleaner signal

$$\Pi(\vec{k}) \sim A(\vec{k})\frac{c_s}{\dot{\tau}}\sin(kr_s + \phi)$$



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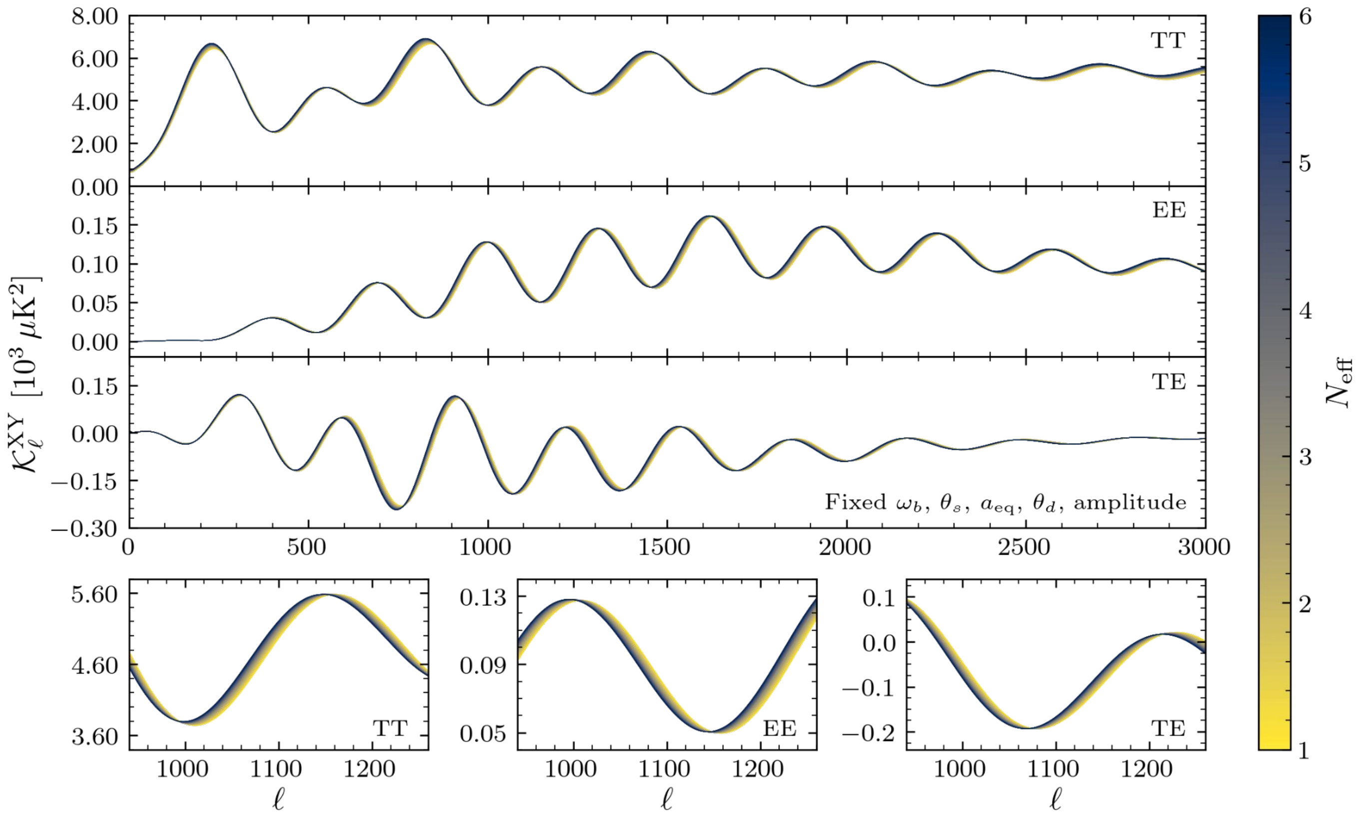


The Multipole Shift in the CMB Power Spectra

Following Follin, Knox, Millea & Pan (2015)

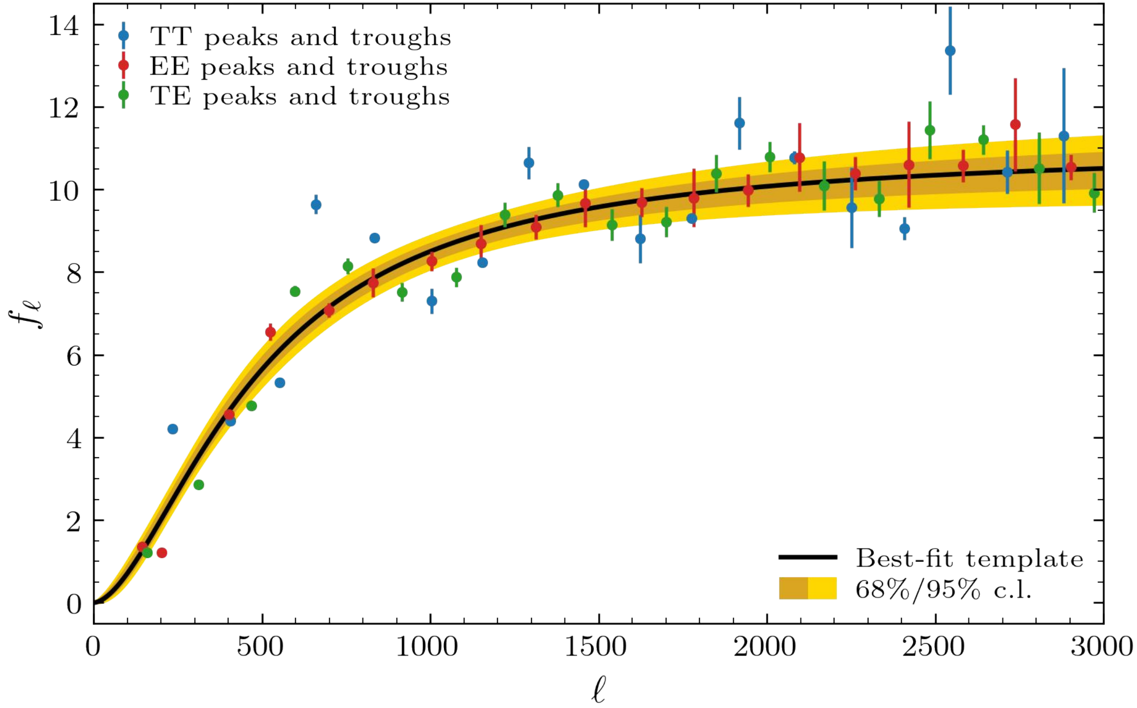
$$\delta\ell(N_{\rm eff}) = A(N_{\rm eff})\, f_\ell$$

$$A(N_{\rm eff}) \equiv \frac{\epsilon(N_{\rm eff}) - \epsilon(3.044)}{\epsilon(1) - \epsilon(3.044)}$$

$$f_\ell = \frac{\ell_\infty}{1 + (\ell/\ell_\star)^\xi}$$

Our Contributions:

- A new analytic form of the template
- Used both temperature and polarization data



GM, Wallisch & Freese (2025)

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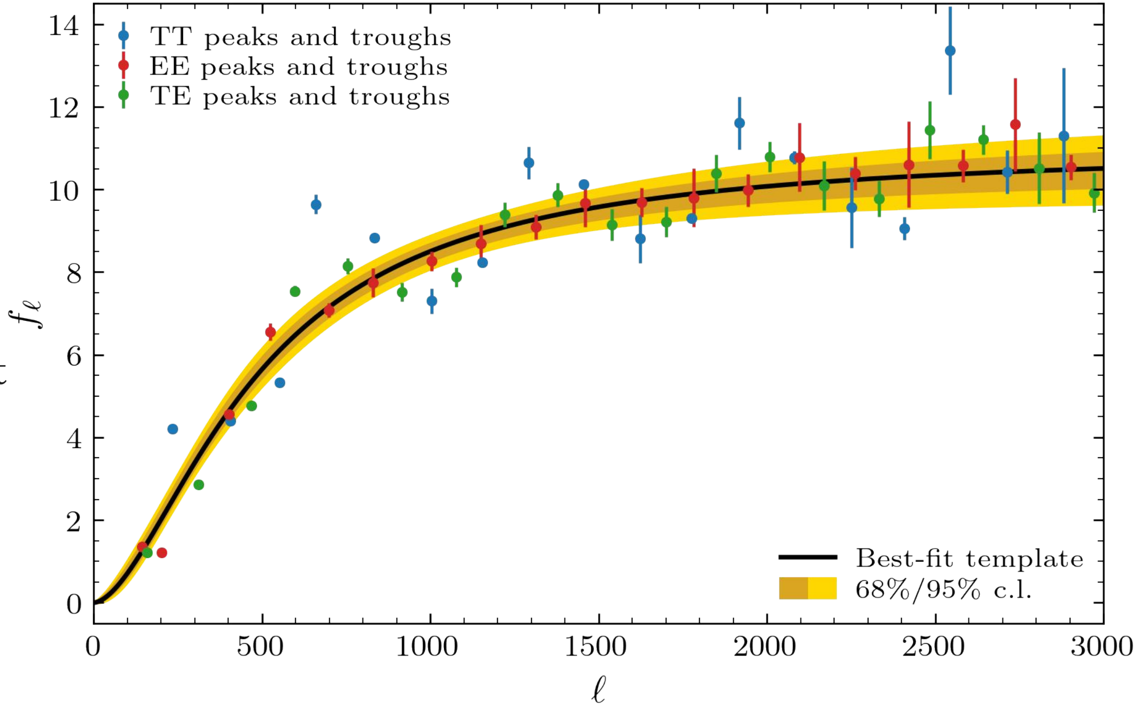
$$f_\ell = \frac{\ell_\infty}{1 + (\ell/\ell_\star)^\xi}$$

- A new parameter to control the shift

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

$$\Delta\ell(N_{\rm eff}^{\delta\ell}, N_{\rm eff}) = \left[A(N_{\rm eff}^{\delta\ell}) - A(N_{\rm eff})\right] f_\ell$$

$$\mathcal{C}_\ell \to \mathcal{C}_{\ell+\Delta\ell}$$



GM, Wallisch & Freese (2025)

The Phase Shift in the Perturbations

- Extract the **phase shift** at the **perturbations** level, instead of the CMB power spectra
    - Cleaner signature: avoids projection and smearing effects

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X Physical Source Term

$S_X(k,\eta)$

$$\begin{cases} S_T(k,\eta) = g_\gamma\,(\delta_\gamma/4 + \Psi) + \ldots \\ S_E(k,\eta) = \sqrt{6}/2\,\cdot g_\gamma\,\Pi \end{cases}$$

↓

X Anisotropies

$$\Delta_\ell^X = \int_0^{\eta_0} d\eta\, S_X(k,\eta)\, P_{X\ell}\underbrace{(k[\eta_0-\eta])}_{\text{Projection}}$$

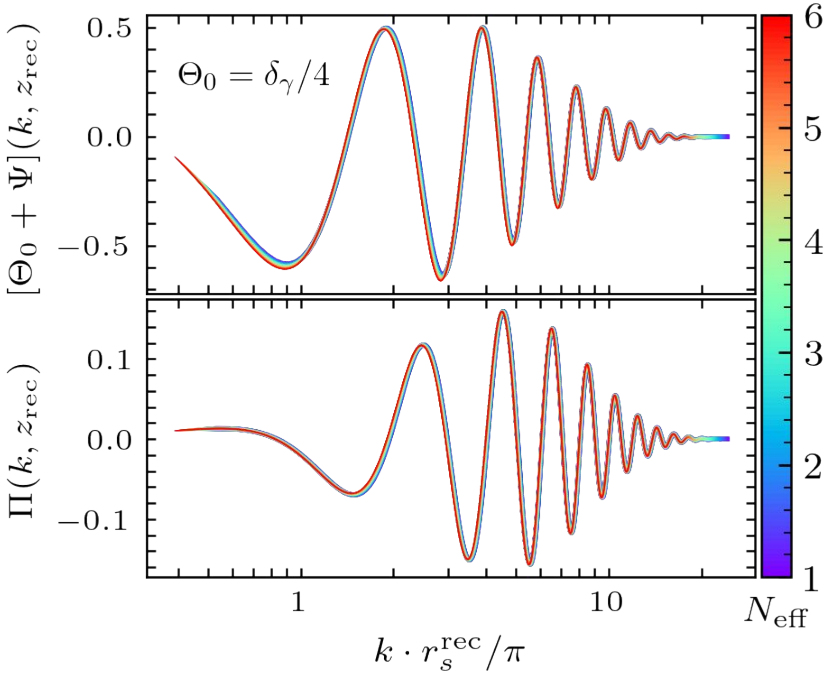
↓

XY Power Spectra

$$\mathcal{C}_\ell^{XY} = \frac{2}{\pi}\int k^2 \underbrace{dk\,\Delta_{\mathcal{R}}^2(k)}_{\text{Primordial Spectrum}}\,\Delta_\ell^X(k)\Delta_\ell^Y(k)$$

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

$$\Pi(\vec{k}) \sim A(\vec{k})\frac{c_s}{\dot{\tau}}\sin(kr_s+\phi)$$



GM, Wallisch & Freese (2025)

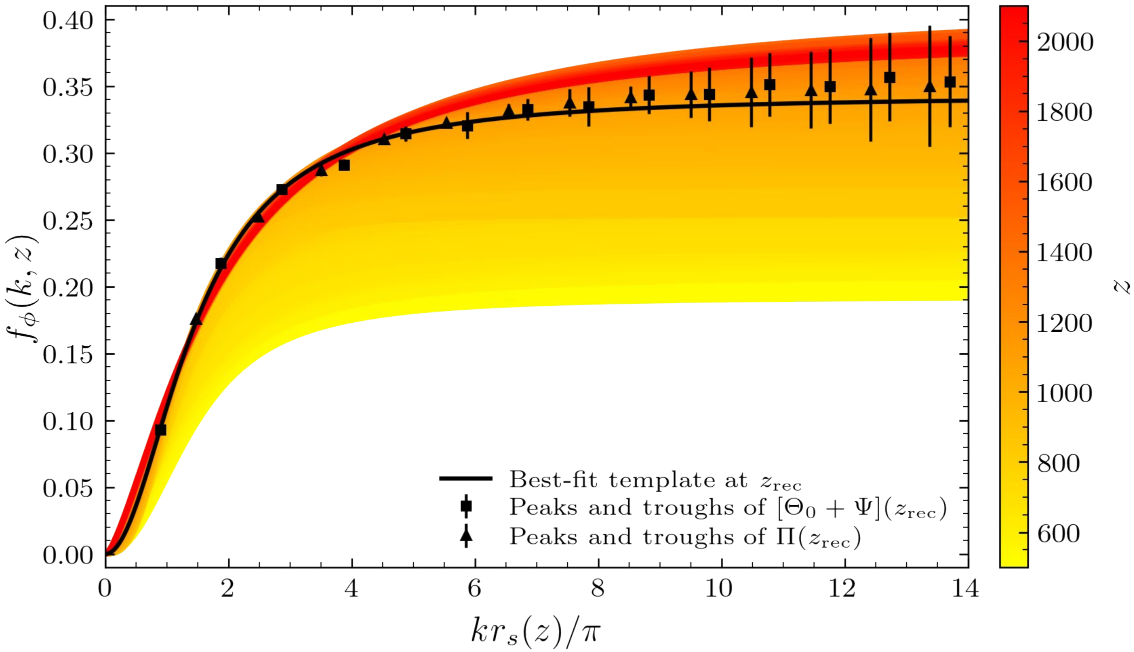
The Phase Shift in the Perturbations

- The neutrino induced phase shift is **redshift** and mode dependent

$$\delta\phi(k, z; N_{\rm eff}) = A(N_{\rm eff})\, f_\phi(k, z)$$

$$A(N_{\rm eff}) \equiv \frac{\epsilon(N_{\rm eff}) - \epsilon(3.044)}{\epsilon(1) - \epsilon(3.044)}$$

$$f_\phi(k, z) = \frac{\phi_\infty}{1 + [kr_s/(kr_s)_\star]^\xi}$$



GM, Wallisch & Freese (2025)

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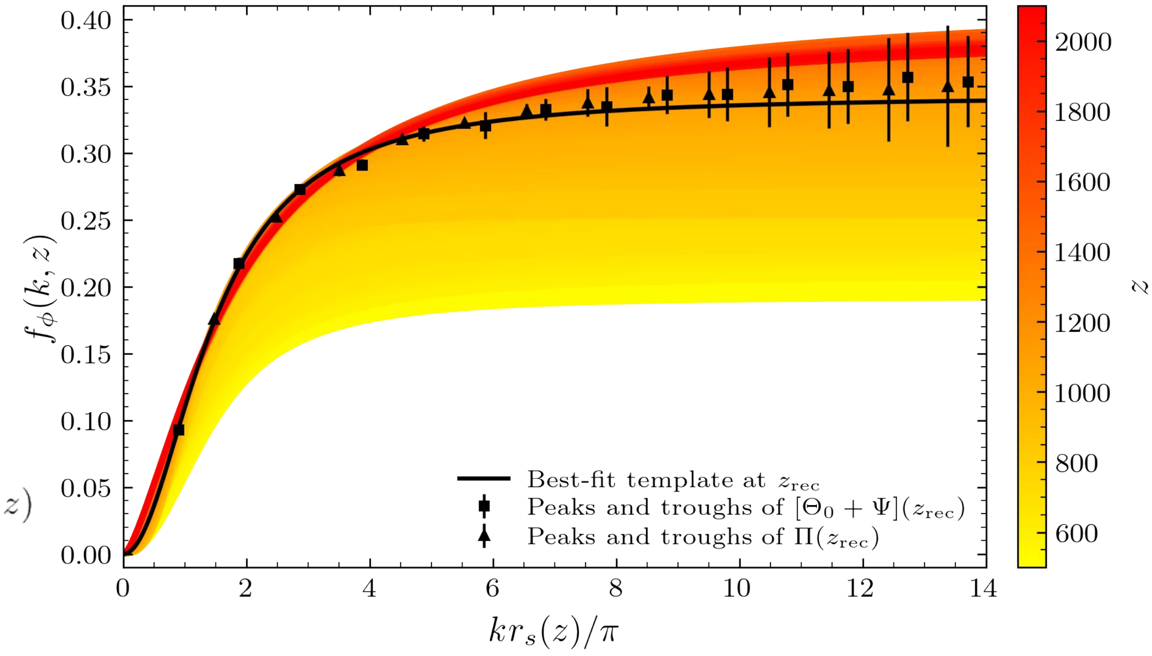
- A new parameter to control the shift

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

$$\Delta\phi(k, z; N_{\rm eff}^{\delta\phi}, N_{\rm eff}) = \left[A(N_{\rm eff}^{\delta\phi}) - A(N_{\rm eff})\right] f_\phi(k, z)$$

$$S_X(k, z) \to S_X(k + \Delta\phi/r_s, z)$$



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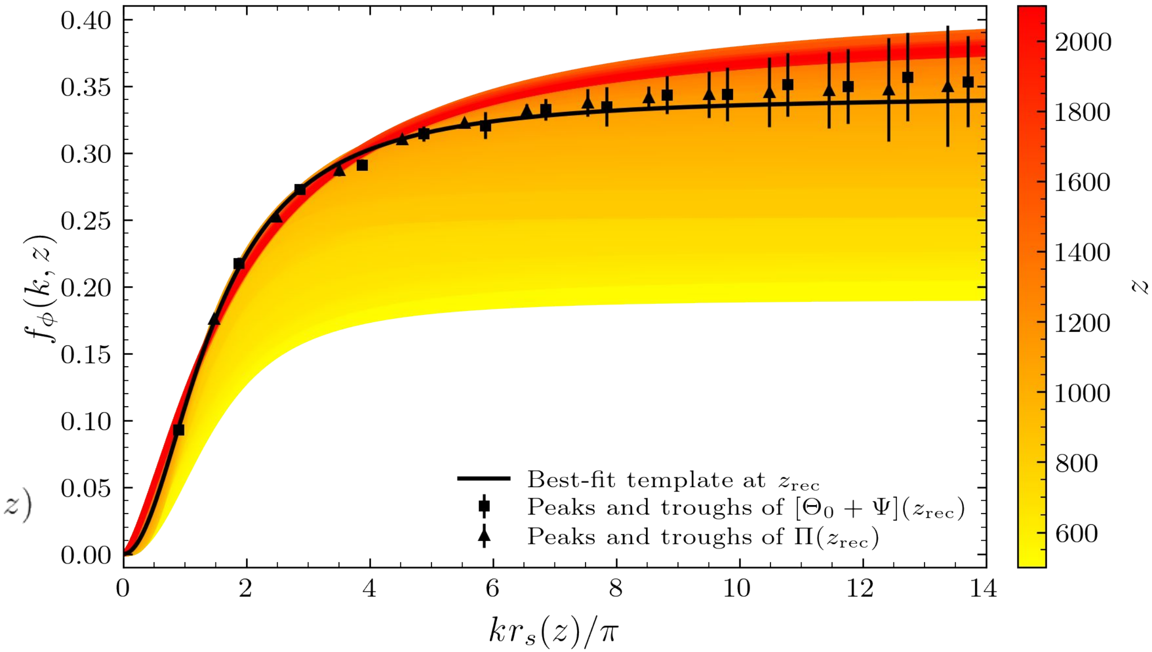
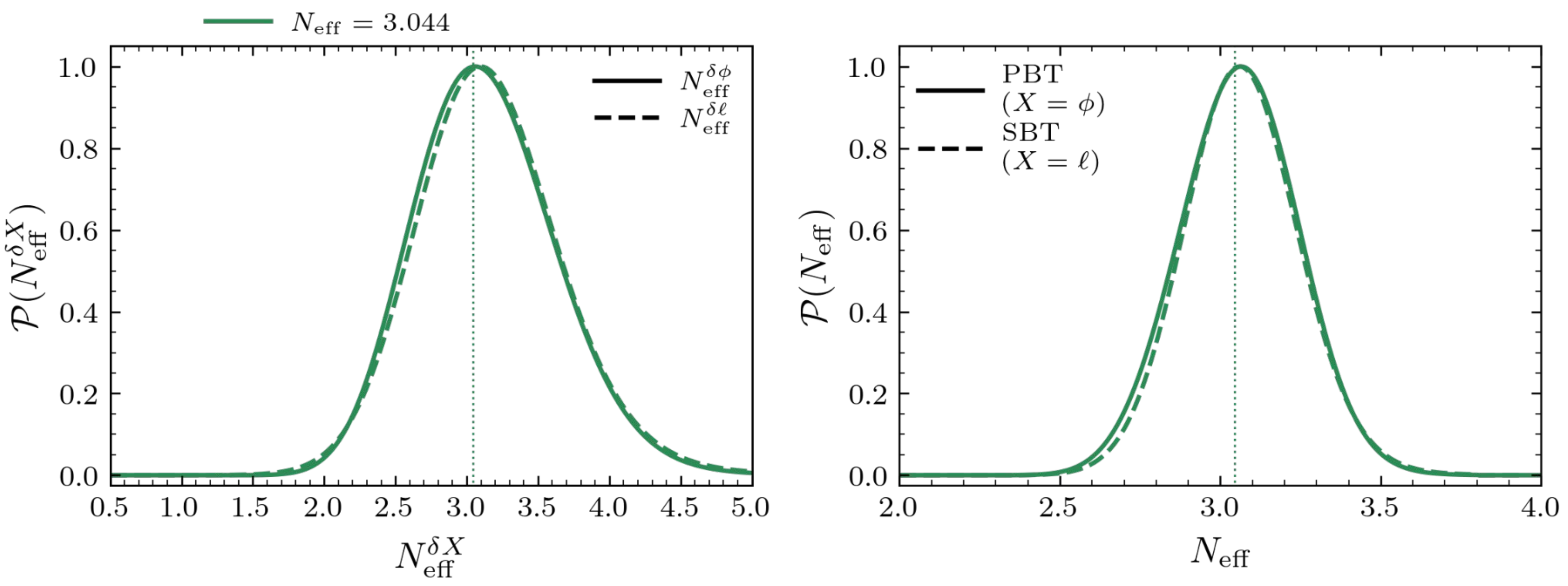
$$S_X(k, z) \rightarrow S_X(k + \Delta\phi/r_s, z)$$



It results in the observed neutrino induced multipole shift in the CMB spectra

GM, Wallisch & Freese (2025)

Validation of Phase Shift Extraction
Planck-like Mock Data Analysis



Both the spectrum and perturbation based approach successfully recover the imprinted phase shift by SM neutrinos

GM, Wallisch & Freese (2025)

Validation of Phase Shift Extraction

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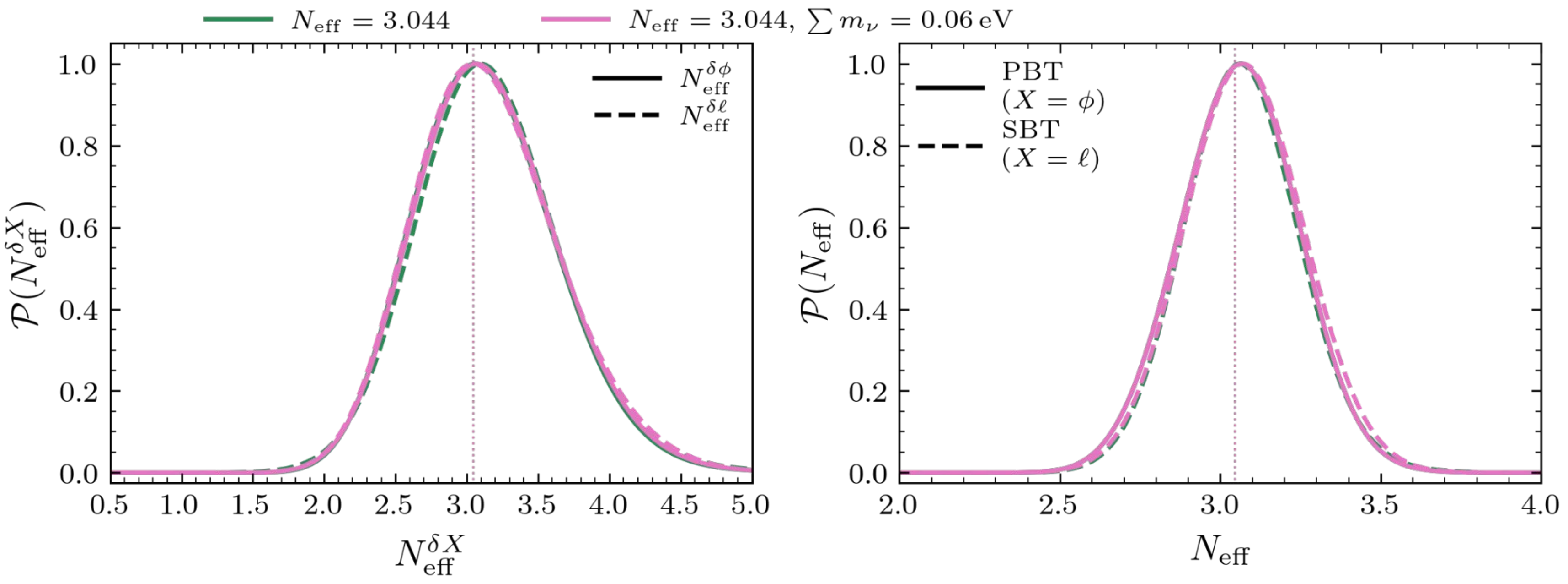

Neutrino masses have negligible impact on the phase shift extraction

GM, Wallisch & Freese (2025)

Validation of Phase Shift Extraction

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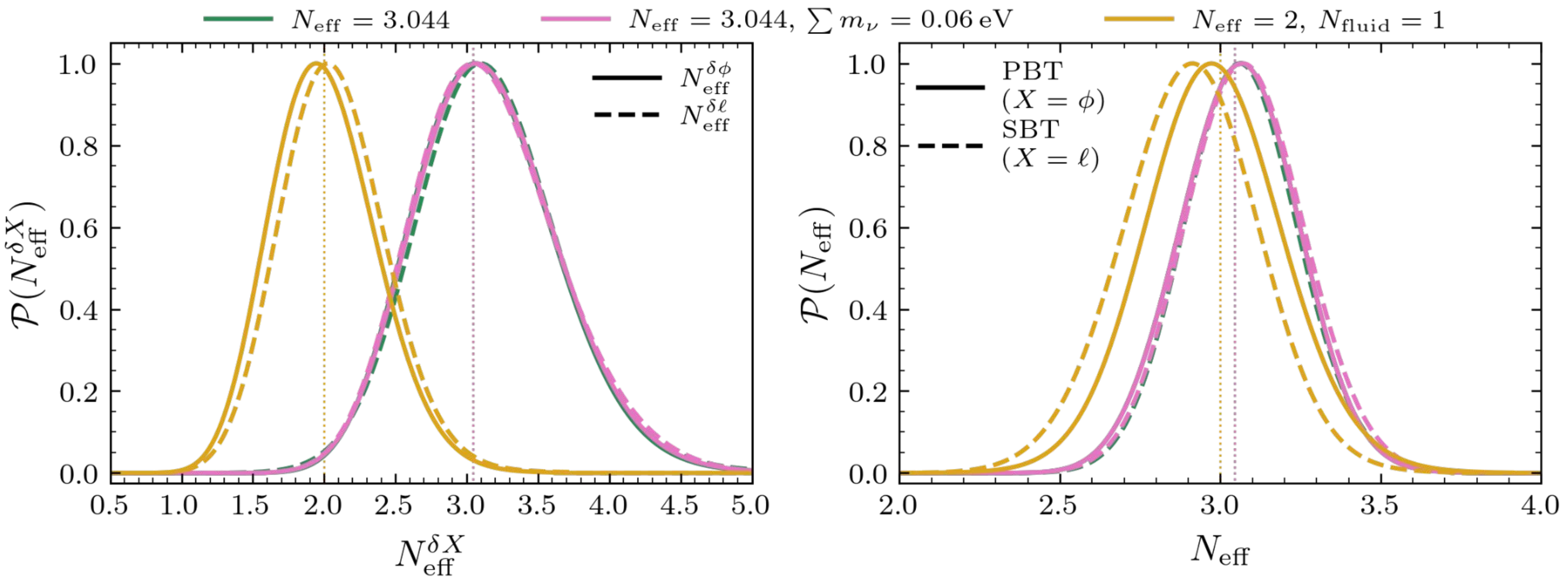


Both the spectrum and perturbation based approach successfully recover the imprinted phase shift by free-streaming radiation

GM, Wallisch & Freese (2025)

Phase Shift Constraints from CMB Data

Spectrum-Based Analysis

- Based on Planck 2013 temperature only:

$$N_{\rm eff}^{\delta\ell} = 2.3^{+1.1}_{-0.4}$$ Follin et al. (2015)

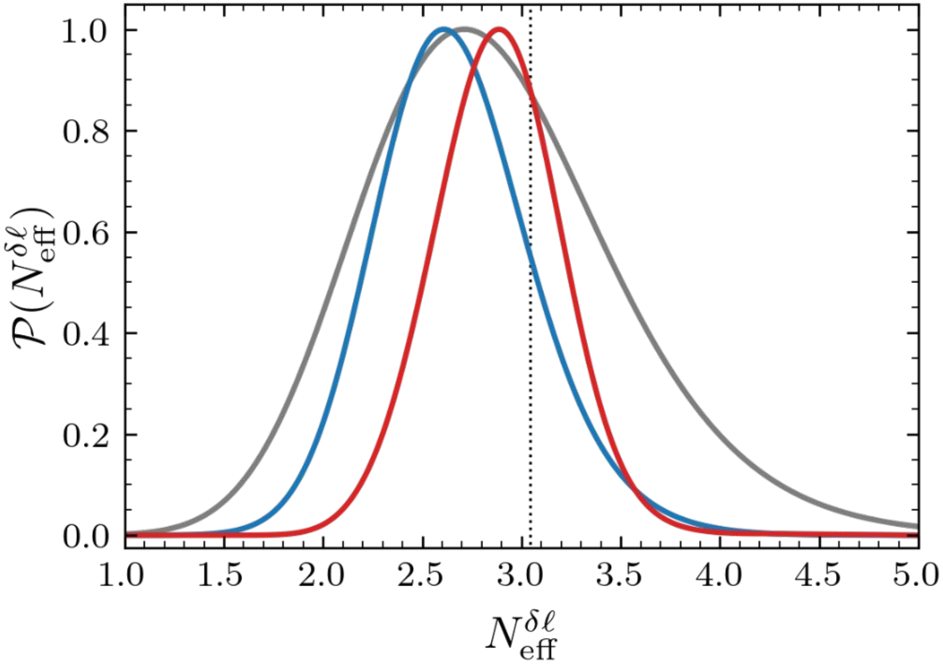
$(\,N_{\rm eff} = N_\nu = 3.044\,)$

- Current Data:
  - Planck 2018 TT only: $N_{\rm eff}^{\delta\ell} = 2.9^{+0.7}_{-0.6}$
  - Including polarization:

Planck 2018: $N_{\rm eff}^{\delta\ell} = 2.7^{+0.5}_{-0.4}$

+ ACT + SPT: $N_{\rm eff}^{\delta\ell} = 2.9^{+0.3}_{-0.3}$

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

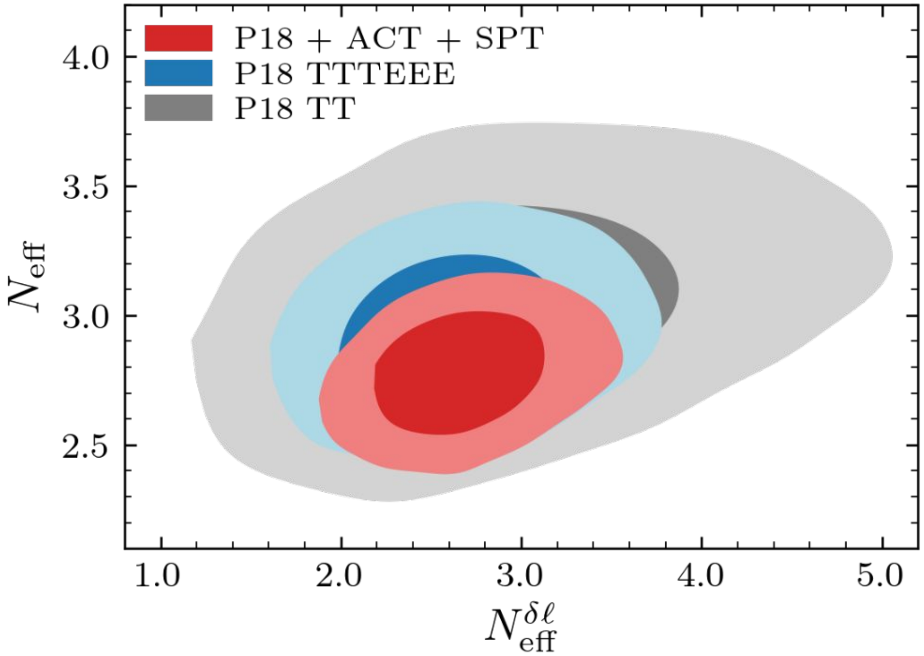


GM, Wallisch & Freese (2025)

Phase Shift Constraints from CMB Data
Spectrum-Based Analysis

- Strong evidence of **free-streaming nature** of neutrinos

- Current CMB data is compatible with the **Standard Model** prediction for free-streaming neutrinos

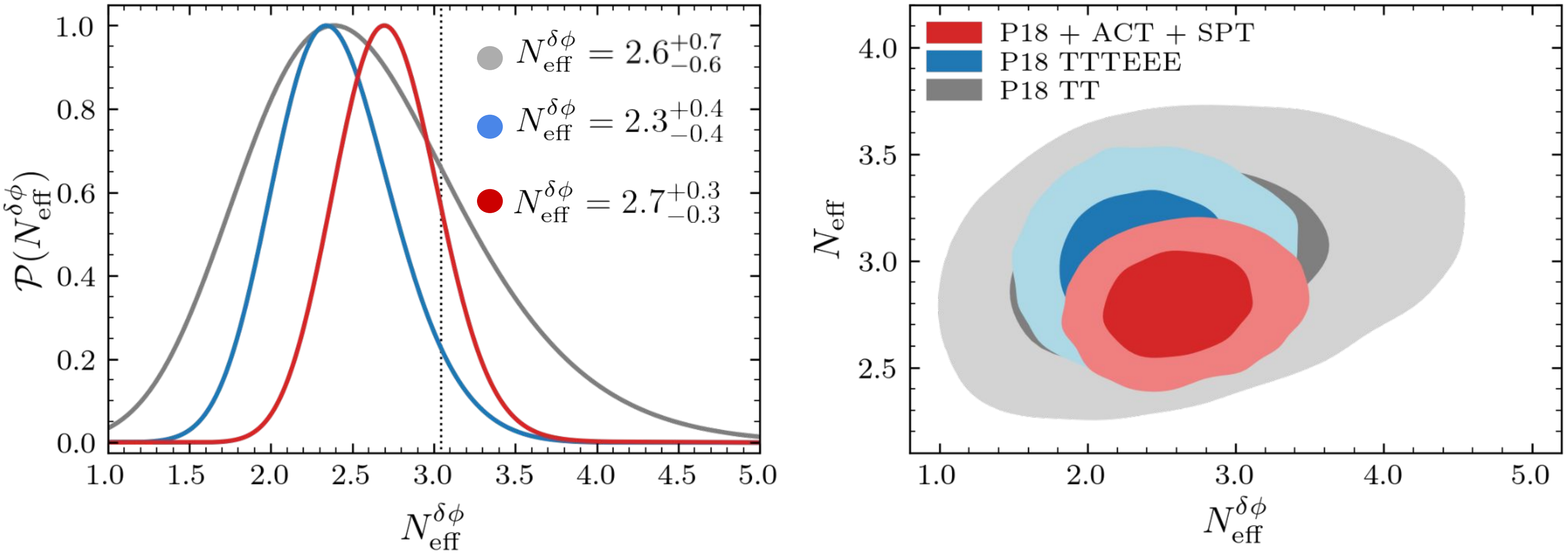


GM, Wallisch & Freese (2025)

Phase Shift Constraints from CMB Data

Perturbation-Based Analysis

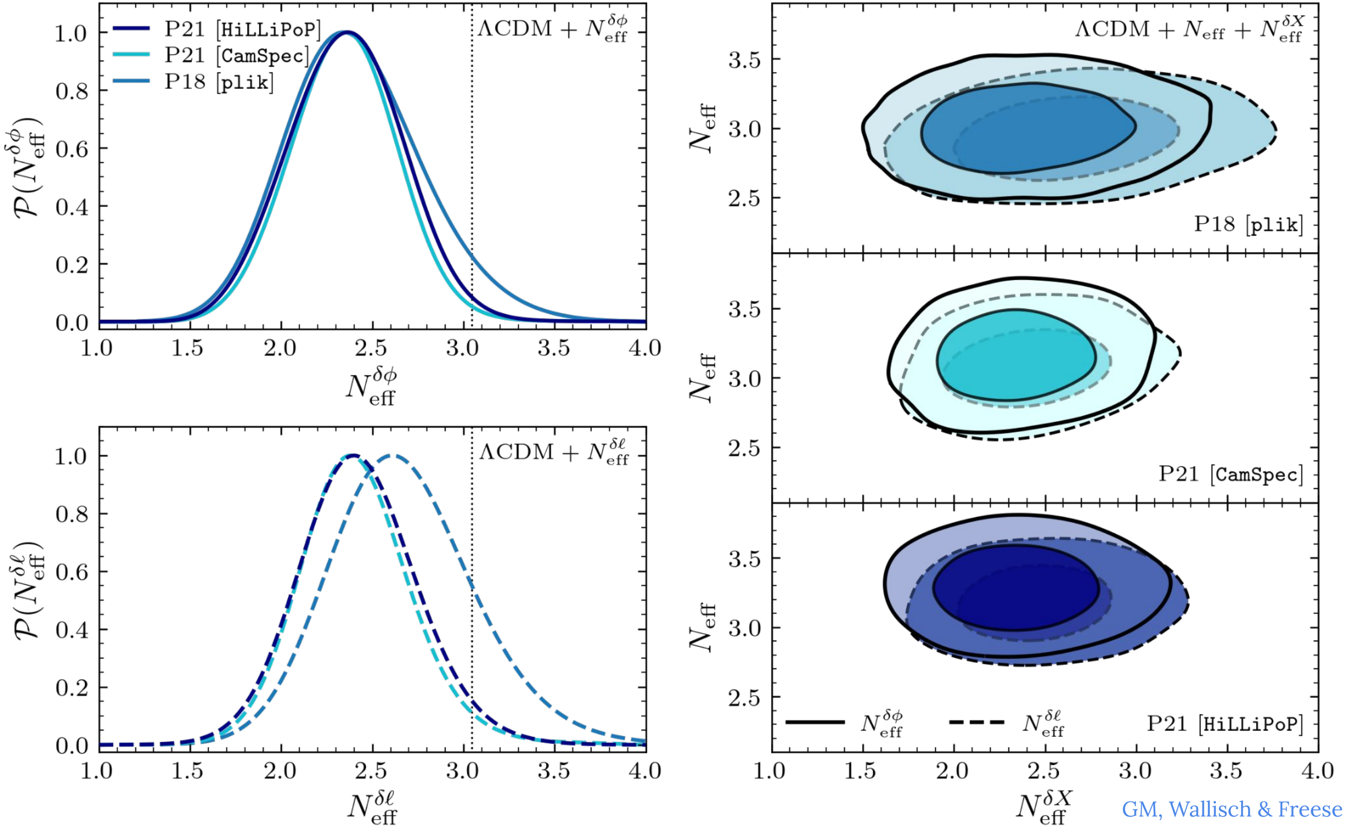
$$\left(N_{\rm eff} = N_\nu = 3.044 \right)$$



GM, Wallisch & Freese (2025)

Planck 2018 vs Planck 2021
Comparison of Spectrum- and Perturbation-Based Approach

The **perturbation-based method** is a more **robust** approach to extract the phase shift



GM, Wallisch & Freese (2025)

Phase Shift Forecasts

	$\Lambda\text{CDM} + N_{\text{eff}}$	$\Lambda\text{CDM} + N_{\text{eff}}^{\delta\phi}$	$\Lambda\text{CDM} + N_{\text{eff}} + N_{\text{eff}}^{\delta\phi}$		$\Lambda\text{CDM} + N_{\text{eff}} + N_{\text{eff}}^{\delta\phi} + Y_p$	
	$\sigma(N_{\text{eff}})$	$\sigma(N_{\text{eff}}^{\delta\phi})$	$\sigma(N_{\text{eff}})$	$\sigma(N_{\text{eff}}^{\delta\phi})$	$\sigma(N_{\text{eff}})$	$\sigma(N_{\text{eff}}^{\delta\phi})$
SO	0.054	0.13	0.054	0.14	0.29	0.14
CMB-S4	0.030	0.078	0.031	0.080	0.20	0.080
CVL	0.012	0.046	0.012	0.048	0.094	0.048

- Delensed (Fisher) forecasts.
- SO: Baseline configuration with 40% of the sky.
- CMB-S4: Restricted to S4-wide survey with noise curves for 62% of the sky .
- CVL: $f_{\text{sky}} = 0.75$ and $\ell \leq 5000$

GM, Wallisch & Freese (2025)

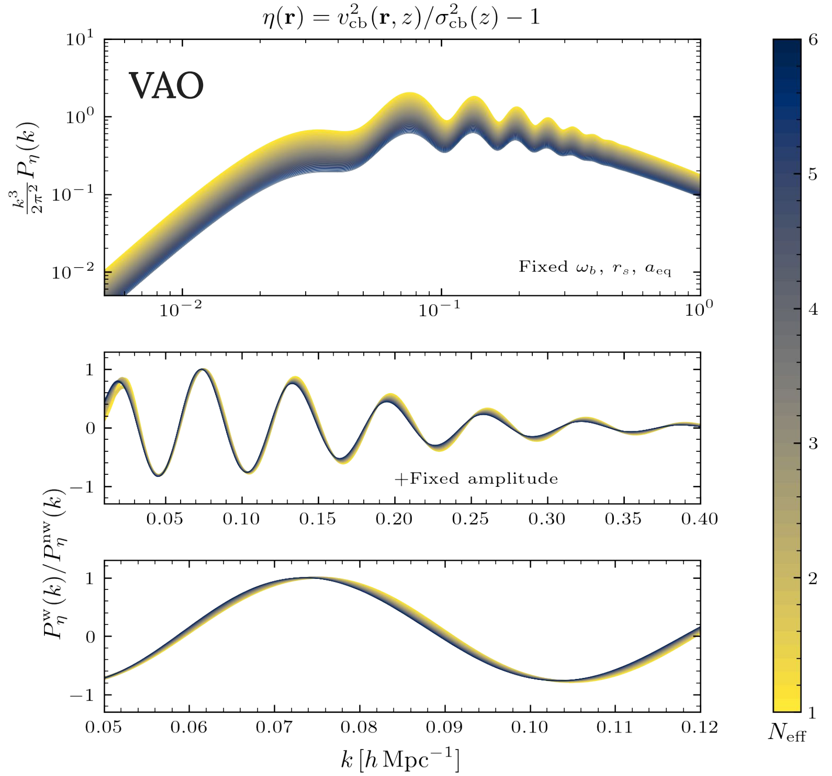
Summary

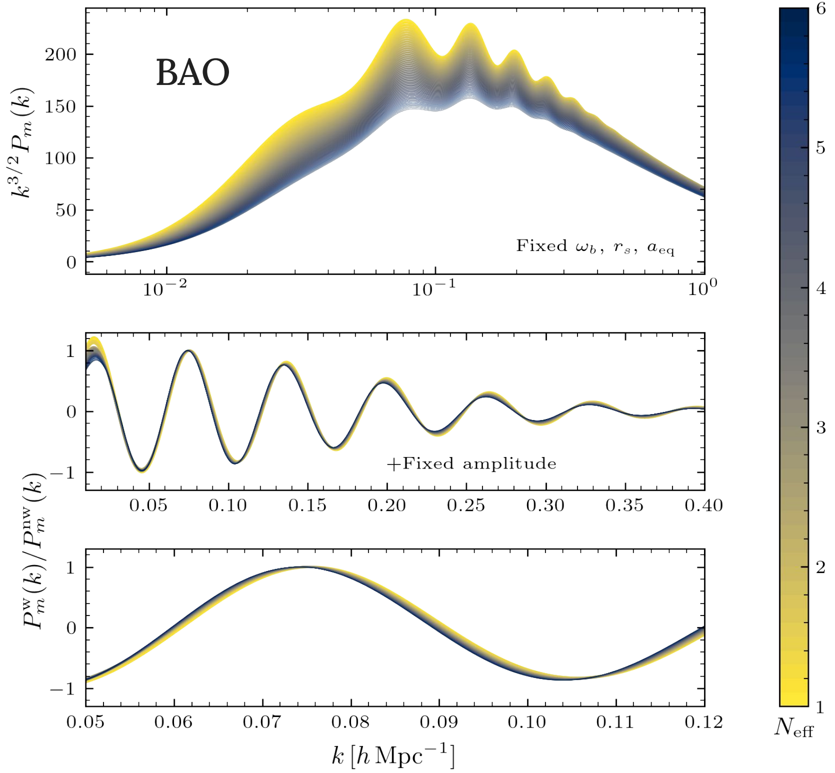
- The **phase shift** is a robust probe of **free-streaming relativistic species**
  - Implications for neutrinos and physics beyond the Standard Model
- Two different model-agnostic and signature-driven approaches:
  - Spectrum-based Template
  - Perturbation-based Template
- **High-significance detection** of free-streaming neutrinos
- Current data are **compatible** with the three **Standard Model** neutrinos
- Upcoming CMB experiments will tighten constraints on the phase shift, reducing uncertainties to about 6% and 3% for SO and CMB-S4, respectively.

Future Directions

The Phase Shift in the 21cm line

VERY PRELIMINARY



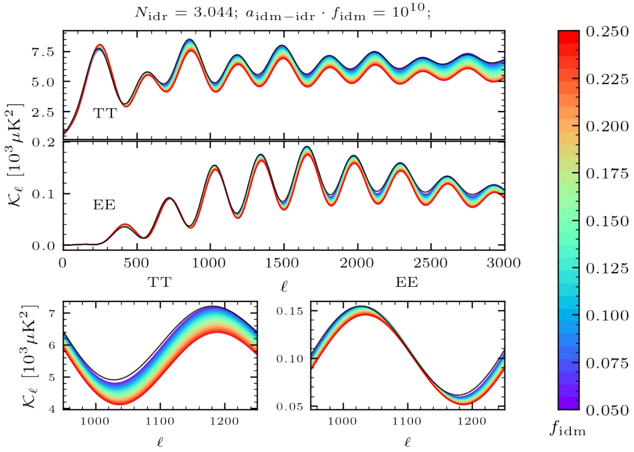


with Julian Muñoz and Ely Kovetz

Future Directions

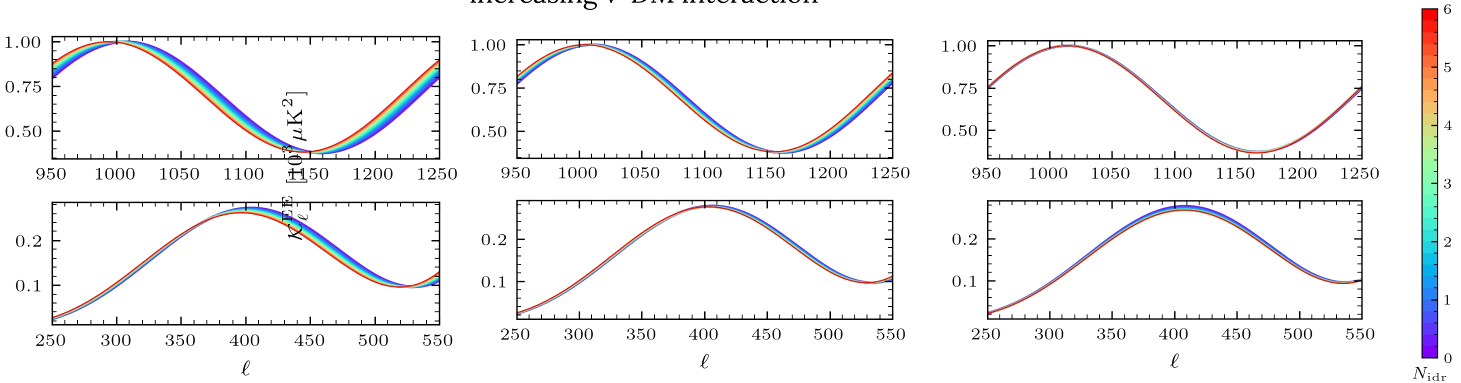
The Phase Shift from ν-DM interactions

DM-loading



Delayed ν-decoupling

increasing ν-DM interaction



with Subhajit Ghosh

Summary

Grazie per l’attenzione!

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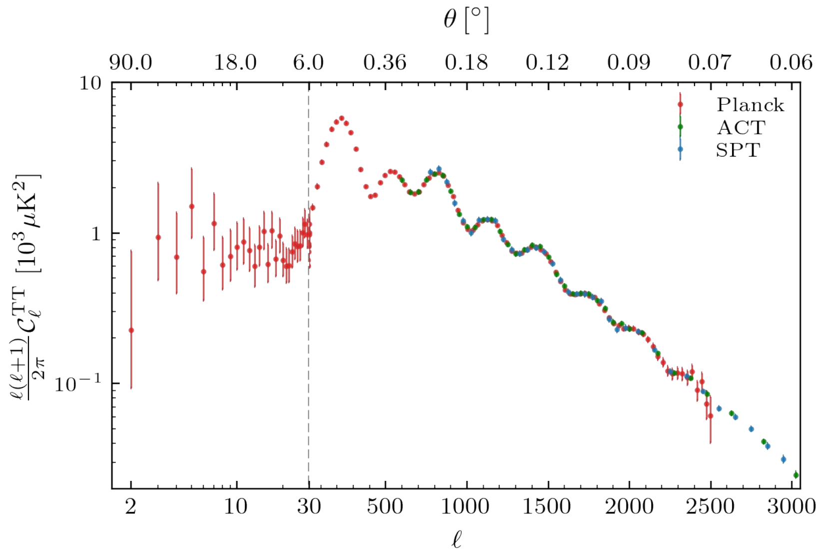
Back-up Slides

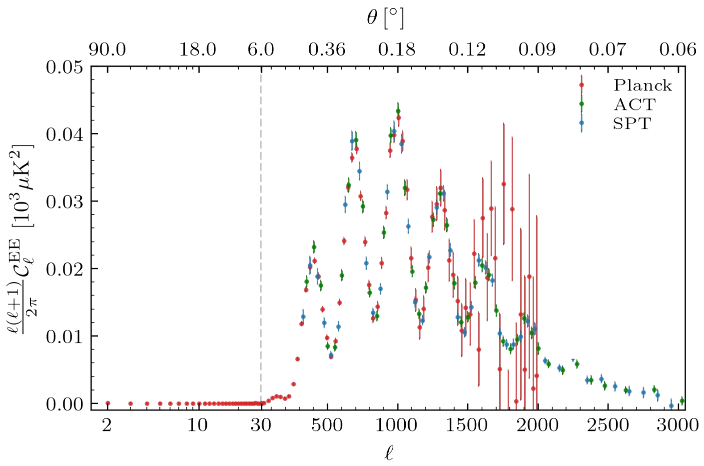
Gabriele Montefalcone
Weinberg Institute for Theoretical Physics, University of Texas at Austin

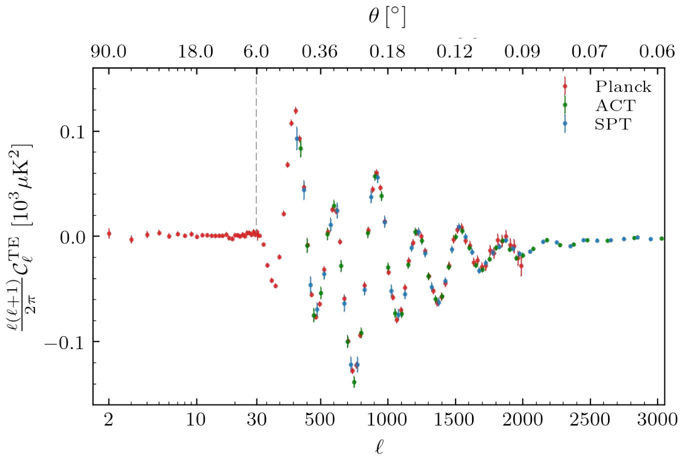
The CMB Power Spectra

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



Polarization spectrum traces **velocity** perturbations

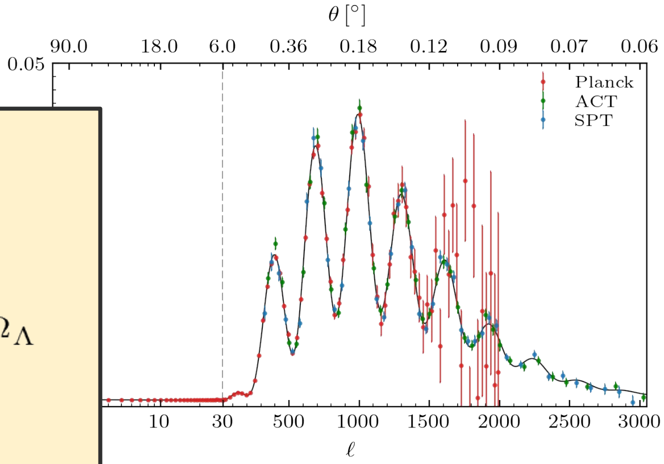




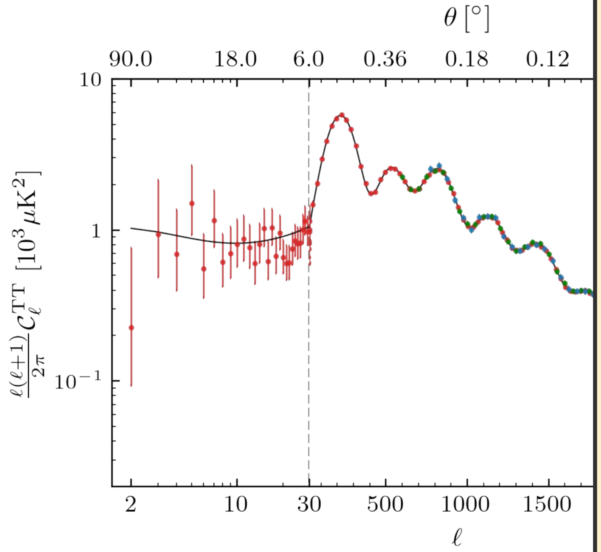
TE spectrum roughly tells us how the plasma is moving into the gravitational potential wells

The CMB Power Spectra

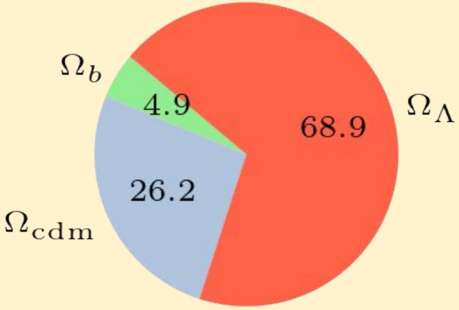
Polarization spectrum traces **velocity** perturbations



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



TE spectrum roughly
moving into the gravit



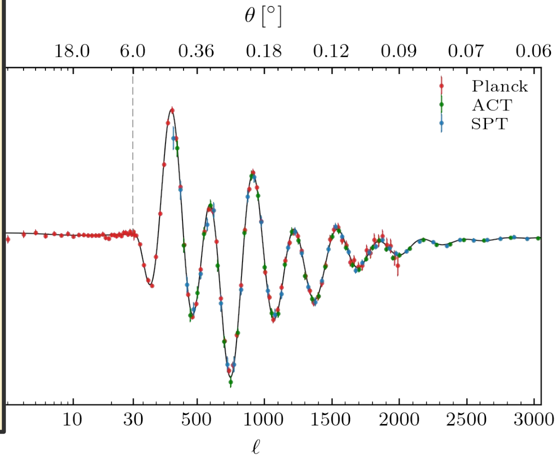
$$\ln\left(10^{10}A_s\right) = 3.045$$

$$n_s = 0.965$$

$$\tau_{\rm reio} = 0.054$$

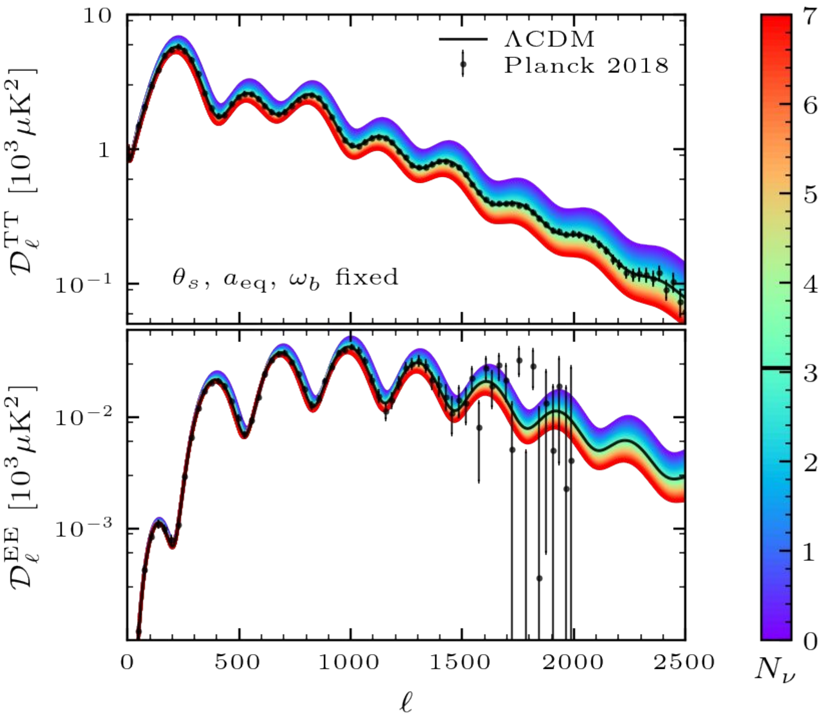
+ SM neutrinos $N_{\rm eff} = 3.044$

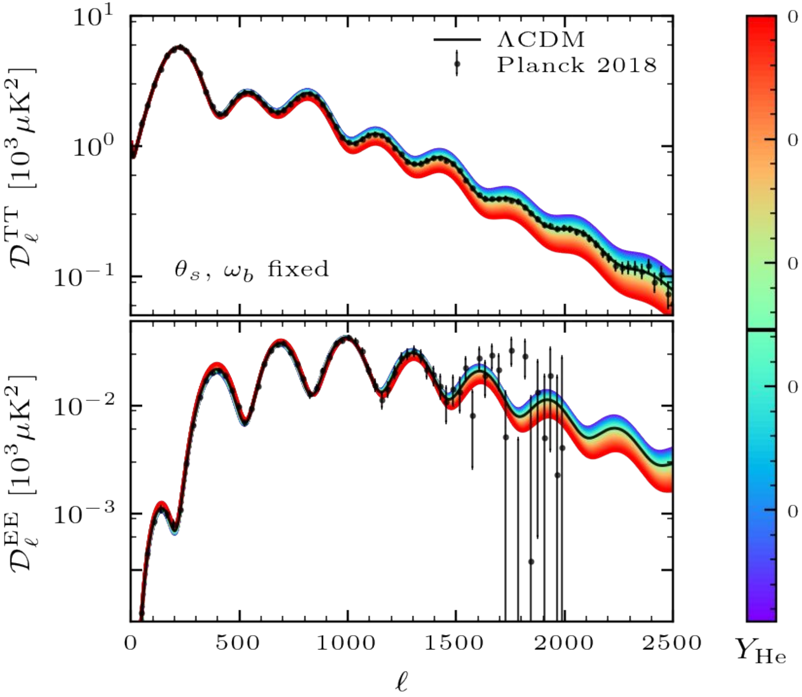
+ ...



Cosmic neutrinos in the CMB
energy density

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

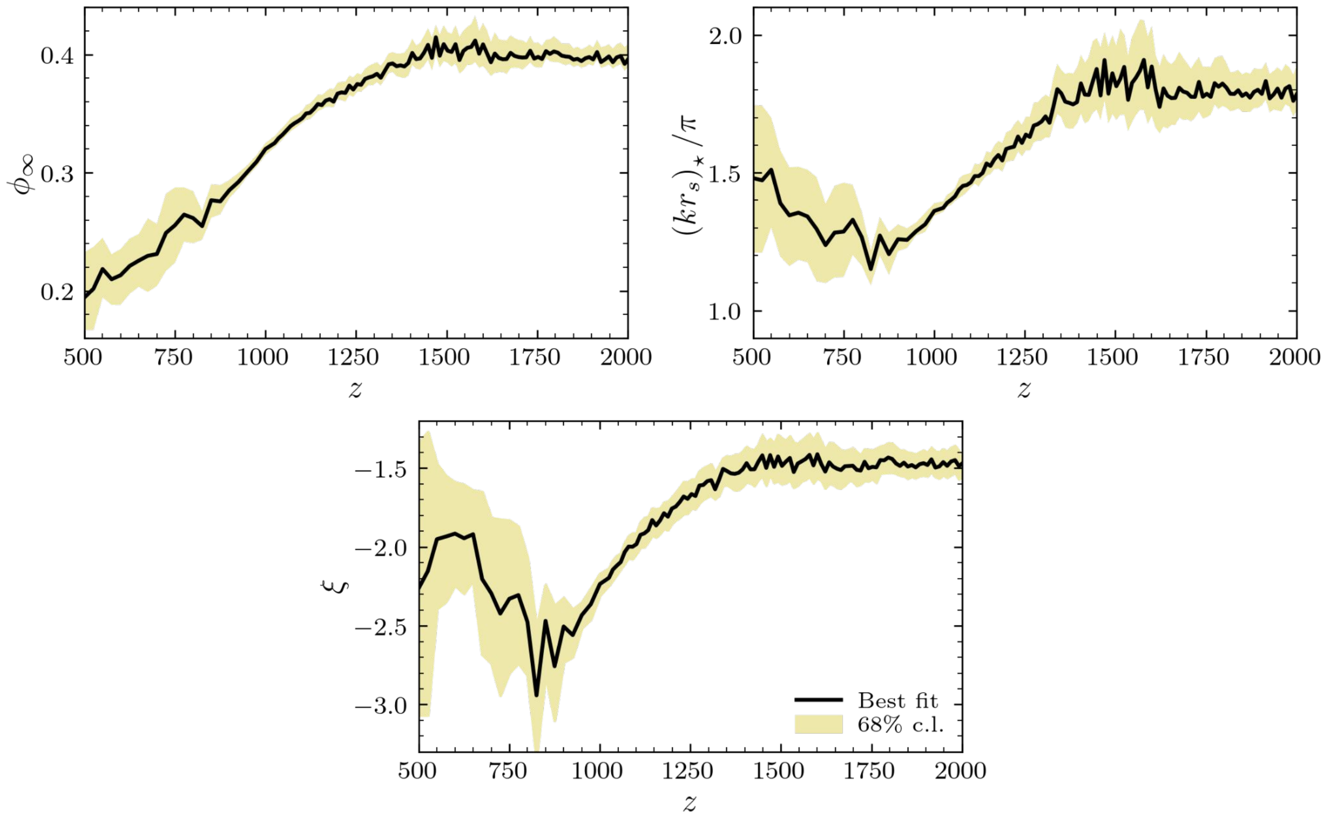




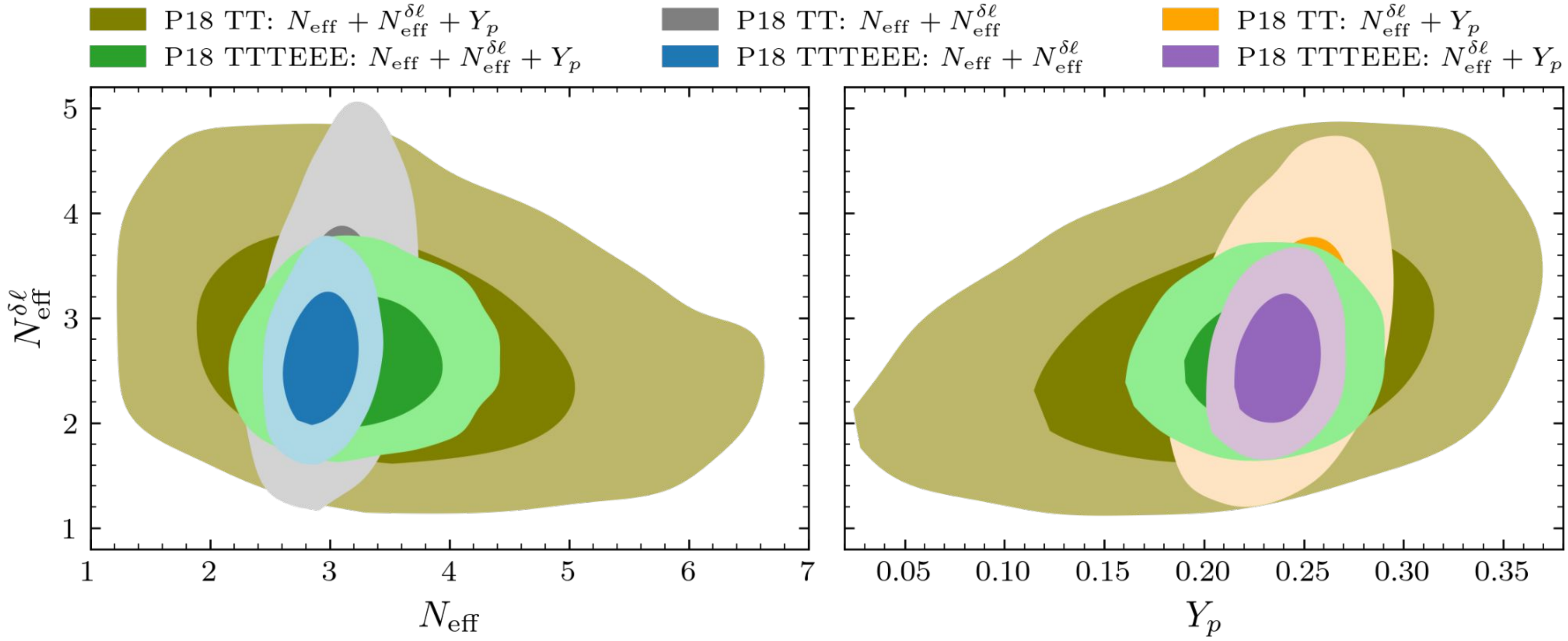
Degeneracy with primordial Helium fraction $\mathbf{Y_{He}}$ via $\mathbf{n_e}$

The Phase shift in the Perturbations

Details on the template extraction



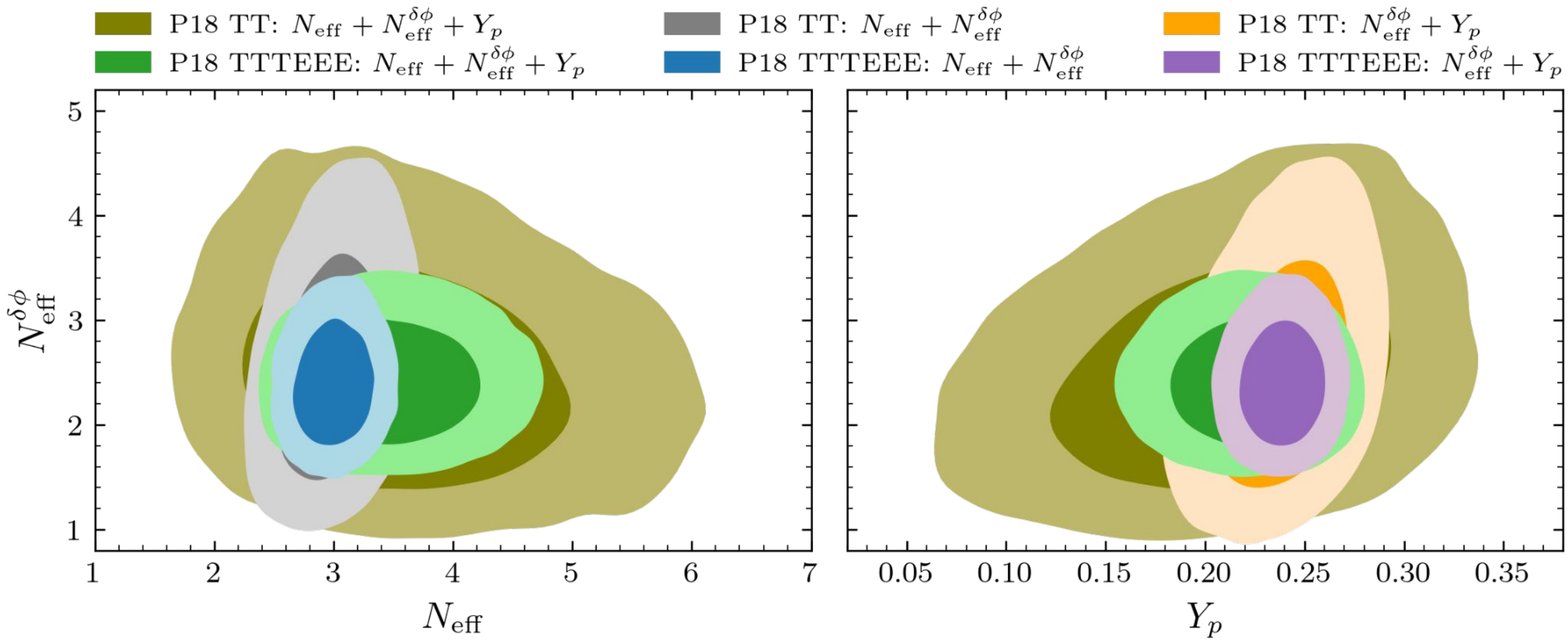
Phase Shift Constraints from CMB Data
Spectrum-Based Analysis



GM, Wallisch & Freese (2025)

Phase Shift Constraints from CMB Data

Perturbation-Based Analysis



GM, Wallisch & Freese (2025)