September 4th 2025

Mitchell Institute for Fundamental Physics & Astronomy
Texas A&M University
College Station, TX

Probing Cosmic Neutrinos & Free-Streaming Radiation with the CMB

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

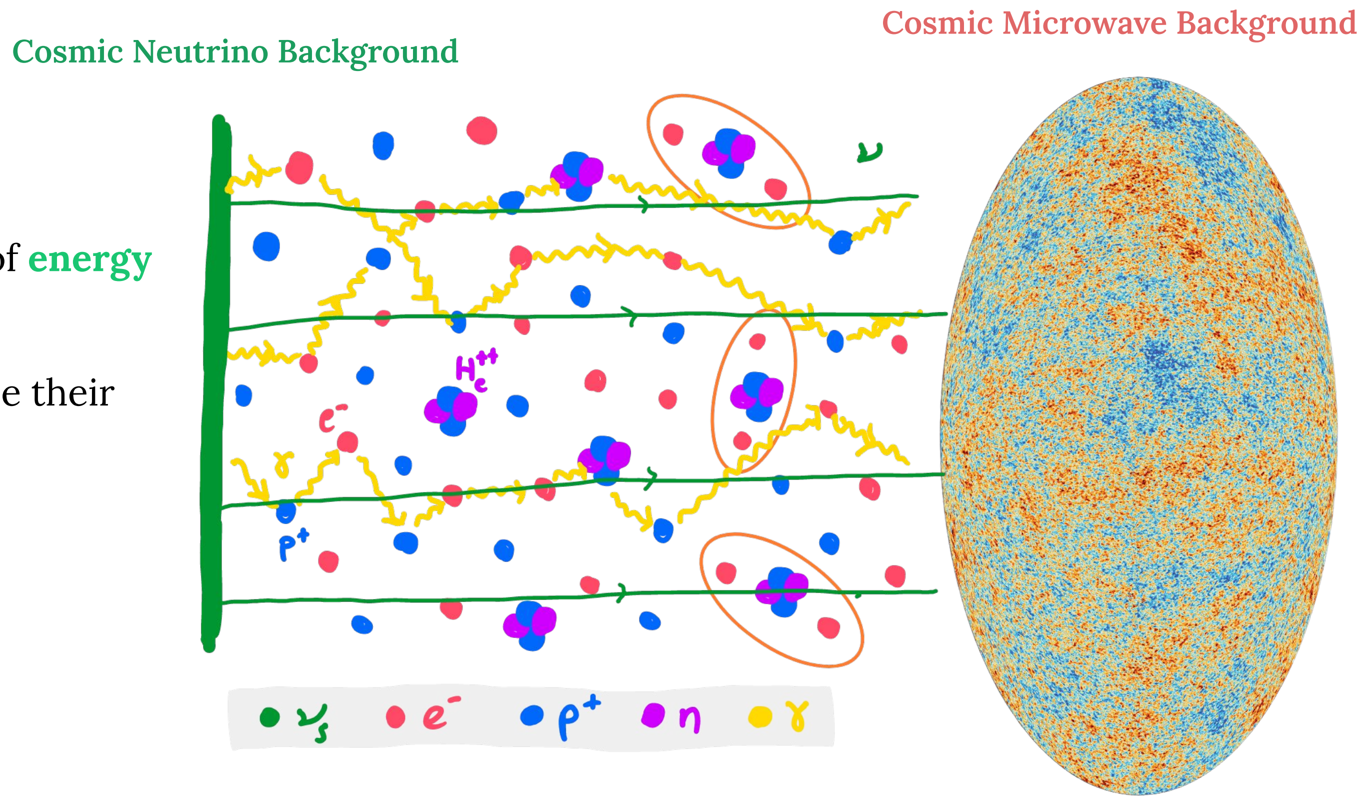
Based on
2501.13788 with Benjamin Wallisch and Katherine Freese
2509.xxxxx with Subhajit Ghosh, Kimberly Boddy, Daven Wei Ren Ho and Yuhsin Tsai
2509.xxxxx (tonight!) with Hector Cruz , Julian Muñoz , Ely Kovetz and Marc Kamionkowski

TEXAS
The University of Texas at Austin

Neutrinos & the CMB

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

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



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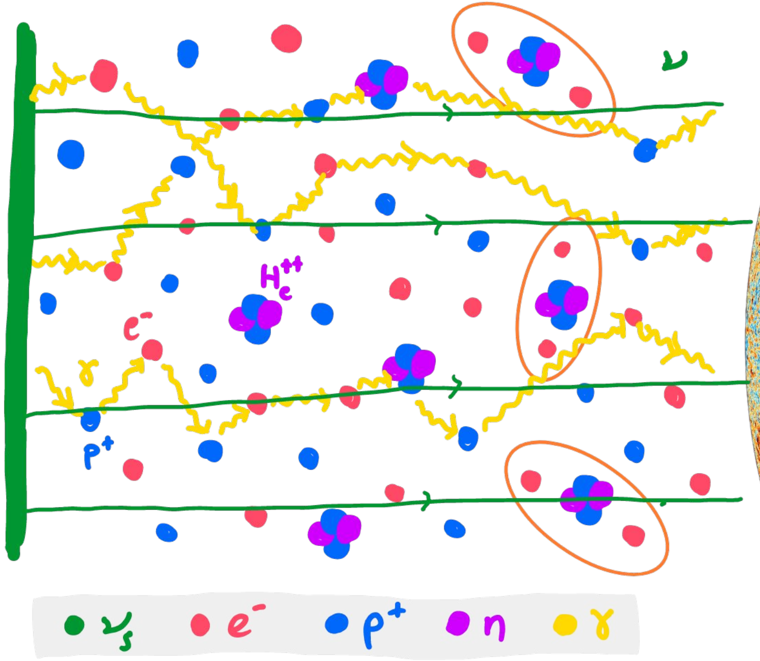
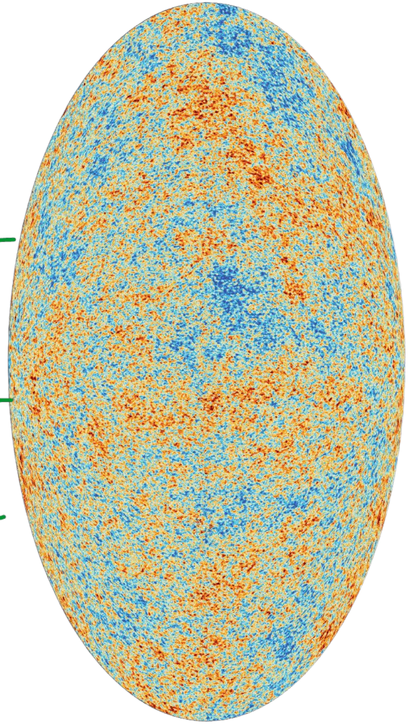
- **Free-streaming** since their decoupling at **t~1 s**

Can we detect this?

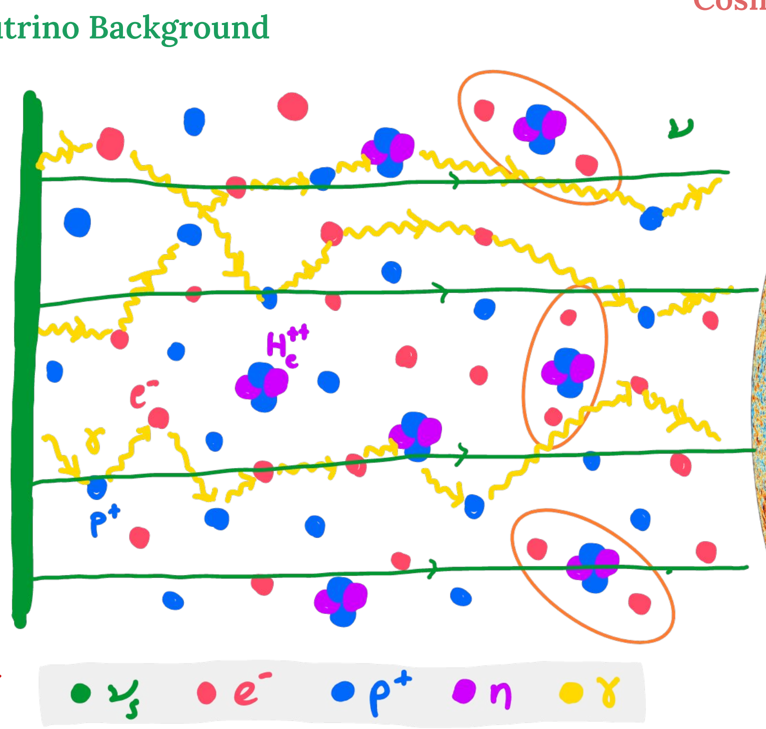
Cosmic Neutrino Background

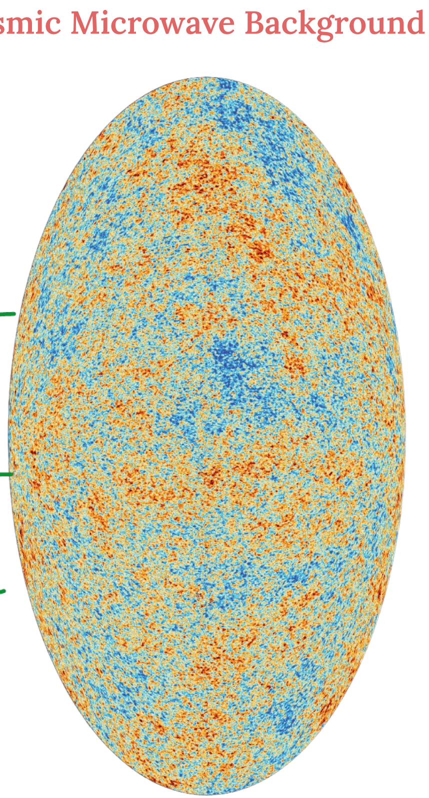


Cosmic Microwave Background



Neutrinos & the CMB





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

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

Can we detect this?

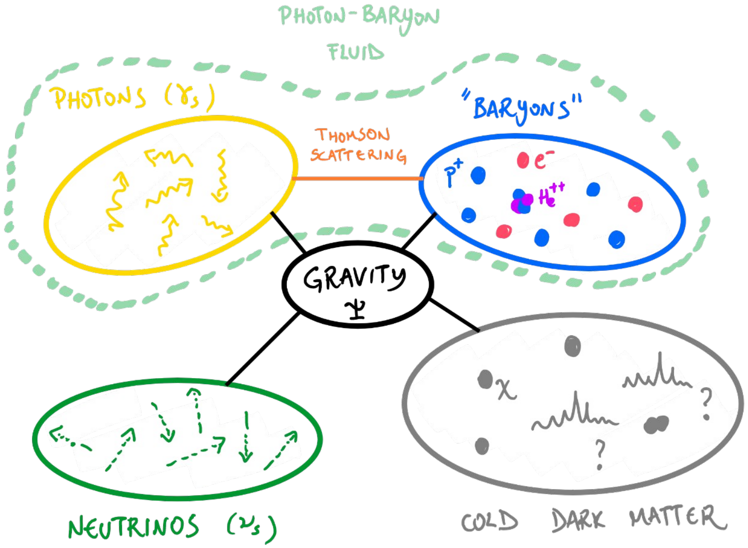
- Neutrino masses $\mathbf{m}_\nu$?
  no detection but **unimportant** in the early universe
  (See Zach's talk!)

Outline

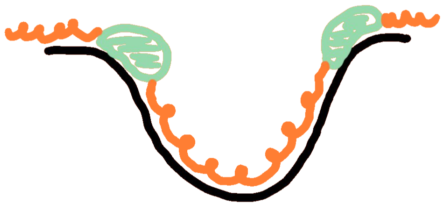
1. Cosmic Sound Waves and Neutrinos in the CMB
2. The Phase Shift in the CMB and Perturbation Spectra
3. CMB Data Analysis and Forecasts
4. The Phase Shift in Realistic Neutrino Interaction Scenarios
5. Direct CMB Constraints on Neutrino Decoupling
6. Summary & Future Directions

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



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

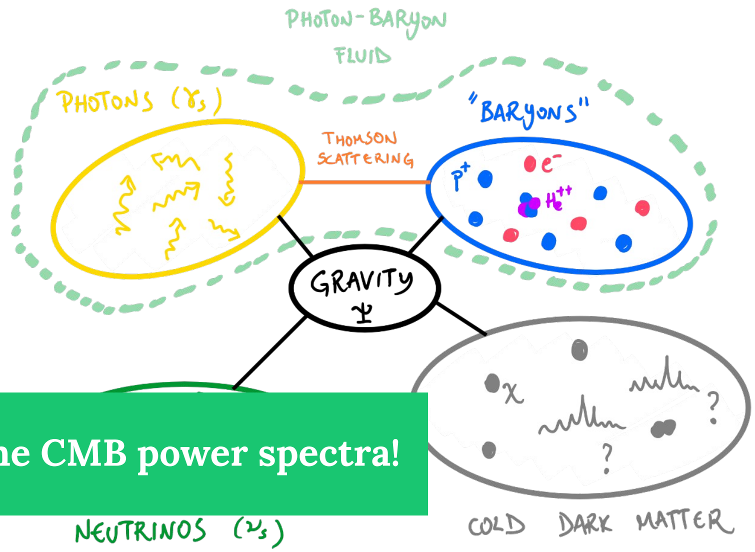


$$\delta_\gamma \sim \underbrace{A_{\vec{k}}}_{\text{Initial condition (inflation)}} \cos(c_s k \tau),$$

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

Baryons add inertia to the fluid

Cosmic Sound Waves



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- Initial fluctuations excited sound waves in the primordial plasma
- **Gravity**
photon-

We observe these acoustic oscillations in the CMB power spectra!

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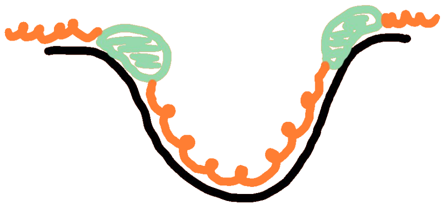

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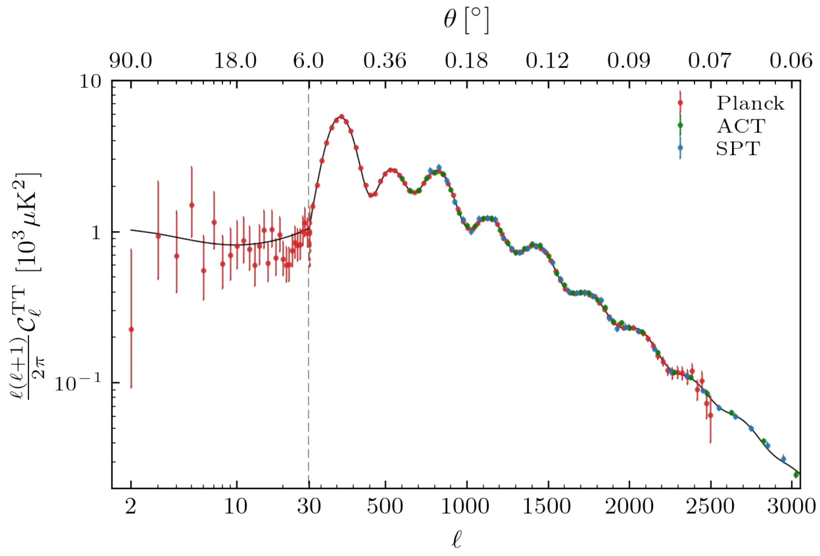
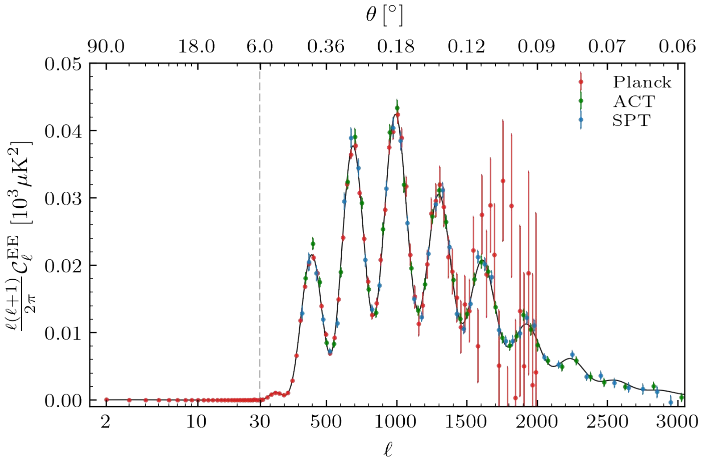
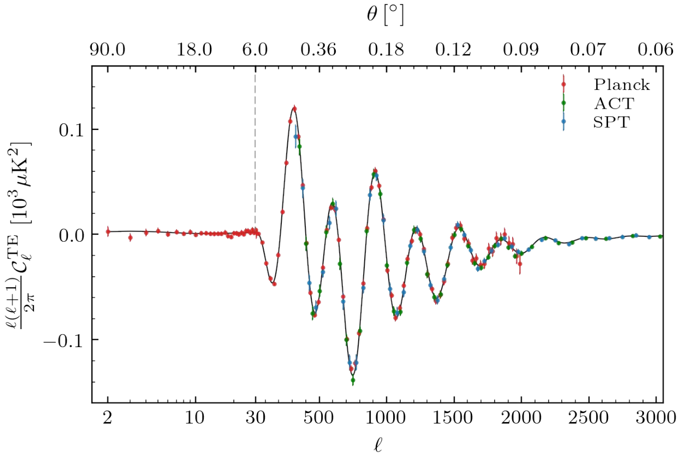
The CMB Power Spectra







We observe these acoustic oscillations in the CMB power spectra!

Cosmic Neutrinos

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

- 41% of the radiation density in the universe
- Parametrized by the observable **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

⟹ CMB measurements are **consistent with SM value** of **N_{eff}**

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

Planck 2018

$$\boxed{N_{\mathrm{eff}} = 2.81 \pm 0.12}$$

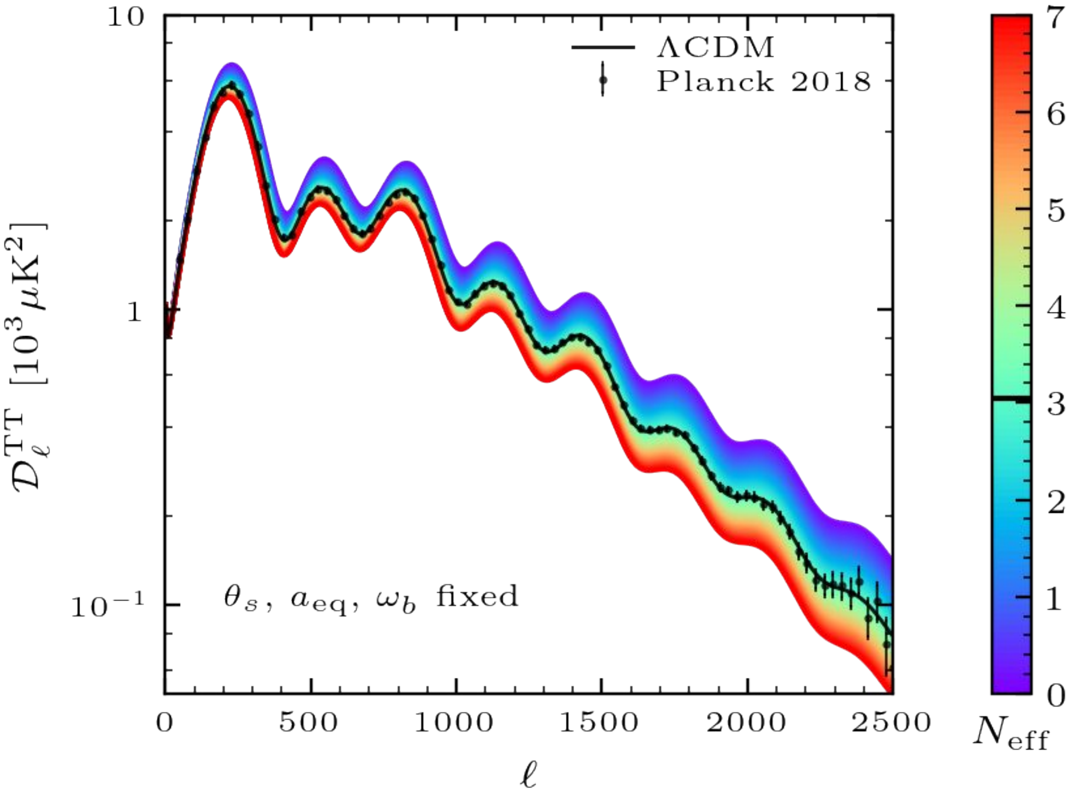
Planck 2018 + ACT DR6 + SPT 3G D1

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**

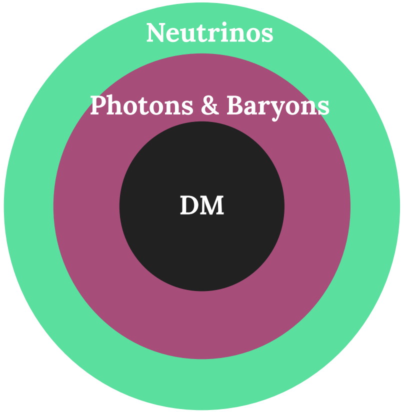


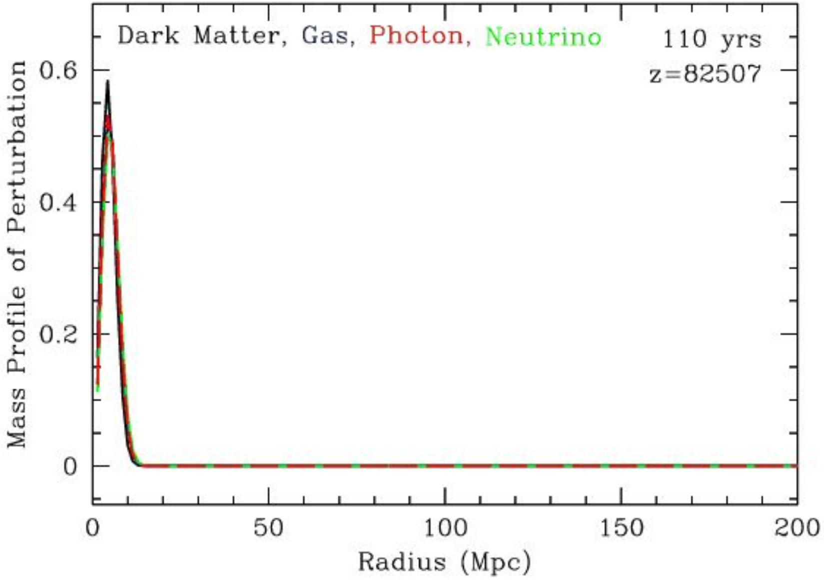
$$\mathcal{D}_\ell^{XY} \equiv \frac{\ell(\ell+1)}{2\pi}\mathcal{C}_\ell^{XY}$$

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

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

  Bashinsky & Seljak (2003)

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

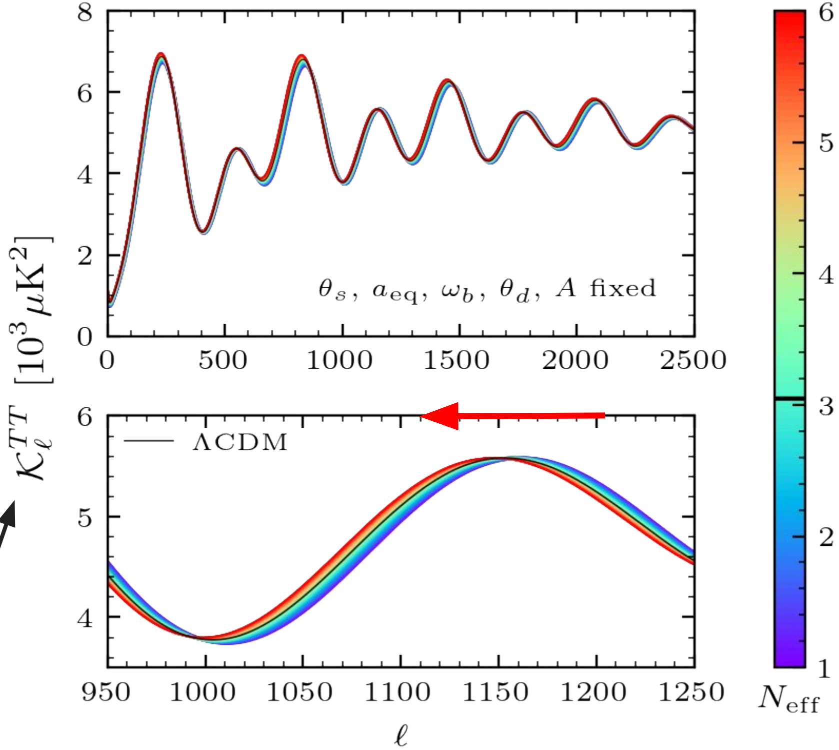
- Difficult to reproduce in the absence of **free-streaming**

  - 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

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



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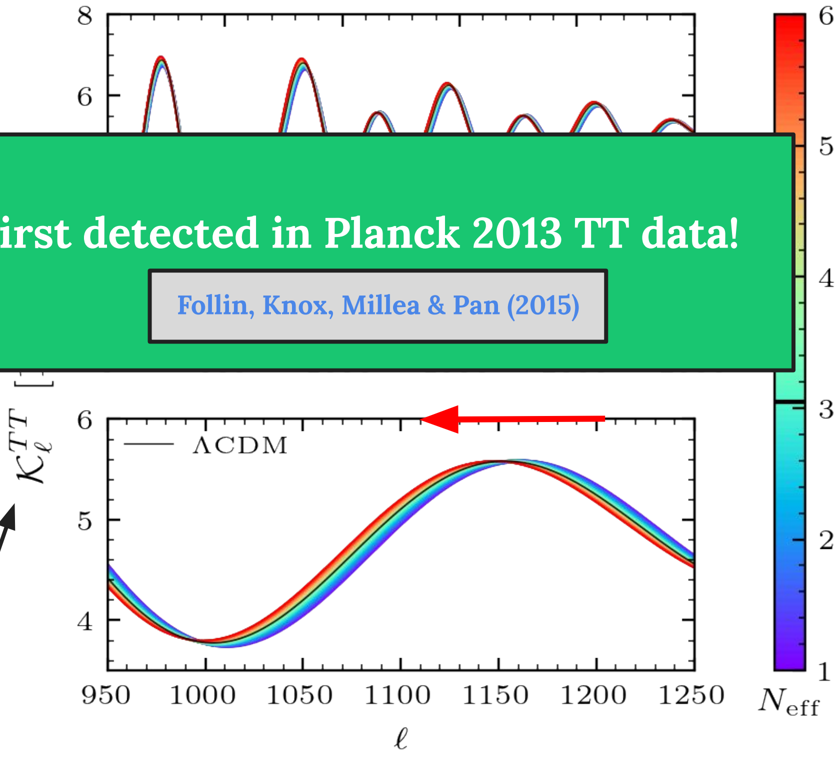


First detected in Planck 2013 TT data!

Follin, Knox, Millea & Pan (2015)

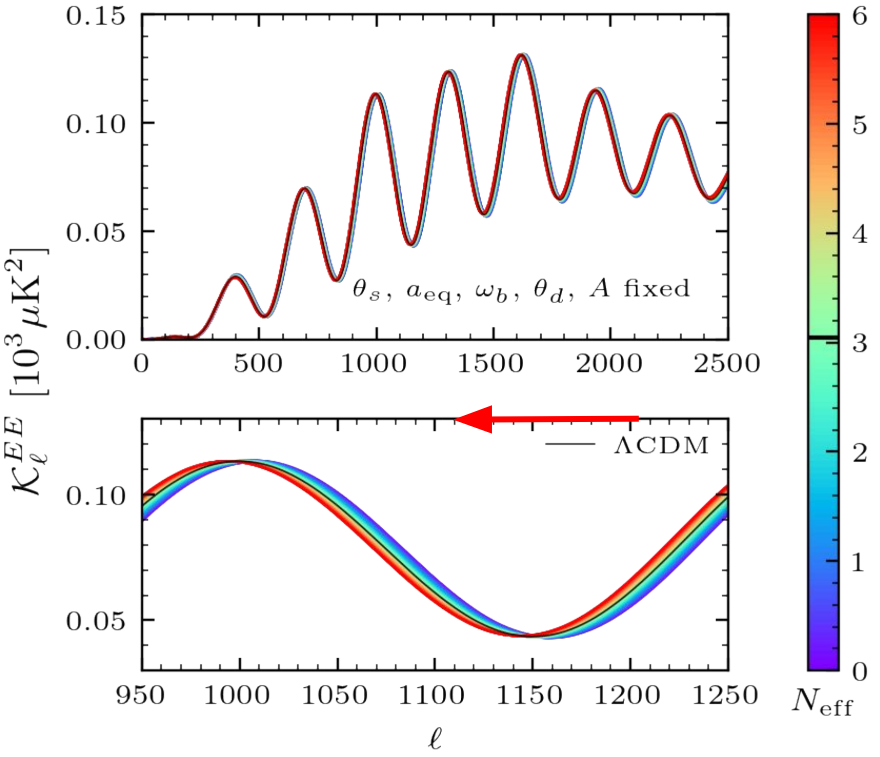
Cosmic Neutrinos in the CMB
Free-Streaming Nature

- Same shift both in temperature and polarization spectrum

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

  - polarization provides cleaner signal

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



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

Cosmic Neutrinos in the CMB
Extraction of the Multipole Shift Template

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

Multipole Dependence

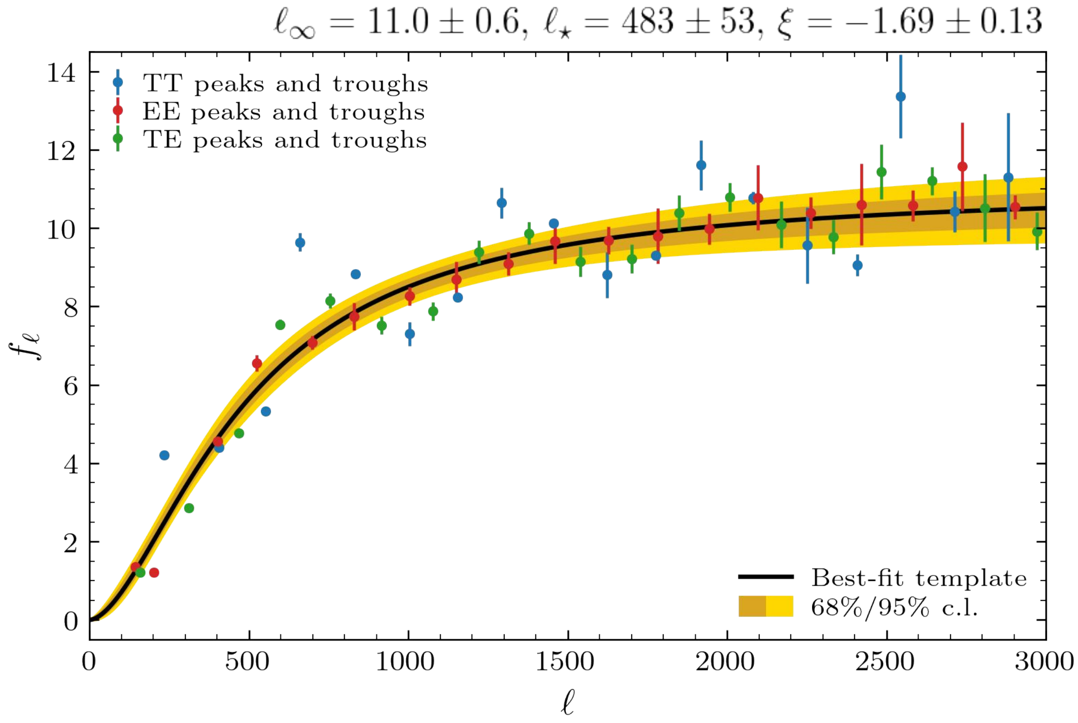
$$f_\ell = \frac{\ell_\infty}{1 + (\ell/\ell_\star)^\xi}$$

Normalized Amplitude

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

Our Contributions:

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



Following Follin, Knox, Millea & Pan (2015)

The Multipole Shift in the CMB Power Spectra

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

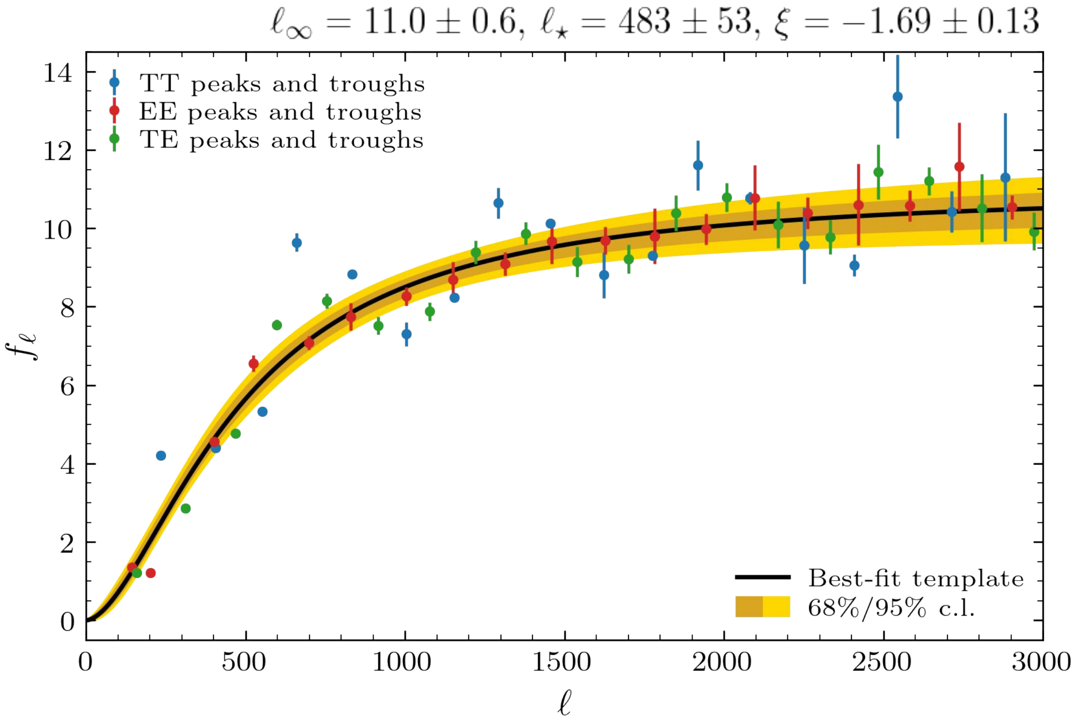
$$f_\ell = \frac{\ell_\infty}{1 + (\ell/\ell_\star)^\xi}$$

- A new parameter to control the shift

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

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

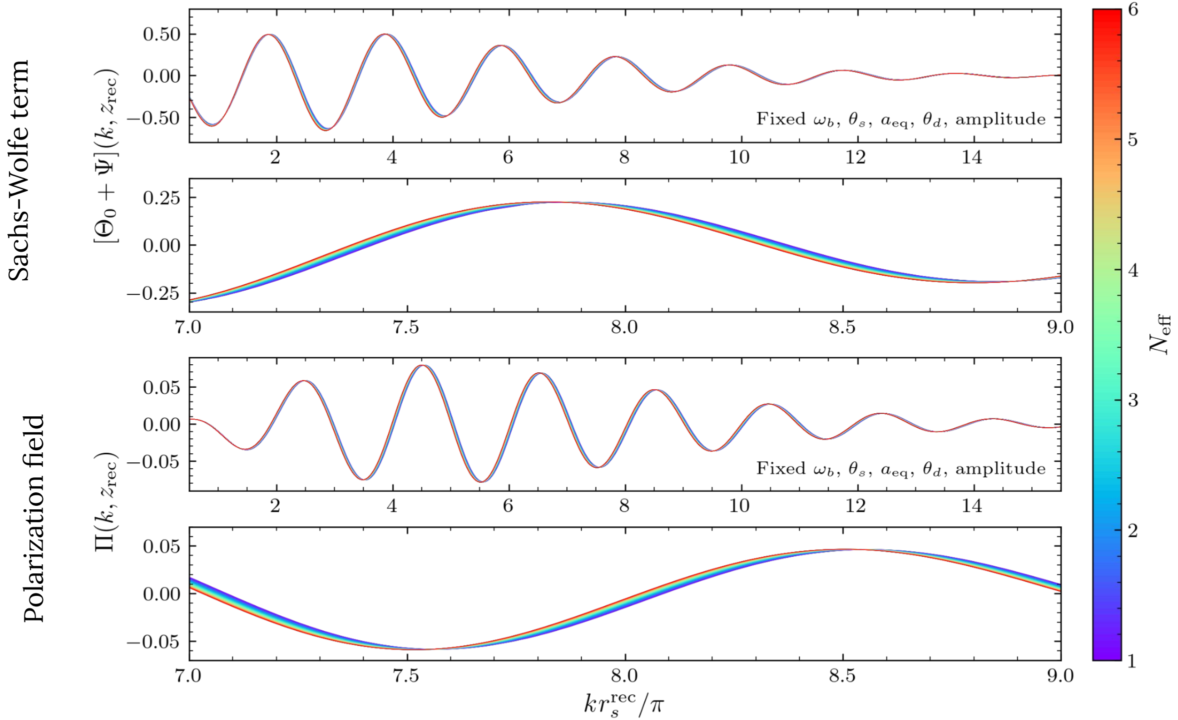
$$\mathcal{C}_\ell \to \mathcal{C}_{\ell+\Delta\ell}$$



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



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

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

GM, Wallisch & Freese (2025)

The Phase Shift in the Perturbations

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

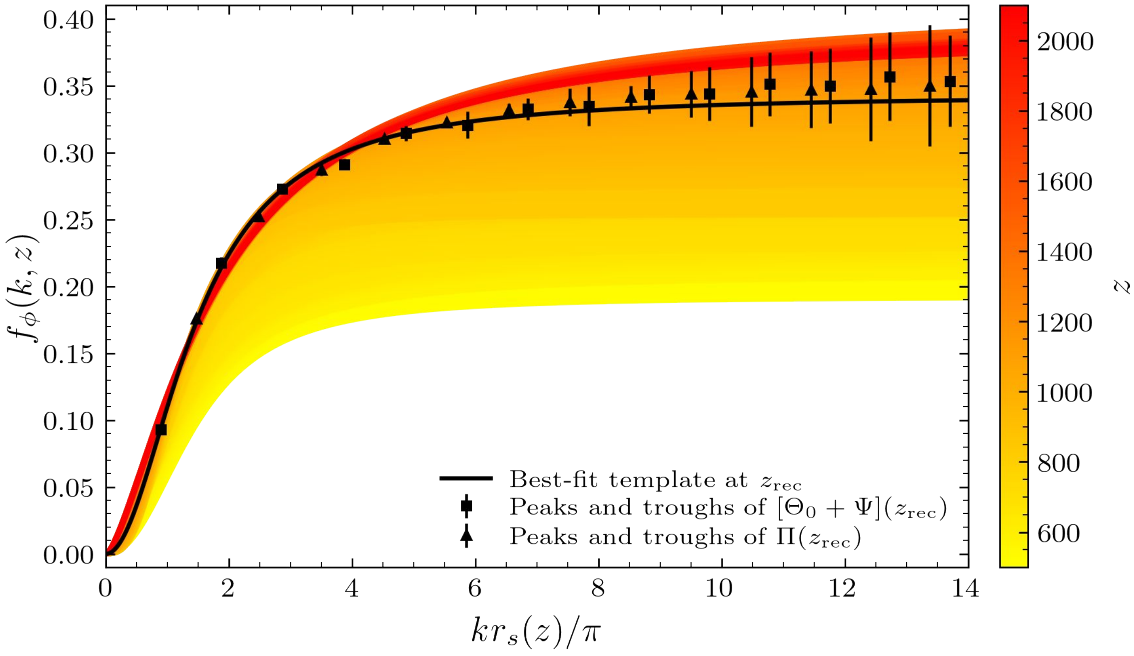
Determine the best-fit parameters in relevant redshift range.

Wavenumber and **Redshift** Dependence

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

Normalized Amplitude

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



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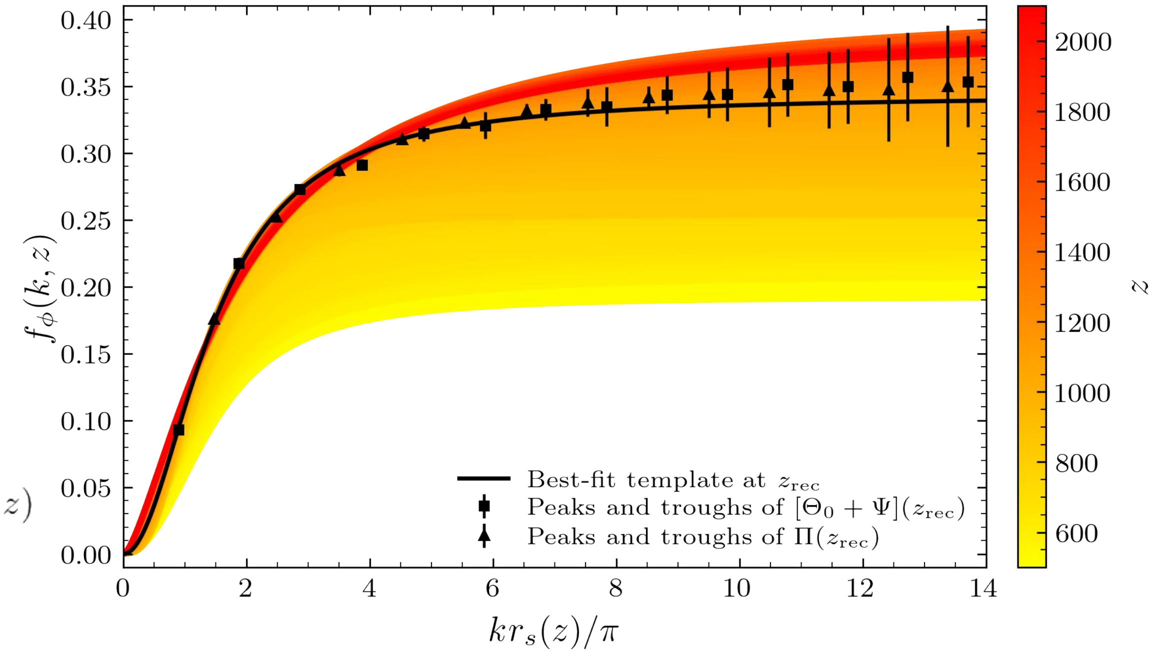
$$f_\phi(k, z) = \frac{\phi_\infty}{1 + [kr_s/(kr_s)_\star]^\xi}$$

- A new parameter to control the shift

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

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

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



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

GM, Wallisch & Freese (2025)

Measuring the Phase Shift with CMB Data
Two Independent Methods

A new parameter that *only* controls the size of the phase shift.

Spectrum-Based Method

Directly in the CMB spectra

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

→ Imprints **multipole** shift

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

in the spectra:

$$C_\ell \to C_{\ell+\Delta\ell}$$

Perturbation-Based Method

Directly in the perturbations

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

→ Imprints **k-mode** shift

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

in the source functions:

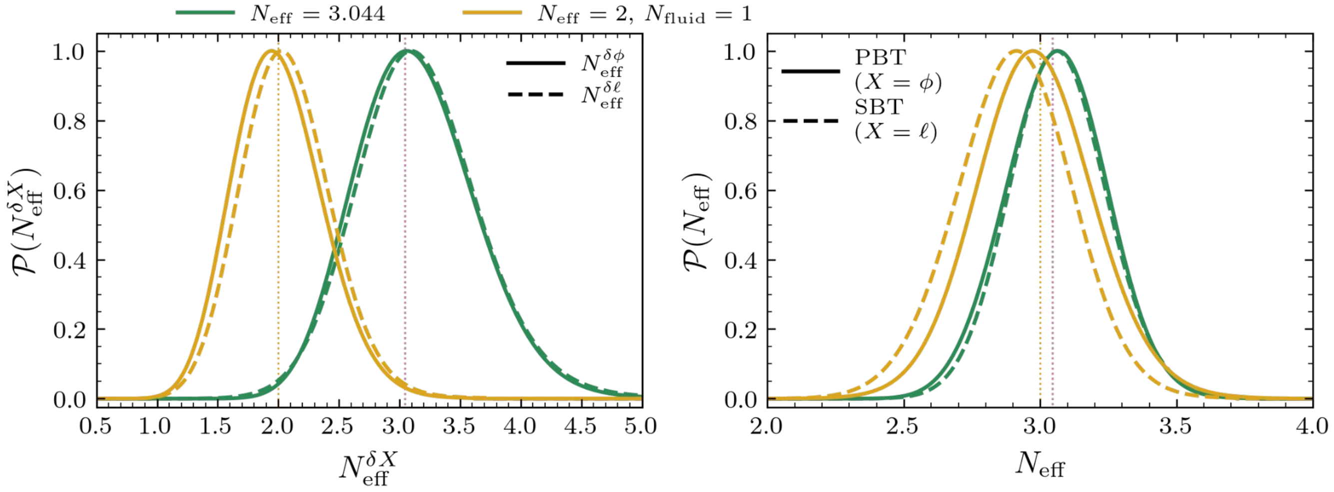
$$S_X(k, z) \to S_X(k + \Delta\phi/r_s, z)$$

→ Results in the observed signature in the CMB spectra.

GM, Wallisch & Freese (2025)

Validation of Phase Shift Extraction
Warm Up with Planck-like Mock Data

- We recover the imprinted phase shift by standard model neutrinos.
- We can *robustly isolate* the induced phase shift by *free-streaming radiation.*



The spectrum and perturbation based approach yield consistent results

GM, Wallisch & Freese (2025)

Phase Shift Constraints from CMB Data
Perturbation-Based Analysis

- Based on Planck 2013 temperature only:

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

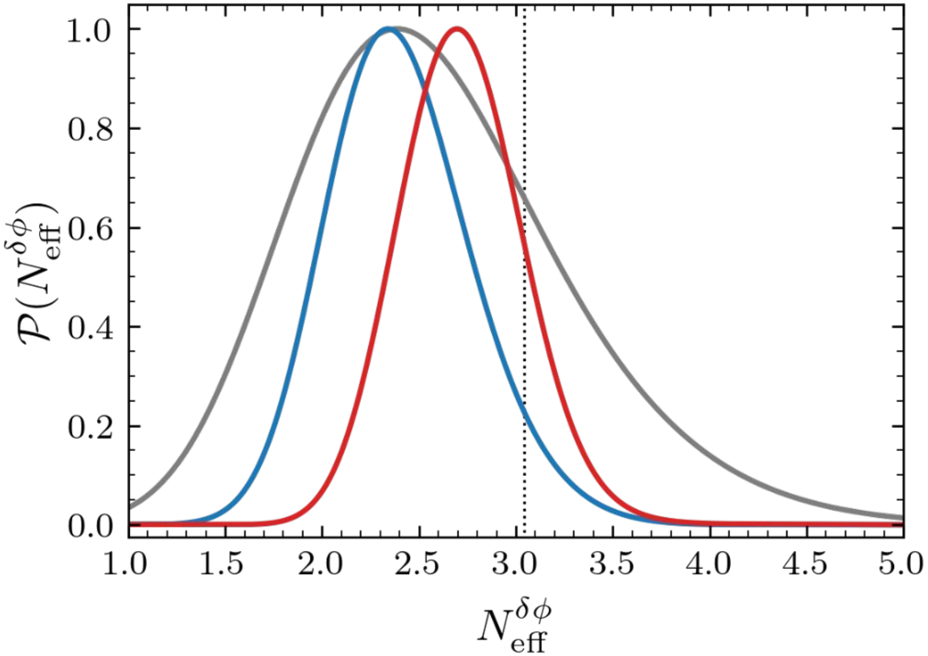
$(\, N_{\rm eff} = N_\nu = 3.044 \,)$

- Current Data:
  - Planck 2018 TT only: $N_{\rm eff}^{\delta\phi} = 2.6^{+0.7}_{-0.6}$
  - Including polarization:

Planck 2018: $N_{\rm eff}^{\delta\phi} = 2.3^{+0.4}_{-0.4}$

+ ACT + SPT: $N_{\rm eff}^{\delta\phi} = 2.7^{+0.3}_{-0.3}$

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

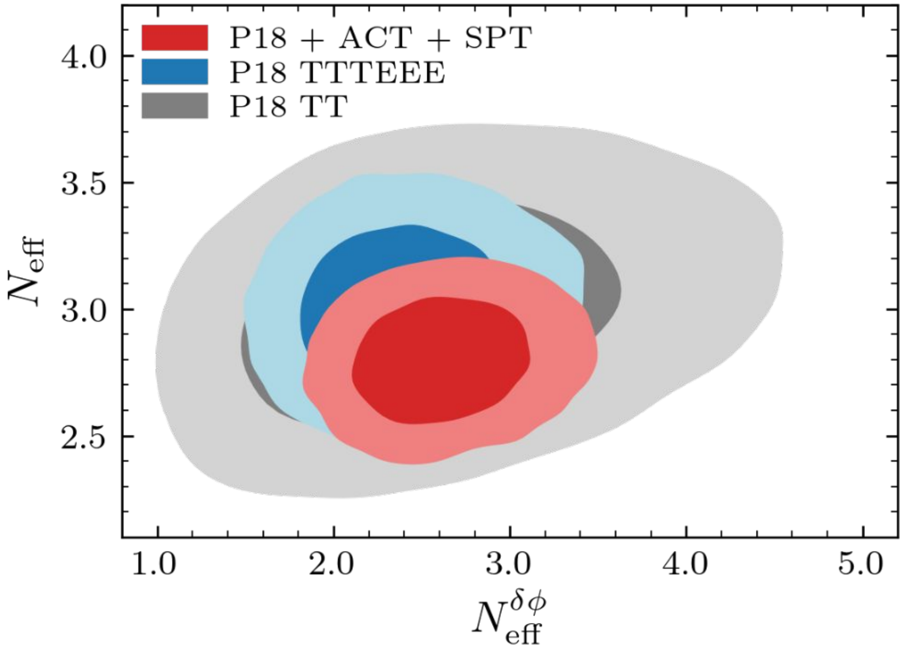


GM, Wallisch & Freese (2025)

Phase Shift Constraints from CMB Data
Perturbation-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 Forecasts

	$\Lambda\mathrm{CDM} + N_{\mathrm{eff}}$	$\Lambda\mathrm{CDM} + N_{\mathrm{eff}}^{\delta\phi}$	$\Lambda\mathrm{CDM} + N_{\mathrm{eff}} + N_{\mathrm{eff}}^{\delta\phi}$		$\Lambda\mathrm{CDM} + N_{\mathrm{eff}} + N_{\mathrm{eff}}^{\delta\phi} + Y_p$	
	$\sigma(N_{\mathrm{eff}})$	$\sigma(N_{\mathrm{eff}}^{\delta\phi})$	$\sigma(N_{\mathrm{eff}})$	$\sigma(N_{\mathrm{eff}}^{\delta\phi})$	$\sigma(N_{\mathrm{eff}})$	$\sigma(N_{\mathrm{eff}}^{\delta\phi})$
SO	0.054	$\boxed{0.13}$	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: $f_{\mathrm{sky}} = 0.75$ 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.

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:

Can we use these phase-shift measurements to directly probe BSM neutrino physics?

- **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.

Neutrino Self-Interactions
A Representative Example

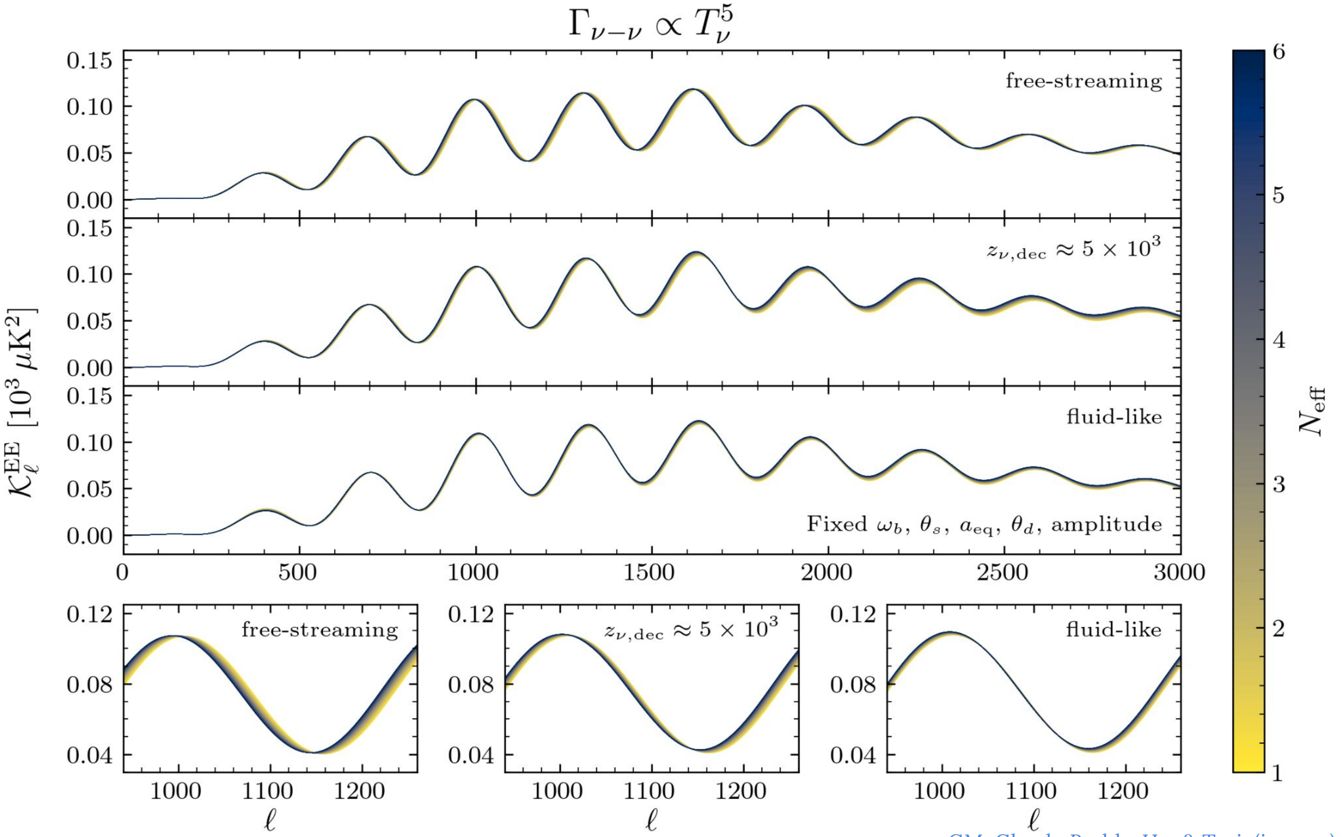
$$\Gamma_{\nu-\nu} = G_{\text{eff}}^2 T_\nu^5$$

$$\mathcal{L}_{\text{int}} \supset \frac{1}{2} G_{\text{eff}} \left(\overline{\nu}\nu\right)\left(\overline{\nu}\nu\right)$$

Kreisch, Cyr-Racine & Dor´ (2019)

Delaying neutrino decoupling **decreases** the size of the imprinted phase shift

$$\Gamma_{\nu-\nu}(G_{\text{eff}}, z_{\nu,\text{dec}})/H(z_{\nu,\text{dec}}) = 1$$



GM, Ghosh, Boddy, Ho & Tsai (in prep)

Neutrino Self-Interactions
A Representative Example

Delaying neutrino decoupling **decreases** the size of the imprinted phase shift

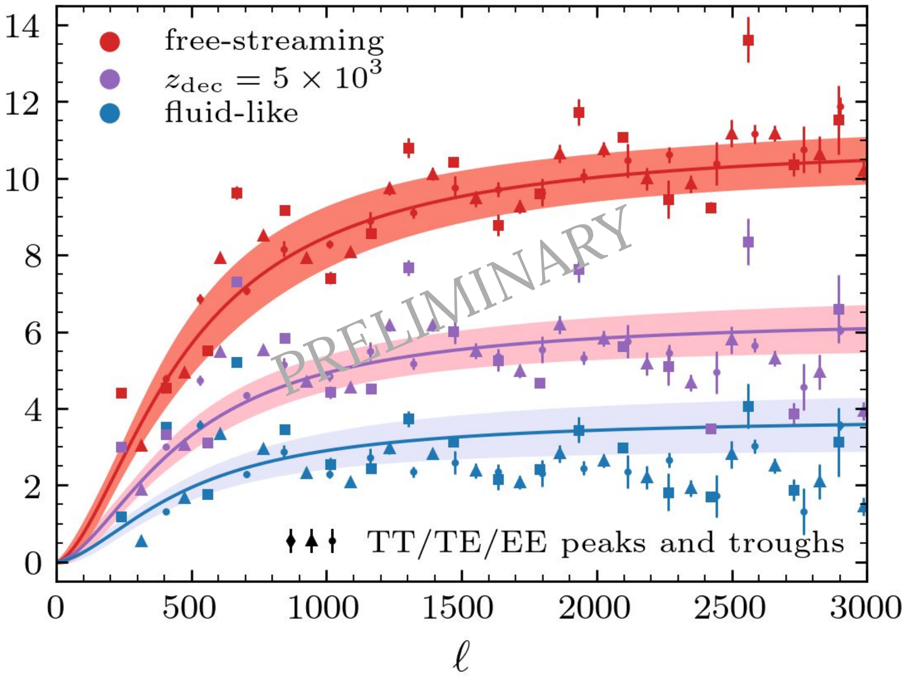
- Well approximated by an **amplitude offset** relative to the free-streaming template

$$f_\ell = \frac{\ell_\infty}{1+(\ell/\ell_\star)^\xi} = f_\ell^{\mathrm{SM}\nu} \times \mathcal{A}_\infty$$

$$\mathcal{A}_\infty \equiv \ell_\infty / \ell_\infty^{\mathrm{SM}\nu}$$ (Asymptotic Amplitude Ratio)

- **No additional multipole dependence** in contrast to expectations from instantaneous decoupling approximation

$\delta\ell(N_{\mathrm{eff}}) = A(N_{\mathrm{eff}})\, f_\ell$ $\Gamma_{\nu-\nu} \propto T_\nu^5$



GM, Ghosh, Boddy, Ho & Tsai (in prep)

Neutrino Self-Interactions
A Representative Example

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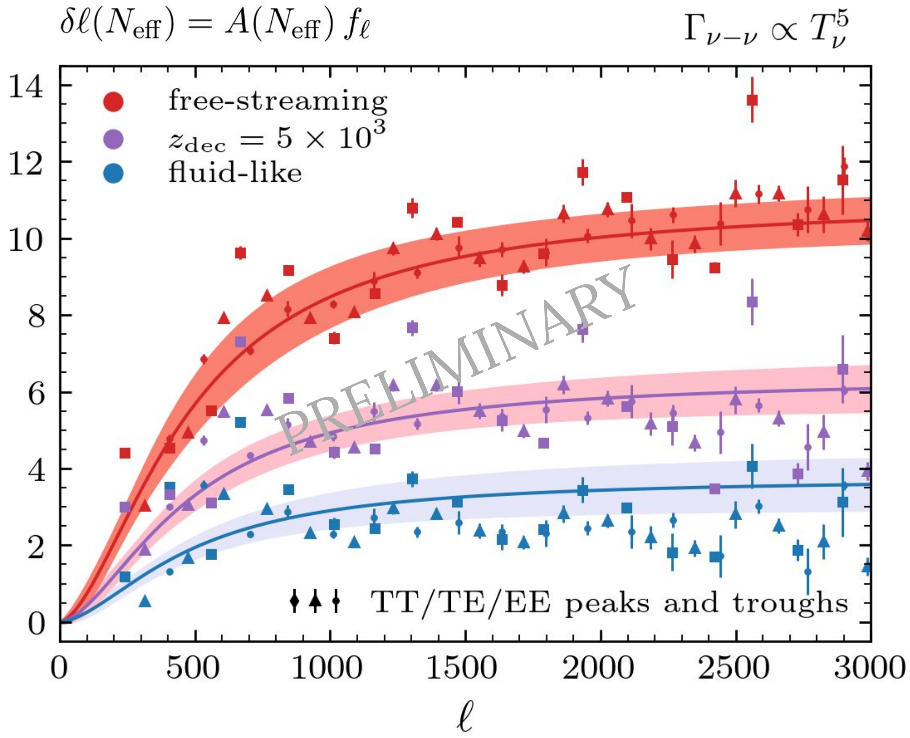
$$\mathcal{A}_\infty \equiv \ell_\infty / \ell_\infty^{\mathrm{SM}\nu}$$ (Asymptotic Amplitude Ratio)

- The **stronger** the interaction, the **smaller** the **propagation speed** of neutrino perturbations and the induced phase shift

$$c_{s,\mathrm{int}\nu} \in [c/\sqrt{3}, c]$$

$$c_{s,\mathrm{int}\nu} > c_{s,\gamma} \equiv c/\sqrt{3\,[1+3\rho_b/(4\rho_\gamma)]}$$



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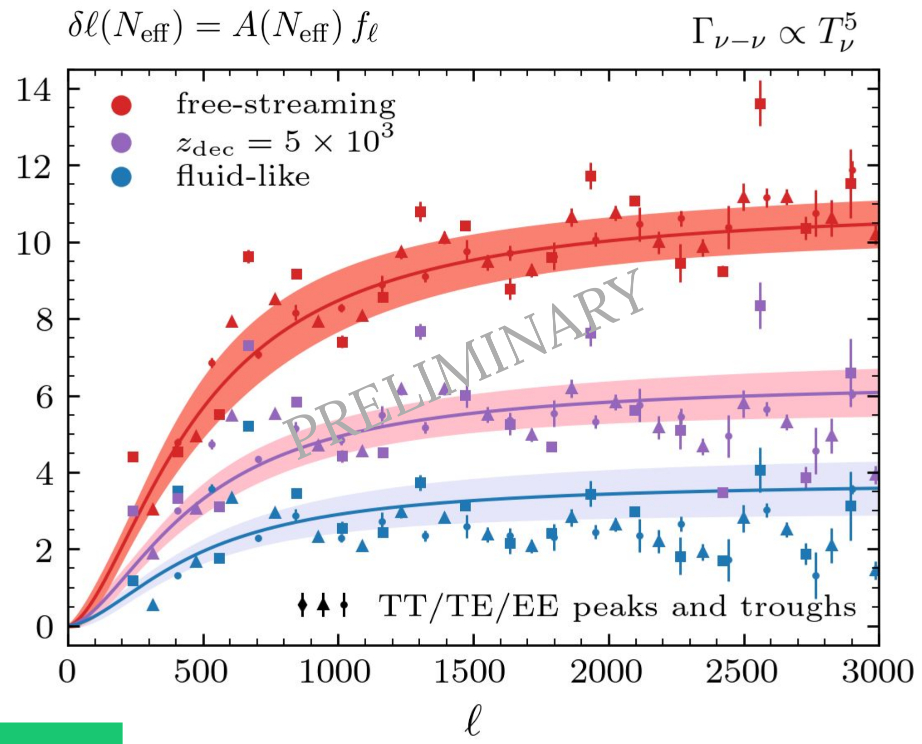


Even fluid-like neutrinos induce a non-negligible phase shift in the CMB spectra

GM, Ghosh, Boddy, Ho & Tsai (in prep)

Realistic Neutrino Interactions
Generalized Multipole Shift Template

$$\Gamma_{\nu-\mathrm{DM}} \propto T_\nu^3 \longrightarrow \mathrm{const.}\ \sigma_{\nu-\mathrm{DM}}$$

(Thomson scattering like)

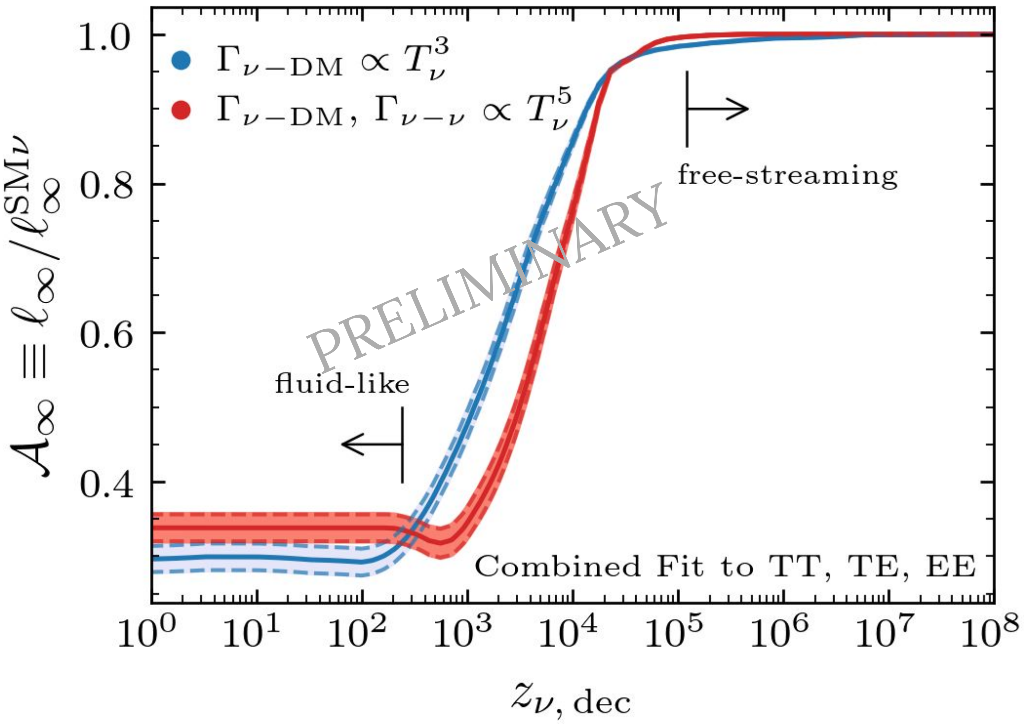
$$\Gamma_{\nu-\mathrm{DM}} \propto T_\nu^5 \longrightarrow \sigma_{\nu-\mathrm{DM}} \propto T_\nu^2$$

(electron-neutrino scattering like)

Wilkinson, Bœhm & Lesgourgues (2014)
Ghosh, Khatri & Tuhin S. Roy (2017)

Direct mapping from phase-shift amplitude to **decoupling redshift**

- fluid-like limit ~30% of (SM) free-streaming limit
- Higher temperature power law means sharper transition from free-streaming to fluid-like

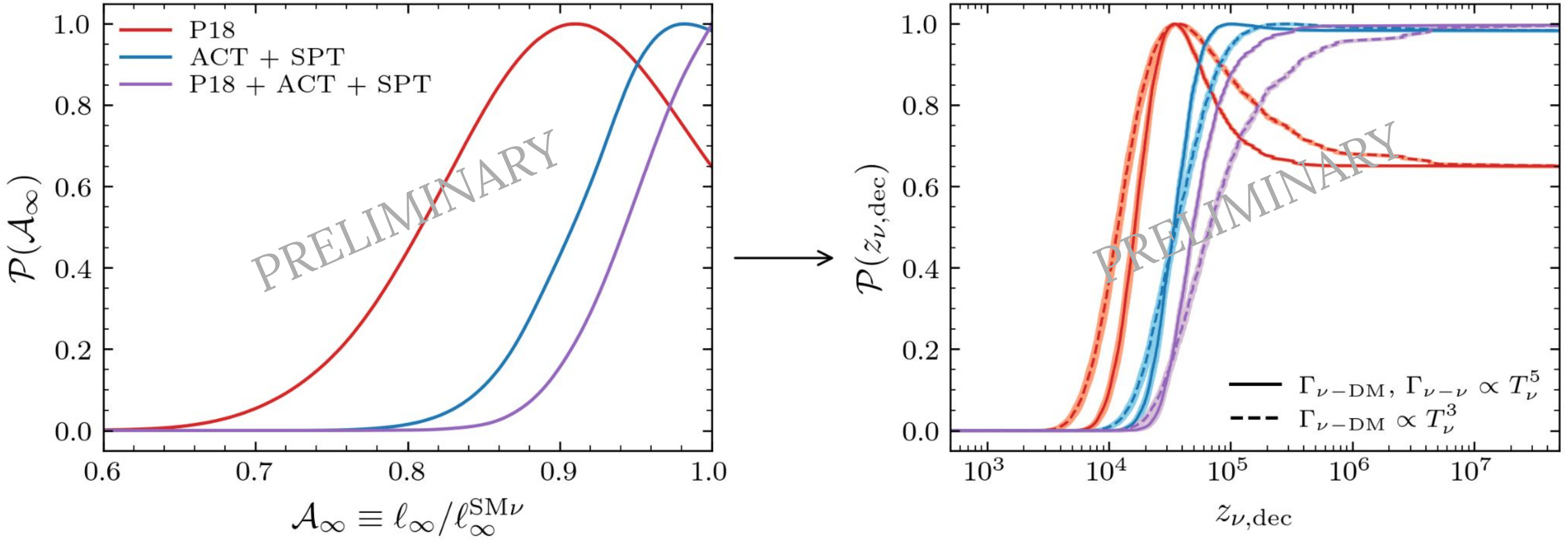


GM, Ghosh, Boddy, Ho & Tsai (in prep)

Realistic Neutrino Interactions

Direct Phase-Shift Constraints from CMB data

$$\Delta\ell(\mathcal{A}_\infty, N_{\rm eff}) \equiv (\mathcal{A}_\infty - 1) \times A(N_{\rm eff}) f_\ell^{{\rm SM}\nu}$$
$$\mathcal{C}_\ell \rightarrow \mathcal{C}_{\ell+\Delta\ell}$$

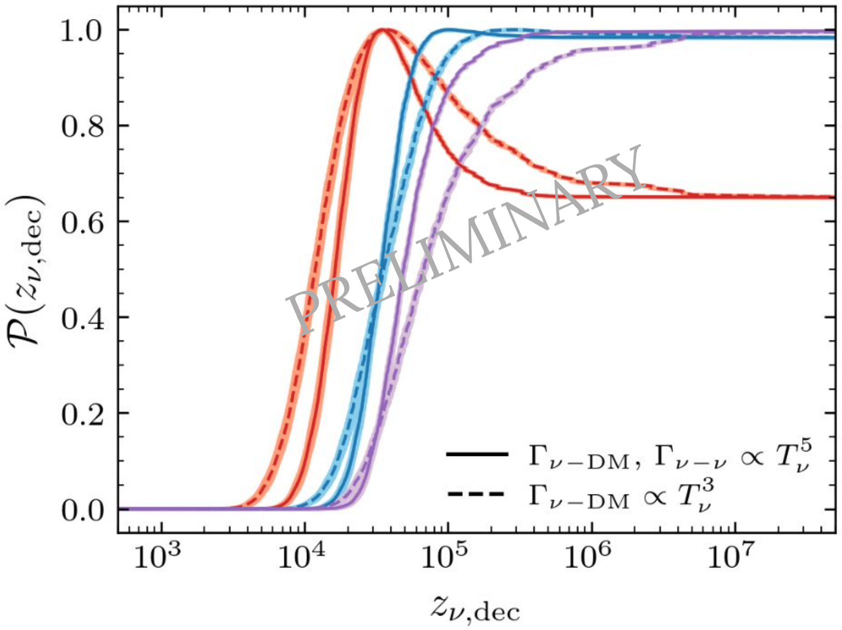


Equivalent to the **spectrum-based analysis**: $\mathcal{A}_\infty = \epsilon(N_{\rm eff}^{\delta\ell})/\epsilon(3.044)$

GM, Ghosh, Boddy, Ho & Tsai (in prep)

Realistic Neutrino Interactions
Direct Phase-Shift Constraints from CMB data

Dataset	$\mathcal{A}_\infty$	$z_{\nu,\rm dec}$: $\Gamma_\nu \propto T_\nu^3$	$z_{\nu,\rm dec}$: $\Gamma_\nu \propto T_\nu^5$
P18	> 0.76	$> 7.9 \times 10^3$	$> 1.27 \times 10^4$
ACT + SPT	> 0.87	$> 1.06 \times 10^4$	$> 1.51 \times 10^4$
P18 + ACT + SPT	> 0.90	$> 1.33 \times 10^4$	$> 1.71 \times 10^4$



- Neutrinos must be already **free-streaming deep** within the **radiation-dominated** epoch
- Ground-based experiments surpassed Planck's sensitivity to the phase shift!

GM, Ghosh, Boddy, Ho & Tsai (in prep)

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:

Can we use these phase-shift measurements to directly probe BSM neutrino physics?
YES!

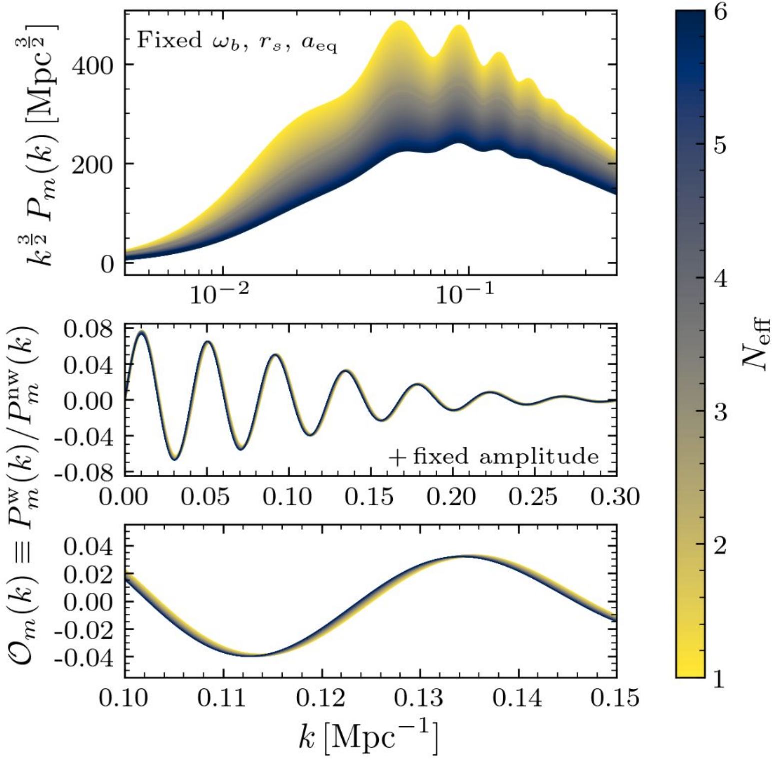
- Current data **strongly constrain** neutrino-interactions, requiring **decoupling deep in the radiation-dominated epoch**
- Robust signature-driven approach to test directly BSM neutrino-physics

What is Next?
The Phase Shift in Large Scale Structures

The same phase shift is naturally imprinted in the spectrum of baryon acoustic oscillations (BAOs) extracted from galaxy surveys

- Extracted in BOSS and DESI data providing independent evidence for the free-streaming nature of neutrinos.

Baumann, Green & Zaldarriaga (2017)
Baumann, Green & Wallisch (2017)
Baumann et. al. (2019)
Whitford et. al. (2024)



What is Next?
The Phase Shift in Large Scale Structures

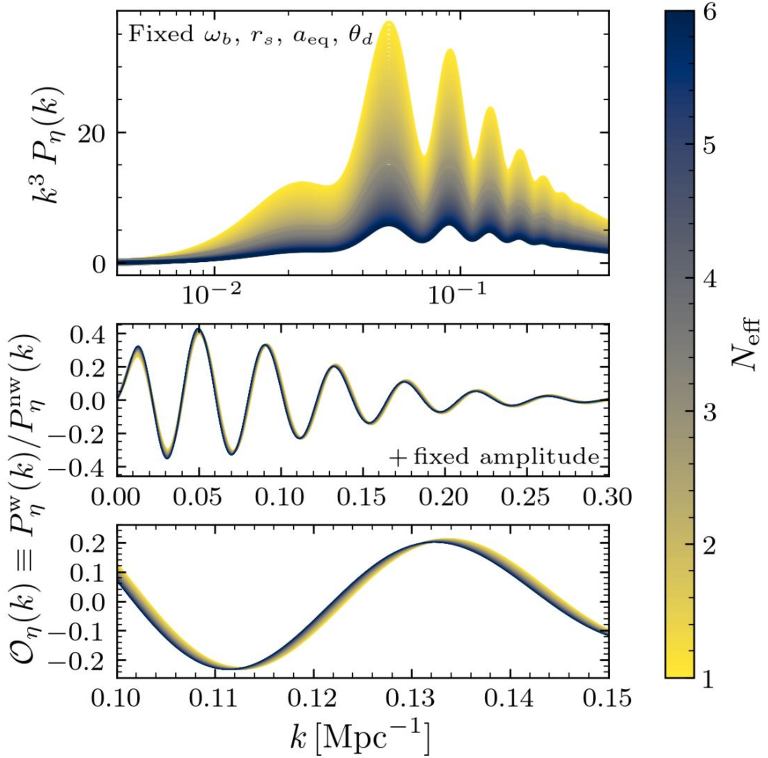
The phase shift will also appear in the 21-cm spectrum at cosmic dawn!

- **Distinct** redshift- and mode-dependence from that observed in the CMB and BAO spectra, due to the presence of **velocity acoustic oscillations** (VAOs) sourced by DM-baryon relative velocities.

- **new avenue** for probing free-streaming relics complementary to existing CMB and BAO measurements

- Also **sensitive to astrophysical processes** that determine the relative contributions of BAOs and VAOs.

$$\eta(\vec{r}) \equiv \frac{v_{\rm cb}^2(\vec{r}, z)}{\langle v_{\rm cb}^2(z)\rangle} - 1$$



GM, Cruz, Munoz, Kovetz, & Kamionkowski (2025)

Grazie per l'attenzione!

Gabriele Montefalcone

Weinberg Institute for Theoretical Physics, University of Texas at Austin

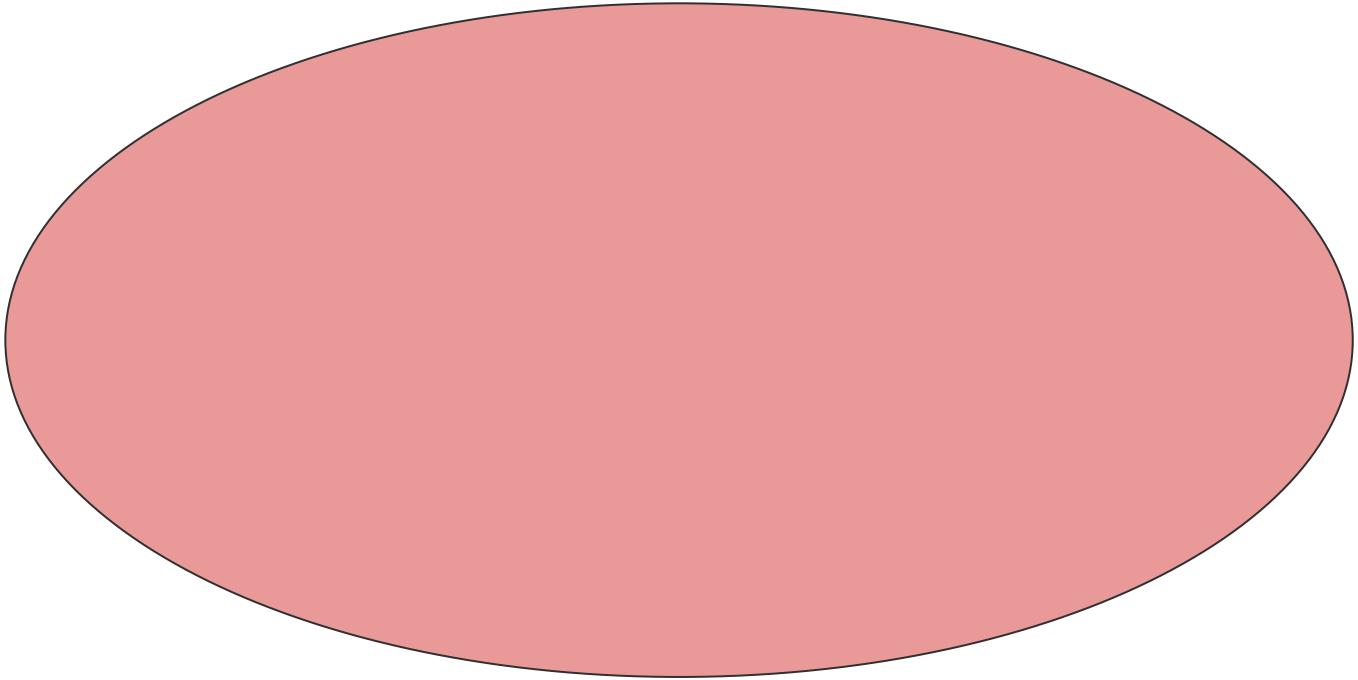
Back-up Slides

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

The Cosmic Microwave Background

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

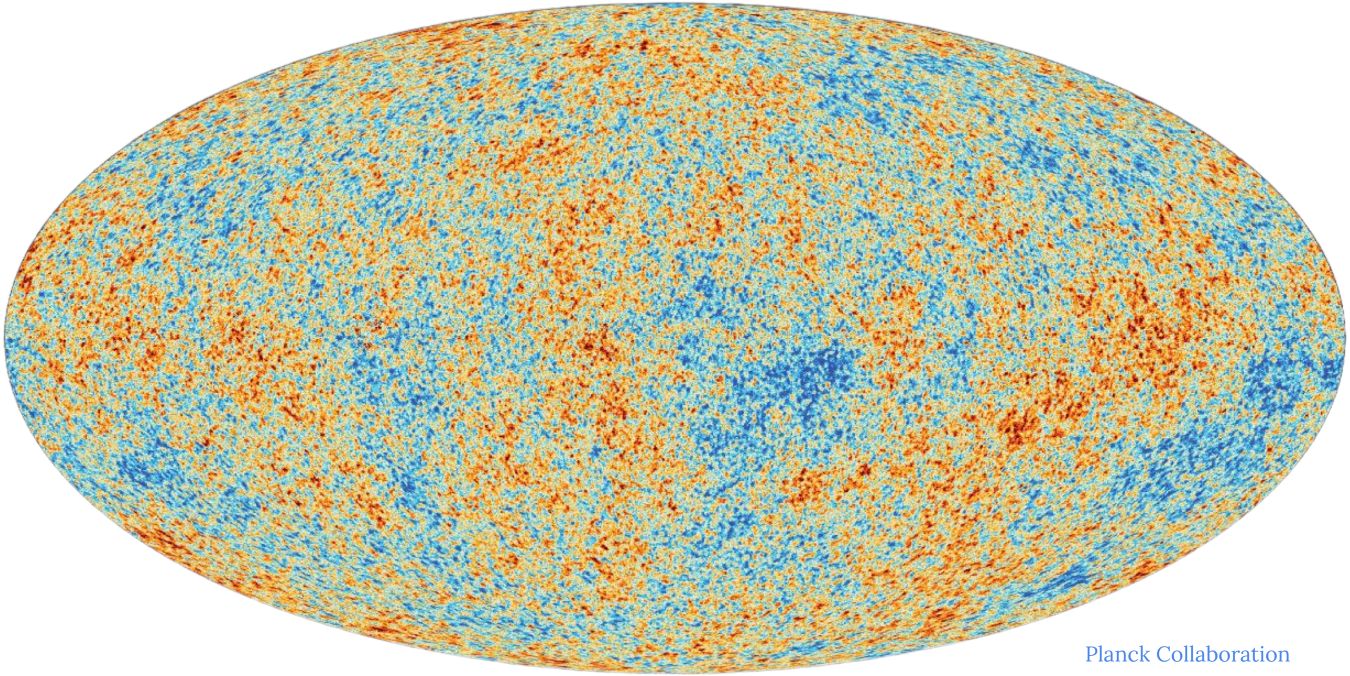
T = 2.7255 K



The Cosmic Microwave Background

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

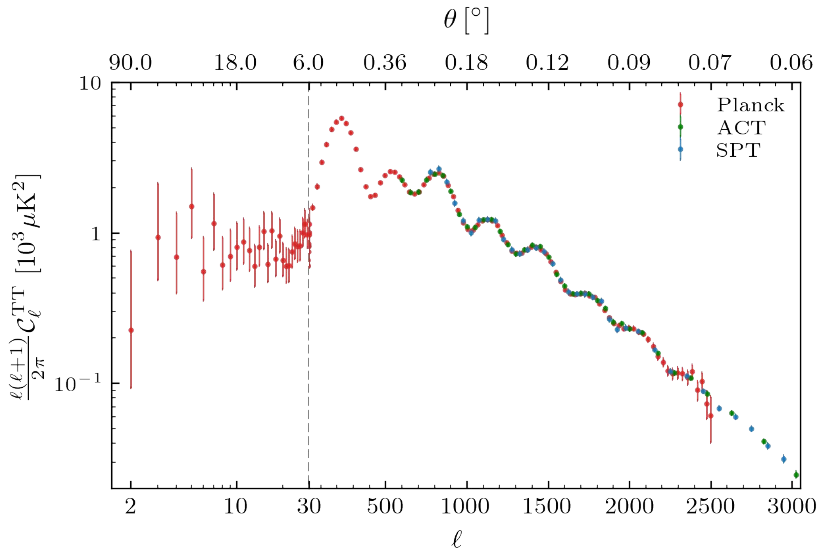
$\Delta T/T \sim 10^{-4}$



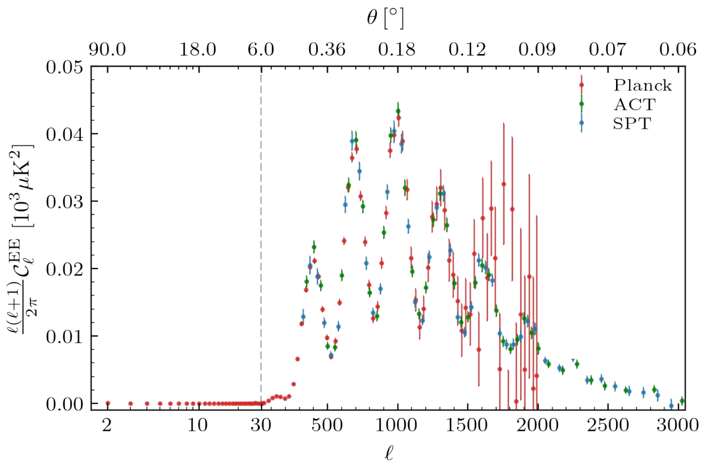
Planck Collaboration

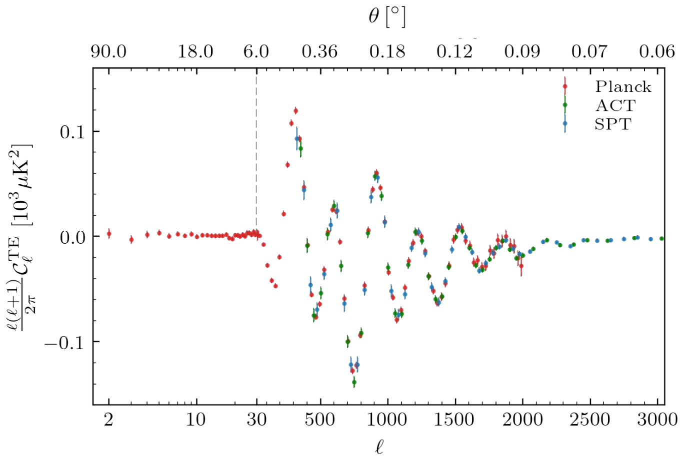
The CMB Power Spectra

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



Polarization spectrum traces **velocity** perturbations

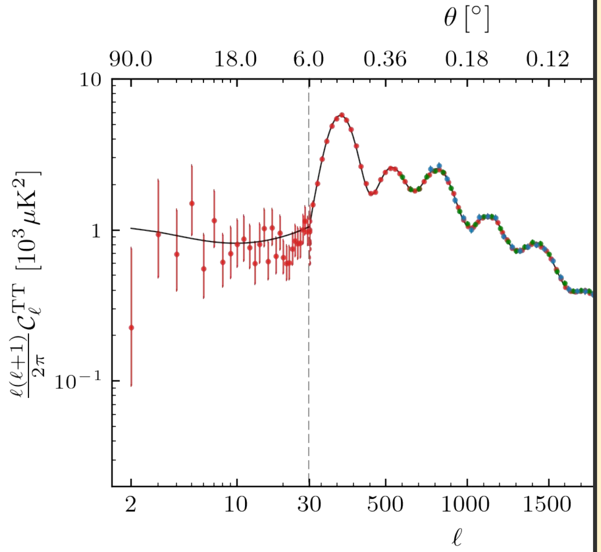


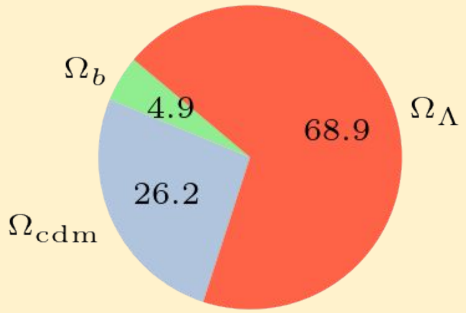


TE spectrum roughly tells us how the plasma is moving into the gravitational potential wells

The CMB Power Spectra

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





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

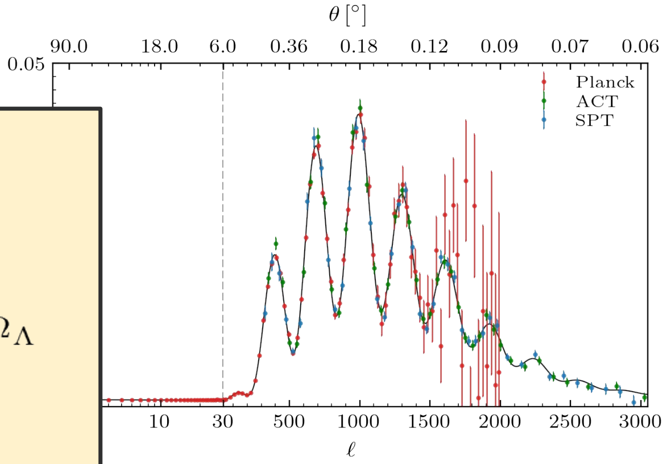
$n_s = 0.965$

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

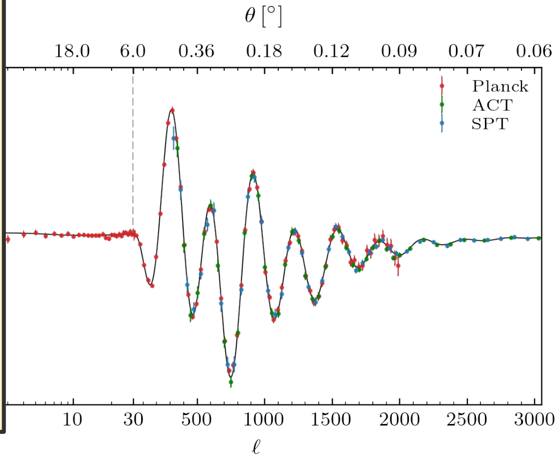
+ SM neutrinos $N_{\mathrm{eff}} = 3.044$

+ ...

Polarization spectrum traces **velocity** perturbations

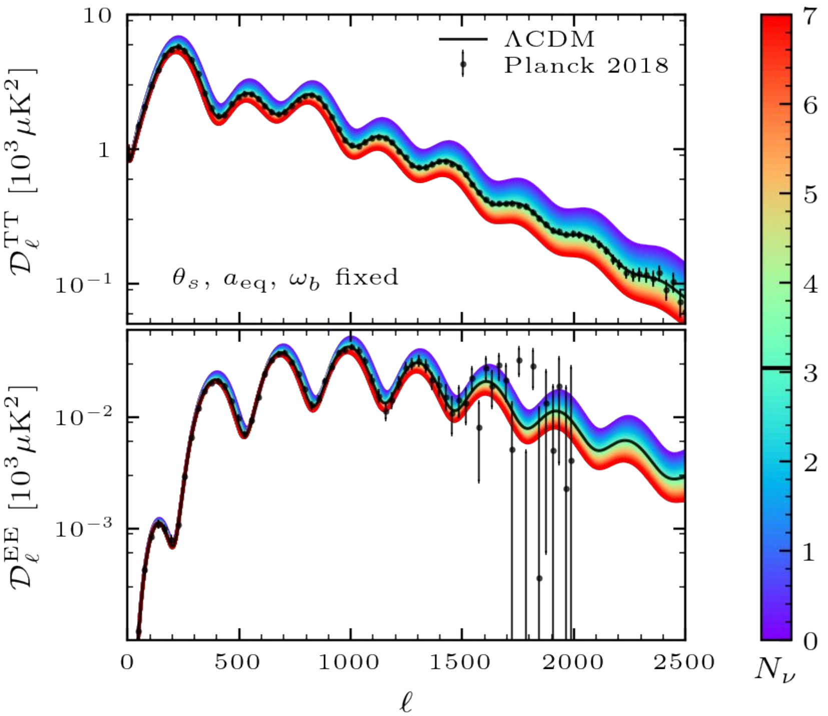


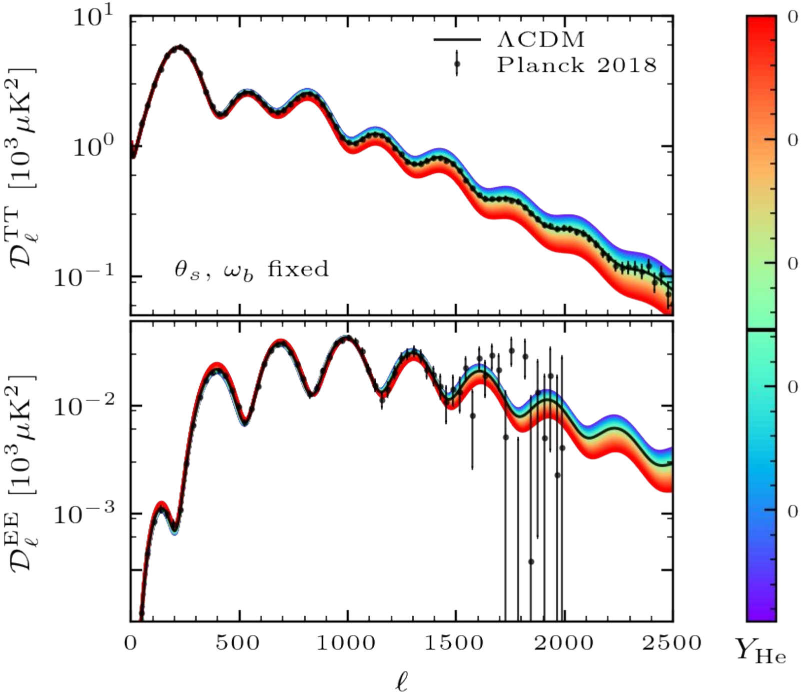
TE spectrum roughly
moving into the gravit



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 $\mathbf{n_e}$

Cosmic Neutrinos in the CMB
Extraction of the Multipole Shift Template

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

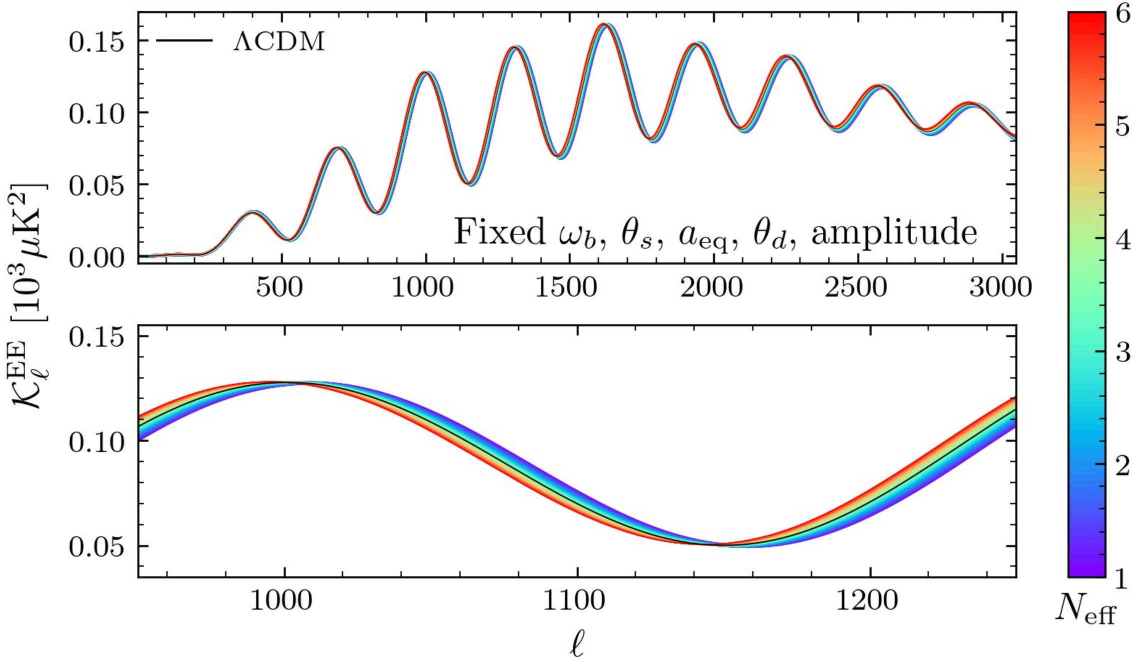
Multipole Dependence

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

Normalized Amplitude

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

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



Following Follin, Knox, Millea & Pan (2015)

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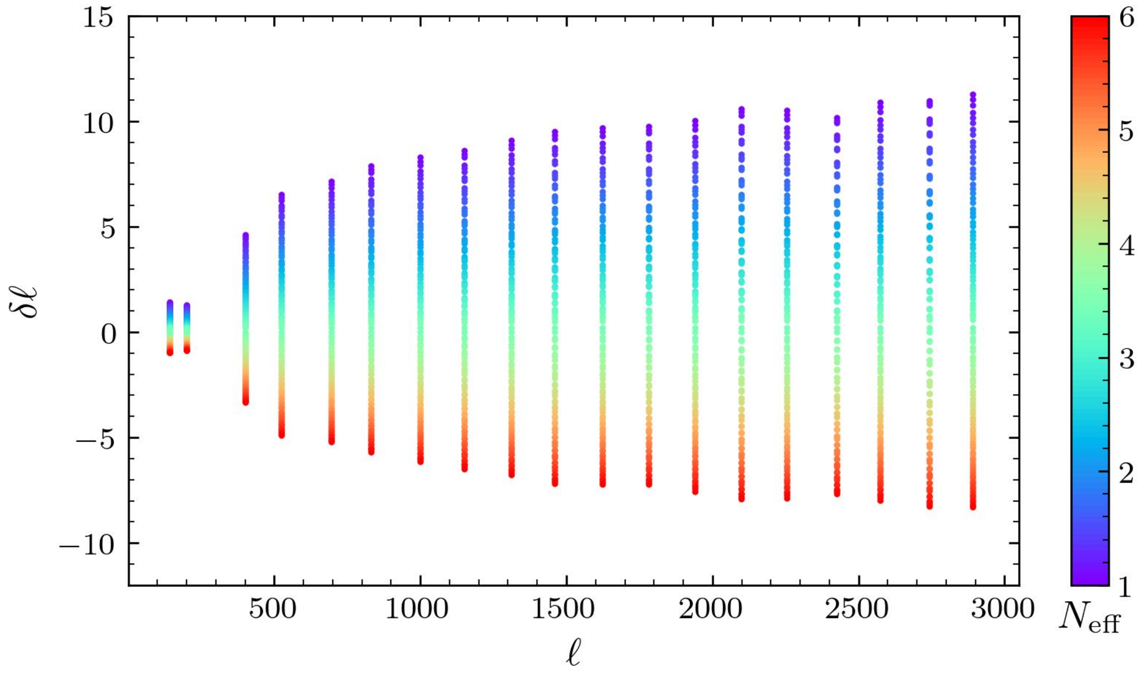
1. Compute the multipole shifts w.r.t. the fiducial cosmology.



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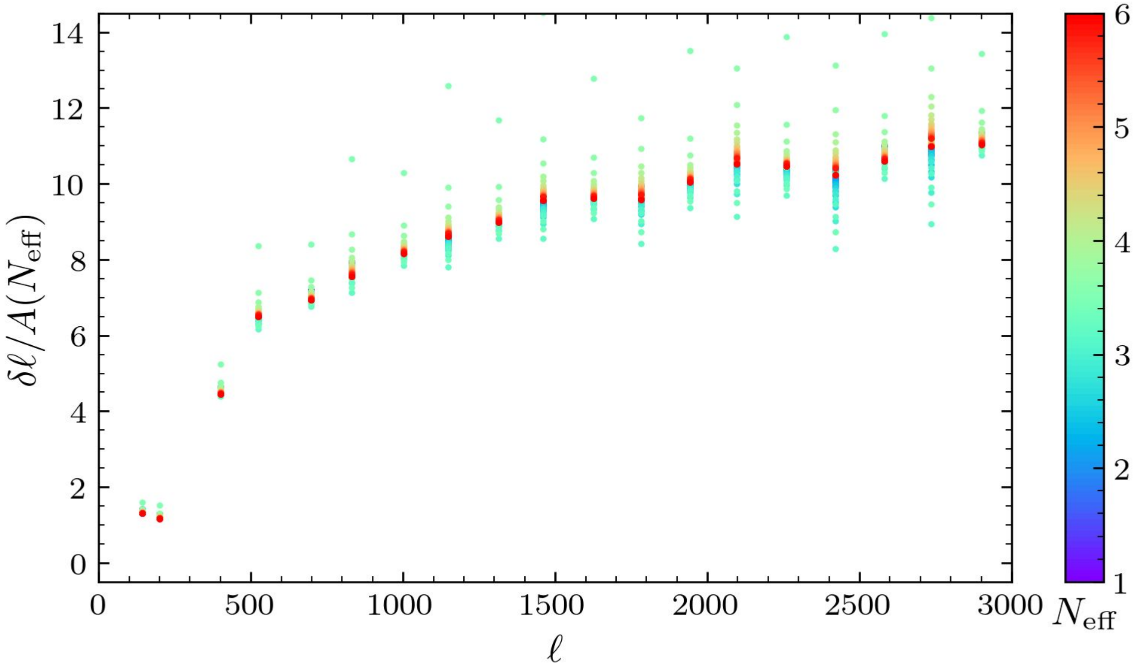
2. Divide by the respective phase shift amplitude.



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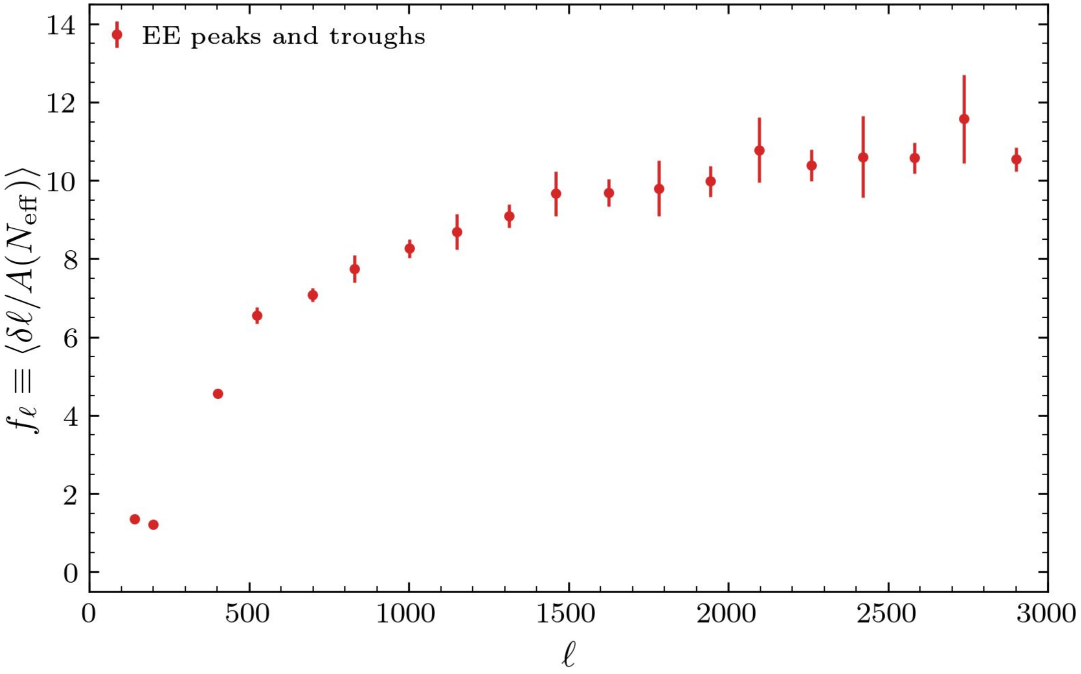
Normalized Amplitude

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

3. Compute the mean/standard deviation per peak/trough.



Following Follin, Knox, Millea & Pan (2015)

Cosmic Neutrinos in the CMB
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Normalized Amplitude

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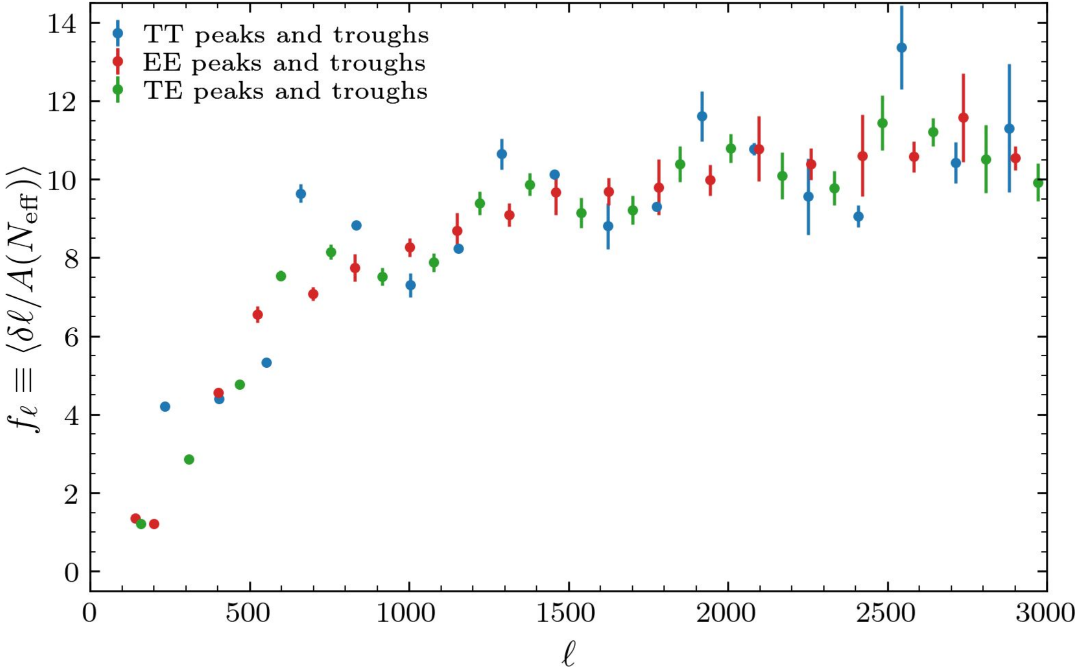
4. Repeat the same process for the TT and TE spectra.



Following Follin, Knox, Millea & Pan (2015)

Cosmic Neutrinos in the CMB
Extraction of the Multipole Shift Template

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Multipole Dependence

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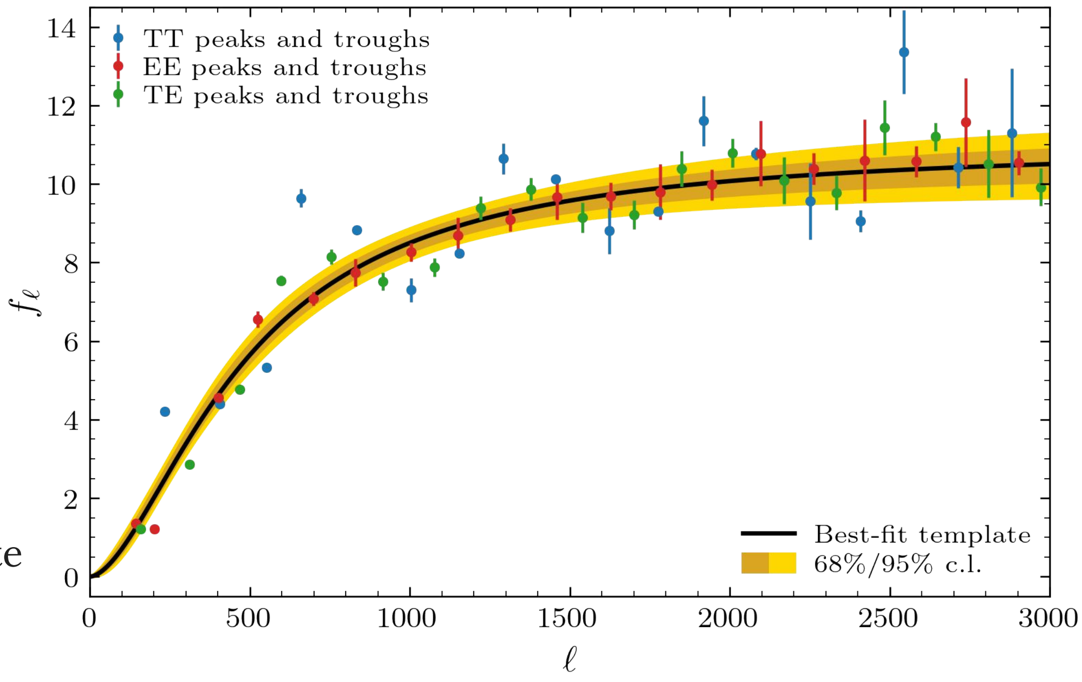
Normalized Amplitude

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

Our Contributions:
- A new analytic form of the template
- Used both temperature and polarization spectra

4. Determine the best-fit parameters



Following Follin, Knox, Millea & Pan (2015)

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

X Physical Source Term

$S_X(k,\eta)$

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

$\downarrow$

X Anisotropies

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

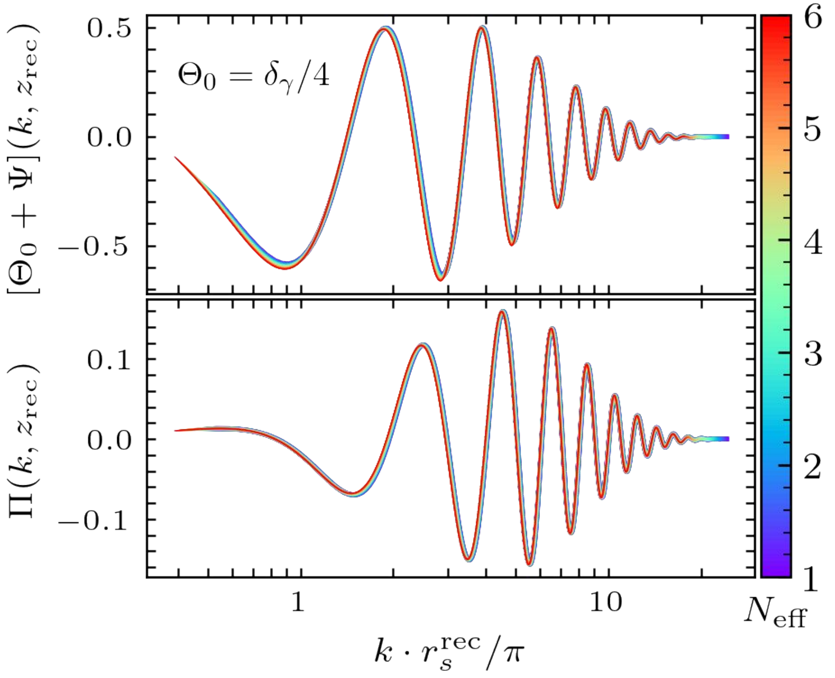
$\downarrow$

XY Power Spectra

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

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

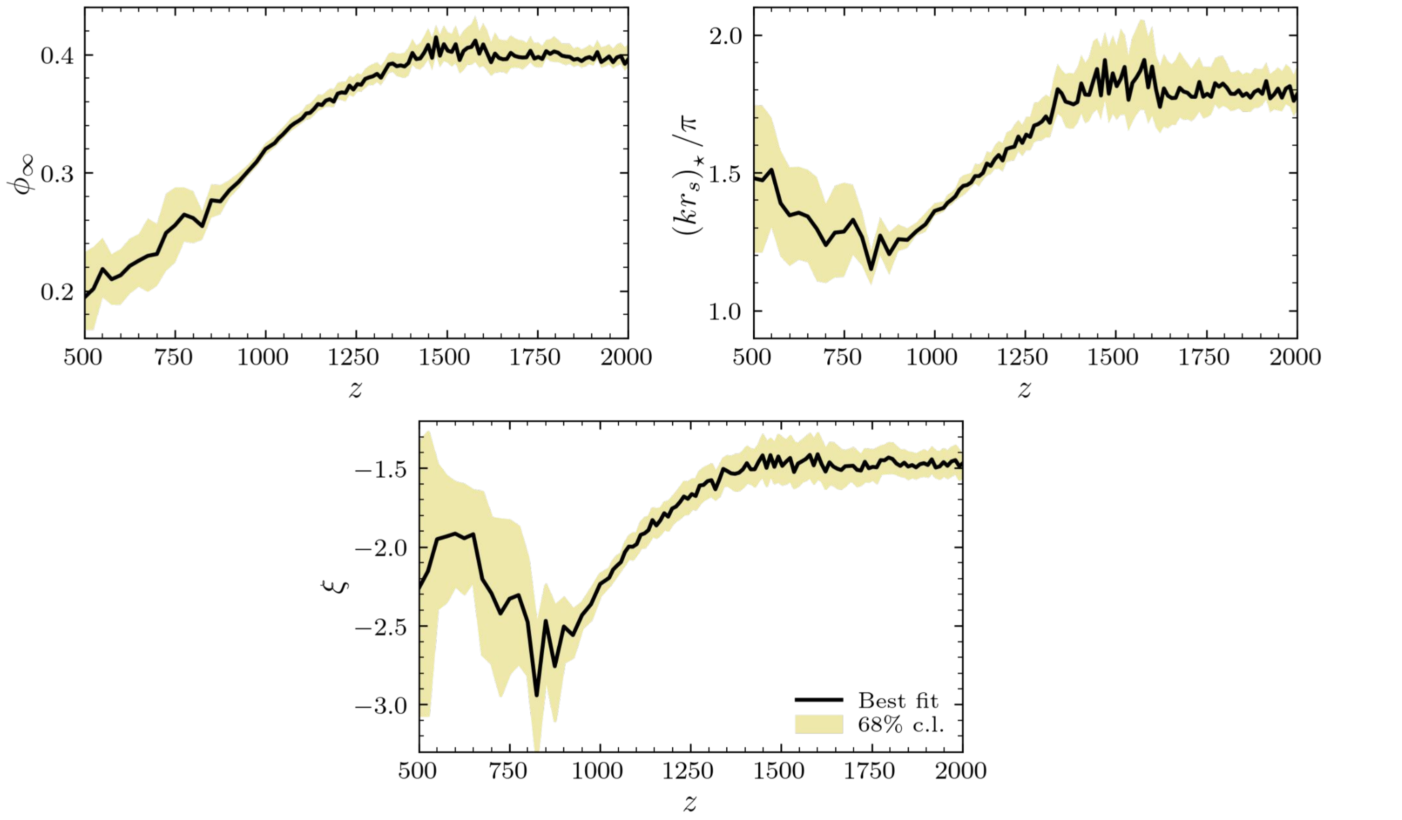
$$\Pi(\vec{k}) \sim A(\vec{k})\frac{c_s}{\dot{\tau}}\sin(kr_s+\phi)$$



GM, Wallisch & Freese (2025)

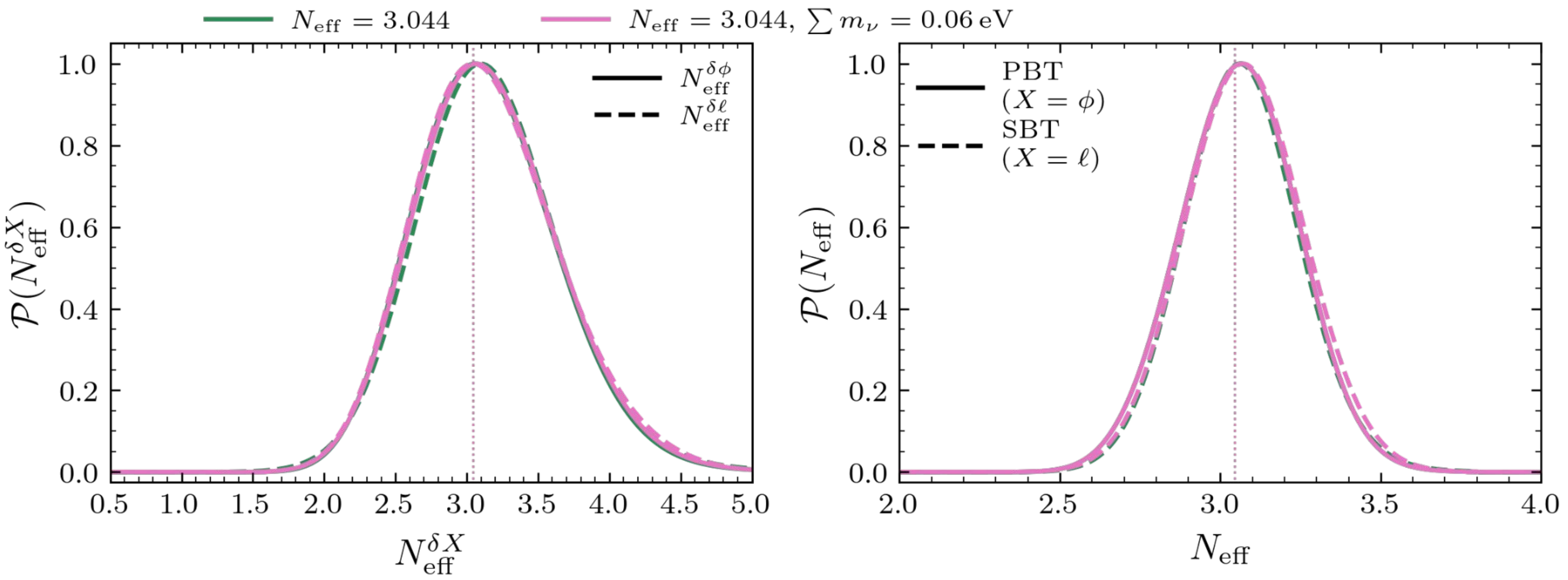
The Phase shift in the Perturbations

Details on the template extraction



Validation of Phase Shift Extraction

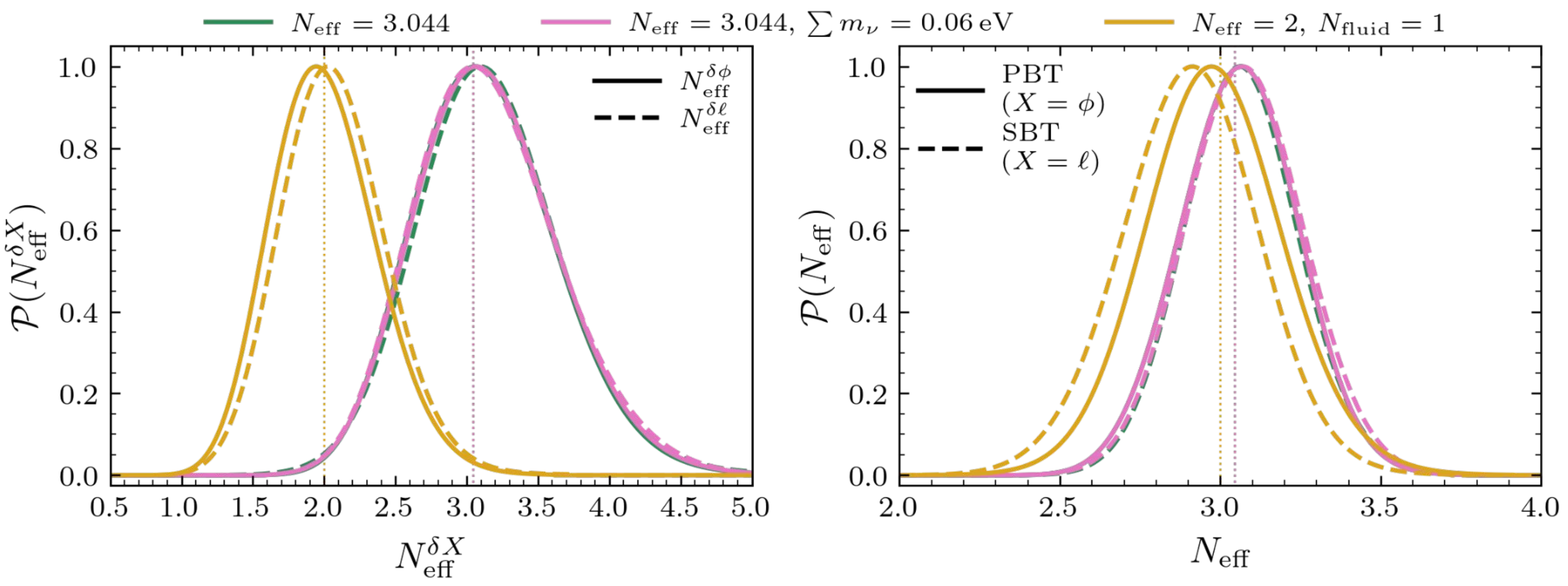
Planck-like Mock Data Analysis



Neutrino masses have negligible impact on the phase shift extraction

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 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)

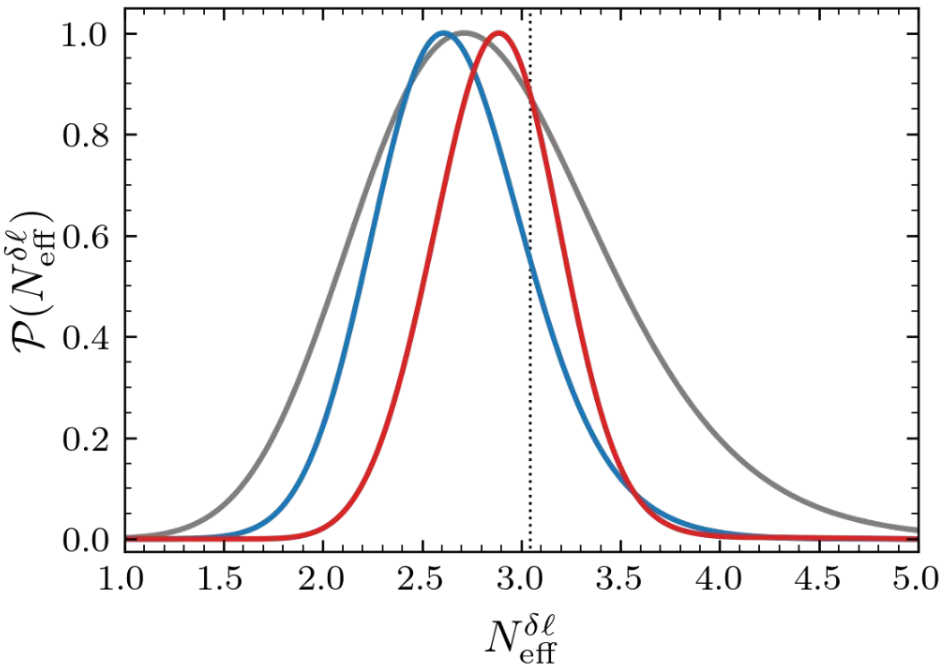
$(N_{\rm eff} = N_\nu = 3.044)$

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

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

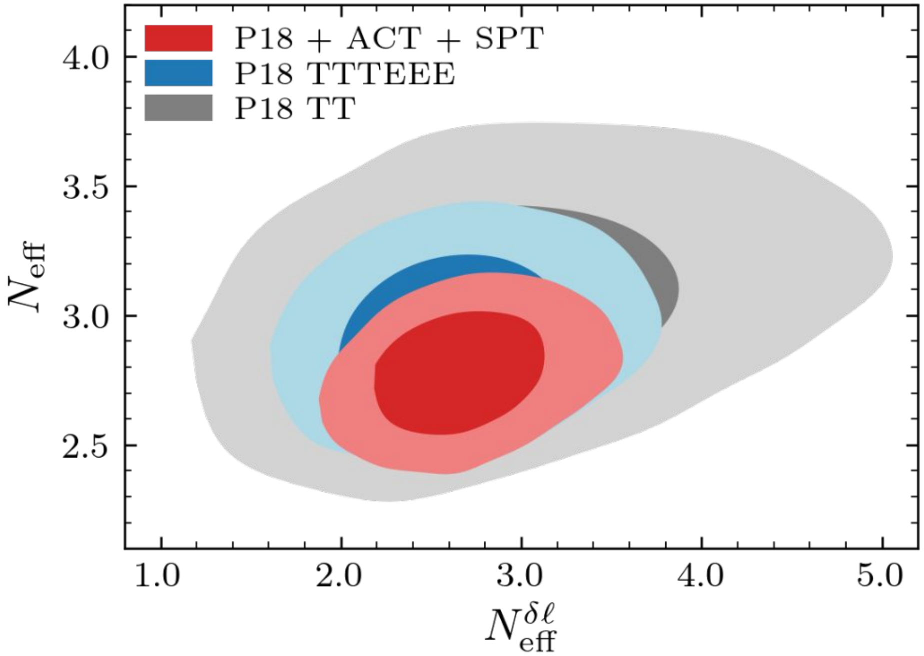


GM, Wallisch & Freese (2025)

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

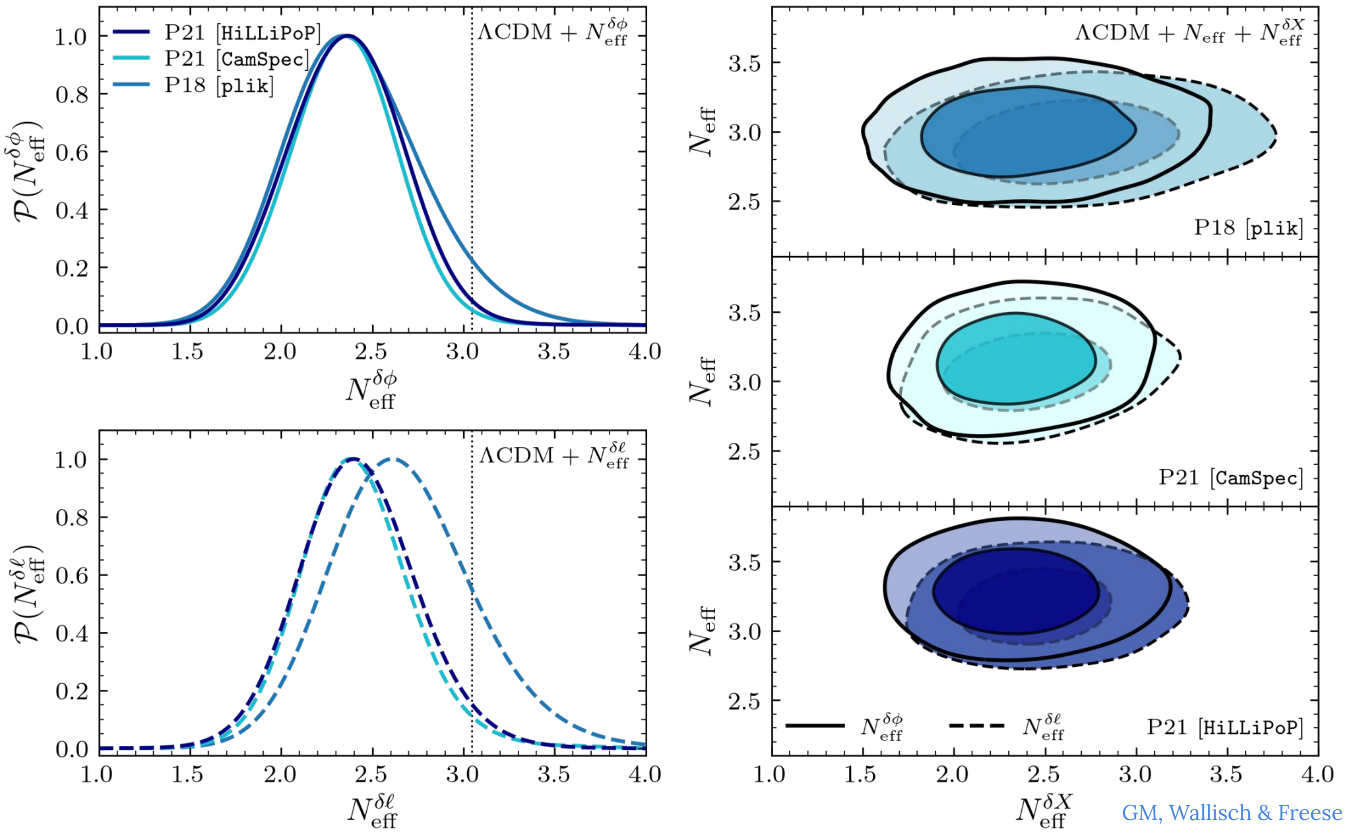


GM, Wallisch & Freese (2025)

Planck 2018 vs Planck 2021

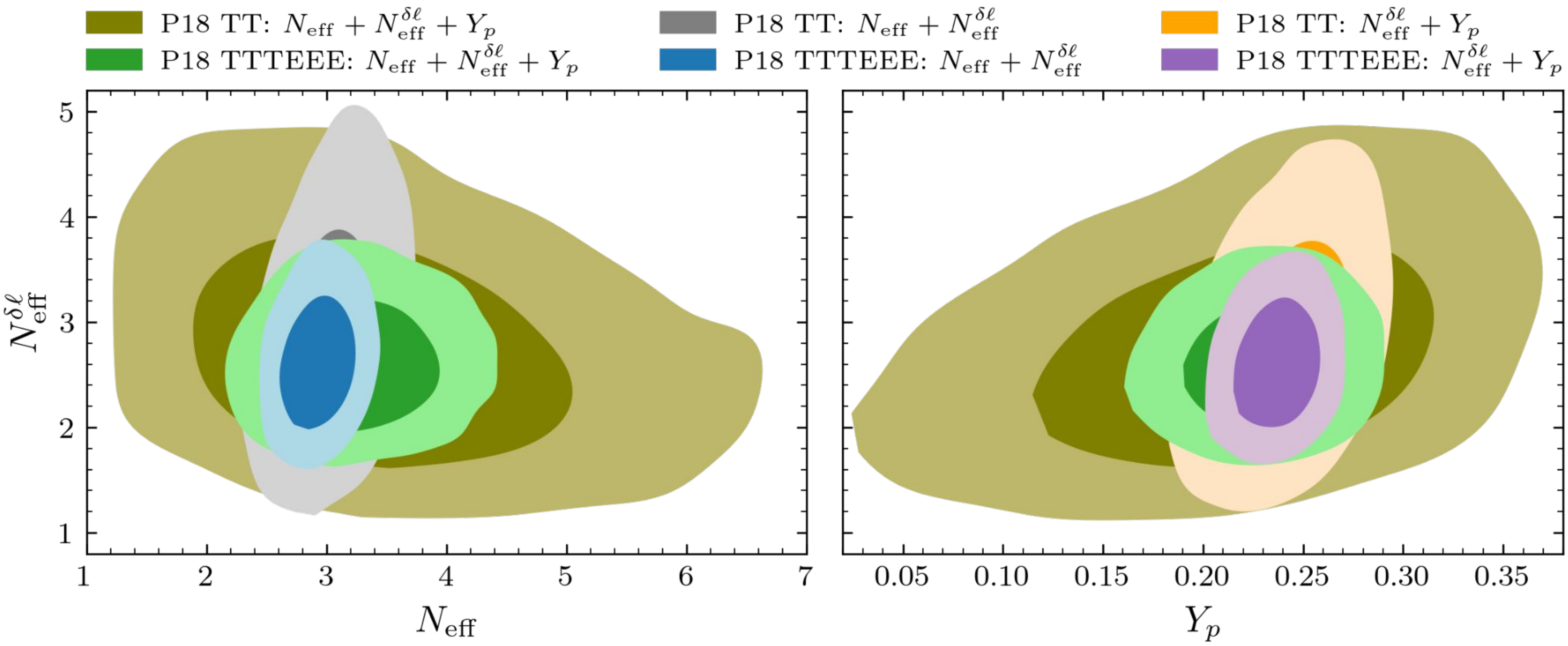
Comparison of Spectrum- and Perturbation-Based Approach

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



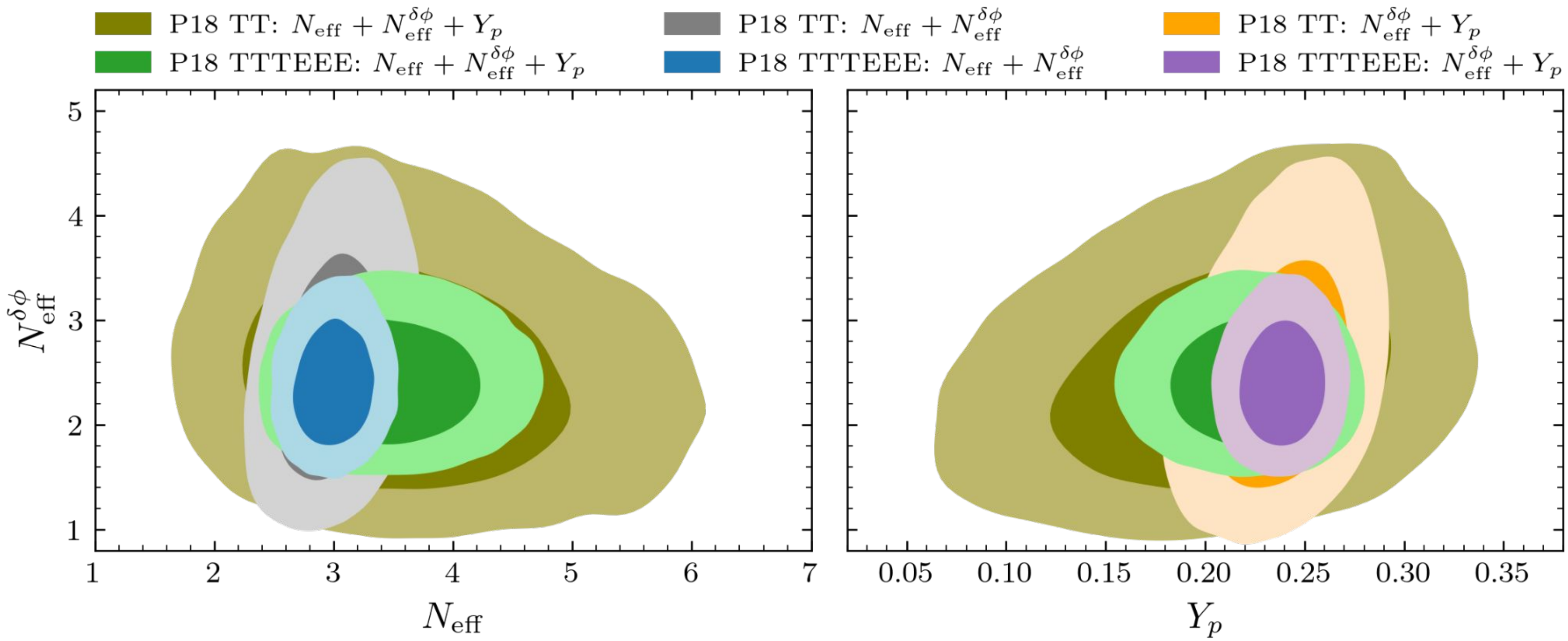
GM, Wallisch & Freese (2025)

Phase Shift Constraints from CMB Data
Spectrum-Based Analysis



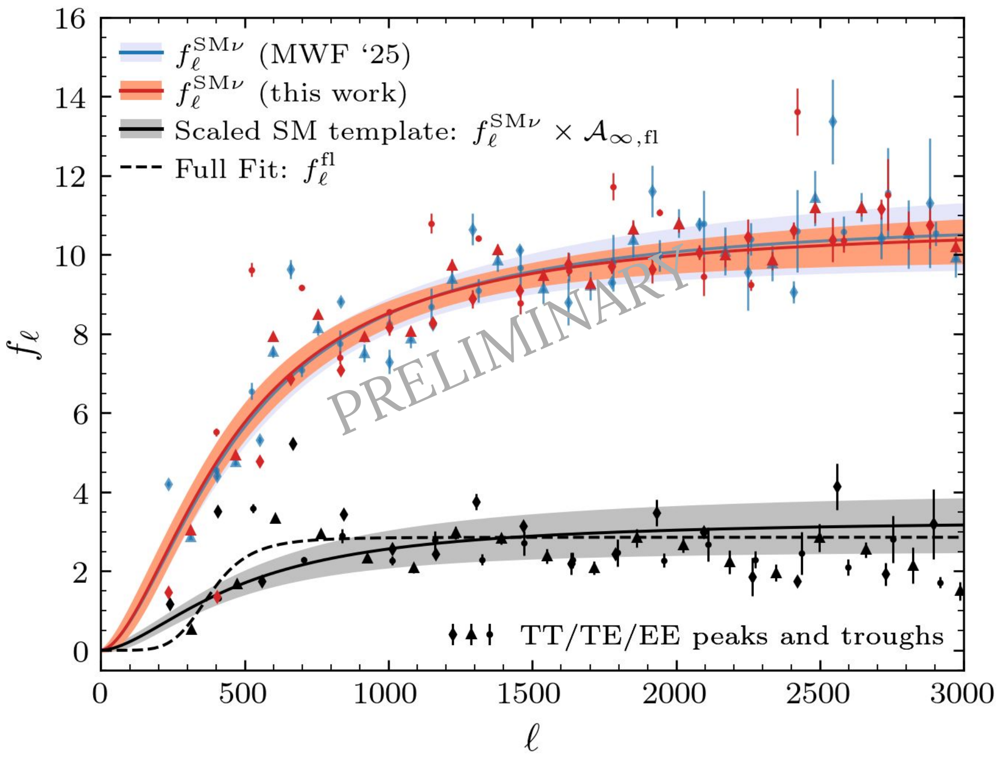
GM, Wallisch & Freese (2025)

Phase Shift Constraints from CMB Data
Perturbation-Based Analysis



GM, Wallisch & Freese (2025)

Realistic Neutrino Interactions
Generalized Multipole Shift Template



GM, Ghosh, Boddy, Ho & Tsai (in prep)

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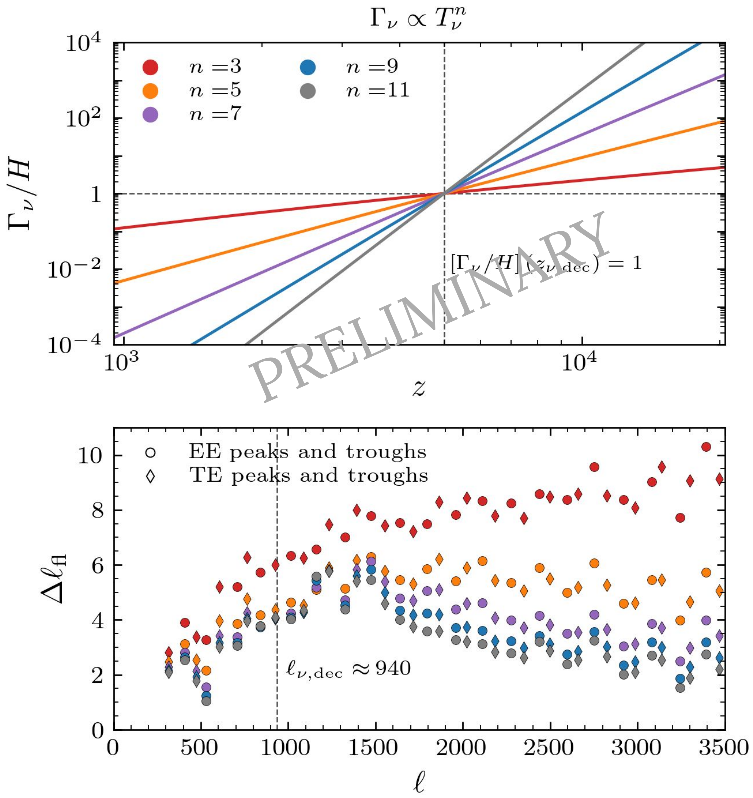

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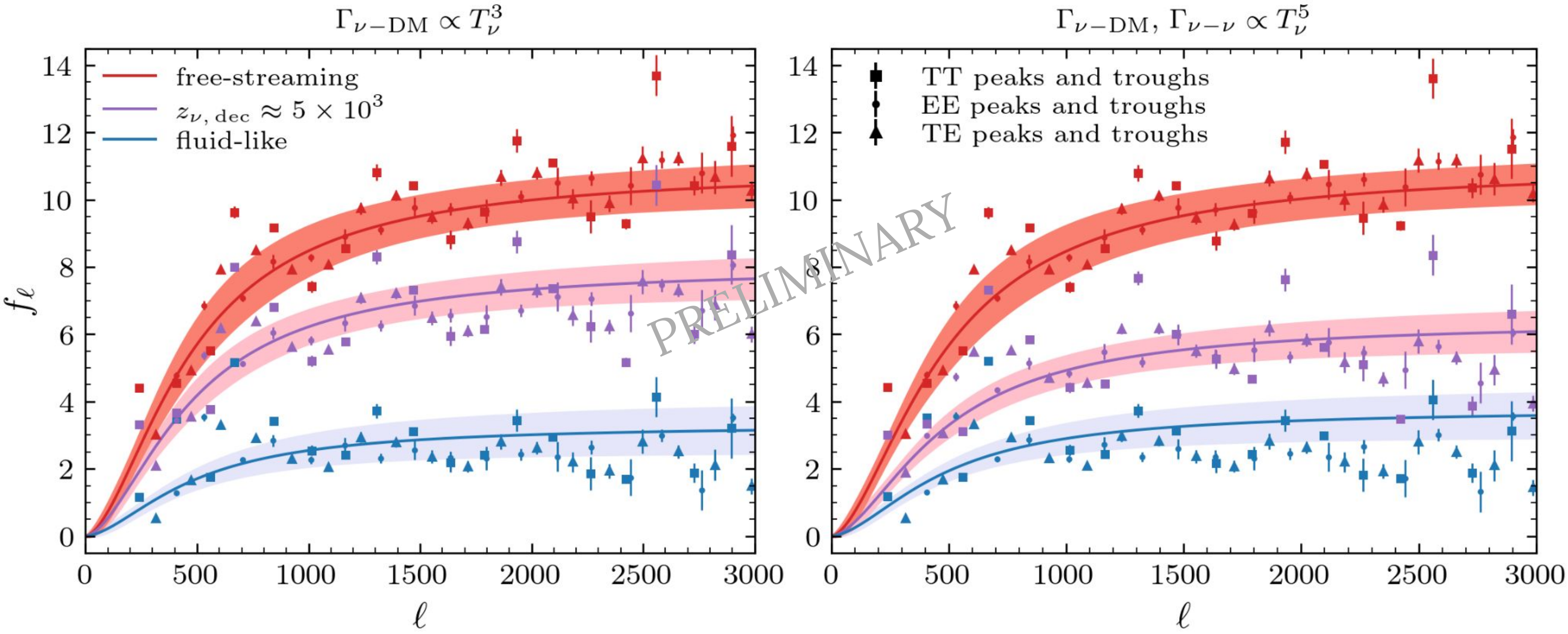

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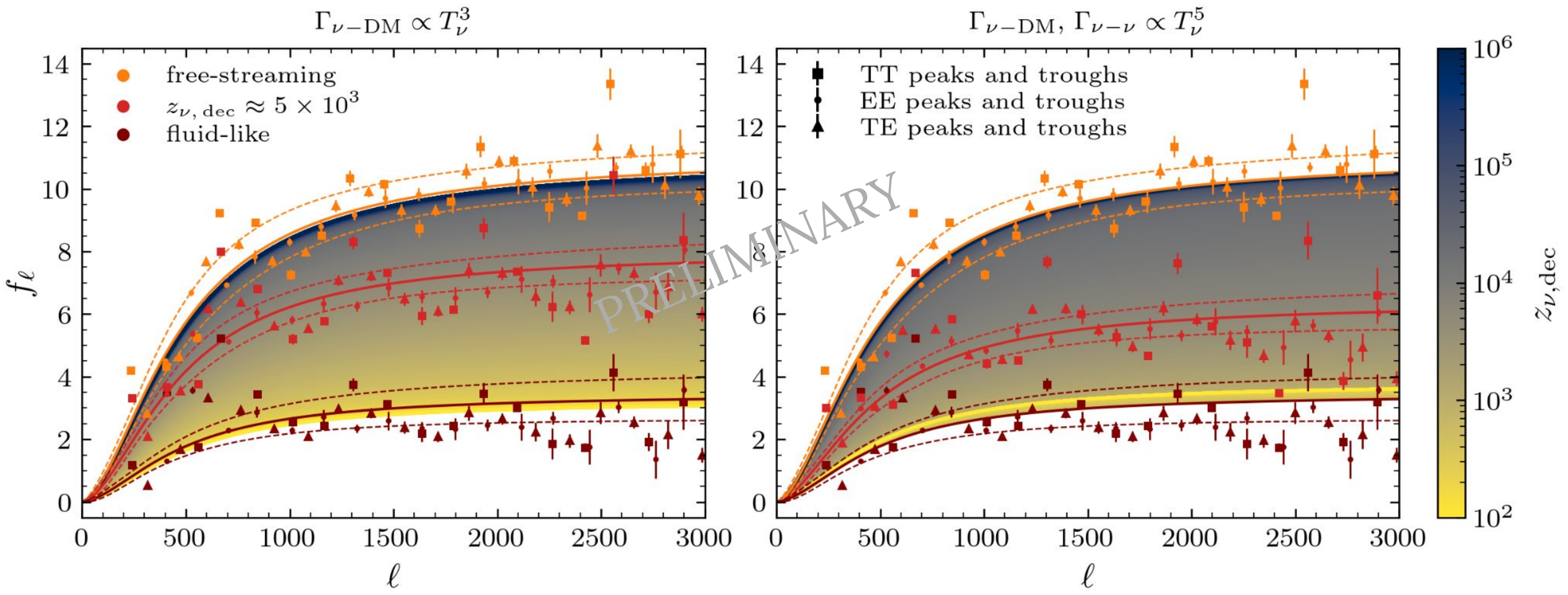

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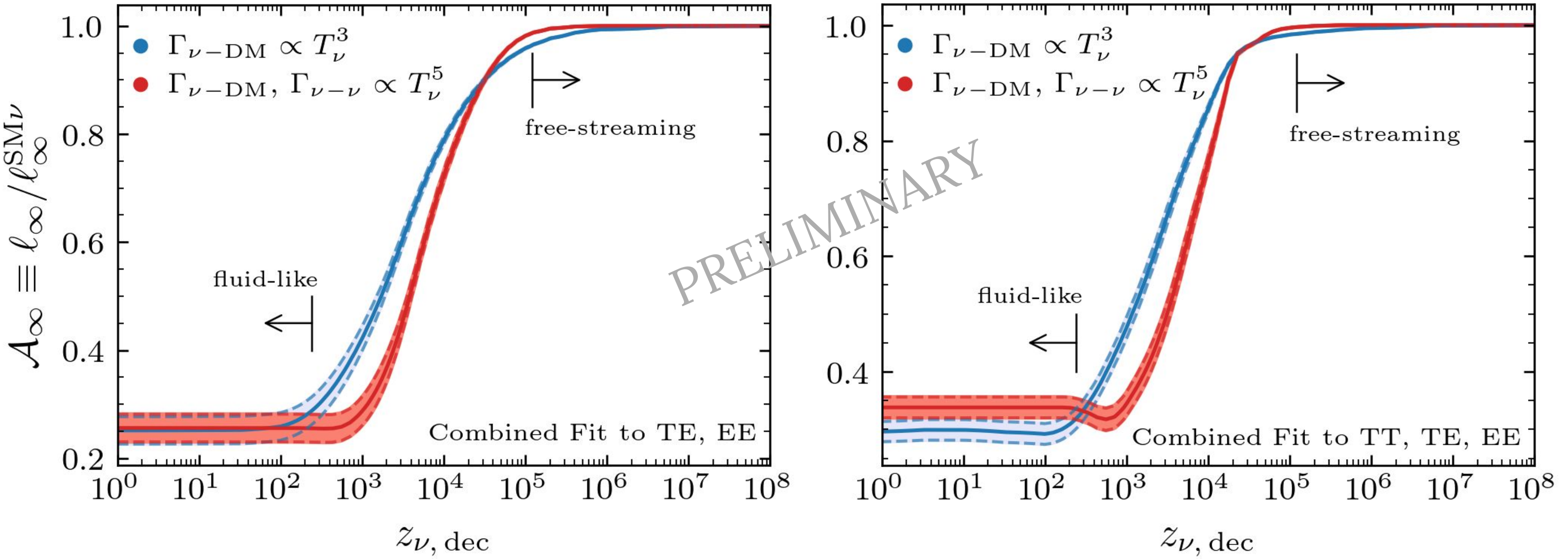
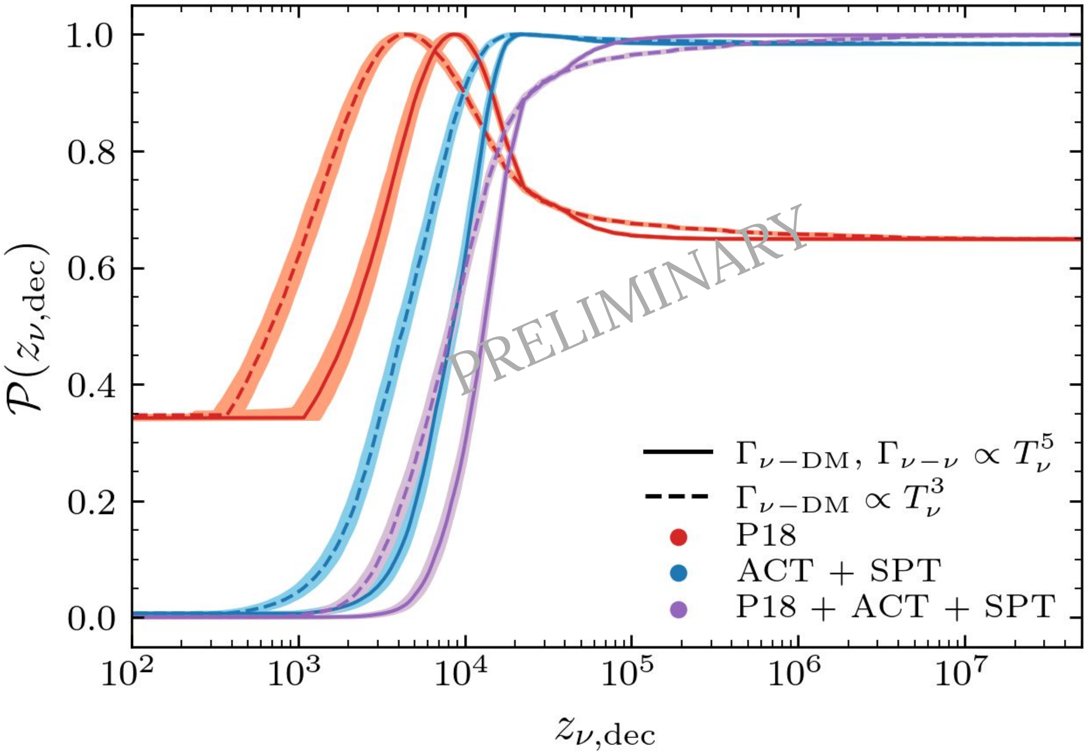


GM, Ghosh, Boddy, Ho & Tsai (in prep)

Realistic Neutrino Interactions
Direct Phase-Shift Constraints from CMB data

Only **one** interacting species



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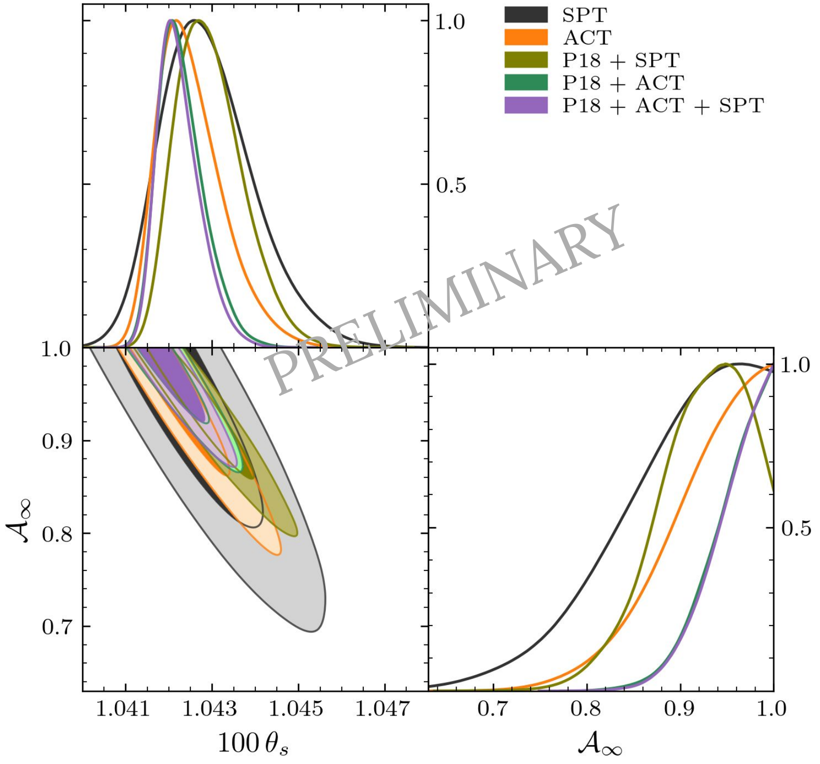

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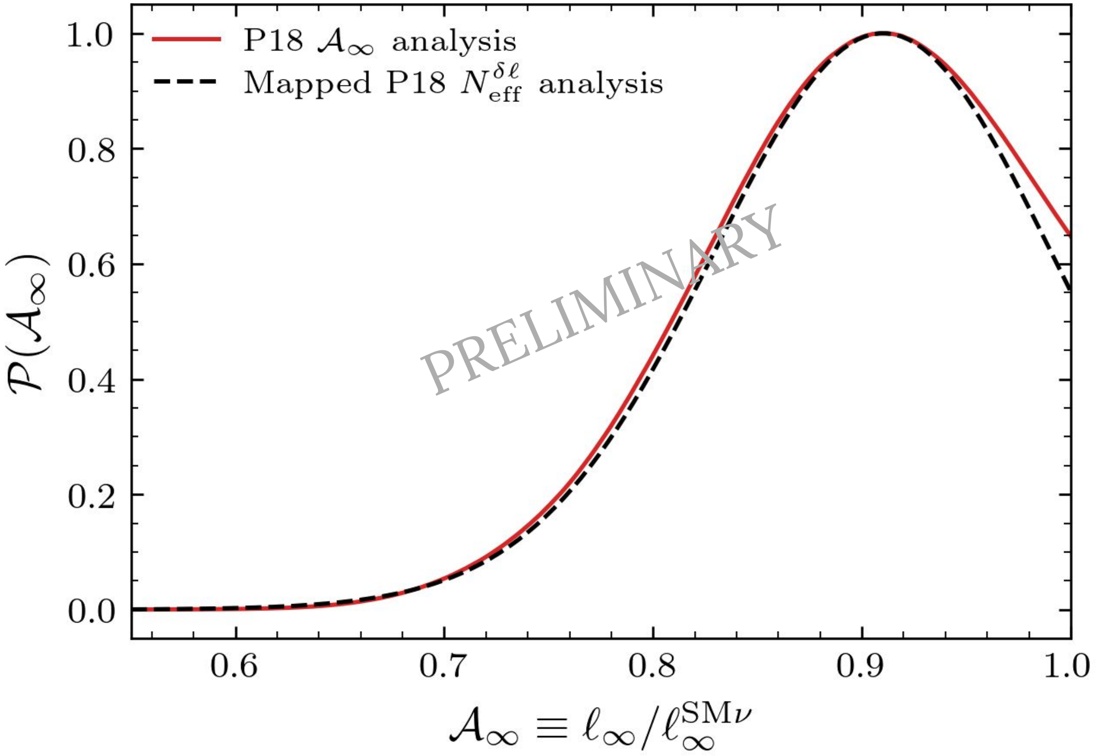
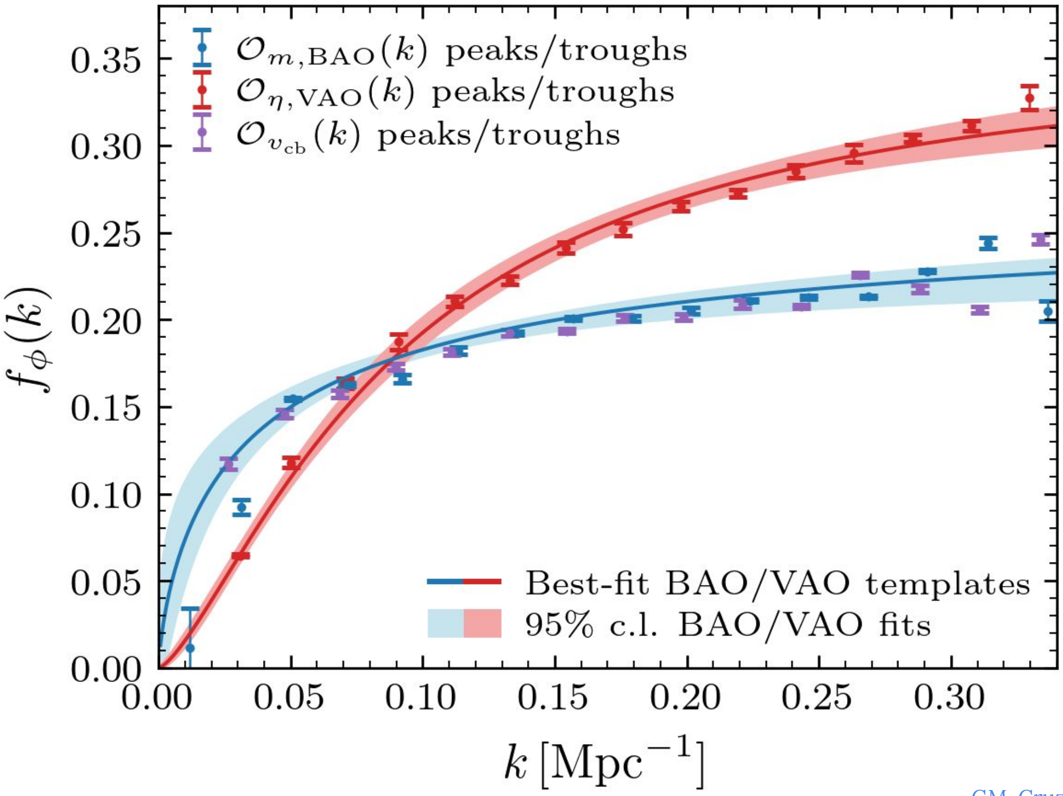


GM, Ghosh, Boddy, Ho & Tsai (in prep)

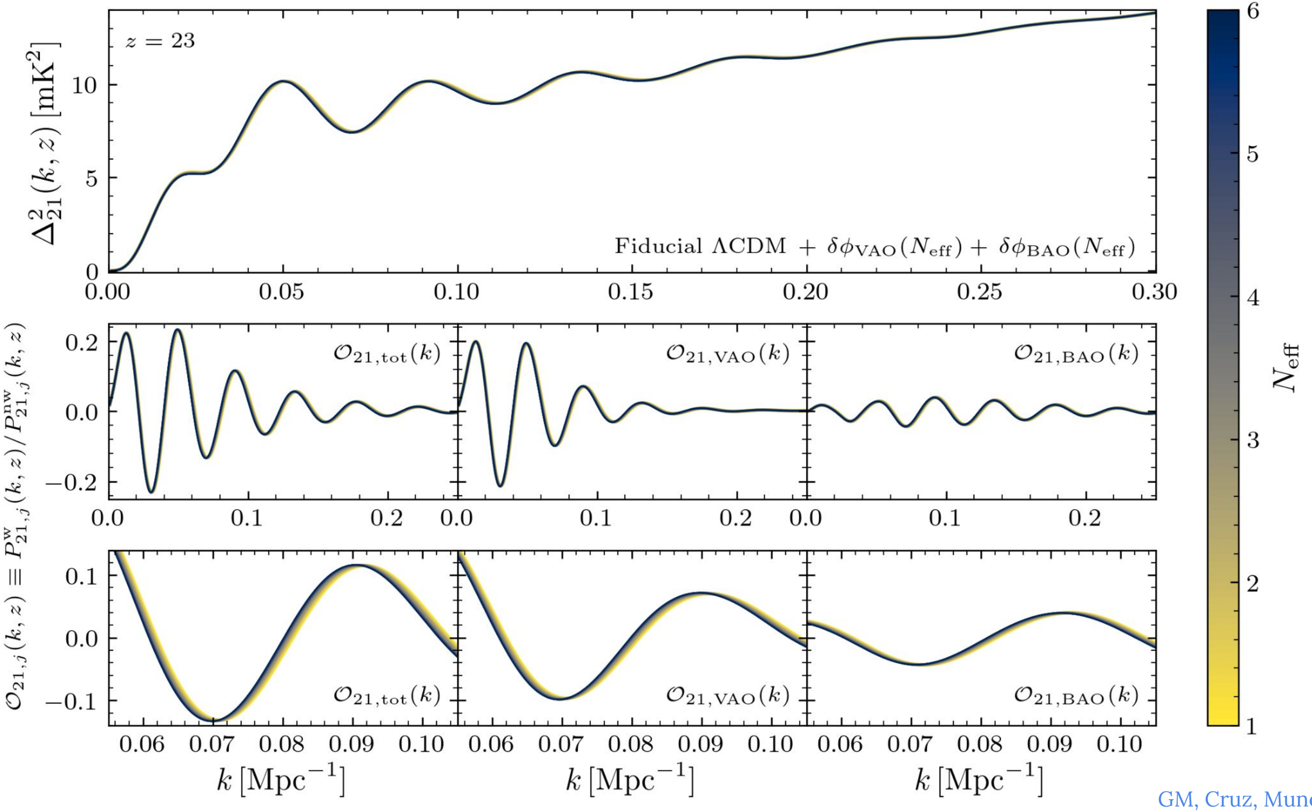
The Phase Shift in the 21-cm Spectrum

BAOs vs VAOs Phase Shift Template



GM, Cruz, Munoz, Kovetz, & Kamionkowski (2025)

The Phase Shift in the 21-cm Spectrum
A distinct redshift- and mode-dependent Signature



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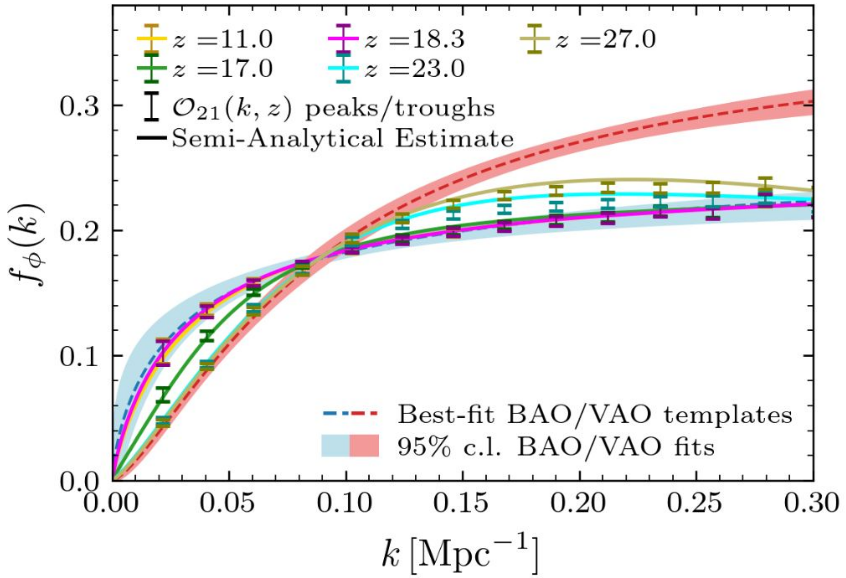

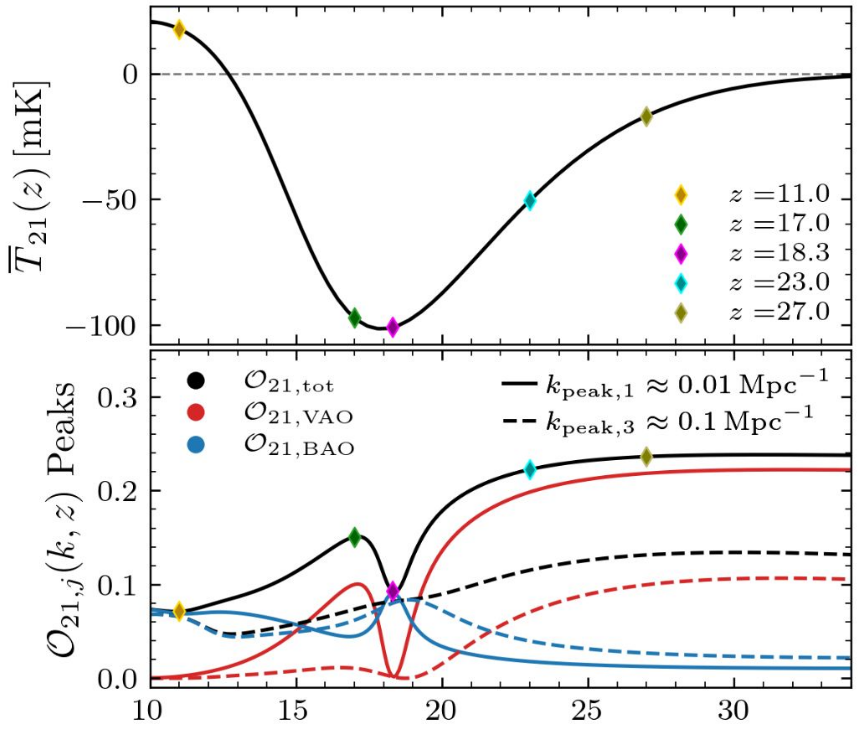

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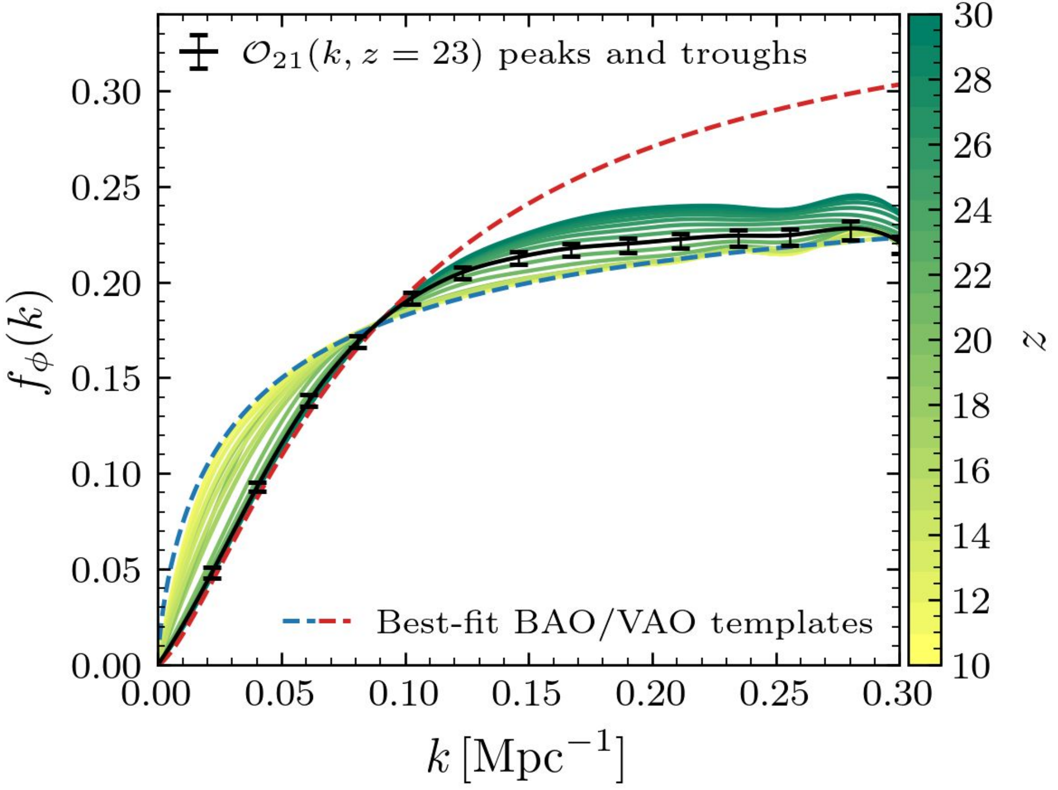

GM, Cruz, Munoz, Kovetz, & Kamionkowski (2025)