November 12th 2024

Pizza Seminar 2024
University of Texas at Austin, TX

Free-streaming neutrinos & the cosmic microwave background

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

TEXAS
The University of Texas at Austin

My Research Journey at UT

MY RESEARCH INTERESTS:

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

CMB

cosmic neutrinos

dark matter - standard model interactions

isocurvature perturbations

warm inflation

cosmological perturbations

dark matter freeze-in

primordial black holes

BBN

eternal inflation

MY COLLABORATORS AT UT:

Prof. Katherine Freese

Dr. Barmak Shams

Dr. Evangelos Sfiakanakis

+

Prof. Kimberly Boddy

Dr. Subhajit Ghosh

Dr. Gilly Elor

+

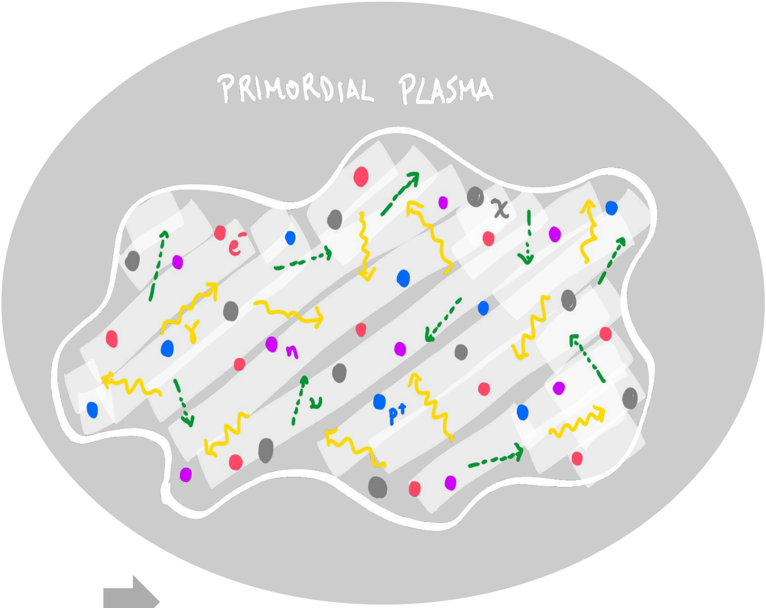
Joshua Ziegler

Jonathan Lozano

Robert Everett

The Big Picture

The Hot Big Bang



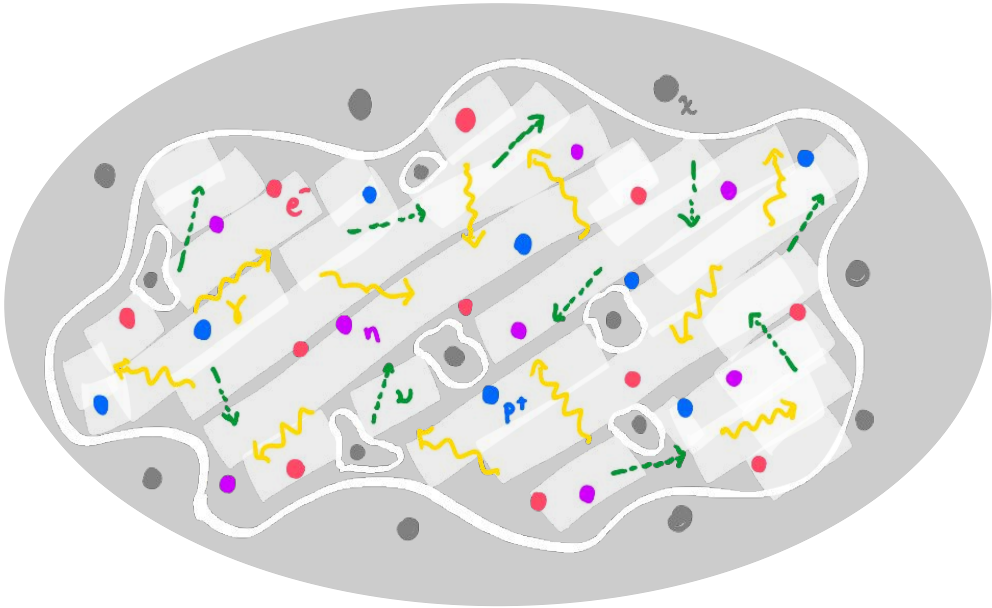
All SM particles species* are in thermal equilibrium at a temperature T

*possibly even dark matter

The Big Picture

$$(T_{\rm dec}) \approx H\,(T_{\rm dec})$$

interaction rate expansion rate



EXPANSION

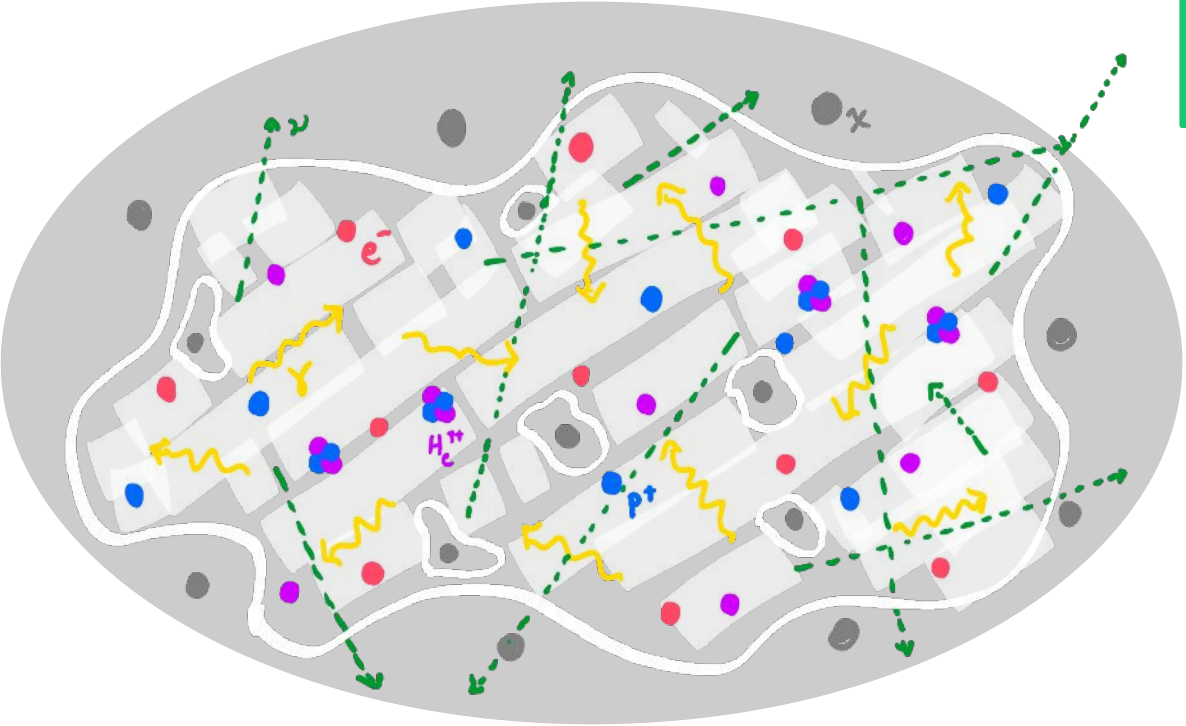
As the Universe expands, it cools and different species decouple from the primordial plasma

- The first one to go is dark matter

The Big Picture

$$(T_{\rm dec}) \approx H\,(T_{\rm dec})$$

interaction rate   expansion rate



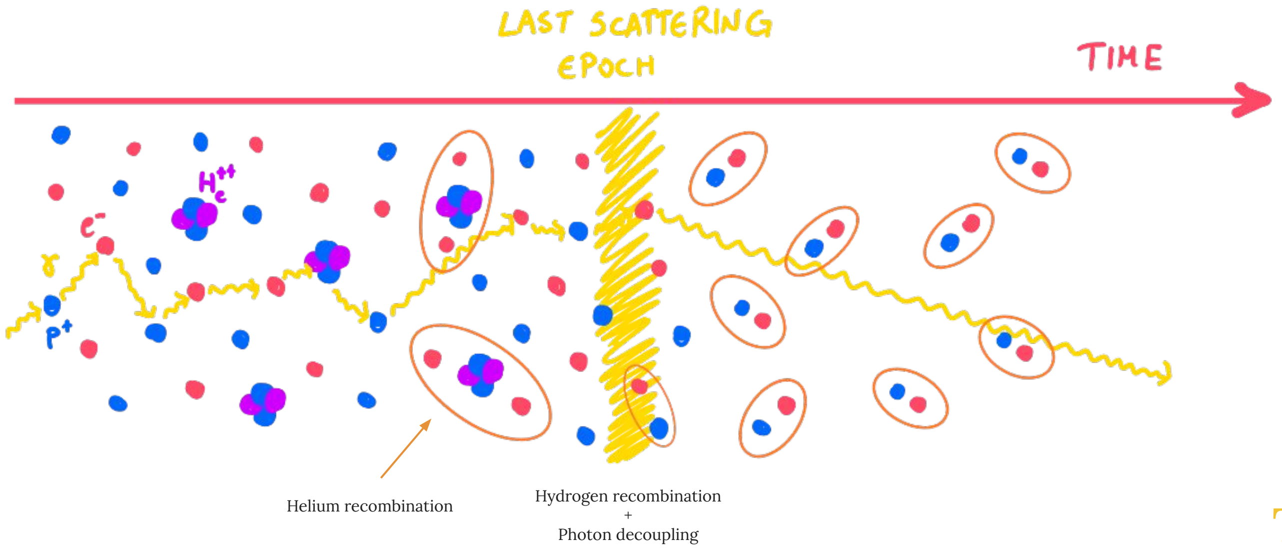
EXPANSION

Then neutrinos decouple, and shortly after nuclei form in the process known as Big Bang Nucleosynthesis

- Mainly ^{4}He
- Also ^{3}He, ^{2}H, ^{7}Li

T~ MeV

The Big Picture



T~ eV

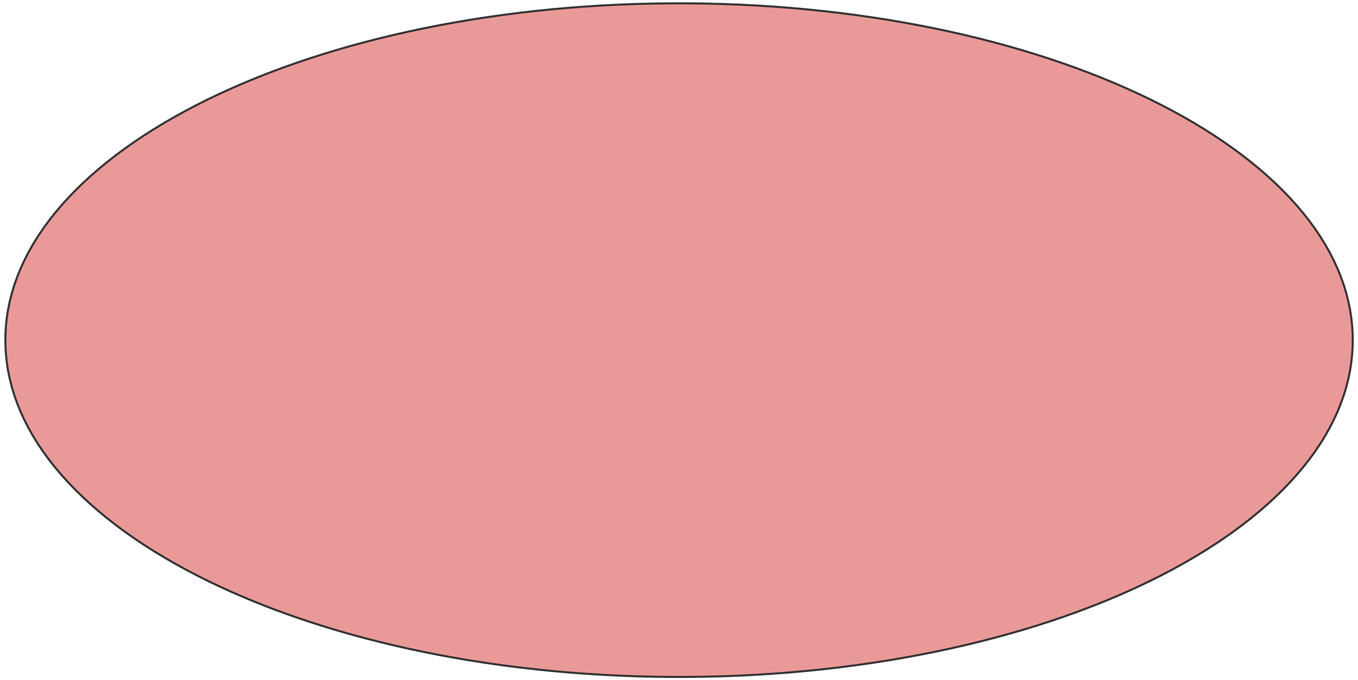
Once the universe is cool enough for neutral Hydrogen to form,
photons are finally free to travel across the universe, reaching us today

EXPANSION

If the Big Bang picture is correct, we expect the universe
to be filled by a Cosmic Background of photons,
all roughly at the same temperature.

The Cosmic Microwave Background

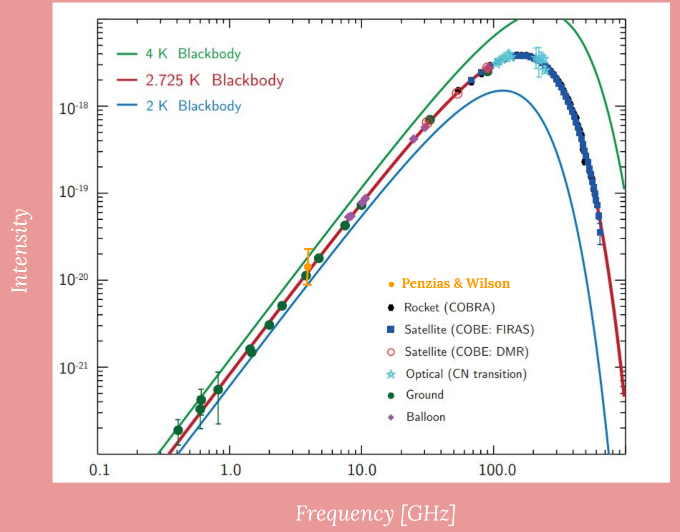
An almost perfect black-body spectrum at a temperature of **T_0 = 2.7255 K** today



The Cosmic Microwave Background

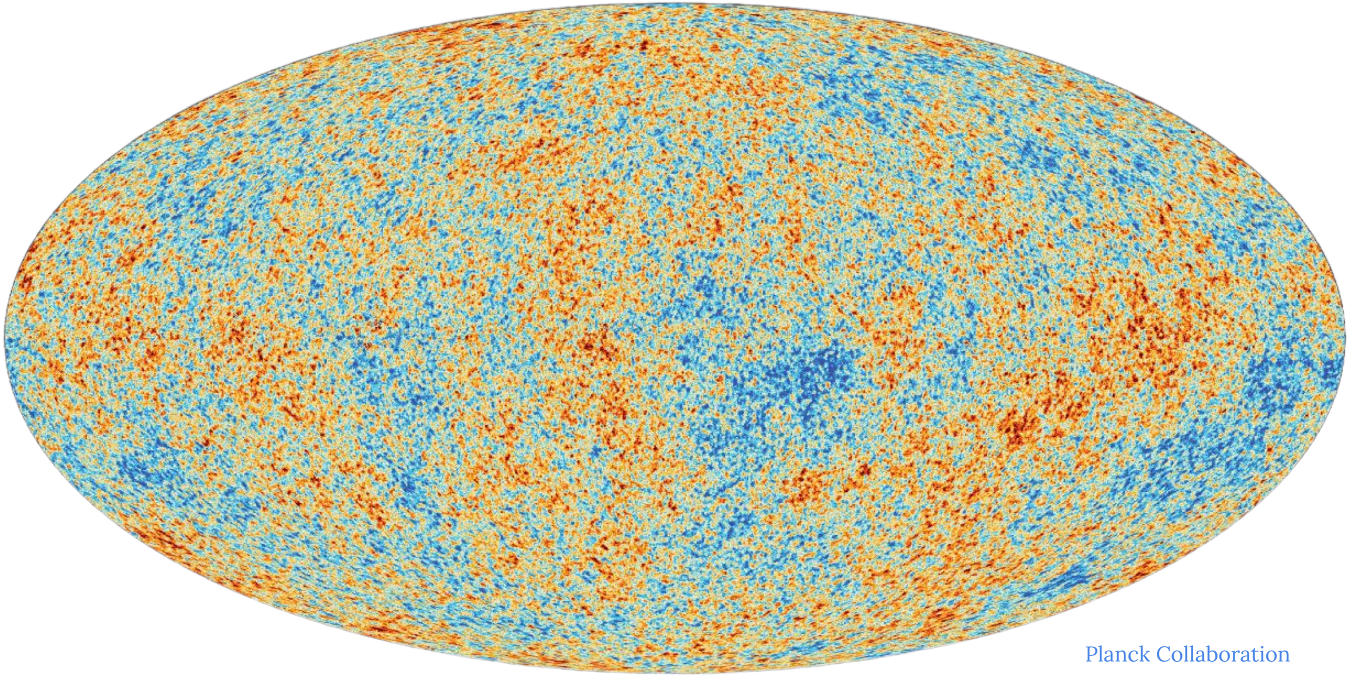
An almost perfect black-body spectrum at a temperature of T_0 = **2.7255 K** today

- Discovered by Penzias & Wilson (1965)
- First spectrum measurement by the **COBE FIRAS** instrument (1990)



The Cosmic Microwave Background

Small temperature anisotropies in the order of $\Delta T/T \sim 10^{-4}$



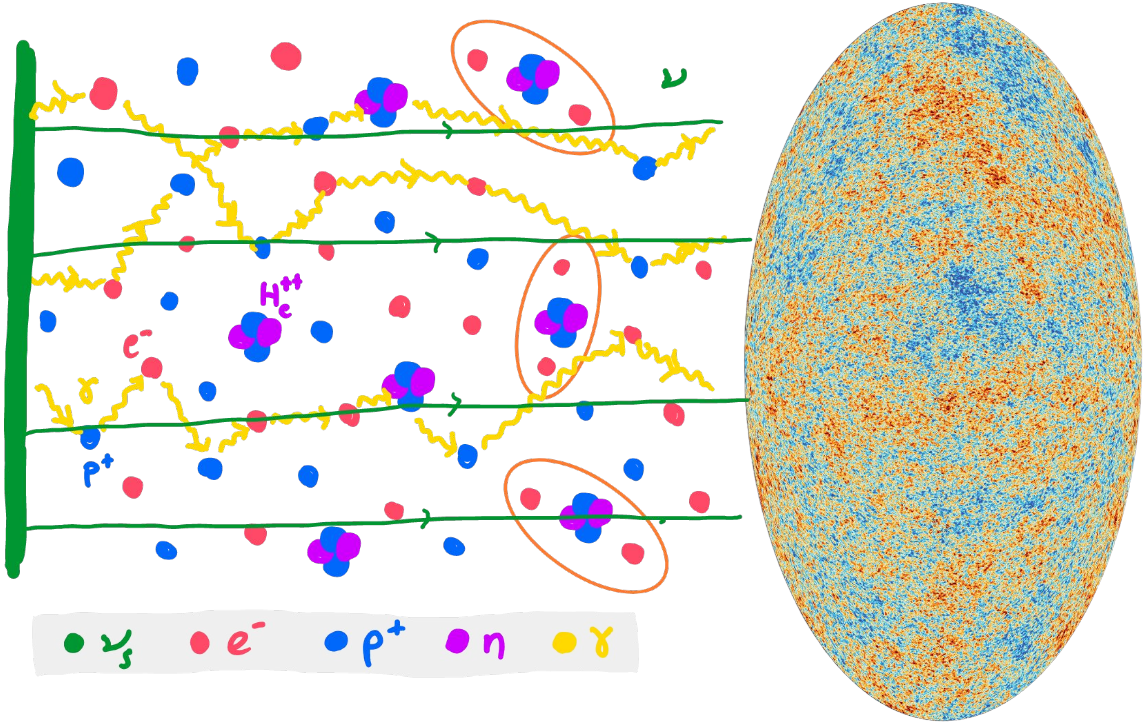
Planck Collaboration

Neutrinos & the CMB

Small temperature anisotropies in the order of $\Delta T/T \sim 10^{-4}$

Cosmic Neutrino Background

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



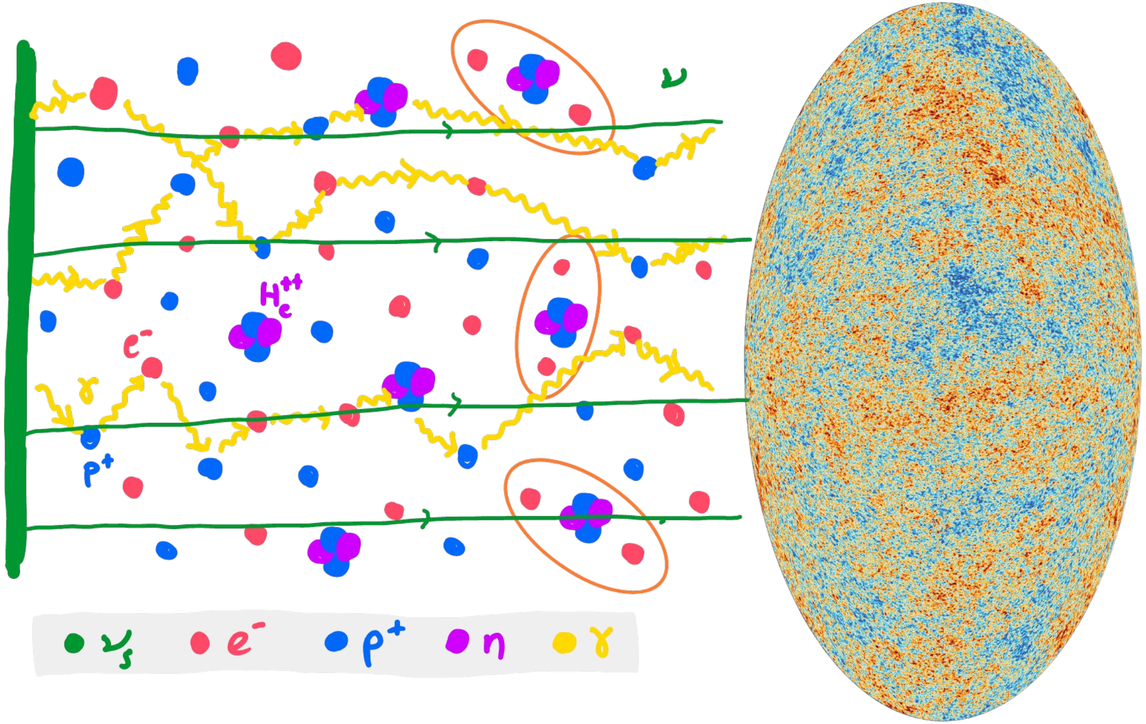
- Significant fraction of **energy density** in neutrinos
- **Free-streaming** since their decoupling at **t~1 s**

Neutrinos & the CMB

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

Cosmic Neutrino Background

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



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Can we detect this?

Neutrinos & the CMB

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

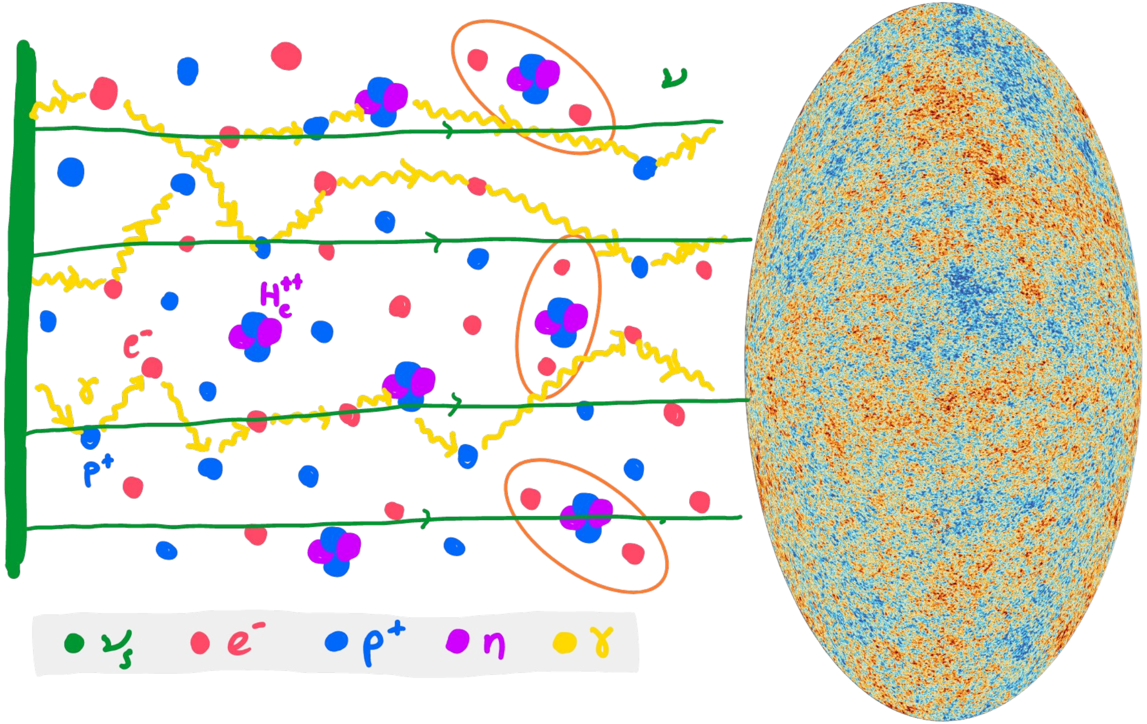
$\Delta T/T \sim 10^{-4}$

Cosmic Neutrino Background

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

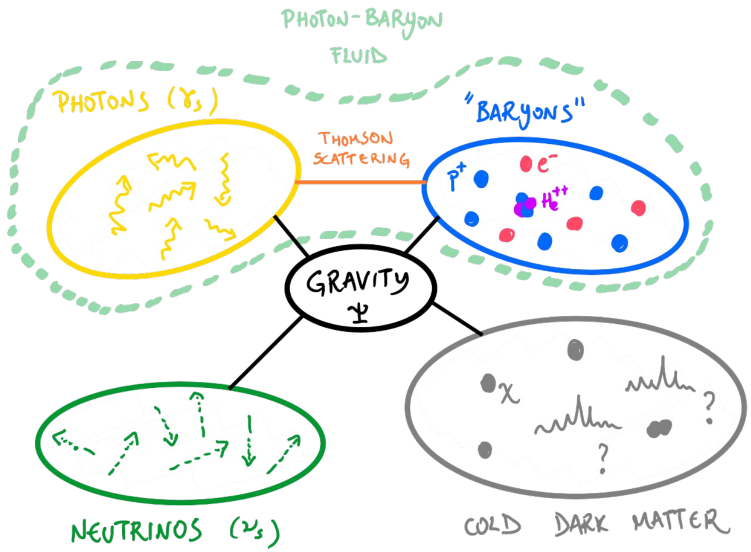
Can we detect this?

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

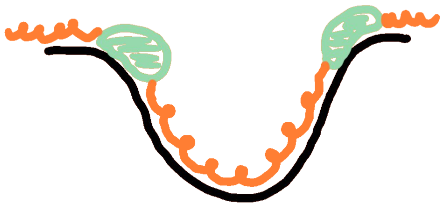


Cosmic sound waves

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



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



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

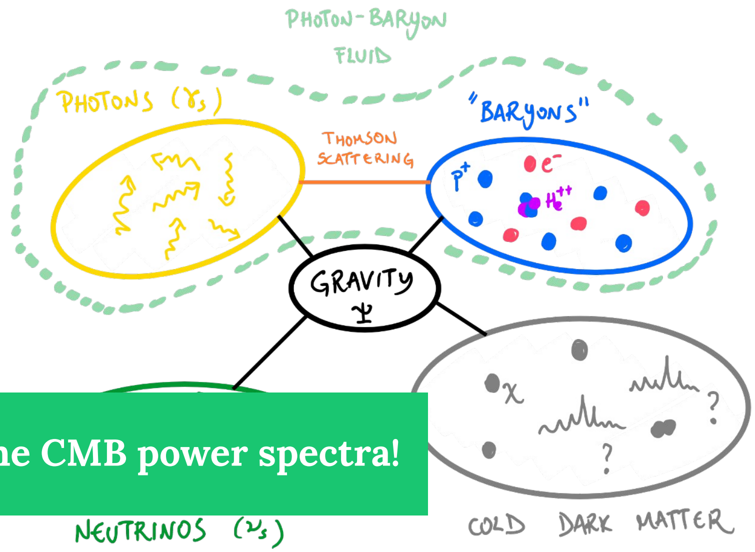
$$c_s^2 \sim \frac{c^2}{3(1+R_b)} \quad R_b \equiv 3\bar{\rho}_b/(4\bar{\rho}_\gamma)$$

Baryons add inertia to the fluid

Cosmic sound waves

- Photons and baryons are **tightly coupled**
- 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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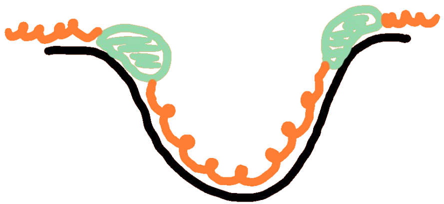

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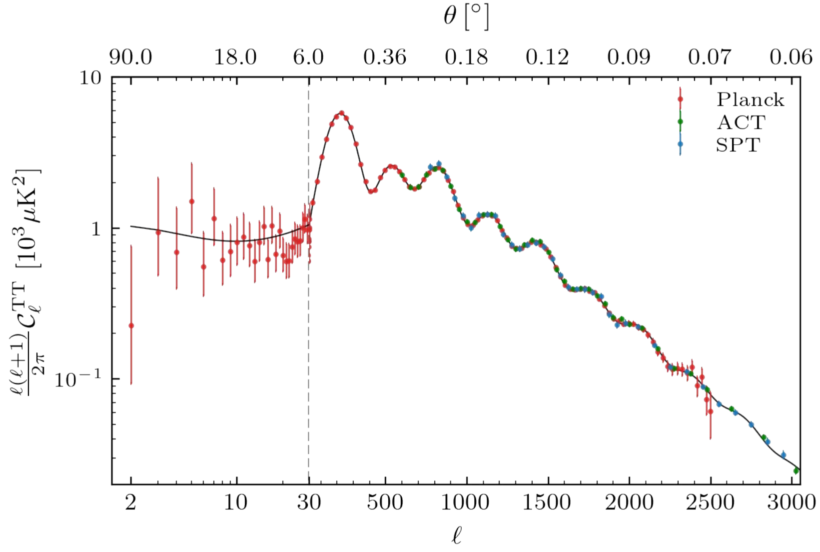
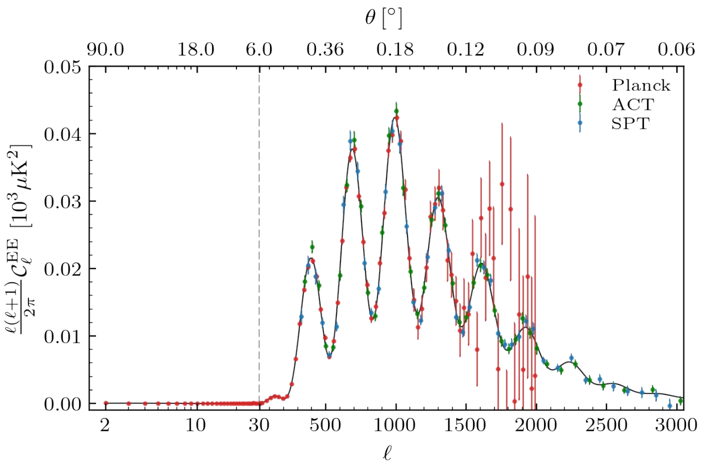
Baryons add inertia to the fluid

The CMB power spectra

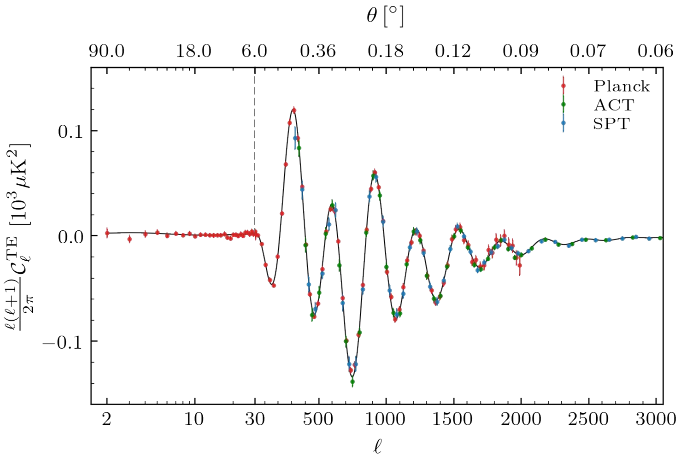
Polarization spectrum traces **velocity** perturbations

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





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



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 $\mathbf{N_{eff}}$, known as *the effective number of relativistic species*
  - In the SM, $\mathbf{N_{eff} = 3.044}$ Akita1, Yamaguchi (2020)
- Cosmology is sensitive to their gravitational effects

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

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

Planck 2018

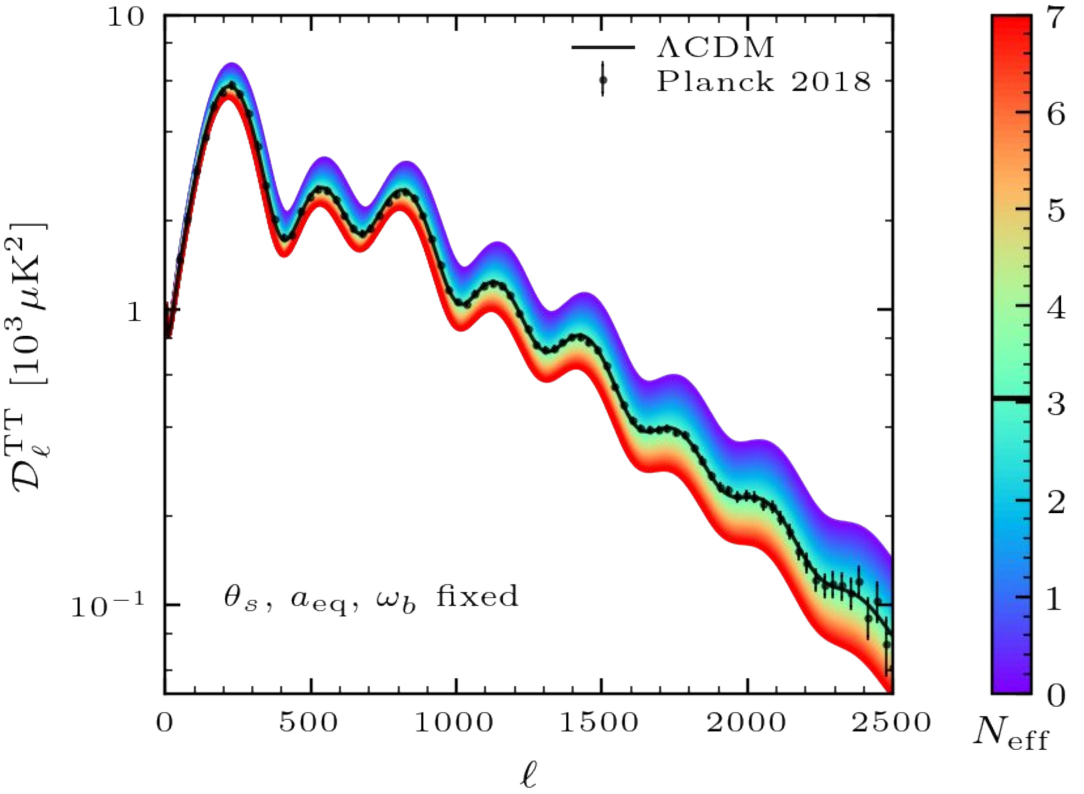
Cosmic neutrinos in the CMB energy density

- 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**

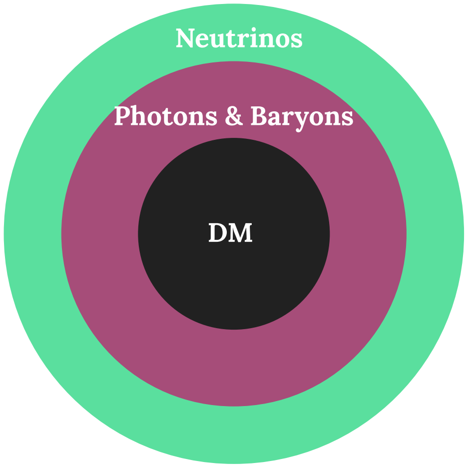
$$\mathcal{D}_\ell^{XY} \equiv \frac{\ell(\ell+1)}{2\pi}\mathcal{C}_\ell^{XY}$$

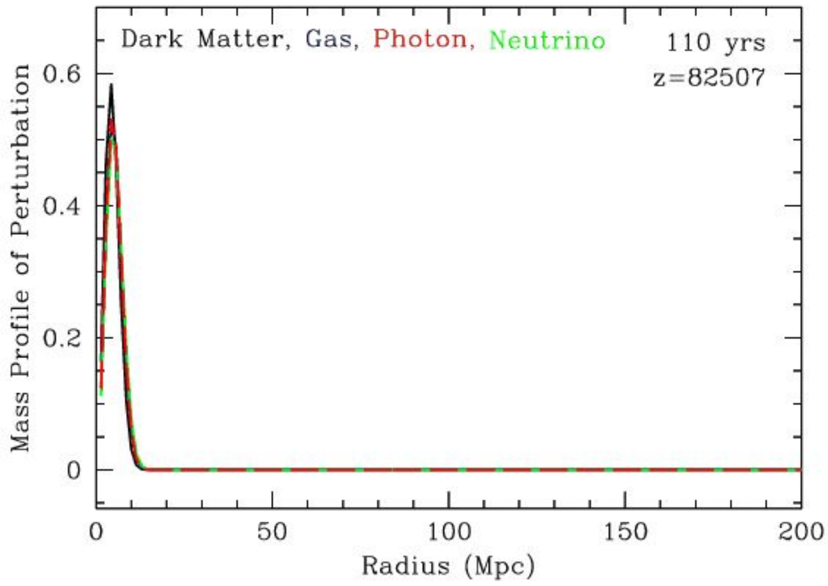


Cosmic neutrinos in the CMB
free-streaming nature

- 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

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

  Bashinsky & Seljak (2003)

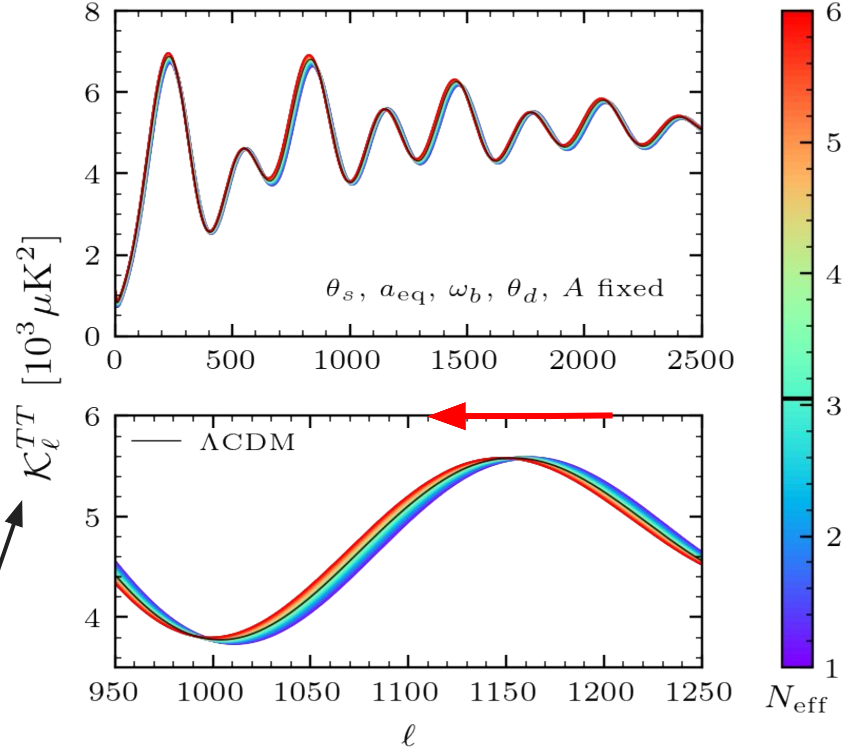
  - Larger radii → smaller multipoles
  - Small effect, prop. to: $\epsilon_\nu \equiv \rho_\nu/\rho_r$

- 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

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



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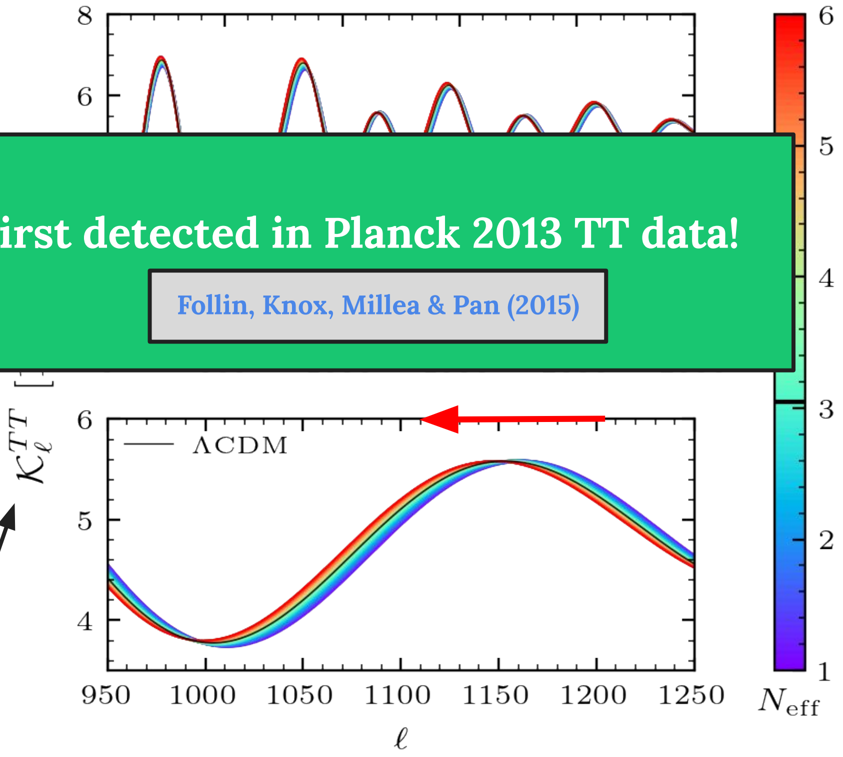


First detected in Planck 2013 TT data!

Follin, Knox, Millea & Pan (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

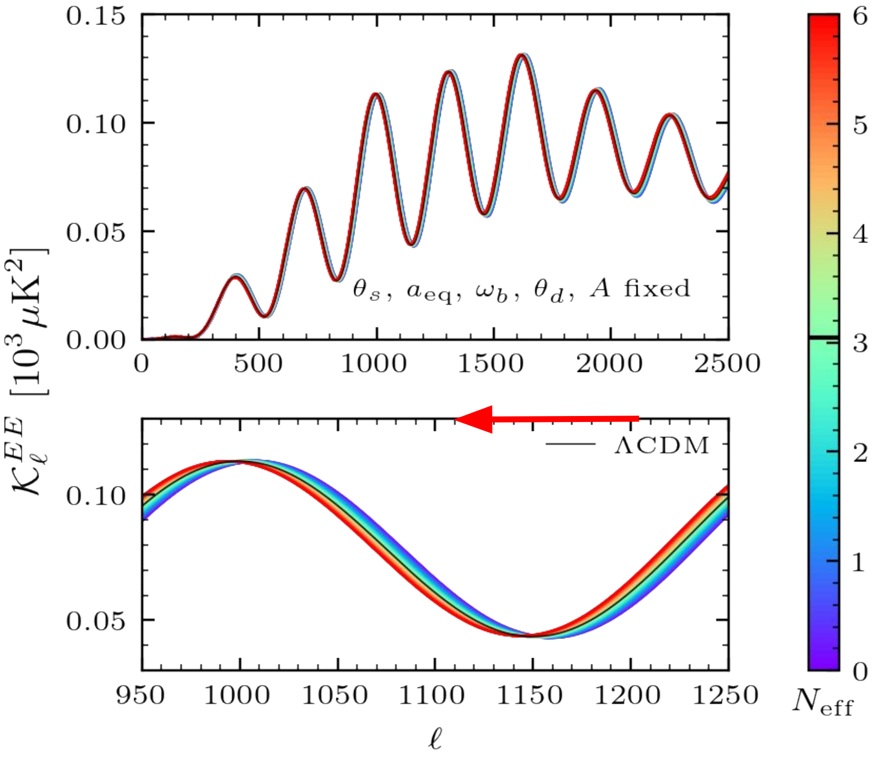
Cosmic neutrinos in the CMB
free-streaming nature

- 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 phase shift in the CMB power spectra

Following Follin, Knox, Millea & Pan (2015)

- A new parameter to control the shift

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

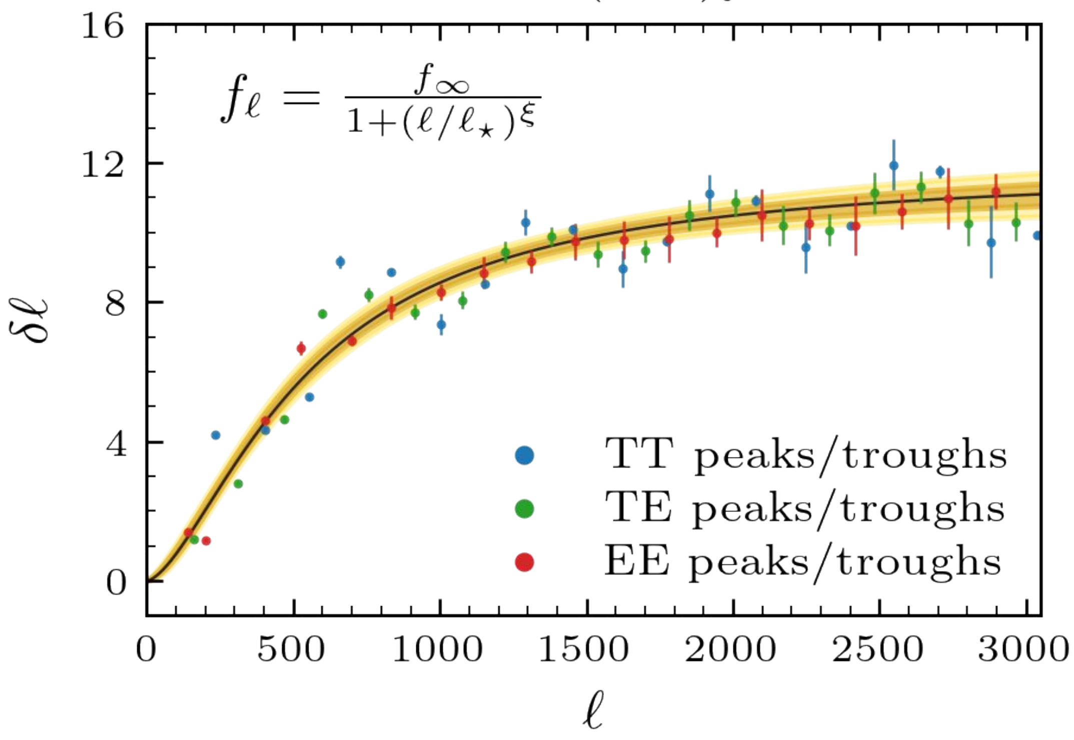
$$\delta\ell = \left[A(N_{\text{eff}}^{\delta\ell}) - A(N_{\text{eff}})\right] f_\ell$$

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

Our Contributions:

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

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



GM, Wallisch & Freese (in prep.)

Phase-shift constraints
spectrum-based analysis

- Based on Planck 2013 temperature only:

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

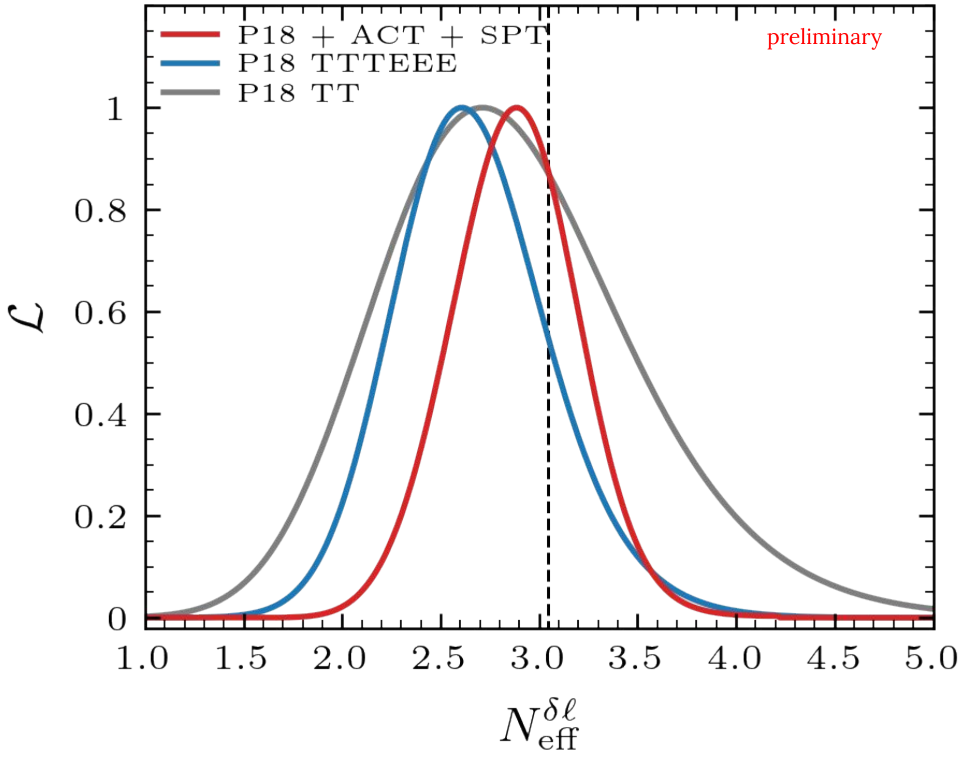
$(\, N_{\rm eff} = N_\nu = 3.044\,)$

- Work in Progress (preliminary)
  - 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: $N_{\rm eff}^{\delta\ell} = 2.9^{+0.3}_{-0.3}$

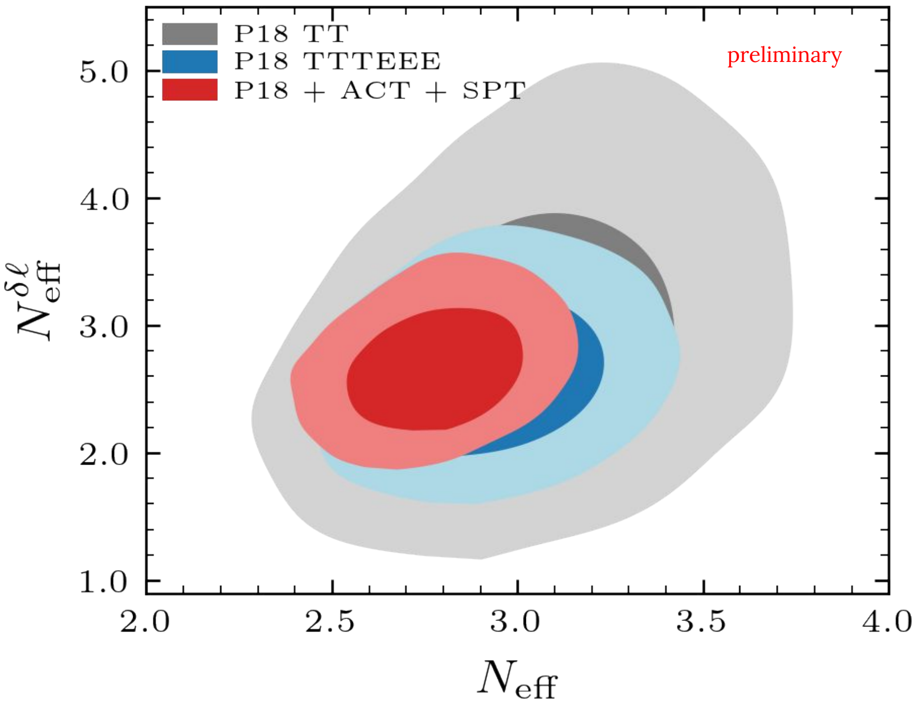
$(\, N_{\rm eff} = N_\nu = 3.044\,)$



GM, Wallisch & Freese (in prep.)

Phase-shift constraints
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 (in prep.)

Main Takeaways

- The CMB is consistent with **a black-body spectrum** at a temperature of **2.7255 K**, providing strong evidence that the early universe was in **near-perfect thermal equilibrium**, thereby confirming the Big Bang Theory.
- The **patterns of fluctuations** in the CMB encode a wealth of information about the **universe's composition** and the physics that governed its **evolution**
- **Neutrinos** leave a sizable **gravitational imprint** in the CMB, which we can use to **constrain their properties**
  - The **phase shift** is a robust probe of **free-streaming neutrinos**
  - Current data are **compatible** with the **Standard Model**, constraining non-standard neutrino physics.

Main Takeaways

Grazie per l’attenzione!

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Back-up Slides

Gabriele Montefalcone

Weinberg Institute for Theoretical Physics, University of Texas at Austin

Cosmic timeline

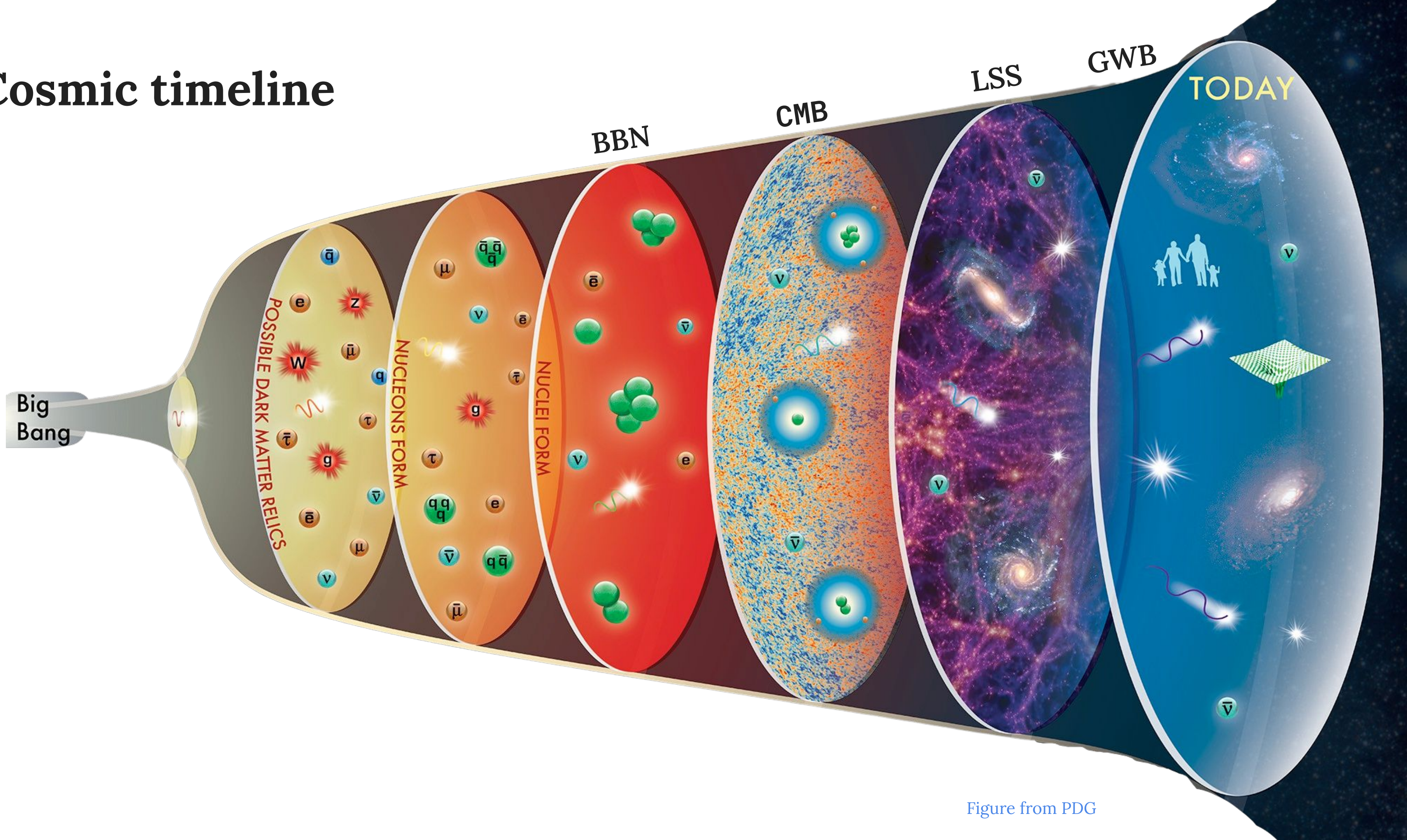
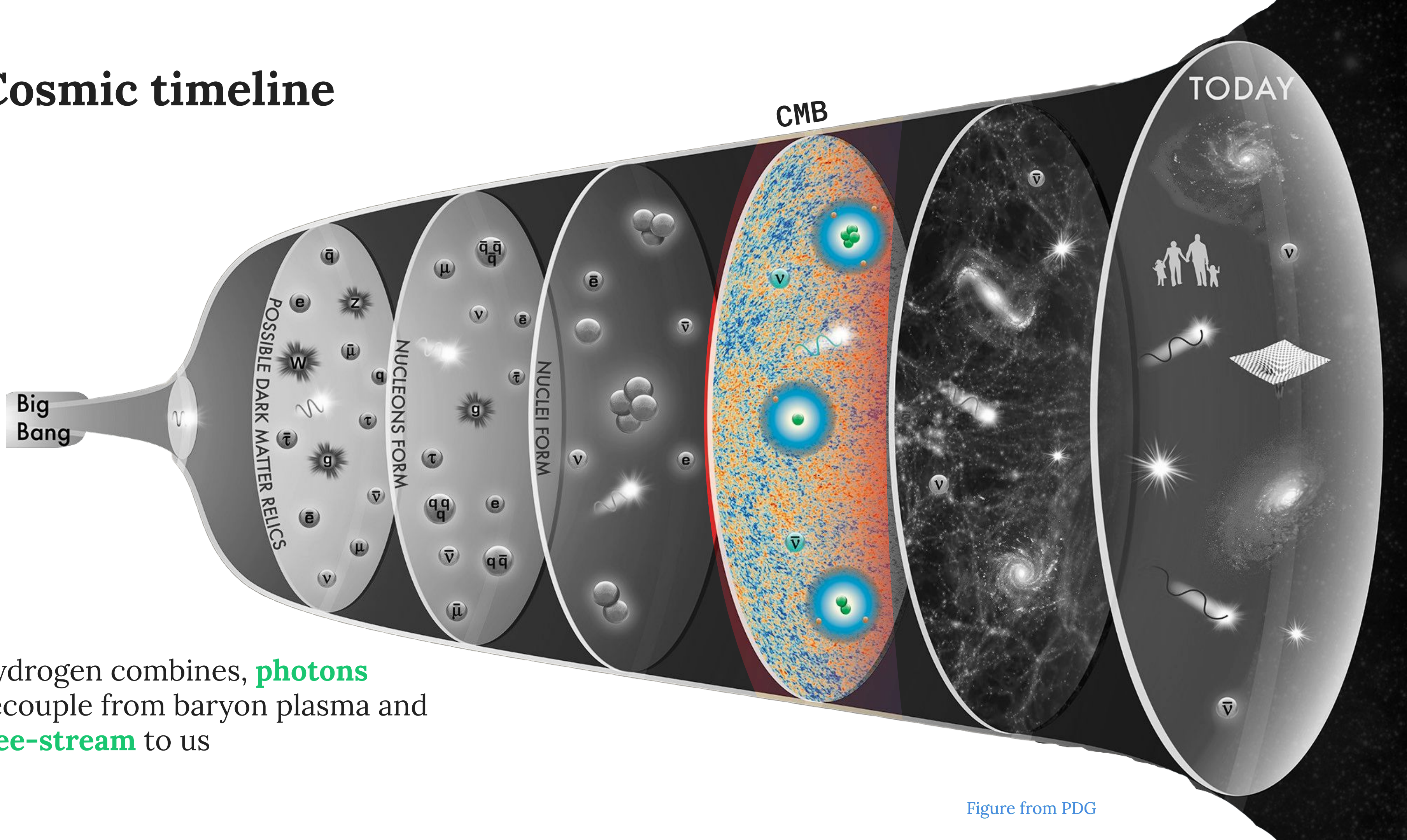


Figure from PDG

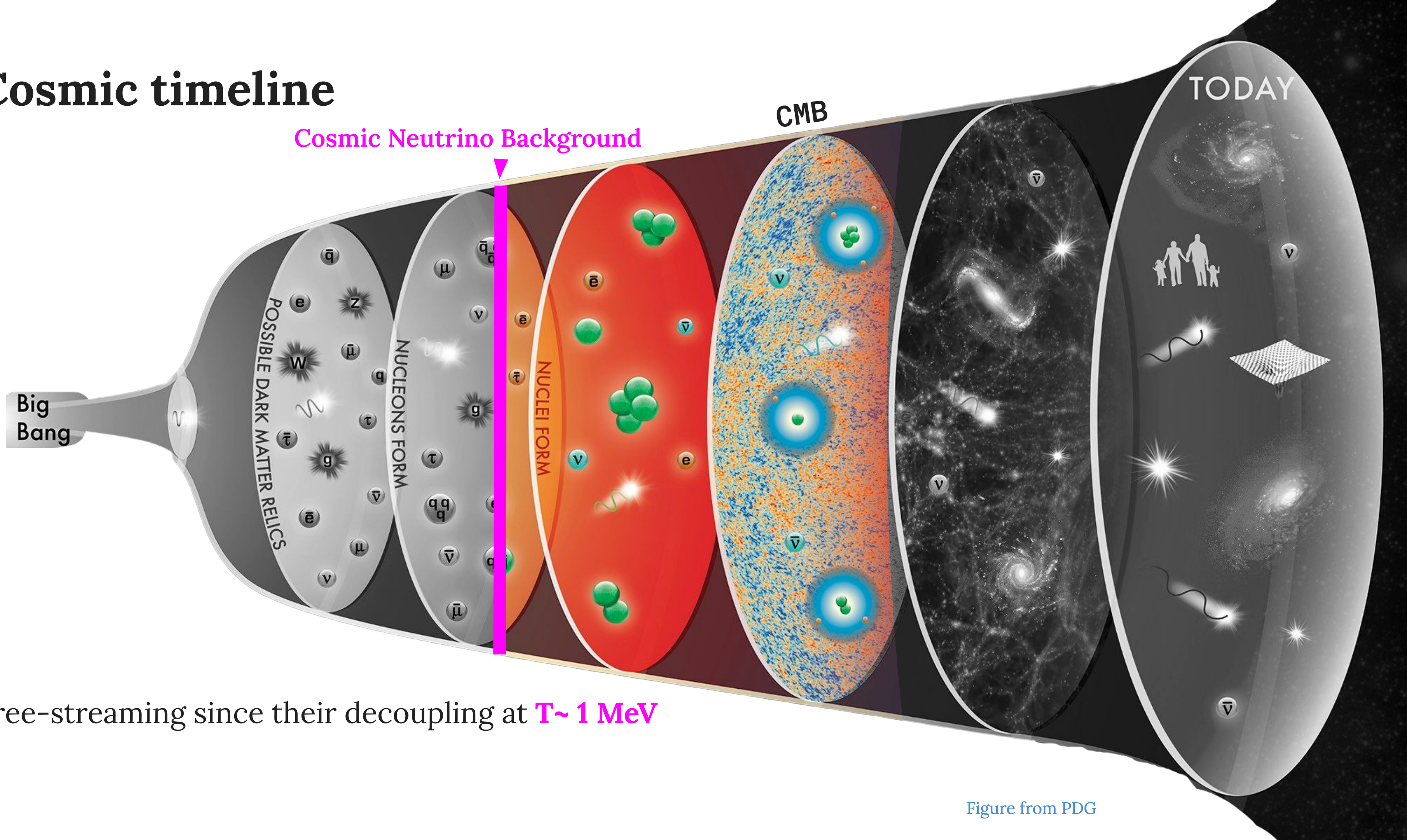
Cosmic timeline



Hydrogen combines, **photons** decouple from baryon plasma and **free-stream** to us

Figure from PDG

Cosmic timeline

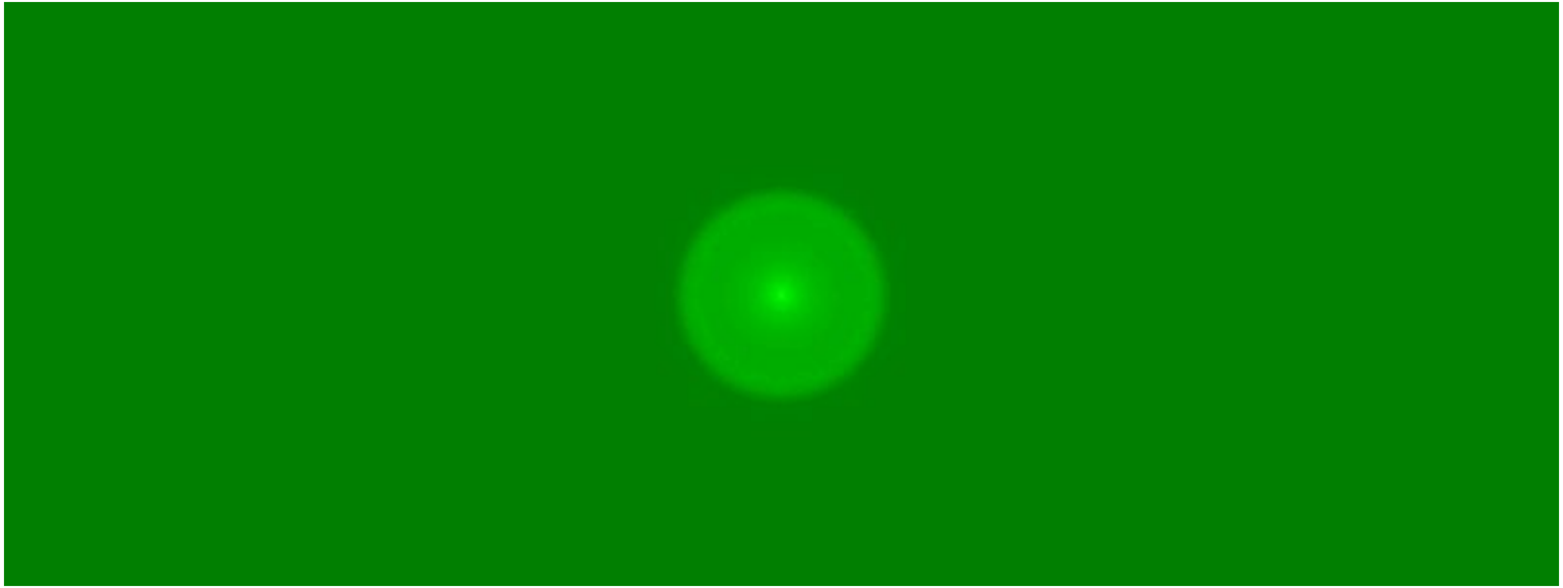


Free-streaming since their decoupling at **T~ 1 MeV**

Figure from PDG

Cosmic sound waves

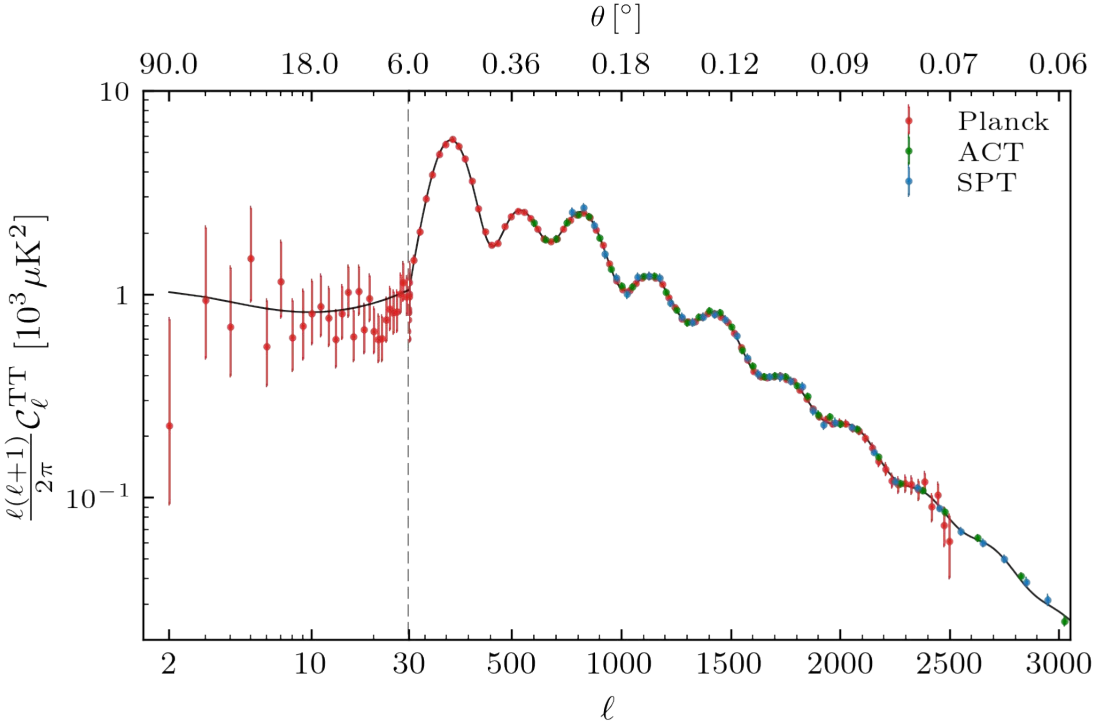
The CMB is the final snapshot of the superposition of many incoherent sound waves, that have been oscillating for ~400,000 years



The state of these oscillations is **frozen** at recombination when the baryons release the photons.

The CMB power spectra

The CMB angular temperature power spectrum represents the variance of temperature fluctuations as a function of angular scale



$$\delta_\gamma \sim A_{\vec{k}} \cos(c_s k \tau)$$

$$C_\ell^{TT} \propto \cos^2(\theta_s \ell)$$

The CMB Power Spectrum

The CMB angular power spectrum represents the variance of temperature fluctuations as a function of angular scale

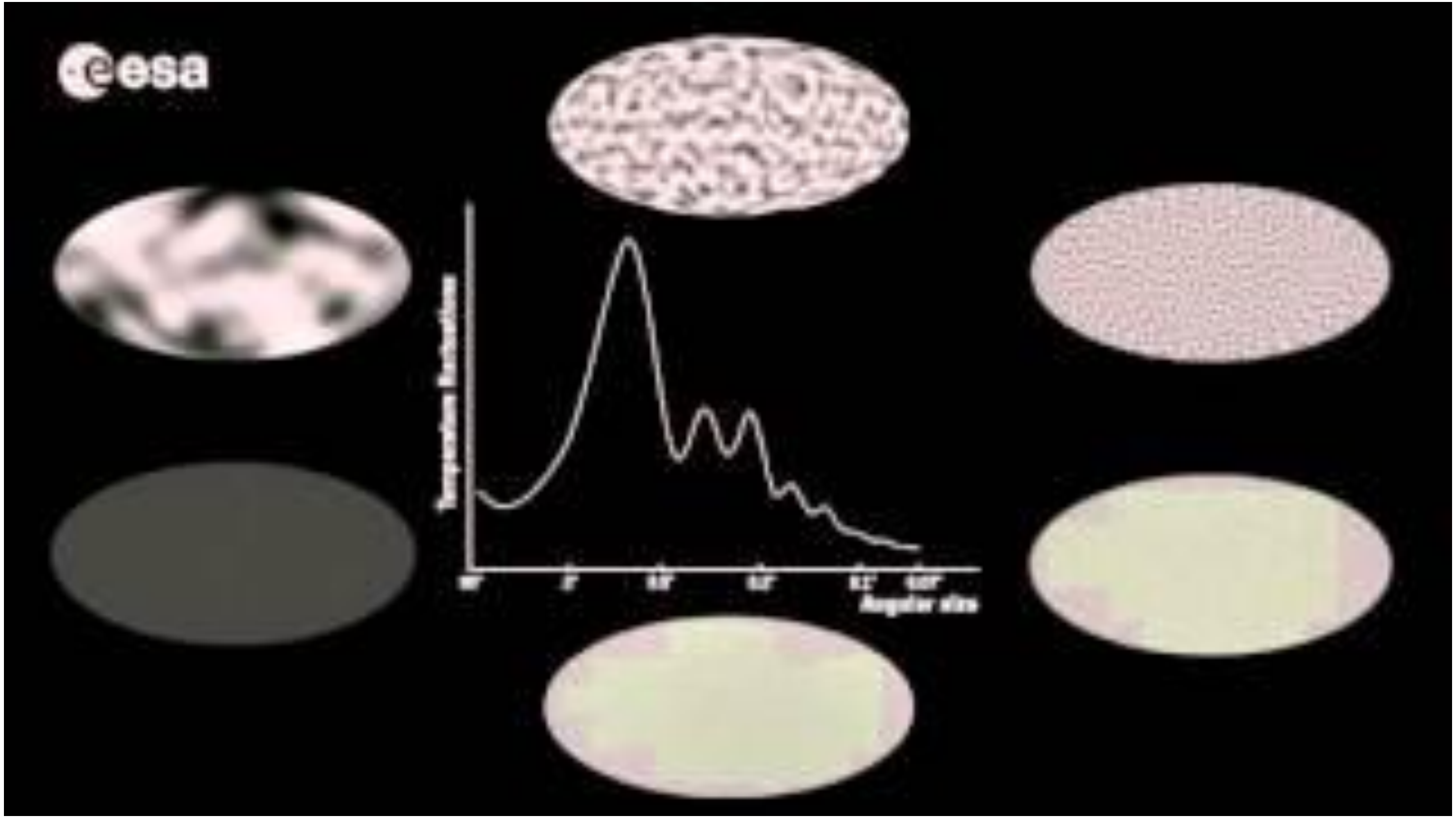
A spherical harmonic expansion of the temperature field

$$\Theta(\hat{\mathbf{n}}) \equiv \frac{\Delta T(\hat{\mathbf{n}})}{\bar{T}} = \sum_{\ell m} \Theta_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

$$C_\ell \equiv \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\Theta_{\ell m}|^2$$

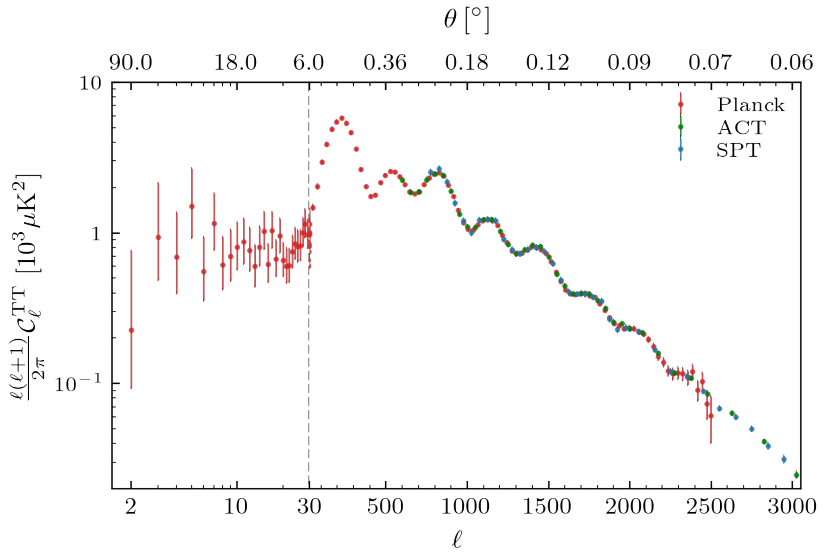
This compresses 10^7 pixels of the CMB map into 10^3 multipole moments

CMB Power Spectrum

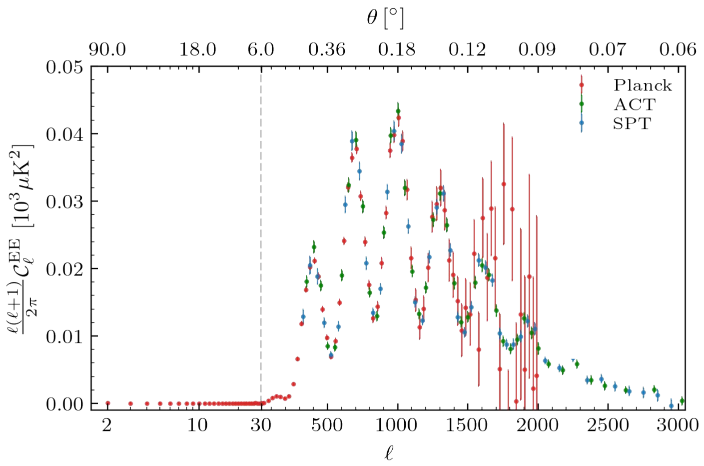


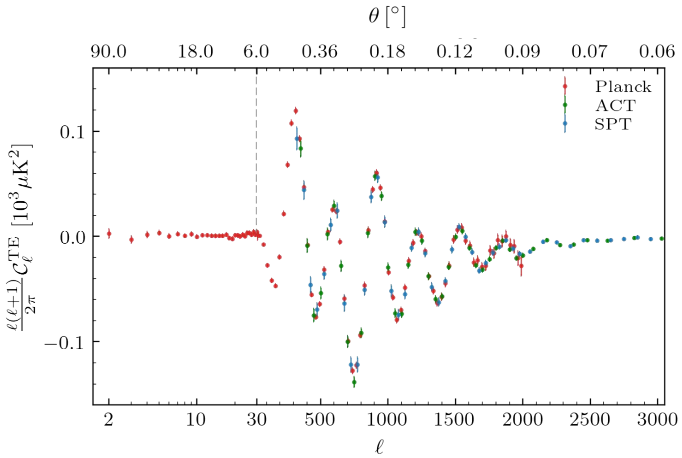
The CMB power spectra

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

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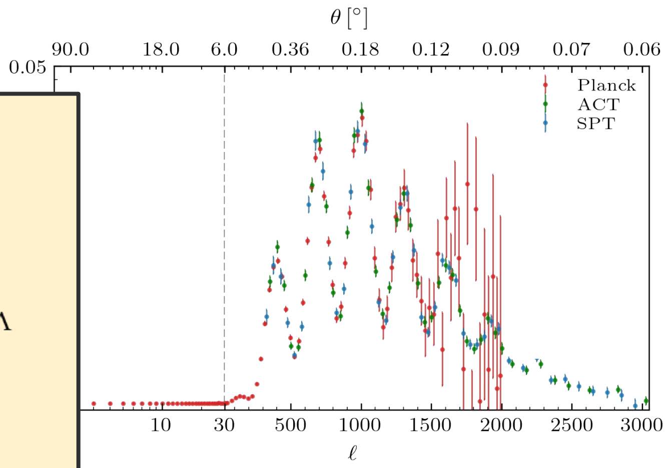
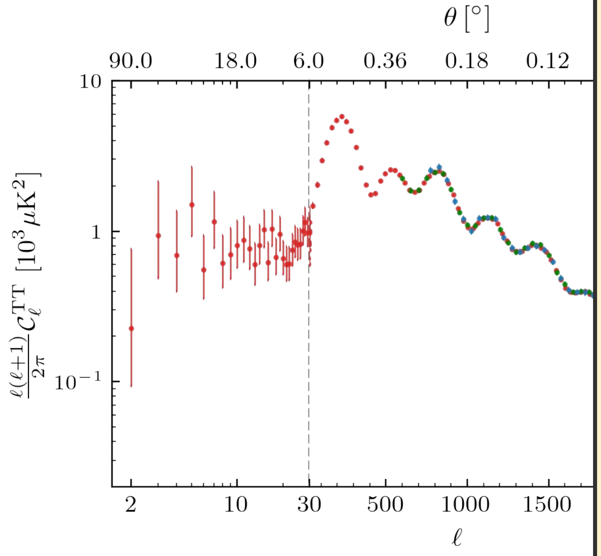
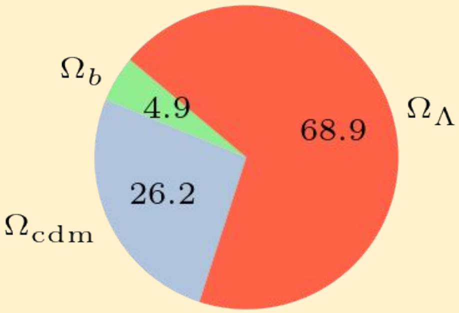


Temperature spectrum traces **density**
roughly the gravitational potential



ΛCDM



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

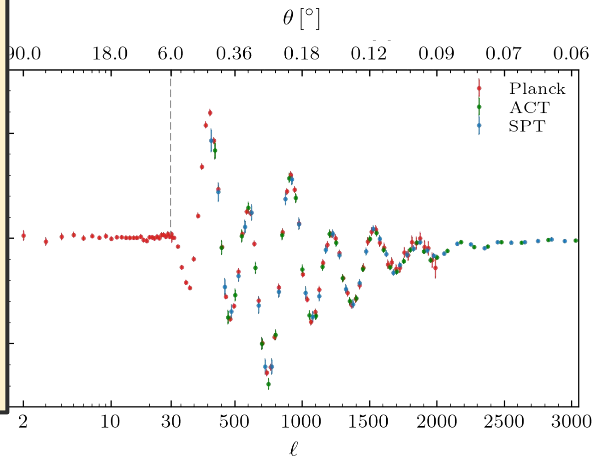
$n_s = 0.965$

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

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

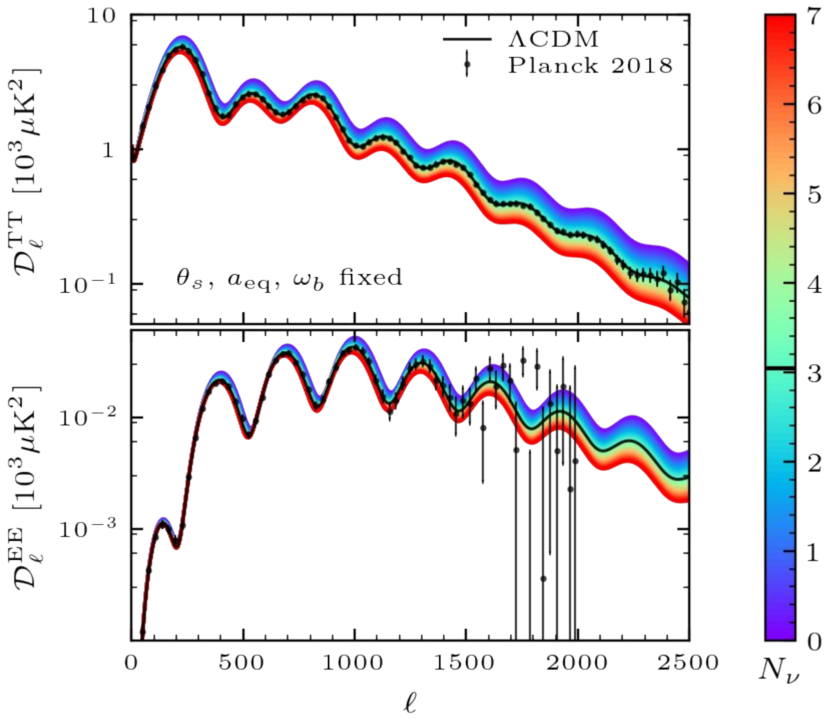
+ ...

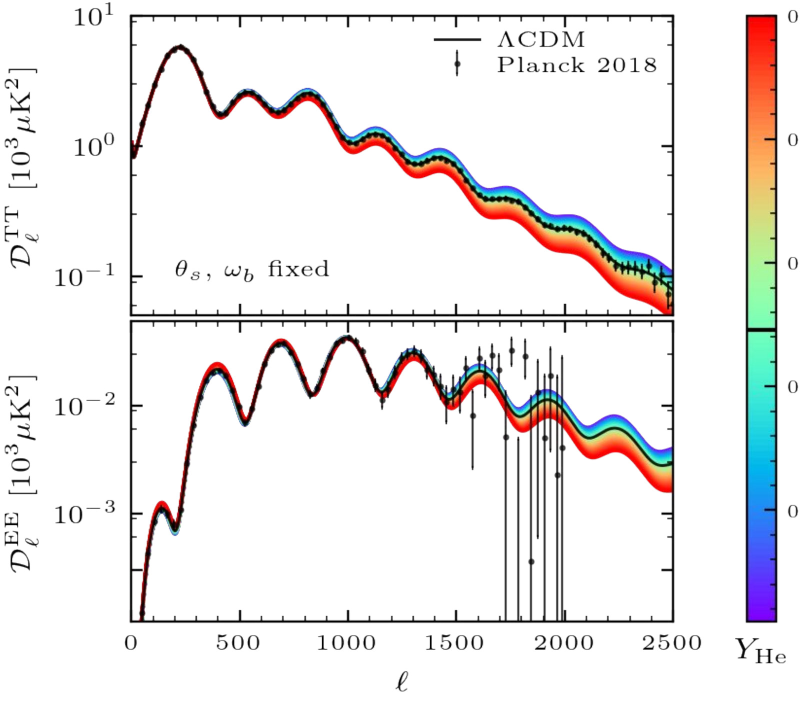
TE spectrum roughly
moving into the gravit



Cosmic neutrinos in the CMB
energy density

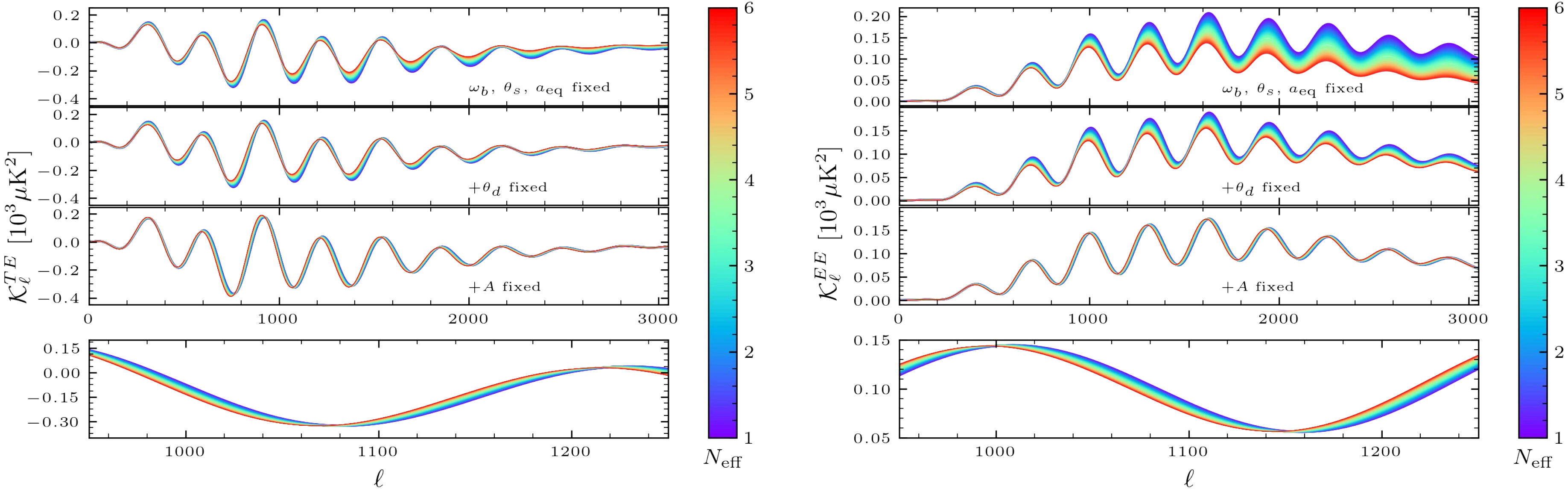
$$\theta_d \propto (H/n_e)^{1/2}\theta_s$$





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

Cosmic neutrinos in the CMB
free-streaming nature



The phase shift in the CMB 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

$$S_X(k,\eta)$$

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

$\downarrow$

X Anisotropies

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

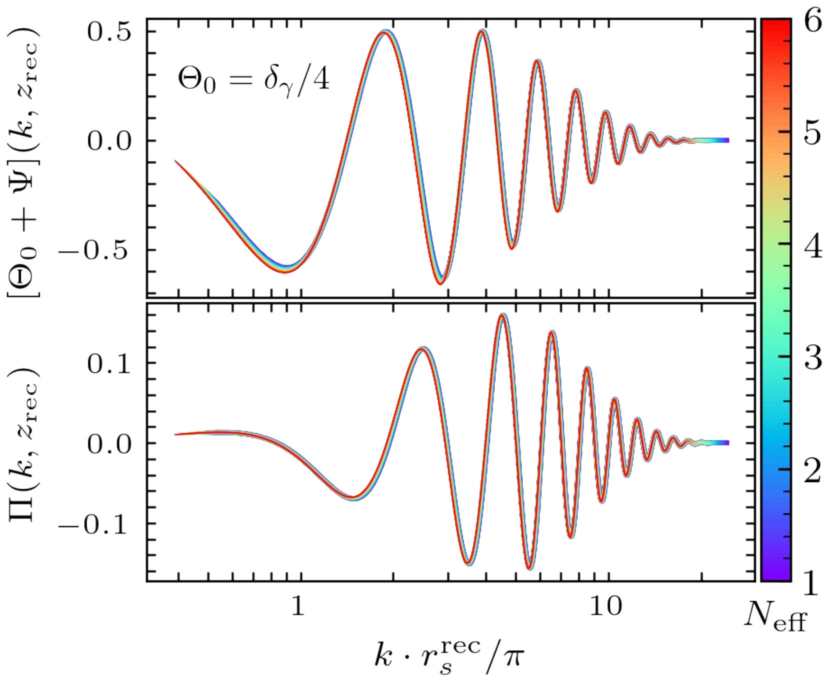
$\downarrow$

XY Power Spectra

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

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

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



GM, Wallisch & Freese (in prep.)

The phase shift in the CMB perturbations

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

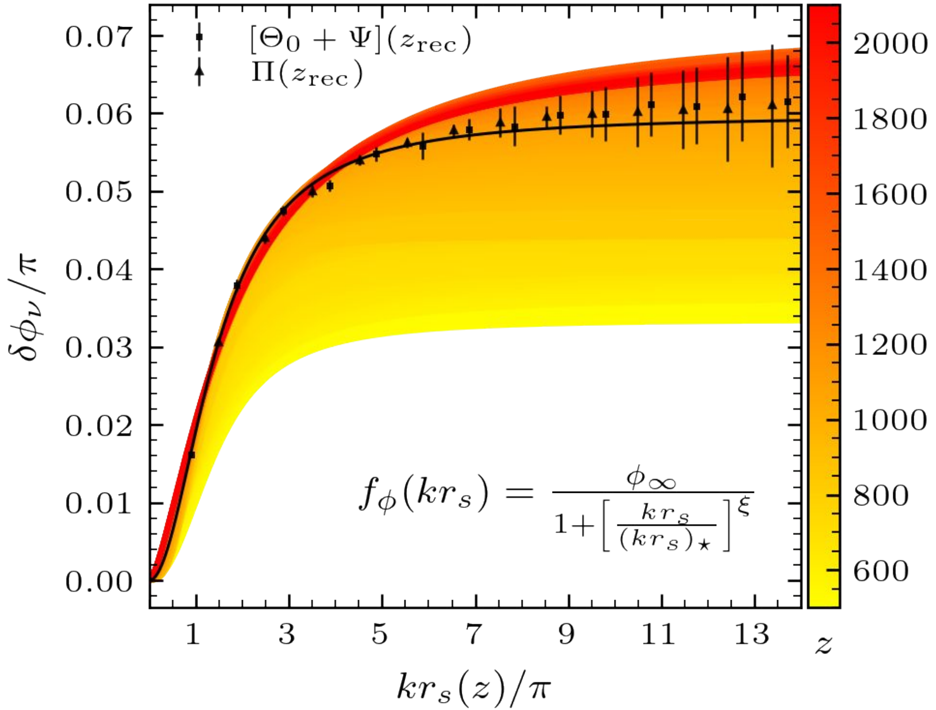
- A new parameter to control the shift

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

$$\delta\phi_\nu = \left[A(N_{\rm eff}^{\delta\phi}) - A(N_{\rm eff})\right] f_\phi$$

$$S_X(k,\eta) \to S_X(k + \delta\phi_\nu / r_s, \eta)$$

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



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

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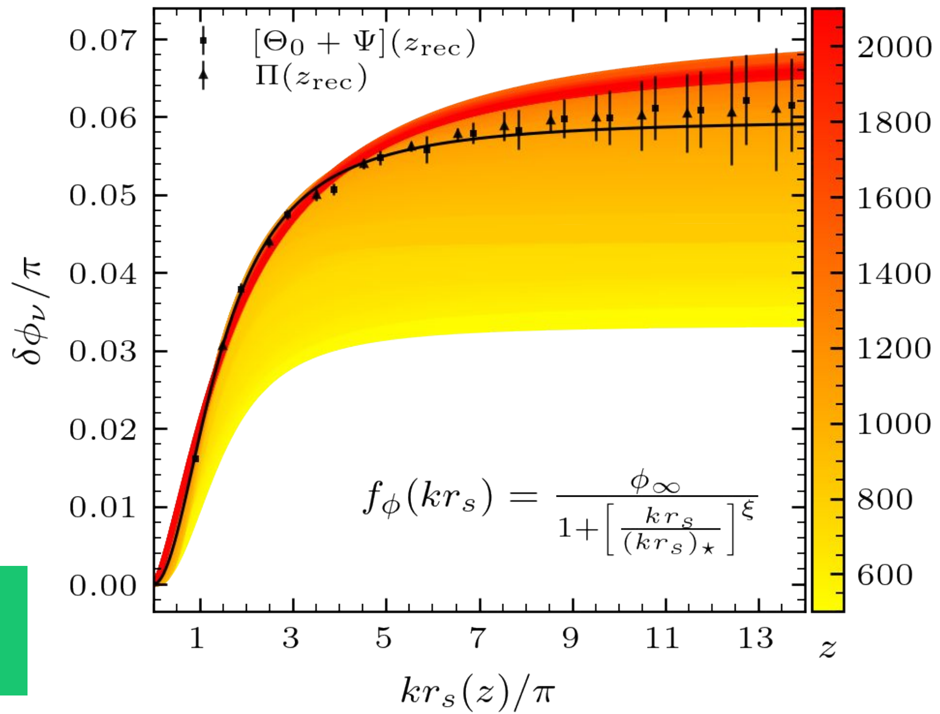

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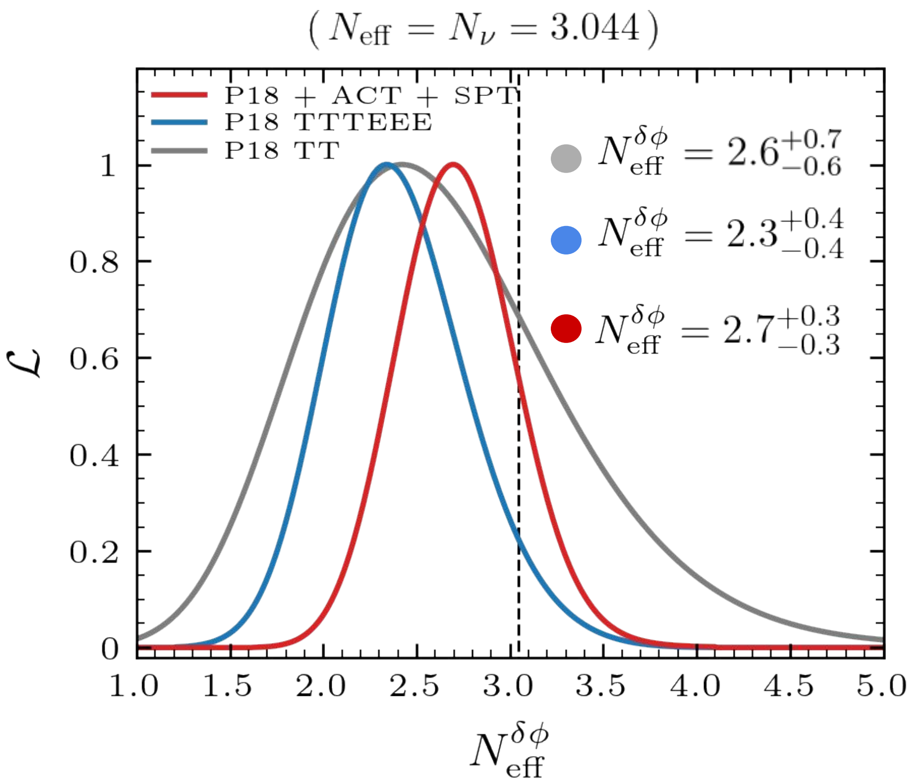
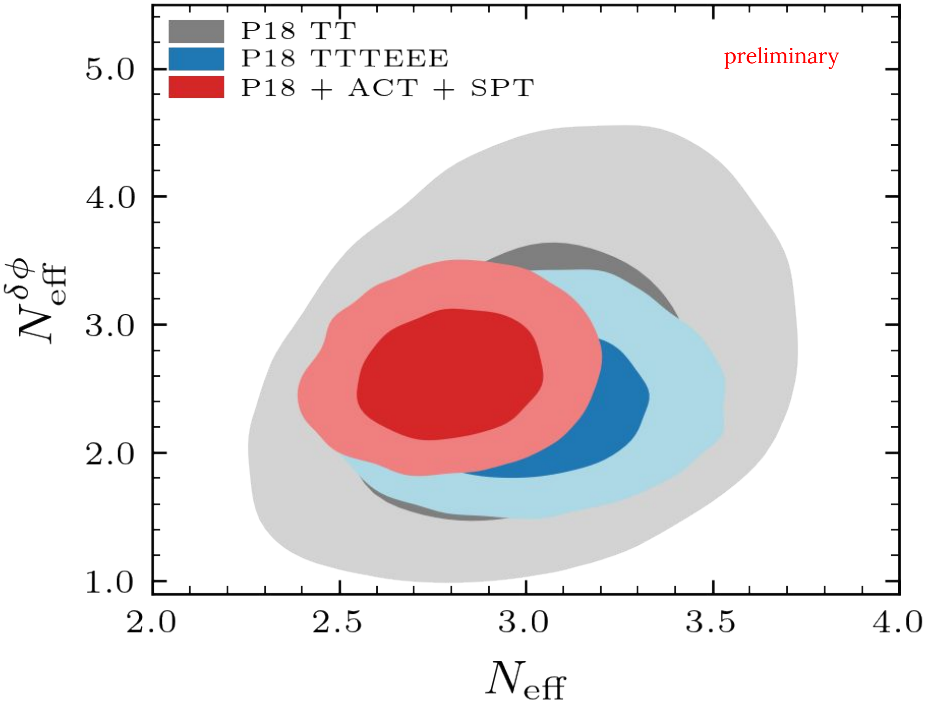
Phase-shift constraints
perturbations-based analysis

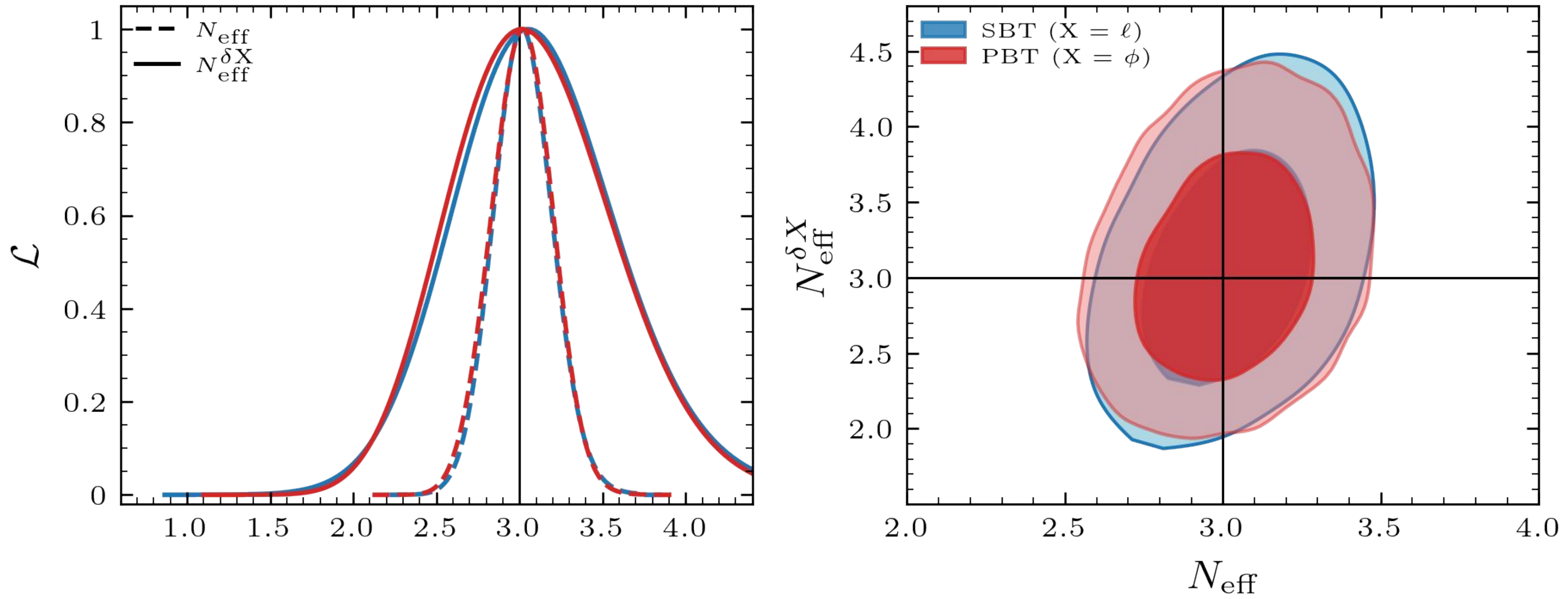




GM, Wallisch & Freese (in prep.)

Phase-shift constraints
validation of phase shift extraction

Planck 2018 Forecast: $\Lambda\text{CDM} + N_{\text{eff}} = 3 \;\; (M_\nu = 0)$

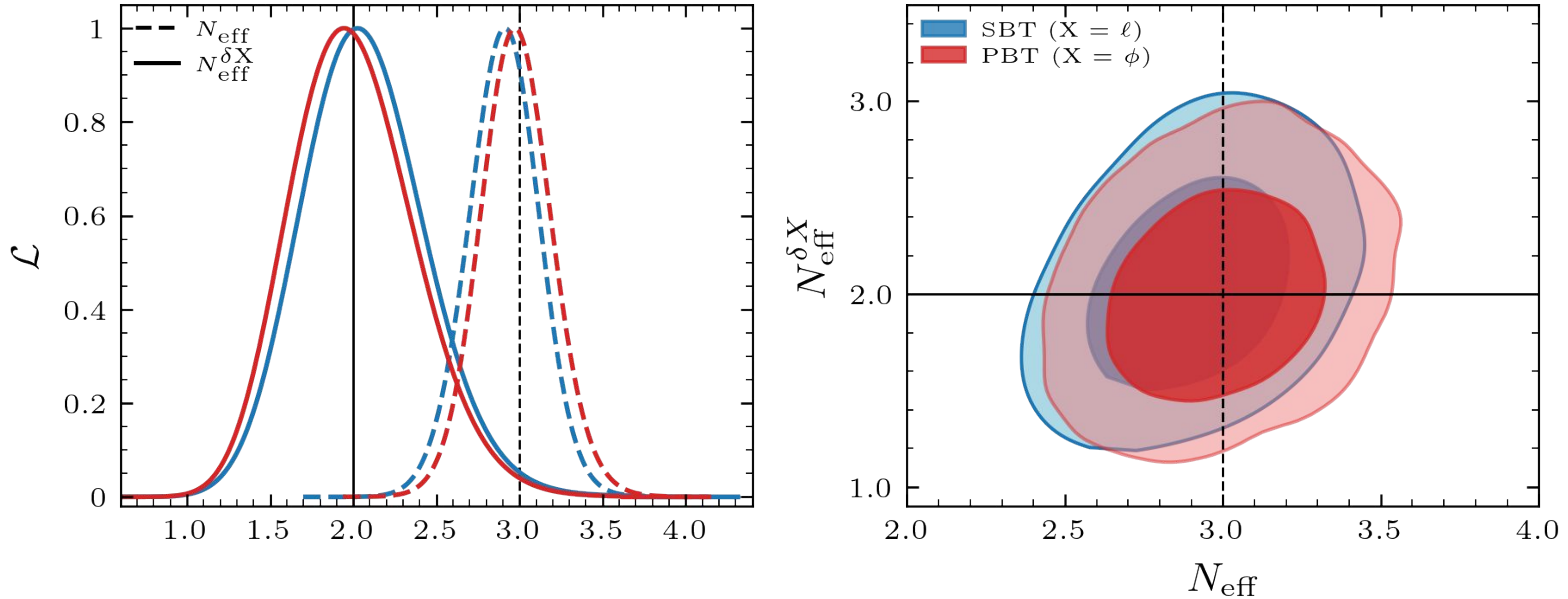


Both the spectrum and perturbation based approach successfully recover the imprinted phase shift by free-streaming neutrinos

GM, Wallisch & Freese (in prep.)

Phase-shift constraints
validation of phase shift extraction

Planck 2018 Forecast: $\Lambda\mathrm{CDM} + N_{\mathrm{eff}} = 2 + N_{\mathrm{fluid}} = 1 \quad (M_\nu = 0)$



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Phase-shift constraints
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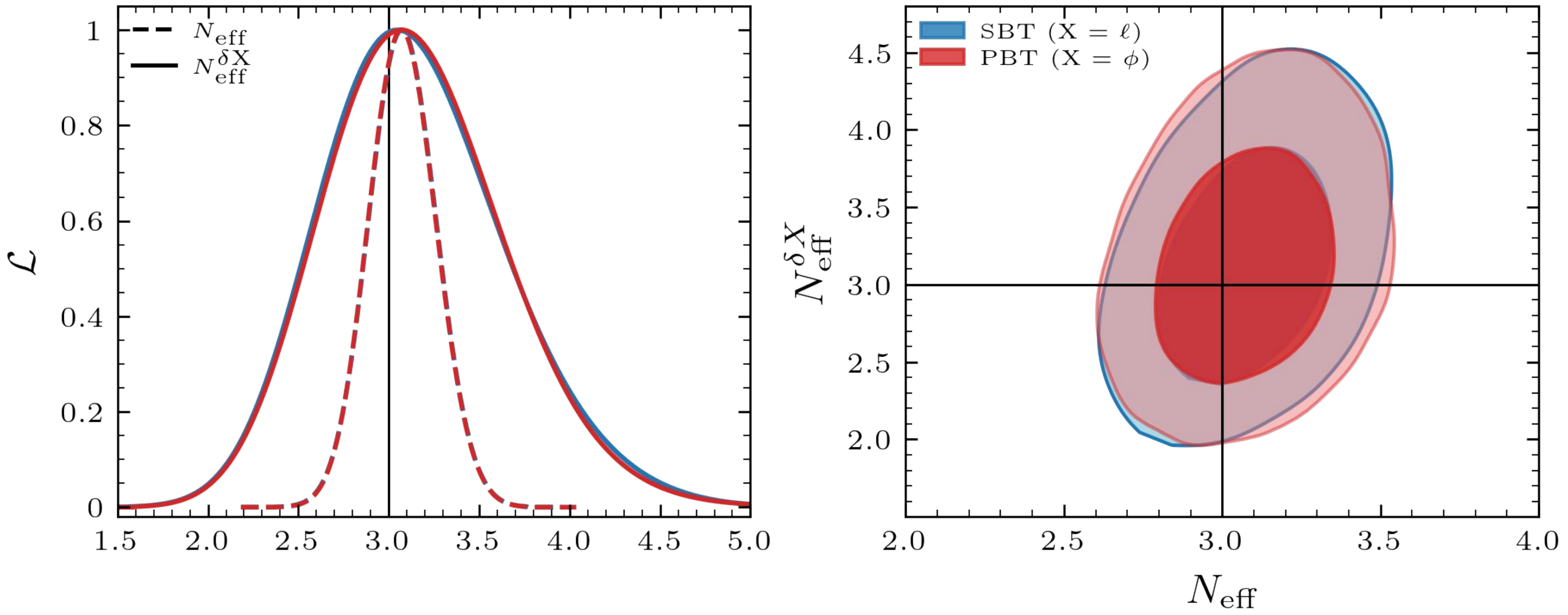
Planck 2018 Forecast: $\Lambda\mathrm{CDM} + N_{\rm eff} = 3.044 \quad (M_\nu = 0.06\,\mathrm{eV})$



Neutrino masses have negligible impact on the phase shift extraction

GM, Wallisch & Freese (in prep.)