Free-Streaming Neutrinos & Their Induced Phase Shift in the CMB Spectra

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Based on ongoing work with Benjamin Wallisch and Katherine Freese

TEXAS
The University of Texas at Austin

Cosmic Timeline

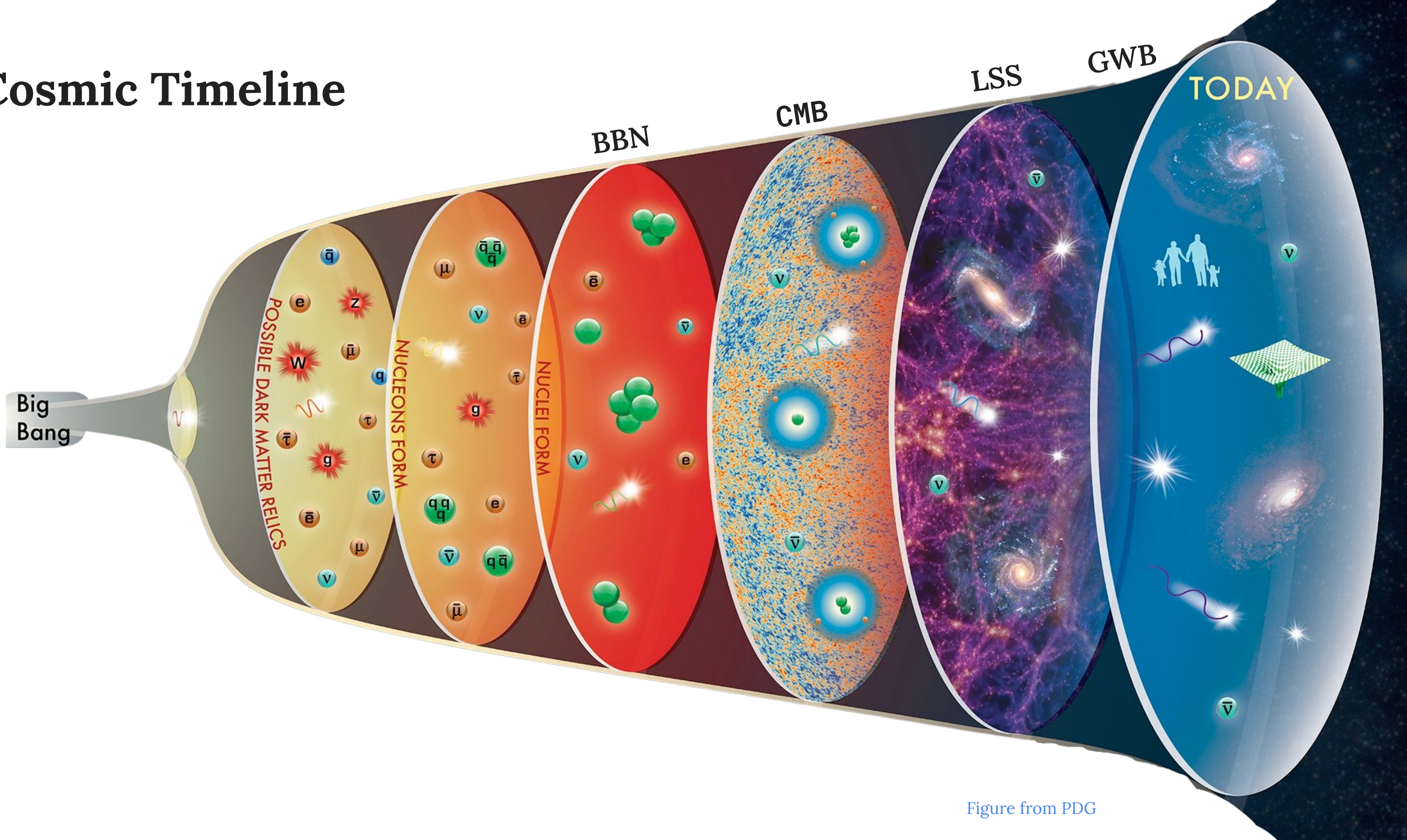
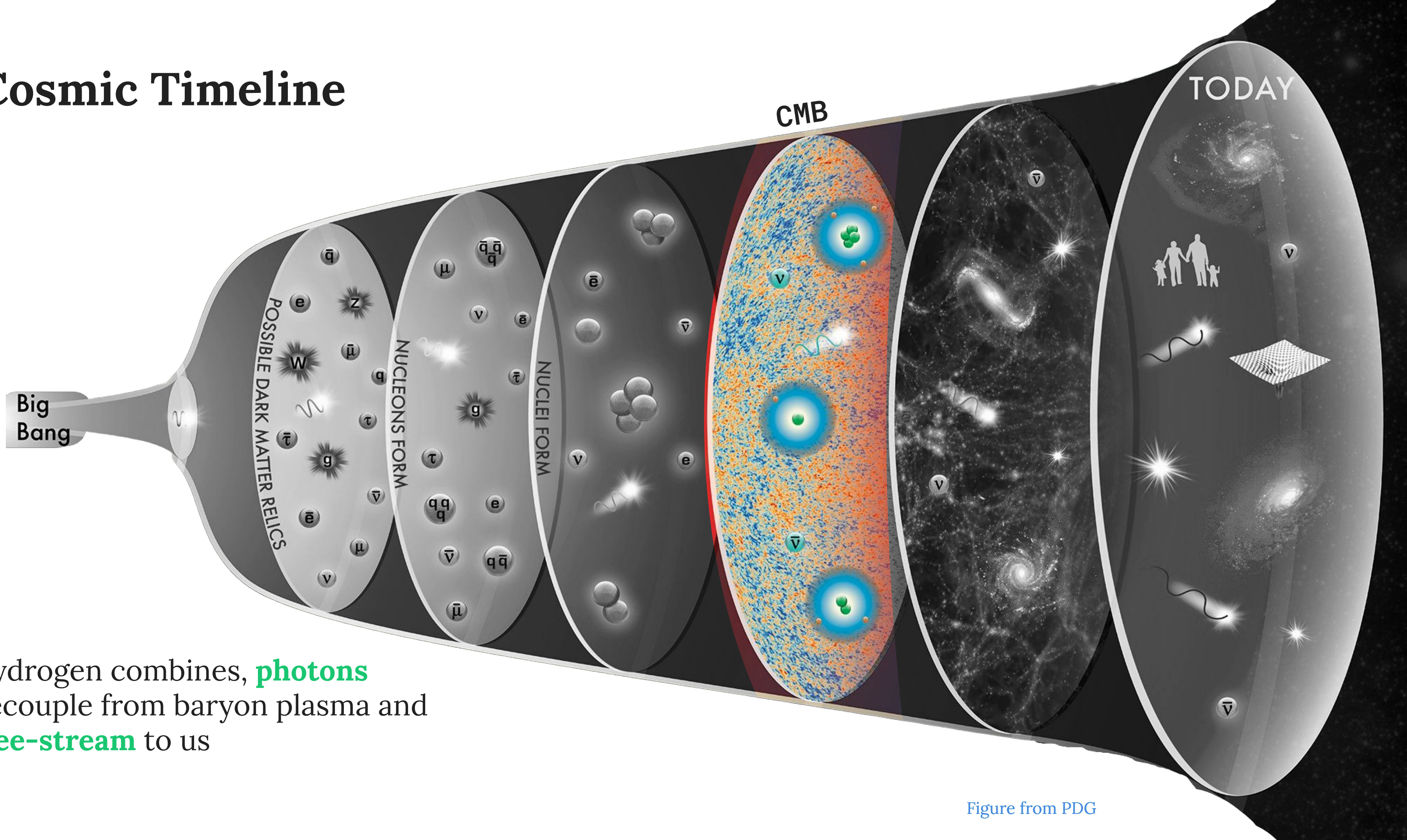


Figure from PDG

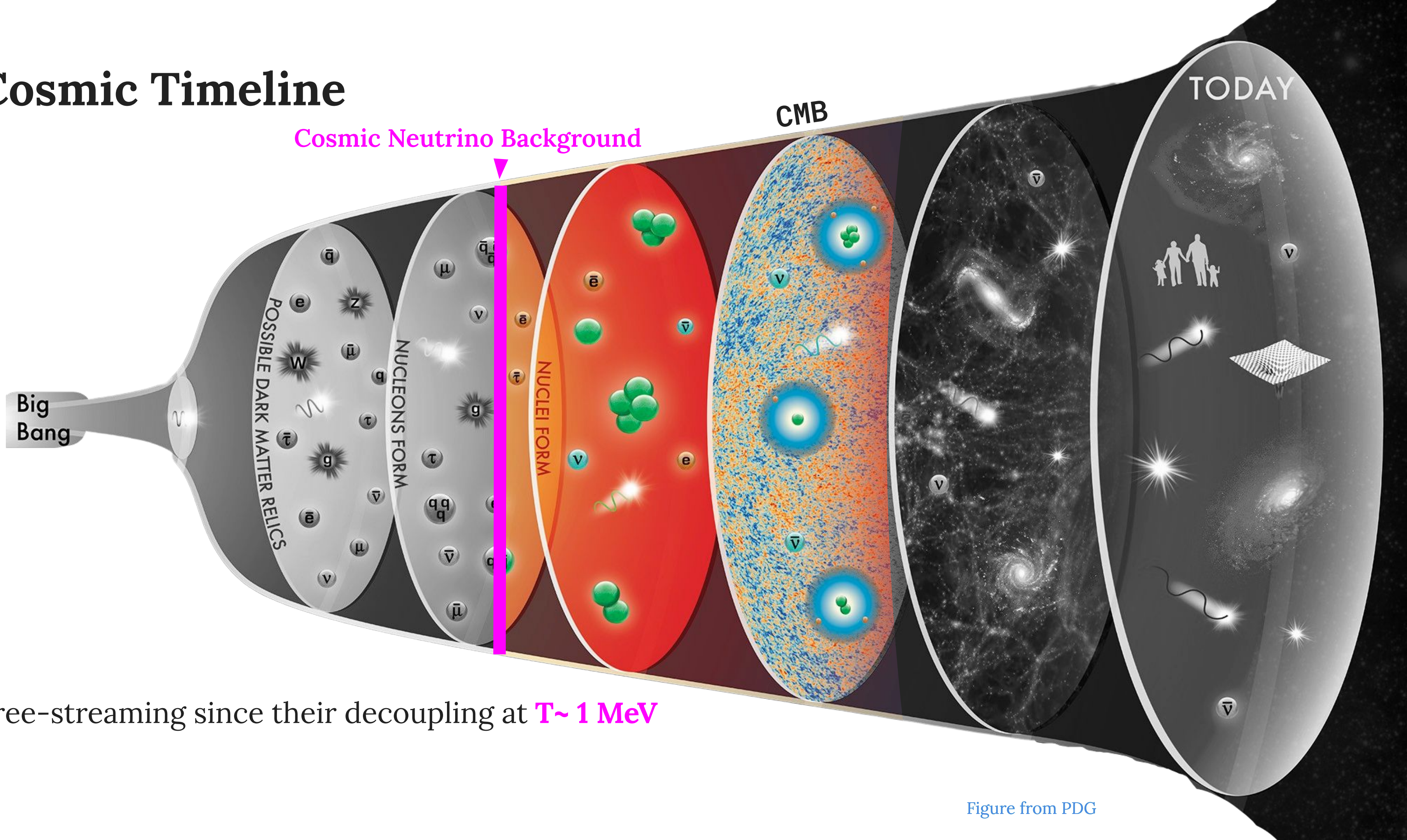
Cosmic Timeline



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

Figure from PDG

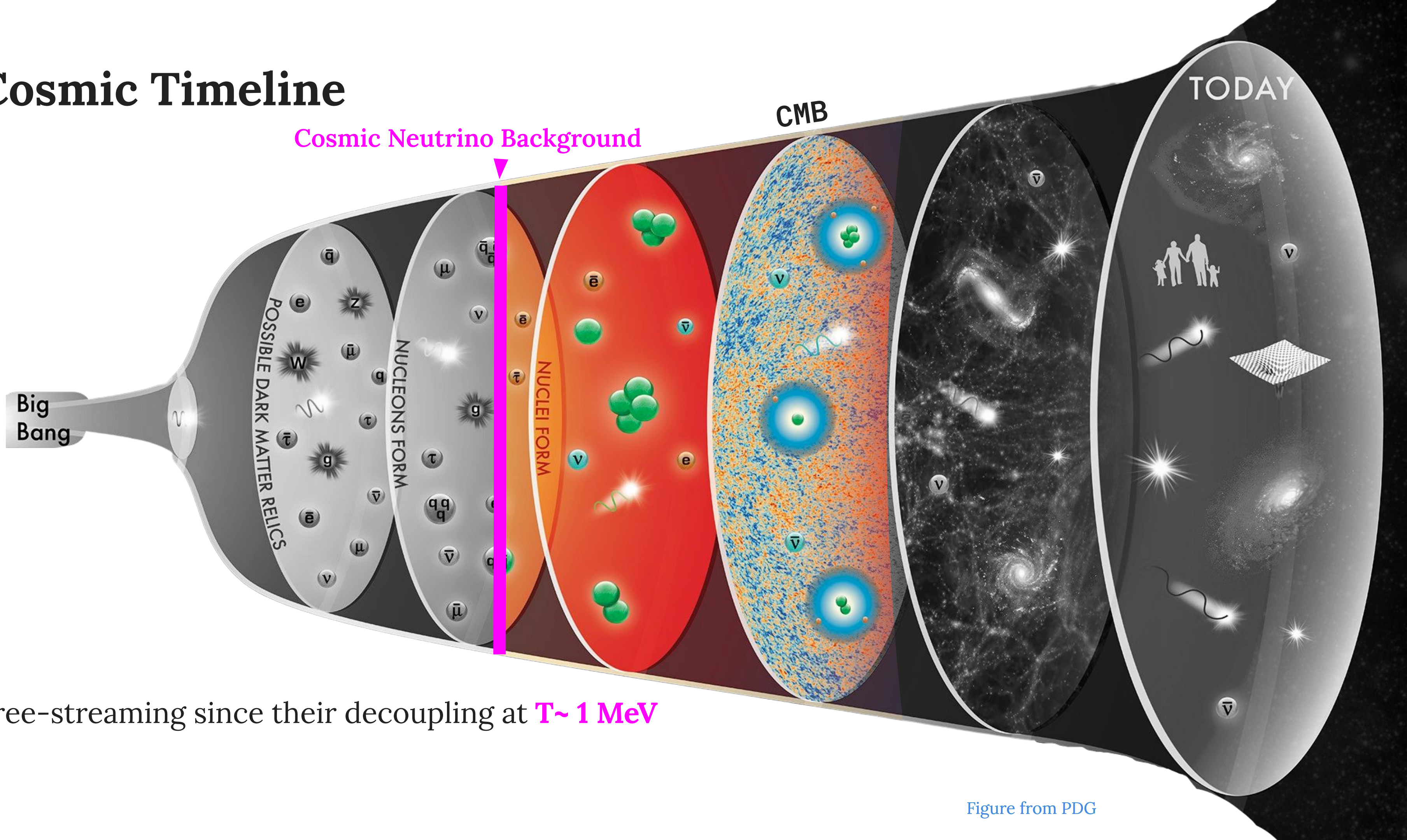
Cosmic Timeline



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

Figure from PDG

Cosmic Timeline

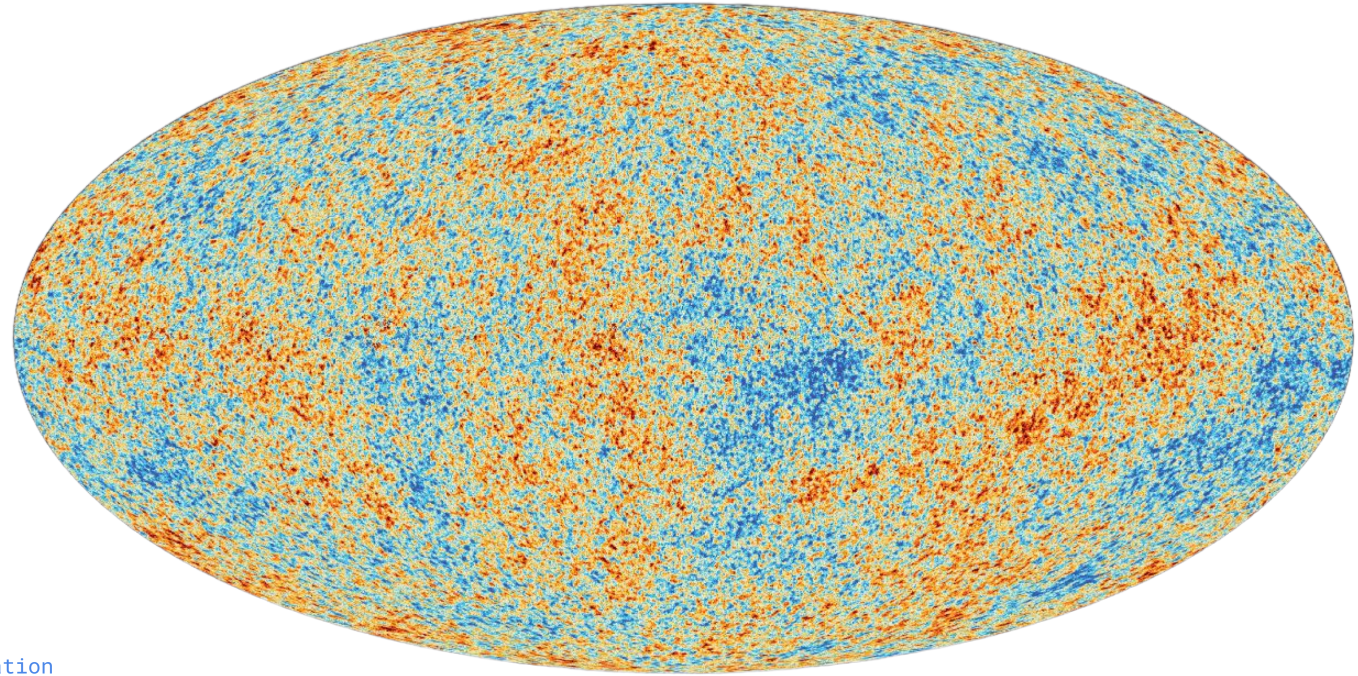


Free-streaming since their decoupling at **T~ 1 MeV**

Figure from PDG

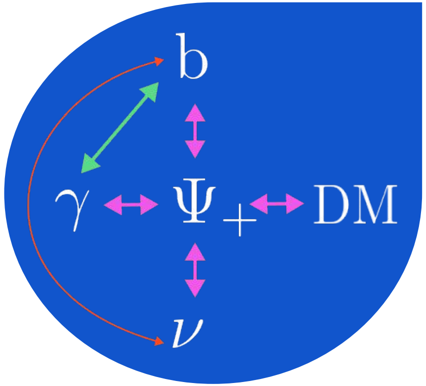
The Cosmic Microwave Background Anisotropies

- 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

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

We observe these acoustic oscillations in the CMB power spectra

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

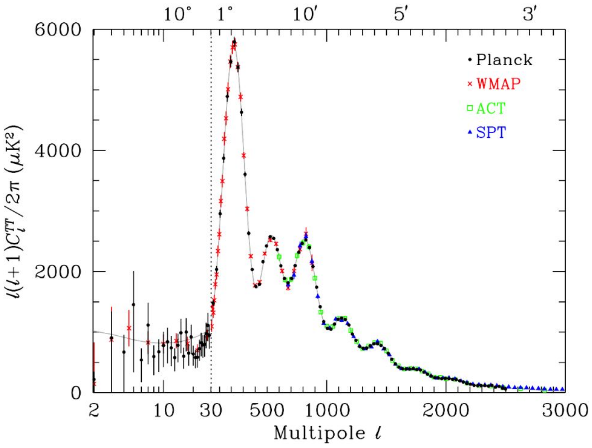
$$c_s^2 \sim \frac{c^2}{3(1+\underbrace{R_b}_{R_b \equiv 3\bar{\rho}_b/(4\bar{\rho}_\gamma)})}$$

Baryons add inertia to the fluid

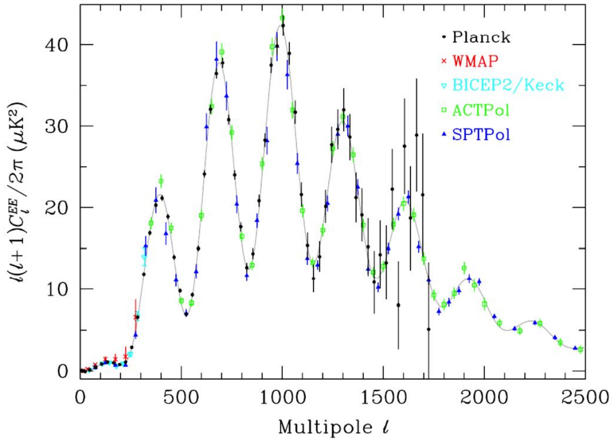
Polarization spectrum traces **velocity** perturbations

CMB Power Spectra

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



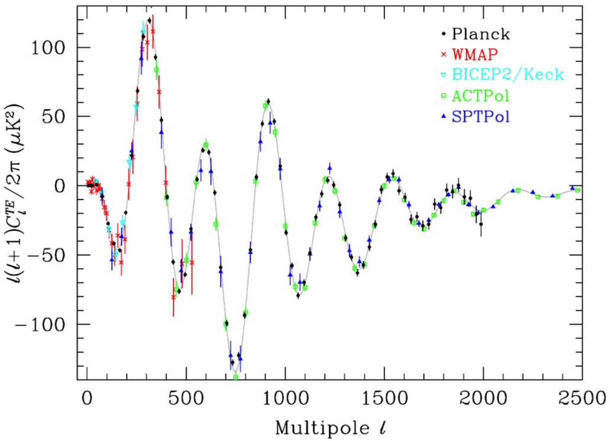
$$\mathcal{D}_\ell^{TT} \propto \cos^2(\ell\theta_s)$$



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

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

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



Planck, WMAP, ACT & SPT Collaborations
Figures from PDG

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
- In the SM, the effective number of neutrinos **N_{eff} = 3.044**

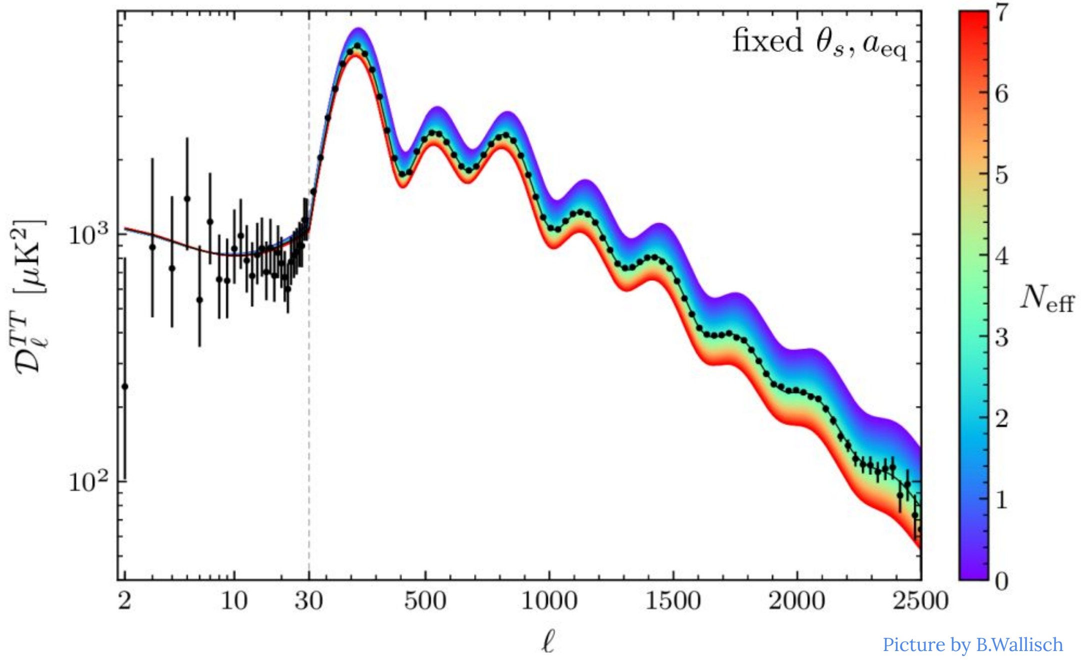
  Akita1, Yamaguchi (2020)
- Cosmology is sensitive to their gravitational effects
  - Both through their energy density and perturbations
  - Planck 2018: $\boxed{N_{\text{eff}}^{\text{CMB}} = 2.99 \pm 0.17}$

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

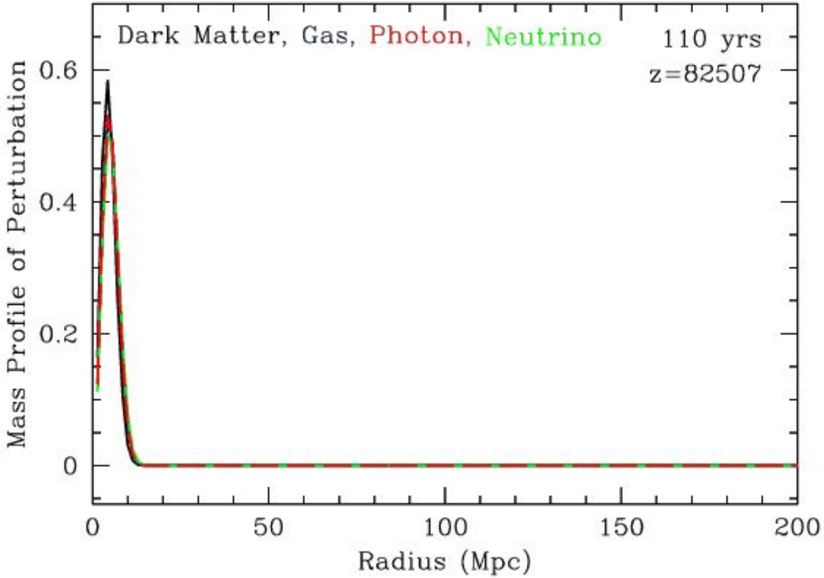


Picture by B.Wallisch

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 **shift in the phase of the acoustic peaks of the CMB**

  Bashinsky & Seljak (2003)

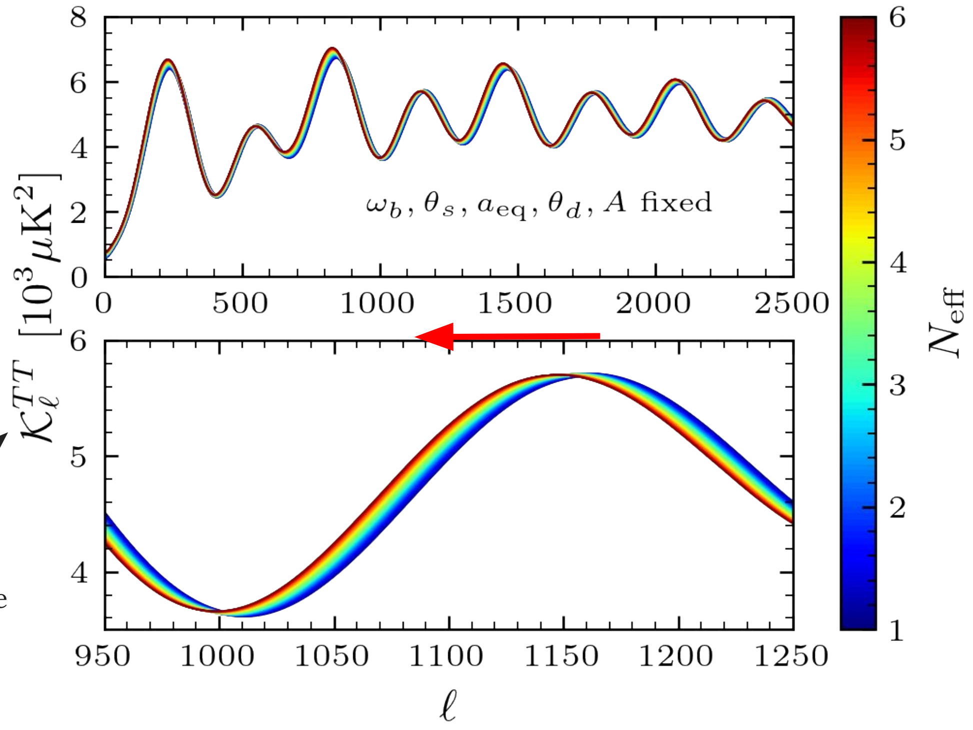
  - Larger radii → smaller multipoles

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

- **Detected in Planck 2013 TT data!**

  Follin, Knox, Millea & Pan (2015)

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

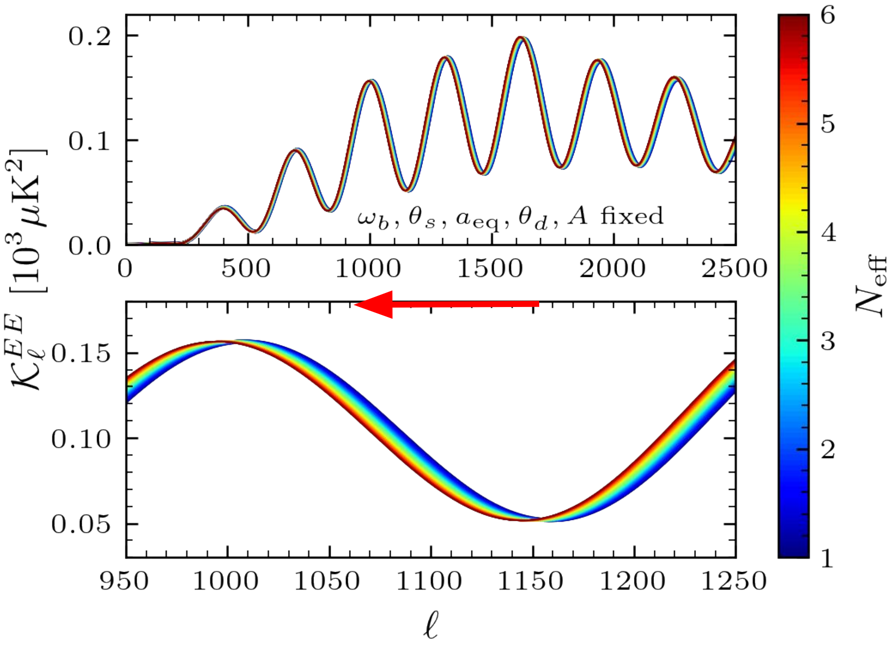


Undamped temperature power spectrum

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 (2015)
- Same shift both in temperature and polarization spectrum
  - polarization provides cleaner signal



The phase shift in the CMB power spectra

Following Follin, Knox, Millea & Pan (2015)

- A new parameter to control the shift

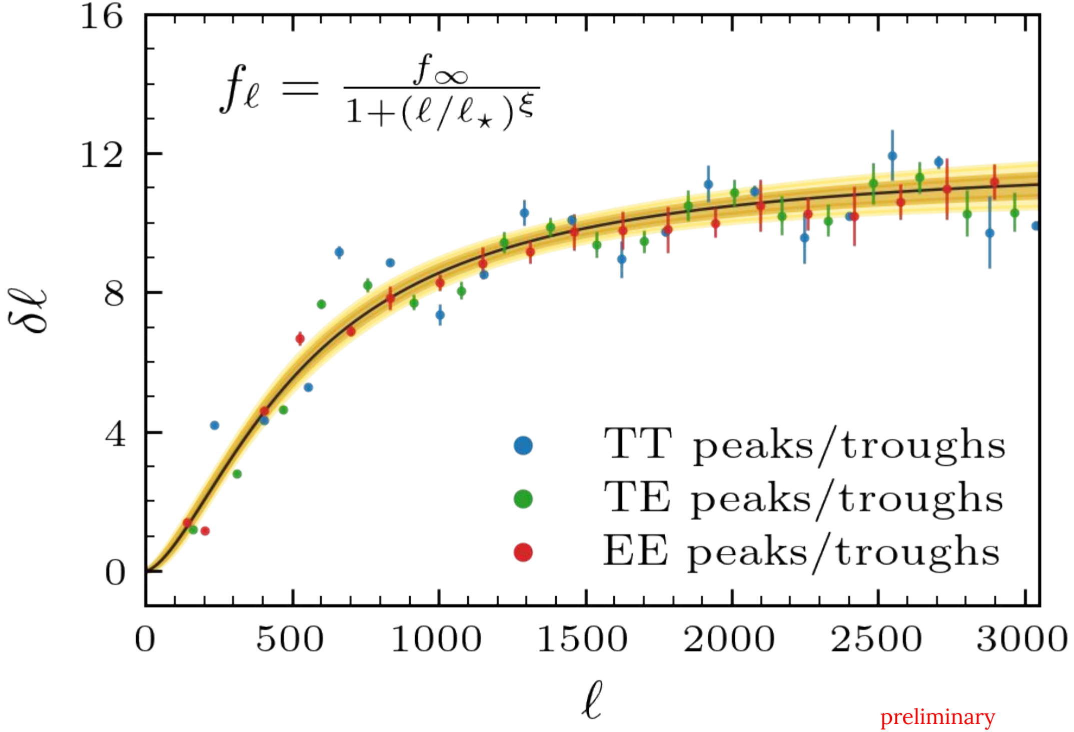
$$N_{\rm eff}^{\delta\phi}$$

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

Our Contributions:

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

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



preliminary

Phase shift constraints

- Based on Planck 2013 temperature only:

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

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

- Work in Progress (preliminary)
  - Current data, including polarization:

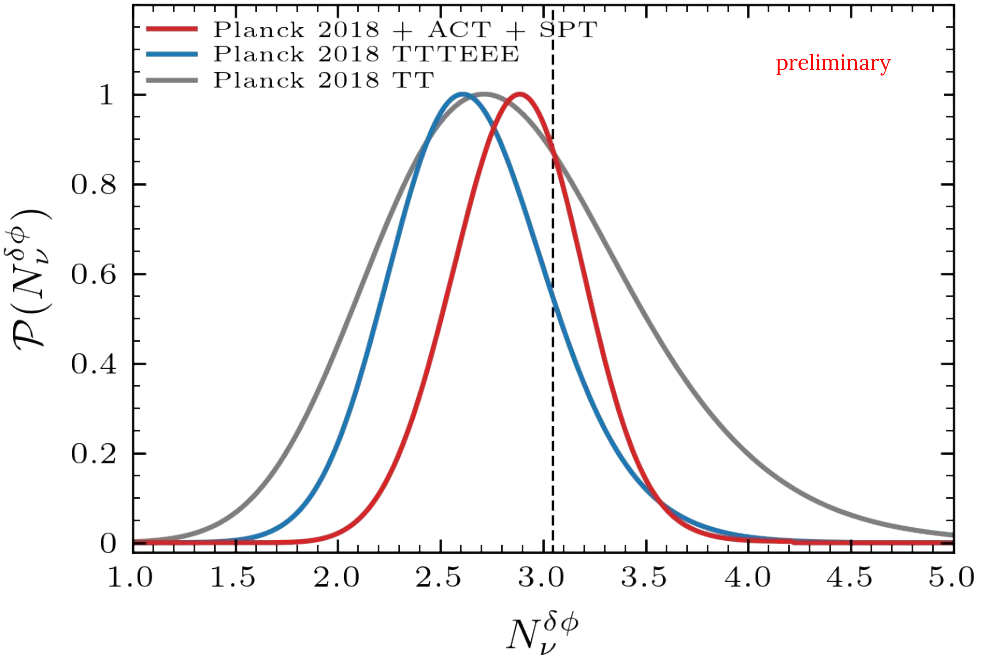
Planck 2018: $N_\nu^{\delta\phi} = 2.7^{+0.5}_{-0.4}$

+ ACT + SPT: $N_\nu^{\delta\phi} = 2.9^{+0.3}_{-0.3}$

  - Forecasts:

SO: $\sigma\left(N_\nu^{\delta\phi}\right) \sim 0.2$

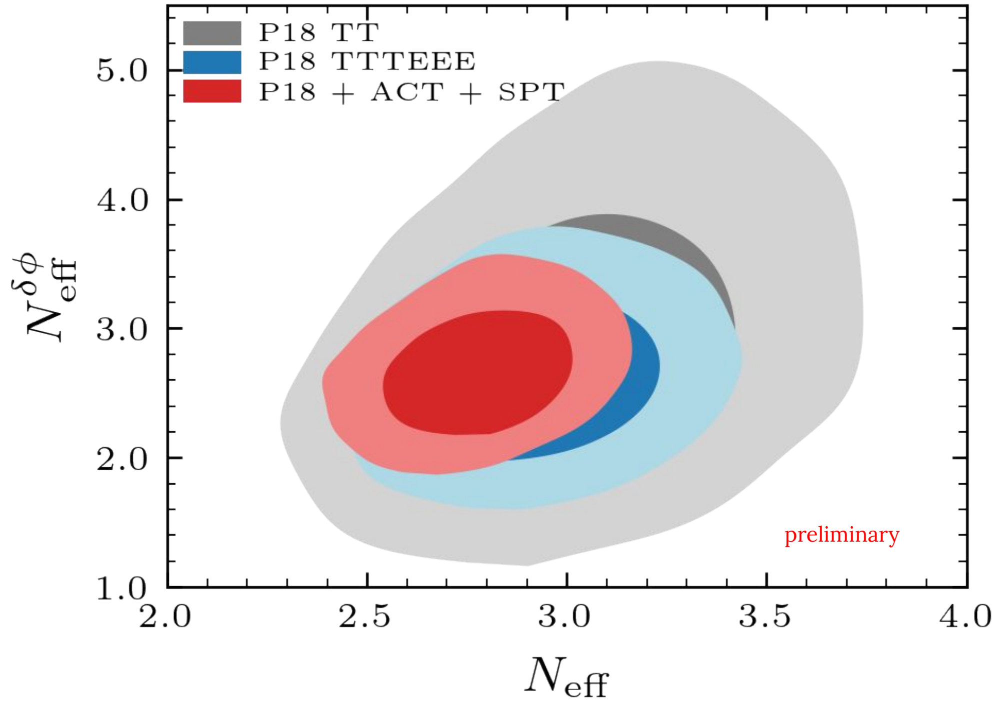
CMB-S4: $\sigma\left(N_\nu^{\delta\phi}\right) \sim 0.1$



Freese, GM & Wallisch (in prep.)

Phase shift constraints

- Strong evidence of **free-streaming nature** of neutrinos
- Current CMB data is compatible with the **Standard Model**



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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

$$S_T(k,\tau) = g\,(\delta_\gamma/4+\psi) + (g\,k^{-2}\theta_b)' + \text{polarization} + \ldots$$

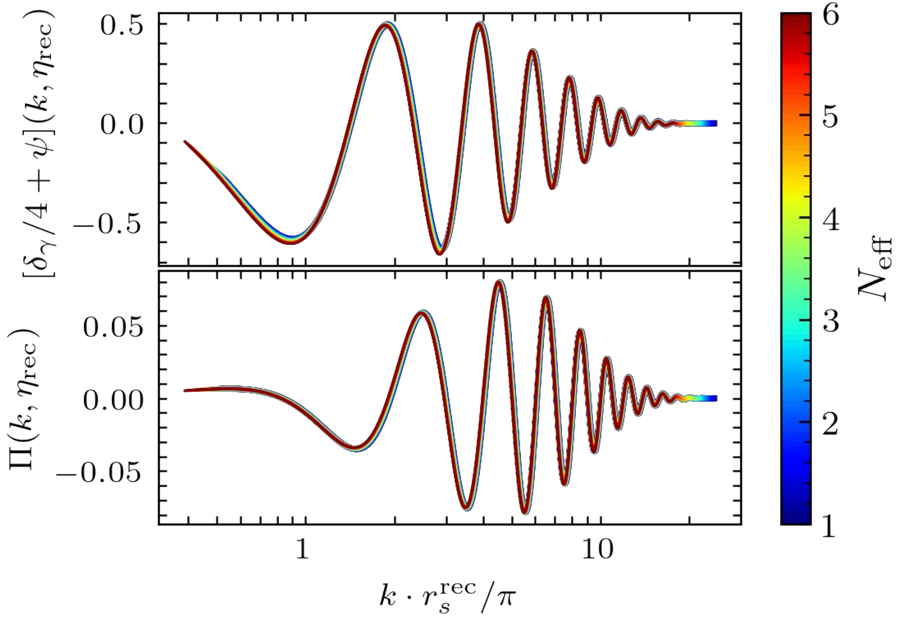
$$S_P(k,\tau) = \sqrt{6}/2\,g\,\Pi$$

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

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

$$\downarrow$$

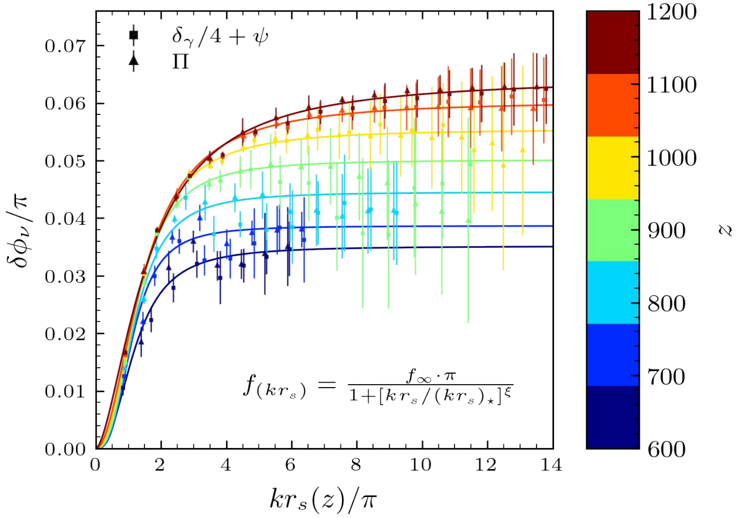
$$\mathcal{C}_\ell^{XY} = \frac{2}{\pi}\int k^2 dk\ \underbrace{P(k)}_{\text{Inflation}}\ \underbrace{\Delta_{X\ell}(k)\Delta_{Y\ell}(k)}_{\text{Anisotropies}}$$

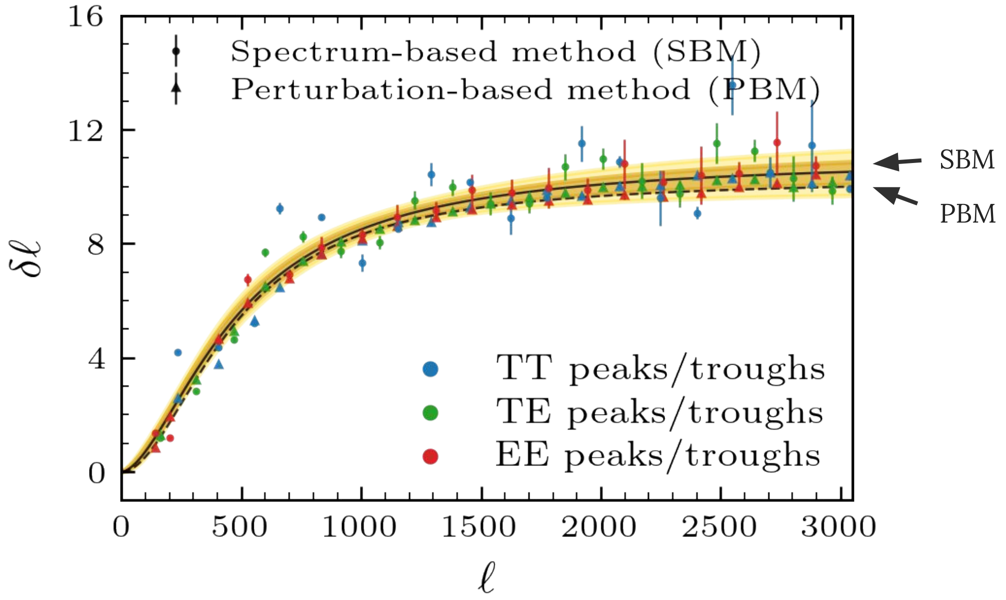


Freese, GM & Wallisch (in prep.)

Perturbation-based method

$$S_X(k,\tau) \longrightarrow \mathcal{C}_\ell^{XY}$$





preliminary

Freese, GM & Wallisch (in prep.)

Phase Shift Constraints

PBT vs SBT

- Perturbation Based Template (PBT)

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

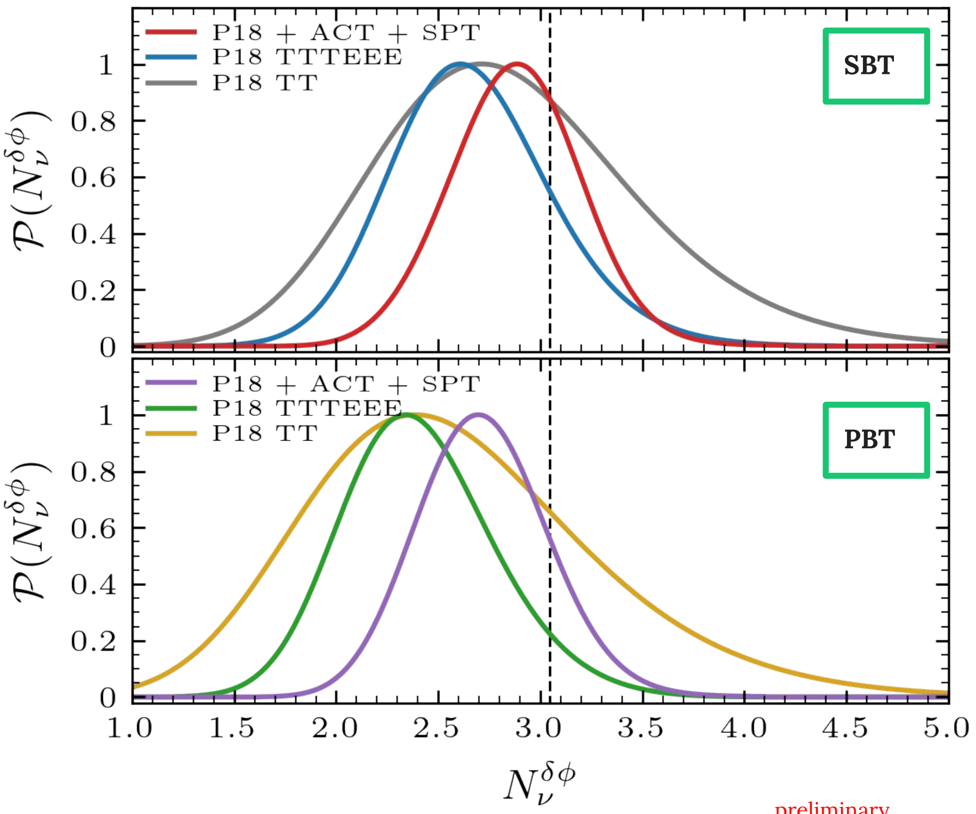
  + ACT + SPT: $N_\nu^{\delta\phi} = 2.7^{+0.3}_{-0.3}$

- Spectrum Based Template (SBT)

  Planck 2018: $N_\nu^{\delta\phi} = 2.7^{+0.5}_{-0.4}$

  + ACT + SPT: $N_\nu^{\delta\phi} = 2.9^{+0.3}_{-0.3}$

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



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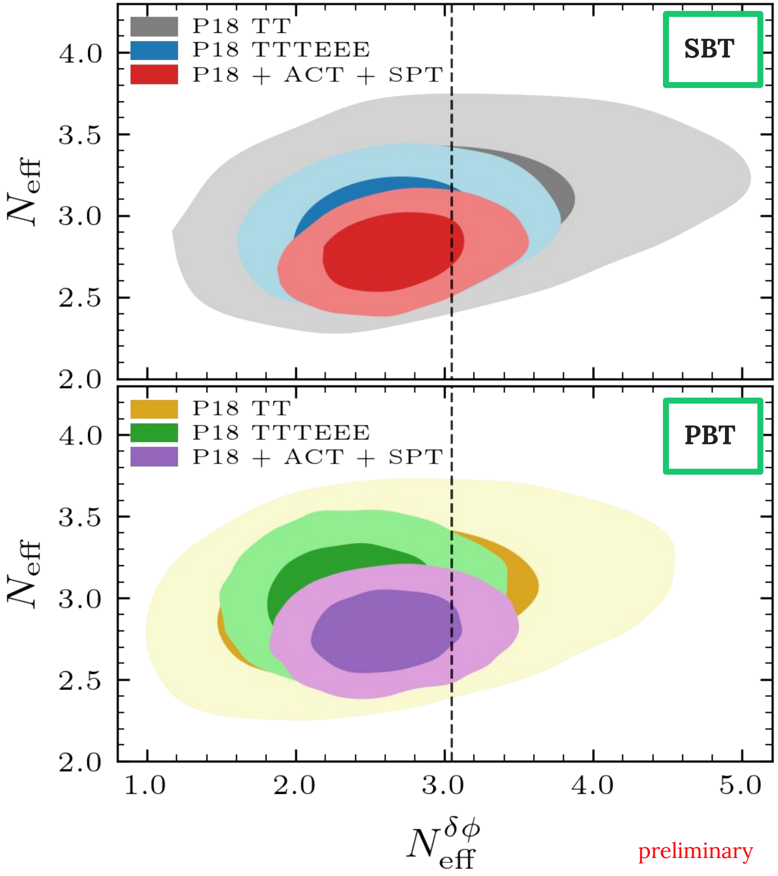
Freese, GM & Wallisch (in prep.)

Phase Shift Constraints
PBT vs SBT

- While a systematic difference is present, the constraints on the phase shift from the PBT and SBT methods are **consistent**

- The PBT method is a more **direct** probe of the **free-streaming nature** of neutrinos



preliminary

Freese, GM & Wallisch (in prep.)

Summary

- The **phase shift** is a robust probe of **free-streaming neutrinos**
  - CMB measurements provide strong evidence of this effect!
  - Current data are **compatible** with the **Standard Model**, constraining non-standard neutrino physics.
- We developed a more **direct** method for the phase shift extraction, at the perturbation level.
  - This will become particularly relevant with the forthcoming improvements in our detectors sensitivity

Grazie per l'attenzione

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Summary Slide

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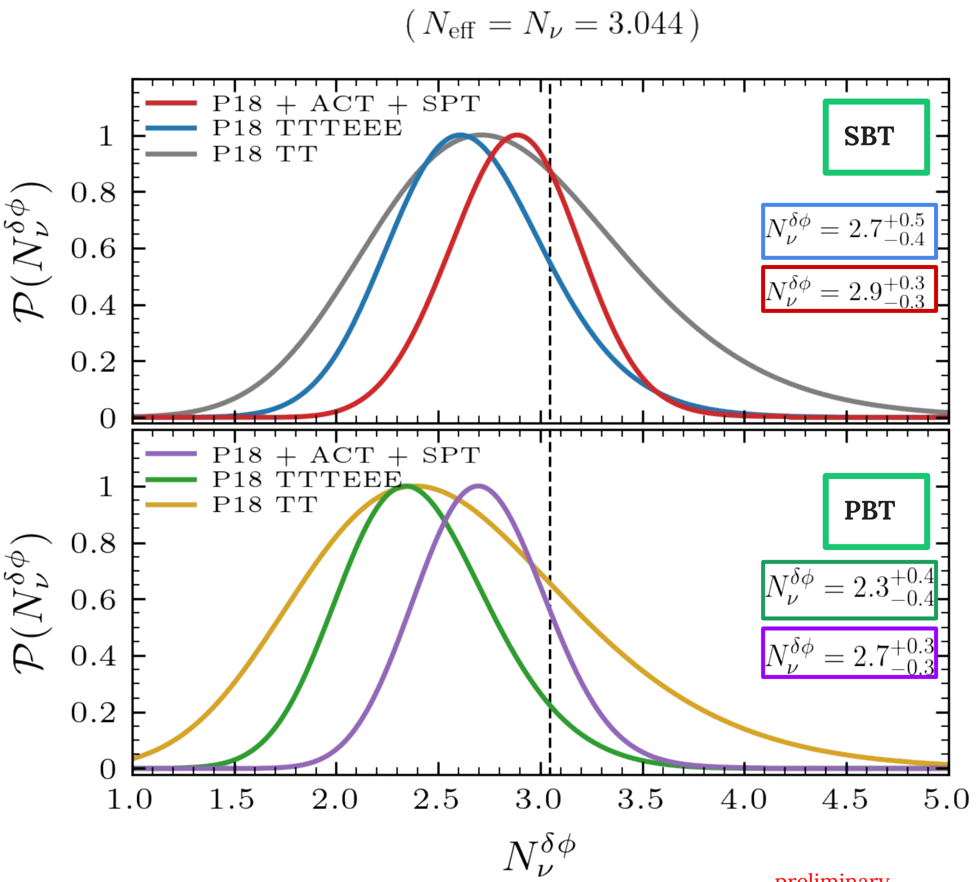
    - Current data are **compatible** with the **Standard Model**, constraining non-standard neutrino physics.
- We developed a more **direct** method for the phase shift extraction, at the perturbation level.



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