November 10th 2023

Brown-bag Seminar
Weinberg Institute for Theoretical Physics, University of Texas at Austin

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

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

Based on ongoing work with Benjamin Wallisch and Katherine Freese

TEXAS
The University of Texas at Austin

Cosmic Timeline

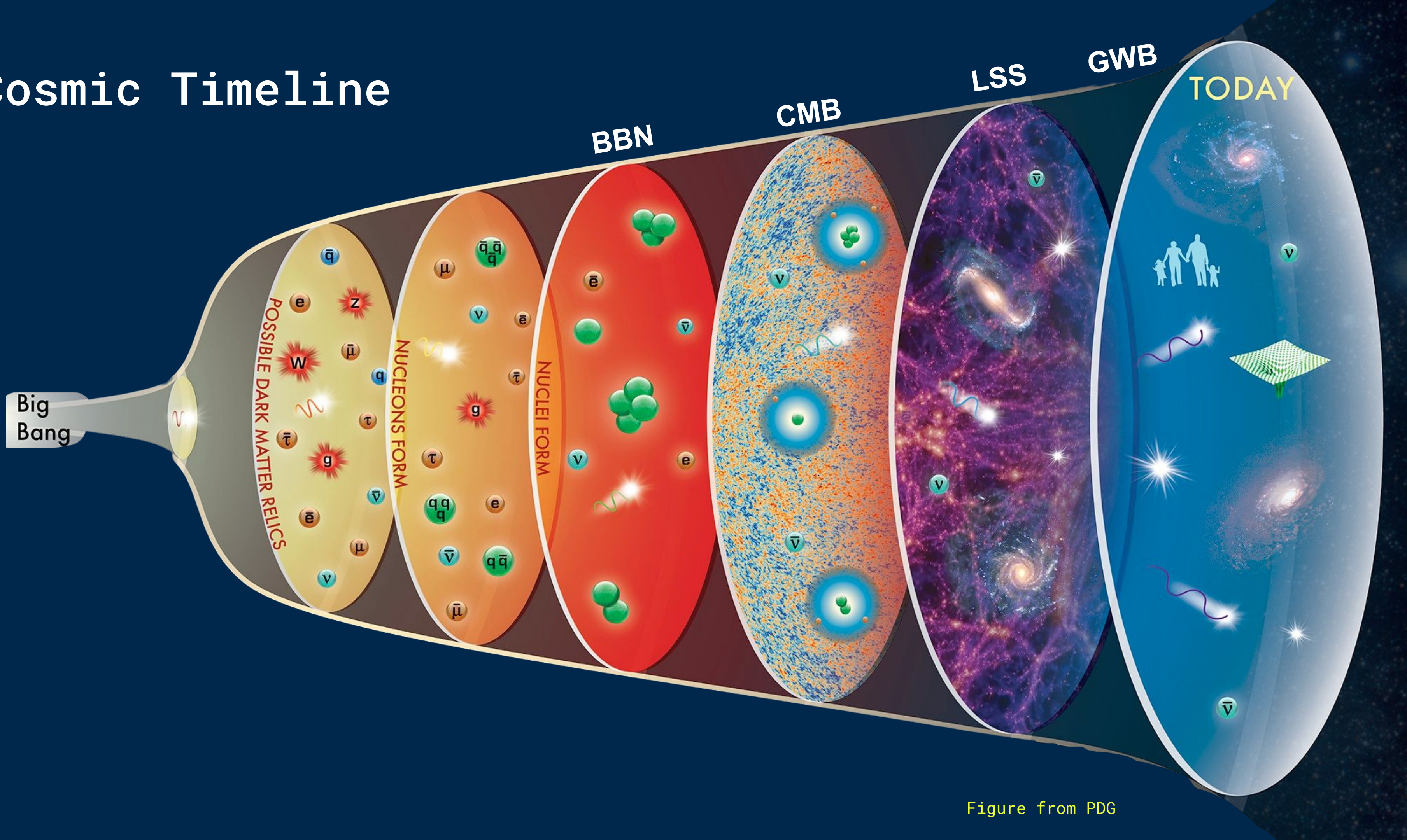
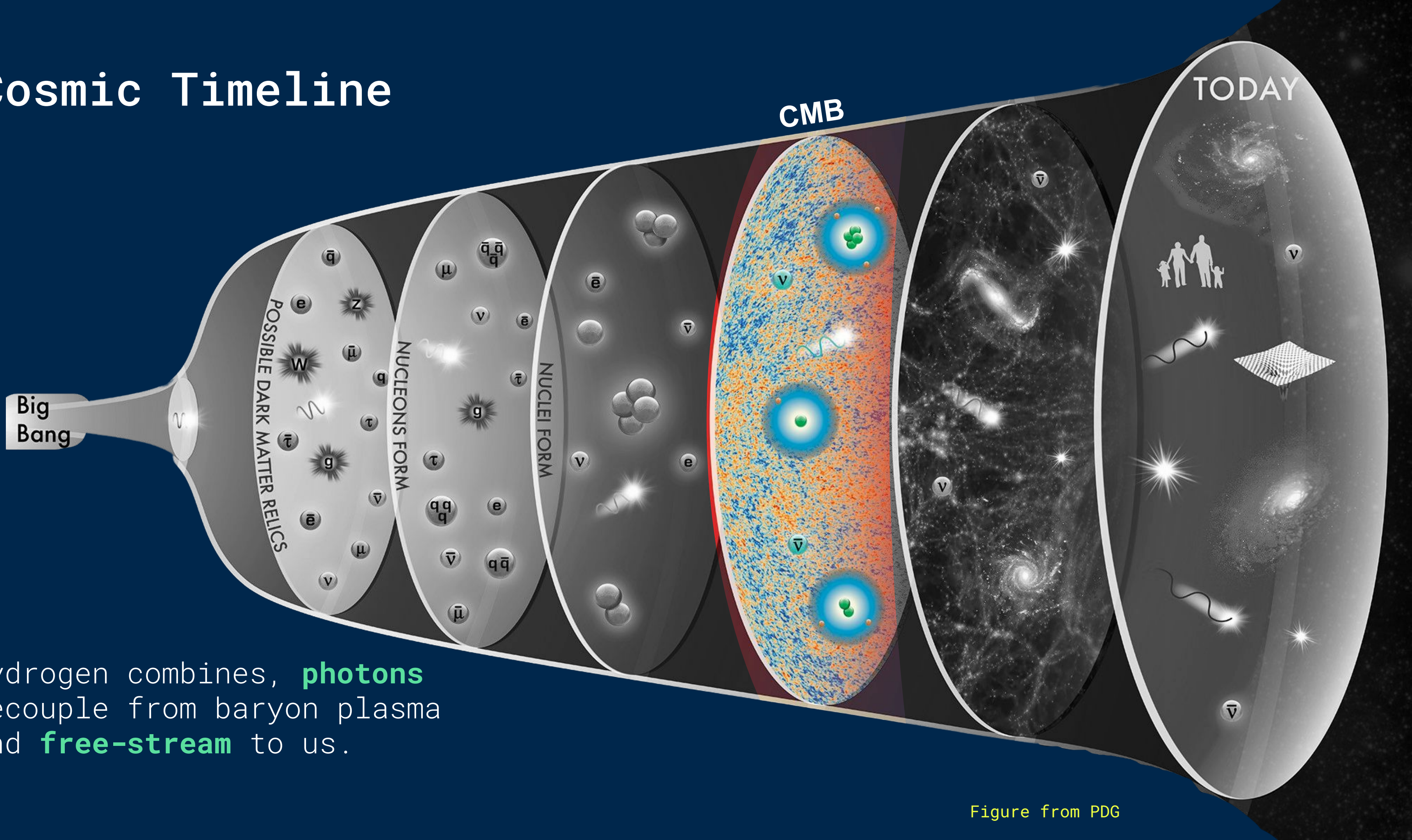


Figure from PDG

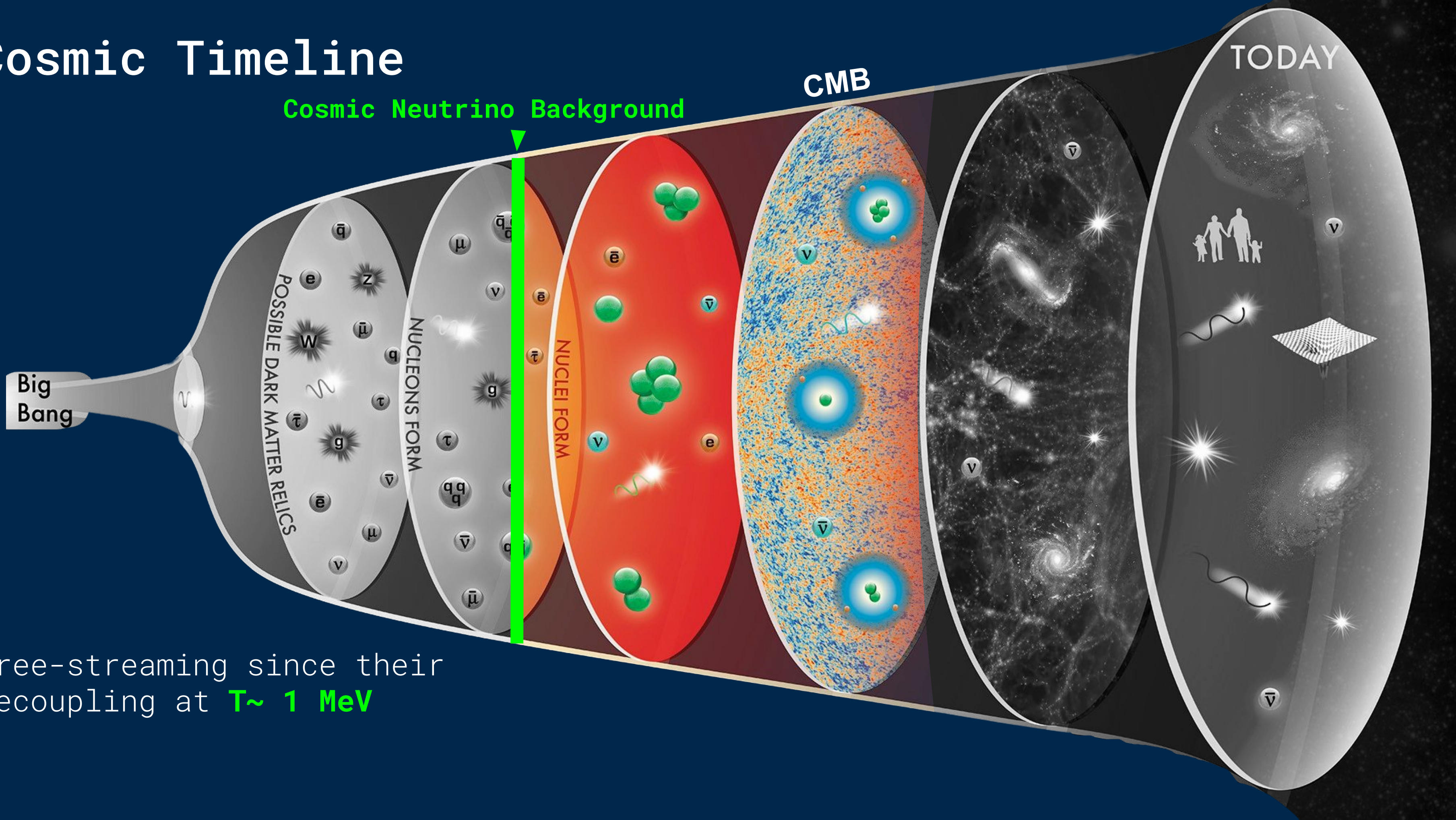
Cosmic Timeline



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

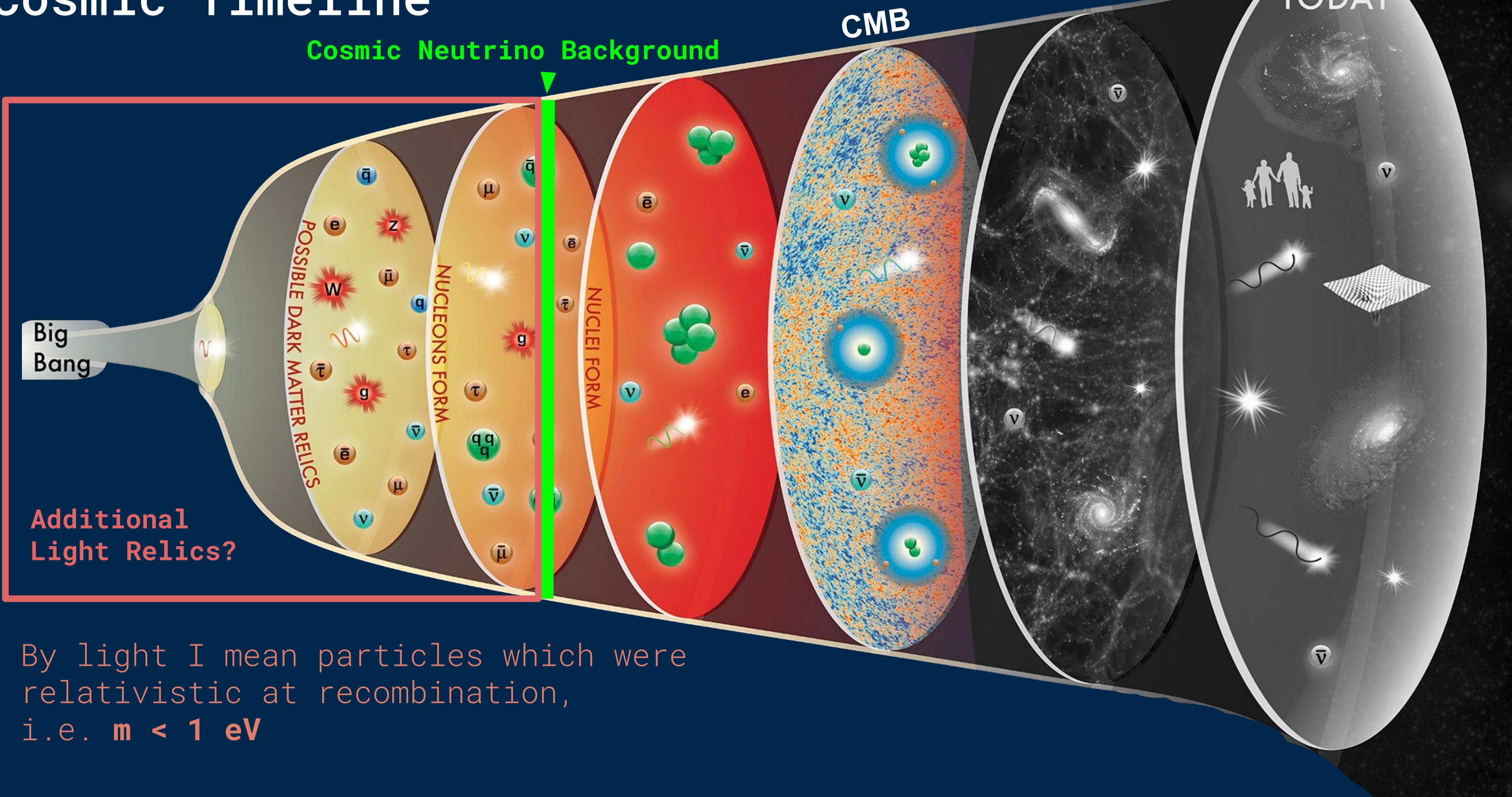
Figure from PDG

Cosmic Timeline



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

Cosmic Timeline



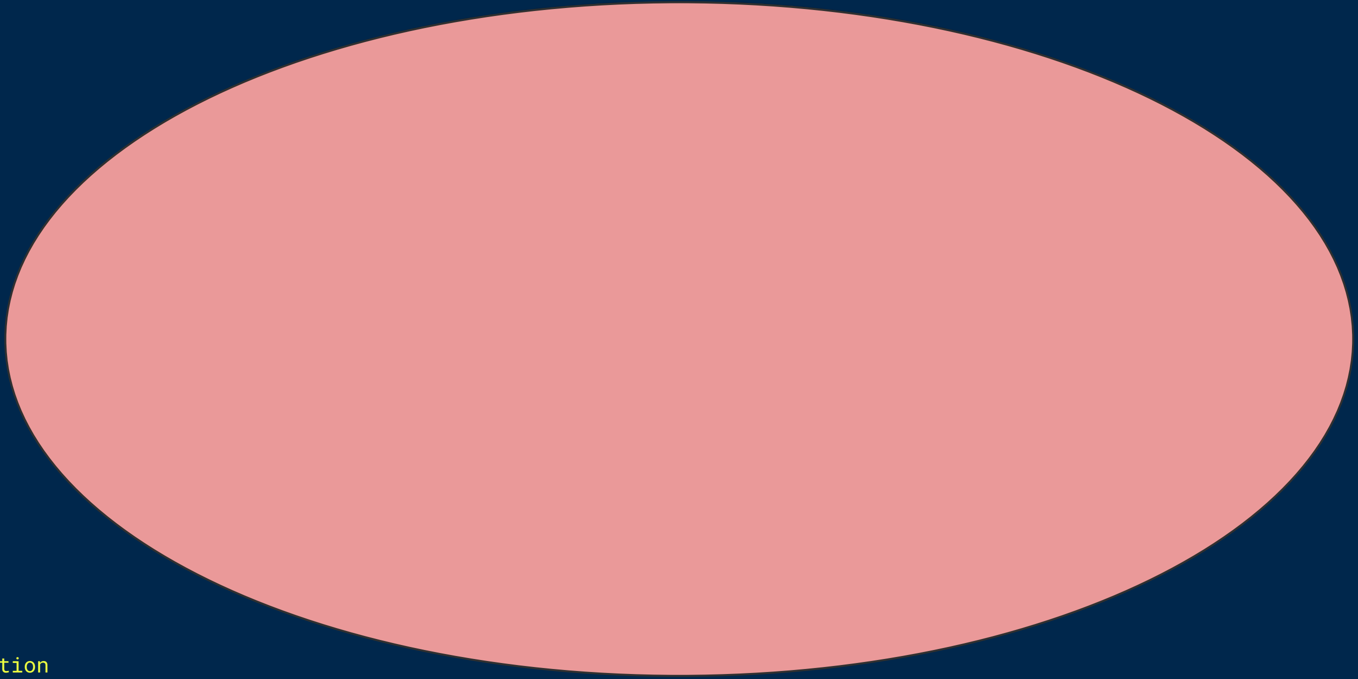
By light I mean particles which were relativistic at recombination, i.e. **m < 1 eV**

Outline of the Talk

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

The Cosmic Microwave Background Anisotropies

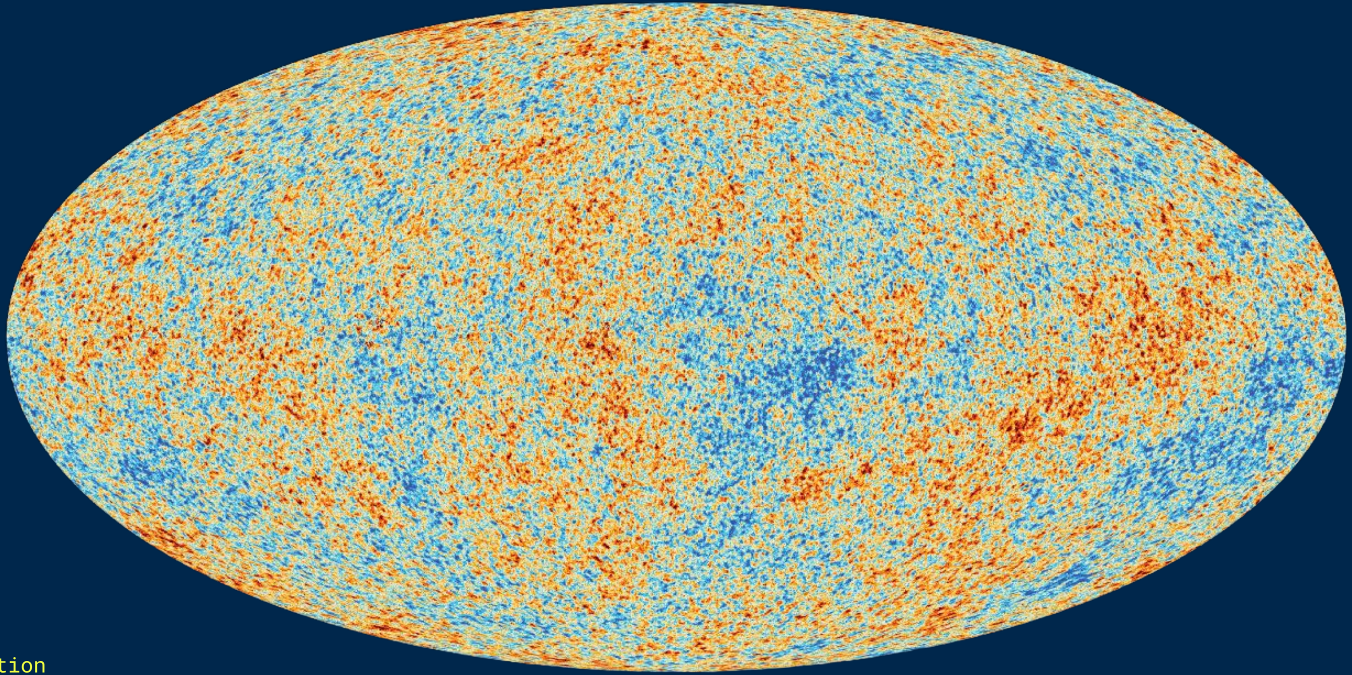
- An almost perfect black-body spectrum at a single temperature of $T_0 = 2.7255$ K today



Planck Collaboration

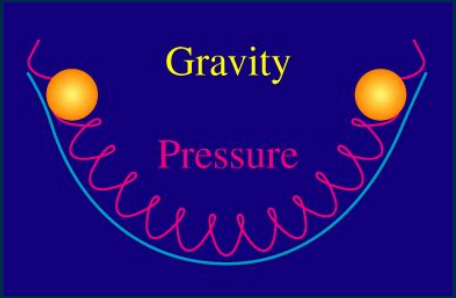
The Cosmic Microwave Background Anisotropies

- 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}

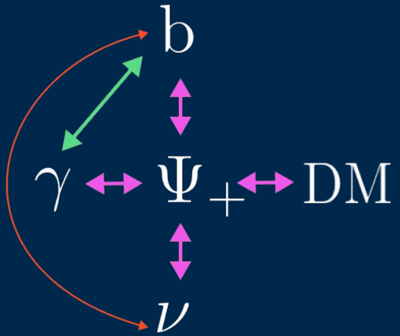


Planck Collaboration

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



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

We observe these acoustic oscillations in the CMB power spectra

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

$$c_s^2 \sim \frac{c}{3\left(1 + \underbrace{R_b}\right)}$$

$$R_b \equiv 3\bar{\rho}_b / \left(4\bar{\rho}_\gamma\right)$$

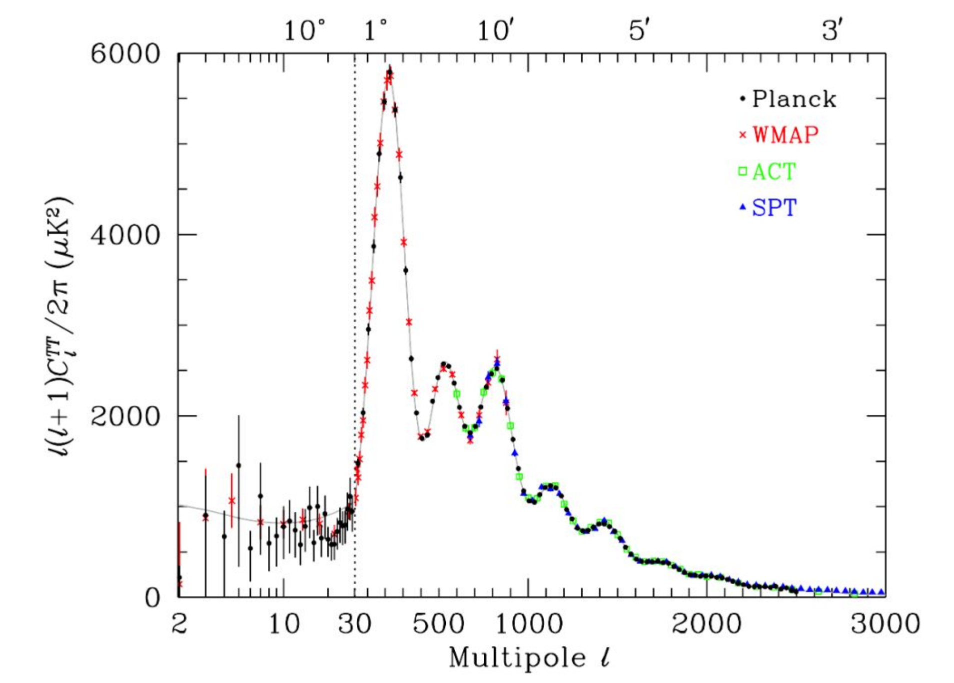
Baryons add inertia to the fluid

Gifs from W. Hu & A. Hincks

The temperature power spectrum

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

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



Planck, WMAP, ACT & SPT Collaborations
Figure from PDG

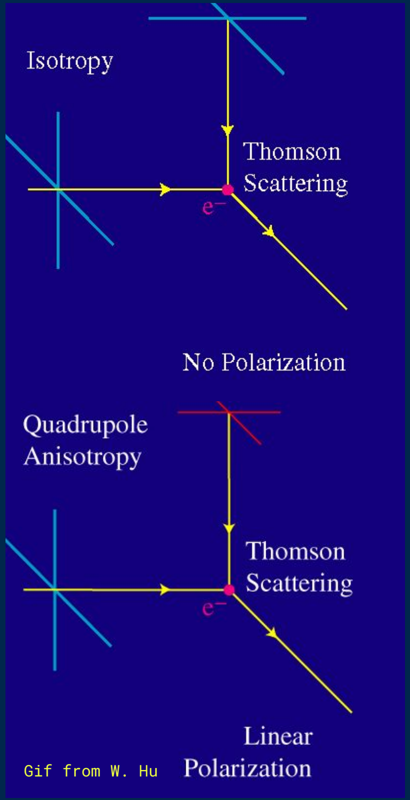
Polarization in the CMB

- A non-vanishing **quadrupole** of the temperature anisotropy generates the linear polarization of the CMB.

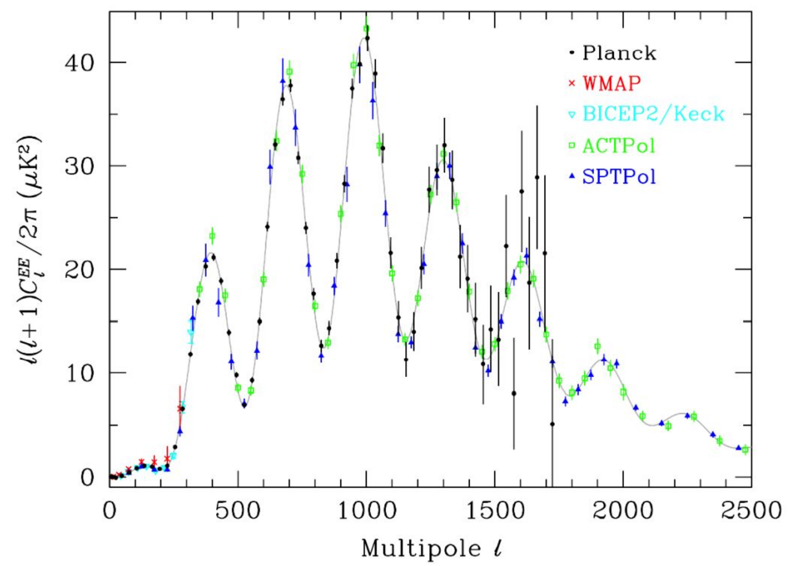
- A local temperature quadrupole can only develop from **a gradient in the velocity field** once the photons have acquired an **appreciable mean free path** just before they decouple

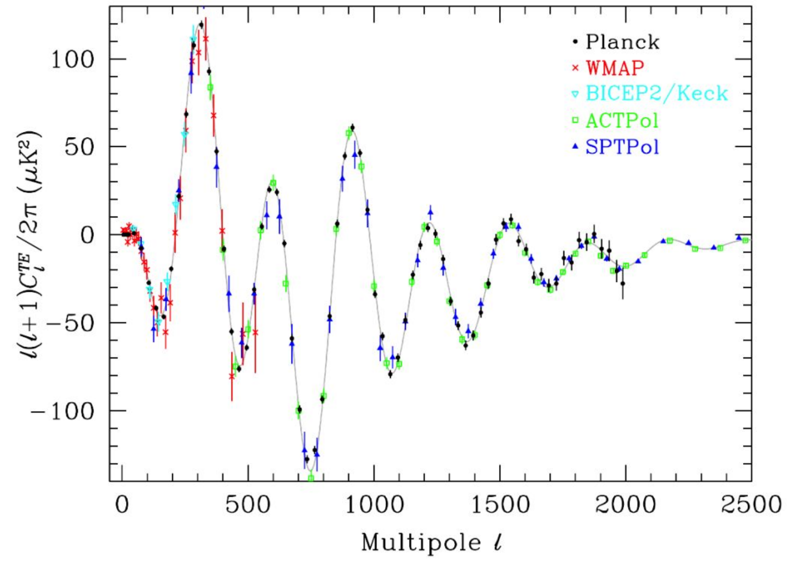
- Less power than temperature spectrum

- A clean probe of the physics at the **very last scattering surface**



Polarization Power Spectra





Polarization spectrum traces **velocity** perturbations

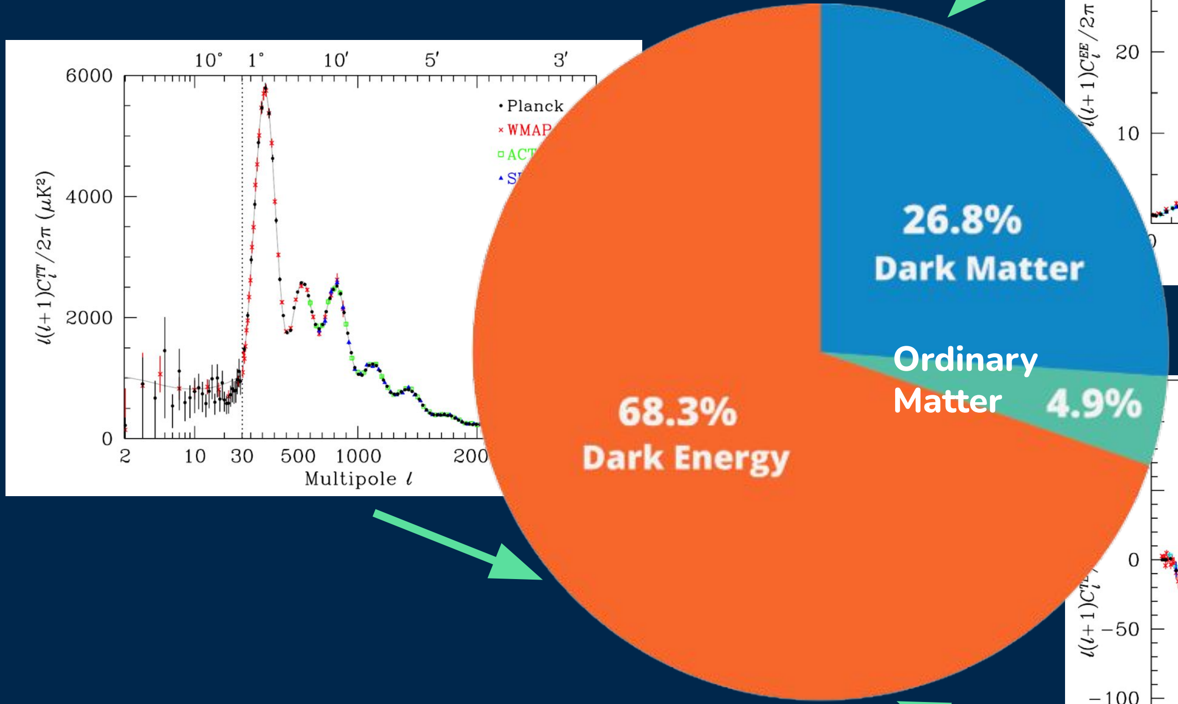
$$\mathcal{D}_\ell^{\rm EE} \propto \sin^2(\ell\theta_s)$$

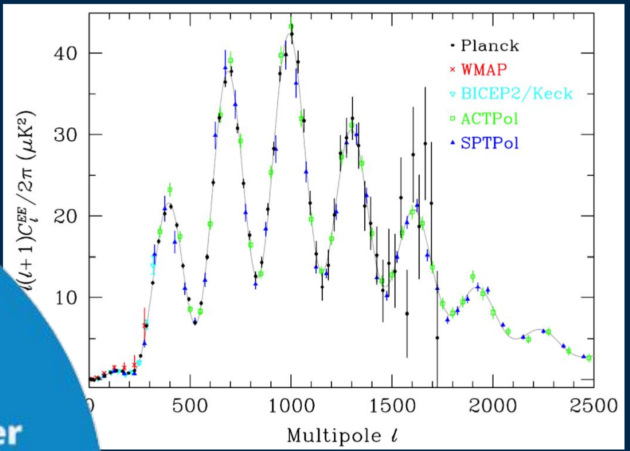
TE spectrum roughly tells us how the plasma is moving into the gravitational potential wells

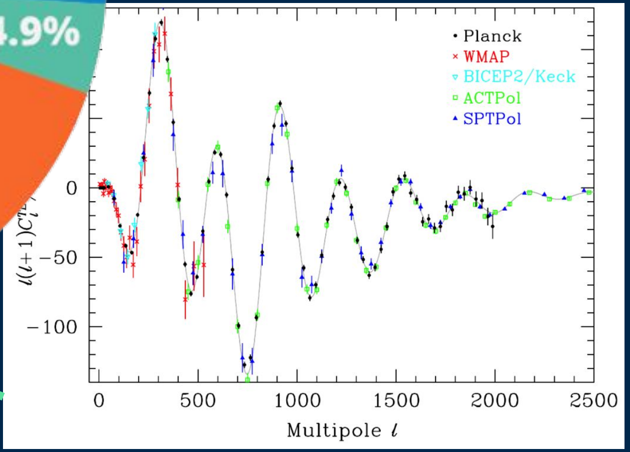
$$\mathcal{D}_\ell^{\rm TE} \propto \sin(\ell\theta_s)\cos(\ell\theta_s)$$

Planck, WMAP, ACT & SPT Collaborations
Figures from PDG

Concordance with Flat ΛCDM

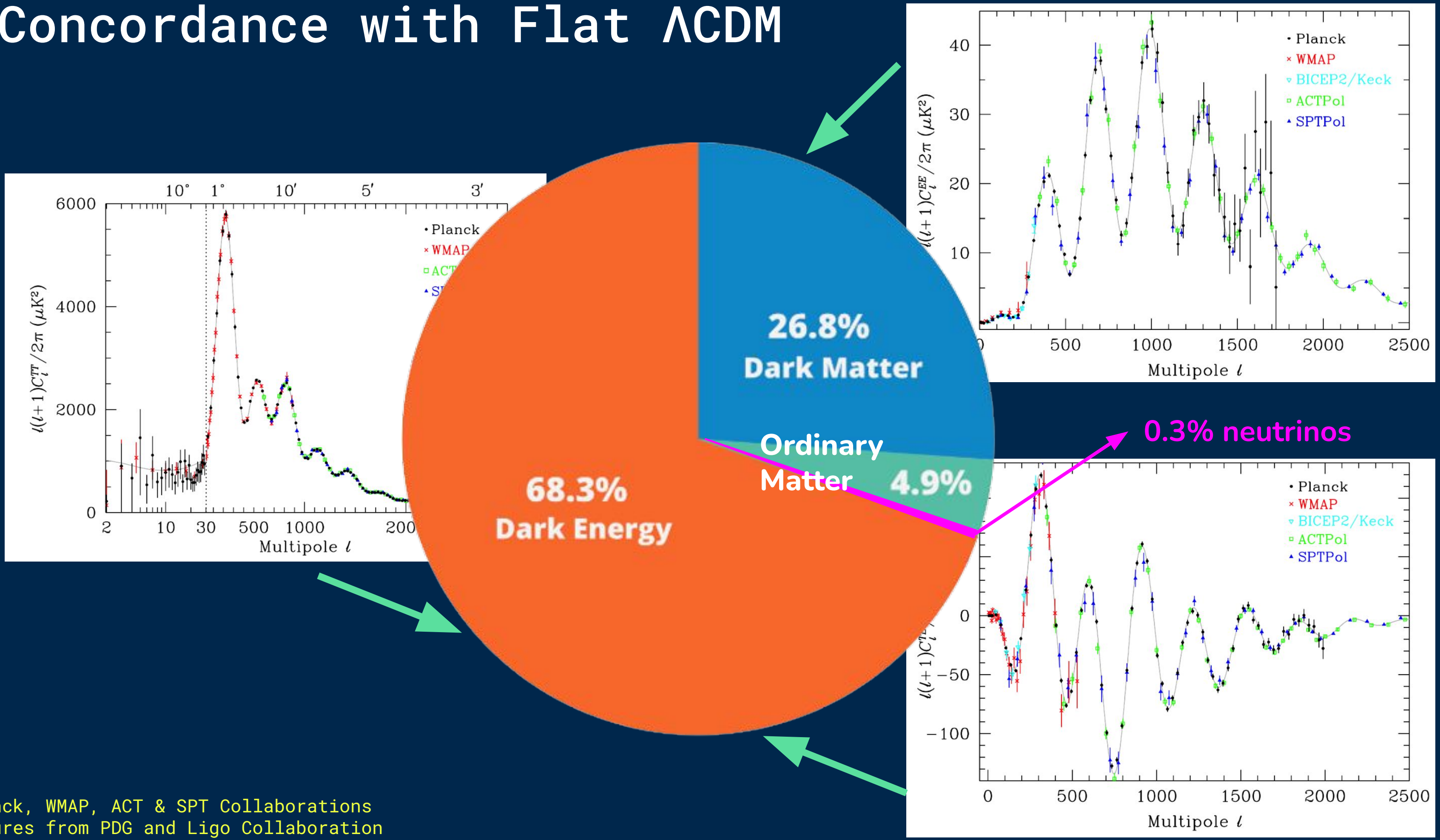






Planck, WMAP, ACT & SPT Collaborations
Figures from PDG and Ligo Collaboration

Concordance with Flat ΛCDM



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

Cosmic Neutrinos
(SM light relics)

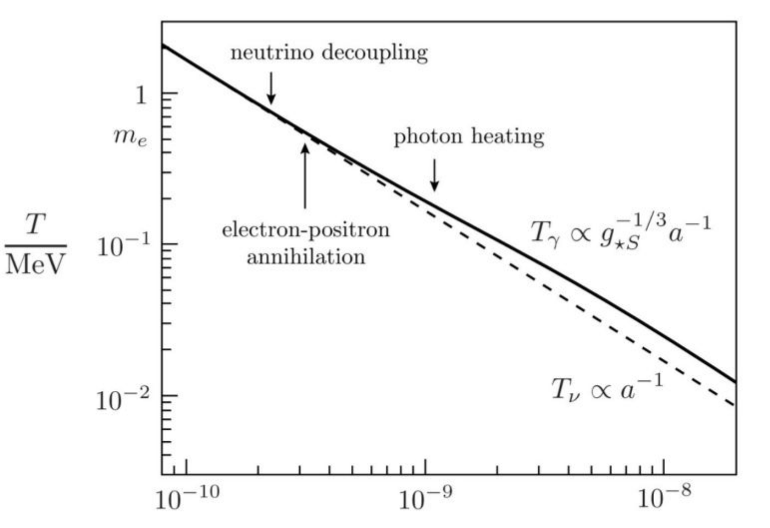
- the most weakly interacting SM particles, they are the first to **decouple** from the primordial plasma.

- Annihilation of electrons and positrons around **T~0.5 MeV** **heated photons** relative to neutrinos

- Entropy conservation gives the temperature ratio after annihilation:

$$T_\nu = \bigg(\underbrace{\frac{g_{*,S}(T_-)}{g_{*,S}(T_+)}}_{}\bigg)^{\frac{1}{3}} = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma$$

(the effective number of relativistic degrees of freedom)



Picture by Baumann

Cosmic Neutrinos
(SM light relics)

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

- They are parametrized by the observable $N_{\rm eff}$ "the effective number of neutrinos"
  - In the SM: $N_{\rm eff}$ = 3.044 Akita1, Yamaguchi 2020
- 41% of the radiation density in the universe

$$a_\nu \equiv \left[\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}\right]^{-1} \simeq 4.40 \longrightarrow \epsilon_\nu \equiv \frac{\rho_\nu}{\rho_\gamma} = \frac{N_{\rm eff}}{a_\nu + N_{\rm eff}} \simeq 0.41$$

- Cosmology is sensitive to their gravitational effects
  - Both through their energy density and perturbations
  - Planck 2018: $\boxed{N_{\rm eff}^{\rm CMB} = 2.92 \pm 0.19}$

Additional Light thermal relics (BSM)

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

$$\rho_r = \rho_\gamma \left(1 + \frac{N_{\text{eff}}}{a_\nu}\right)$$

N_{eff} parametrizes any contribution* to radiation beyond photons normalized to energy density of a single neutrino.

* Strictly speaking, the parameter **N_{eff}** is usually taken to capture neutrinos and neutrino-like species, i.e. free-streaming radiation. Non-free streaming radiation can be captured by:

$$N_{\text{fluid}} \equiv a_\nu \frac{\rho_Y}{\rho_\gamma} \longrightarrow \rho_r = \rho_\gamma \left(1 + \frac{N_{\text{eff}} + N_{\text{fluid}}}{a_\nu}\right)$$

Additional Light thermal relics (BSM)

$$\rho_r = \rho_\gamma \left(1 + \frac{N_{\rm eff}}{a_\nu}\right)$$

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

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

$$\underbrace{\mathcal{L} \subset \frac{\mathcal{O}_X \mathcal{O}_{\rm SM}}{\Lambda^\Delta}}_{\text{coupling to SM}} \longrightarrow \underbrace{\Gamma\left(\Lambda, T_{\rm dec}\right) \approx H\left(T_{\rm dec}\right)}_{\text{decoupling}} \longrightarrow \underbrace{\rho_X(\Lambda)}_{\text{relic density}}$$

$$\Delta N_{\rm eff}\left(T_{\rm dec}\right) = \frac{\rho_X}{\rho_{\nu_i}} = \underbrace{0.027}_{\left(\frac{10.75}{g_{*,SM}}\right)^{4/3}} g_{*,X} \left(\frac{g_{*,\rm SM}}{g_*\left(T_{\rm dec}\right)}\right)^{4/3}$$

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

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

Additional Light thermal relics (BSM)

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

Planck 2018 constraint:

$$N_{\mathrm{eff}}^{\mathrm{CMB}} = 2.92 \pm 0.19$$

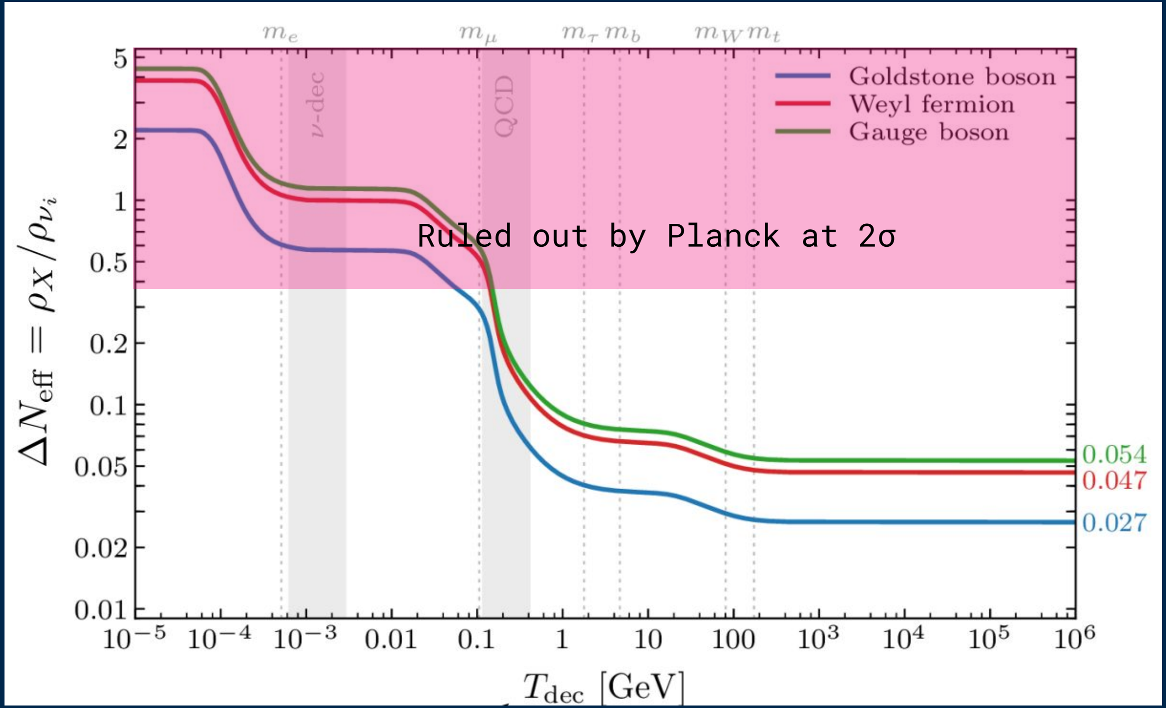


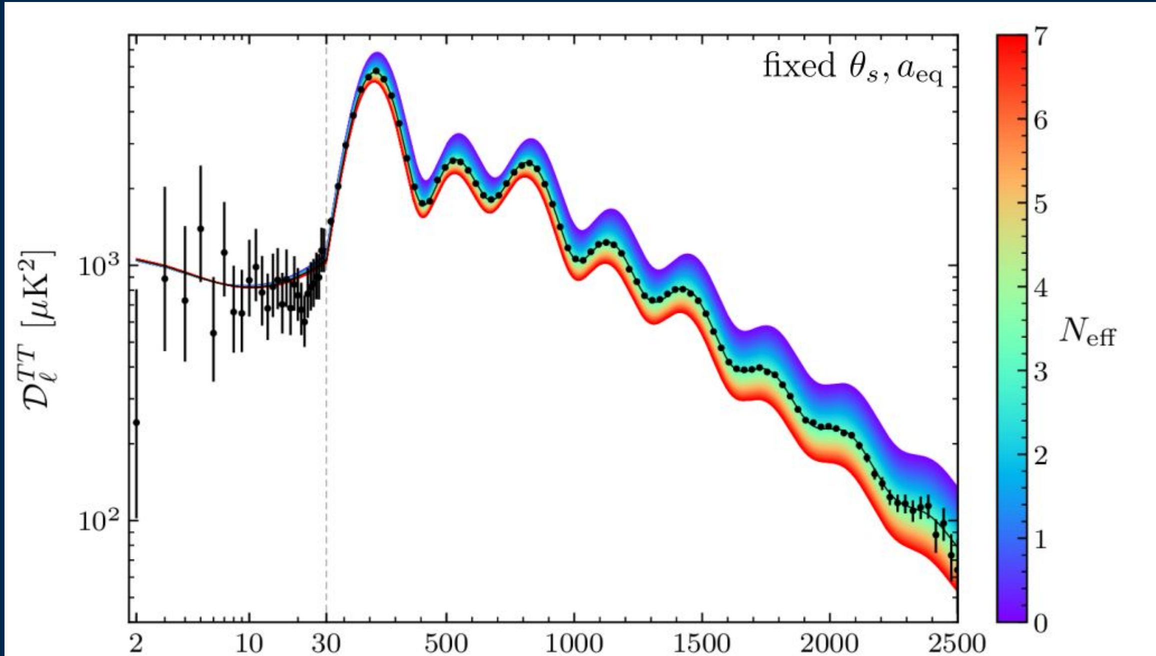
Figure from B. Wallisch

Light relics in the CMB

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

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

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

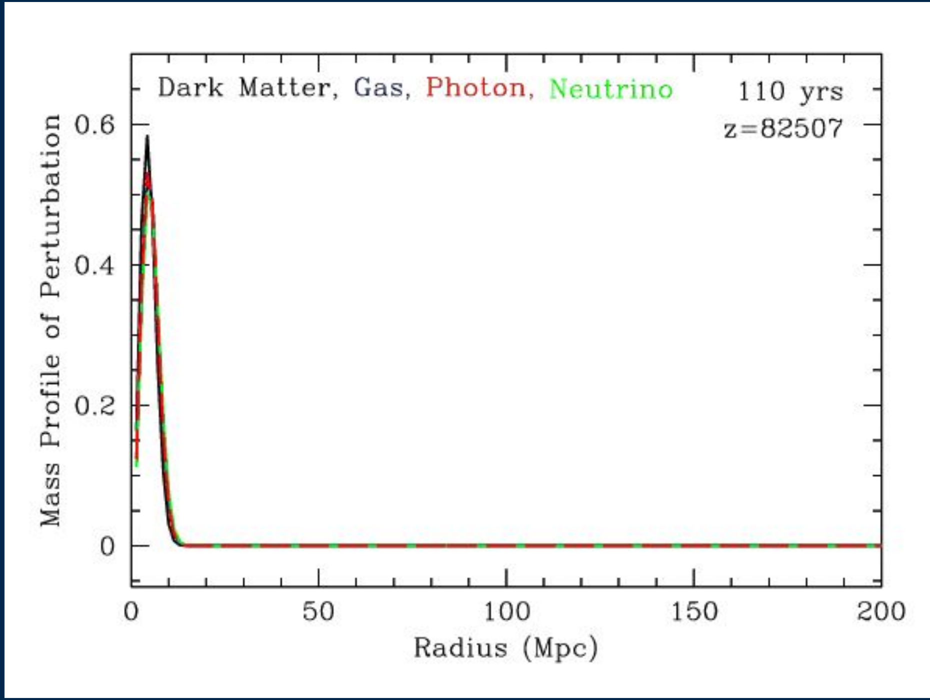


Picture by B.Wallisch

Light relics in the CMB

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

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



Eisenstein, Seo and White

Light relics in the CMB

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

Bashinsky & Seljak

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

Undamped power spectrum

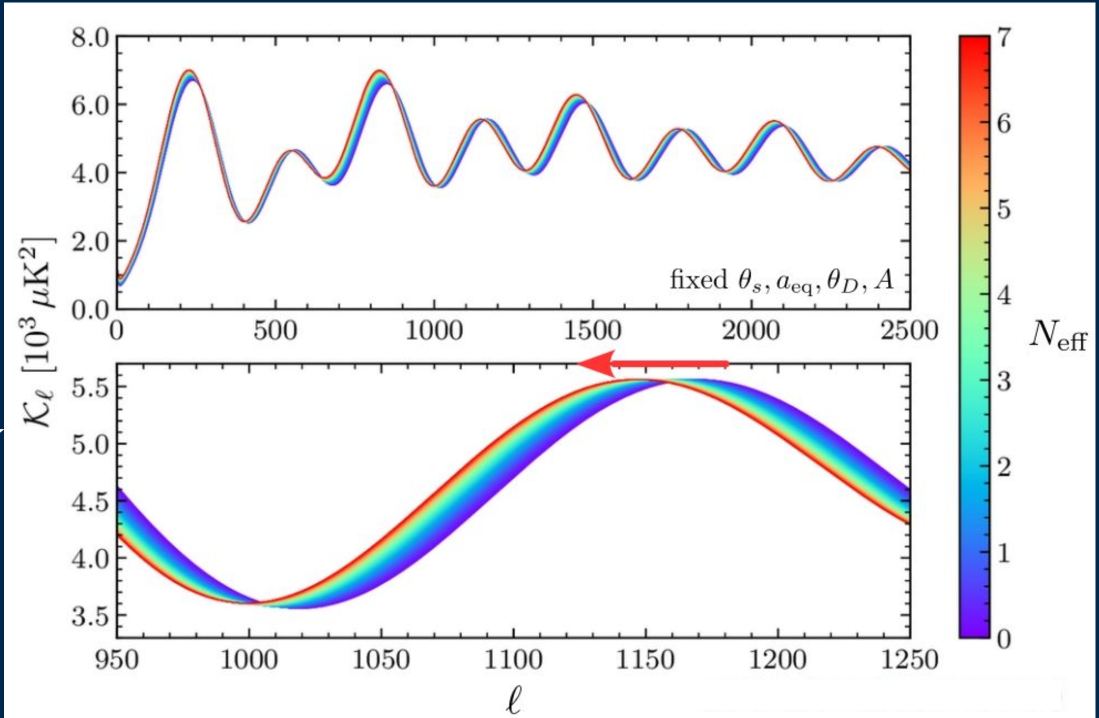
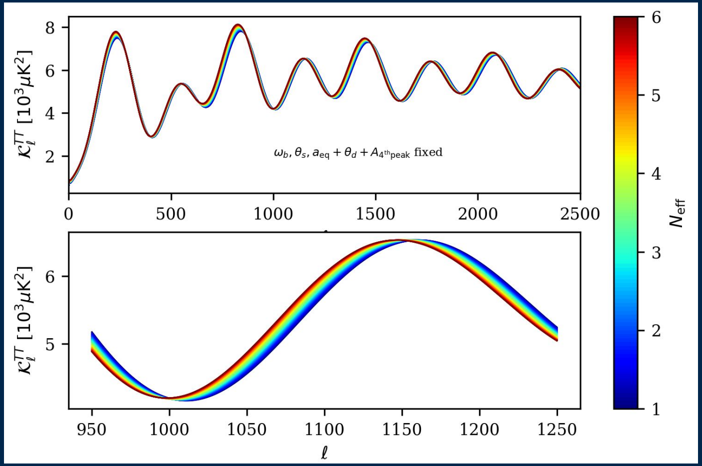


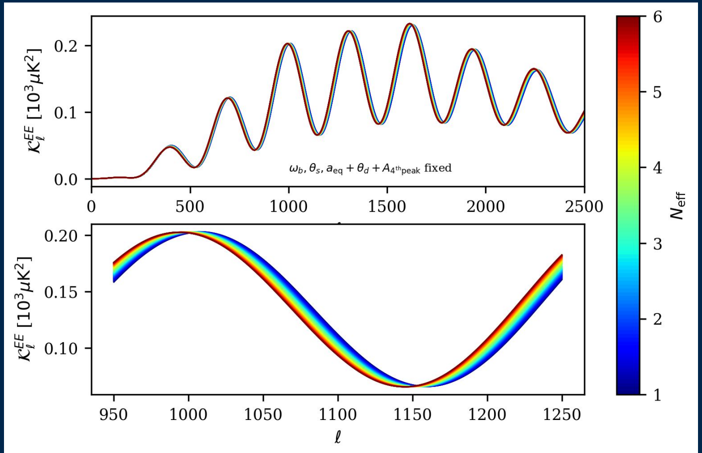
Figure from B. Wallisch

The special role of the Phase shift

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

We follow their approach!



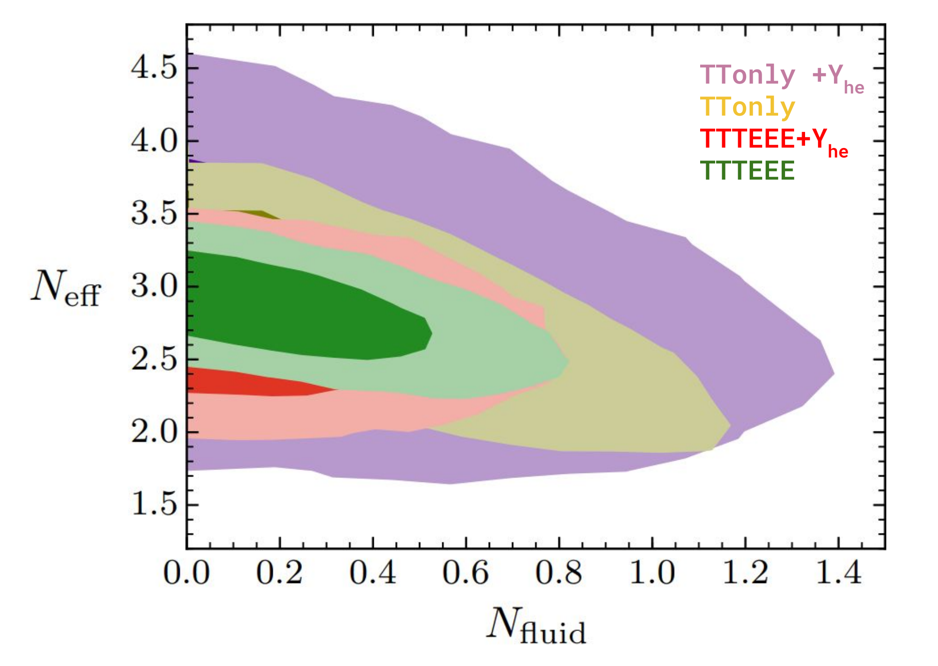


Constraints from Planck 2015 data via N_{fluid}

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

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

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



Baumann, Green, Meyers & Wallisch

Results are consistent with absence of non-free streaming neutrinos

The Phase shift in the CMB spectrum

Following Follin, Knox, Millea & Pan

- A new parameter to control the shift

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

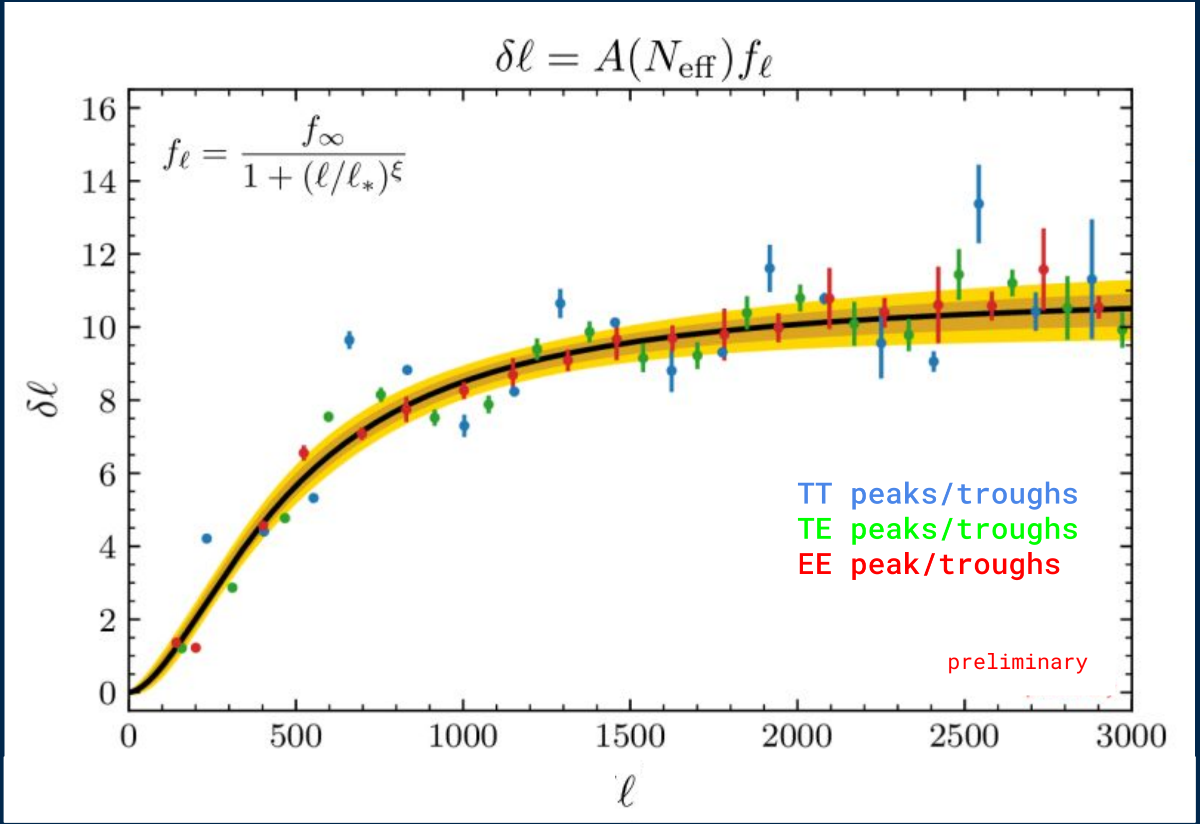
$$\downarrow$$

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

Bashinsky & Seljak

$$\downarrow$$

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



The Phase shift in the CMB spectrum

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- A new parameter to control the shift

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

$$\downarrow$$

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

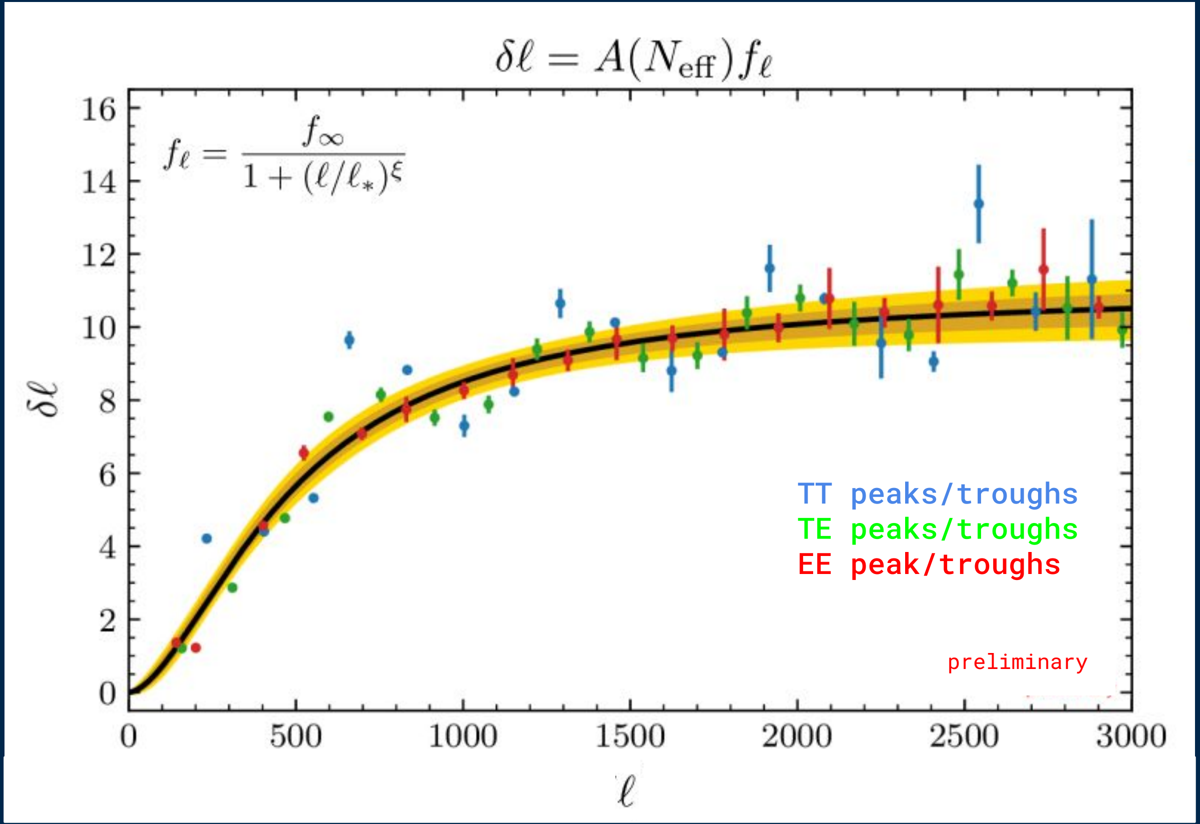
Bashinsky & Seljak

$$\downarrow$$

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

$$^{*}A(N_{\rm eff}^{\delta\phi}, N_{\rm eff}) \equiv \frac{\epsilon(N_{\rm eff}^{\delta\phi}) - \epsilon(N_{\rm eff})}{\epsilon(1) - \epsilon(3.044)}$$

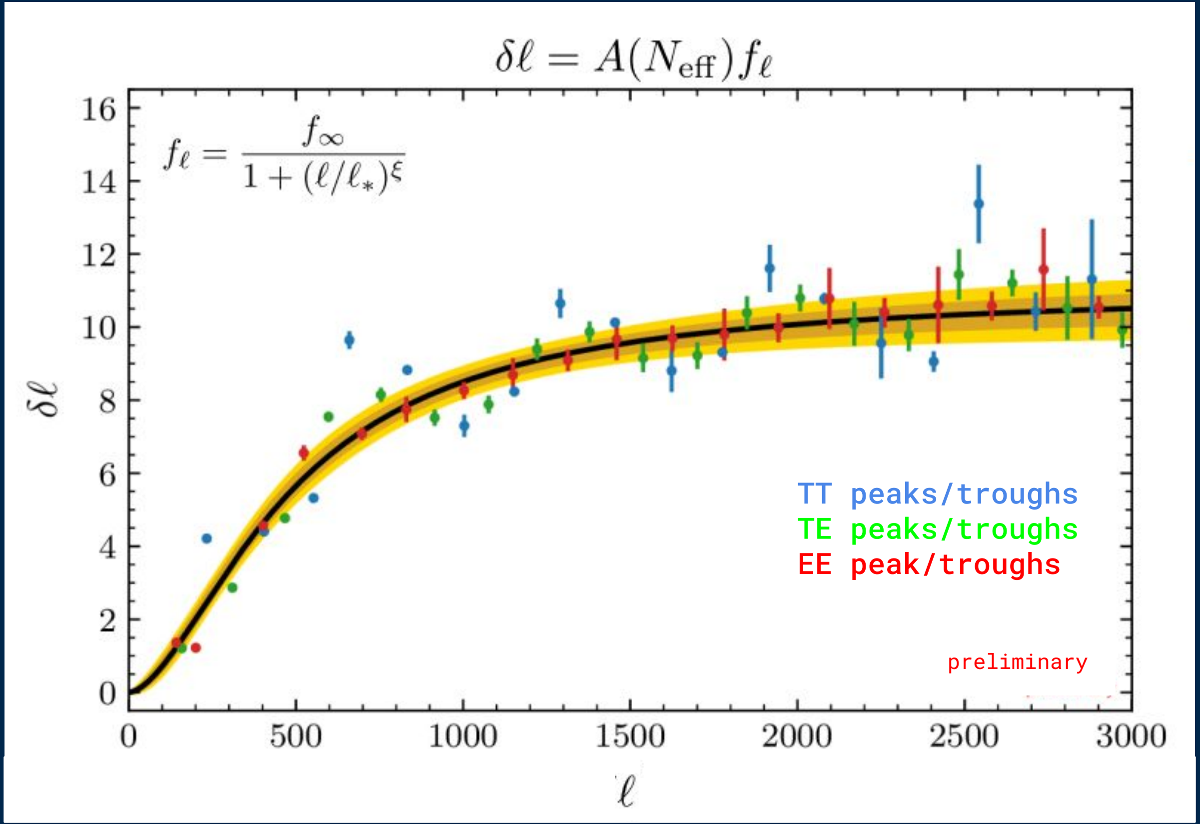
$$\left.\epsilon(N_{\rm eff}) \equiv \frac{N_{\rm eff}}{a_\nu + N_{\rm eff}}\right\}$$ (fraction of radiation energy in neutrinos)



The Phase shift in the CMB spectrum

Our Contributions:

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



Constraints on the phase shift from Planck 2018

- Based on Planck 2013 TT:

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

- Planck 2018 (preliminary):

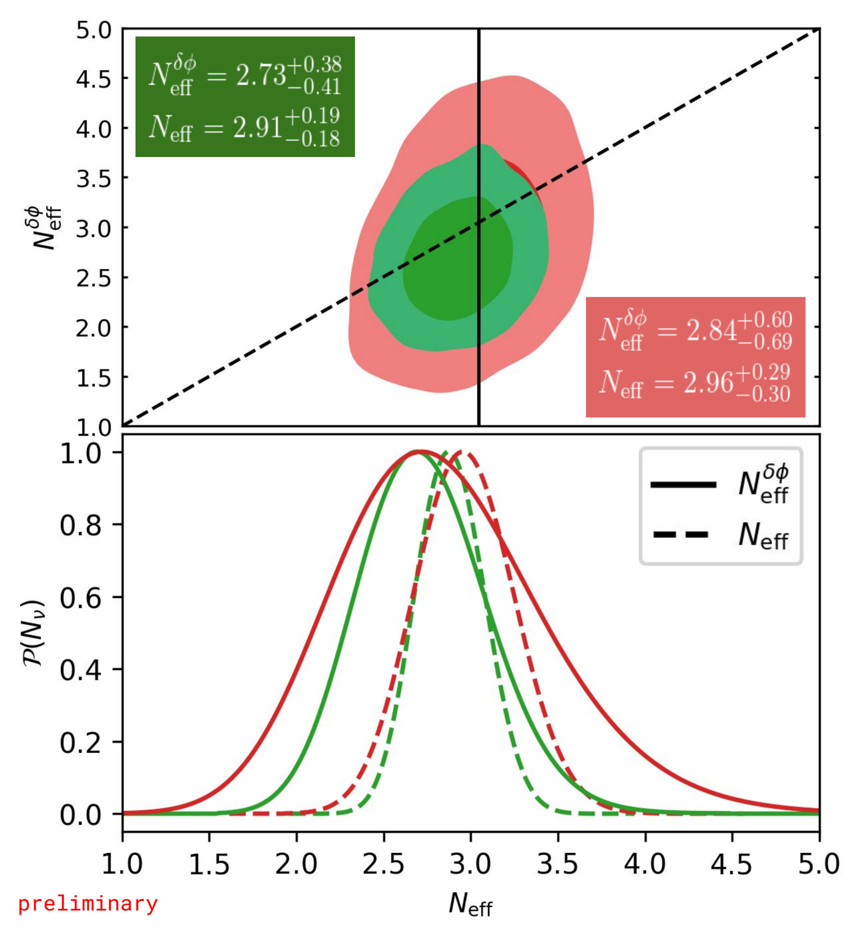
TTTEEE

$$\boxed{N_{\rm eff}^{\delta\phi} = 2.73^{+0.38}_{-0.41}}$$

TTonly

$$\boxed{N_{\rm eff}^{\delta\phi} = 2.84^{+0.60}_{-0.69}}$$

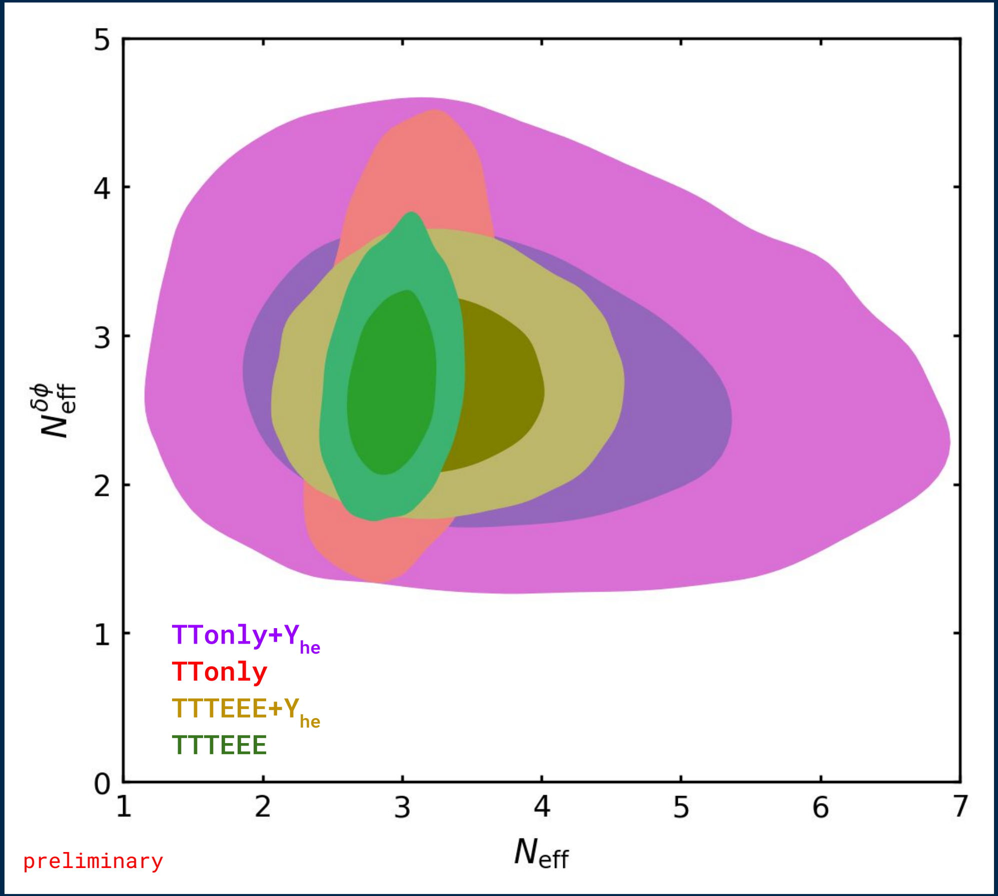
  - Strong evidence of **free-streaming** nature of **neutrinos!**
  - Planck 2018 is still compatible with **SM**
  - **1st template-based measurement** of the phase shift using **Polarization data**



Freese, Wallisch & GM (in prep.)

Constraints on the phase shift from Planck 2018

- The phase shift is a **robust** probe of free-streaming radiation
- **No degeneracy** with the Helium fraction $\mathbf{Y_{He}}$



Freese, Wallisch & GM (in prep.)

But, do we really learn anything new by directly constraining the Phase shift?

- When constraining N_{eff}, we are implicitly assuming all of our radiation is free-streaming.
  - $N^{\delta\phi}_{eff}$ provides a robust way to independently test this property
  - How free streaming are neutrinos? fix N_{eff}=3.044 and vary $N^{\delta\phi}_{eff}$

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

- Expect improvements, particularly from higher sensitivity of ground-based experiments to larger multipoles

- PLanck 2018 + ACT + SPT **(see back-up slides)**

  $$N_{\rm eff}^{\delta\phi} = 2.91^{+0.31}_{-0.33}$$

  [Errobars reduced ~0.1 from Planck 2018 only analysis]

- Forecasts: **(work in progress)**
  - SO $\sigma(N_{\rm eff}^{\delta\phi}) \sim 0.2$
  - CMB-S4 $\sigma(N_{\rm eff}^{\delta\phi}) \sim 0.1$

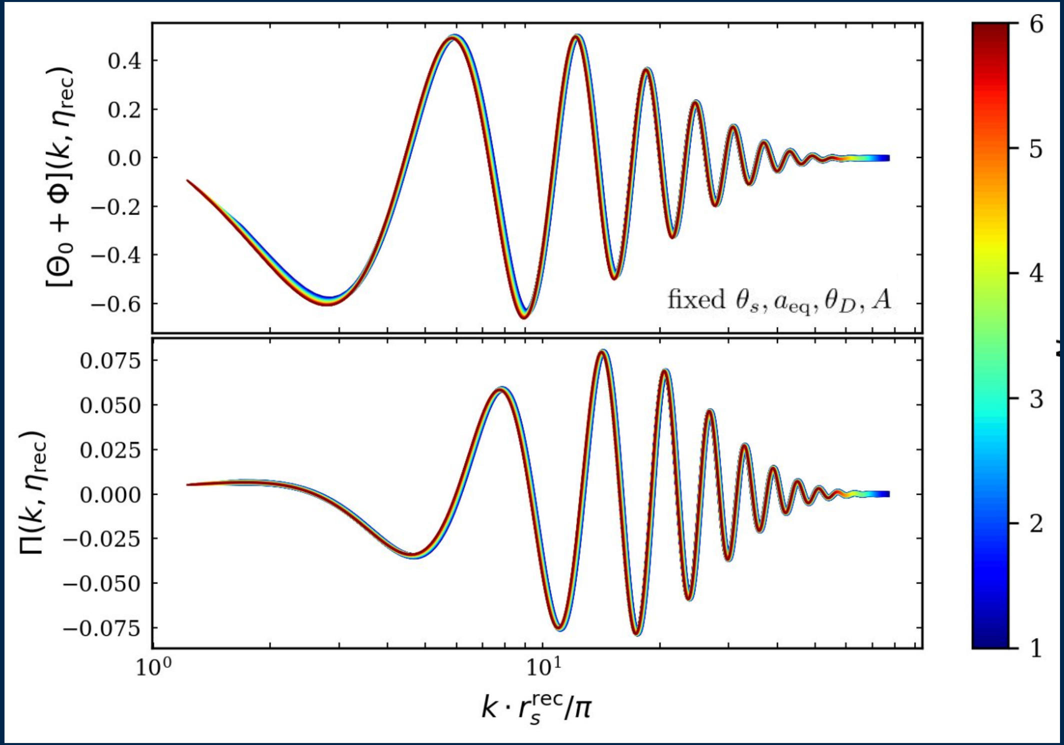
Freese, Wallisch & GM (in prep.)

Can we do better?
A perturbation-based template

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

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

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



Freese, Wallisch & GM (in prep.)

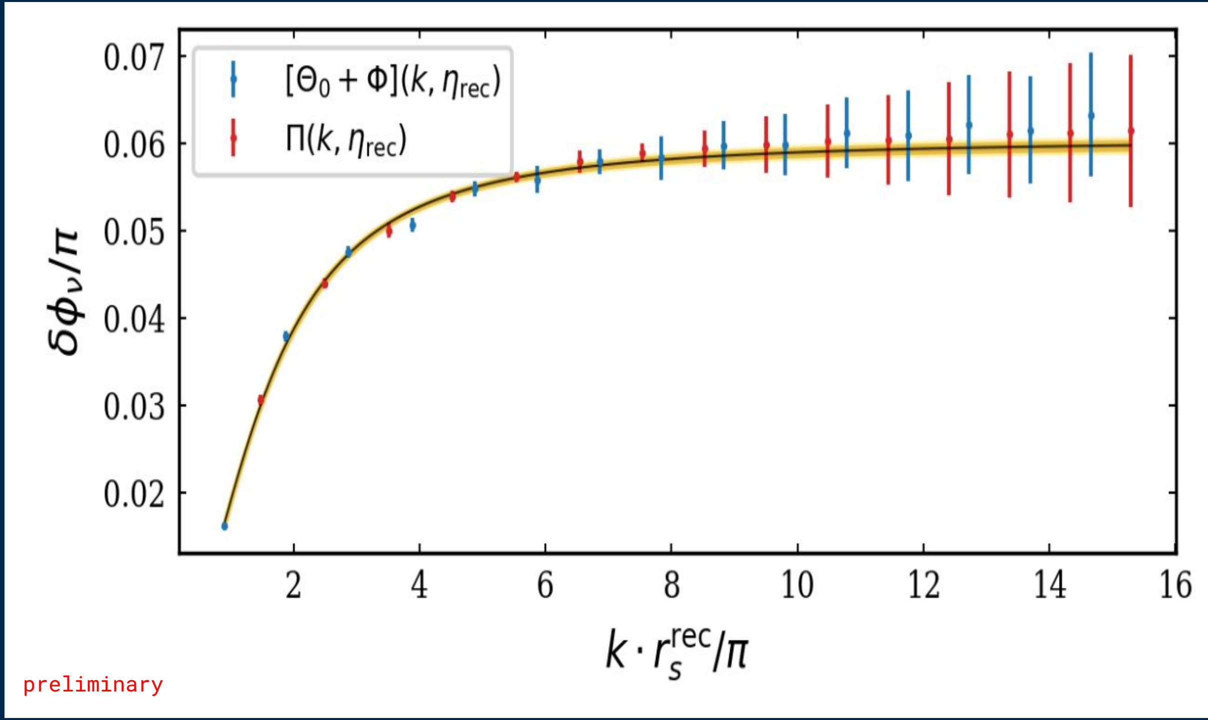
Can we do better?
A perturbation-based template

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

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

- Less scatter in the obtained template

- Complex implementation (Work in progress)



Freese, Wallisch & GM (in prep.)

Summary

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

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

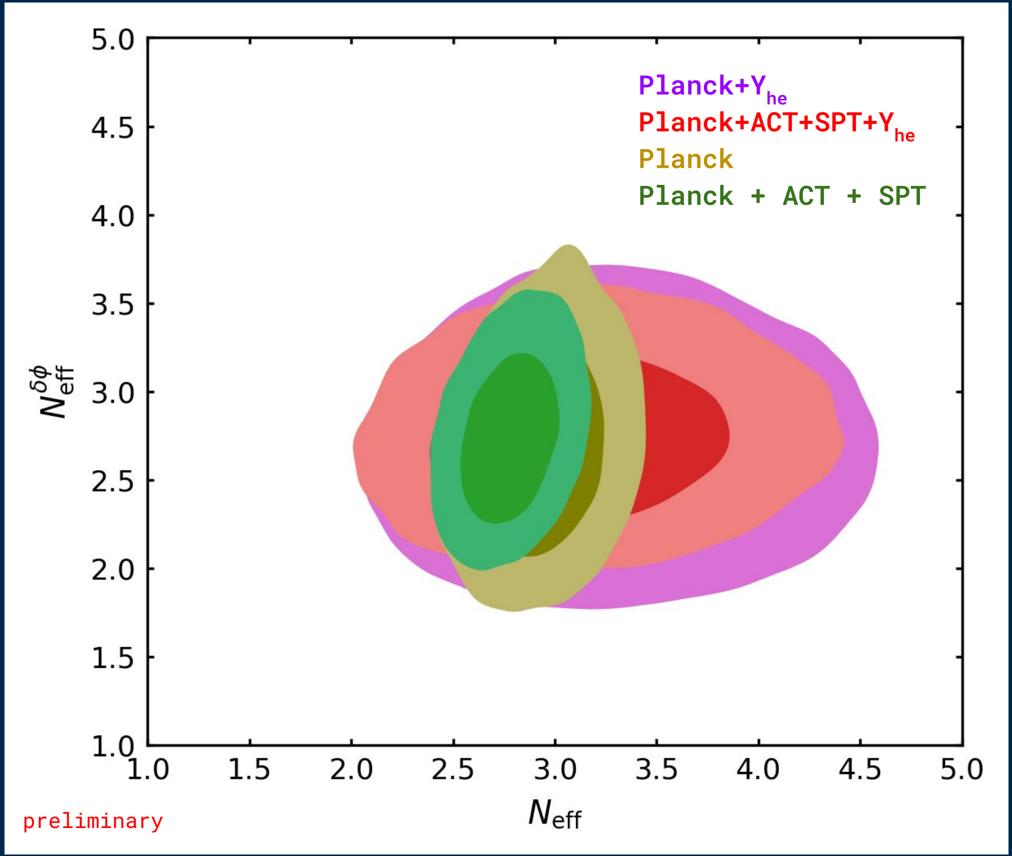
Grazie per l’attenzione

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

Based on ongoing work with Benjamin Wallisch and Katherine Freese

BACK-UP SLIDES

Phase shift analysis: Planck 2018 + ACT-DR4 + SPT-g3



Analysis done with TT+TE+EE data

Freese, Wallisch & GM (in prep.)

The origin of the phase shift

$$\ddot{d}_\gamma - c_\gamma^2 \nabla^2 d_\gamma = \nabla^2 \Phi_+$$

$$\underbrace{d_\gamma(y)}_{y \equiv c_\gamma k \tau} = \left[d_{\gamma,\,\mathrm{in}} + c_\gamma^{-2} A(y)\right] \cos y - c_\gamma^{-2} B(y) \sin y \quad \begin{cases} A(y) \equiv \int_0^y \mathrm{d}y' \Phi_+(y') \sin y' \\ B(y) \equiv \int_0^y \mathrm{d}y' \Phi_+(y') \cos y' \end{cases}$$

$$\sin\phi = \frac{B}{\sqrt{(A + c_\gamma^2 d_{\gamma,\mathrm{in}})^2 + B^2}}$$

A non-zero $B \equiv \lim_{y \to \infty} B(y)$ will produce a **constant phase-shift**

Baumann, Green, Meyers & Wallisch

The origin of the phase shift

$$B = \frac{1}{2}\int_{-\infty}^{+\infty} e^{iy}\Phi_+^{(s)}(y) \neq 0$$

(i) Rapid growth of $\mathbf{\Phi}_+^{(s)}(y)$ → mode travelling **faster than c_s**

(ii) Non-analytic behaviour of $\mathbf{\Phi}_+^{(s)}(y)$

$$\Phi_+ \propto e^{-ic_s k\tau} = e^{-i(c_s/c_\gamma)y}$$

$$c_s > c_\gamma$$

$$\sin\phi = \frac{B}{\sqrt{(A + c_\gamma^2 d_{\gamma,\mathrm{in}})^2 + B^2}}$$

A non-zero $B \equiv \lim_{y\to\infty} B(y)$ will produce a **constant phase-shift**

Baumann, Green, Meyers & Wallisch

Diffusion Damping in the CMB

- The mean free path of photons is small but finite

$$\lambda_{\text{mfp}} = 1/(a\sigma_T n_e)$$

- At scales below $\boldsymbol{\lambda}_{\text{mfp}}$, random walk of photons **mixes hot and cold spots**, washing out inhomogeneities

- If there are more electrons ($\mathbf{n_e}$ is larger), $\boldsymbol{\lambda}_{\text{mfp}}$ gets smaller hence we expect diffusion damping to take over at even larger multipoles (smaller scales)