

Cosmological Probes of Particle Physics

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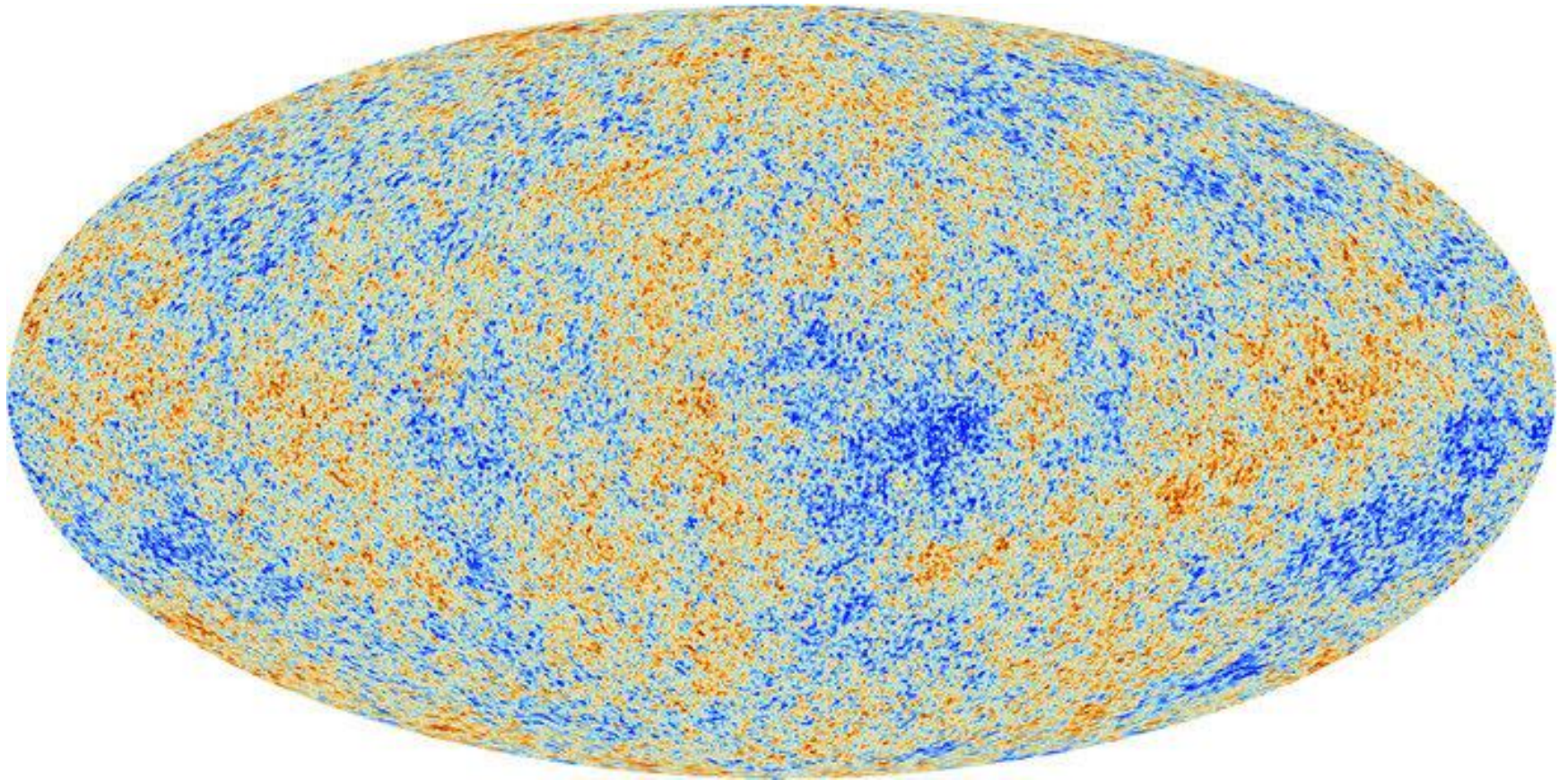
Lake Louise Winter Institute

February 20, 2018



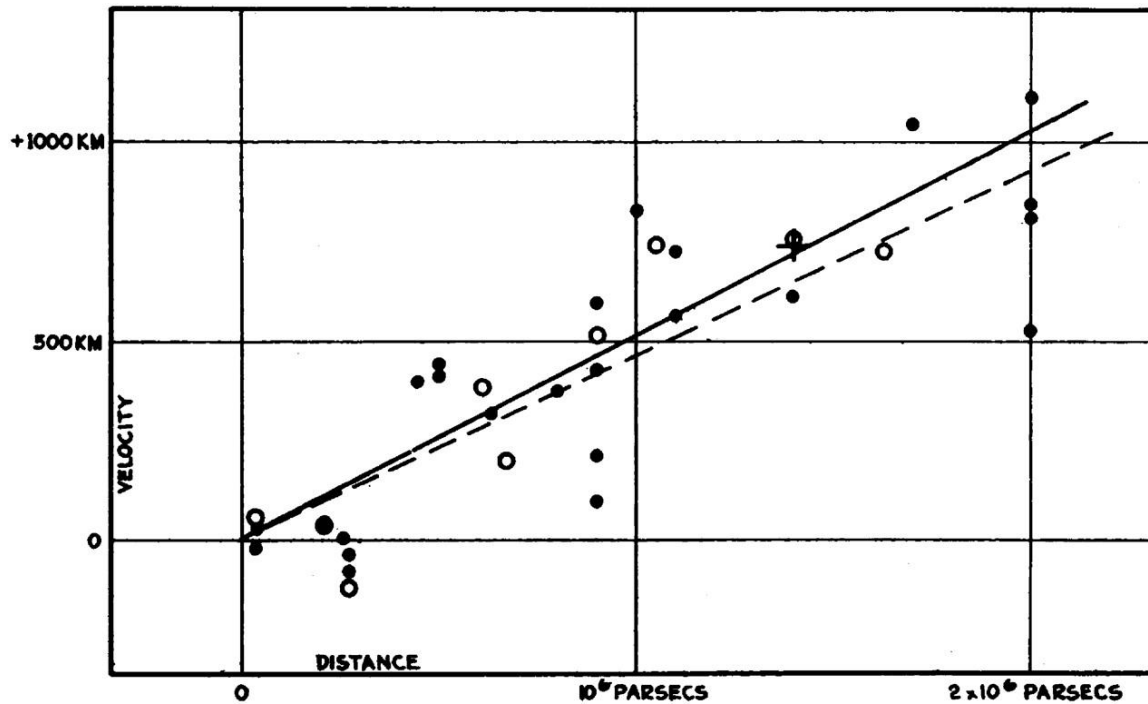
Image Credits: Planck, ANL

Cosmic Microwave Background (CMB)



Distance – Redshift Relation

The Expanding Universe - 1929



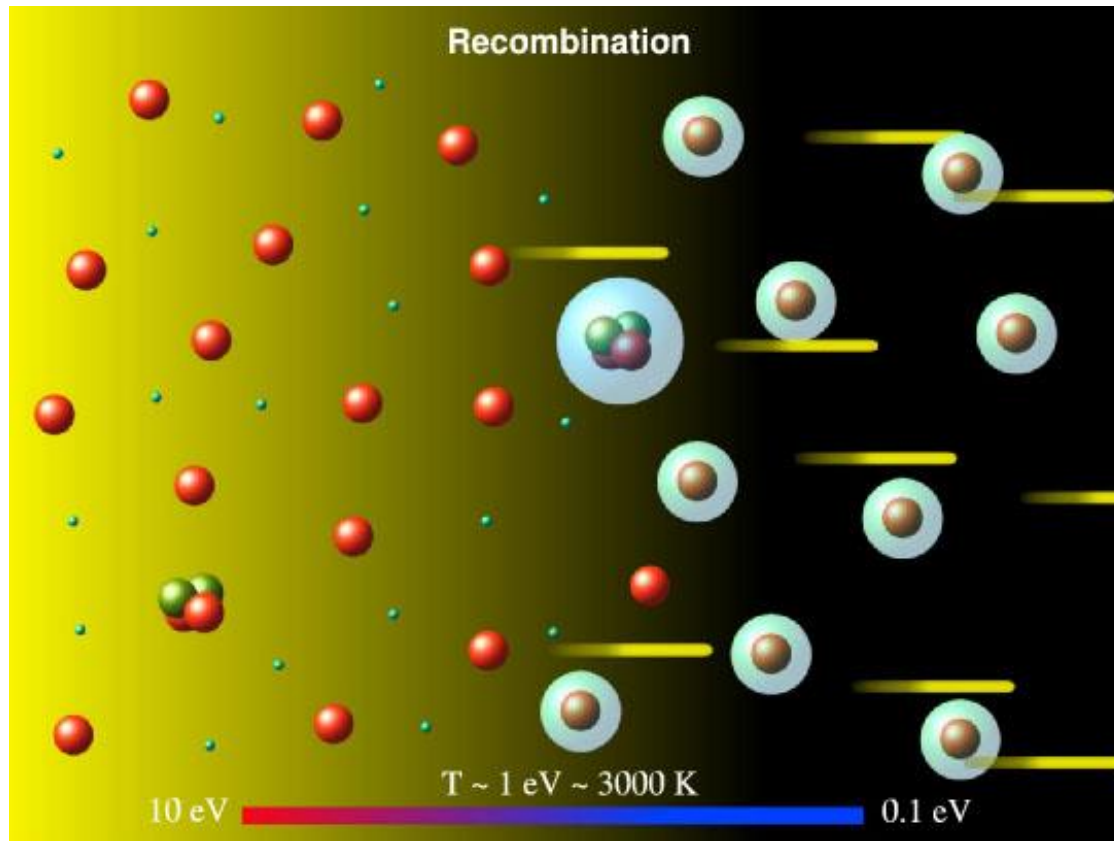
Hubble (1929)

Image Credit: Observatories of the Carnegie Institute of Washington



Big Bang Cosmology

Prediction of Cosmic Microwave Background - 1948



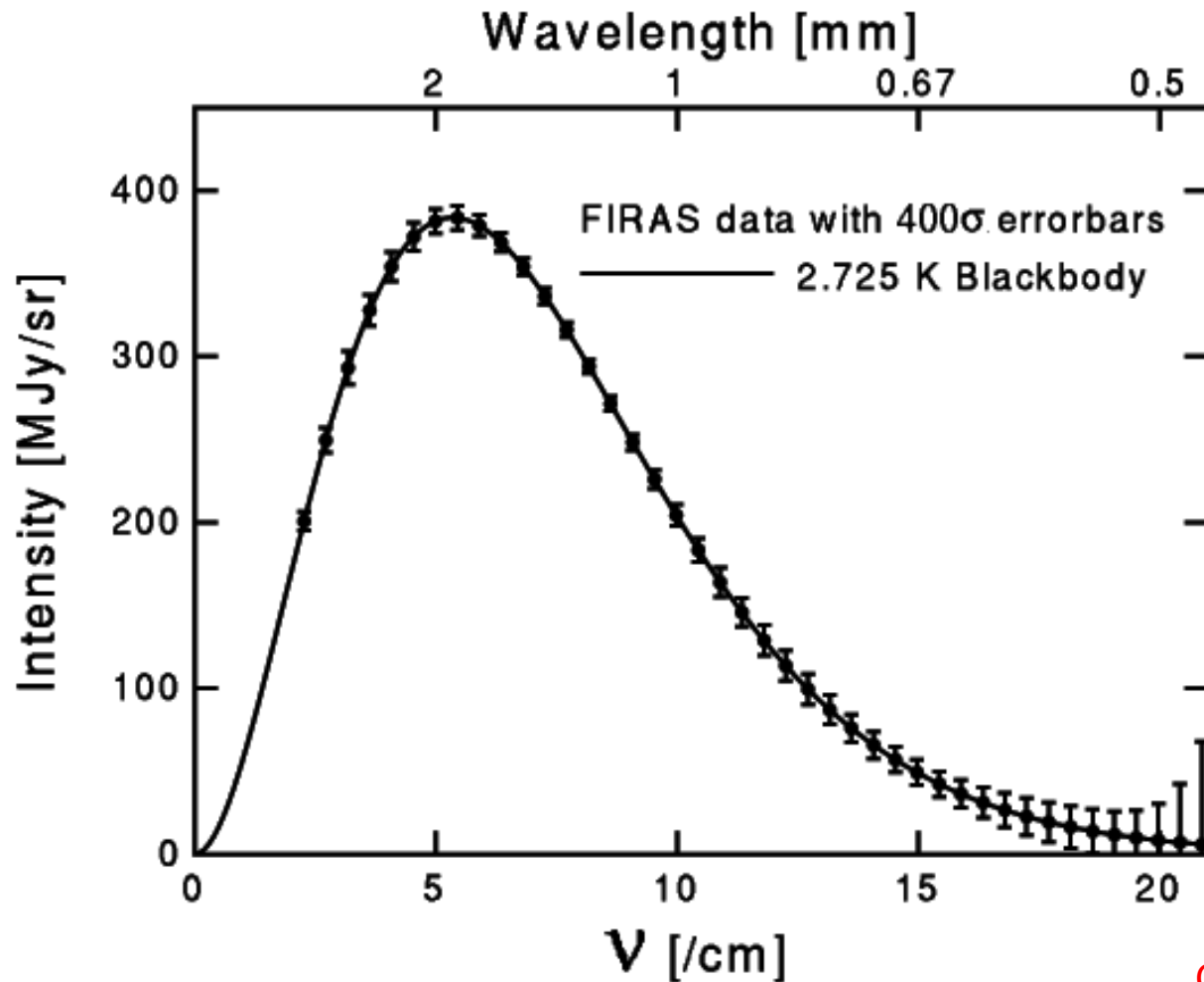
Alpher, Bethe, Gamow (1948); Alpher, Herman (1948); Gamow (1948)

Image Credit: William Kinney

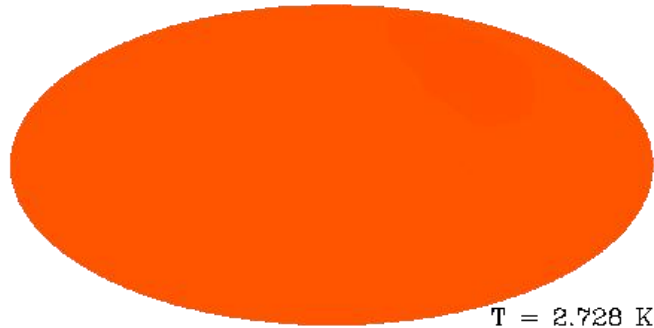


Thermal Spectrum

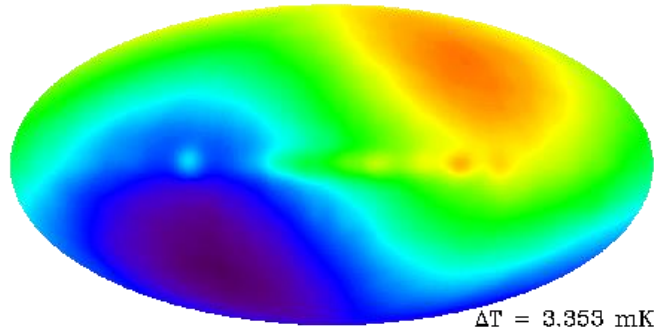
Confirmation of Hot Big Bang Cosmology - 1994



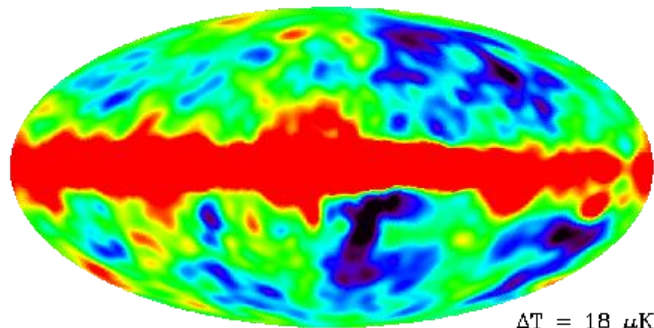
Temperature Anisotropies



Nearly Isotropic



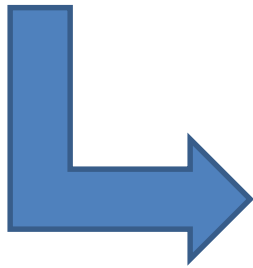
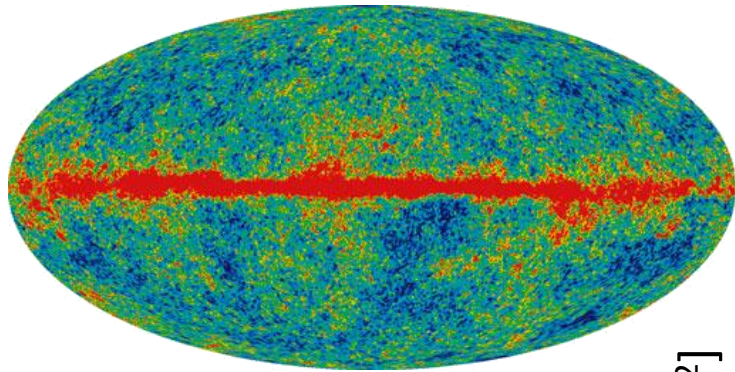
Motion-Induced Dipole



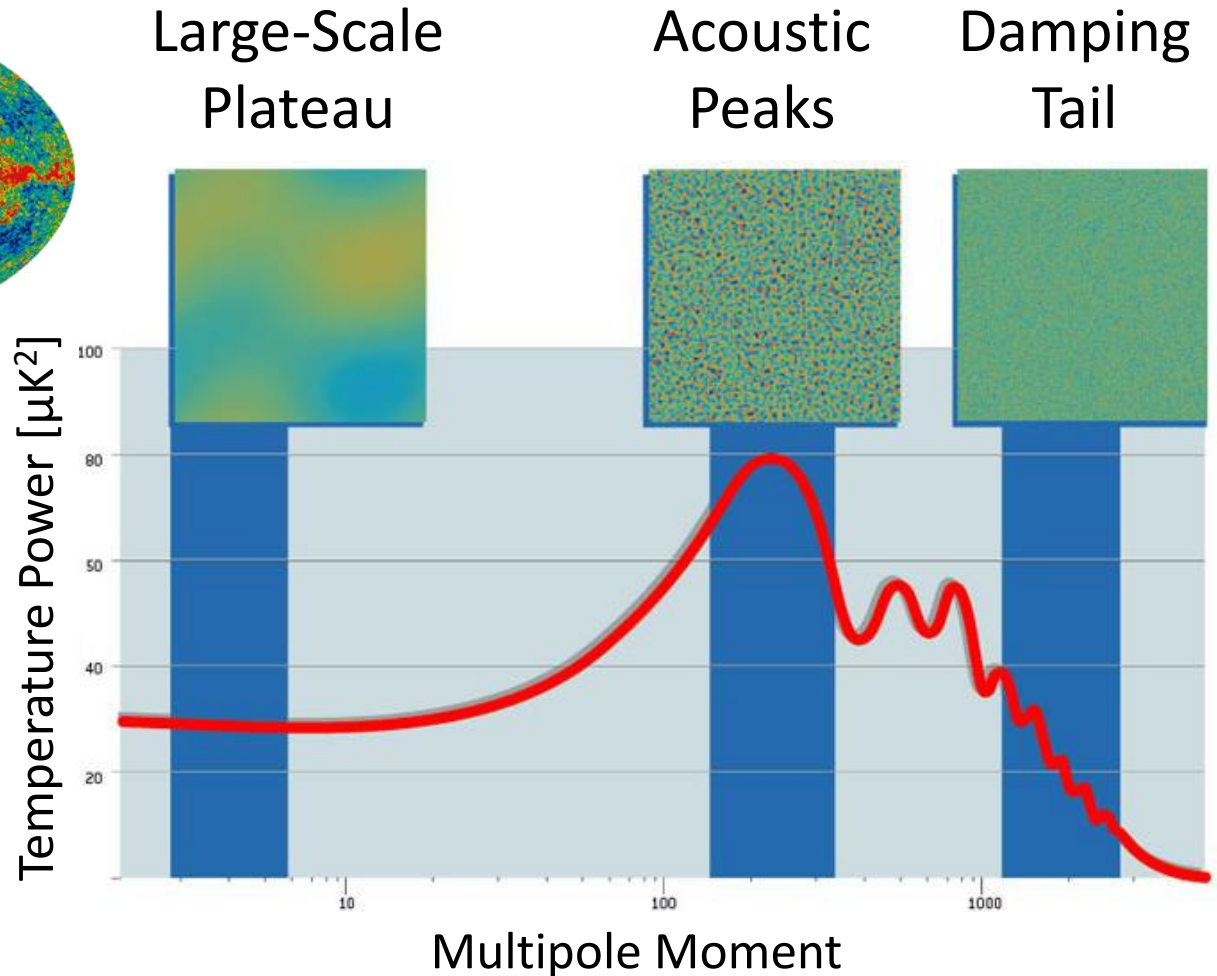
Small Primary Anisotropies



CMB Angular Power Spectrum

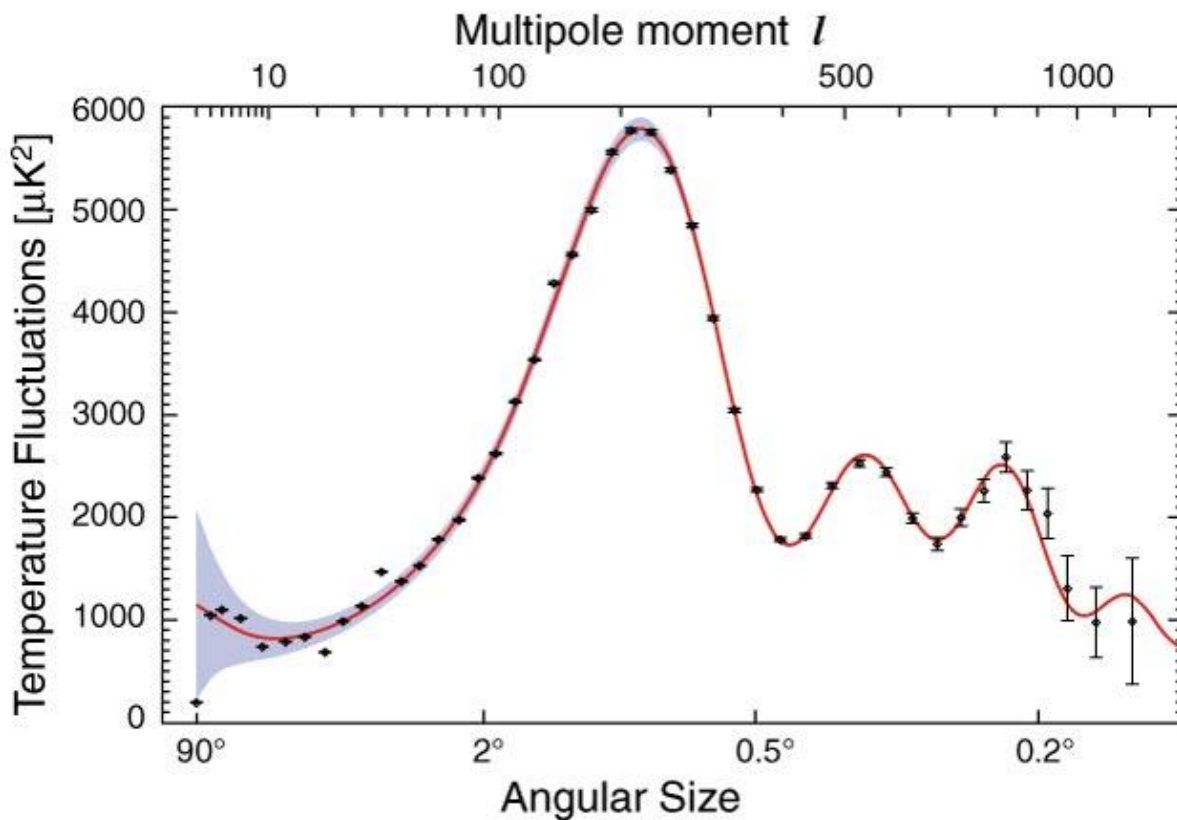


Harmonic Transform
of Two-Point
Correlation Function



Standard Model of Cosmology

Flat Λ CDM Universe



Primordial Fluctuations

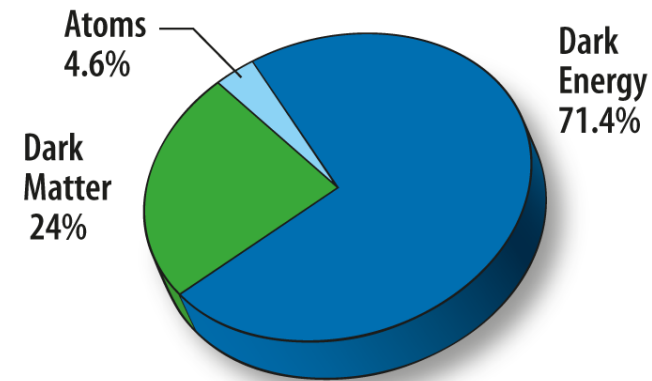
A_s n_s

Contents

ω_b ω_c θ_s

Rescattering

τ

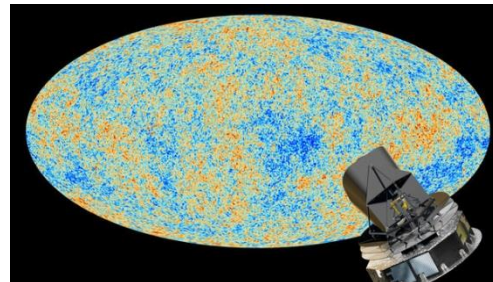
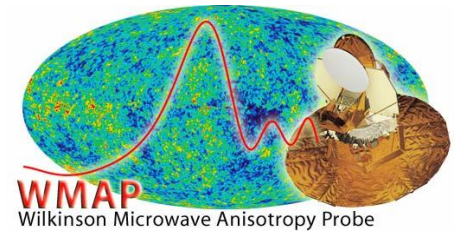
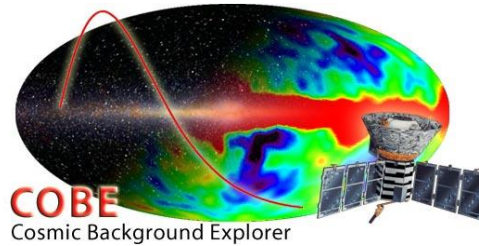


WMAP (2008)



CMB Timeline

- 1948 – Theoretical Prediction
- 1964 – First Detection
- 1992 – Spectrum and Anisotropies
- 2003 – Λ CDM Cosmology
- 2013 – Beyond the Power Spectrum
- 2018+ – Beyond the Standard Model



SIMONS OBSERVATORY



Next Generation CMB Experiments

SIMONS OBSERVATORY



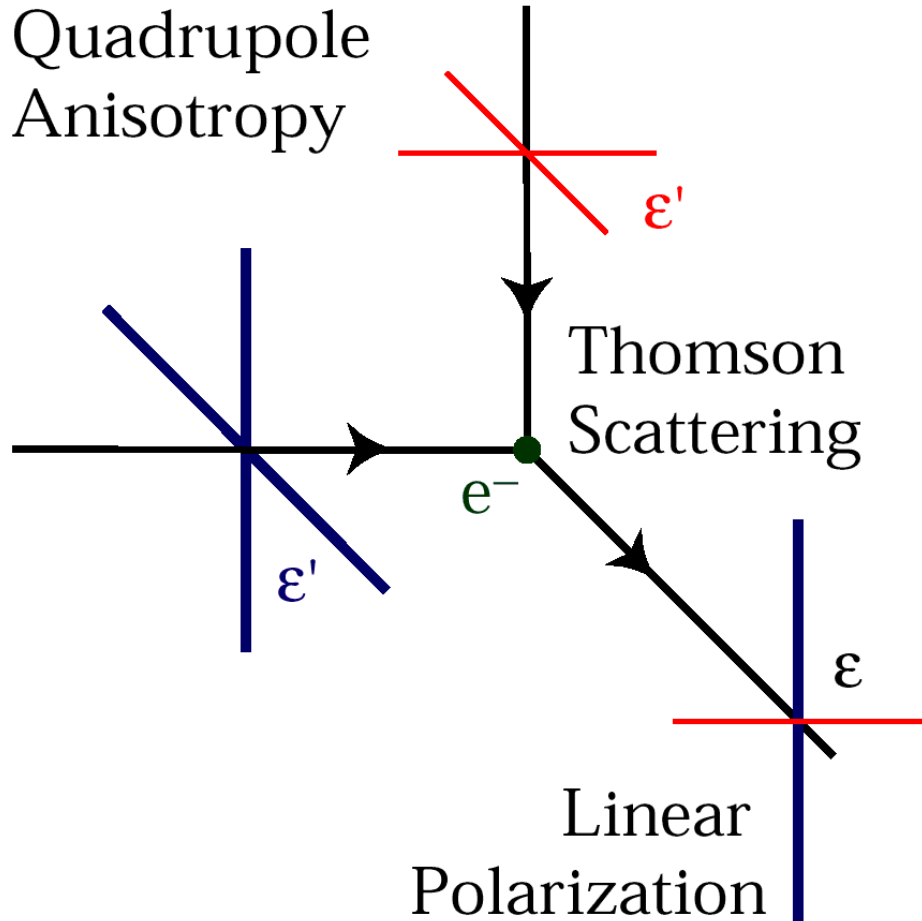
- Observing 2021-2022
- Telescope array in Atacama Desert in Chile
- Observing mid-2020s
- Multiple telescopes in Atacama Desert and at South Pole

Science Goals:

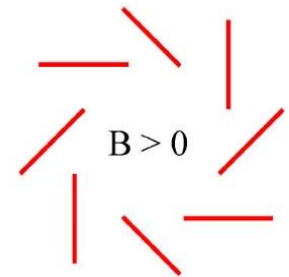
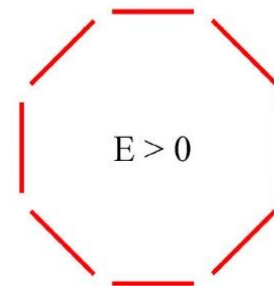
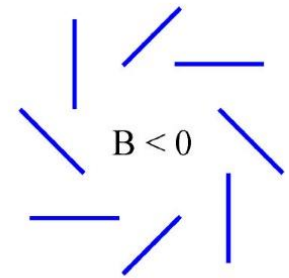
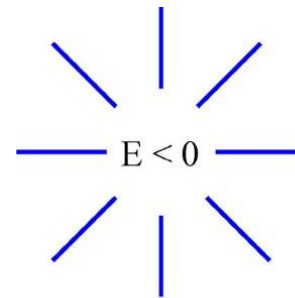
- **Fundamental Physics:** Primordial Gravitational Waves, Neutrino Properties, Light Relics
- **Astrophysics:** Mass Maps, Clusters, Cross-Correlations



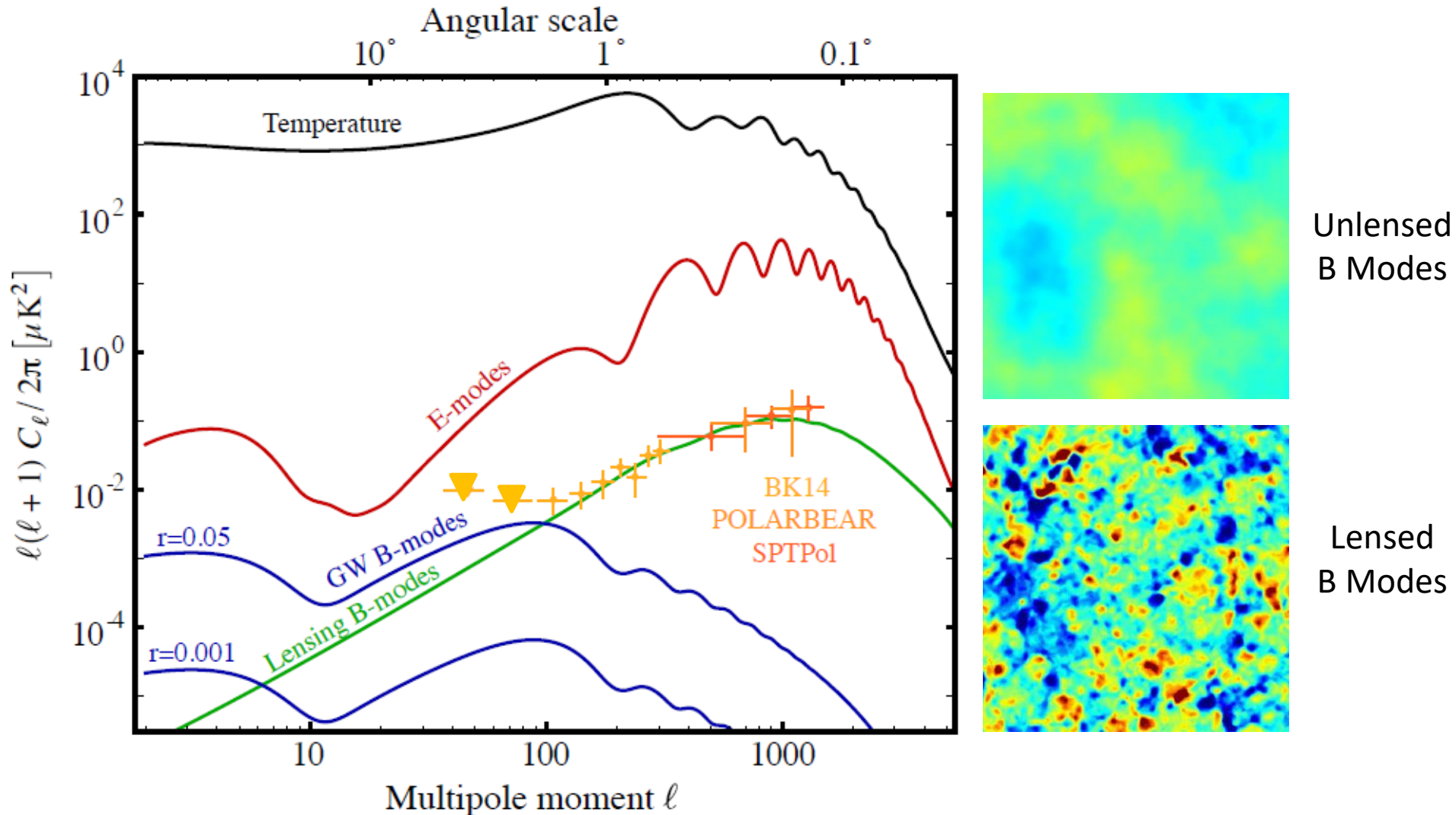
CMB Polarization



Density Perturbations \rightarrow T, E
Gravitational Waves \rightarrow T, E, B



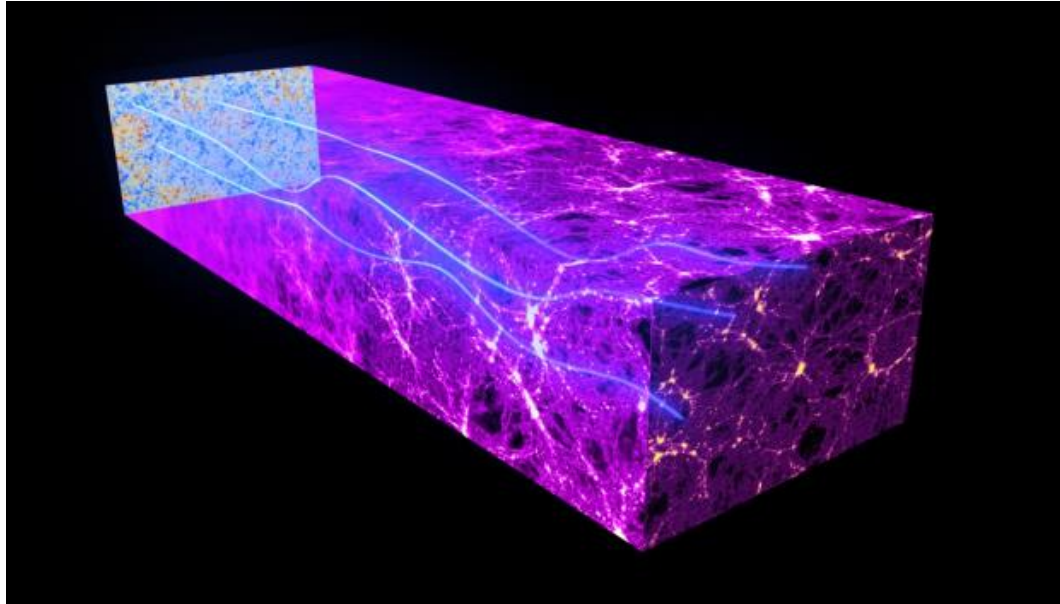
Primordial Gravitational Waves



Zaldarriaga, Seljak (1998); Kesden, Cooray, Kamionkowski (2002);
Lyth (1997) ; CMB-S4 Science Book (including JM) (2016)



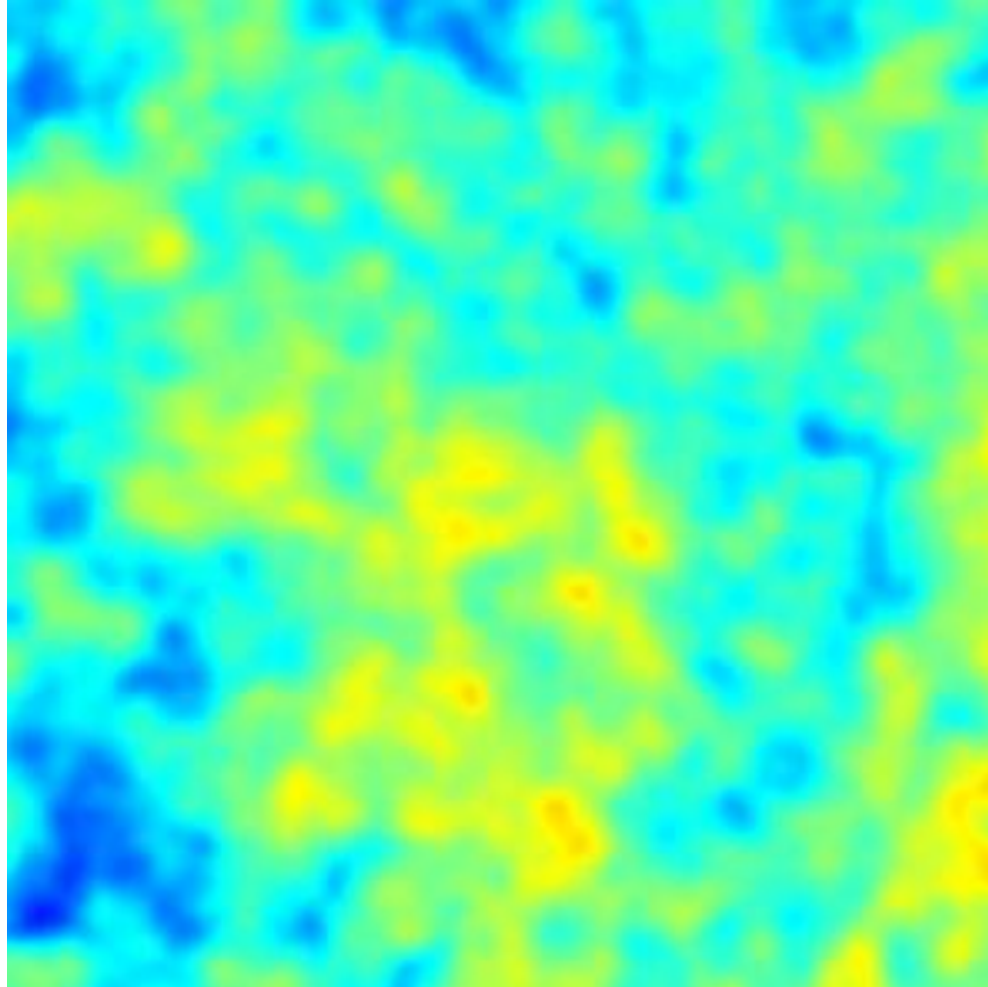
Gravitational Lensing



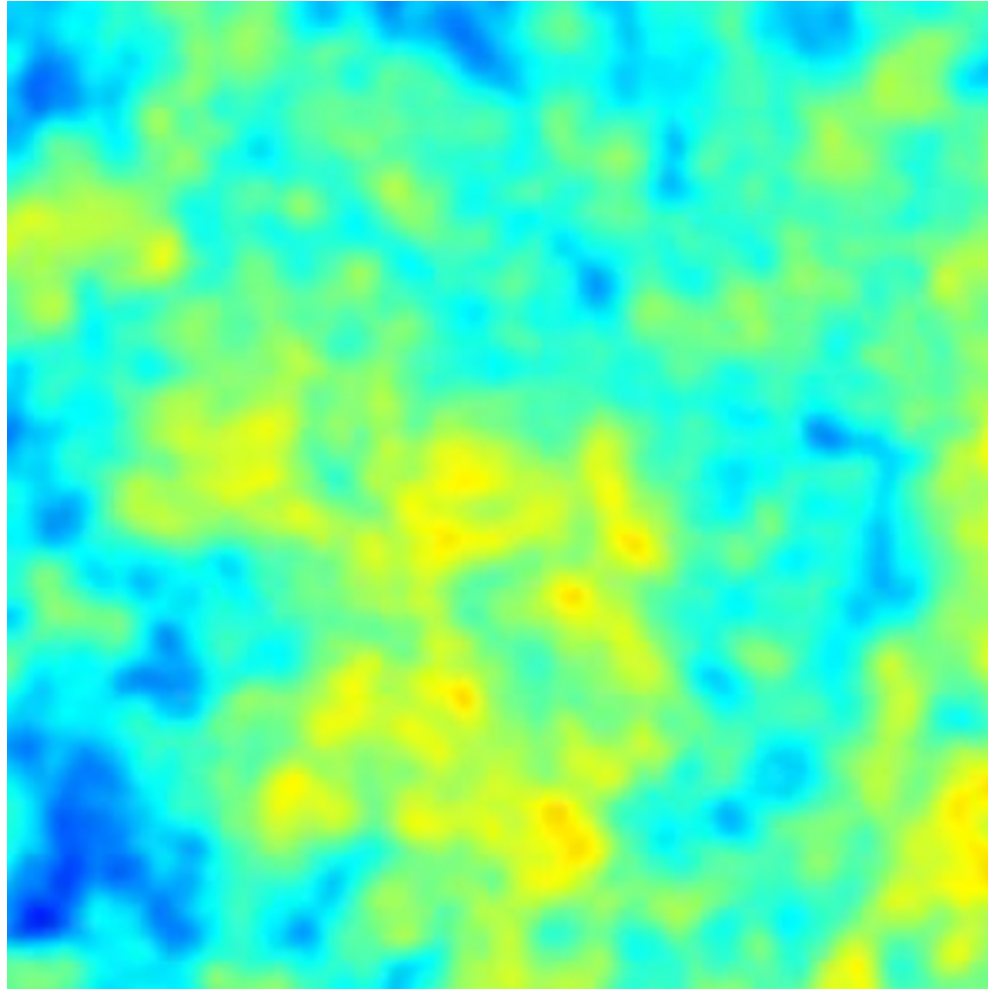
- CMB photons are deflected by the gravitational potential of structures which intervene along our line of sight
- Gravitational lensing results in statistical anisotropy of CMB maps, thereby allowing for reconstruction of the lenses



CMB Lensing

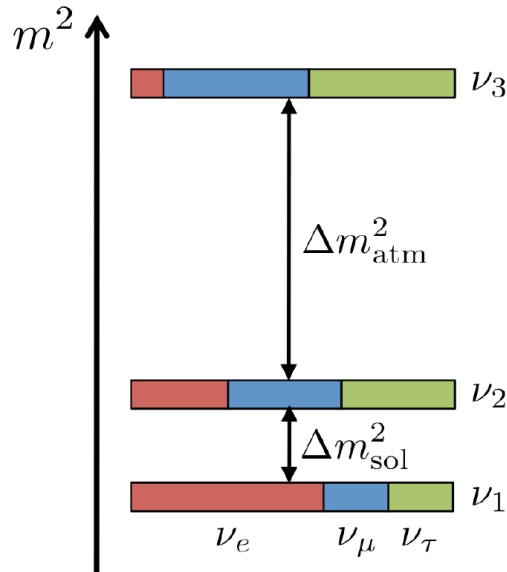


CMB Lensing



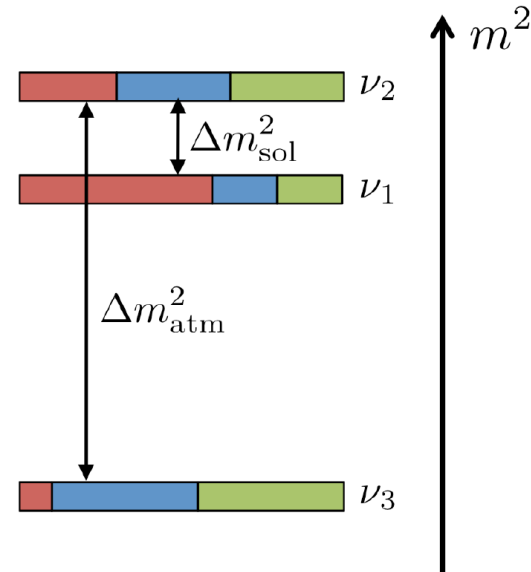
Neutrino Mass

normal hierarchy (NH)



$$\sum m_\nu \gtrsim 58 \text{ meV}$$

inverted hierarchy (IH)



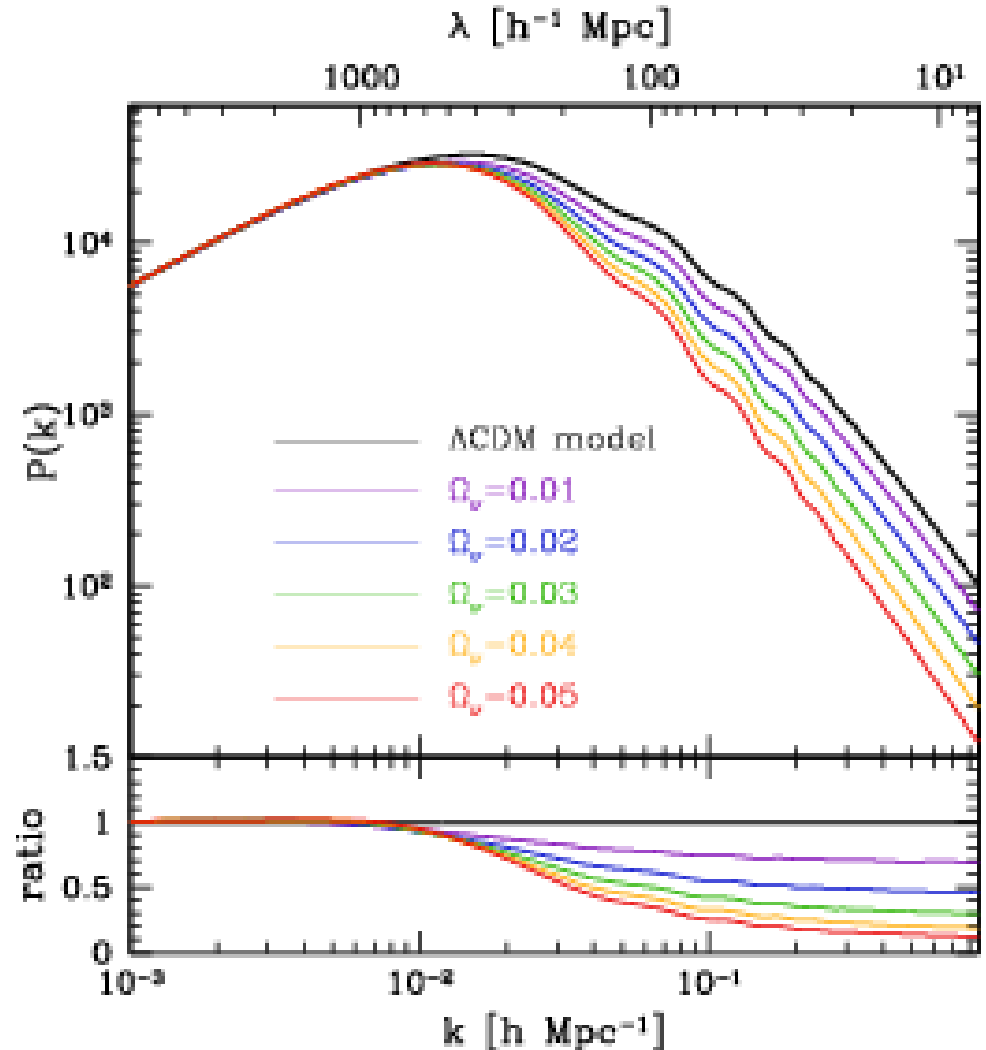
$$\sum m_\nu \gtrsim 105 \text{ meV}$$

- Neutrino oscillation experiments give evidence for neutrino mass and provide clear theoretical thresholds for mass scale measurements
- The overall mass scale of neutrinos is accessible with cosmological observations since cosmic neutrinos are very abundant and at least two species are non-relativistic today

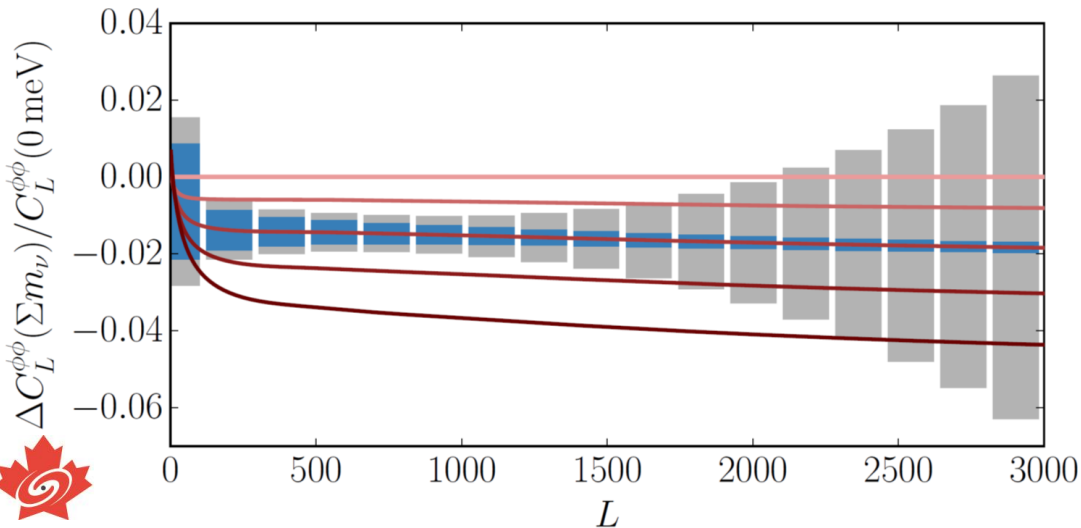
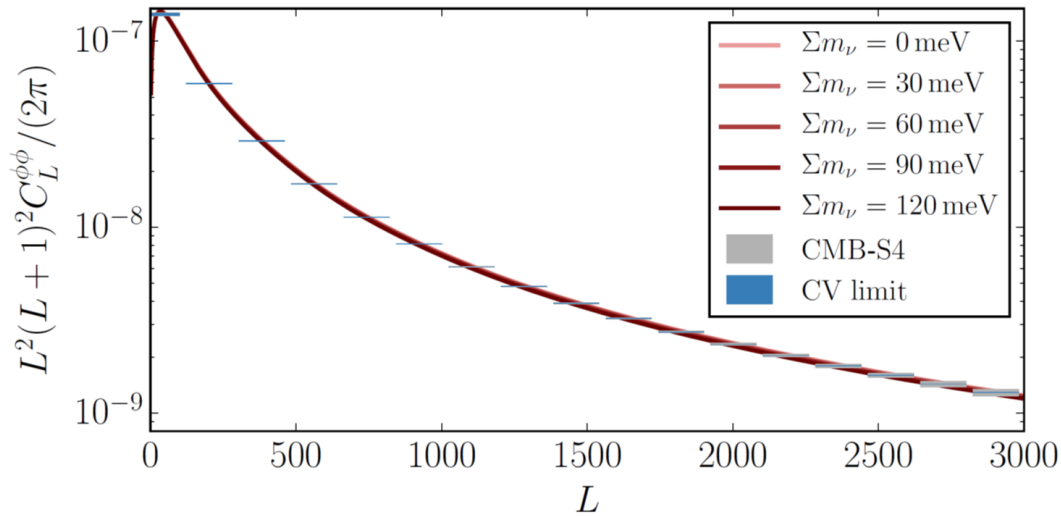


Effect of Neutrino Mass

- Massive neutrinos are non-relativistic at late times and contribute to the matter power spectrum
- On small scales, neutrinos free stream out of potential wells and suppress the growth of structure
- The matter power suppression is observable in CMB lensing



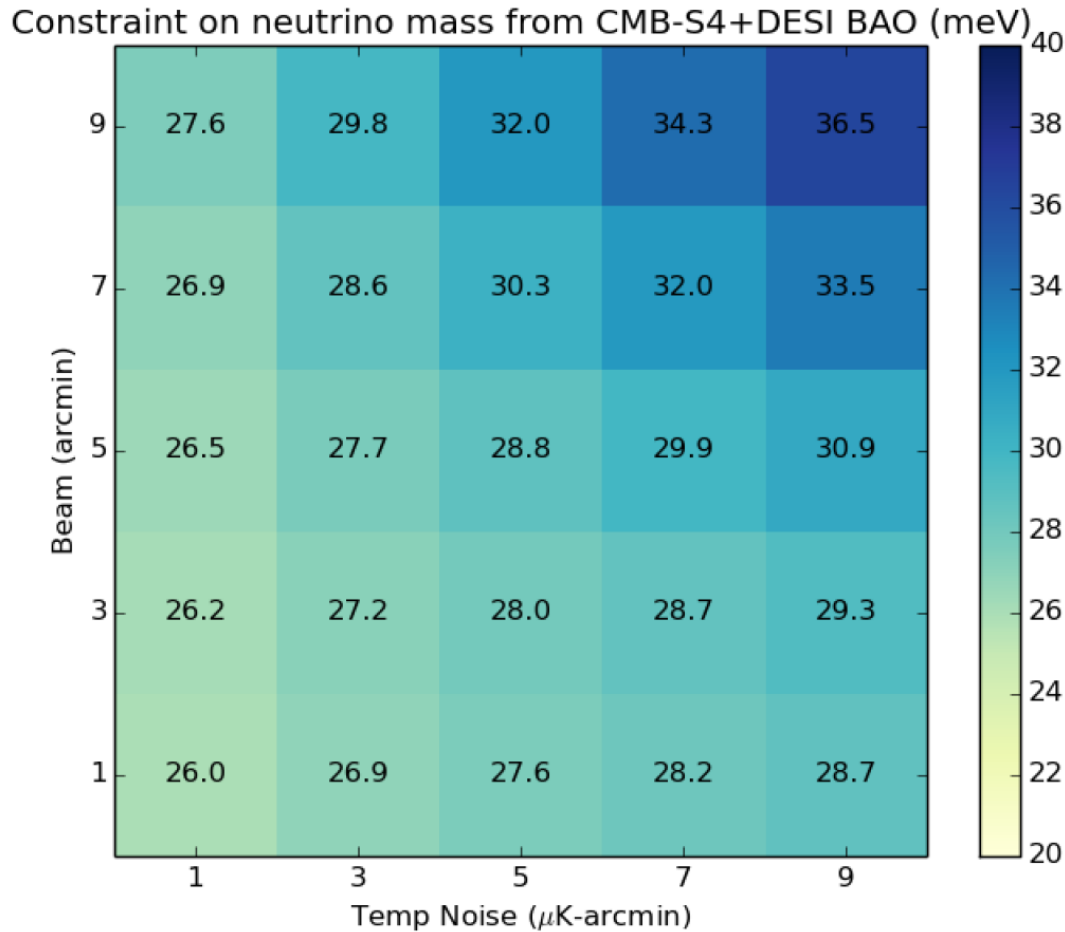
CMB-S4 Lensing Power Spectrum



- CMB-S4 will make a very precise measurement of the lensing power spectrum
- The neutrino mass measurement depends on the ability to break degeneracies
 - Optical Depth τ
 - Matter Density $\Omega_m h^2$



CMB-S4 + DESI BAO Forecasts



CMB-S4 Specs:

$$\ell \geq 30$$

$$f_{\text{sky}} = 0.4$$

+

$$\tau = 0.06 \pm 0.01$$

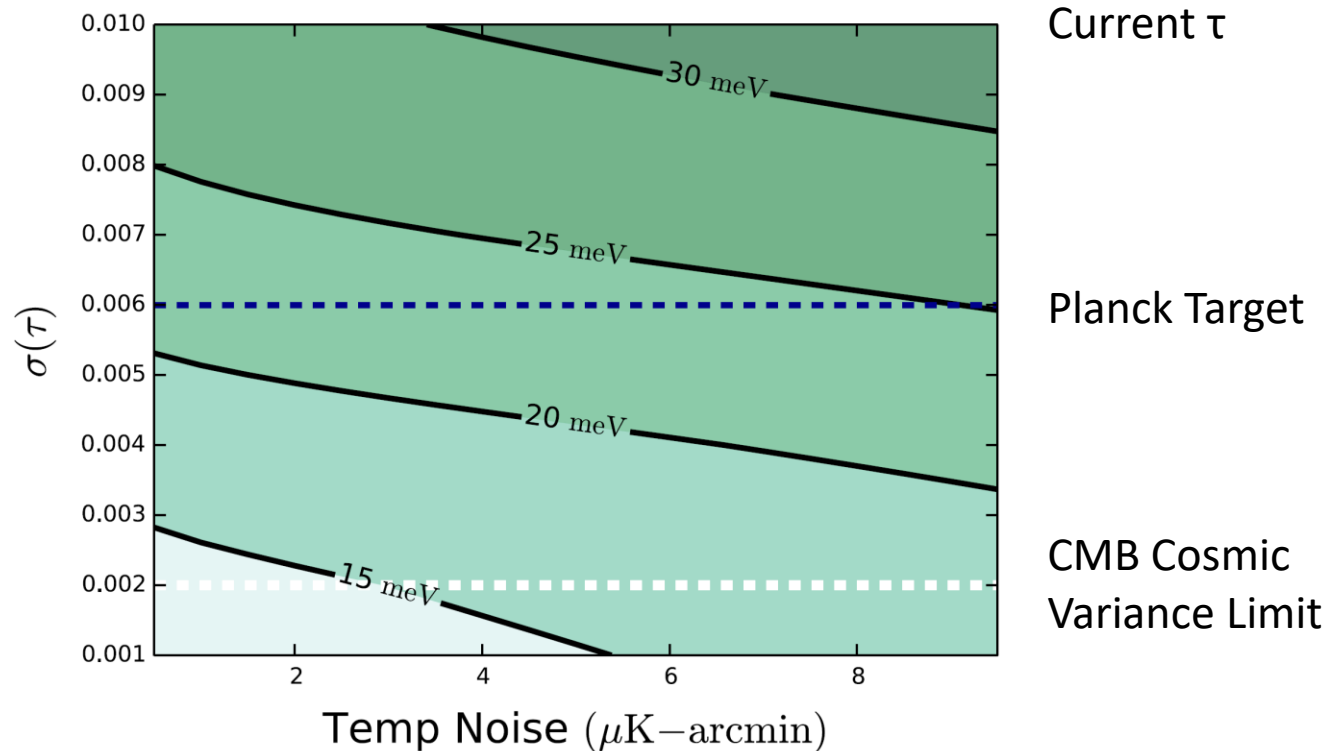
(Current Planck)

+

DESI BAO



Optical Depth and Neutrino Mass

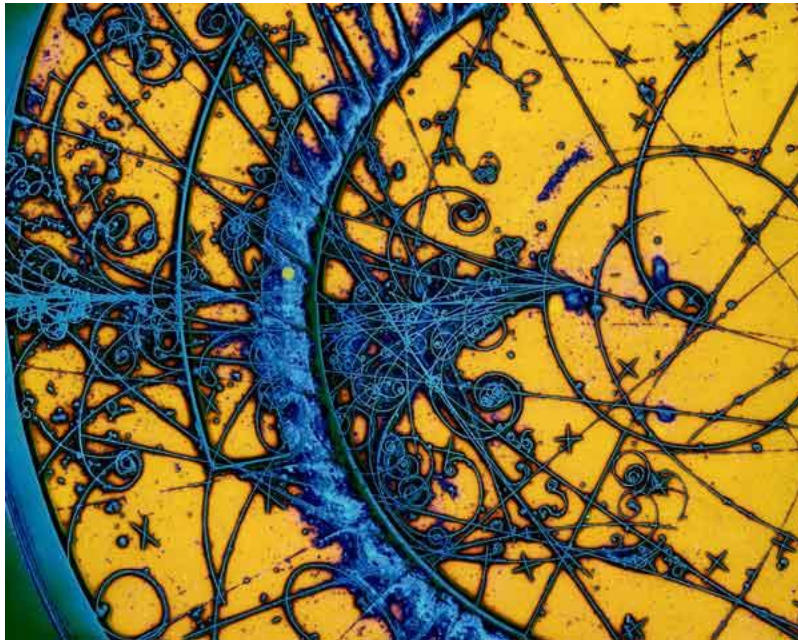


- Forecasted cosmological constraints on neutrino mass are limited by measurements of the optical depth
- Significant improvements could be achieved with satellite-based CMB observations to improve τ measurement



Light Relics

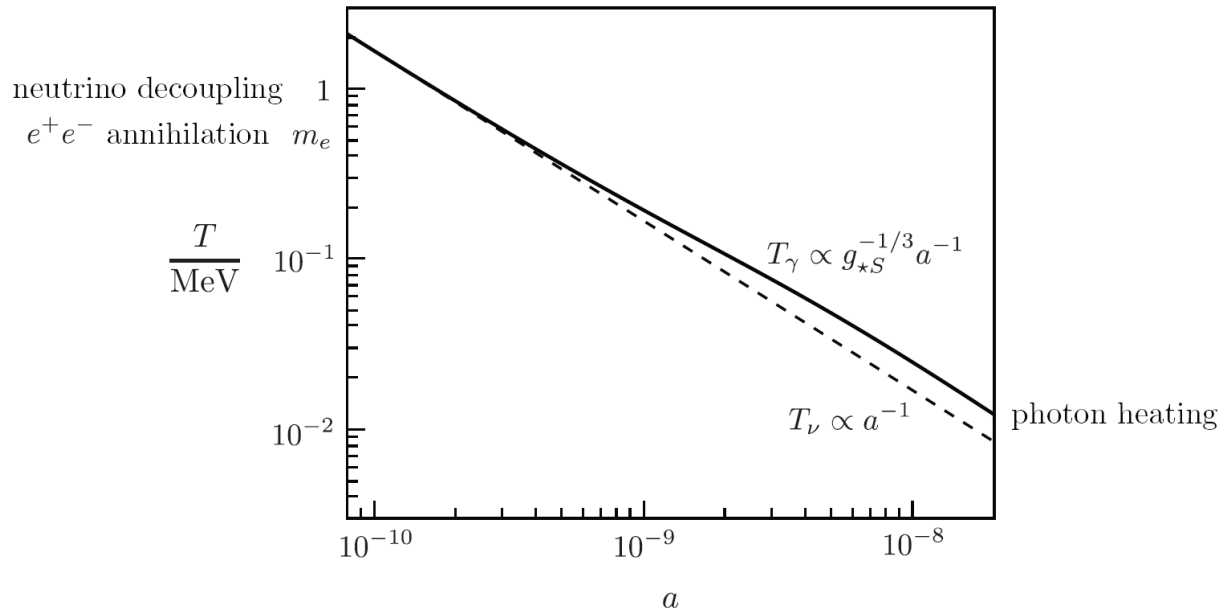
$$\rho_r = \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\text{eff}} \right)$$



- The “effective number of neutrino species” N_{eff} measures the total energy density in radiation excluding photons
- Because it receives contributions from all sorts of radiation, N_{eff} need not have anything to do with neutrinos
- N_{eff} is observable due to the gravitational influence of the radiation in the early universe, leading to BSM constraints from cosmology



CvB Contribution to N_{eff}



$$N_{\text{eff}}^{\text{SM}} = 3.046$$

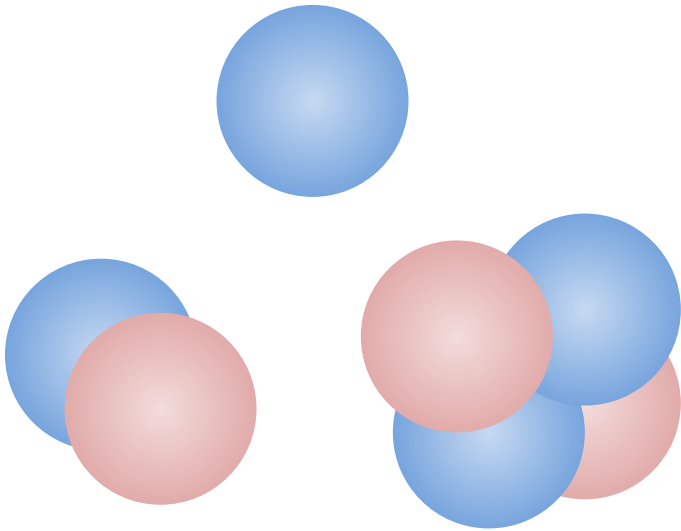
- Electron positron pairs annihilated after neutrino decoupling, heating photons relative to neutrinos
- Comoving entropy conservation fixes the neutrino temperature relative to photon temperature
- Residual coupling of neutrinos leads to a slight increase in energy density over the simple instantaneous decoupling picture



Observing Light Relics

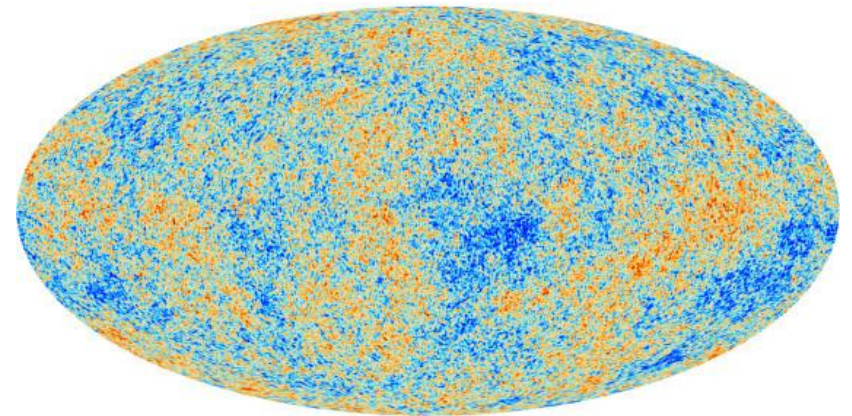
Primordial Abundances

$$N_{\text{eff}}^{\text{BBN}} = 3.28 \pm 0.28$$

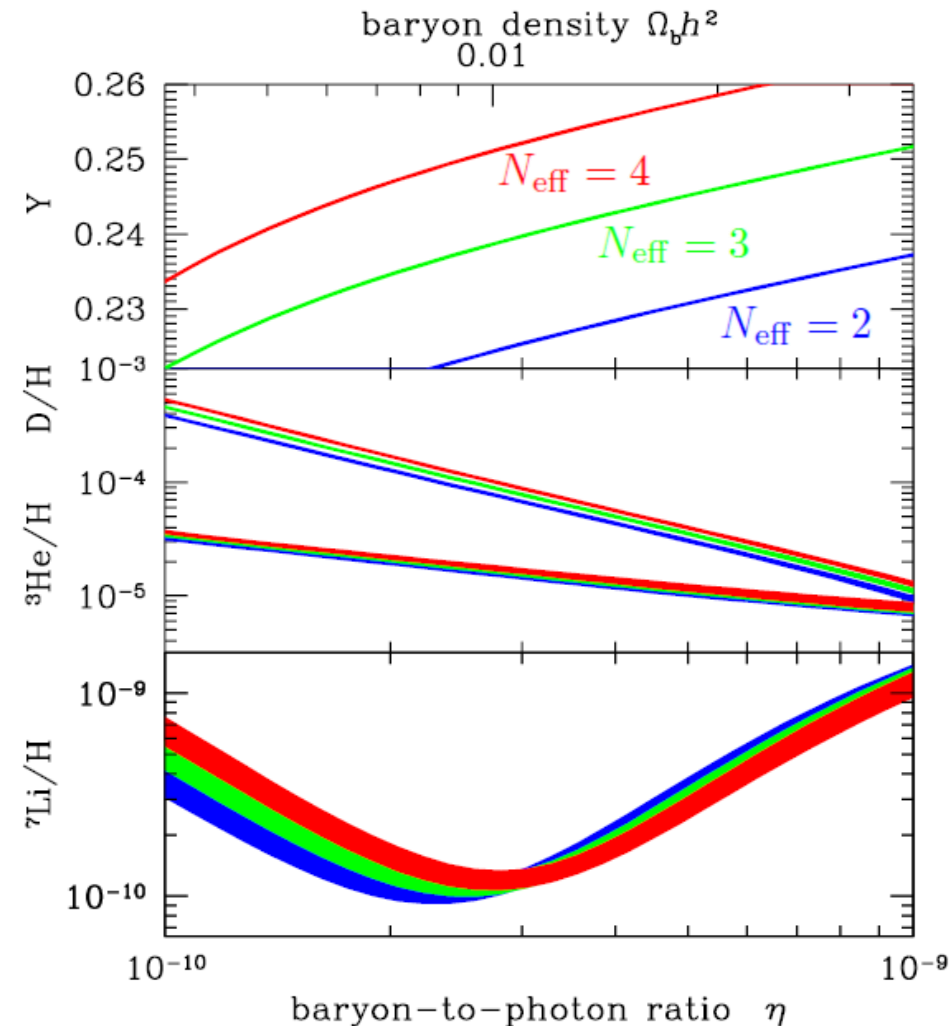


CMB Measurements

$$N_{\text{eff}}^{\text{CMB}} = 3.04 \pm 0.18$$



Big Bang Nucleosynthesis



$$N_{\text{eff}}^{\text{BBN}} = 3.28 \pm 0.28$$

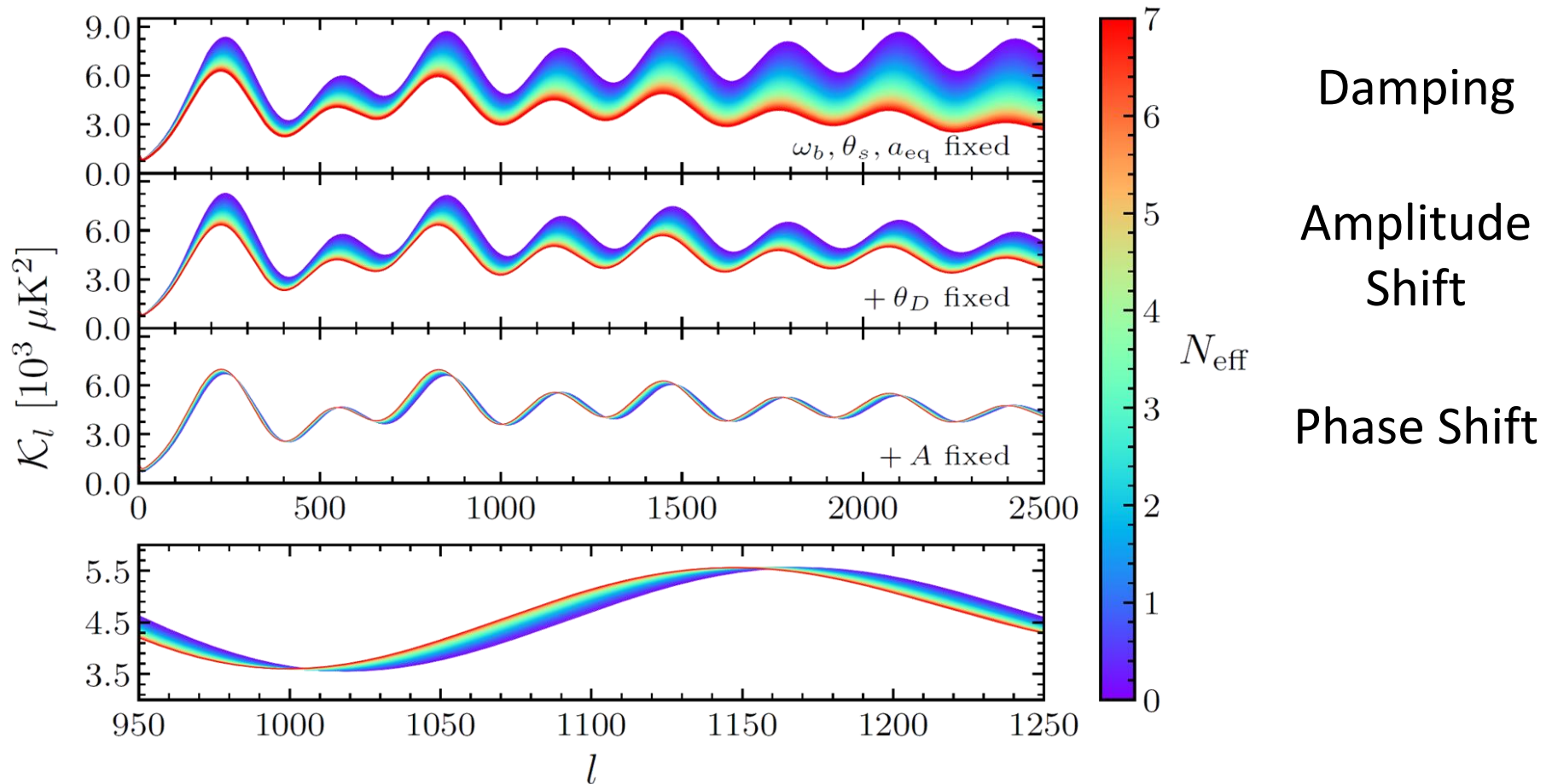
Increased N_{eff} leads to:

- Increased Expansion Rate
- Decreased Time for Free Neutron Decay
- More Neutrons Available for Deuterium Formation
- Increased Helium-4 Density



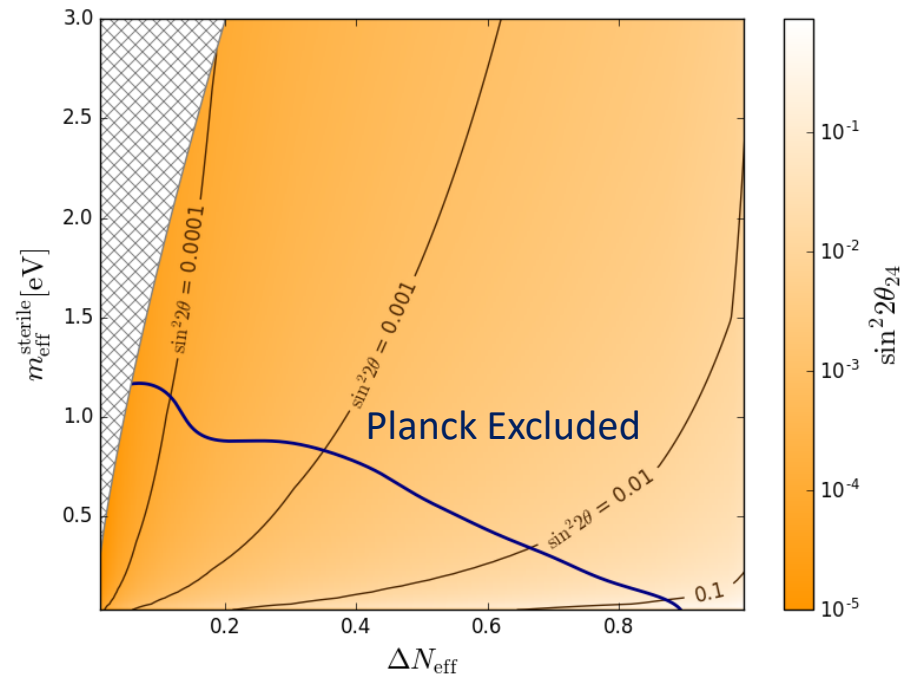
Effects of Light Relics on the CMB

$$N_{\text{eff}}^{\text{CMB}} = 3.04 \pm 0.18$$

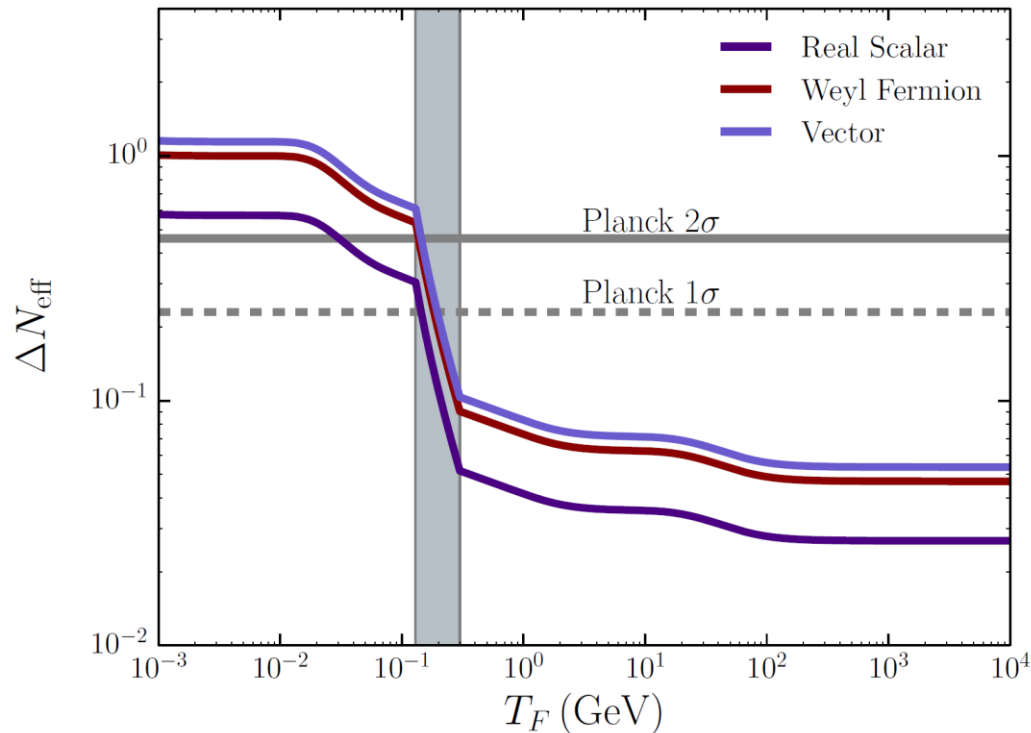


Dark Radiation

- Current observations agree with the standard model predictions for the cosmic neutrino background
- Measurements of N_{eff} give constraints on all forms of decoupled radiation, including:
 - Axions
 - Sterile neutrinos
 - Dark photons
 - Gravitational waves
 - Many others



Thermal Relics and N_{eff}

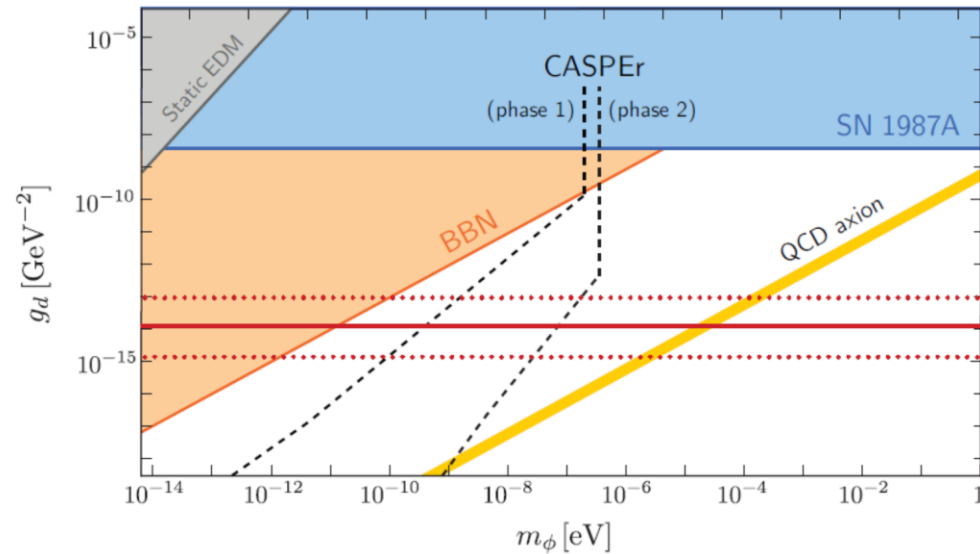
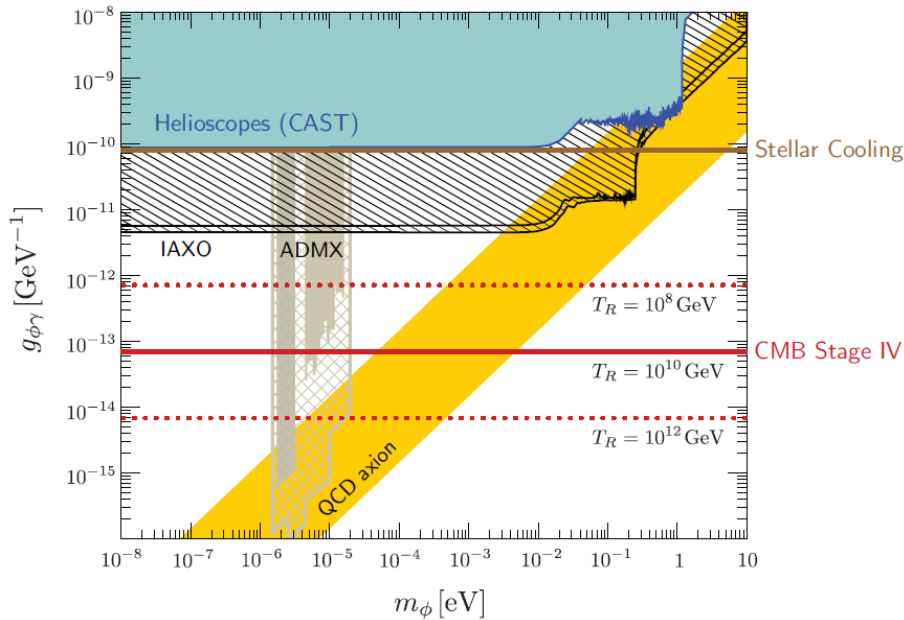


- Light thermal relics contribute a predictable amount to N_{eff} based on their spin and decoupling temperature
 - Minimum for scalars: $\Delta N_{\text{eff}} \geq 0.027$
 - Minimum for fermions: $\Delta N_{\text{eff}} \geq 0.047$

Brust, Kaplan, Walters (2013); Chacko, Cui, Hong, Okui (2015);
Adshead, Cui, Shelton (2016); CMB-S4 Science Book (2016)



Axion Constraints

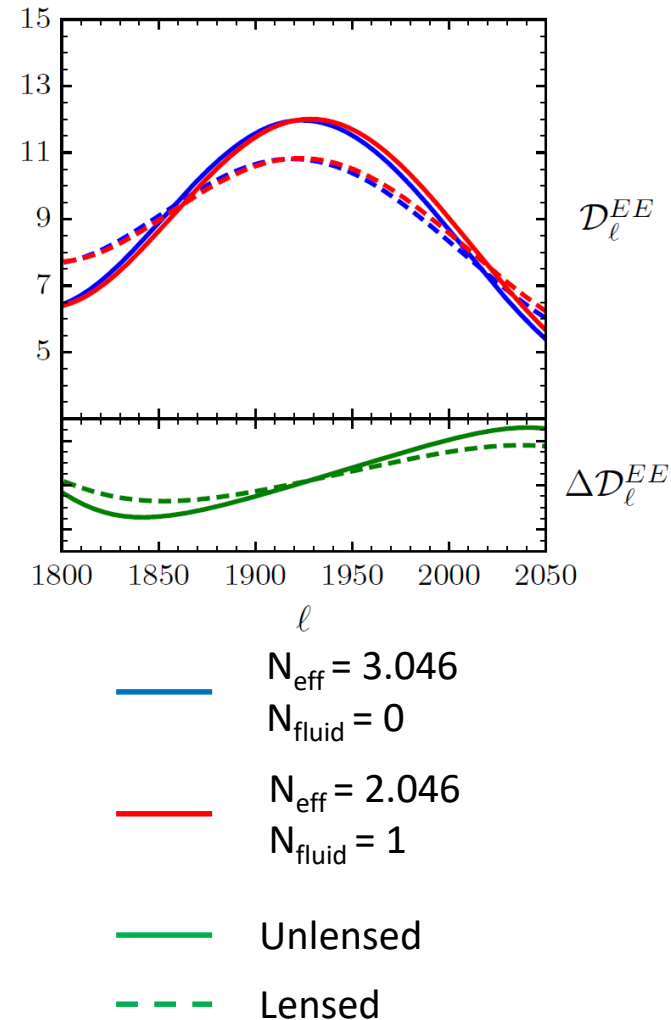


- An observation of N_{eff} ruling out scalar thermal relics would put extremely strong essentially mass independent constraints on axion like particles
- These constraints do not require that the axions are the dark matter (in contrast to e.g. ADMX)



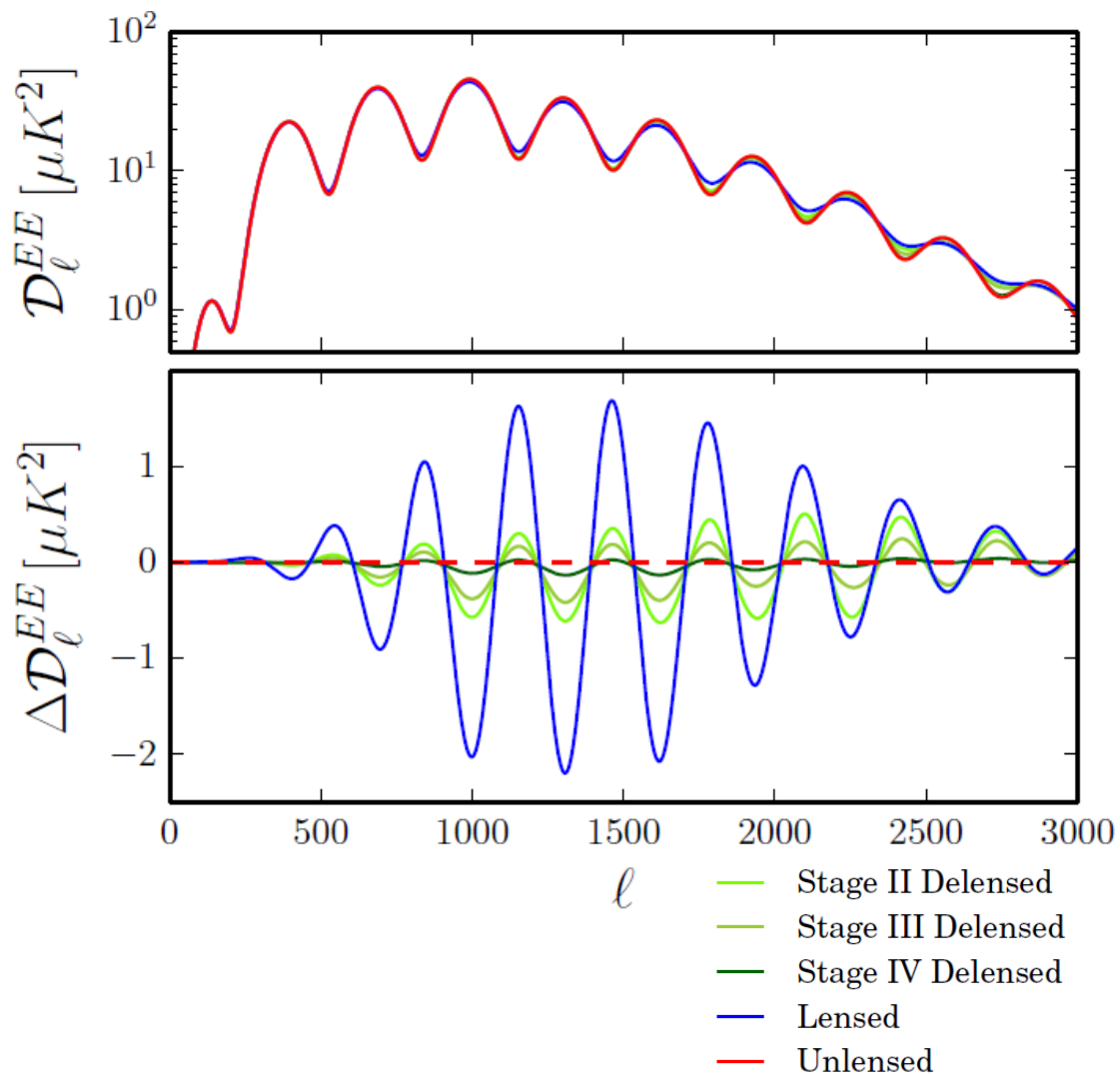
The Special Role of the Phase Shift

- Fluctuations in free-streaming radiation lead to a characteristic phase shift of the acoustic peaks of the CMB (and LSS) power spectrum at small angular scales
- This phase shift is particularly important for several reasons:
 - It is difficult to reproduce in the absence of free-streaming radiation
 - The phase shifts break degeneracies which would otherwise be present
 - Various forms of dark radiation can be distinguished by the phase shift
 - Future constraints will be driven by the phase shift

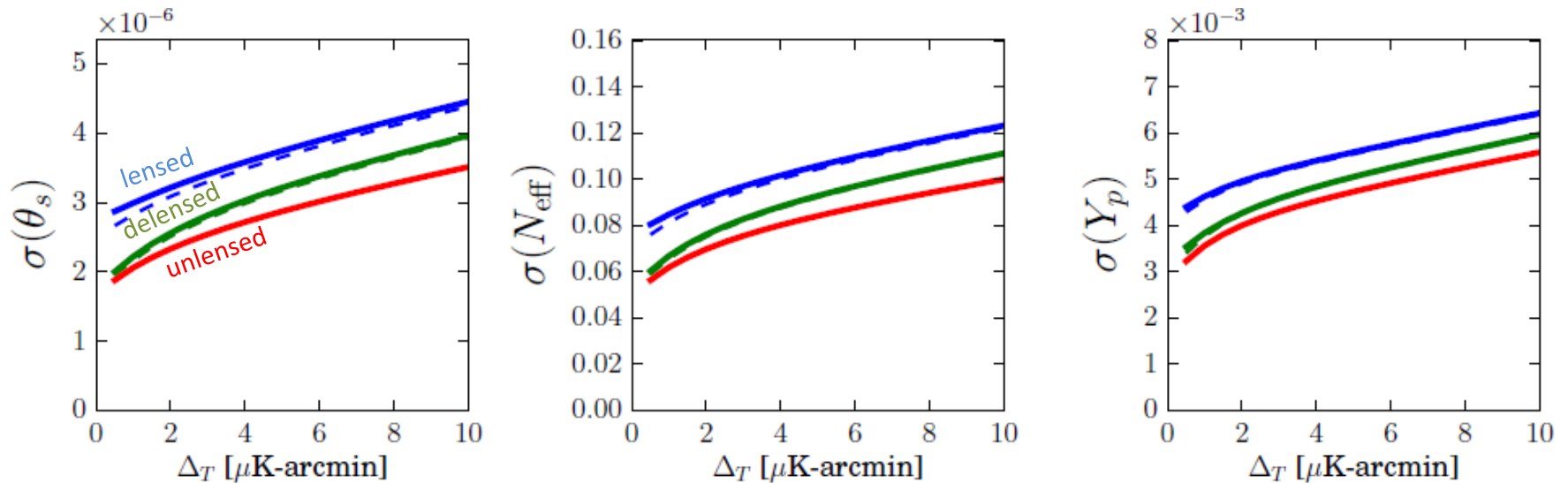


Benefits of Delensing

- Delensing sharpens peaks and reduces lensing-induced covariance, thereby tightening errors on parameters like N_{eff}
- Using unlensed power spectra results in overly optimistic forecasts
- Realistic forecasts need to include delensing in the presence of noise



Delensing and Parameter Constraints

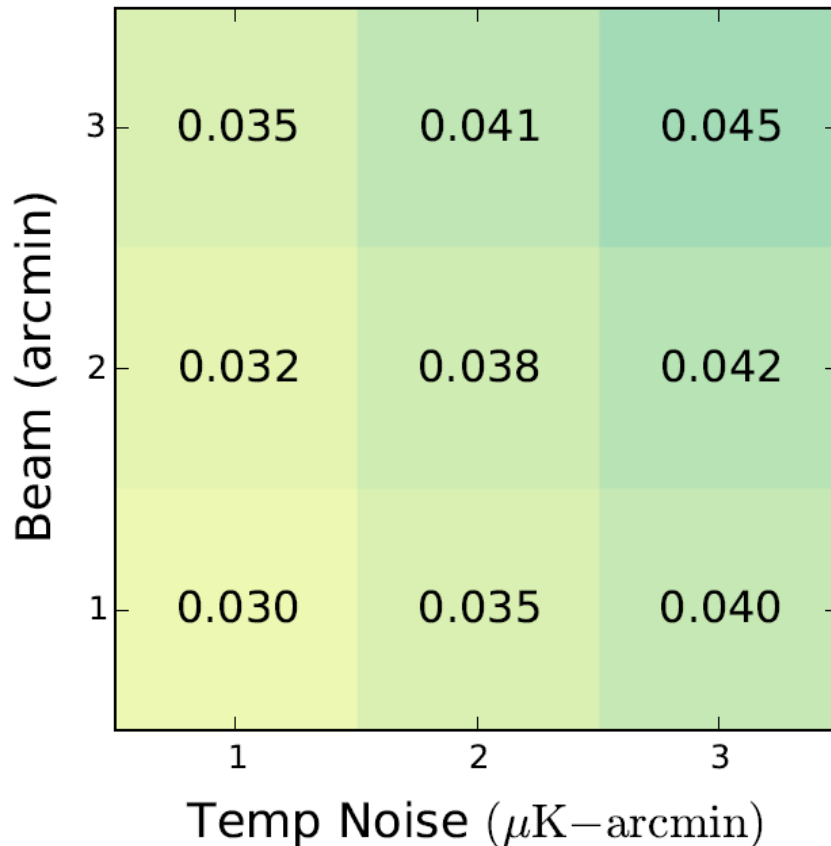


- Parameters which determine peak positions are better constrained with delensed spectra
- Delensing helps to break the degeneracy with N_{eff} and Y_p due to the phase shift



CMB-S4 N_{eff} Forecasts

CMB-S4 Forecasts for $\sigma(N_{\text{eff}})$



- For plausible design parameters, the projected 1σ CMB-S4 constraint on N_{eff} is very near important theoretical thresholds:

- $\Delta N_{\text{eff}} = 0.027$ for scalars
- $\Delta N_{\text{eff}} = 0.047$ for fermions
- $\Delta N_{\text{eff}} = 0.054$ for vectors

CMB-S4 Specs:

$$\ell \geq 30$$

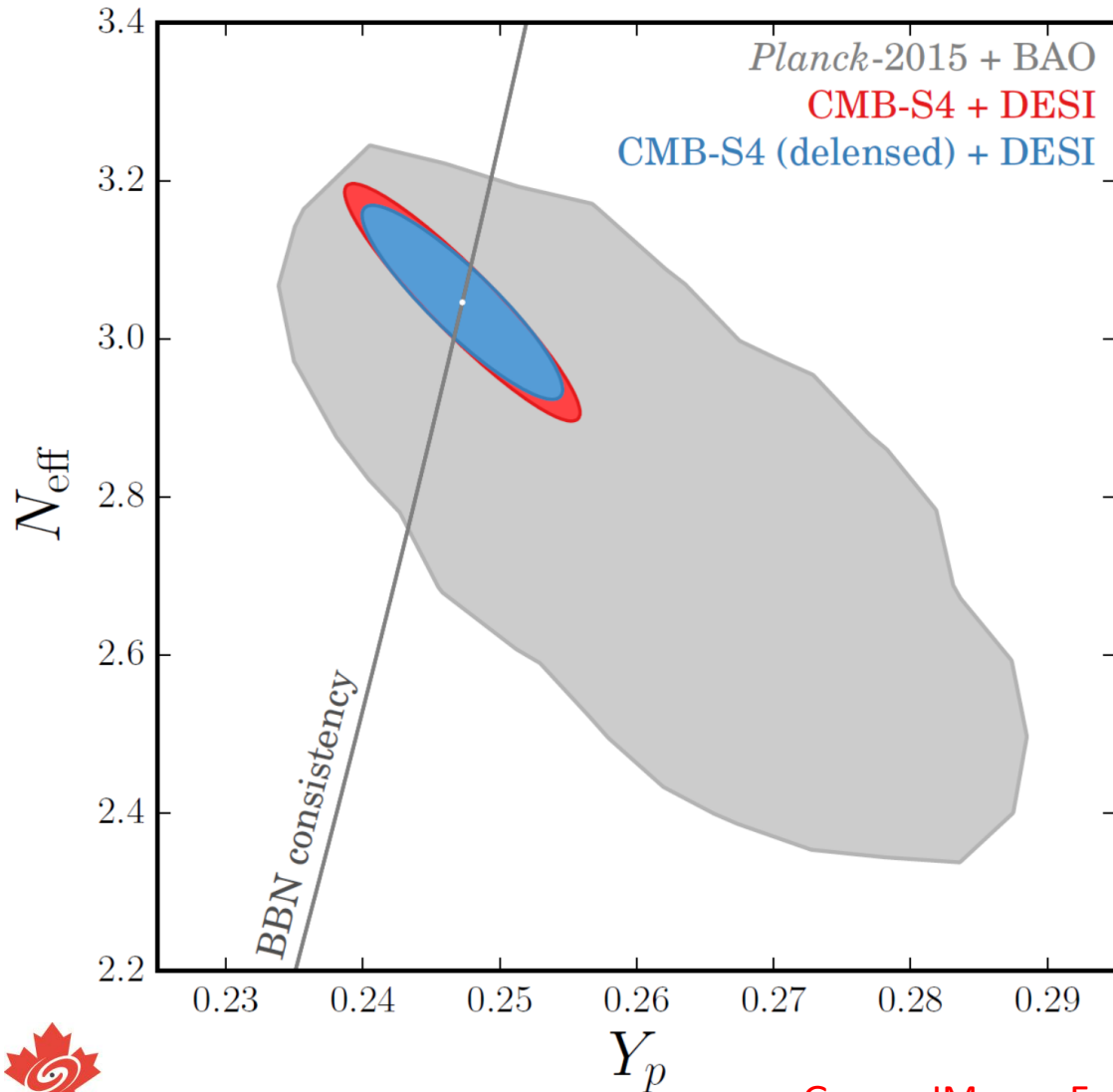
$$f_{\text{sky}} = 0.4$$

+

BBN Consistency



Testing BBN

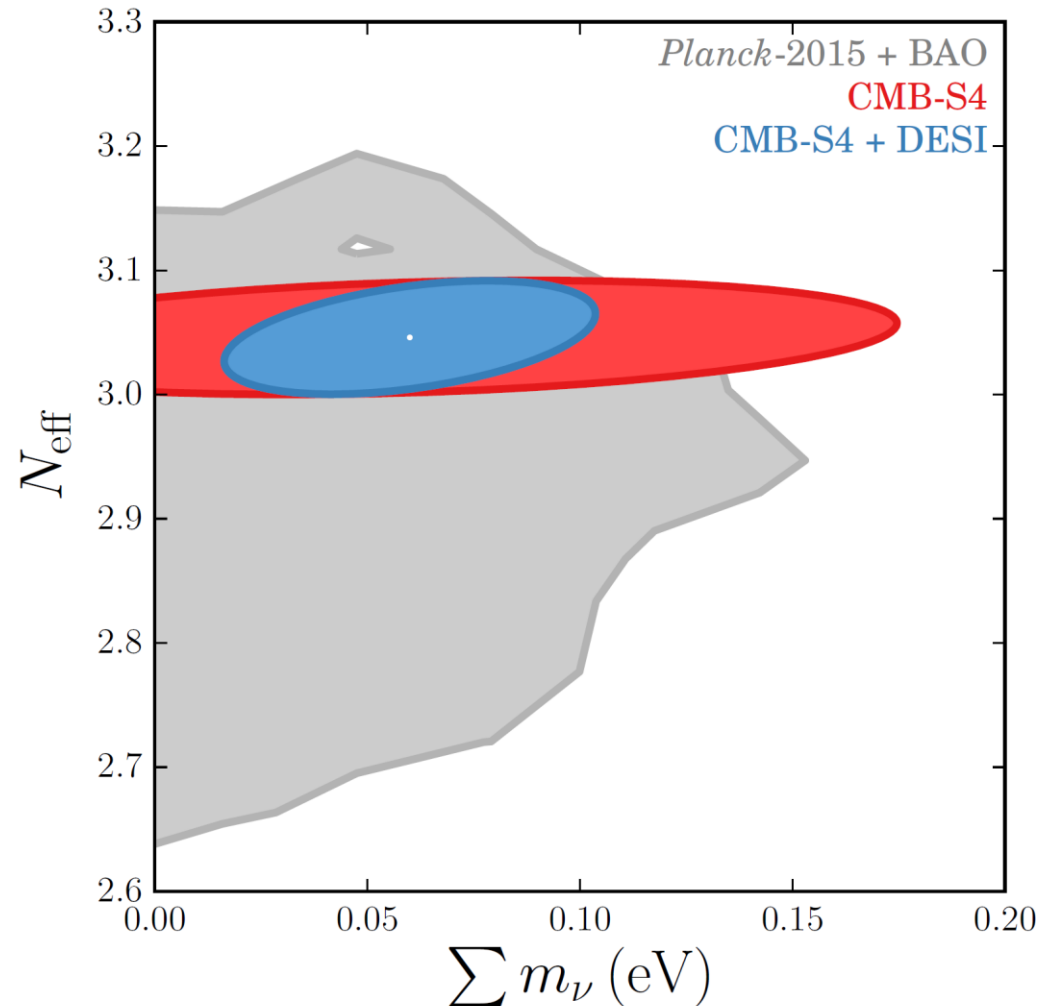


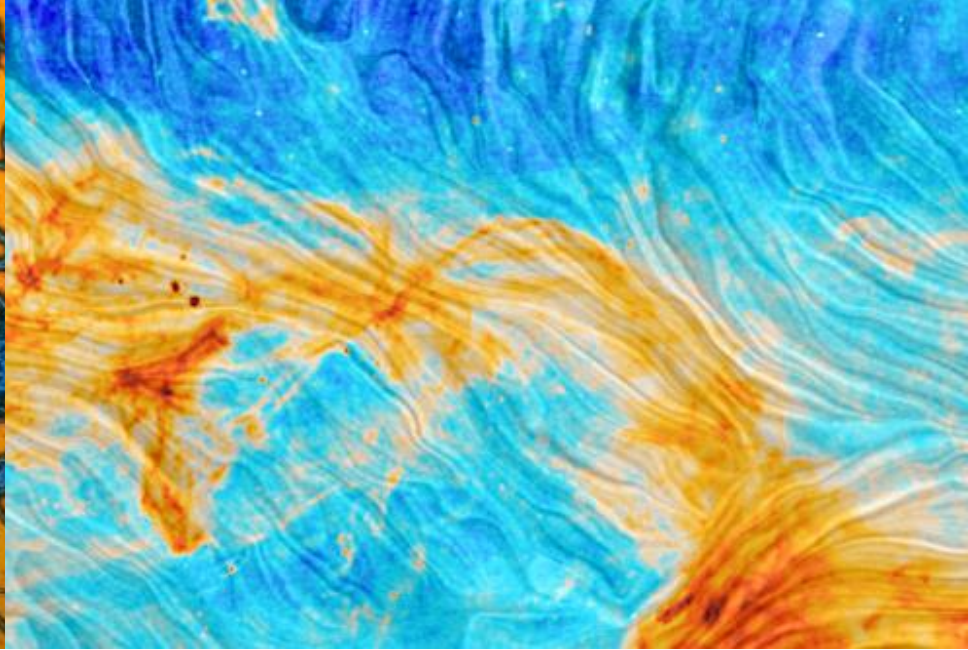
- Upcoming CMB experiments will provide improved constraints on the primordial helium abundance allowing sensitivity to BBN physics
- Delensing T and E spectra helps to break the degeneracy between N_{eff} and Y_p



Sterile and Exotic Neutrinos

- Sterile neutrinos hinted by short baseline anomalies would be detected at high significance with CMB-S4
- Modified thermal histories could also dilute neutrinos compared to standard expectations





Thank You!

