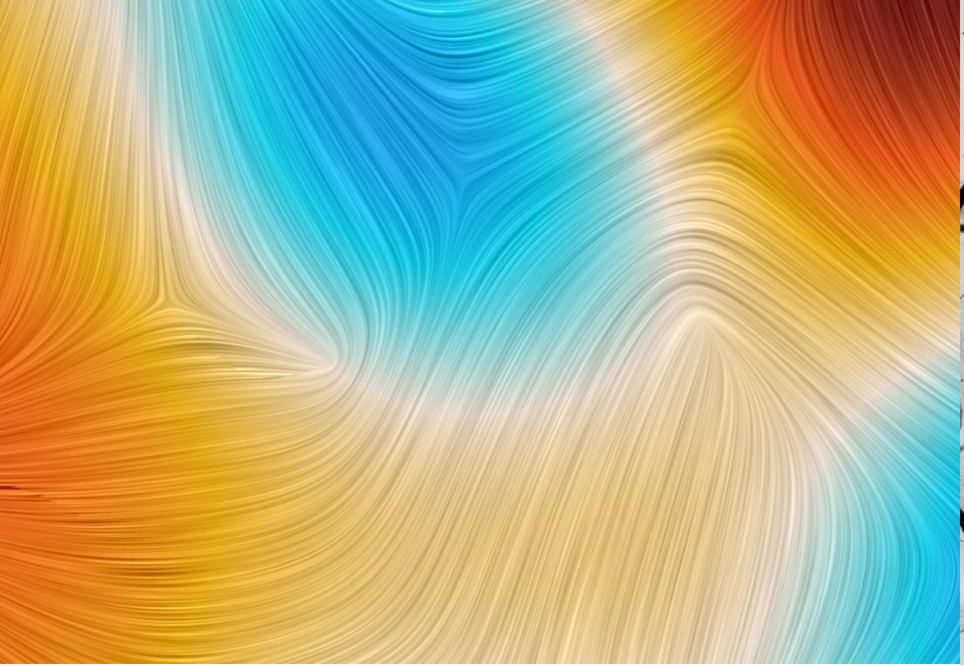
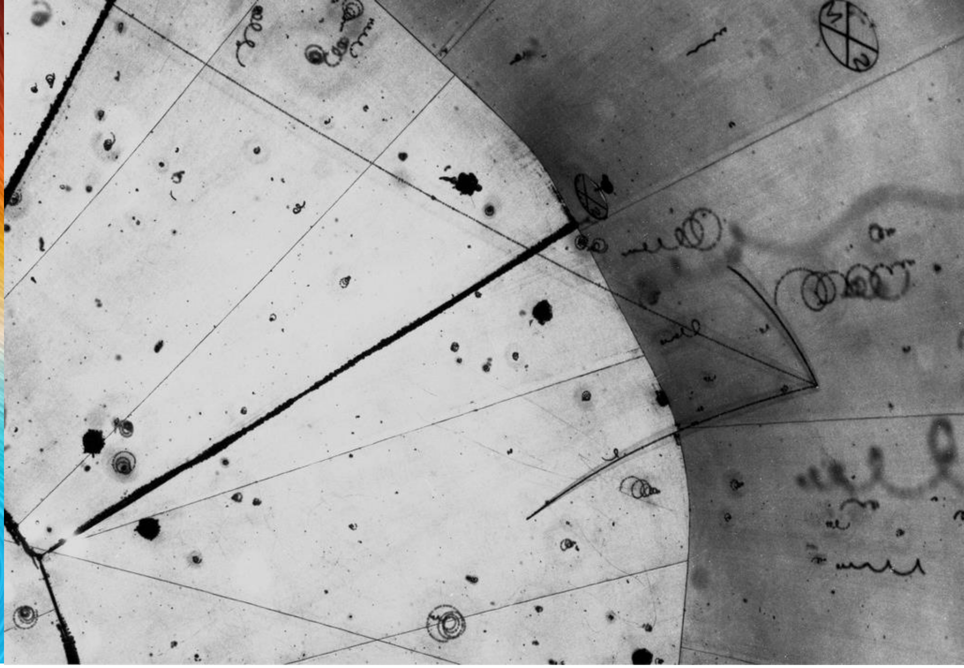




Cosmological Probes of Particle Physics

Joel Meyers

Canadian Institute for Theoretical Astrophysics

Pheno 2017 Symposium

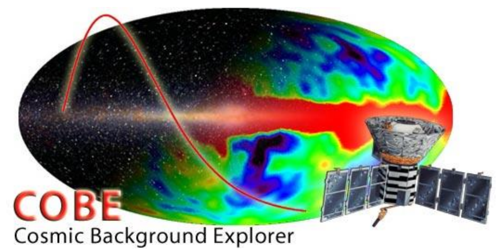
University of Pittsburgh

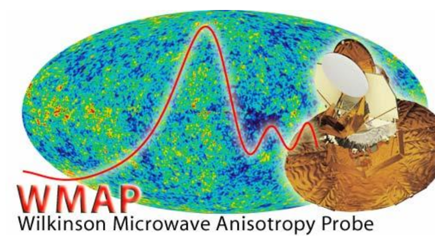
May 10, 2017

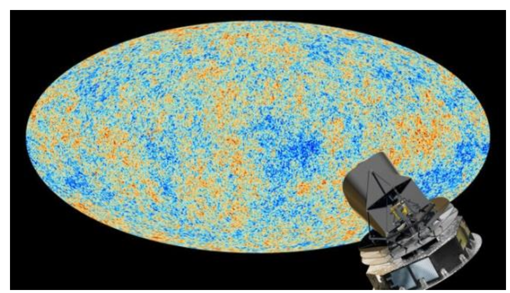
Image Credits: Planck, ANL

Cosmic Microwave Background Timeline

- 1948 – Theoretical Prediction
- 1964 – First Detection
- 1992 – Spectrum and Anisotropies
- 2003 – ΛCDM Cosmology
- 2013 – Beyond the Power Spectrum
- 2017+ – Beyond the Standard Model







SIMONSOBSERVATORY

Next Generation CMB Experiments

SIMONSOBSERVATORY

- Observing 2021-2022
- Telescope array in Atacama Desert in Chile
- Funded, construction starting in 12-18 months

CMB-S4
Next Generation CMB Experiment

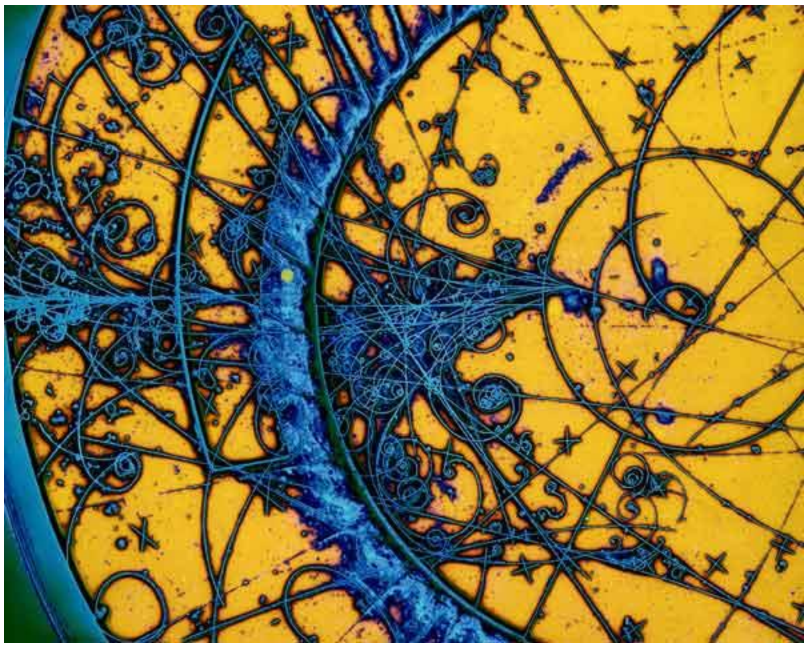
- Observing mid-2020s
- Multiple telescopes in Atacama Desert, at South Pole, and perhaps a Northern Site
- Strong support from DOE and NSF

Science Goals:

- **Fundamental Physics:** Inflation, Light Relics, Neutrino Properties, Big Bang Nucleosynthesis, …
- **Astrophysics:** Mass Maps, Cluster Science, Cross-Correlations, …

Light Relics

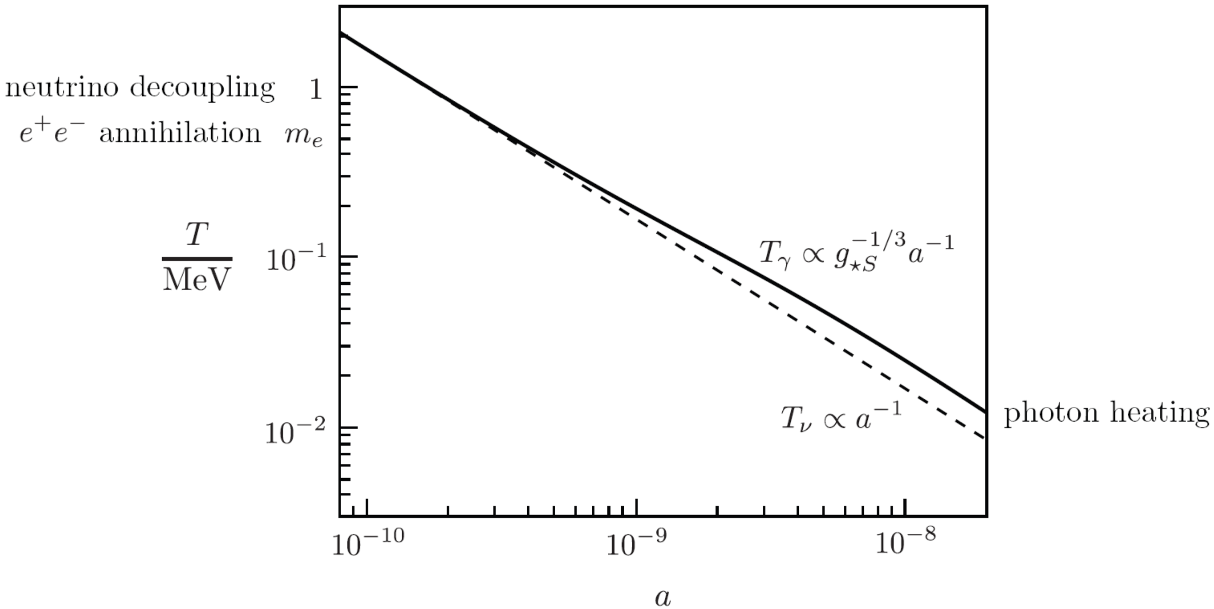
$$\rho_{\rm r} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$



- 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

PDG(2013); Image Credit: CERN

CvB Contribution to N_{eff}

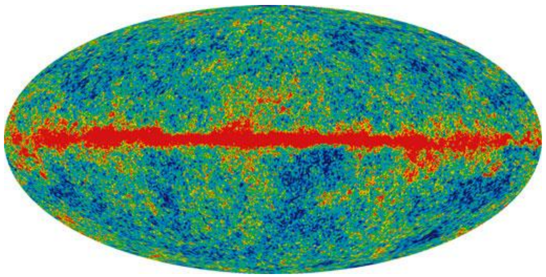


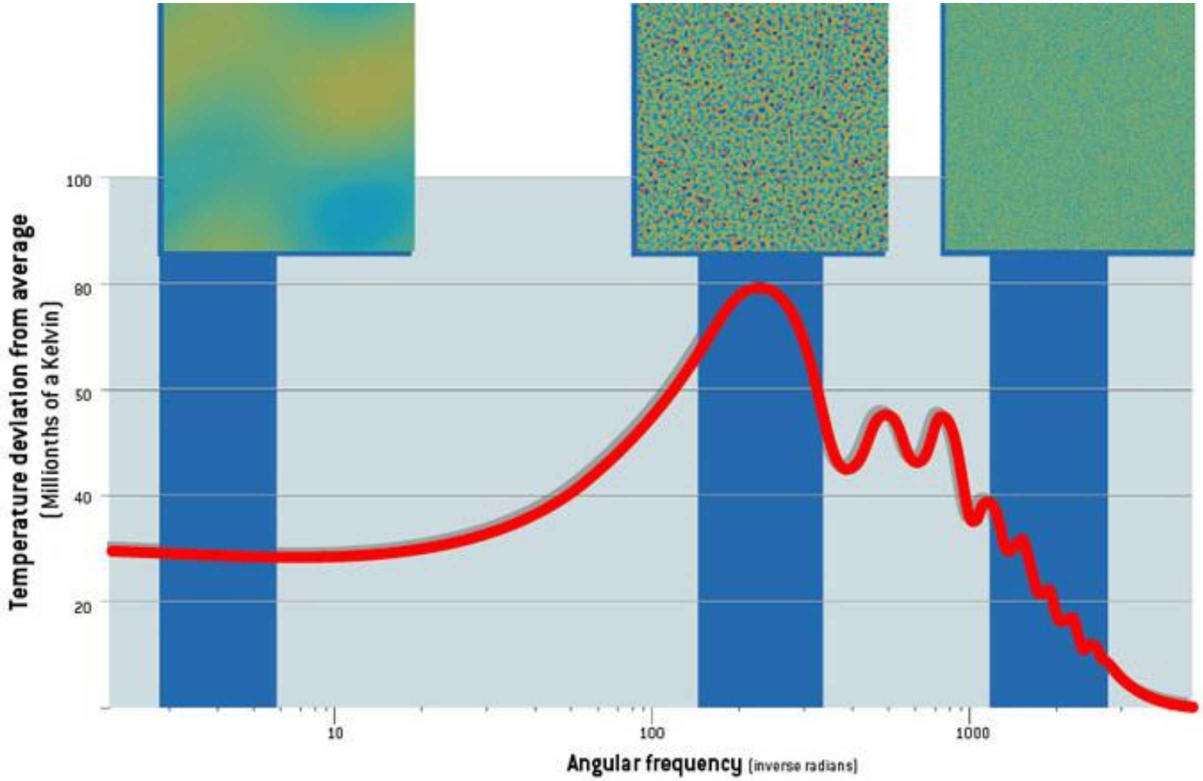
$$N_{\mathrm{eff}}^{\mathrm{SM}} = 3.046$$

- 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

PDG (2013); Mangano, et al. (2005); de Salas, Pastor (2016)

Angular Power Spectrum

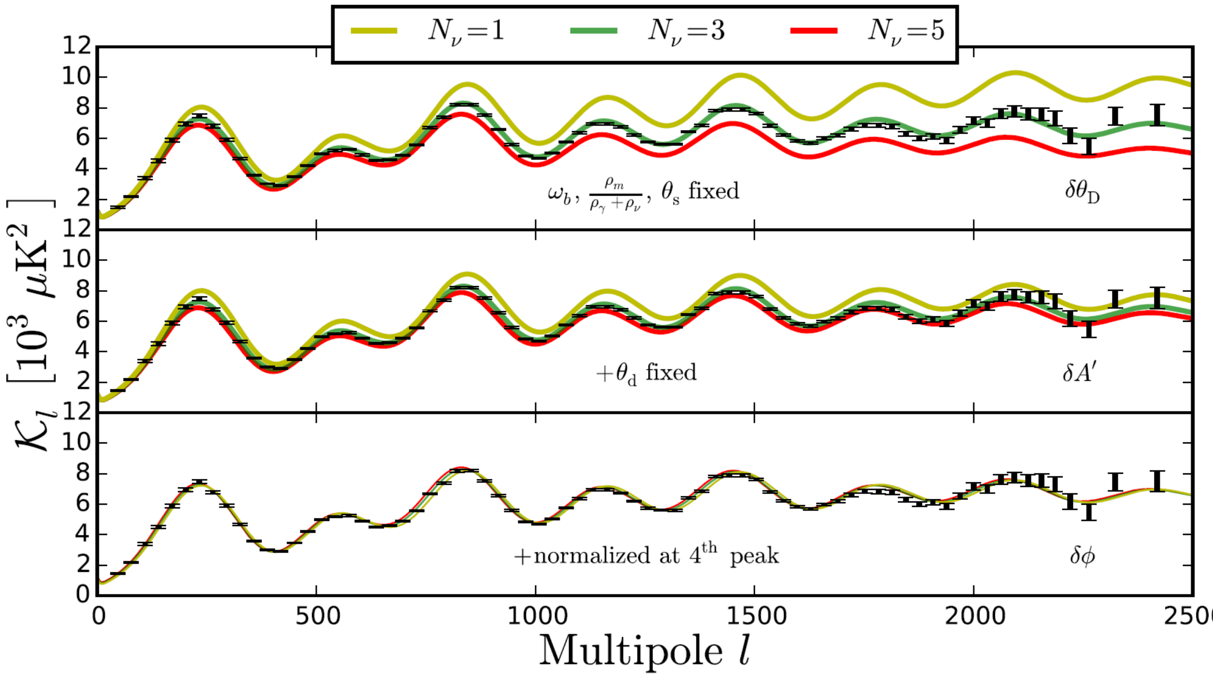




- The harmonic transform of the two-point correlation function of CMB fluctuations is known as the angular power spectrum
- Most of the statistical information of CMB maps is described by the angular power spectrum

Image Credits: WMAP, Hu/Scientific American

Effects of Light Relics on the CMB



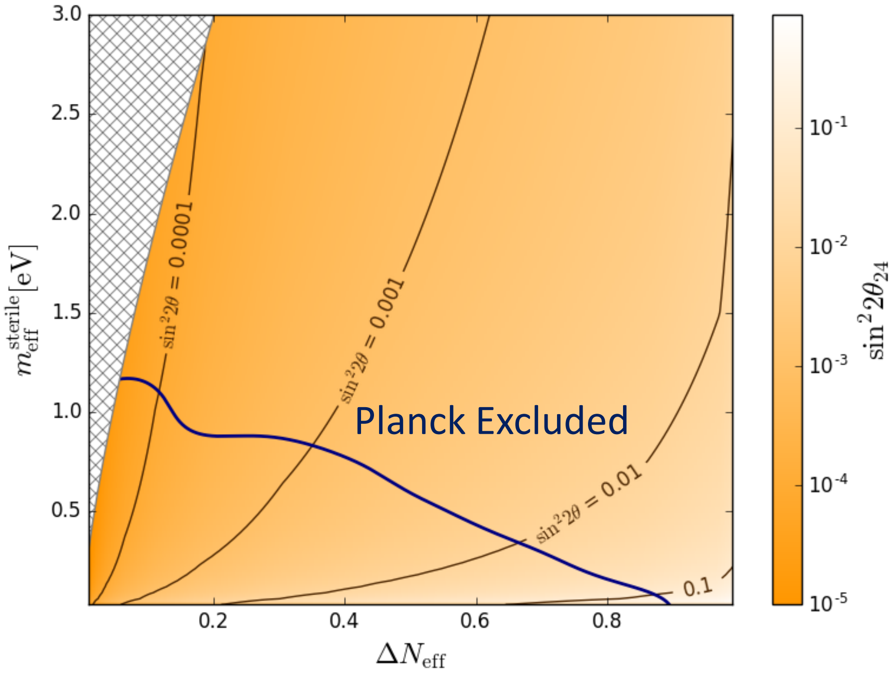
- Increased radiation density leads to increased damping (when holding the scale of matter-radiation equality fixed)
- Anisotropic stress due to radiation free streaming has two effects:
  - Shift in amplitude at small scales
  - Phase shift of acoustic peaks at small scales

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

Bashinsky, Seljak (2004), Hou, Keisler, Knox, Millea, Reichardt (2012), Follin, Knox, Millea, Pan (2015)

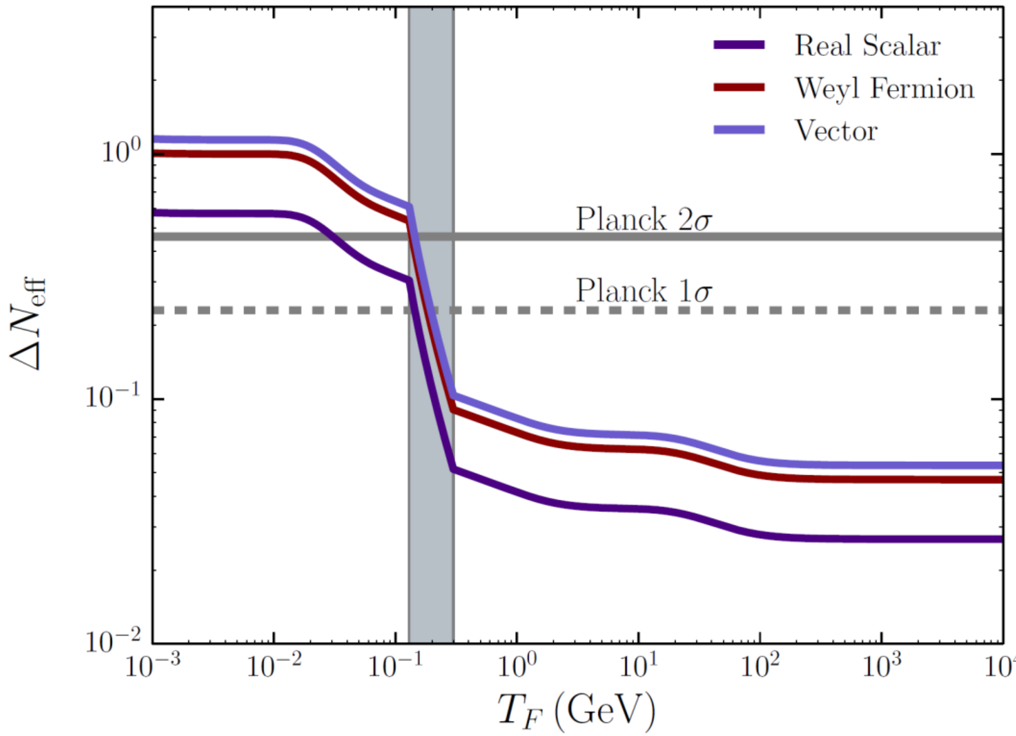
Dark Radiation

- 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



Chu, Cirelli (2006); Boyle, Buonanno (2007); Ackerman, et al. (2008); Steigman (2012); Meerburg, Hadzhiyska, Hlozek, JM (2015); Bridle, et al. (2016); …

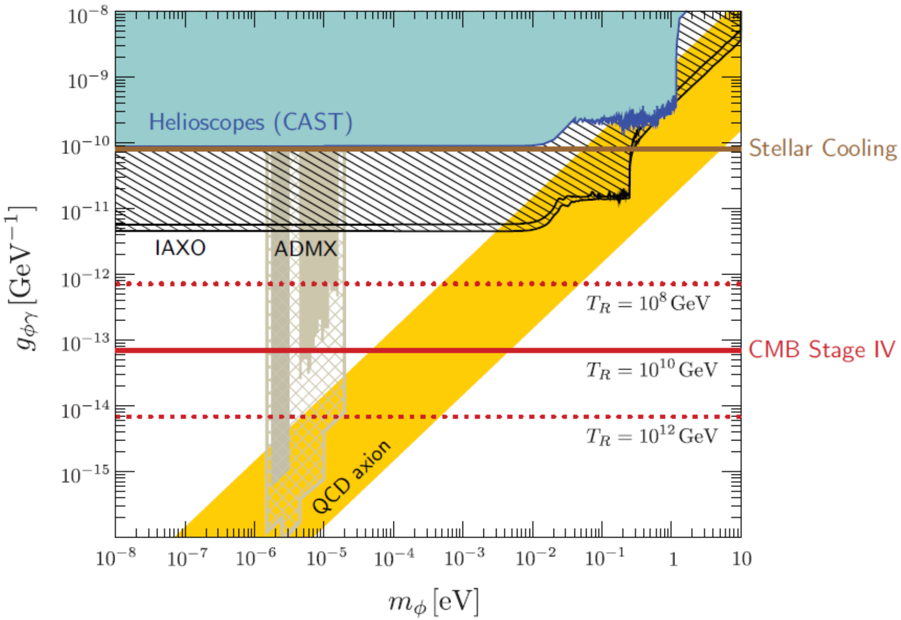
Thermal Relics and N_{eff}

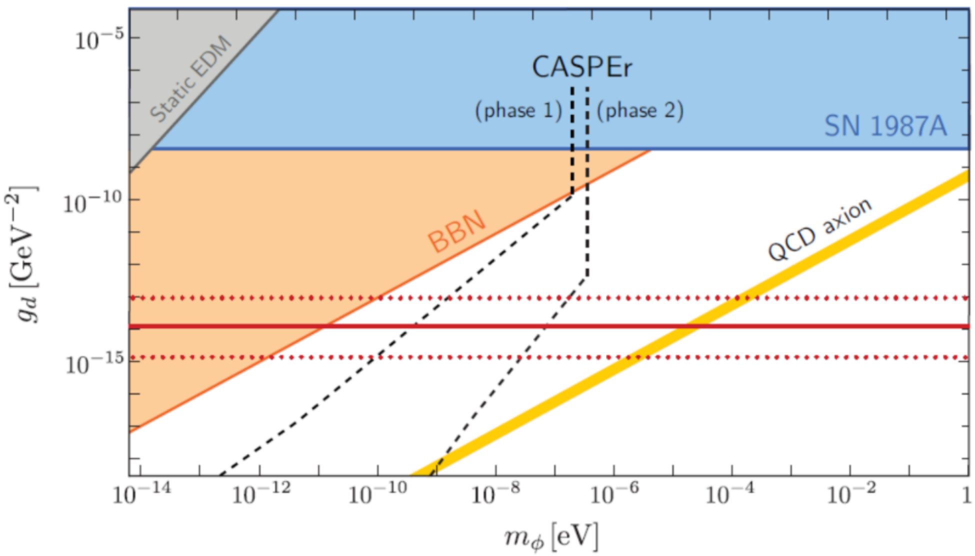


- Light thermal relics contribute a predictable amount to N_{eff} based on their spin and decoupling temperature
  - Minimum for scalars: $\Delta N_{\rm eff} \geq 0.027$
  - Minimum for fermions: $\Delta N_{\rm eff} \geq 0.047$

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

Axion Constraints



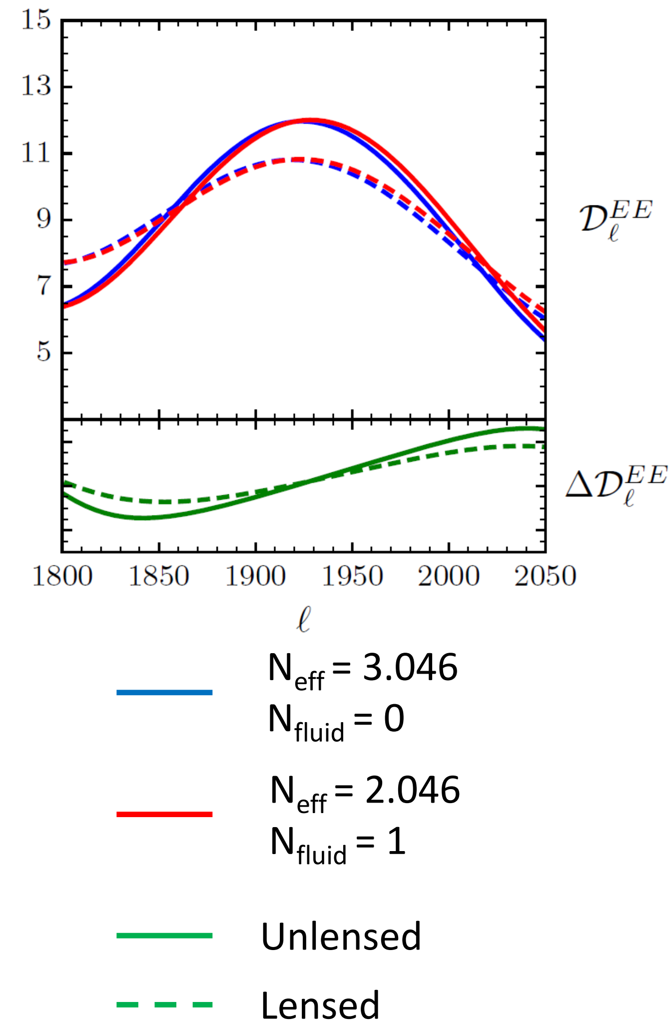


- An observation of N_{eff} ruling out scalar thermal relics would put extremely strong essentially mass independent constraints on axion like particles
- These constraints do not require that the axions are the dark matter (in contrast to e.g. ADMX)

Baumann, Green, Wallisch (2016)

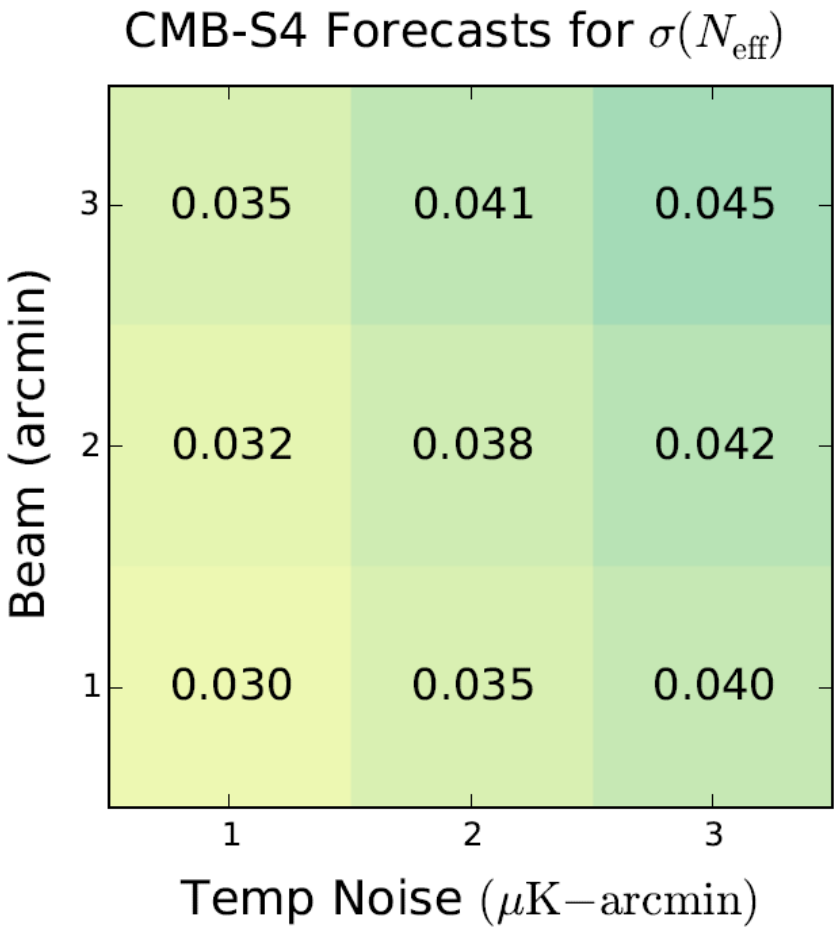
The Special Role of the Phase Shift

- 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



Bashinsky, Seljak (2004); Baumann, Green, JM, Wallisch (2015); Baumann, Green, Zaldarriaga (2017)

CMB-S4 N_{eff} Forecasts



- For plausible design parameters, the projected 1σ CMB-S4 constraint on N_{eff} is very near important theoretical thresholds:
  - ΔN_{eff} = 0.027 for scalars
  - ΔN_{eff} = 0.047 for fermions
  - ΔN_{eff} = 0.054 for vectors

CMB-S4 Specs:

$$\ell \geq 30$$

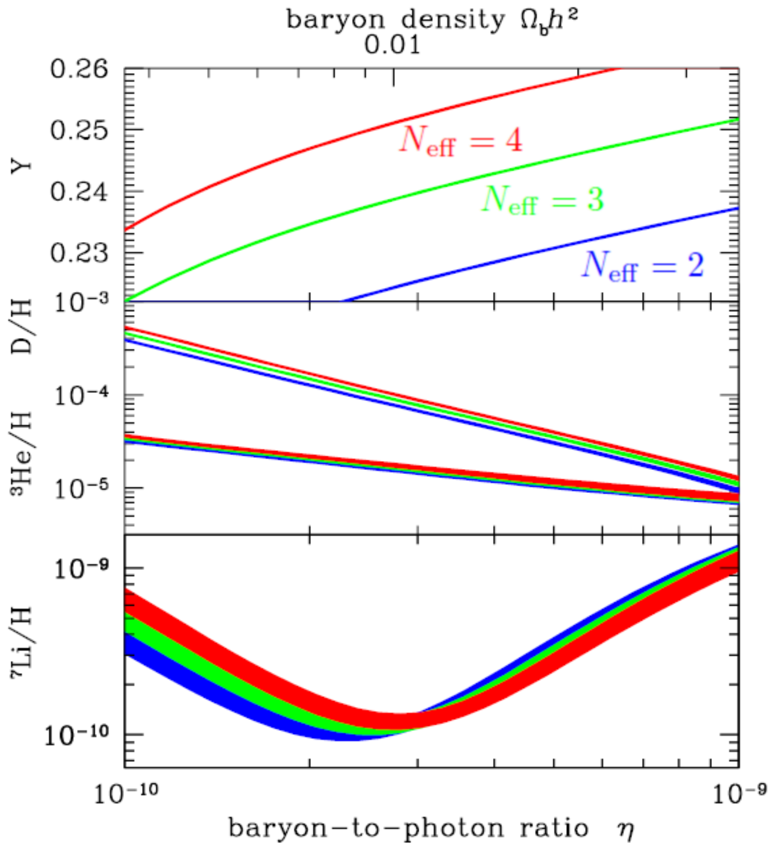
$$f_{\rm sky} = 0.4$$

+

BBN Consistency

CMB-S4 Science Book (2016)

Big Bang Nucleosynthesis

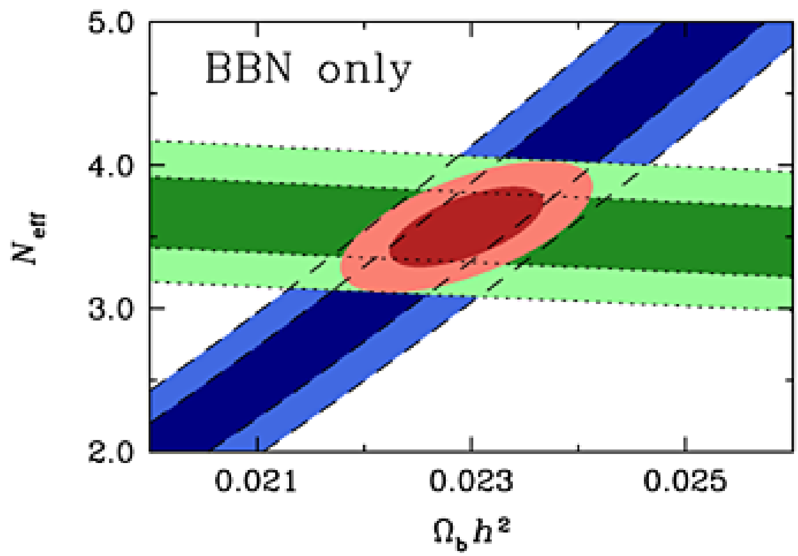


- Measurements of primordial light element abundances (Helium-4 and Deuterium) put a constraint on N_{eff} at around 3 minutes after the end of inflation
- BBN is weakly sensitive to the neutrino energy spectrum as well as the total radiation energy density

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

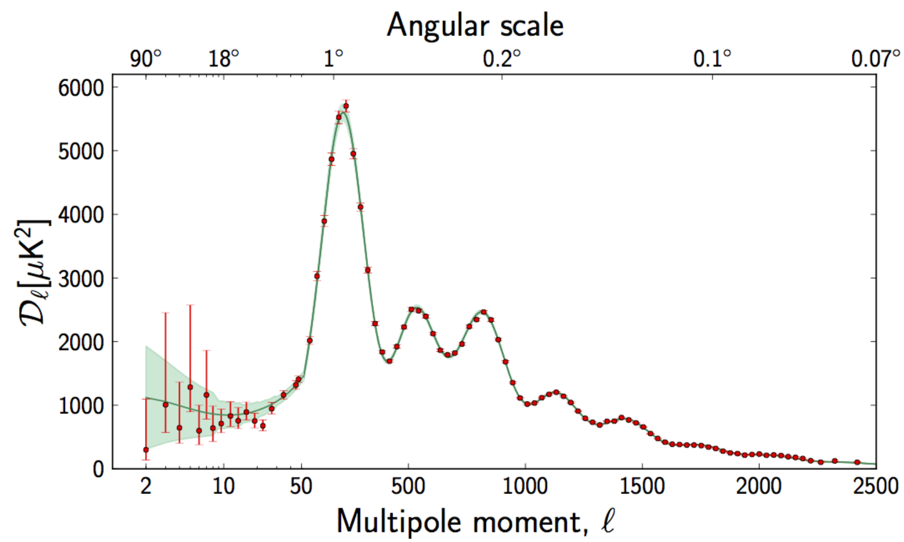
PDG (2013); Cooke, et al. (2014); Cyburt, et al. (2015); Bond, Fuller, Grohs, JM, Wilson (In prep.)

Time-Dependent Density



Primordial Abundances

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



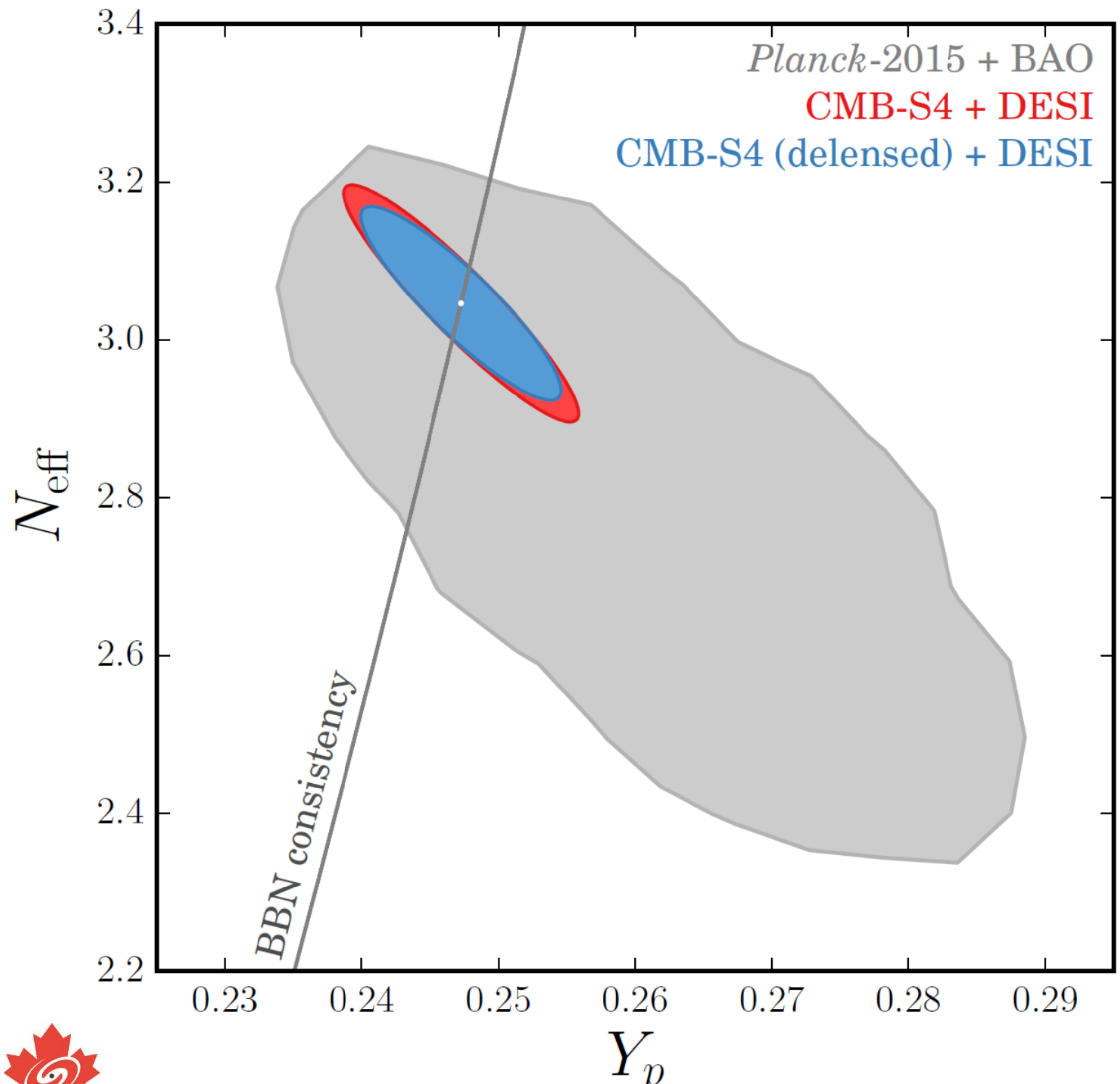
CMB Measurements

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

- Current constraints agree with one another and with the SM prediction
- Combining these constraints gives insight into time-dependent changes in N_{eff}

Cooke, et al. (2014); Cyburt, et al. (2015), Planck (2015); Fischler, JM (2010); Millea, Knox, Fields (2015)

Testing BBN

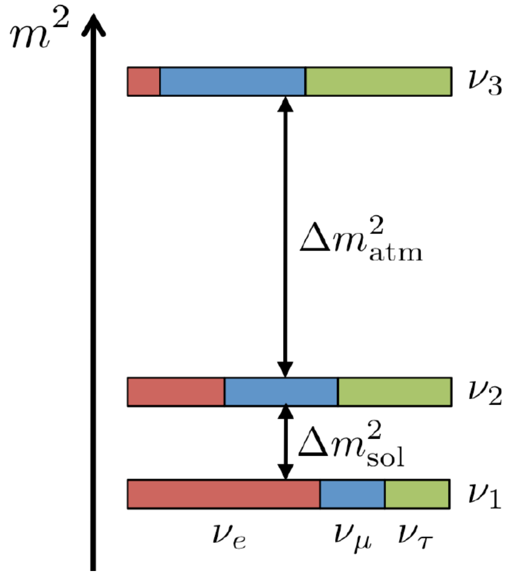


- Upcoming CMB experiments will provide improved constraints on the primordial helium abundance allowing sensitivity to BBN physics
- Delensing T and E spectra helps to break the degeneracy between N_{eff} and Y_p

Green, JM, van Engelen (2016); CMB-S4 Science Book (2016)

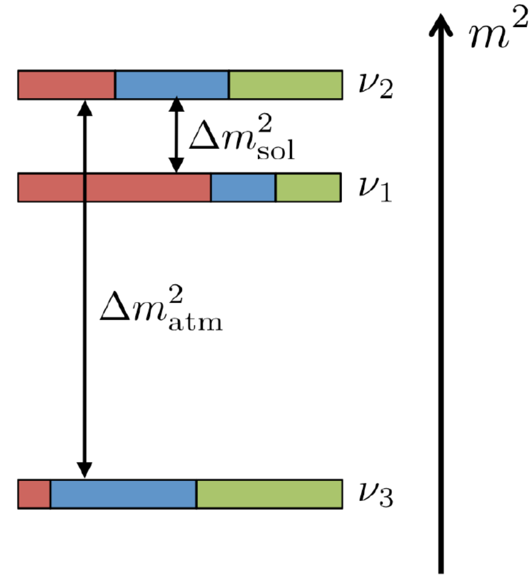
Neutrino Mass

normal hierarchy (NH)



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

inverted hierarchy (IH)



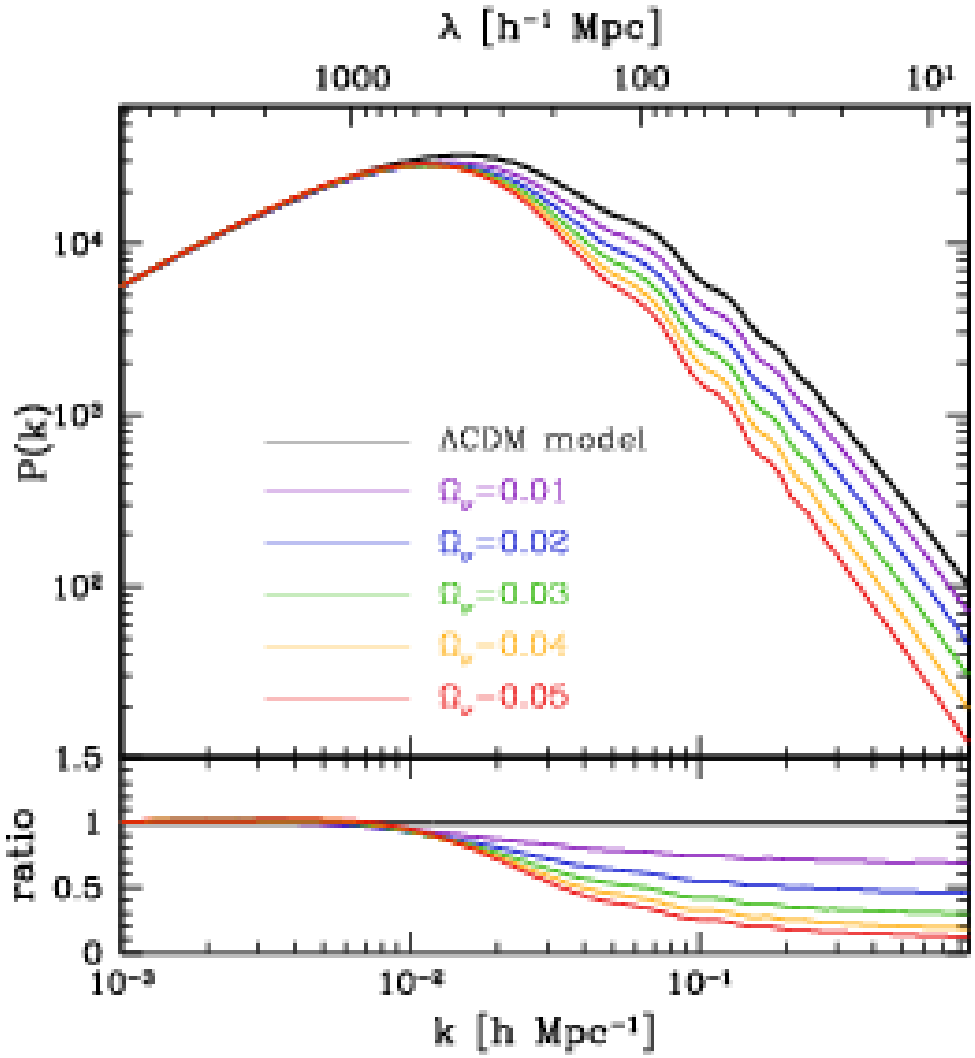
$$\sum m_\nu \gtrsim 105\,\mathrm{meV}$$

- Neutrino oscillation experiments give evidence for neutrino mass and provide clear theoretical thresholds for mass scale measurements
- The overall mass scale of neutrinos is very difficult to observe in laboratory experiments, but is accessible with cosmological observations

Super-Kamiokande (1999); Sudbury Neutrino Observatory (2001); CMB-S4 Science Book (2016)

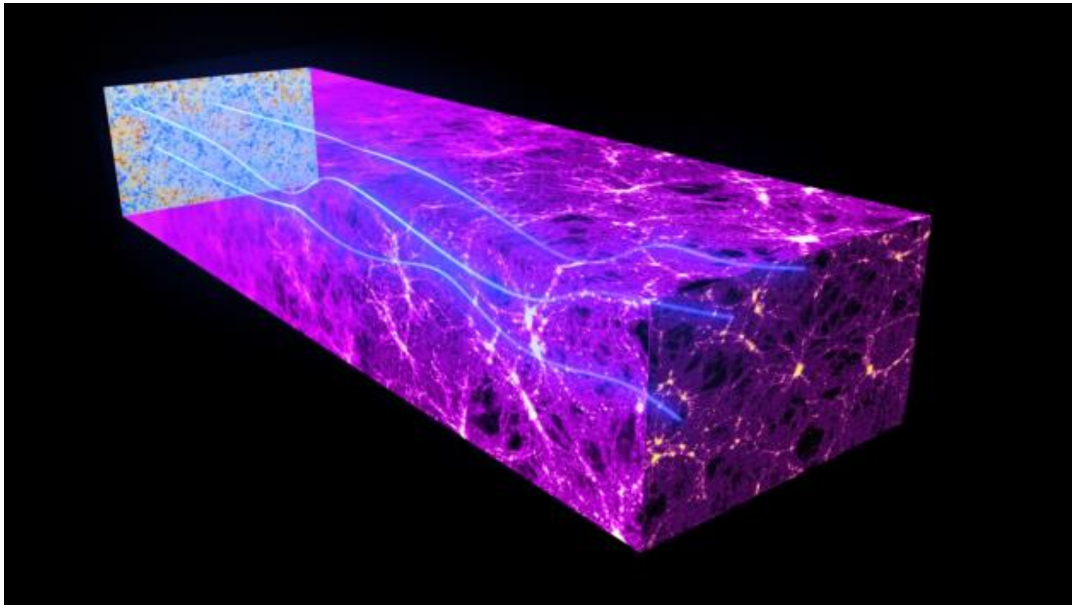
Effect of Neutrino Mass

- 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



Eisenstein, Hu (1997); Kaplinghat, Knox, Song (2003); Park, et al. (2016); CMB-S4 Science Book (2016)

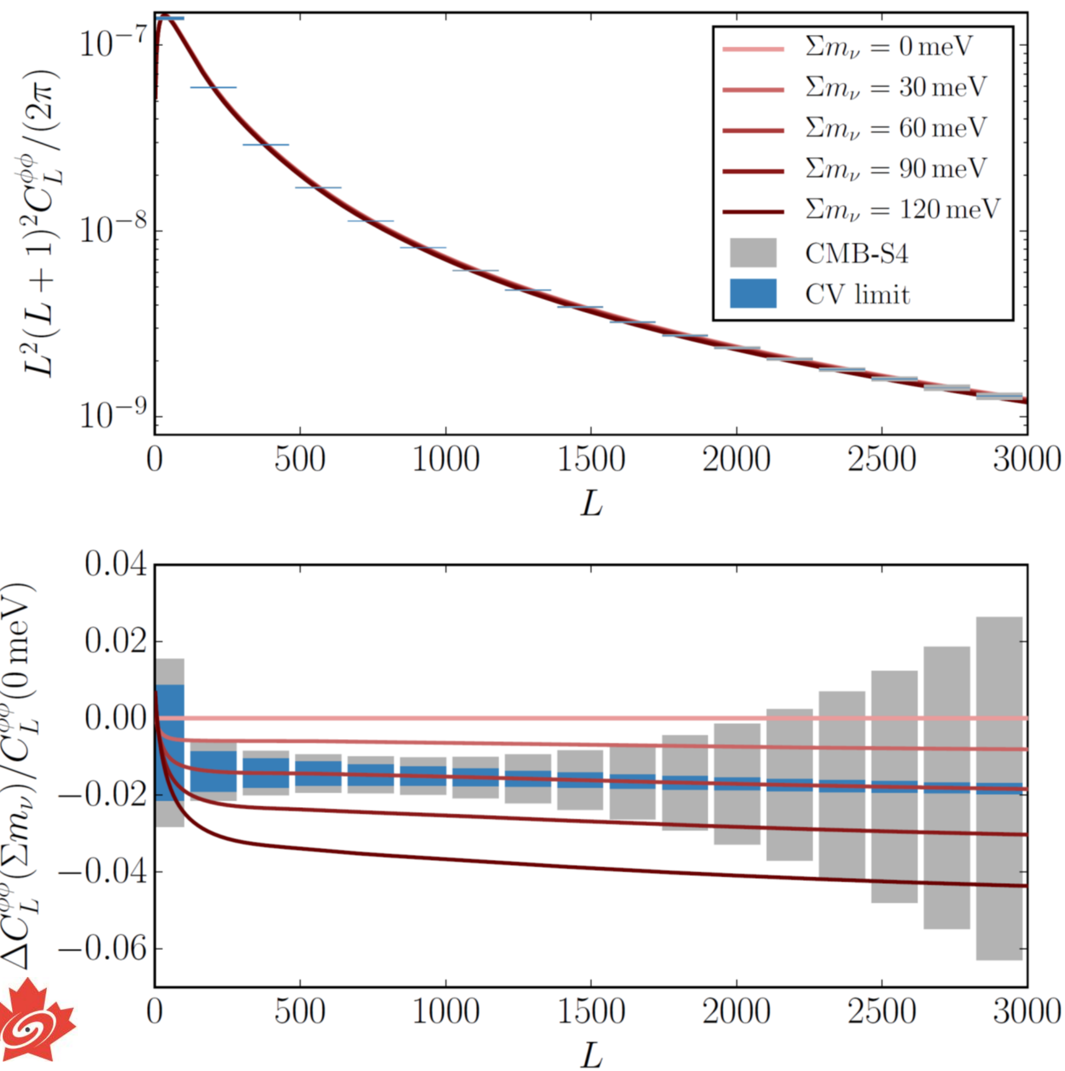
Gravitational Lensing



- 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

Hu, Okamoto (2002); Image Credit: Planck

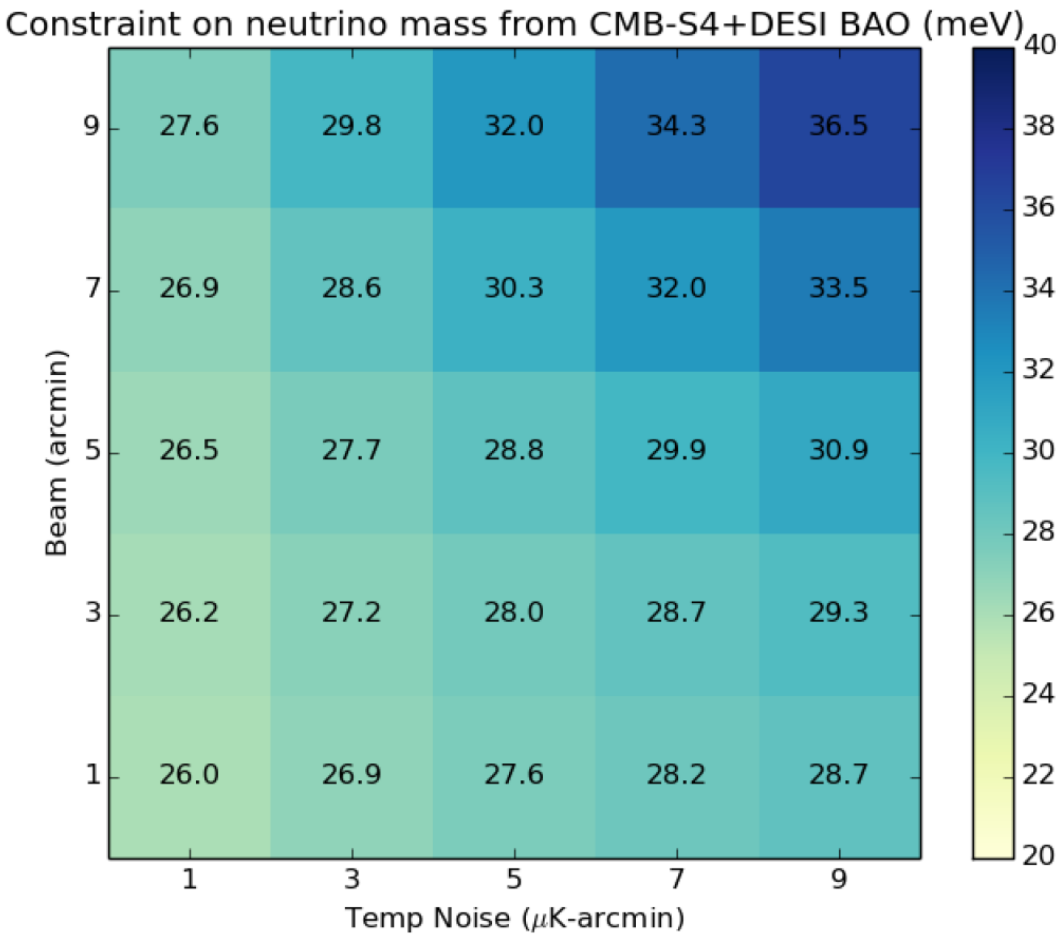
CMB-S4 Lensing Power Spectrum



- 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 Science Book (2016)

CMB-S4 + DESI BAO Forecasts



CMB-S4 Specs:

$$\ell \geq 30$$

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

+

$$\tau = 0.06 \pm 0.01$$

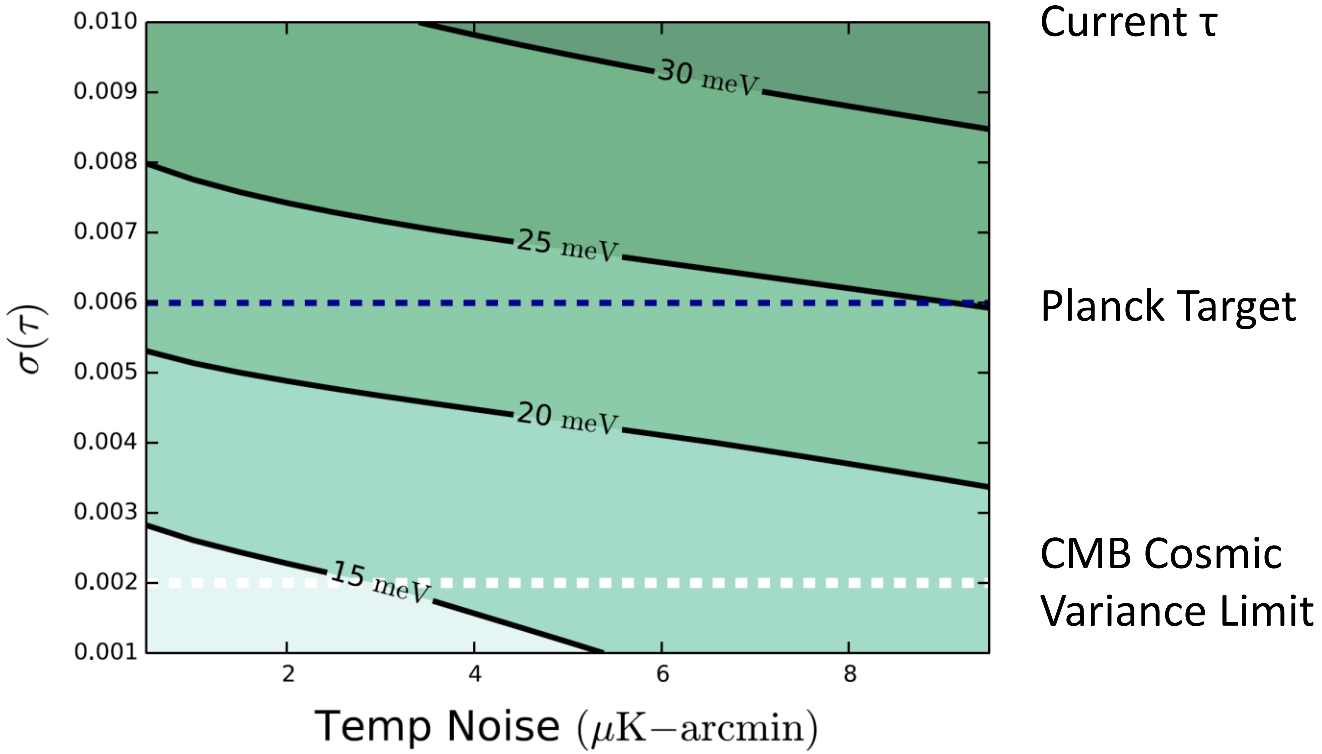
(Current Planck)

+

DESI BAO

CMB-S4 Science Book (2016)

Optical Depth and Neutrino Mass

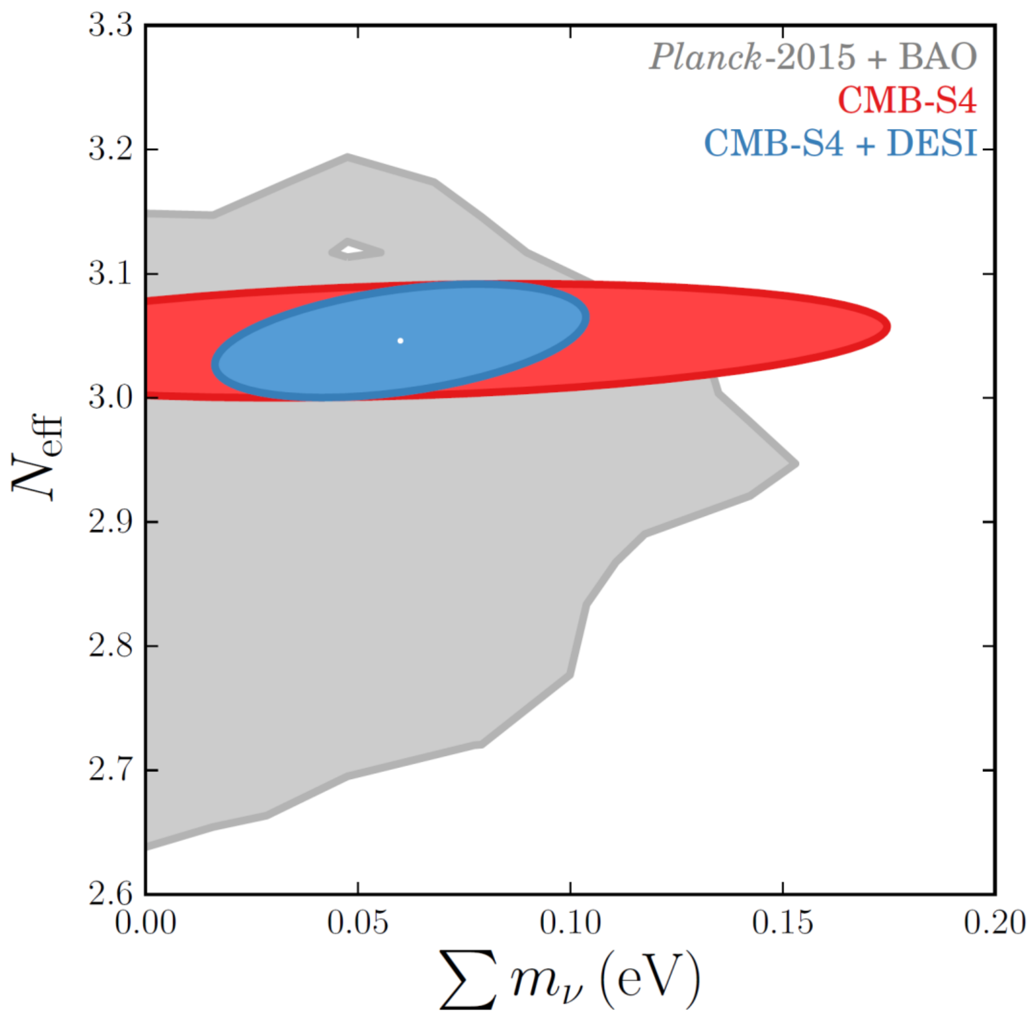


- Forecasted cosmological constraints on neutrino mass are limited by measurements of the optical depth
- Significant improvements could be achieved with satellite-based CMB observations to improve τ measurement

CMB-S4 Science Book (2016)

Sterile and Exotic Neutrinos

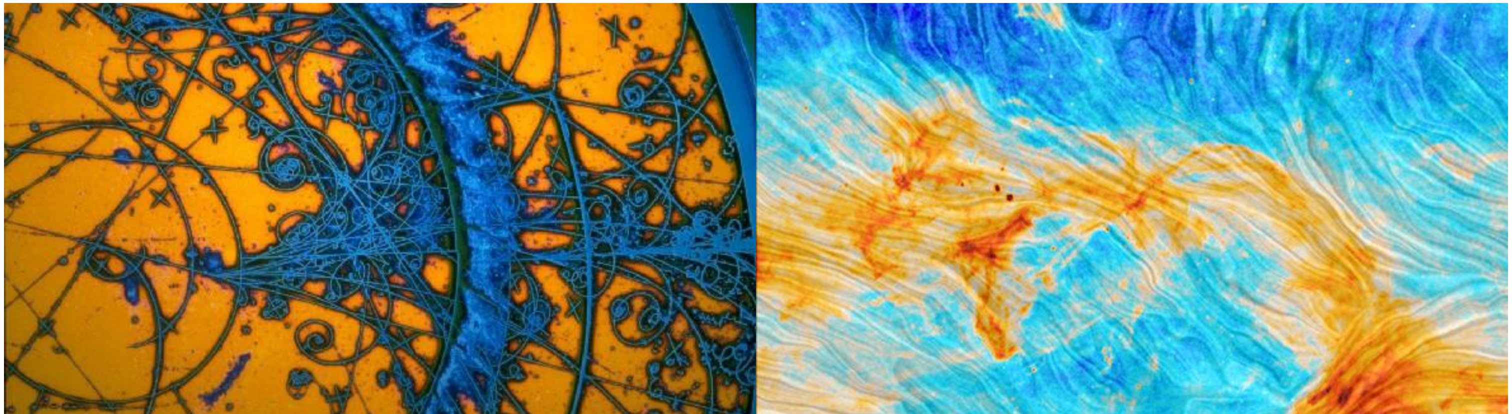
- Sterile neutrinos hinted by short baseline anomalies would be detected at high significance with CMB-S4
- Modified thermal histories could also dilute neutrinos compared to standard expectations

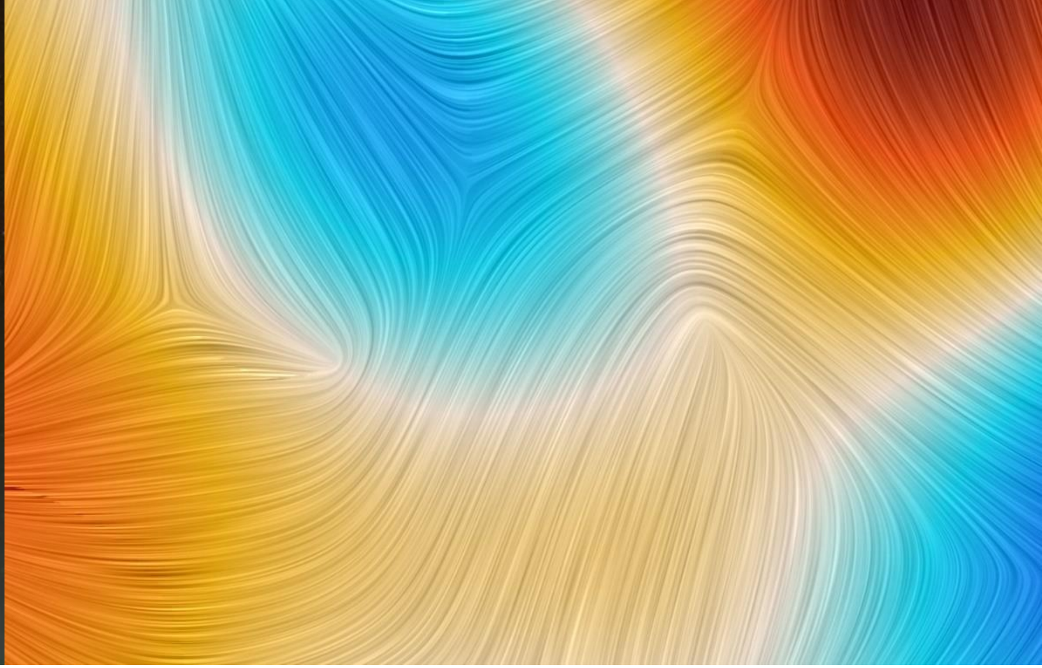


CMB-S4 Science Book (2016)

Conclusions

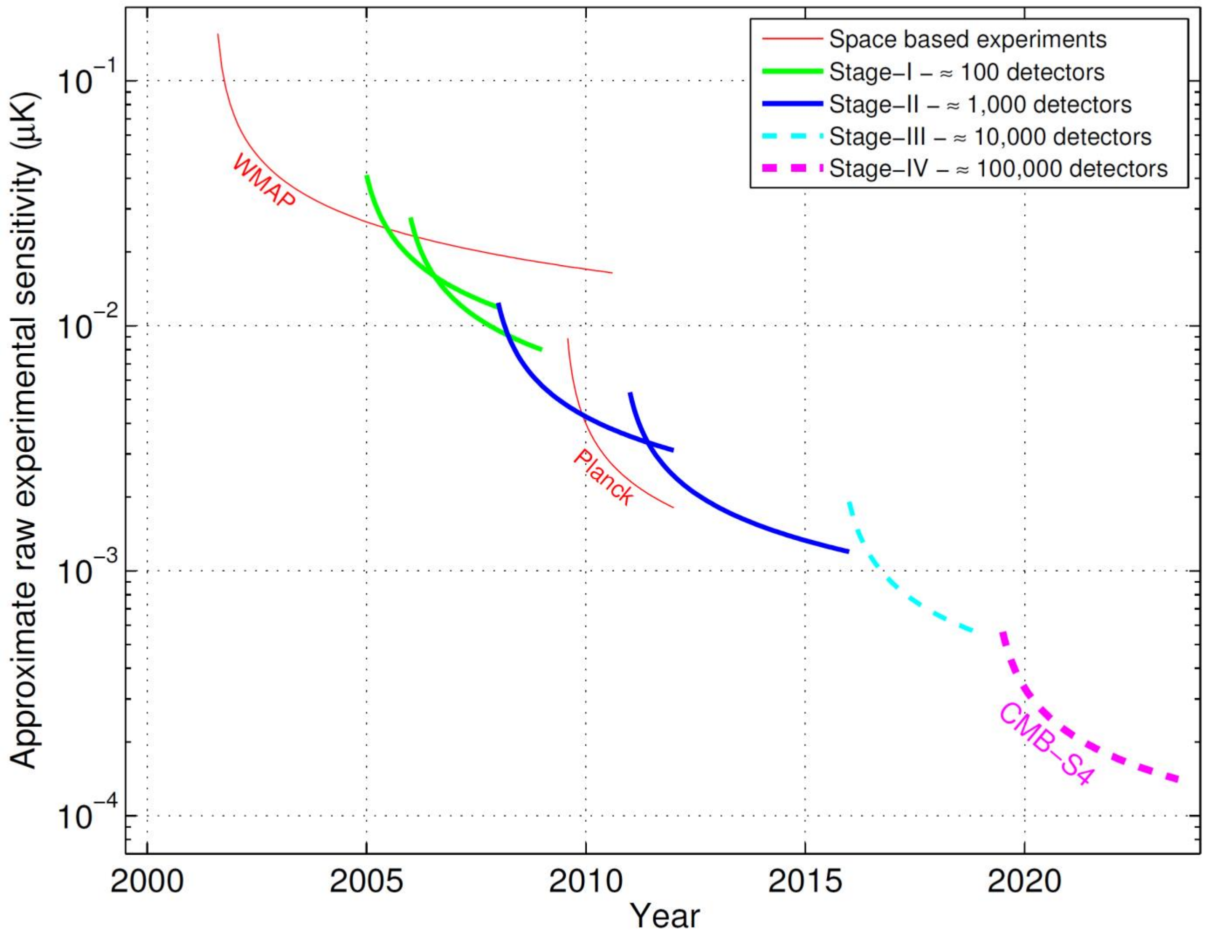
- Next generation CMB observations will provide deep insights into cosmology and fundamental physics
- N_{eff} in particular holds a great deal of promise for constraining physics beyond the standard model, and has a well motivated theoretical target at $\Delta N_{eff} = 0.027$ within reach of CMB-S4
- We stand to learn a huge amount by measuring N_{eff} even without a significant deviation from the standard model prediction
- Joint constraints on Neff and primordial helium abundance will allow probes of big bang nucleosynthesis and neutrino physics
- Cosmology will make a detection of the sum of neutrino masses



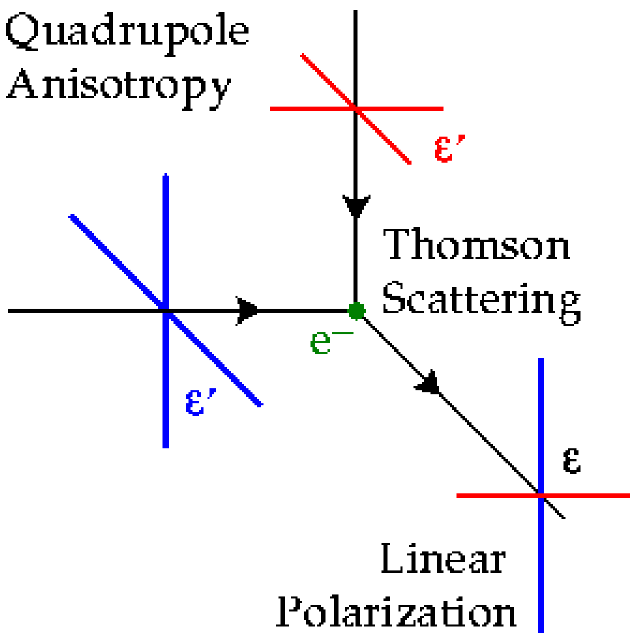
Backup Slides

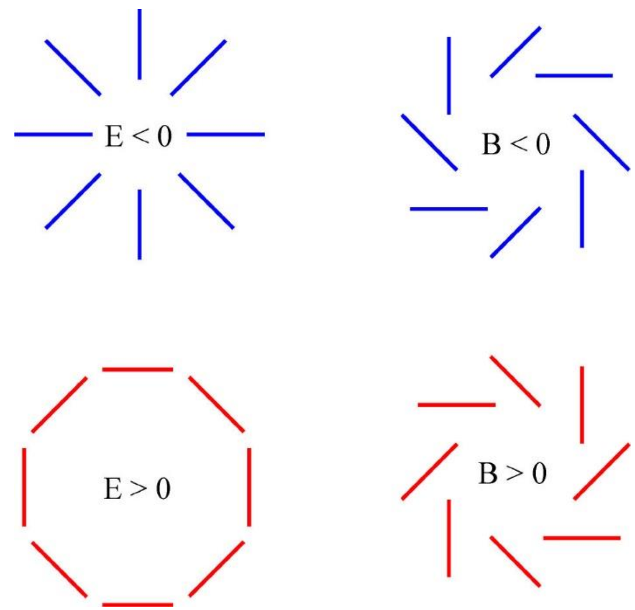
Moore's Law for CMB Experiments



Snowmass (2013); CMB-S4 Science Book (2016)

Polarization





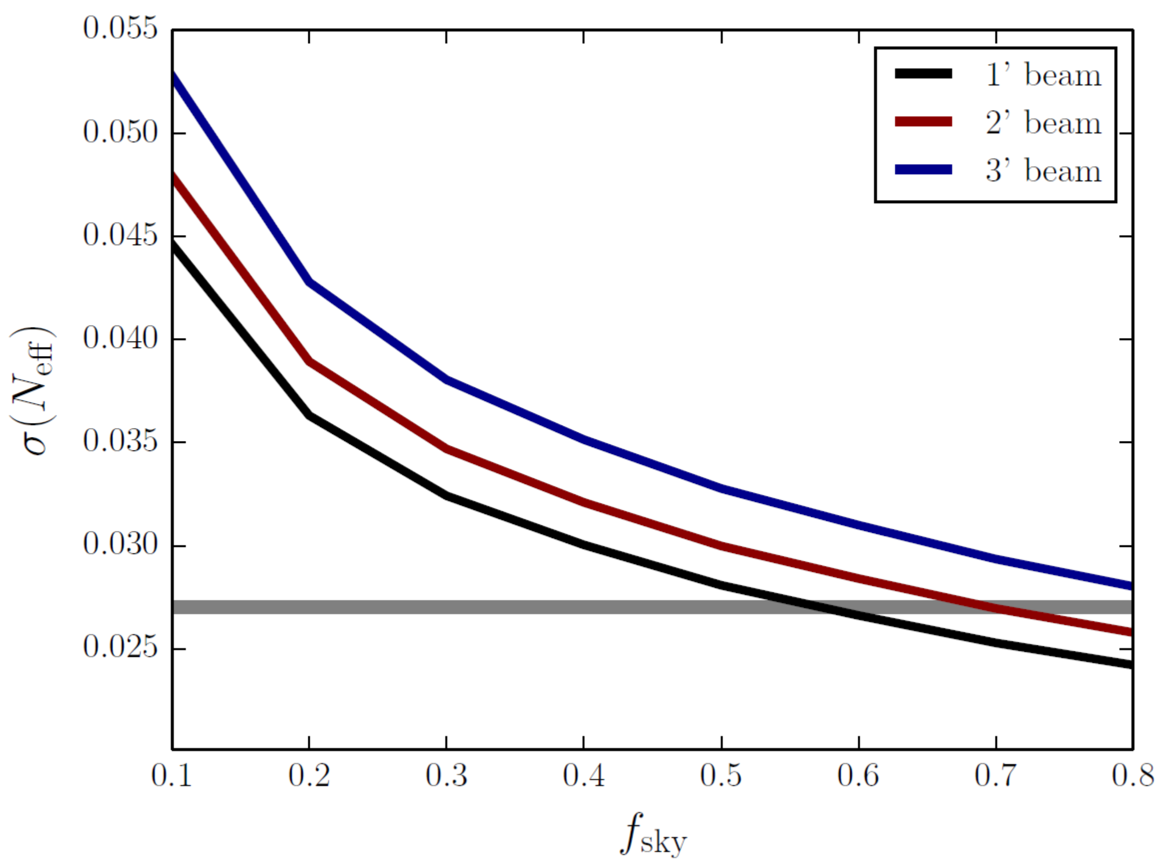
$\varphi \rightarrow$ T, E
$h \rightarrow$ T, E, B

- Linear polarization of CMB photons is generated by quadrupole anisotropy at last scattering
- Only E modes are produced by density fluctuations, while E and B modes are sourced by primordial gravitational waves

Kamionkowski, Kosowsky, Stebbins (1997); Seljak, Zaldarriaga (1997)
Image Credit: Hu

Improvements with Sky Fraction

- Light relic constraints favor larger sky fraction at fixed effort
- With f_{sky} = 0.6 any scalar thermal relic could be detected at 1σ and any vector thermal relic could be detected at 2σ



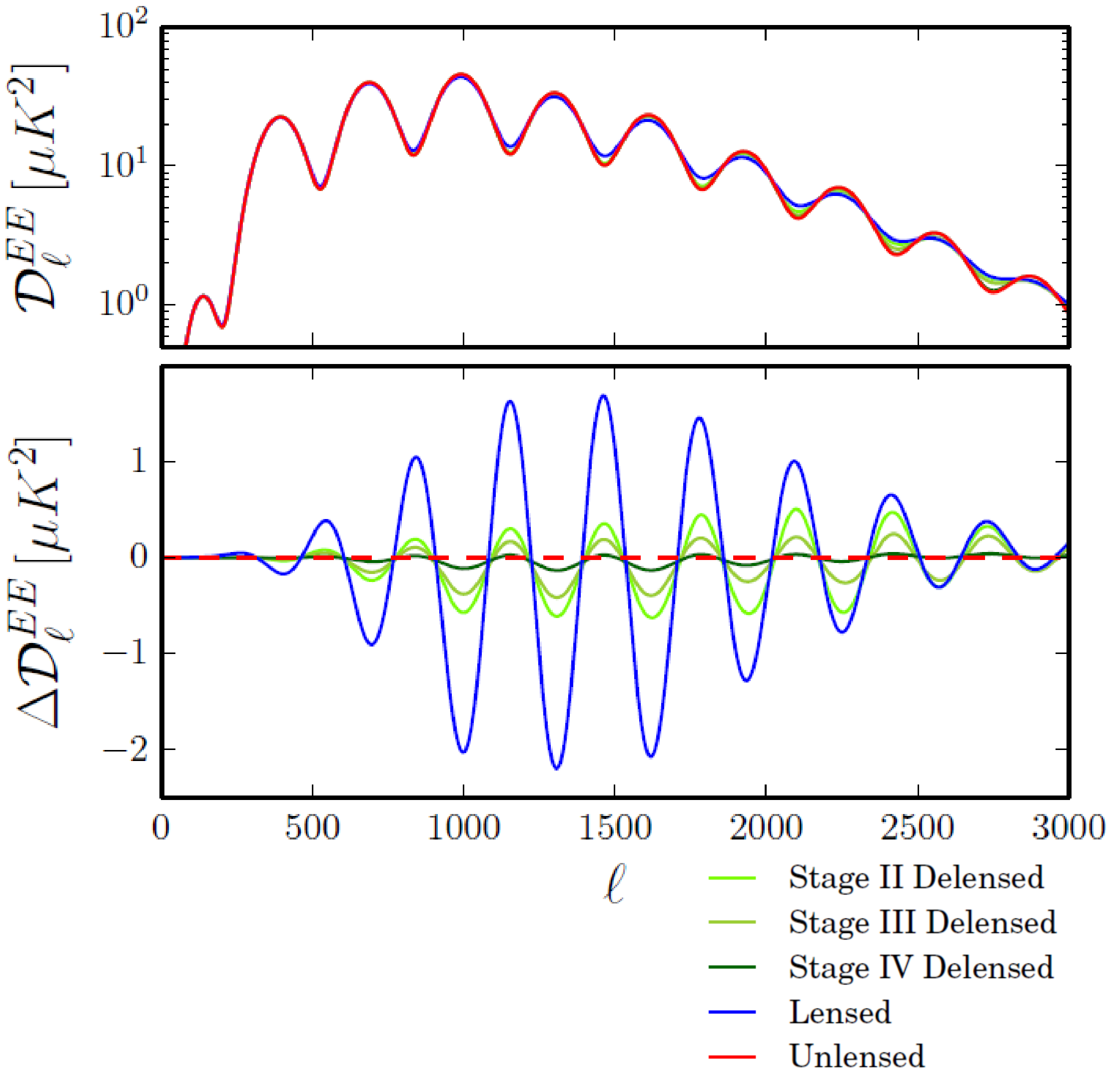
$1\ \mu K\text{-arcmin for } f_{\rm sky} = 0.4$

$$S \propto f_{\rm sky}^{1/2}$$

CMB-S4 Science Book (2016)

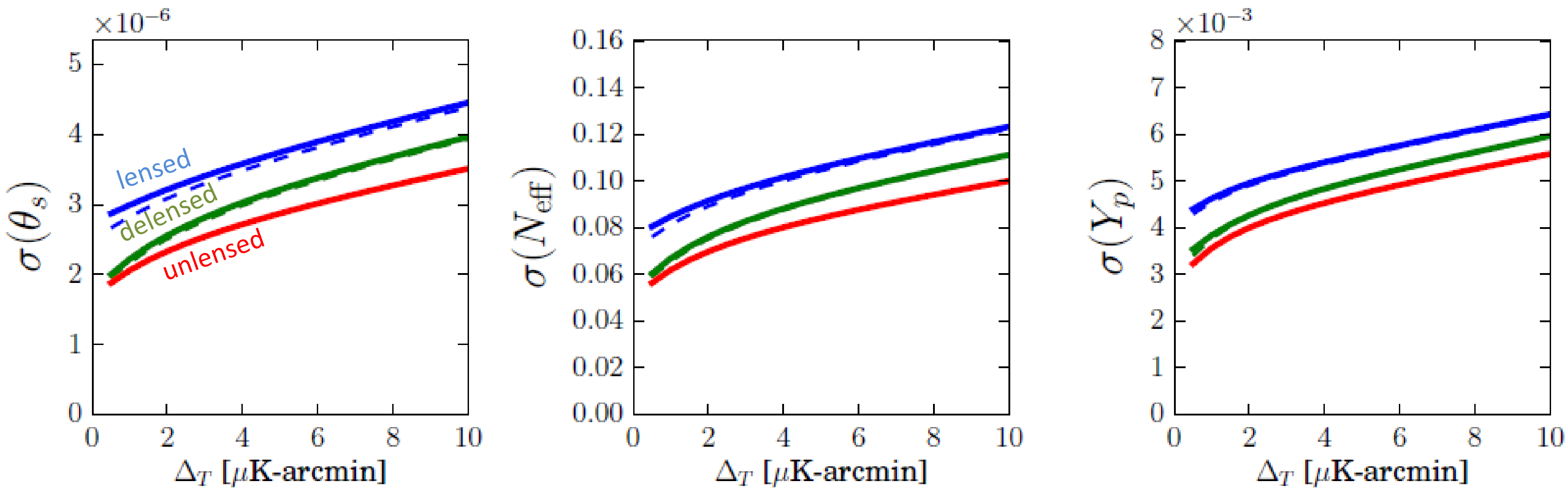
Benefits of Delensing

- 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



Green, JM, van Engelen (2016)

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

Green, JM, van Engelen (2016)