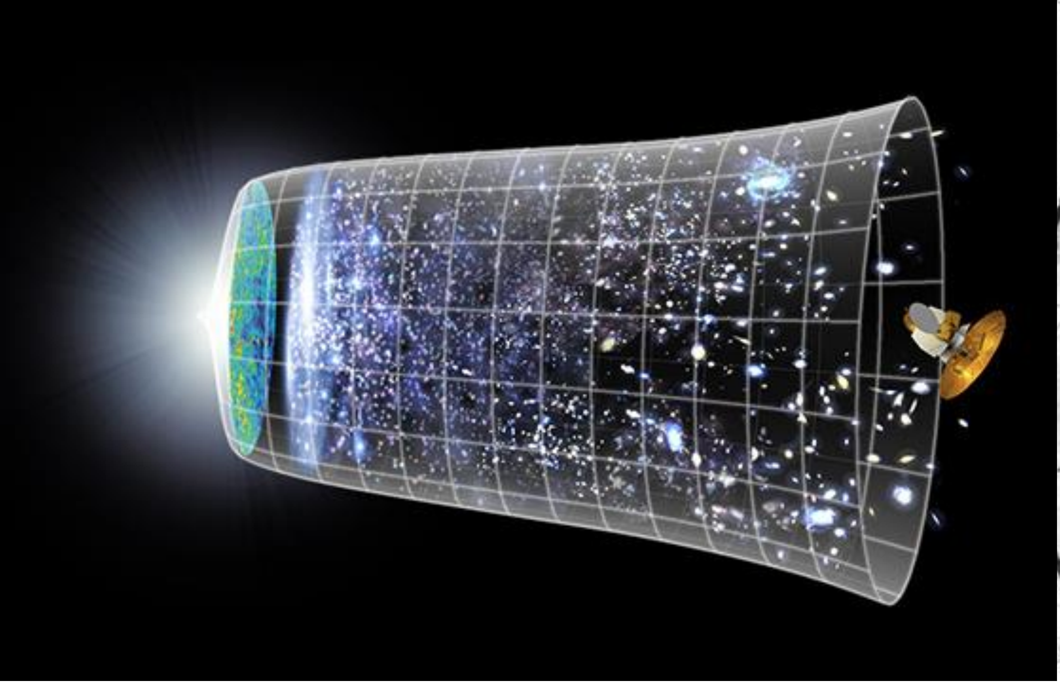 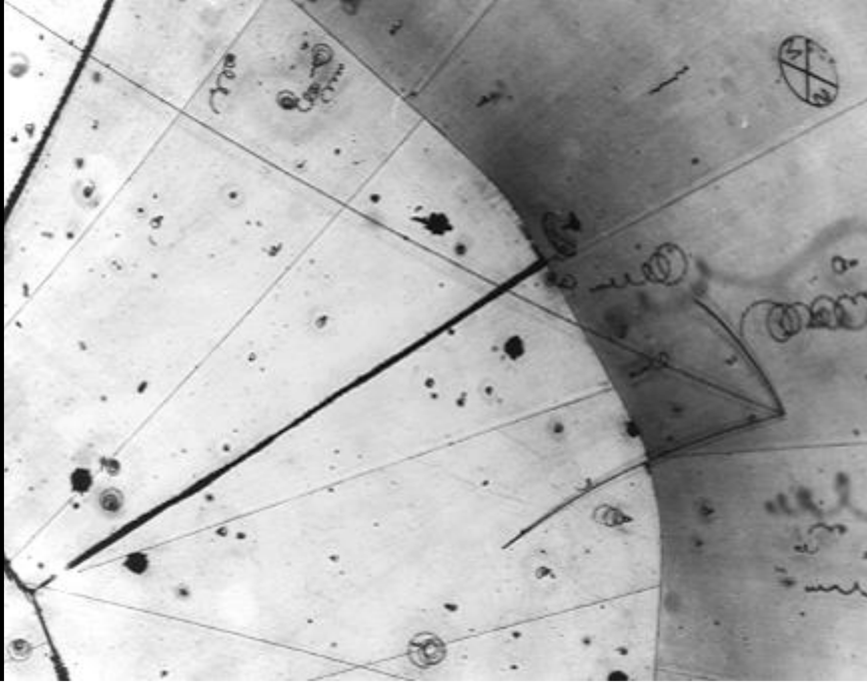

Cosmic Neutrinos and Other Light Relics

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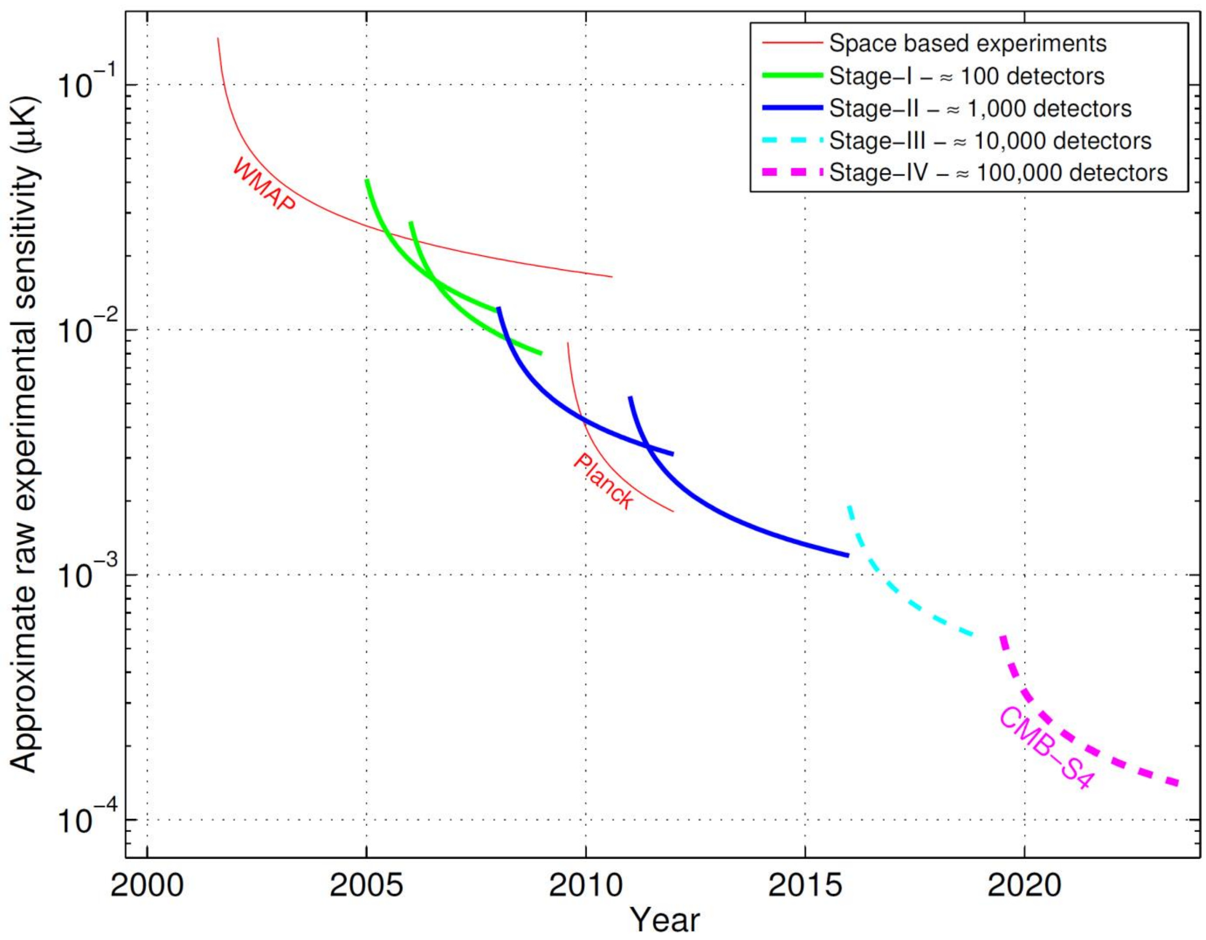
Moriond Cosmology
March 21, 2016

Based on:
arXiv:1508.06342 with Daniel Baumann, Dan Green, and Benjamin Wallisch
arXiv:1604.xxxxx with Dan Green and Alex van Engelen

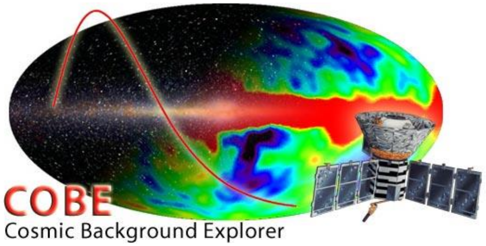
Moore's Law for CMB Experiments

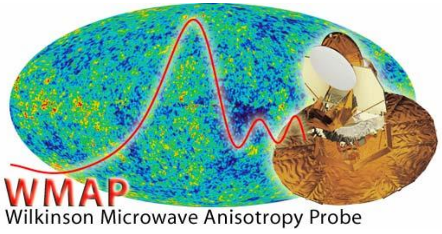


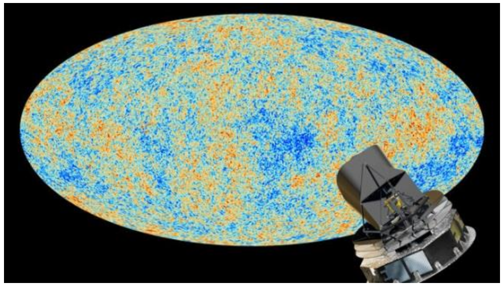
Snowmass (2013)

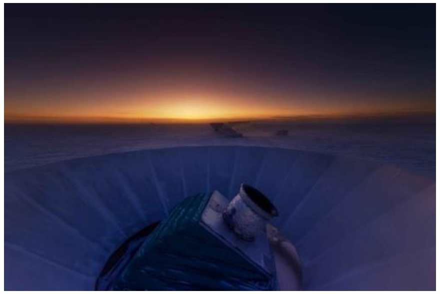
A Theorist's (Abridged and Biased) Timeline of CMB Science

- 1948 – Alpher, Gamow, and Herman predict existence of CMB
- 1964 – Penzias and Wilson accidentally make first measurements of CMB
- 1992 – COBE – Big Bang Cosmology, Anisotropies
- 2003 – WMAP – ΛCDM Cosmology
- 2013 – Planck – Non-Gaussianity
- 2015+ – CMB Stage III and CMB Stage IV – Gravitational Waves, Neutrino Mass, and N_{eff}







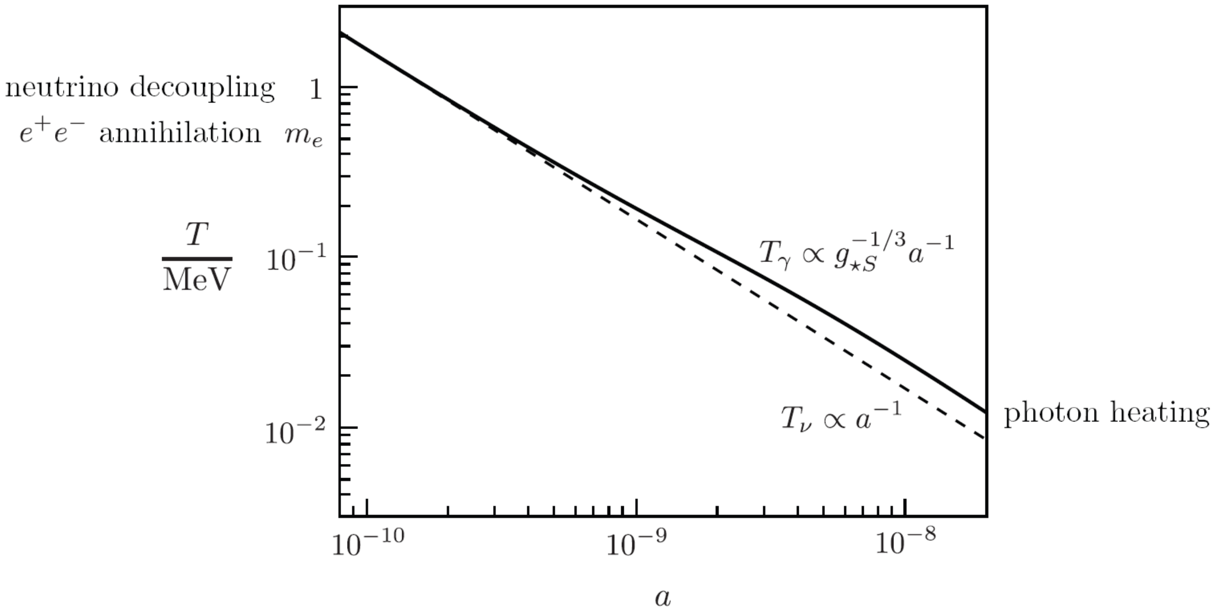


N_{eff}

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

- 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

CvB Contribution to N_{eff}

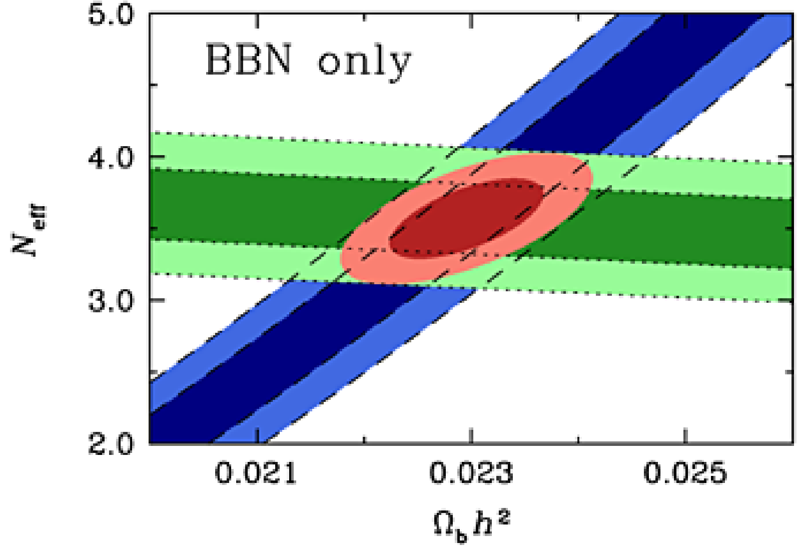


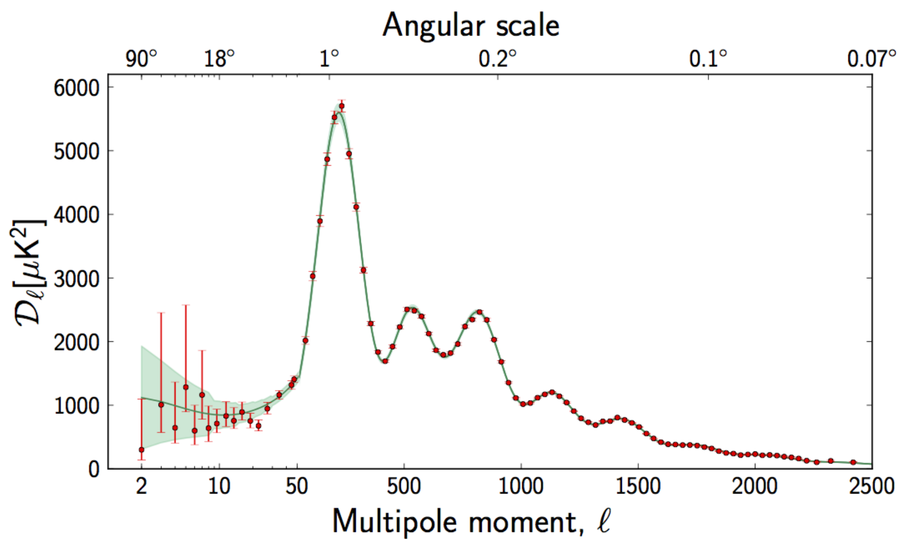
$$N_{\text{eff}}^{\text{SM}} = 3.046$$

- 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

PDG (2013); Mangano, et al. (2005)

Observing N_{eff}





Primordial Abundances

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

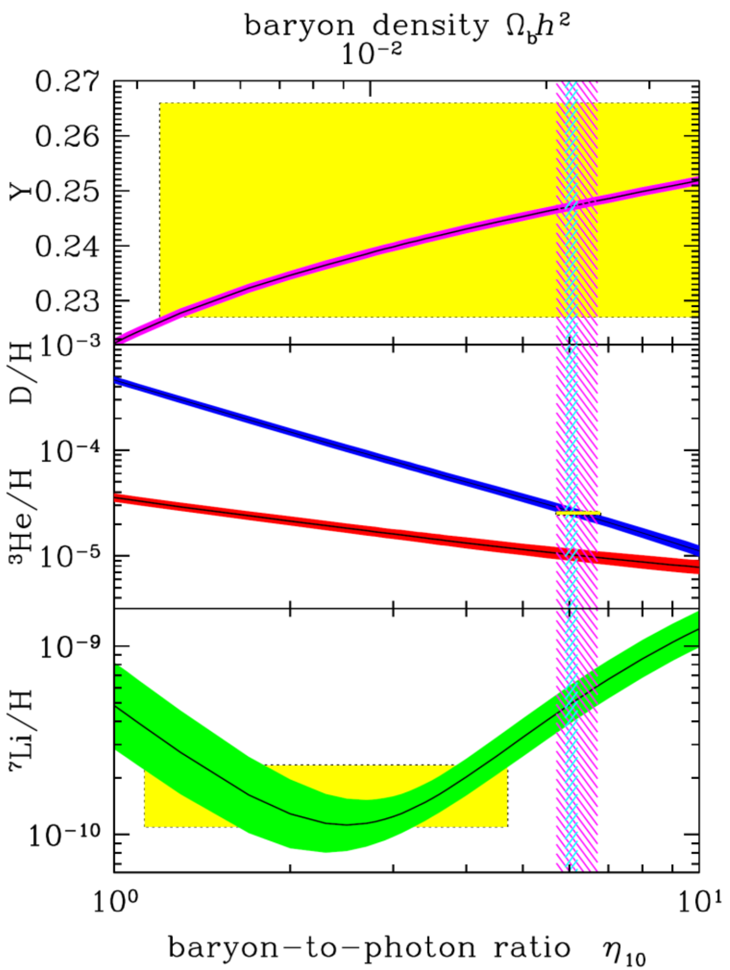
CMB Measurements

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

- 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)

Big Bang Nucleosynthesis

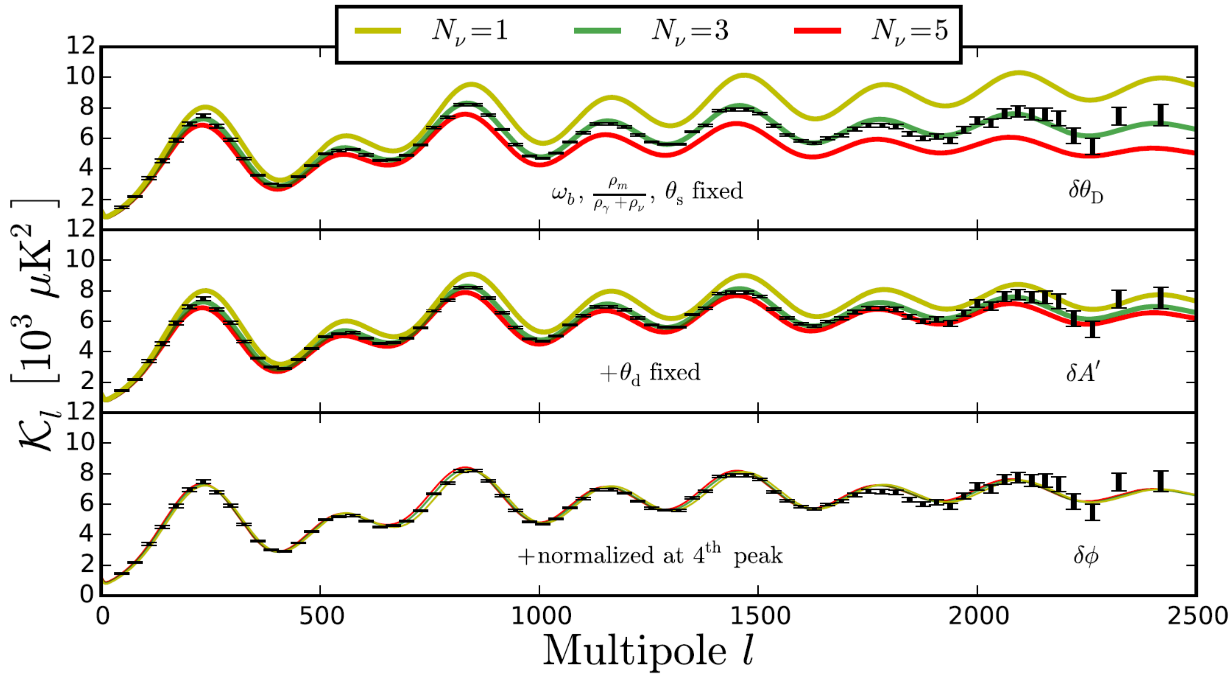


- Measurements of primordial light element abundances put a constraint on N_{eff} at around 3 minutes after the end of inflation
- BBN is weakly sensitive to the neutrino spectrum as well as the total radiation energy density

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

PDG (2013); Cooke, et al. (2014); Cyburt, et al. (2015)

Effects of Neutrinos 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)

Forecasted Constraints

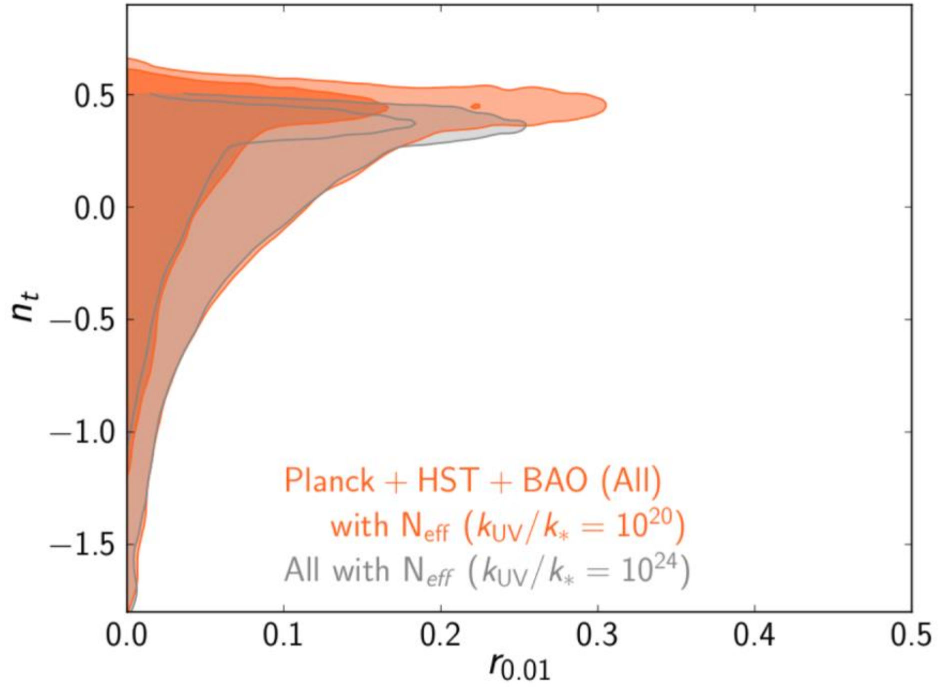
Experiment	Timeline	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$ (eV)
Planck	Present	0.18	0.23
AdvACT/SPT3G	2016-2019	0.06	0.06
CMB-S4	2020-?	0.02	0.016 (with DESI)

- CMB constraints on N_{eff} are rapidly improving due to several ongoing and future observations
- Errors are likely to shrink by an order of magnitude within the next decade due to high resolution ground-based measurements of CMB temperature and polarization

Benson, et al. (2014); Naess, et al. (2014); Snowmass (2013)

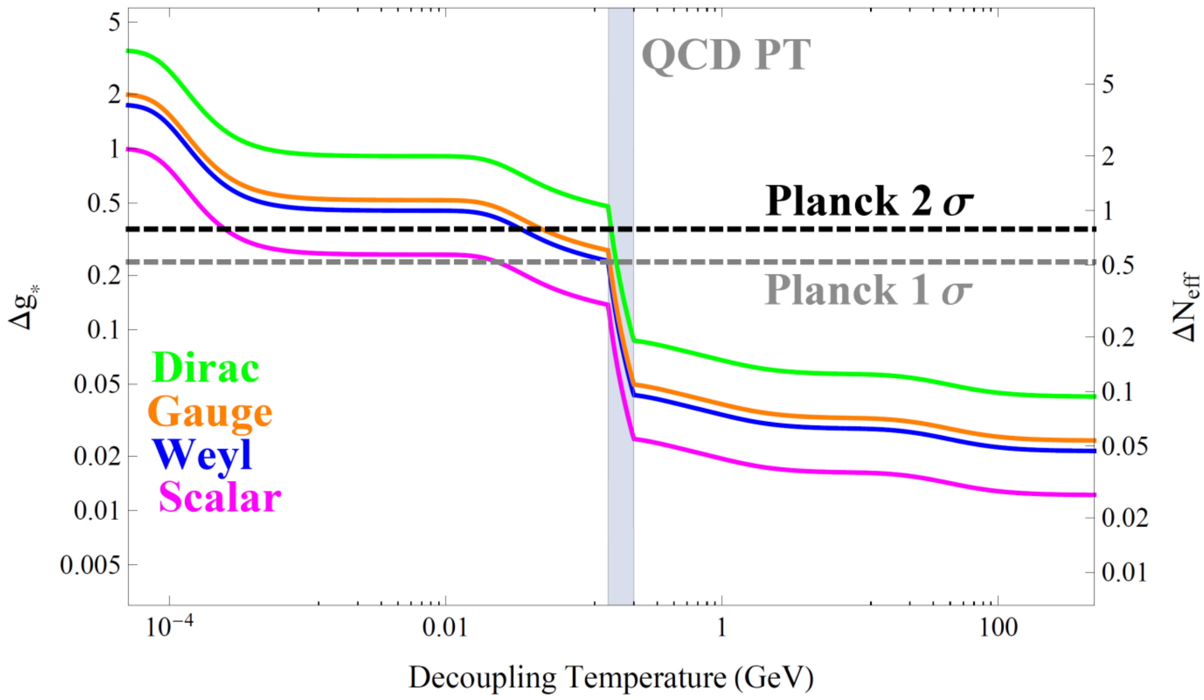
Dark Radiation

- 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:
  - Gravitational waves
  - Sterile neutrinos
  - Dark photons
  - Many others



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

Light Thermal Relics



- Planck mostly rules out particles which decouple after the QCD phase transition
- CMB-S4 has the reach to exclude or detect all thermal relics which decoupled at essentially arbitrarily high temperature

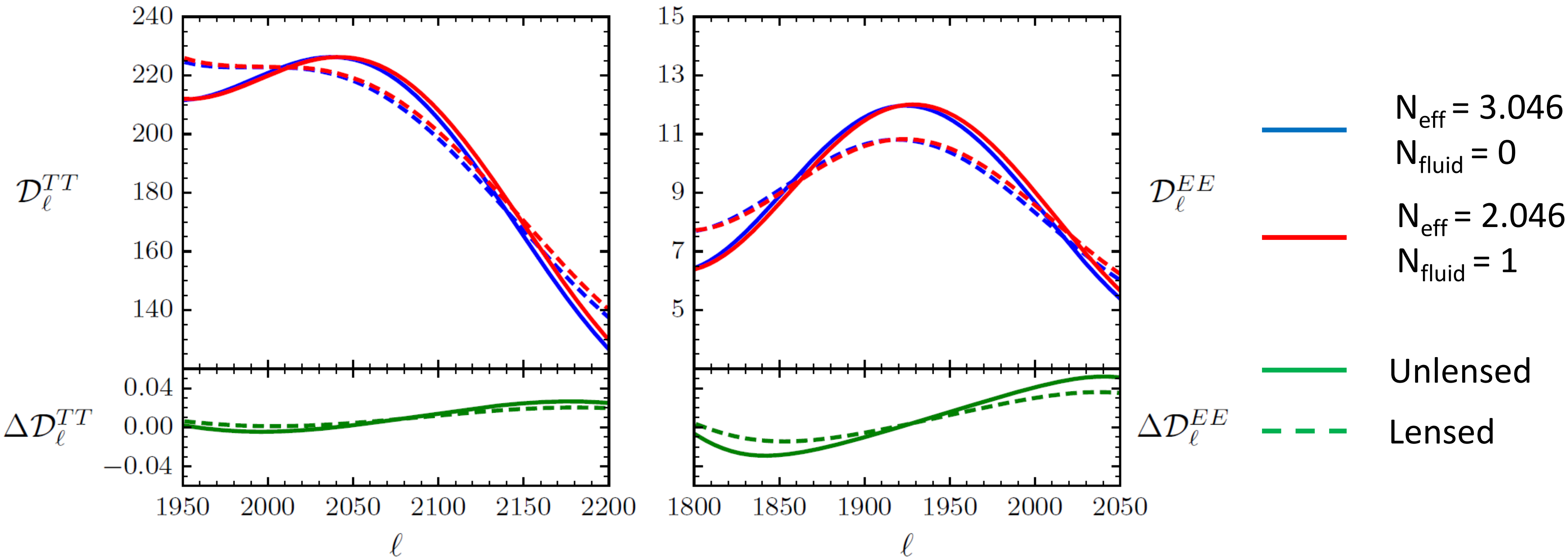
Brust, Kaplan, Walters (2013); Chacko, Cui, Hong, Okui (2015)

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 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)

Free Streaming and the Phase Shift

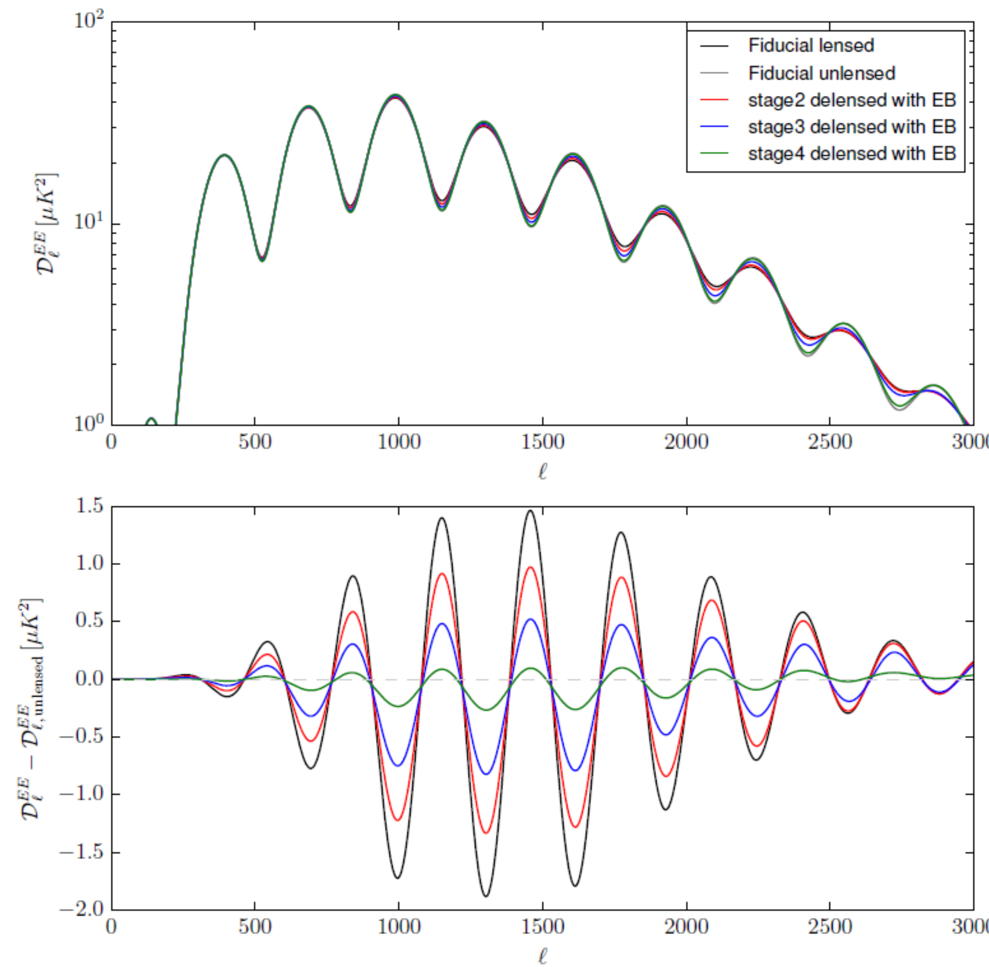


- The phase shift can be used to distinguish between free streaming and non-free streaming radiation species
- The phase shift is most easily detectable in the delensed EE spectrum due to the sharper peaks

Baumann, Green, JM, Wallisch (2015)

Delensing Forecasts

- Delensing sharpens peaks and reduces lensing-induced covariance, thereby tightening errors on 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 (In Prep.)

Conclusions

- There is a great deal of interesting physics left to be explored with ongoing measurements of the CMB
- 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
- The phase shift which results from free-streaming radiation breaks degeneracies, drives constraints on N_{eff} and distinguishes various forms of radiation
- We stand to learn a huge amount by measuring N_{eff} even without a significant deviation from the standard model prediction

10^9 cosmic neutrinos pass through this snowflake each second!