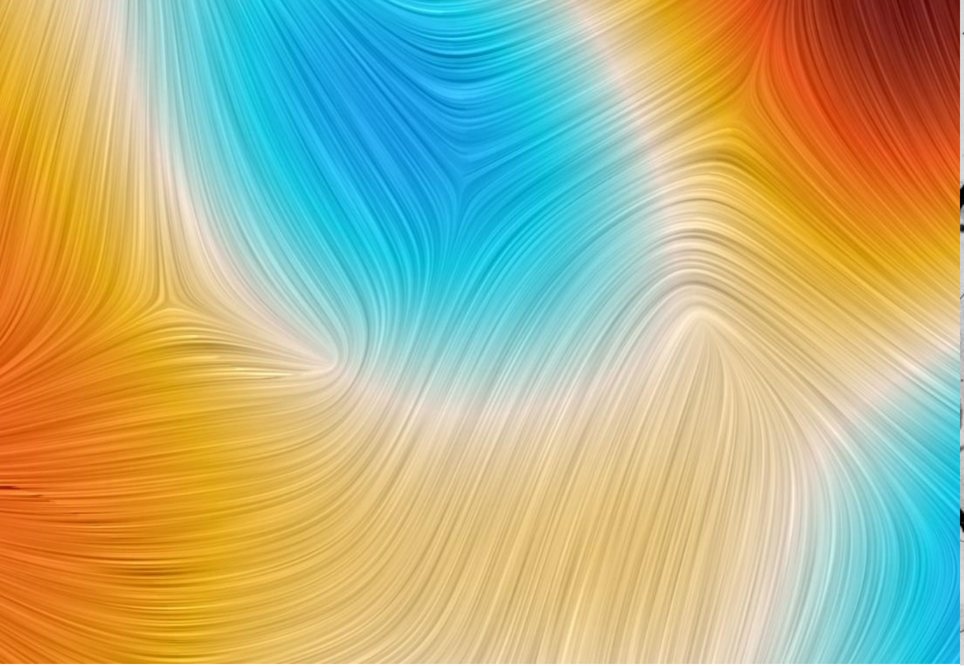
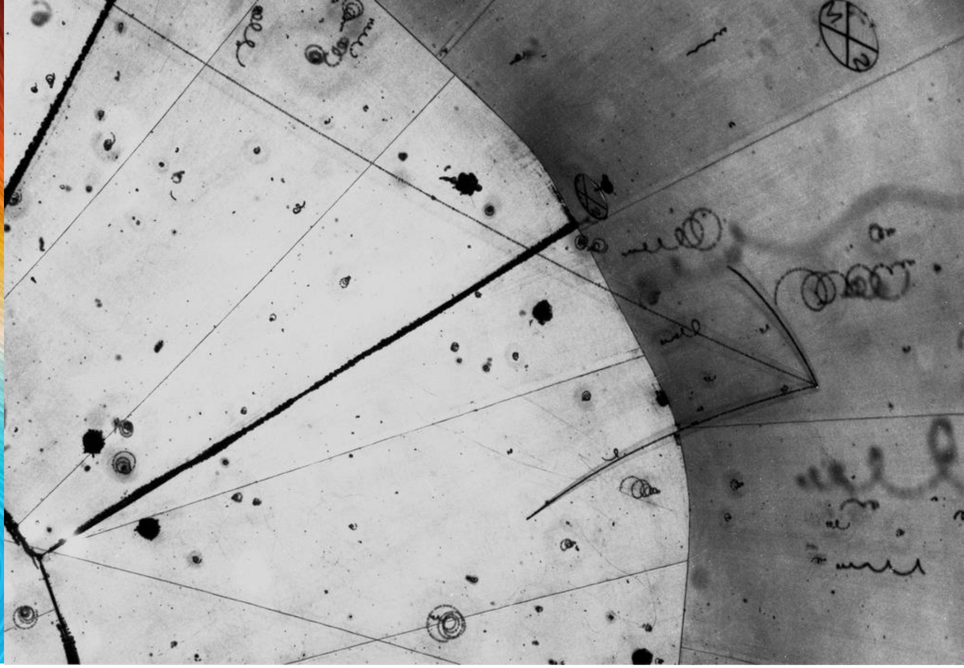


CMB & Light Degrees of Freedom

Joel Meyers

Canadian Institute for Theoretical Astrophysics

SLAC Summer Institute 2017

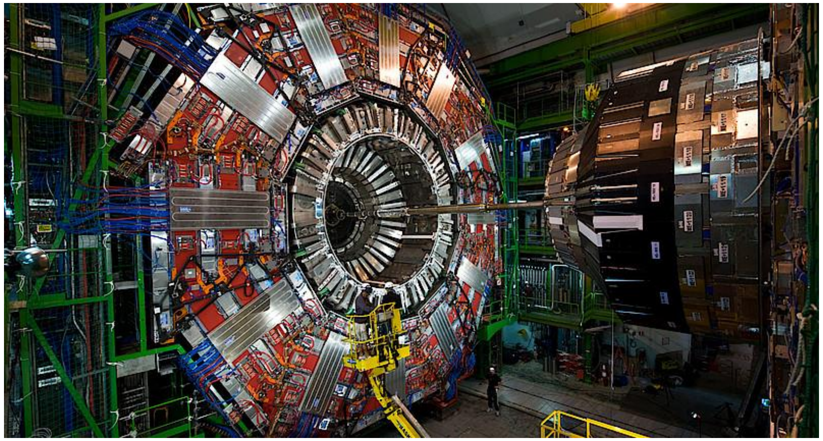
Cosmic Opportunities

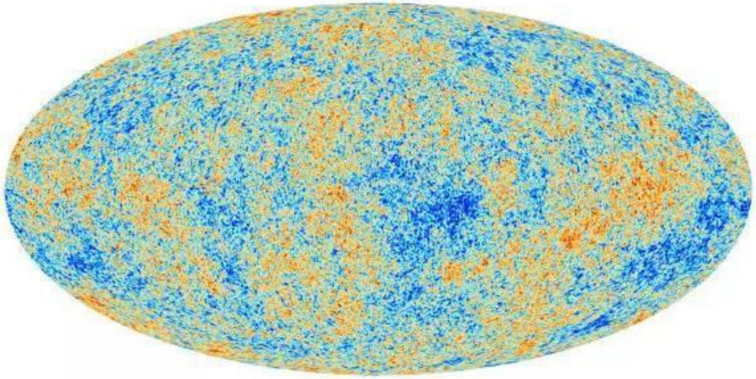
August 21, 2017

Image Credits: Planck, ANL

Light Relics – What and Why?

- **Light** – Particles which were relativistic at recombination (m < 1 eV)
- **Relics** – Left over from the early universe (non-negligible energy density at early times)



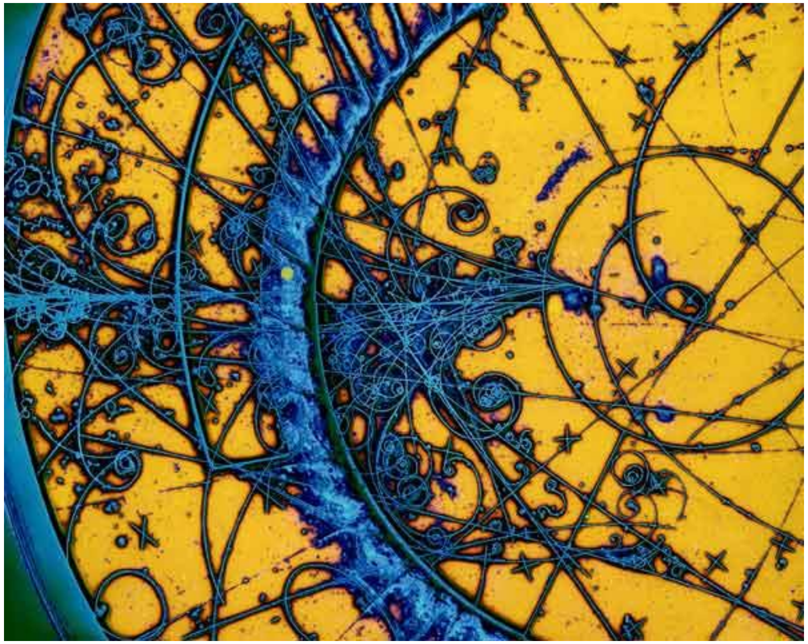


- Cosmology in general, and the CMB in particular, provides a window into very high energy physics through sensitivity to light relics

Image Credits: Planck, CMS

Parametrization – N_{eff}

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



- The "effective number of neutrino species" N_{eff} measures the total energy density in radiation excluding photons
- Because it receives contributions from all light relics, N_{eff} need not have anything to do with neutrinos
- N_{eff} is a cosmological observable due to the gravitational influence of the radiation in the early universe

PDG(2013); Image Credit: CERN

Relativistic Particles in Equilibrium

- The distribution function for relativistic particles in thermal equilibrium and vanishing chemical potential is given by

$$f(p) = \frac{1}{\exp(p/T) \mp 1}$$

- The energy density of a thermal bath of massless particles is

$$\rho(T) = \int \mathrm{d}p \, \frac{4\pi p^3 g}{\exp(p/T) \mp 1} = \begin{cases} g\frac{\pi^2}{30}T^4 & \text{Bosons} \\ \frac{7}{8}g\frac{\pi^2}{30}T^4 & \text{Fermions} \end{cases}$$

Thermodynamics

- Let us define the quantity $g_\star(T)$ which counts the number of spin states for all particles and antiparticles in equilibrium, including a factor 7/8 for fermions, which then gives

$$\rho(T) = g_\star(T)\frac{\pi^2}{30}T^4$$

- The pressure and entropy density for massless particles in thermal equilibrium are

$$P(T) = \frac{\rho(T)}{3} \qquad s(T) = \frac{\rho(T) + P(T)}{T} = \frac{4\rho(T)}{3T}$$

Entropy Conservation

- The comoving entropy is conserved in thermal equilibrium, and so

$$\frac{\mathrm{d}}{\mathrm{d}t}(a^3 s(T)) = 0 \qquad\qquad T \propto g_\star(T)^{-1/3} a^{-1}$$

- Away from mass thresholds, $g_\star(T)$ is constant, and the temperature falls as the inverse of the scale factor $T \propto a^{-1}$
- When particles fall out of equilibrium and annihilate, the particles remaining in equilibrium are heated relative to a free expansion

Neutrino Decoupling

- Let us see how this works for neutrinos in the instant decoupling limit
- Above about 1 MeV, weak interactions kept neutrinos in thermal equilibrium with the plasma of photons, electrons, and positrons
- Below 1 MeV (about 1 second after inflation) neutrinos decoupled and began a free expansion
- From this point on, we must separately keep track of the neutrino and photon temperatures

Neutrino Decoupling

- Shortly after neutrinos decoupled, the photon temperature fell below the electron mass, and electrons and positrons annihilated

$$g_\star^{\text{before}} = 2 + \frac{7}{8}(2+2) = \frac{11}{2} \qquad\qquad g_\star^{\text{after}} = 2$$

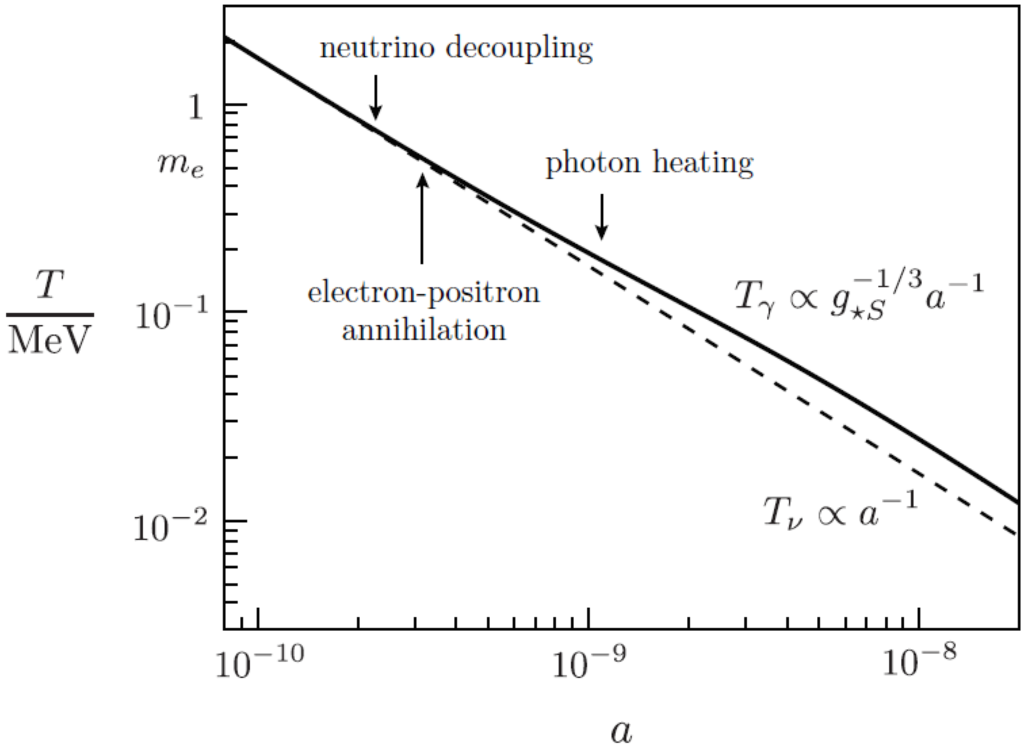
photons e^- e^+ photons

- Noting that photons and neutrinos had a common temperature before decoupling, and neutrinos underwent free expansion after decoupling, we find

$$\frac{g_\star^{\text{before}} T_{\gamma,\text{before}}^3}{T_{\nu,\text{before}}^3} = \frac{g_\star^{\text{after}} T_{\gamma,\text{after}}^3}{T_{\nu,\text{after}}^3} \qquad\qquad \frac{T_{\nu,\text{after}}}{T_{\gamma,\text{after}}} = \left(\frac{4}{11}\right)^{1/3}$$

Neutrino Decoupling

- After neutrinos decoupled, photons were heated due to the annihilation of electrons and positrons
- Entropy conservation allows us to calculate the relative temperatures simply by counting states



$$\frac{T_{\gamma,\mathrm{after}}}{T_{\nu,\mathrm{after}}} = \left(\frac{11}{4}\right)^{1/3} = 1.401$$

$$T_{\gamma,0} = 2.725\,\mathrm{K}$$

$$T_{\nu,0} = 1.945\,\mathrm{K}$$

Image Credit: Baumann

N_{eff} Revisited

$$\rho_{\mathrm{r}} = \rho_{\gamma}\left(1 + \underbrace{\frac{7}{8}}_{\text{Fermions}}\underbrace{\left(\frac{4}{11}\right)^{4/3}}_{\text{(Temperature Ratio)}^4} N_{\mathrm{eff}}\right)$$

- We can now see that the definition of N_{eff} was chosen to count the number of species of neutrinos (assuming one massless helicity state per species and instantaneous decoupling)
- Non-instantaneous decoupling and small non-equilibrium corrections slightly increase the prediction in the standard model

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

Mangano, et al. (2005)

BSM Contributions to N_{eff}

- We can apply the same techniques to calculate the contribution of any light thermal relic to N_{eff} by comparing the relic temperature to the neutrino temperature

$$\left(\frac{T_{\mathrm{relic}}}{T_\nu}\right)^3 = \frac{g_\star(T_{\nu-\mathrm{decoupling}})}{g_\star(T_F)} = \frac{43/4}{g_\star(T_F)}$$

$$g_\star(T_{\nu-\mathrm{decoupling}}) = 2+\frac{7}{8}(2+2+3\times 2) = 43/4$$

photons

e^-

e^+

3 neutrinos
3 antineutrinos

BSM Contributions to N_{eff}

- As a result, we find the contribution of a light thermal relic to N_{eff} is determined only by the number of spin states g and its decoupling temperature T_F

$$\Delta N_{\rm eff} = \begin{cases} \frac{4g}{7}\left(\frac{43/4}{g_\star(T_F)}\right)^{4/3} & \text{Boson} \\ \frac{g}{2}\left(\frac{43/4}{g_\star(T_F)}\right)^{4/3} & \text{Fermion} \end{cases}$$

Standard Model Degrees of Freedom

- Since the masses and spin states of the particles of the Standard Model are known, we can easily calculate $g_\star(T)$
- At early times and high temperatures $T \gtrsim 100\,\mathrm{GeV}$

$$g_\star = g_b + \frac{7}{8} g_f \;=\; 106.75$$

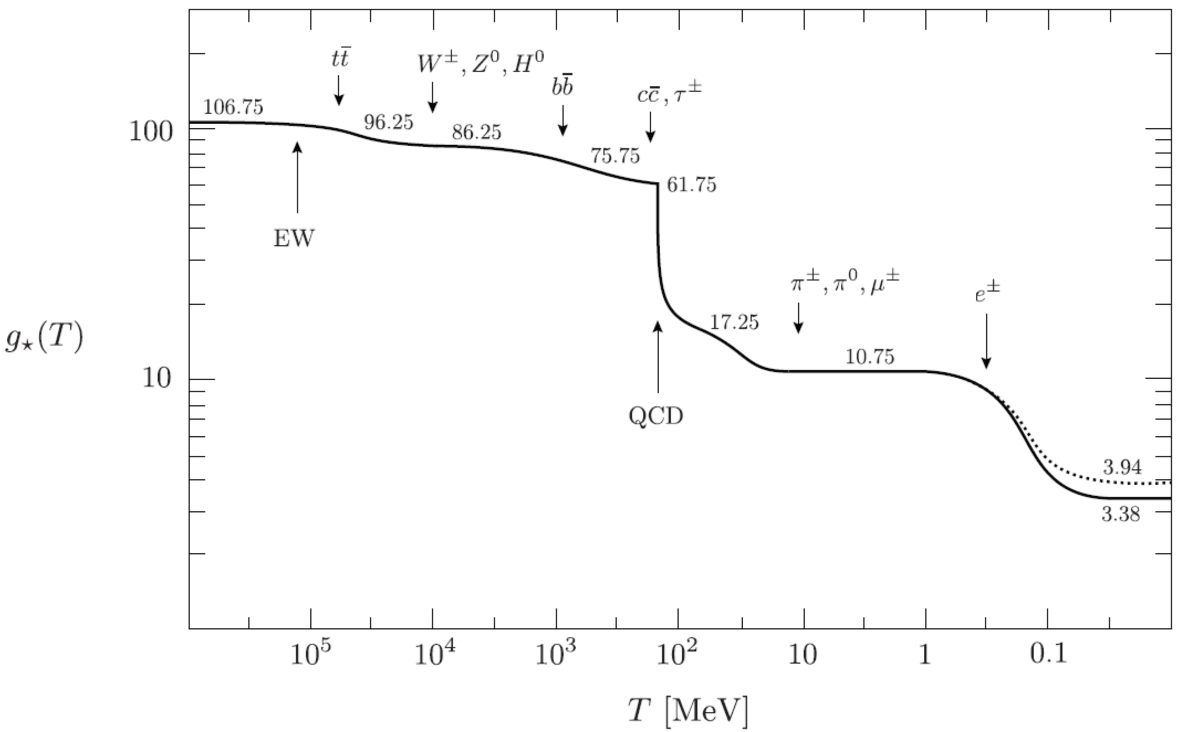
type		mass	spin	g
quarks	$t, \bar{t}$	173 GeV	$\frac{1}{2}$	$2 \cdot 2 \cdot 3 = 12$
	$b, \bar{b}$	4 GeV		
	$c, \bar{c}$	1 GeV		
	$s, \bar{s}$	100 MeV		
	$d, \bar{s}$	5 MeV		
	$u, \bar{u}$	2 MeV		
gluons	g_i	0	1	$8 \cdot 2 = 16$
leptons	$\tau^\pm$	1777 MeV	$\frac{1}{2}$	$2 \cdot 2 = 4$
	$\mu^\pm$	106 MeV		
	$e^\pm$	511 keV		
	$\nu_\tau, \bar{\nu}_\tau$	< 0.6 eV	$\frac{1}{2}$	$2 \cdot 1 = 2$
	$\nu_\mu, \bar{\nu}_\mu$	< 0.6 eV		
	$\nu_e, \bar{\nu}_e$	< 0.6 eV		
gauge bosons	W^+	80 GeV	1	3
	W^-	80 GeV		
	Z^0	91 GeV		
	γ	0		2
Higgs boson	H^0	125 GeV	0	1

$$g_b = 28 \qquad \text{photons}\,(2),\ W^\pm \text{ and } Z^0\,(3\cdot 3),\ \text{gluons}\,(8\cdot 2),\ \text{and Higgs}\,(1)$$

$$g_f = 90 \qquad \text{quarks}\,(6\cdot 12),\ \text{charged leptons}\,(3\cdot 4),\ \text{and neutrinos}\,(3\cdot 2)$$

Table Credit: Baumann

Standard Model Thermal History



- As the temperature drops below particle masses, those particles fall out of equilibrium and $g_\star(T)$ decreases
- There is a large drop in $g_\star(T)$ at the QCD phase transition, when the degrees of freedom change from quarks and gluons to mesons and baryons

$$g_\star(T > \Lambda_{\mathrm{QCD}}) = \underbrace{2}_{\text{photons}} + \underbrace{2 \times 8}_{\text{gluons}} + \frac{7}{8}(\underbrace{3 \times 12}_{\text{u, d, s}} + \underbrace{4}_{\text{e}} + \underbrace{4}_{\mu} + \underbrace{3 \times 2}_{\nu}) = 61.75$$

$$g_\star(T < \Lambda_{\mathrm{QCD}}) = \underbrace{2}_{\text{photons}} + \underbrace{3}_{\pi} + \frac{7}{8}(\underbrace{4}_{\text{e}} + \underbrace{4}_{\mu} + \underbrace{3 \times 2}_{\nu}) = 17.25$$

Image Credit: Baumann

Natural Targets for N_{eff}

- This analysis shows that there is a minimum contribution to N_{eff} for any light thermal relic (assuming only Standard Model states)

$$\Delta N_{\rm eff} \geq \begin{cases} 0.027 & \text{Real Scalar} \\ 0.047 & \text{Weyl Fermion} \\ 0.054 & \text{Vector} \end{cases}$$

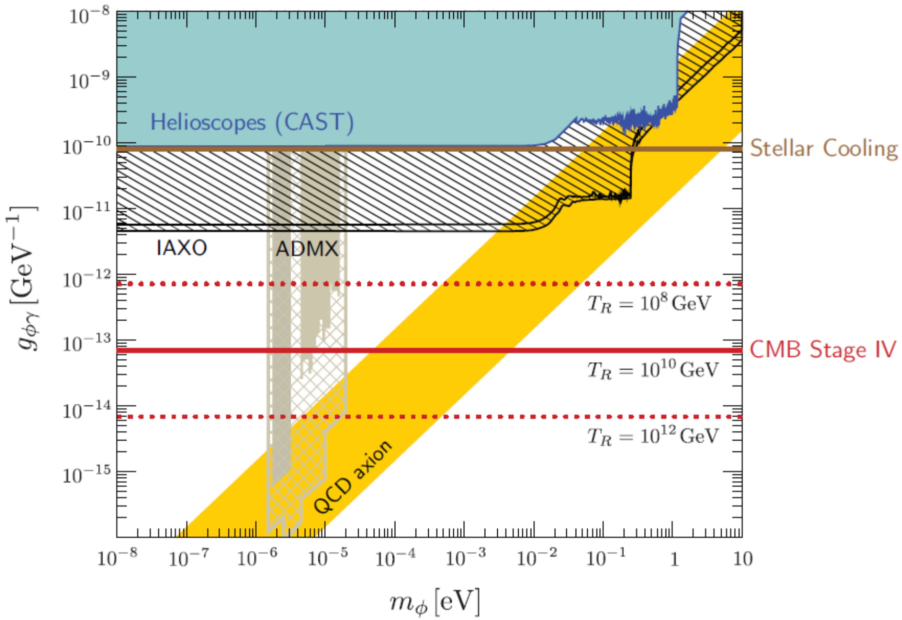
- These lower bounds apply if the relic was in thermal equilibrium at *any time* after inflation

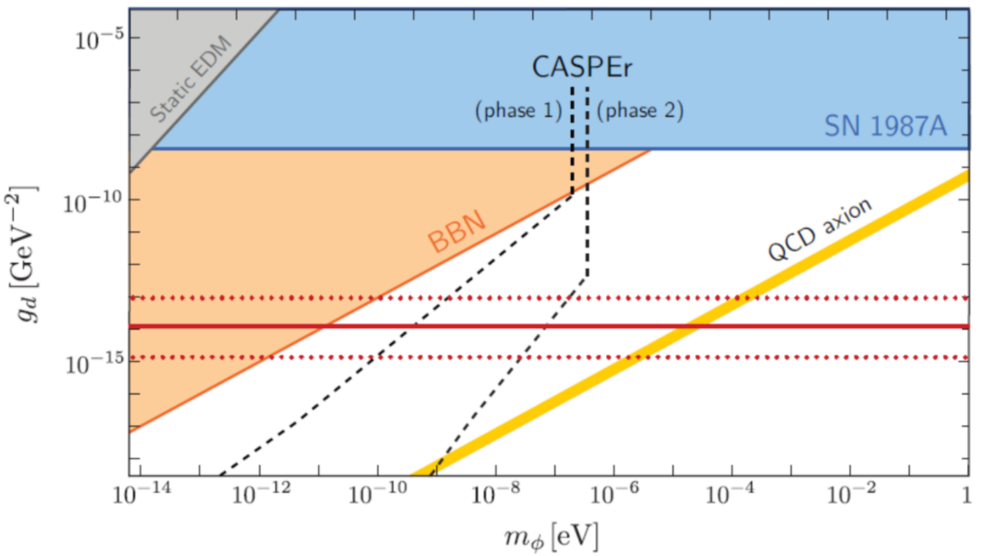
Cosmology: Low Energy Probe of High Energy Physics

• CMB temperature today:	2.725 K (= 2*10^{-4} eV)
• Photon decoupling:	3000 K (=0.25 eV)
• Neutrino decoupling:	10^{10} K (=1 MeV)
• QCD phase transition:	10^{12} K (=150 MeV)
• EW phase transition:	10^{15} K (= 100 GeV)
• Reheating:	As large as 10^{15} GeV

- Constraints on N_{eff} probe physics all the way up to the reheating scale

Application: Axion Constraints

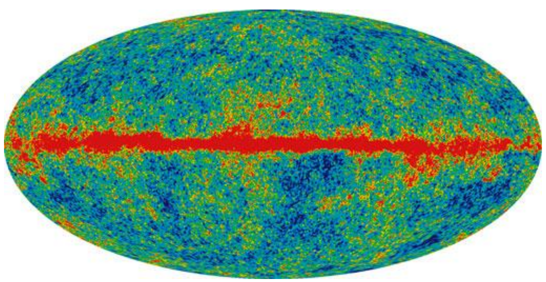


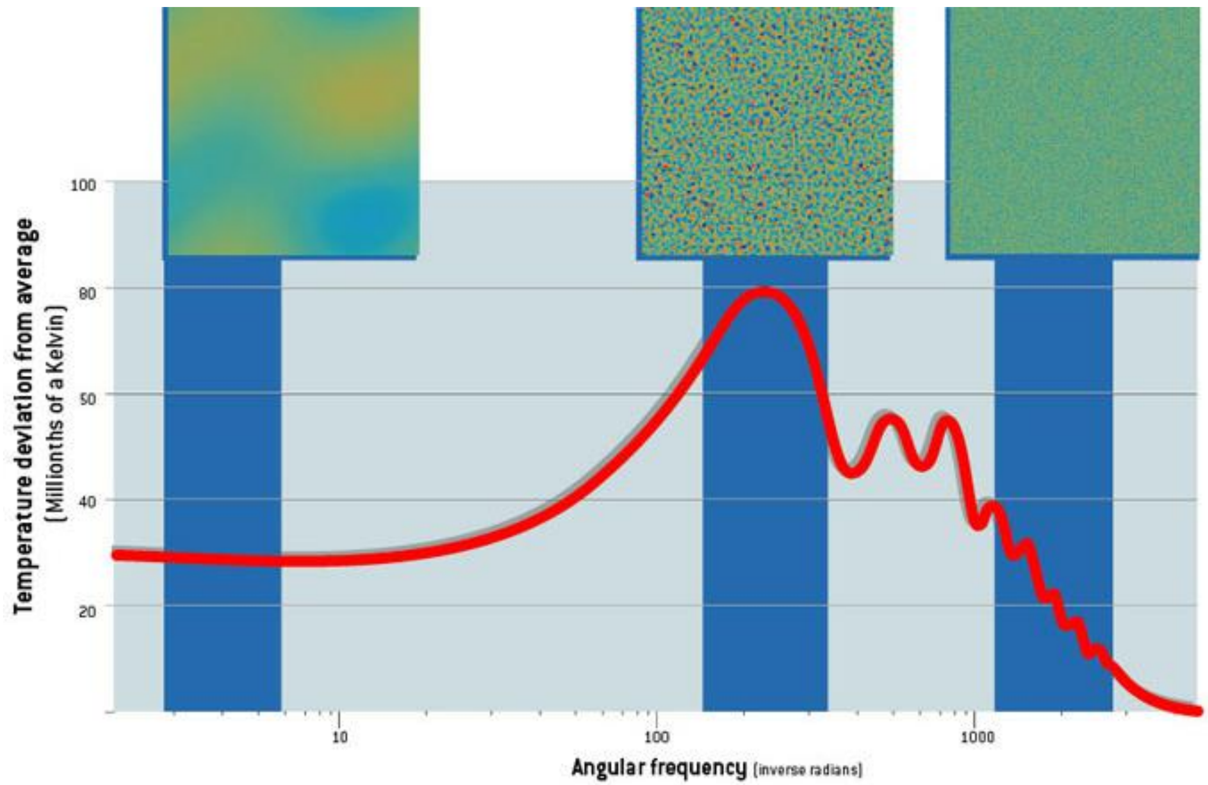


- An observation of N_{eff} ruling out scalar thermal relics would put extremely strong essentially mass independent constraints on axion-like particles
- These constraints do not require that the axions are the dark matter (in contrast to e.g. ADMX)

Baumann, Green, Wallisch (2016)

CMB Angular Power Spectrum

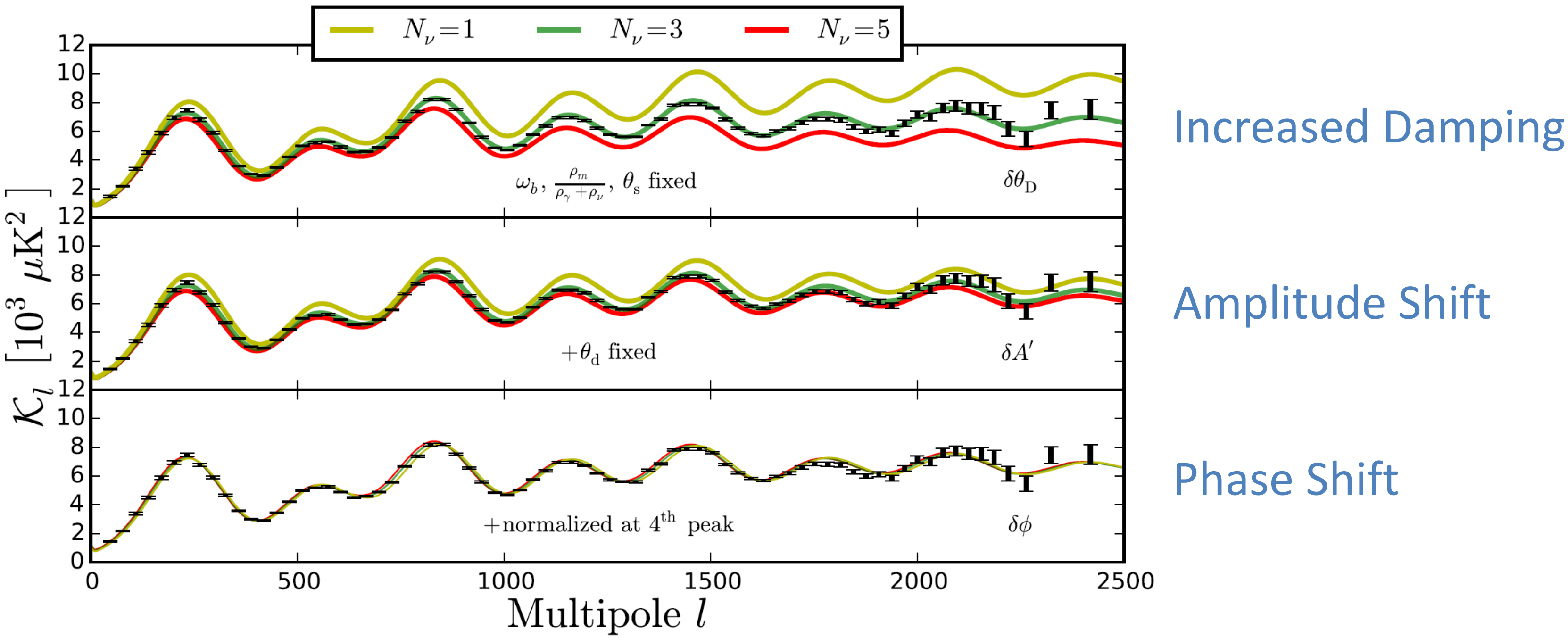




- The harmonic transform of the two-point correlation function of CMB fluctuations is known as the angular power spectrum
- Most of the statistical information of CMB maps is described by the angular power spectrum

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

Bashinsky, Seljak (2004); Hou, Keisler, Knox, Millea, Reichardt (2012);
Follin, Knox, Millea, Pan (2015); Baumann, Green, JM, Wallisch (2015);

Diffusion Damping of the CMB

- The free streaming of photons during recombination smooths out fluctuations on scales smaller than the damping scale

$$\Delta(k) \propto \exp\left(-(k/k_D)^2\right) \qquad k_D^{-2} \propto (n_e H)^{-1}$$

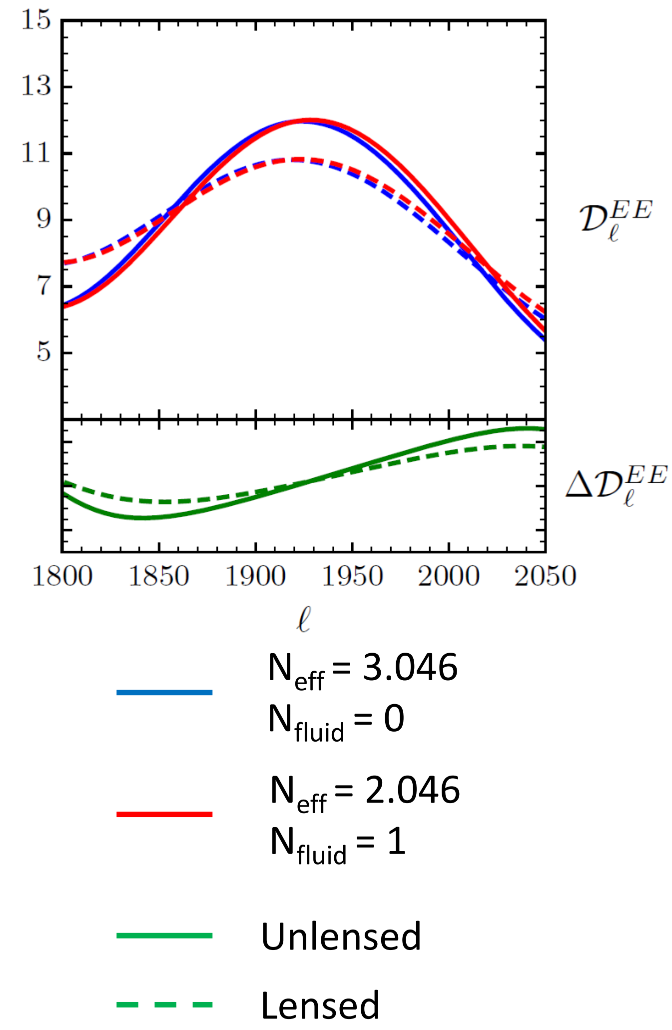
- $N_{\rm eff}$ affects the expansion rate during radiation domination, and thus the damping scale

$$3M_{\rm pl}^2 H^2 \simeq \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

- The change to the damping scale is the most prominent effect of $N_{\rm eff}$ on the CMB, but it is degenerate with changes to the free electron fraction (due to e.g. changes to the primordial helium abundance)

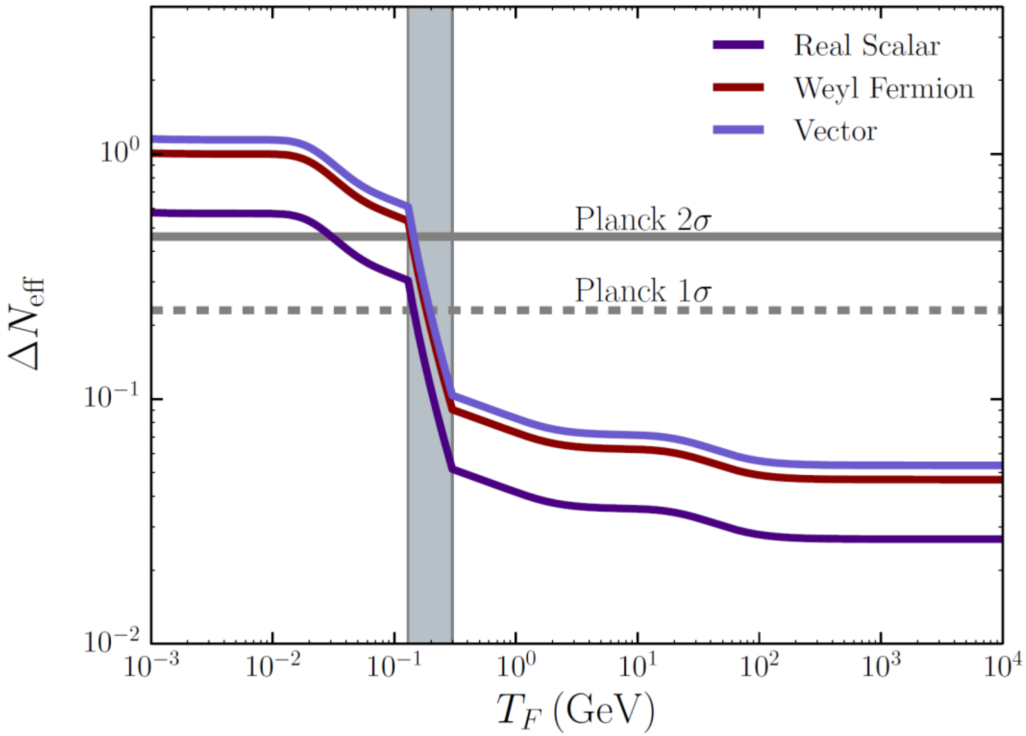
The Special Role of the Phase Shift

- Fluctuations in free-streaming radiation travel faster than the sound speed of the photon-baryon plasma
- These fluctuations lead to a characteristic phase shift (and amplitude shift) of the acoustic peaks of the CMB (and LSS) power spectrum at small angular scales
- The 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)

Current Constraints on Thermal Relics



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

Reminder:

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

$$\Delta N_{\rm eff} \geq \begin{cases} 0.027 & \text{Real Scalar} \\ 0.047 & \text{Weyl Fermion} \\ 0.054 & \text{Vector} \end{cases}$$

- Current constraints on N_{eff} agree with the Standard Model prediction and disfavor light relics which decoupled after the QCD phase transition

Planck (2015); CMB-S4 Science Book (2016)

Next Generation CMB Experiments

SIMONSOBSERVATORY

- Observing 2021-2022
- Telescope array in Atacama Desert in Chile
- Funded, construction starting soon

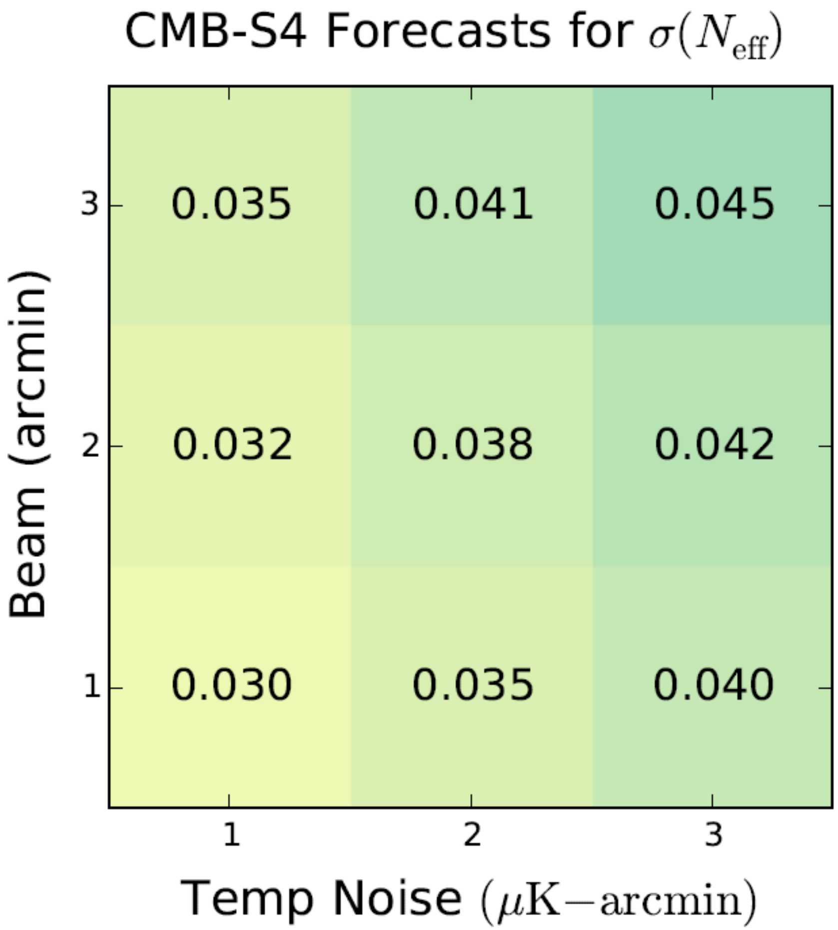
CMB-S4
Next Generation CMB Experiment

- Observing mid- to late-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, …
- **Astrophysics:** Mass Maps, Cluster Science, Cross-Correlations, …

CMB-S4 N_{eff} Forecasts



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

CMB-S4 Specs:

$$\ell \geq 30$$

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

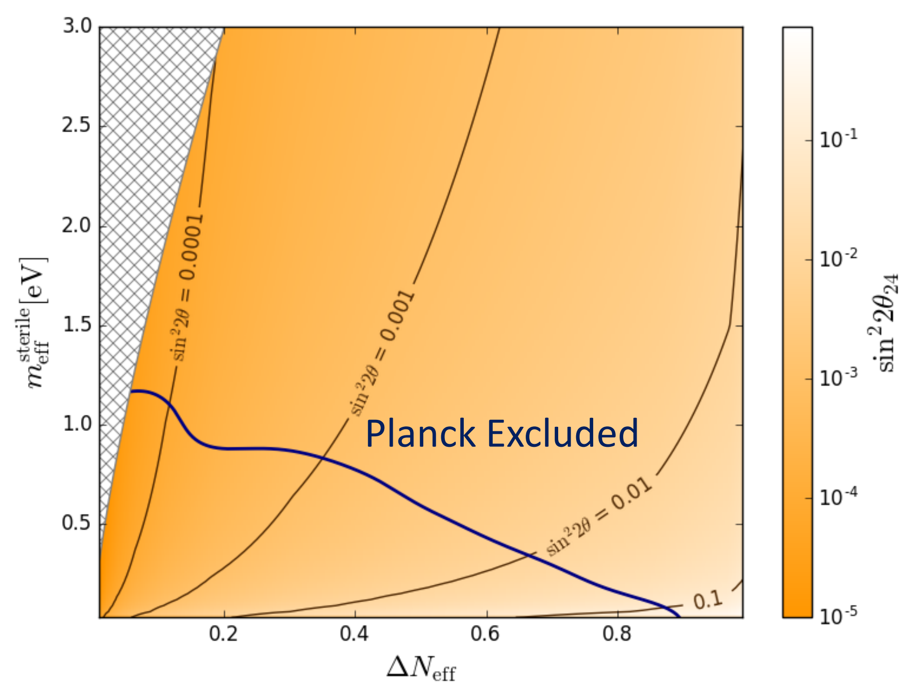
+

BBN Consistency

CMB-S4 Science Book (2016)

Non-Thermal Light Relics

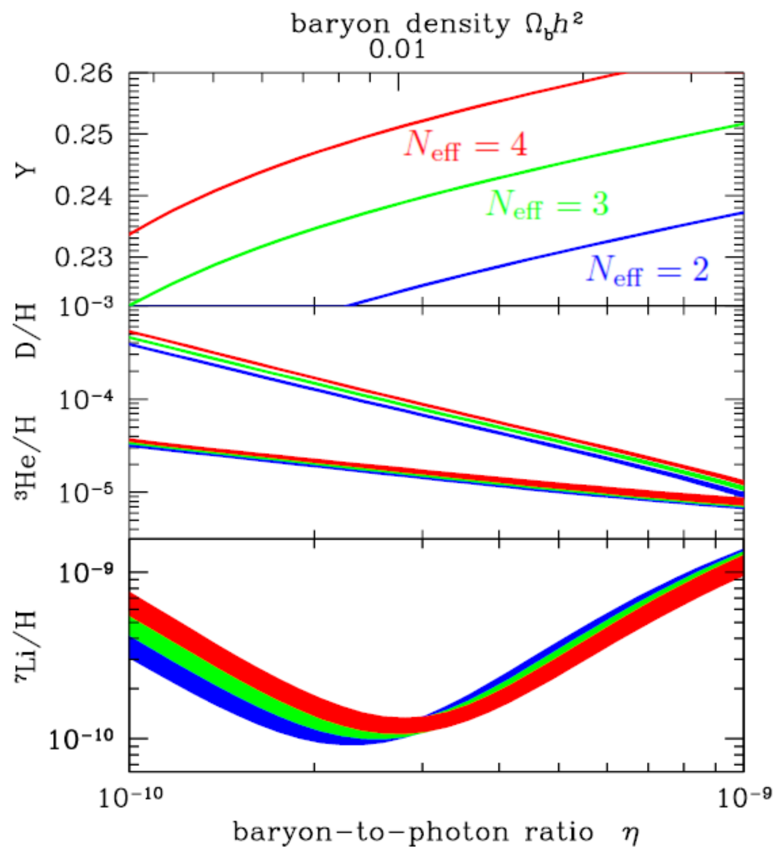
- Light states need not have been in thermal equilibrium with the Standard Model to contribute to the radiation energy density
- Measurements of N_{eff} give constraints on all forms of decoupled radiation, including:
  - Sterile neutrinos
  - Gravitational waves
  - Dark photons
  - Many others



Sterile Neutrino Constraints from the CMB

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

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

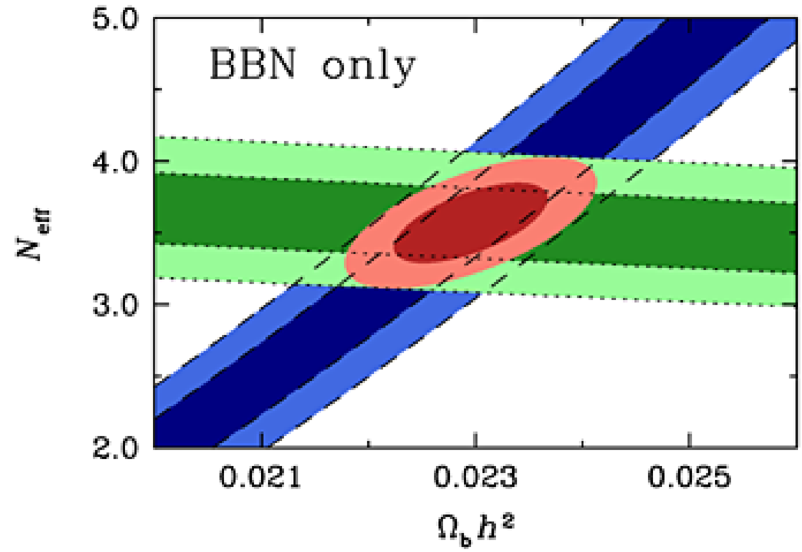
PDG (2013); Cooke, et al. (2014); Cyburt, et al. (2015); Bond, Fuller, Grohs, JM, Wilson (In prep.)

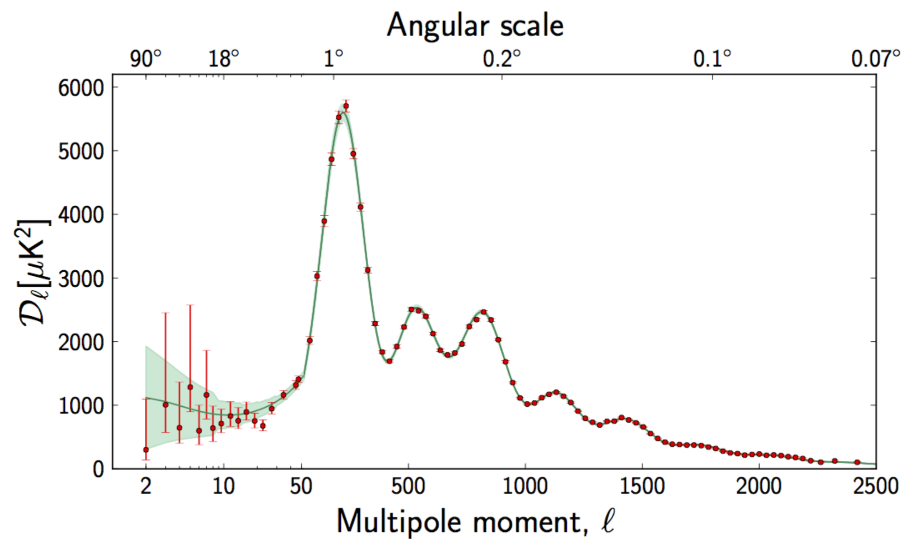
N_{eff} Impact on BBN

- Big Bang Nucleosynthesis is the process by which light elements were formed in the early universe
- After weak decoupling, protons and neutrons only interconverted by free neutron decay which occurred until neutrons became bound into stable nuclei (mostly helium-4) when the temperature was low enough for deuterium to form
- Increasing N_{eff} increases the expansion rate, thereby decreasing the time for free neutron decay, increasing the neutron survival fraction, thus increasing the helium-4 abundance

$\uparrow N_{eff}$ $\uparrow H$ Time for free neutron decay $\downarrow$ $\uparrow n_n(T_D)$ $\uparrow Y_p$

Time-Dependent Density





Primordial Abundances

CMB Measurements

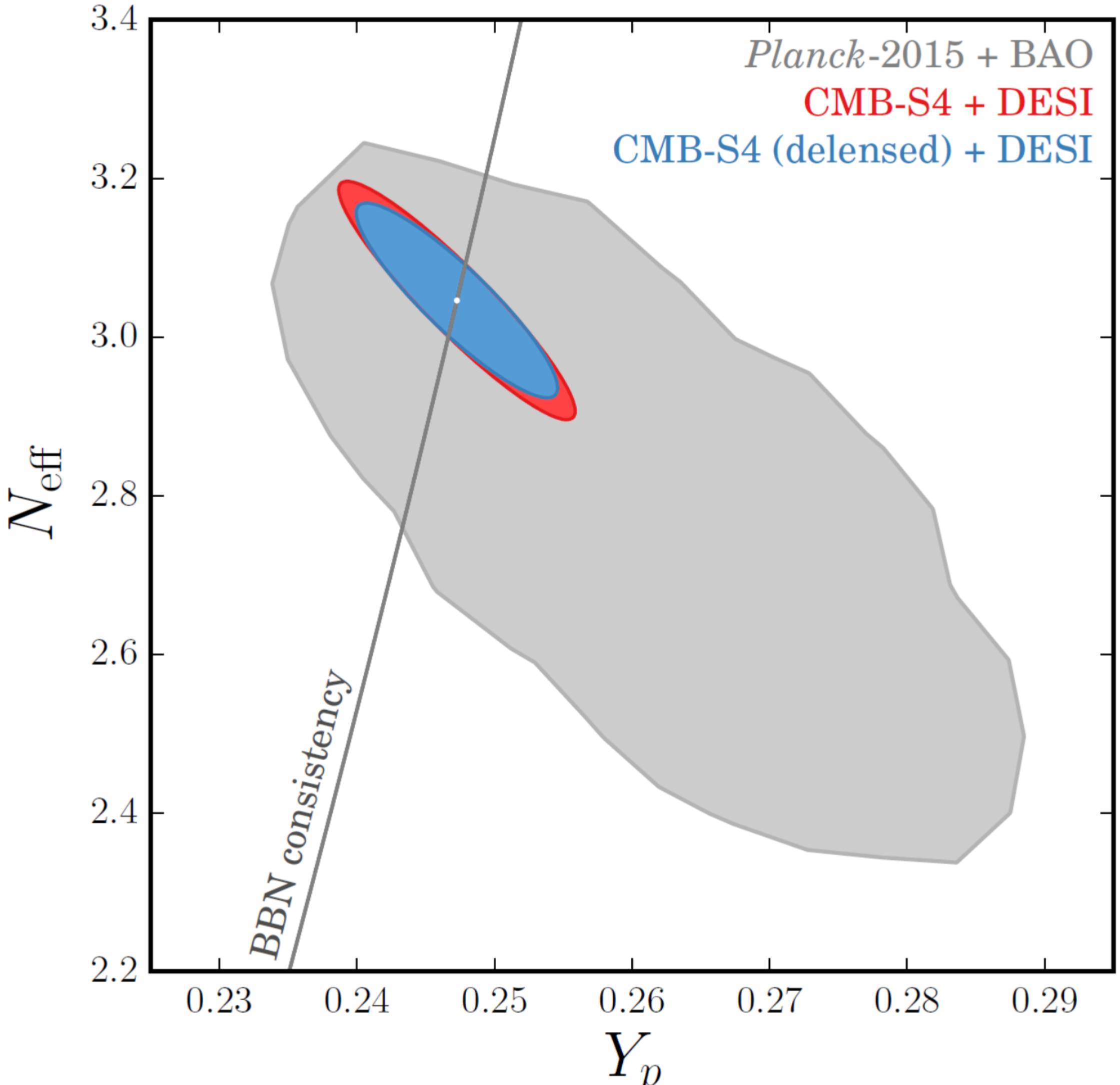
$$N_{\rm eff}^{\rm BBN} = 3.28 \pm 0.28$$

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

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

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

Testing BBN



- Upcoming CMB experiments will provide joint constraints on N_{eff} and 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)

Standard Model Light Relics – The CνB

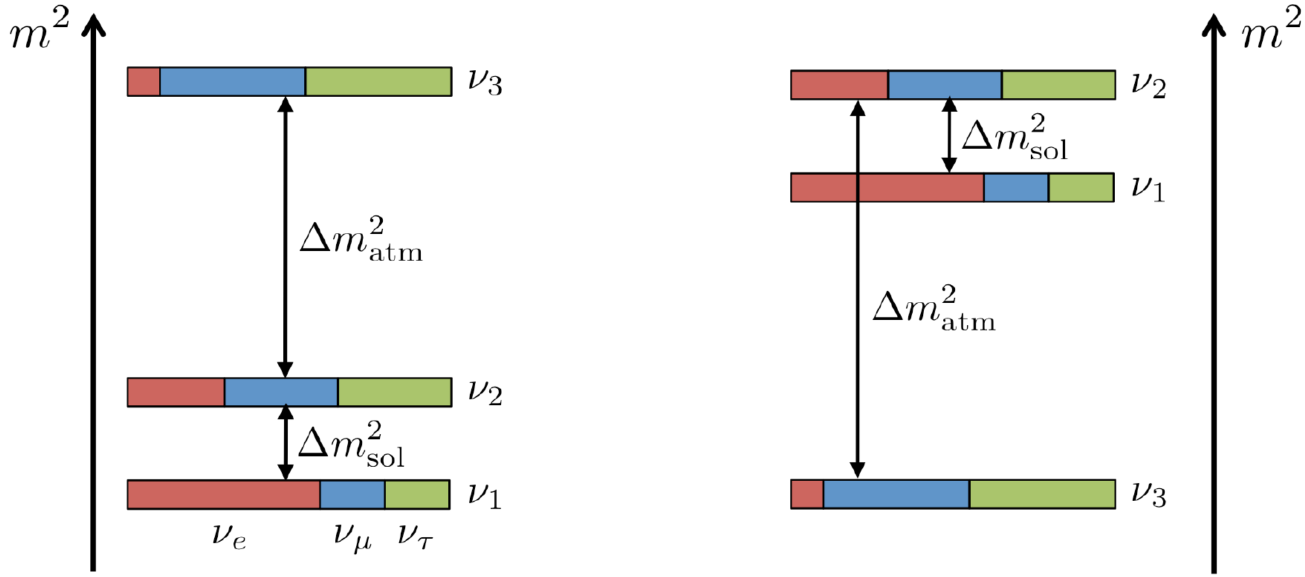
- Neutrinos were abundantly produced in the early universe and decoupled at a temperature of about 1 MeV
- Relic neutrinos remain very abundant today, with a mean density of 112 cm^{-3} per species

$$T_{\nu,0} = 1.945\,\mathrm{K} = 0.17\,\mathrm{meV} \qquad \Omega_\nu h^2 \simeq \frac{\sum m_\nu}{94\,\mathrm{eV}}$$

- The non-negligible energy density of the cosmic neutrino background provides cosmology a unique opportunity to study neutrinos in the low energy regime

Neutrino Mass

normal hierarchy (NH) **inverted hierarchy (IH)**



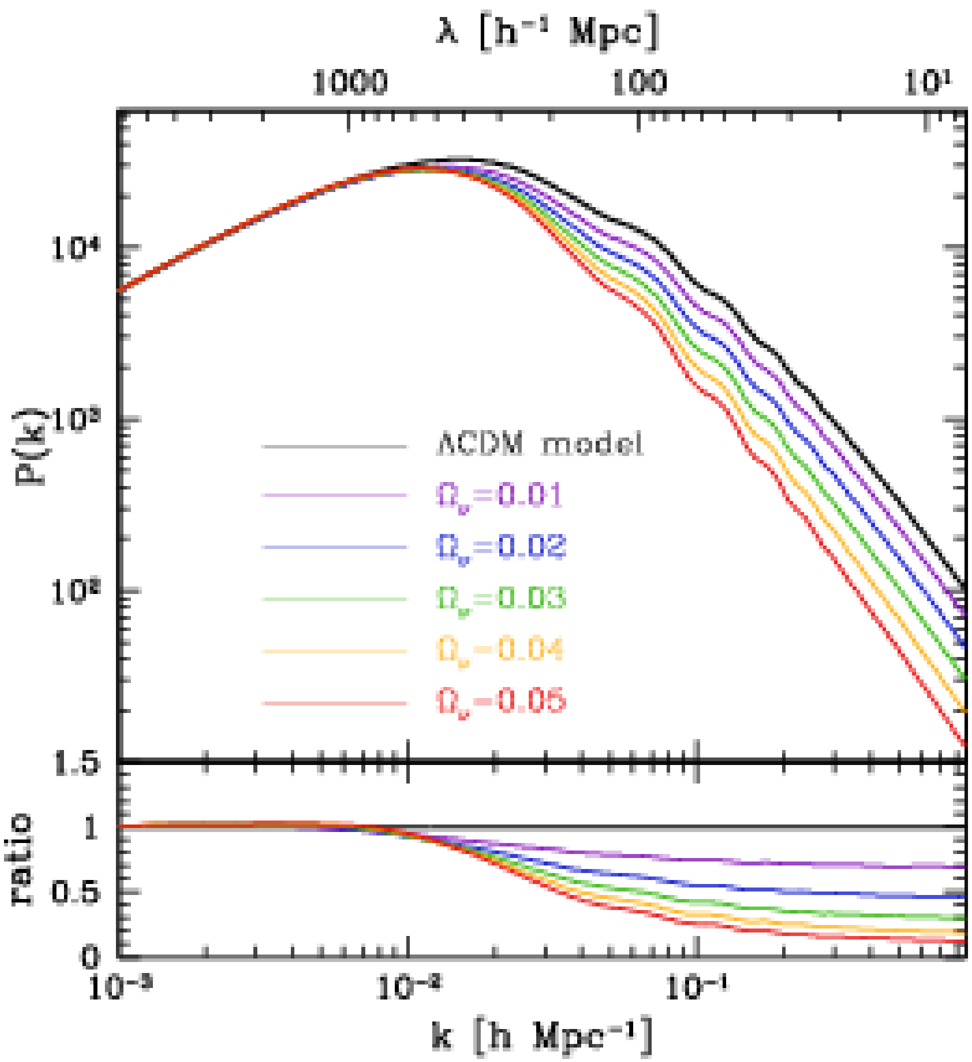
$\sum m_\nu \gtrsim 58\ \mathrm{meV}$ $\sum m_\nu \gtrsim 105\,\mathrm{meV}$

- 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)

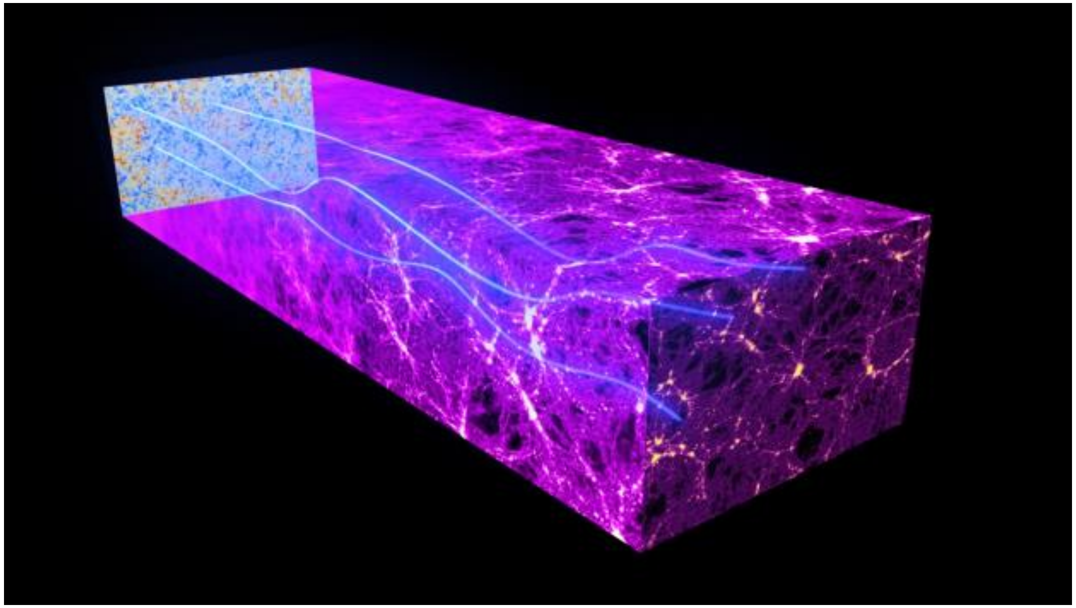
Effect of Neutrino Mass

- At least two species of 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)

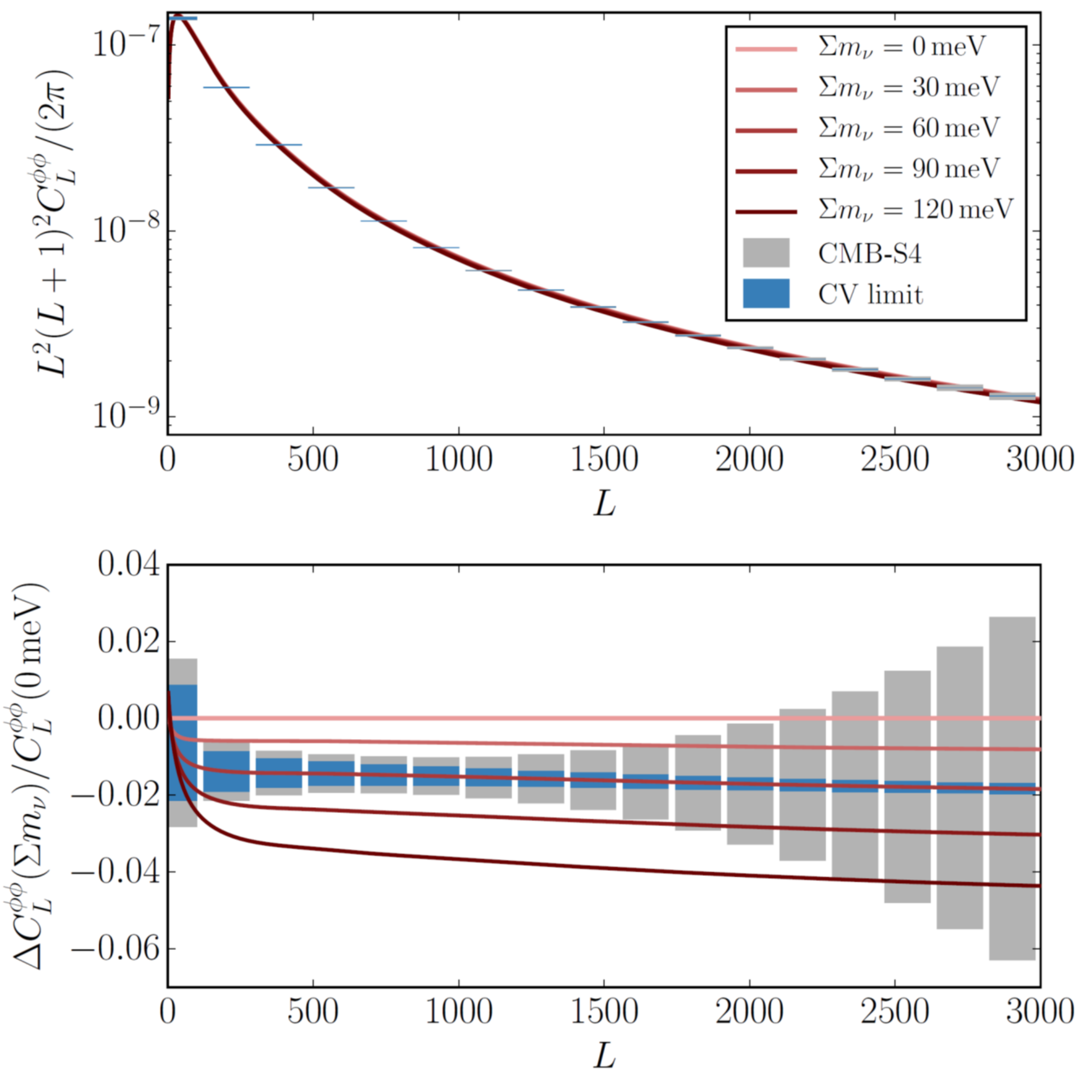
Gravitational Lensing



- 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

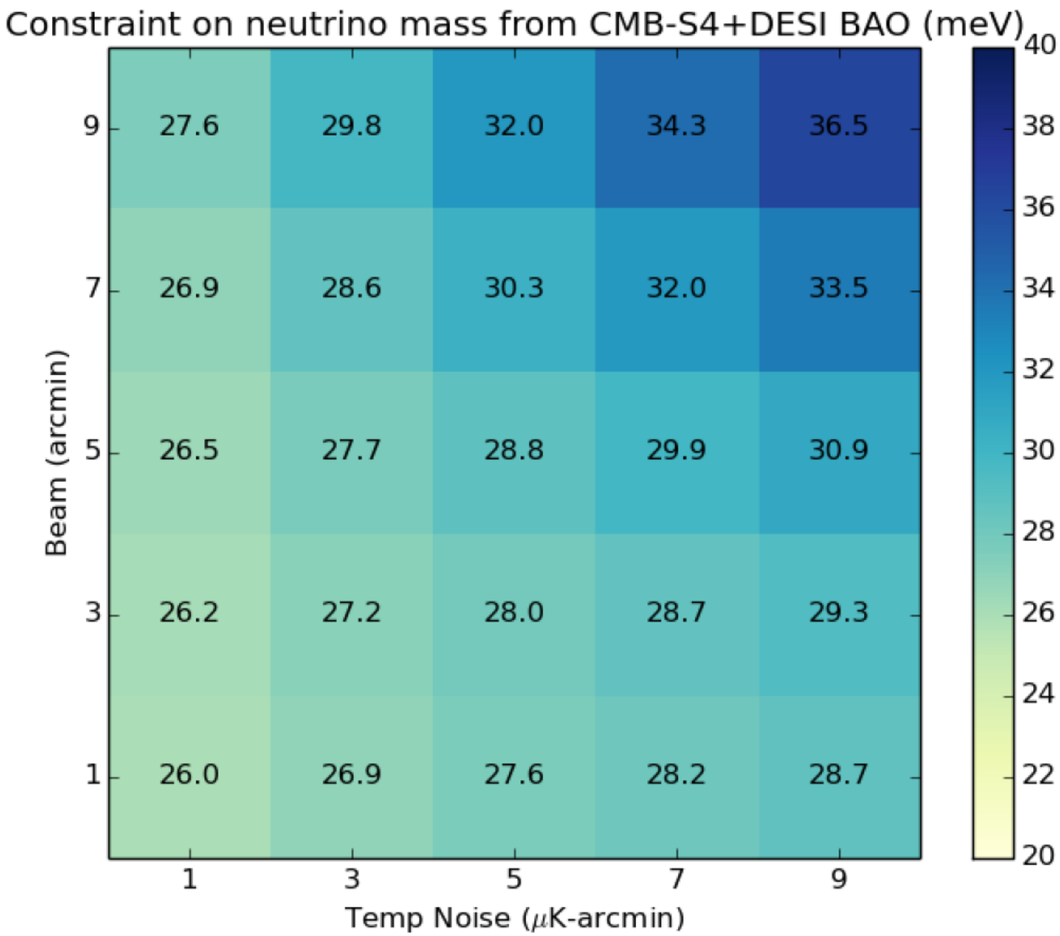
CMB-S4 Lensing Power Spectrum



- 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:

$$\ell \geq 30$$

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

+

$$\tau = 0.06 \pm 0.01$$

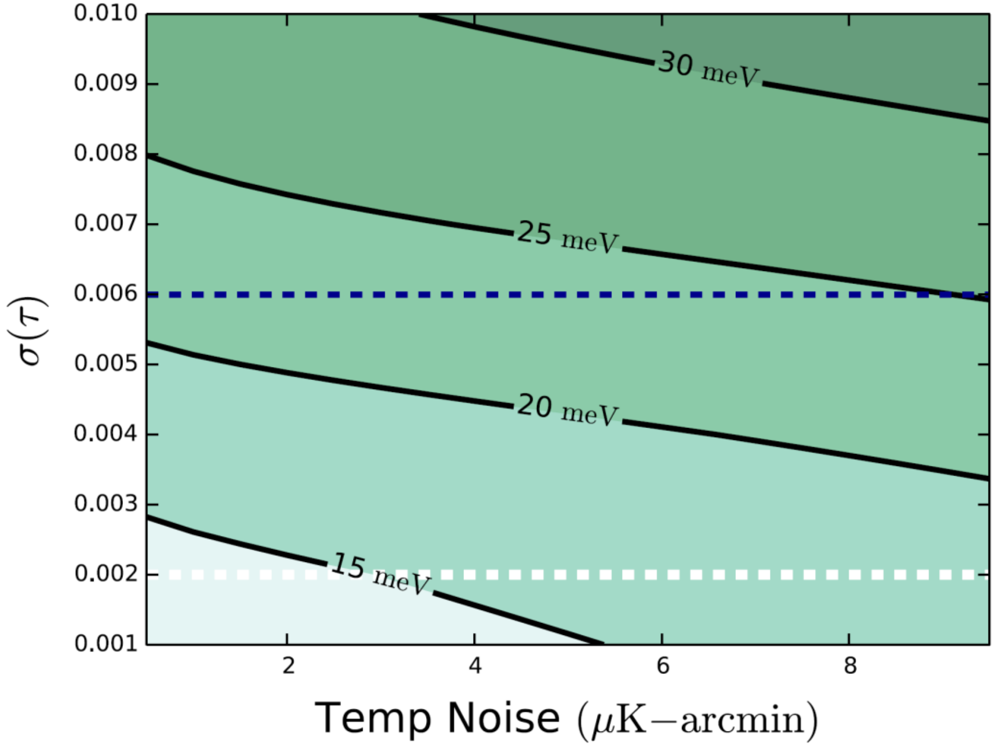
(Current Planck)

+

DESI BAO

CMB-S4 Science Book (2016)

Optical Depth and Neutrino Mass

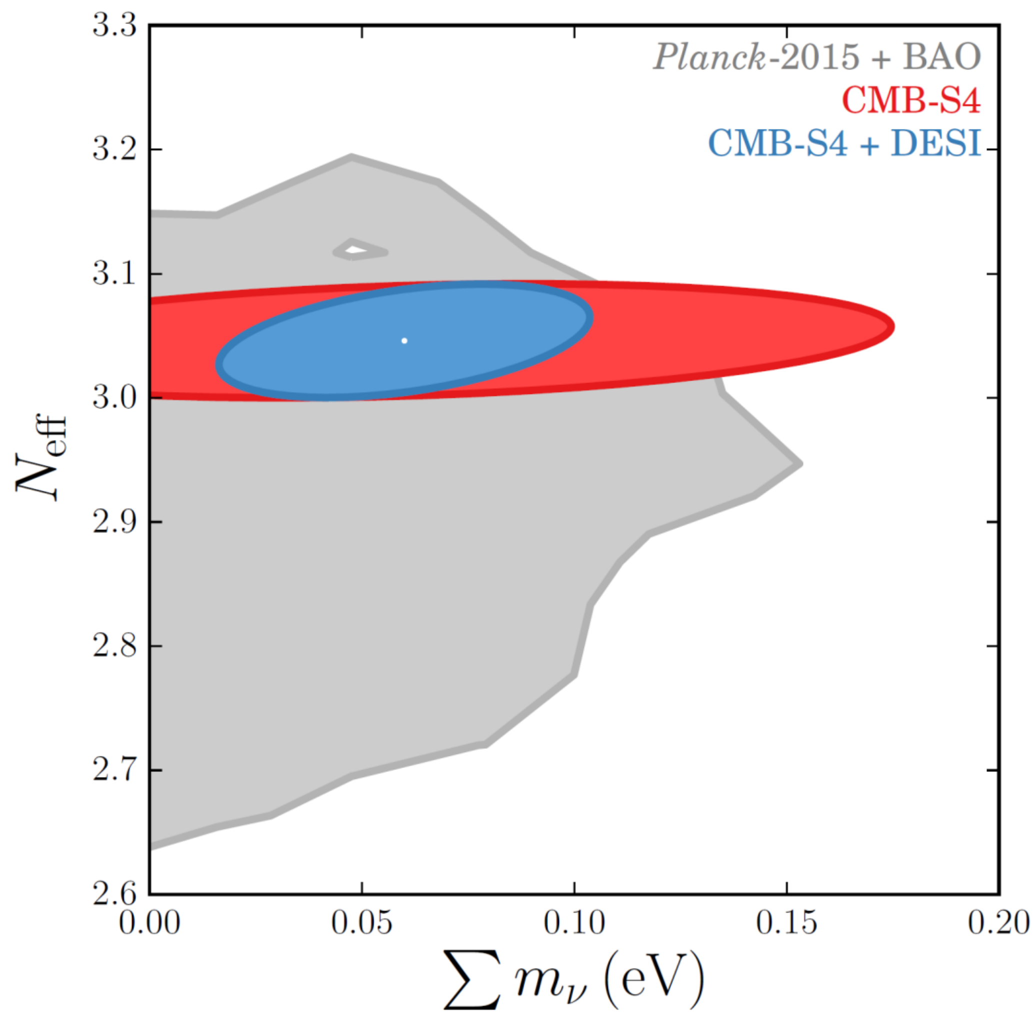


- Forecasted cosmological constraints on neutrino mass are limited by measurements of the optical depth
- Significant improvements could be achieved with satellite-based CMB observations to improve τ measurement

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 and may distinguish the mass hierarchy