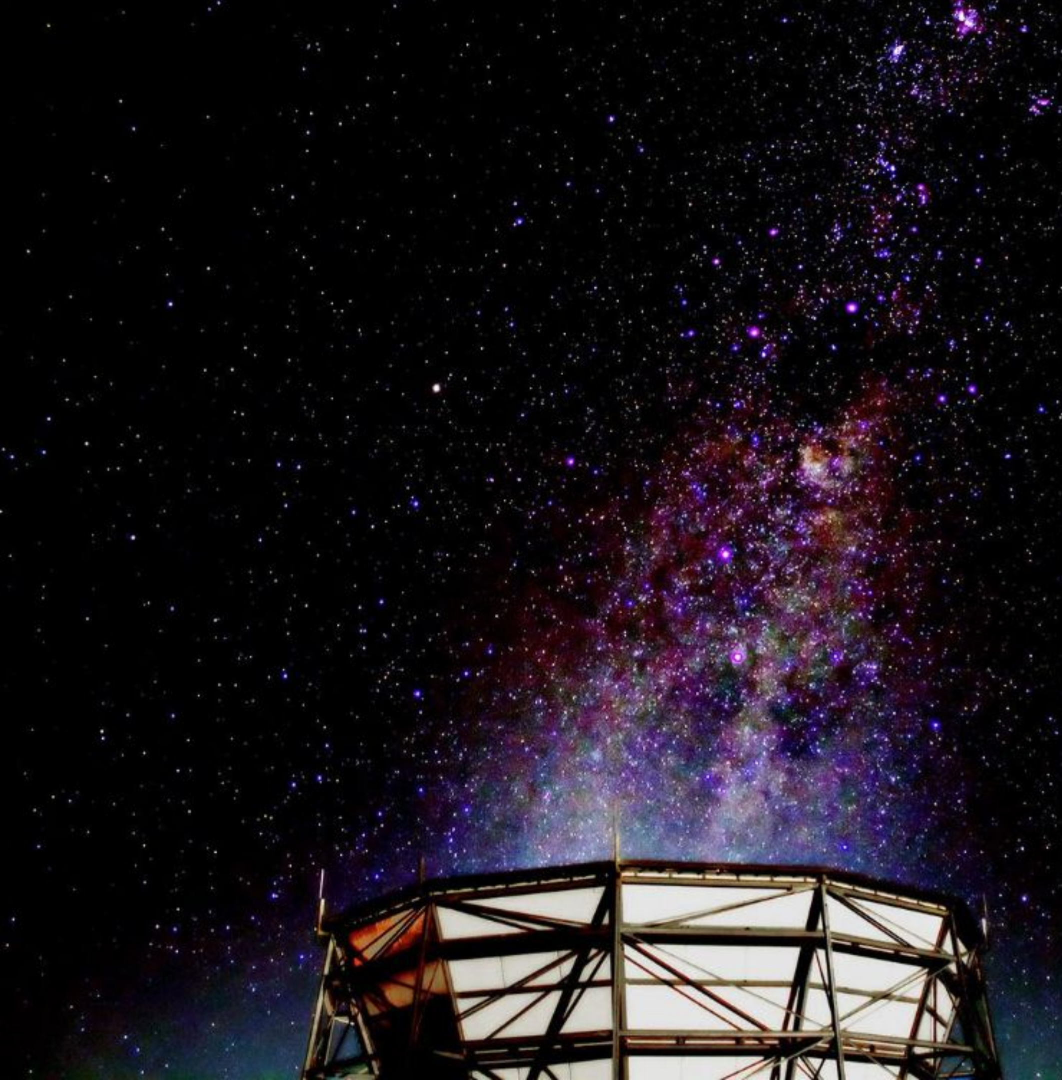


Cosmic Neutrinos and Other Light Relics with the CMB

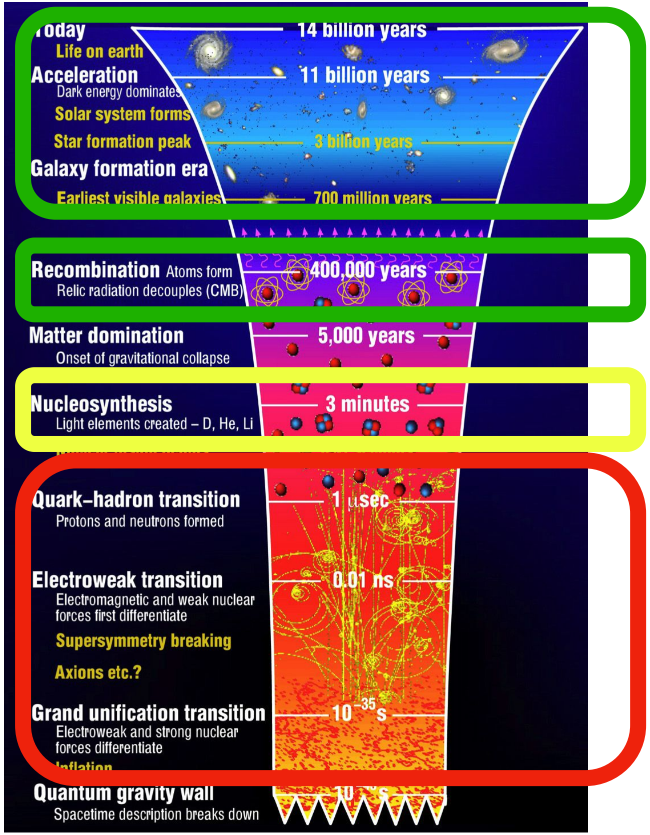
Joel Meyers

Michigan Cosmology Summer School 2023

6-5-2023

Image Credit: ACT / Princeton

History of the Universe



Direct Observations

Indirect Sensitivity

Discovery Space

Cosmology describes 13.8 billion years of cosmic history

Direct observations are limited to a relatively small range of redshifts and energy scales

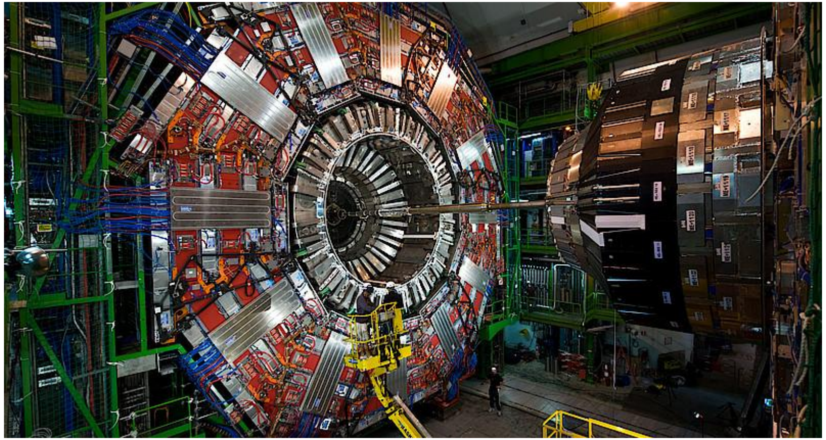
The CMB carries imprints from much earlier times and much higher energies:

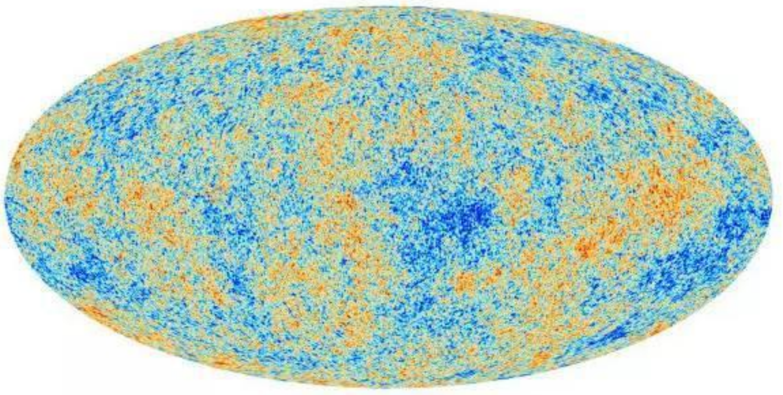
- **Lecture 1: Light Relics**
- Lecture 2: Inflation

Image Credit: Center for Theoretical Cosmology, Cambridge

Light Relics – What and Why?

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





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

Thermal History

Thermal Plasma

- The early universe was filled with a relativistic neutral plasma
- For each species with m << T, the distribution function is

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

- Species with m >> T are Boltzmann suppressed: n~exp(-m/T)
- The energy density of each relativistic species is

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

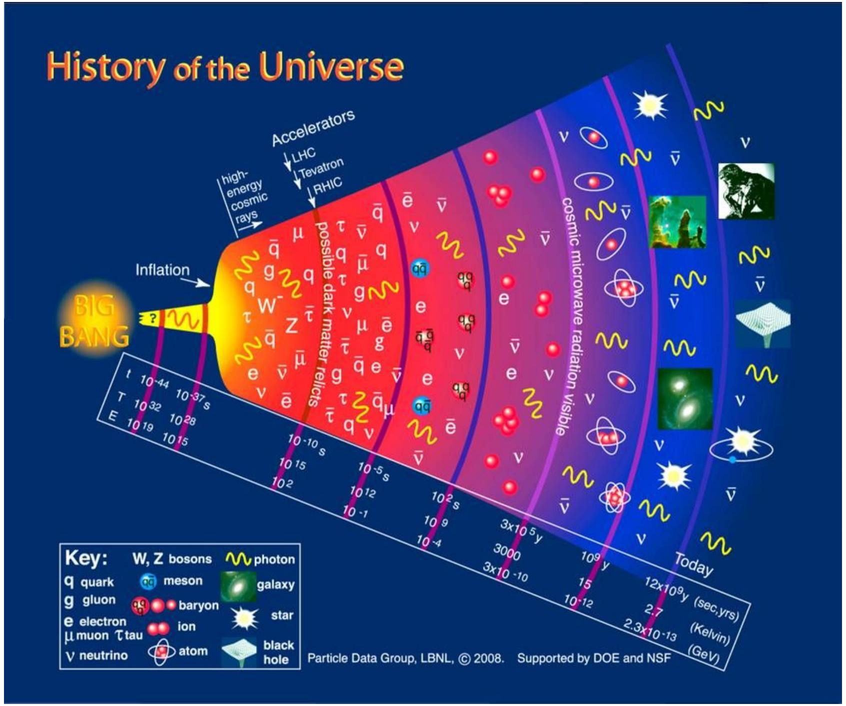


Image Credit: PDG

Evolution of Plasma Particle Content

- We can define the effective number of relativistic degrees of freedom in equilibrium

$$g_\star^{\rm th}(T) \equiv \sum_{i \in \rm bosons} g_i + \frac{7}{8} \sum_{j \in \rm fermions} g_j$$

- Decouplied species contribute with a different temperature

$$g_\star^{\rm dec}(T) \equiv \sum_{i \in \rm bosons} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{j \in \rm fermions} g_j \left(\frac{T_j}{T}\right)^4$$

- The total energy density then takes a simple form

$$g_\star(T) = g_\star^{\rm th}(T) + g_\star^{\rm dec}(T) \qquad \rho(T) = g_\star(T)\frac{\pi^2}{30}T^4$$

- We know the particle content of the Standard Model, so we know how $g_\star(T)$ evolves

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

Table Credit: Baumann

Entropy Conservation

- Entropy is conserved, even as the particle content of the plasma changes

$$\frac{\mathrm{d}}{\mathrm{d}t}(a^3 s(T)) = 0 \qquad s(T) = \frac{\rho(T) + P(T)}{T} = \frac{4\rho(T)}{3T}$$

- We can define an effective number of relativistic species for entropy

$$s(T) = g_{\star S}(T)\frac{2\pi^2}{45}T^3 \qquad g_{\star S}(T) = g_{\star S}^{\mathrm{th}}(T) + g_{\star S}^{\mathrm{dec}}(T)$$

$$g_{\star S}^{\mathrm{th}}(T) = g_{\star}^{\mathrm{th}}(T) \qquad g_{\star S}^{\mathrm{dec}}(T) \equiv \sum_{i\in\mathrm{bosons}} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8}\sum_{j\in\mathrm{fermions}} g_j \left(\frac{T_j}{T}\right)^3$$

- Conservation of entropy allows us to calculate the temperature evolution

$$T \propto g_{\star S}(T)^{-1/3} a^{-1}$$

Standard Model Particle Content

- Particle species disappear from equilibrium when the plasma temperature drops below their mass
- The sharp dip in $g_\star(T)$ around 150 MeV results from the QCD phase transition where the relevant degrees of freedom change from quarks and gluons to baryons and hadrons

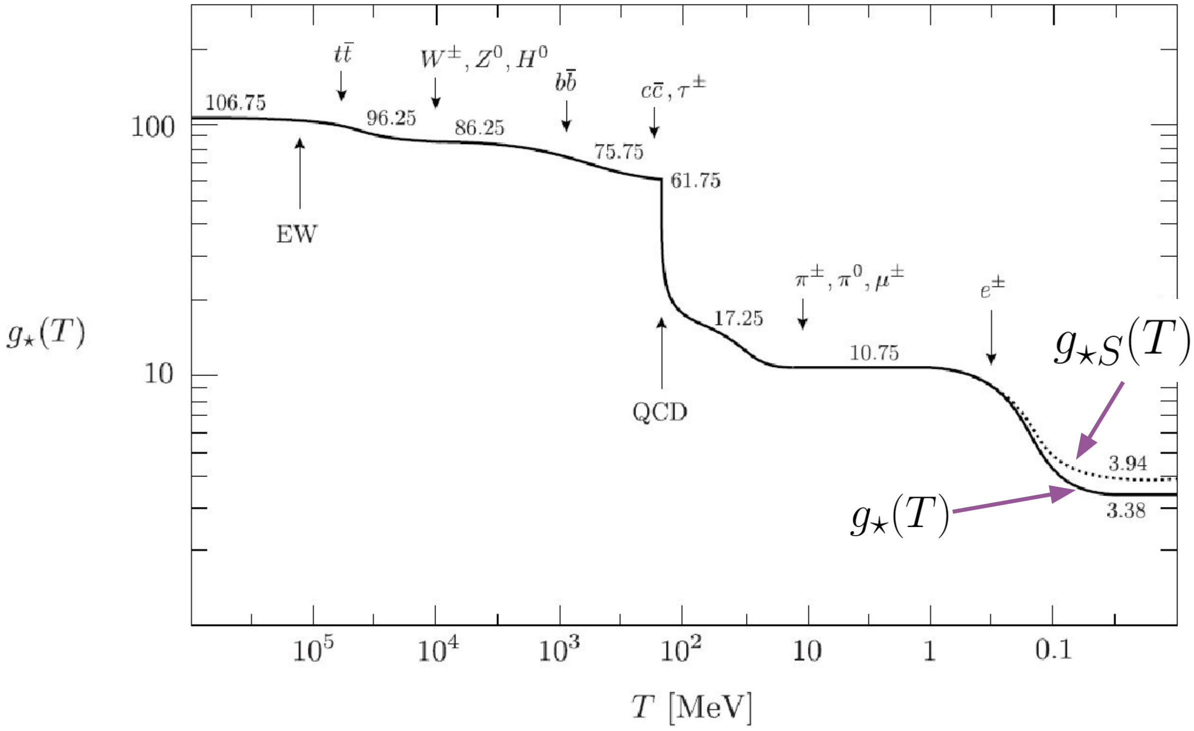


Image Credit: Baumann

Cosmic Neutrinos

Standard Model Light Relics - Cosmic Neutrinos

- Neutrinos were in thermal equilibrium with the plasma until the weak interaction rate became inefficient compared to the Hubble expansion rate around T~1 MeV
- After decoupling, the cosmic neutrino background persisted, undergoing free expansion
- Annihilation of electrons and positrons around T~0.5 MeV heated photons relative to neutrinos

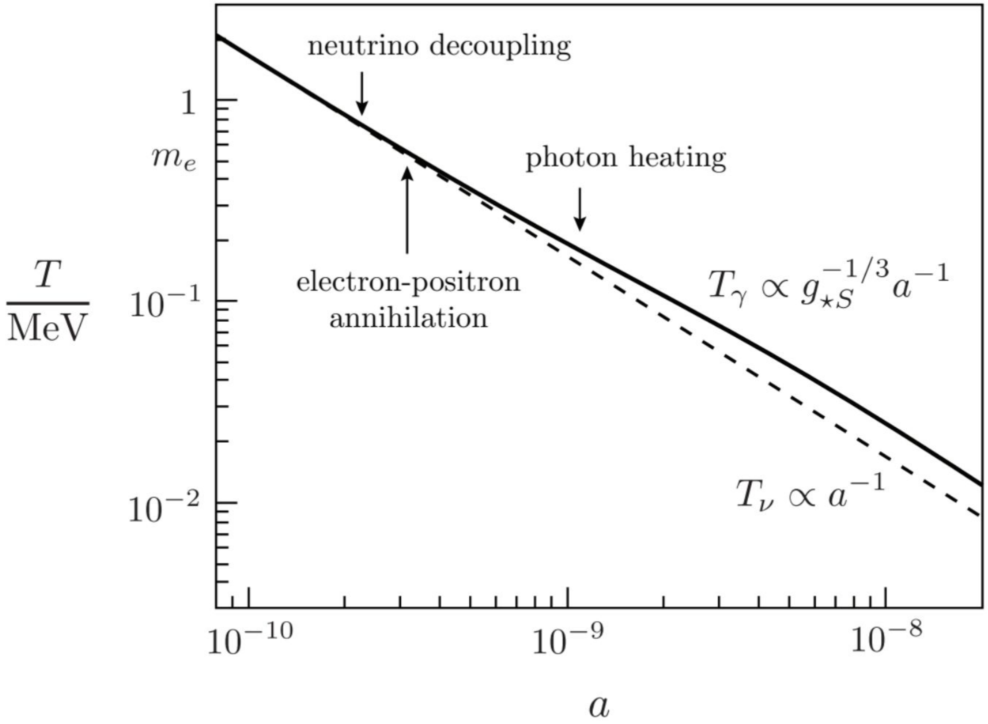


Image Credit: Baumann

Cosmic Neutrino Background Temperature

- We can calculate the temperature of cosmic neutrinos relative to photons
- After neutrino decoupling, prior to electron-positron annihilation, we have:

$$g_{\star S}^{\rm th}(T_+) = 2 + \frac{7}{8}(2+2) = \frac{11}{2}$$

γ e^+ e^-

- After electron-positron annihilation, we have only photons:

$$g_{\star S}^{\rm th}(T_-) = 2$$

- Entropy conservation gives the temperature ratio after annihilation:

$$T_\nu = \left(\frac{g_{\star S}^{\rm th}(T_-)}{g_{\star S}^{\rm th}(T_+)}\right)^{1/3} T_\gamma = \left(\frac{4}{11}\right)^{1/3}$$

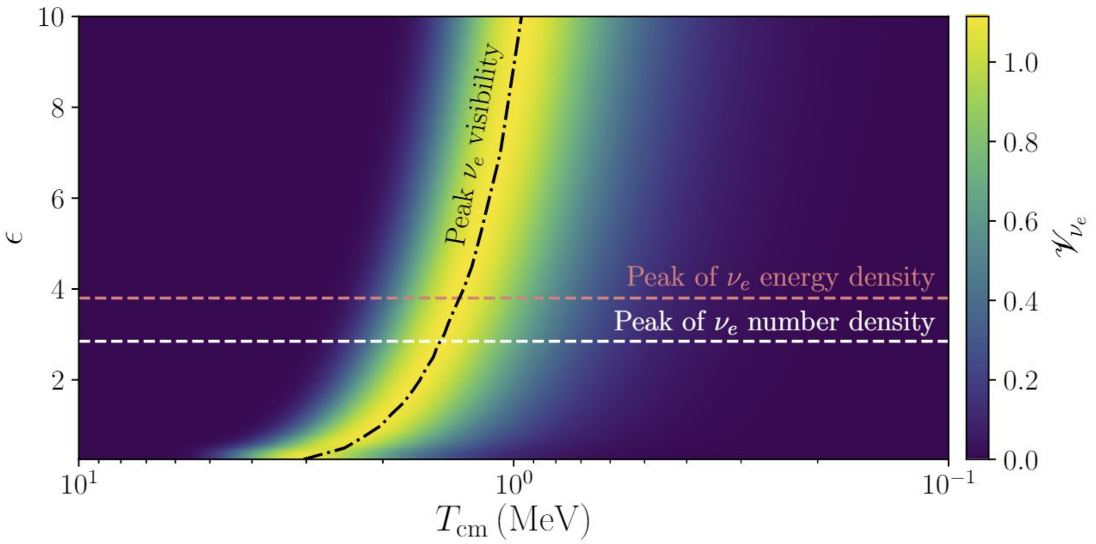
Effective Number of Neutrino Species

- We can measure the gravitational influence of cosmic neutrinos
- One way this shows up is through the total energy density of neutrinos

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

- For instantaneous decoupling, $N_{\rm eff}$ counts the number of neutrino species
- A complete treatment of neutrino transport gives a slightly larger number in the Standard Model

$$N_{\rm eff}^{\rm SM} = 3.044(1)$$

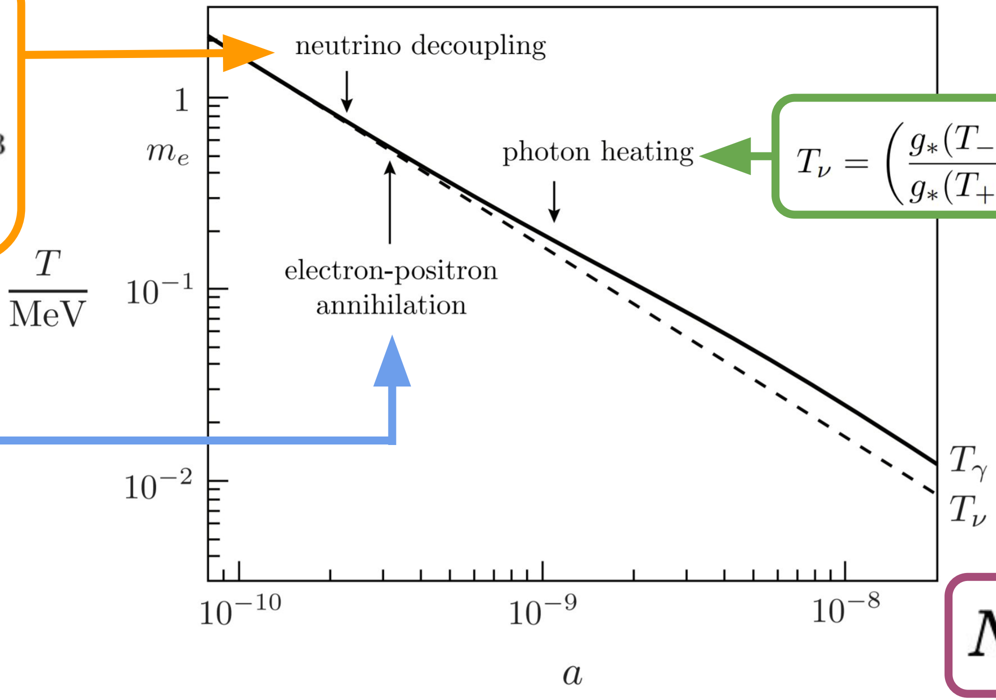


Escudero Abenza (2020); Akita, Yamaguchi (2020); Froustey, Pitrou, Volpe (2020); Bennett, et al (2021); Bond, Fuller, Grohs, JM, Wilson (In Prep.)

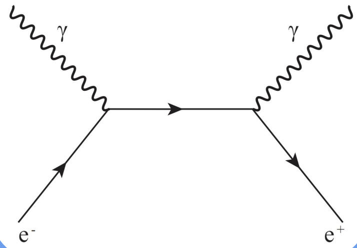
Summary of Cosmic Neutrino Decoupling

$$\sigma \sim \left| \times \right|^2 \sim G_F^2 T^2$$

$$\frac{\Gamma}{H} \sim \frac{\alpha^2 M_{\rm pl} T^3}{M_W^4} \sim \left(\frac{T}{1\,\mathrm{MeV}}\right)^3$$



$$T_\nu = \left(\frac{g_*(T_-)}{g_*(T_+)}\right)^{1/3} T_\gamma = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

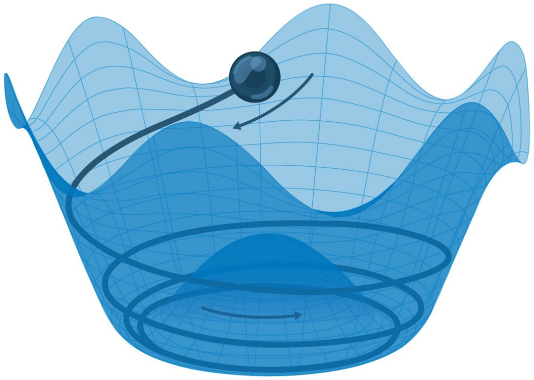


$$N_{\rm eff}^{\rm SM} = 3.044$$

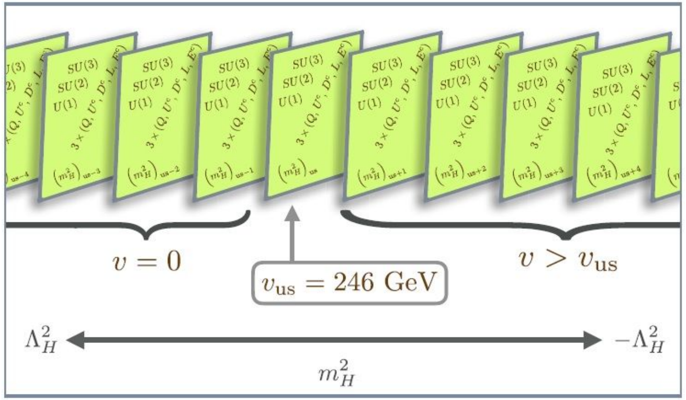
Baumann (2018); Akita, Yamaguchi (2020)

Light Relics Beyond the Standard Model

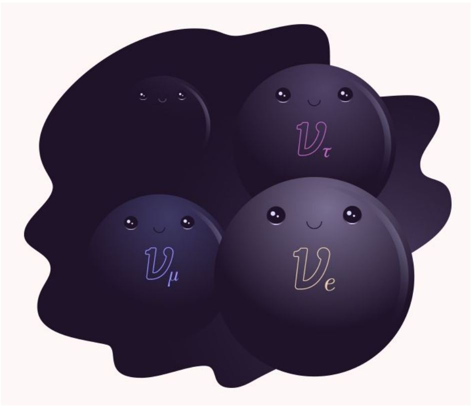
New Light Species are Ubiquitous in Standard Model Extensions



Axions and Axion-Like Particles



Complex Dark Sectors

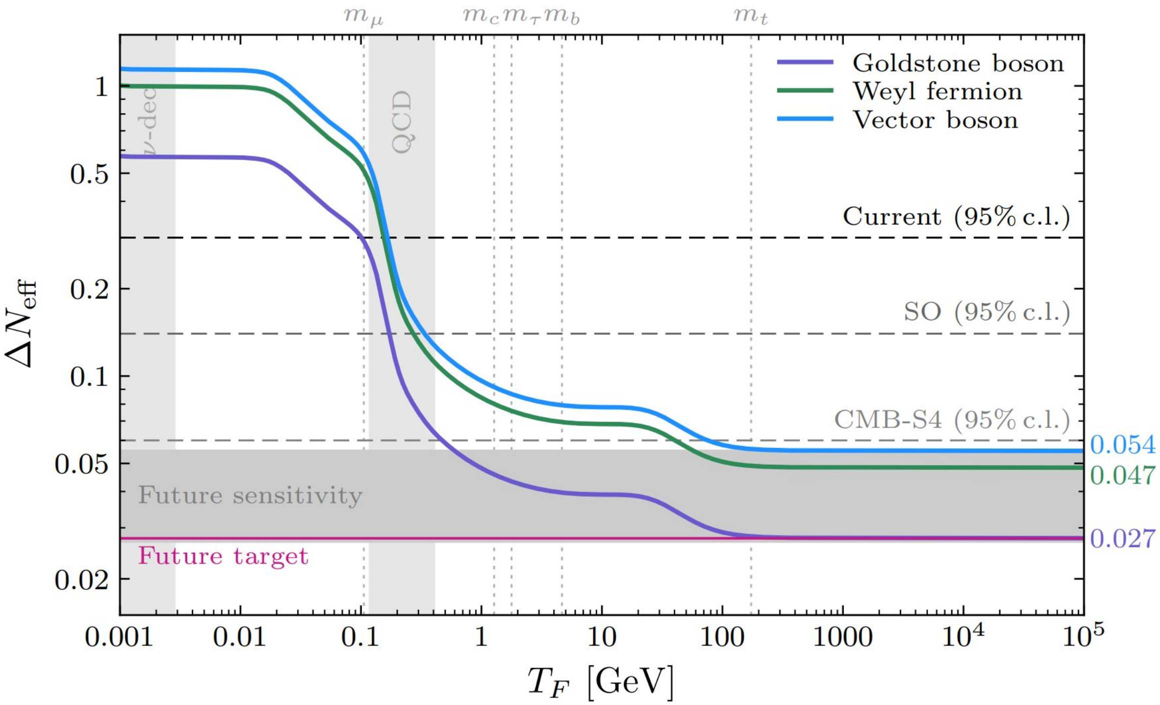


Sterile Neutrinos

… and many more

Green, Amin, JM, Wallisch, et al (2019); Dvorkin, JM, et al (2022)
Image Credits: Quanta Magazine; Arkani-Hamed, et al (2016); Symmetry Magazine

Light Thermal Relics Set Useful Targets



The relic density of any new light species that was ever in thermal equilibrium with the Standard Model plasma can be computed from its spin and decoupling temperature, setting clear targets for future surveys

$$\Delta N_{\rm eff} = \frac{4}{7} g_s \left(\frac{43/4}{g_\star(T_{\rm F})} \right)^{4/3}$$

Freeze-out occurs when production rate falls below Hubble rate

$$\Gamma \sim \frac{T^{2n+1}}{\Lambda^n} \qquad H \sim \frac{T^2}{M_{\rm pl}}$$

CMB-S4 (2016); Green, Amin, JM, Wallisch, et al (2019); Dvorkin, JM, et al (2022)

Measuring Light Relics

CMB Diffusion Damping

- Random walk of CMB photons prior to recombination smooths out fluctuations below the free streaming length of photons
- The damping scale of photons is affected by the scattering rate and expansion rate

$$r_d^2 \sim (\sigma_T n_e H)^{-1}$$

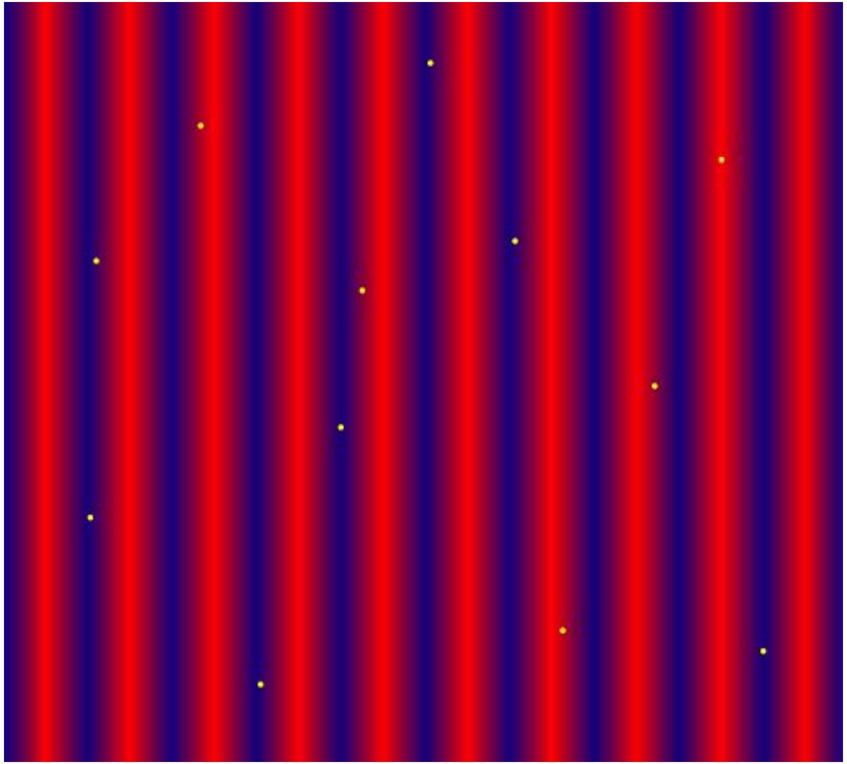
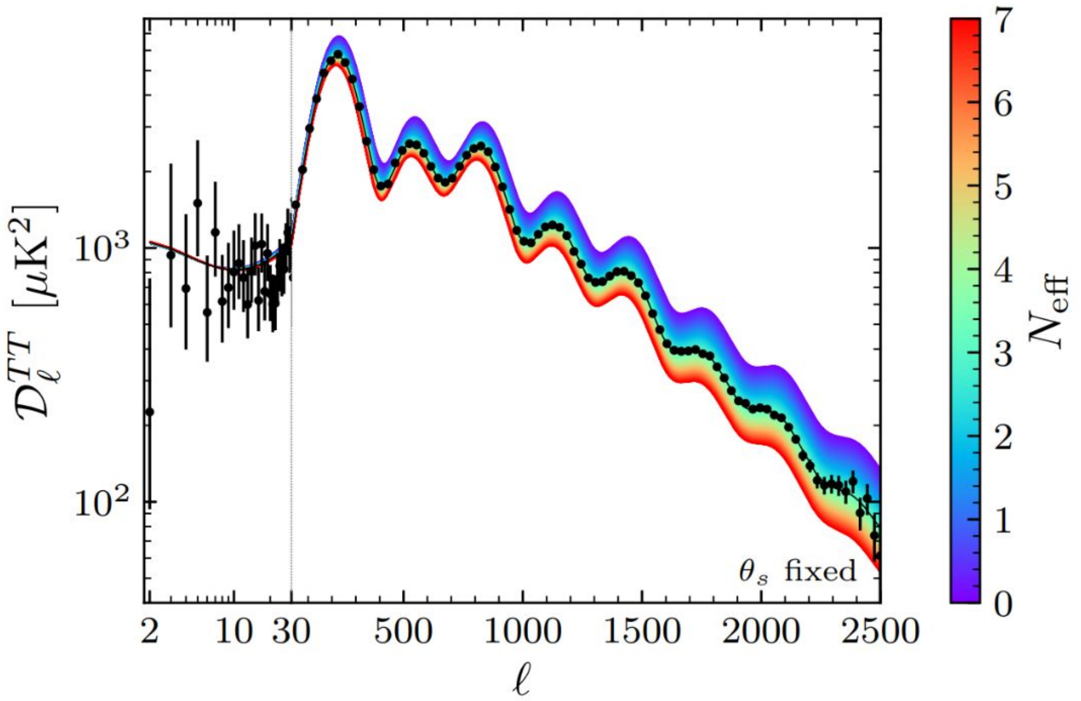


Image Credit: Hu

Light Relics Affect CMB Damping Scale

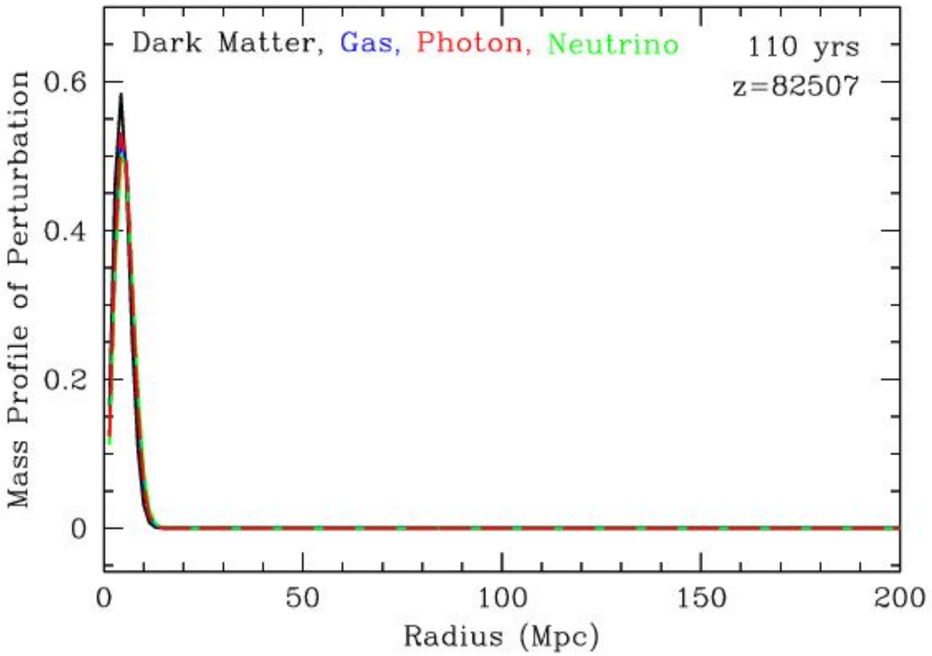


- Increasing N_{eff} increases the expansion rate prior to recombination
- With θ_s fixed (which is measured very well with current observations), increasing N_{eff} leads to increased damping
- The damping scale is also impacted by the free electron density around recombination, which is affected by the primordial helium abundance

Image Credit: Wallisch (2018)

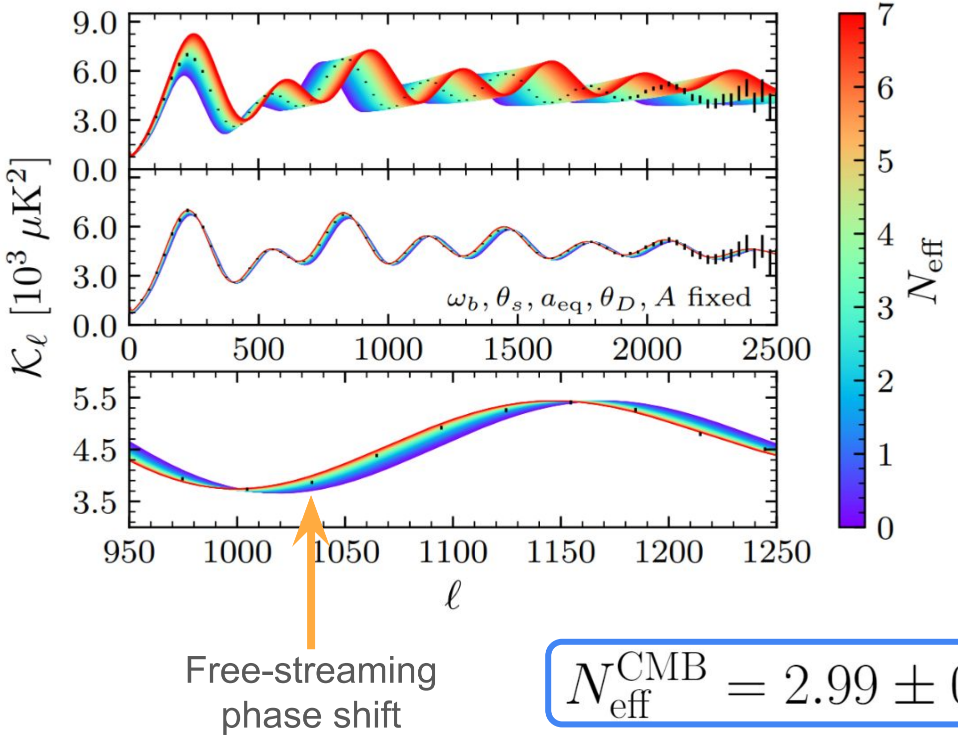
Light Relics Density Perturbations

- The density of light relics are perturbed in the same way as the other components (for adiabatic initial conditions)
- The fluctuations of free-streaming light relics propagate at the speed of light, faster than the sound speed of the photon baryon plasma ($c_s^2 \approx c^2/3$)
- The gravitational attraction of the light relics pulls the acoustic peak to a larger radius



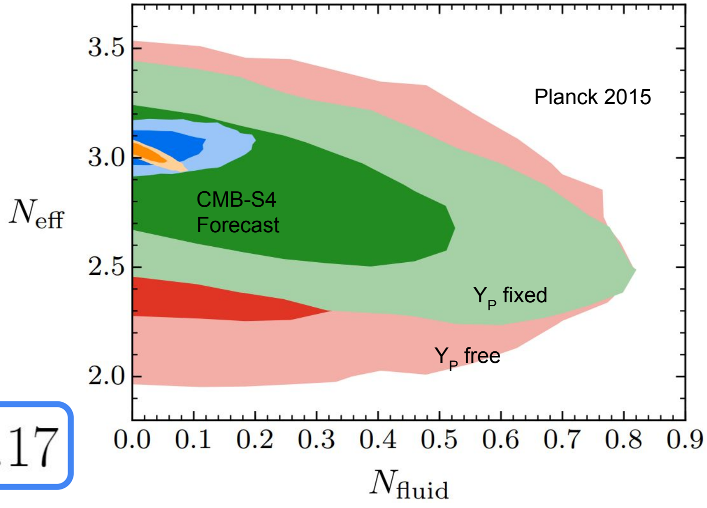
Bashinsky, Seljak (2004); Baumann, Green, JM, Wallisch (2016); Image Credit: Eisenstein

Free-Streaming Light Relics and the Phase Shift



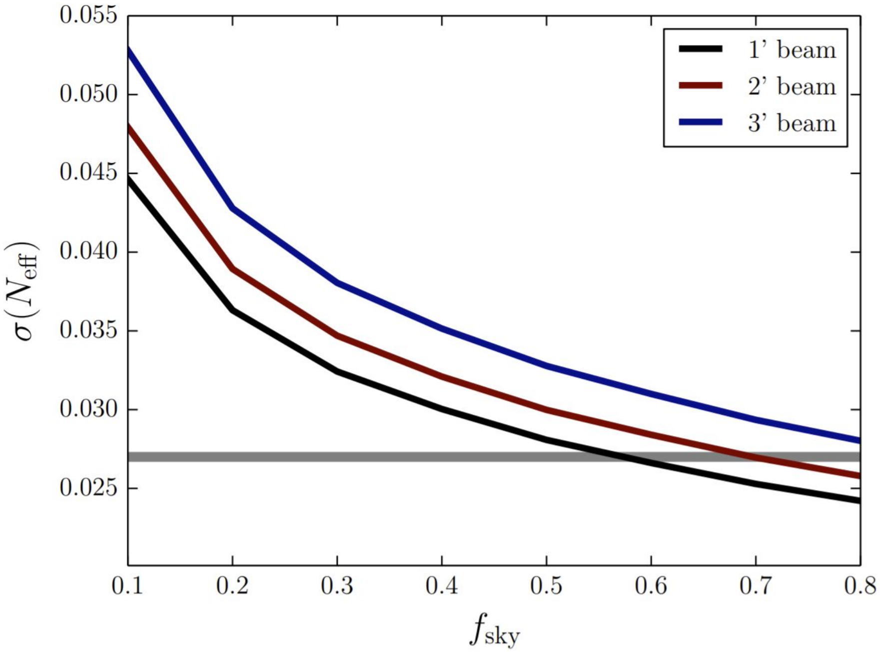
$$N_{\rm eff}^{\rm CMB} = 2.99 \pm 0.17$$

Fluctuations in the density of free-streaming light relics leads to a phase shift of the CMB acoustic peaks, allowing them to be distinguished from fluid-like radiation and changes to primordial helium



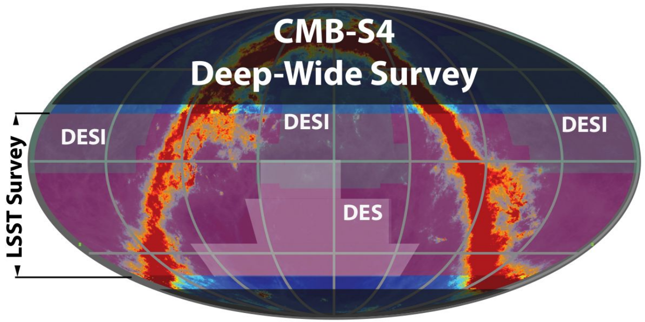
Bashinsky, Seljak (2004); Baumann, Green, JM, Wallisch (2016); Image Credit: Wallisch (2018)

Light Relics Measurements Favor Wide Surveys



Forecasted errors at fixed effort, normalized to 1μK-arcmin at f_{sky}=0.4

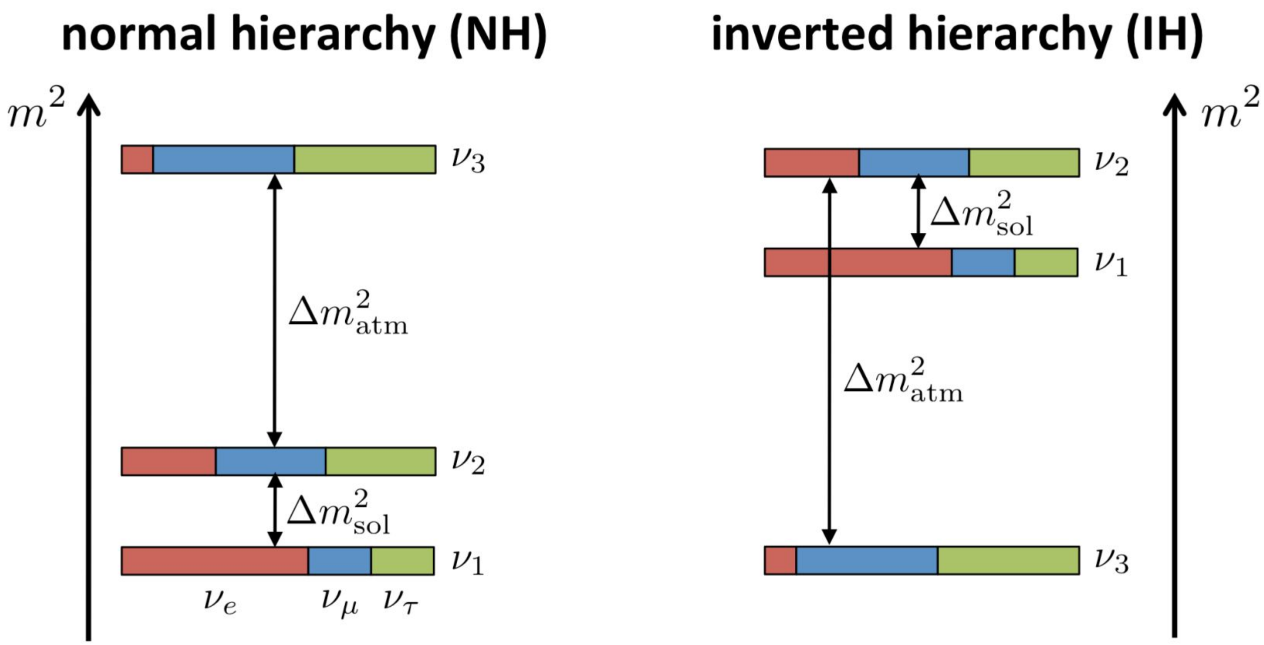
Light relics are best measured with the CMB damping tail, meaning that at fixed effort, more unique modes are available in a wide survey compared to a deep survey - we designed the CMB-S4 wide survey scan strategy to maximize sky coverage in order meet our target for light relics



Planck (2108); CMB-S4 (2016); CMB-S4 (2019)

Massive Cosmic Neutrinos

Neutrino Mass



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

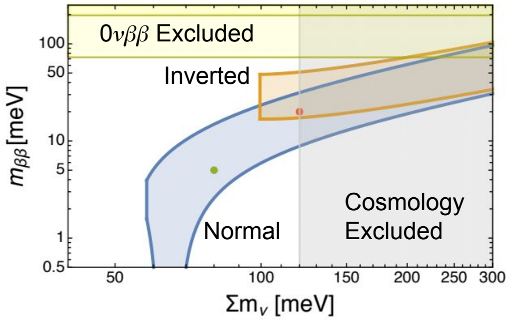
Cosmology is sensitive to the gravitational effects of the cosmic neutrino background, allowing a measurement of a sum of neutrino masses

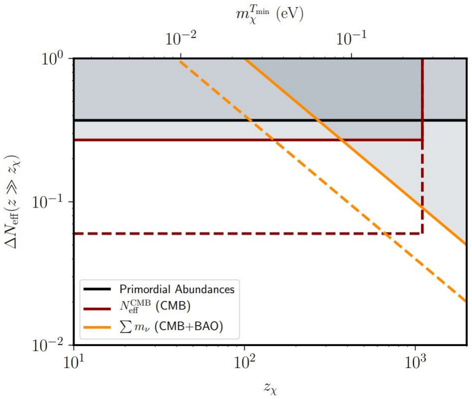
Current Planck 2018 constraint:

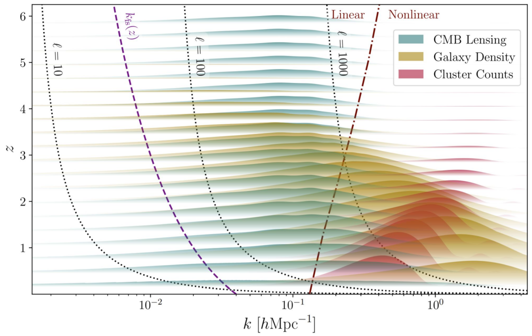
$$\sum m_\nu < 120 \text{ meV (95\% CL)}$$

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

Value of Cosmological Neutrino Mass Measurement







Particle Physics

- Absolute neutrino mass scale sets a target for complementary lab-based searches for neutrino mass

Cosmology

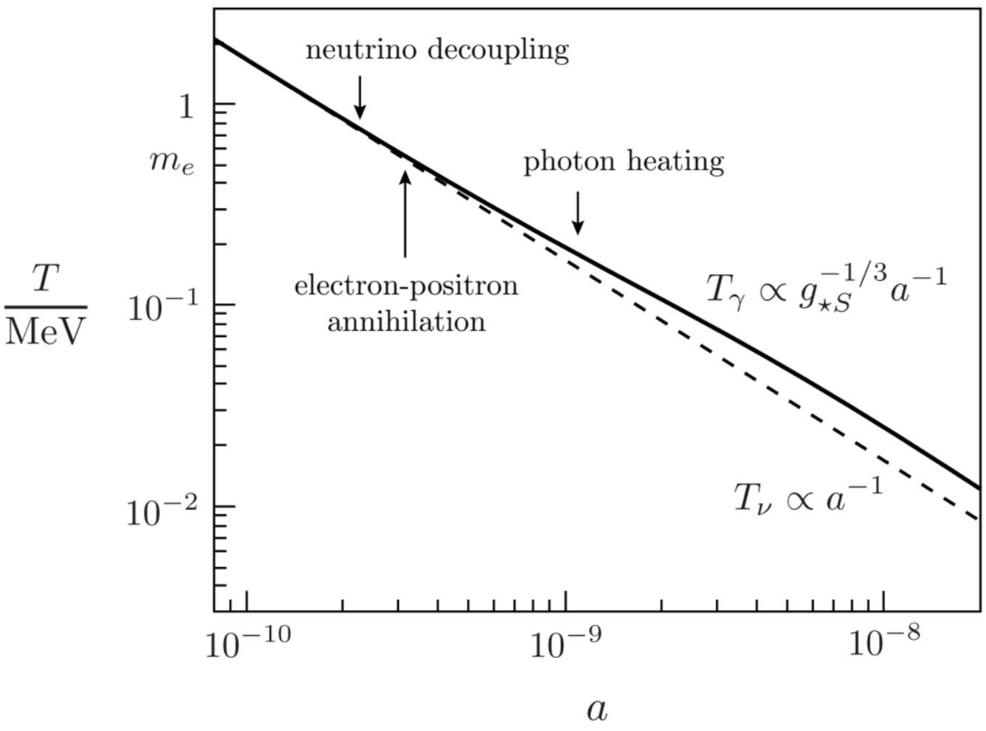
- Provides end-to-end test of cosmic history and is sensitive to new massive species (including gravitinos)

Astrophysics

- Multiple probes of matter power allow neutrino mass to be disentangled from nonlinear and baryonic effects

Green, JM (2021); Gerbino, Grohs, Lattanzi, et al (2022)

Cosmic Neutrino Background



Cosmic neutrinos decoupled from the thermal plasma around 1 MeV, and were then diluted relative to photons by electron-positron annihilation

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

Cosmic neutrino background properties today:

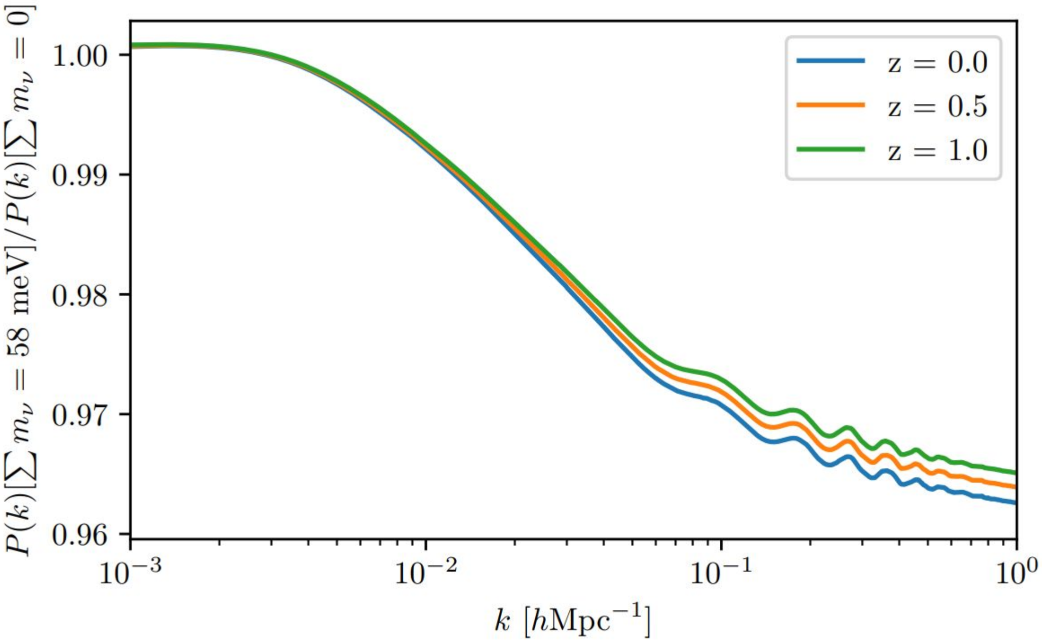
$$\begin{aligned} T_{\nu,0} &= 1.95\,\mathrm{K} \\ &= 1.68 \times 10^{-4}\,\mathrm{eV} \end{aligned}$$

$$n_{\nu_i,0} = 112\,\mathrm{cm}^{-3}$$

Cosmic neutrino background provides an abundance of non-relativistic neutrinos

Image Credit: Baumann

Massive Neutrinos Suppress Matter Clustering



Suppression of matter clustering due to massive neutrinos
(A_s, $\Omega_m h^2$, $\Omega_b h^2$, H_0 fixed)

The large velocities of cosmic neutrinos causes them to free stream out of potential wells and suppress the growth of structure on scales smaller than their free-streaming length

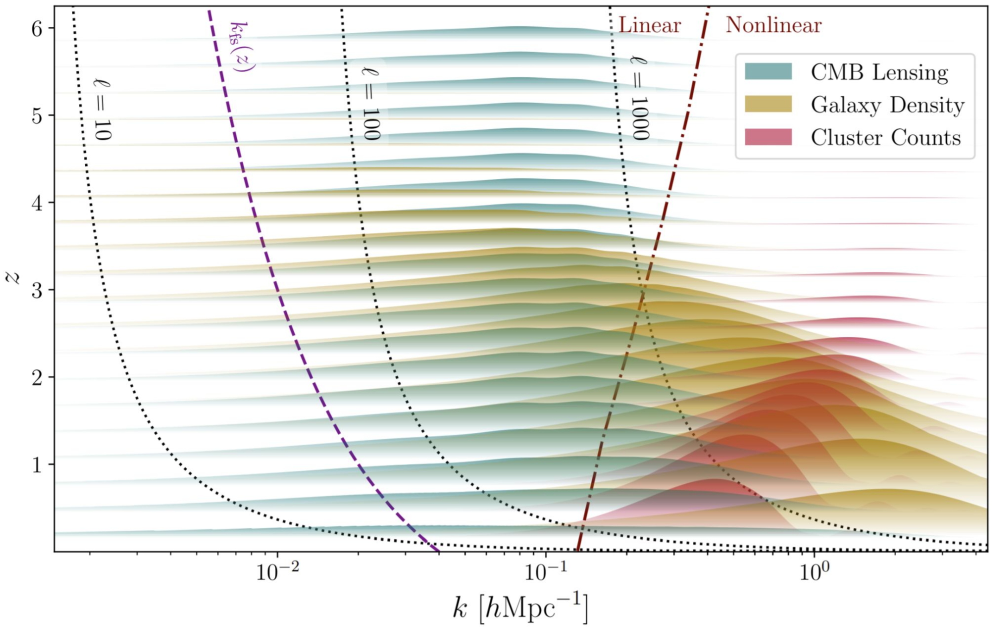
$$k_{\mathrm{fs}} = 0.04\,h\,\mathrm{Mpc}^{-1} \times \frac{1}{1+z}\left(\frac{\sum m_\nu}{58\,\mathrm{meV}}\right)$$

$$P_{\sum m_\nu}(k \gg k_{\mathrm{fs}}, z) \approx \left(1 - 2f_\nu - \frac{6}{5} f_\nu \log\frac{1+z_\nu}{1+z}\right) P_{\sum m_\nu = 0}(k \gg k_{\mathrm{fs}}, z)$$

$$f_\nu \equiv \frac{\Omega_\nu}{\Omega_{\mathrm{m}}} \simeq 4.3\times 10^{-3}\left(\frac{\sum m_\nu}{58\ \mathrm{meV}}\right)$$

Hu, Eisenstein, Tegmark (1998); Cooray (1999); Abazajian, et al (2011); Green, JM (2021); Gerbino, Grohs, Lattanzi, et al (2022)

Measuring Clustering with Cosmological Surveys



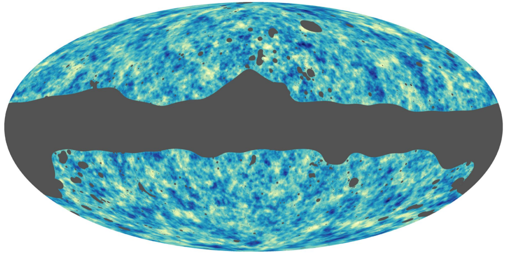
Sensitivity regimes of various probes of clustering

- Galaxy number density, galaxy weak lensing, counts of galaxy clusters, and weak lensing of the cosmic microwave background (among other probes) are sensitive to the clustering of matter across a wide range of scales and redshifts
- Unfortunately, the free-streaming scale cannot be resolved, and we must rely on a **comparison of power at late and early times** in order to measure neutrino mass

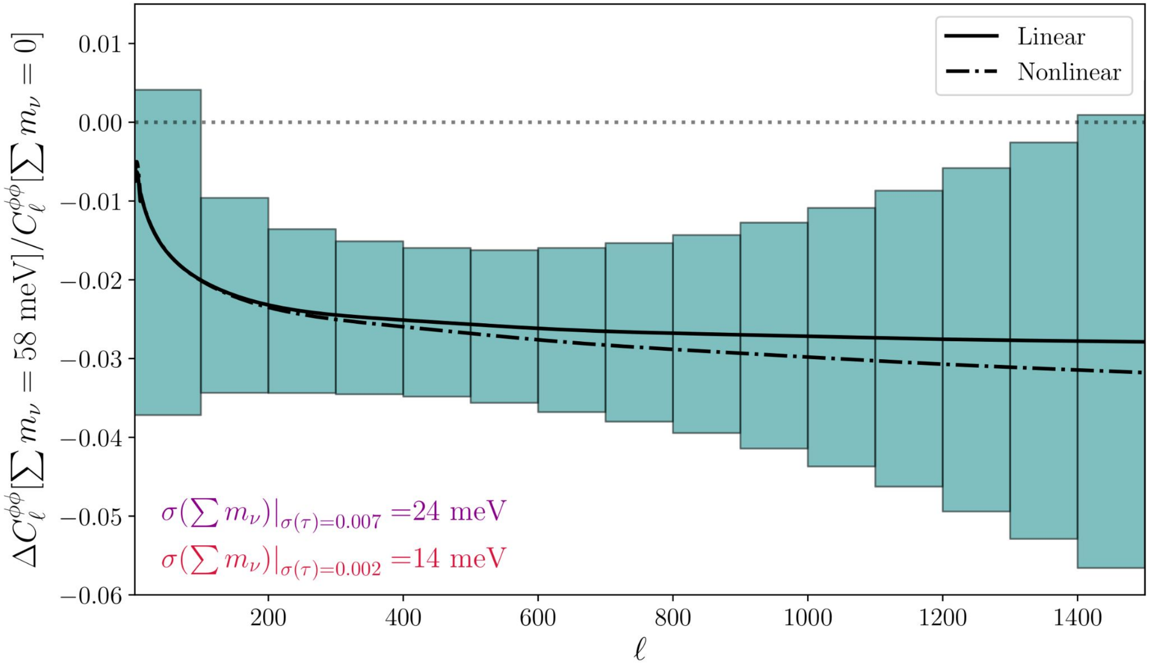
Green, JM (2021)

Neutrino Mass with CMB Lensing

See Gil's Tuesday Lecture!



- Suppression will be clearly visible with upcoming experiments, but is subject to two important degeneracies:
  - Matter density
  - Primordial Amplitude / Optical depth

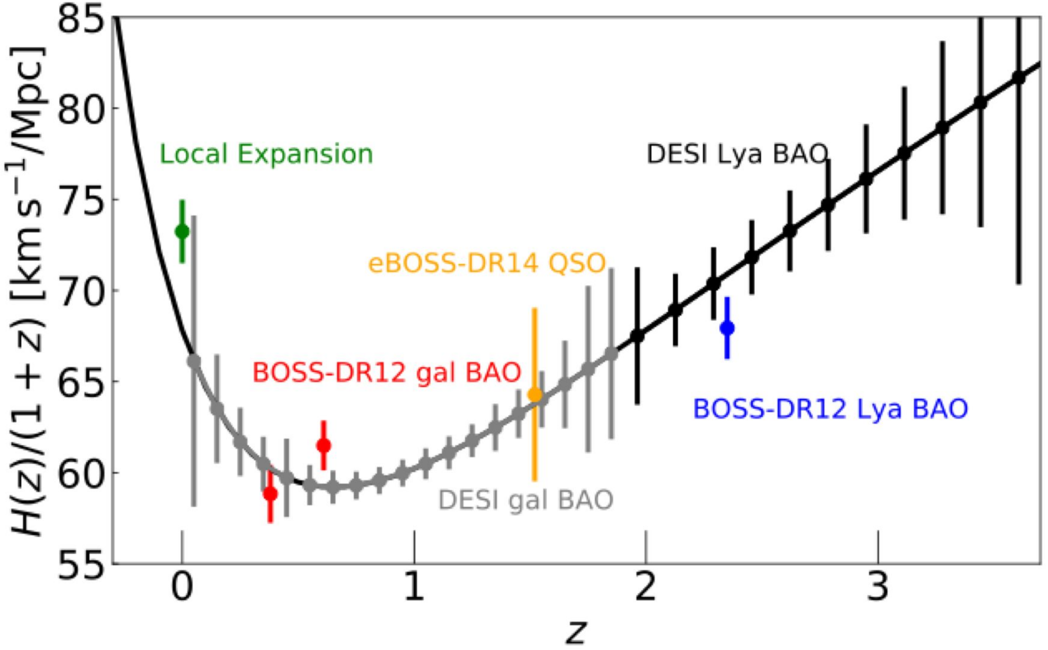


Measuring suppression of clustering with CMB-S4 lensing

Planck (2018); CMB-S4 (2016); Green, JM (2021)

Matter Density with Baryon Acoustic Oscillations

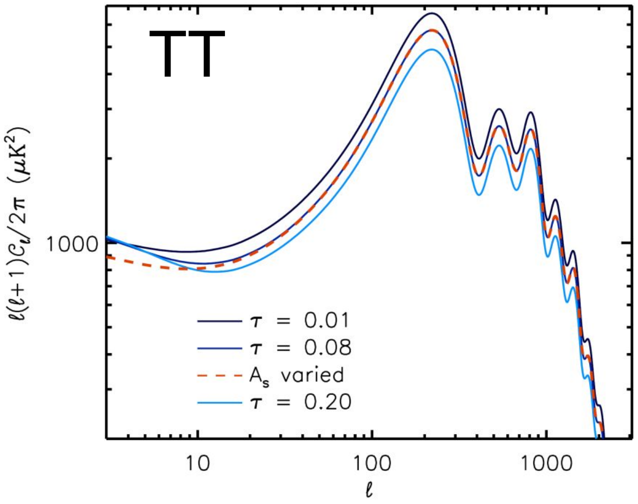
DESI projections (Font-Ribera++ 2014b)

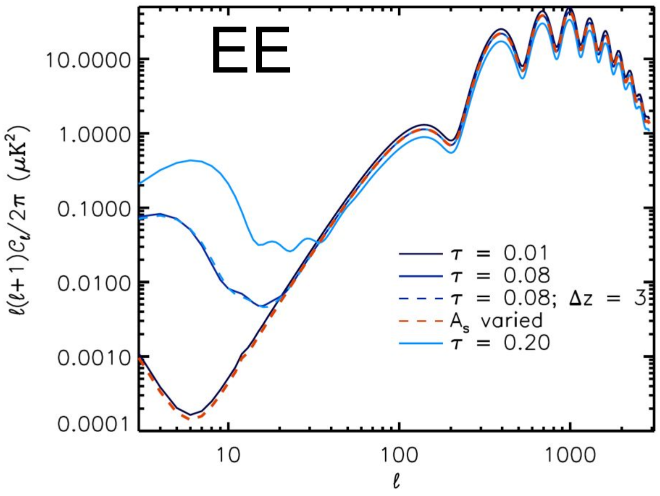


- Spectroscopic galaxy surveys such as DESI will precisely measure the expansion history using Baryon Acoustic Oscillations (BAO) as a standard ruler
- This provides a precise determination of the matter density, essential for a calibration of the amplitude of the matter power spectrum

Font-Ribera, et al (2014)

CMB Measurements of the Primordial Amplitude

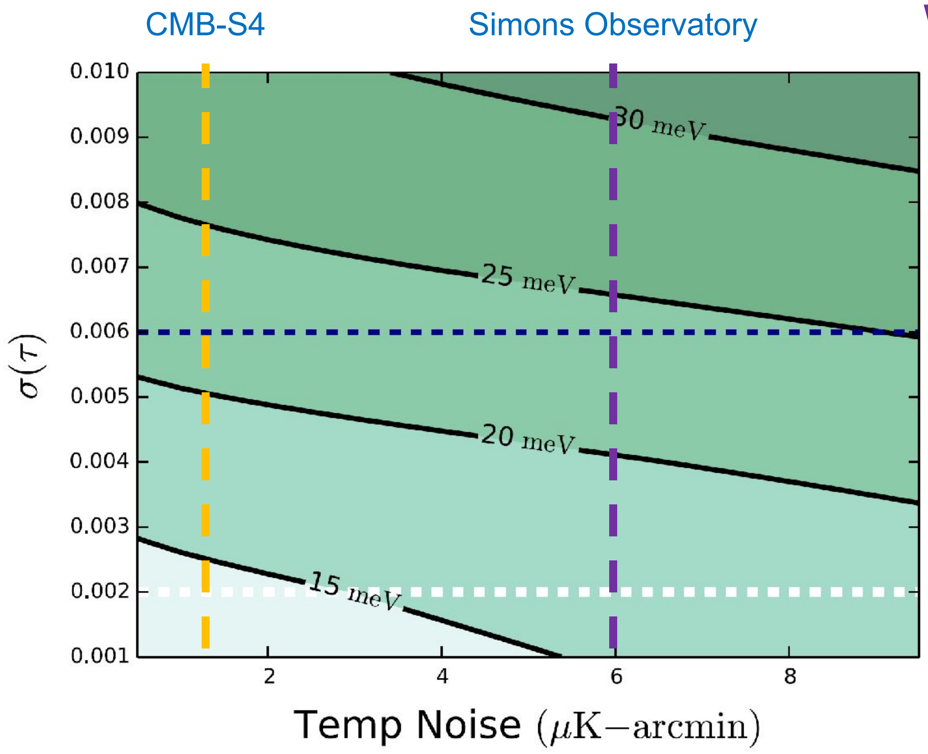




- Measurements of the CMB power spectra at $\ell>30$ tightly constrain the combination $A_s e^{-2\tau}$, while polarization at $\ell<20$ is sensitive to τ^2
- Large scale polarization is most easily measured with a CMB satellite or balloon-borne CMB experiment

Figure Credit: Reichardt (2015)

CMB + BAO Forecasts for Neutrino Mass Constraints



With DESI BAO

Planck τ

CMB Cosmic Variance Limit

LiteBIRD / PICO

Current constraint:

$$\sum m_\nu < 120 \text{ meV } (95\% \text{ CL})$$

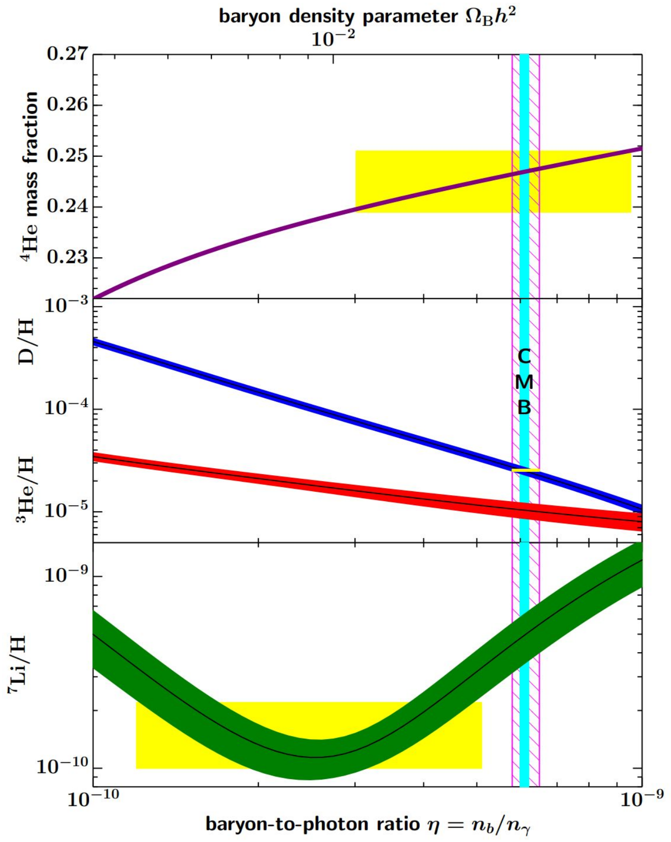
(Planck + BAO)

CMB lensing reconstruction with upcoming surveys, combined with DESI BAO, will enable significant measurement of even minimal $\sum m_\nu$ especially with improved τ measurement

CMB-S4 (2016); Simons Observatory (2018); Planck (2018)

Big Bang Nucleosynthesis

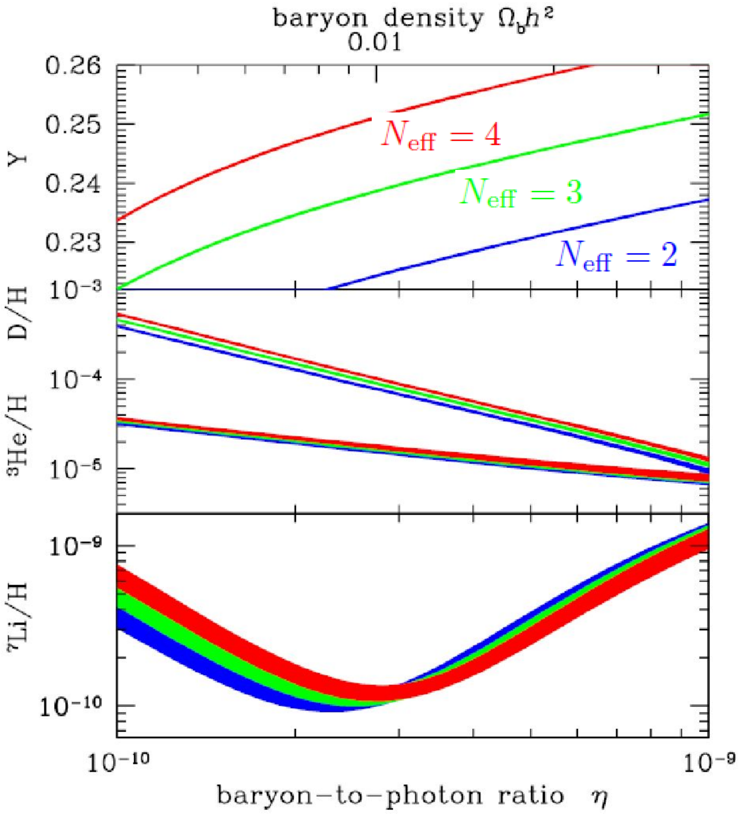
Standard Big Bang Nucleosynthesis



- Big Bang Nucleosynthesis (BBN) is the process by which protons and neutrons became bound into light nuclei in the early universe
- Standard BBN depends only on a single parameter, the baryon-to-photon ratio
- Precise measurements of the primordial abundance of helium-4 and deuterium constrain deviations from the standard cosmic history

Figure Credit: PDG (2021)

BBN and Light Relics

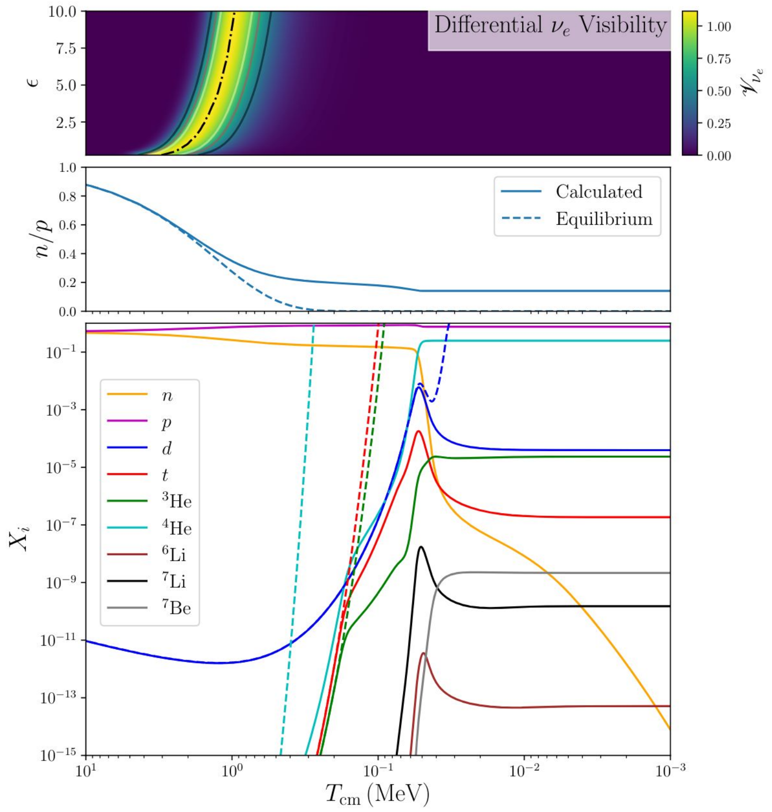


- The light relic density affects the expansion rate during BBN, and thus affects the predicted abundances
- Increasing N_{eff} leads to larger expansion rate, leading to higher weak freeze-out temperature, and thus larger neutron-to-proton ratio, ultimately giving a larger helium abundance
- Combined with the CMB constraint on the baryon-to-photon ratio, measurements of the primordial helium-4 and deuterium abundances gives a constraint on N_{eff}

$$N_{\text{eff}}^{\text{BBN}} = 2.93 \pm 0.23$$

Yeh, Shelton, Olive Fields (2022);
Figure Credit: Cyburt, et al (2015)

BBN and New Physics in the Neutrino Sector



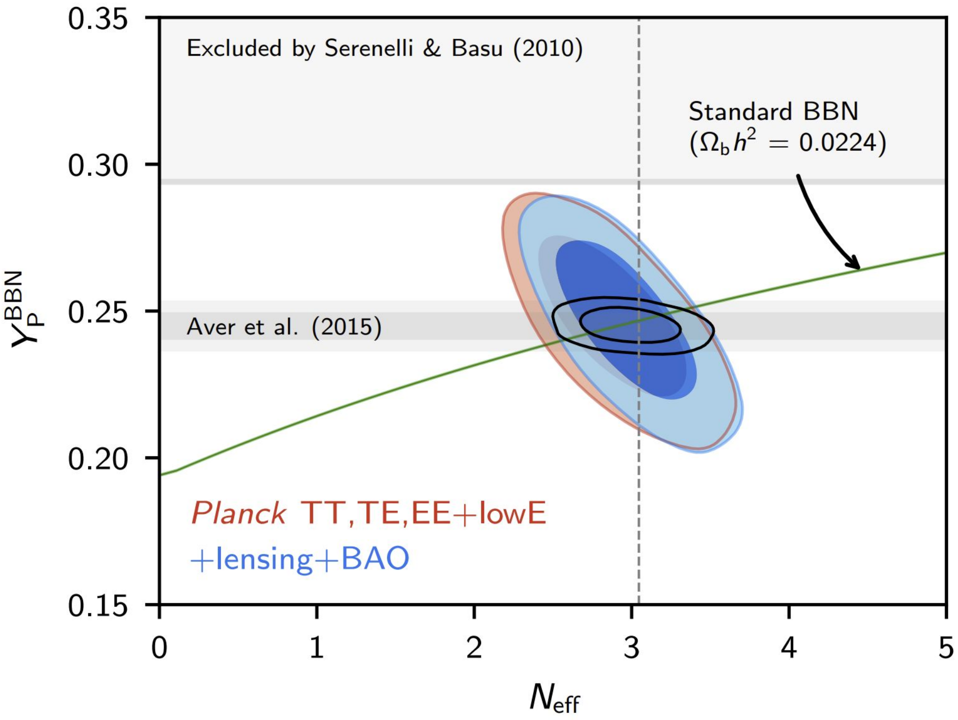
The precision with which we can measure primordial light element abundances (especially deuterium and Helium-4) allows us to use BBN as a powerful probe of new physics

This becomes an even sharper test when combined with CMB constraints

Bond, Fuller, Grohs, JM, Wilson (In Prep.)

CMB Tests of BBN

- The CMB power spectrum is sensitive to both N_{eff} and Y_P and can therefore be used to test BBN
- Both parameters affect the damping scale, but they are not totally degenerate because N_{eff} has other effects (including the phase shift)
- BBN predicts a particular relationship between N_{eff} and Y_P
- Current observations are consistent with standard BBN, and place constraints on non-standard scenarios (like time-dependent N_{eff})



Planck (2018)

Conclusion

Conclusion

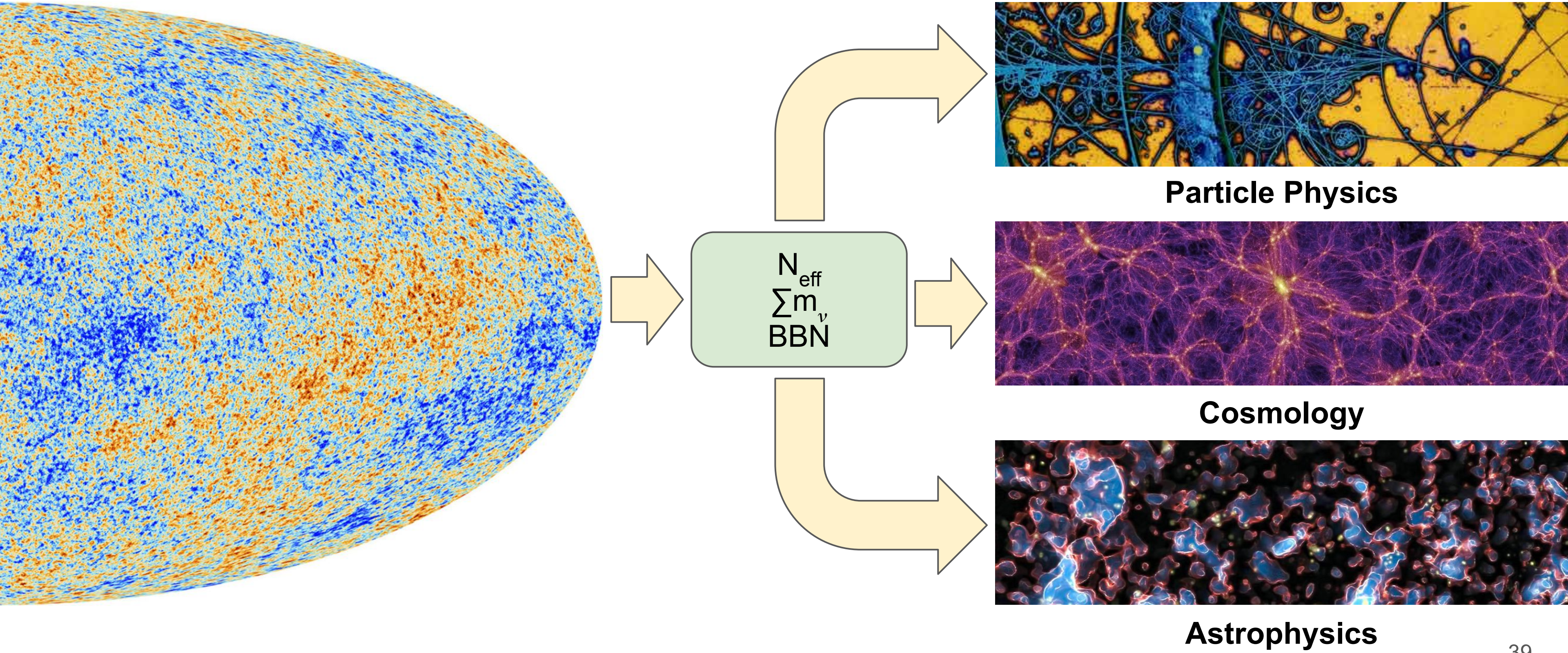
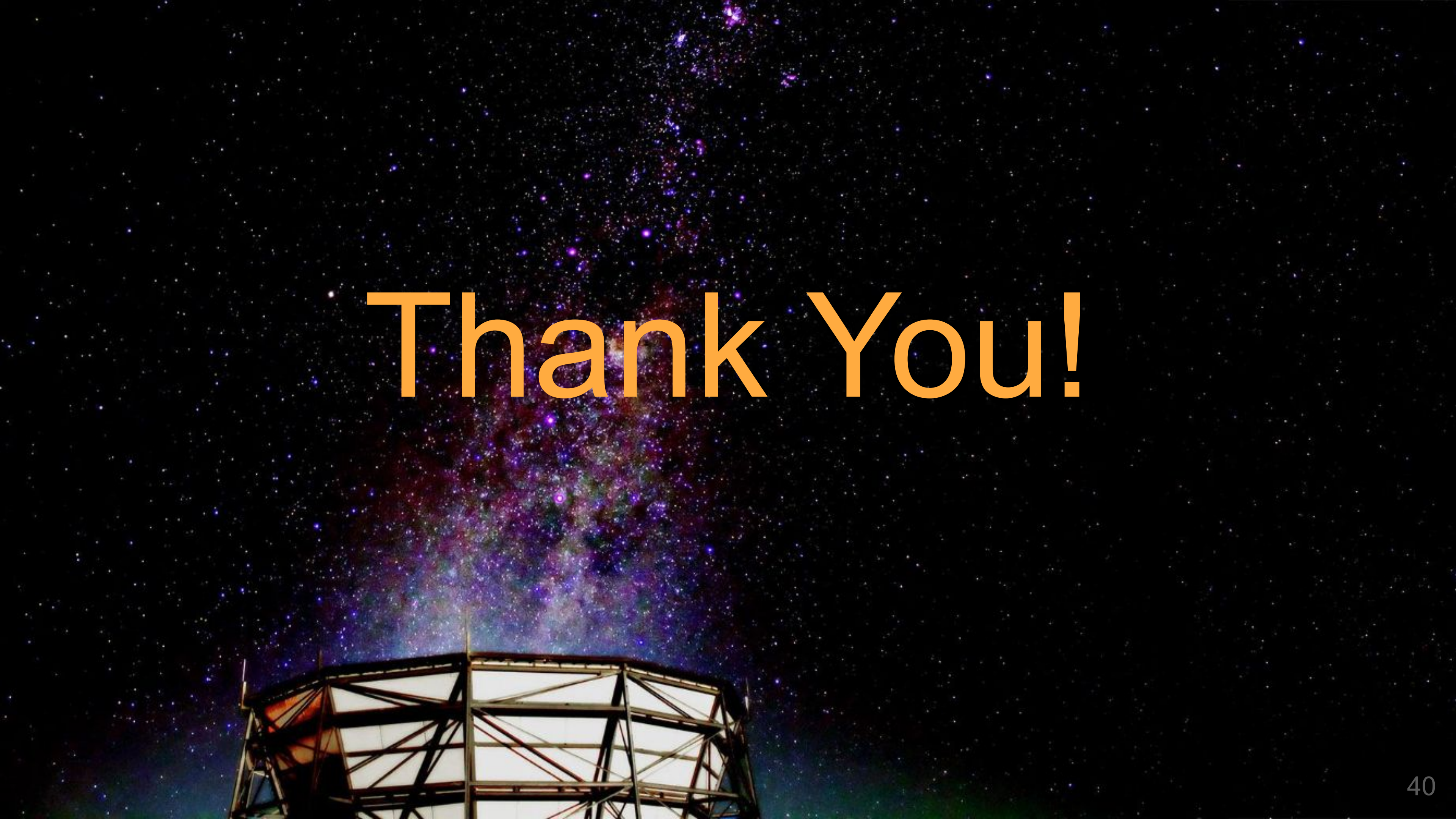


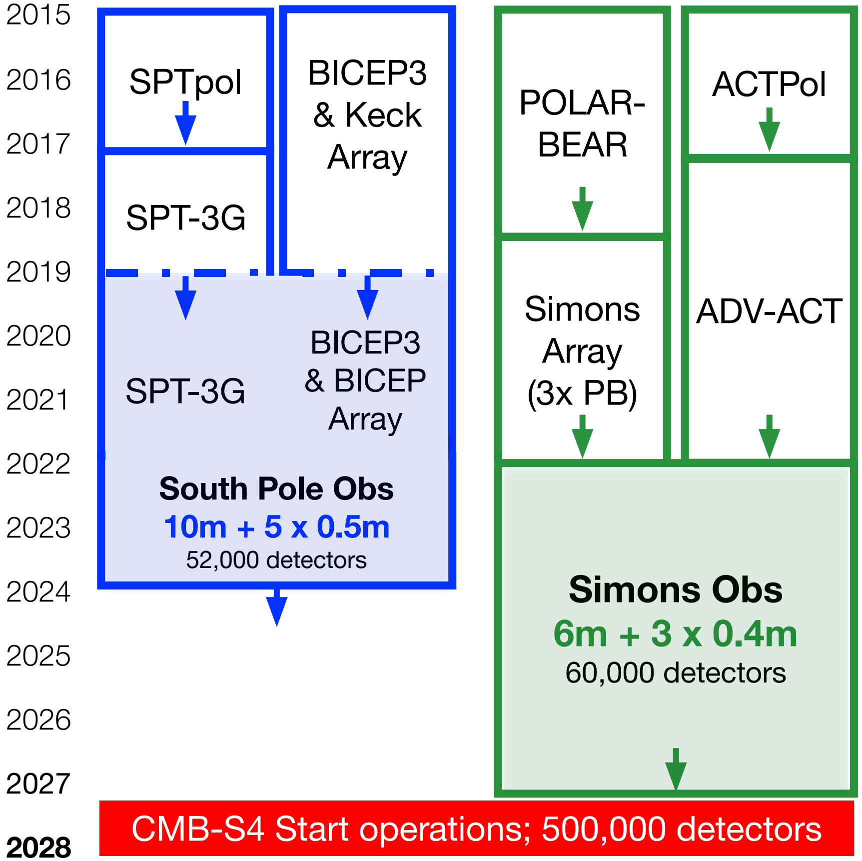
Image Credits: Planck; BEBC/CERN; Springel, et al; Alvarez, Kaehler, Abel



Thank You!

Backup Slides

Evolution of Ground-Based CMB Surveys



Science-driven expansion of capabilities + cost-driven consolidation of teams

- Late 2010s:
  - single-site, single resolution
  - O(10K) detectors
  - ACT, BICEP/Keck, POLARBEAR, SPT, etc
- Early 2020s:
  - single-site, dual-resolution
  - O(50K) detectors
  - Simons Observatory (SO), South Pole Observatory (SPO)
- Late 2020s:
  - dual-site, dual-resolution
  - O(500K) detectors
  - CMB-S4

Slide Credit: CMB-S4