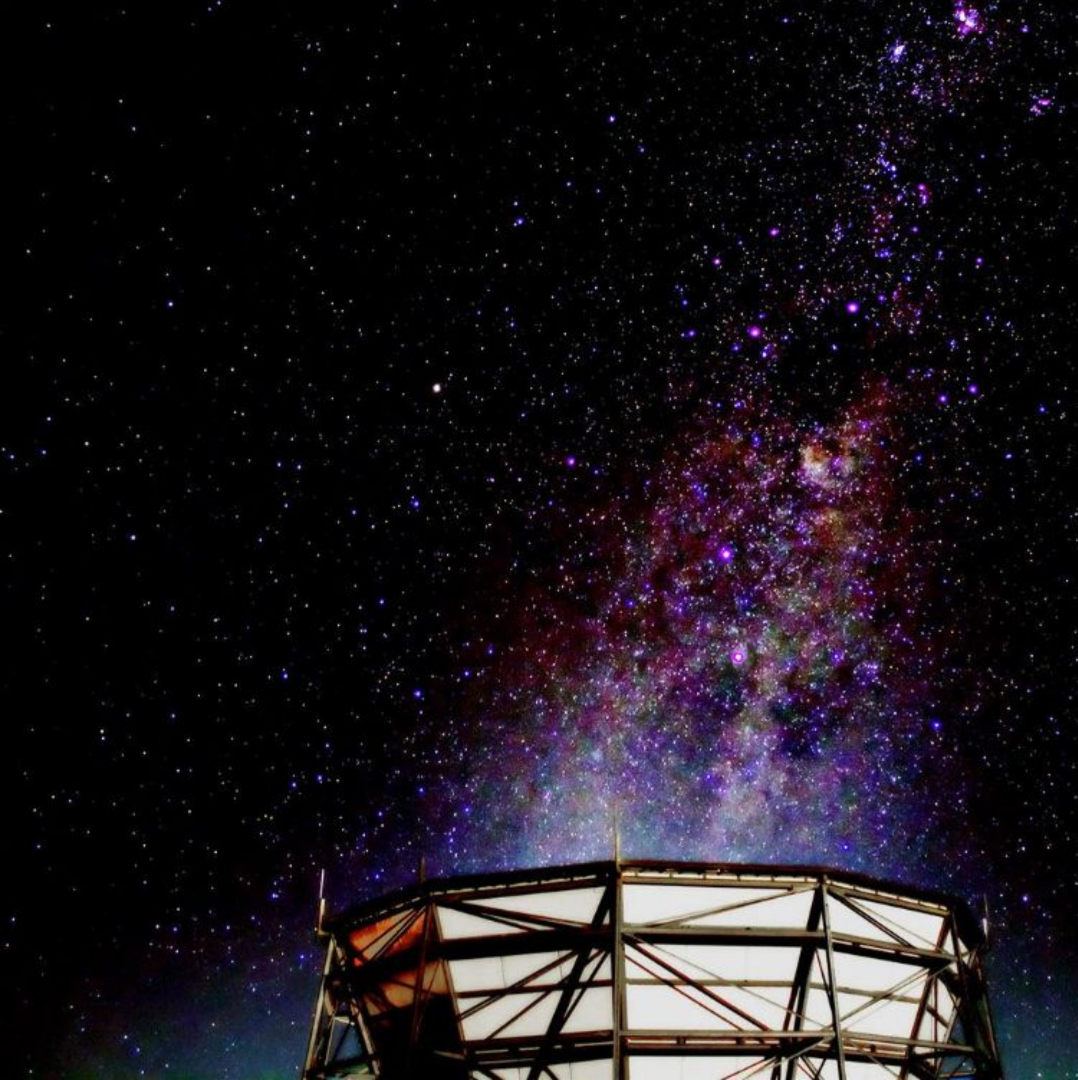


Neutrinos and Cosmology I

Joel Meyers

International Neutrino Summer School 2023

8-17-2023

Image Credit: ACT / Princeton

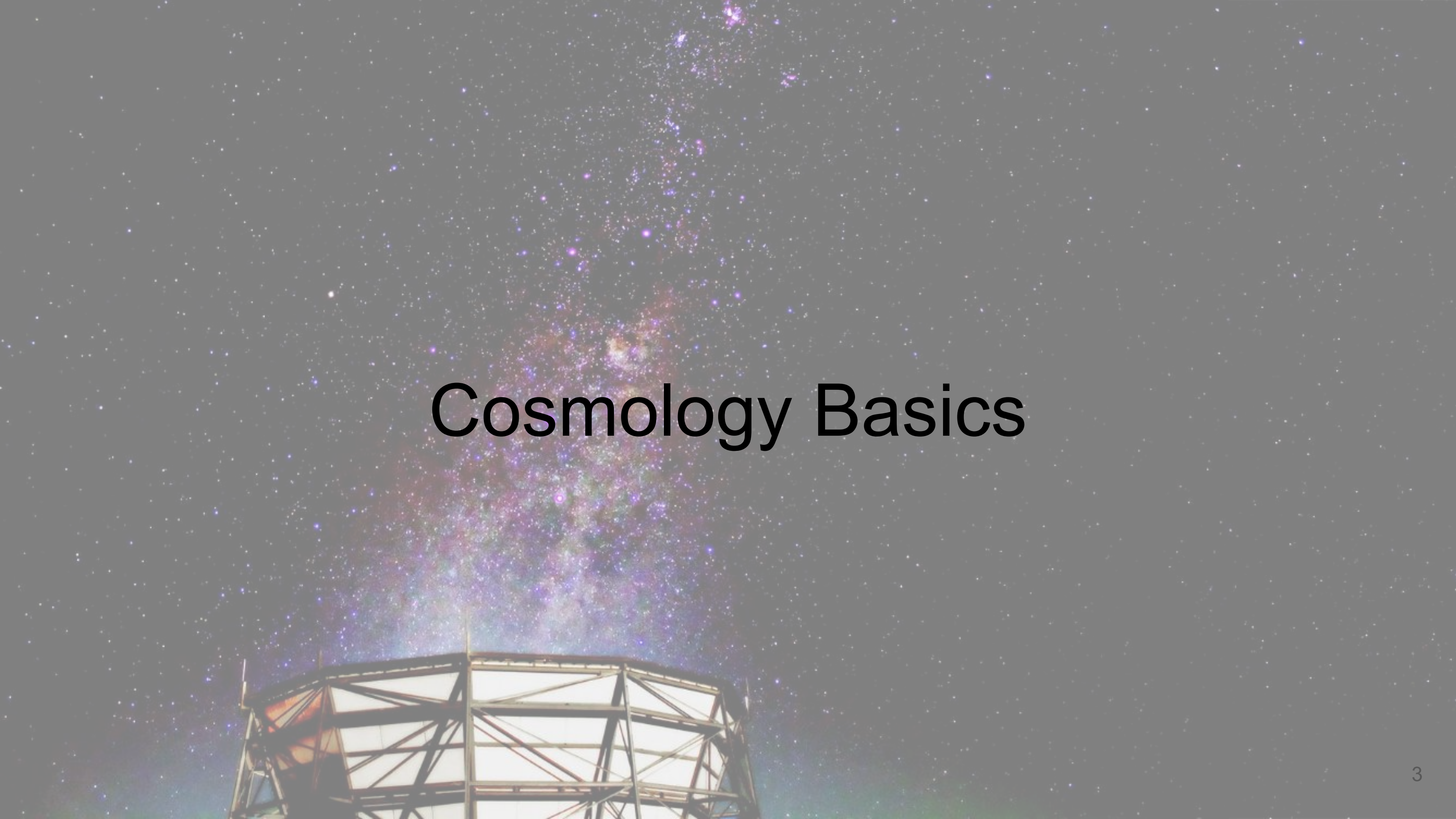
Outline

Lecture I

- Cosmology Basics
- Thermal History
- Cosmic Neutrino Background
- Light Relics Beyond the Standard Model
- Big Bang Nucleosynthesis
- Cosmic Microwave Background Basics

Lecture II

- Measuring Light Relics
- Massive Cosmic Neutrinos
- CMB Lensing and Neutrino Mass
- Other Cosmic Probes of Neutrino Mass
- Cosmology/Lab Complementarity



Cosmology Basics

The Universe is Expanding

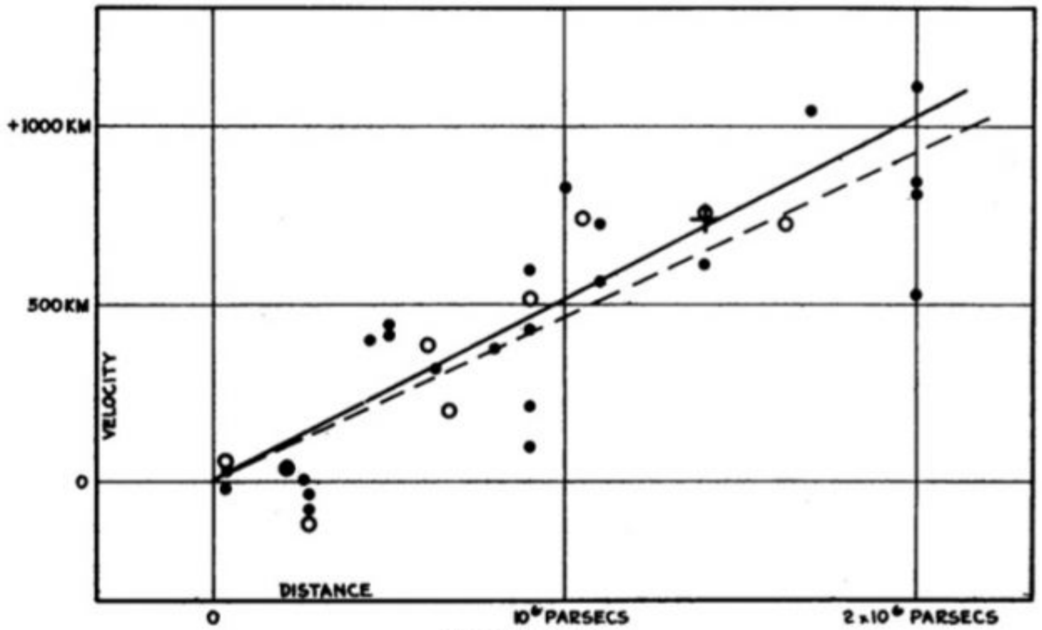


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble (1929)

Physics of Expansion

Einstein Field Equations

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

"Matter tells spacetime how to curve; spacetime tells matter how to move" - *Wheeler*

Homogeneous, Isotropic Universe

Friedmann Equation

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

Expansion Rate

Scale Factor

Energy Density

$$\rho_m \propto a^{-3}$$

Non-Relativistic Matter

$$\rho_r \propto a^{-4}$$

Relativistic Radiation

History of the Universe

Cosmic Neutrino Decopuling

BBN

Recombination (CMB Decoupling)

Large Scale Structure

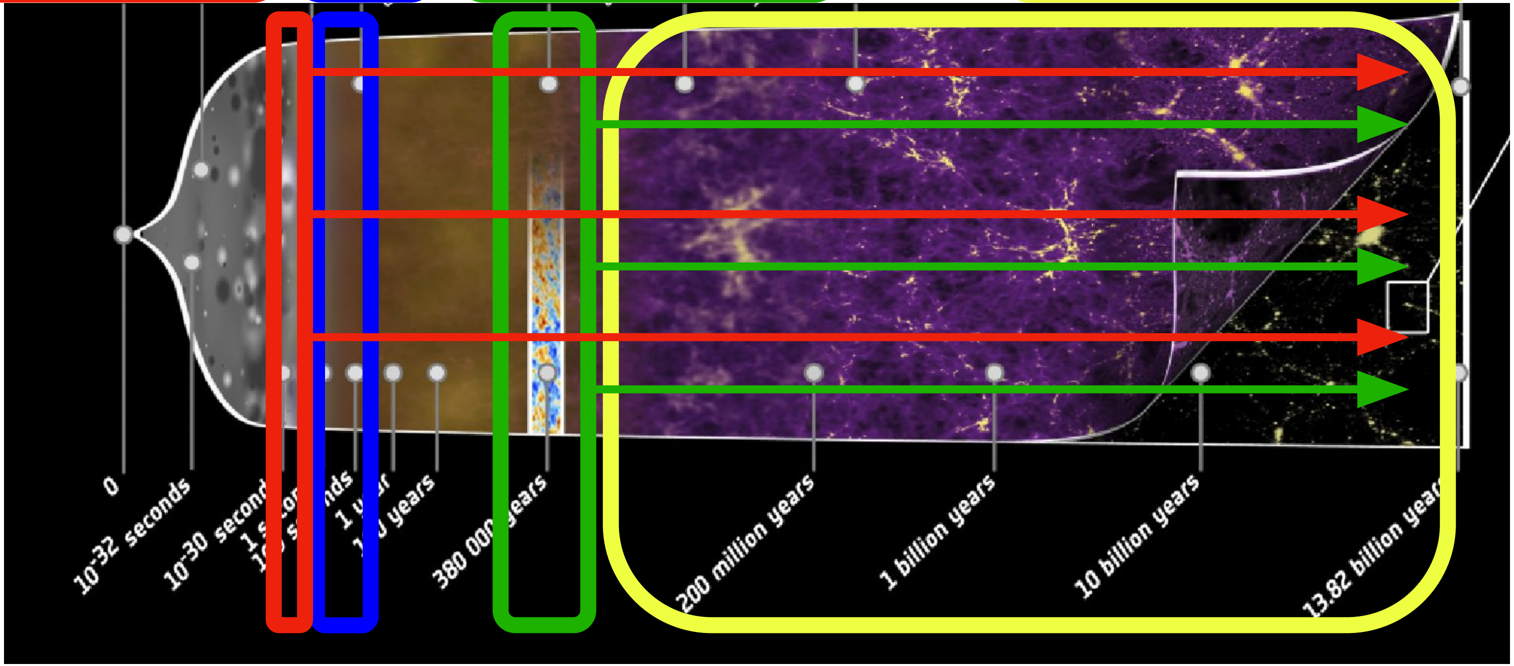


Image Credit: NASA

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

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

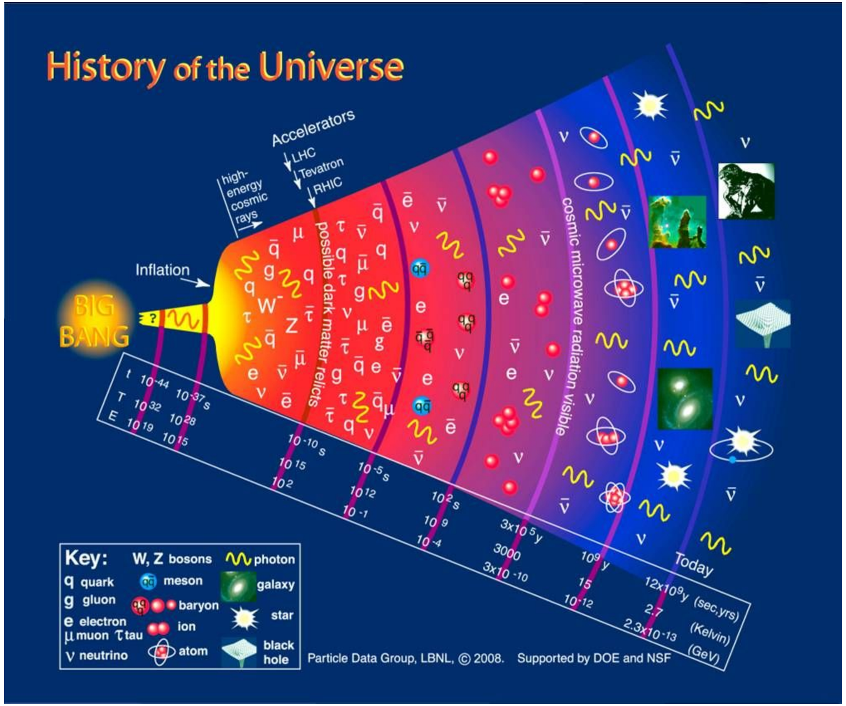


Image Credit: PDG

Evolution of Plasma Particle Content

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

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

- Decouplied species contribute with a different temperature

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

- 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

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

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

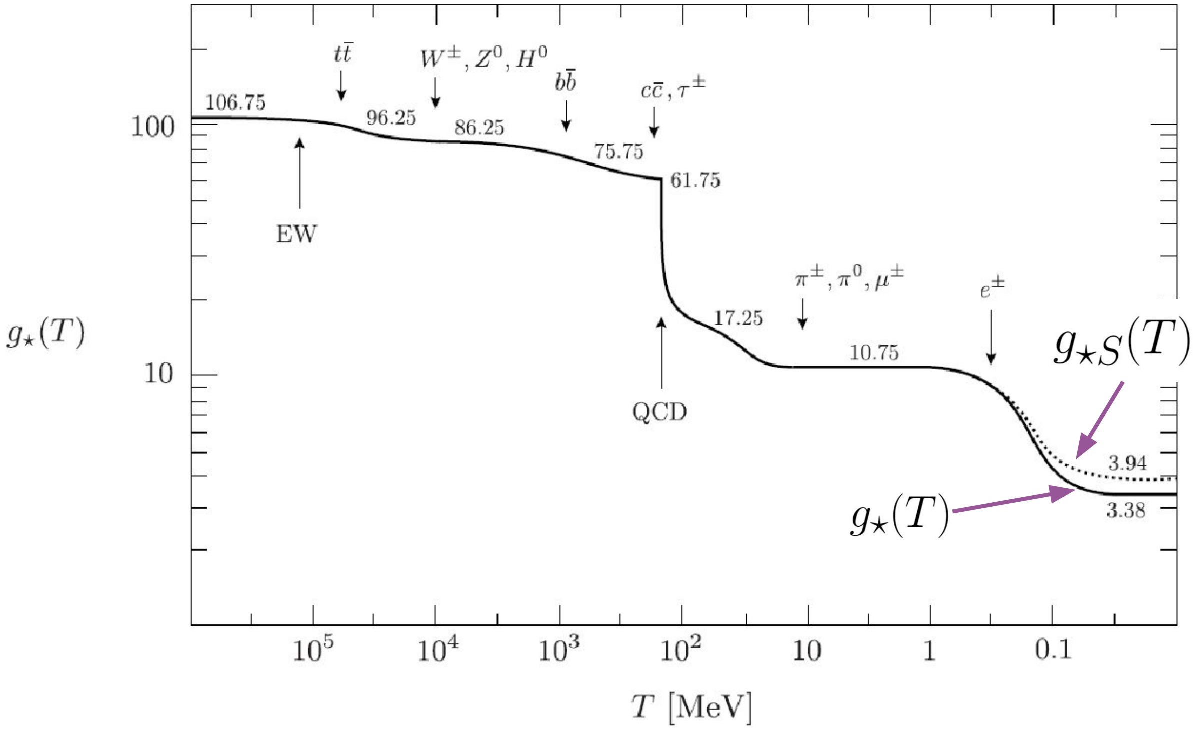
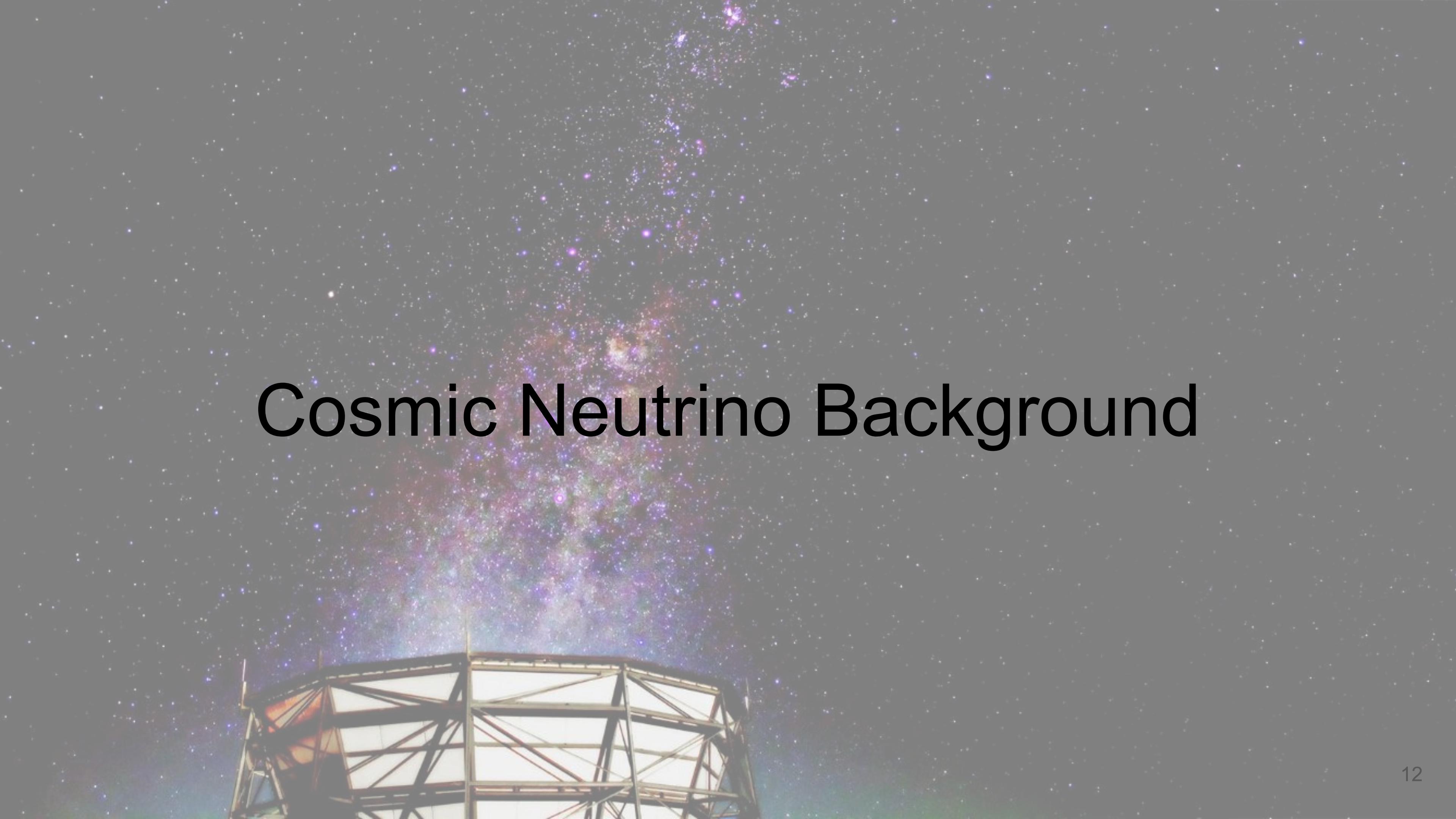


Image Credit: Baumann

Cosmic Neutrino Background



Cosmic Neutrinos as Light Thermal Relics

- 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

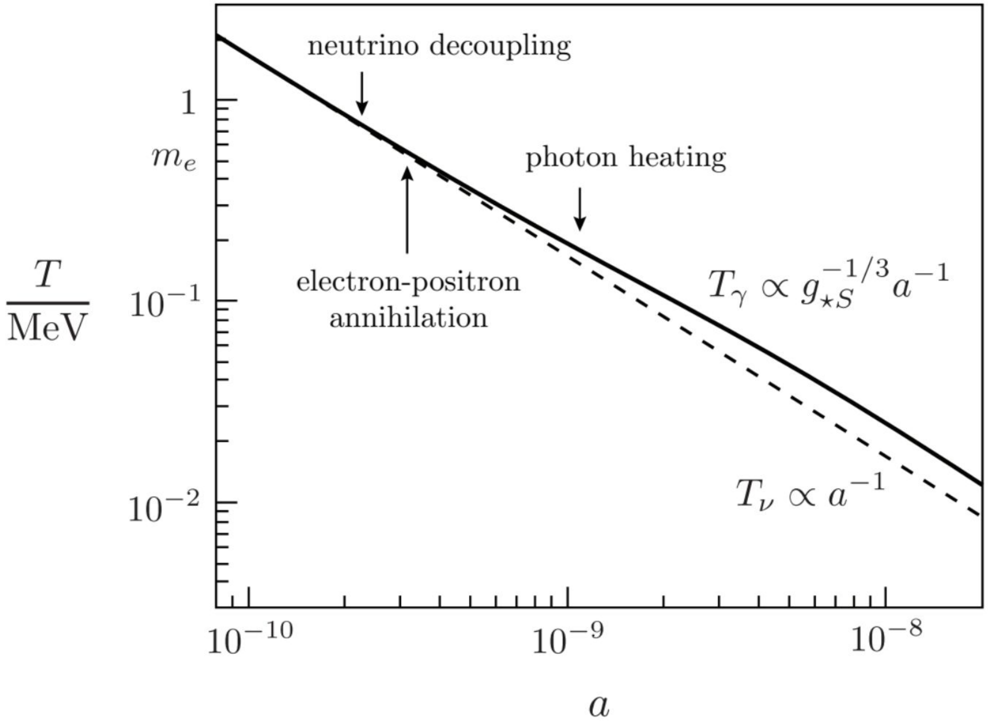


Image Credit: Baumann

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:

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

γ e^+ e^-

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

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

- Entropy conservation gives the temperature ratio after annihilation:

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

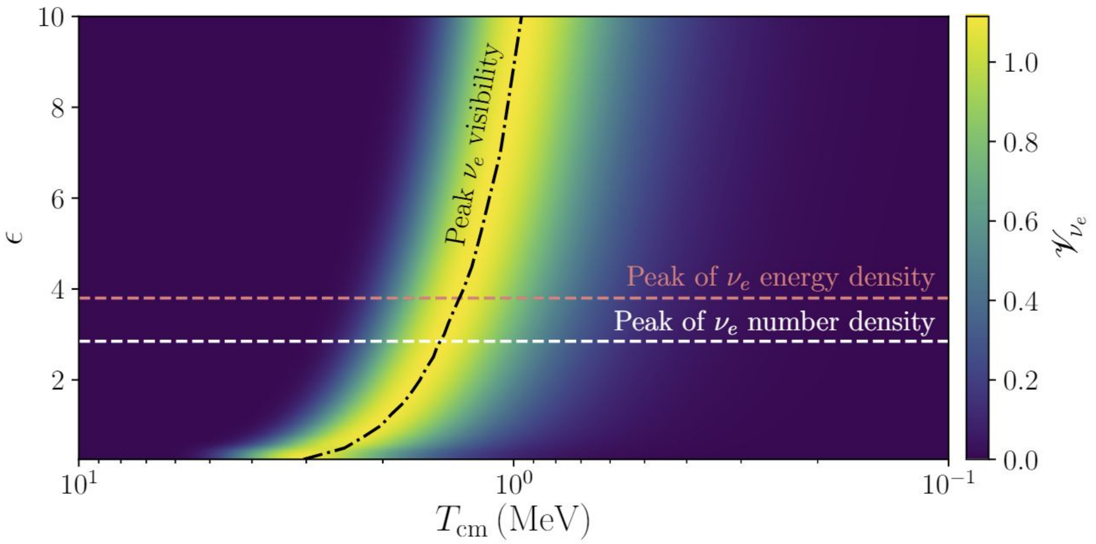
Effective Number of Neutrino Species

- 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

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

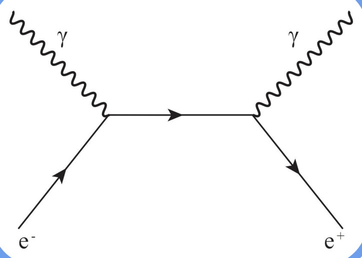


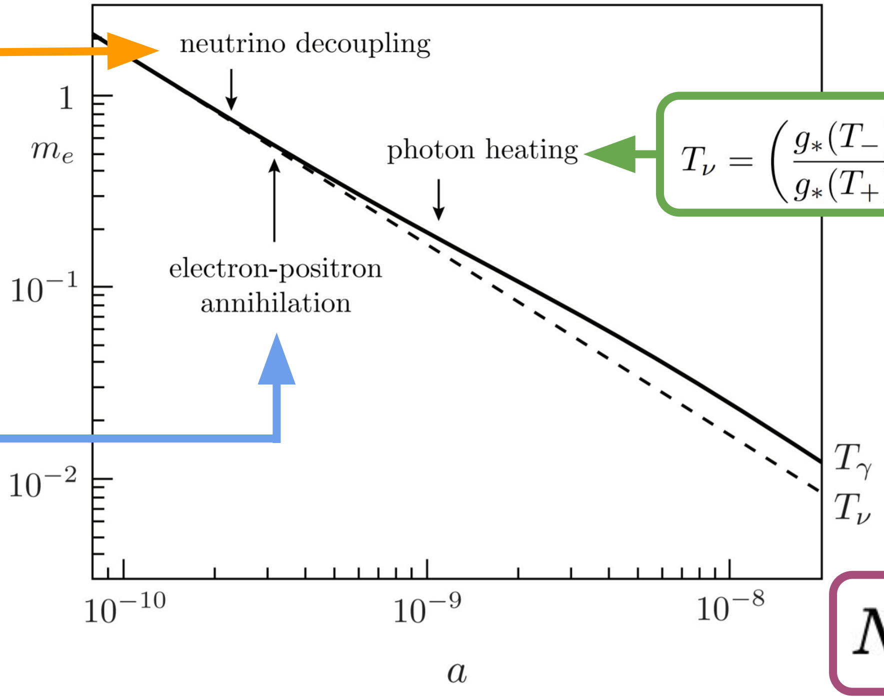
Escudero Abenza (2020); Akita, Yamaguchi (2020); Froustey, Pitrou, Volpe (2020); Bennett, et al (2021); Bond, Fuller, Grohs, JM, Wilson (In Prep.)

Summary of Cosmic Neutrino Decoupling

$\sigma \sim$  $\sim G_F^2 T^2$

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





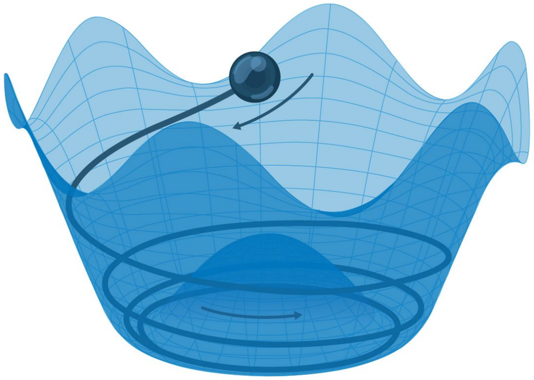
$$T_\nu = \left(\frac{g_*(T_-)}{g_*(T_+)}\right)^{1/3} T_\gamma = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

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

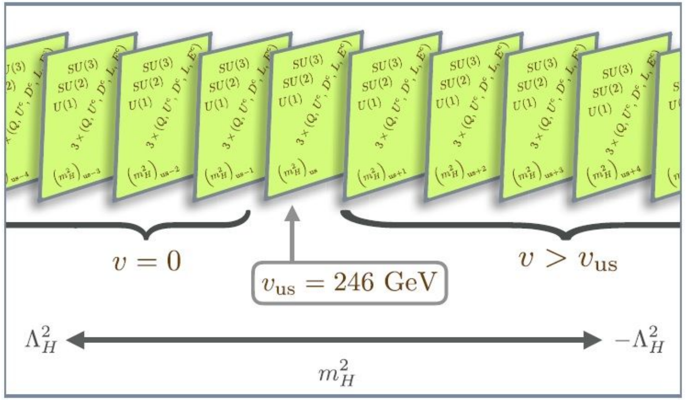
Baumann (2018); Akita, Yamaguchi (2020)

Light Relics Beyond the Standard Model

New Light Species are Ubiquitous in Standard Model Extensions



Axions and Axion-Like Particles



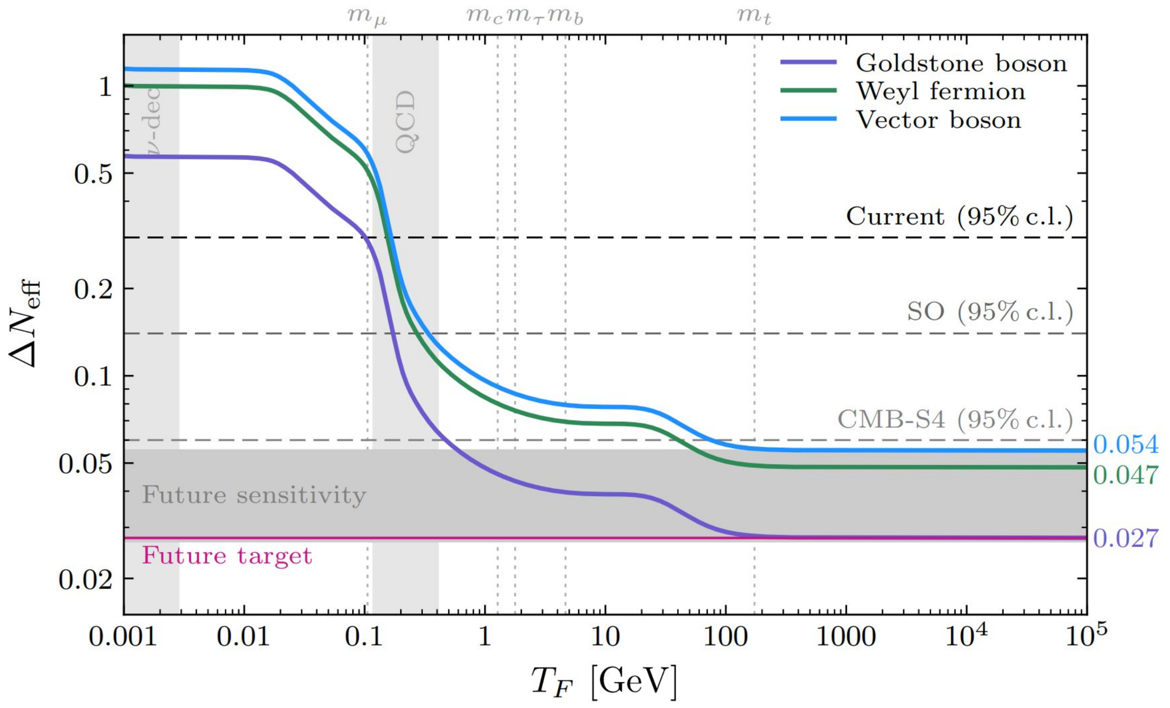
Complex Dark Sectors

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

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

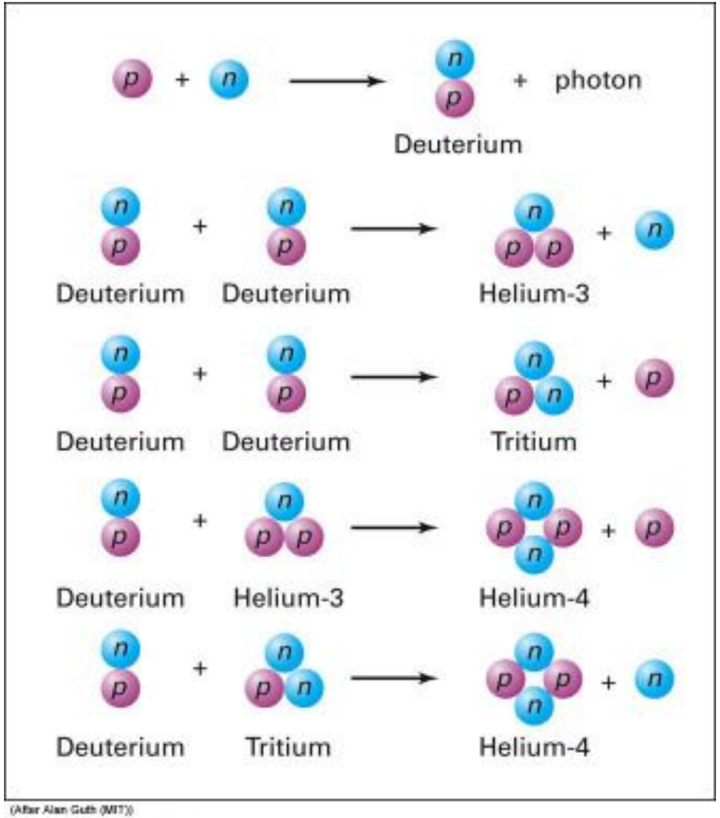
Freeze-out occurs when production rate falls below Hubble rate

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

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

Big Bang Nucleosynthesis

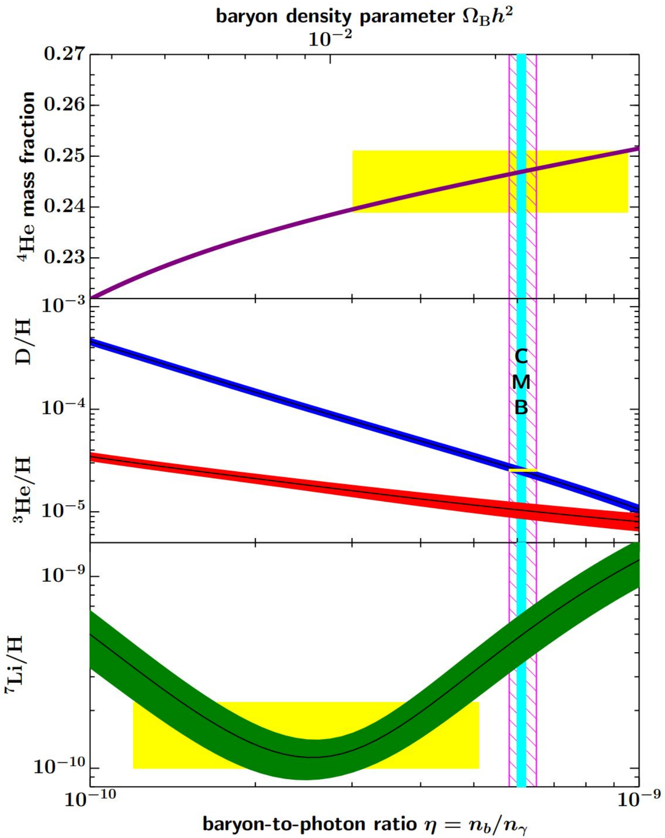
Standard Big Bang Nucleosynthesis



- Big Bang Nucleosynthesis (BBN) is the process by which protons and neutrons became bound into light nuclei in the early universe (around 3 minutes)
- Astronomical measurements of pristine systems allow for inference of the primordial abundances of light elements
  - D: Quasar Absorption Spectra
  - He-4: Emission from Extragalactic HII Regions
  - Li-7: Metal-poor Milky Way Halo Stars (??)

Figure Credit: Barnes (2006)

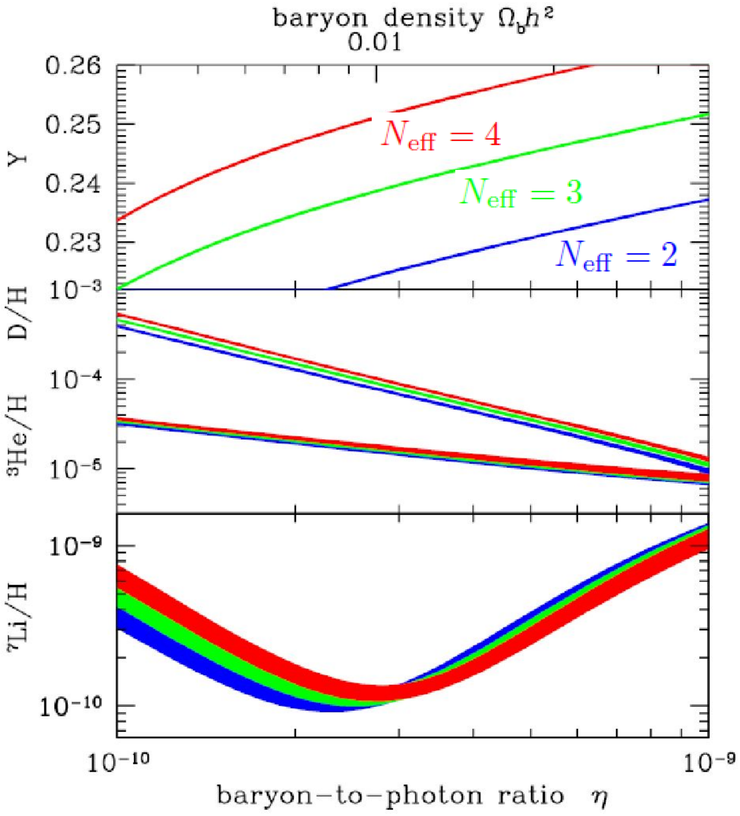
Standard Big Bang Nucleosynthesis



- 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
- The best estimates of the primordial lithium-7 abundance disagree with the standard theoretical prediction, though the astrophysical inference is suspect

Figure Credit: PDG (2021)

BBN and Light Relics

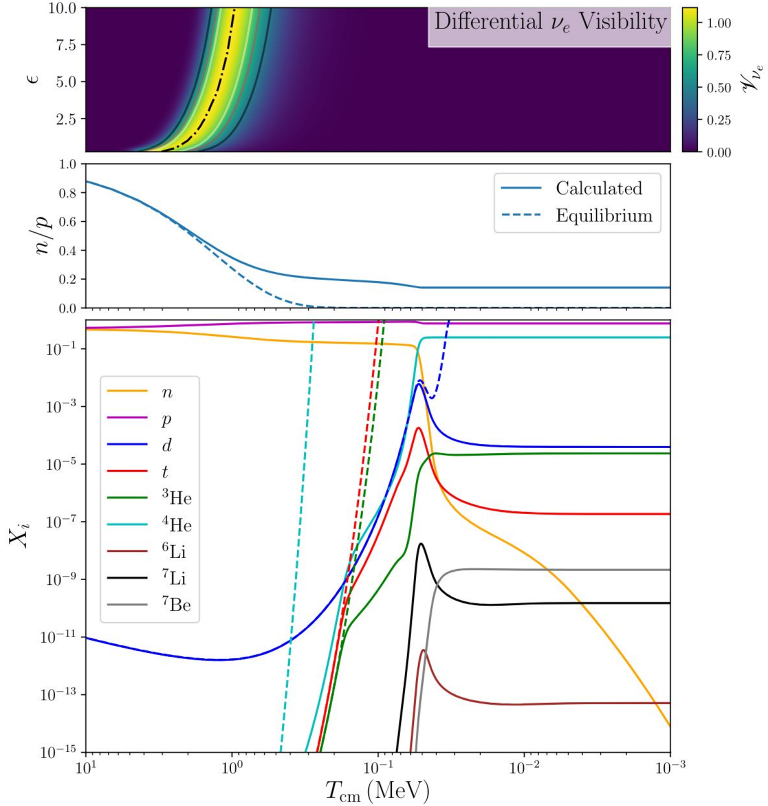


- The light relic density affects the expansion rate during BBN, and thus affects the predicted abundances
- Increasing N_{eff} leads to larger expansion rate, leading to higher weak freeze-out temperature, and thus larger neutron-to-proton ratio, ultimately giving a larger helium abundance
- Combined 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}

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

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

BBN and New Physics in the Neutrino Sector

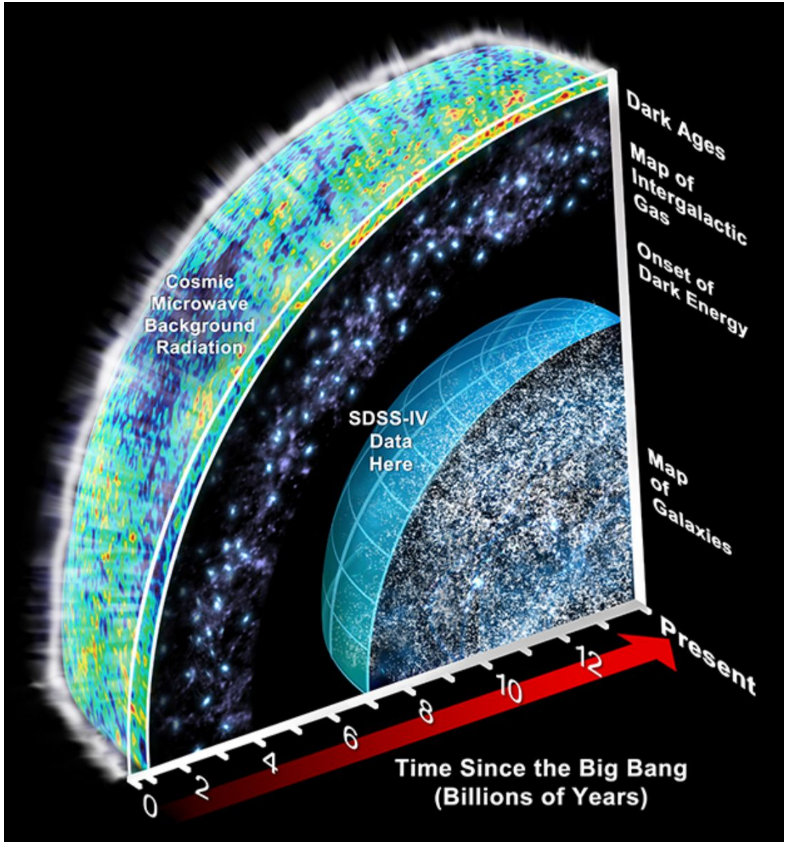


- The precision with which we can measure primordial light element abundances (especially deuterium and Helium-4) allows us to use BBN as a powerful probe of new physics (in particular in the neutrino sector)
- This becomes an even sharper test when combined with CMB constraints

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

Cosmic Microwave Background Basics

The Cosmic Microwave Background



Cosmic Microwave Background (CMB) Spectrum

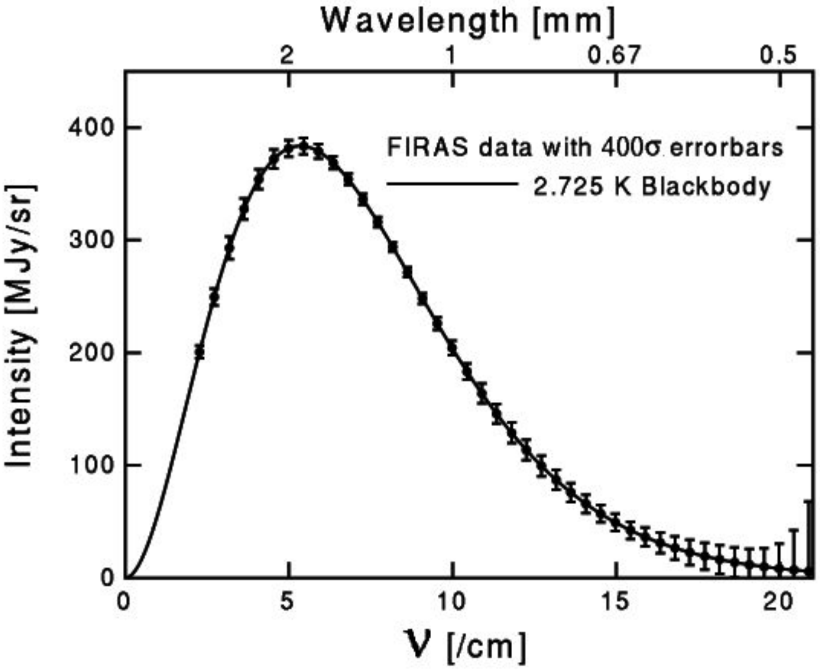
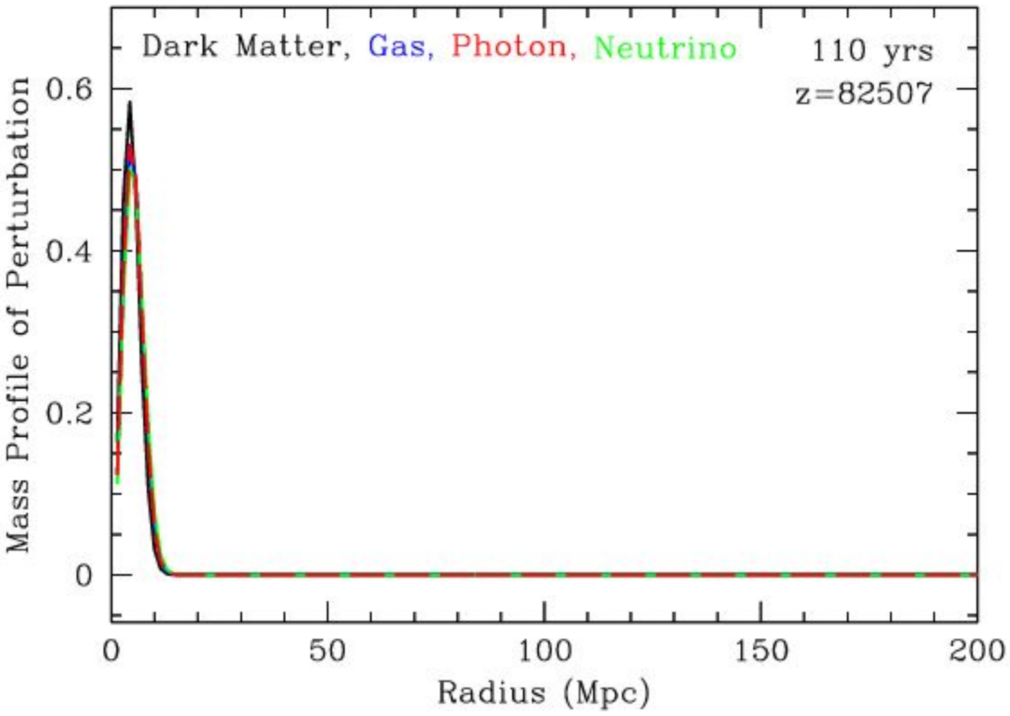


Image Credits: SDSS, COBE FIRAS

Sound Waves in the Primordial Plasma



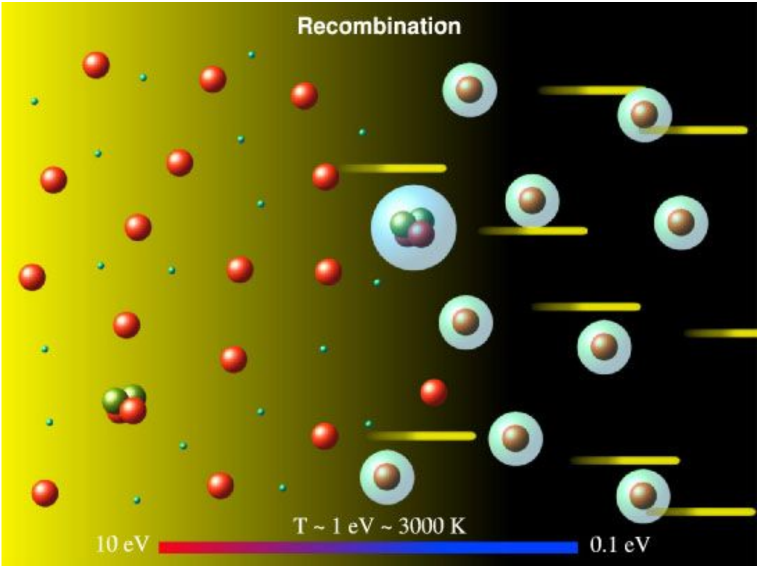


Image Credits: Eisenstein, Kinney

Superposition of Sound Waves

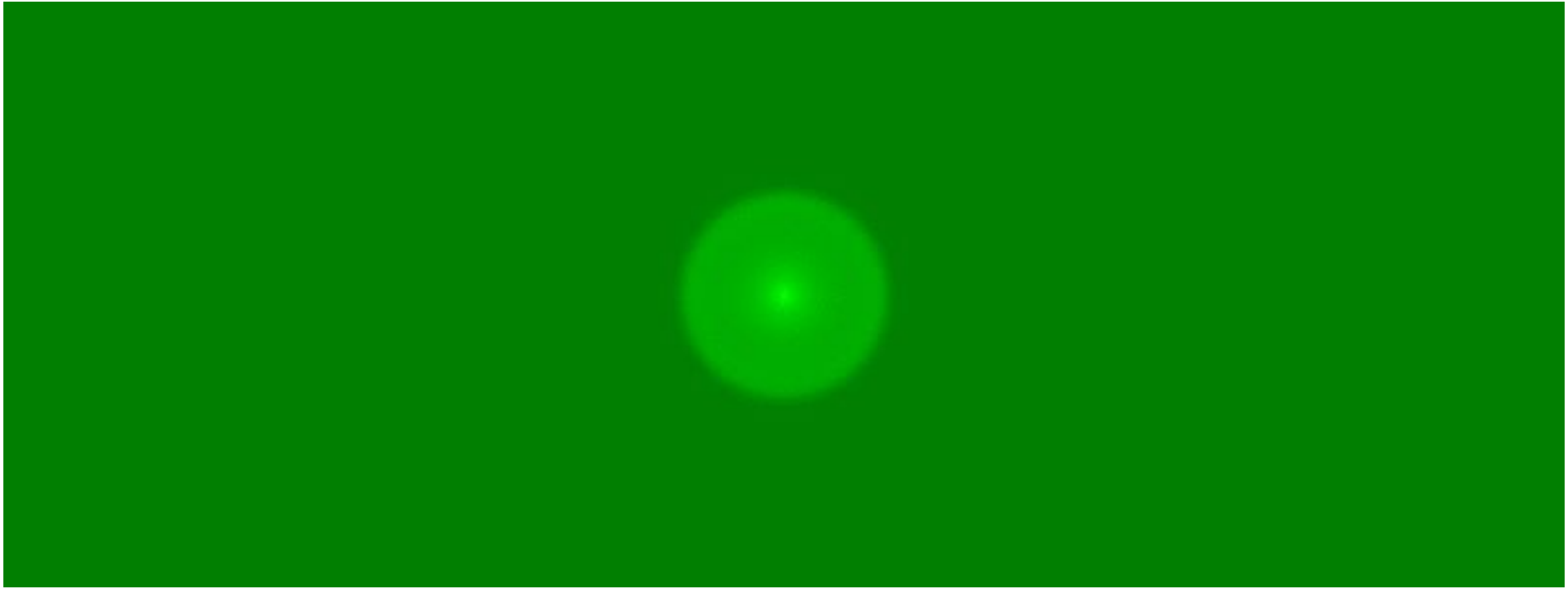
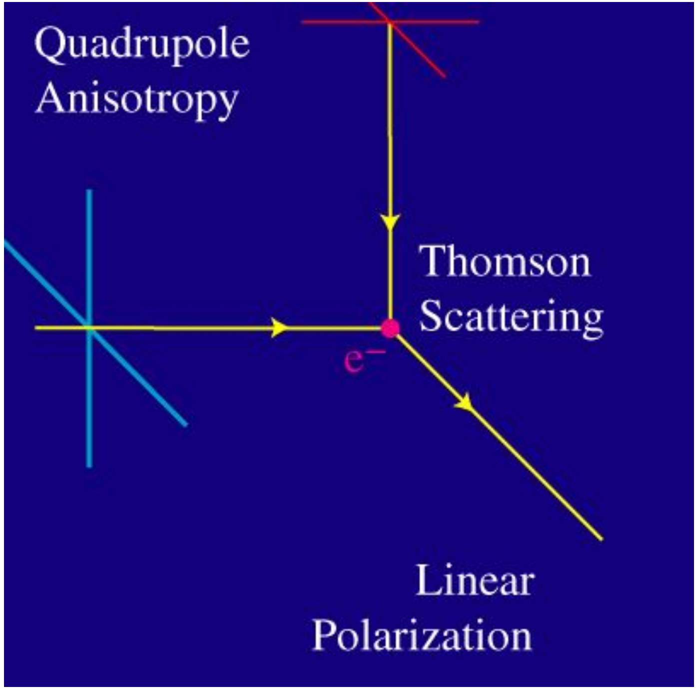


Image Credit: Hincks

Linear Polarization of the CMB



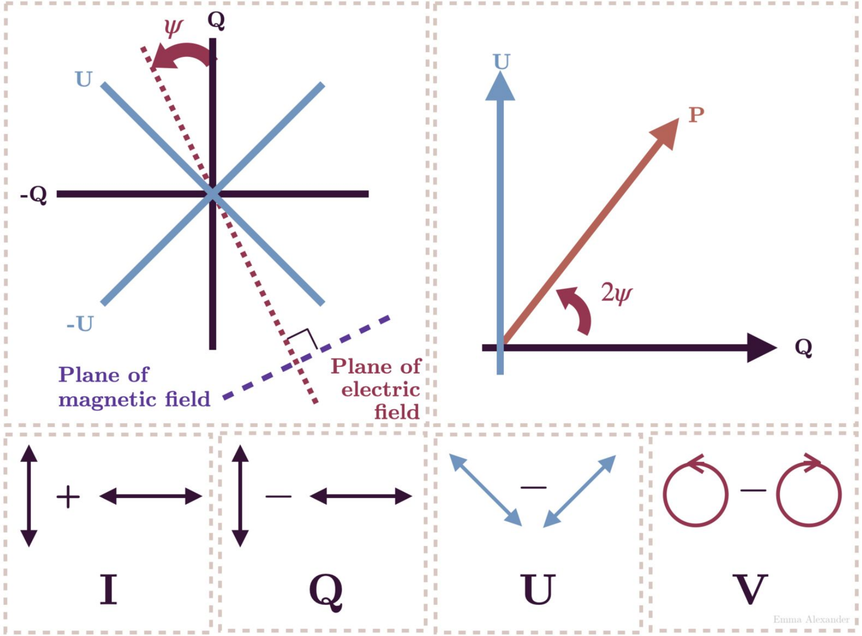
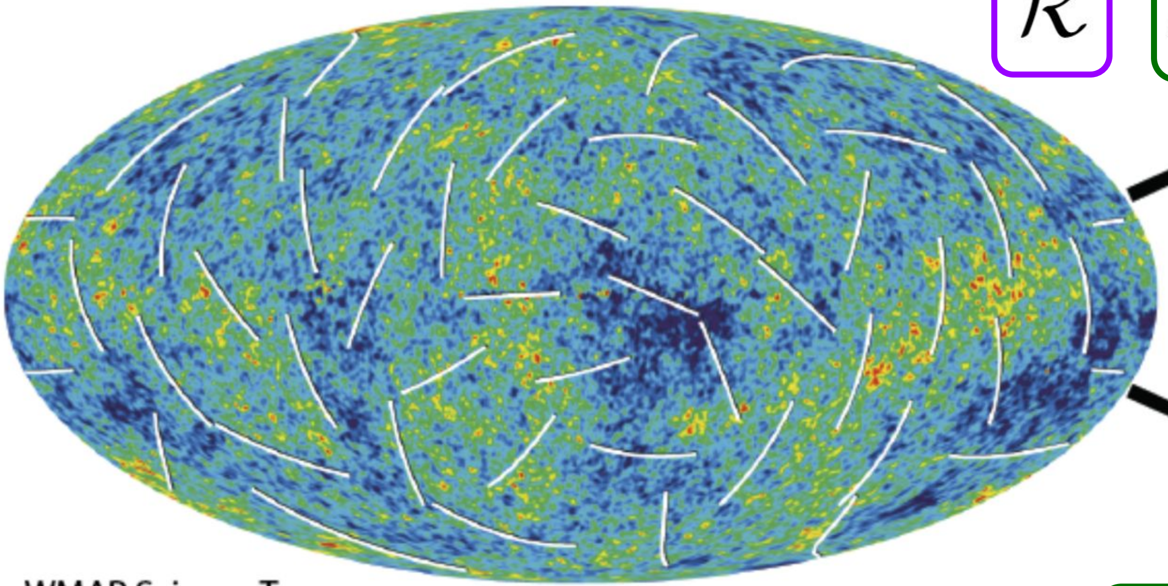


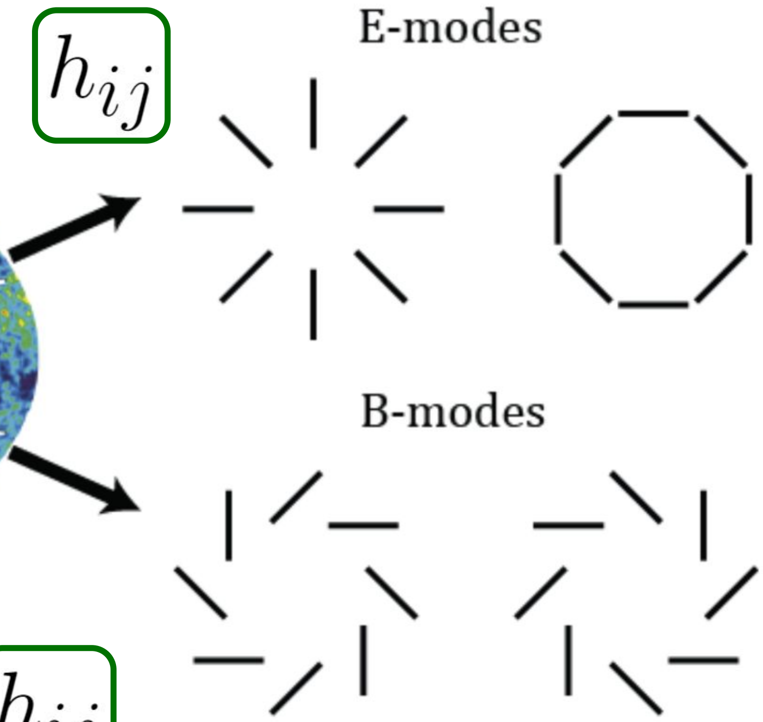
Image Credits: Hu, Alexander

E and B Modes

$\boxed{\mathcal{R}}$ $\boxed{h_{ij}}$



WMAP Science Team

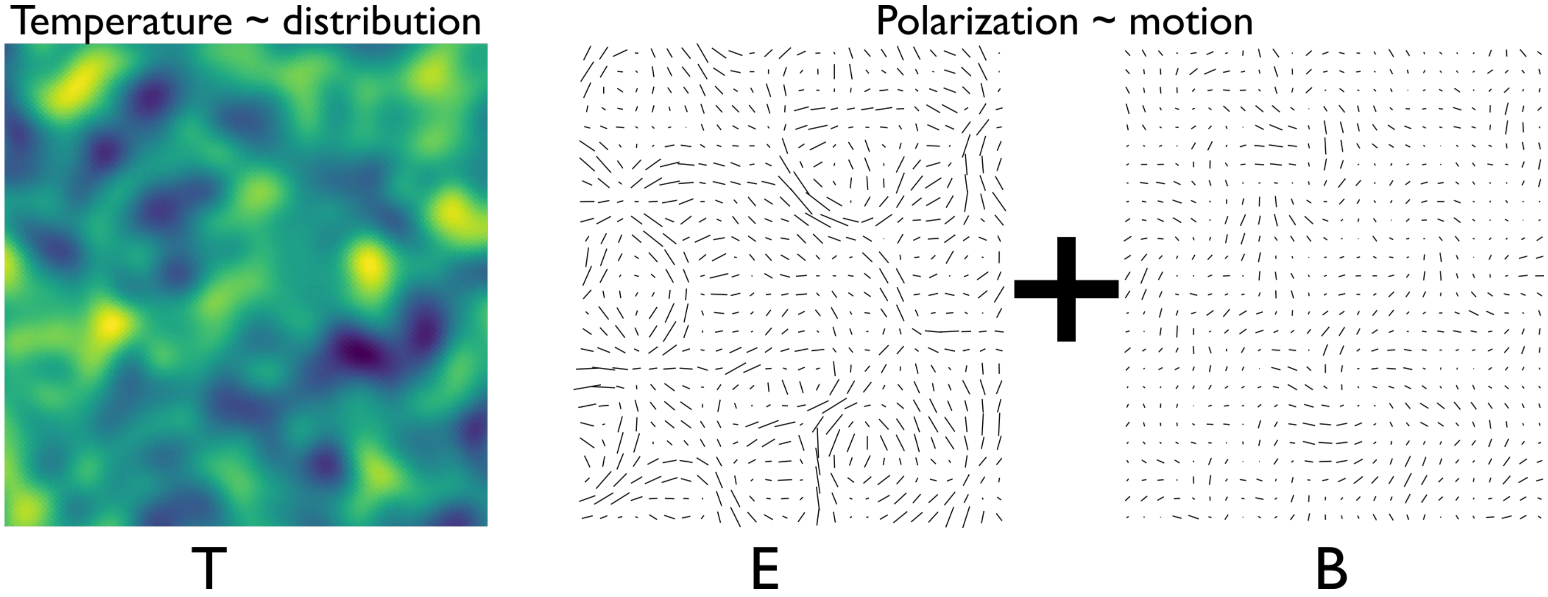


$\boxed{h_{ij}}$

Kamionkowski, Kosowsky, Stebbins (1997); Zaldarriaga, Seljak (1997); Image Credit: PIPER (2014)

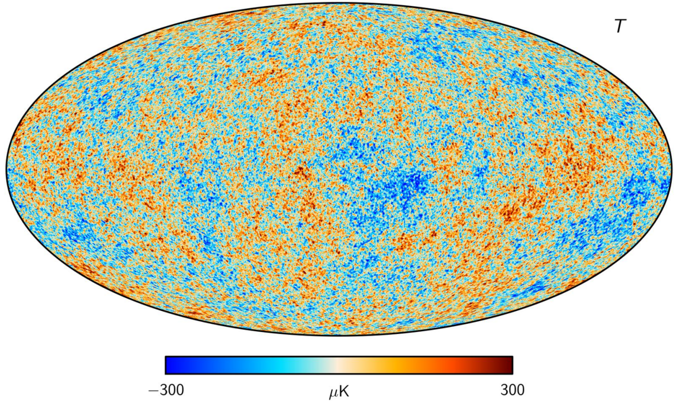
Information In The Cosmic Microwave Background

The CMB provides a snapshot of the universe as it existed during recombination

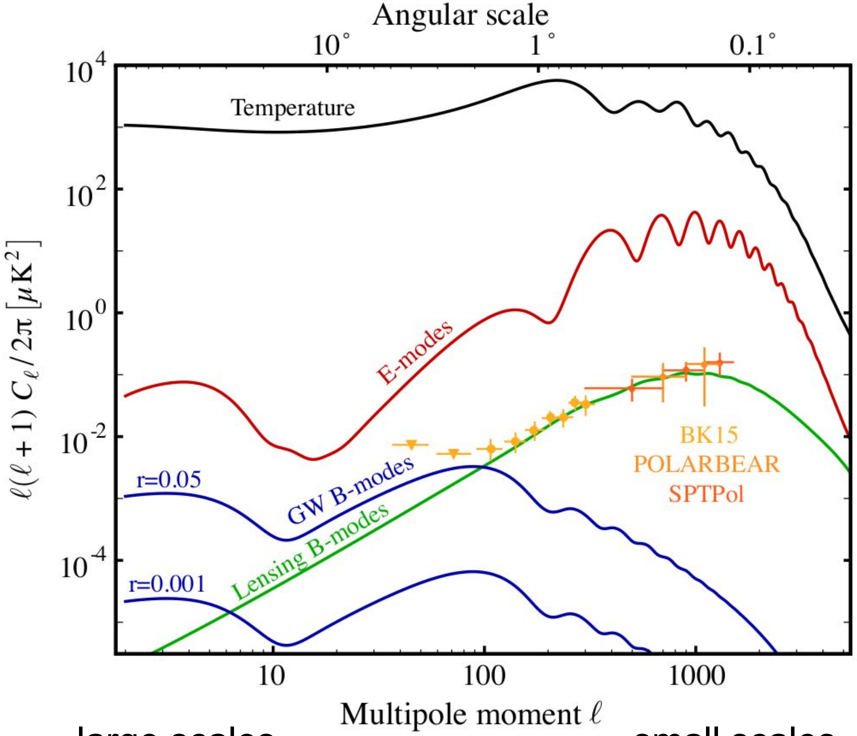


…plus the imprints of the structure between us and the last scattering surface.

Statistical Information and Angular Power Spectra



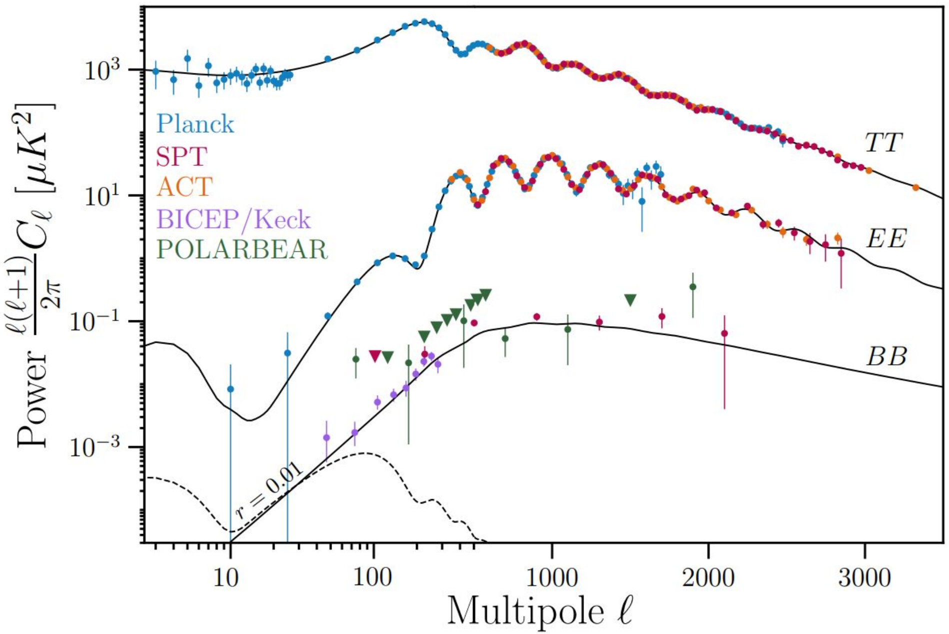
Variance

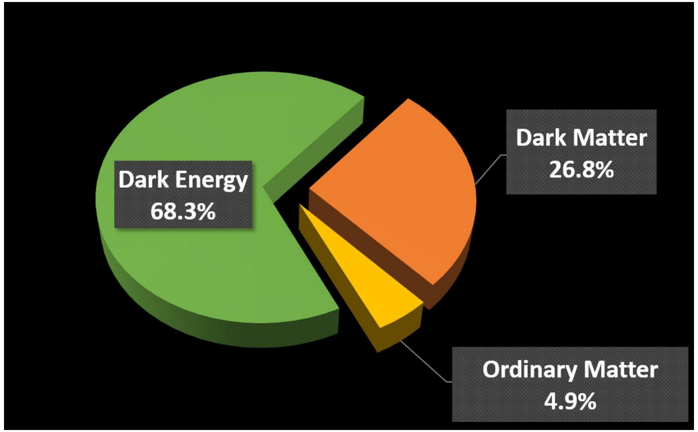


←large scales small scales →

Image Credits: Planck (2018); CMB-S4 (2019)

CMB Observations and Concordance Flat ΛCDM





Planck (2018); Chang, Huffenberger, 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

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

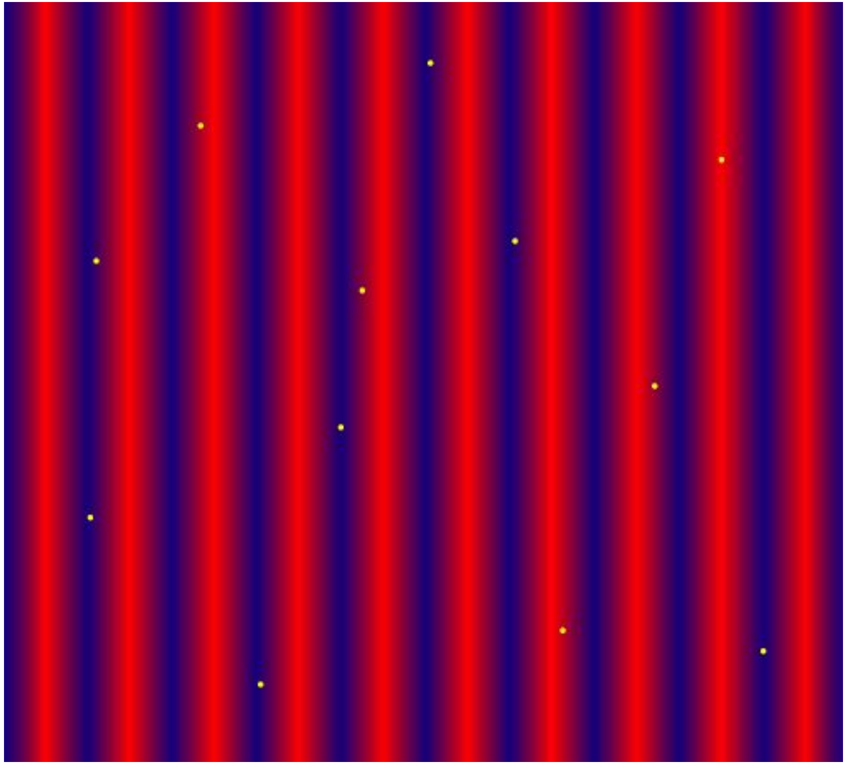
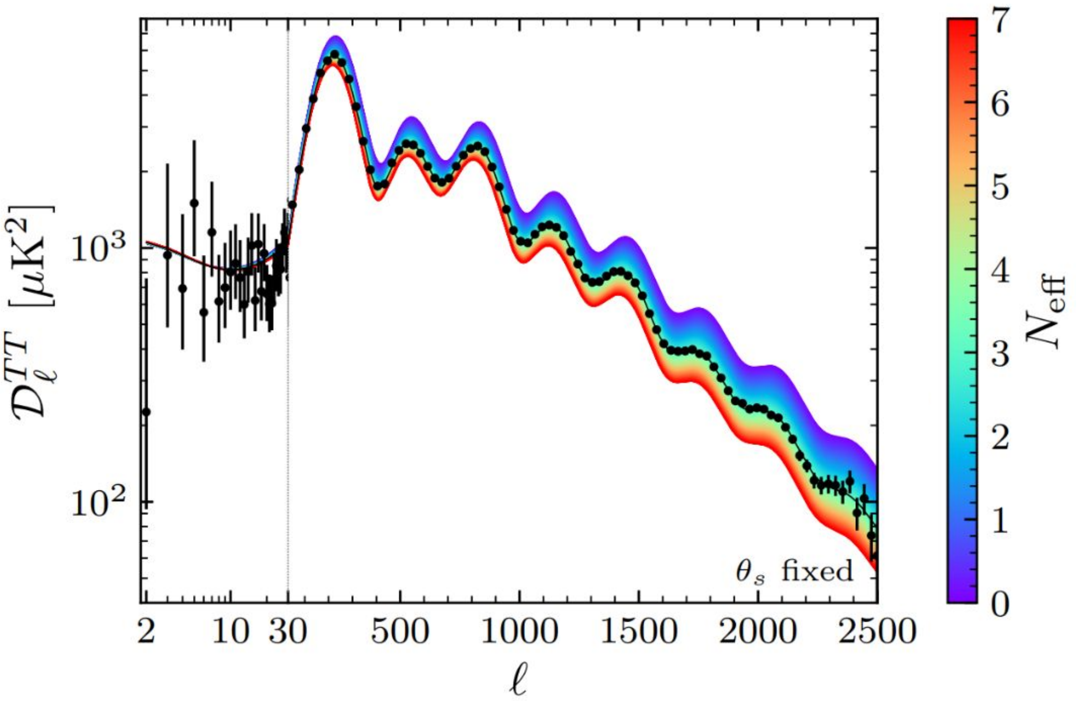


Image Credit: Hu

Light Relics Affect CMB Damping Scale

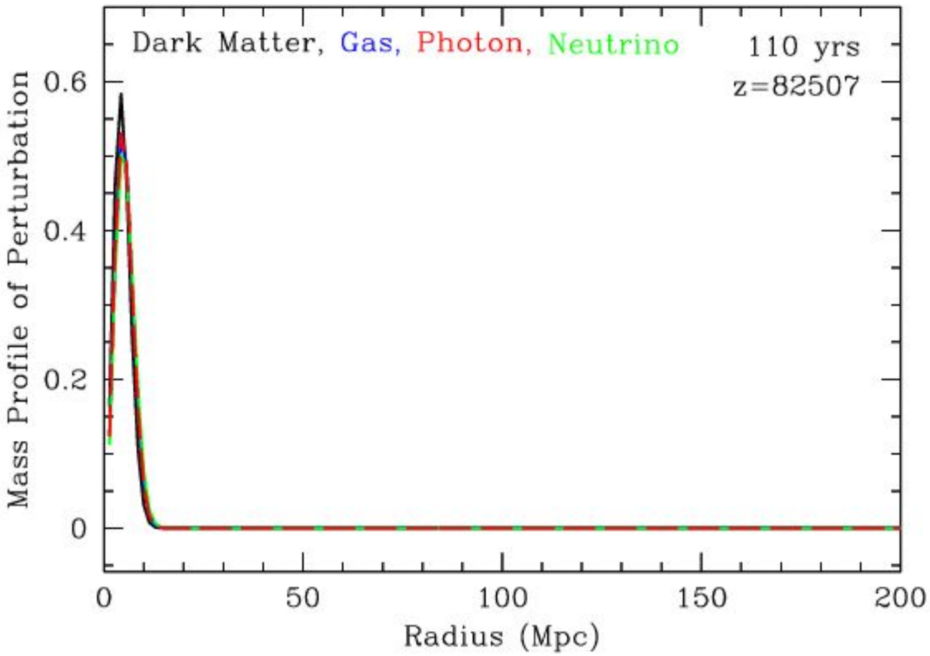


- Increasing N_{eff} increases the expansion rate prior to recombination
- With θ_s fixed (which is measured very well with current observations), increasing N_{eff} leads to increased damping
- The damping scale is also impacted by the free electron density around recombination, which is affected by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

Image Credit: Wallisch (2018)

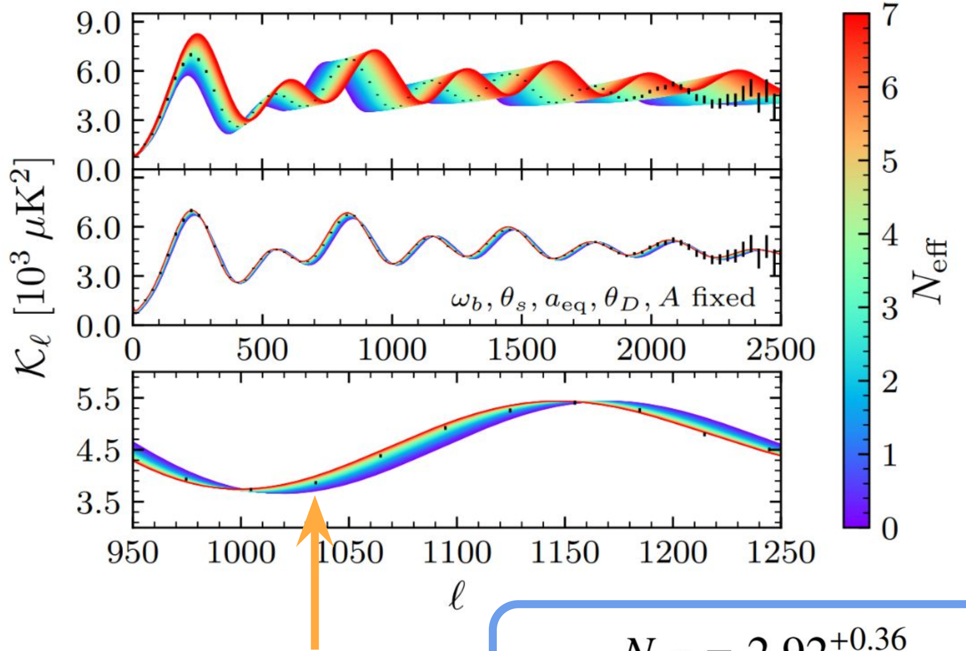
Light Relics Density Perturbations

- 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



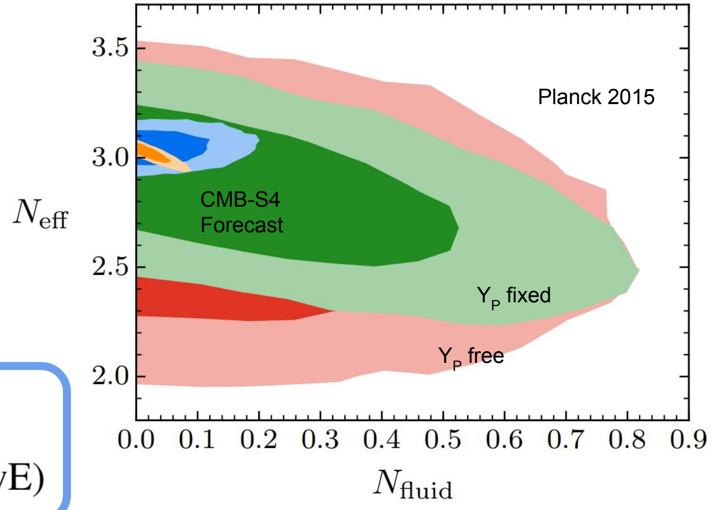
Bashinsky, Seljak (2004); Baumann, Green, JM, Wallisch (2016); Image Credit: Eisenstein

Free-Streaming Light Relics and the Phase Shift



Free-streaming
phase shift

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



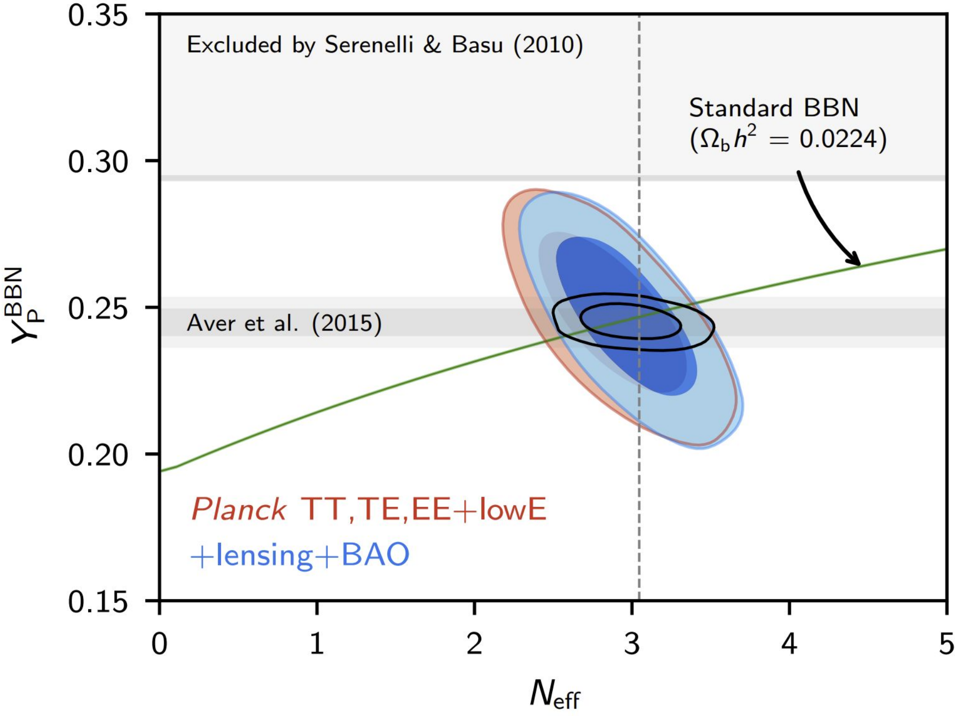
$$N_{\rm eff} = 2.92^{+0.36}_{-0.37}$$

(95 %, *Planck* TT,TE,EE+lowE)

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

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)

Constraints on the Light Relic Density

Current Constraint

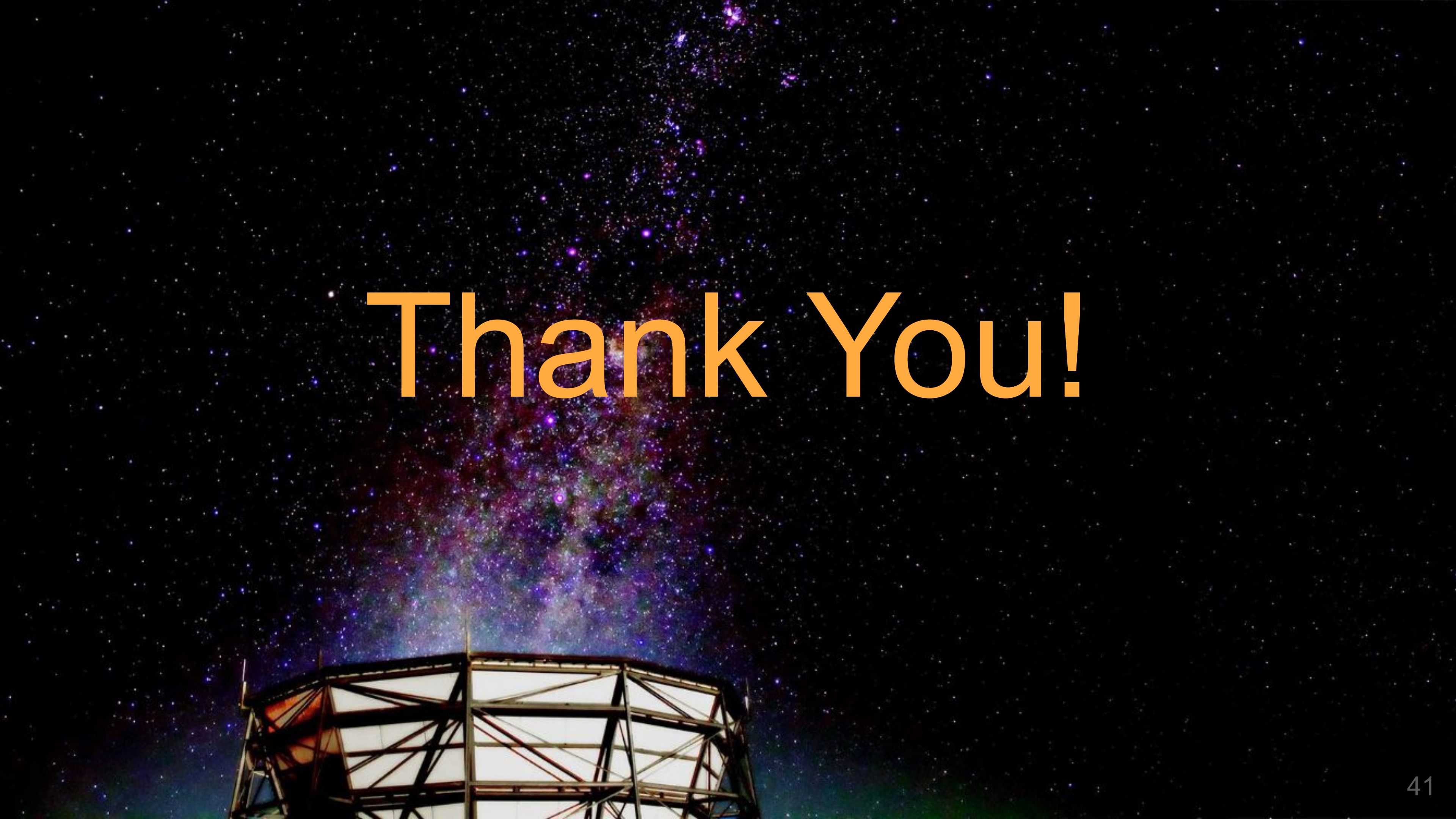
$$N_{\mathrm{eff}} = 2.92^{+0.36}_{-0.37}$$

(95 %, *Planck* TT,TE,EE+lowE)

CMB-S4 Target

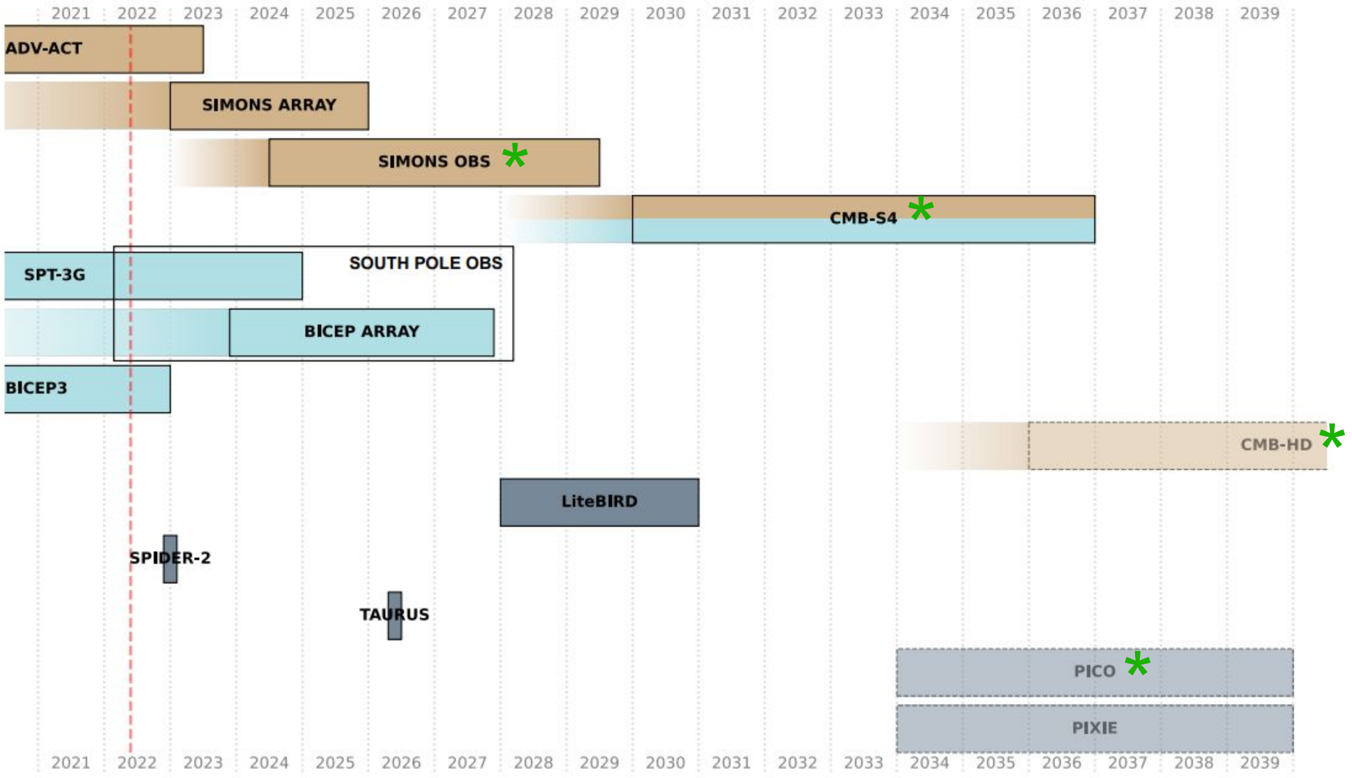
$$\Delta N_{\mathrm{eff}} \leq 0.060\ (95\%)$$

Planck (2018), CMB-S4 (2019)


Thank You!

Backup Slides

Timeline of Upcoming CMB Surveys



Chang, Huffenberger, et al (2022)