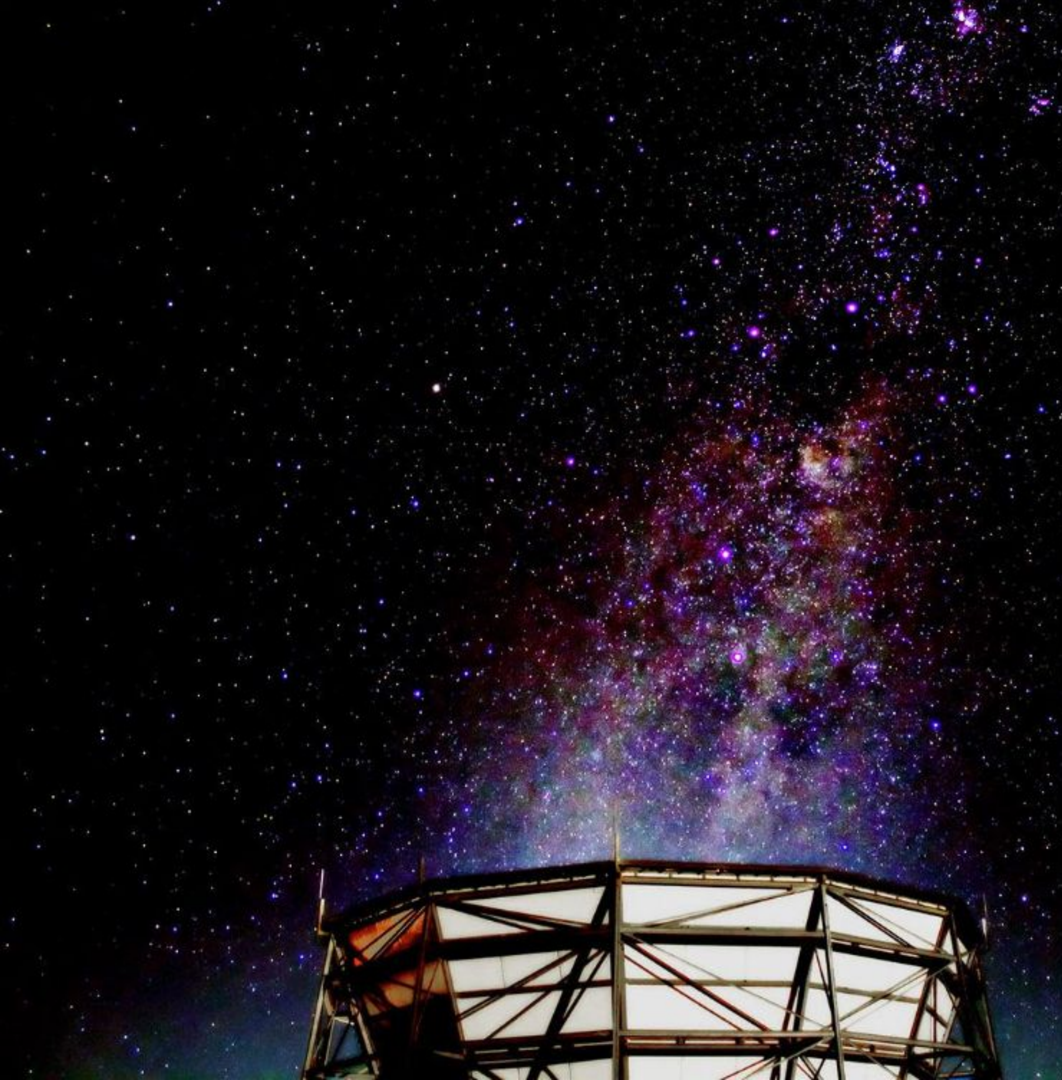


Neutrinos and Cosmology II

Joel Meyers

International Neutrino Summer School 2023

8-18-2023

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

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

History of the Universe

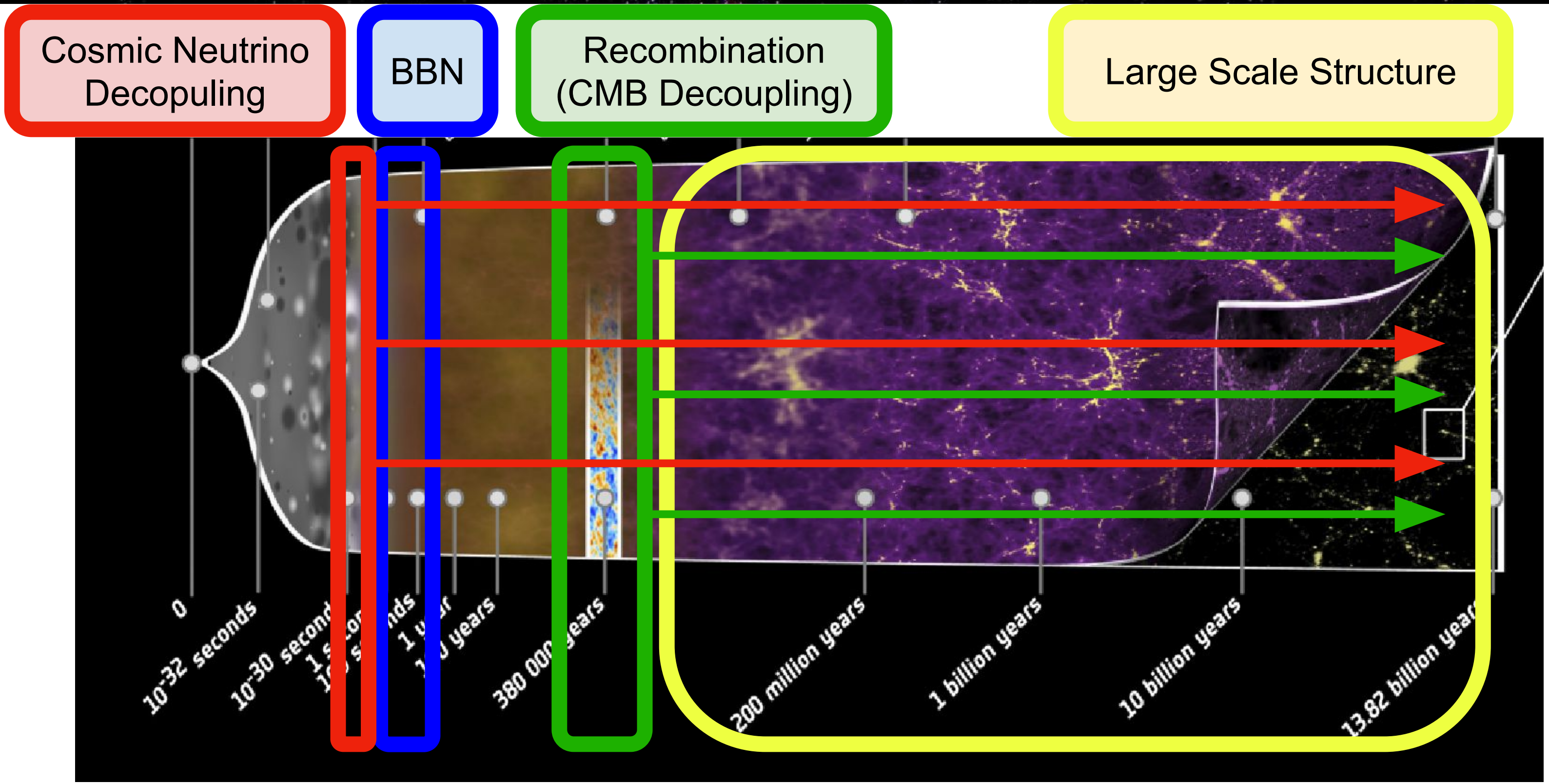
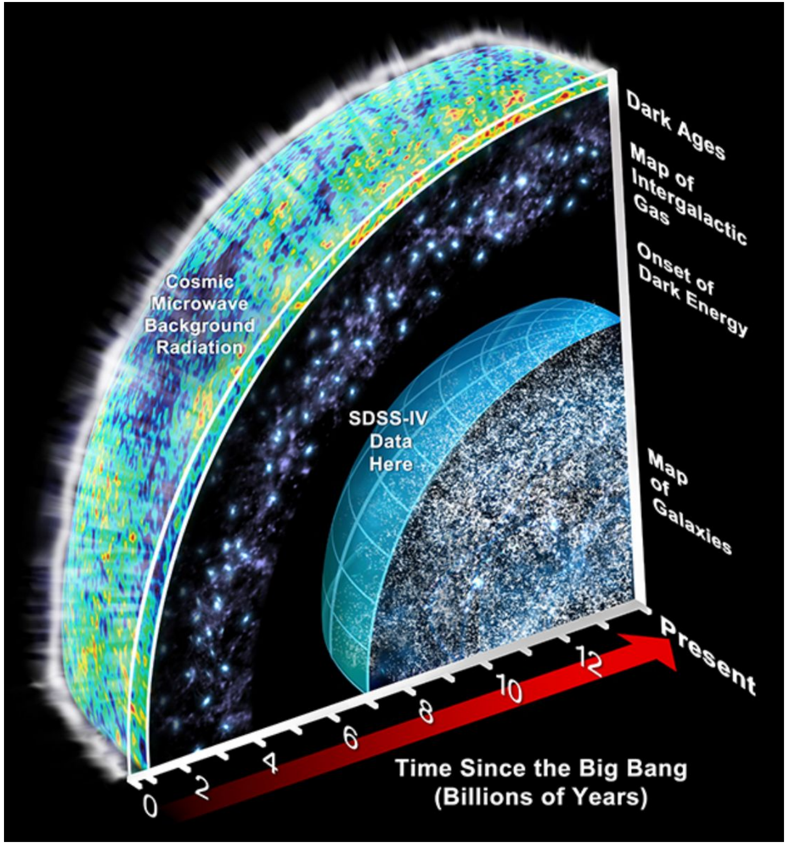


Image Credit: NASA

Cosmic Microwave Background Basics

The Cosmic Microwave Background



Cosmic Microwave Background (CMB) Spectrum

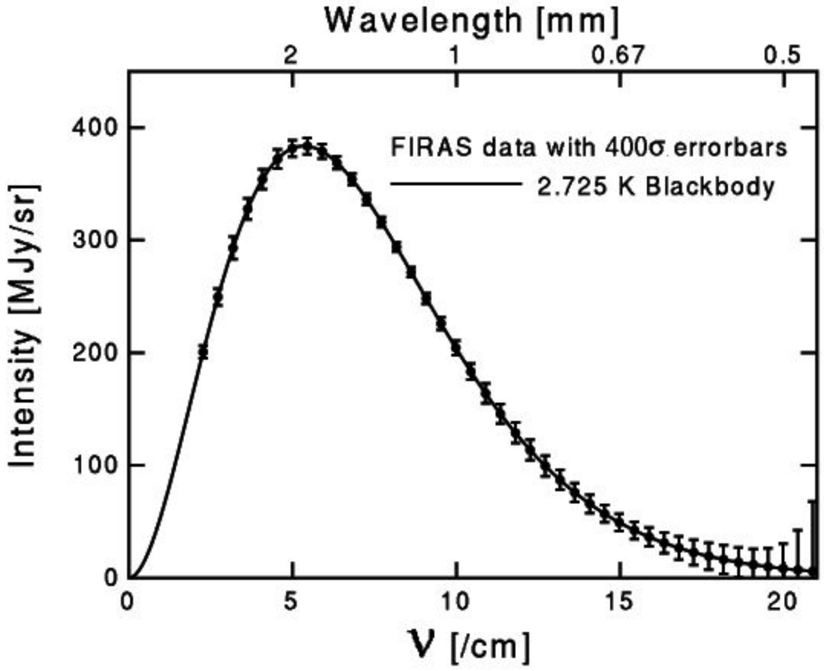
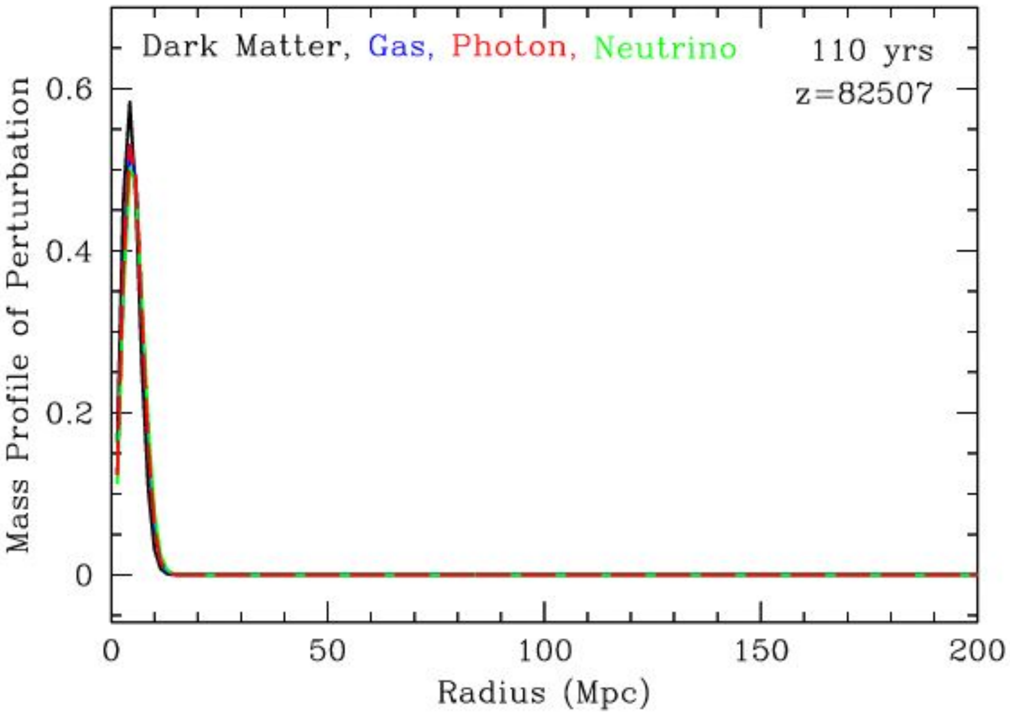


Image Credits: SDSS, COBE FIRAS

Sound Waves in the Primordial Plasma



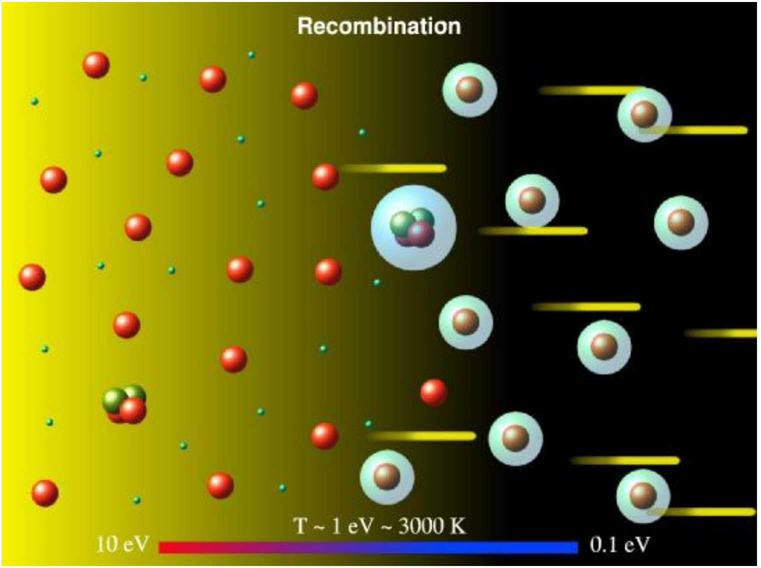


Image Credits: Eisenstein, Kinney

Superposition of Sound Waves

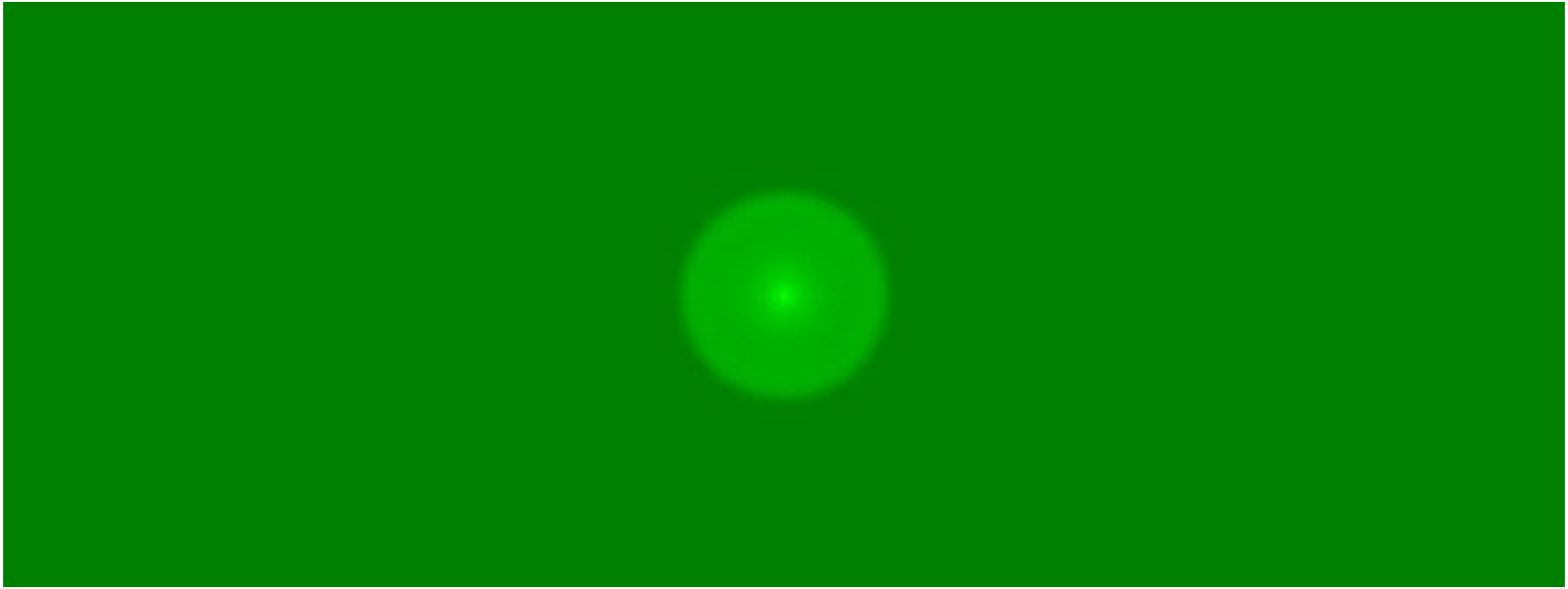
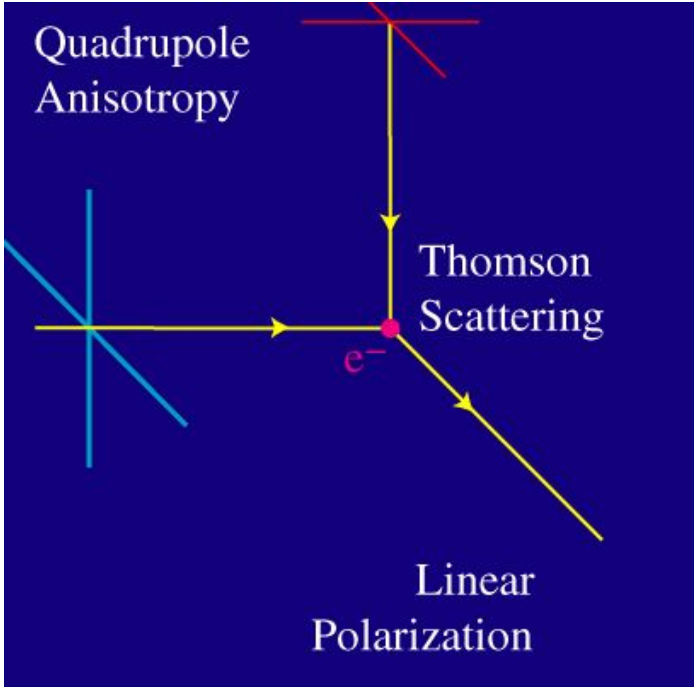


Image Credit: Hincks

Linear Polarization of the CMB



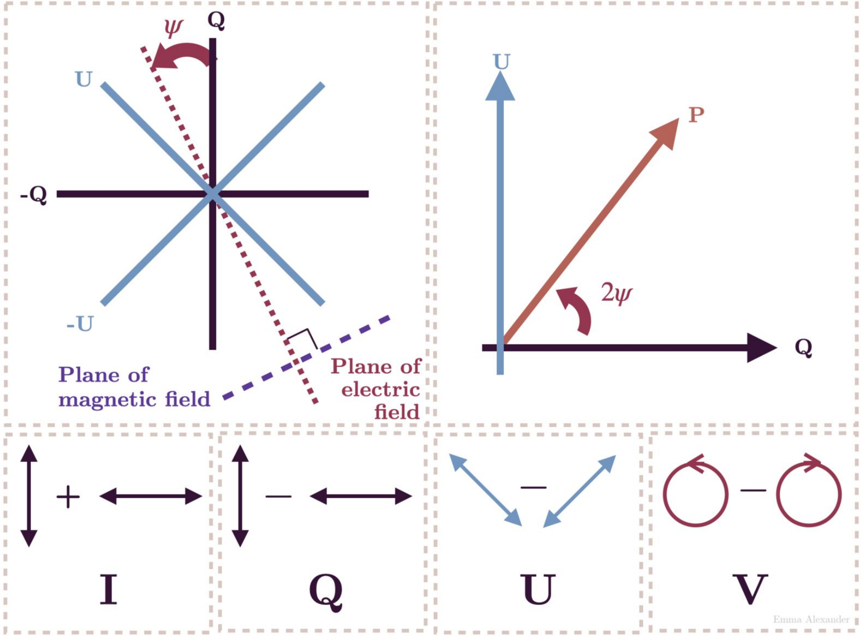
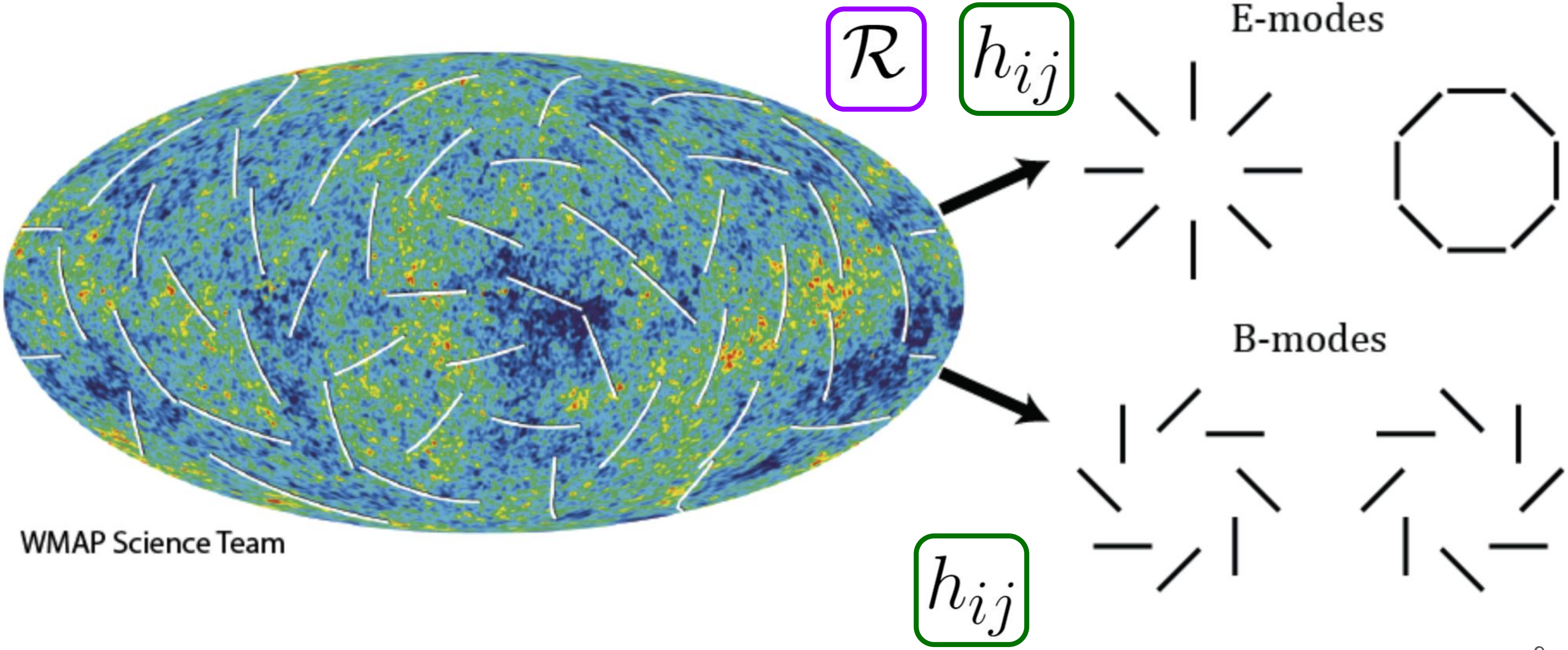


Image Credits: Hu, Alexander

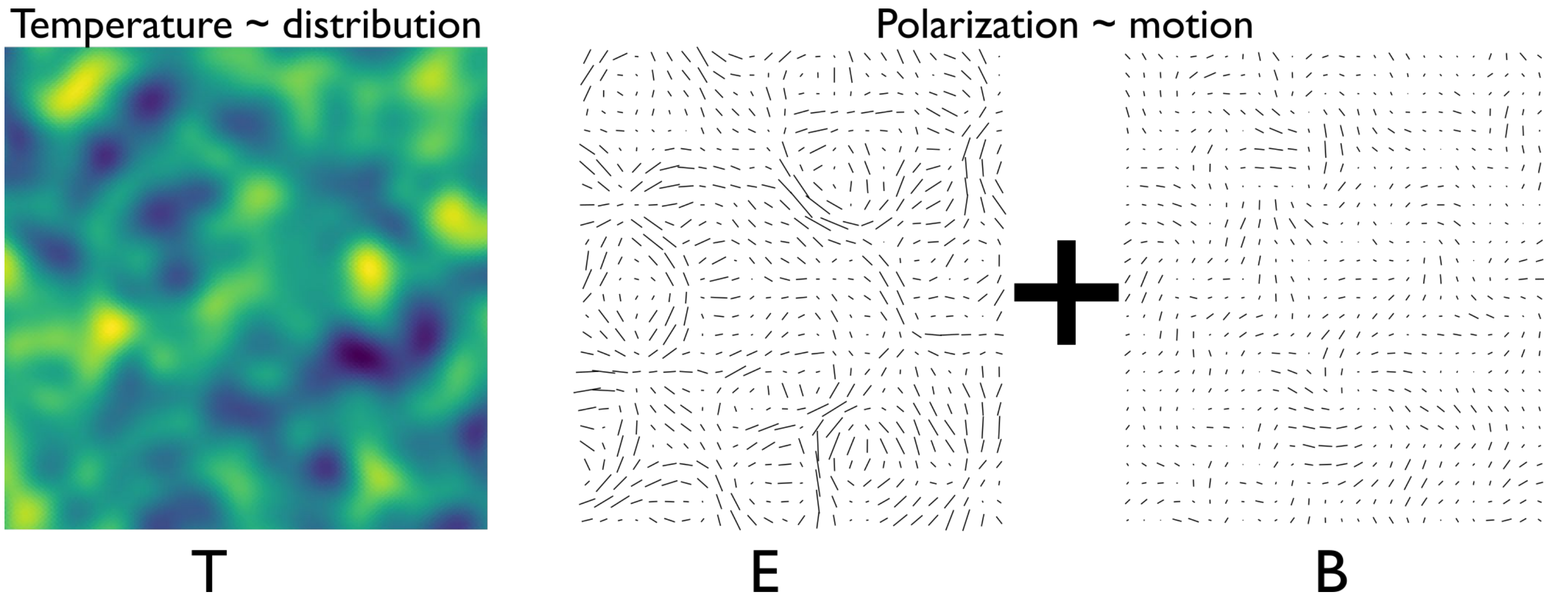
E and B Modes



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

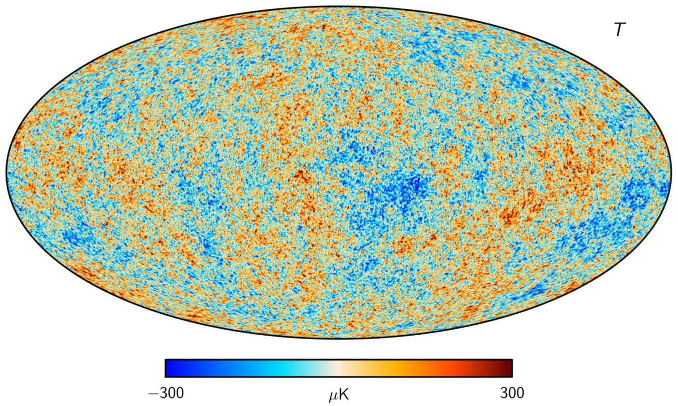
Information In The Cosmic Microwave Background

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

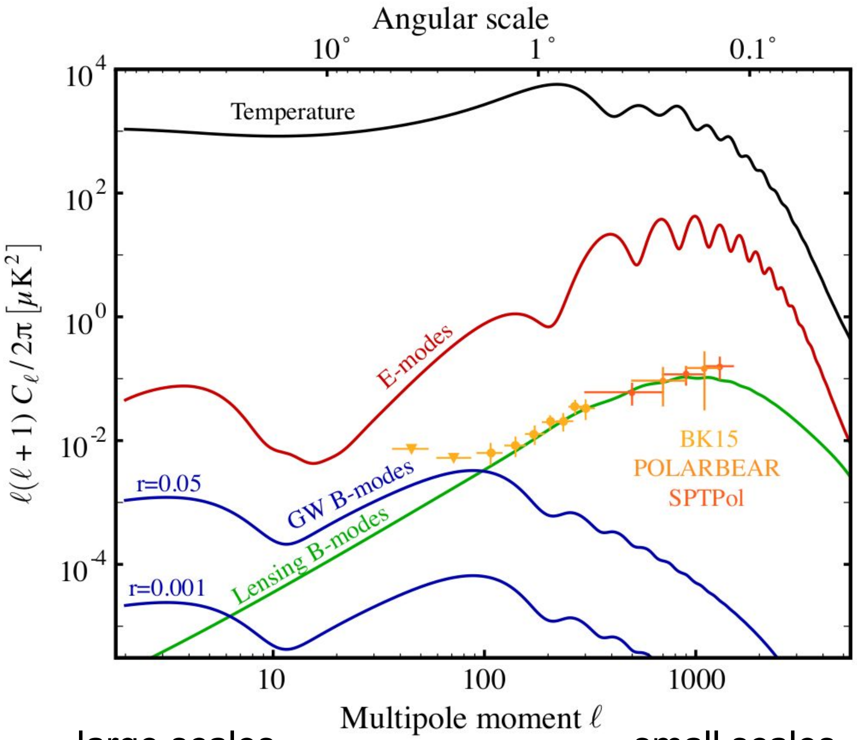


…plus the imprints of the structure between us and the last scattering surface.

Statistical Information and Angular Power Spectra



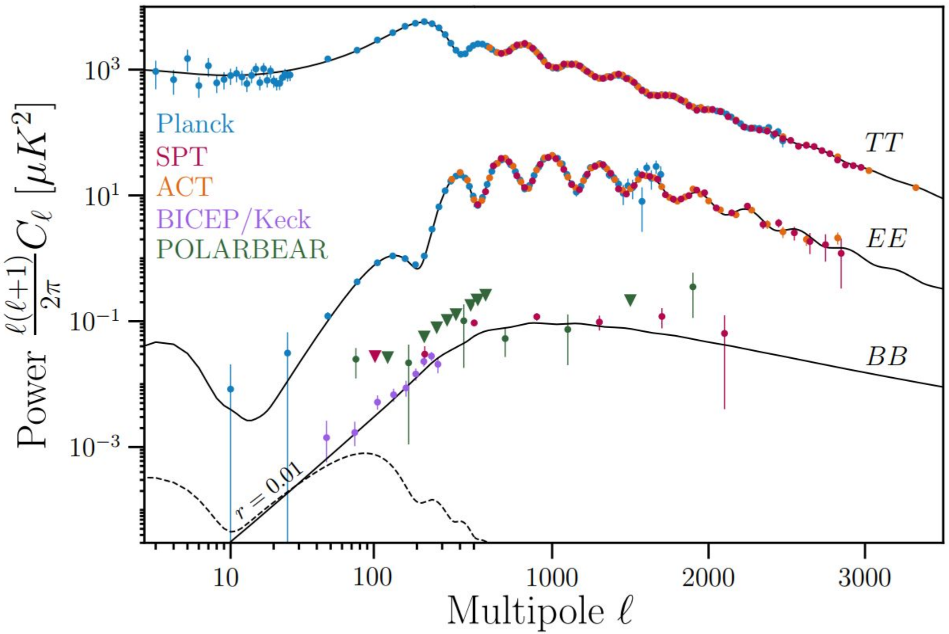
Variance

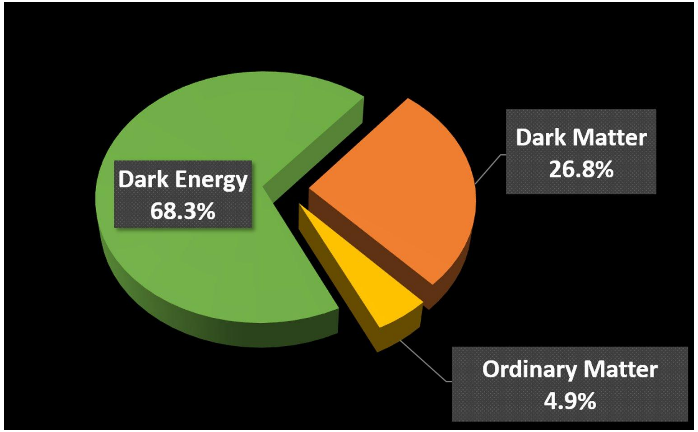


←large scales small scales →

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

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

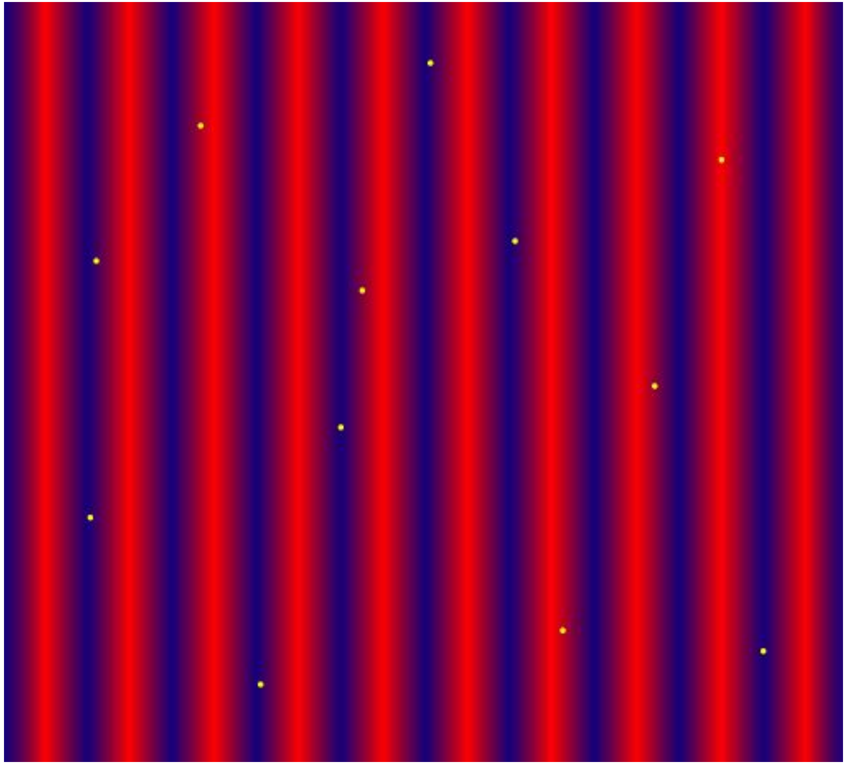
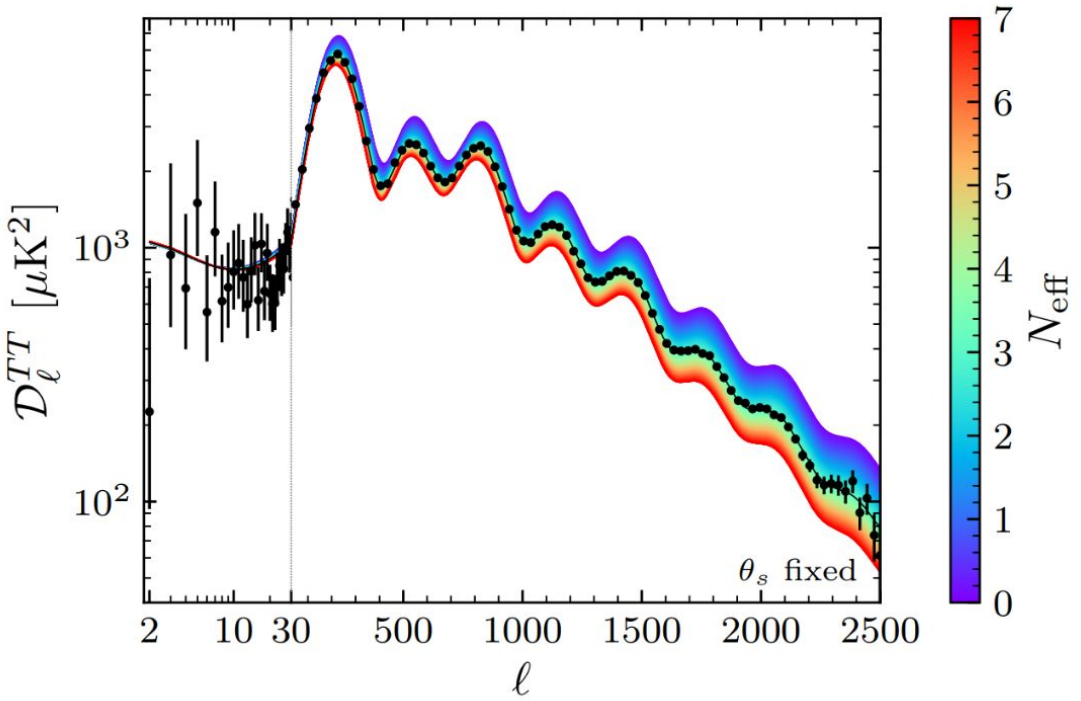


Image Credit: Hu

Light Relics Affect CMB Damping Scale

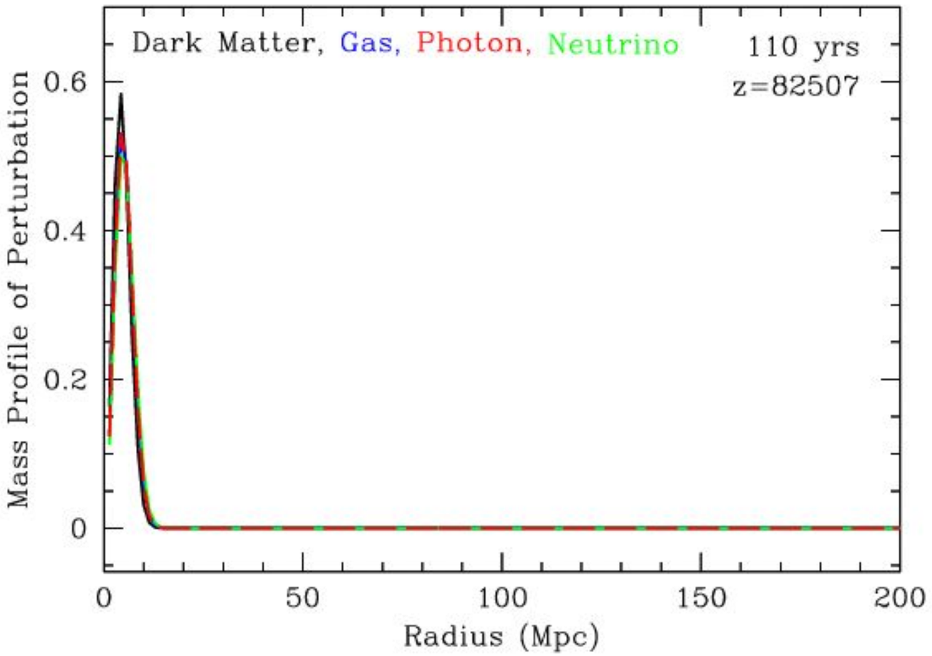


- Increasing N_{eff} increases the expansion rate prior to recombination
- With θ_s fixed (which is measured very well with current observations), increasing N_{eff} leads to increased damping
- The damping scale is also impacted by the free electron density around recombination, which is affected by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

Image Credit: Wallisch (2018)

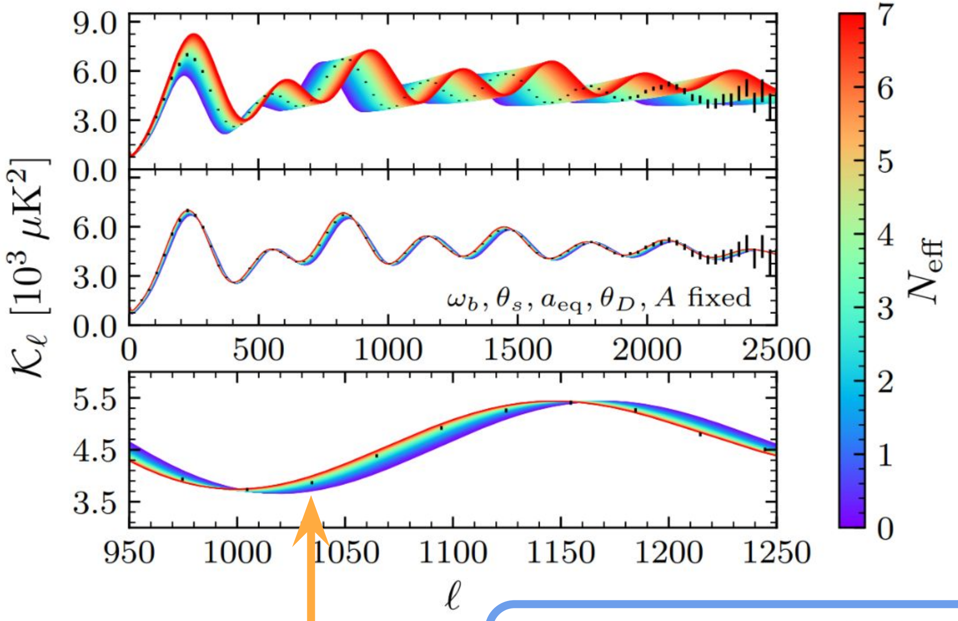
Light Relics Density Perturbations

- 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



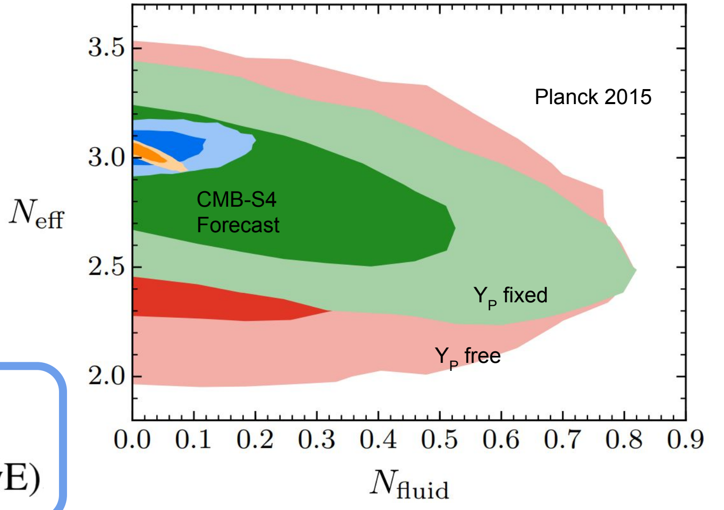
Bashinsky, Seljak (2004); Baumann, Green, JM, Wallisch (2016); Image Credit: Eisenstein

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

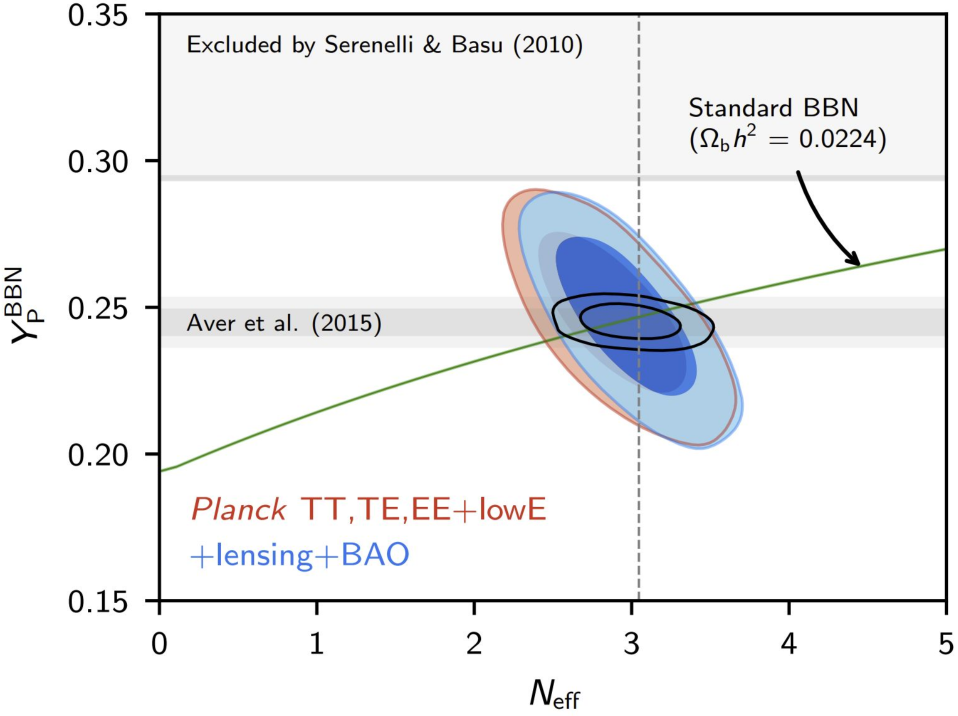


$$\boxed{N_{\rm eff} = 2.92^{+0.36}_{-0.37} \quad (95\,\%, \textit{Planck}\ \text{TT,TE,EE+lowE})}$$

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

$$N_{\rm eff} = 2.92^{+0.36}_{-0.37}$$
(95 %, *Planck* TT,TE,EE+lowE)

CMB-S4 Target

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

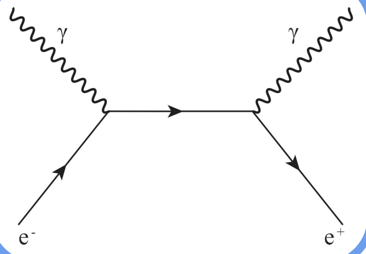
Planck (2018), CMB-S4 (2019)

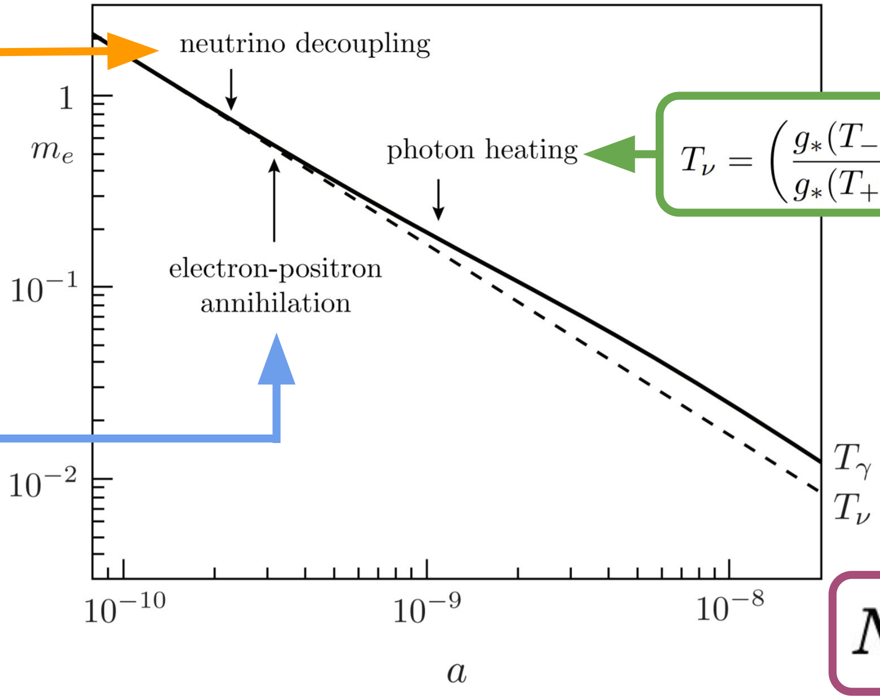
Massive Cosmic Neutrinos

Summary of Cosmic Neutrino Decoupling

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

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



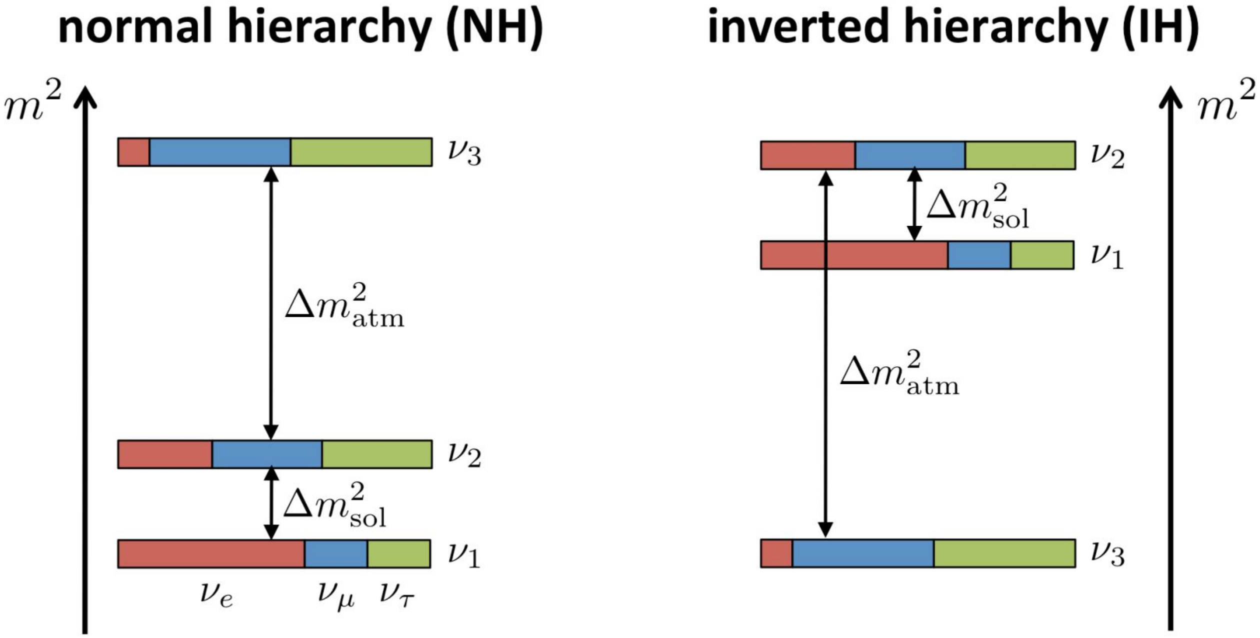


$$T_\nu = \left(\frac{g_*(T_-)}{g_*(T_+)}\right)^{1/3} T_\gamma = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

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

Baumann (2018); Akita, Yamaguchi (2020)

Massive Cosmic Neutrinos



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

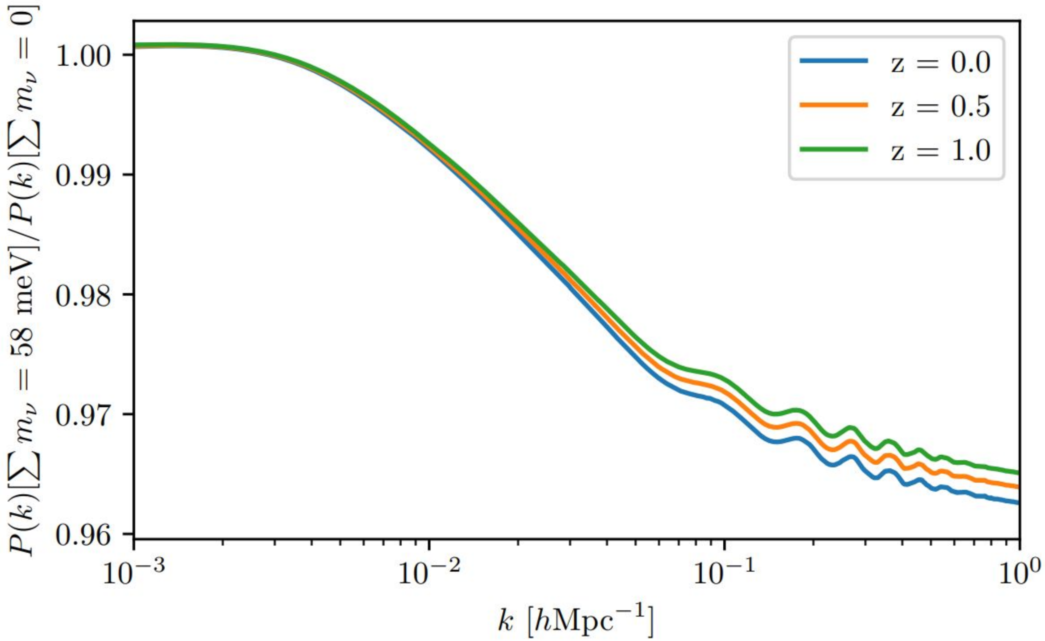
The low temperature of cosmic neutrinos and the mass-squared splittings measured from neutrino flavor oscillations imply that at least two mass eigenstates are non-relativistic today

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

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

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

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

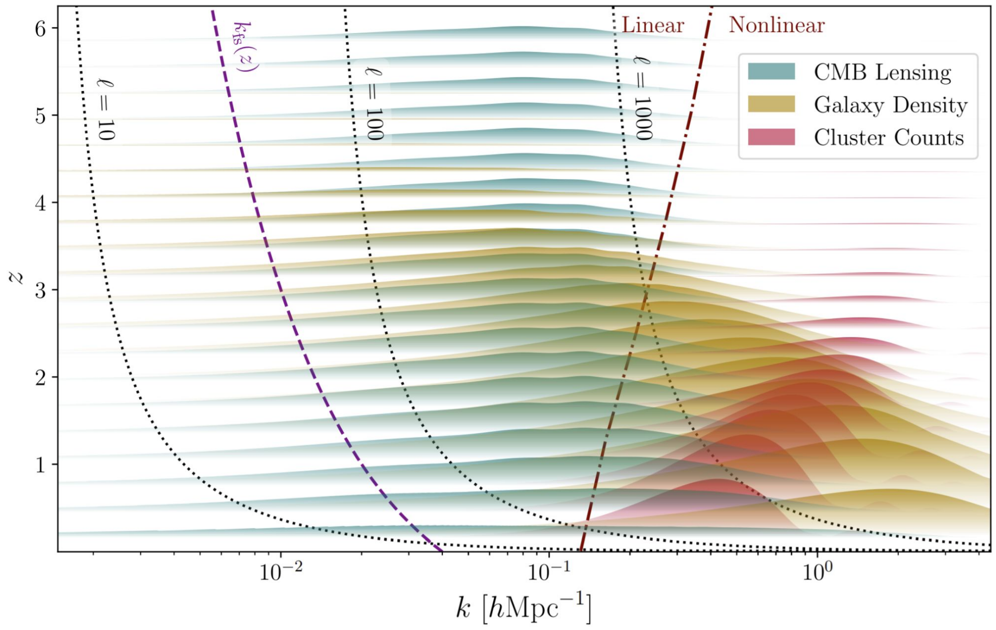
$$k_{\rm fs} = 0.04\, h\, \mathrm{Mpc}^{-1} \times \frac{1}{1+z}\left(\frac{\sum m_\nu}{58\,\mathrm{meV}}\right)$$

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

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

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

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)

CMB Lensing and Neutrino Mass

Gravitational Lensing of the CMB

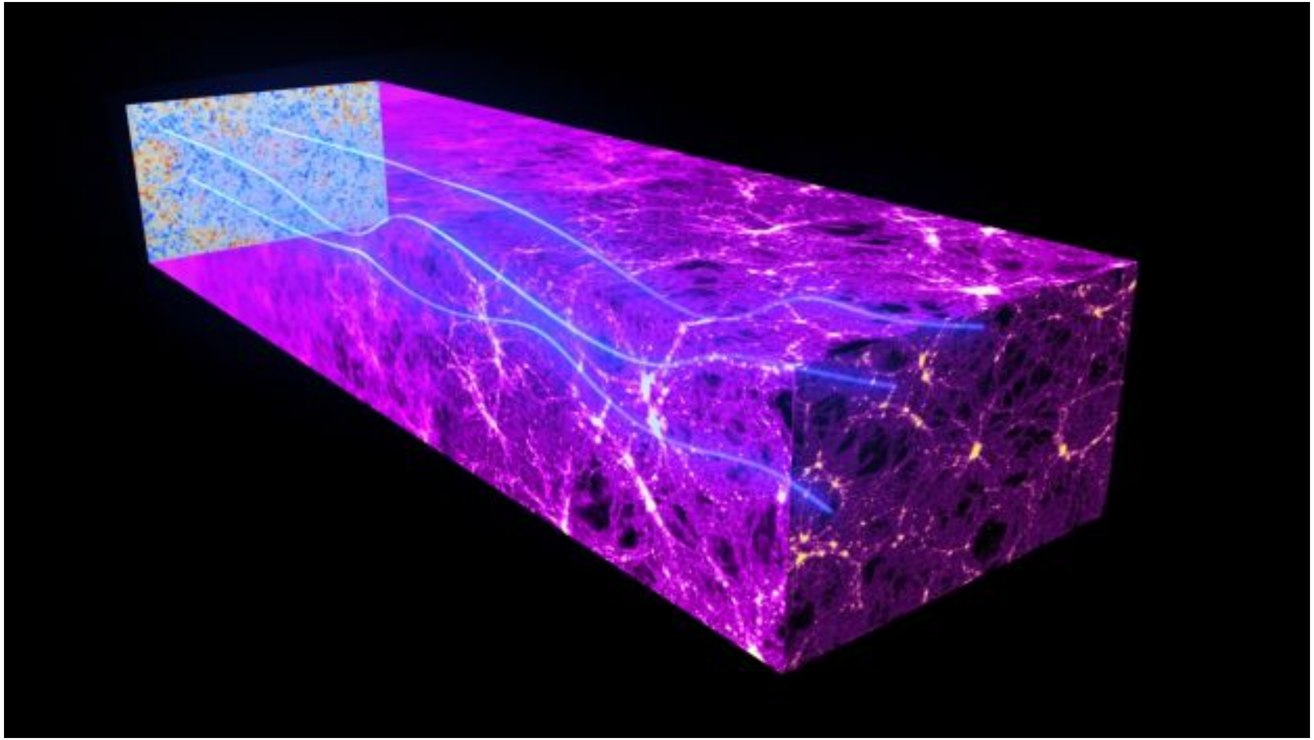
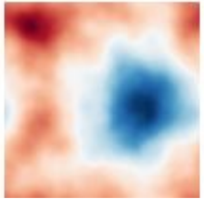


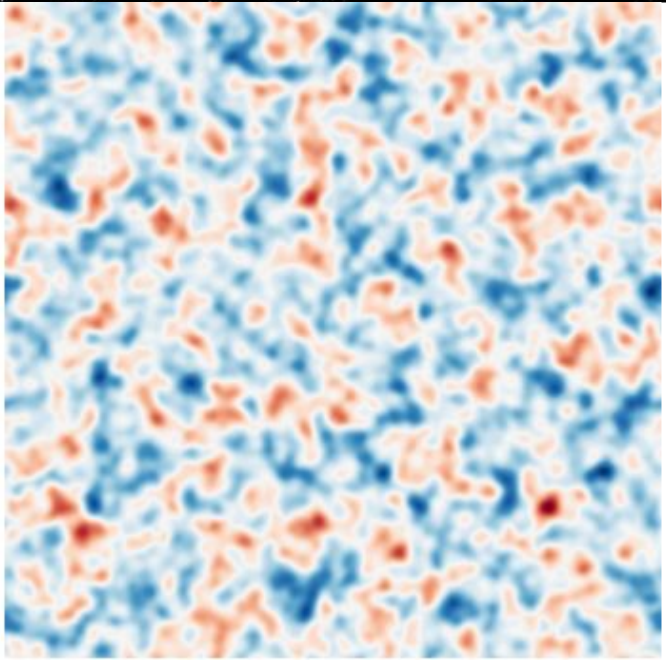
Image Credit: Planck / ESA

Unlensed CMB Polarization

Unlensed B

ϕ

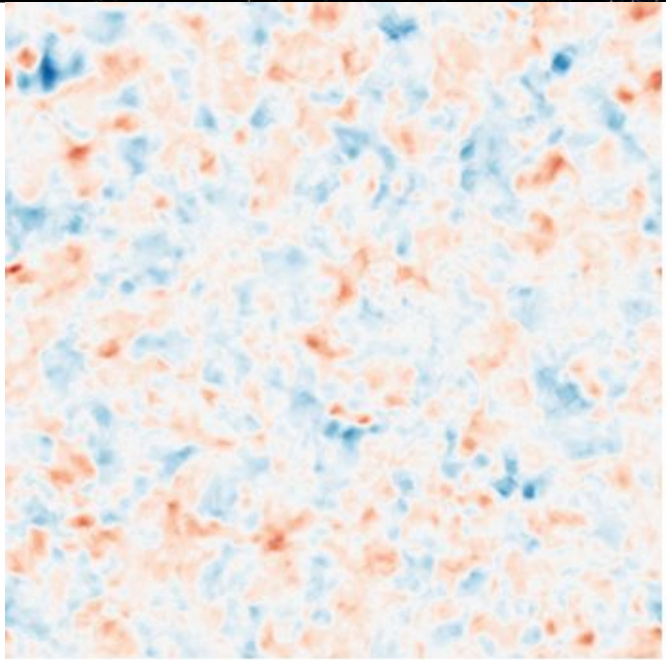




Unlensed E

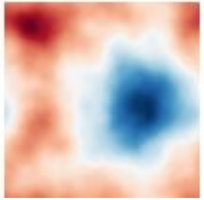
Image Credit: Guzman

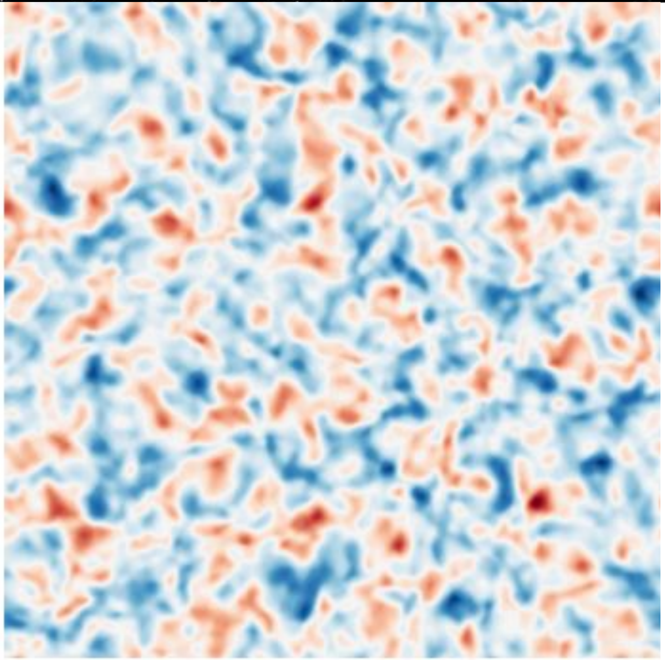
Lensed CMB Polarization



Lensed B

ϕ

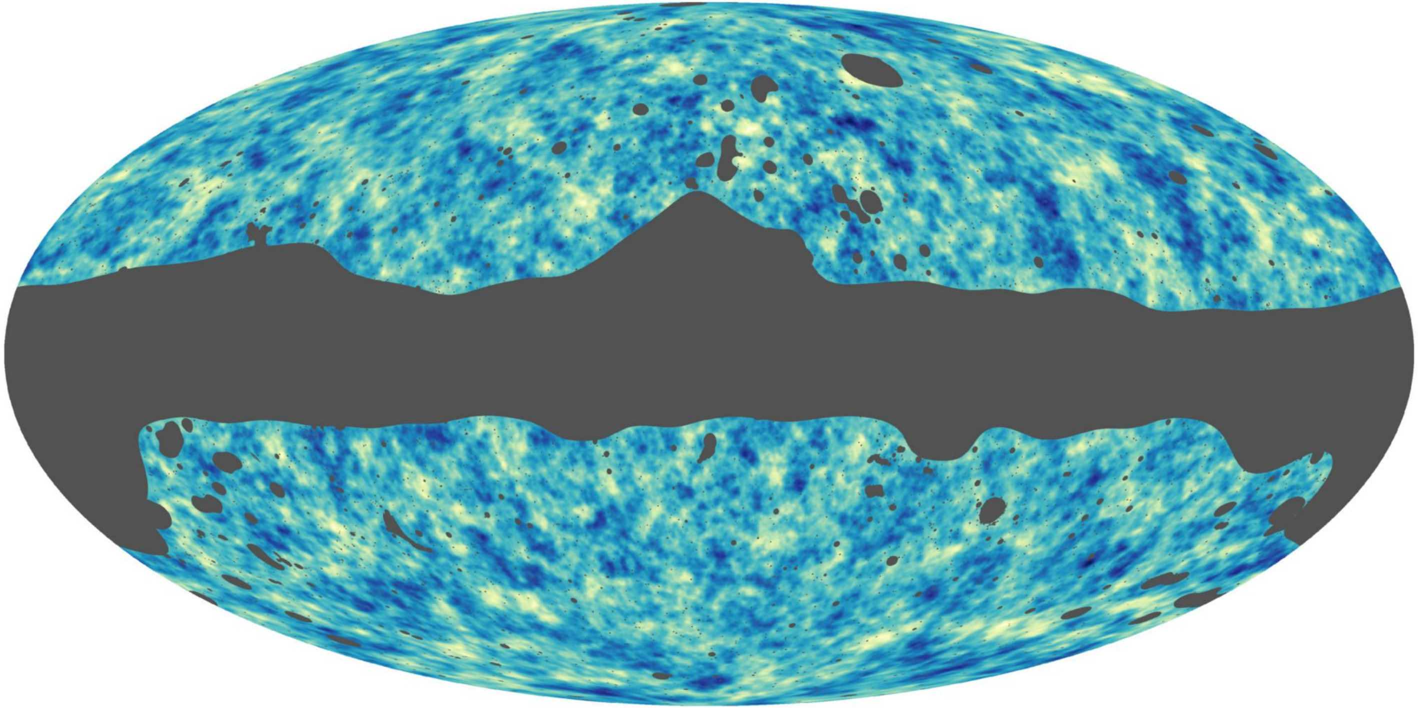




Lensed E

Image Credit: Guzman

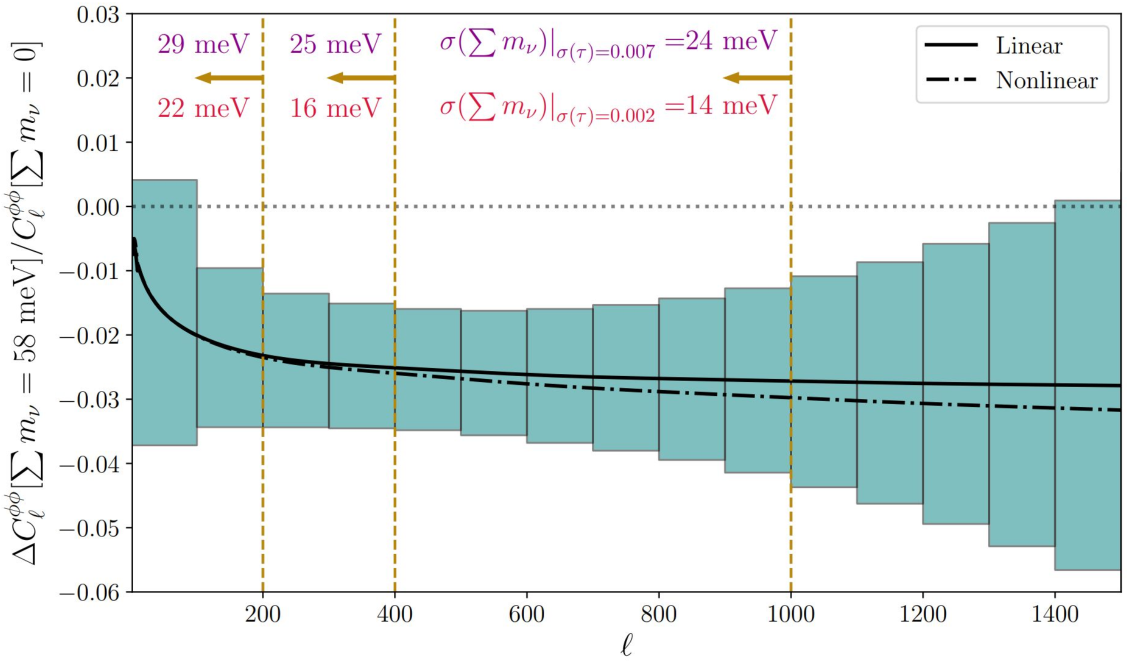
CMB Lensing Reconstruction Maps Matter Overdensities



40σ Measurement

Planck (2018)

Neutrino Mass with CMB Lensing

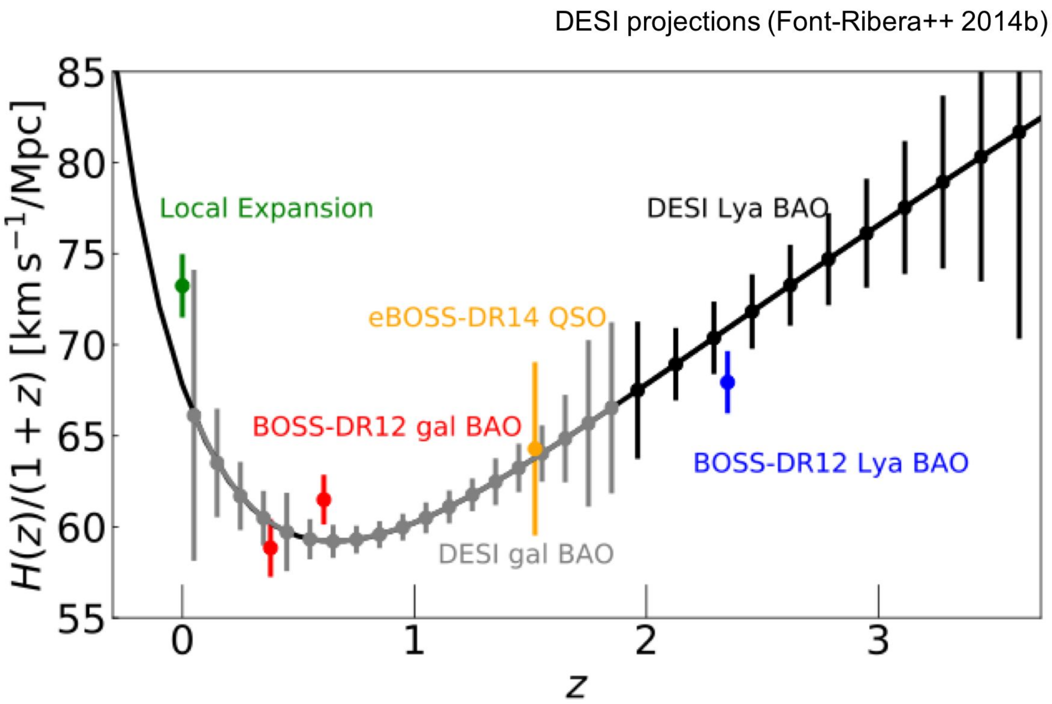


Measuring suppression of clustering with CMB-S4 lensing

- CMB lensing provides a clean probe of matter clustering in a regime that is mostly insensitive to details of nonlinear growth and astrophysical baryonic feedback effects
- Suppression will be clearly visible with upcoming experiments, but is subject to two important degeneracies:
  - Matter density
  - Primordial Amplitude / Optical depth

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

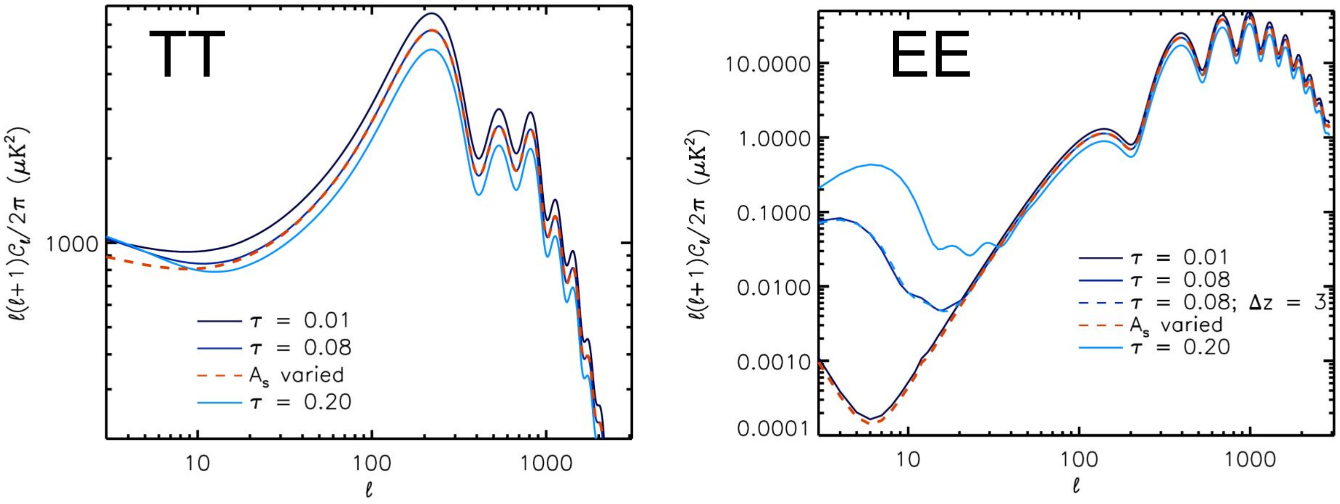
Matter Density with Baryon Acoustic Oscillations



- 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)

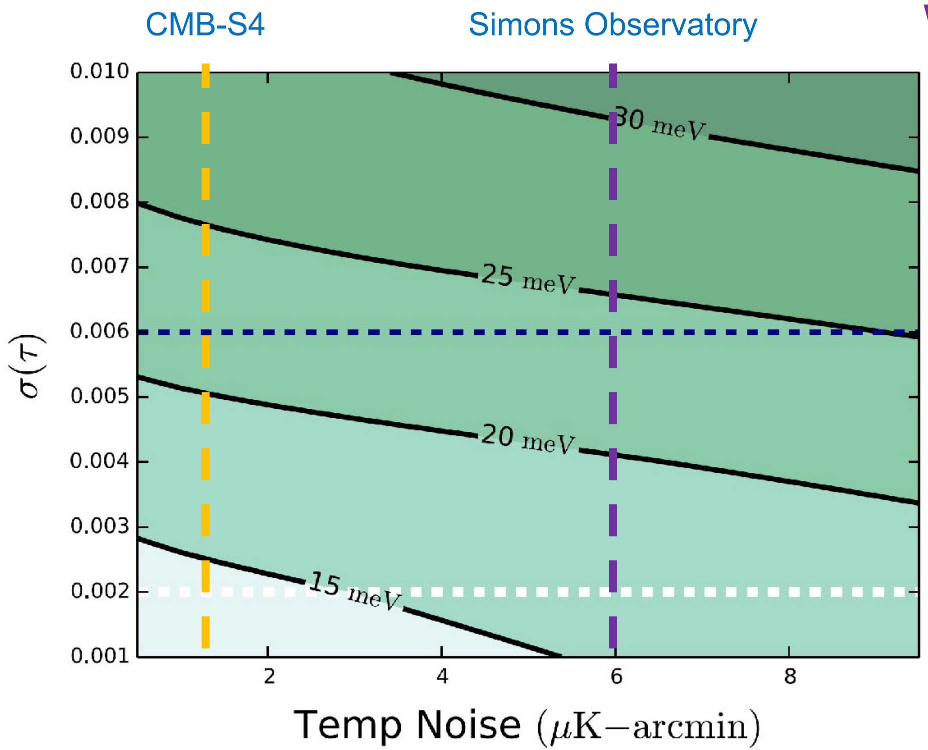
CMB Measurements of the Primordial Amplitude



- Measurements of the CMB power spectra at ℓ>30 tightly constrain the combination $A_s e^{-2\tau}$, while polarization at ℓ<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

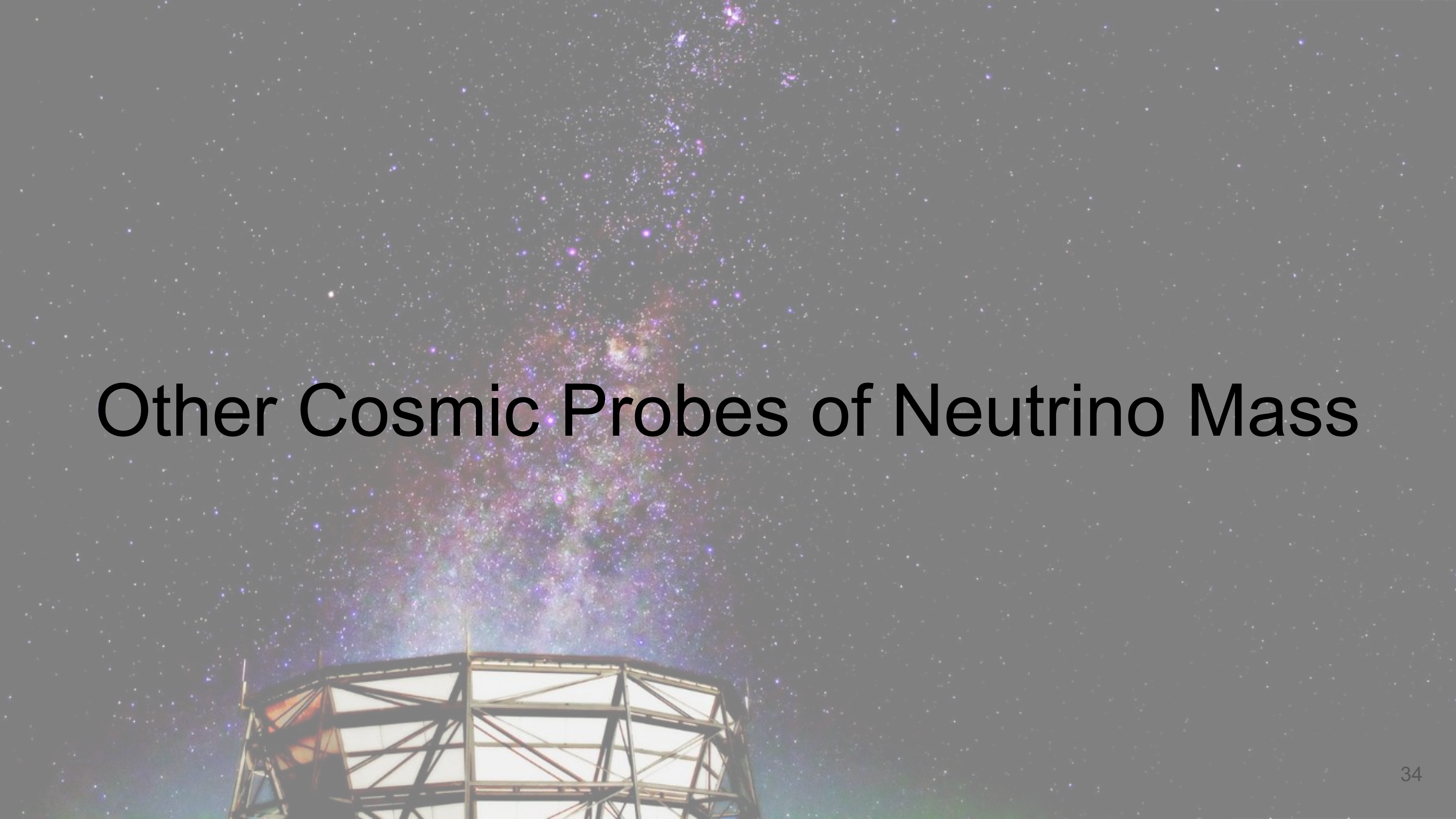
Current constraint:

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

(Planck + BAO)

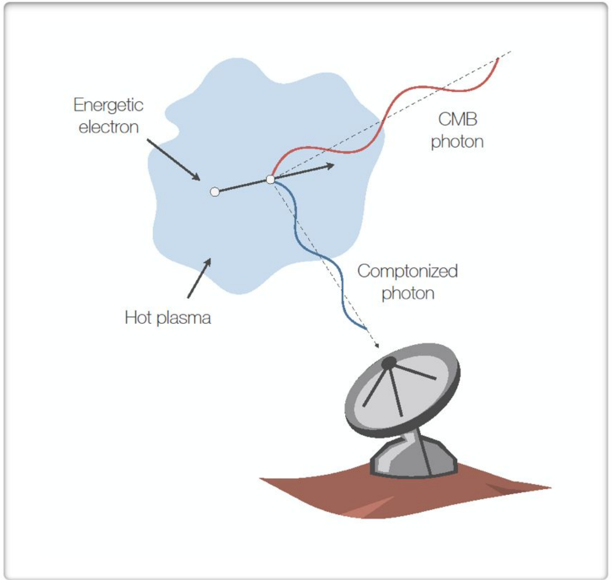
CMB lensing reconstruction with upcoming surveys, combined with DESI BAO, will enable significant measurement of even minimal $\sum m_\nu$ especially with improved τ measurement

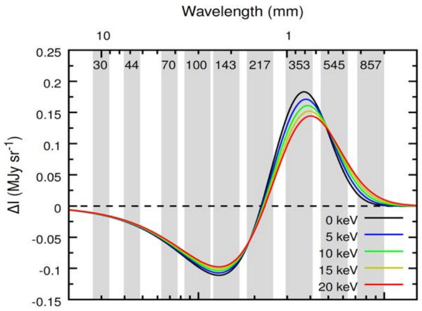
CMB-S4 (2016); Simons Observatory (2018); Planck (2018)

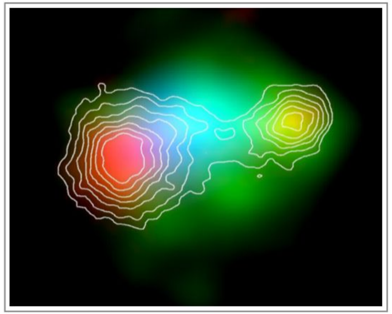


Other Cosmic Probes of Neutrino Mass

Galaxy Clusters with the Sunyaev-Zeldovich Effect



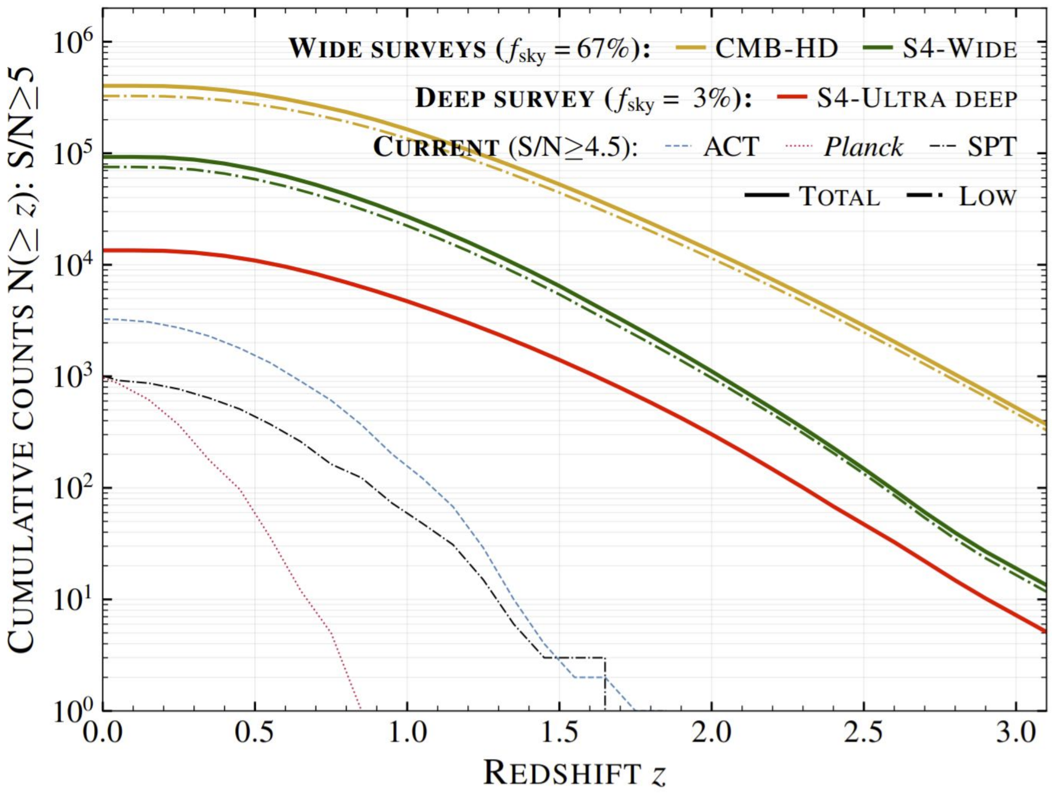




- Galaxy clusters are the most massive bound structures in the universe
- Cluster abundance depends on the underlying cosmology
- CMB photons are up-scattered by the hot gas in galaxy clusters, leading to a spectral distortion that allows CMB surveys to detect galaxy clusters to high redshift

Sunyaev, Zeldovich (1970, 1972); Image Credit: Basu, et al

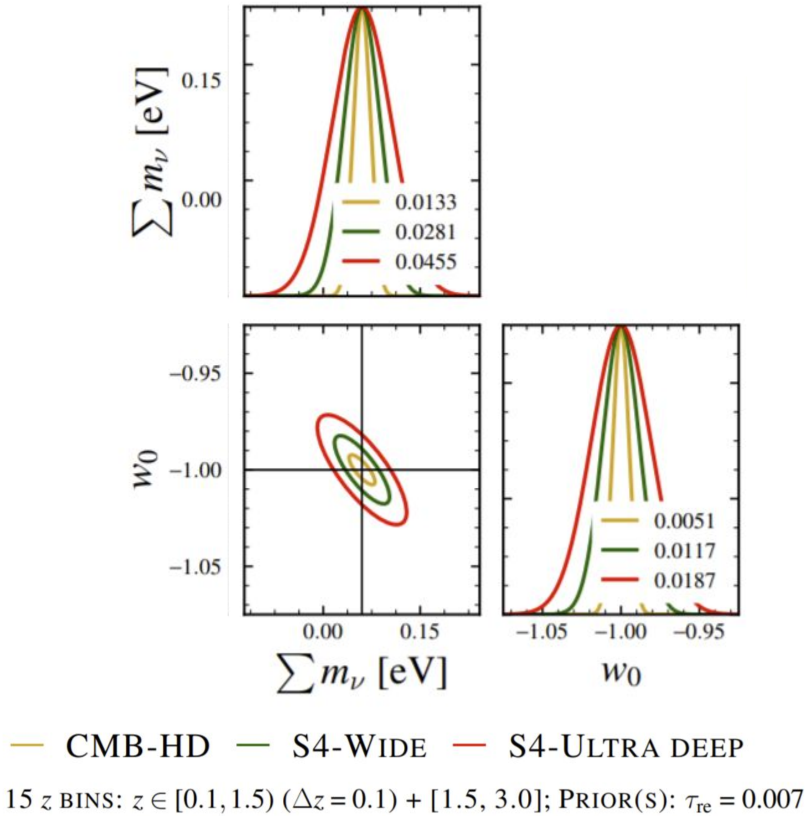
Galaxy Clusters with Upcoming CMB Surveys



- Upcoming CMB surveys will create a huge catalog of galaxy clusters, including thousands at high redshift, enabling insights into the growth of cosmic structure
- Cluster masses can be calibrated with measurements of gravitational lensing of galaxies and/or the CMB

Raghunathan, et al (2021)

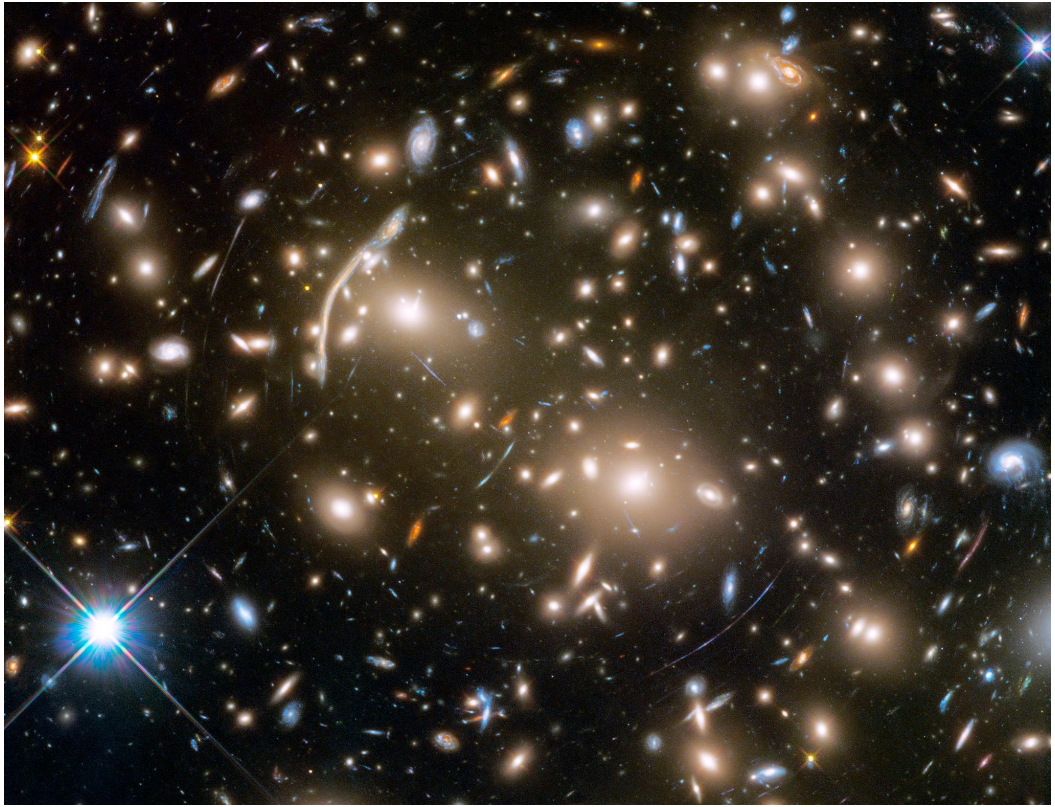
CMB + Cluster Forecasts for Neutrino Mass Constraints



- The abundance of galaxy clusters is sensitive to the suppression of matter clustering imprinted by massive neutrinos
- Combined with a measurement of the primordial amplitude from the CMB, cluster abundances can measure neutrino mass with similar precision to CMB lensing
- The redshift dependence of the cluster abundance also allows simultaneous constraints on other physics that may impact structure growth, like the dark energy equation of state

Raghunathan, et al (2021)

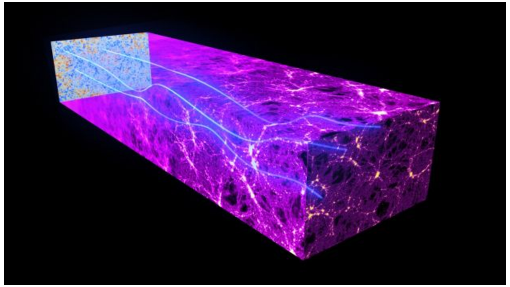
Galaxy Lensing and Clustering

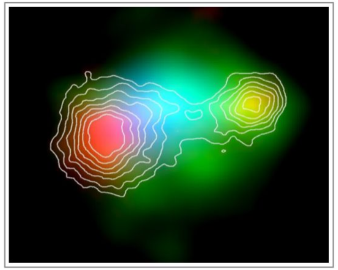


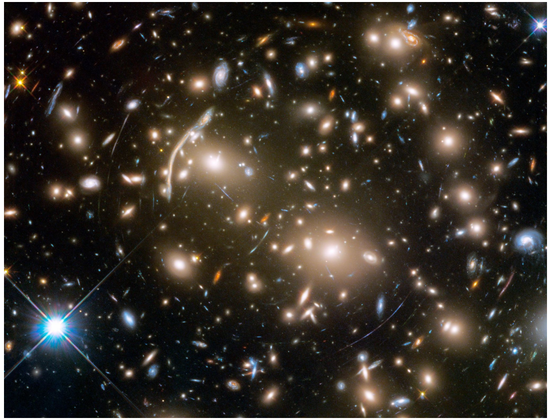
- Imaging surveys like LSST with the Rubin Observatory will perform measurements of weak lensing and clustering of galaxies, thereby probing the matter power spectrum
- Galaxy bias and baryonic feedback pose some challenges for accurate measurement of the underlying spectrum
- Constraints are expected to be comparable to those from CMB lensing, though with a different set of systematic errors

Image Credit: NASA, ESA, STScI

Multiple Probes of Neutrino Mass Improve Robustness





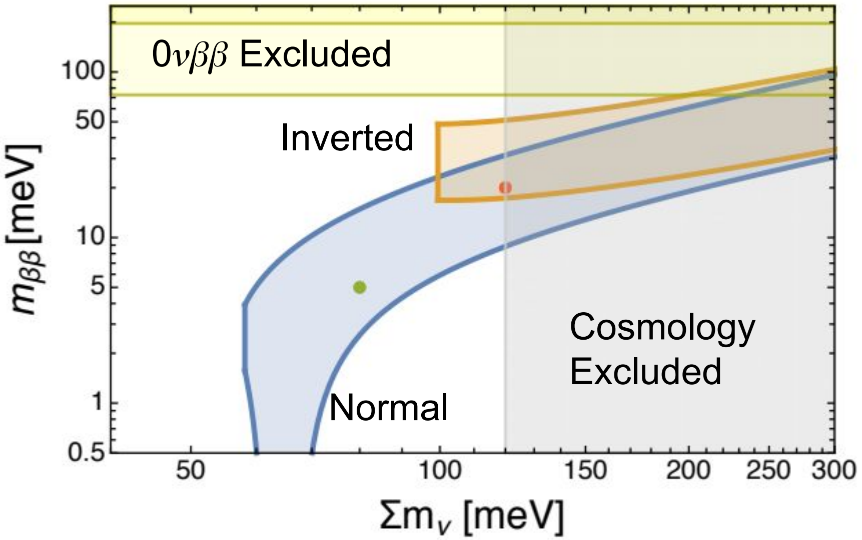


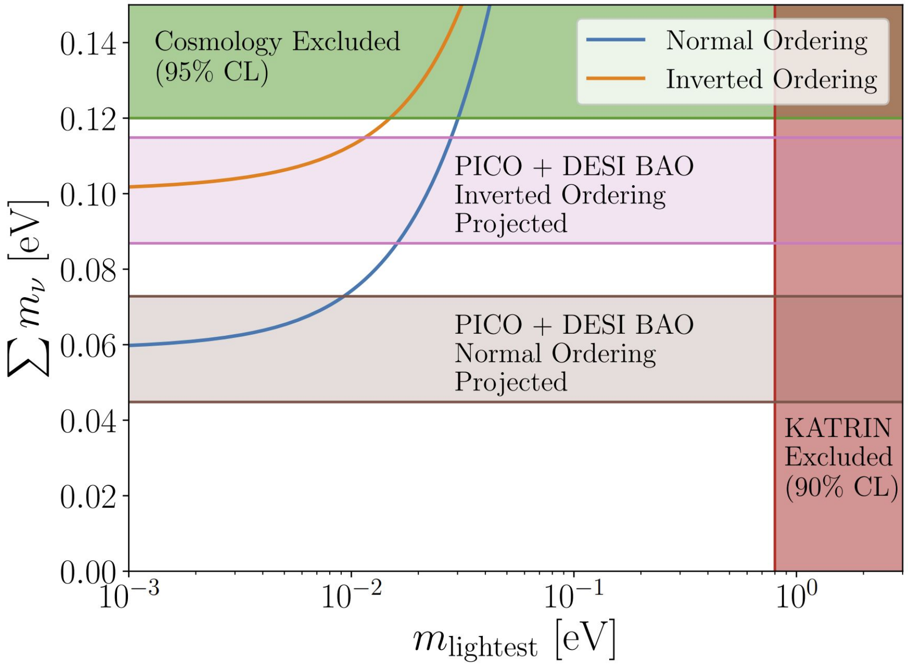
- Upcoming cosmological surveys offer several paths to measure the absolute mass scale of neutrinos, all utilizing the suppression of matter clustering due to massive neutrinos
- These measurements are subject to different systematic errors
- Combining these probes will provide useful cross-checks and ensure that neutrino mass measurements are robust even in models beyond ΛCDM

Madhavacheril, Battaglia, Miyatake (2018); Mishra-Sharma, Alonso, Dunkley (2018); Yu, et al (2018)

Cosmology/Lab Complementarity

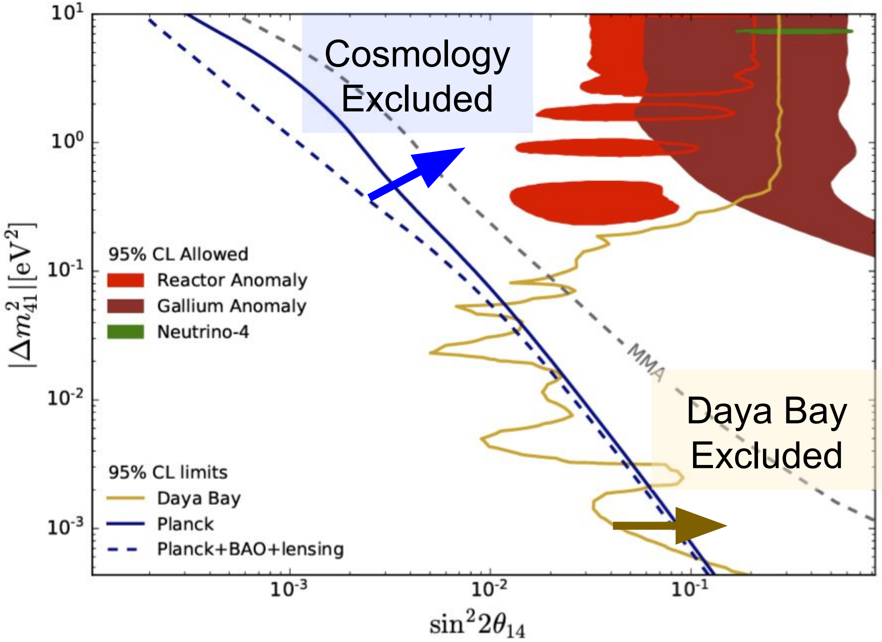
Mass Measurements

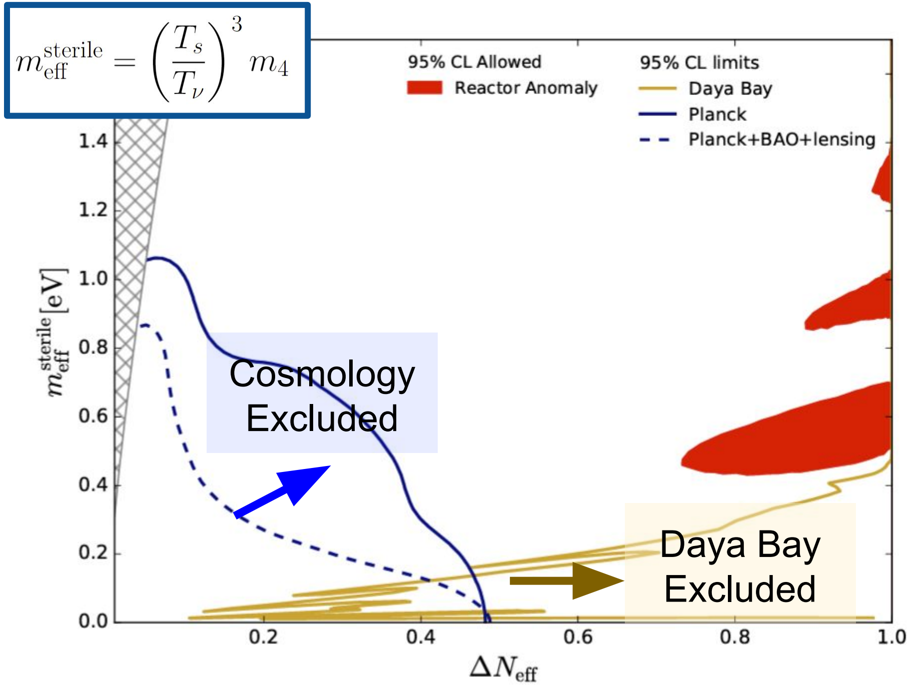




PICO (2022); Gerbino, Grohs, Lattanzi, et al (2022)

eV-Scale Sterile Neutrinos



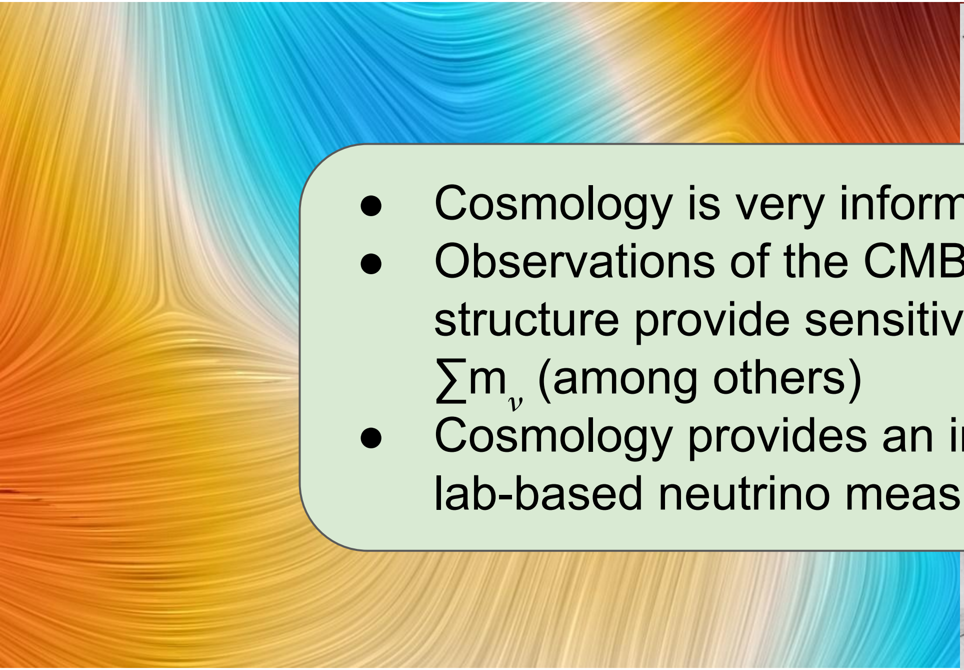


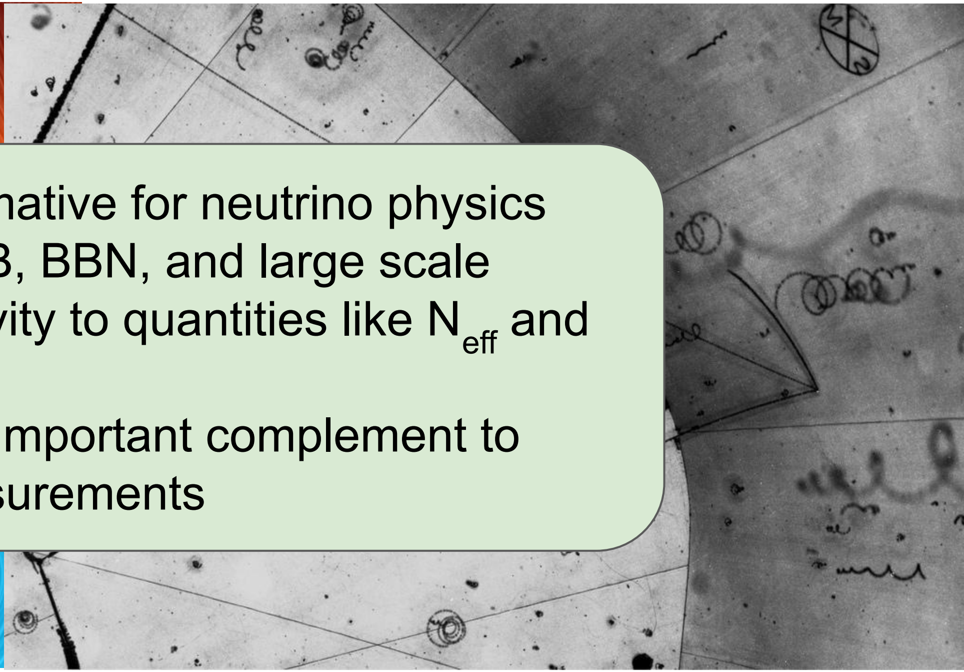
eV-Scale Sterile Neutrino favored by short baseline anomalies excluded by 7σ with cosmological measurements

Planck (2018); Adams, et al (2020)

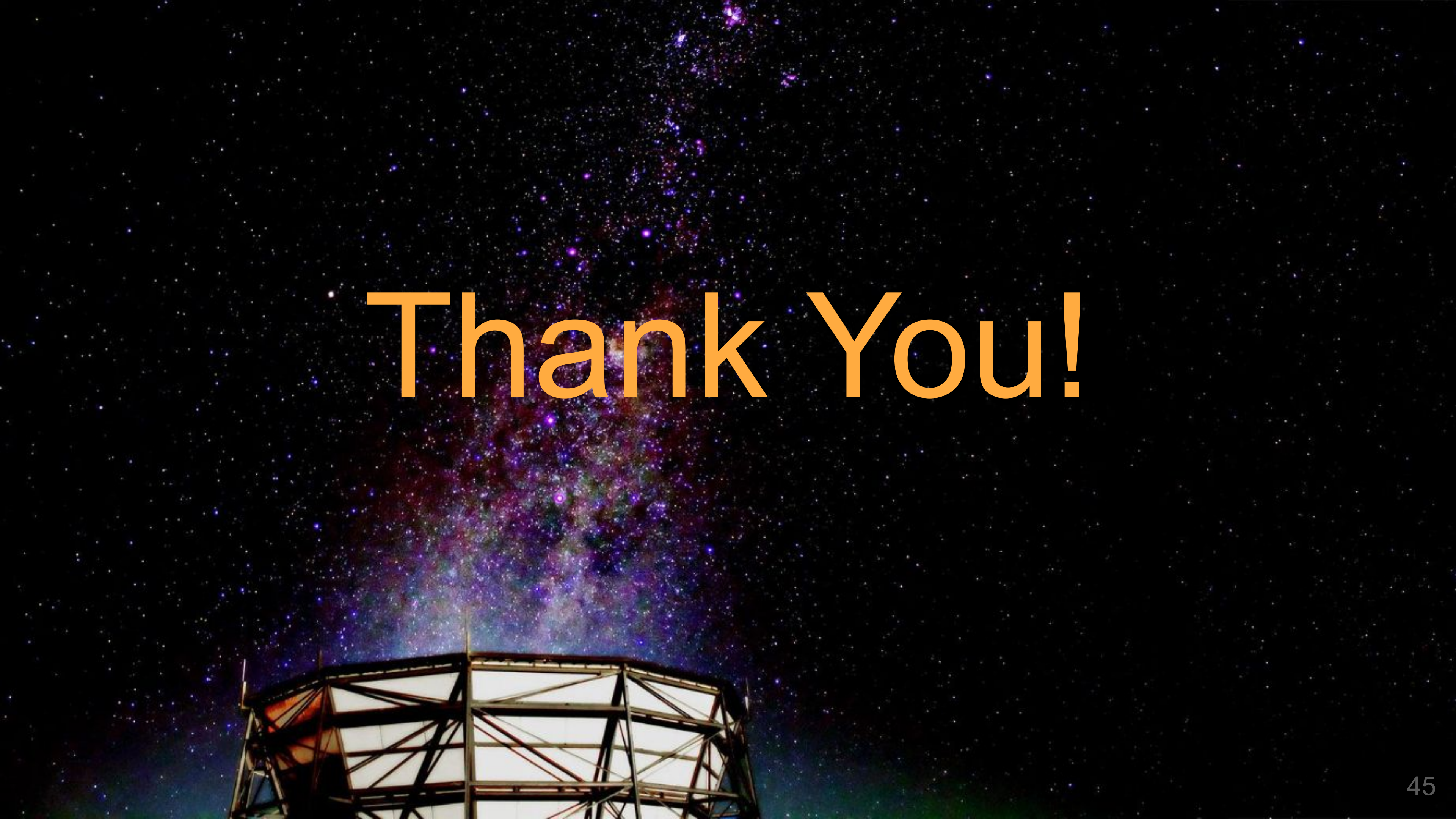
Conclusion

Conclusion



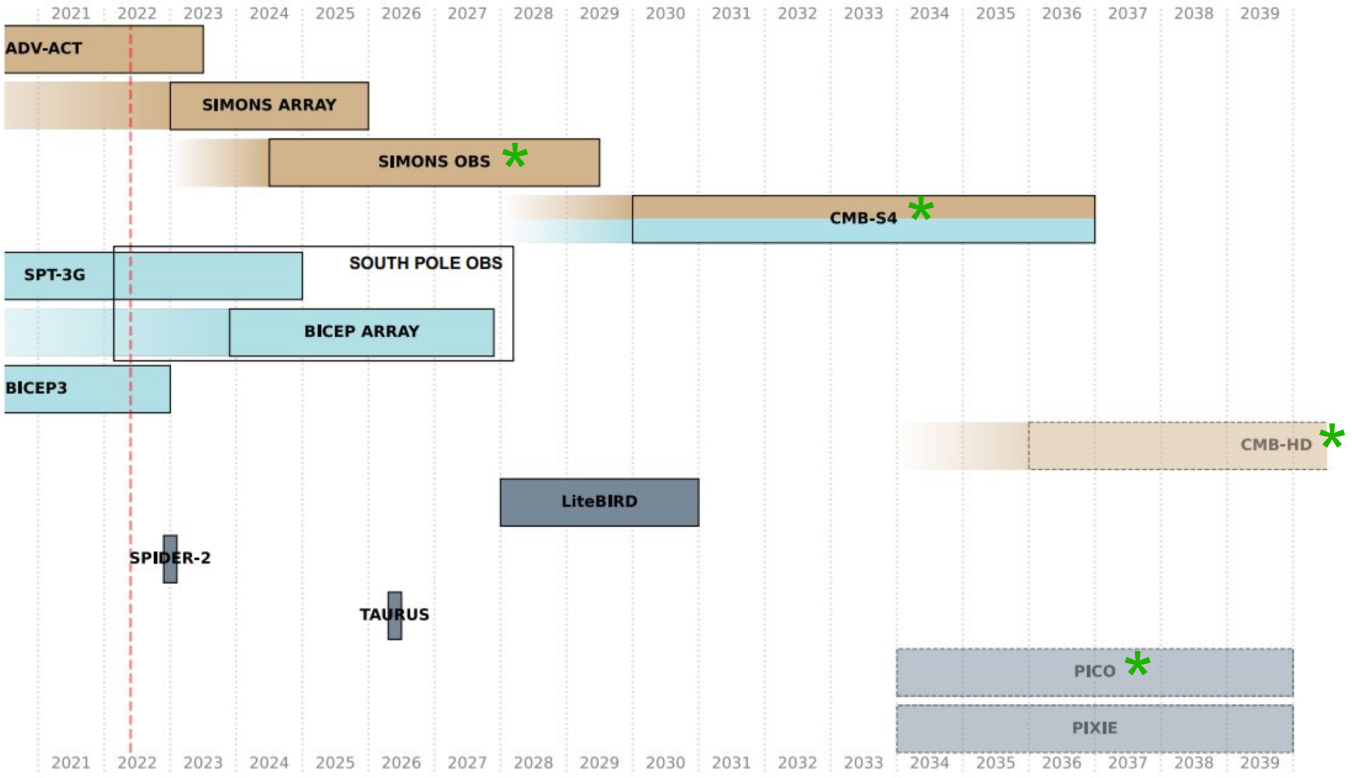


- Cosmology is very informative for neutrino physics
- Observations of the CMB, BBN, and large scale structure provide sensitivity to quantities like N_{eff} and $\sum m_\nu$ (among others)
- Cosmology provides an important complement to lab-based neutrino measurements


Thank You!

Backup Slides

Timeline of Upcoming CMB Surveys



Chang, Huffenberger, et al (2022)