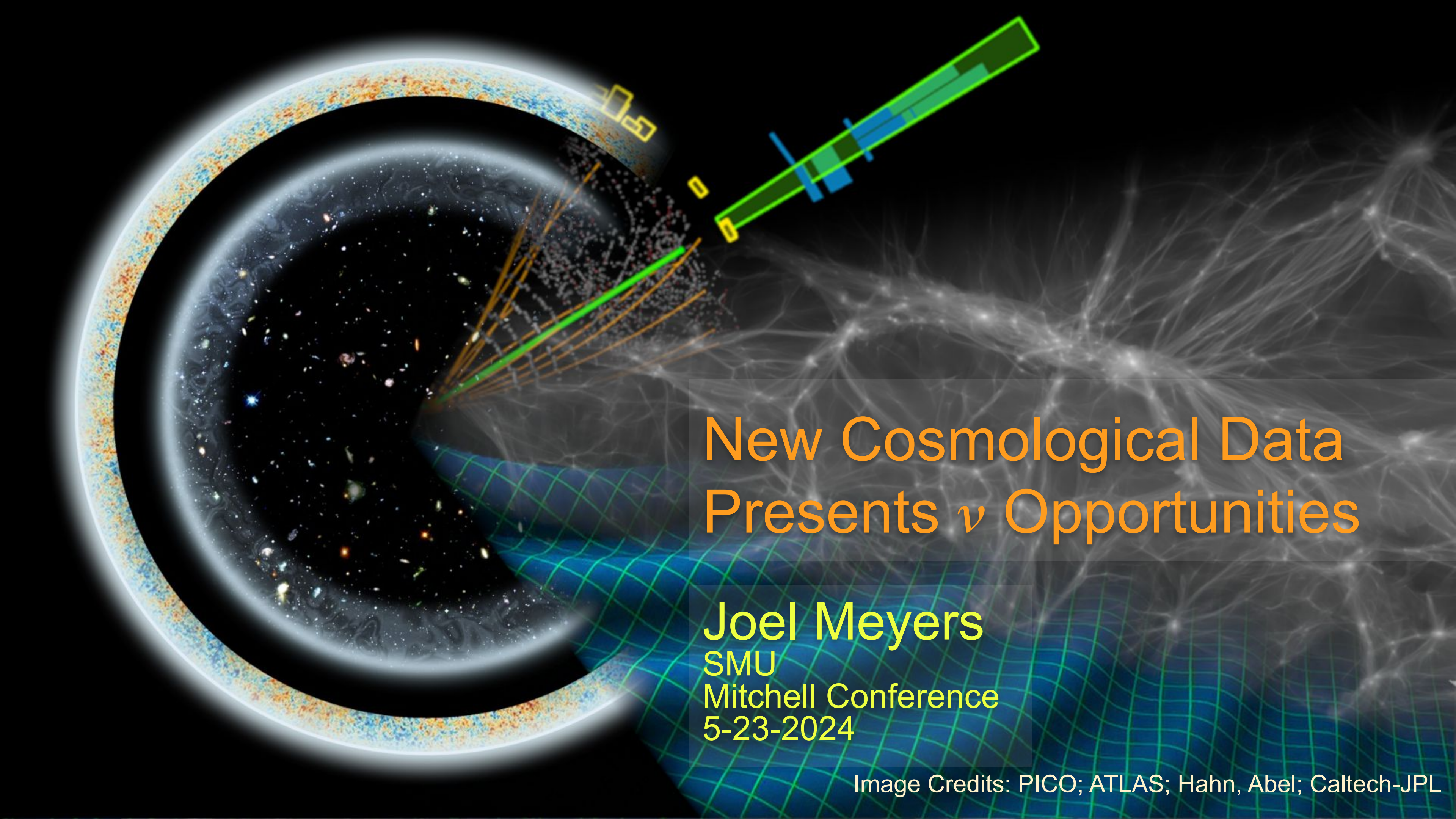


New Cosmological Data Presents ν Opportunities

Joel Meyers
SMU
Mitchell Conference
5-23-2024

Image Credits: PICO; ATLAS; Hahn, Abel; Caltech-JPL

History of the Universe

Cosmic Neutrino Background

Cosmic Microwave Background

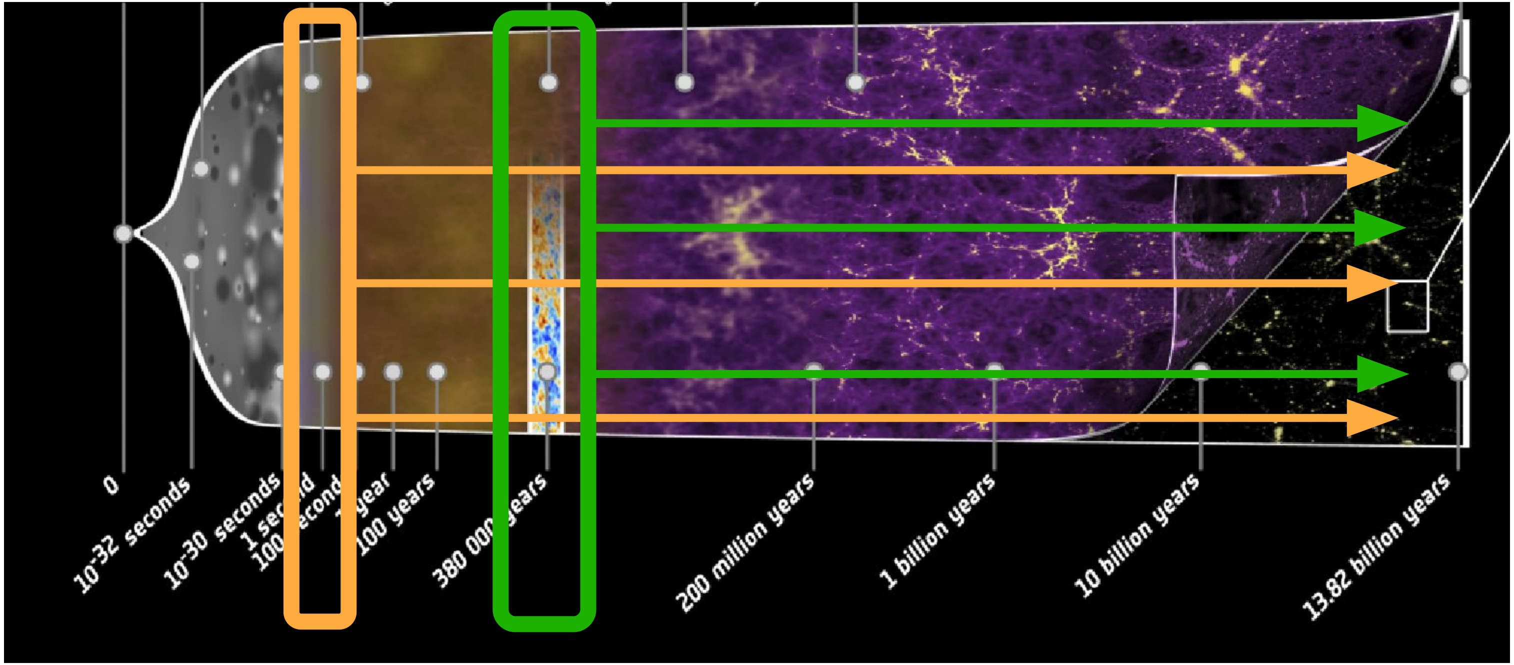
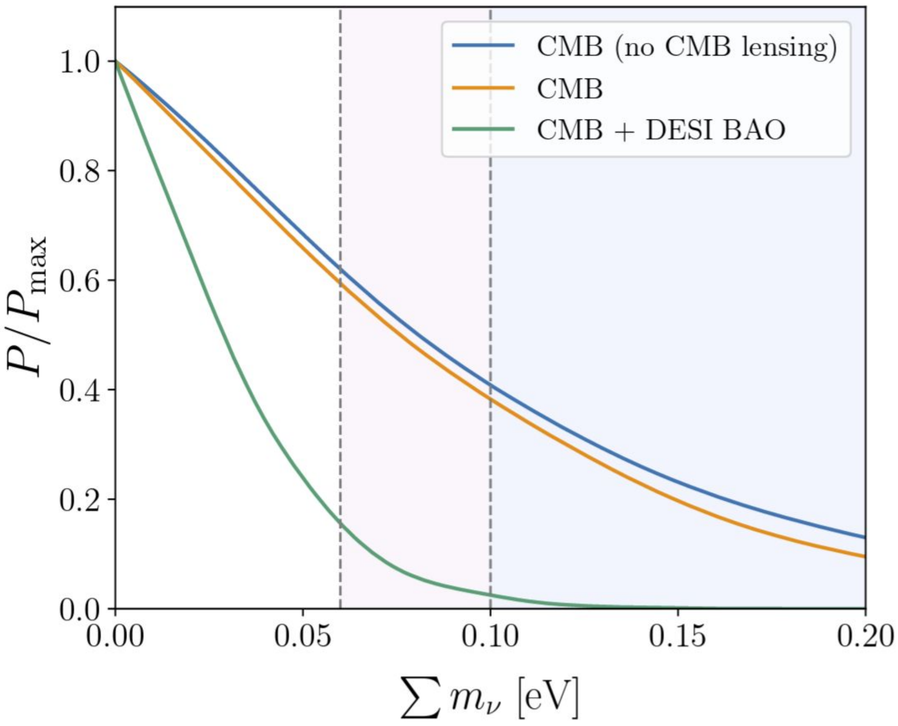


Image Credit: NASA

Cosmological Measurement of Neutrino Mass



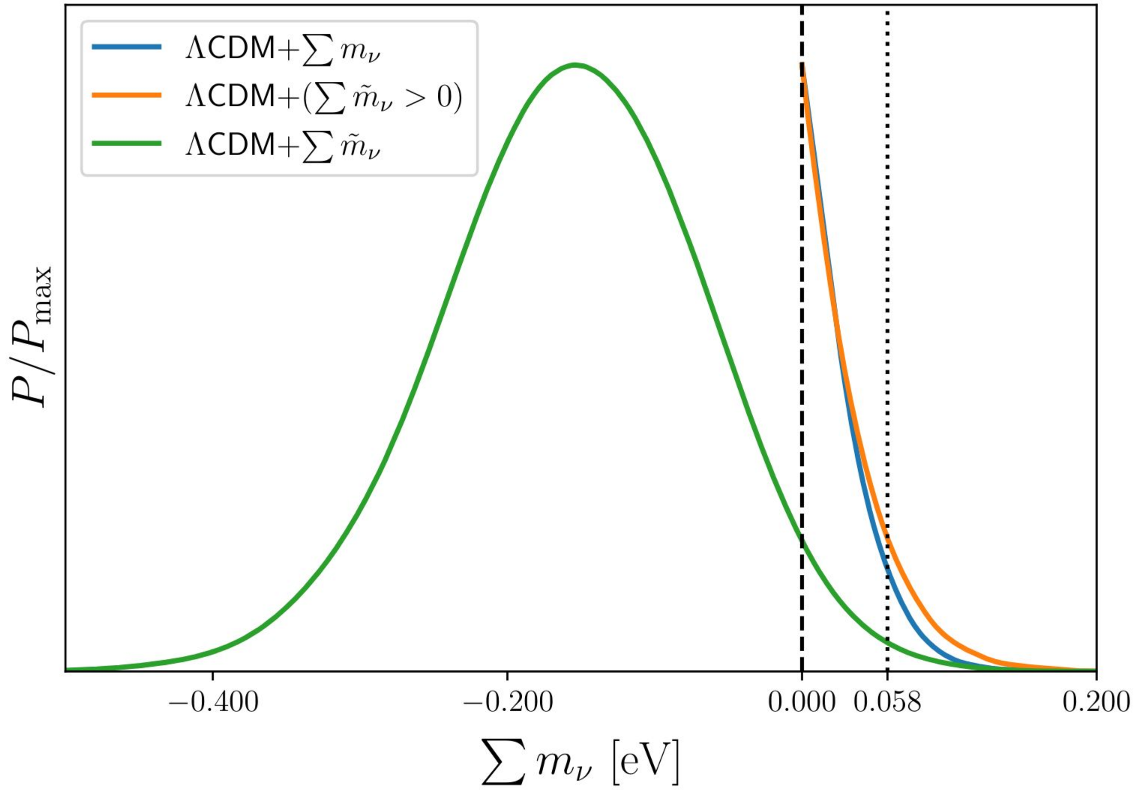
- DESI BAO, combined with CMB data, now allows for tightest yet constraint on sum of neutrino masses

$$\sum m_\nu < 72 \text{ meV} \ (95\%)$$

- Uncertainty is approaching level necessary for detection of minimum mass implied by flavor oscillations

DESI (2024)

Negative Neutrino Mass?

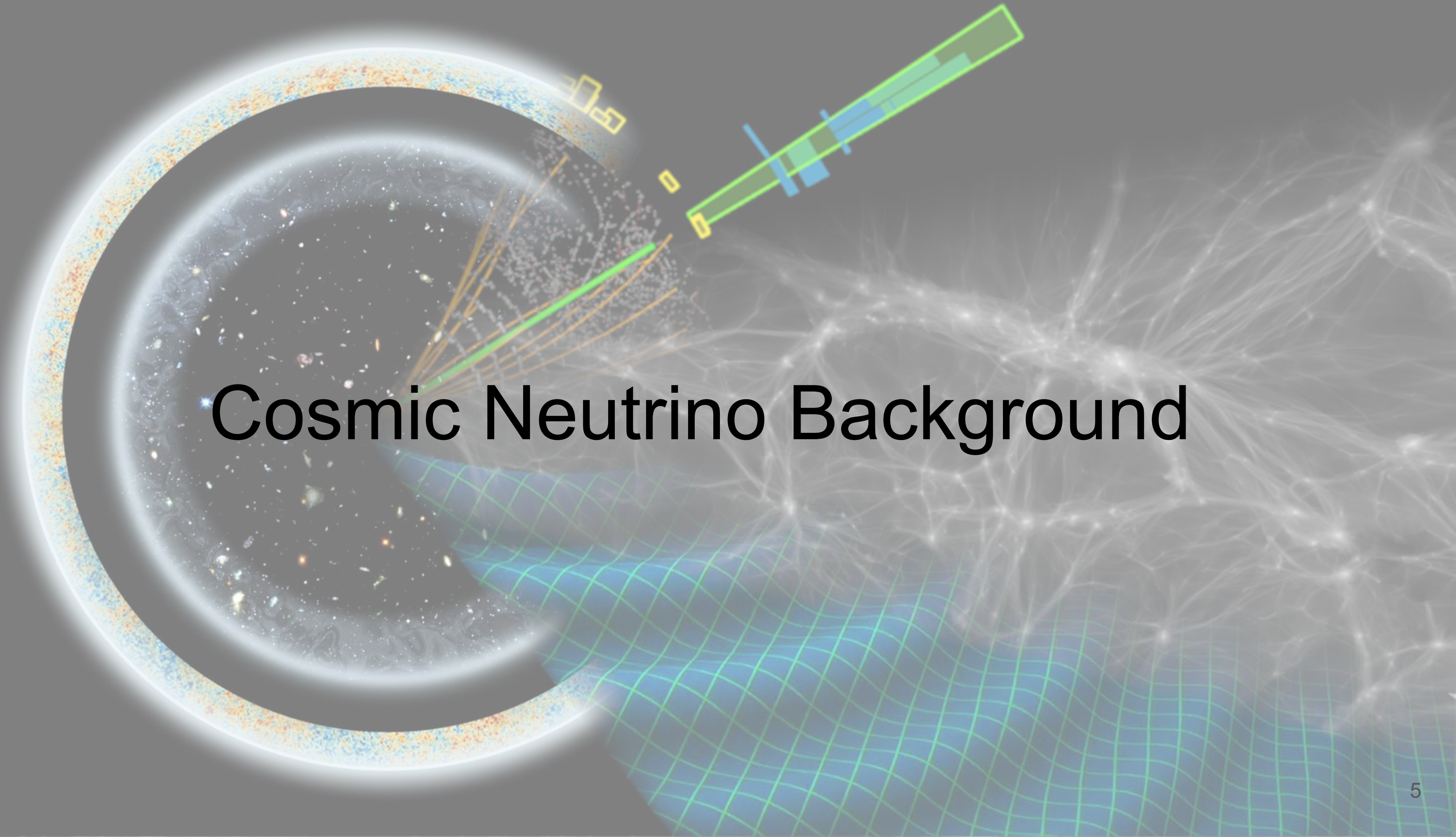


- Measurements actually favor negative neutrino mass

$$\sum m_\nu = -160 \pm 90 \text{ meV} \ (68\%)$$

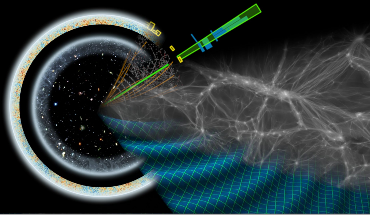
- This measurement disfavors the minimal mass for the normal hierarchy (58 meV) at 99% confidence

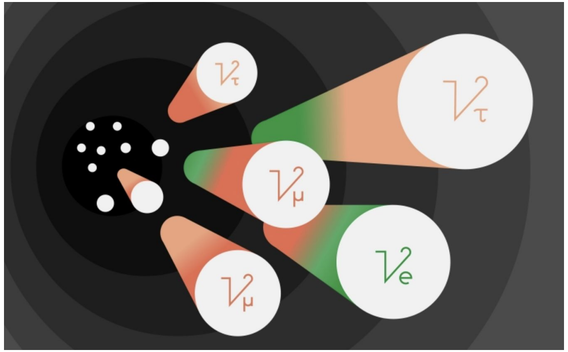
Craig, Green, JM, Rajendran (2024)



Cosmic Neutrino Background

Cosmic Neutrino Background





Cosmic neutrinos are light thermal relics from the early universe

$$\nu + \bar{\nu} \longleftrightarrow e^+ + e^-$$

$$e + \nu \longleftrightarrow e + \nu$$

$$\frac{\Gamma}{H} \sim \left(\frac{T}{1\,\mathrm{MeV}}\right)^3$$

$$N_{\mathrm{eff}}$$

CνB makes up significant fraction of radiation energy density at early times

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

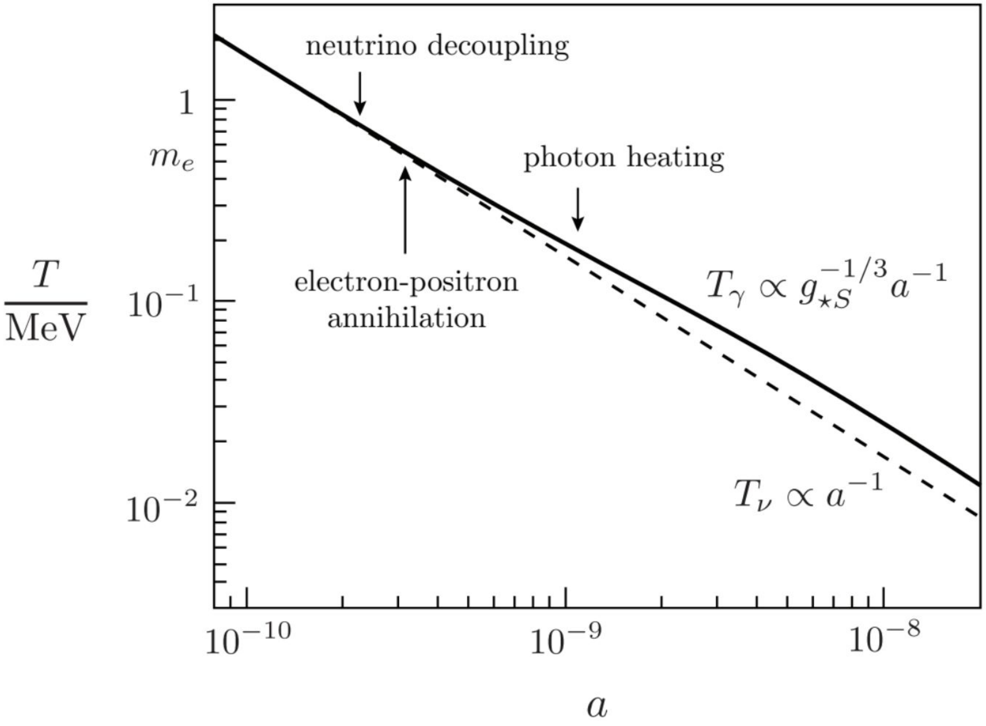
$$\sum m_\nu$$

Massive neutrinos act like hot dark matter affecting structure growth at more recent times

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

Image Credit: Symmetry Magazine

Cosmic Neutrino Background - Instantaneous Decoupling Model



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

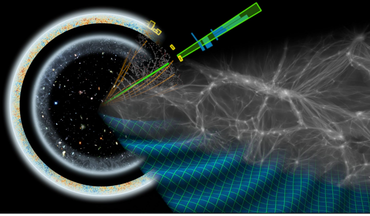
$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

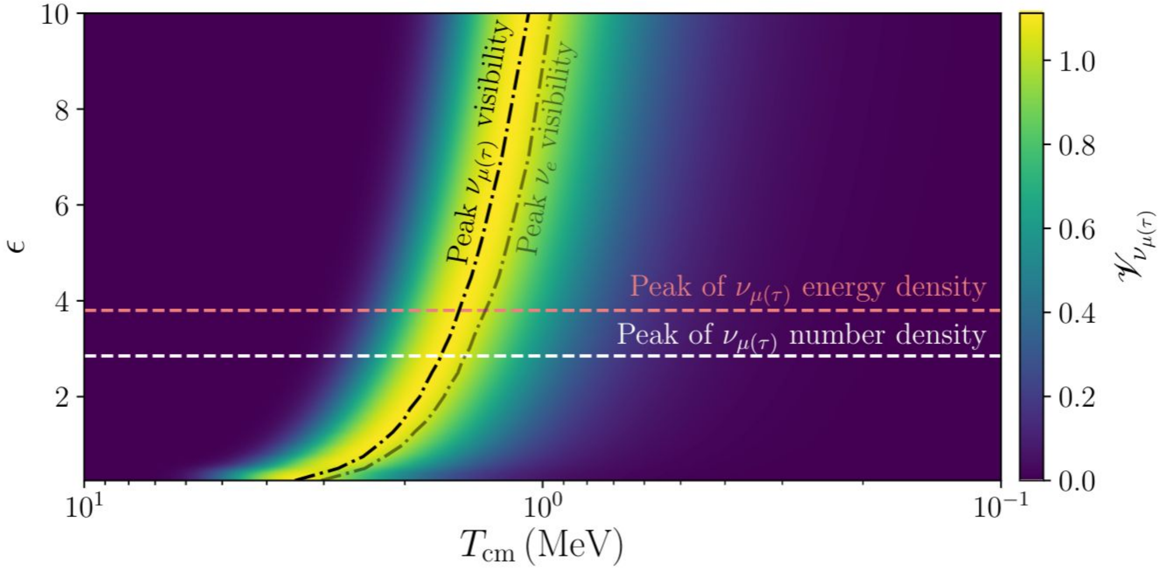
Cosmic neutrino background makes up a significant fraction of the energy density prior to recombination

$$\rho_\nu \simeq 0.471\rho_r$$

Image Credit: Baumann

Cosmic Neutrino Background - Precision Model





Neutrino Differential Visibility

The energy density of the cosmic neutrino background can be calculated precisely, including the effects of non-instantaneous weak decoupling

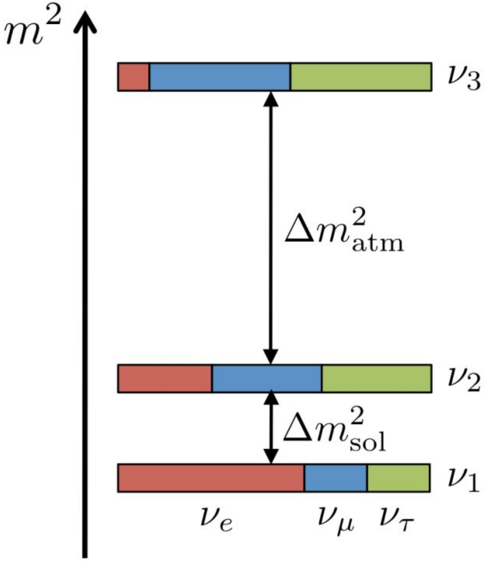
$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

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

Escudero Abenza (2020); Akita, Yamaguchi (2020); Froustey, Pitrou, Volpe (2020); Bennett, et al (2021); Bond, Fuller, Grohs, JM, Wilson (2024)

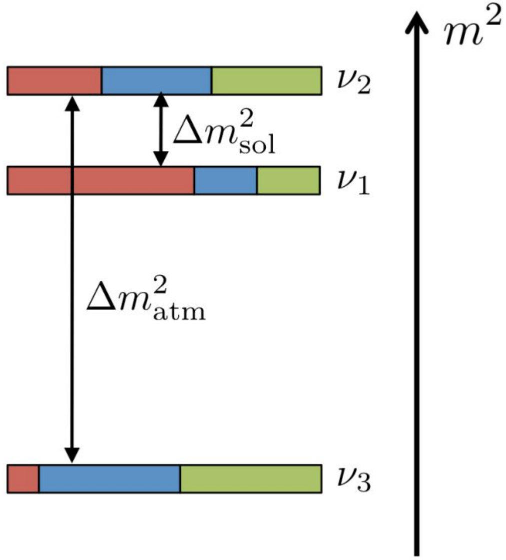
Massive Cosmic Neutrinos

normal hierarchy (NH)



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

inverted hierarchy (IH)



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

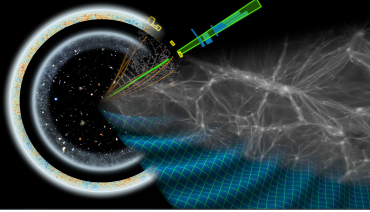
Cosmic neutrino background provides an abundance of non-relativistic neutrinos

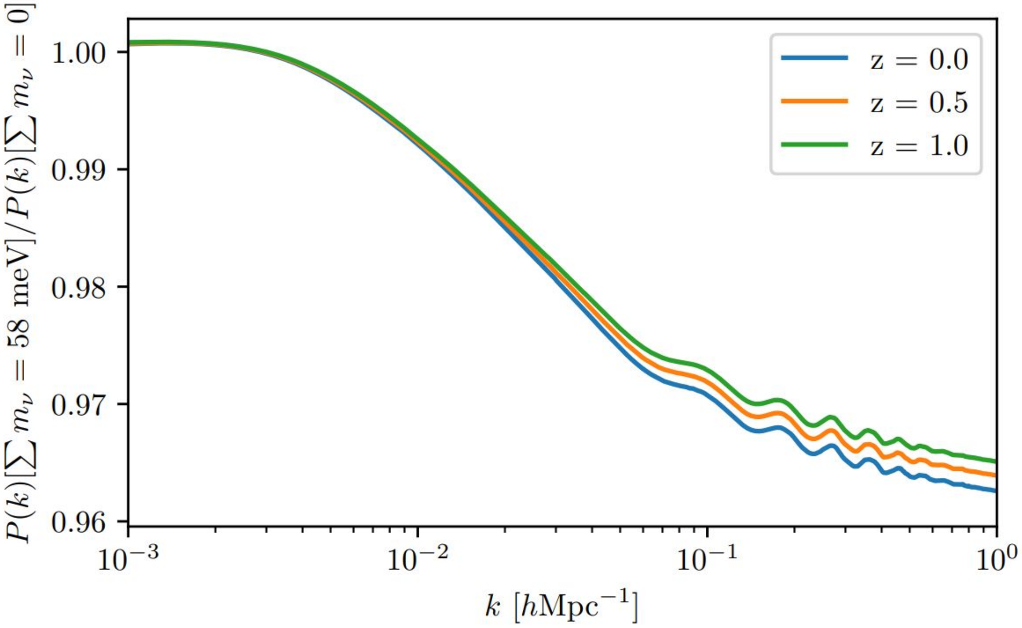
$$n_{\nu_i,0} = 112\,\mathrm{cm}^{-3}$$

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

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

Massive Neutrinos Suppress Matter Clustering





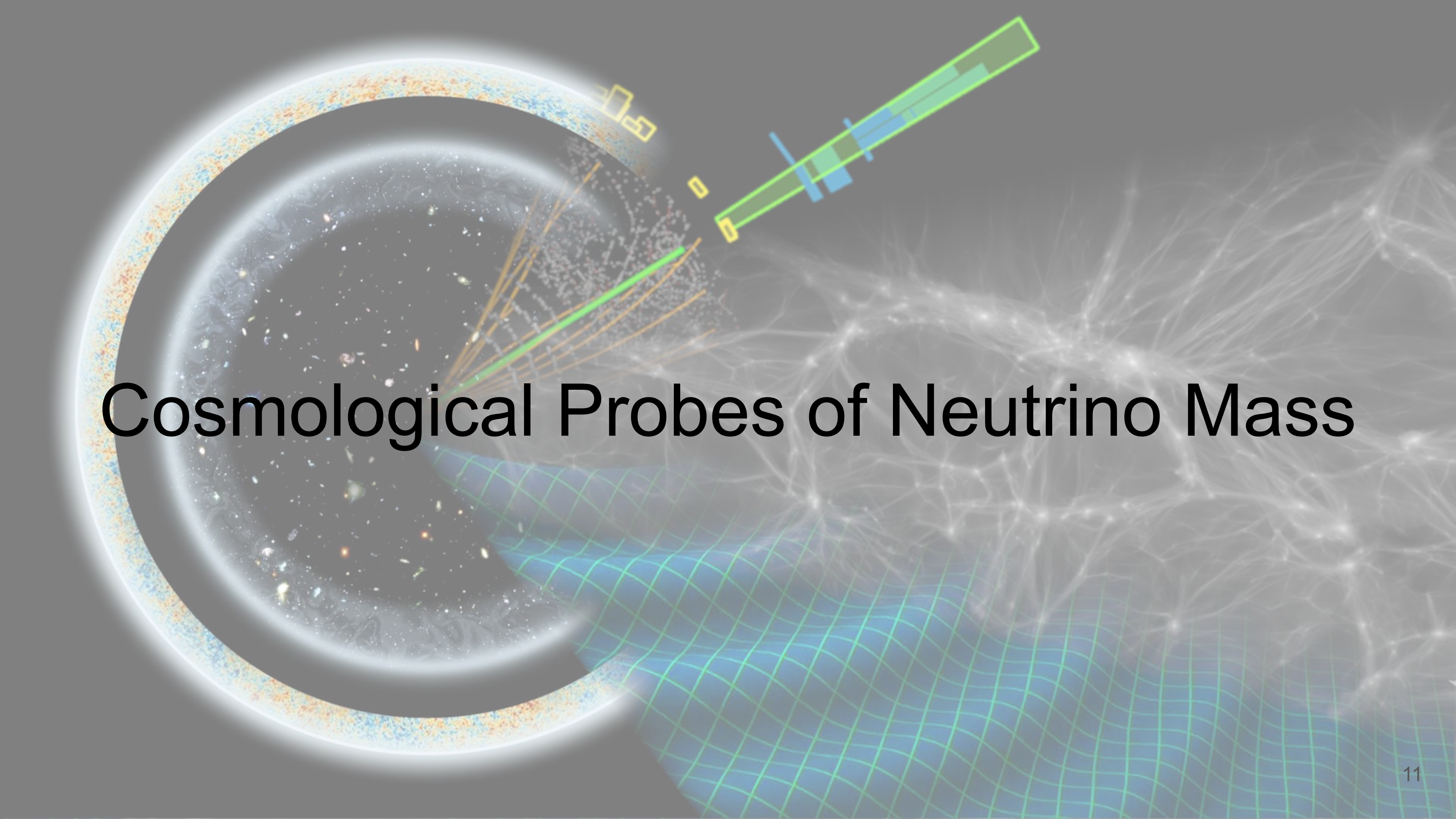
Suppression of matter clustering due to massive neutrinos
(A_s, $\Omega_m h^2$, $\Omega_b h^2$, H_0 fixed)

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

$$f_\nu \equiv \frac{\Omega_\nu}{\Omega_\mathrm{m}} \simeq 4.3\times10^{-3}\left(\frac{\sum m_\nu}{58\ \mathrm{meV}}\right)$$

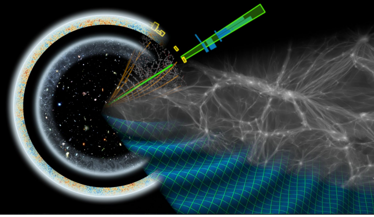
$$P(k > k_\mathrm{fs}) \simeq (1 - 8f_\nu)P(k > k_\mathrm{fs})|_{\sum m_\nu = 0}$$

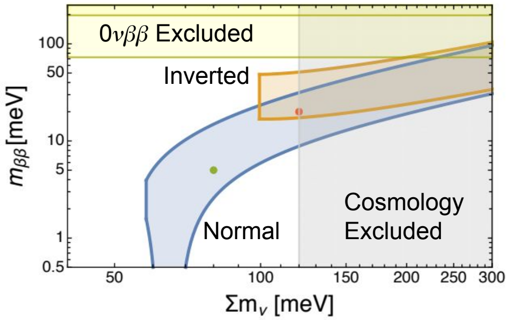
Hu, Eisenstein, Tegmark (1998); Cooray (1999); Abazajian, et al (2011);
Green, JM (2021); Gerbino, Grohs, Lattanzi, et al (2022)

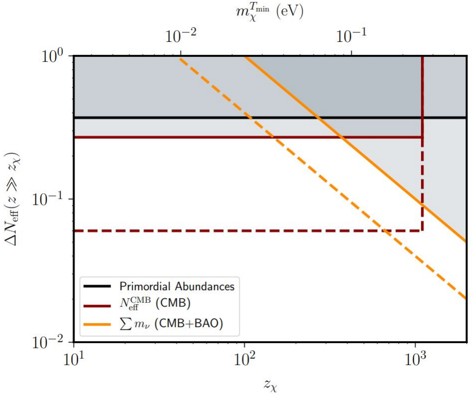


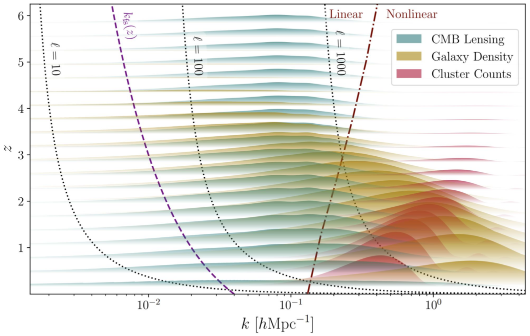
Cosmological Probes of Neutrino Mass

Value of Cosmological Neutrino Mass Measurement









Particle Physics

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

Cosmology

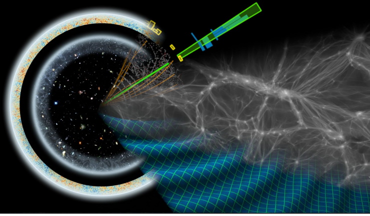
- Provides end-to-end test of cosmic history and is sensitive to new massive species (including gravitinos)

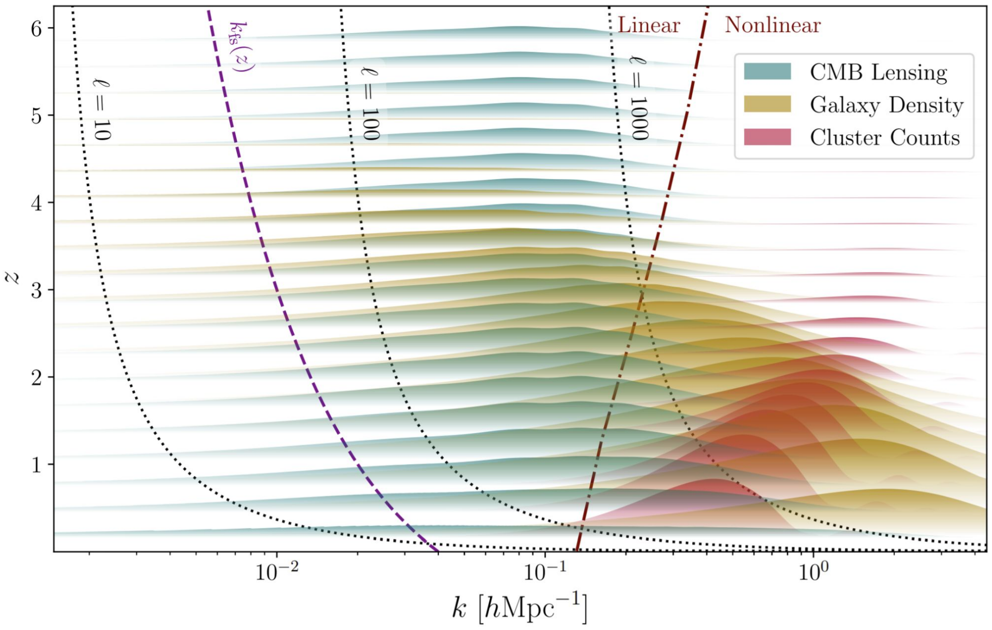
Astrophysics

- 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)

Measuring Clustering with Cosmological Surveys



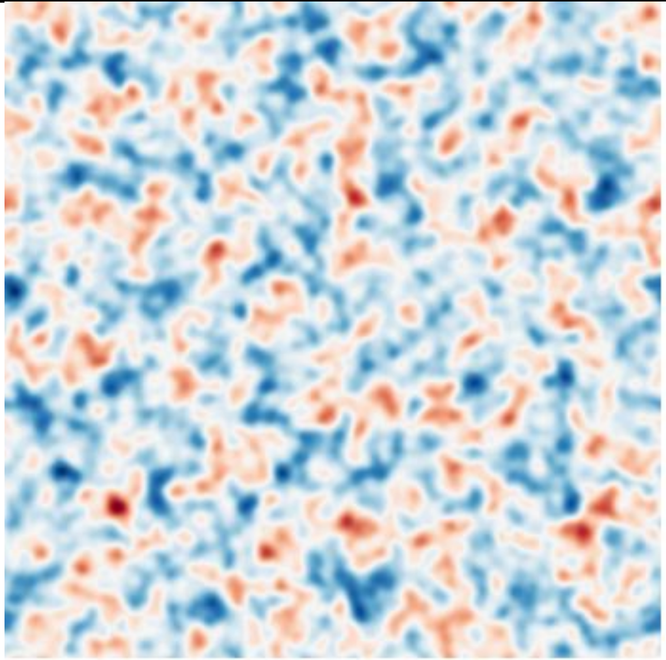


Sensitivity regimes of various probes of clustering

- 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
- CMB lensing provides an unbiased measurement of integrated matter clustering in the linear regime

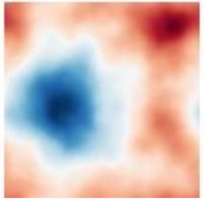
Green, JM (2021)

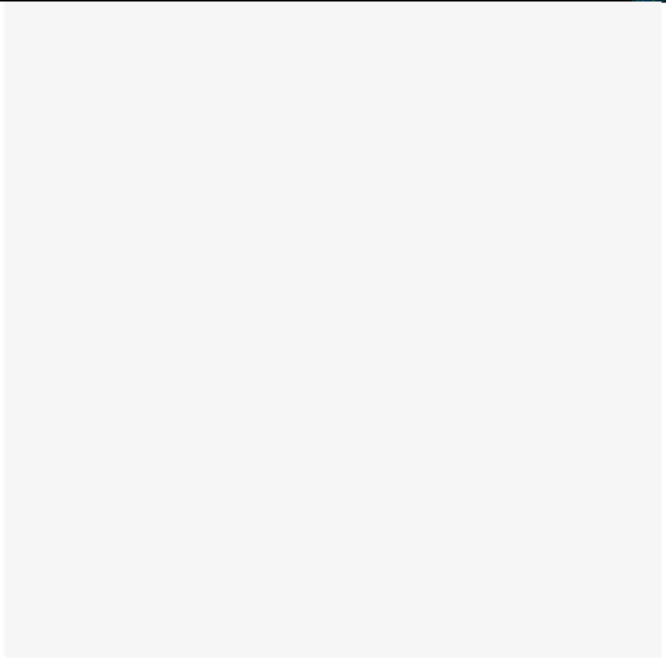
Unlensed CMB Polarization



Unlensed E

ϕ



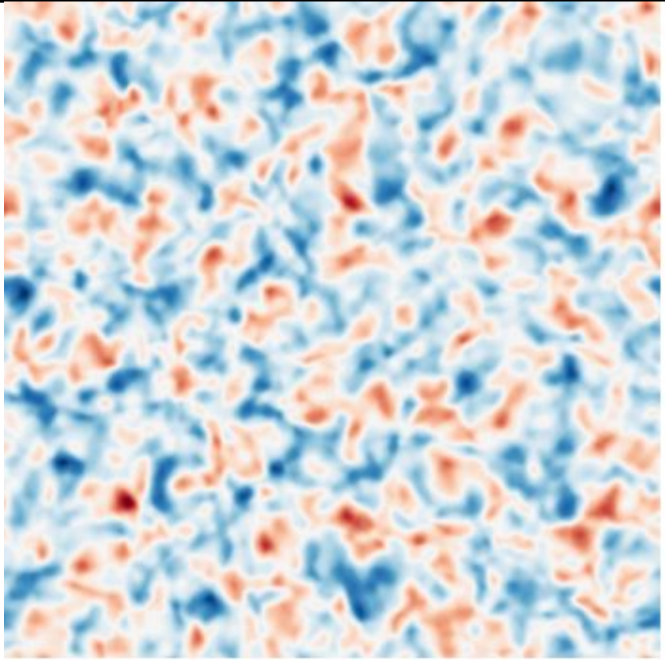


Unlensed B

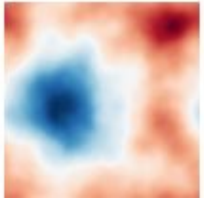
5°×5° simulated maps

Image Credit: Guzman

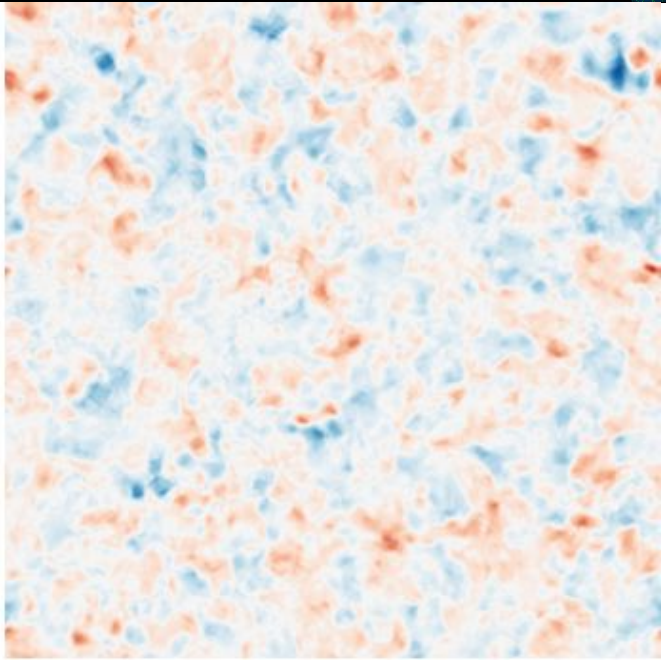
Lensed CMB Polarization



Lensed E



ϕ

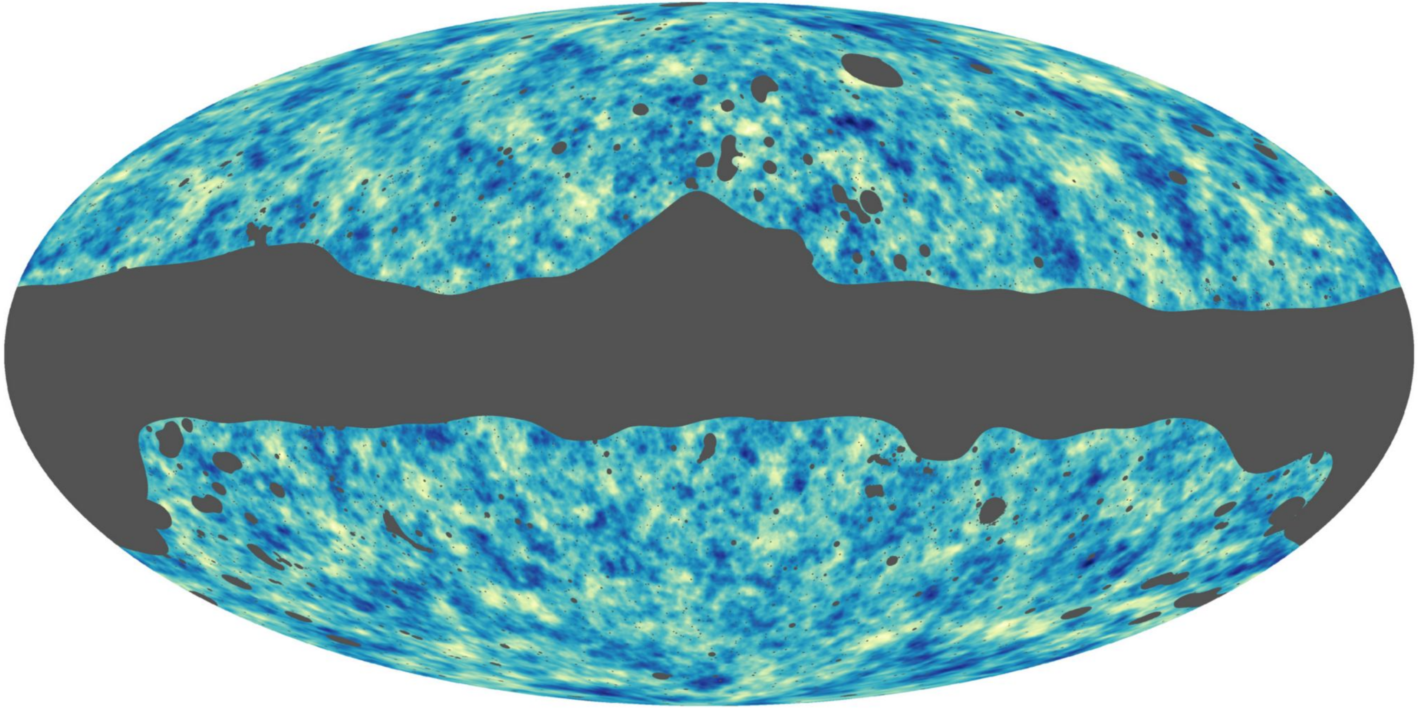


Lensed B

5°×5° simulated maps

Image Credit: Guzman

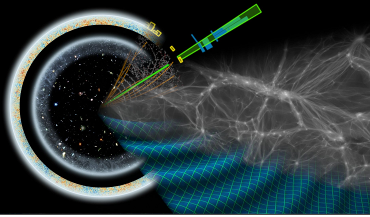
CMB Lensing Reconstruction

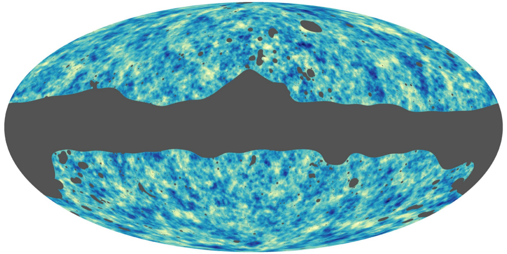


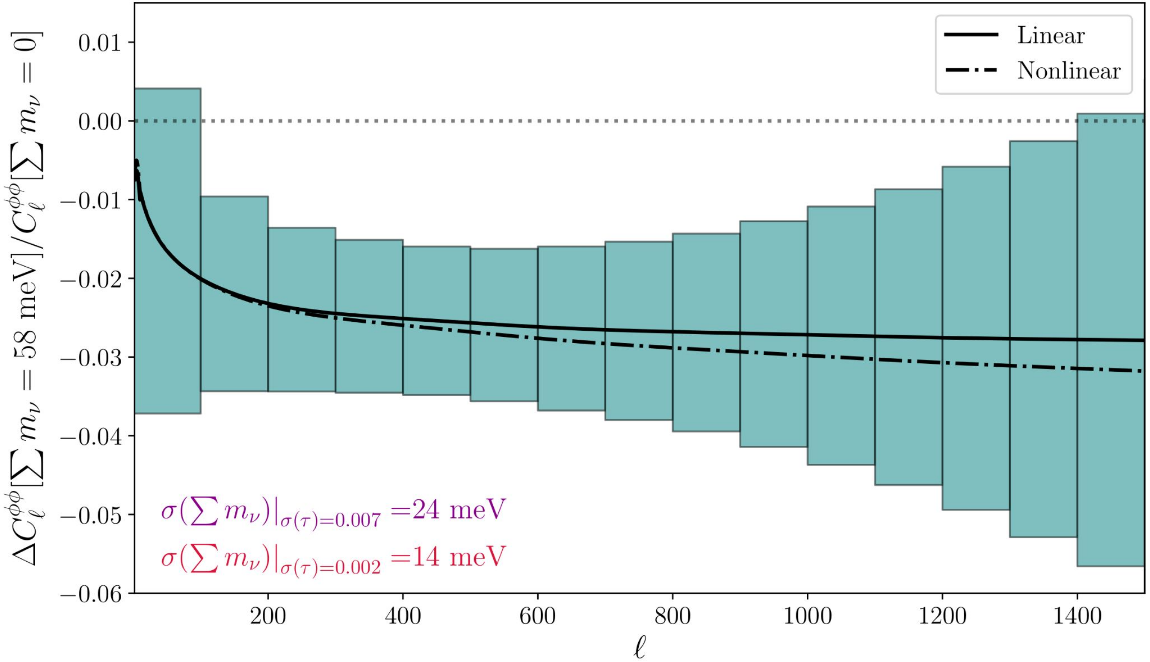
40σ observation

Planck (2018)

Neutrino Mass with CMB Lensing



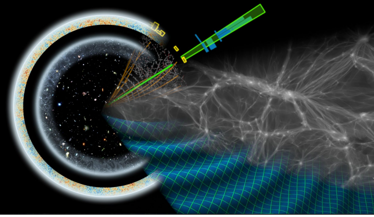


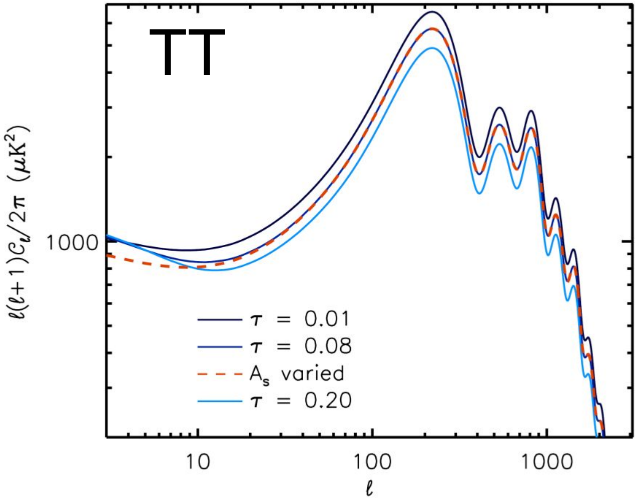


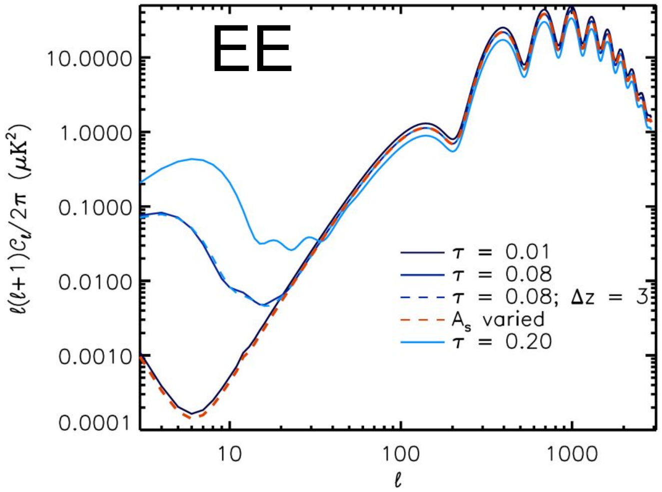
Measuring suppression of clustering with CMB-S4 lensing

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

CMB Measurements of the Primordial Amplitude







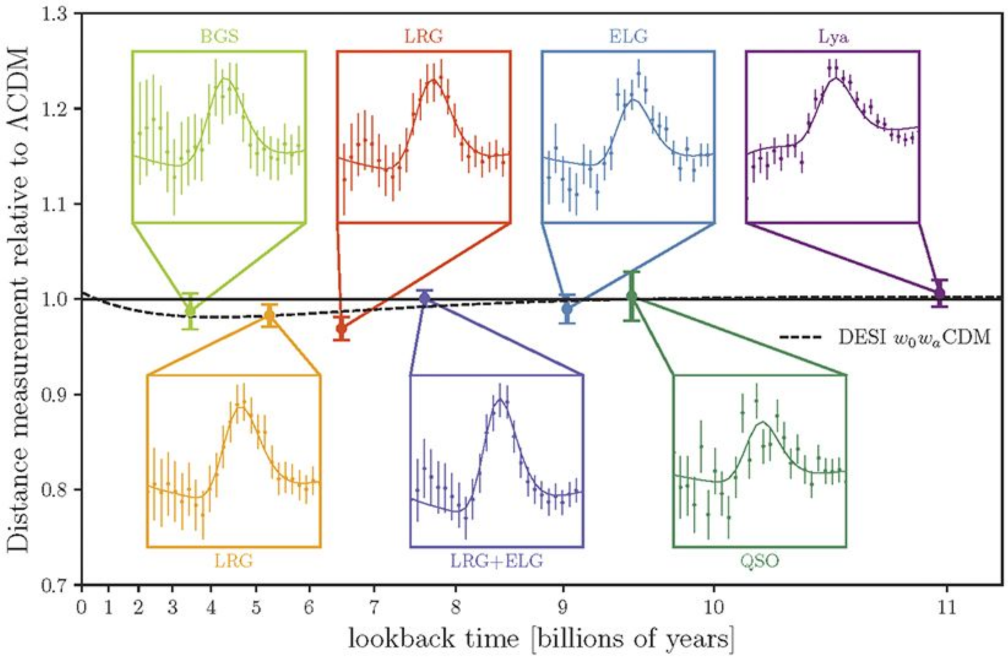
- Measurements of the CMB power spectra at $\ell>30$ tightly constrain the combination $A_s e^{-2\tau}$, while polarization at $\ell<20$ is sensitive to τ^2
- Large scale polarization is most easily measured with a CMB satellite or balloon-borne CMB experiment

Planck 2018:

$$\tau = 0.054 \pm 0.007$$

Planck (2018); Figure Credit: Reichardt (2015)

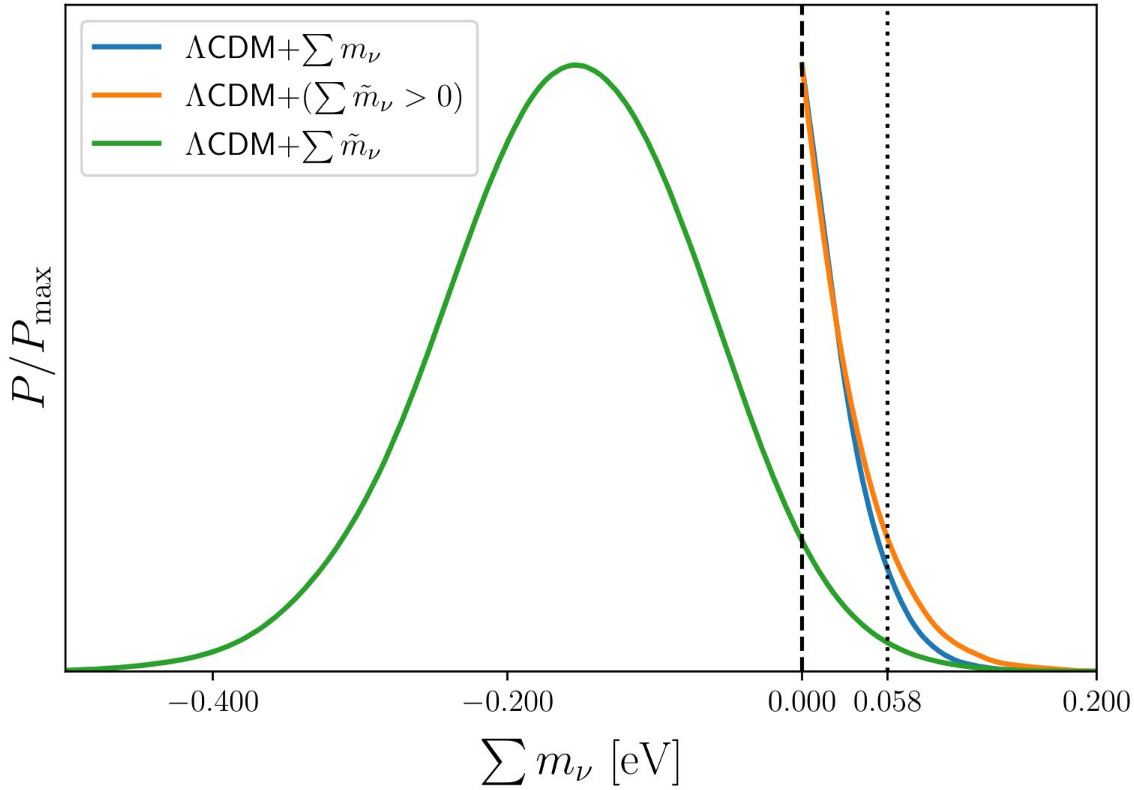
Matter Density with Baryon Acoustic Oscillations



- Spectroscopic galaxy surveys such as DESI 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

DESI (2024)

Current Measurement

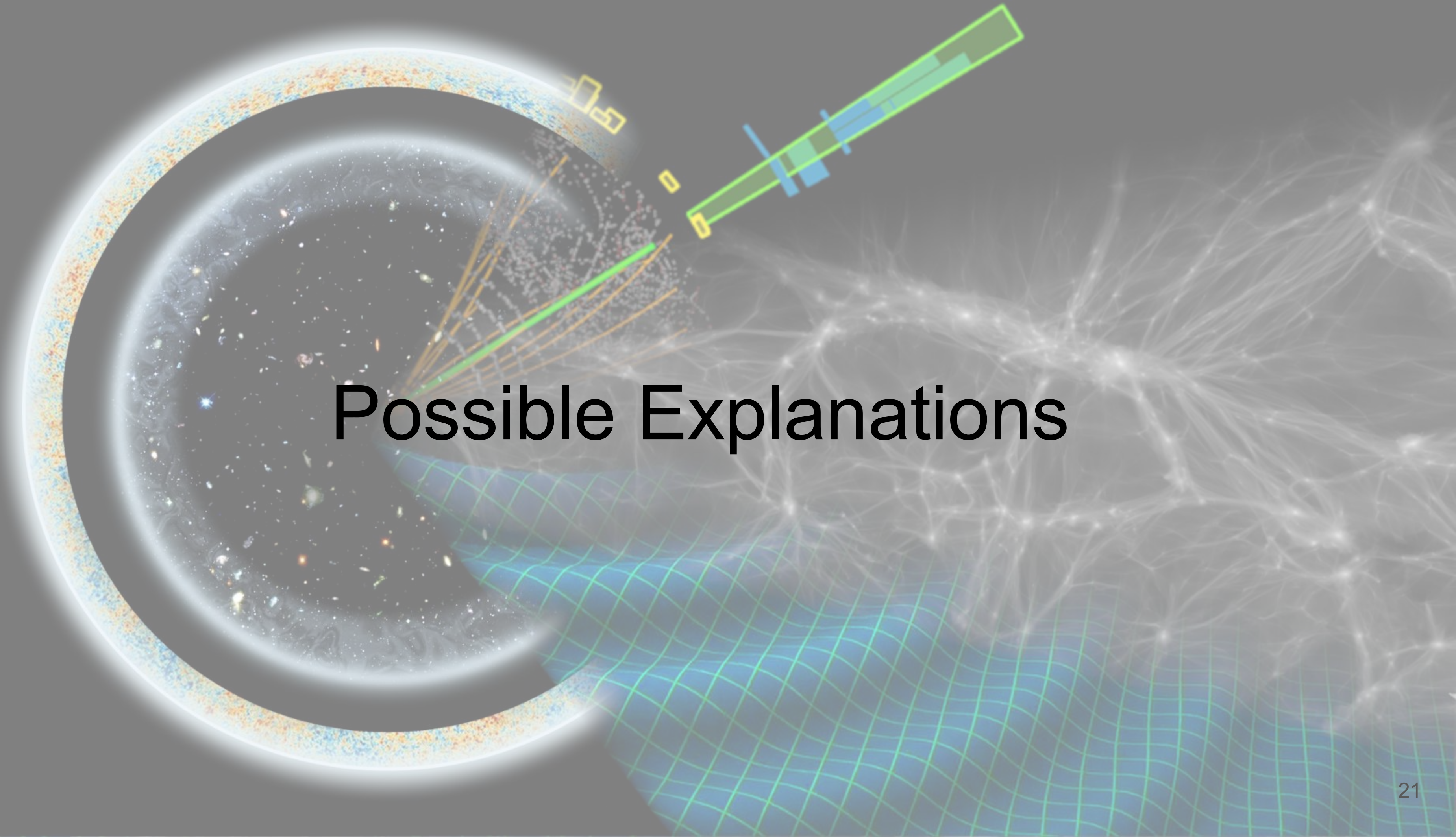


- Planck + ACT Lensing + DESI BAO measurements favor negative neutrino mass

$$\sum m_\nu = -160 \pm 90 \text{ meV} \quad (68\%)$$

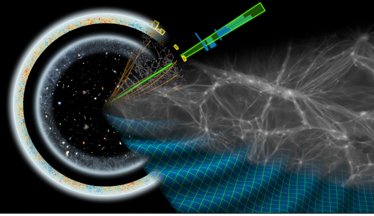
- This measurement disfavors the minimal mass for the normal hierarchy (58 meV) at 99% confidence

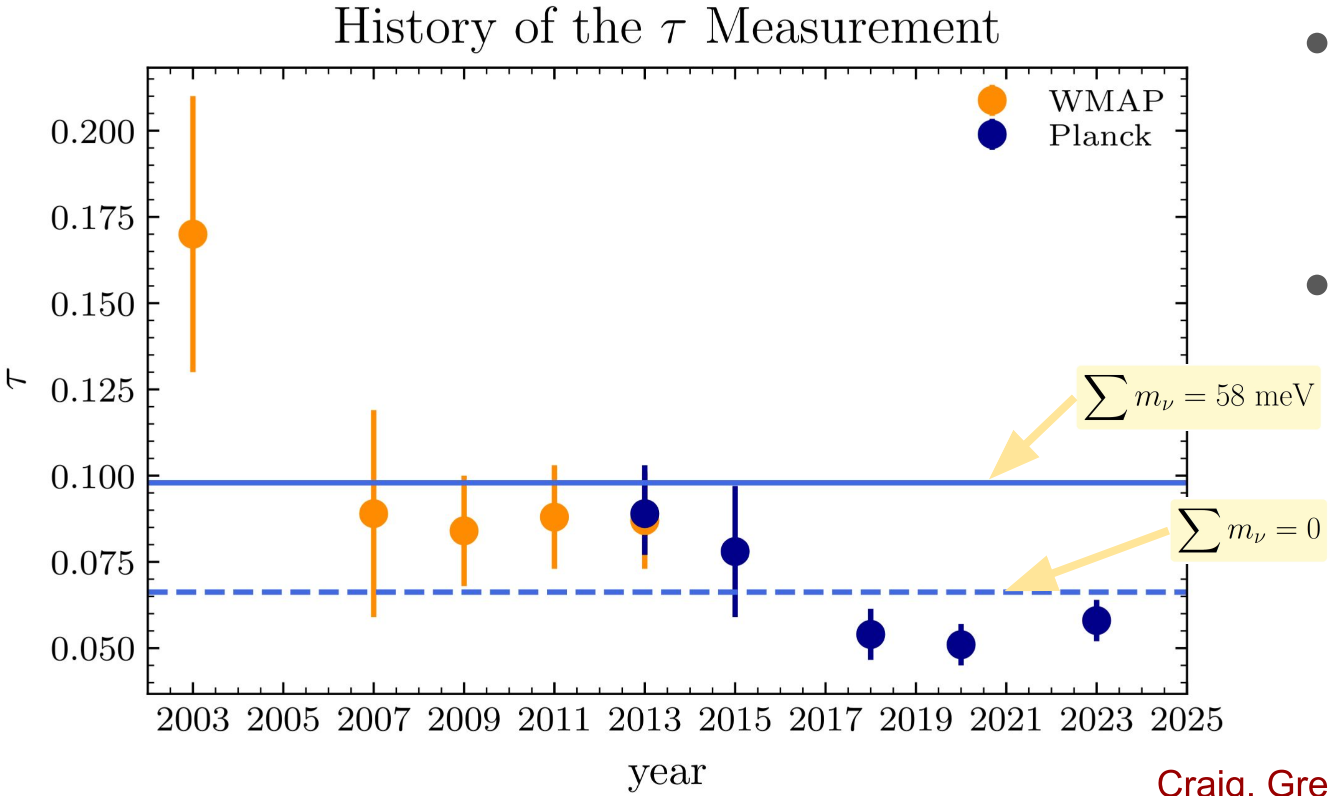
Craig, Green, JM, Rajendran (2024)



Possible Explanations

Optical Depth Systematic

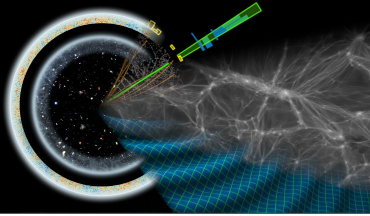


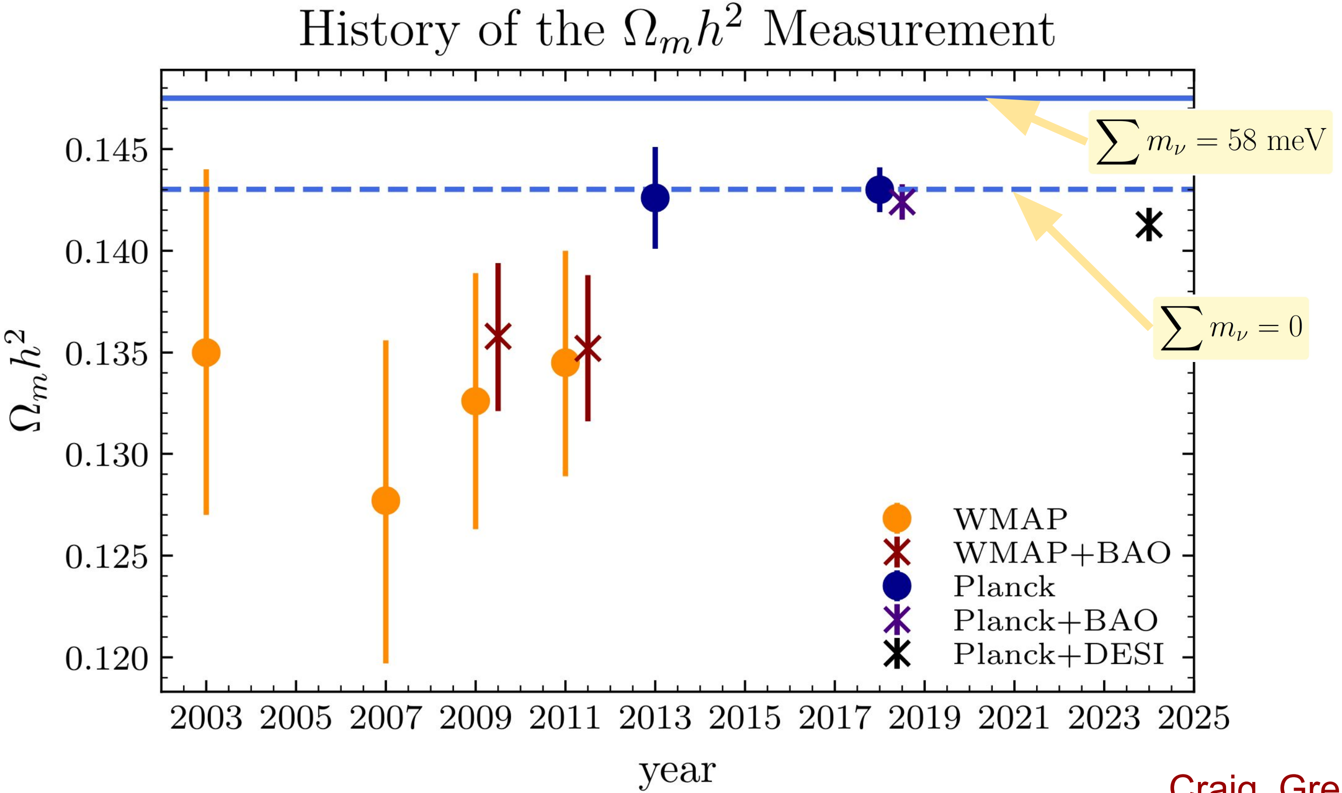


- The best-fit value of the optical depth has evolved over time
- A shift much larger than the statistical error on τ would be required to explain inference of negative neutrino mass

Craig, Green, JM, Rajendran (2024)

Matter Density Systematic

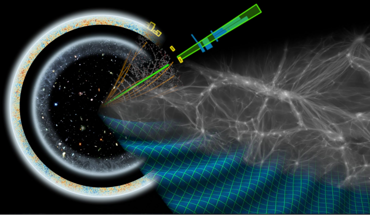




- The preference for negative neutrino mass could be explained by a shift to the matter density
- Measurements of matter density have remained roughly consistent over time

Craig, Green, JM, Rajendran (2024)

New Physics?



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

Massive neutrinos do not cluster like cold dark matter

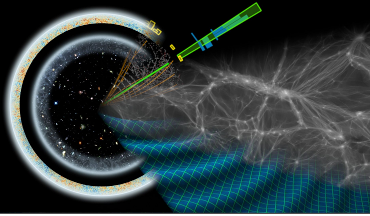
Dark matter clustering is suppressed in presence of free-streaming neutrinos

$$z_\nu \approx 100 \left(\frac{m_\nu}{50\ \mathrm{meV}}\right)$$

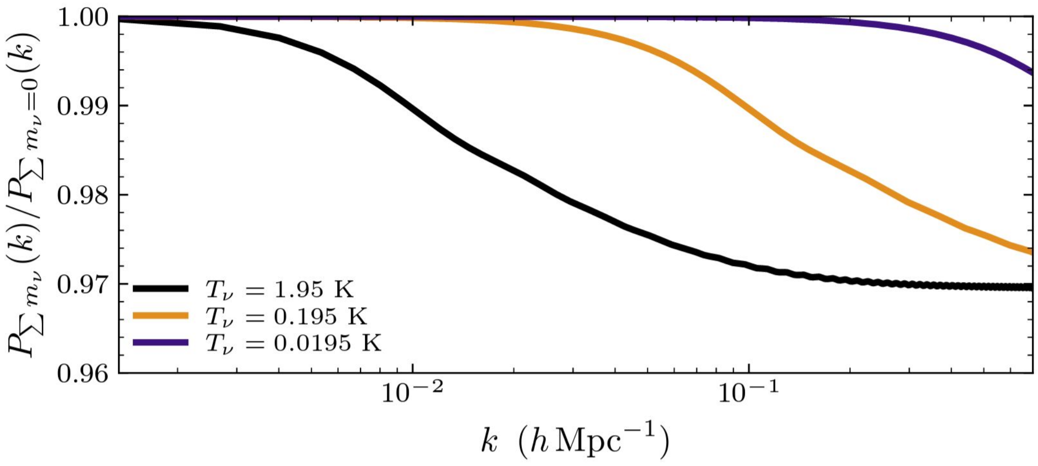
Neutrinos become non-relativistic at high redshift

Craig, Green, JM, Rajendran (2024)

New Physics for Vanishing Neutrino Mass



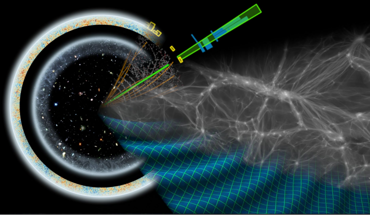
$$\mathcal{L}_\phi \supset \frac{\lambda_{ij}}{2}\bar{\nu}_i\nu_j\phi + \frac{\tilde{\lambda}_{ij}}{2}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$



- Neutrino decay
- Neutrino annihilation
- Neutrino cooling or heating
- Time-varying mass

Craig, Green, JM, Rajendran (2024)

New Physics for Negative “Neutrino Mass”



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

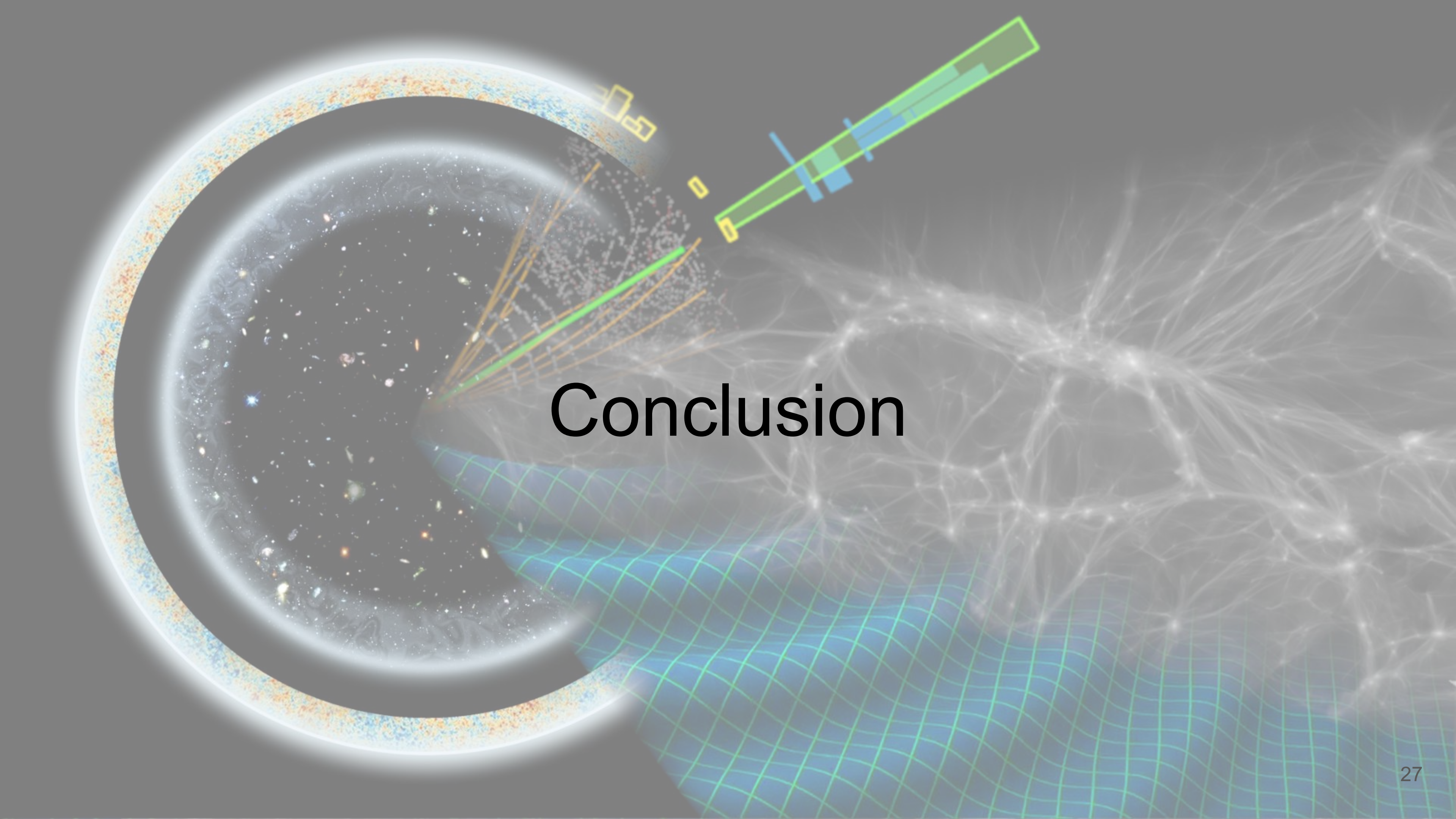
Enhancement from long-range force on dark matter

$$\zeta(\vec{x}) = \zeta_{\mathrm{G}}(\vec{x}) + \sqrt{\tau_{\mathrm{NL}}^{\sigma}}\,\zeta_{\mathrm{G}}(\vec{x})\sigma(\vec{x})$$

$$\left\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\zeta_{\vec{k}_4} \right\rangle' = \tau_{\mathrm{NL}}^{\sigma} P_\zeta(k_1) P_\zeta(k_3) P_\sigma(|\vec{k}_1 + \vec{k}_2|) + \text{permutations}$$

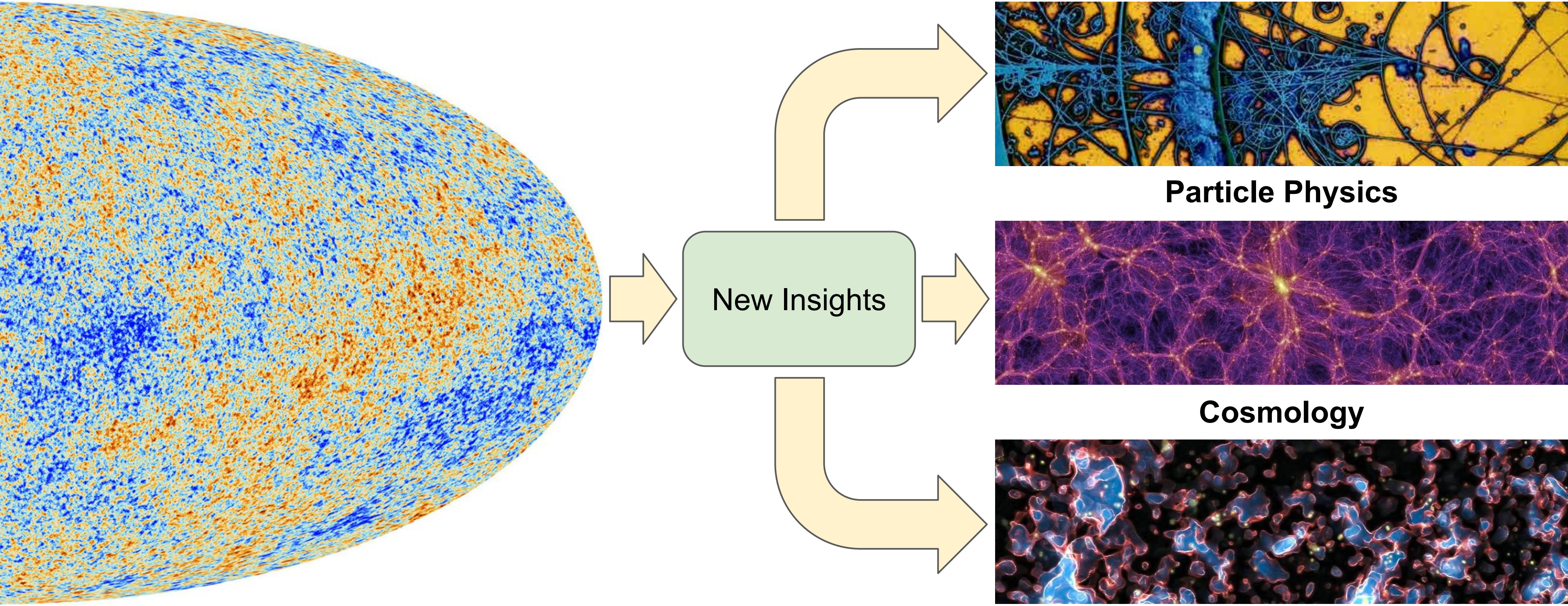
- New long-range force for dark matter
- Primordial trispectrum that mimics CMB lensing

Craig, Green, JM, Rajendran (2024)



Conclusion

Conclusion



New Insights

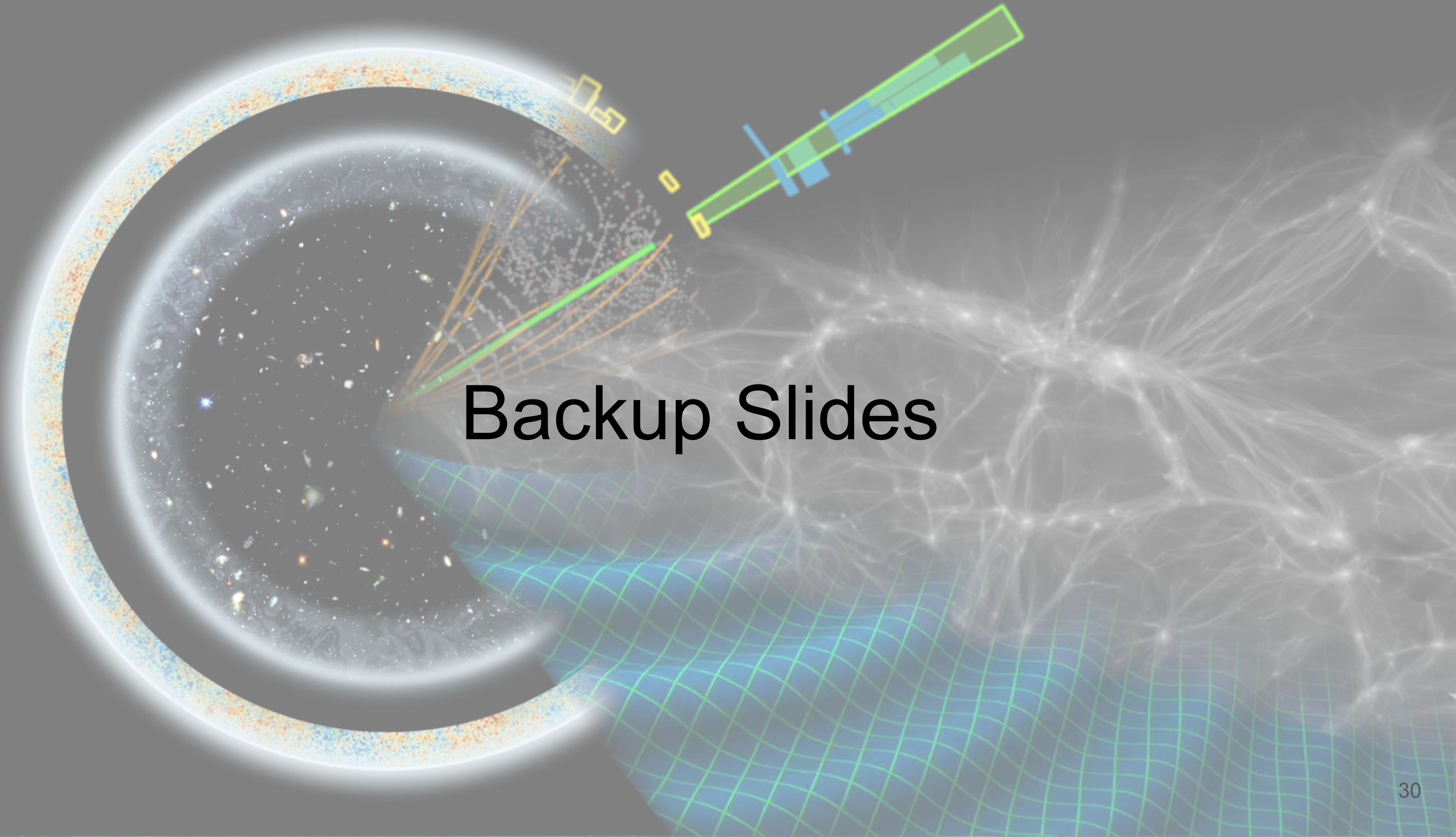
Particle Physics

Cosmology

Astrophysics

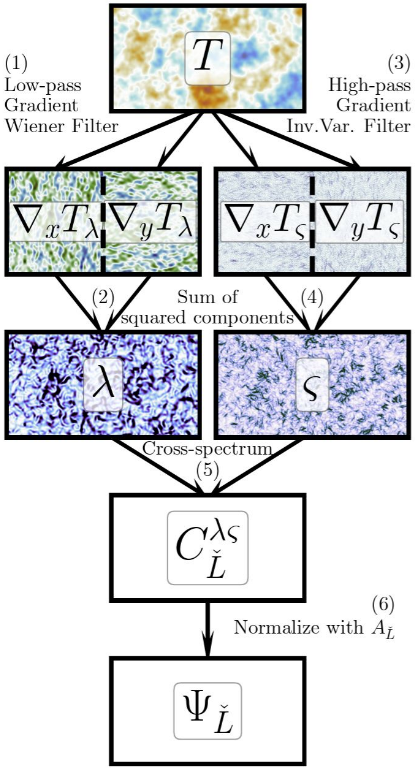
Image Credits: Planck; BEBC/CERN; Springel, et al; Alvarez, Kaehler, Abel

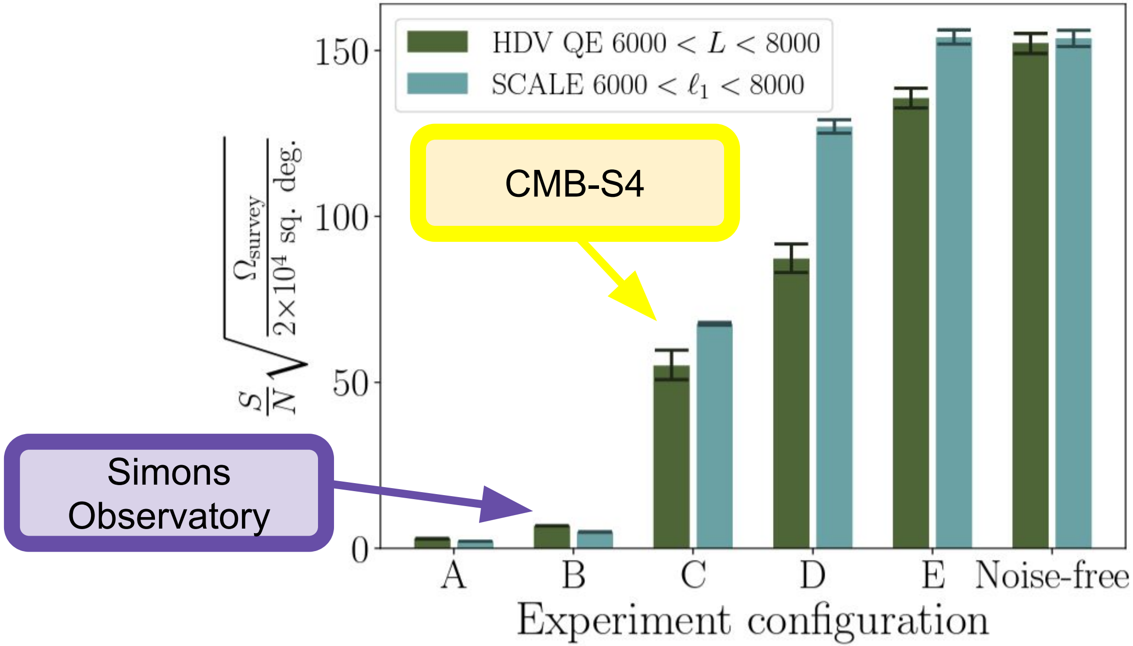
Thank You!



Backup Slides

Improved Lensing Measurement with Small Correlated Against Large Estimator (SCALE)

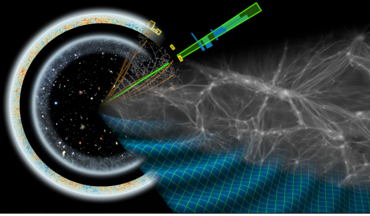




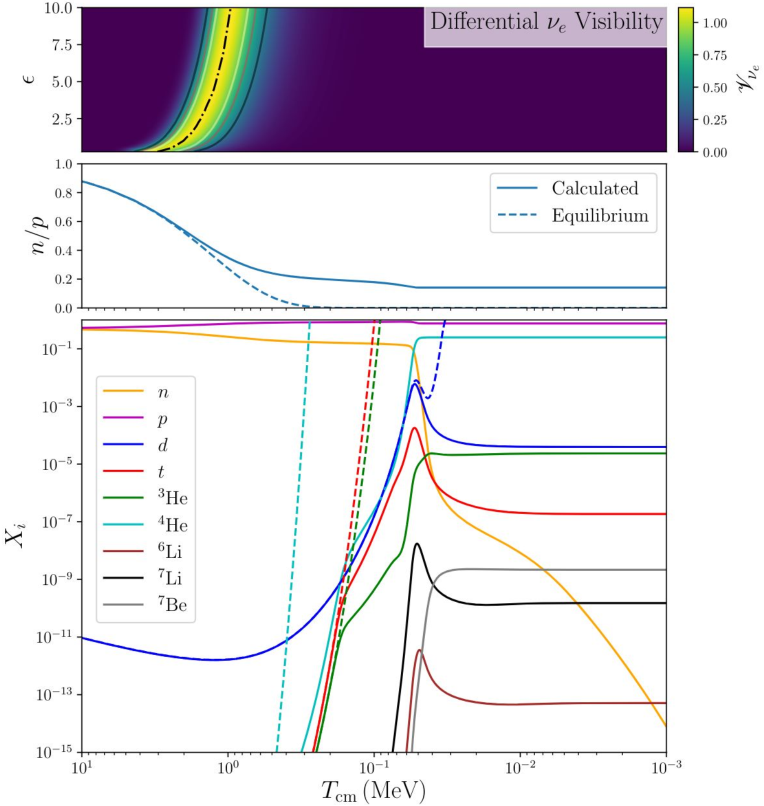
CMB-S4

Simons Observatory

Chan, Hlozek, JM, van Engelen (2023)



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

Fischler, JM (2010); Lague, JM (2020);
Bond, Fuller, Grohs, JM, Wilson (2024);
Yeh, Shelton, Fields, Olive (2022)