New Opportunities and New Challenges with Upcoming CMB Surveys

Joel Meyers
SMU

TACOS at Rice
10-9-2023

Image Credit: ACT / Princeton

History of the Universe

High Energy Sensitivity

Recombination

Imprints of Structure

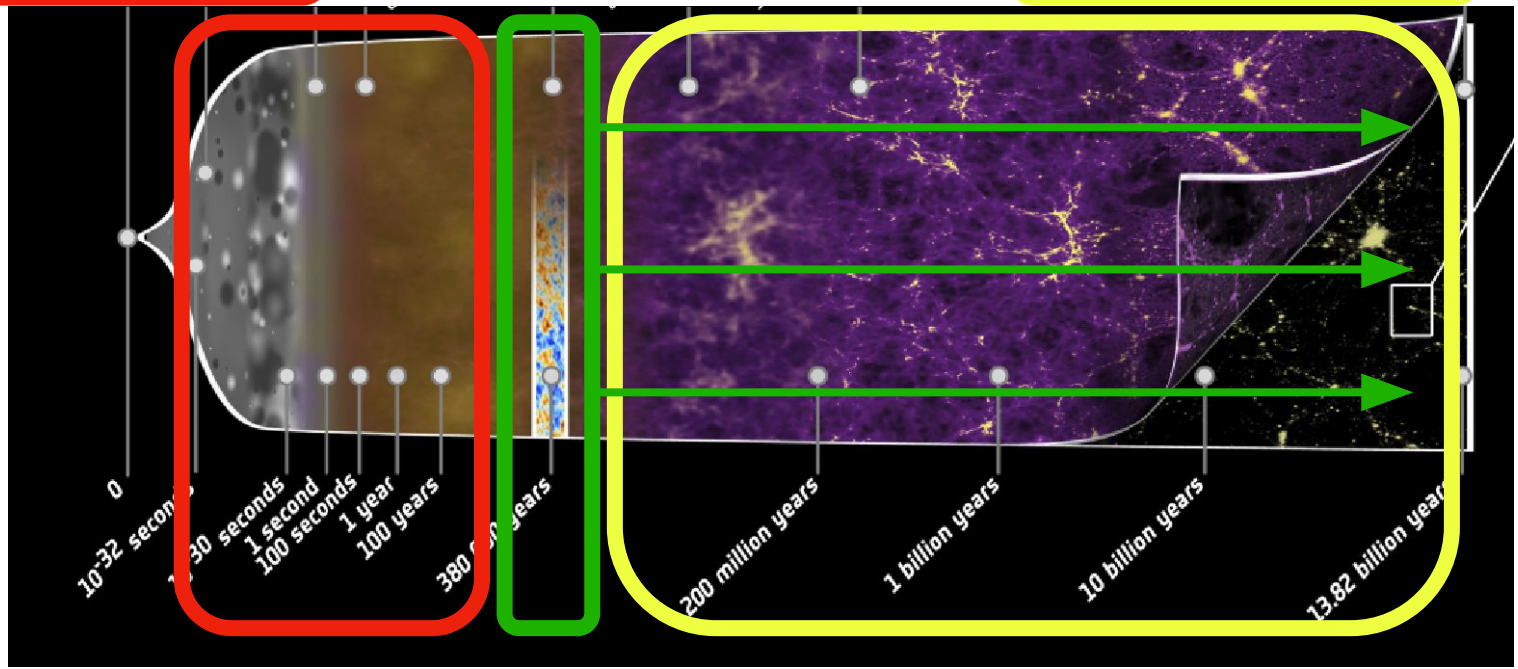


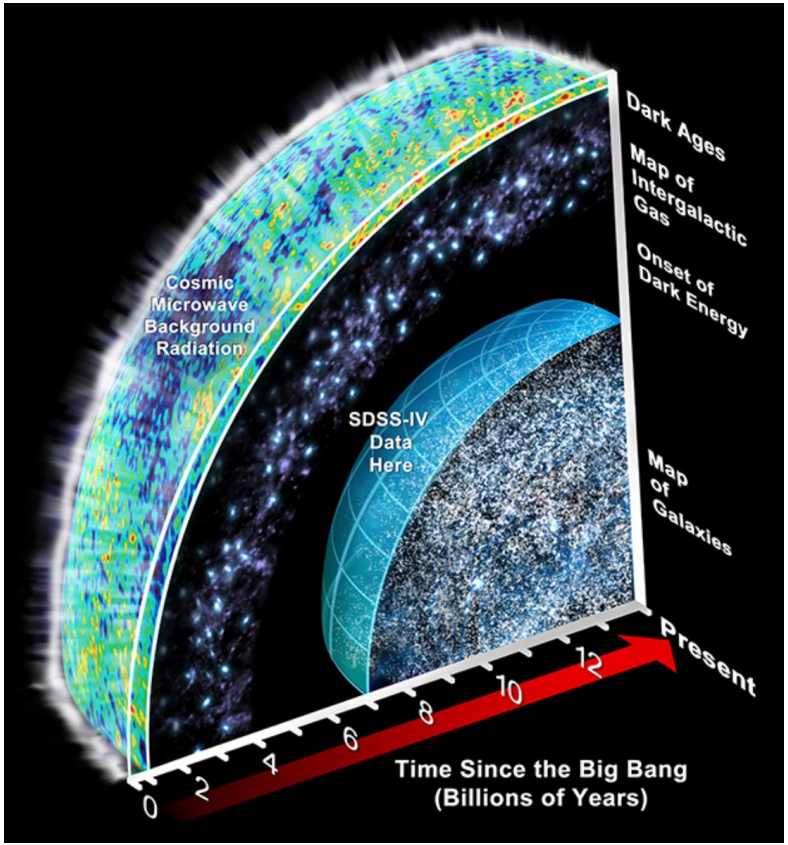
Image Credit: NASA

Outline

- Cosmic Microwave Background Review
- Gravitational Lensing of the CMB
- Example of CMB Lensing Application: Cosmic Neutrinos
- Improving CMB Lensing Estimates
- The Benefits of CMB Delensing
- Machine Learning for CMB Secondaries
- Conclusion

CMB Review

The Cosmic Microwave Background



Cosmic Microwave Background (CMB) Spectrum

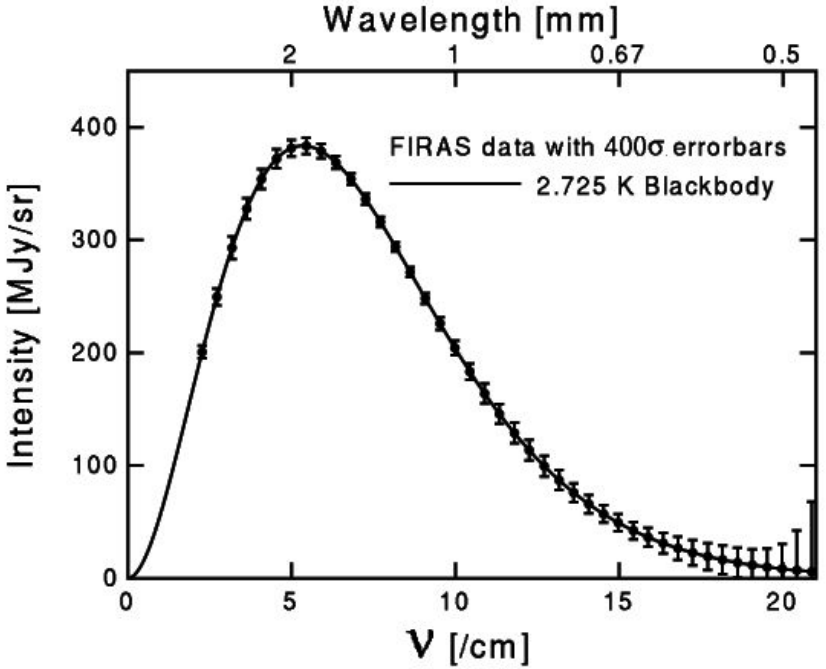
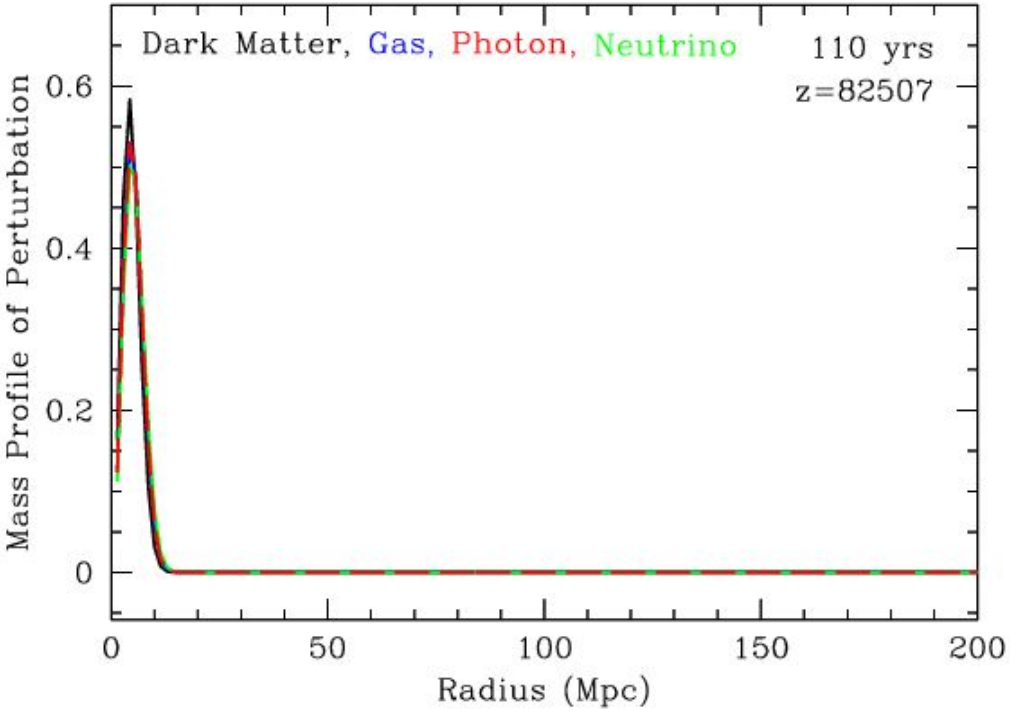


Image Credits: SDSS, COBE FIRAS

Sound Waves in the Primordial Plasma



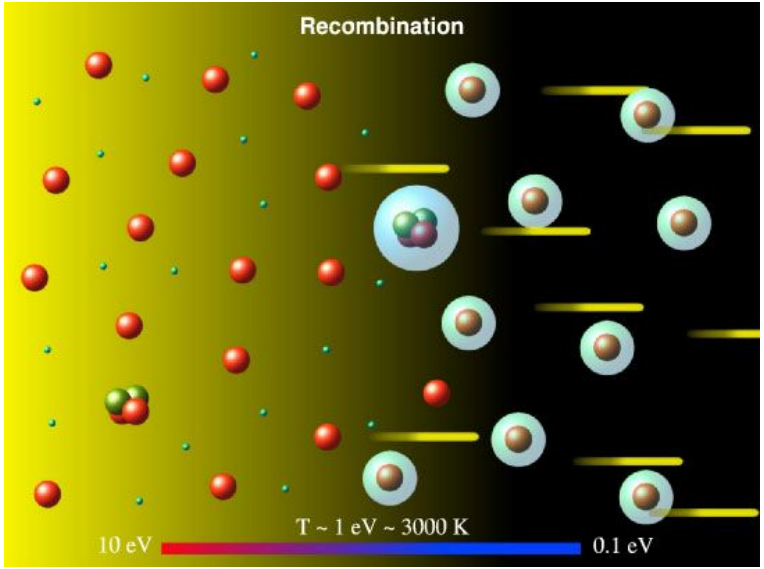


Image Credits: Eisenstein, Kinney

Superposition of Sound Waves

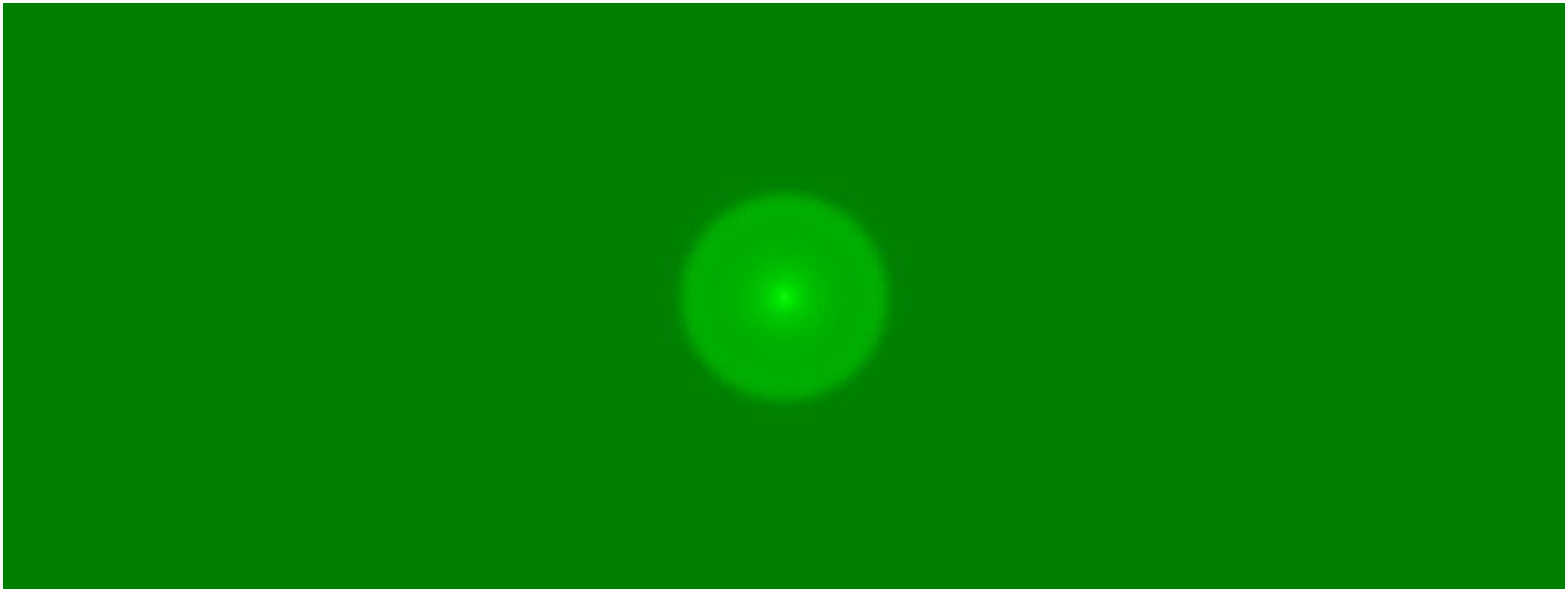
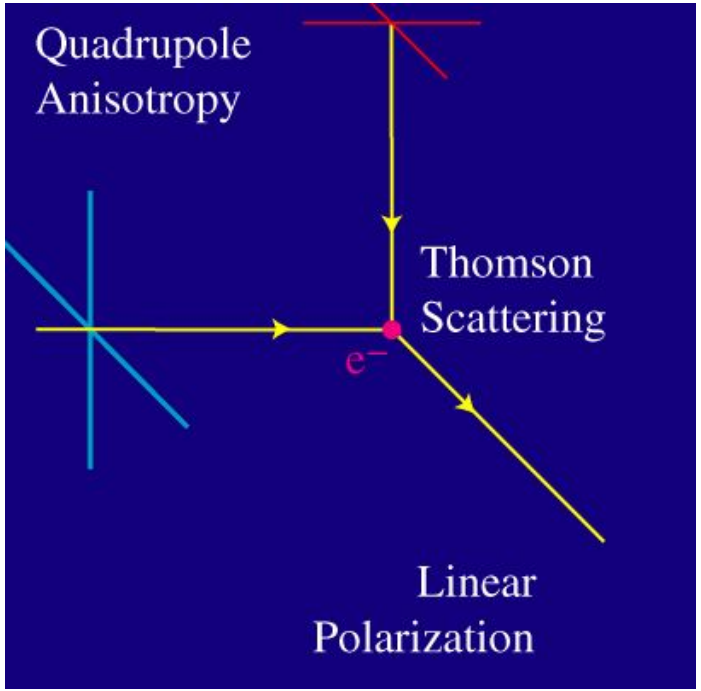


Image Credit: Hincks

Linear Polarization of the CMB



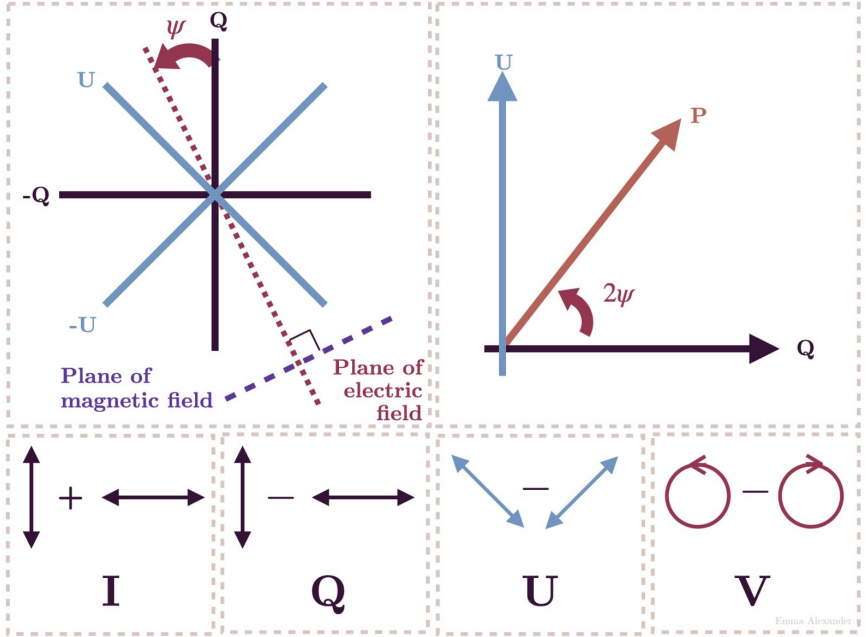
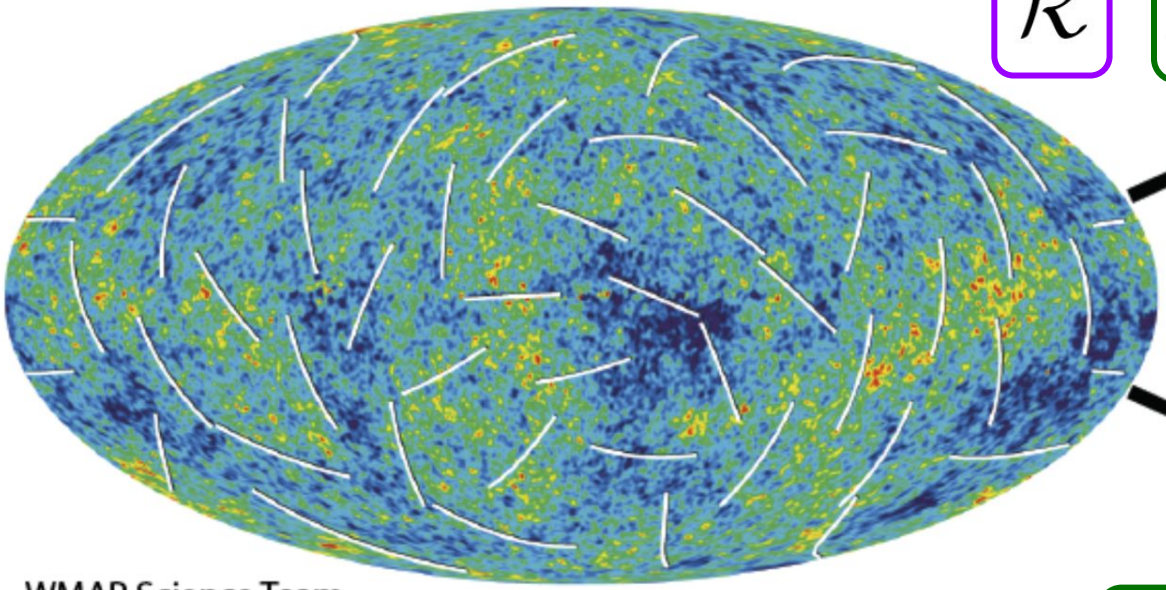


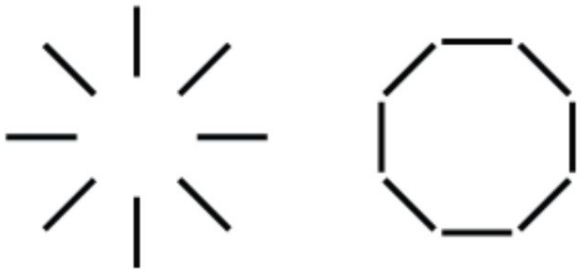
Image Credits: Hu, Alexander

E and B Modes

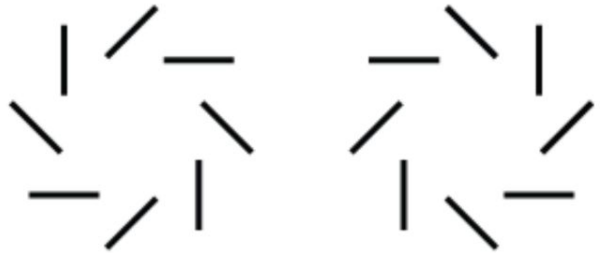


$\mathcal{R}$ h_{ij}

E-modes



B-modes



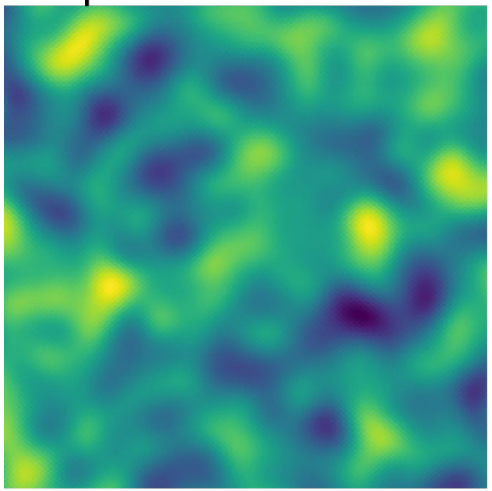
h_{ij}

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

Information In The Cosmic Microwave Background

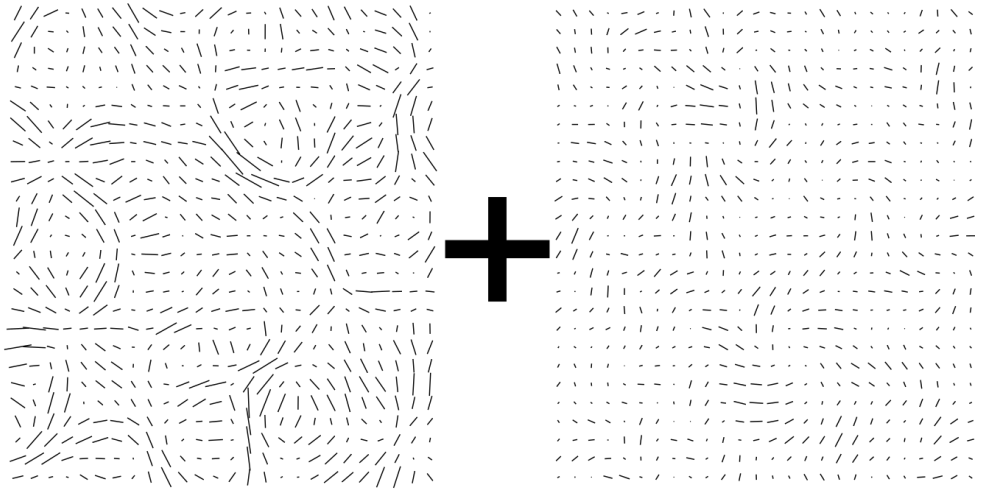
The CMB provides a snapshot of the universe as it existed during recombination

Temperature ~ distribution



T

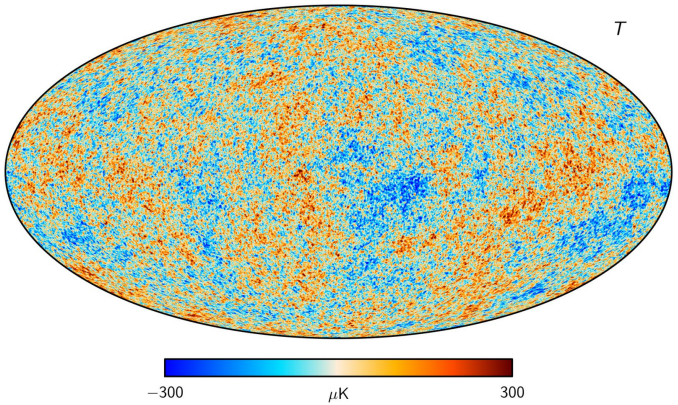
Polarization ~ motion



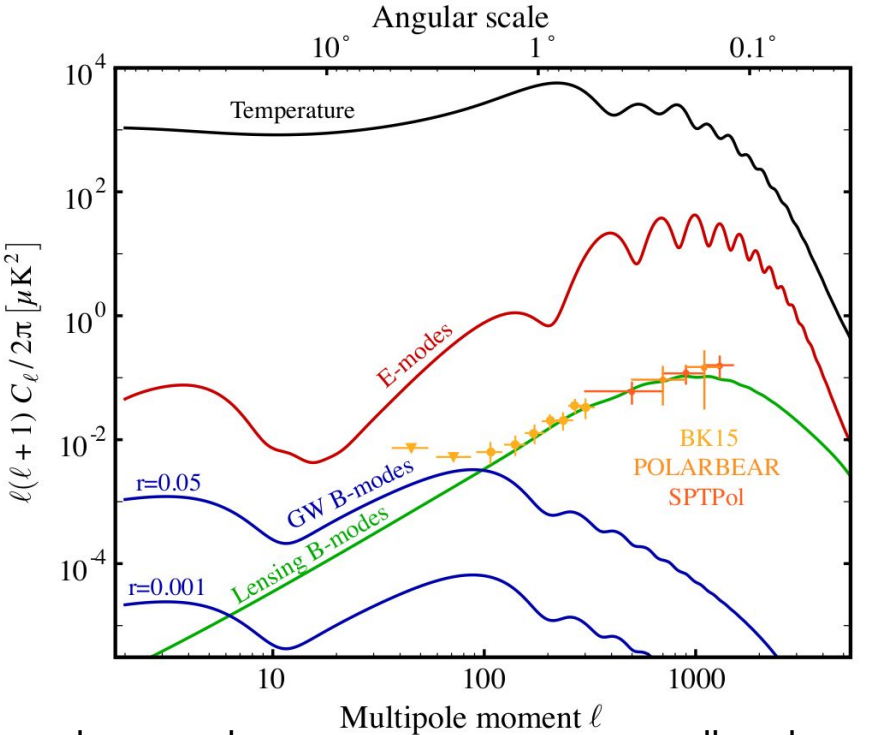
E B

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

Statistical Information and Angular Power Spectra



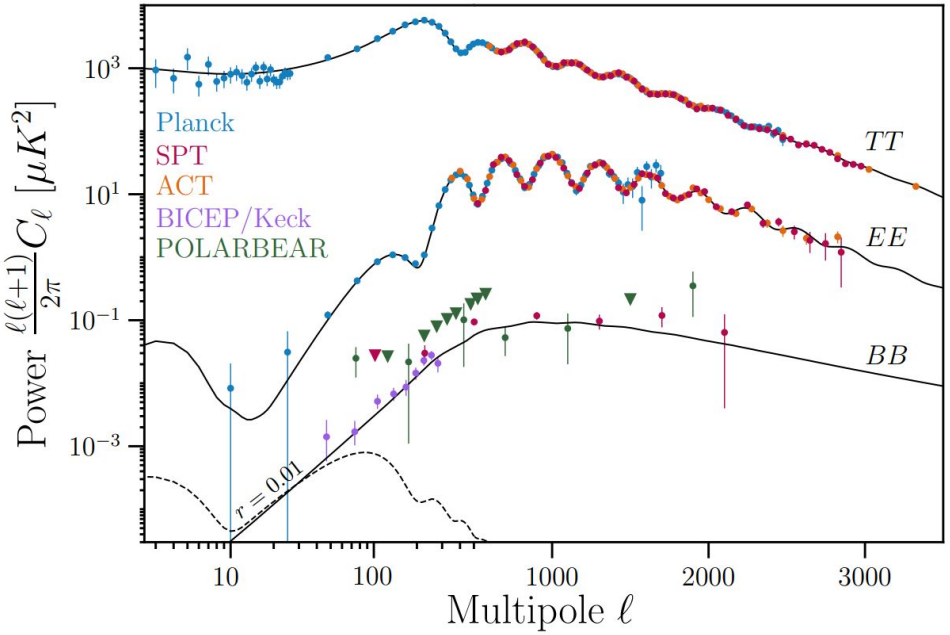
Variance

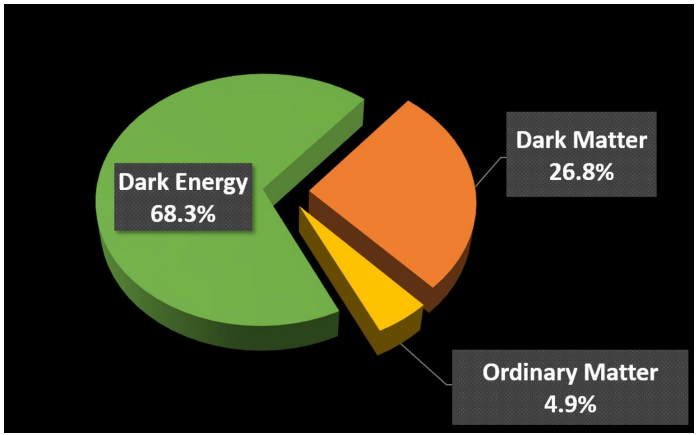


←large scales small scales →

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

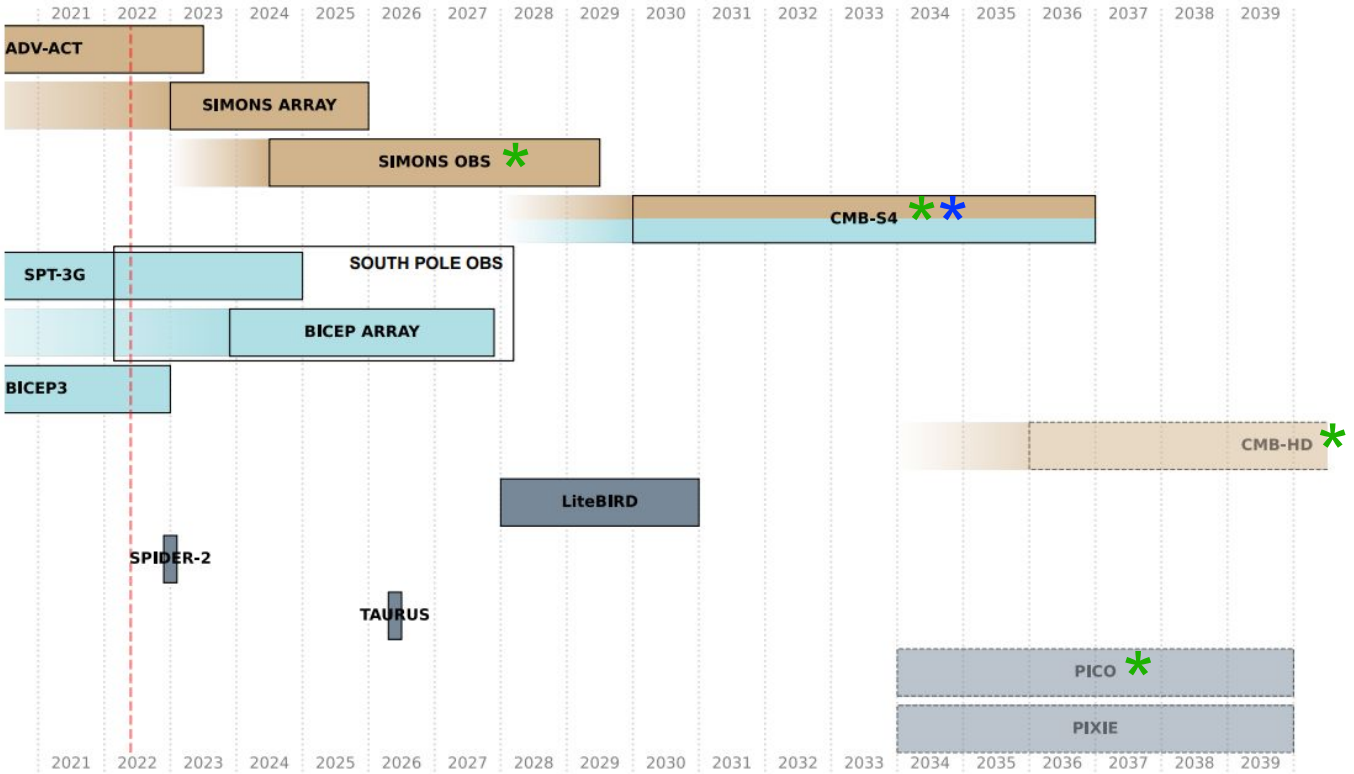
CMB Observations and Concordance Flat ΛCDM





Planck (2018); Chang, Huffenberger, et al (2022)

Timeline of Upcoming CMB Surveys



Chang, Huffenberger, et al (2022)

Gravitational Lensing of the CMB

Gravitational Lensing of the CMB

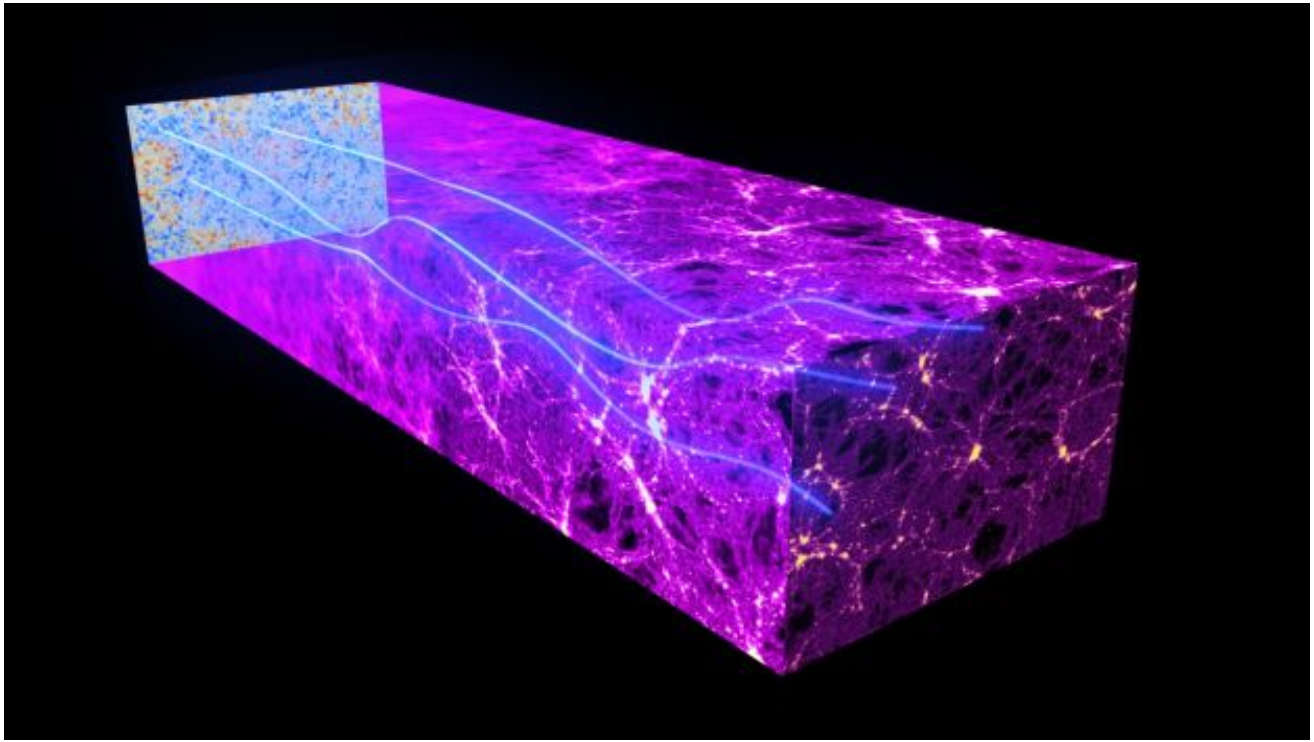
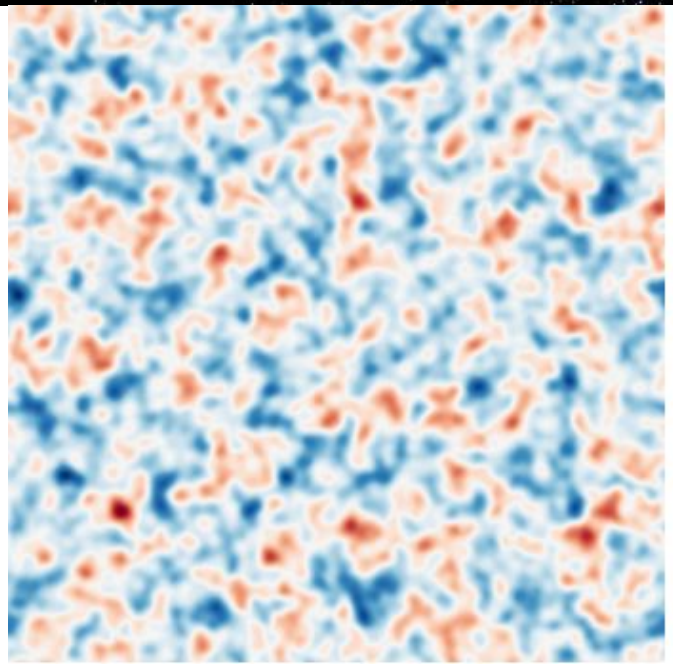


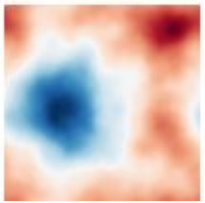
Image Credit: Planck / ESA

Unlensed CMB Polarization



Unlensed E

ϕ

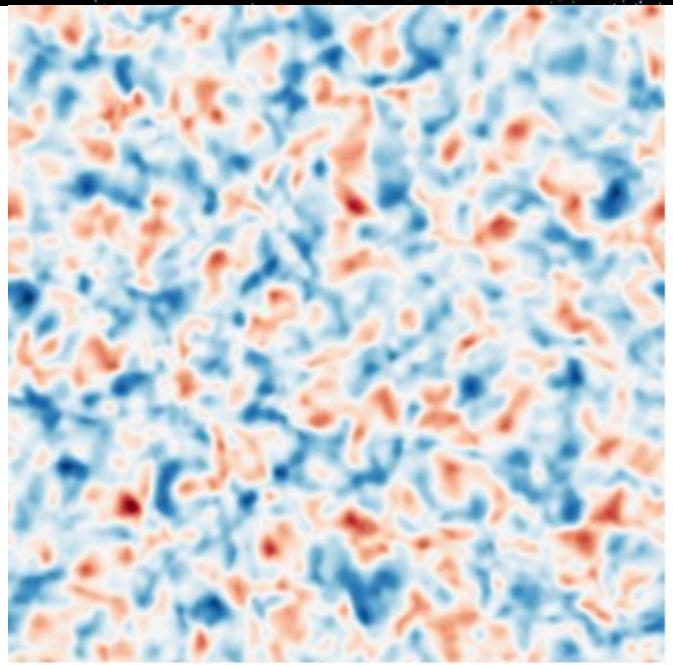


Unlensed B

5°×5° simulated maps

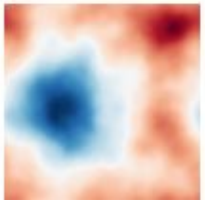
Image Credit: Guzman

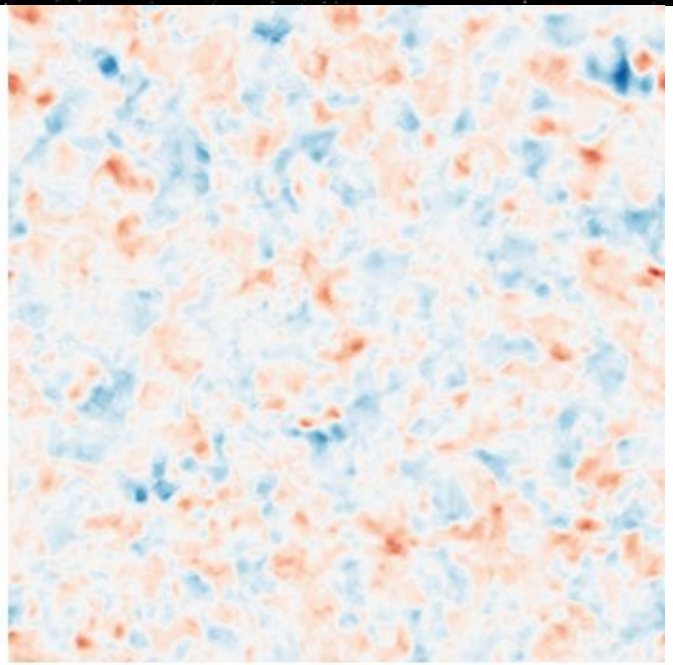
Lensed CMB Polarization



Lensed E

ϕ



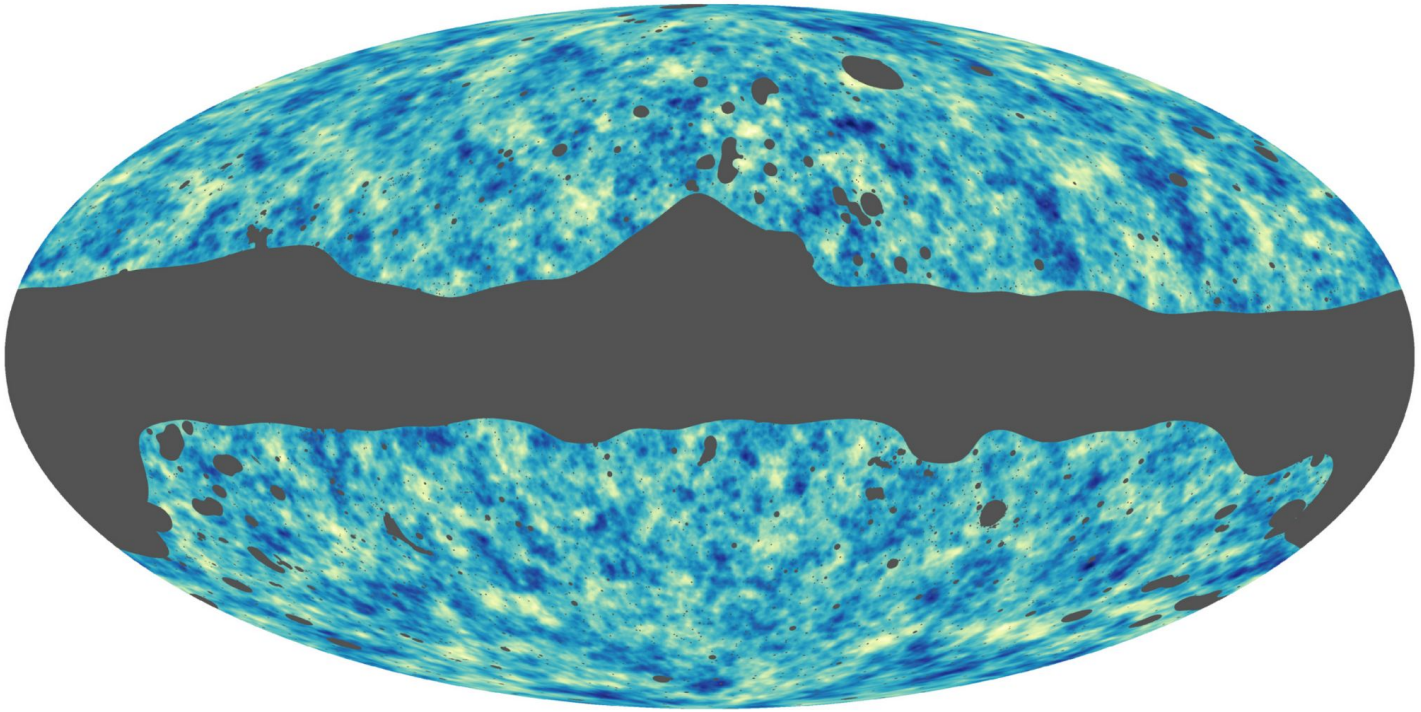


Lensed B

5°×5° simulated maps

Image Credit: Guzman

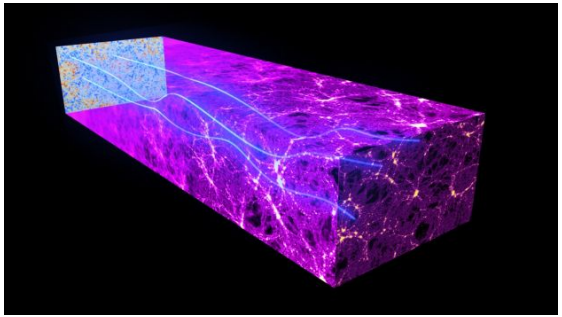
CMB Lensing Reconstruction



40σ observation

Planck (2018)

CMB Lensing is a Blessing and a Curse

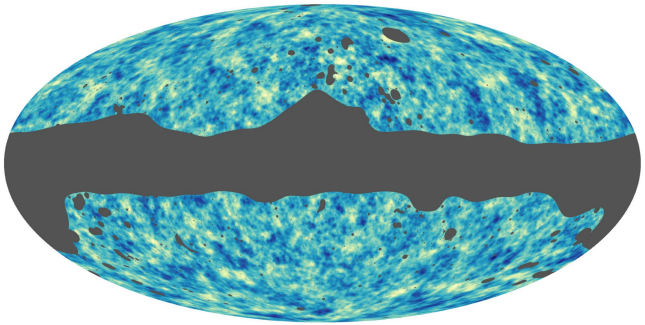


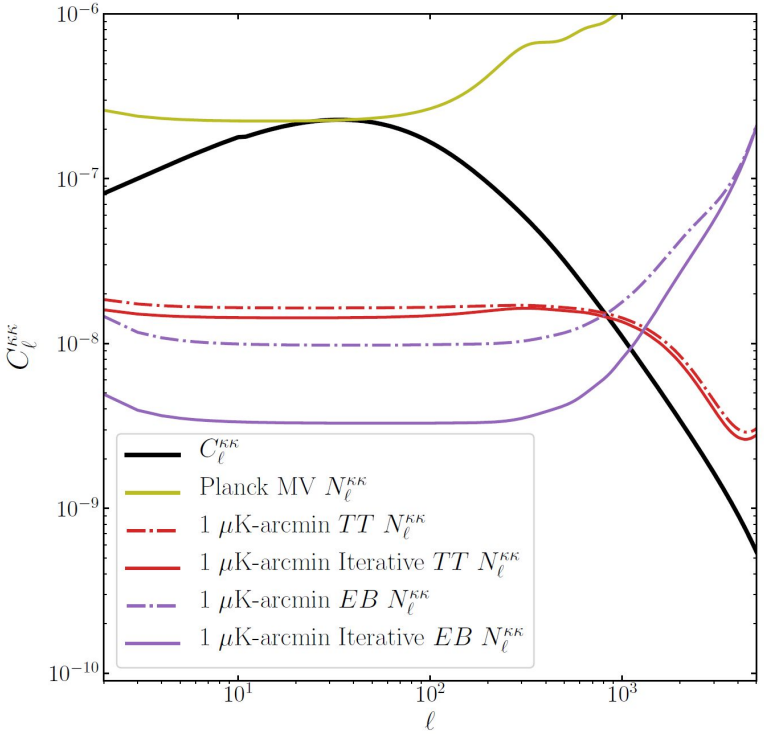
CMB lensing field is sensitive to growth of cosmological structure

Lensing distortion hinders pristine view of CMB last scattering surface

Image Credit: Planck / ESA

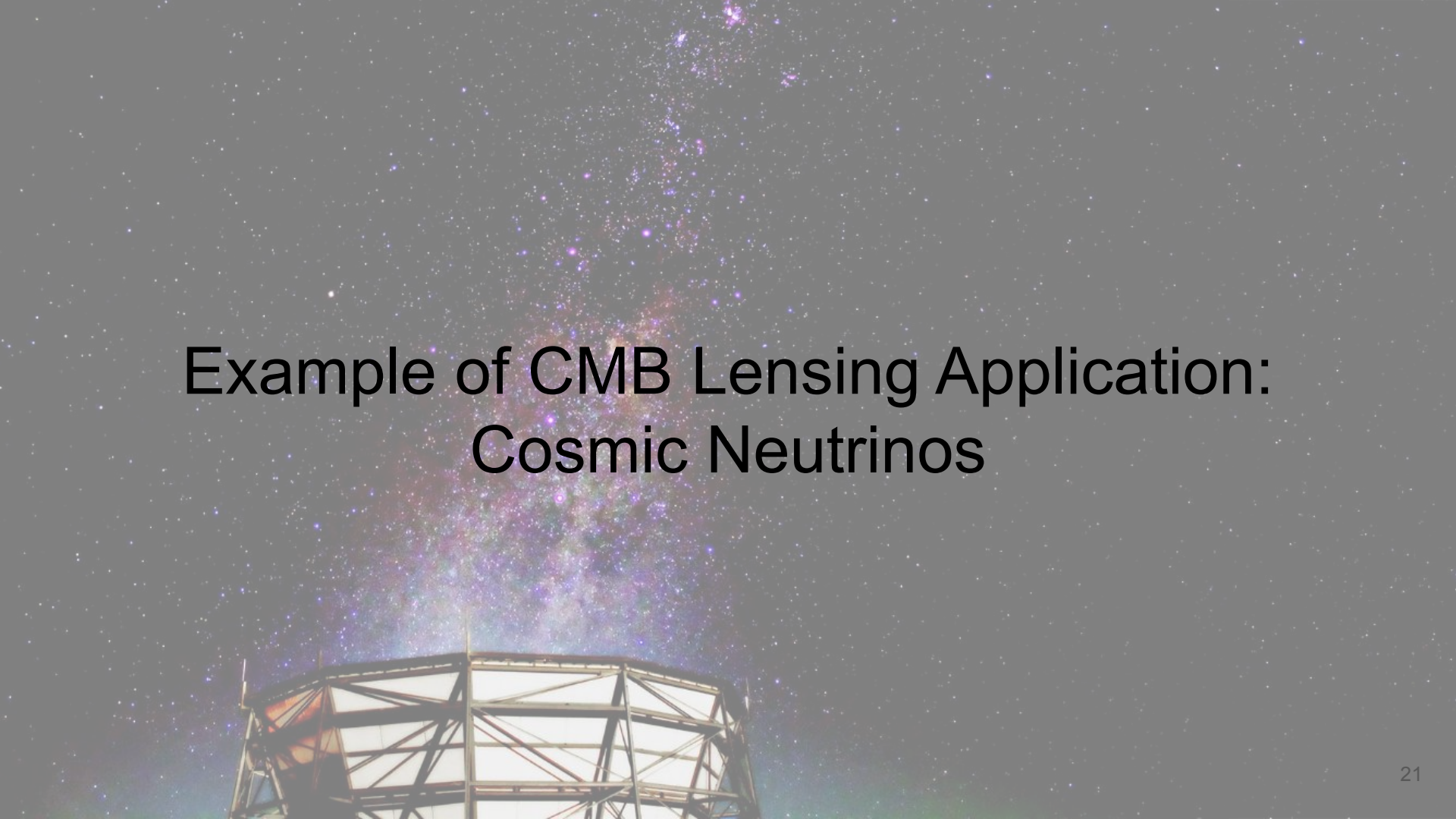
Measurements of CMB Lensing Will Improve Dramatically





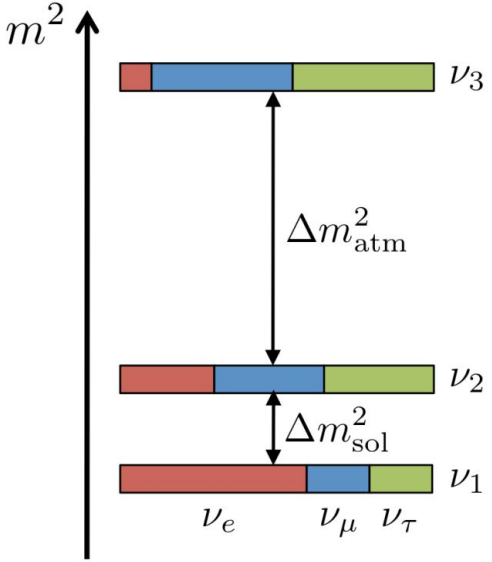
Planck (2018); CMB-S4 (2016); Hotinli, JM, Trendafilova, Green, van Engelen (2022)

Example of CMB Lensing Application: Cosmic Neutrinos



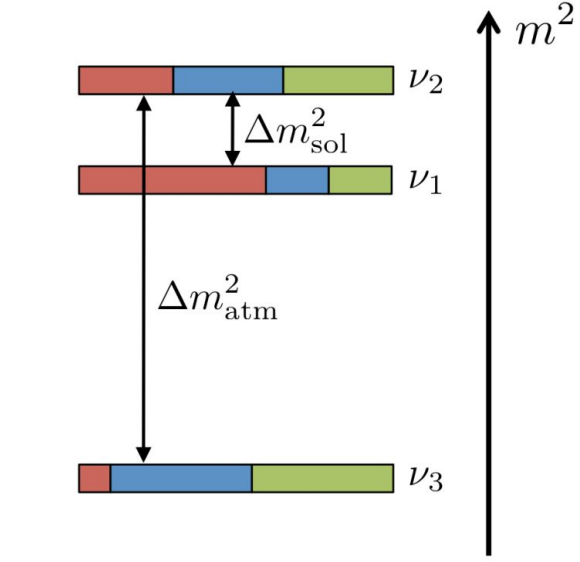
Massive Cosmic Neutrinos

normal hierarchy (NH)



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

inverted hierarchy (IH)



$$\sum m_\nu \gtrsim 105 \text{ meV}$$

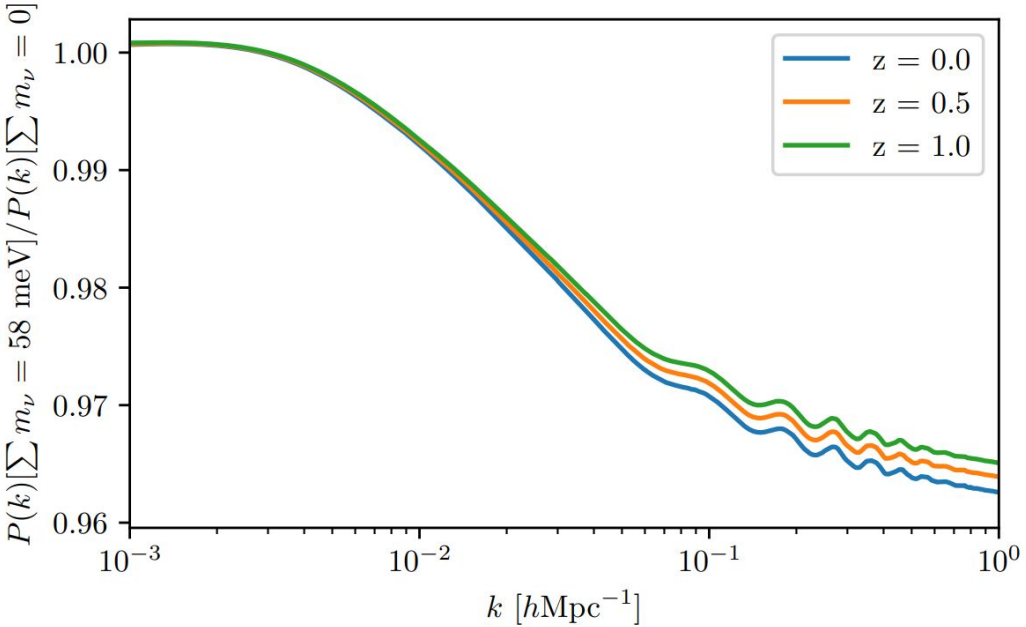
Cosmology is sensitive to the gravitational effects of the cosmic neutrino background, allowing a measurement of a sum of neutrino masses

Current Planck 2018 constraint:

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

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

Massive Neutrinos Suppress Matter Clustering



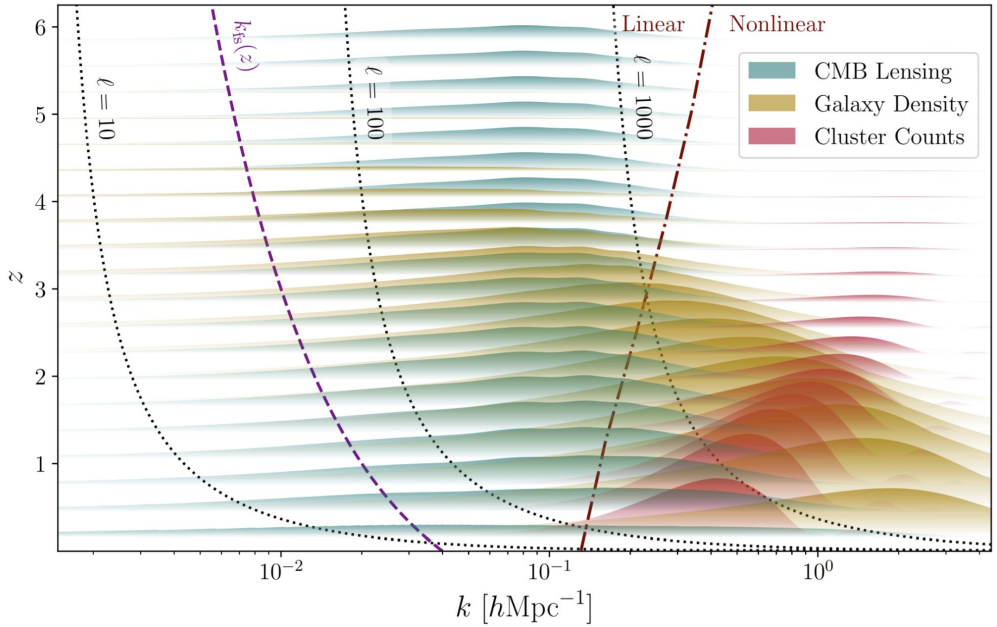
Suppression of matter clustering due to massive neutrinos
(A_s, $\Omega_m h^2$, $\Omega_b h^2$, H_0 fixed)

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

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

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

Measuring Clustering with Cosmological Surveys

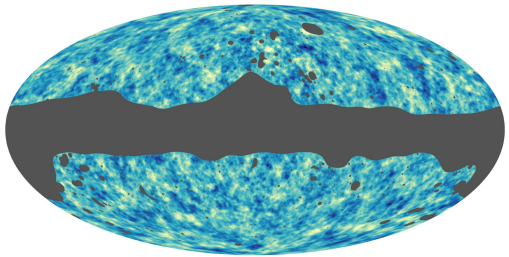


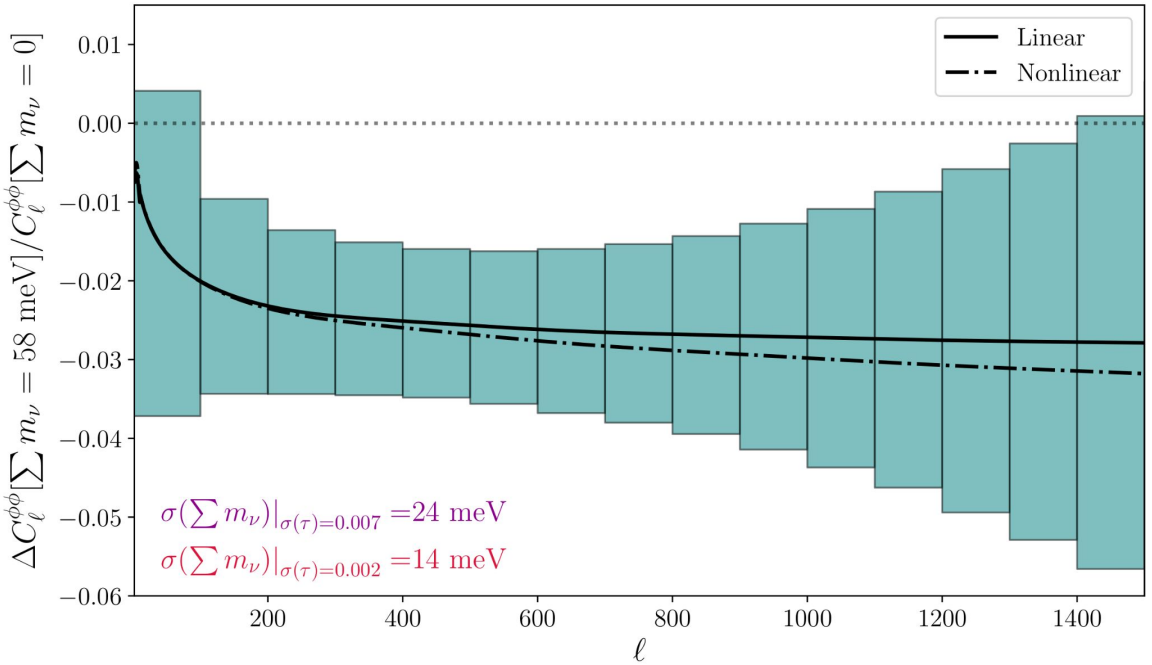
Sensitivity regimes of various probes of clustering

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

Green, JM (2021)

Neutrino Mass with CMB Lensing

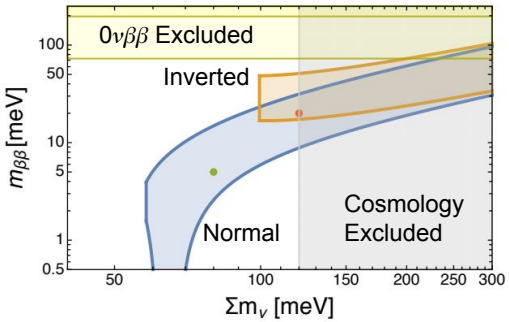


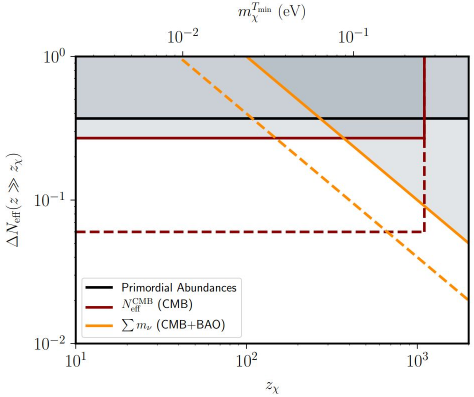


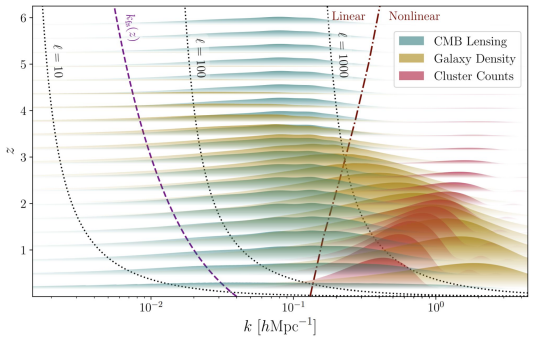
Measuring suppression of clustering with CMB-S4 lensing

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

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)

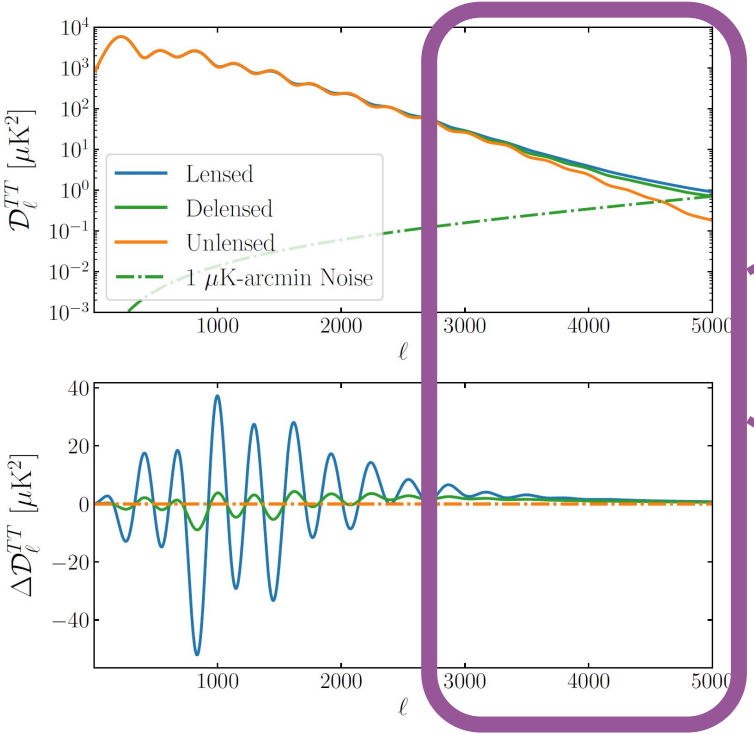
Astrophysics

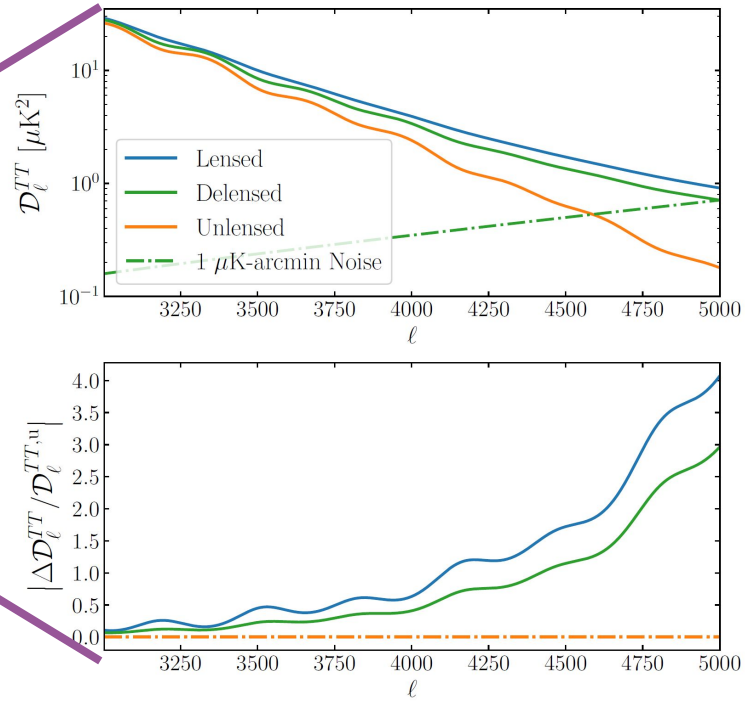
- Multiple probes of matter power allow neutrino mass to be disentangled from nonlinear and baryonic effects

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

Improving CMB Lensing Estimates

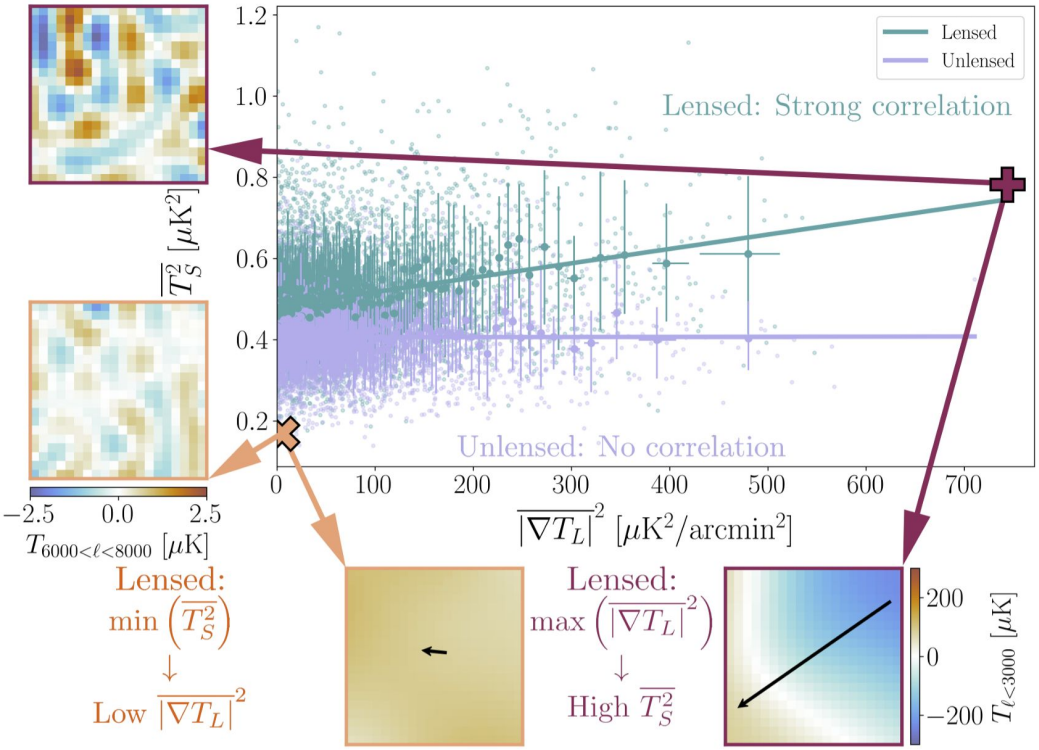
Lensed CMB Temperature Power





Hotinli, JM, Trendafilova, Green, van Engelen (2022)

Small-Scale Power Varies with Large-Scale Gradient



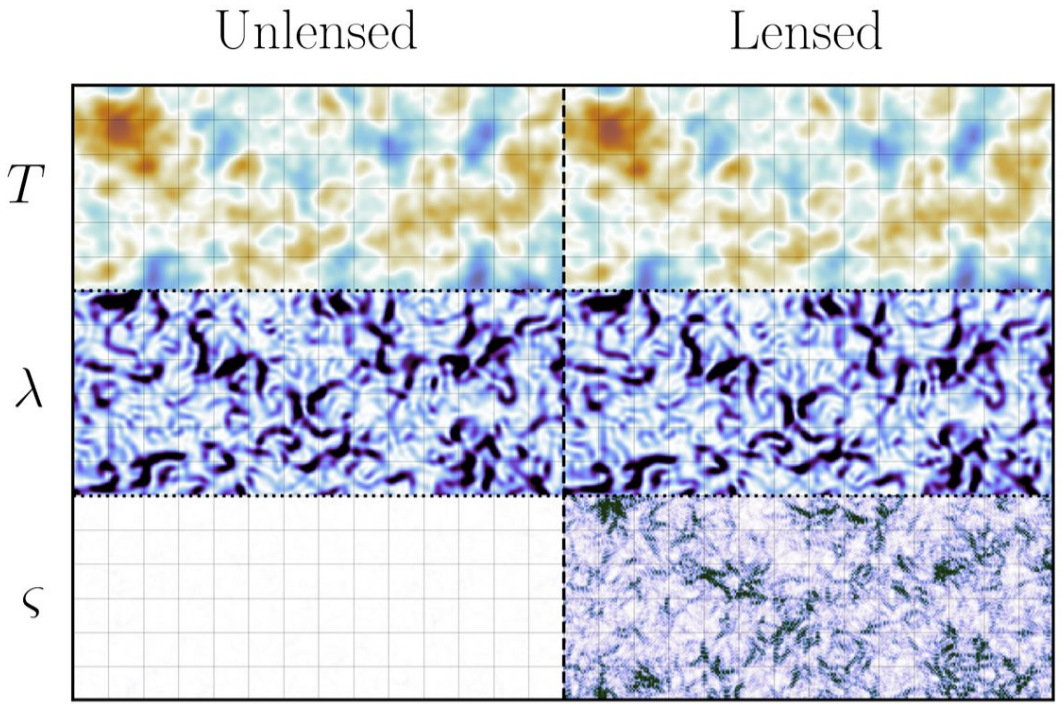
Chan, Hlozek, JM, van Engelen (2023)

Maps of Small-Scale Power and Large-Scale Power Are Correlated

Temperature

Large-Scale Gradient Power

Small-Scale Gradient Power

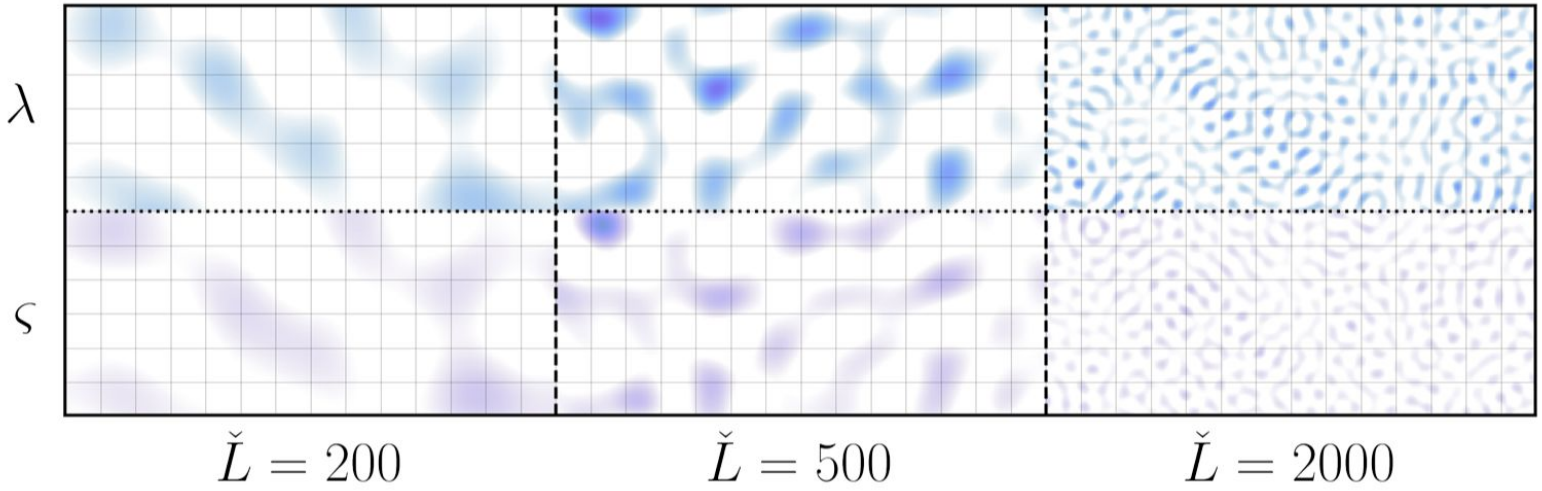


Chan, Hlozek, JM, van Engelen (2023)

Maps of Small-Scale Power and Large-Scale Power Are Correlated

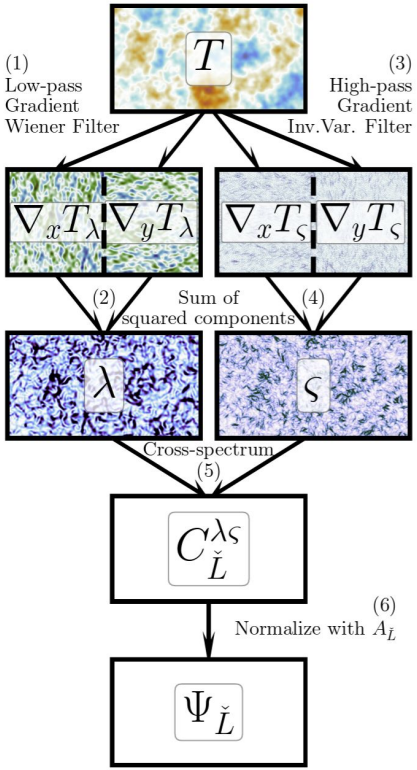
Large-Scale Gradient Power

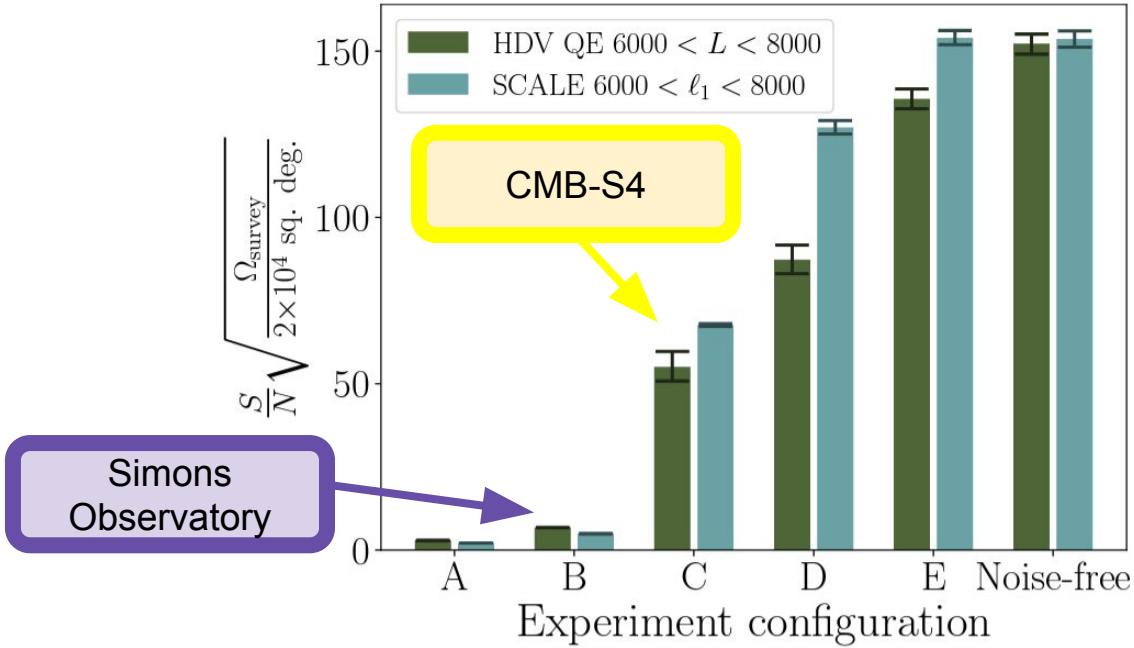
Small-Scale Gradient Power



Chan, Hlozek, JM, van Engelen (2023)

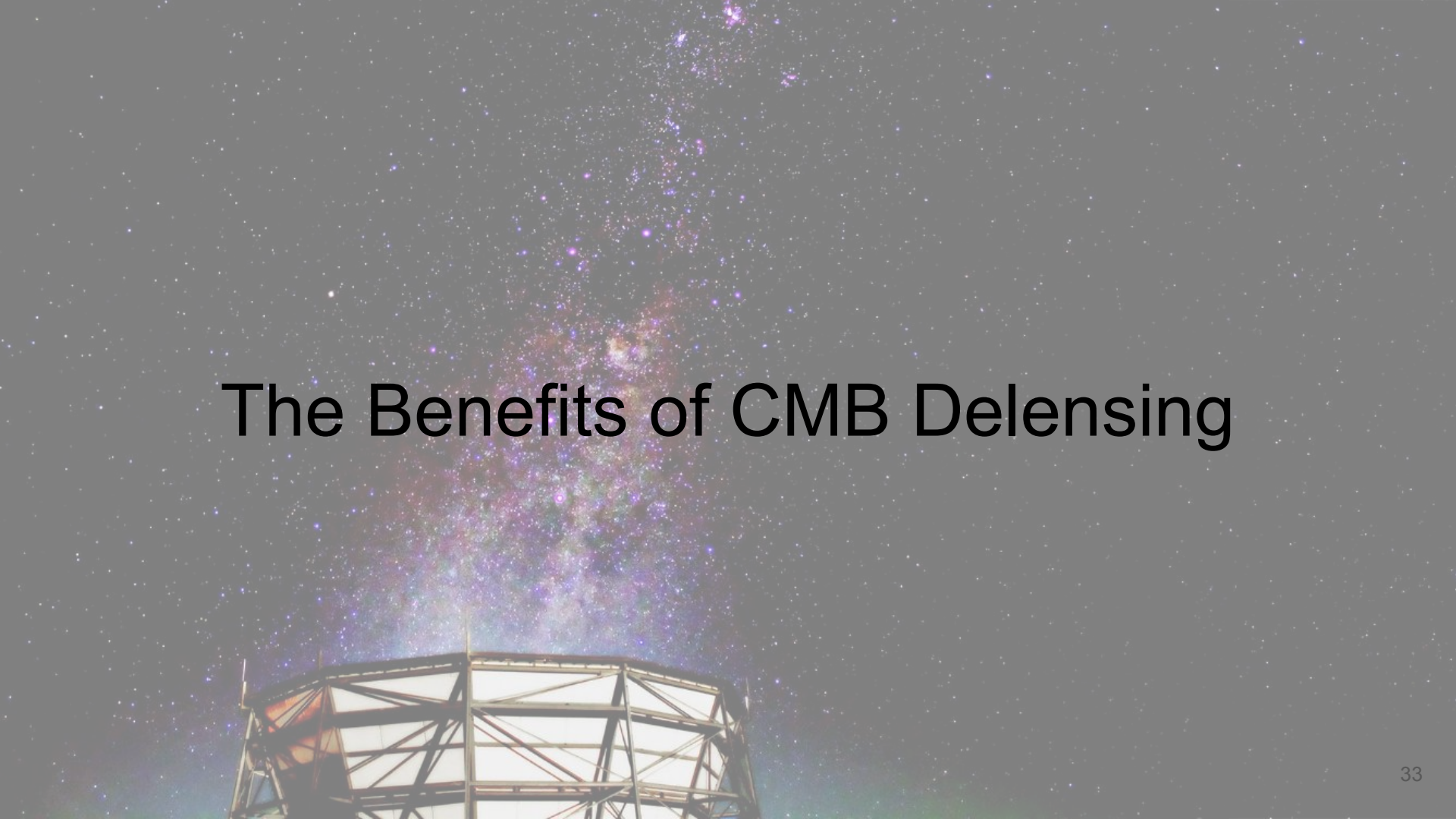
Small Correlated Against Large Estimator (SCALE)





Chan, Hlozek, JM, van Engelen (2023)

The Benefits of CMB Delensing



Gravitational Lensing Smooths Acoustic Peaks

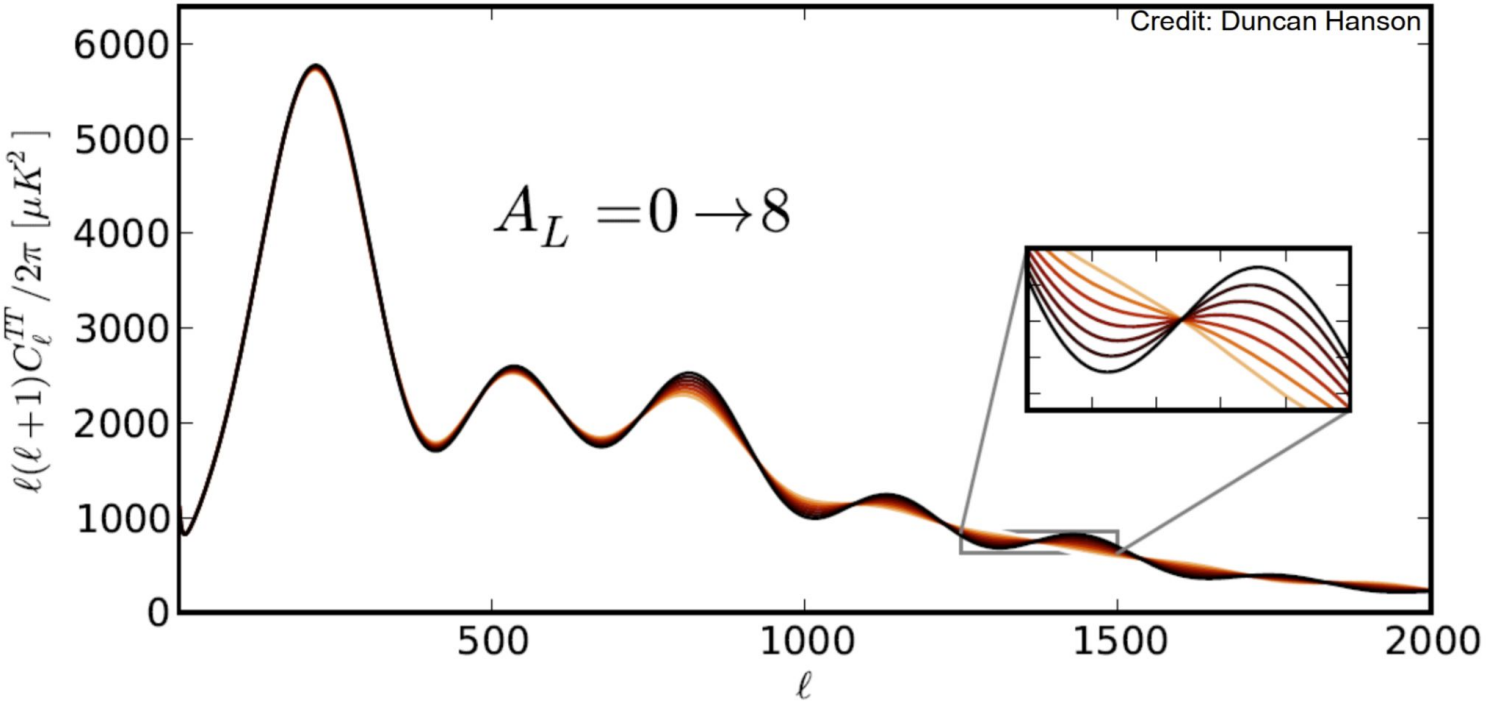
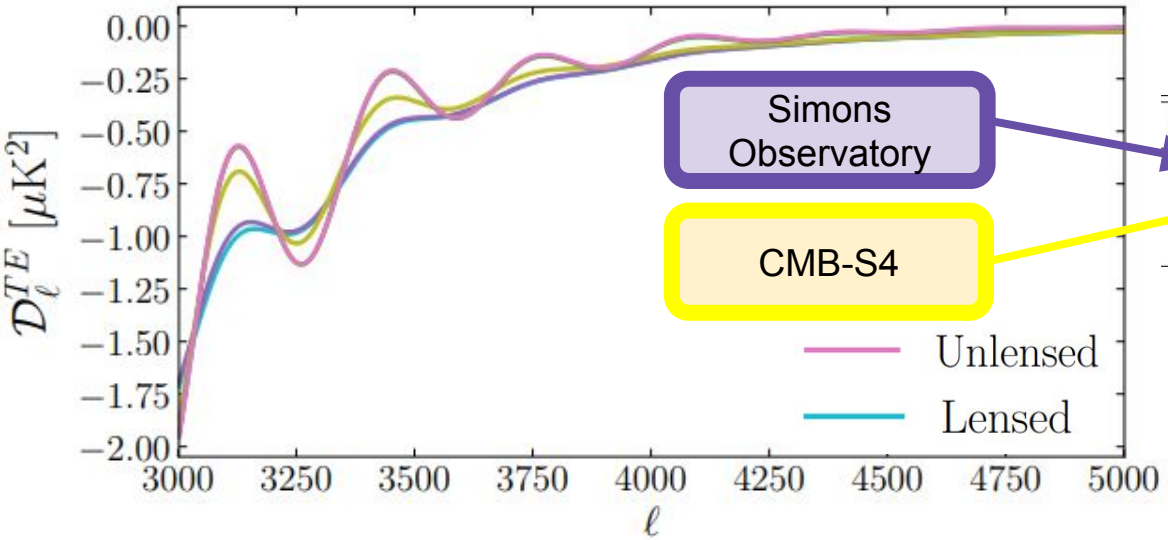


Image Credit: Hanson

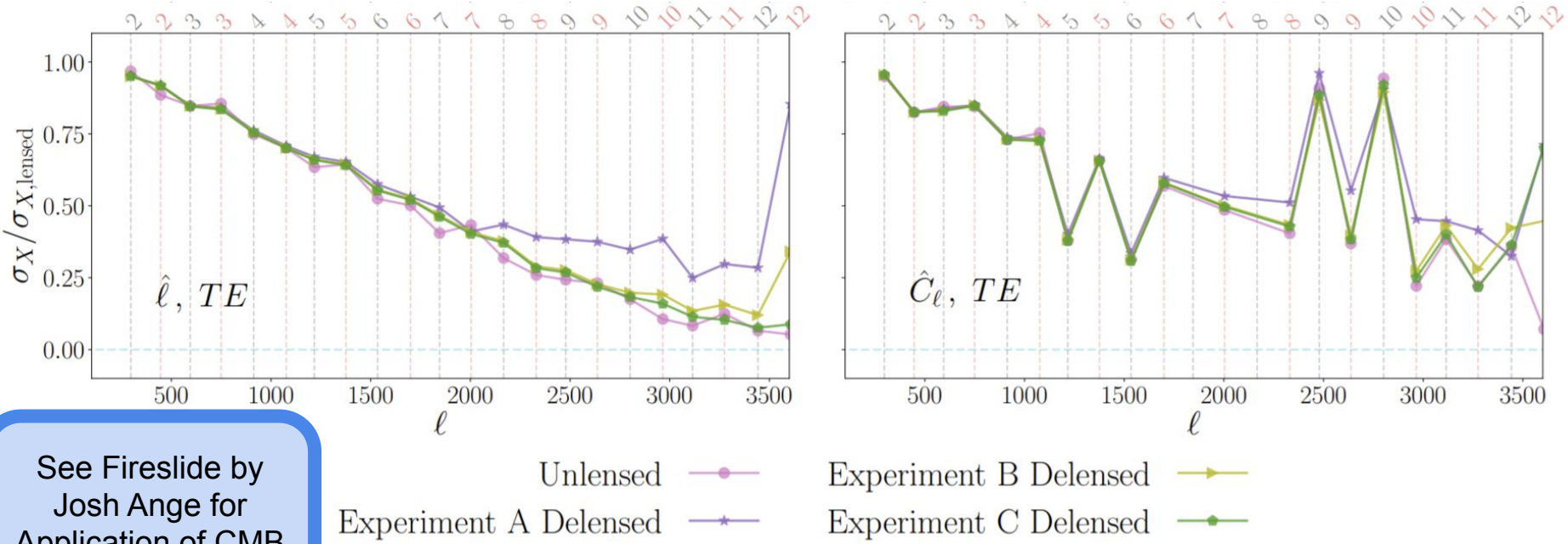
CMB Delensing Sharpens Peaks



Δ_T (μK-arcmin)	$\theta_{\rm FWHM}$ (arcmin)	Color
5	1.4	Purple
1	1.4	Yellow
0.1	0.1	Green

Green, JM, van Engelen (2016); Hotinli, JM, Trendafilova, Green, van Engelen (2022)

Sharper Delensed Peaks Can Be Better Localized

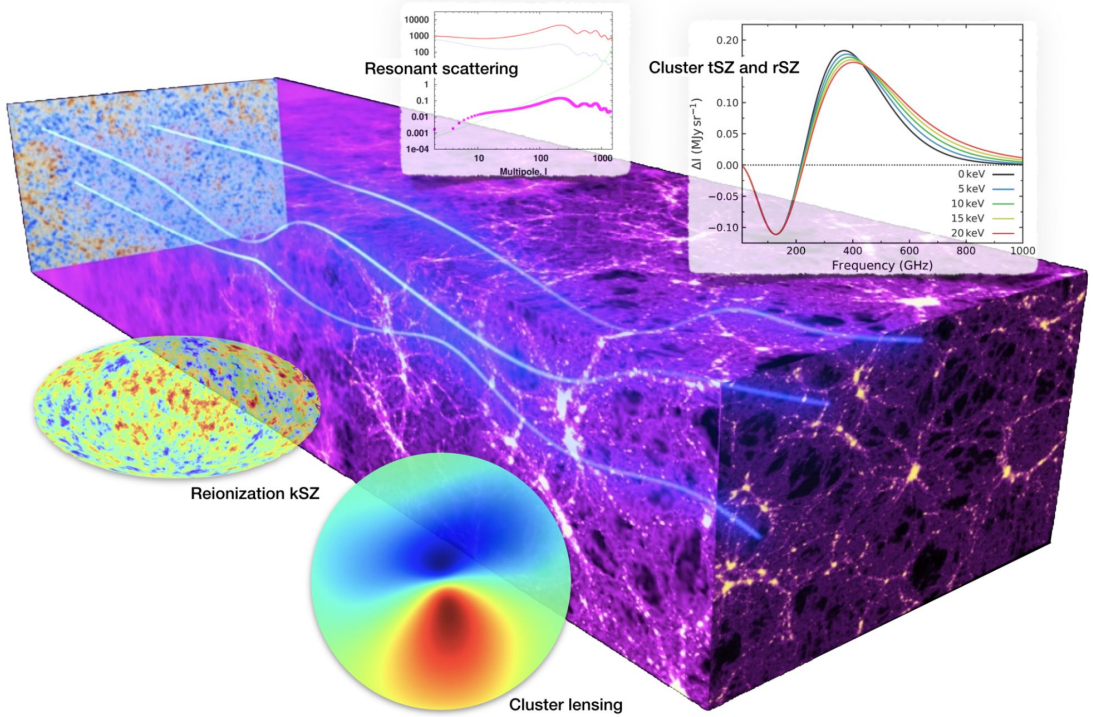


See Fireslide by Josh Ange for Application of CMB Delensing!

Green, JM, van Engelen (2016); Hotinli, JM, Trendafilova, Green, van Engelen (2022)

Machine Learning for CMB Secondaries

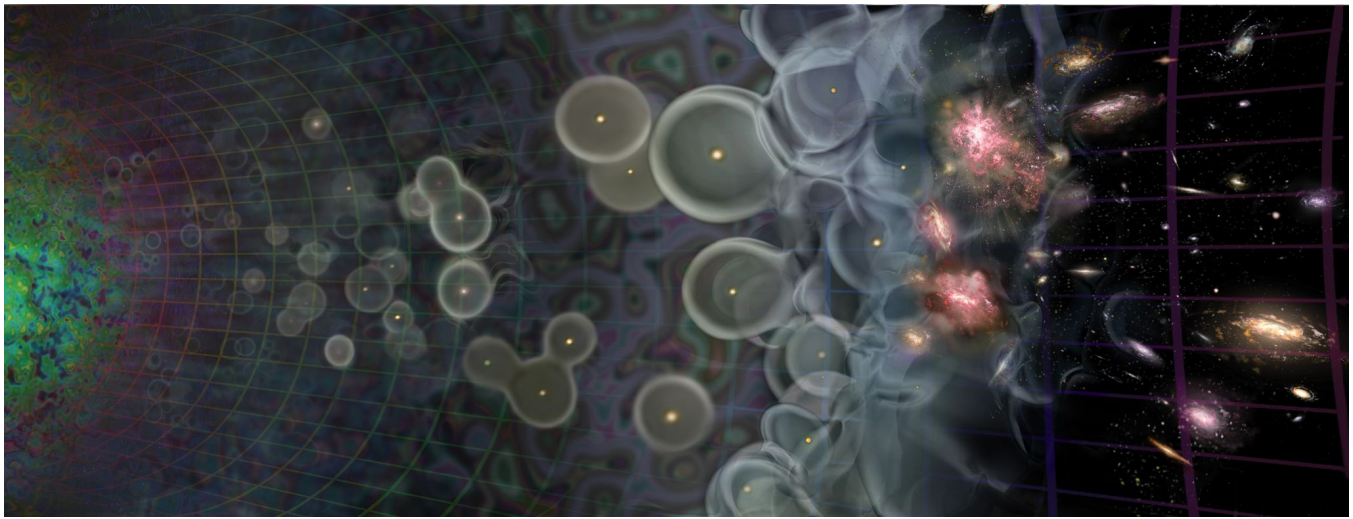
CMB as a Universal Backlight



Credits — Main image: ESA and the Planck collaboration; Resonant scattering: Basu et al. (2004); Cluster tSZ and rSZ: Erler et al. (2018); Cluster lensing: Horowitz et al. (2019); Reionization kSZ: Alvarez (2016)

Image Credit: Basu, et al (2019)

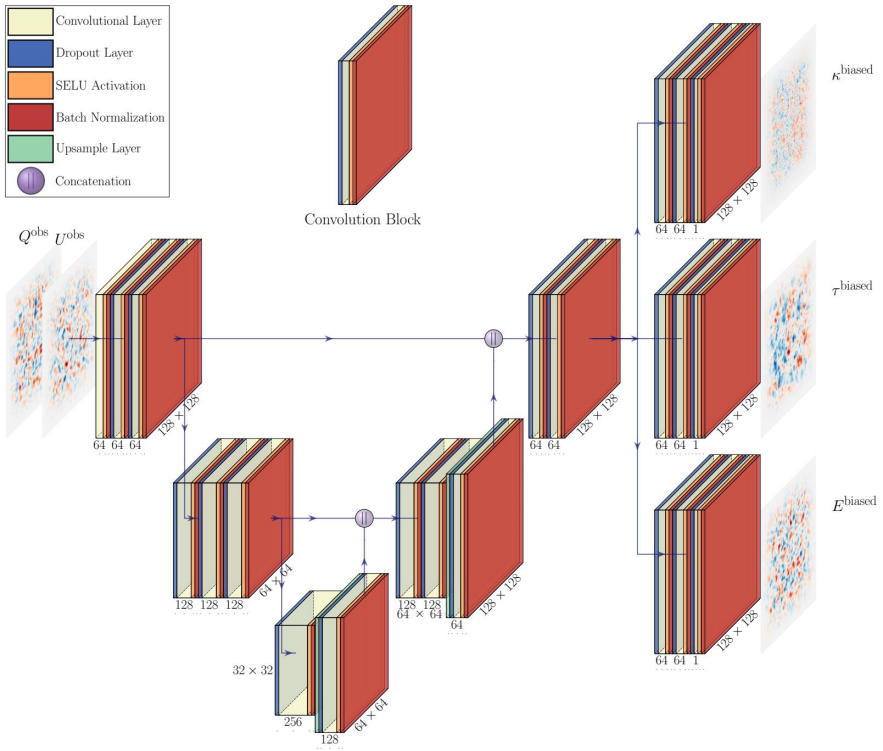
Patchy Reionization Modulates CMB Fluctuations

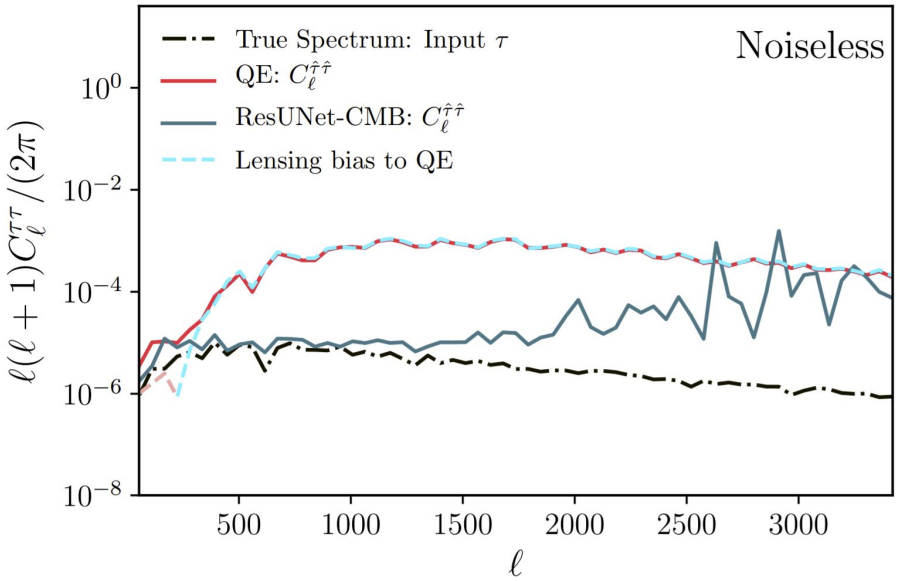


- The effect of patchy reionization on the CMB is not entirely distinct from gravitational lensing
- Standard reconstruction of patchy reionization is therefore biased by gravitational lensing

Su, Yadav, et al (2011); Image Credit: Scientific American

Deep Learning Secondary Reconstruction - ResUNet-CMB

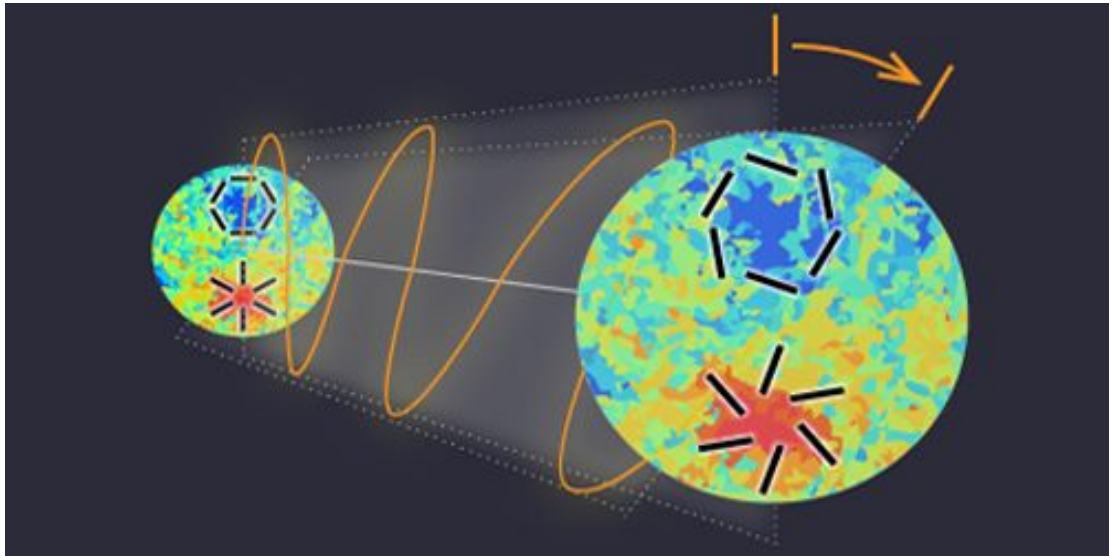




ResUNet-CMB provides a nearly optimal, unbiased reconstruction of patchy reionization

Guzman, JM (2021)

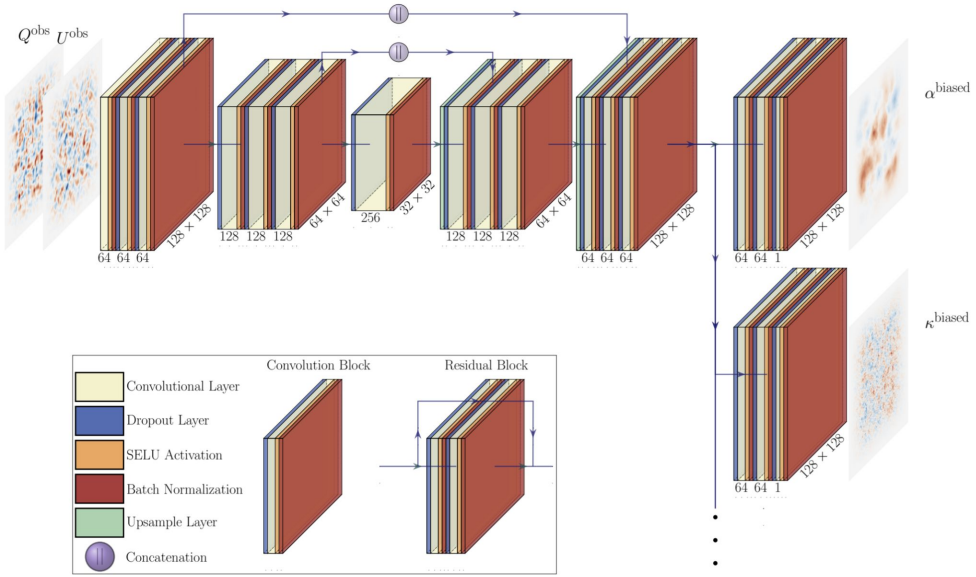
Birefringence and Magnetic Fields Rotate CMB Polarization

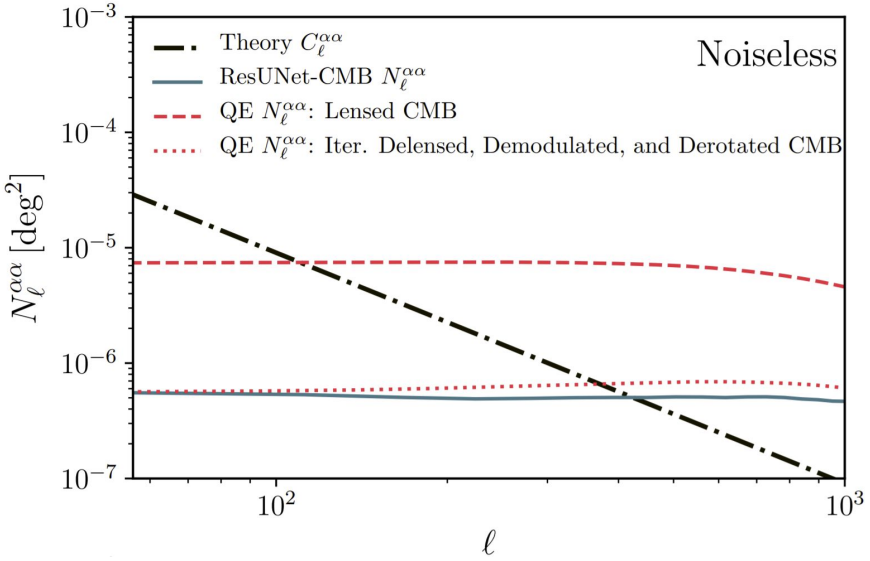


- Cosmic birefringence may result from axion-like particles with Chern-Simons coupling to electromagnetism
- Primordial magnetic fields can also rotate CMB polarization angles due to Faraday rotation

Carroll, Field, Jackiw (1990); Kosowsky, Loeb (1996); Image Credit: Minami

Birefringence Reconstruction with ResUNet-CMB

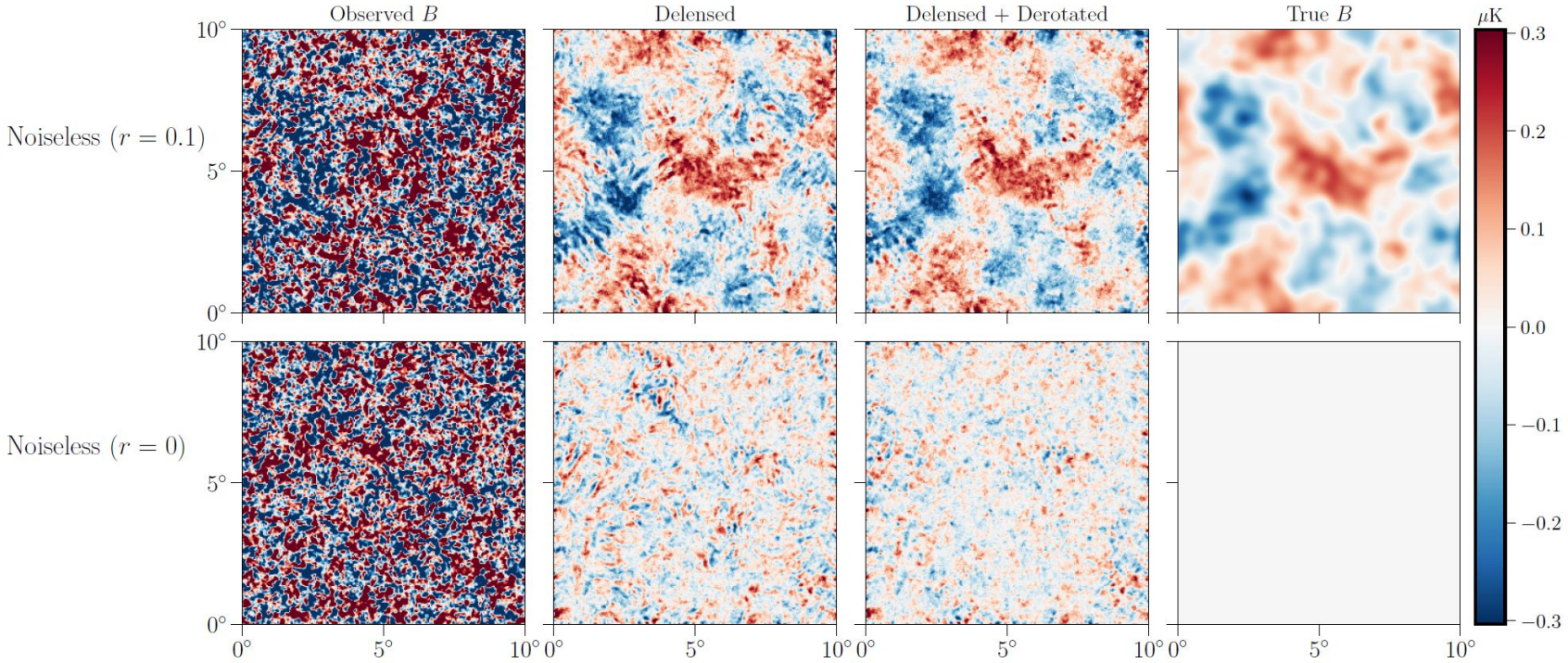




ResUNet-CMB provides a nearly optimal simultaneous reconstruction of lensing and cosmic polarization rotation

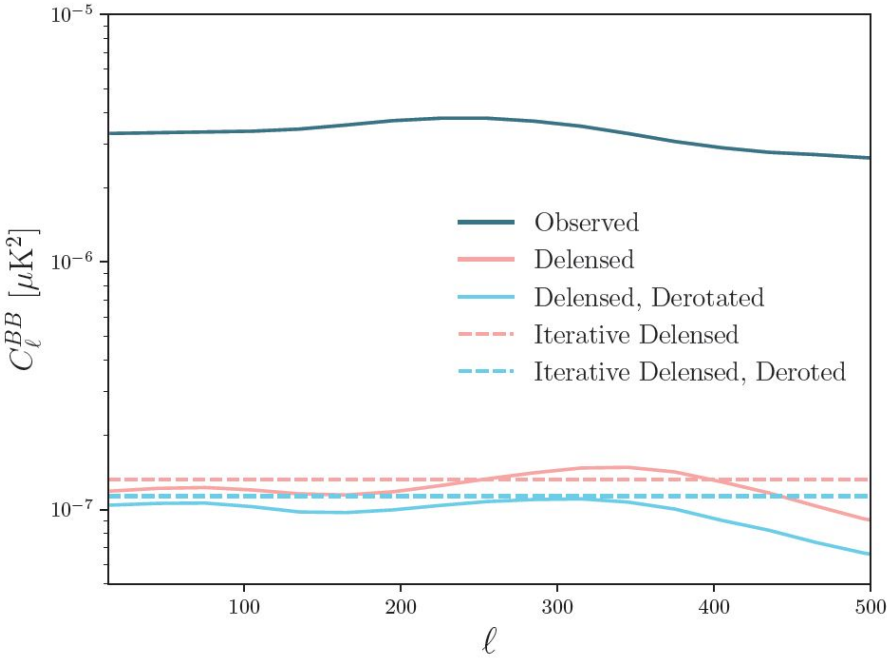
Guzman, JM (2022)

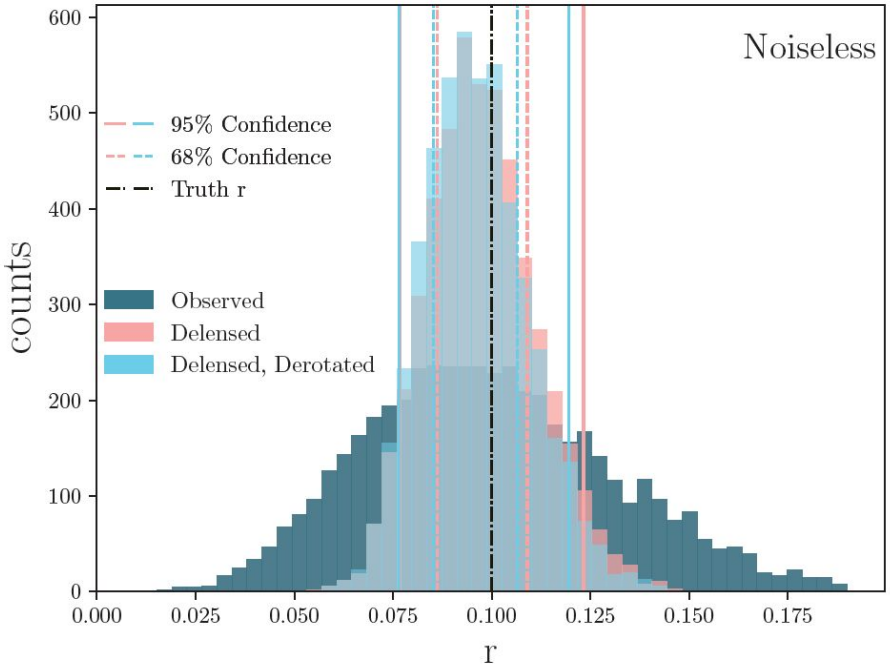
Recovering Primordial B Modes with ResUNet-CMB



Guzman, JM (In Prep.)

Searching for Primordial Gravitational Waves with ResUNet-CMB

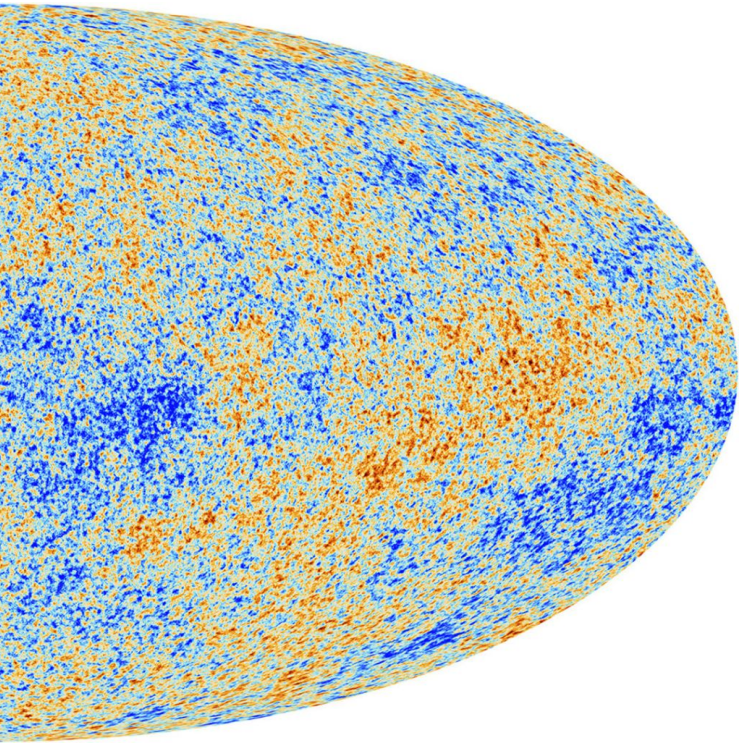




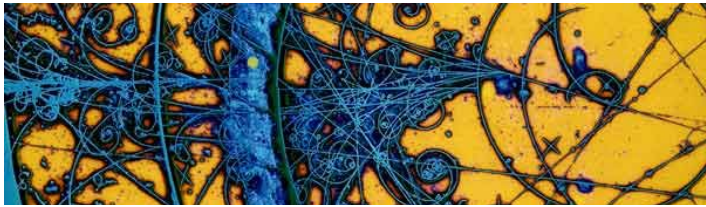
Guzman, JM (In Prep.)

Conclusion

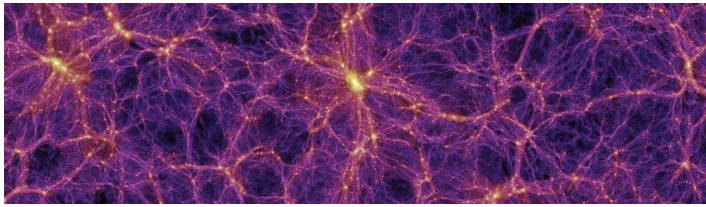
Conclusion



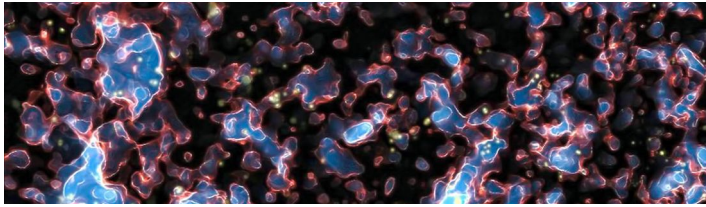
New Opportunities



Particle Physics

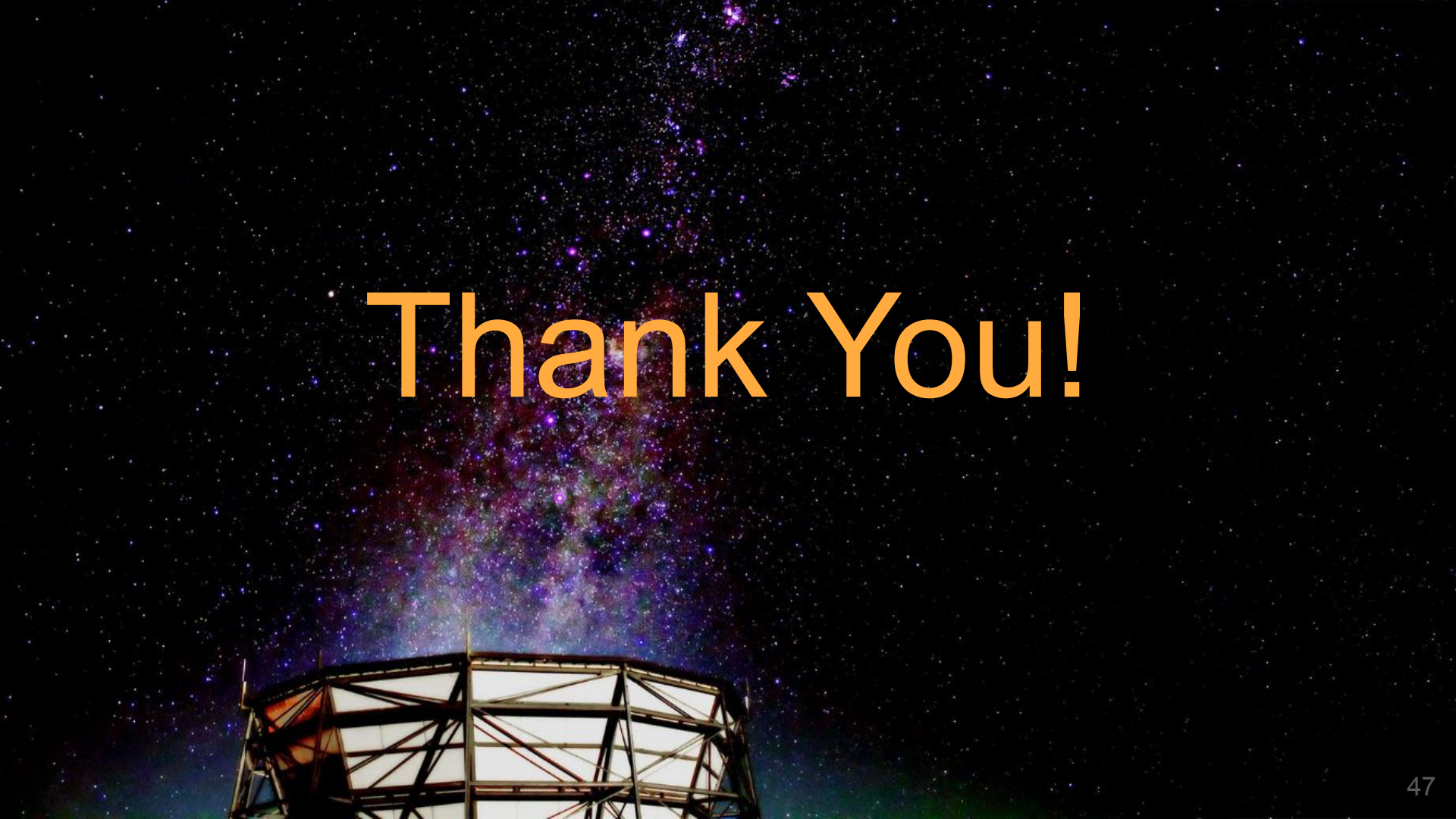


Cosmology



Astrophysics

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


Thank You!