Title: New Opportunities and New Challenges with Upcoming CMB Surveys

Speakers: Joel Meyers

Series: Cosmology & Gravitation

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Abstract: Future surveys will map the cosmic microwave background (CMB) with unprecedented precision. The high fidelity of the data will present new opportunities to extract deep insights about the history, contents, and evolution of our universe. However, new tools and techniques will be required to maximize the potential of the forthcoming data. I will describe the techniques necessary to address the emerging challenges and to harness the exciting opportunities provided by future CMB observations.

Zoom link https://pitp.zoom.us/j/92999899446?pwd=YTNEUkMrV2RXOWE0Mk11b2tDQ2Q0Zz09


New Opportunities and New Challenges with Upcoming CMB Surveys
Joel Meyers
SMU
Perimeter Institute
1-9-2024
Image Credit: ACT / Princeton

History of the Universe

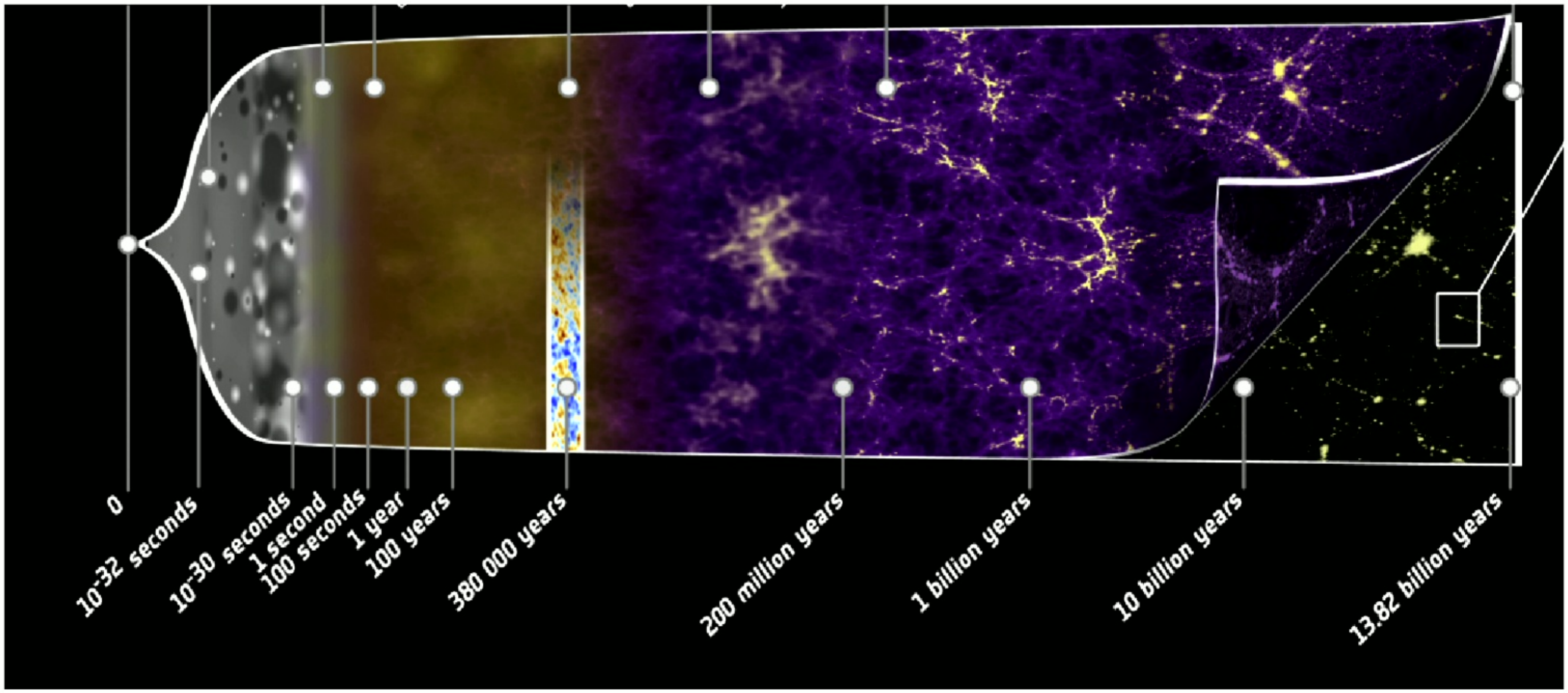

Image Credit: NASA

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Outline

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

CMB Review

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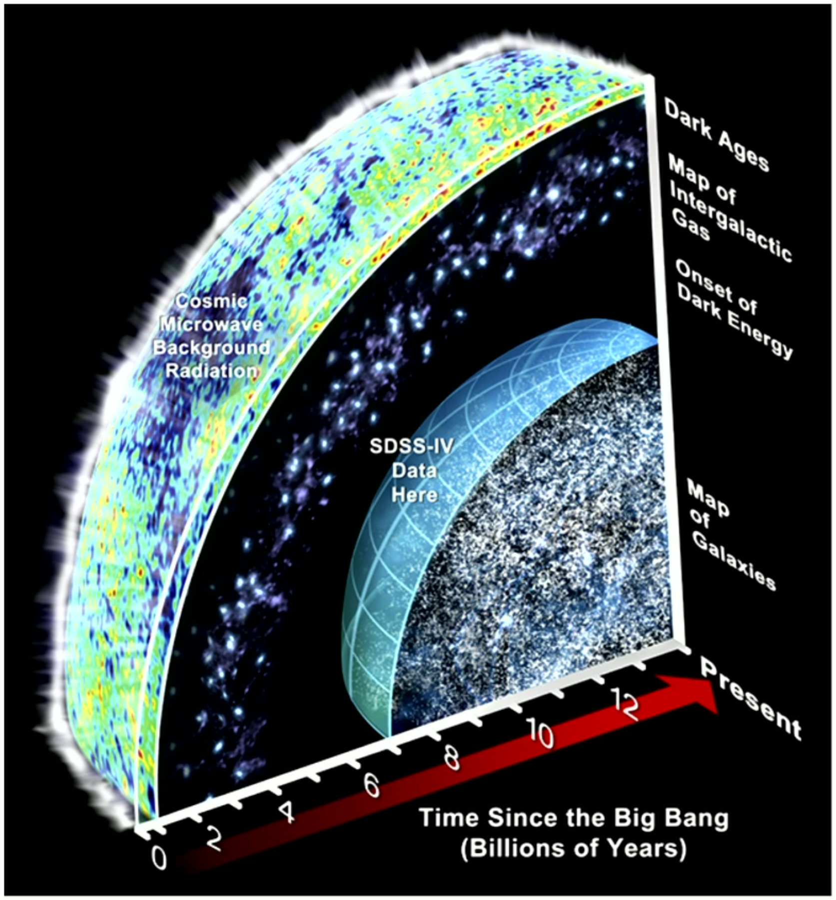
The Cosmic Microwave Background



Cosmic Microwave Background (CMB) Spectrum

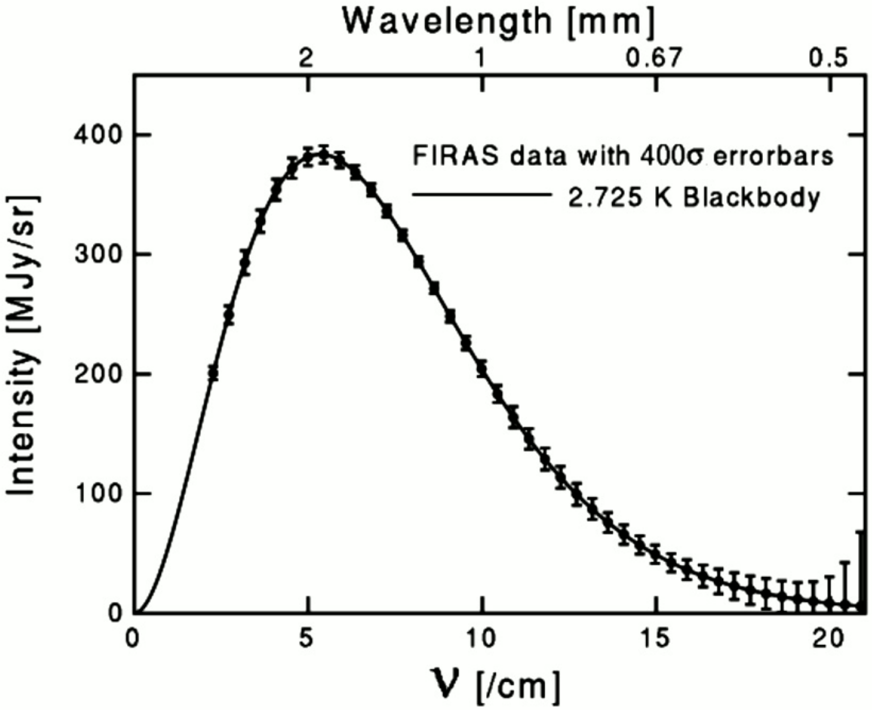
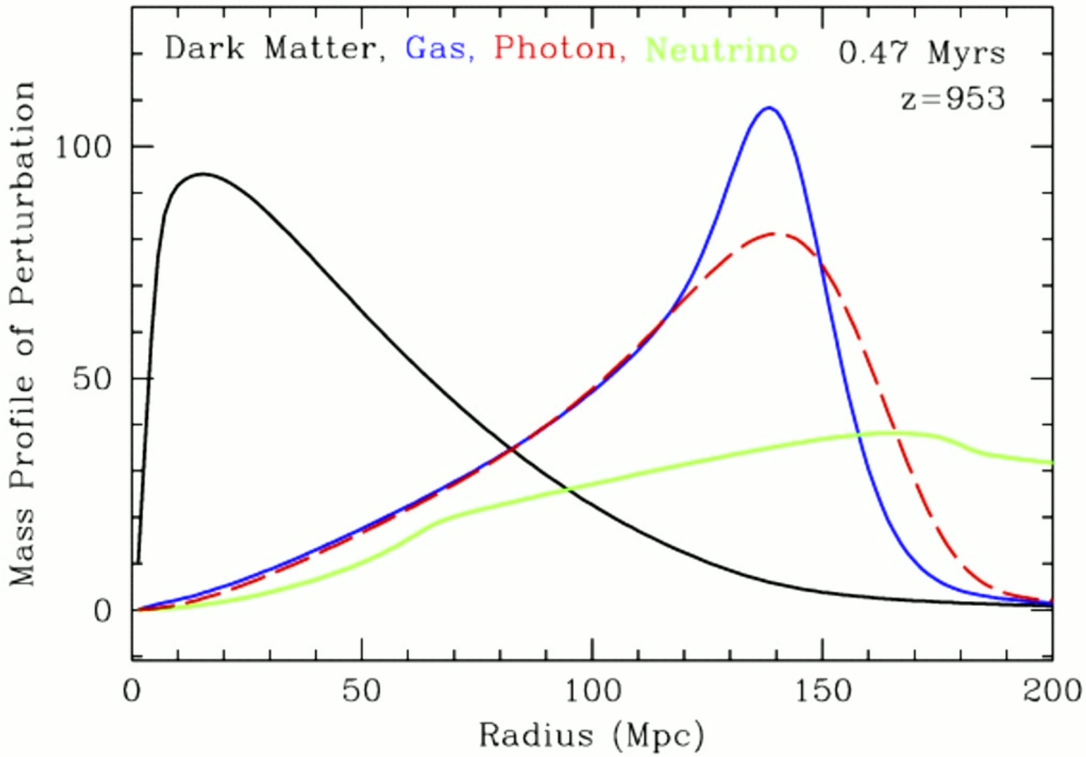


Image Credits: SDSS, COBE FIRAS

Sound Waves in the Primordial Plasma



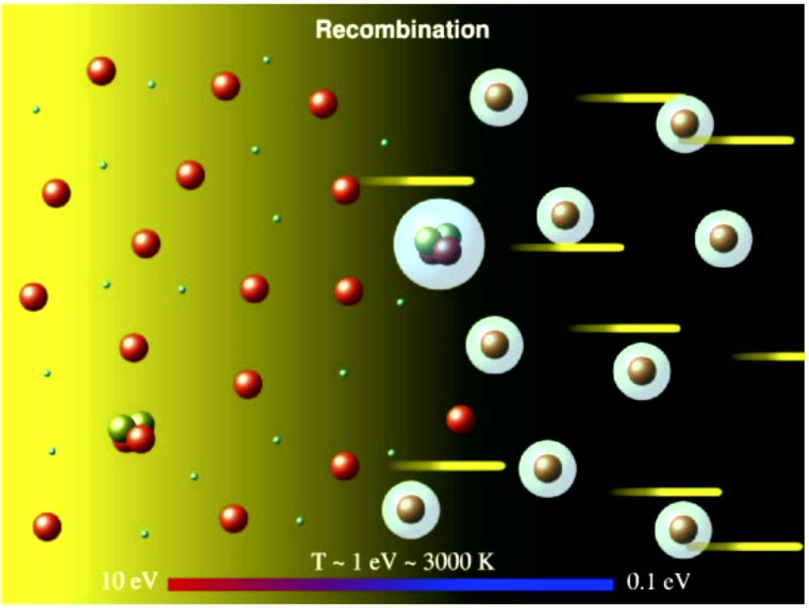


Image Credits: Eisenstein, Kinney

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Superposition of Sound Waves

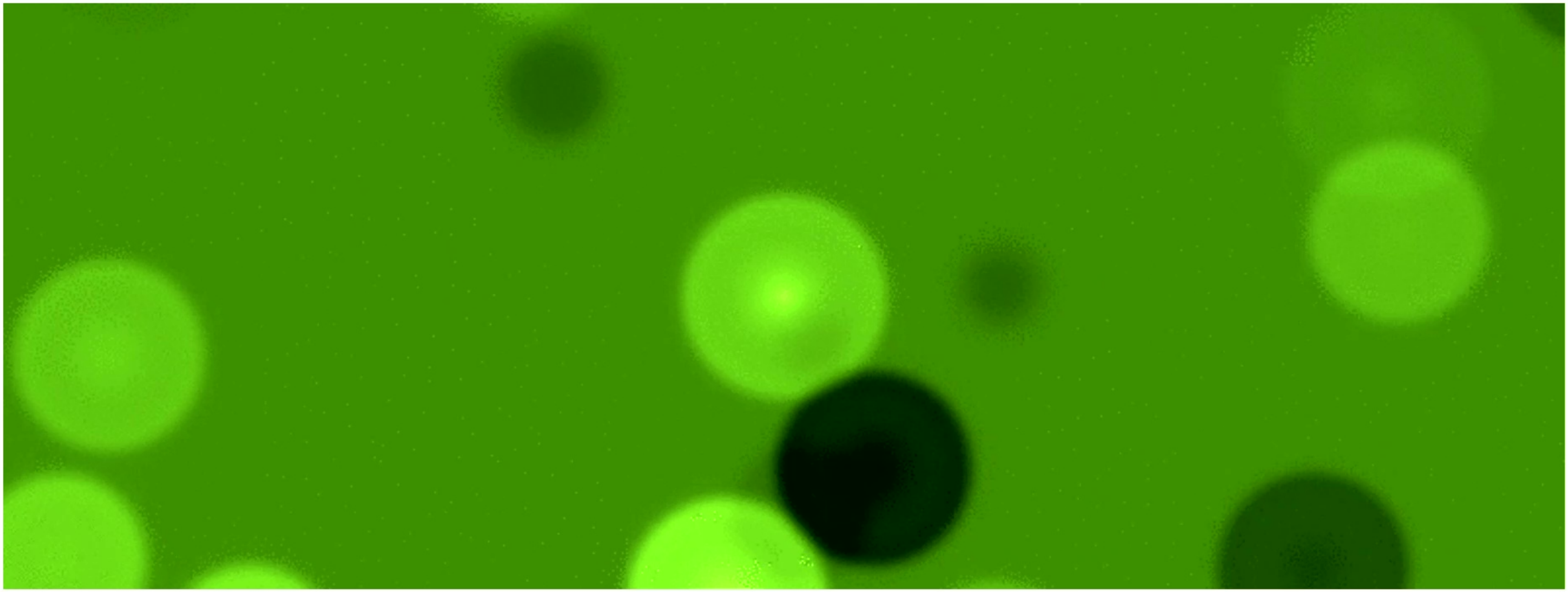
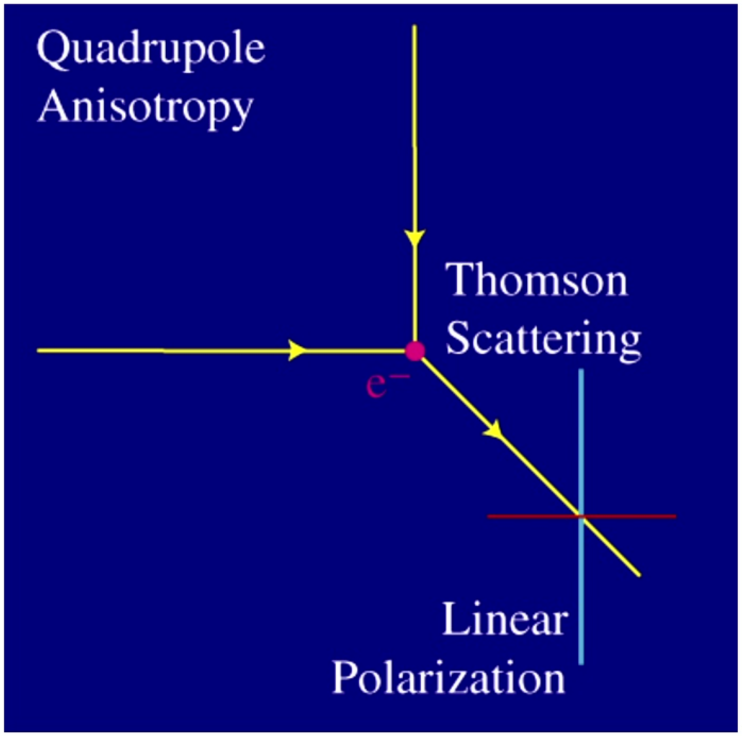


Image Credit: Hincks

Linear Polarization of the CMB



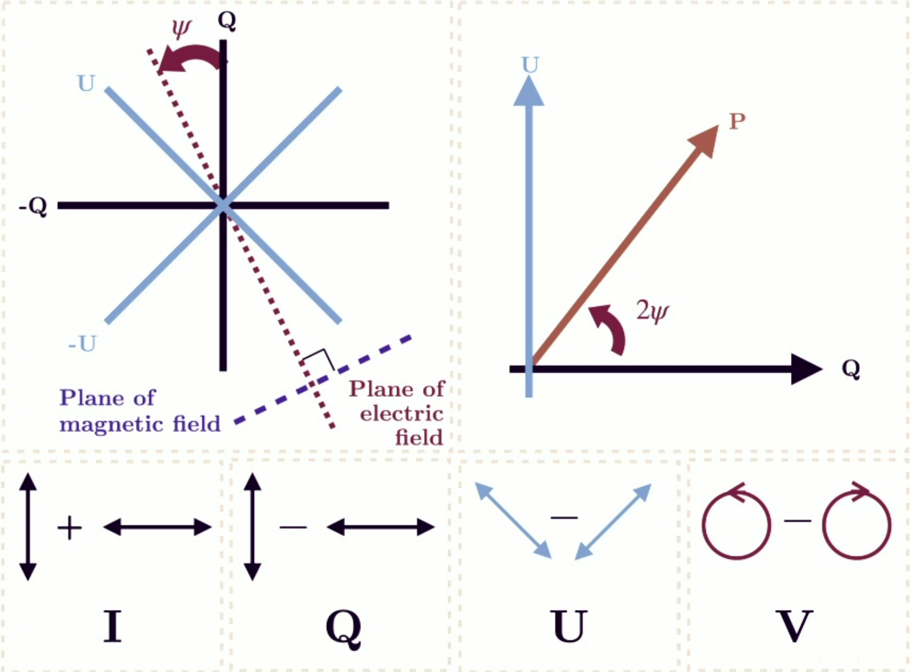


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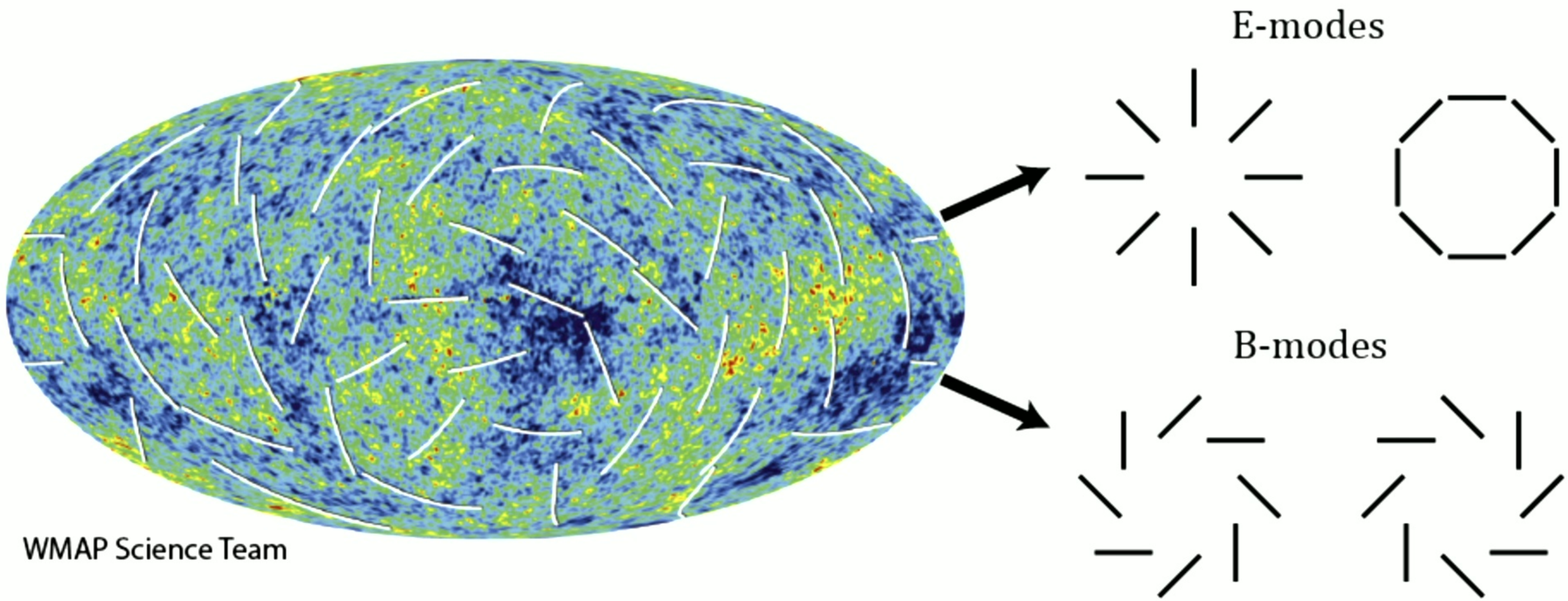
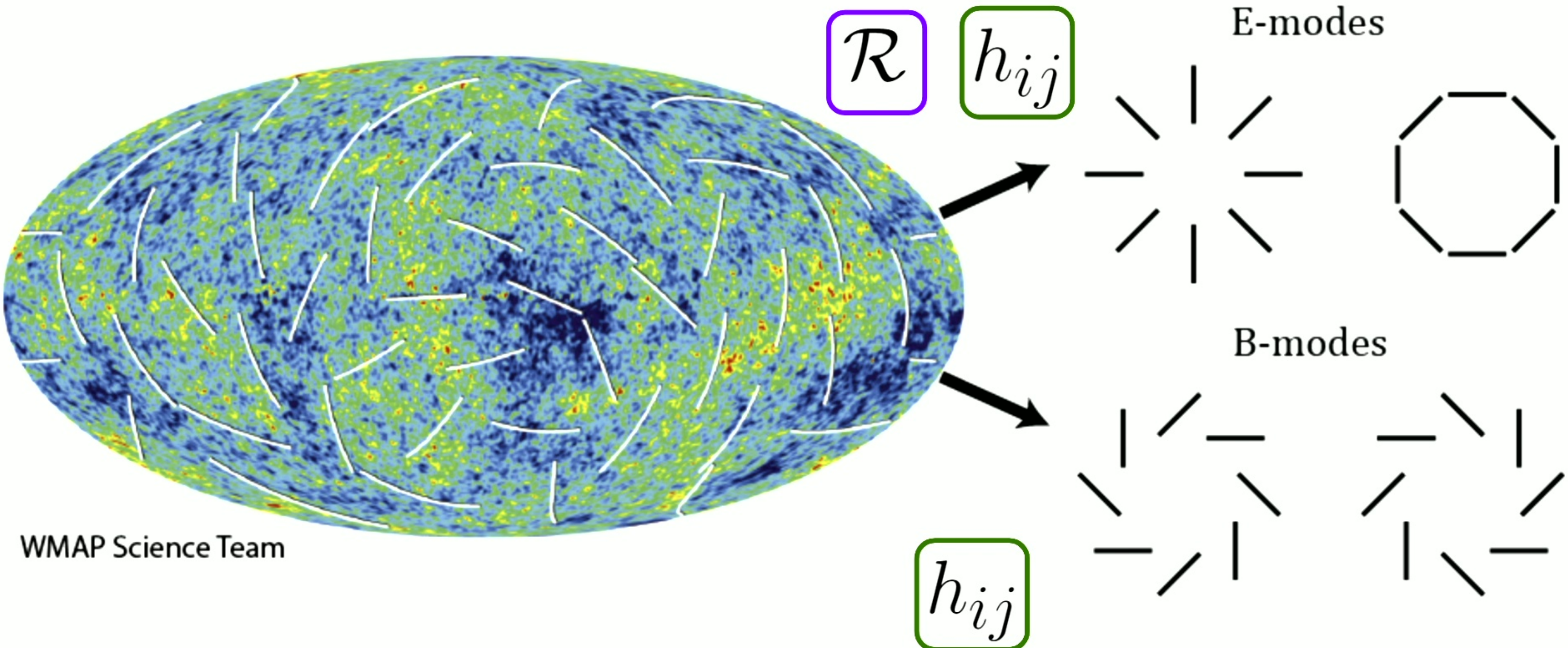
Image Credits: Hu, Alexander

E and B Modes



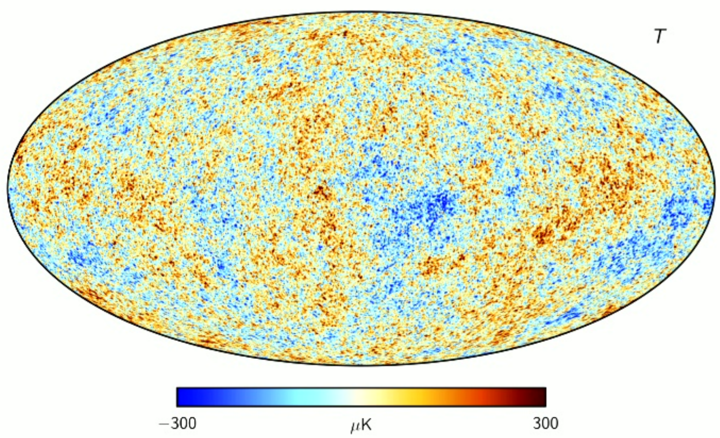
Kamionkowski, Kosowsky, Stebbins (1997); Zaldarriaga, Seljak (1997); Image Credit: PIPER (2014)

E and B Modes

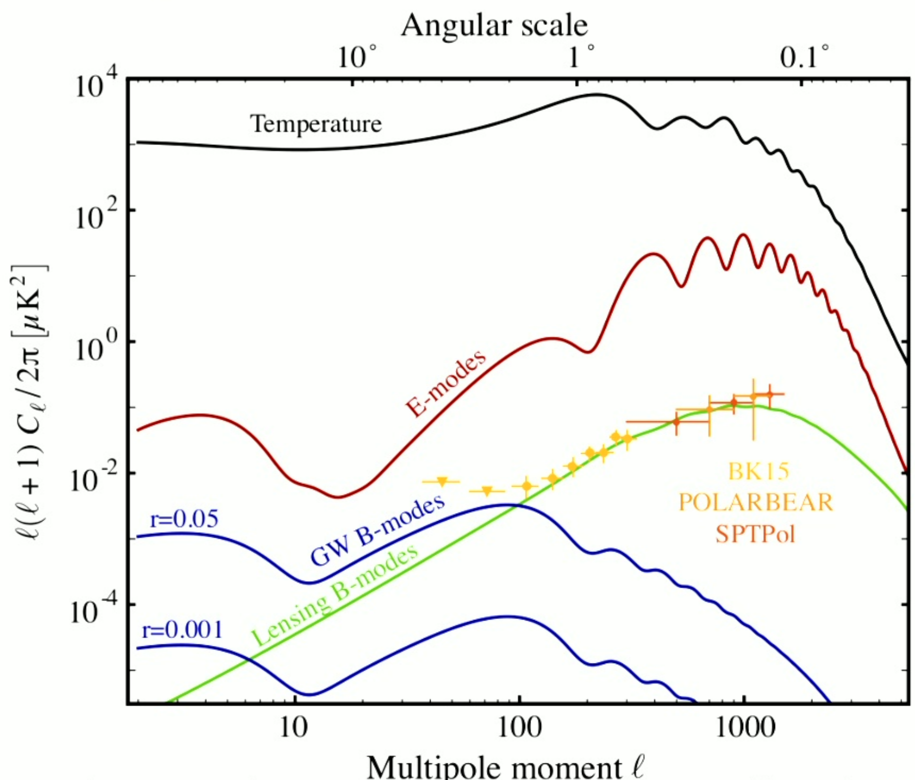


Kamionkowski, Kosowsky, Stebbins (1997); Zaldarriaga, Seljak (1997); Image Credit: PIPER (2014)

Statistical Information and Angular Power Spectra



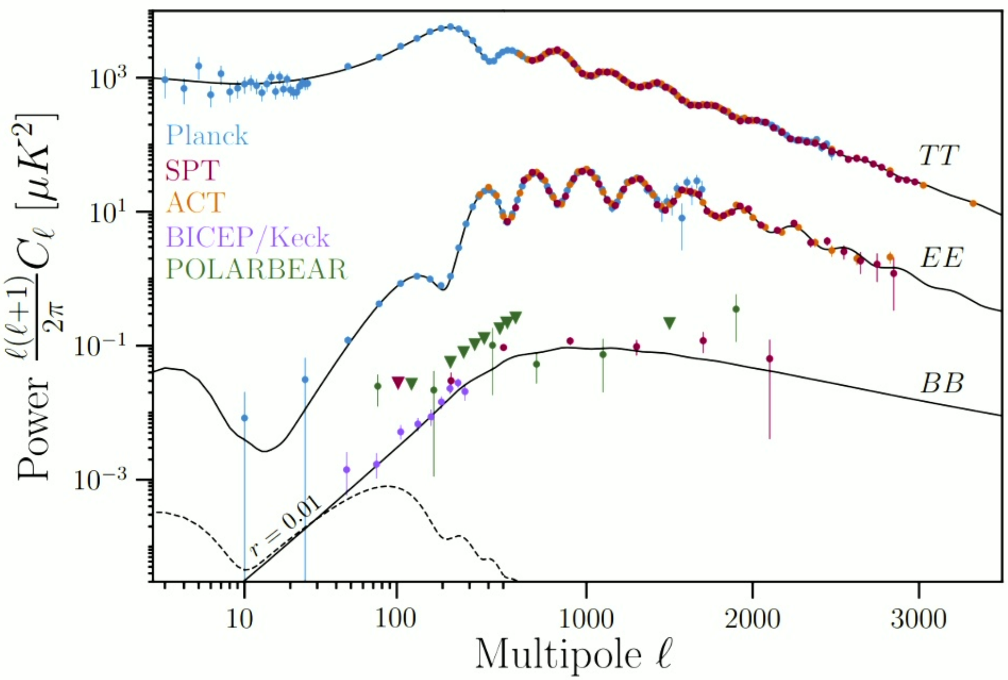
Variance

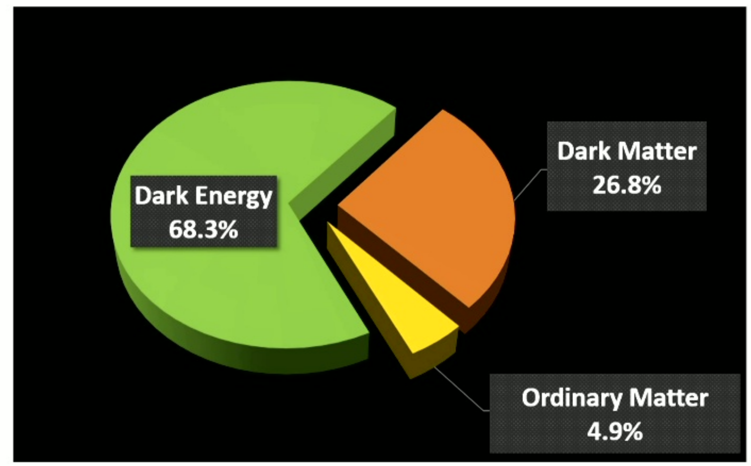


←large scales small scales →

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

CMB Observations and Concordance Flat ΛCDM





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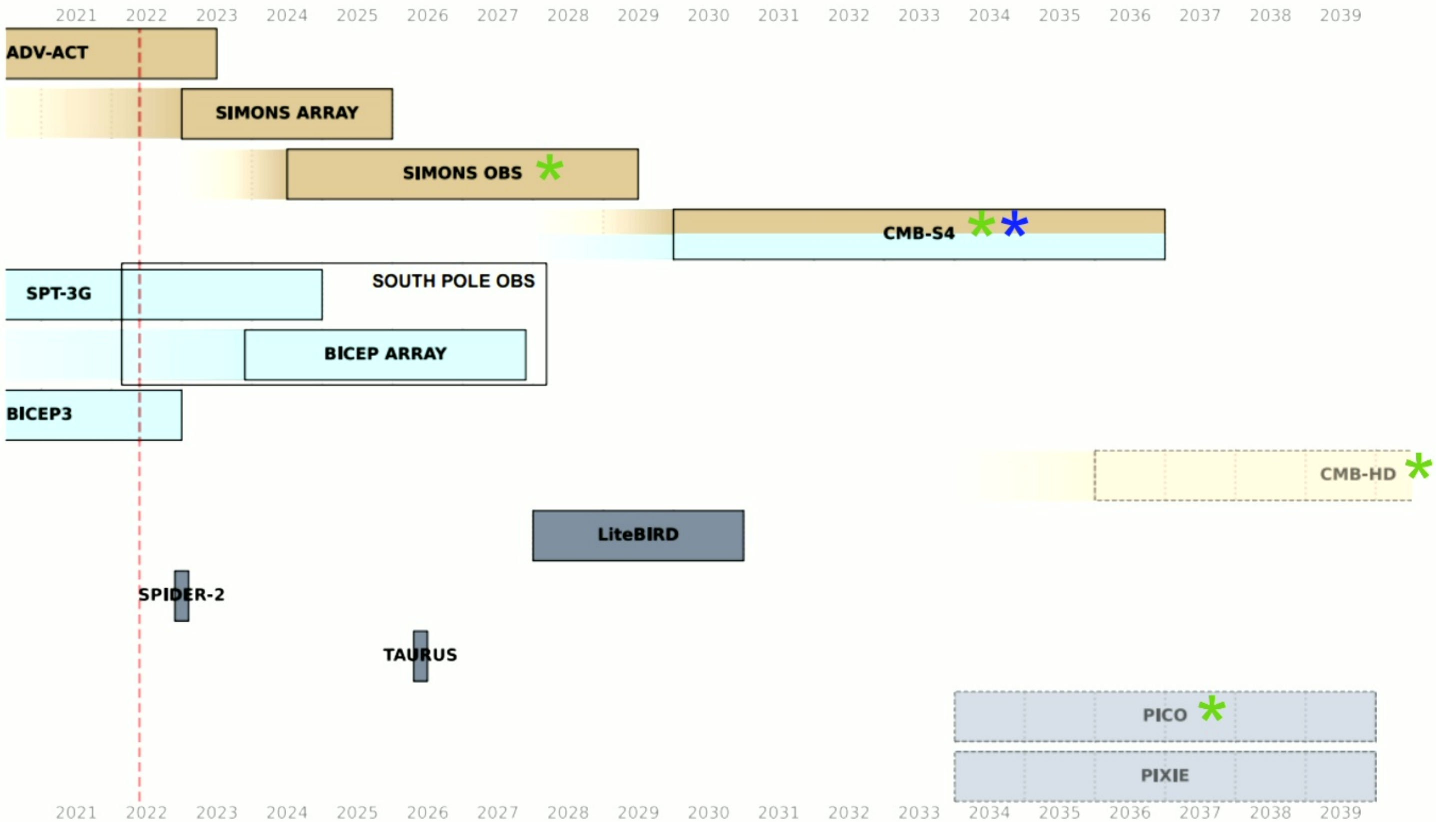
Planck (2018); Chang, Huffenberger, et al (2022)

Timeline of Upcoming CMB Surveys



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Chang, Huffenberger, et al (2022)


Gravitational Lensing of the CMB
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Gravitational Lensing of the CMB

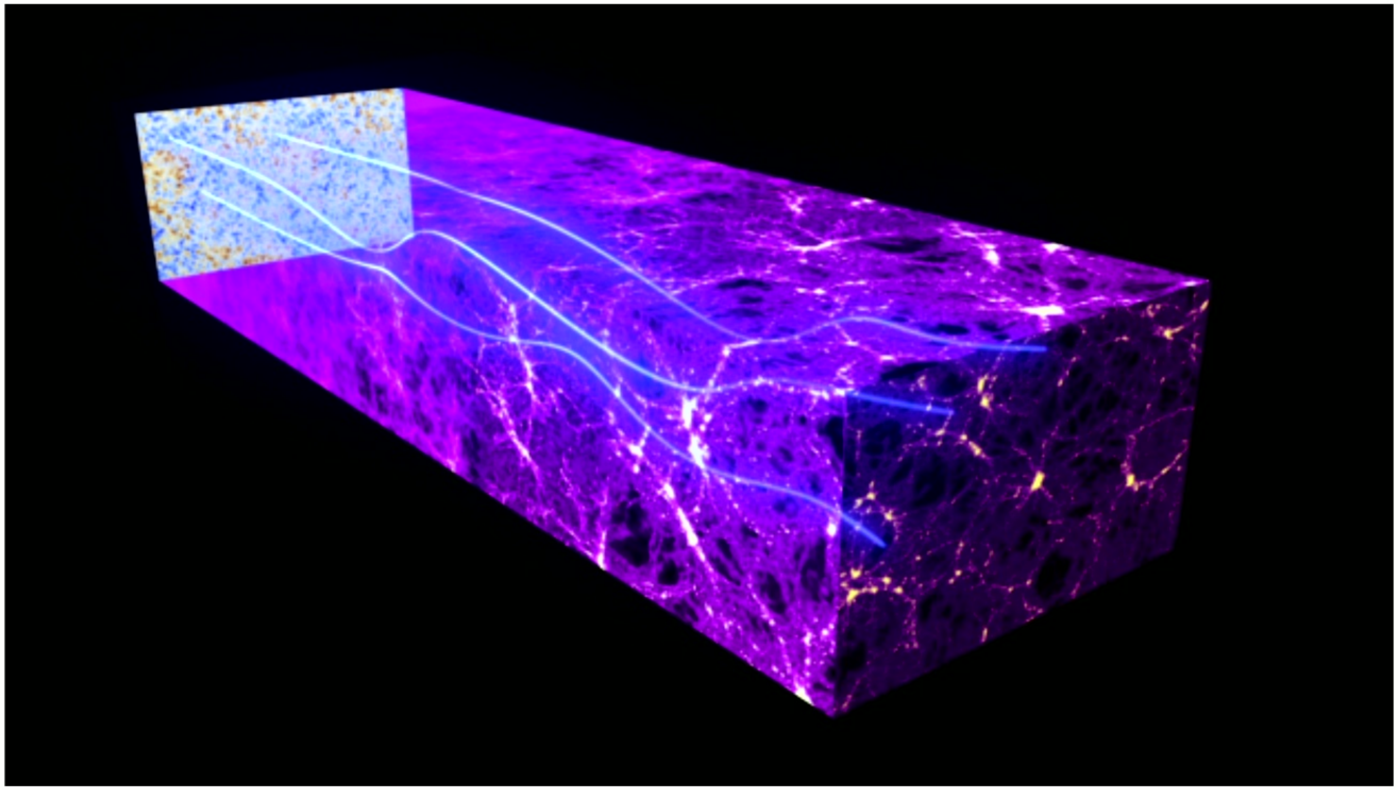

Image Credit: Planck / ESA

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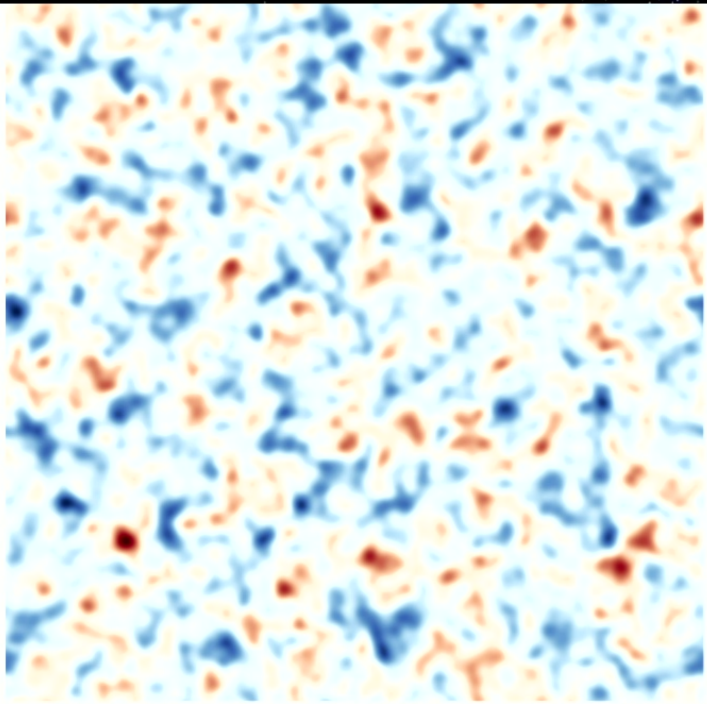
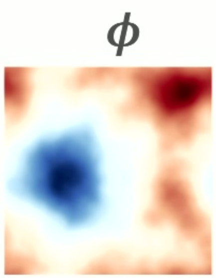
Unlensed CMB Polarization





Unlensed E

Unlensed B

5°×5° simulated maps

Image Credit: Guzman

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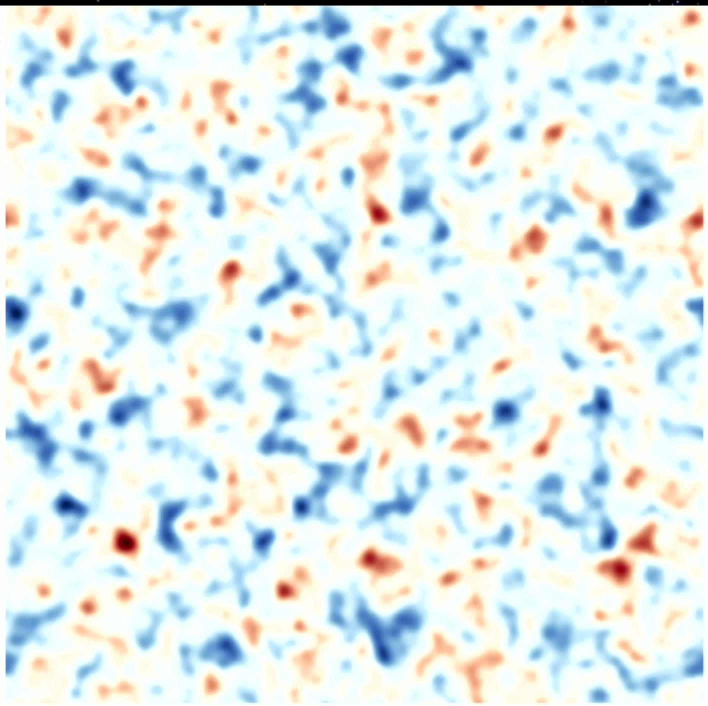
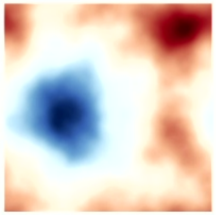
Unlensed CMB Polarization



Unlensed E

ϕ



Unlensed B

5°×5° simulated maps

Image Credit: Guzman

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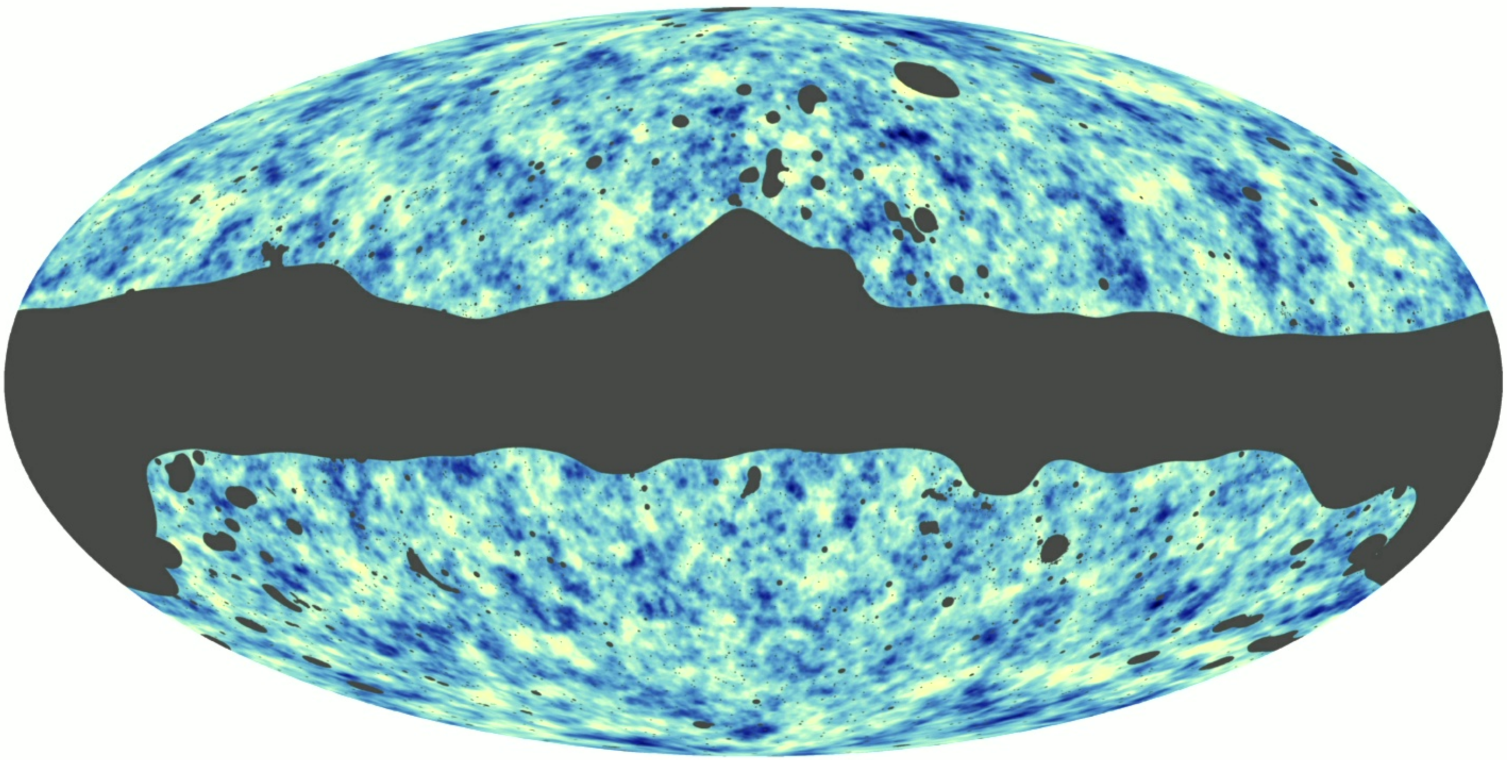
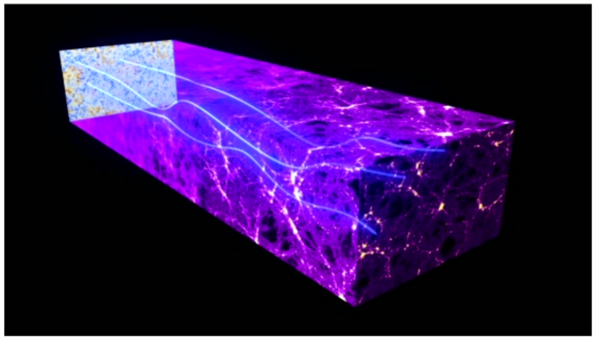
CMB Lensing Reconstruction



40σ observation

Planck (2018)

CMB Lensing is a Blessing and a Curse

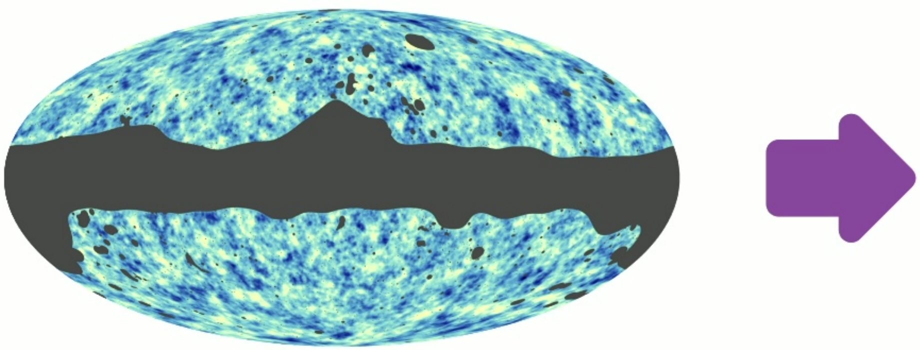


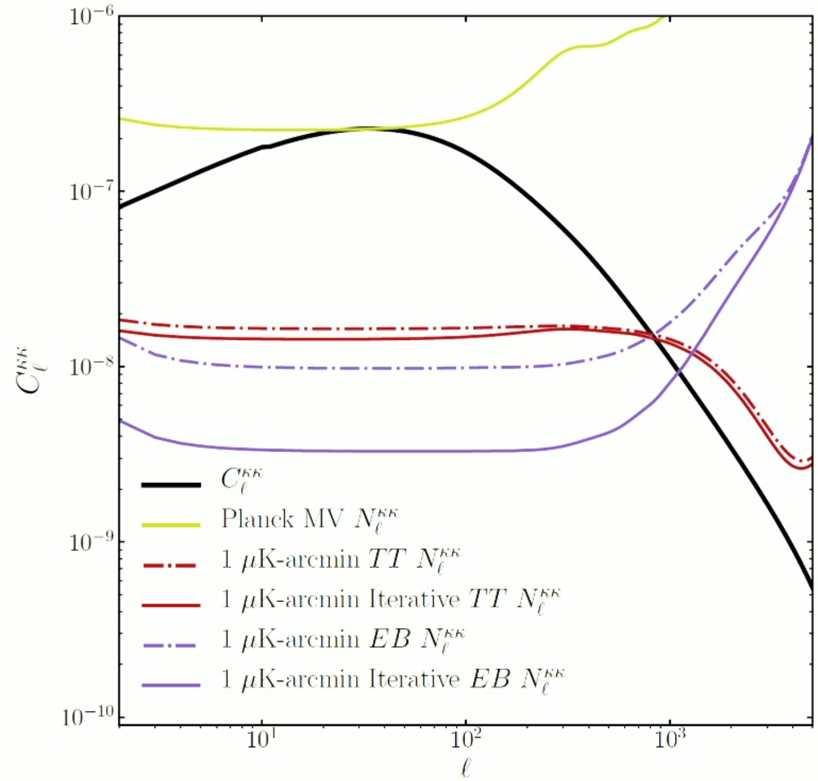
CMB lensing field is sensitive to growth of cosmological structure

Lensing distortion hinders pristine view of CMB last scattering surface

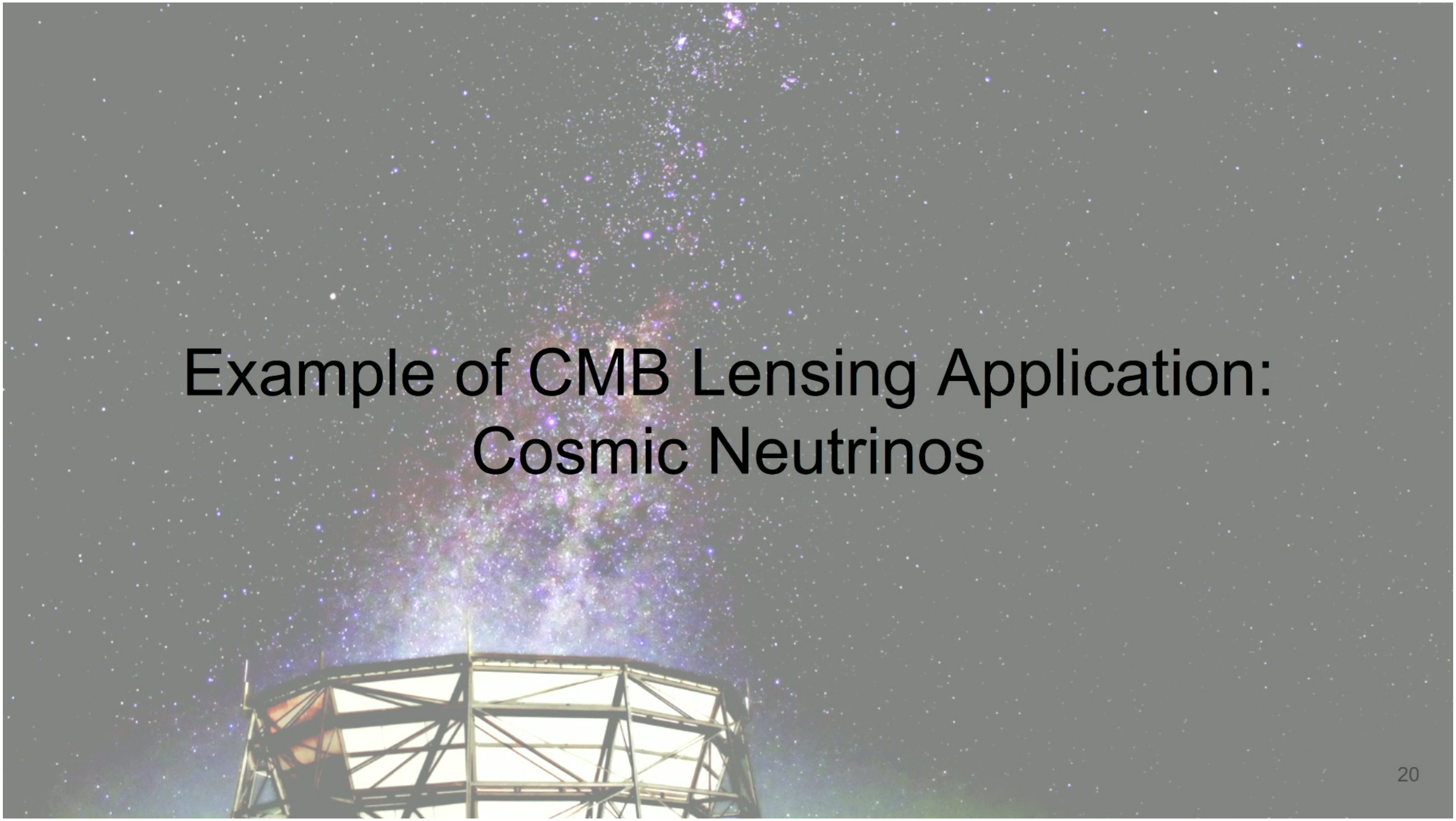
Image Credit: Planck / ESA

Measurements of CMB Lensing Will Improve Dramatically





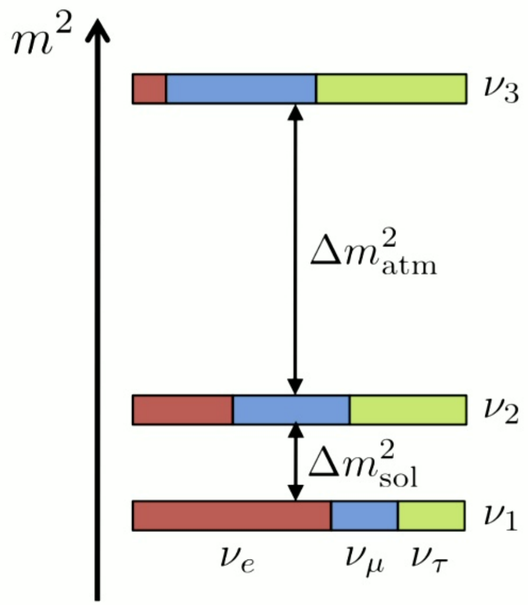
Planck (2018); CMB-S4 (2016); Hotinli, JM, Trendafilova, Green, van Engelen (2022)



Example of CMB Lensing Application: Cosmic Neutrinos

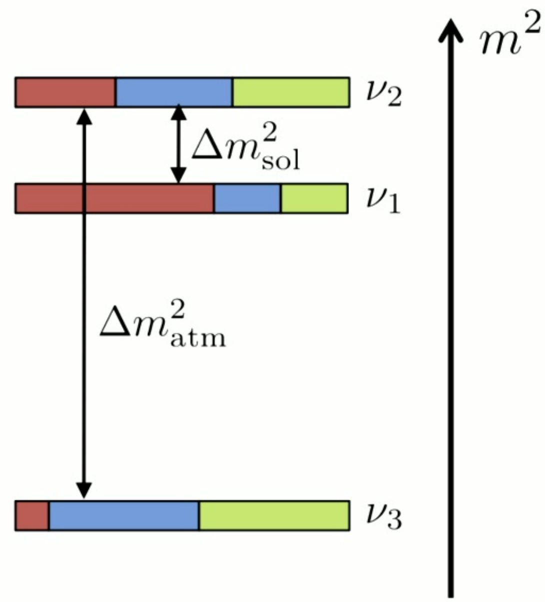
Massive Cosmic Neutrinos

normal hierarchy (NH)



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

inverted hierarchy (IH)



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

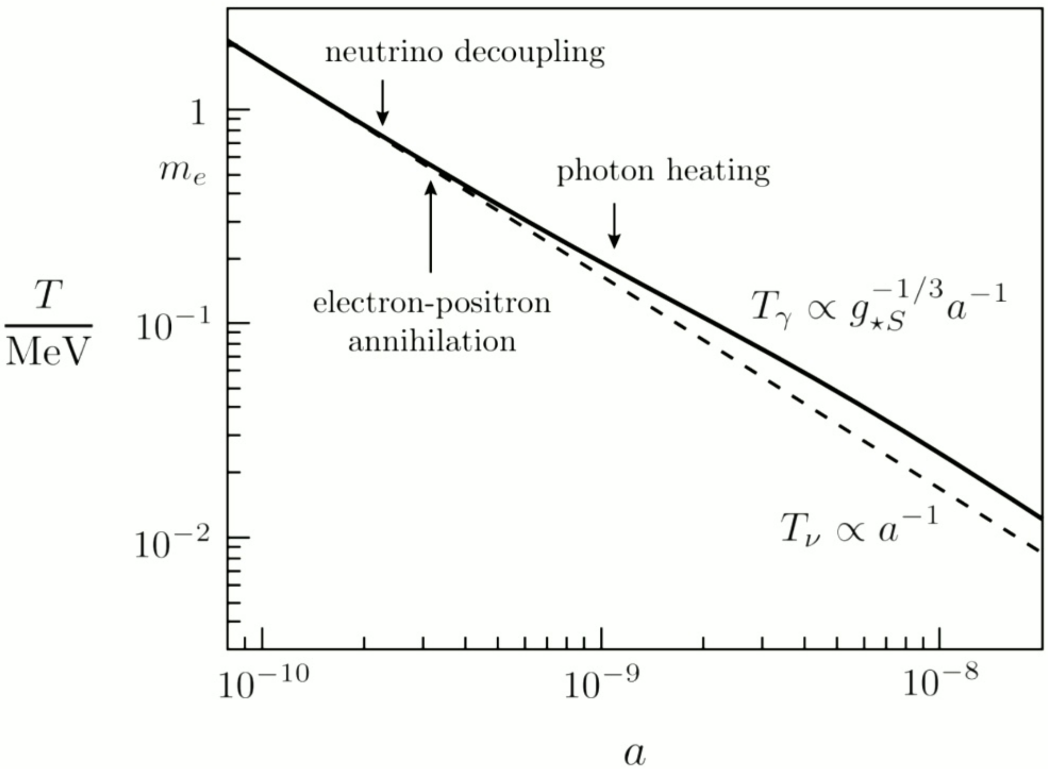
Cosmology is sensitive to the gravitational effects of the cosmic neutrino background, allowing a measurement of the sum of neutrino masses

Current Planck 2018 constraint:

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

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

Cosmic Neutrino Background



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

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

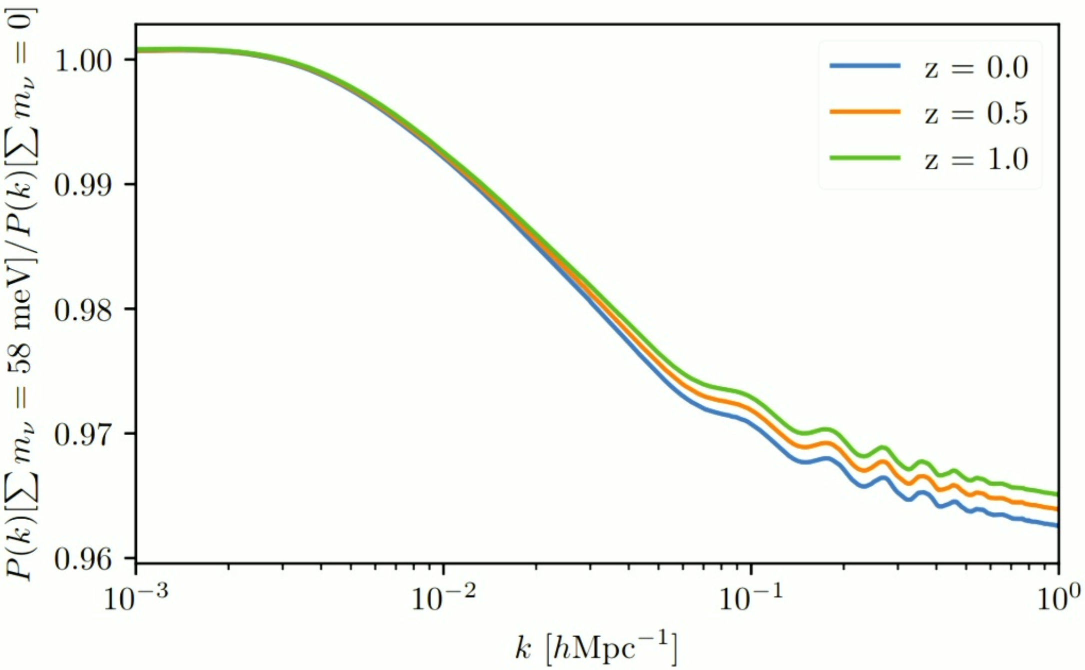
Cosmic neutrino background properties today:

$$T_{\nu,0} = 1.95\,\mathrm{K}$$
$$= 1.68 \times 10^{-4}\,\mathrm{eV}$$
$$n_{\nu_i,0} = 112\,\mathrm{cm}^{-3}$$

Cosmic neutrino background provides an abundance of non-relativistic neutrinos

Image Credit: Baumann

Massive Neutrinos Suppress Matter Clustering



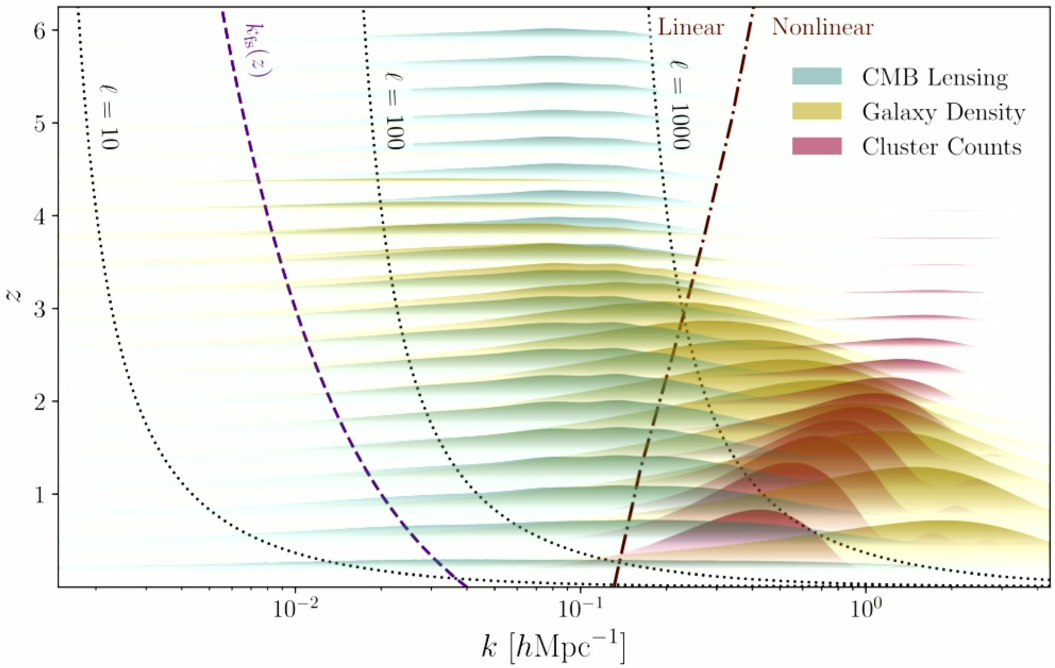
Suppression of matter clustering due to massive neutrinos
(A_s, $\Omega_m h^2$, $\Omega_b h^2$, H_0 fixed)

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

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

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

Measuring Clustering with Cosmological Surveys

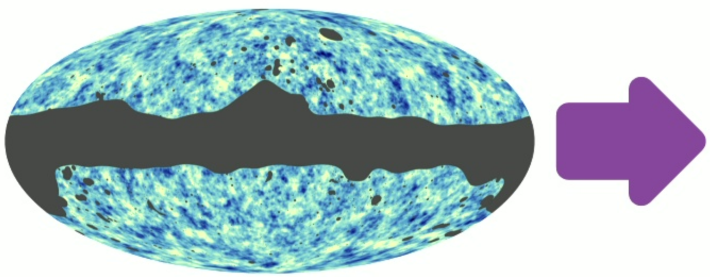


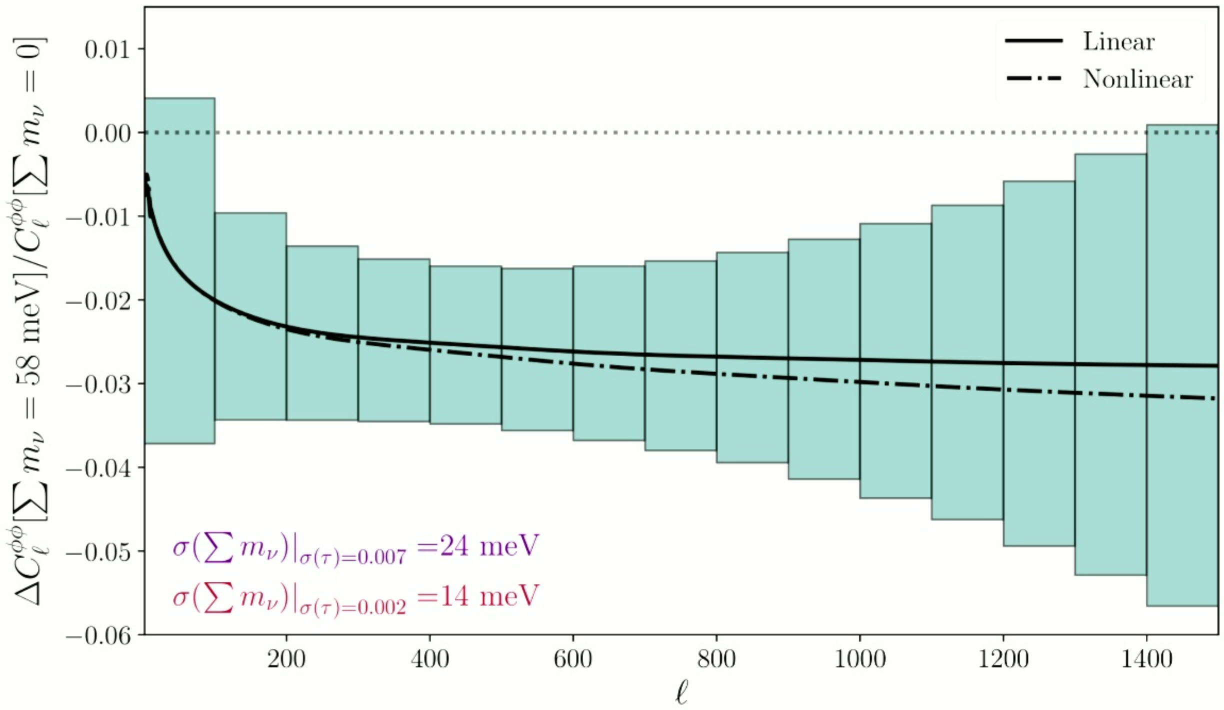
Sensitivity regimes of various probes of clustering

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

Green, JM (2021)

Neutrino Mass with CMB Lensing

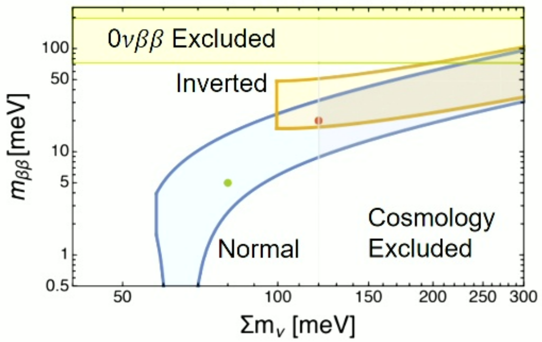


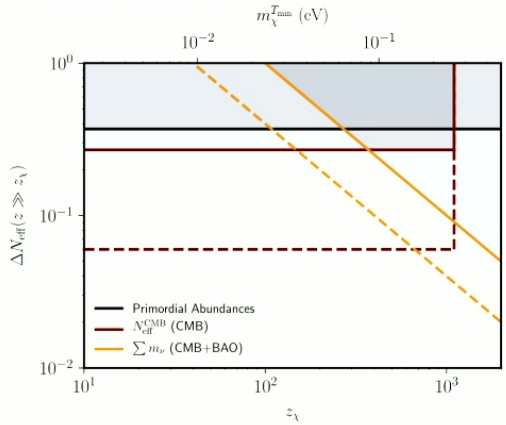


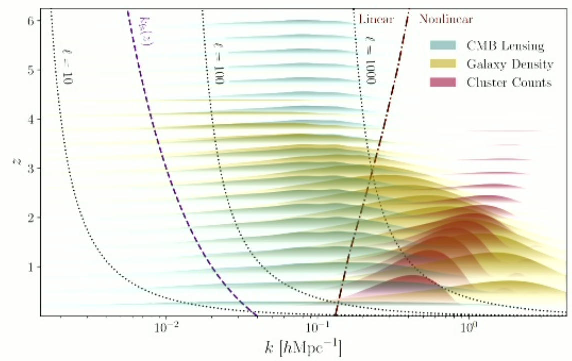
Measuring suppression of clustering with CMB-S4 lensing

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

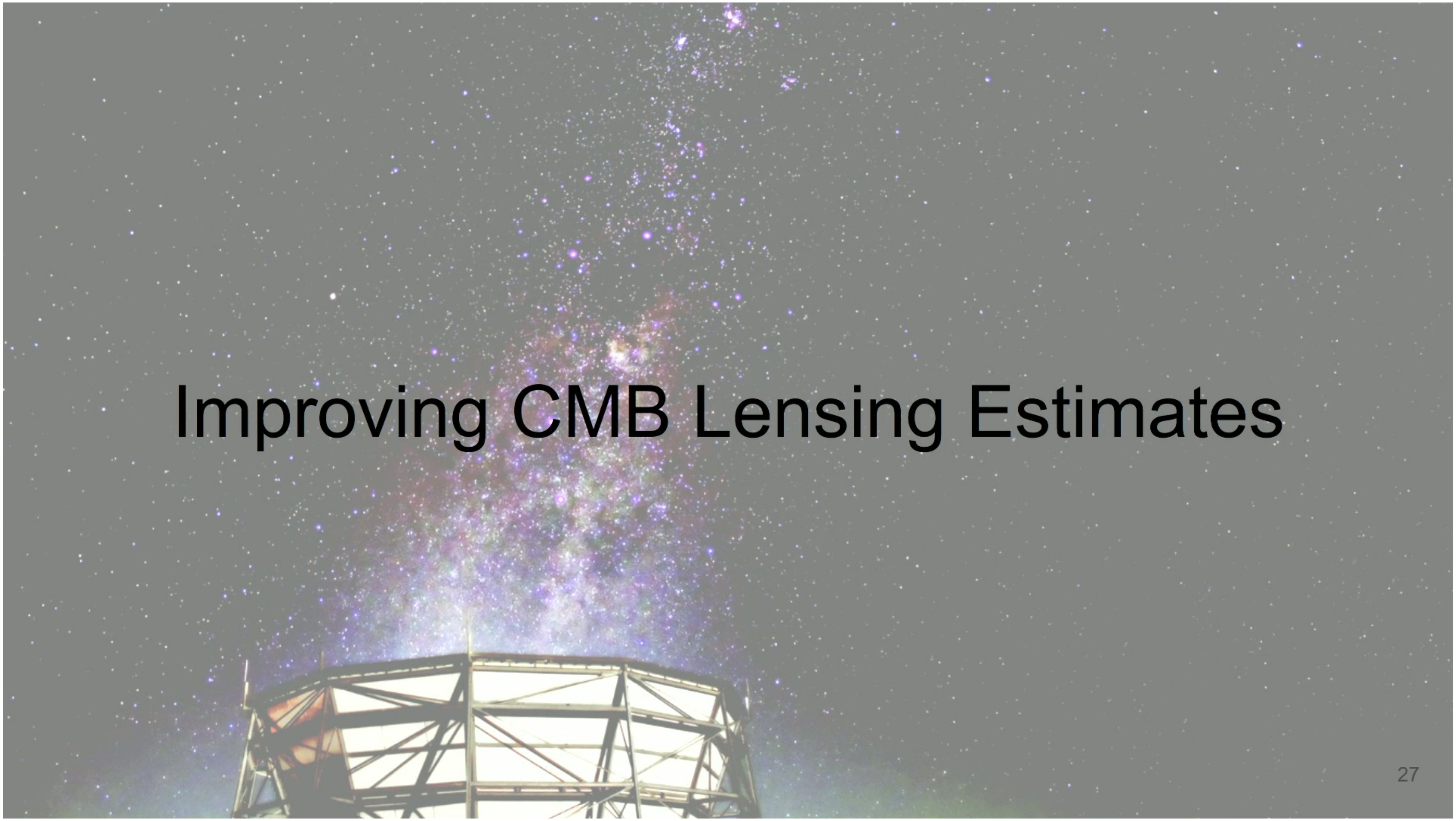
Cosmology

- 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
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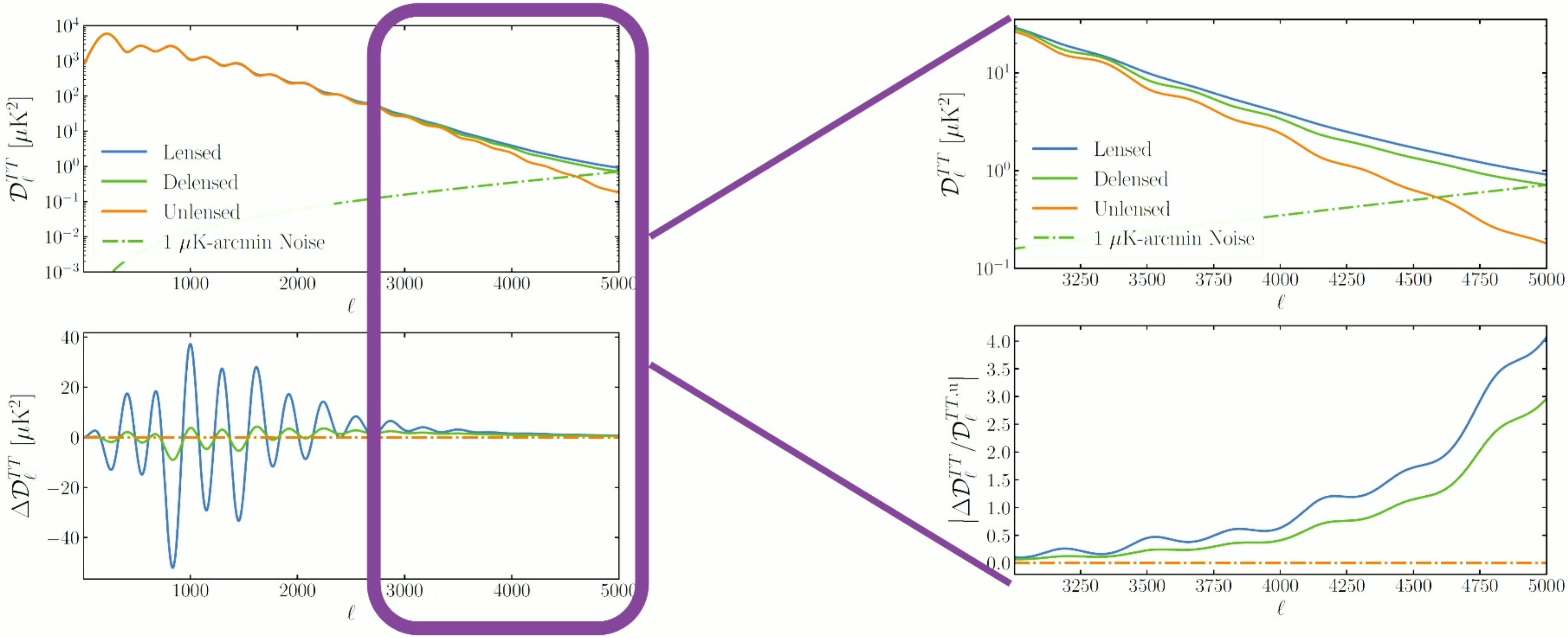
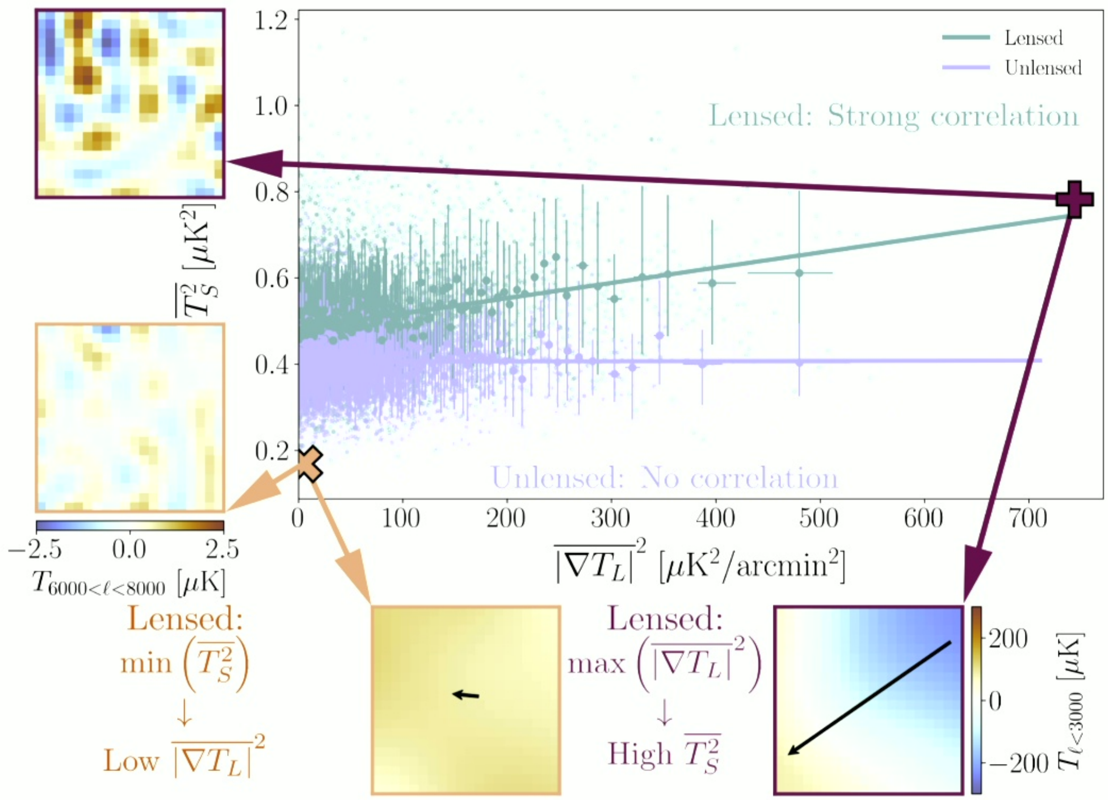
Lensed CMB Temperature Power



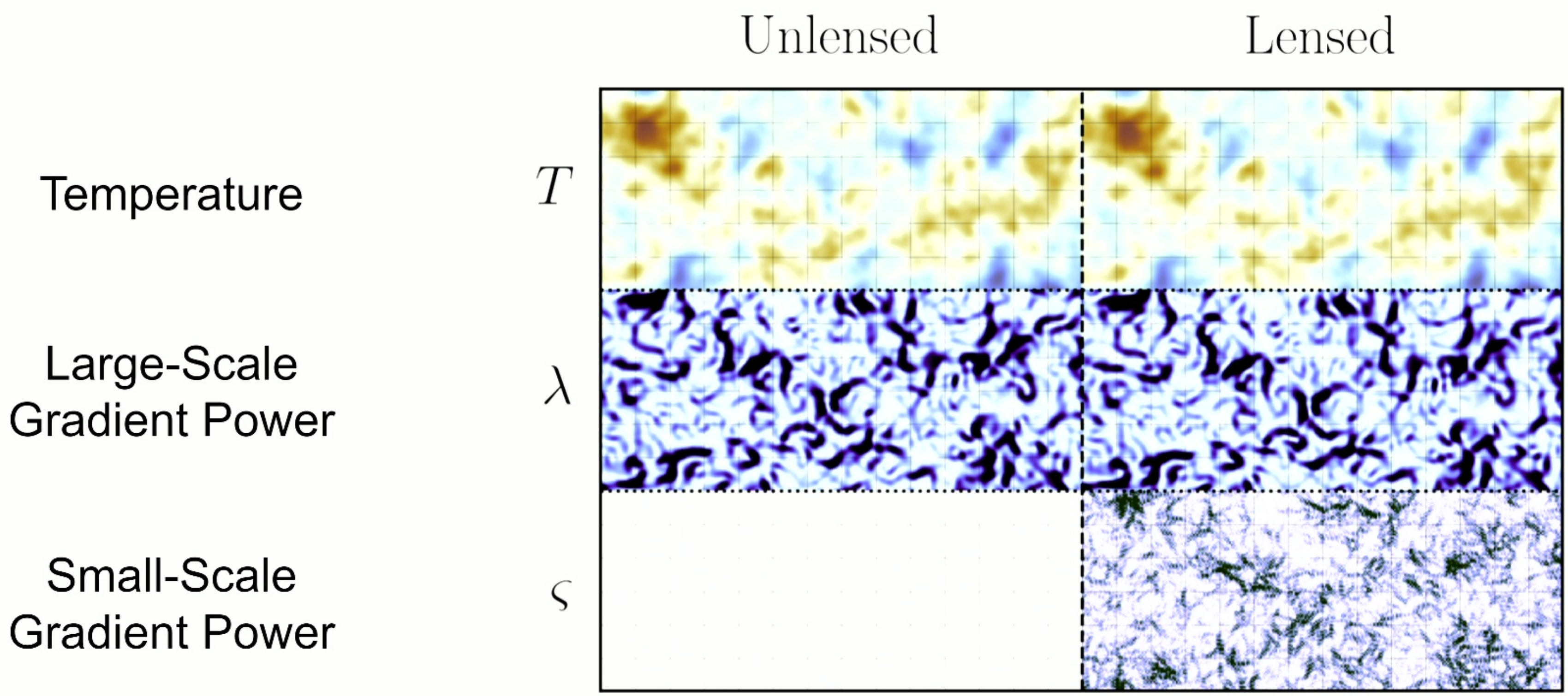
Hotinli, JM, Trendafilova, Green, van Engelen (2022)

Small-Scale Power Varies with Large-Scale Gradient



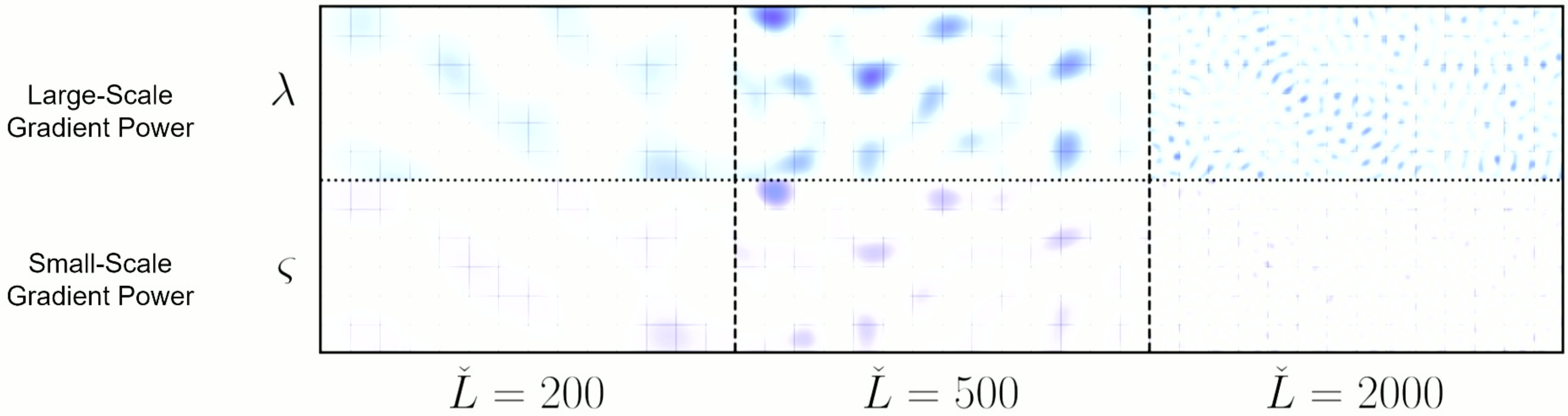
Chan, Hlozek, JM, van Engelen (2023)

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



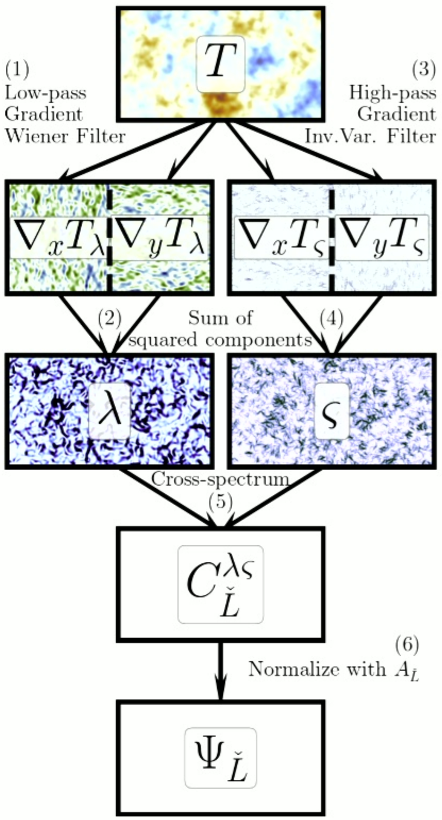
Chan, Hlozek, JM, van Engelen (2023)

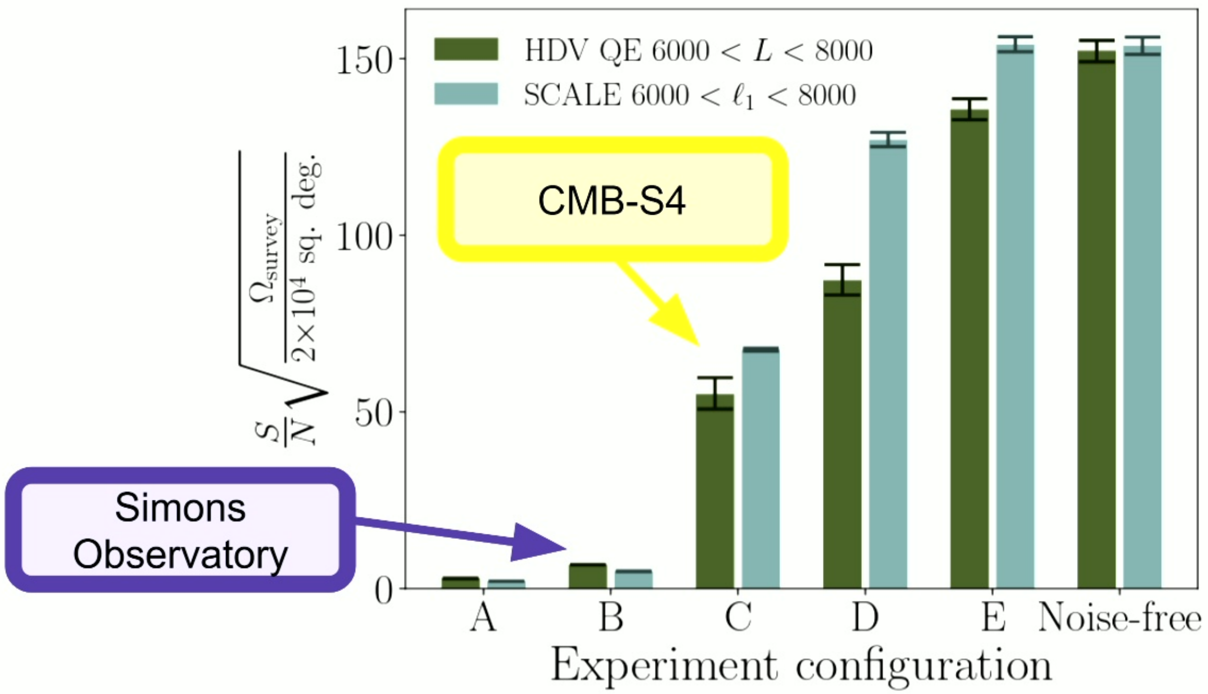
Maps of Small-Scale Power and Large-Scale Power Are Correlated



Chan, Hlozek, JM, van Engelen (2023)

Small Correlated Against Large Estimator (SCALE)





Chan, Hlozek, JM, van Engelen (2023)

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Light Relics
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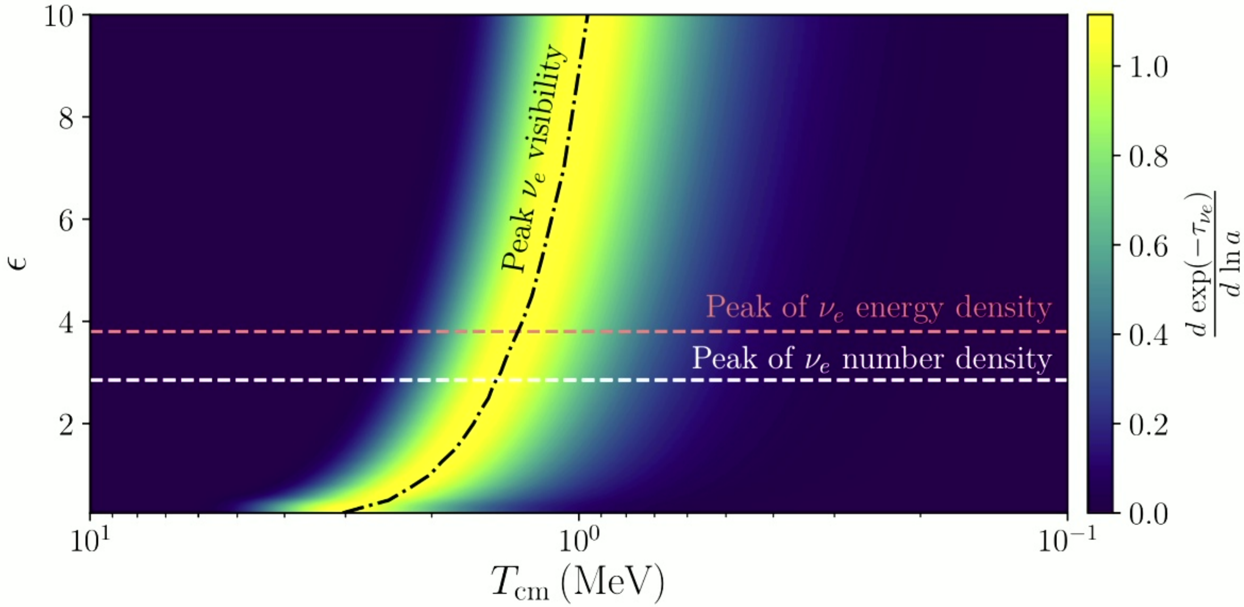
Cosmic Neutrinos as Standard Model Light Relics

Neutrino Differential Visibility



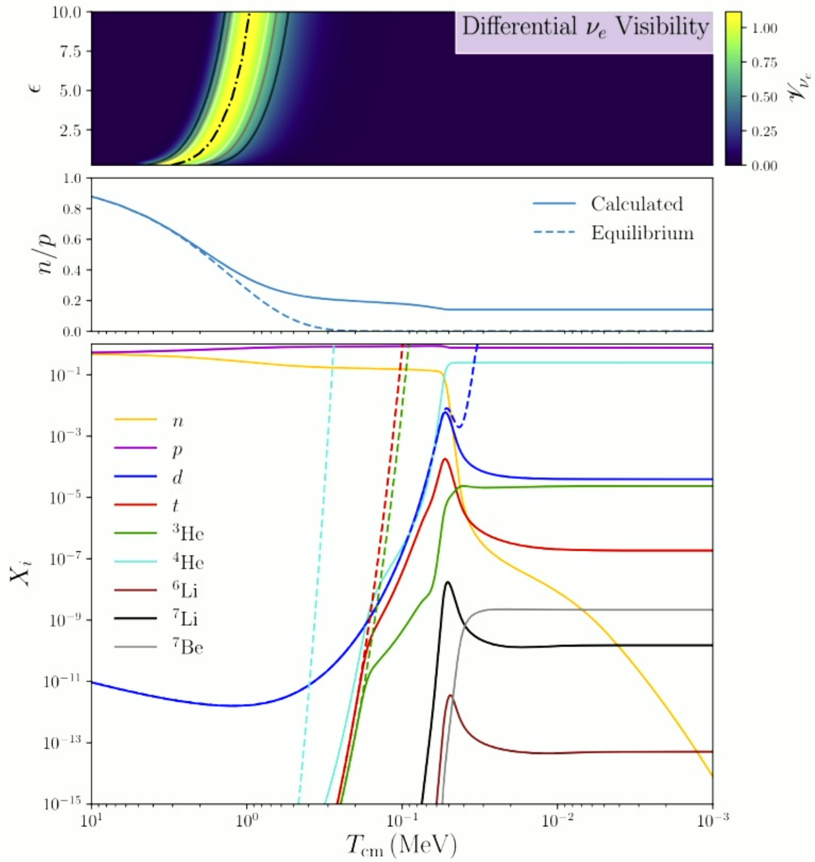
The energy density of the cosmic neutrino background can be calculated precisely, including the effects of non-instantaneous weak decoupling

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

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

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

BBN and New Physics in the Neutrino Sector

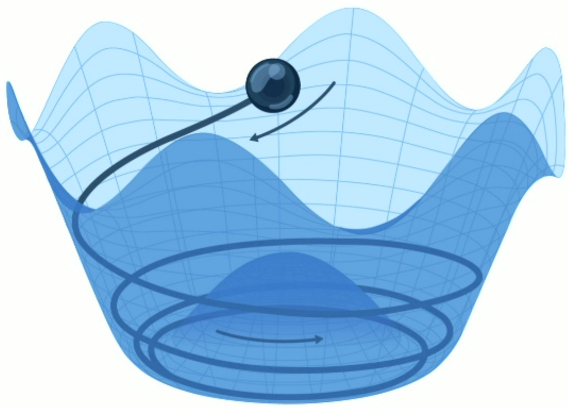


The precision with which we can measure primordial light element abundances (especially deuterium and Helium-4) allows us to use BBN as a powerful probe of new physics

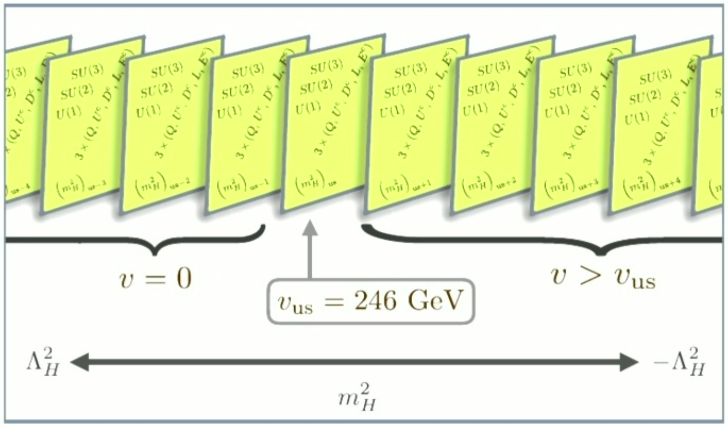
This becomes an even sharper test when combined with CMB constraints

Bond, Fuller, Grohs, JM, Wilson (In Prep.);
Yeh, Shelton, Fields, Olive (2022)

New Light Species are Ubiquitous in Standard Model Extensions



Axions and Axion-Like Particles



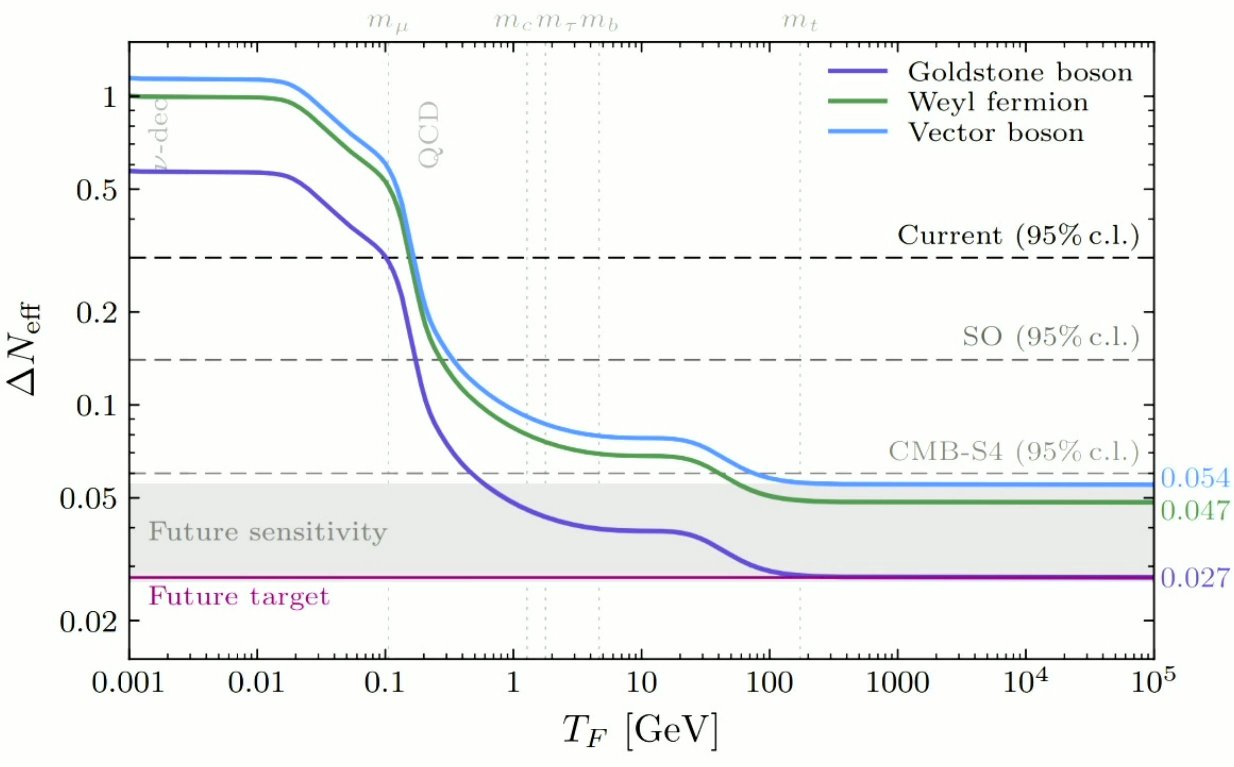
Complex Dark Sectors

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



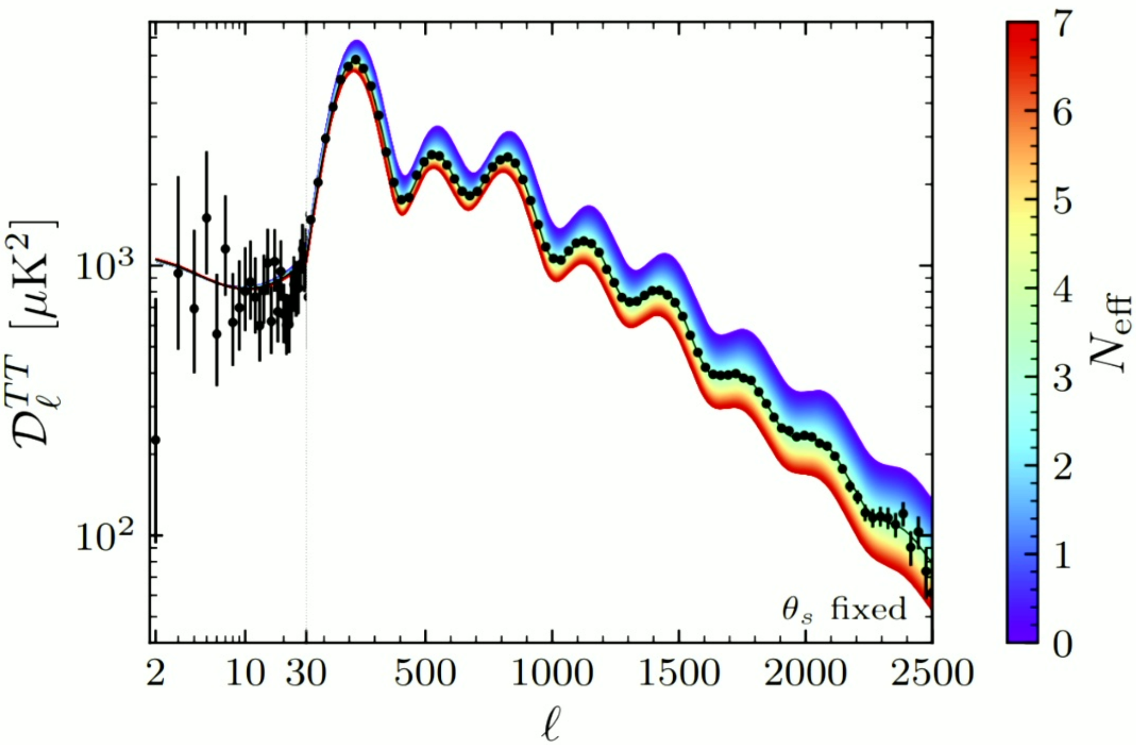
The relic density of any new light species that was ever in thermal equilibrium with the Standard Model plasma can be computed from its spin and decoupling temperature, setting clear targets for future surveys

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)

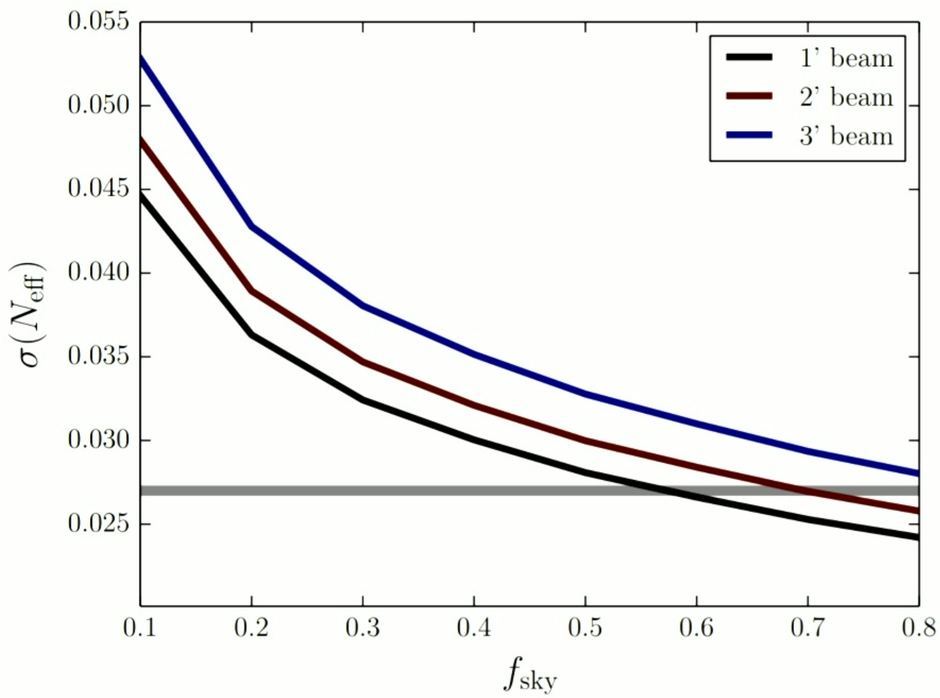
Light Relics Affect CMB Damping Scale



The mean density of light relics affects the expansion rate in the early universe and therefore impacts the damping scale of CMB anisotropies

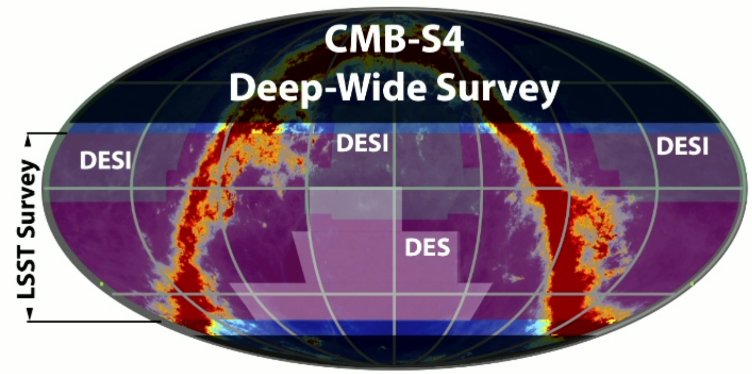
Image Credit: Wallisch (2018)

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



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

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The Benefits of CMB Delensing
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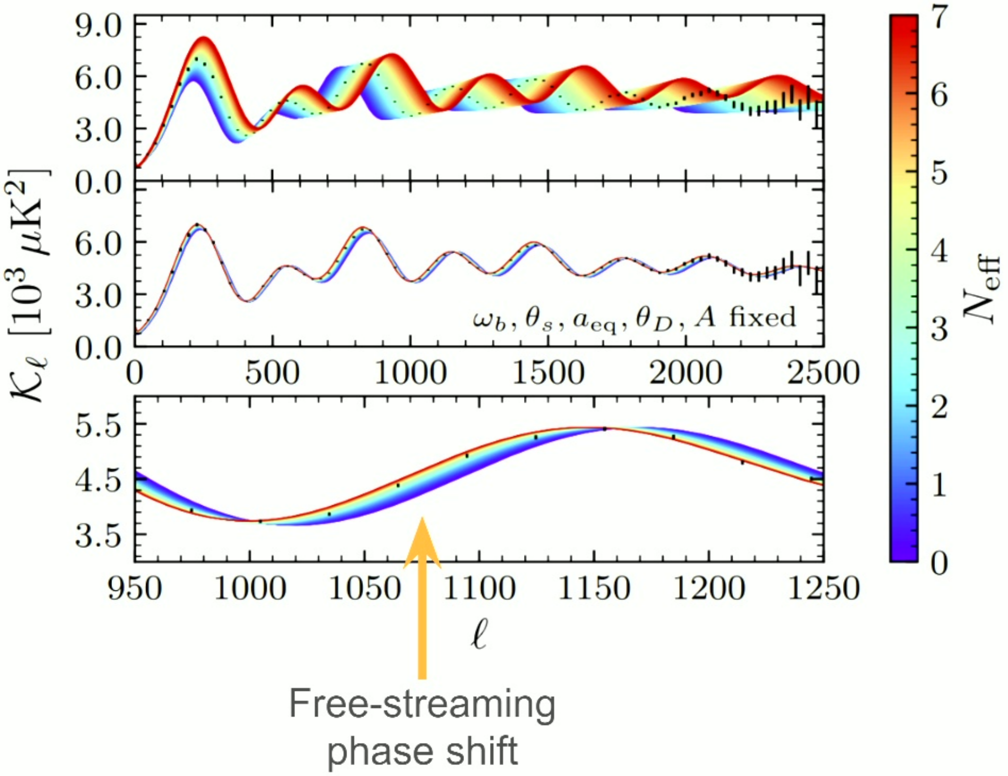
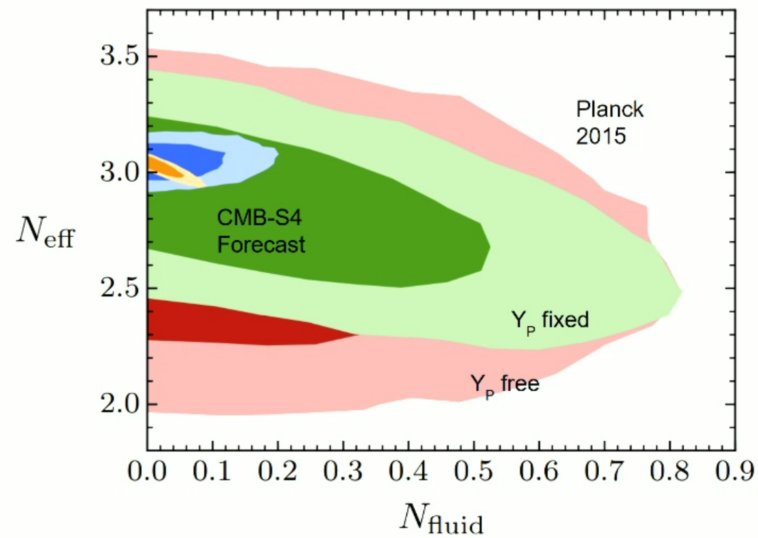
Free-Streaming Light Relics and the Phase Shift



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



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

Gravitational Lensing Smooths Acoustic Peaks

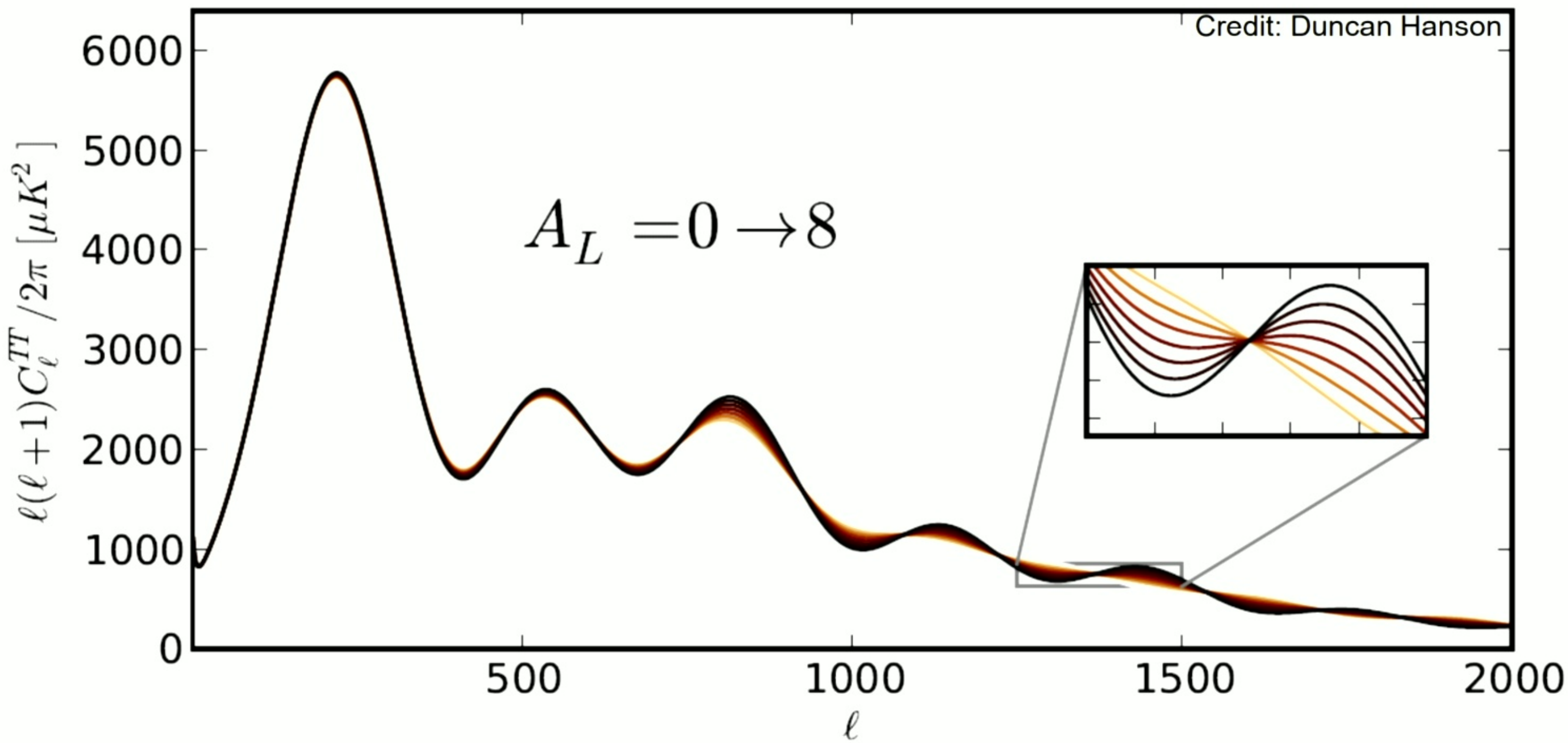


Image Credit: Hanson

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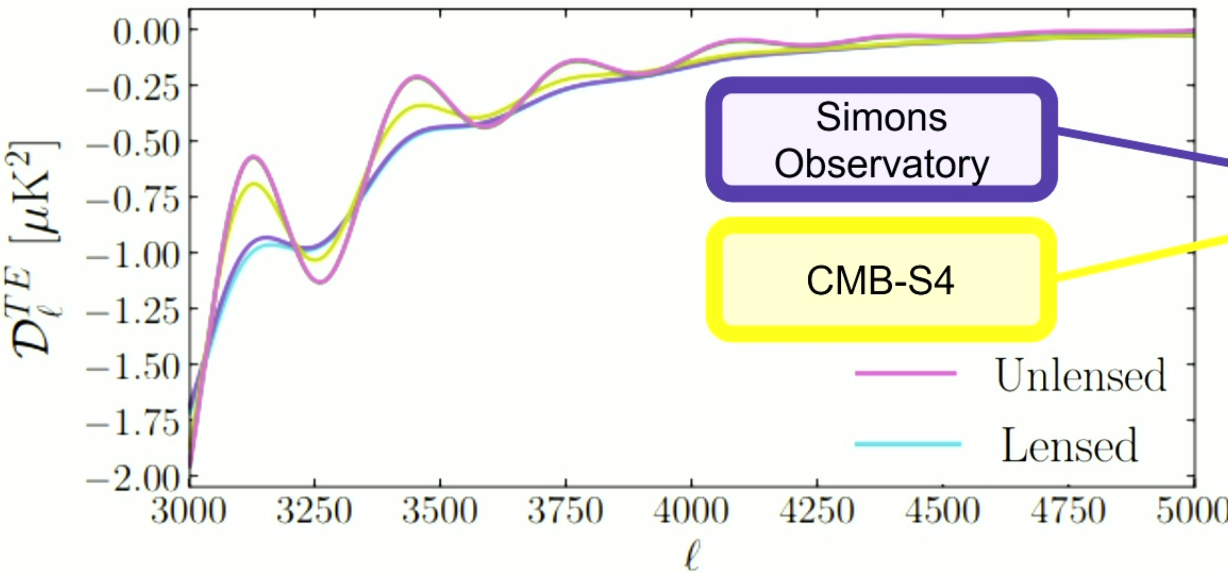
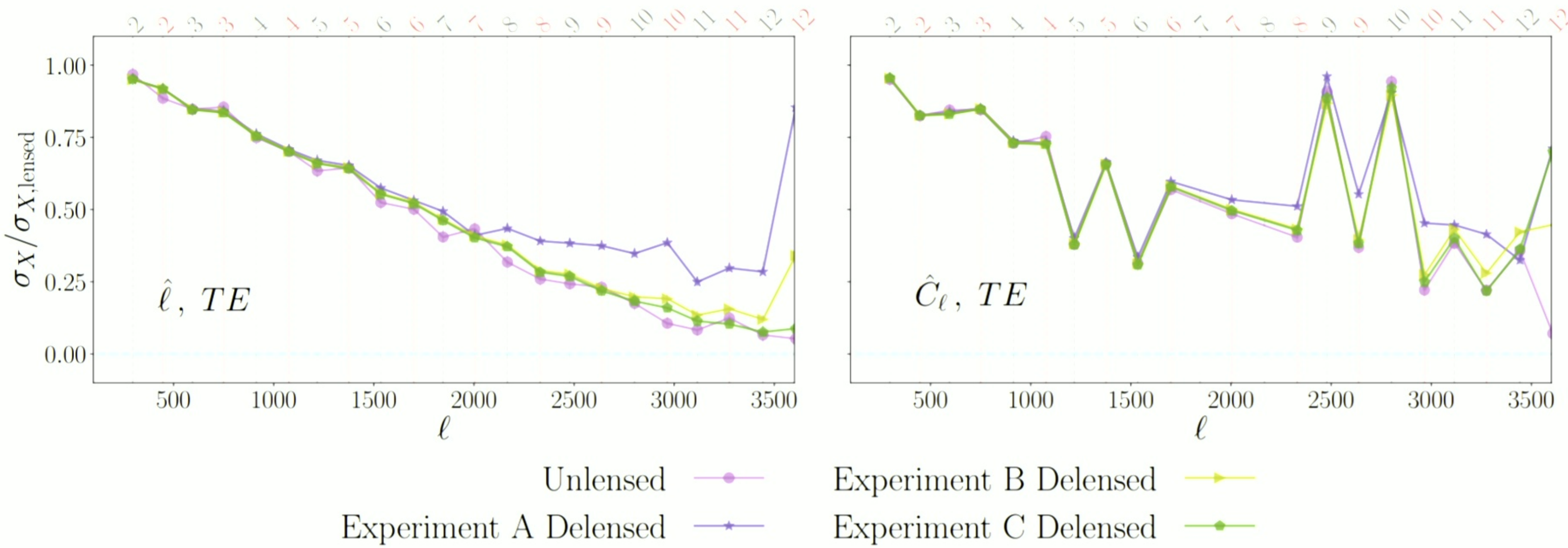
CMB Delensing Sharpens Peaks



Δ_T (μK-arcmin)	θ_{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



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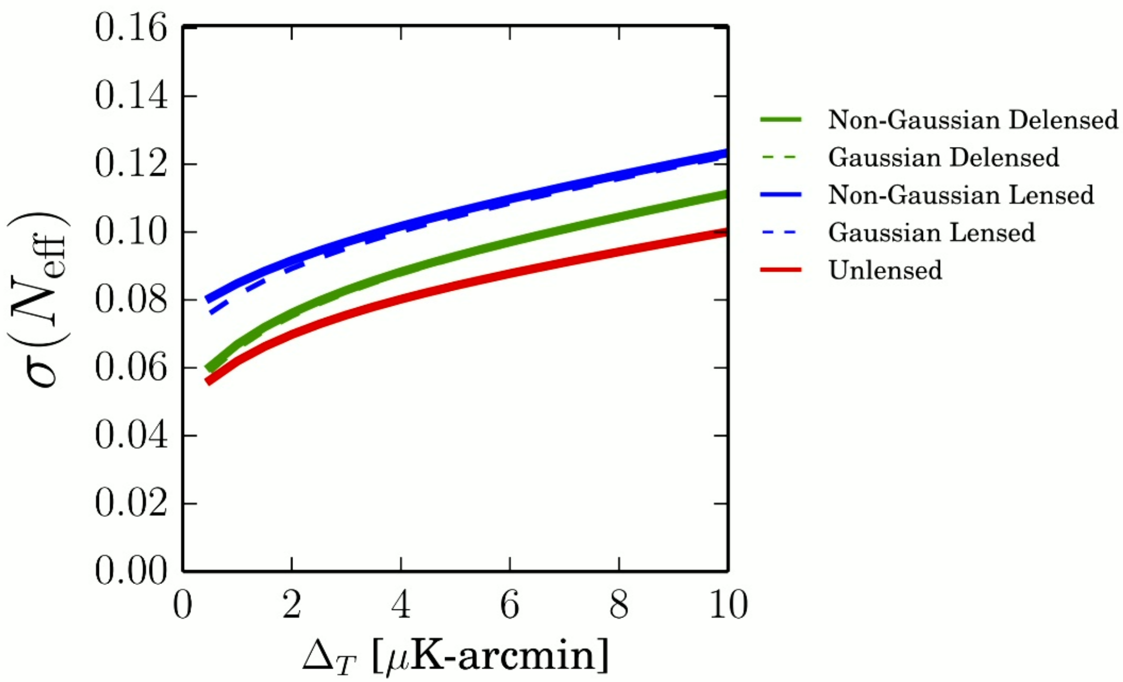
Green, JM, van Engelen (2016); Hotinli, JM, Trendafilova, Green, van Engelen (2022)

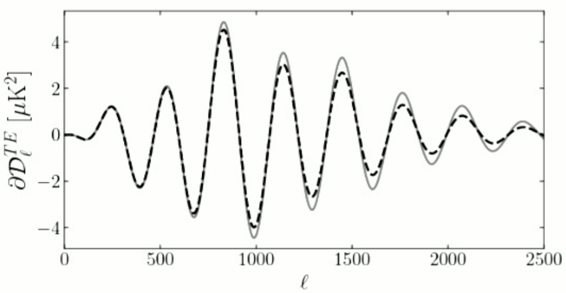
Delensing Enables Tighter Constraints on Light Relics



Delensing improves the constraining power for parameters that impact primary spectra, and in particular enhances our ability to measure the light relic density

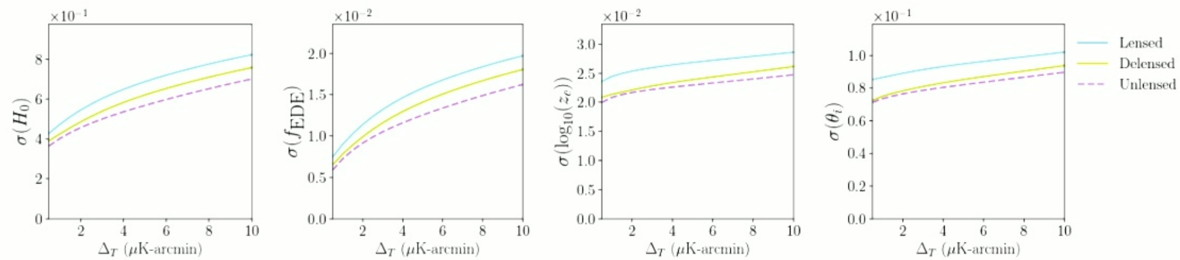
Green, JM, van Engelen (2016); Hotinli, JM, Trendafilova, Green, van Engelen (2022)

Delensing Betters Constrains Models Aimed at H_0 Tension

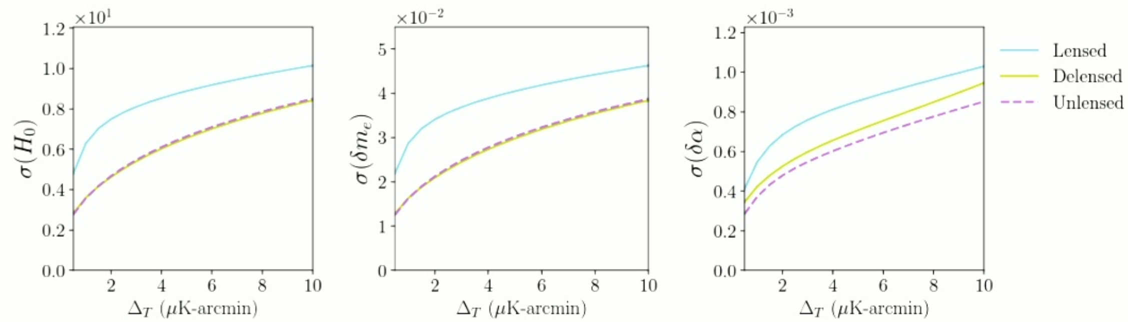


Hubble constant is inferred from size of sound horizon at last scattering, via peak positions

Delensing improves constraints on early dark energy

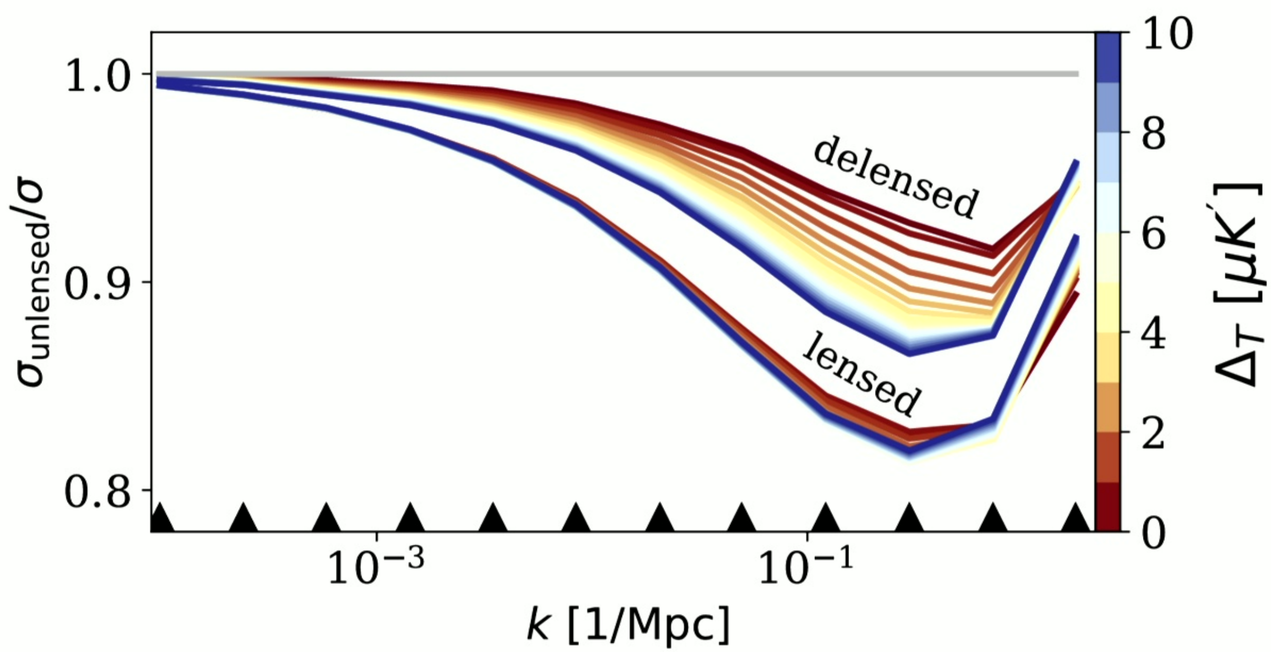


Delensing improves constraints on varying fundamental constants



Knox, Millea (2019); Ange, JM (2023)

Delensing Tightens Constraints on Primordial Fluctuations



Delensing improves constraints on primordial power spectrum P(k)

Delensing also provides tighter constraints on:

- Primordial features
- Spatial curvature
- Isocurvature fluctuations
- Primordial tensor spectrum

Trendafilova, Hotinli, JM (2023)


Machine Learning for CMB Secondaries
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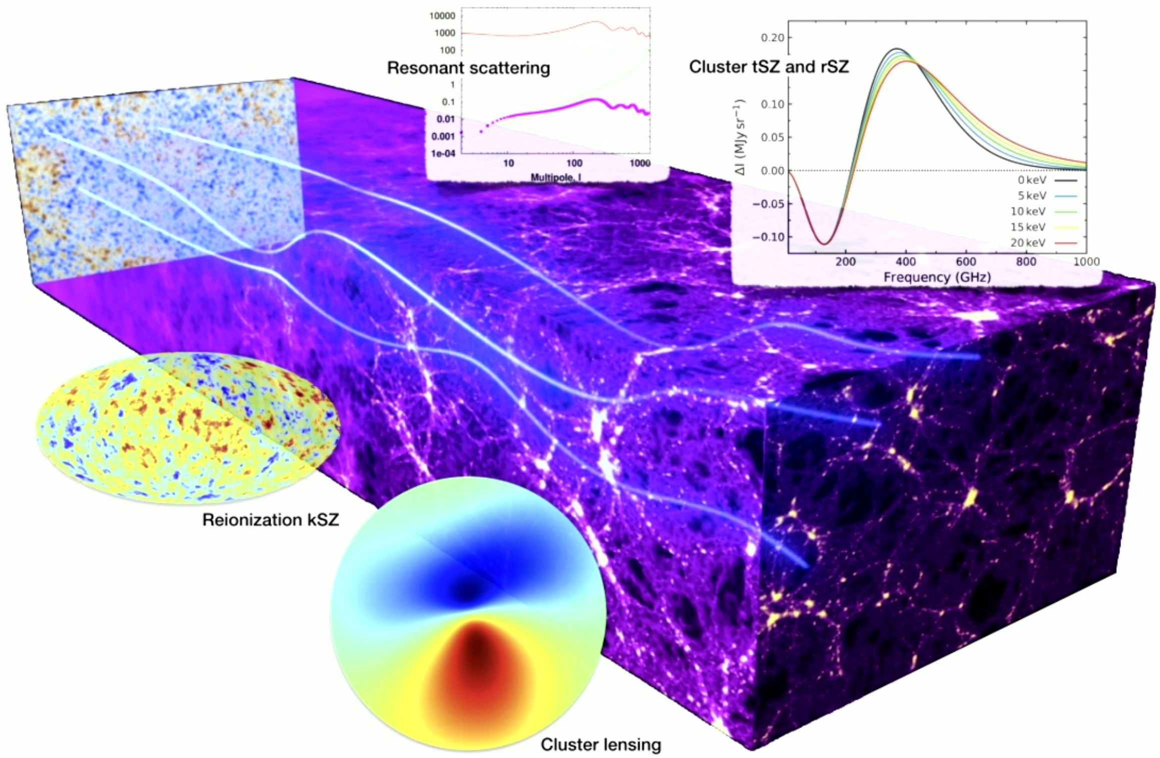
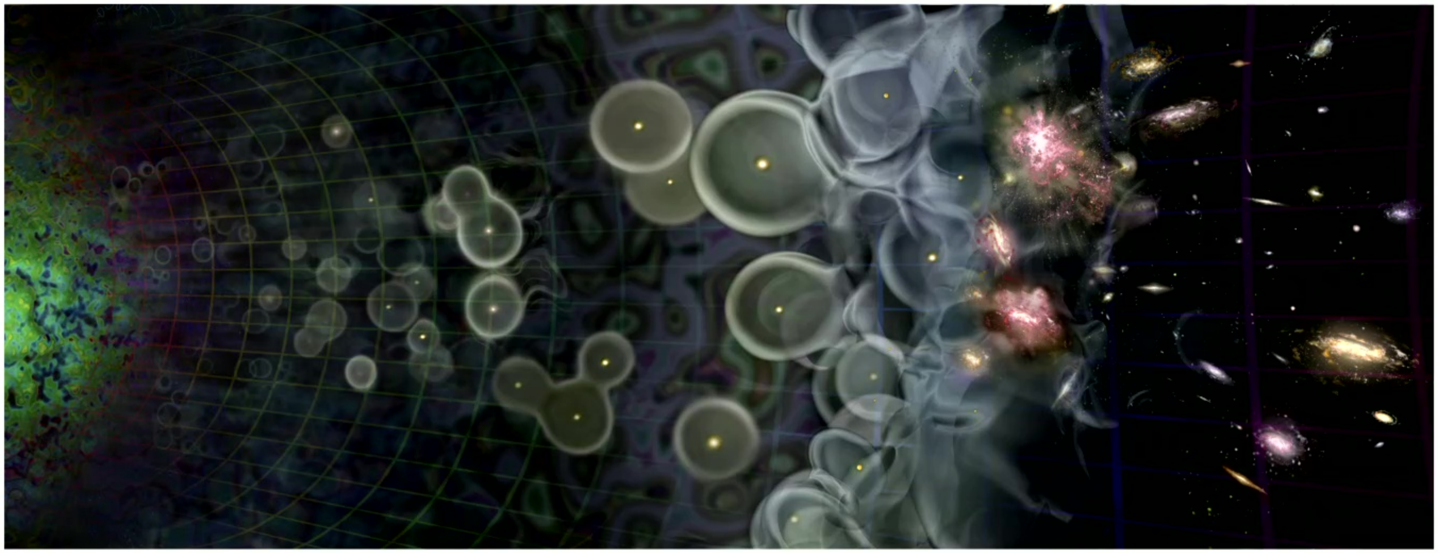
CMB as a Universal Backlight



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)

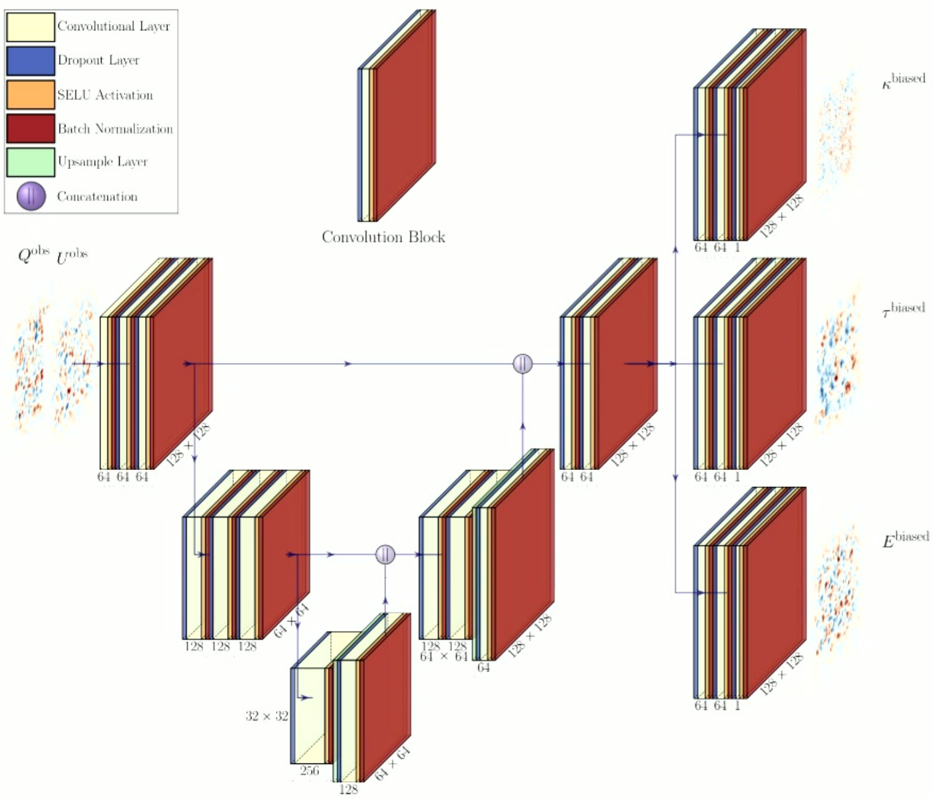
Patchy Reionization Modulates CMB Fluctuations

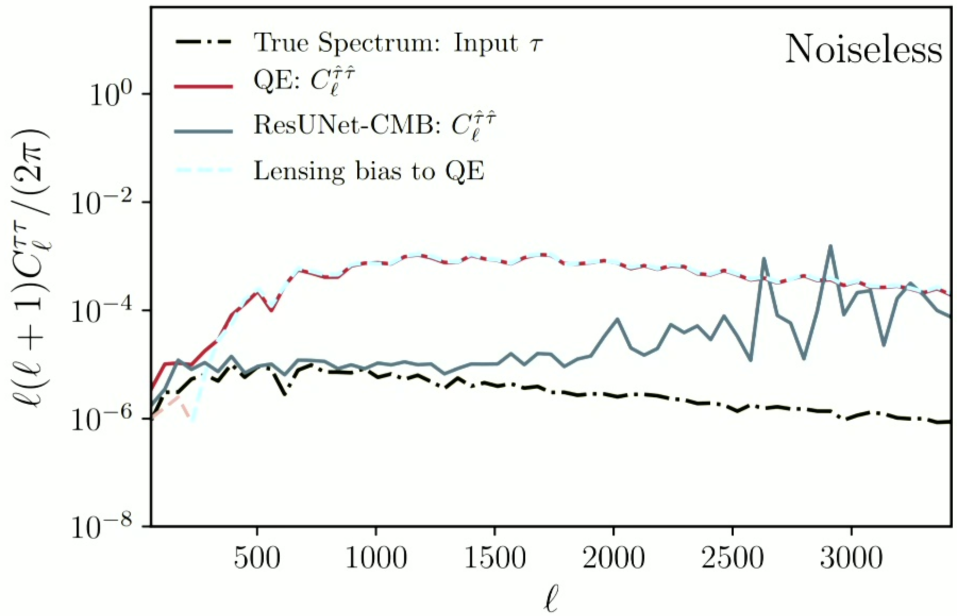


- The effect of patchy reionization on the CMB is not entirely distinct from gravitational lensing
- Standard reconstruction of patchy reionization is therefore biased by gravitational lensing

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

Deep Learning Secondary Reconstruction - ResUNet-CMB

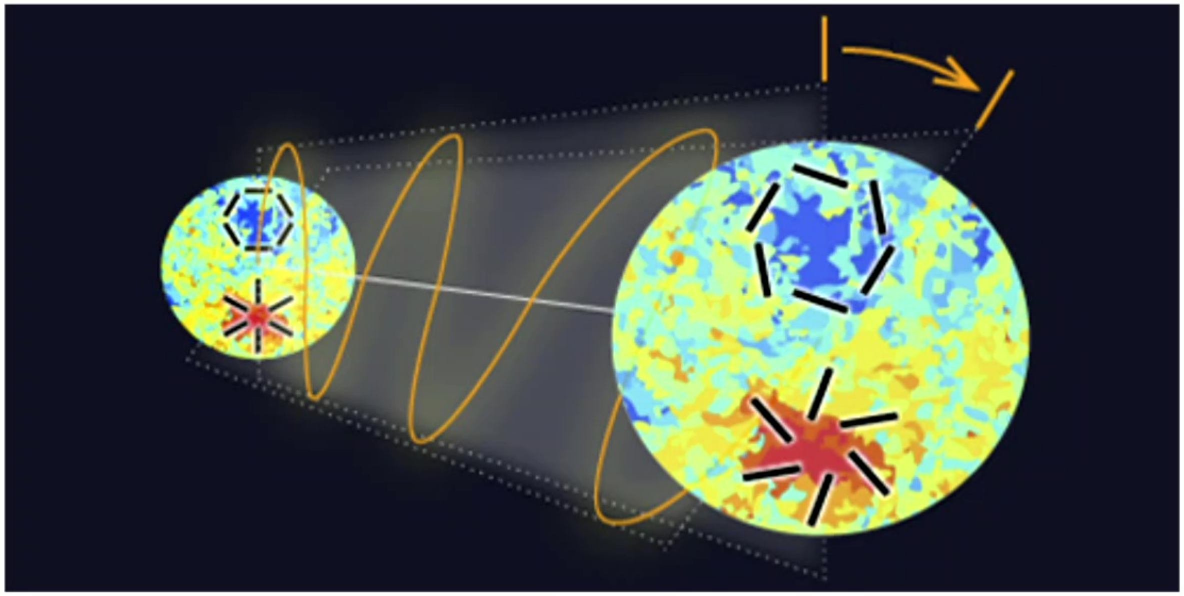




ResUNet-CMB provides a nearly optimal, unbiased reconstruction of patchy reionization

Guzman, JM (2021)

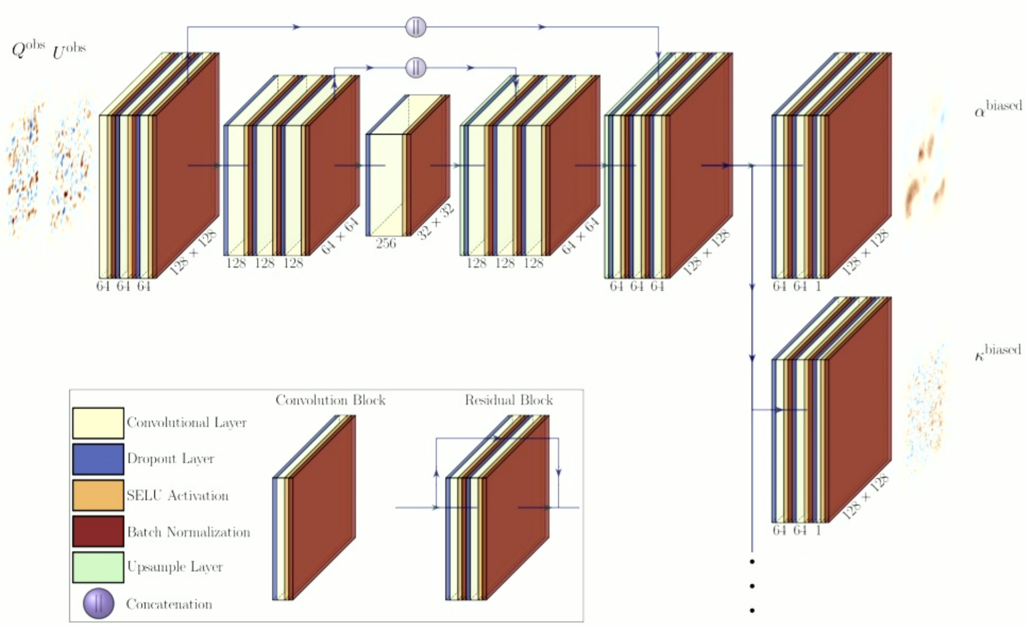
Birefringence and Magnetic Fields Rotate CMB Polarization

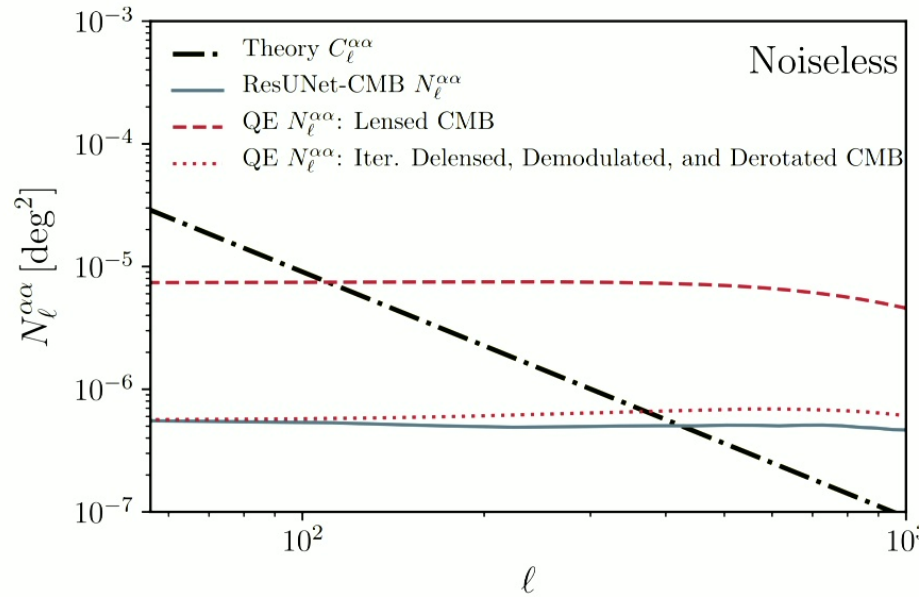


- Cosmic birefringence may result from axion-like particles with Chern-Simons coupling to electromagnetism
- Primordial magnetic fields can also rotate CMB polarization angles due to Faraday rotation

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)

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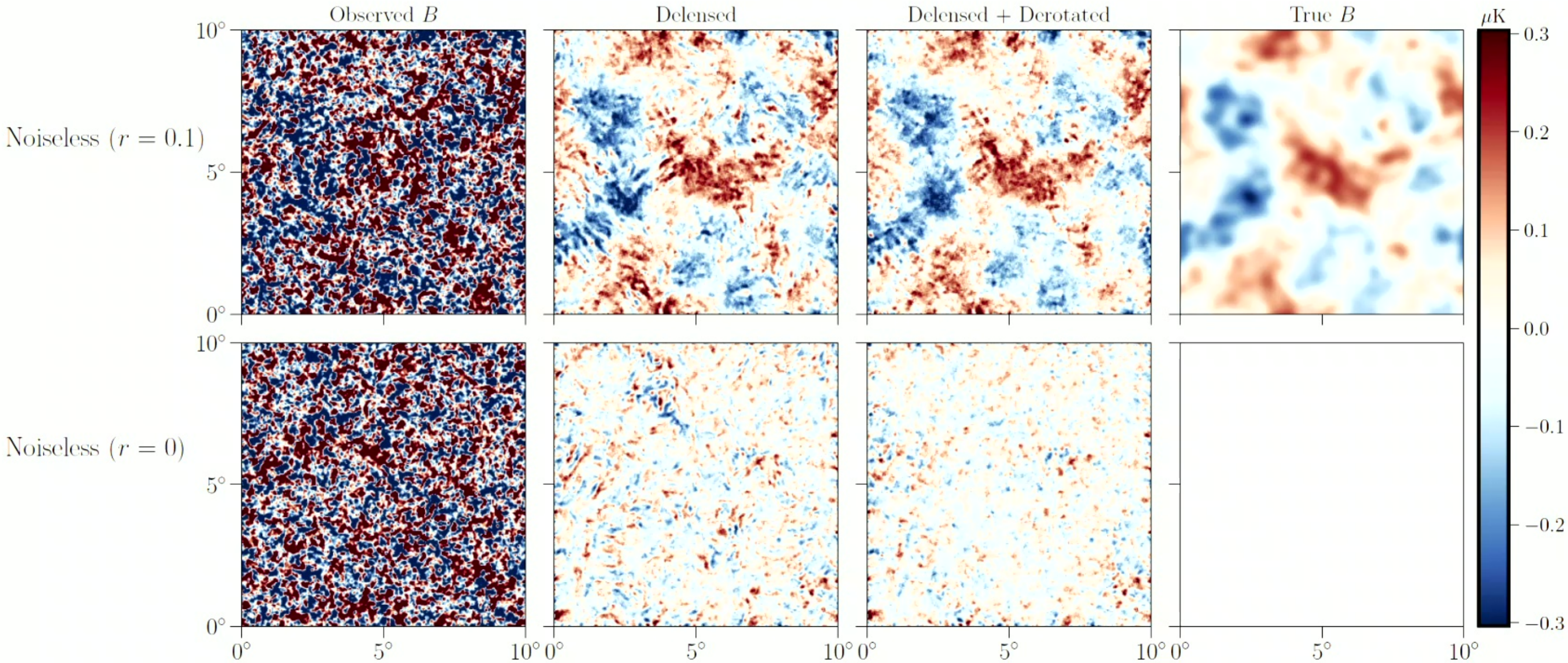
Recovering Primordial B Modes with ResUNet-CMB



Guzman, JM (In Prep.)

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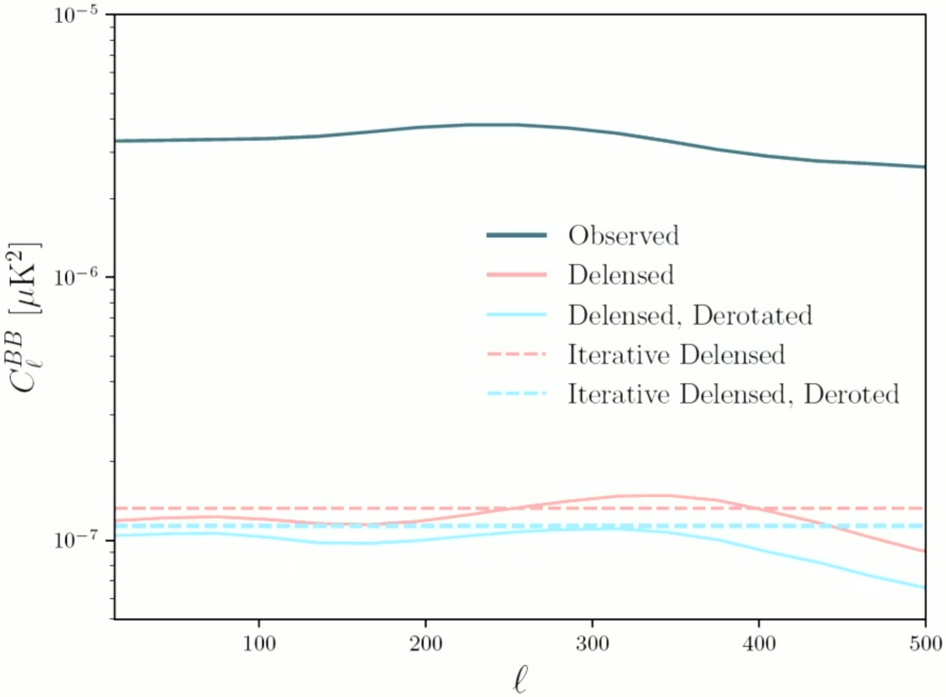
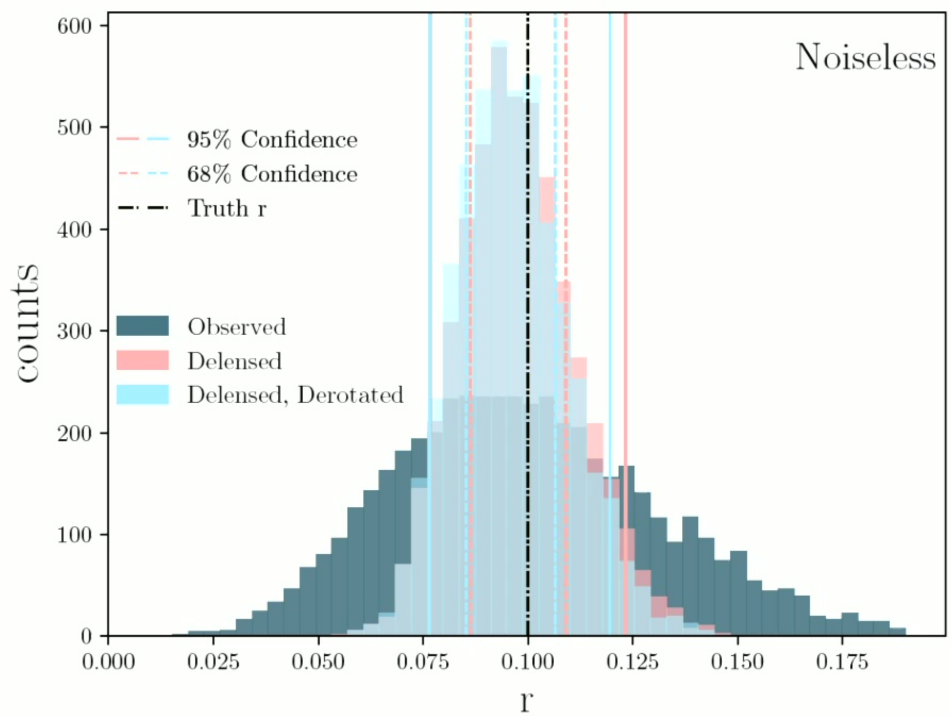
Searching for Primordial Gravitational Waves with ResUNet-CMB





Guzman, JM (In Prep.)

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Conclusion
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Conclusion

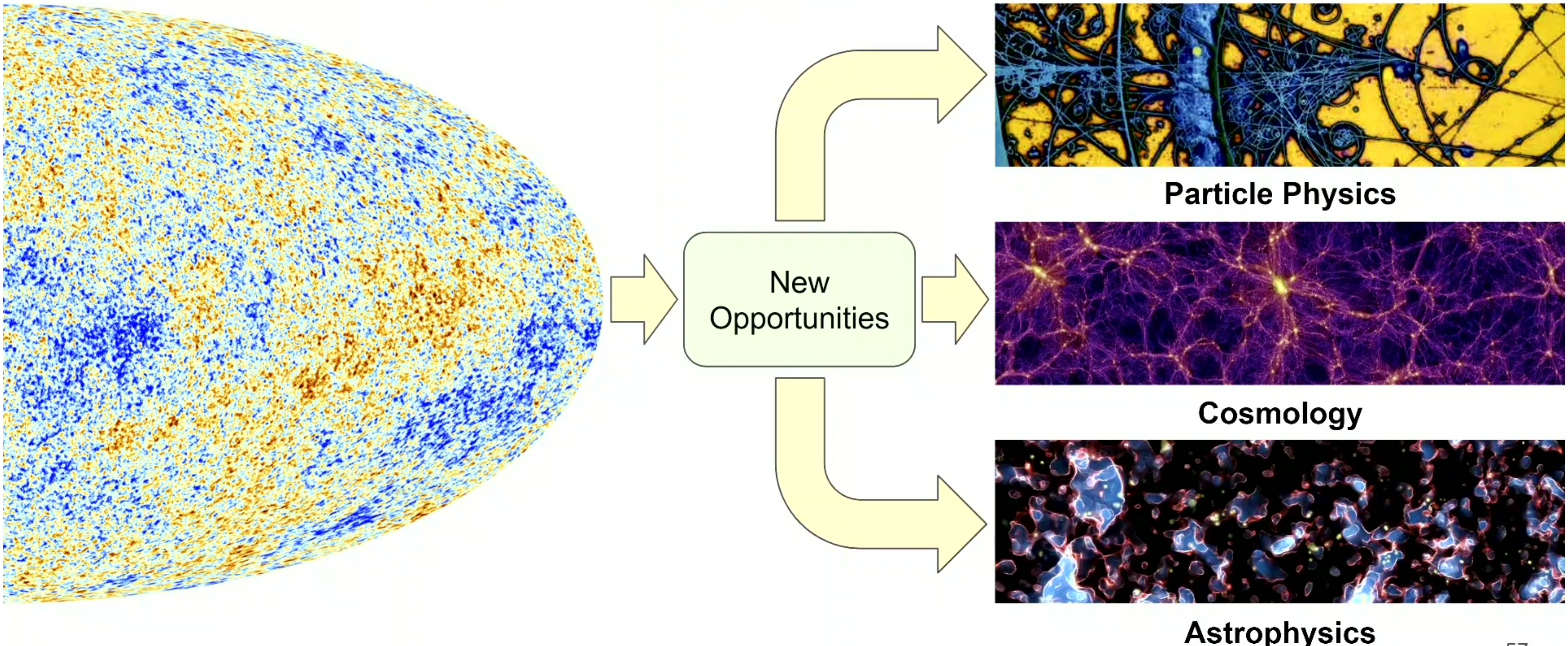

Image Credits: Planck; BEBC/CERN; Springel, et al; Alvarez, Kaehler, Abel