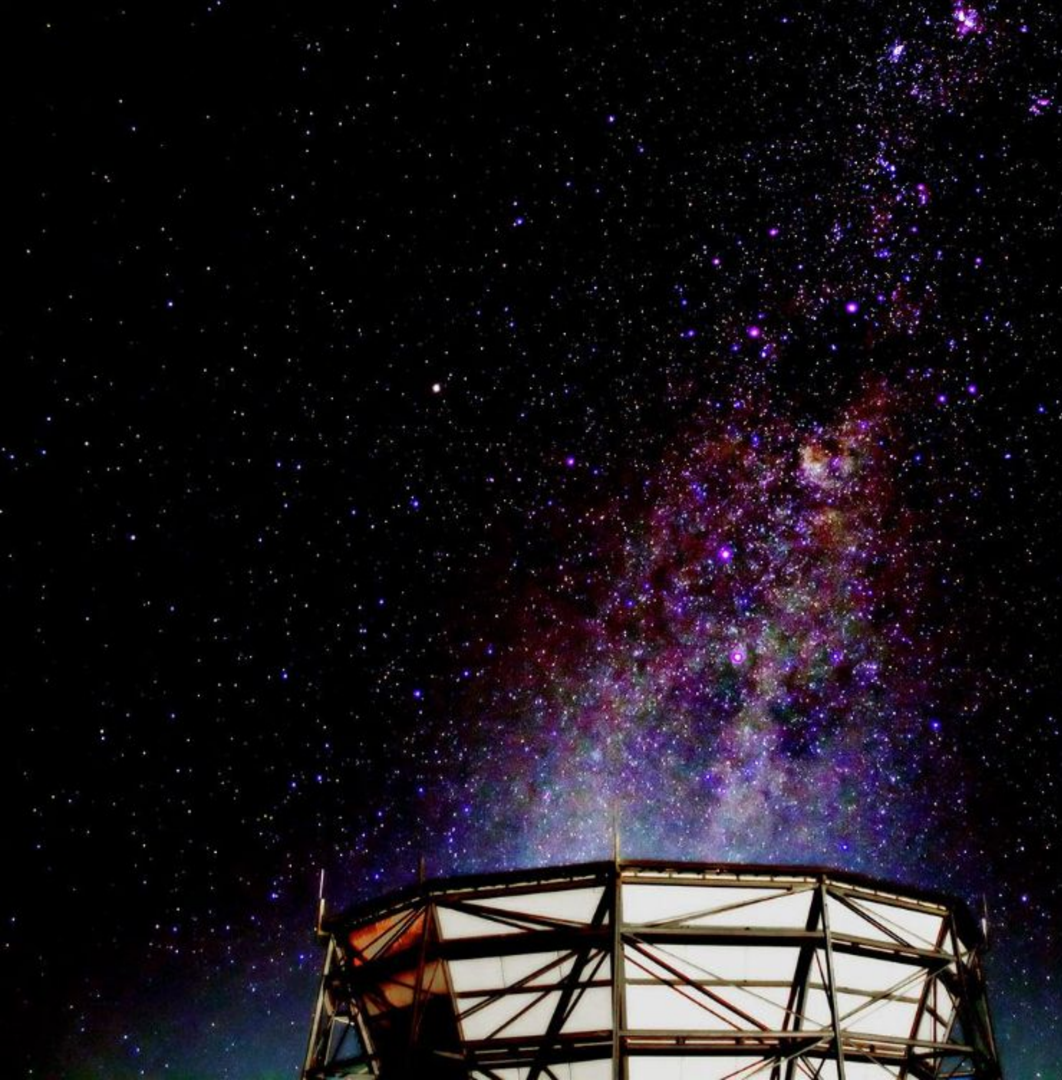
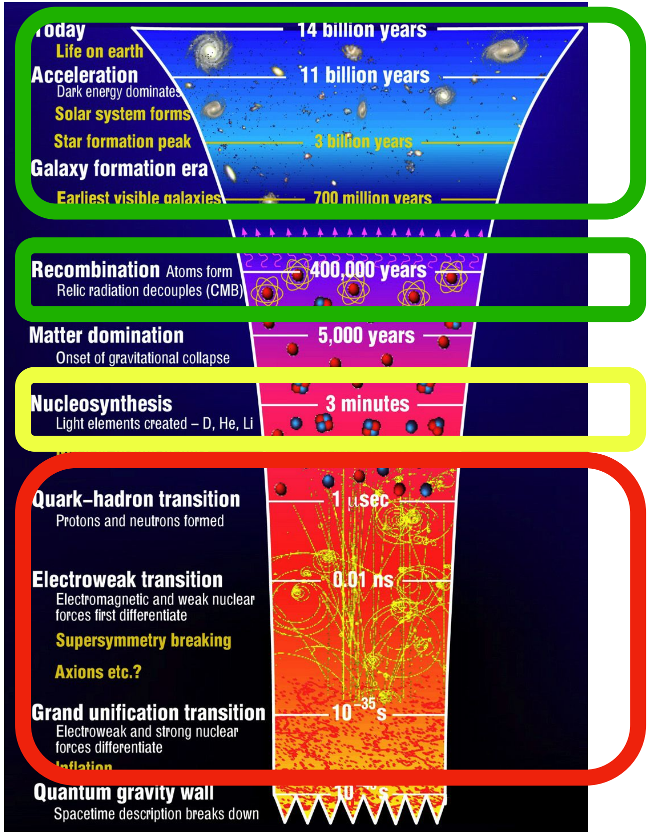


Dark Sector Insights with Upcoming CMB Observations

Joel Meyers
SMU
5-26-2022

Image Credit: ACT / Princeton

History of the Universe



Cosmology describes 13.8 billion years of cosmic history

Direct Observations

Direct observations are limited to a relatively small range of redshifts and energy scales

Indirect Sensitivity

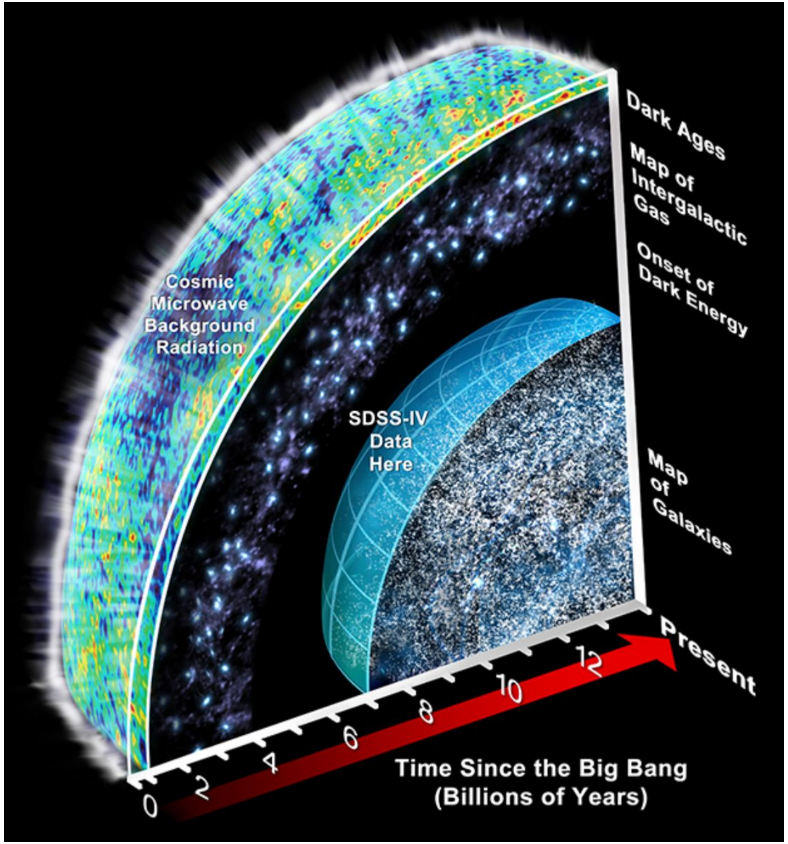
Discovery Space

Future surveys will create new opportunities for insights into much higher energies and earlier times

Image Credit: Center for Theoretical Cosmology, Cambridge

Review of CMB Basics

The Cosmic Microwave Background



Cosmic Microwave Background (CMB) Spectrum

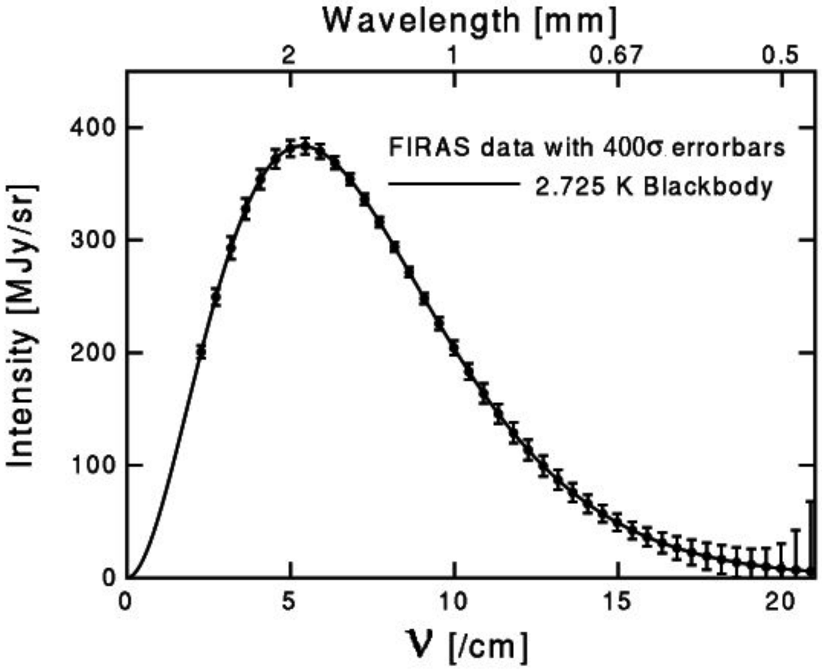
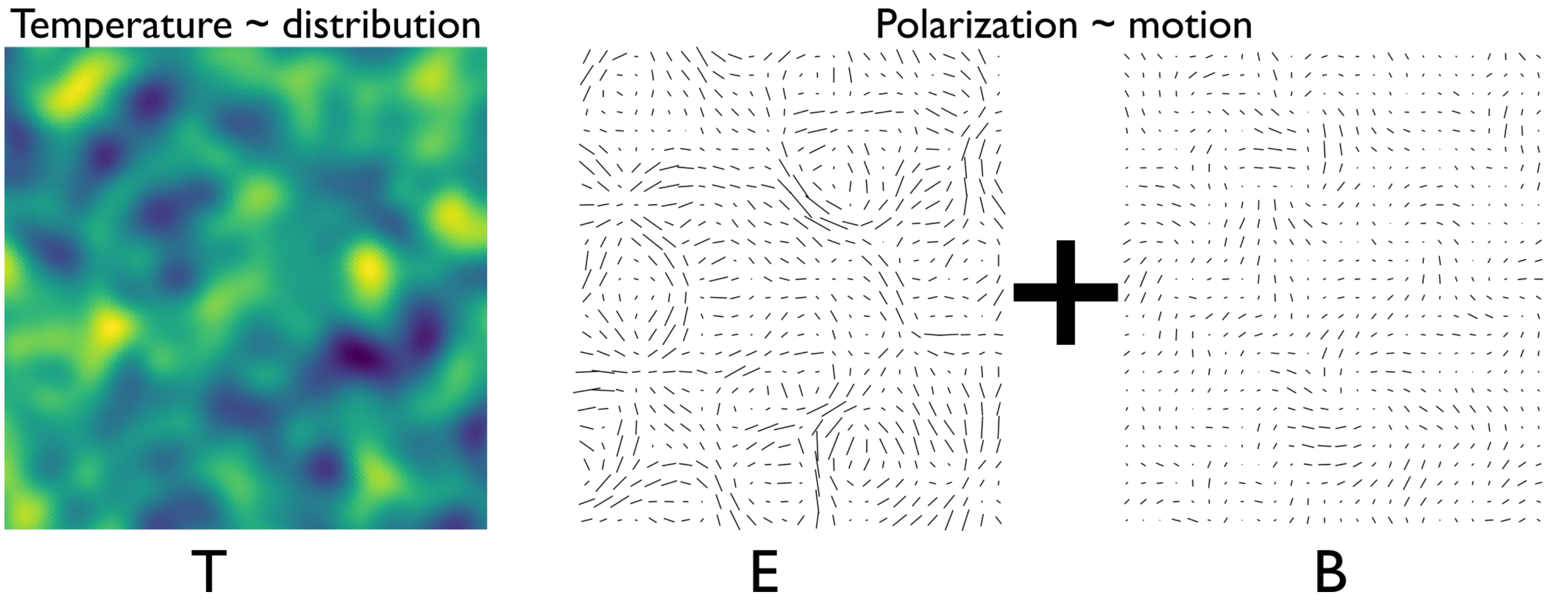


Image Credits: SDSS, COBE FIRAS

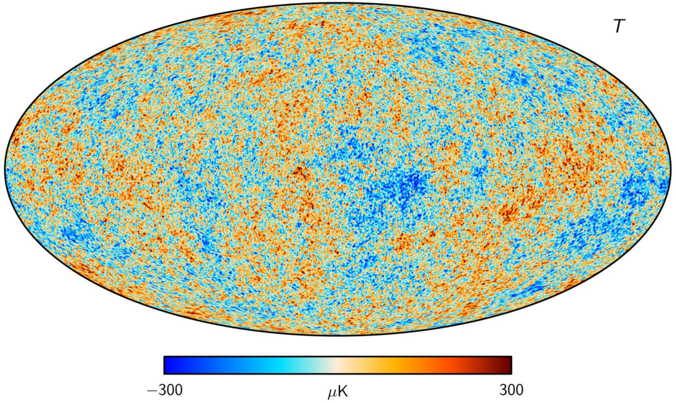
Information In The Cosmic Microwave Background

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

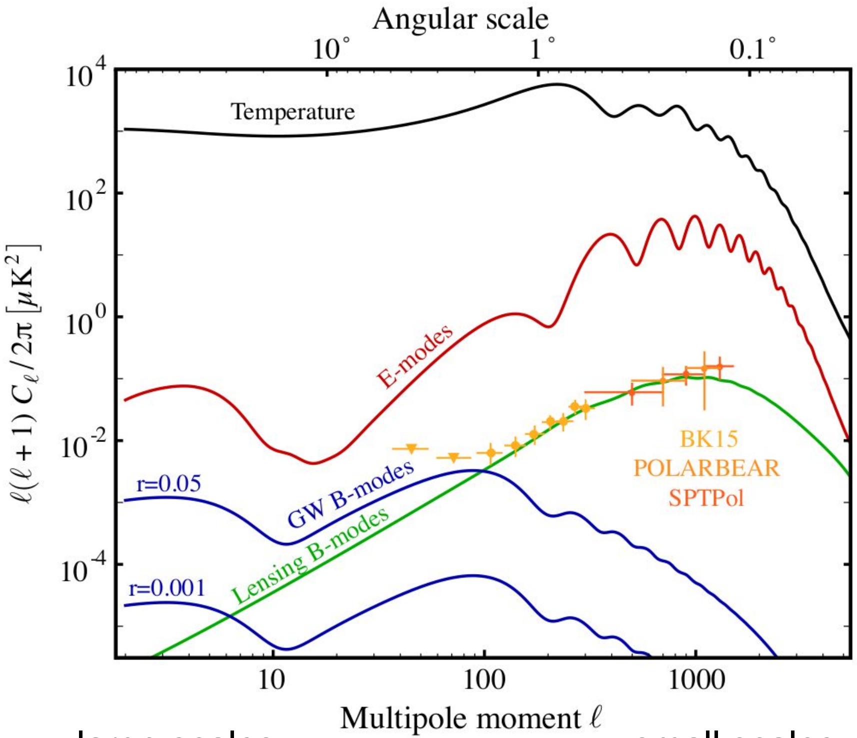


…plus the imprints of the structure between us and the last scattering surface.

Statistical Information and Angular Power Spectra



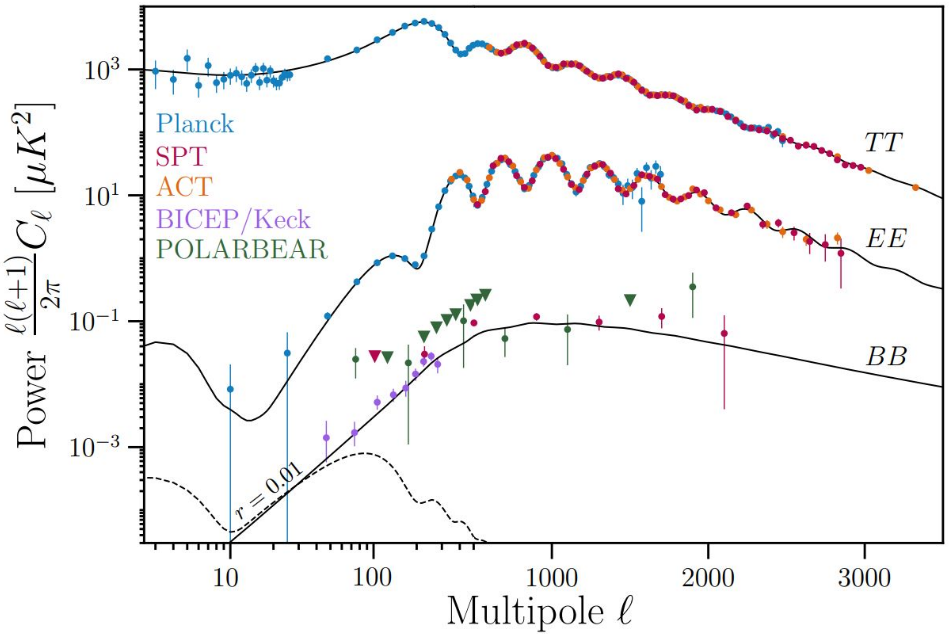
Variance

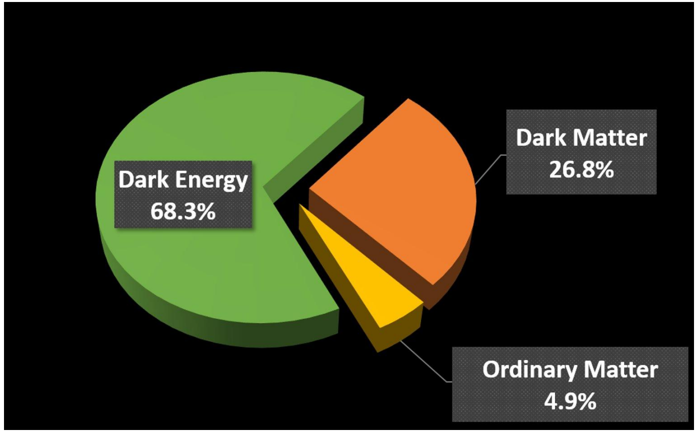


←large scales small scales →

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

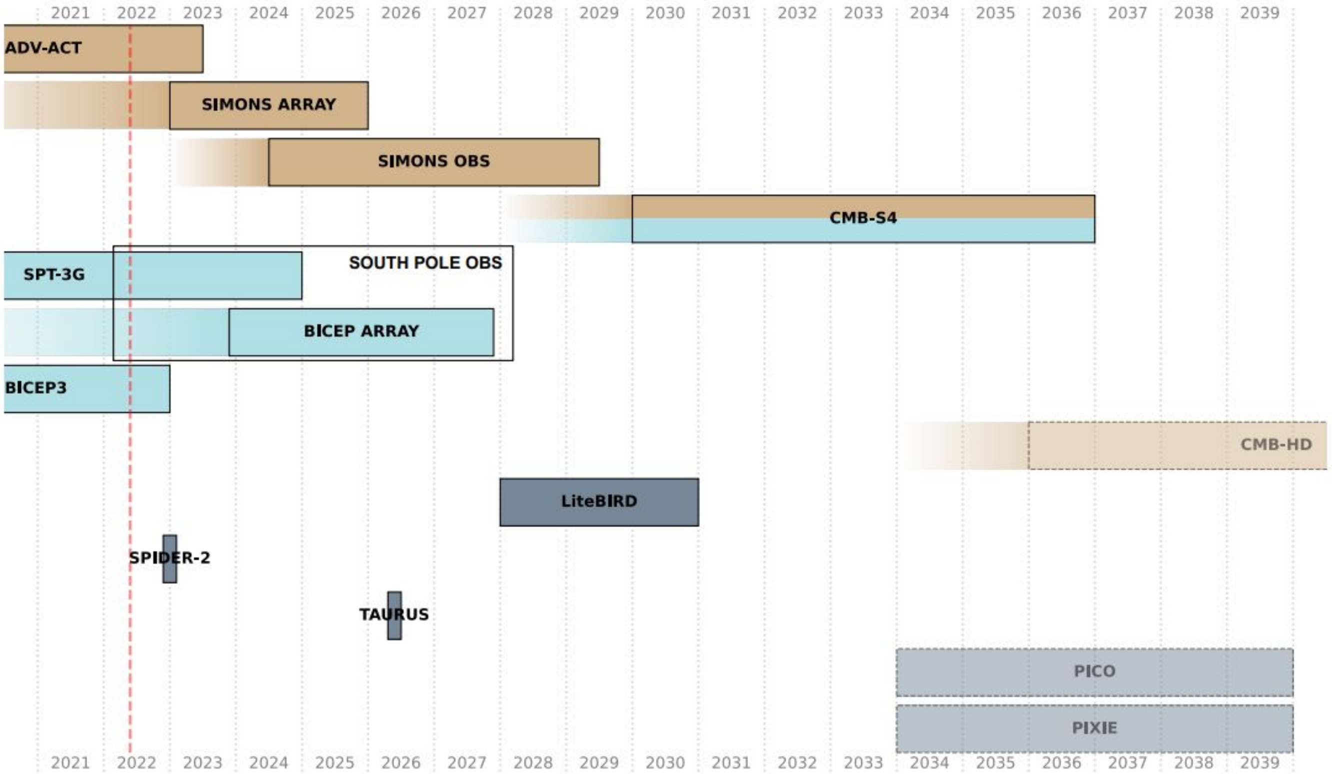
CMB Observations and Concordance Flat ΛCDM





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

Timeline of Upcoming CMB Surveys



Chang, Huffenberger, et al (2022)

Gravitational Lensing of the CMB

Gravitational Lensing of the CMB

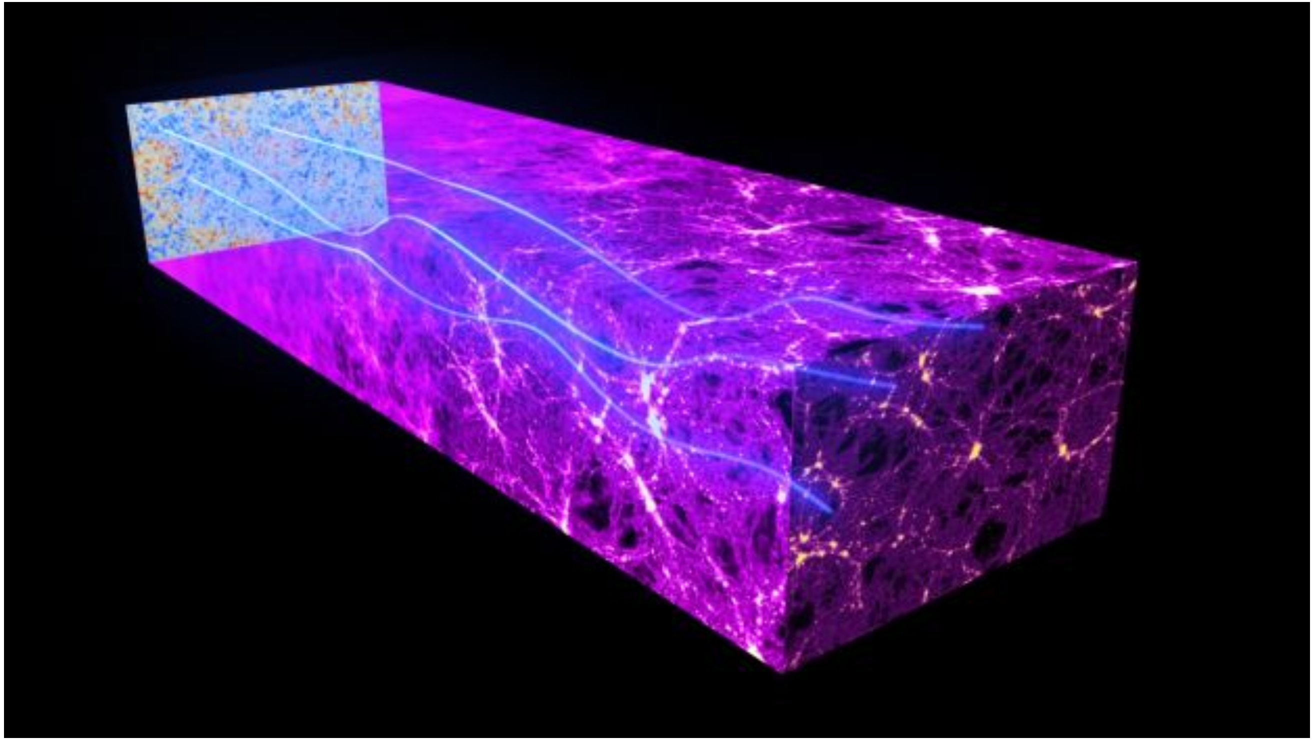
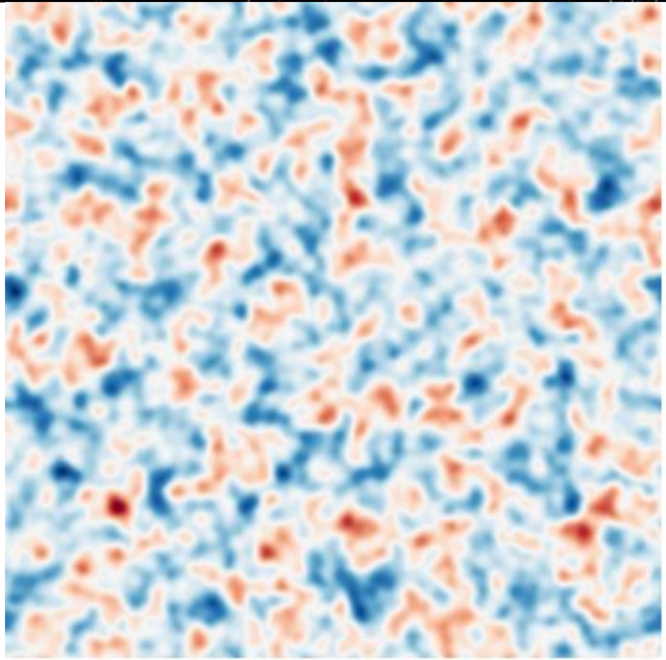


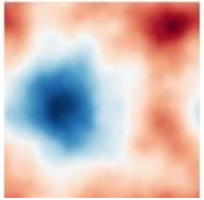
Image Credit: Planck / ESA

Unlensed CMB Polarization



Unlensed E

ϕ

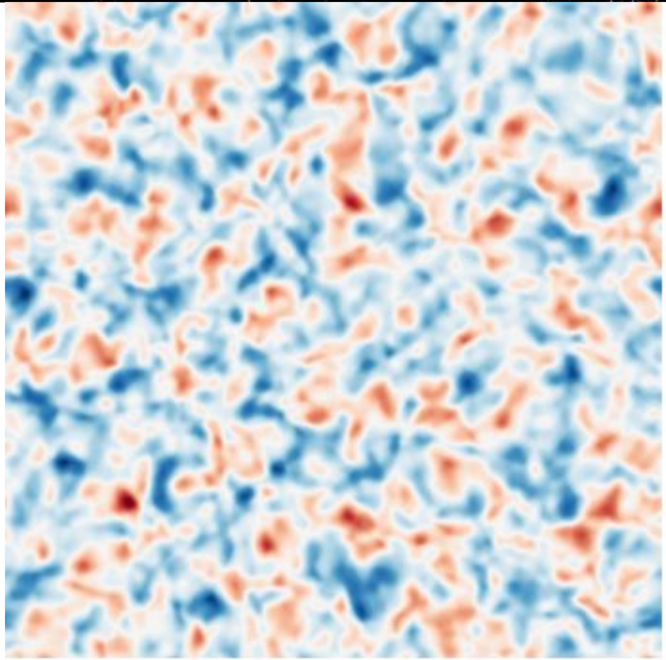


Unlensed B

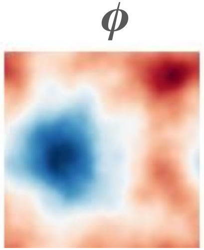
5°✕5° simulated maps

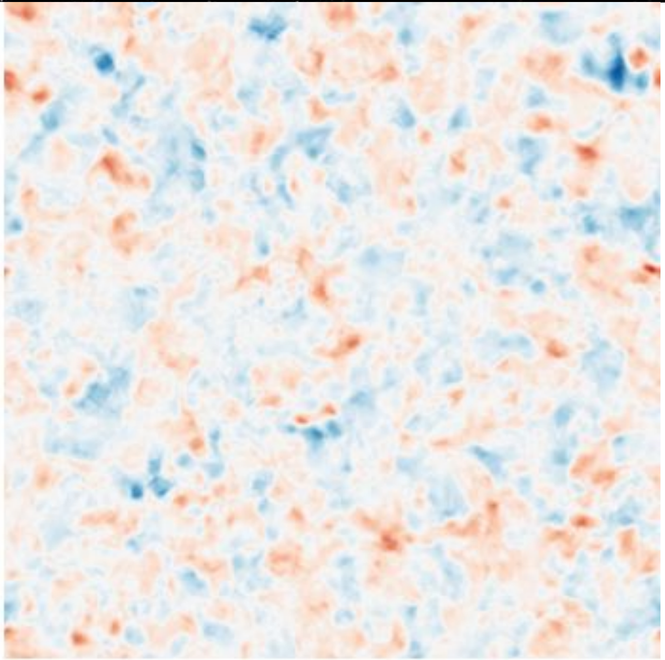
Image Credit: Guzman

Lensed CMB Polarization



Lensed E



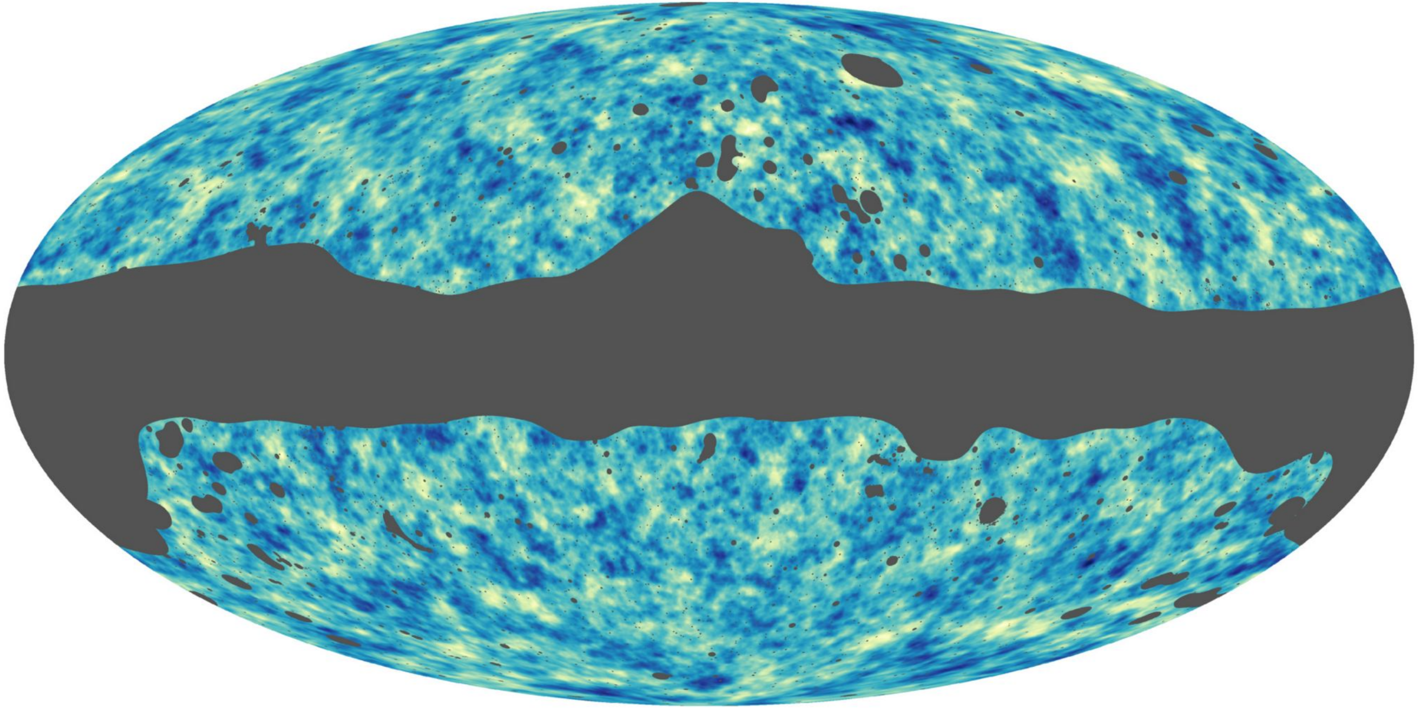


Lensed B

5°✕5° simulated maps

Image Credit: Guzman

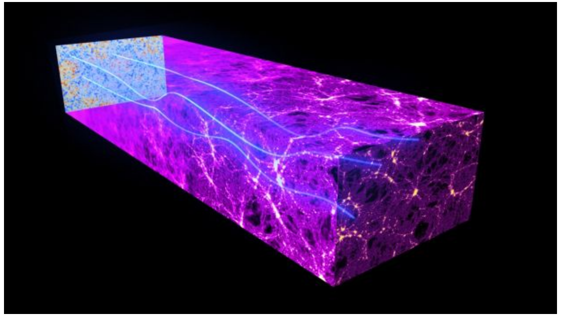
CMB Lensing Reconstruction



40σ observation

Planck (2018)

CMB Lensing is a Blessing and a Curse



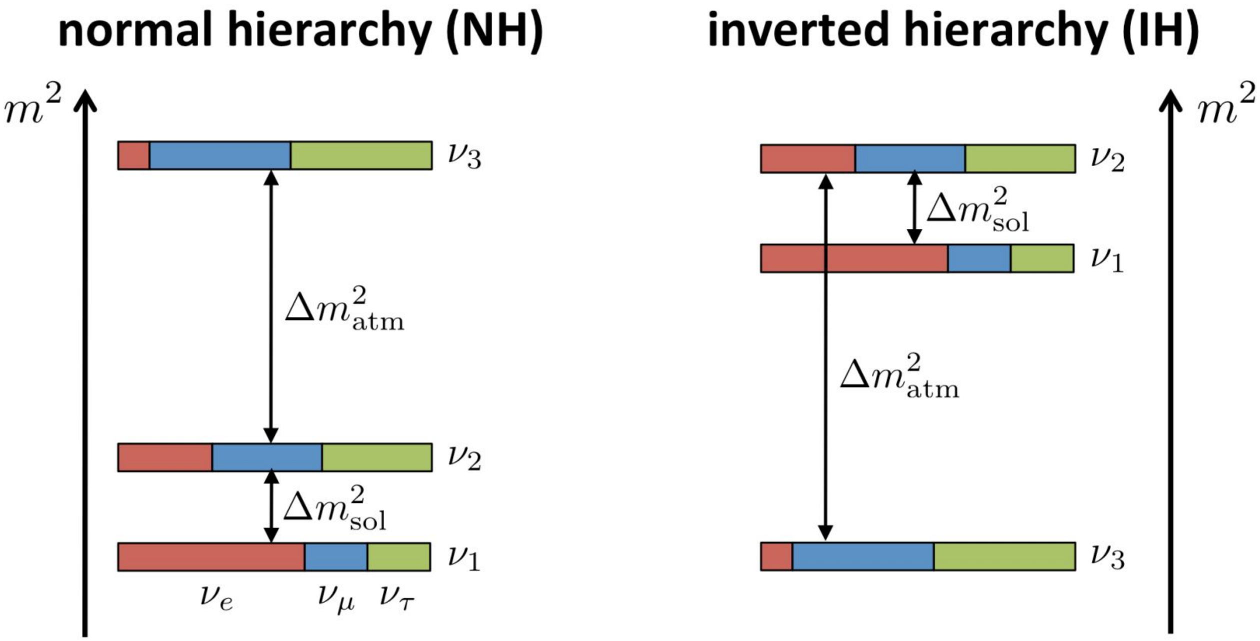
CMB lensing field is sensitive to growth of cosmological structure

Lensing distortion hinders pristine view of CMB last scattering surface

Image Credit: Planck / ESA

Cosmic Neutrinos

Massive Cosmic Neutrinos



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

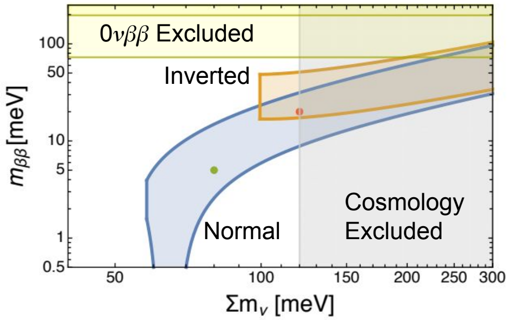
Cosmology is sensitive to the gravitational effects of the cosmic neutrino background, allowing a measurement of a sum of neutrino masses

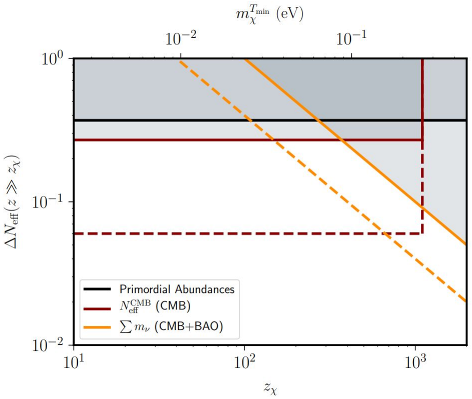
Current Planck 2018 constraint:

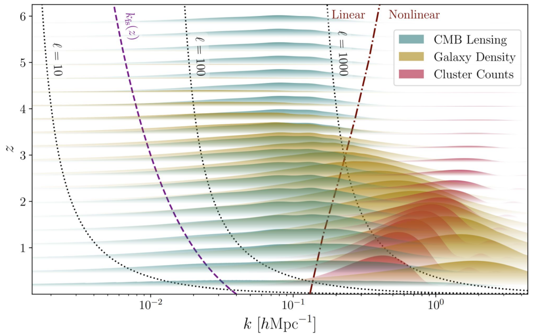
$$\sum m_\nu < 120\ \text{meV (95\% CL)}$$

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

Value of Cosmological Neutrino Mass Measurement







Particle Physics

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

Cosmology

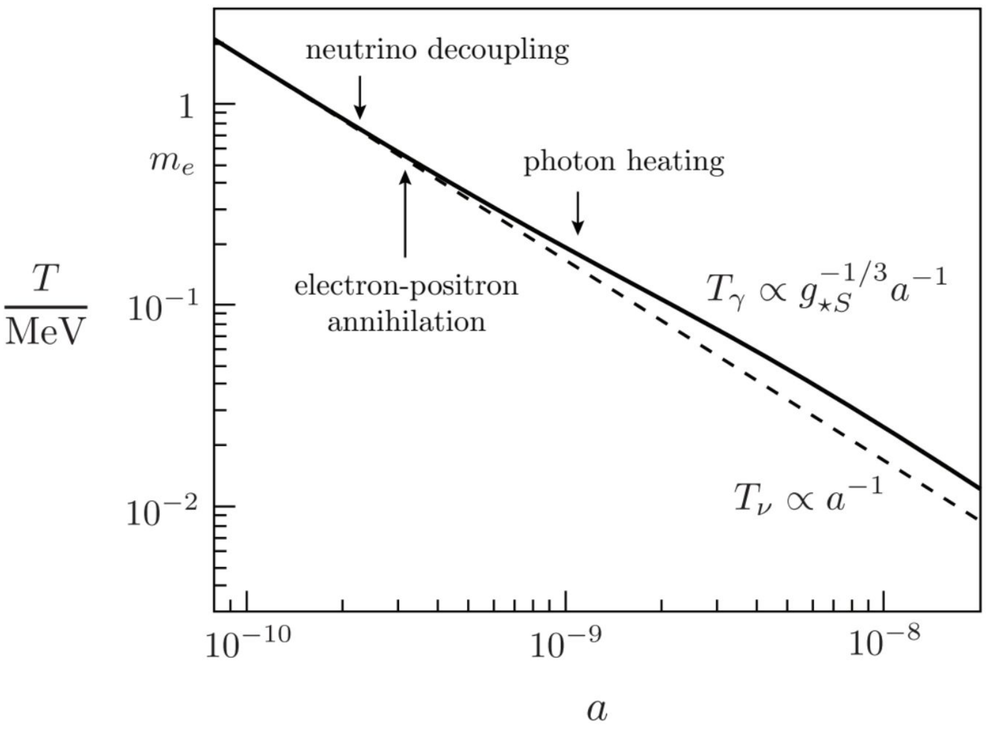
- Provides end-to-end test of cosmic history and is sensitive to new massive species (including gravitinos)

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)

Cosmic Neutrino Background



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

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

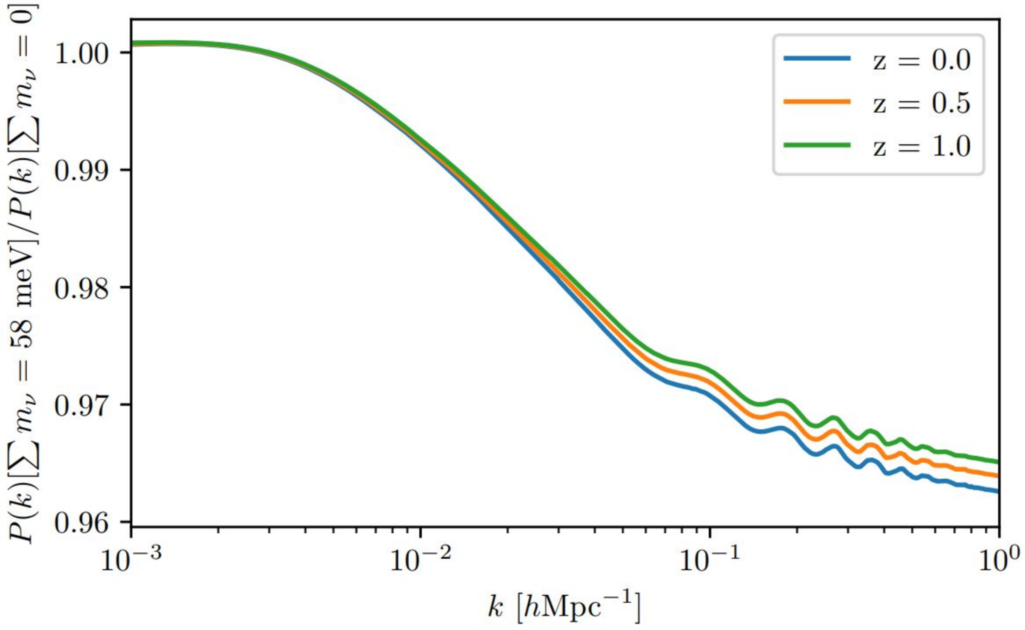
Cosmic neutrino background properties today:

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

Cosmic neutrino background provides an abundance of non-relativistic neutrinos

Image Credit: Baumann

Massive Neutrinos Suppress Matter Clustering



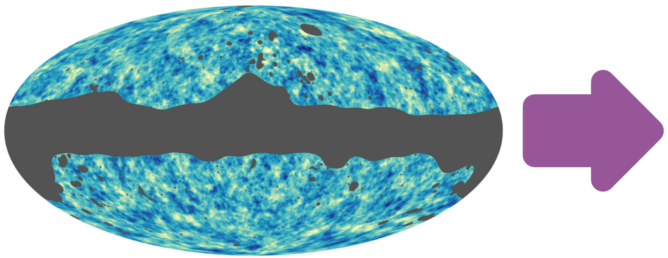
Suppression of matter clustering due to massive neutrinos
(A_s, $\Omega_m h^2$, $\Omega_b h^2$, H_0 fixed)

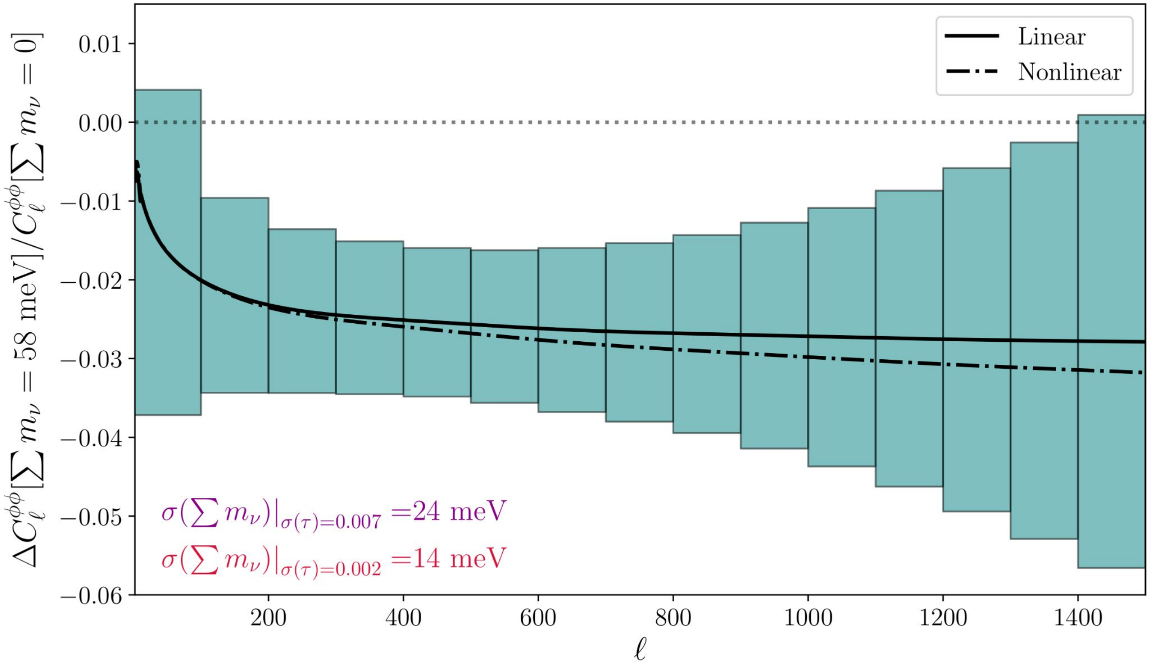
The large velocities of cosmic neutrinos causes them to free stream out of potential wells and suppress the growth of structure on scales smaller than their free-streaming length

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

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

Neutrino Mass with CMB Lensing





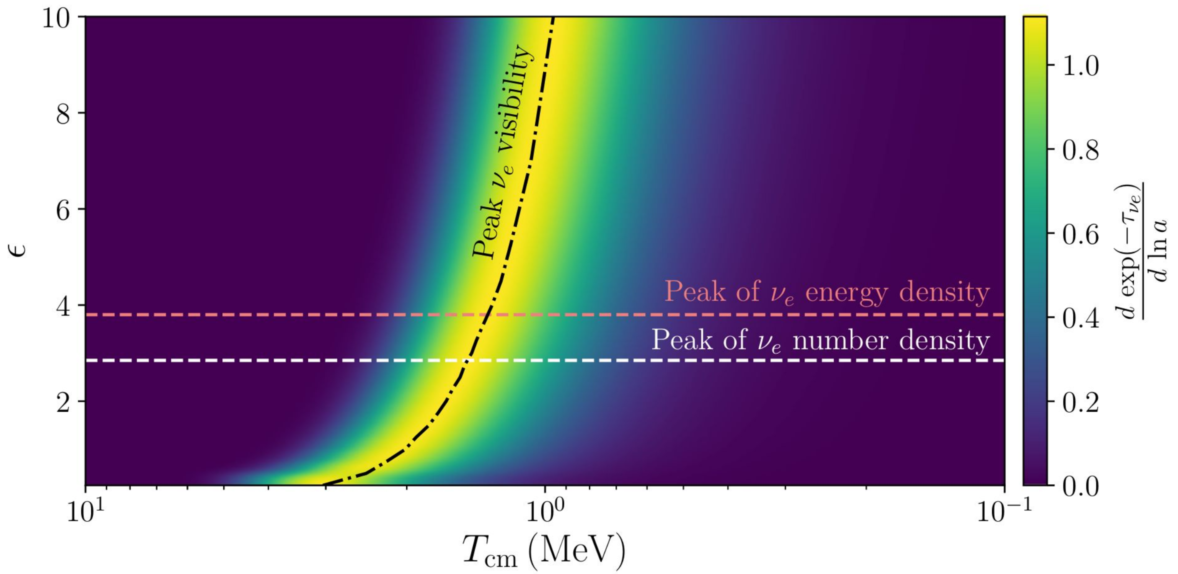
Measuring suppression of clustering with CMB-S4 lensing

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

Light Relics

Cosmic Neutrinos as Standard Model Light Relics

Neutrino Differential Visibility



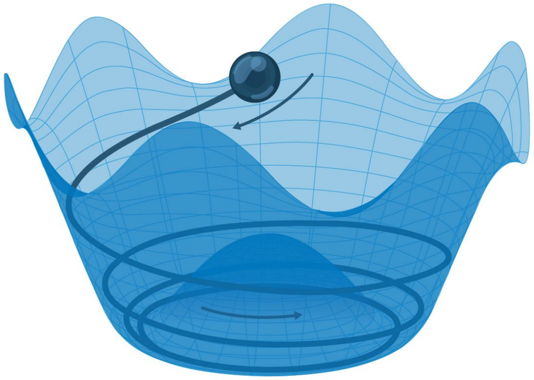
The energy density of the cosmic neutrino background can be calculated precisely, including the effects of non-instantaneous weak decoupling

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

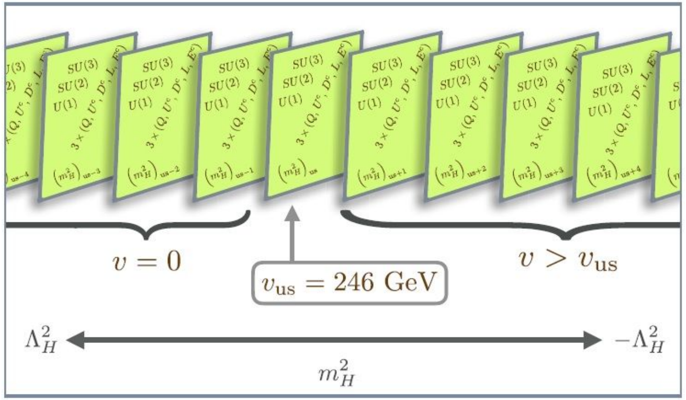
$$N_{\rm eff}^{\rm SM} = 3.044(1)$$

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

New Light Species are Ubiquitous in Standard Model Extensions



Axions and Axion-Like Particles



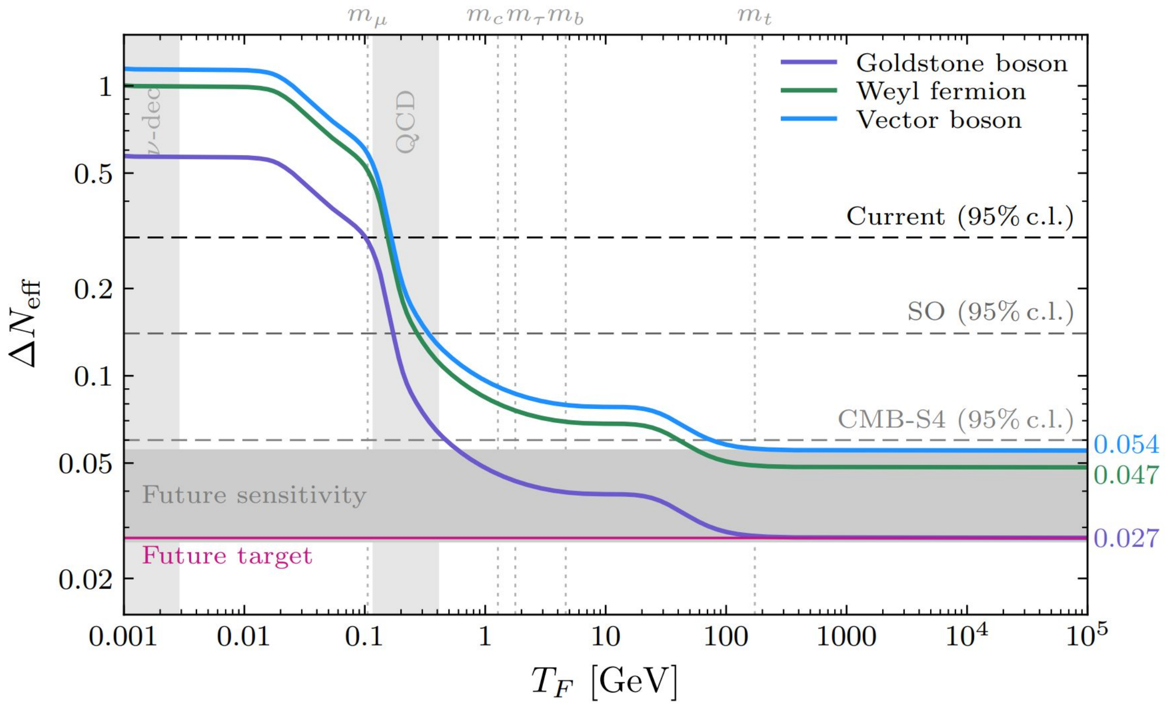
Complex Dark Sectors

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



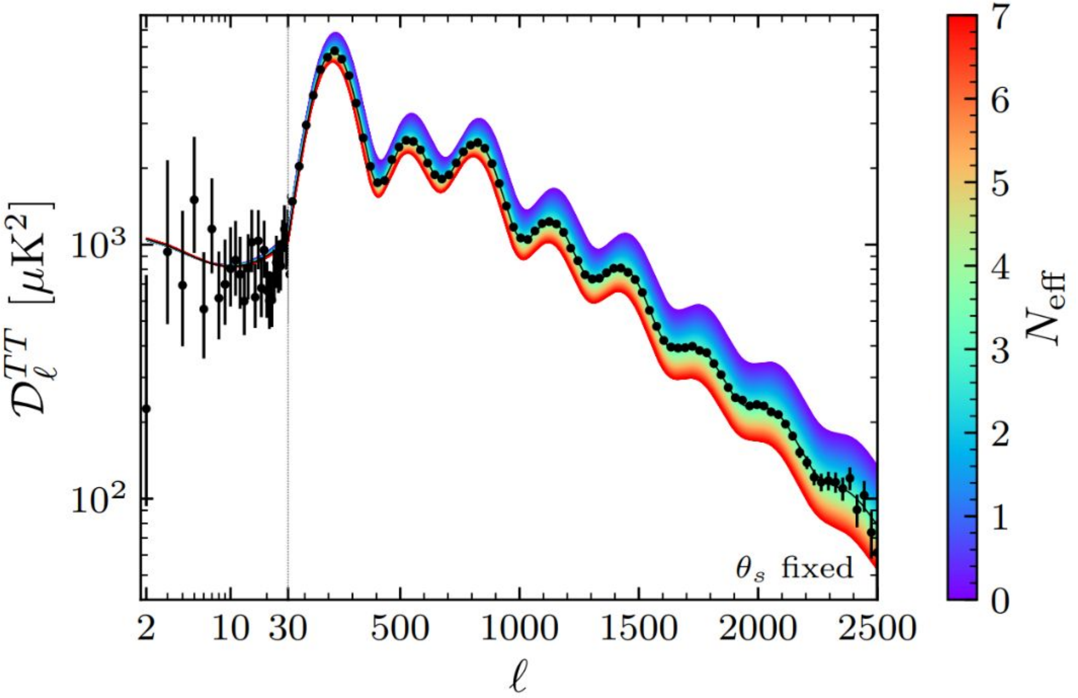
The relic density of any new light species that was ever in thermal equilibrium with the Standard Model plasma can be computed from its spin and decoupling temperature, setting clear targets for future surveys

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)

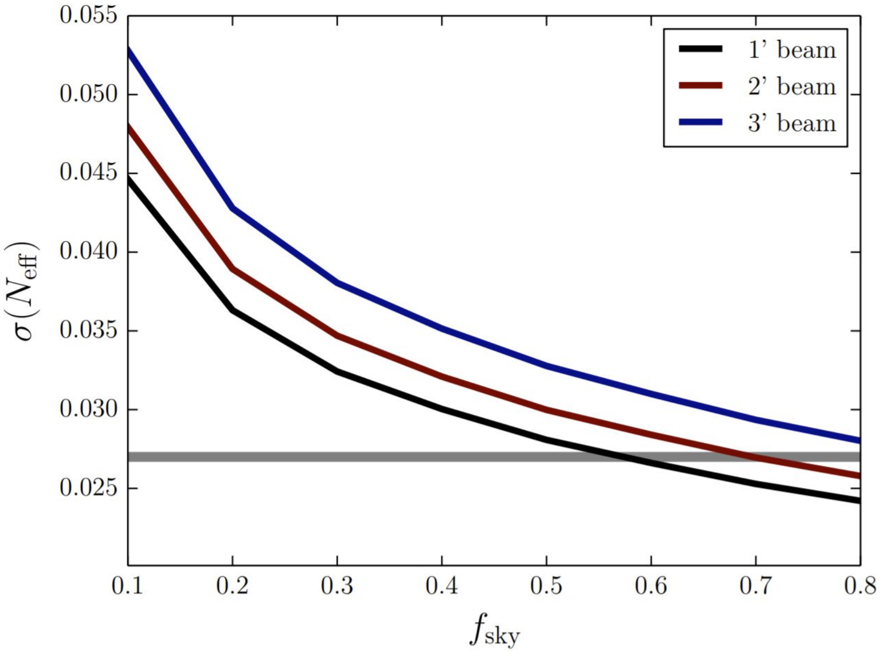
Light Relics Affect CMB Damping Scale



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

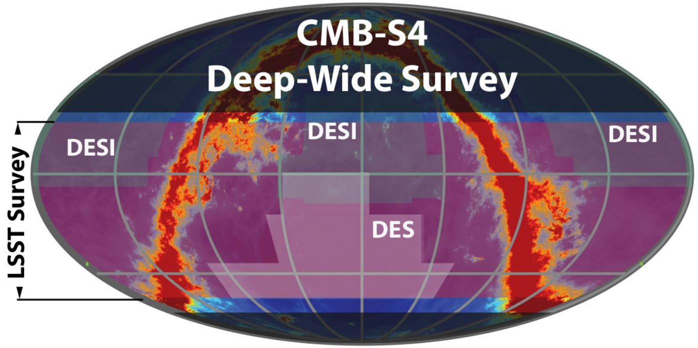
Image Credit: Wallisch (2018)

Light Relics Measurements Favor Wide Surveys

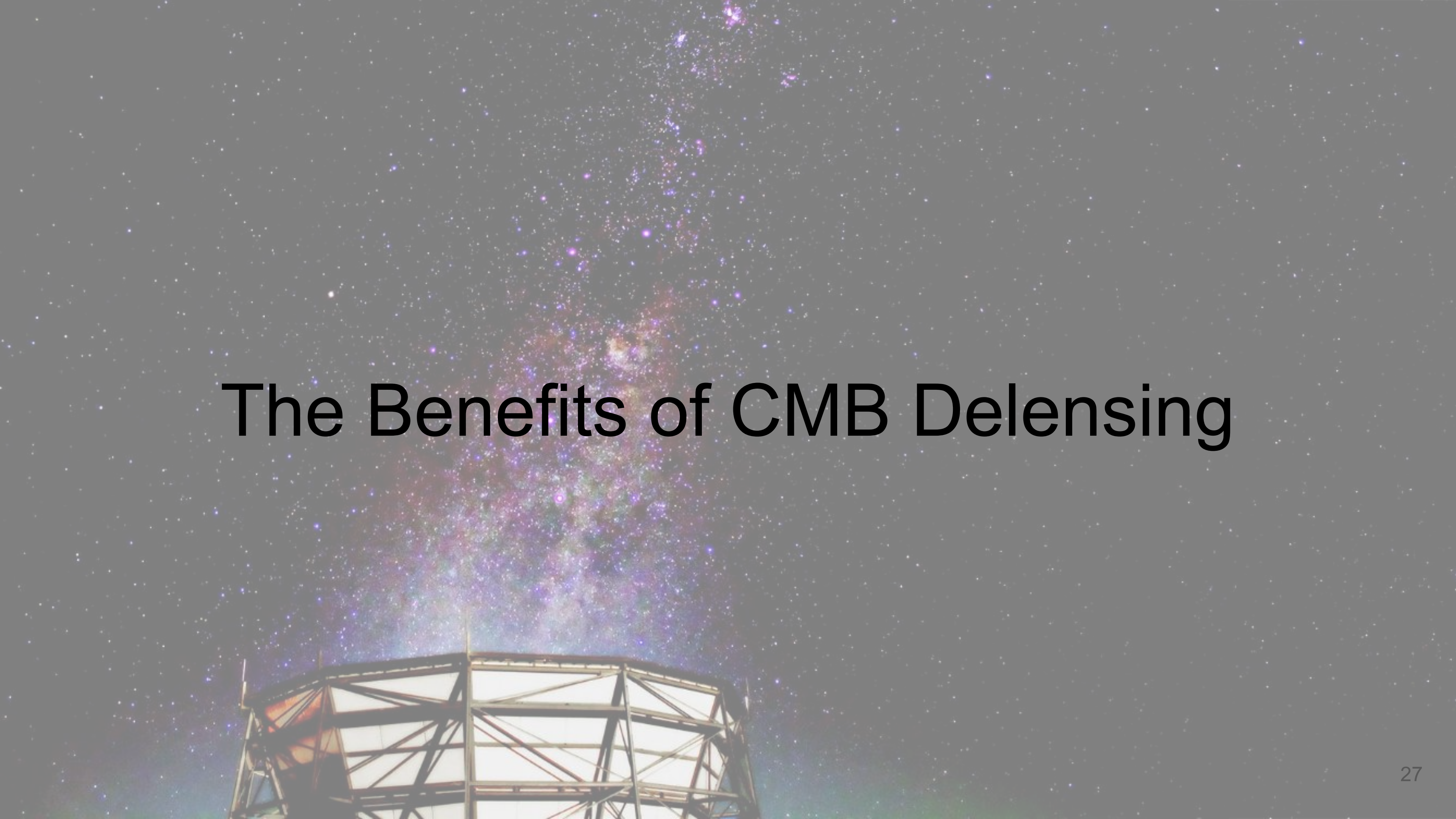


Forecasted errors at fixed effort, normalized to 1μK-arcmin at f_{sky}=0.4

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

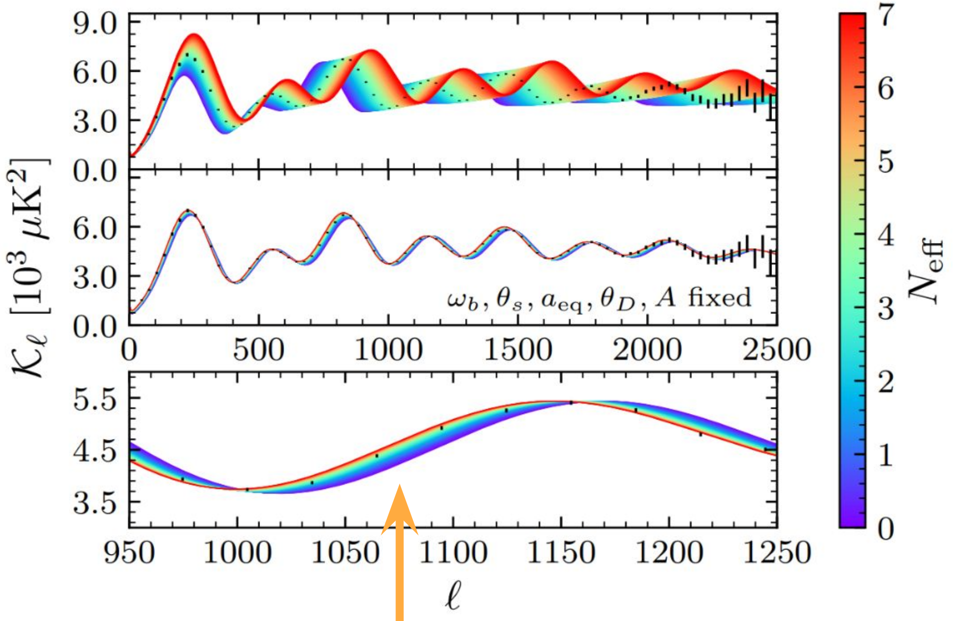


CMB-S4 (2016); CMB-S4 (2019)



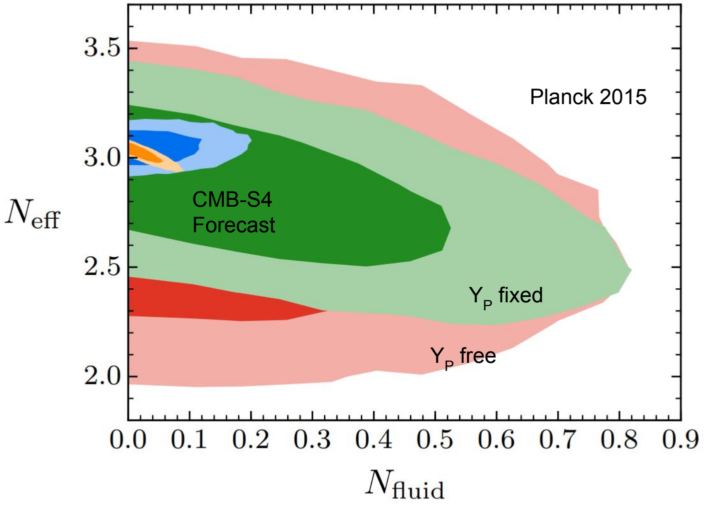
The Benefits of CMB Delensing

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



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

Gravitational Lensing Smooths Acoustic Peaks

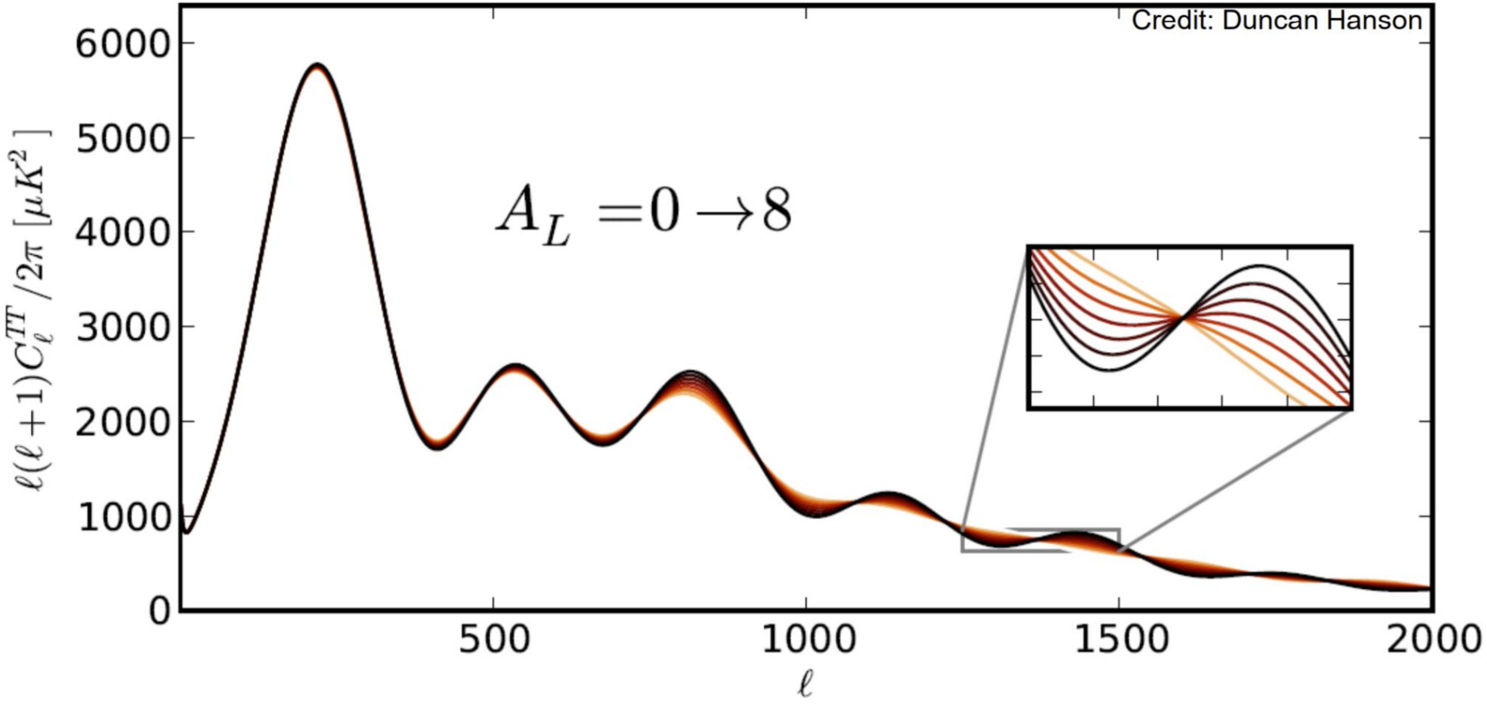
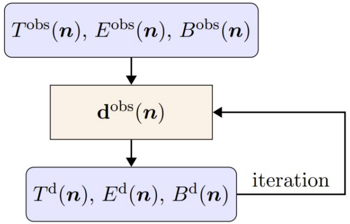
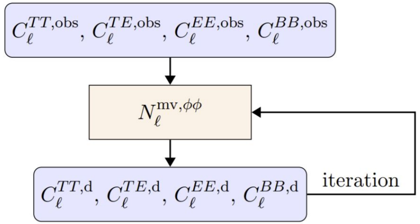


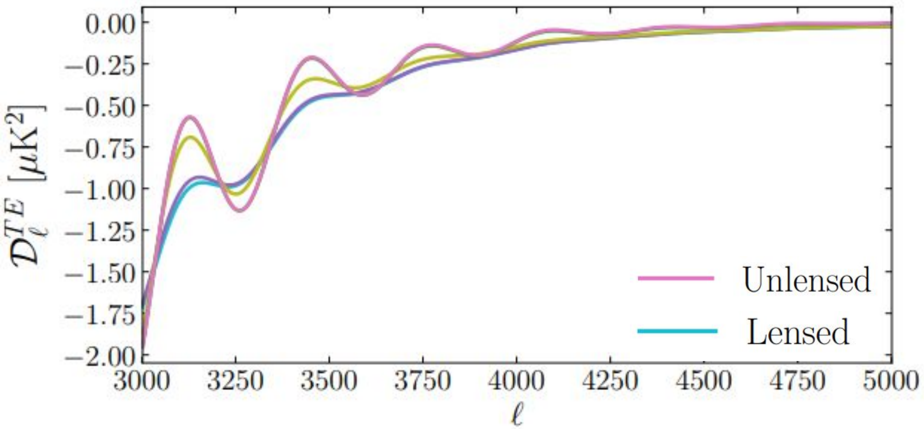
Image Credit: Hanson

CMB Delensing

- The reconstructed lensing map can be used to reverse lensing effects on the CMB
- We showed that delensing is valuable for temperature and E modes as well as for B modes, and we developed a technique to self-consistently forecast iterative delensing of all CMB spectra



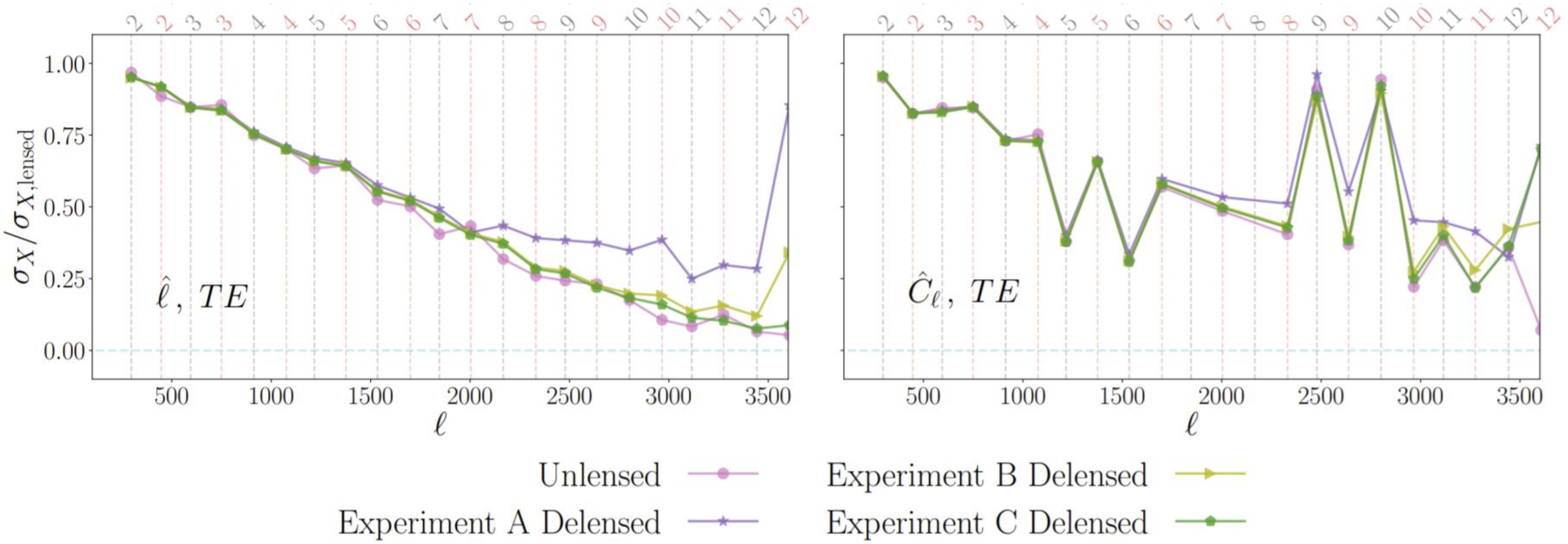




Label	Δ_T (μK-arcmin)	$\theta_{\rm FWHM}$ (arcmin)	Color
Experiment A	5	1.4	Purple
Experiment B	1	1.4	Yellow
Experiment C	0.1	0.1	Green

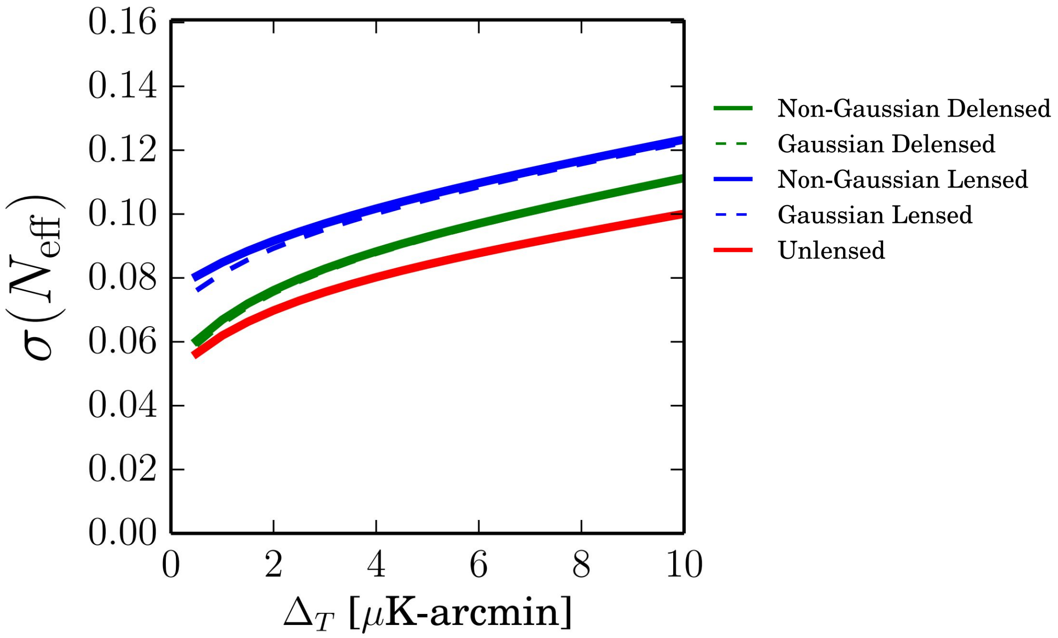
Green, JM, van Engelen (2016); Hotinli, JM, Trendafilova, Green, van Engelen (2022)

Sharper Delensed Peaks Can Be Better Localized



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

Delensing Enables Tighter Parameter Constraints



- Delensing improves the constraining power for parameters that impact primary spectra, and in particular enhances our ability to measure the light relic density
- Delensing also improves constraints on primordial isocurvature and primordial non-Gaussianity

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

The Broad Value of Delensing

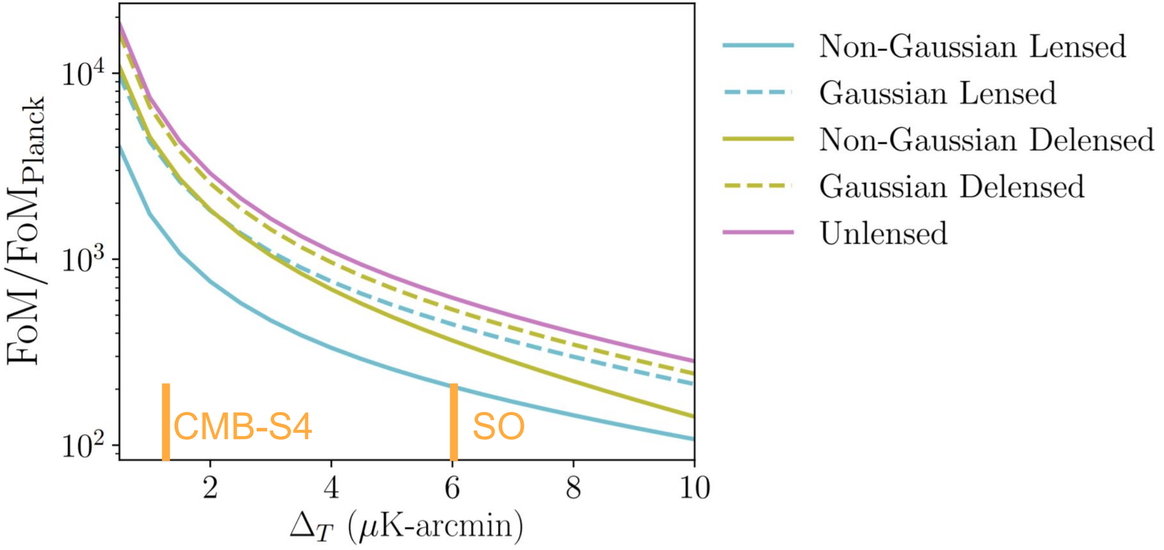


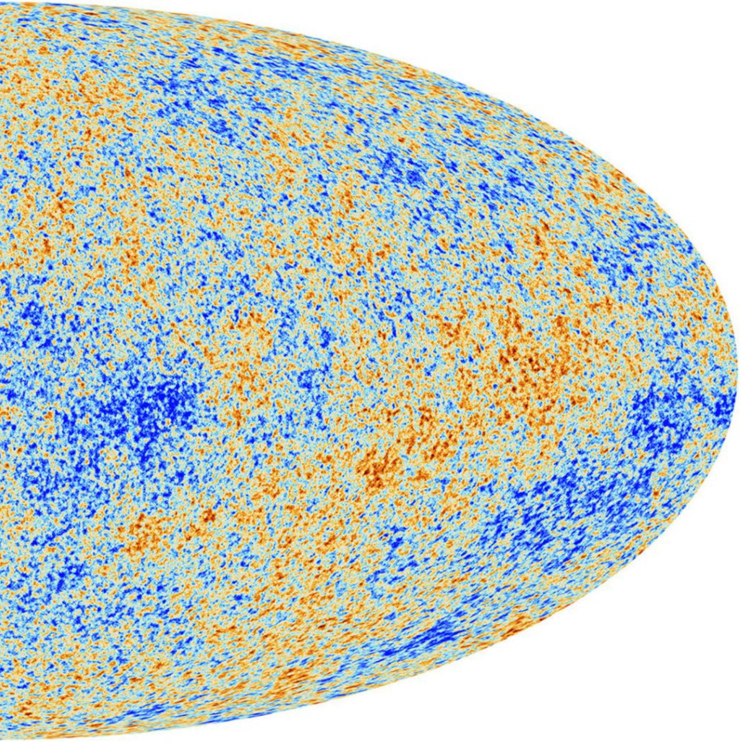
Figure of Merit (FoM) for ΛCDM compared to Planck

- Delensing holds broad benefit for improving CMB constraining power and can be achieved with data that will already be collected
- Delensing also reduces variance when reconstructing secondary anisotropies (including lensing itself)

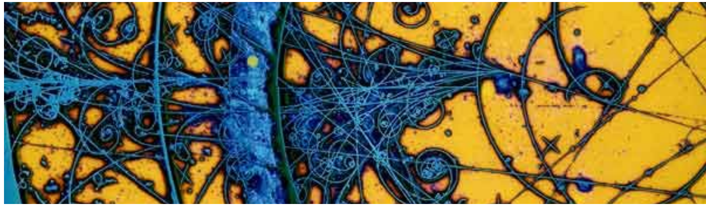
Green, JM, van Engelen (2016); Hotinli, JM, Trendafilova, Green, van Engelen (2022)

Conclusion

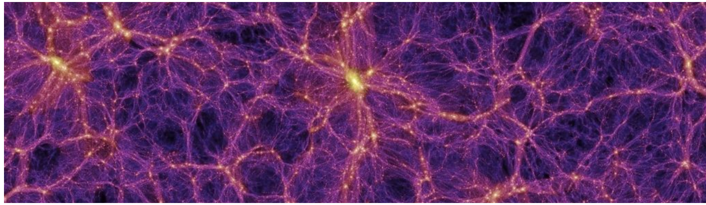
Conclusion



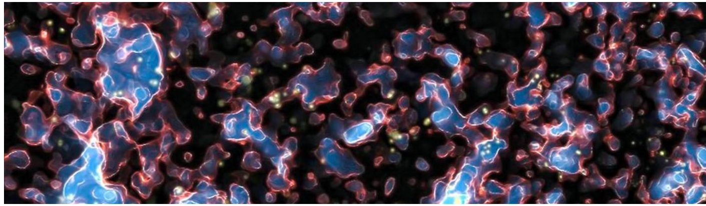
New Targets
and
New Tools



Particle Physics

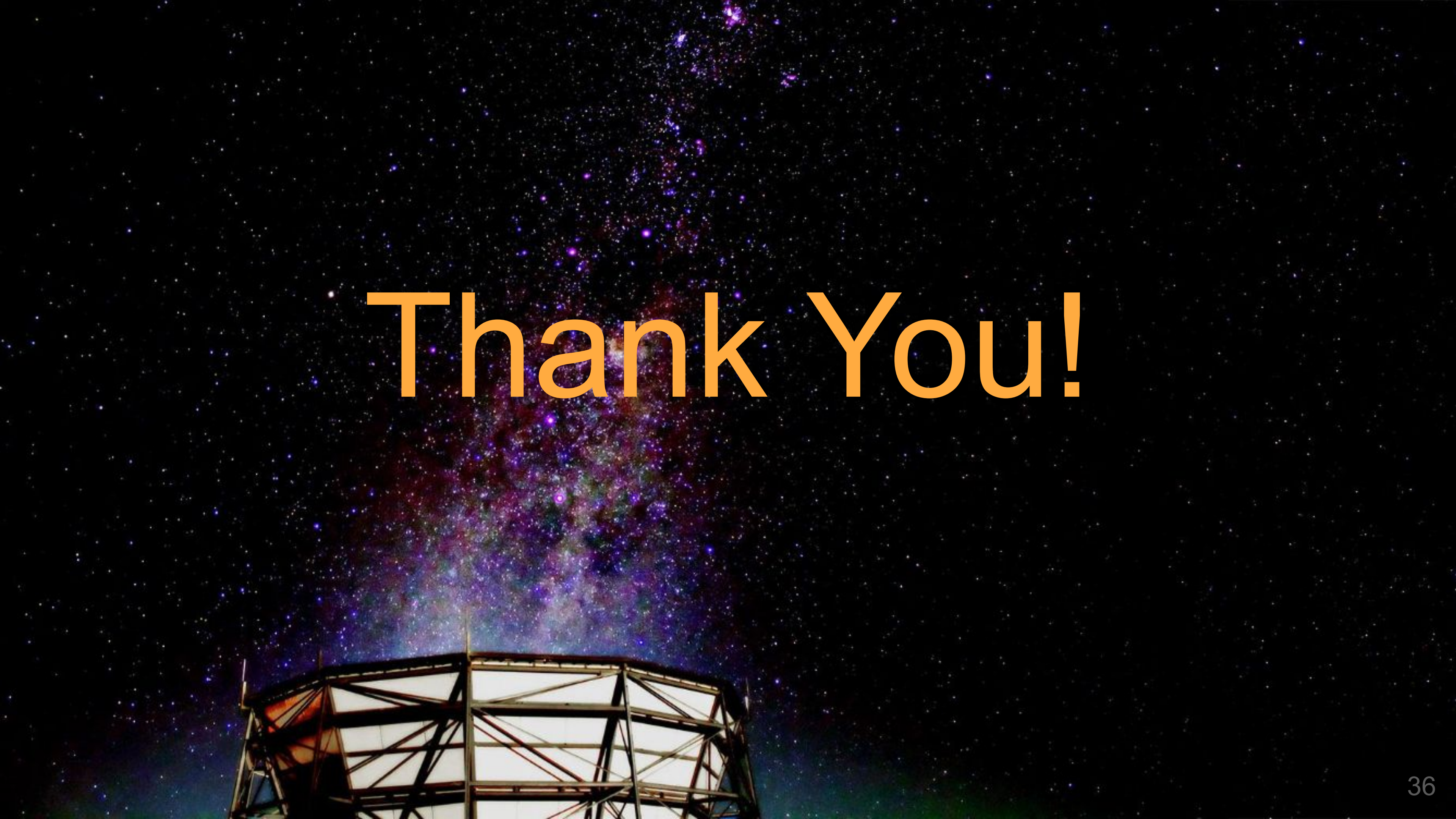


Cosmology



Astrophysics

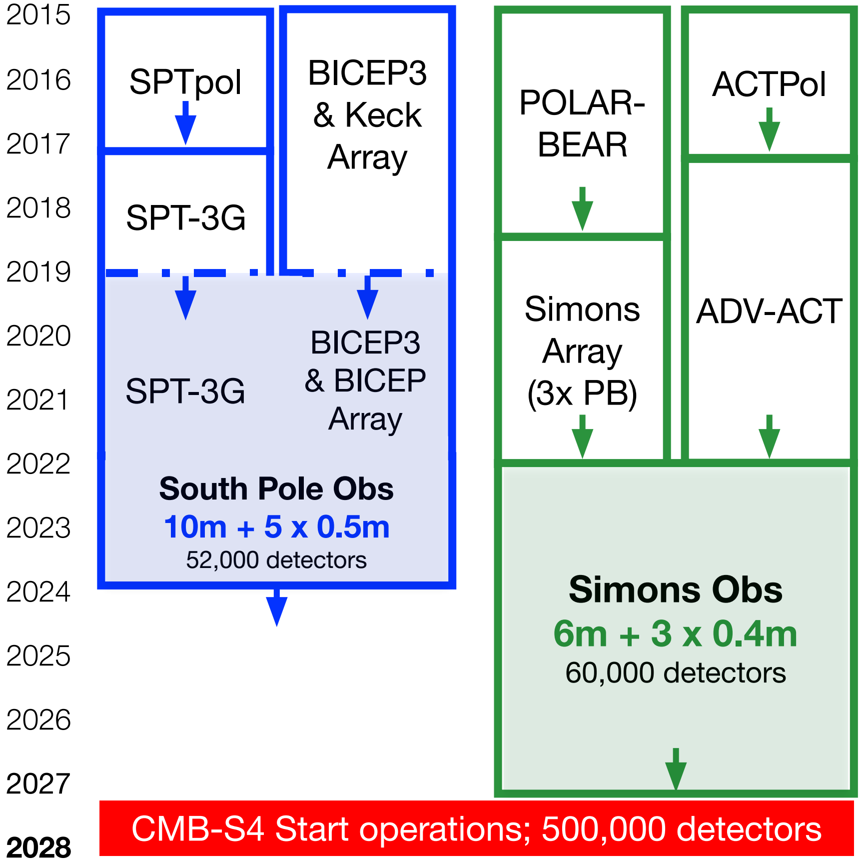
Image Credits: Planck; BEBC/CERN; Springel, et al; Alvarez, Kaehler, Abel



Thank You!

Backup Slides

Evolution of Ground-Based CMB Surveys

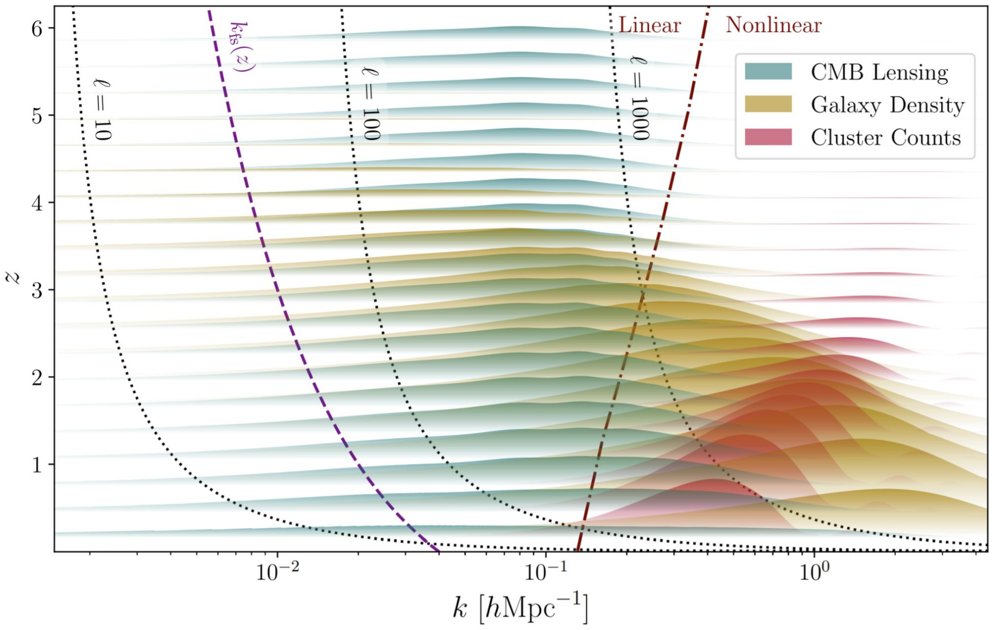


Science-driven expansion of capabilities + cost-driven consolidation of teams

- Late 2010s:
  - single-site, single resolution
  - O(10K) detectors
  - ACT, BICEP/Keck, POLARBEAR, SPT, etc
- Early 2020s:
  - single-site, dual-resolution
  - O(50K) detectors
  - Simons Observatory (SO), South Pole Observatory (SPO)
- Late 2020s:
  - dual-site, dual-resolution
  - O(500K) detectors
  - CMB-S4

Slide Credit: CMB-S4

Measuring Clustering with Cosmological Surveys

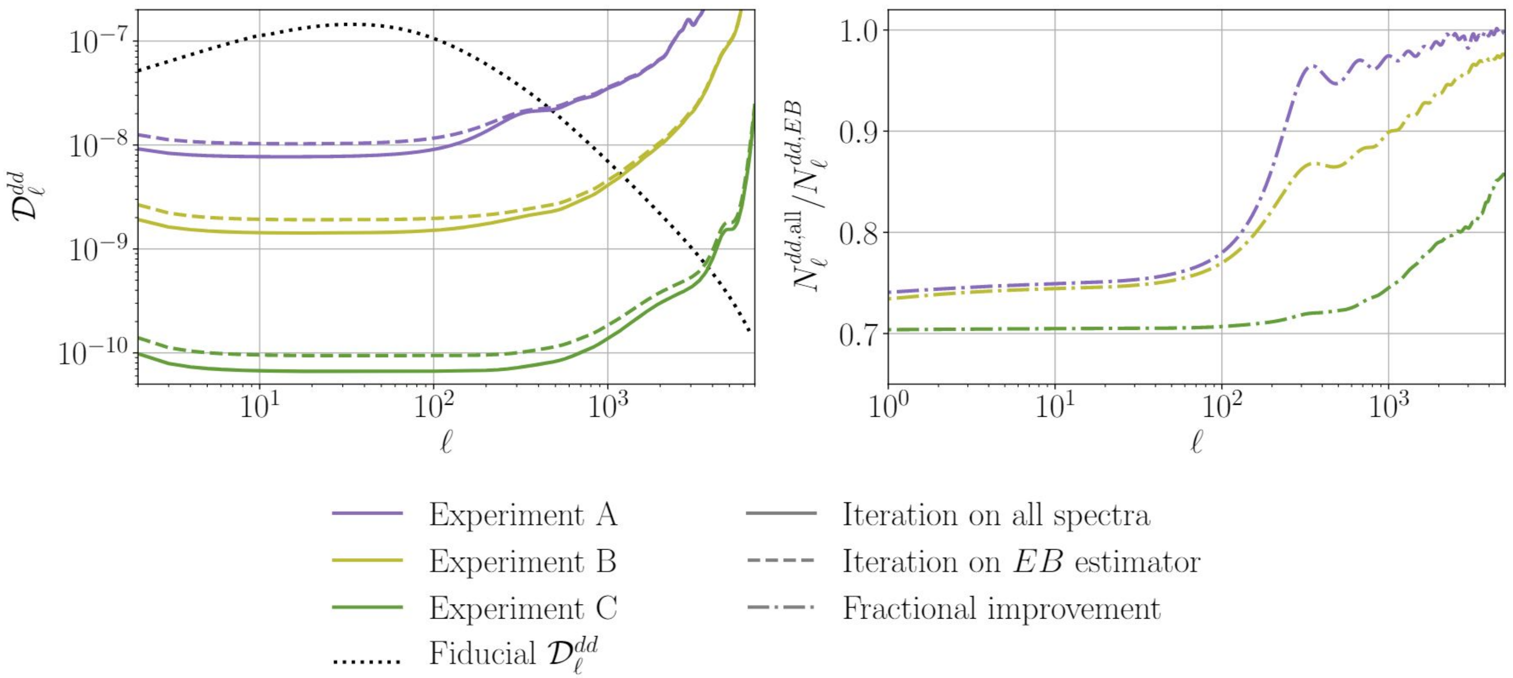


Sensitivity regimes of various probes of clustering

- 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

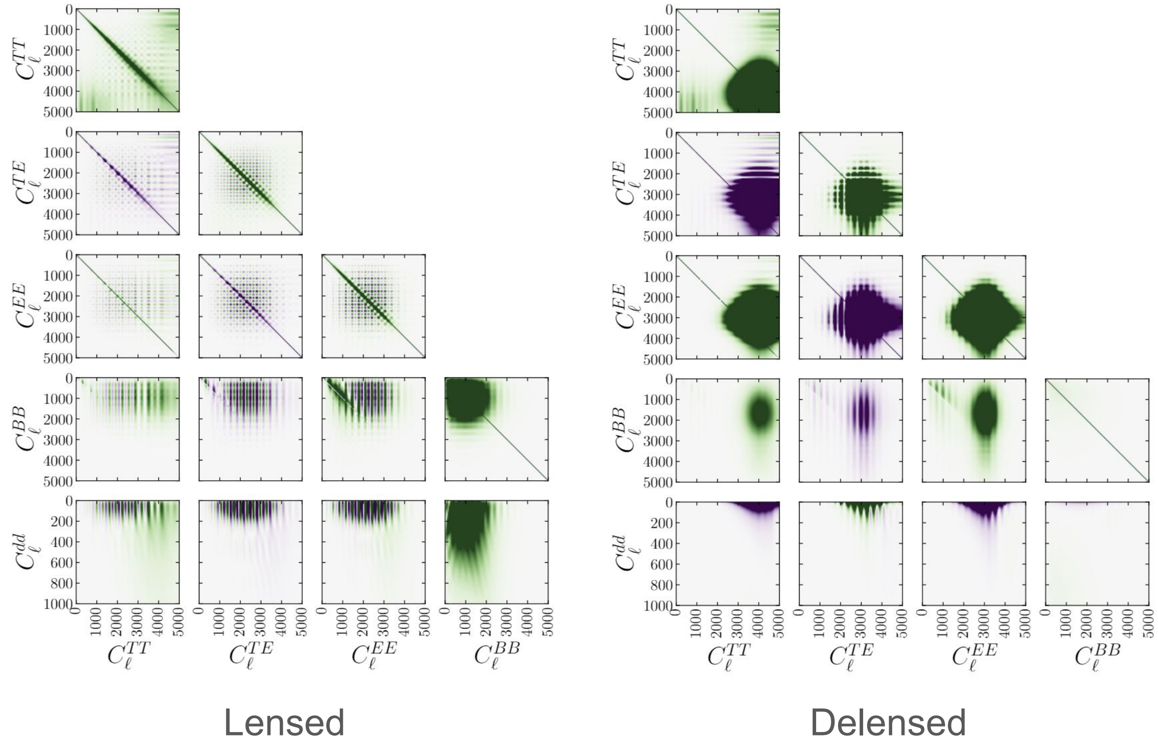
Green, JM (2021)

Delensing Improves Lensing Reconstruction



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

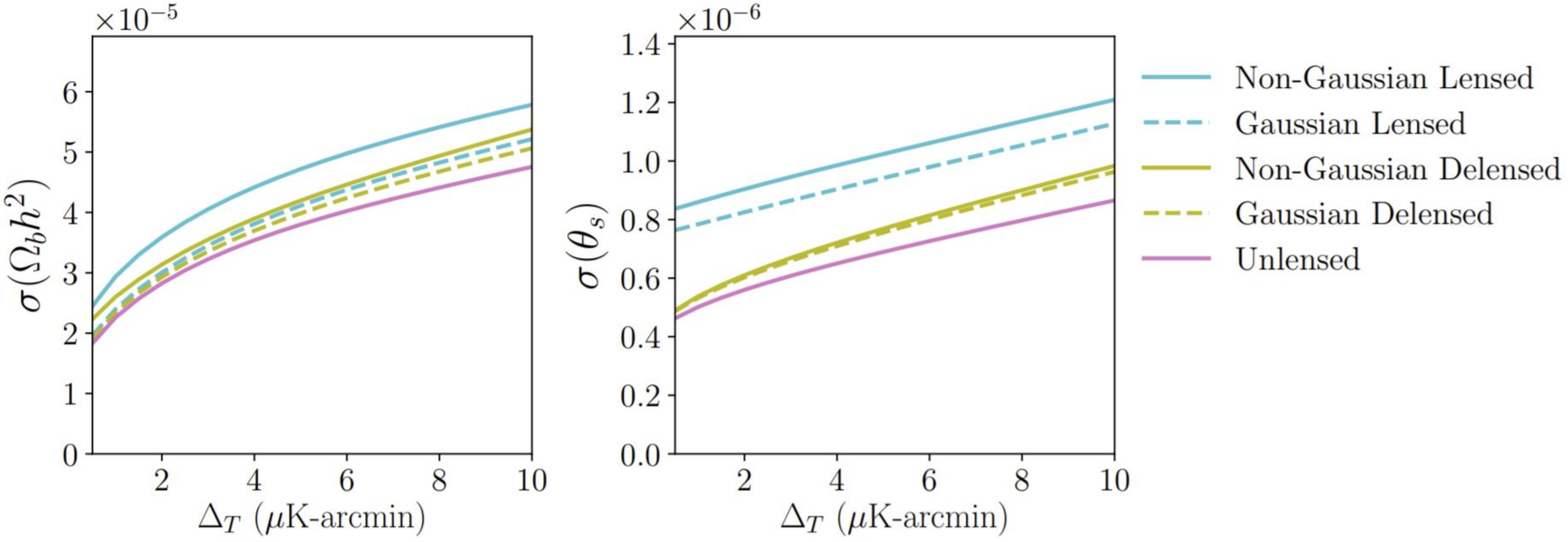
Delensing Reduces Non-Gaussian Covariance



Delensing reduces off-diagonal power spectrum covariance for well-measured modes

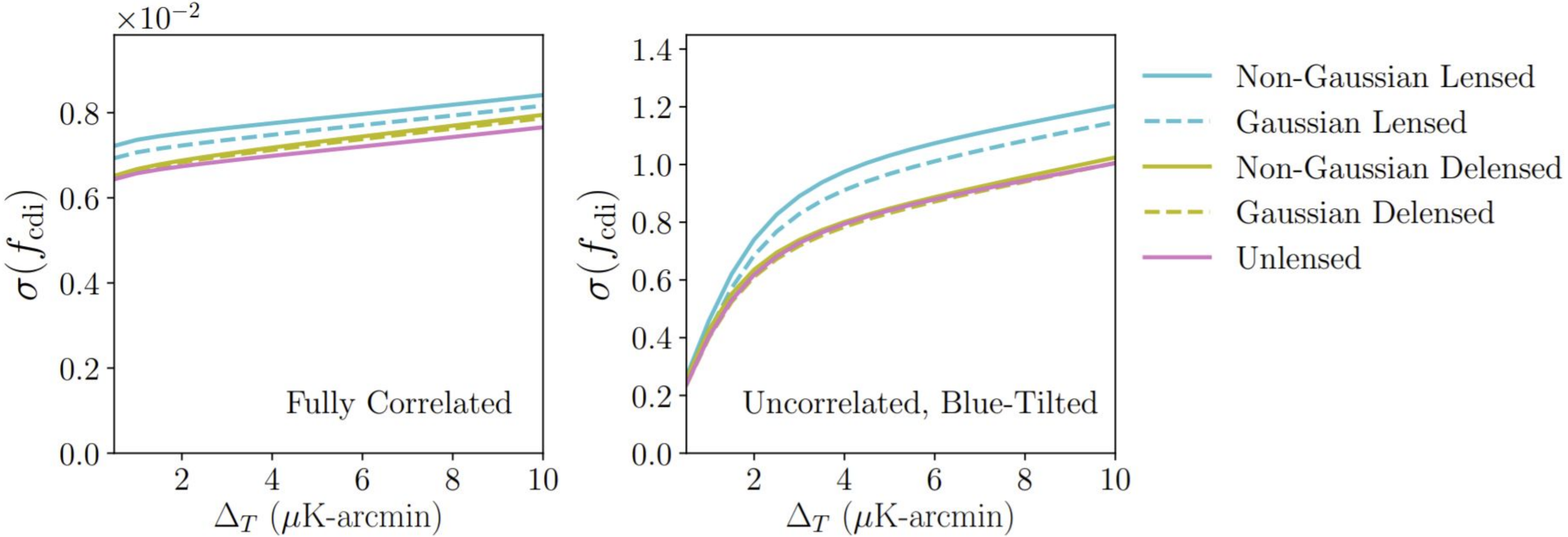
Green, JM, van Engelen (2016); Hotinli, JM, Trendafilova, Green, van Engelen (2022)

Delensing Improves Constraints on ΛCDM Parameters



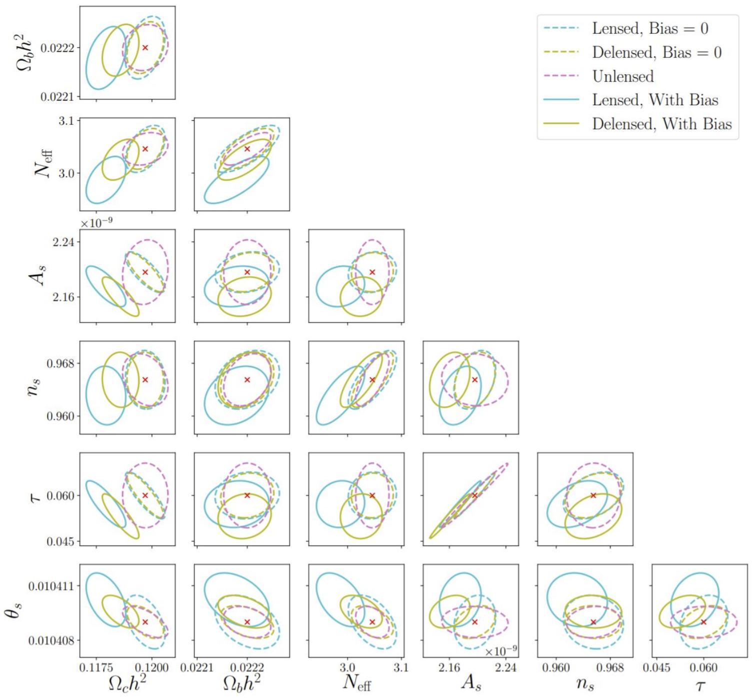
Green, JM, van Engelen (2016); Hotinli, JM, Trendafilova, Green, van Engelen (2022)

Delensing Improves Constraints on Isocurvature



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

Delensing Mitigates Bias from Mis-modeled Lensing



- Non-linear structure growth, baryonic feedback, and physics beyond the Standard Model can lead to lensing spectra that differ from our expectations
- These mis-modeled lensing spectra can lead to biased parameter inferences if we try to forward-model lensing effects
- Delensing removes the realization of the lensing, thereby reducing our need to accurately model the spectrum

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