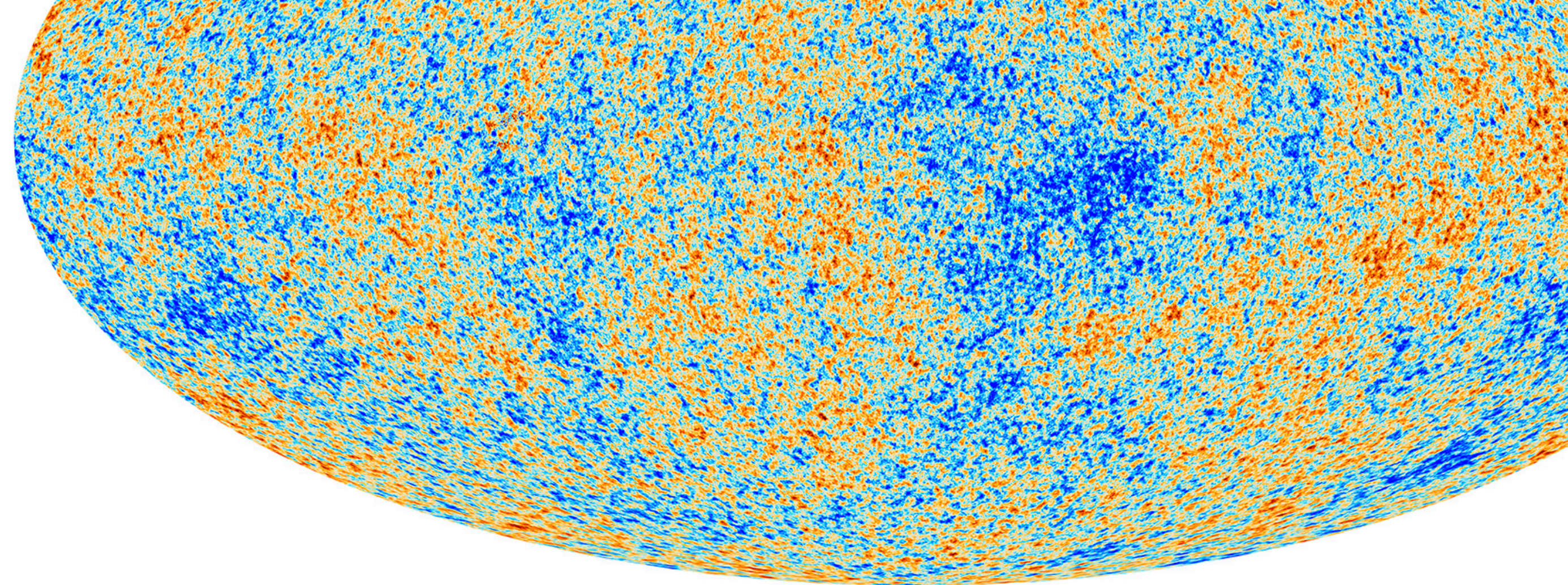




Prospects of CMB B-modes

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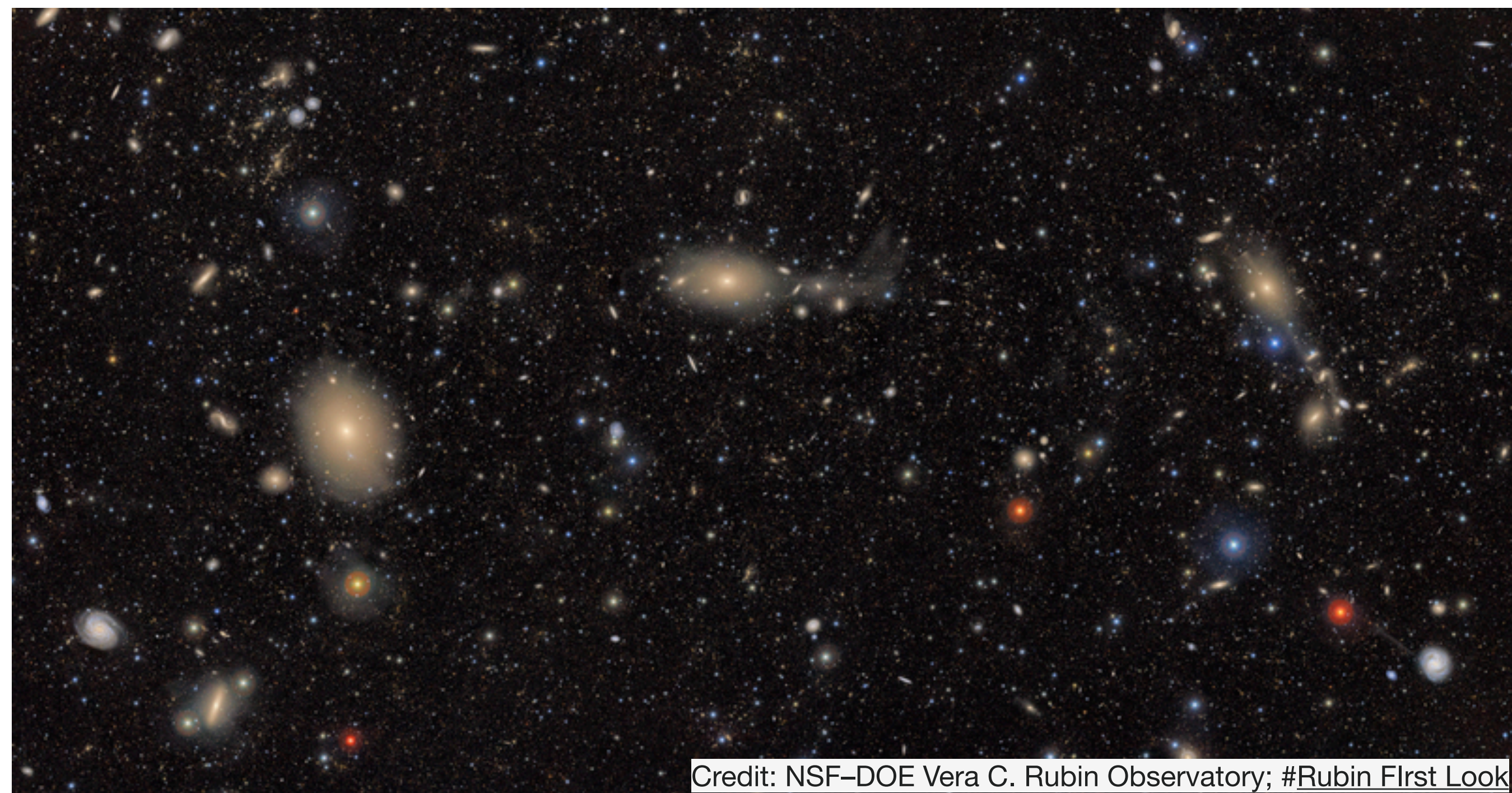
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In collaboration with:

David Parkinson, Kishan Deka, Pawel Bielewicz, Jacobo Asorey

December 17 , 2025

Saturnalia 2025, Facultad de Ciencias, Universidad de Zaragoza

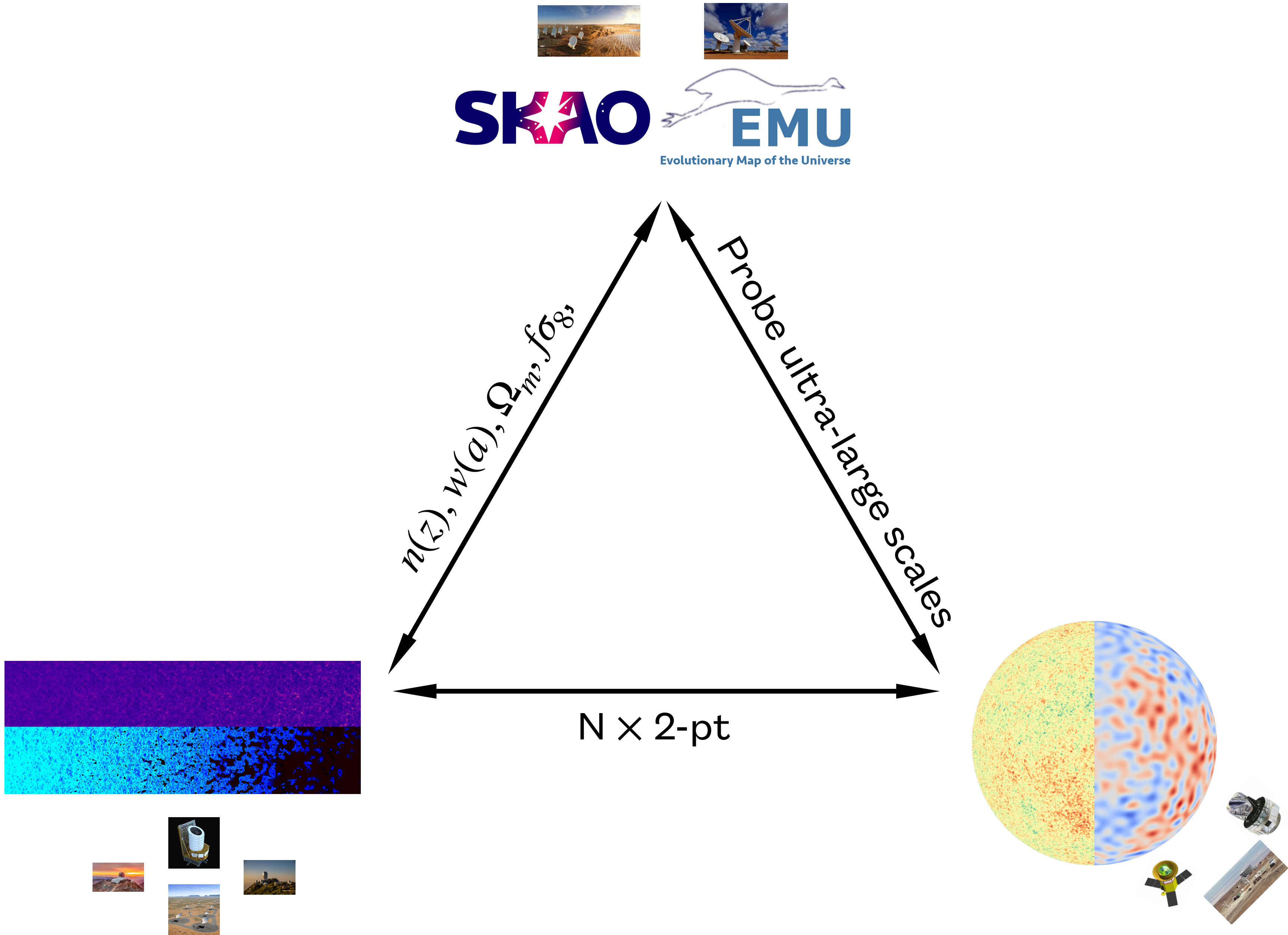


Credit: NSF-DOE Vera C. Rubin Observatory; #Rubin First Look

2023-



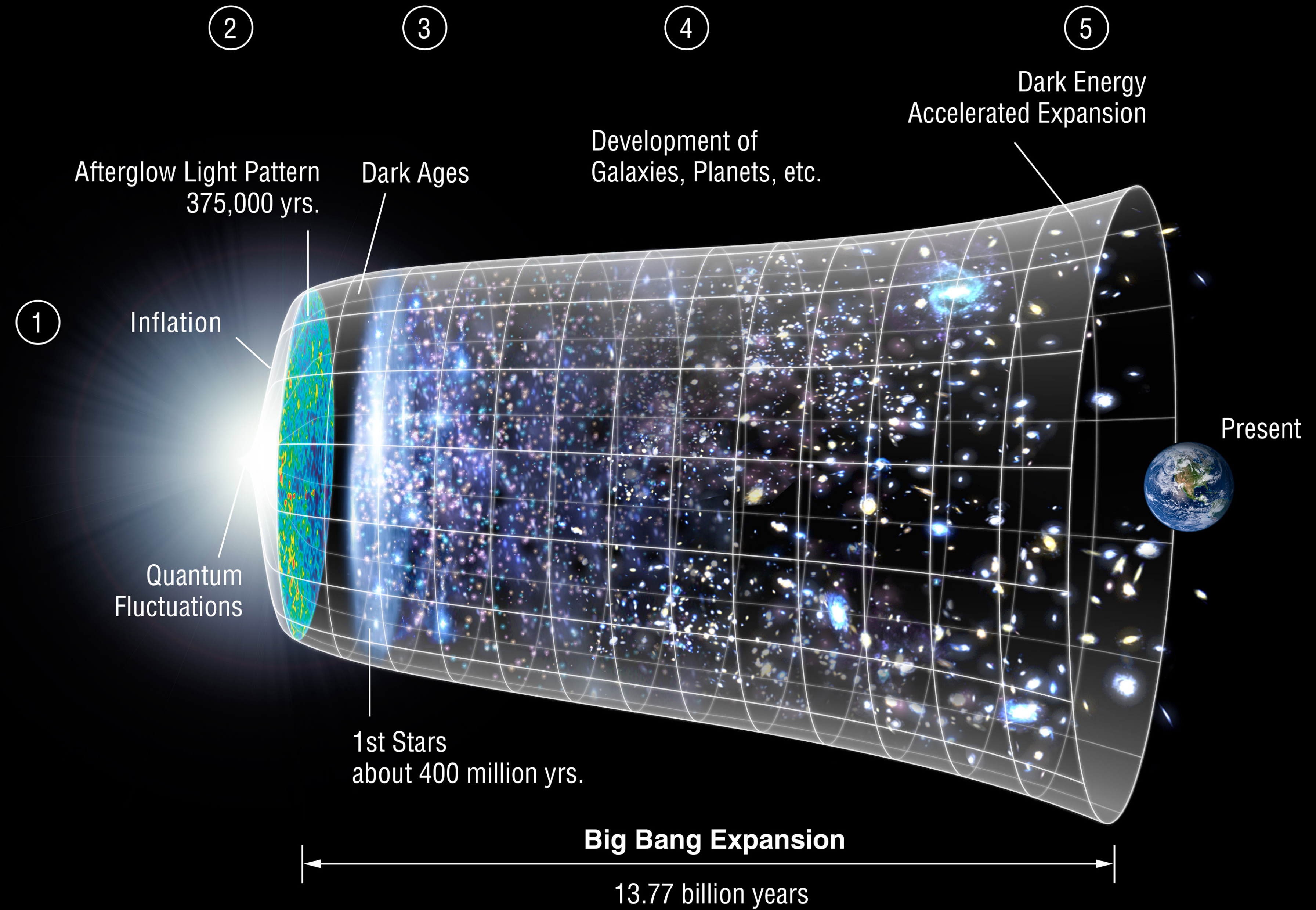
All I get paid for...



Research motivations

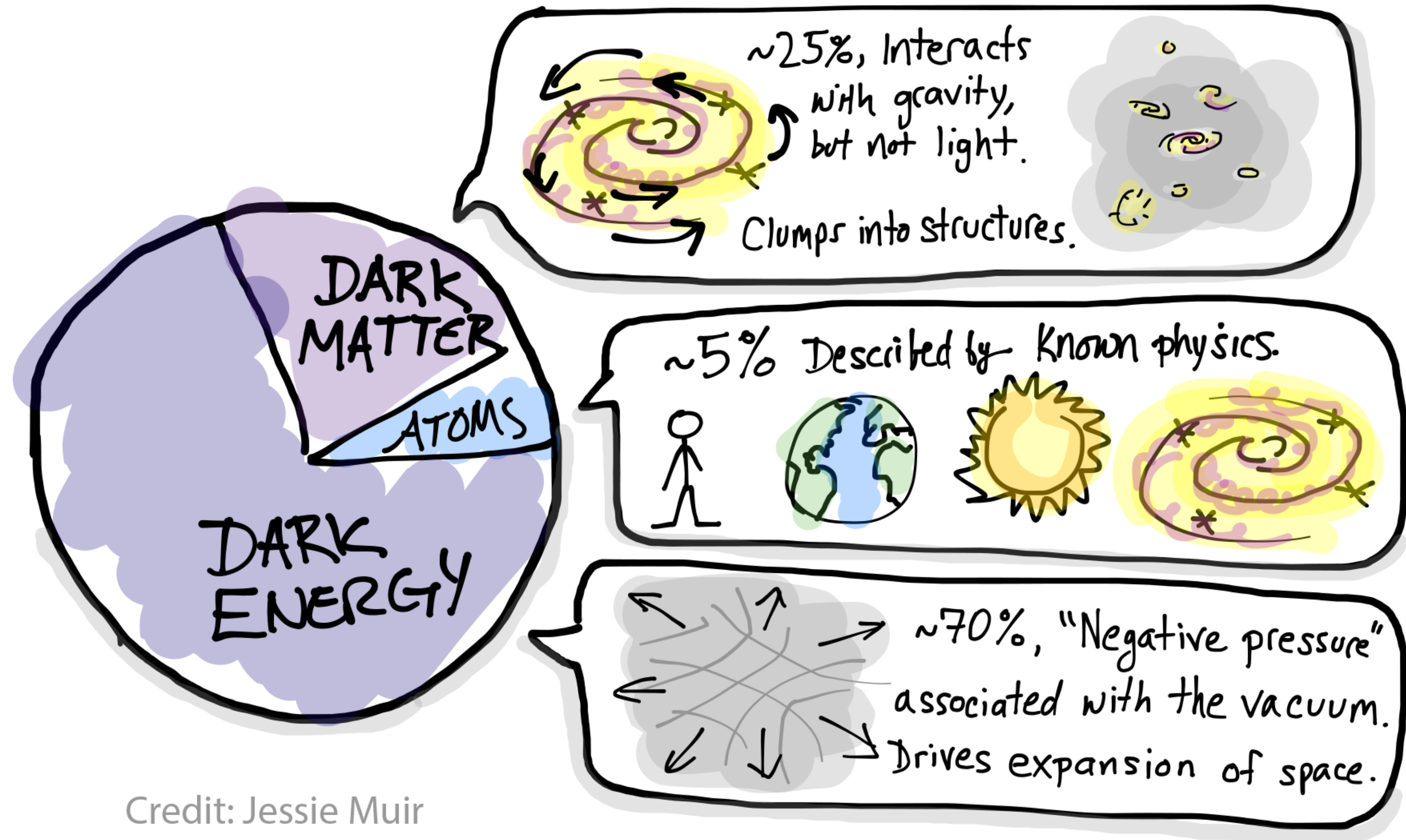
- Test cosmological models of the Universe with CMB and large scale structure tracers (galaxies, quasars, HI).
- Impact of different systematics on cosmological parameters with Monte Carlo simulations.
- New techniques for optimal analyses of cosmological datasets and uncertainty mitigation.
- Redshift space clustering of galaxies in standard perturbation theory.
- Detection of new observables like the moving lens effect.
- Early Universe cosmology with CMB (primordial non-Gaussianity, primordial B-modes)

Our Universe



Key ingredients of Universe

1. Dark Energy
2. Cold Dark Matter (CDM)
3. Baryonic matter
4. Neutrinos
5. Inflation
6. Homogeneity
7. Isotropy

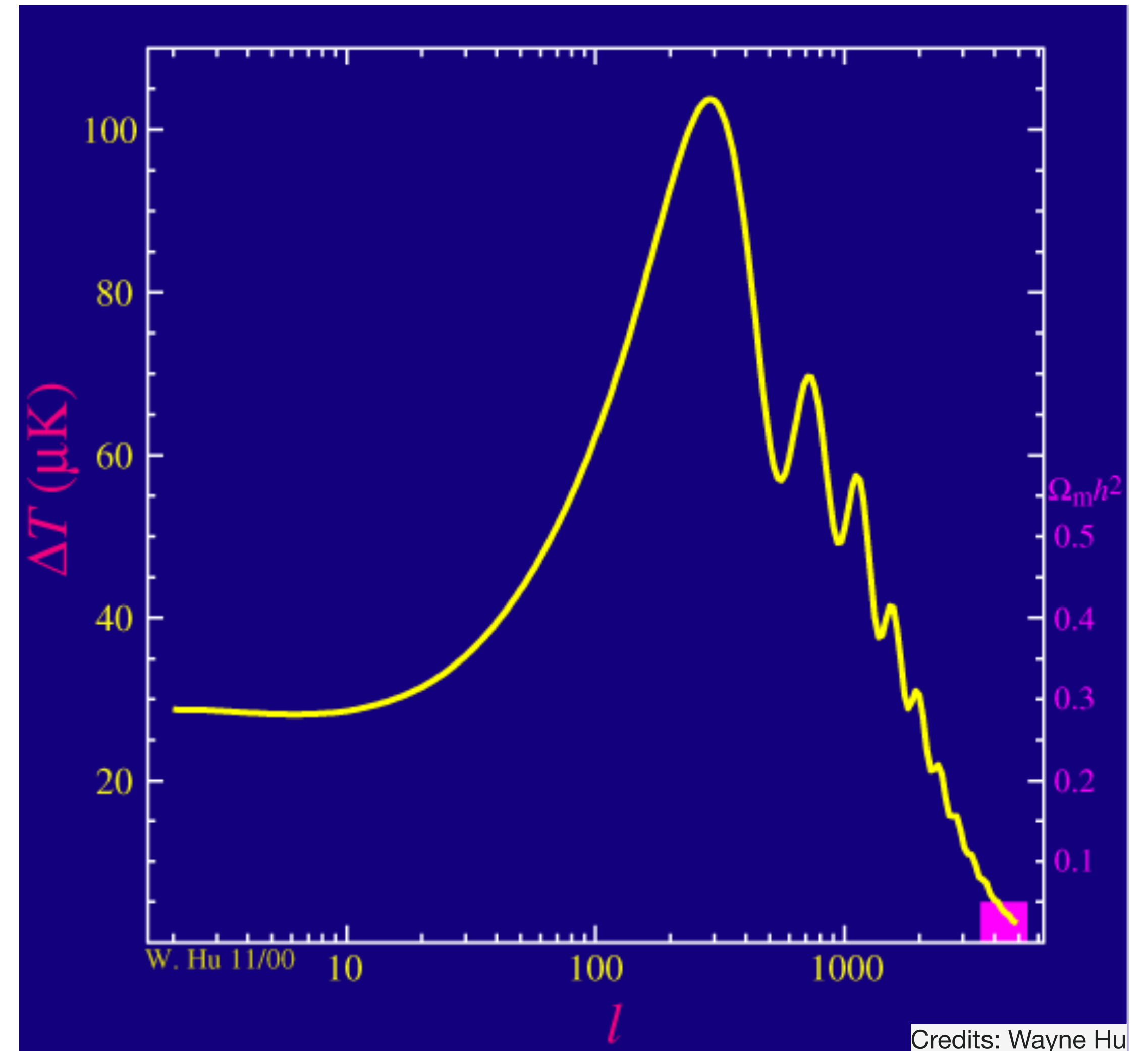


The Early Universe

- Inflation—A brief epoch of exponential expansion in the early universe ($\sim 10^{-35}$ s after the Big Bang).
- Stretches quantum fluctuations to cosmic scales, seeding large-scale structure formation.
- Inflation widely accepted to explain the observed statistical isotropy and homogeneity in the Universe. ([Guth 1981](#); [Linde 1982](#); [Albrecht & Steinhardt 1982](#))
- The characteristics of the field(s) that drove inflationary expansion remains unknown.
- Observables today encode — field content, symmetries and energy scale.
- Analogous philosophy to DM searches : indirect, statistical and background limited.

Link to dark matter

- Inflation sets initial conditions for :
 - Dark Matter density perturbations
 - structure formation
- Many dark matter models affect early-Universe observables.
- Probes of inflation provides constraints inaccessible to direct detection.



Examples

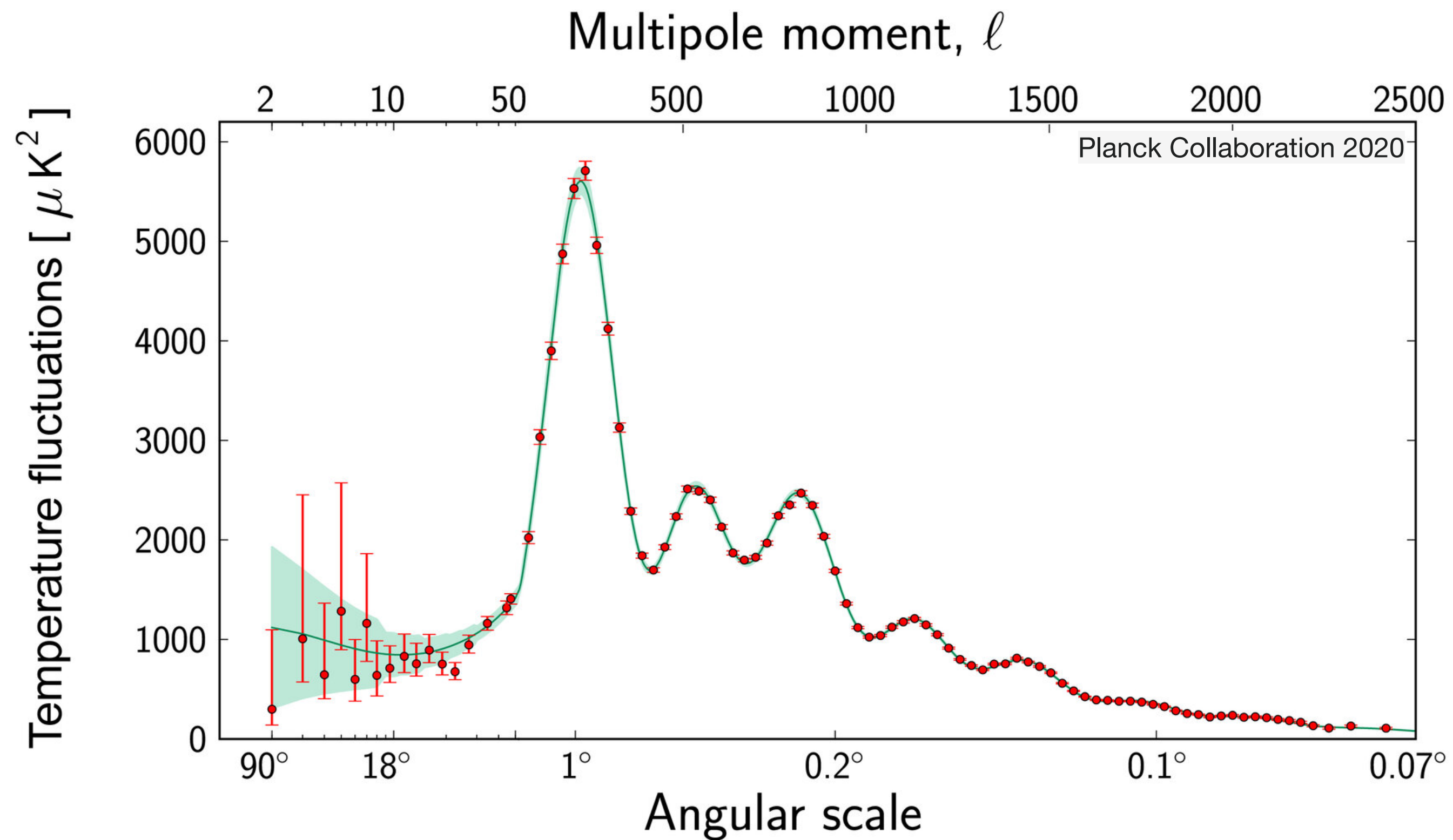
- Axions :
 - Isocurvature constraints
 - Connection to inflation energy scale
- Dark Radiation :
 - Effective number of species N_{eff}
- Heavy fields during inflation :
 - Leave imprints on primordial spectrum

Why care about CMB?

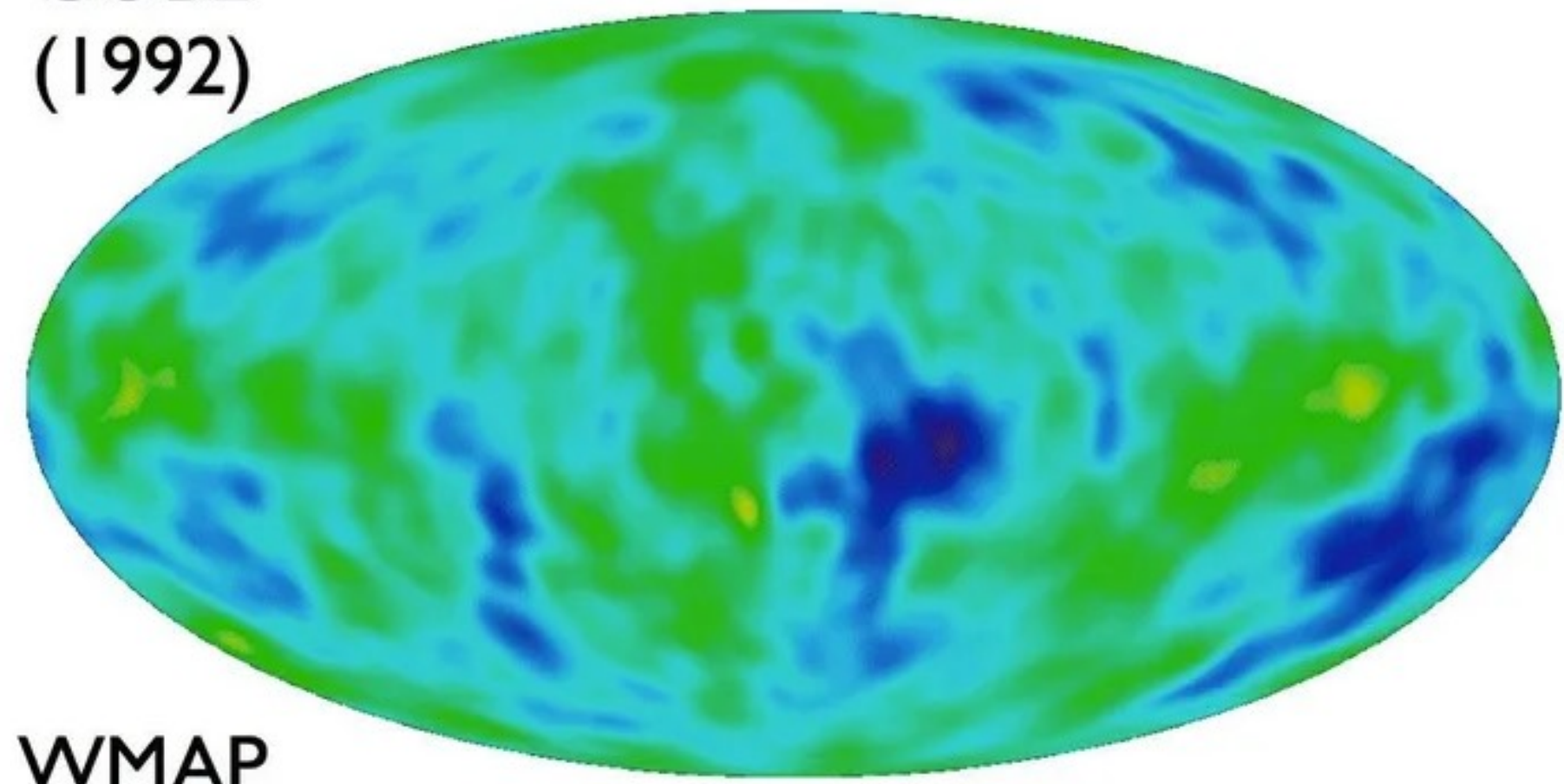
- Inflation connects:
 - Quantum fields
 - Gravity
 - Structure formation
- The characteristics of inflation are imprinted on CMB.
- CMB probes energy scales beyond colliders, $\sim 10^{16}$ GeV, through gravitational imprints.
- Complementary to laboratory and astrophysical dark matter searches.
- Precision experiment for QFT in curved spacetime.

CMB

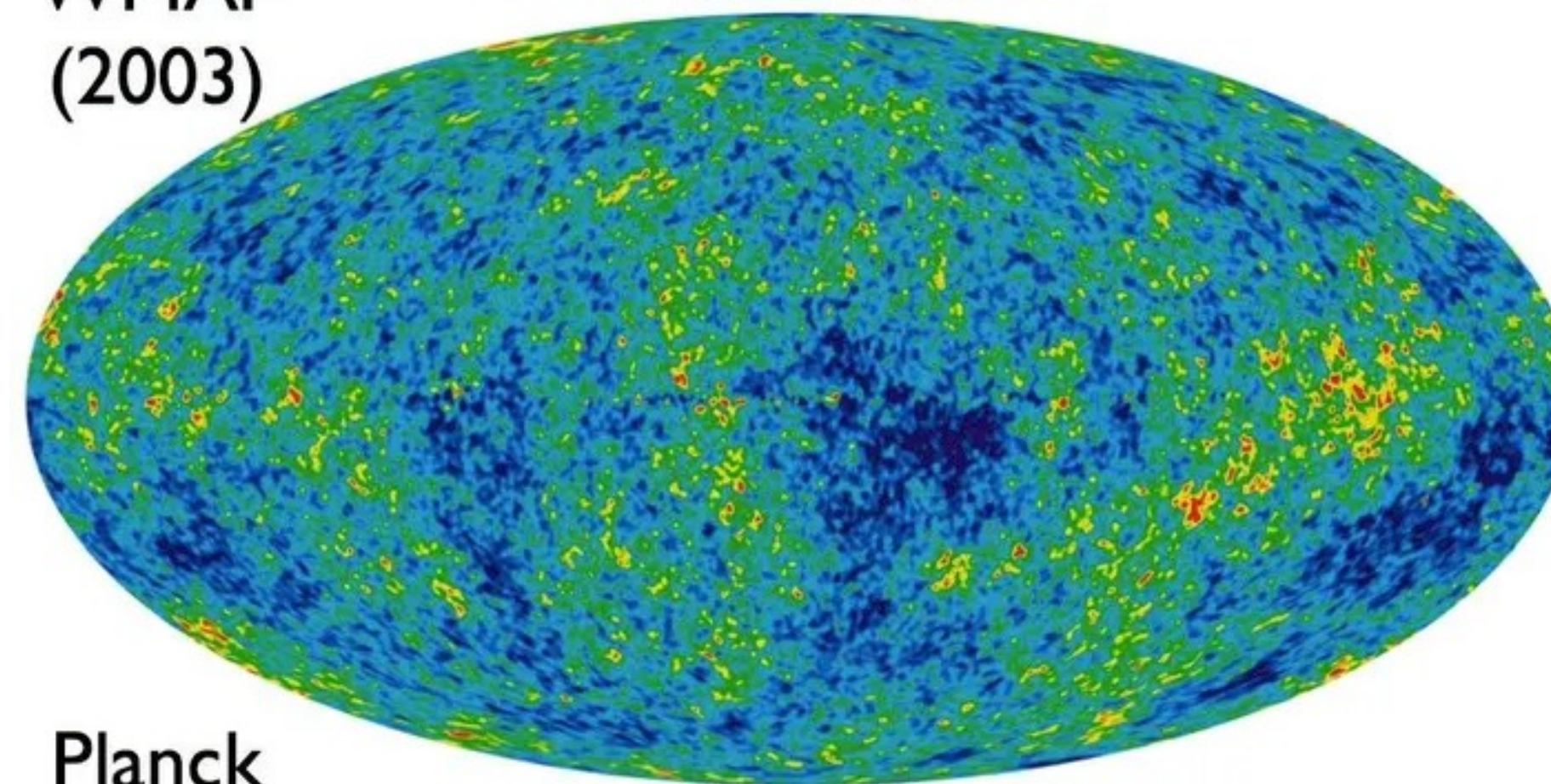
- Oldest EM Radiation in the Universe, $\sim 380,000$ years post Big Bang.
- First detection: Arno Penzias and Robert Wilson, 1965.
- $\sim 2.73\text{ K}$, $\mathcal{O}(10^{-5})$ anisotropies
- One of the cornerstones of modern cosmology.



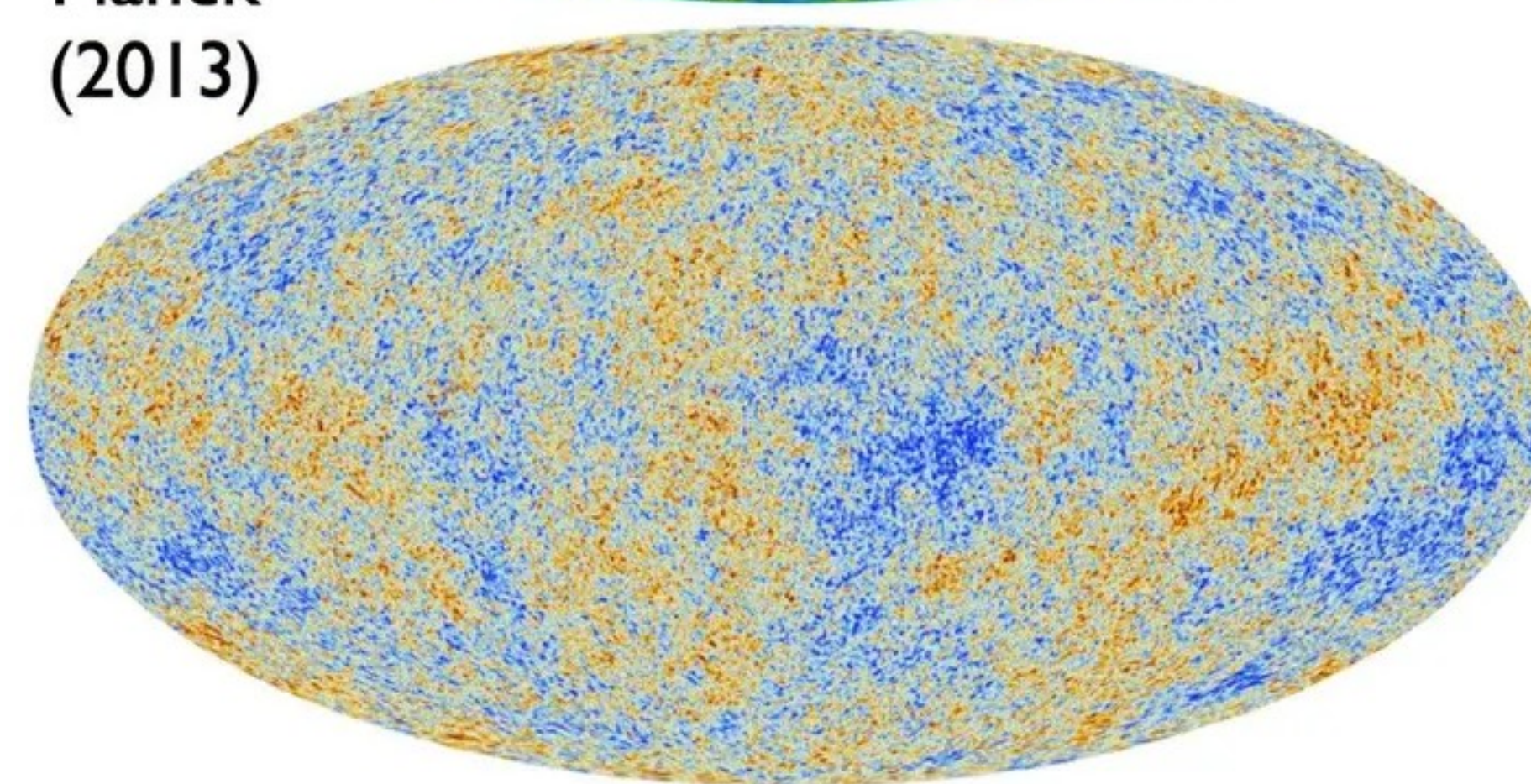
COBE
(1992)



WMAP
(2003)



Planck
(2013)



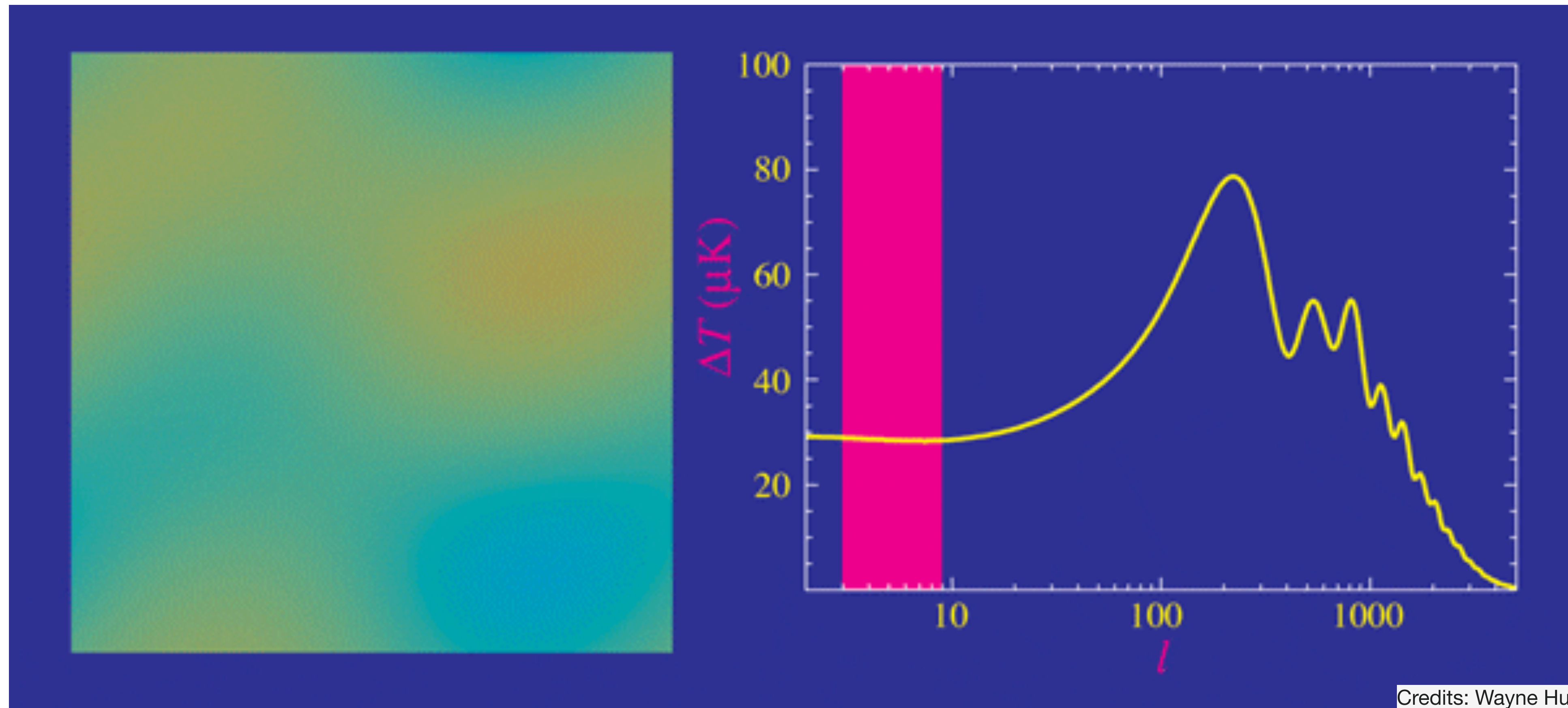
Angular Power Spectrum

Expansion of a random field with spherical harmonics.

$$X(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^l a_{lm}^X Y_l^m(\theta, \phi)$$

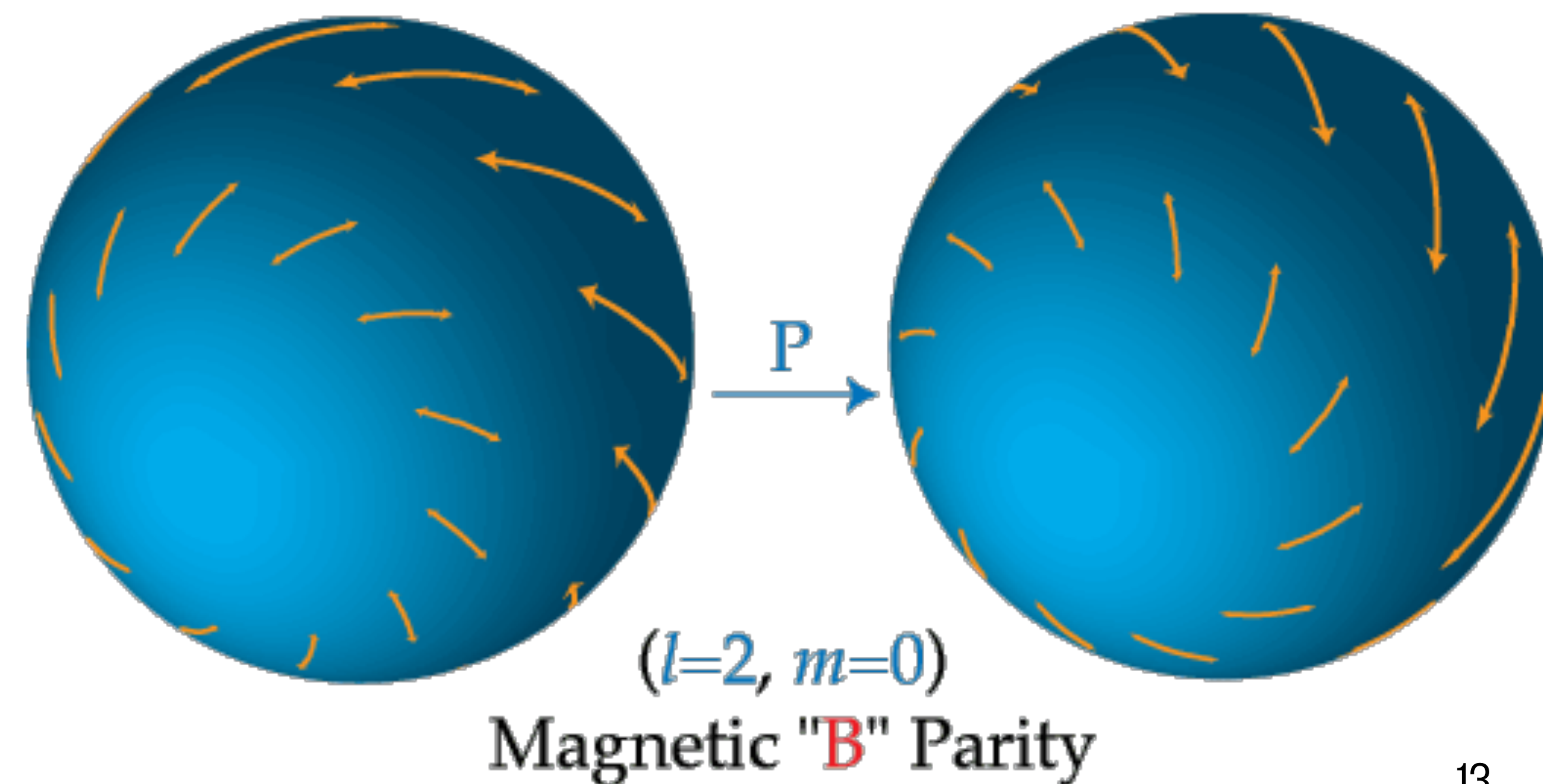
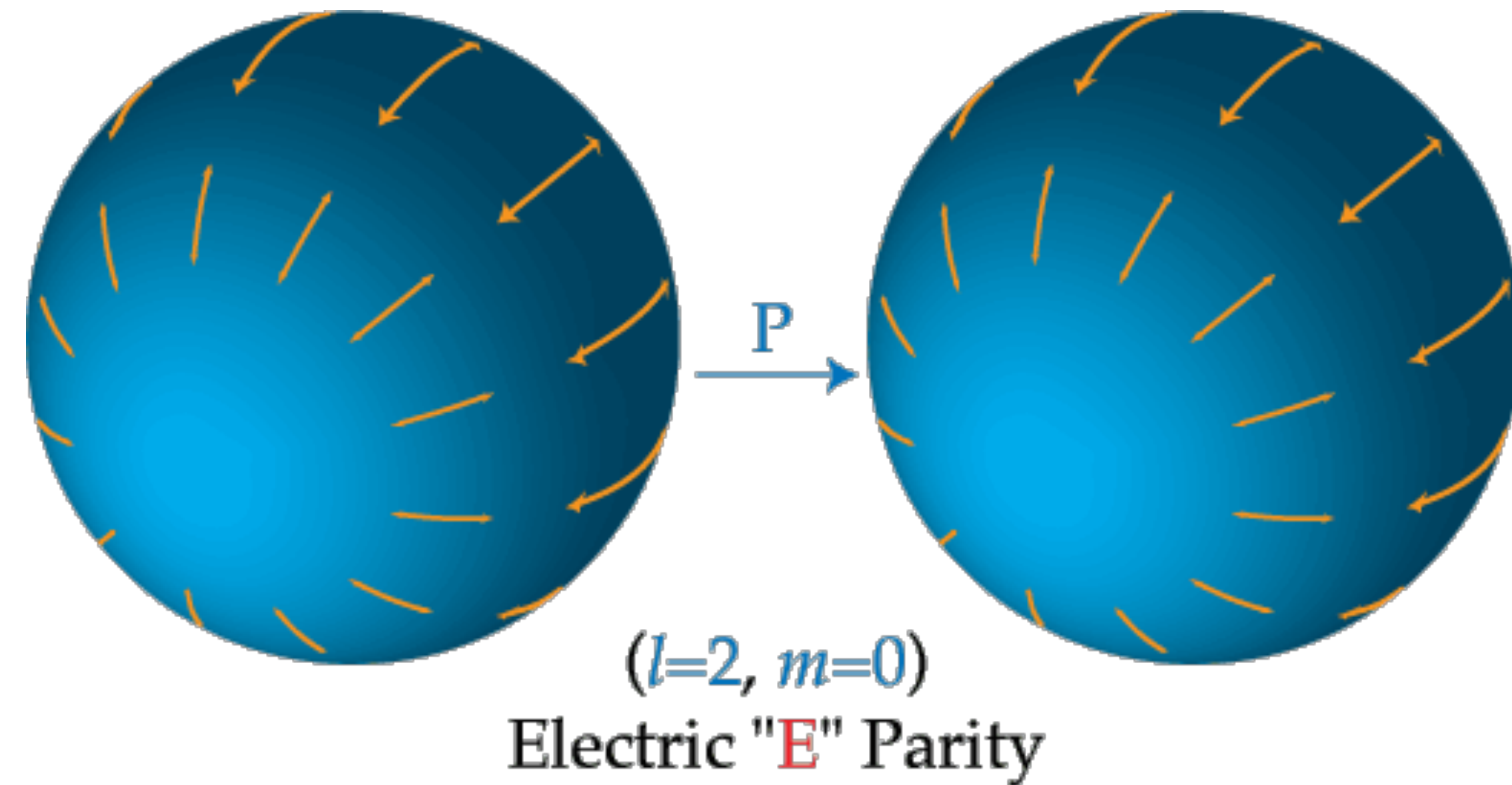
Distribution of power as a function of angular scale

$$C_{\ell}^{XY} = \langle a_{\ell m}^X a_{\ell m}^{Y*} \rangle, \quad \theta \propto \frac{1}{\ell}$$



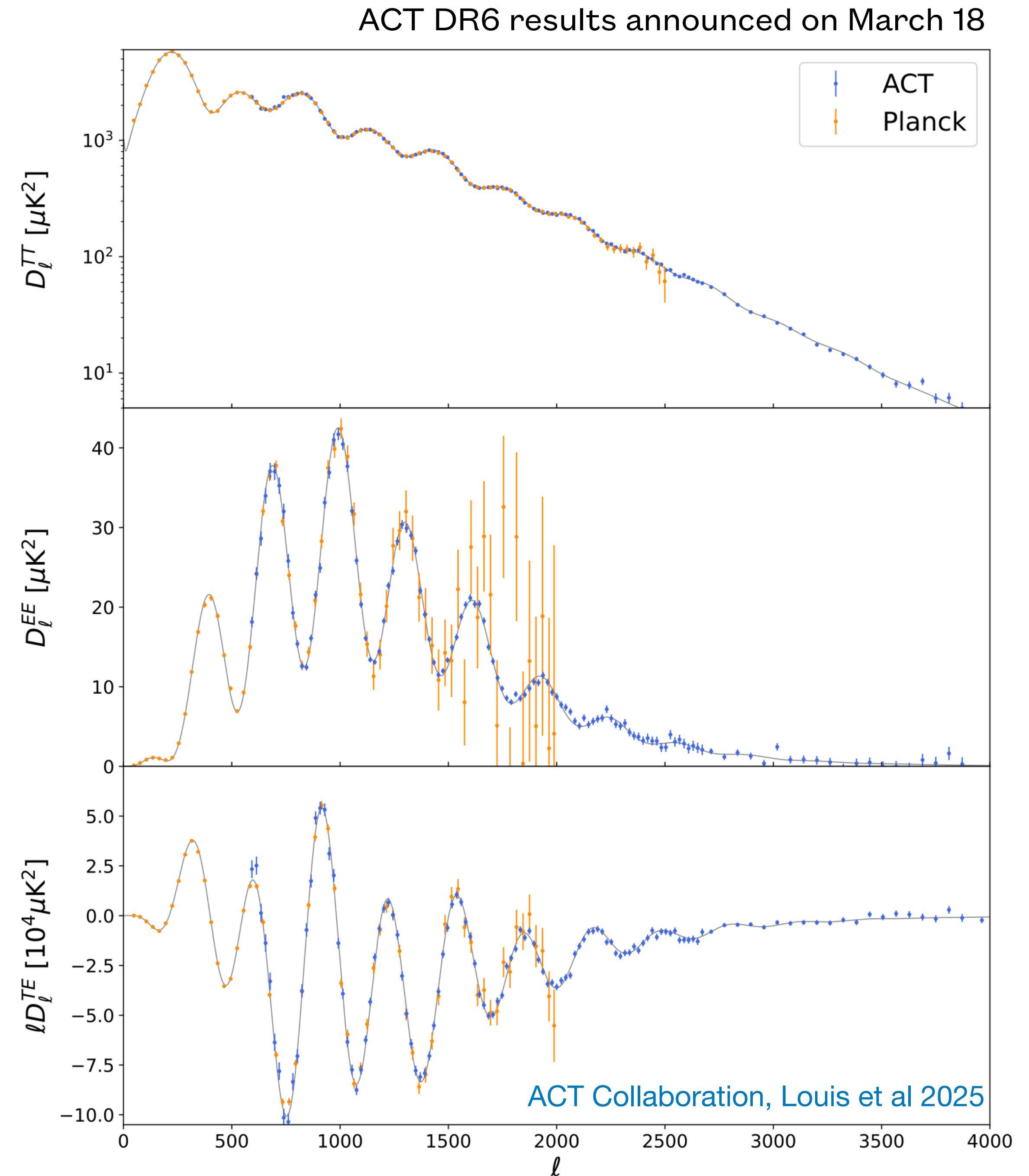
Scalar vs Tensor Perturbations

- Scalar modes:
 - Density fluctuations
 - Generates temperature anisotropies
 - Generates curl-free E-mode polarisation
 - Seeds galaxies and large scale structure
- Tensor modes:
 - Primordial gravitational waves
 - Direct signature of inflation
 - No late-time contamination at generation
 - Generated divergence free B-mode polarisation
 - Smoking gun for inflation

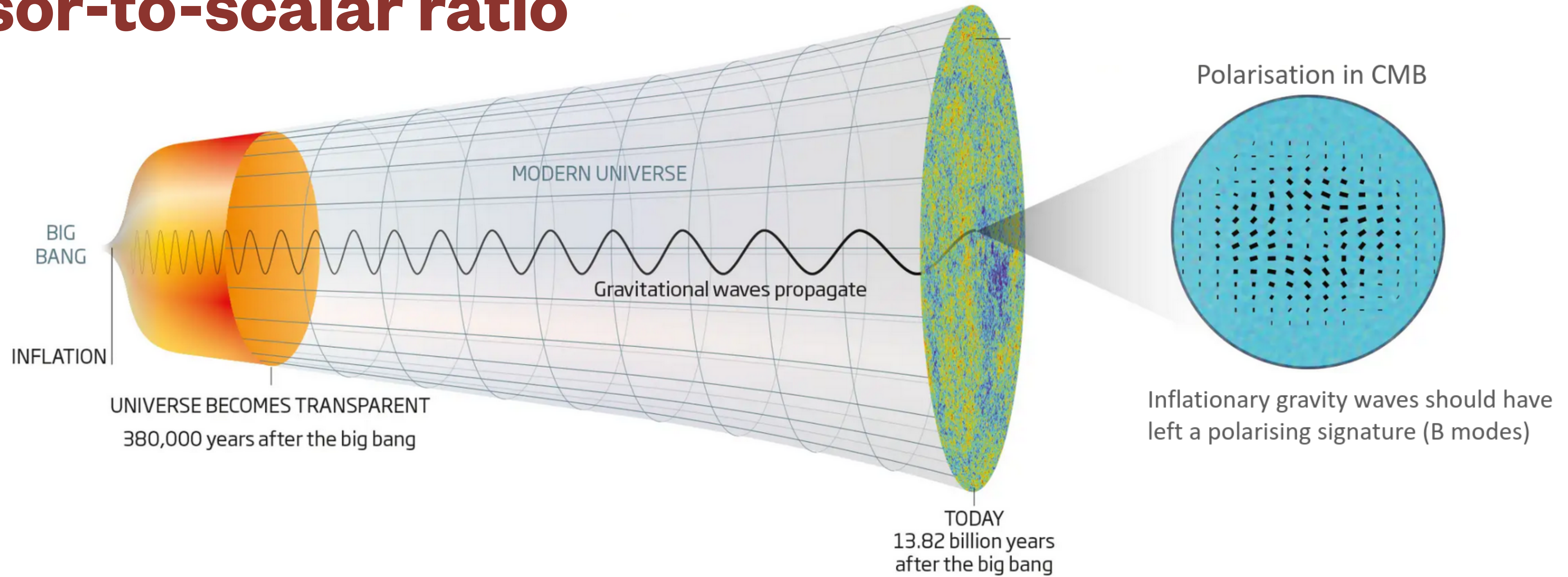


ACT temperature and polarisation

- Atacama Cosmology Telescope—ACT
- CMB experiment in the Atacama desert.
- Measuring the CMB sky at arcminute resolution.
- Very precise CMB polarisation measurements
- First detection of seven acoustic peaks in CMB
- Consistent with the Λ CDM model



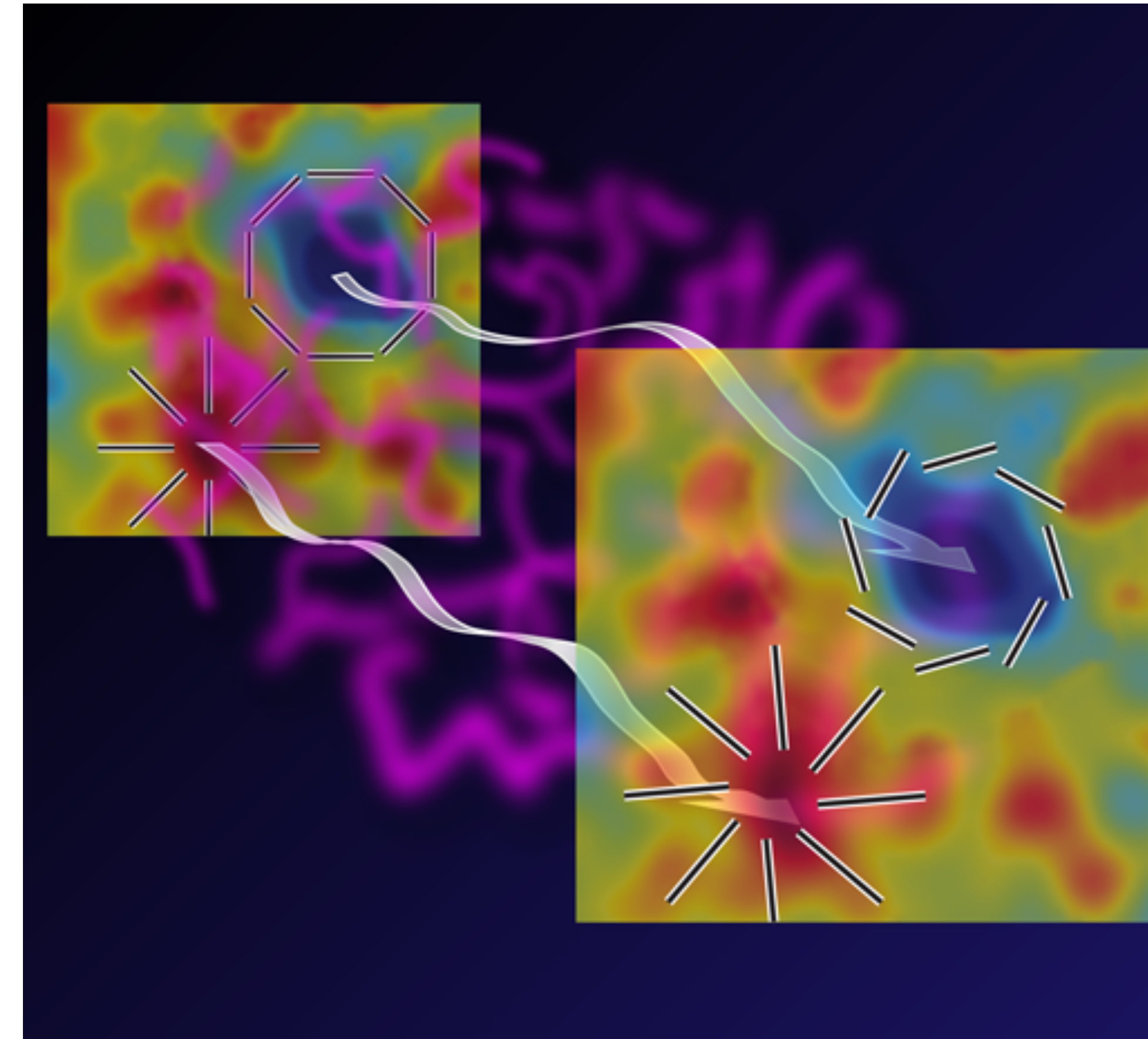
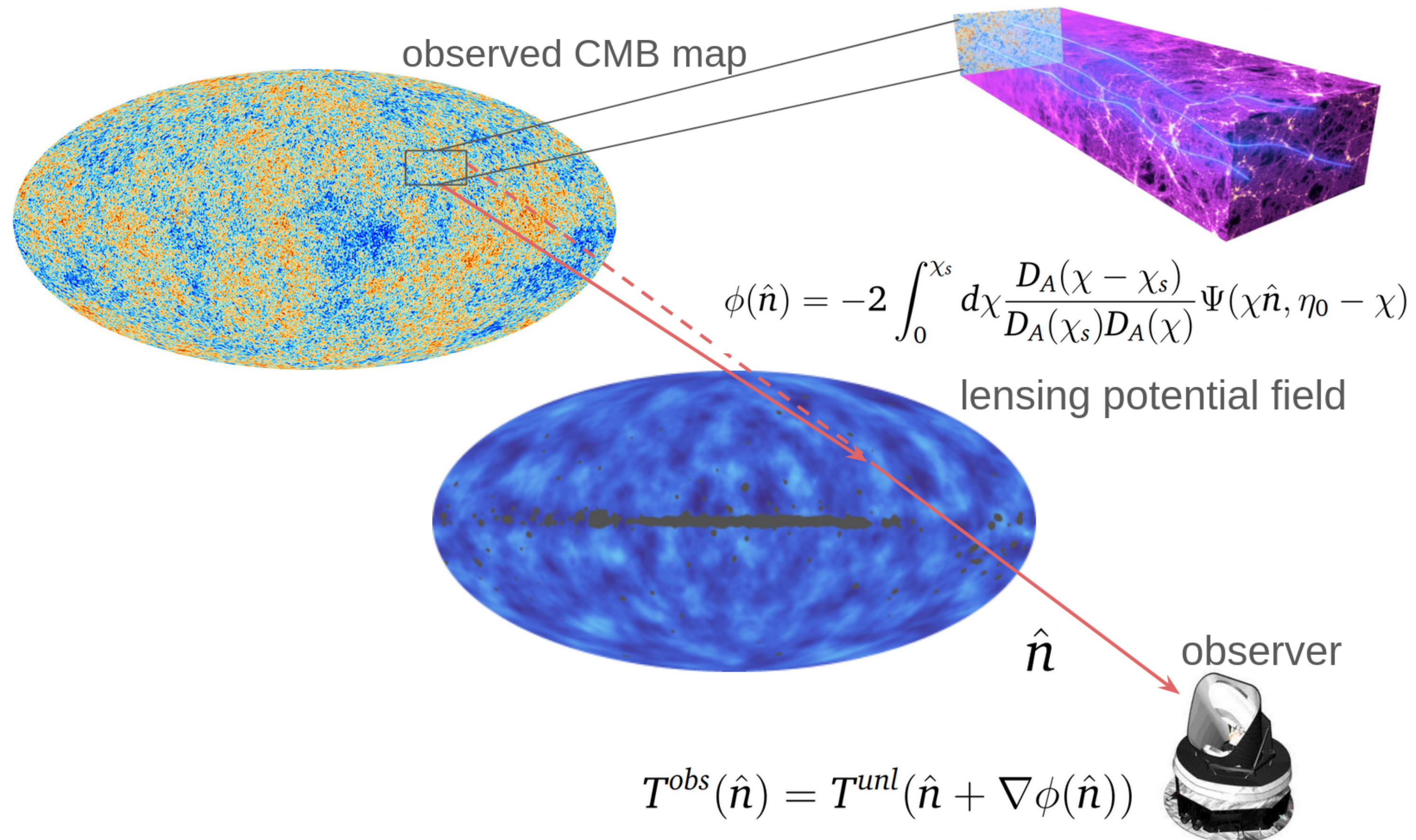
Tensor-to-scalar ratio



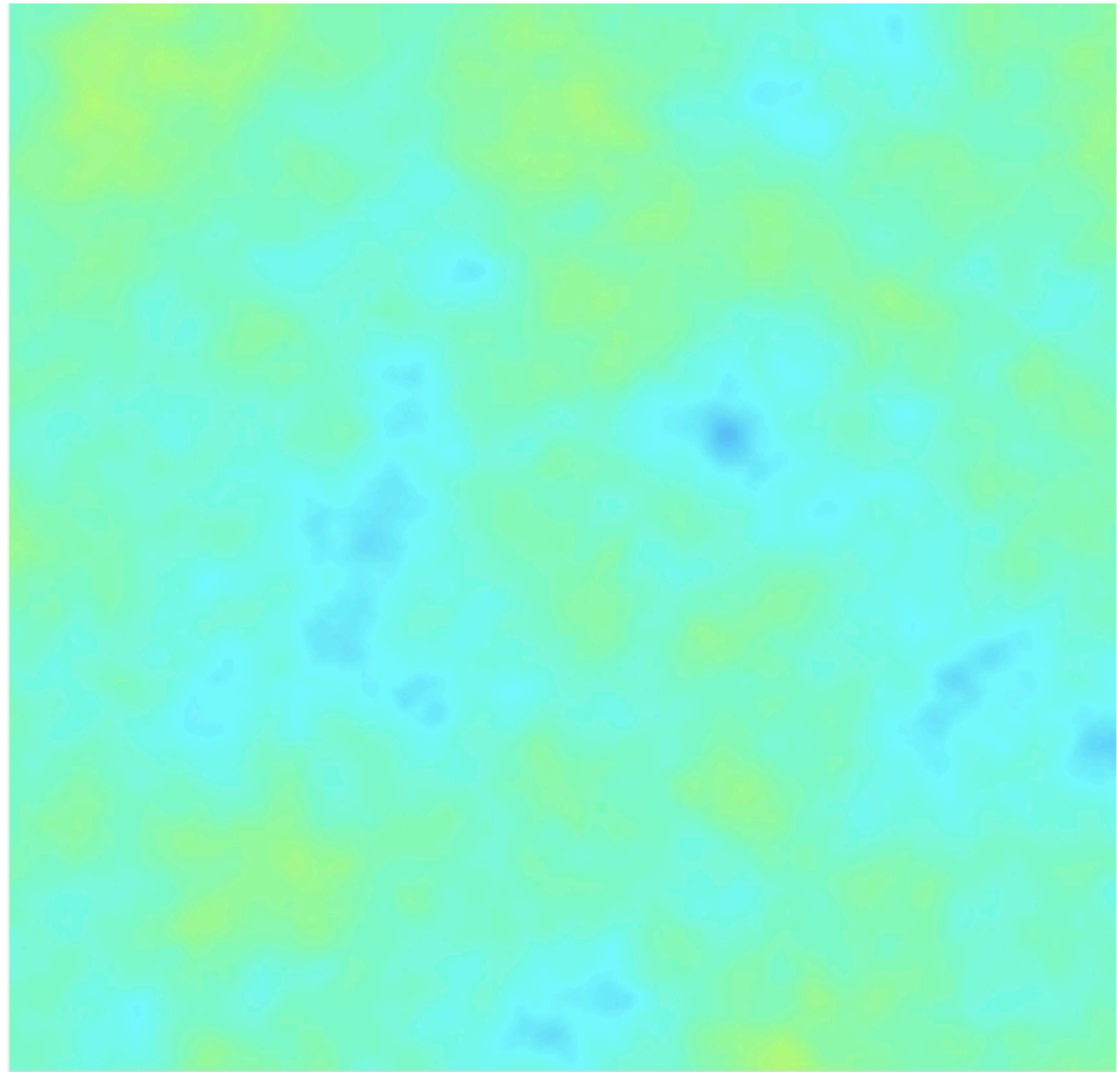
- tensor-to-scalar ratio $r = \frac{\text{amplitude of tensor fluctuations}}{\text{amplitude of scalar fluctuations}}$
- Sets amplitude of primordial gravitational waves.
- Directly related to inflationary energy scale: $V^{1/4} \sim 10^{16} \text{ GeV} \times r^{1/4}$
- Planck survey + BICEP-Keck $r < 0.032$; future surveys target $r < 0.003$.

Measuring r is hard

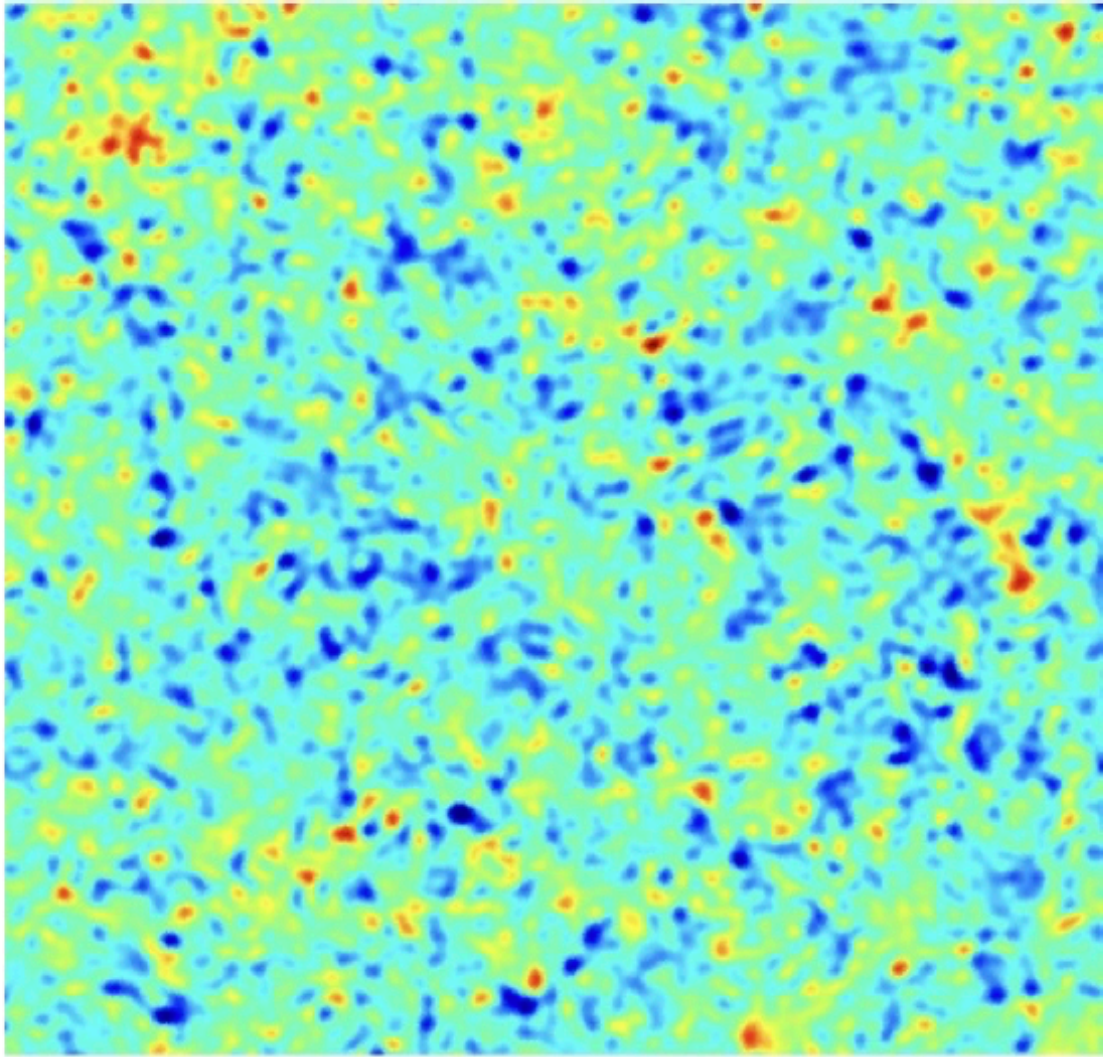
- B-modes signal is very weak.
- Contaminated by foregrounds like galactic dust, synchrotron, free-free radiations.
- Lensing twists primordial E-modes to B-modes



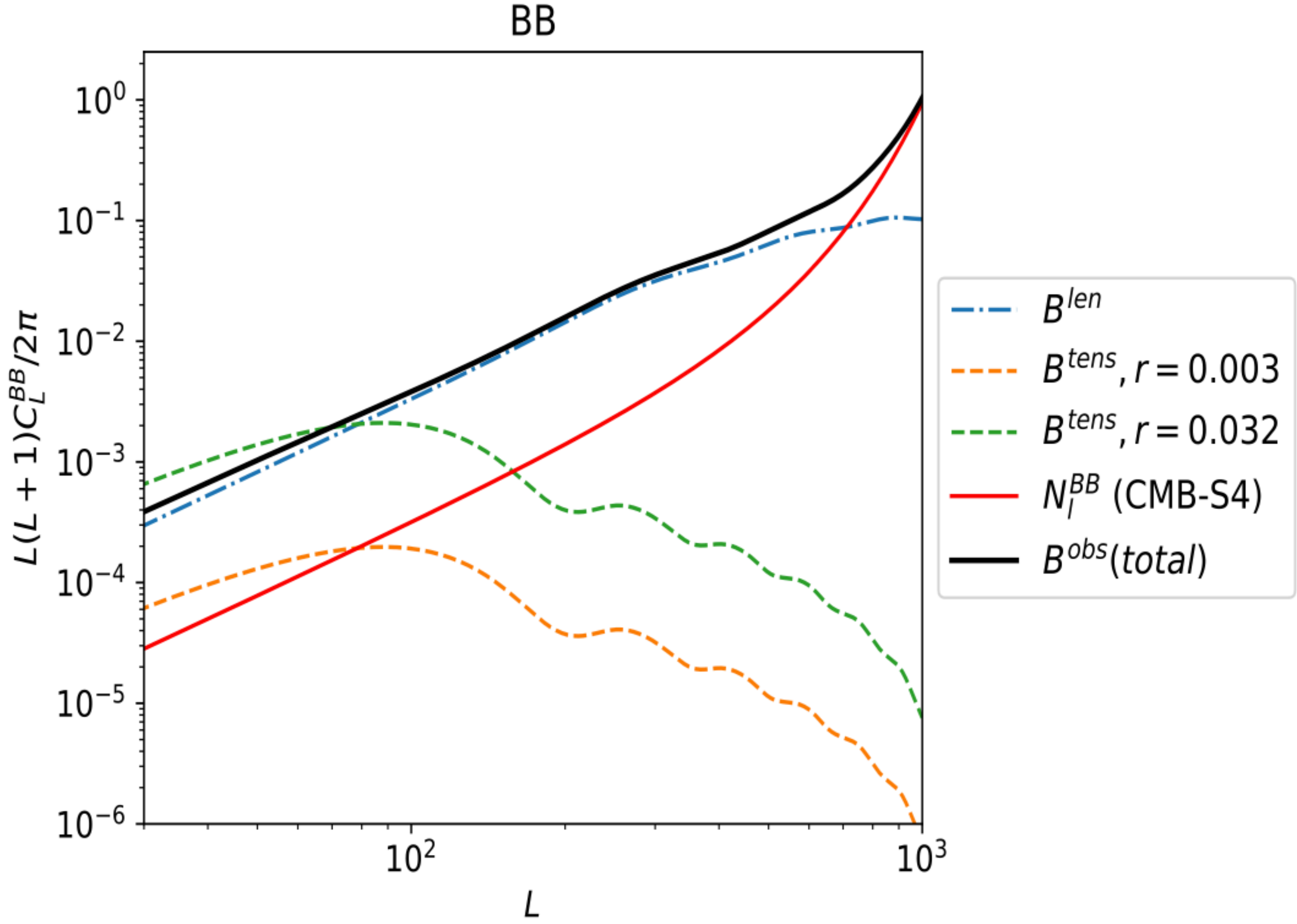
Lensing B-modes dominates



unlensed B for $r=0.2$ (x10)



lensed B for $r=0.2$ (x10)



Simons Observatory

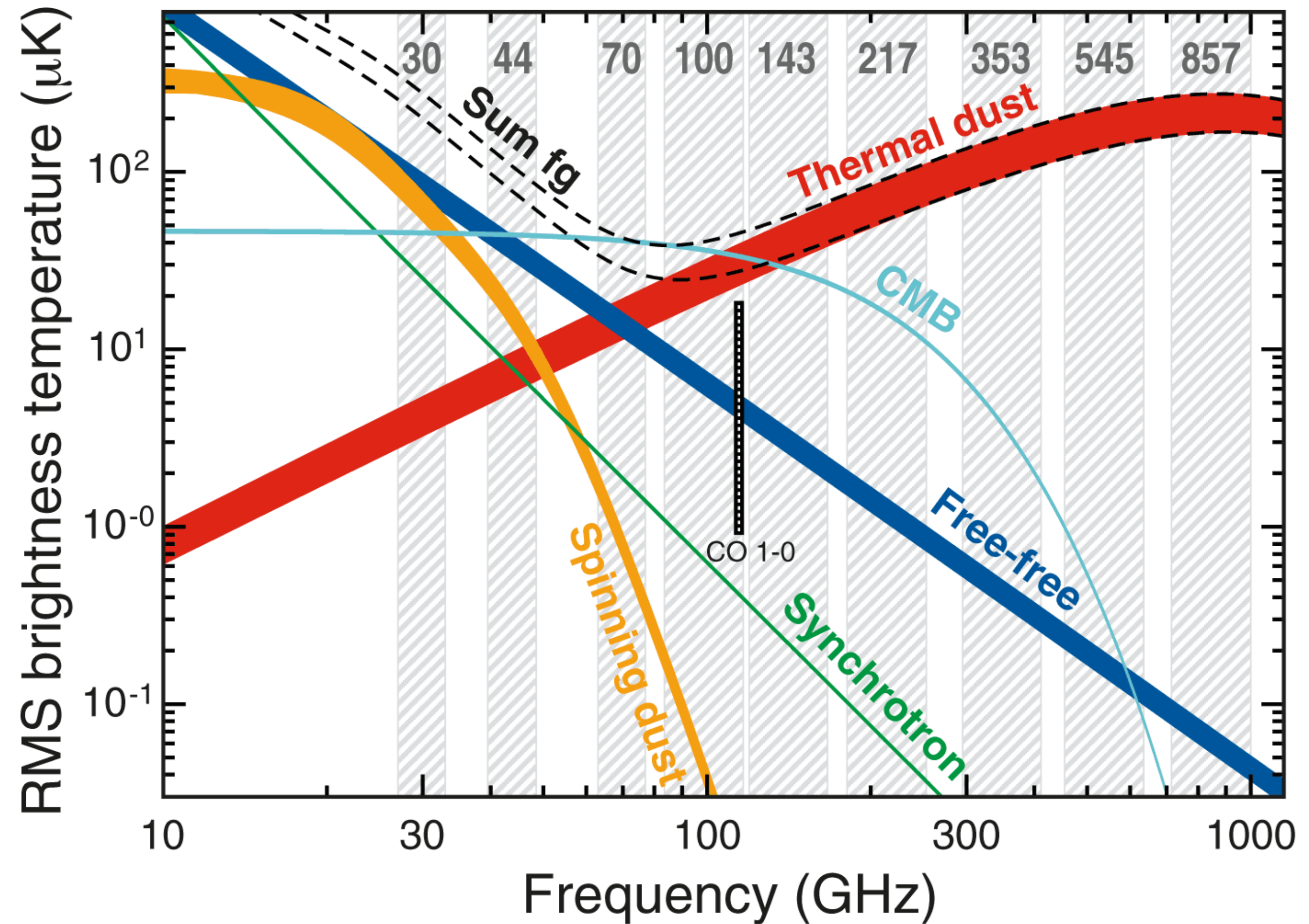
- CMB polarisation experiment in Chile
- Large Aperture Telescopes (LATs):
 - 40% of sky
 - $\sim 6 \mu\text{K-arcmin}$ noise (pol.)
 - Delensing
- Small Aperture Telescopes (SATs):
 - 10% of sky
 - $\sim 2 - 3 \mu\text{K-arcmin}$ noise (pol.)
 - Tensor-to-scalar ratio
- *Planck* had $\sim 40 - 60 \mu\text{K-arcmin}$ noise level.

Credits: simonsobservatory.org



Delensing with SO

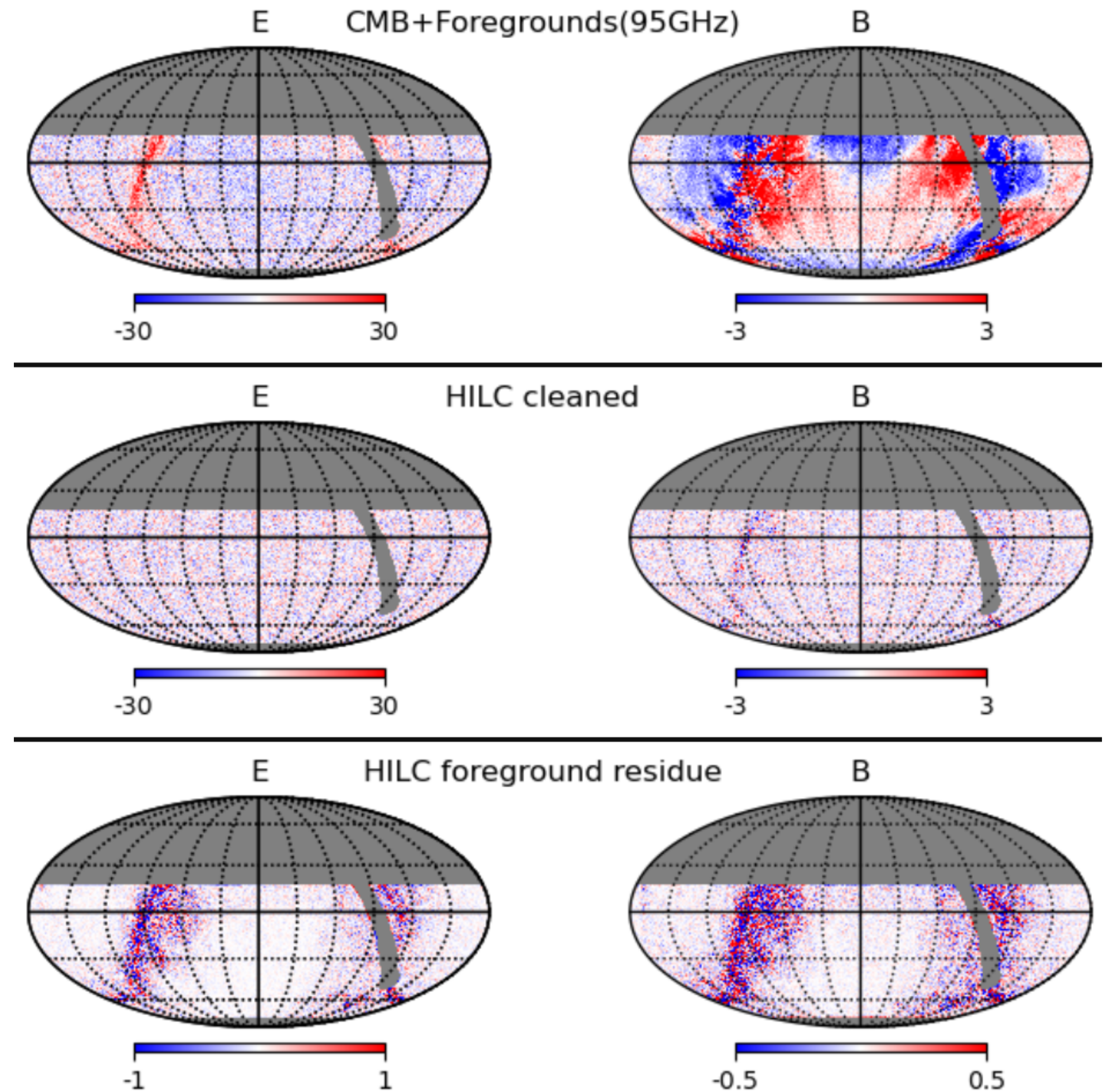
- Delensing = removing lensing induced B-mode component.
- Foreground cleaning essential — done with component separation in harmonic space



Foreground cleaning

Harmonic Internal Linear Combination (HILC)

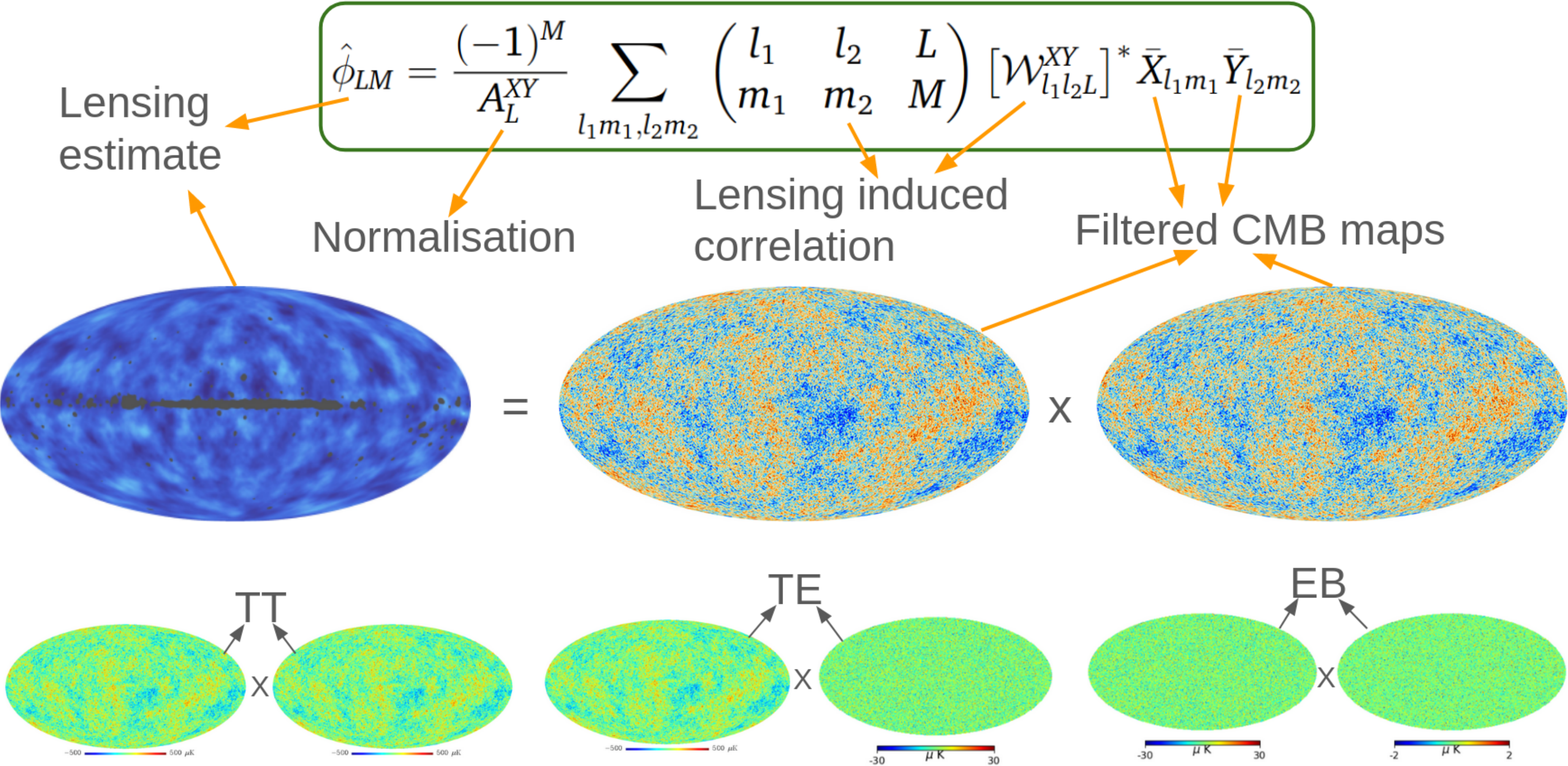
- Decompose maps in spherical harmonics
- Foreground dominates different scales



Delensing with SO

- Delensing = removing lensing induced B-mode component.
- Foreground cleaning essential — done with component separation
- Internal delensing:
 - Using only CMB data
 - Combine CMB T, E, B maps

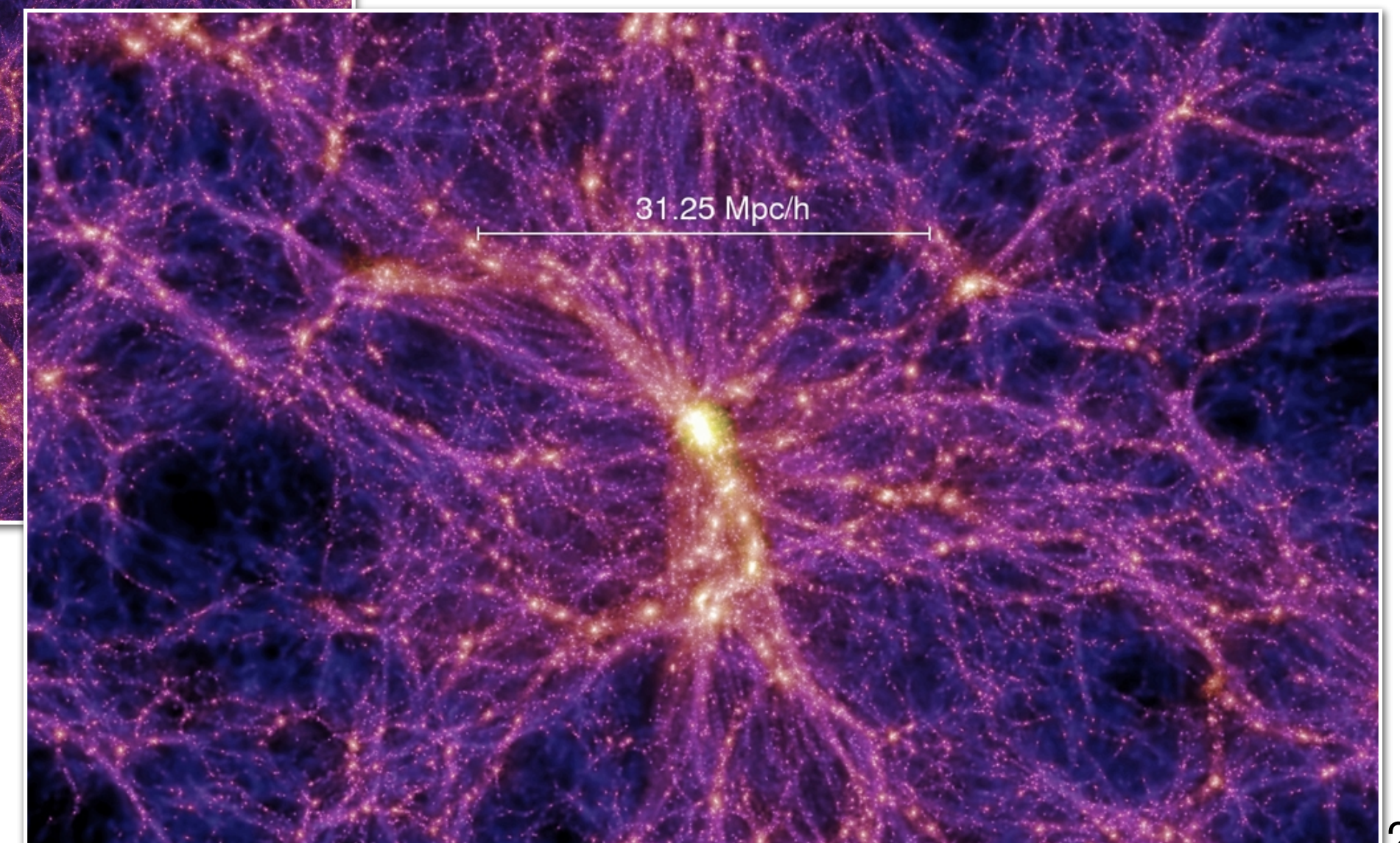
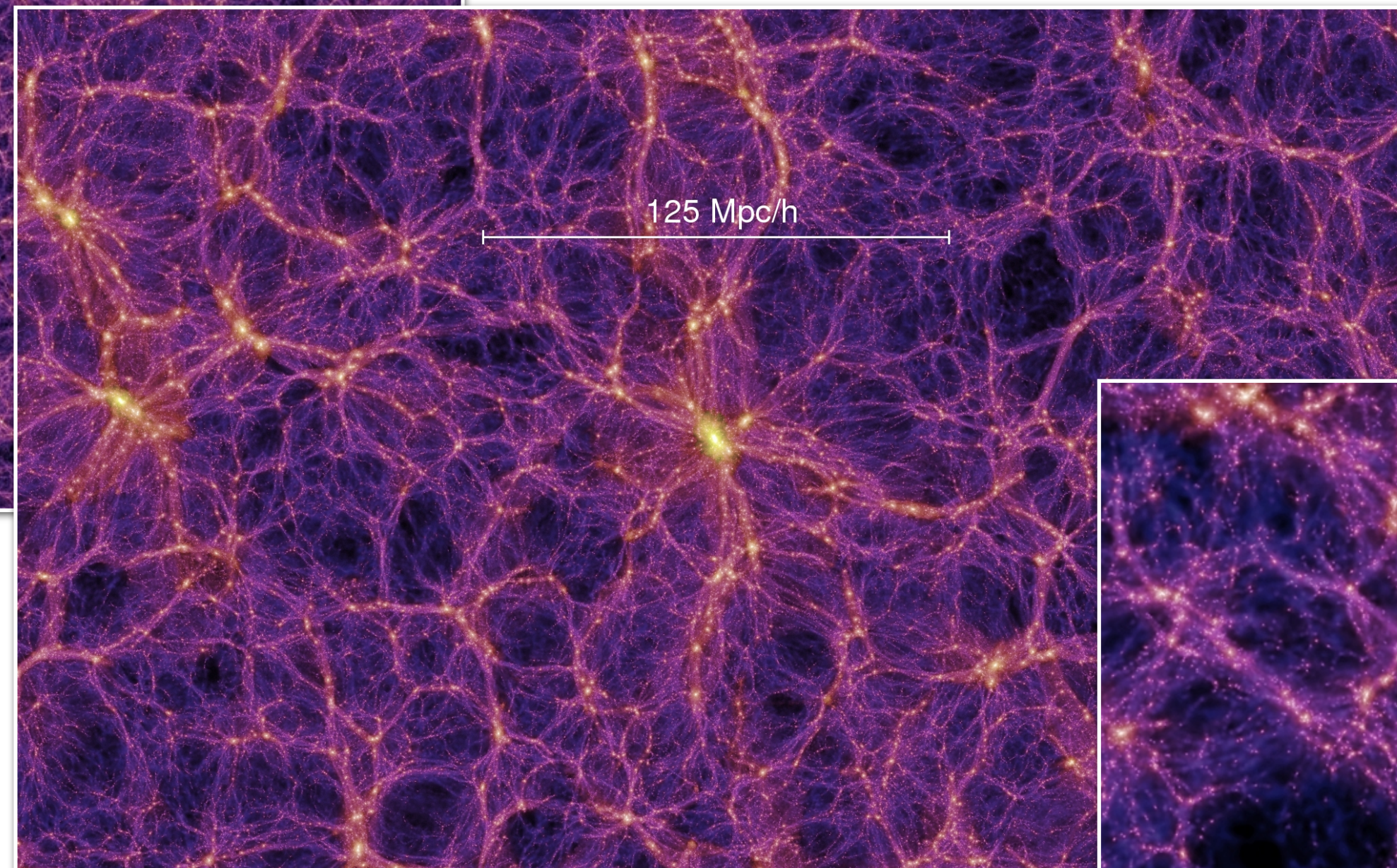
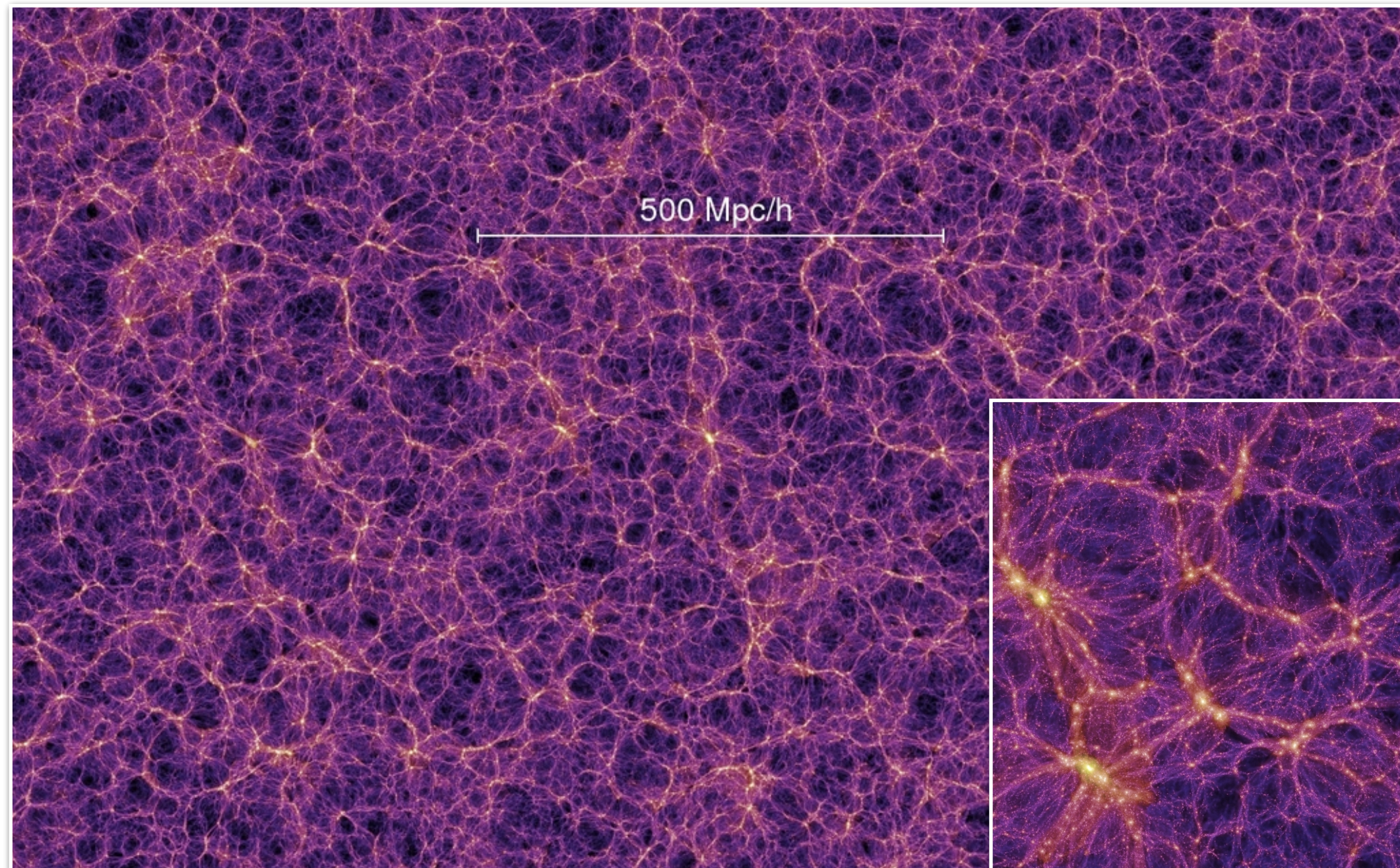
Internal delensing — Quadratic estimator



Delensing with SO

- Delensing = removing lensing induced B-mode component.
- Foreground cleaning essential — done with component separation
- Internal delensing:
 - Using only CMB data
 - Combine CMB T, E, B maps
- Delensing with LSS tracers:
 - Use CMB + other tracers (Euclid, LSST, SKA)
 - Improves delensing efficiency at smaller angular scales

Large Scale Structure



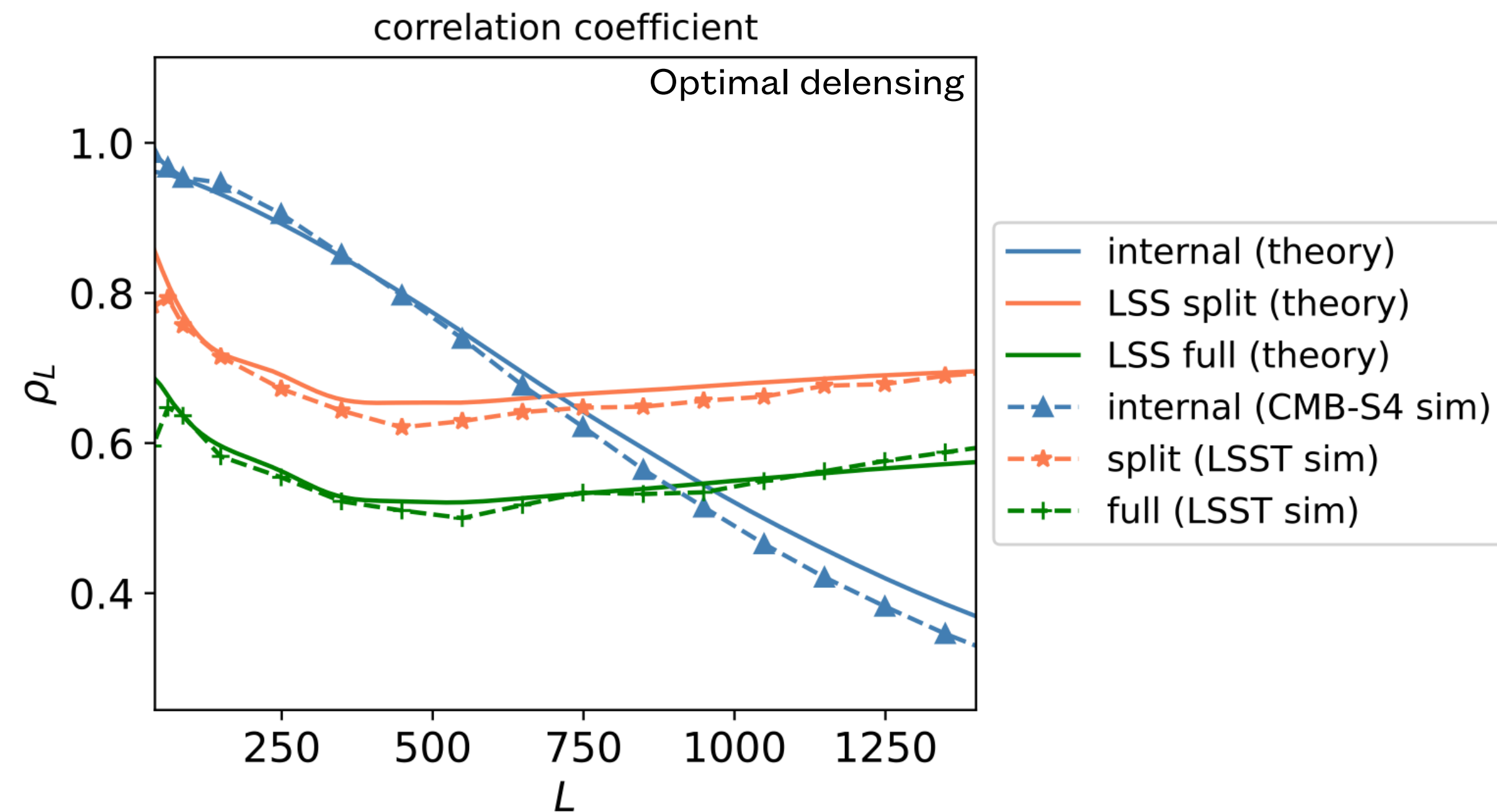
Delensing with LSS tracers

- Residual power spectrum: total observed - contribution from weak lensing

$$C_{\ell}^{B,\text{res}} = \frac{1}{2\ell + 1} \sum_{\ell' L} |f_{\ell\ell'L}^{EB}|^2 C_{\ell'}^{EE} C_L^{\phi\phi} \left(1 - \frac{C_{\ell'}^{EE}}{C_{\ell'}^{EE} + N_{\ell'}^{EE}} \rho_L^2 \right)$$

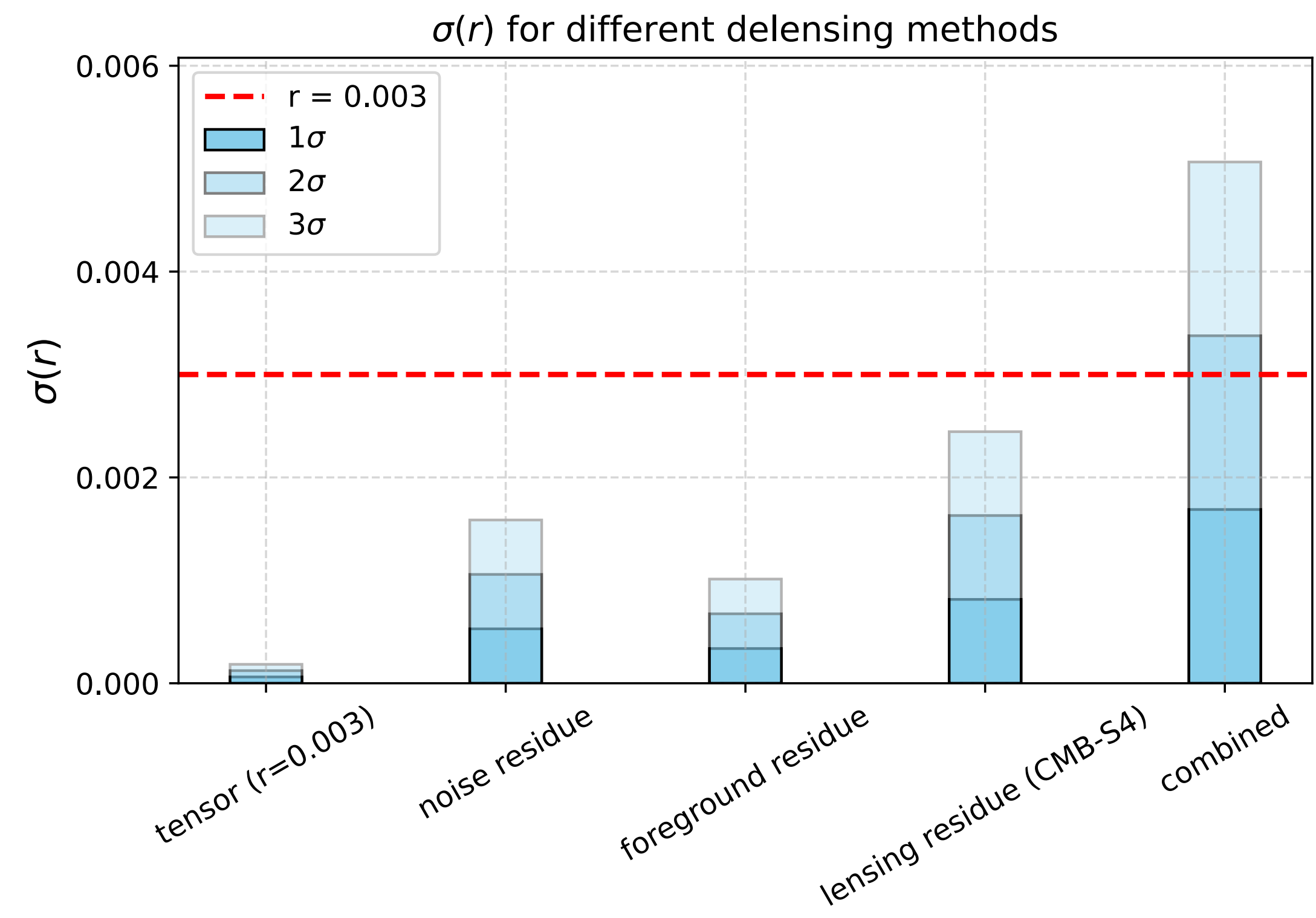
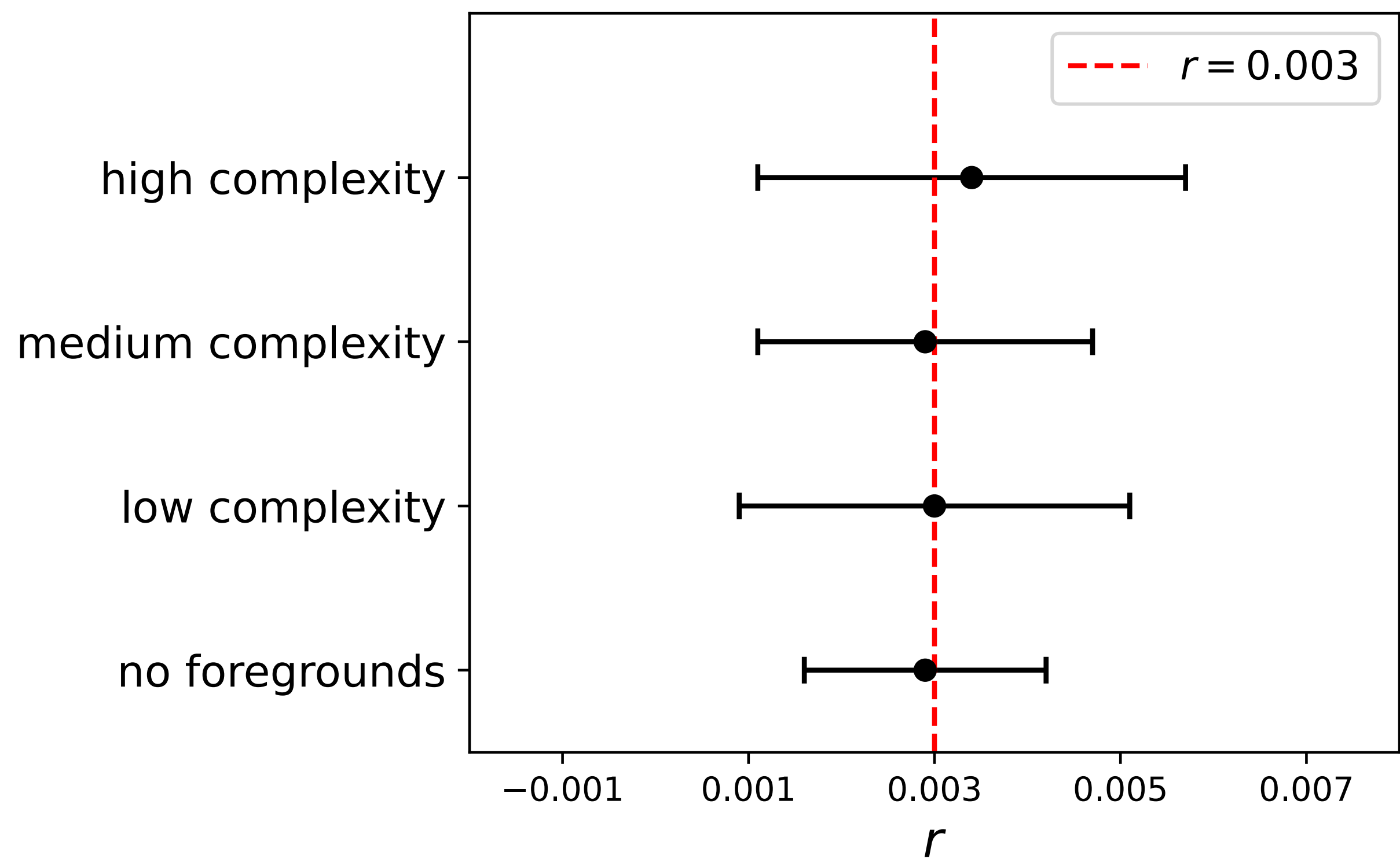
- Correlation coefficient (measures delensing performance):

$$\rho_{\ell}^2 = \sum_{i,j} \frac{C_{\ell}^{\phi I^i} (C_{\ell}^{II})_{ij}^{-1} C_{\ell}^{\phi I^j}}{C_{\ell}^{\phi\phi}}$$



Constraining r — internal

100 simulations with fiducial $r = 0.003$



Summary

- Detecting primordial B-modes will confirm tensor perturbations during inflation.
- Provide hints to dark matter from early Universe.
- Lensing reconstruction is crucial to remove lensing B modes.
- Foreground contamination impacts lensing reconstruction and delensing efficiency.
- Component separation reduces the biases in reconstruction and delensing.
- Cross-correlation with LSS tracer useful for improving delensing efficiency and constraints on the tensor-to-scalar ratio.



Credit: NSF-DOE Vera C. Rubin Observatory; #Rubin First Look

THANK YOU

