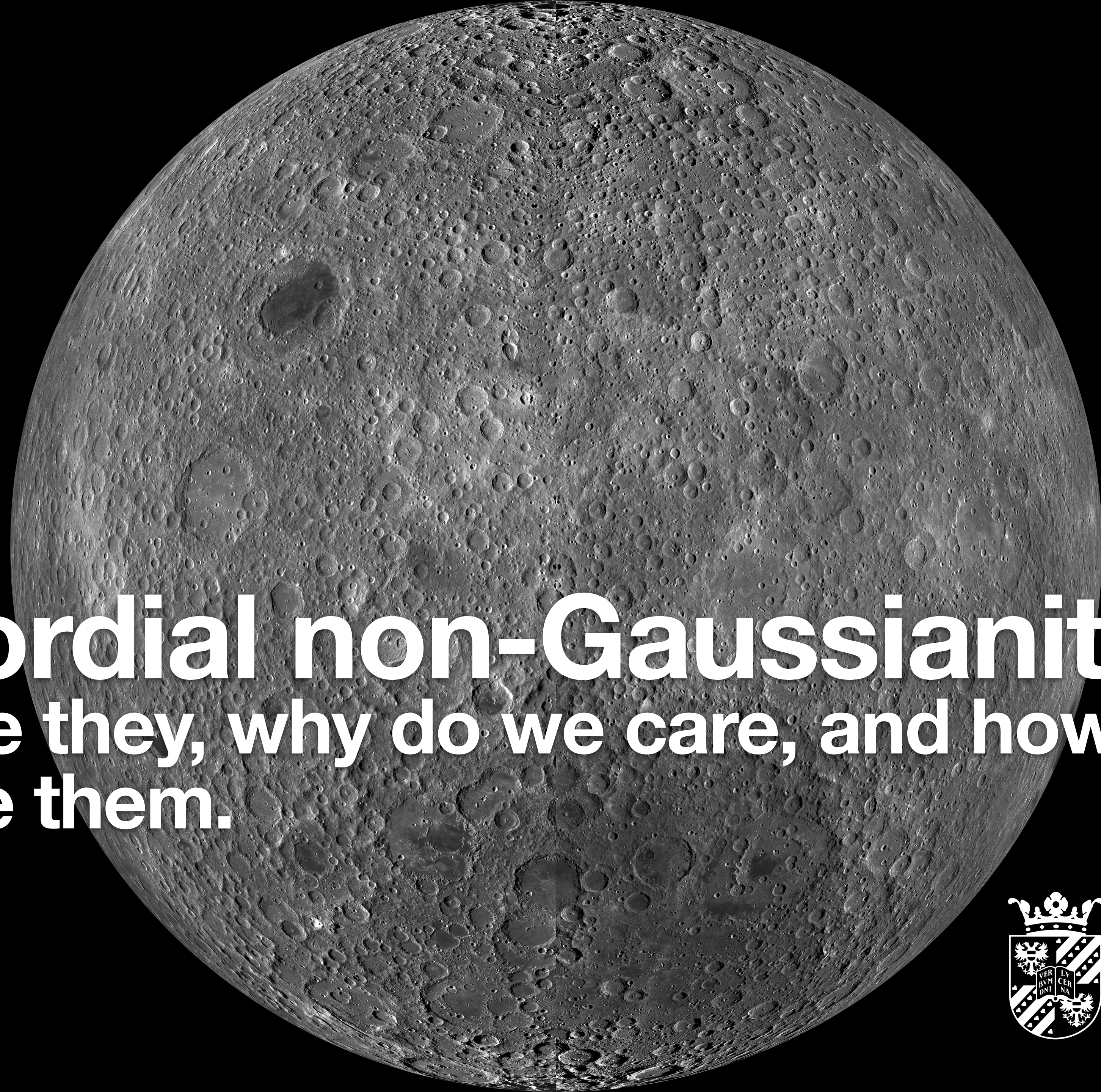




Primordial non-Gaussianities

What are they, why do we care, and how do we measure them.

NNV 2025



university of
groningen

Outline

- Cosmology 101
- What we know, and what we hope to learn
 - Gaussian universe
 - Non-Gaussian universe
- Towards a detection of non-Gaussianities:
 - Cosmic Microwave Background
 - 21cm Cosmology
 - Machine Learning
- Conclusions

Big Bang Expansion

13.7 billion years

Dark ages

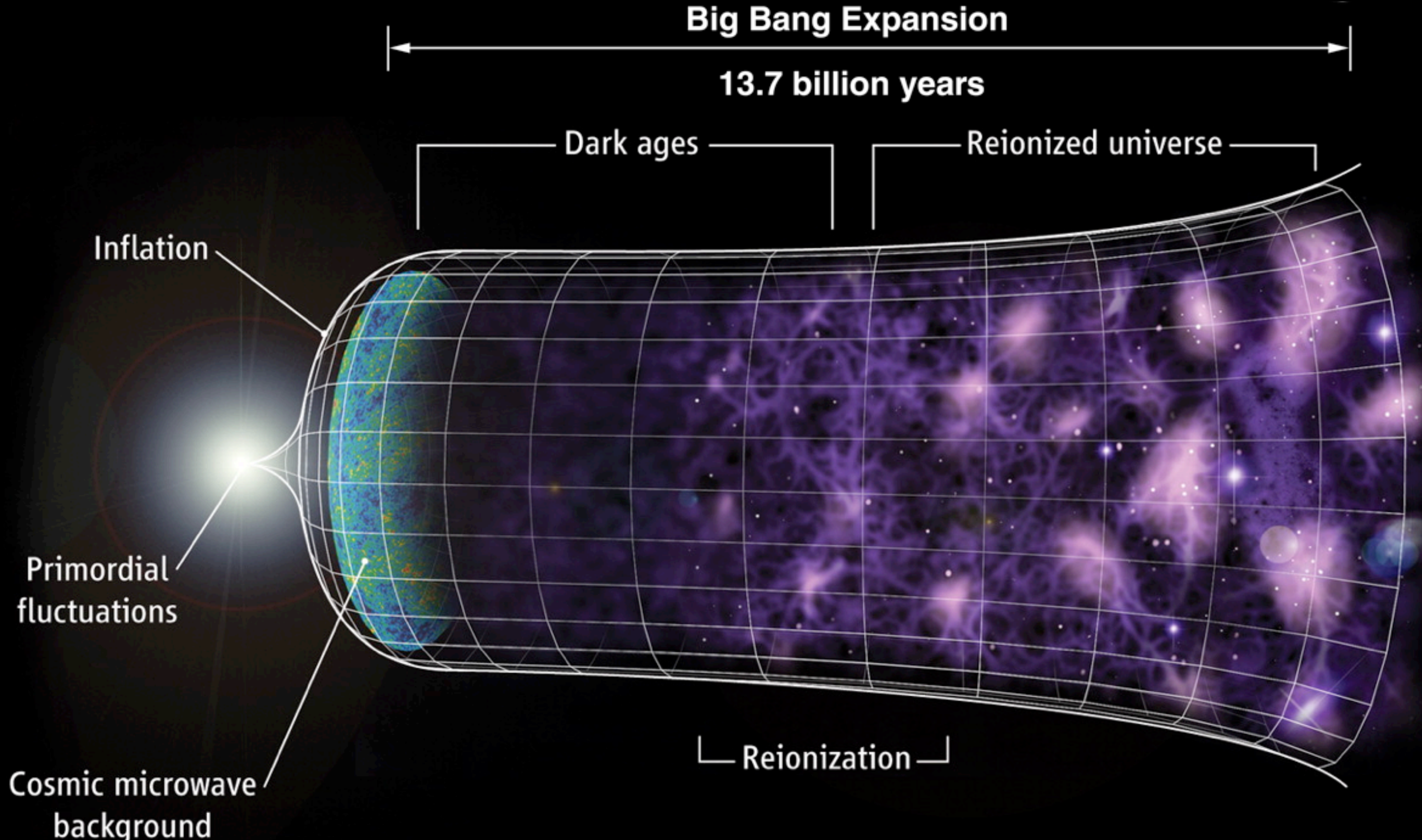
Reionized universe

Inflation

Primordial
fluctuations

Cosmic microwave
background

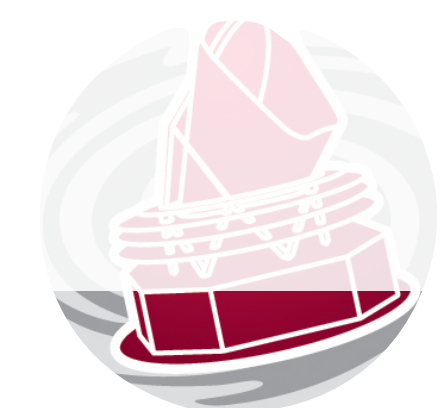
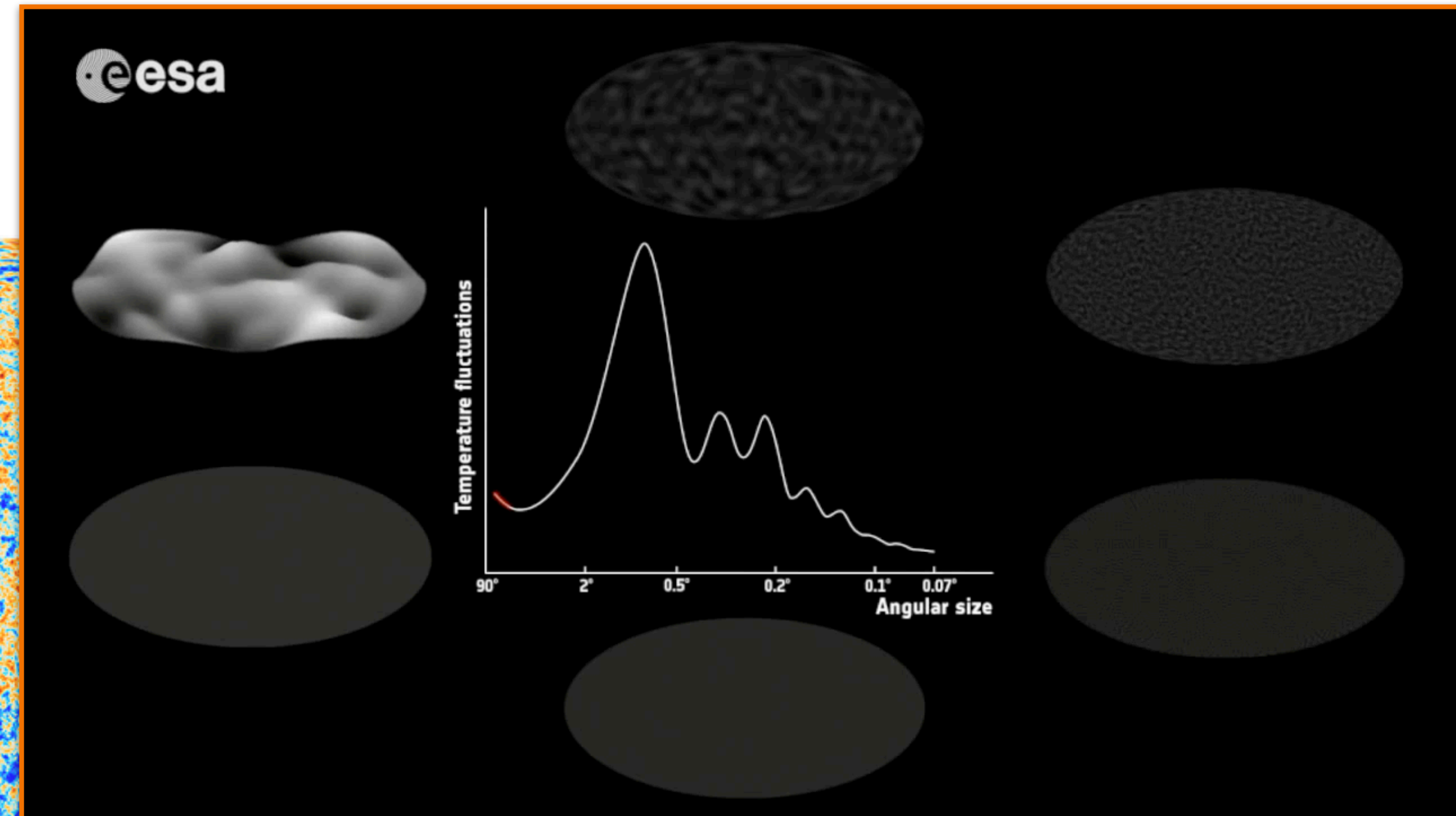
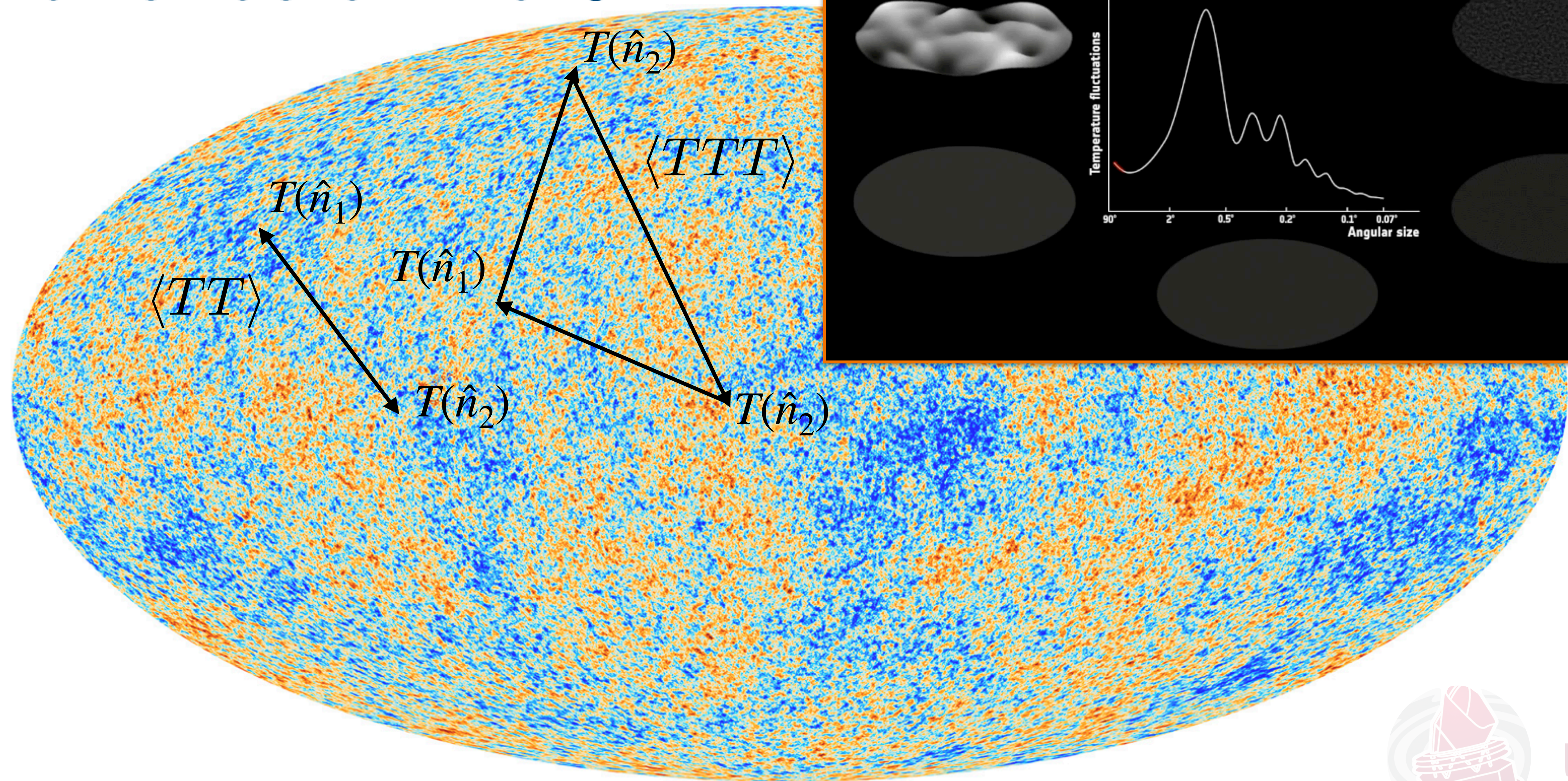
Reionization



Cosmology 101

- **Limited** absolute knowledge
- Rely on **statistical** and relative measures
- We measure the **statistical properties** of a cosmological observable, e.g. moments such as variance, skewness, kurtosis...
- At the **field level**, these are promoted to n -point **correlators**, and to **$n-1$ spectra** in harmonic (ℓ) or momentum space (k)
- If the field is Gaussian, the **power spectrum ($n = 2$)** contains all information

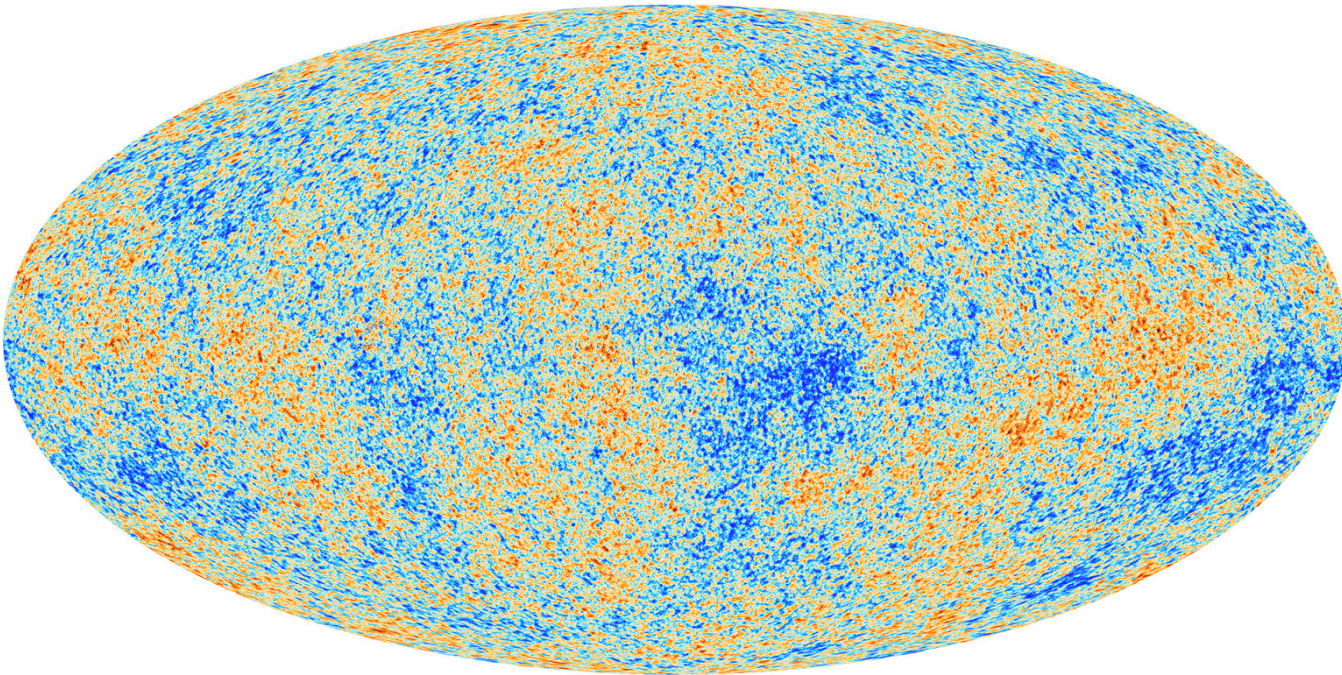
Statistics of the CMB



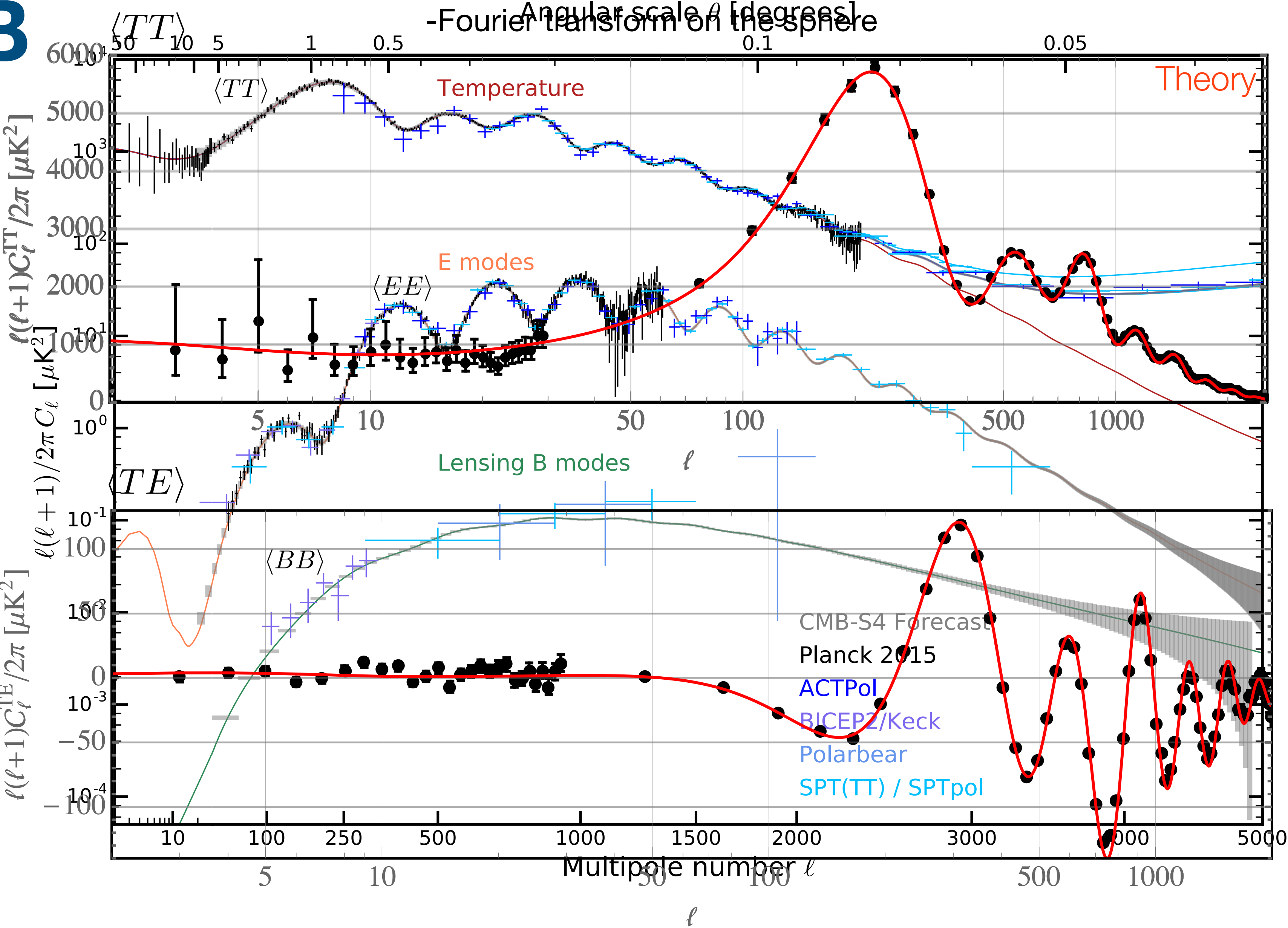
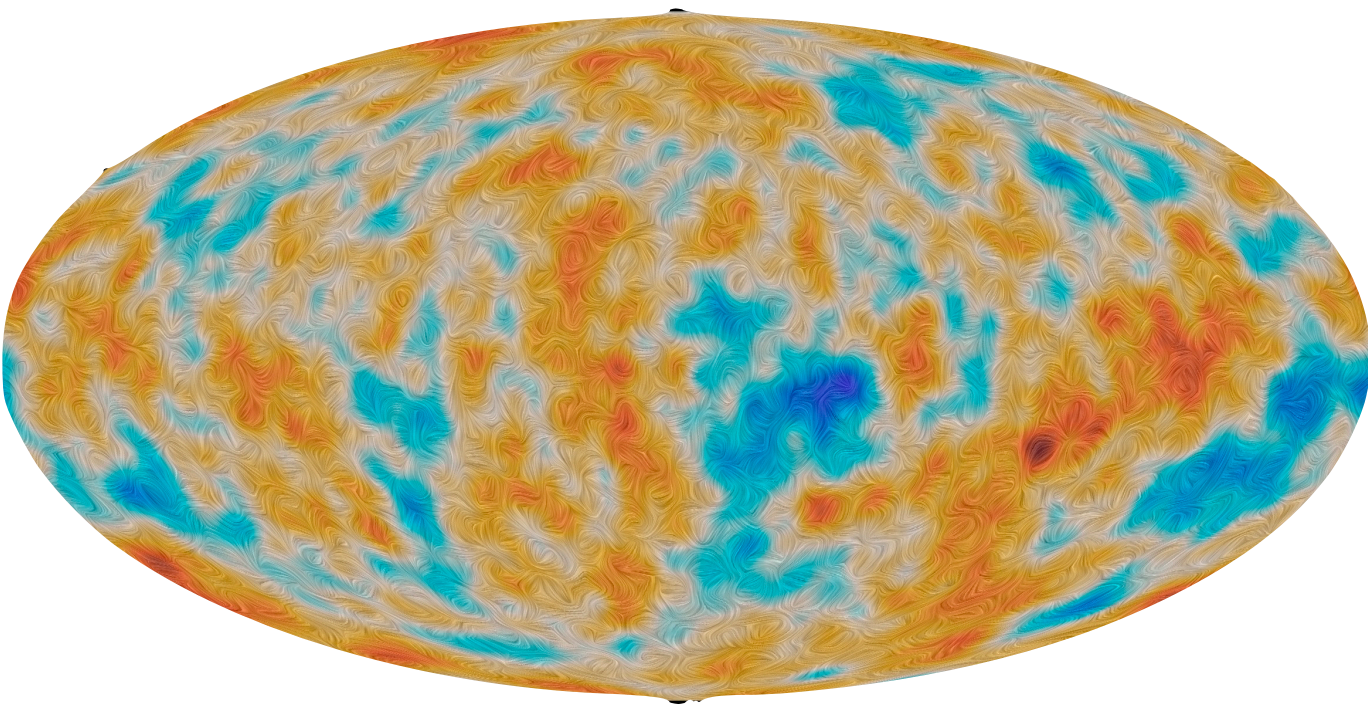
planck

Planck CMB

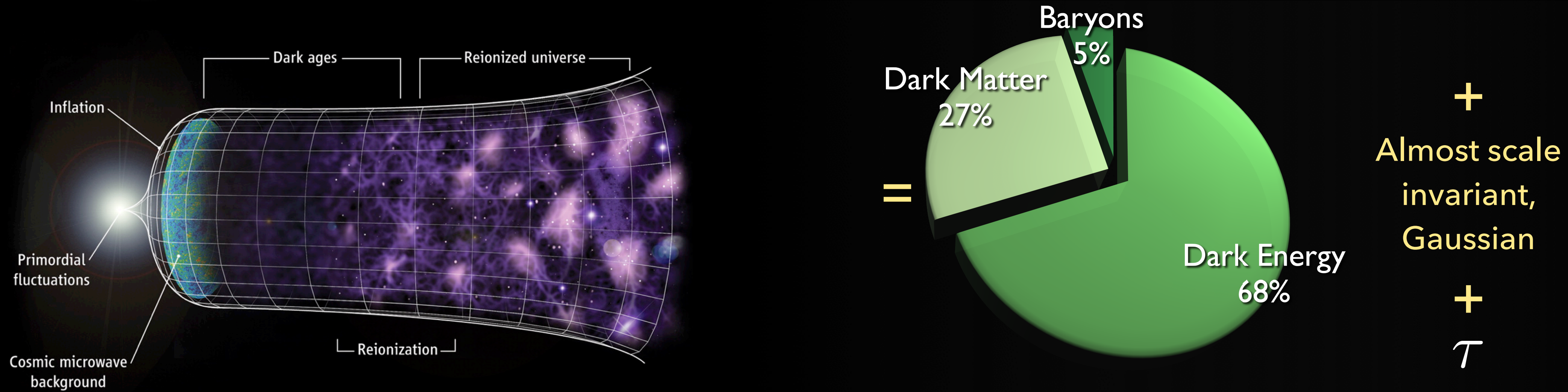
Temperature



Polarisation



The Concordance Model

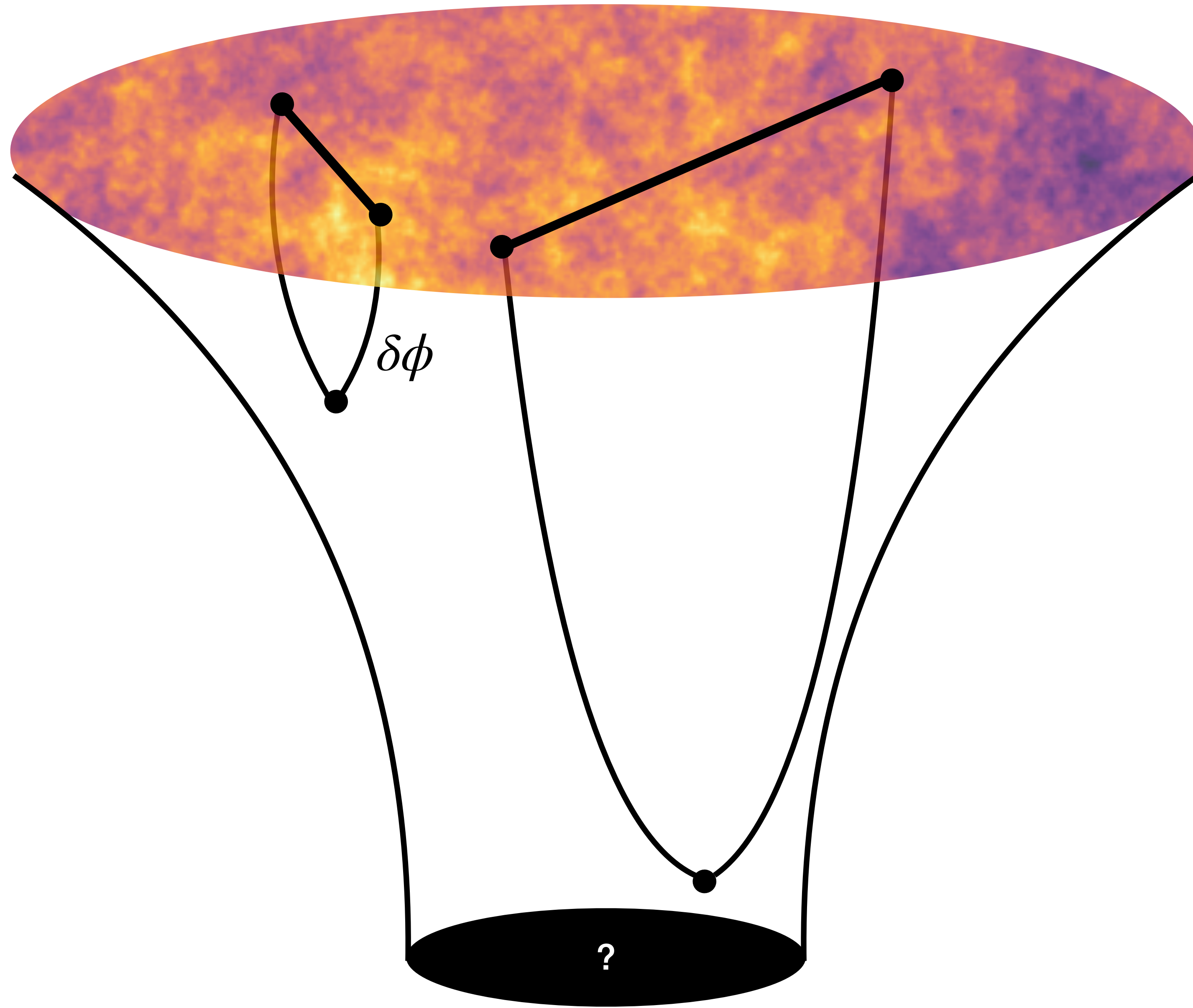


- Concordance model: Lambda Cold Dark Matter model (LCDM) ; Hot Big Bang
- **Only 6 parameters.** Empirical Evidence for Dark Matter, Dark energy, and Inflation
- **Densities:** $\Omega_b h^2$ $\Omega_c h^2$ $H_0 = 100h$ ▸ **Initial conditions:** A_s n_s
- Gravitational waves are not part of LCDM, but are natural prediction

The early universe

- Want to learn about the **very early Universe**
- Particularly, physics of **inflation** (or alternatives)
- At the Gaussian level, only the power spectrum
- **Any model of the early universe** is constrained only by
 - The scale dependence of the power spectrum (n_s)
 - The presence of primordial gravitational waves (r)

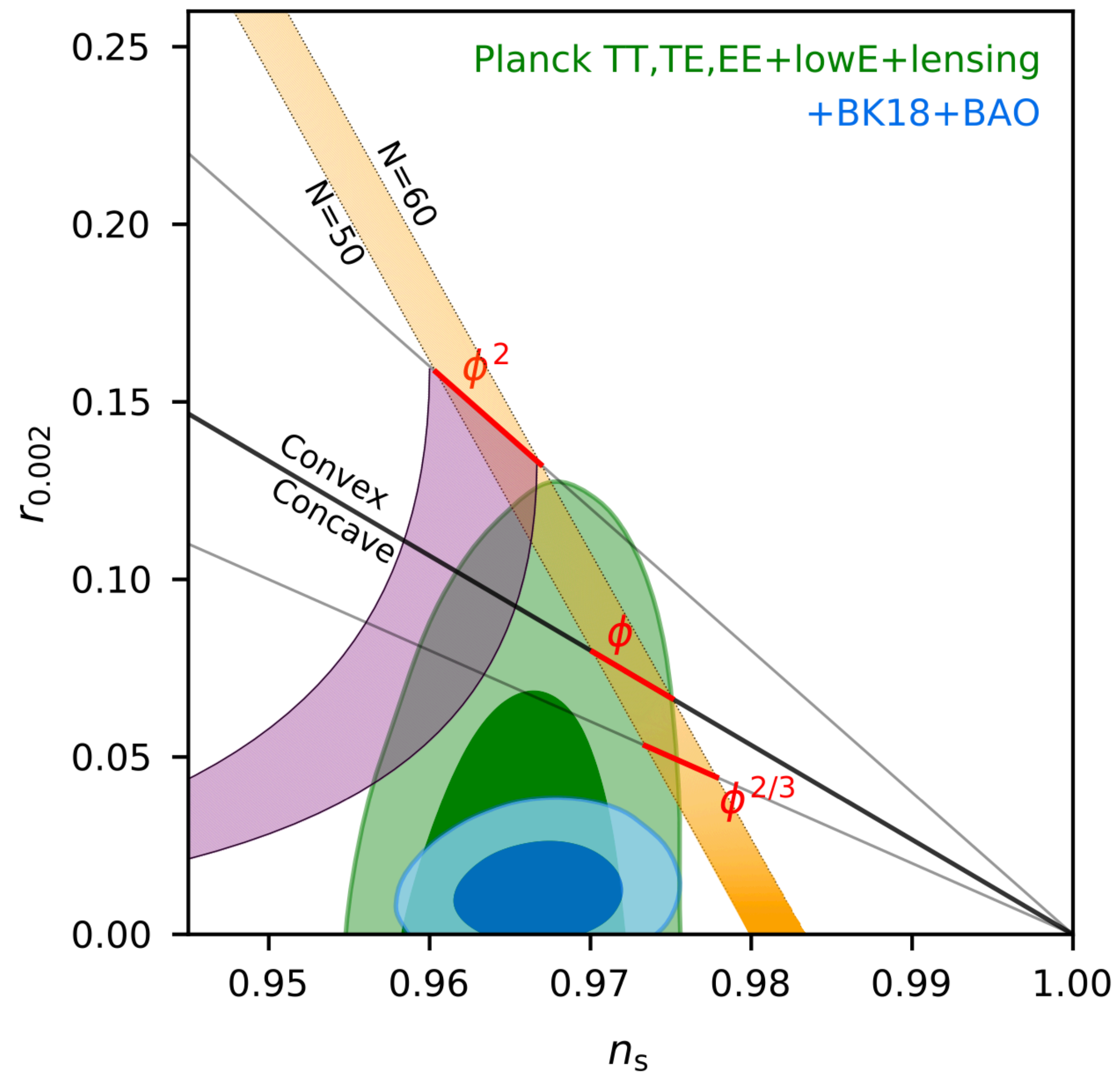
Inflation



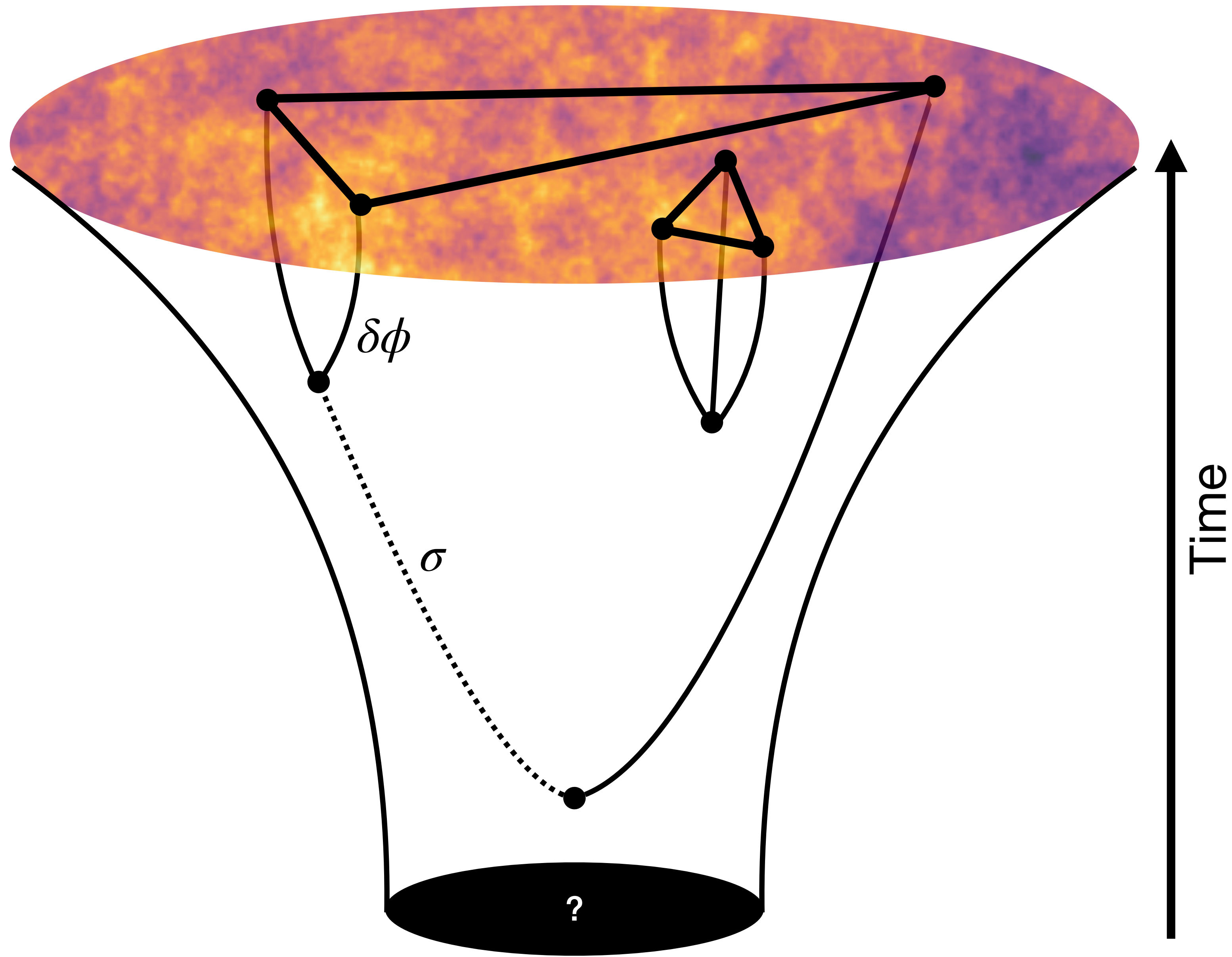
End ($t \sim 10^{-33}$ sec)

Time

Beginning



Beyond Gaussian Statistics



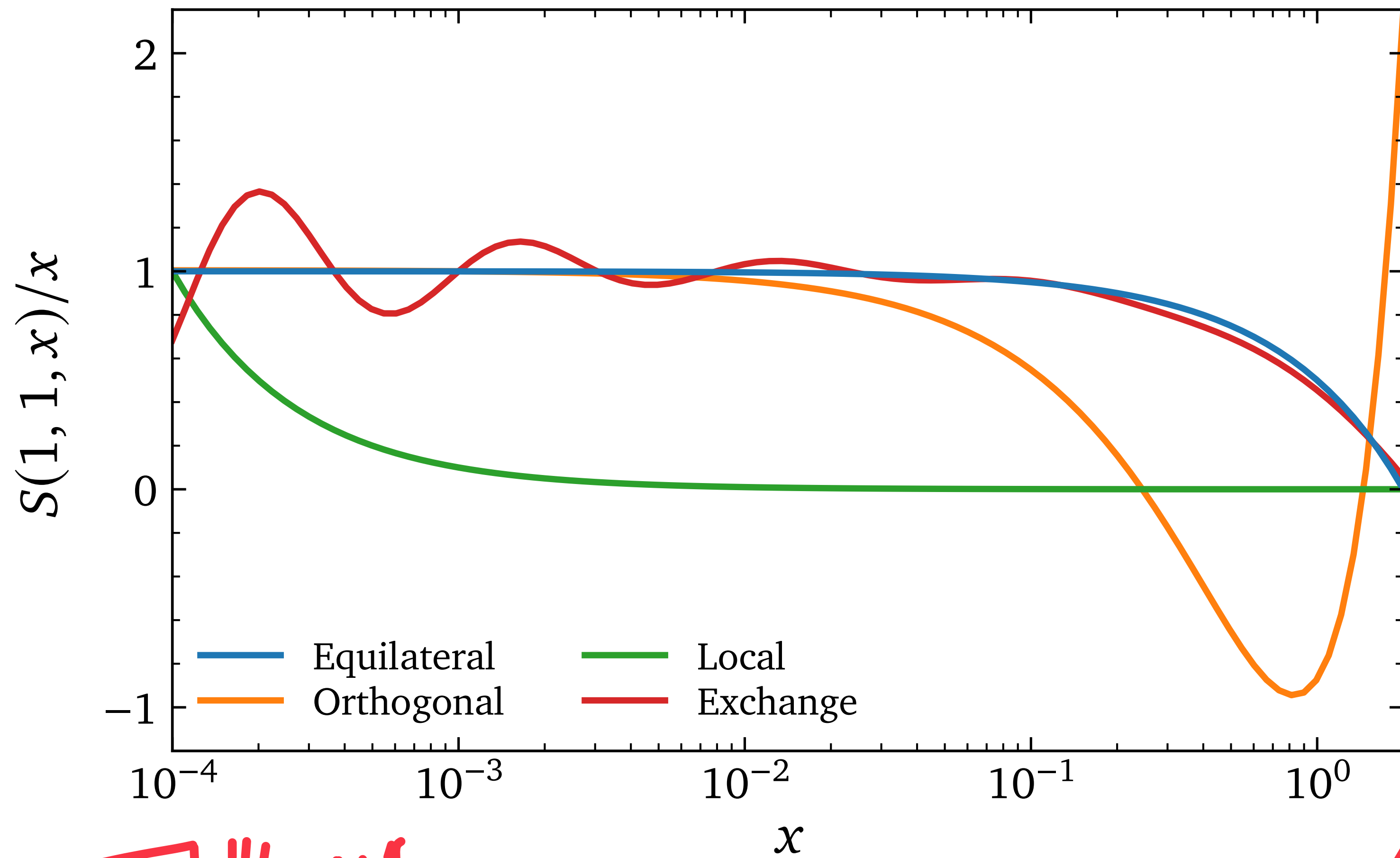
Primordial Non-Gaussianities

Theory: sources of non-Gaussianity

- (Large) non-Gaussianities can be realised through many mechanisms:
 - Additional fields
 - Strong self-interactions
 - Non-standard vacuum
 - Heavy particles (cosmological collider)
 - Non-attractor dynamics
 - Classical production
 - Magnetic fields?
 - Strings?
 - Alternative models?
 - ...

$$\langle \delta\phi_{\mathbf{k}_1} \delta\phi_{\mathbf{k}_2} \delta\phi_{\mathbf{k}_3} \rangle \propto \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) f_{\text{NL}}^{\text{type}} \frac{S^{\text{type}}(k_1, k_2, k_3)}{k_1^2 k_2^2 k_3^2}$$

Achucarro et al 2022



"LOCAL"

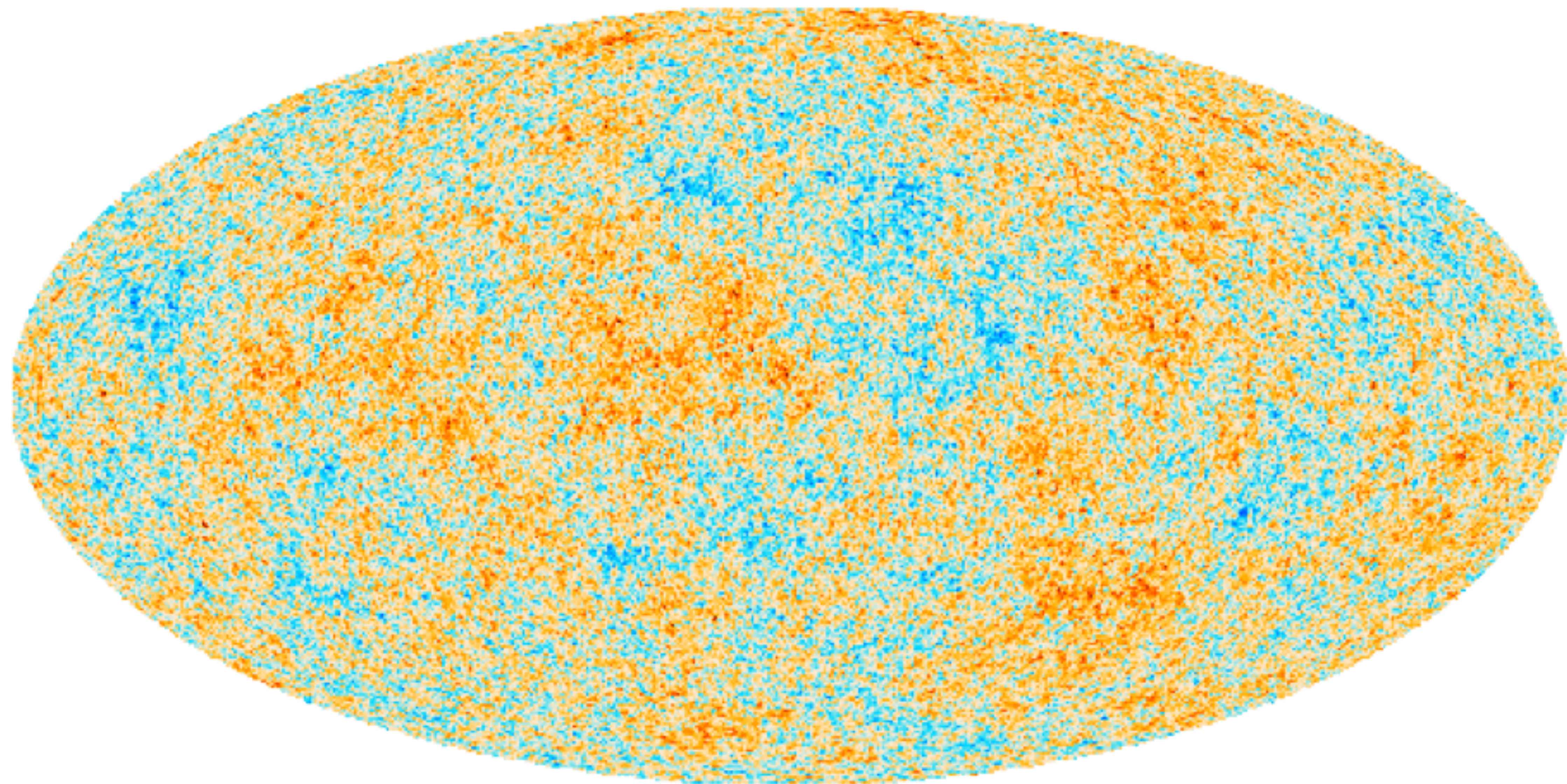
"EQUILATERAL"

$$x \equiv k_{1,2}/k_3$$

	$f_{\text{NL}}^{\text{loc}} \lesssim 1$	$f_{\text{NL}}^{\text{loc}} \gtrsim 1$
$f_{\text{NL}}^{\text{eq, orth}} \lesssim 1$	Single-field slow-roll	Multi-field
$f_{\text{NL}}^{\text{eq, orth}} \gtrsim 1$	Single-field non-slow-roll	Multi-field

Detecting Non-Gaussianities

$$f_{\text{NL}} = 0$$



State-of-the-art and beyond

- Current CMB (Planck) consistent with zero and $\sigma(f_{\text{NL}}) \sim \mathcal{O}(10 - 100)$
- What is next?
- Simons Observatory
- Let us take a peek!

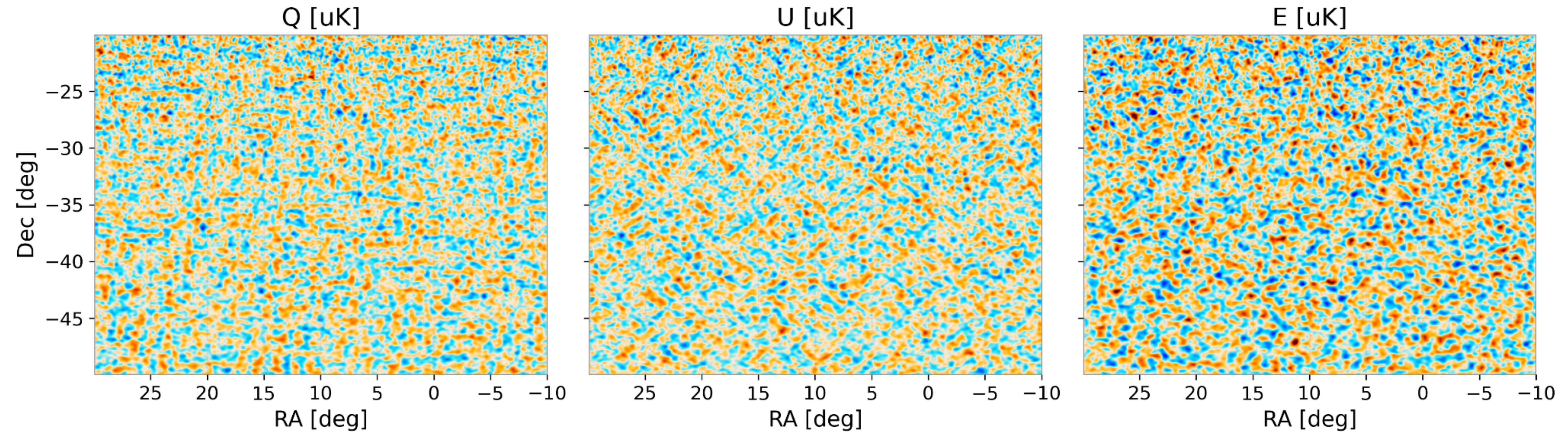
Simons Observatory

- Atacama, 5000m
- 7 telescopes: 1 LAT and 6 SAT's
- Up to 100.000 detectors, 6 frequencies (27-280GHz)
- Mapping speed is 5 times faster compared to best-of-the-rest
- Initial science observation runs



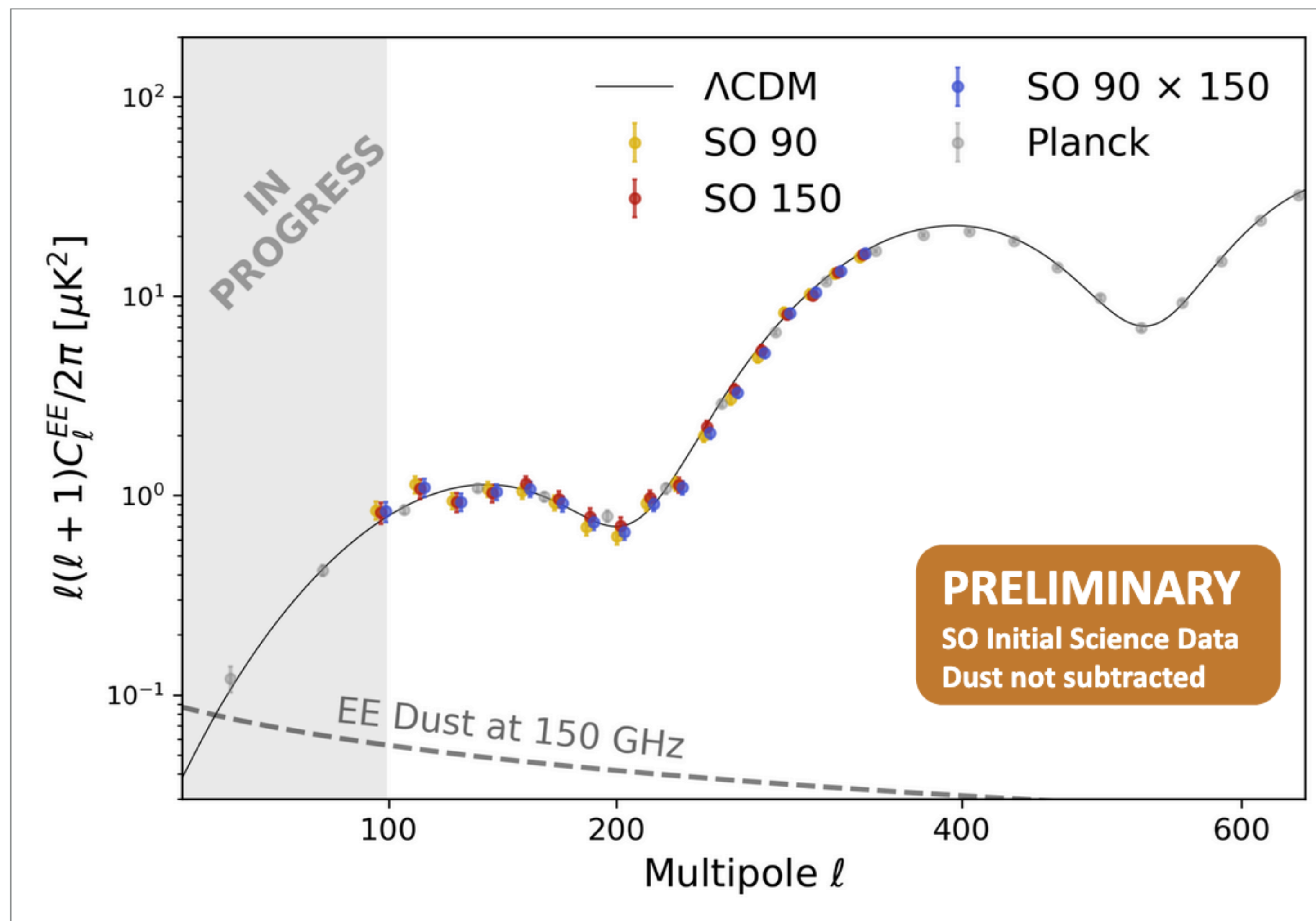
Simons Observatory (SAT)

PRELIMINARY
SO Initial Science Data

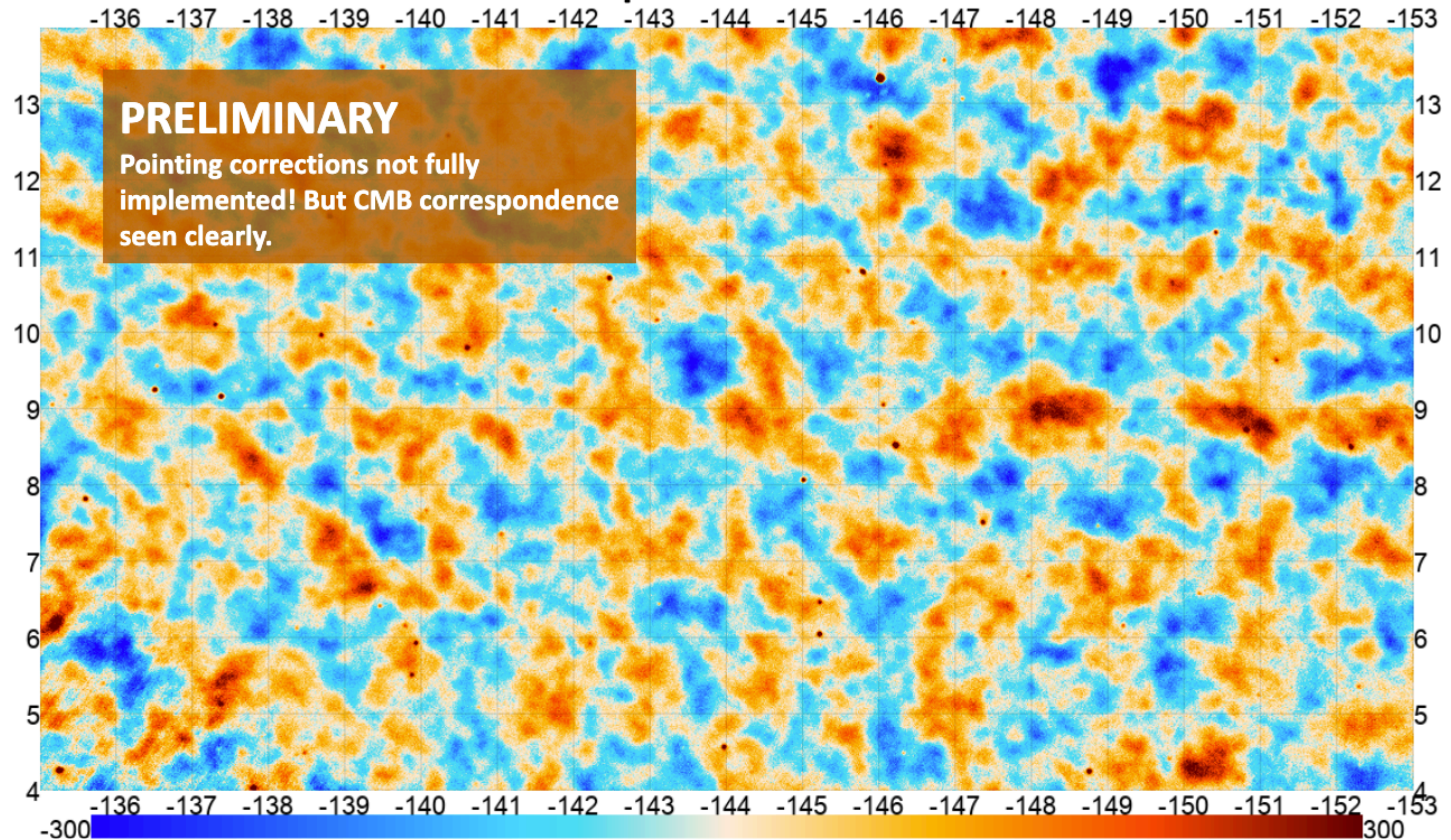


Simons Observatory (SAT)

CMB polarization power spectrum

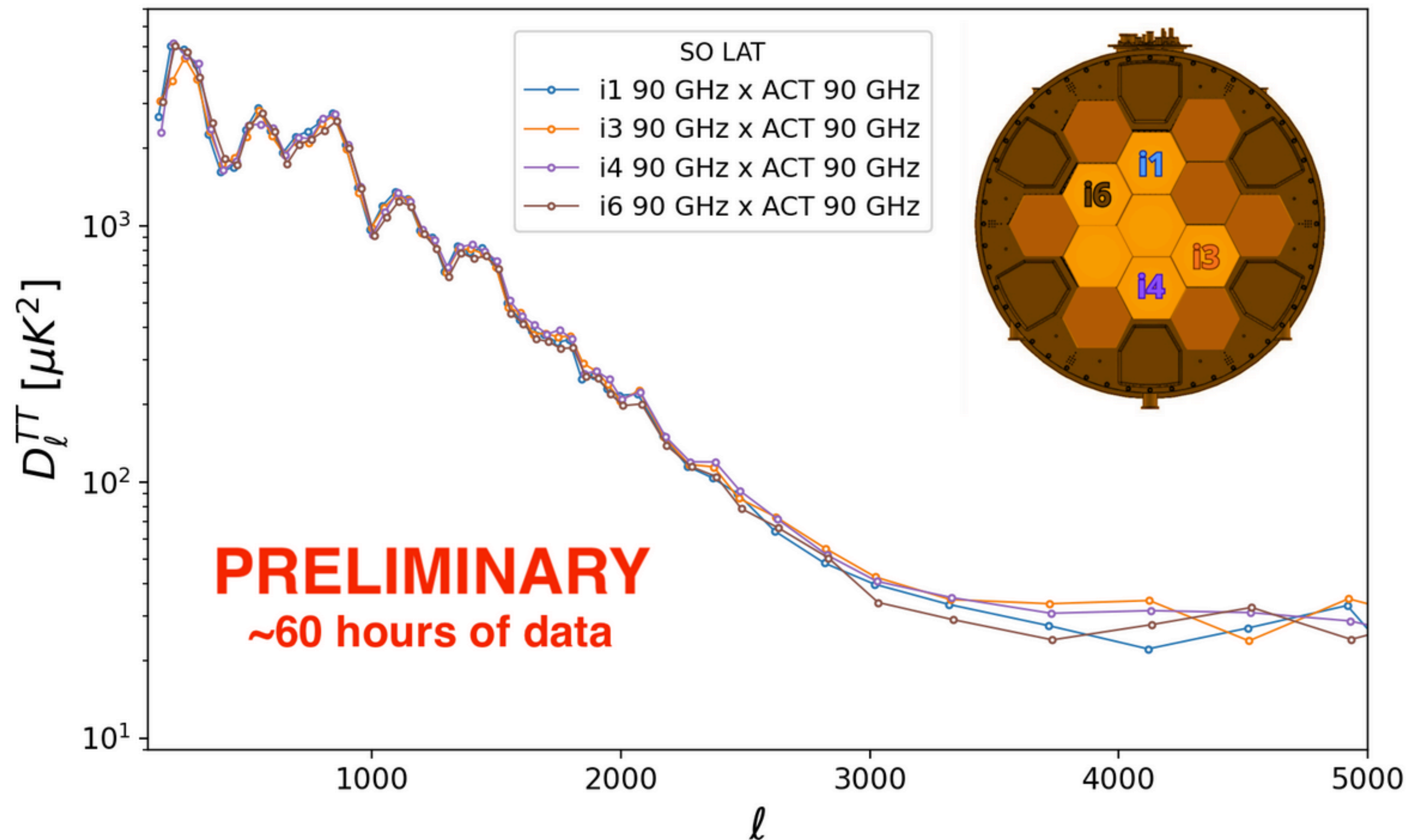


Simons Observatory (LAT)

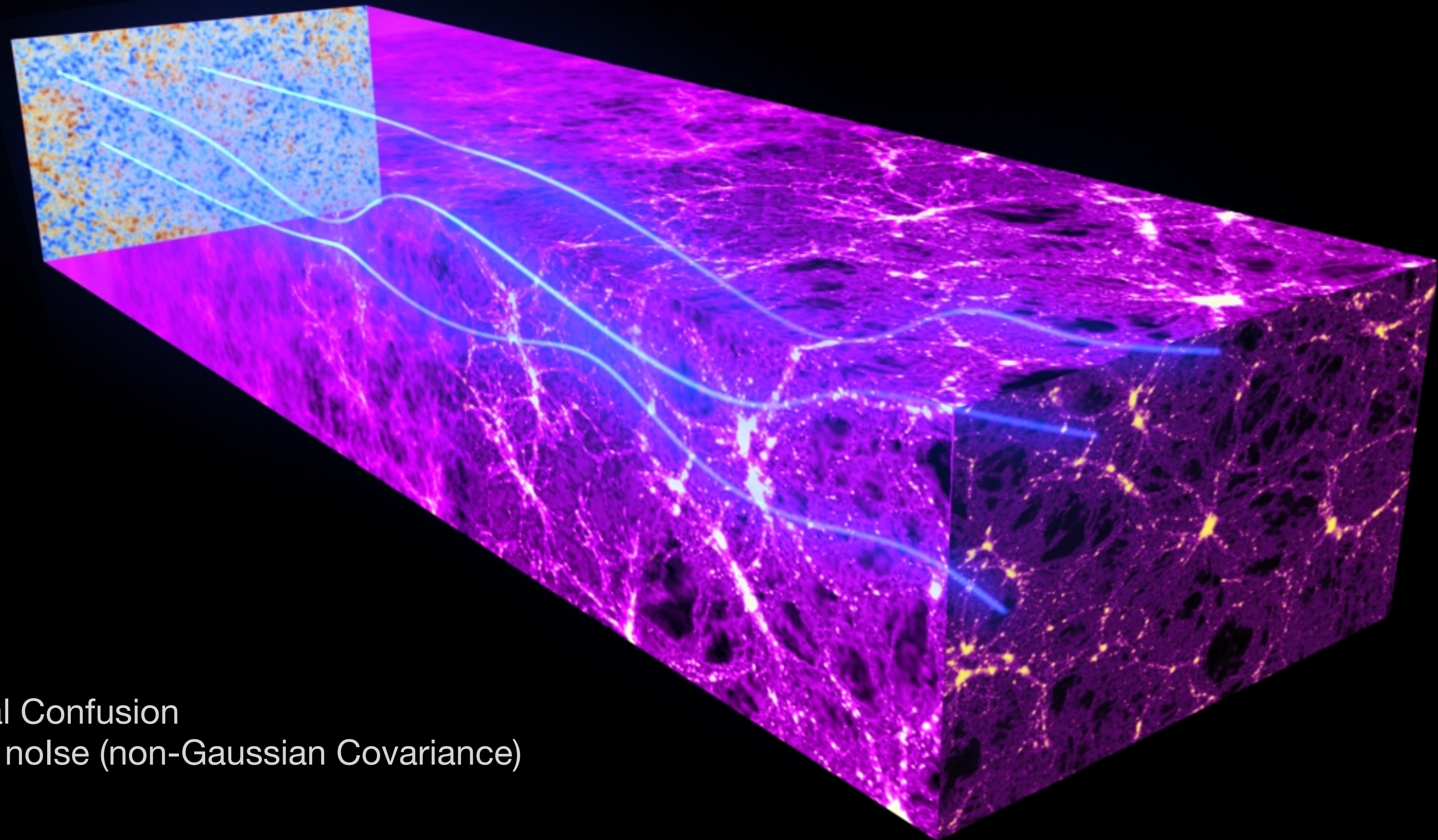


Simons Observatory (LAT)

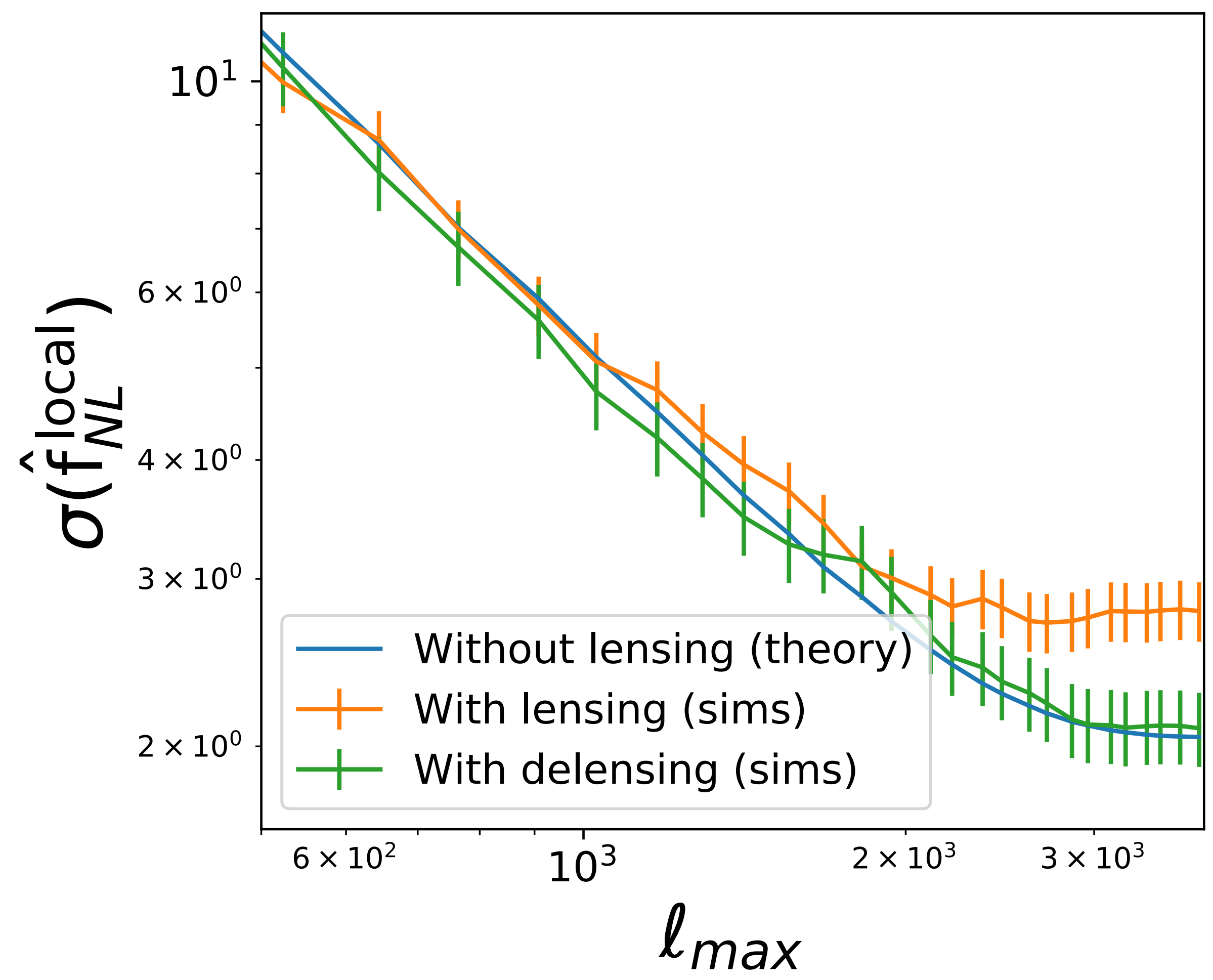
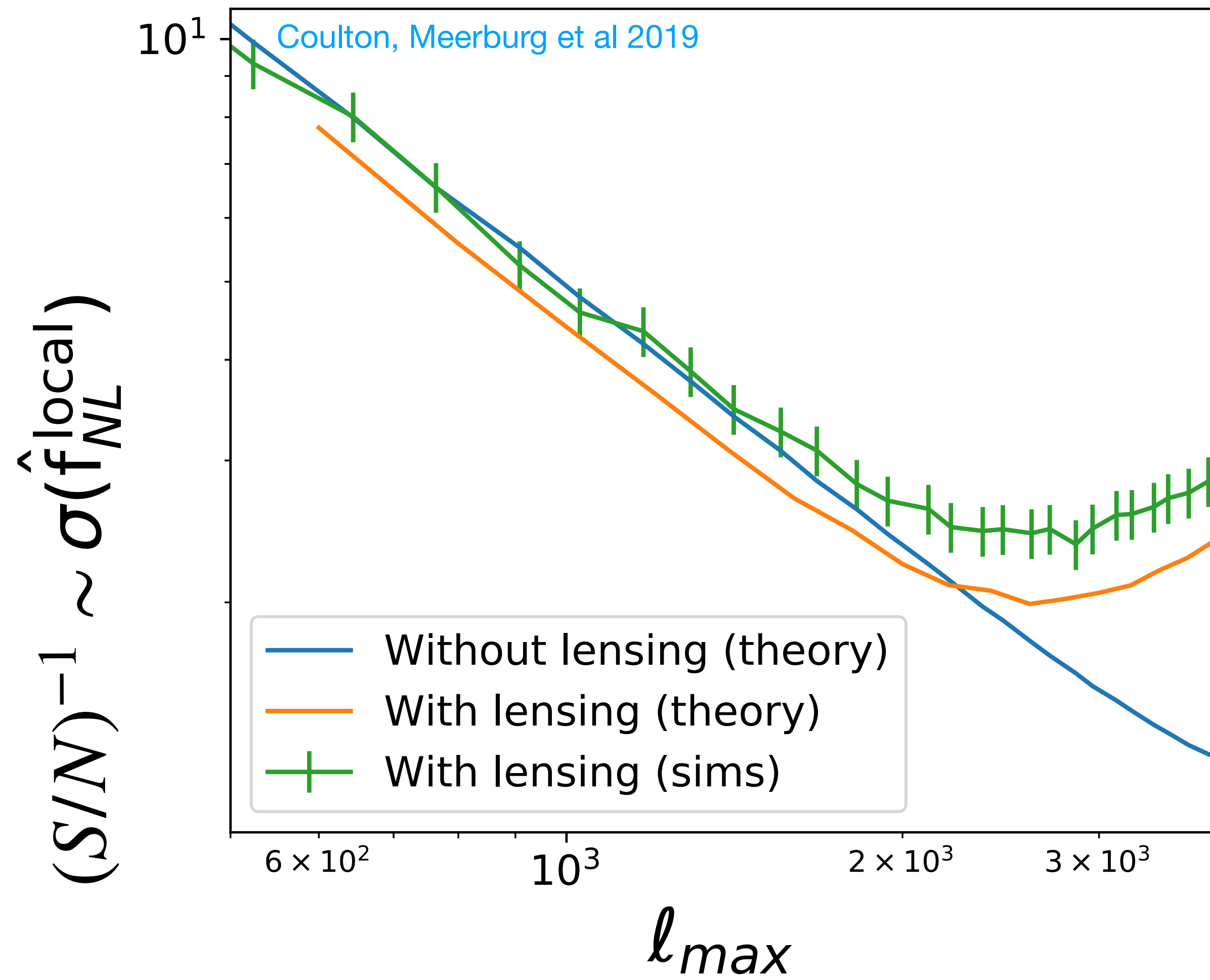
CMB temperature power spectrum



What about non-Gaussianities



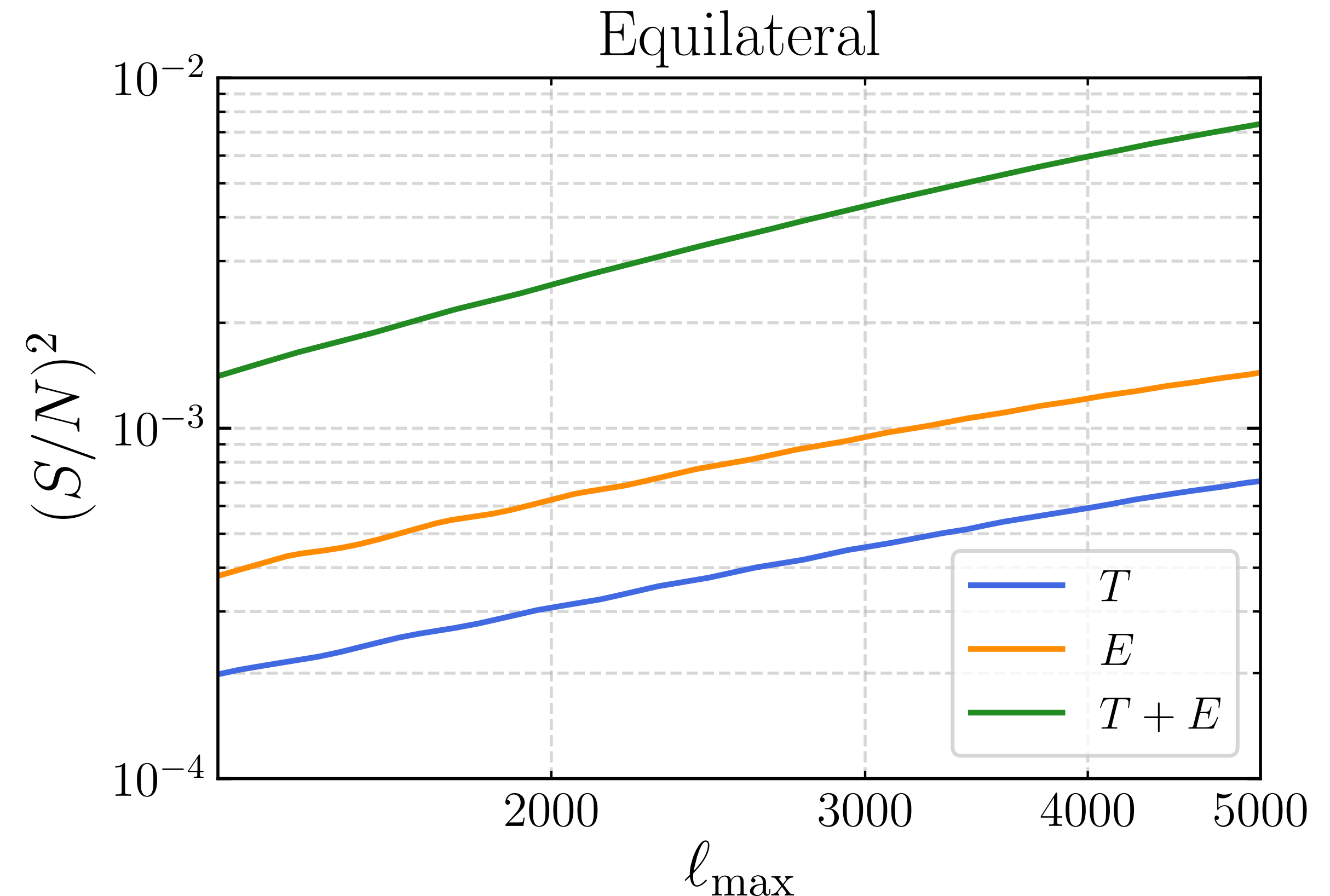
- Signal Confusion
- Extra noise (non-Gaussian Covariance)



Beyond SO

- Forecasted signal to noise, assuming no thermal noise, full sky, no secondaries
- Temperature and E-mode polarisation
 - S/N = signal to noise
 - $S/N = 3 = 3$ sigma
- Power law growth is indicative of measuring independent scales (“modes”)
- Main conclusion: hard to reach thresholds with CMB measurements

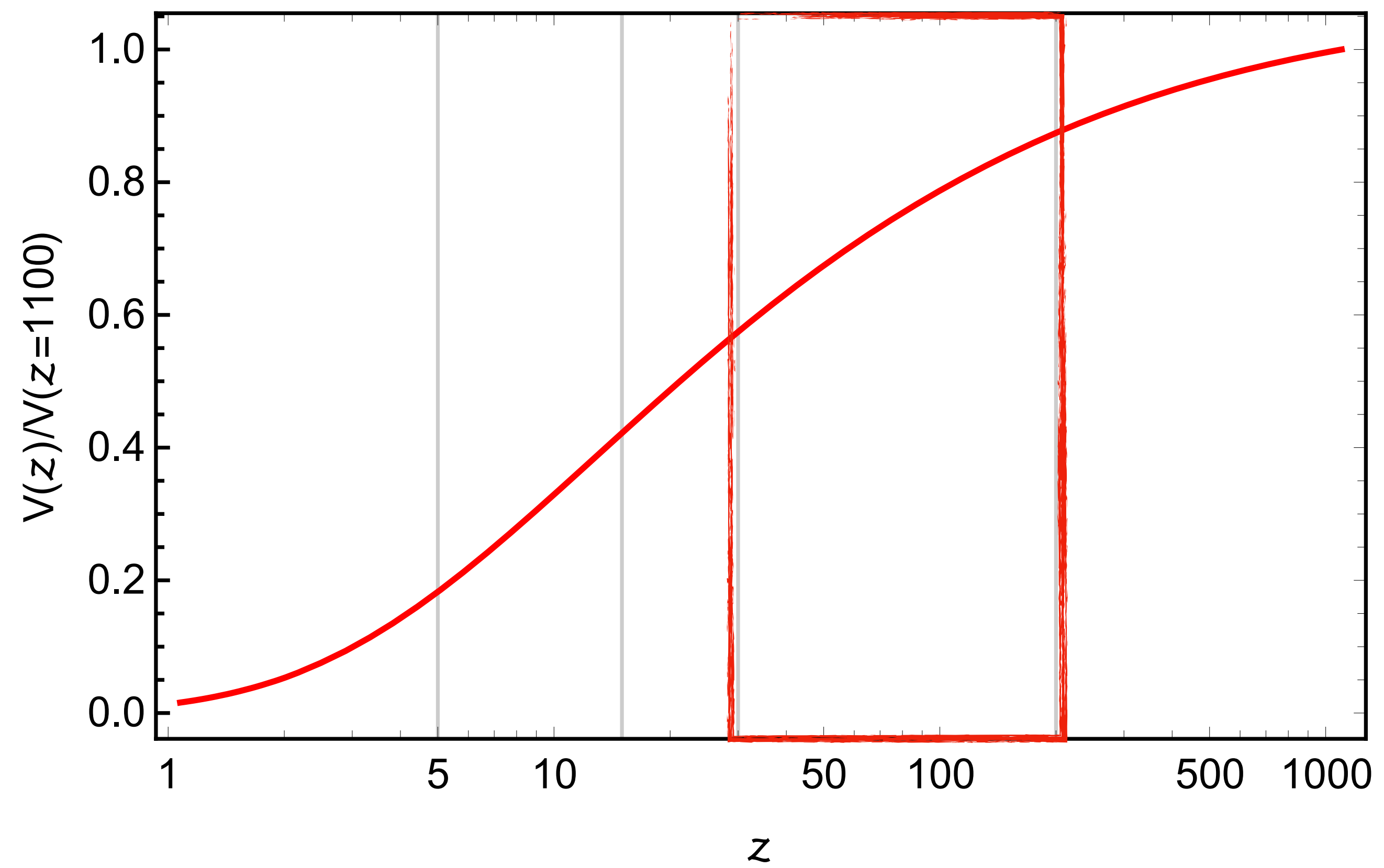
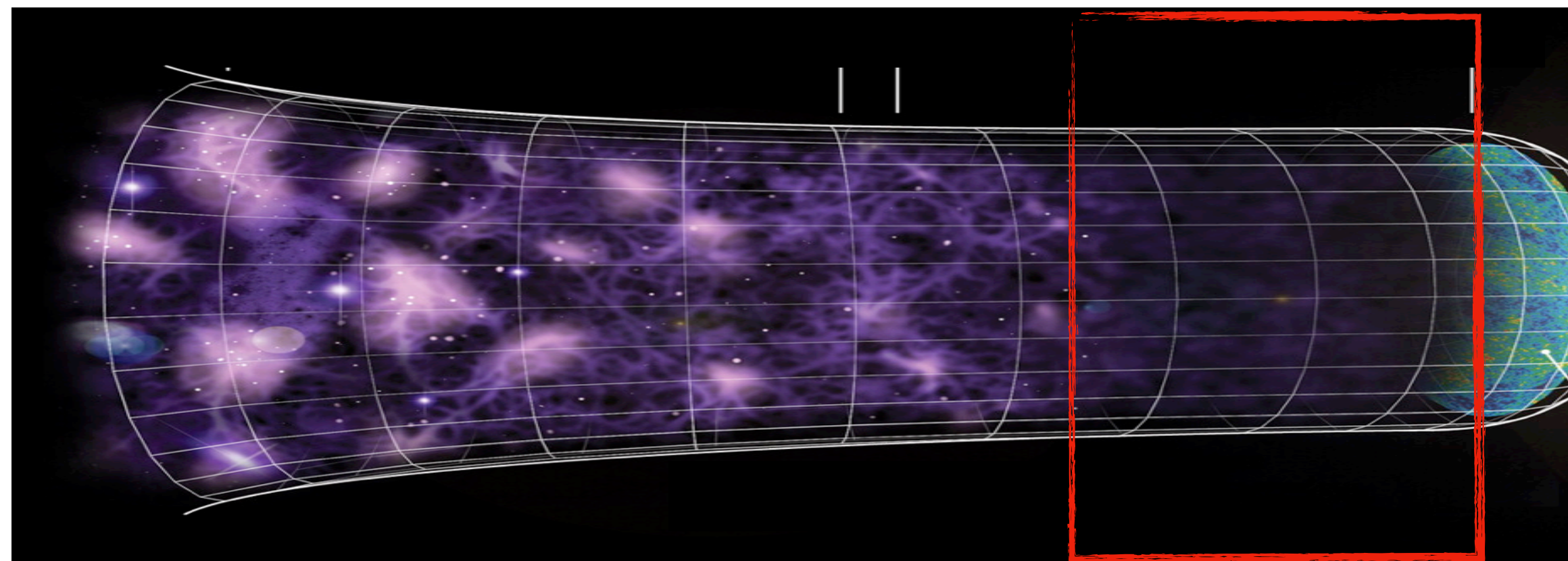
Kalaja, Pimentel, Meerburg, Coulton 2020



Future of cosmology

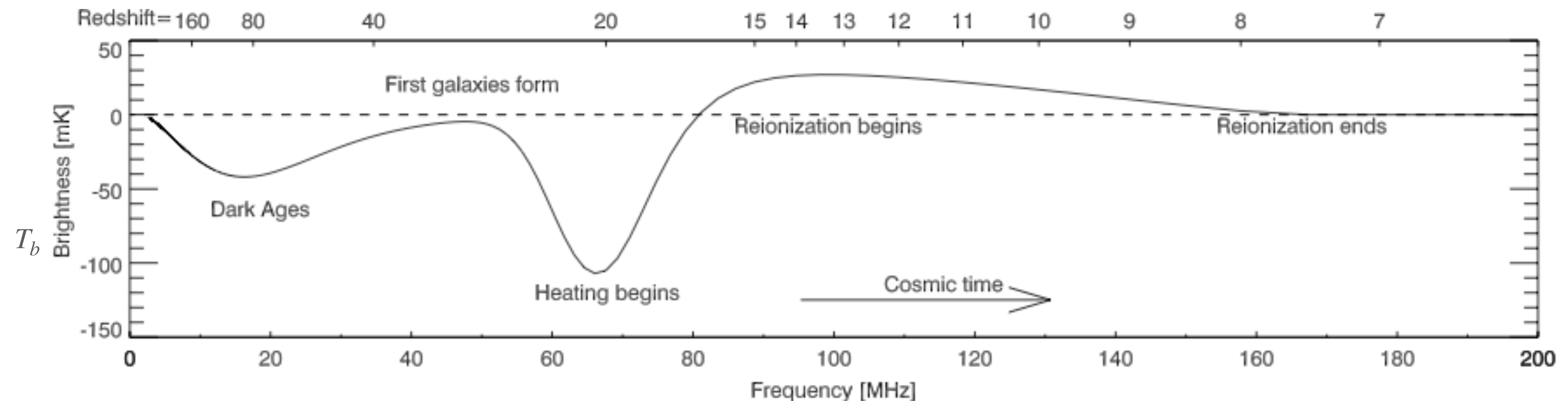
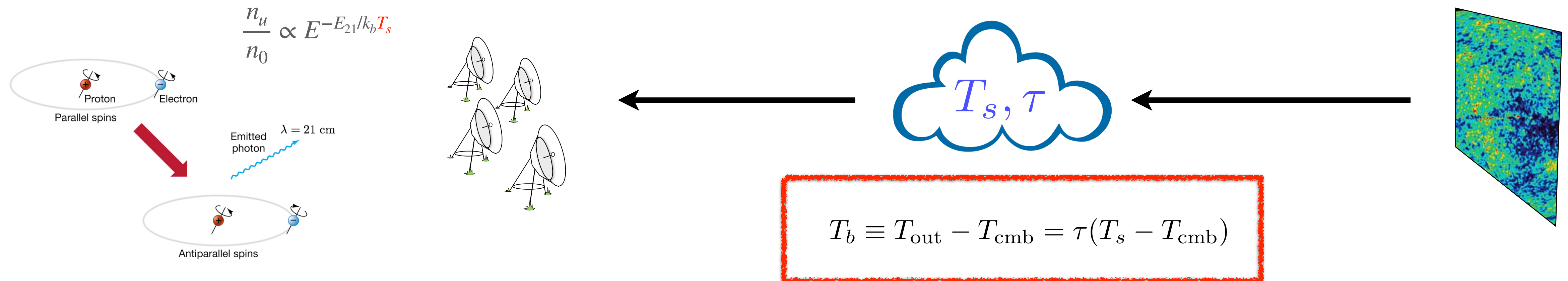
Extracting information

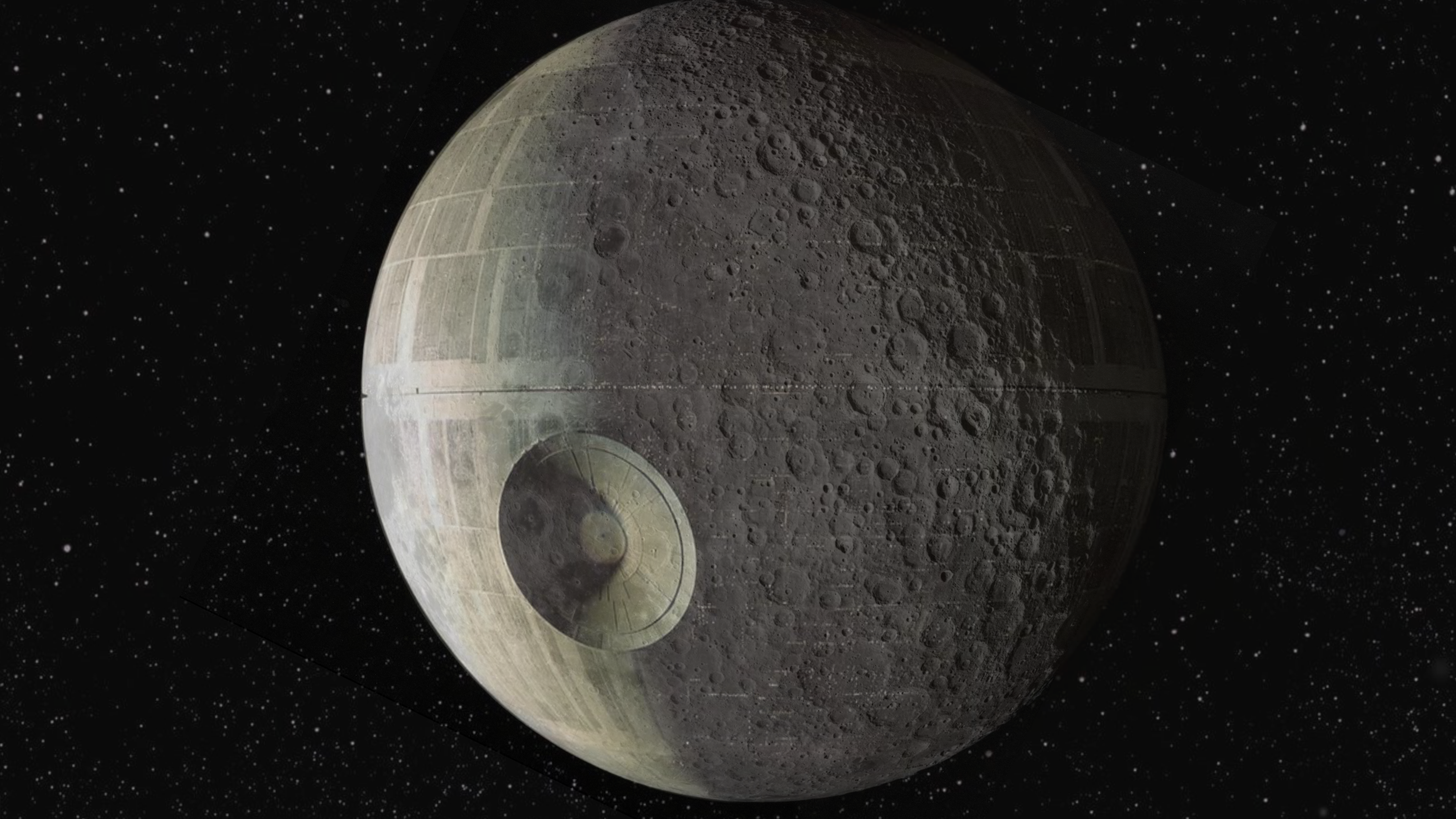
- Suppose you had infinite money, Cosmological inference is limited by
 - The Horizon
 - Cosmic variance
 - Information loss
 - Lack of tracers
 - Foregrounds
 - Technology
 - Systematics
 - Cosmic coincidence



21 cm cosmology

Mapping the entire universe





How crazy is this anyways?

2020:

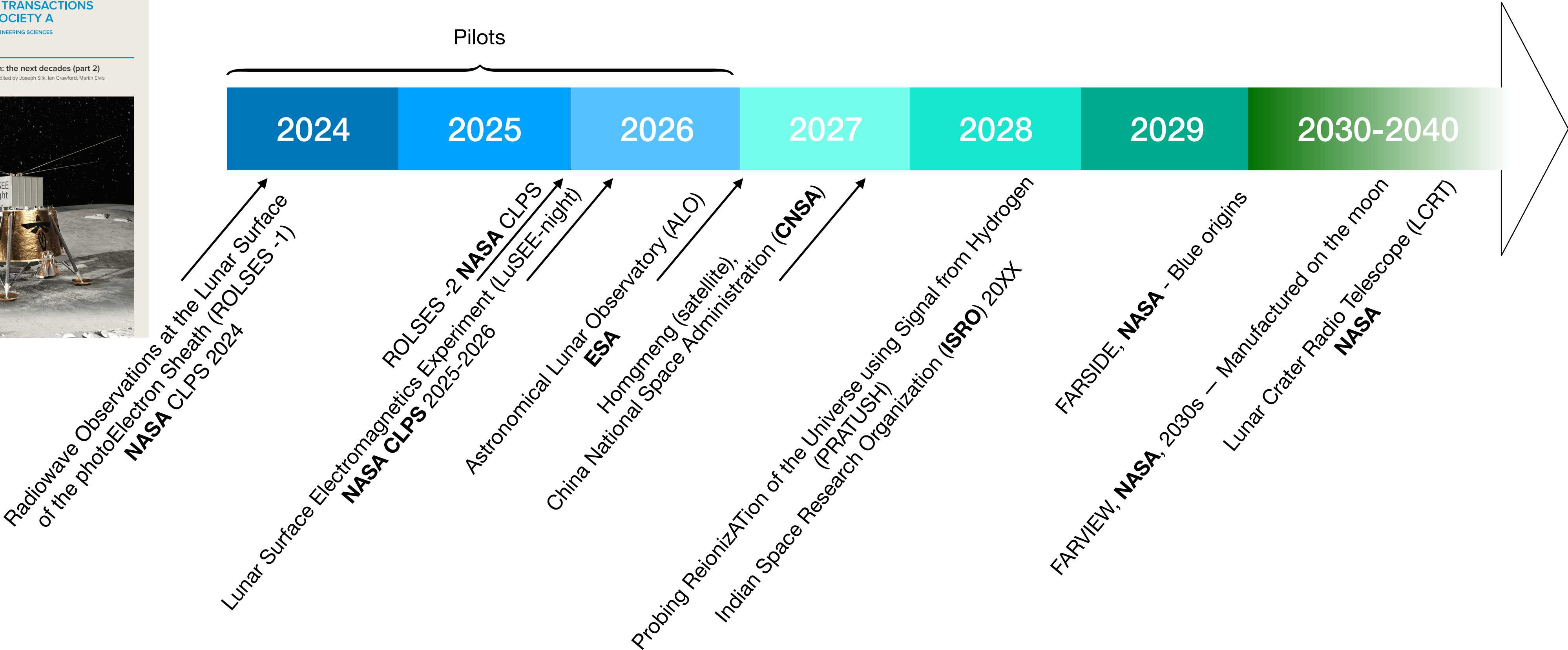
The limits of cosmology: role of the Moon

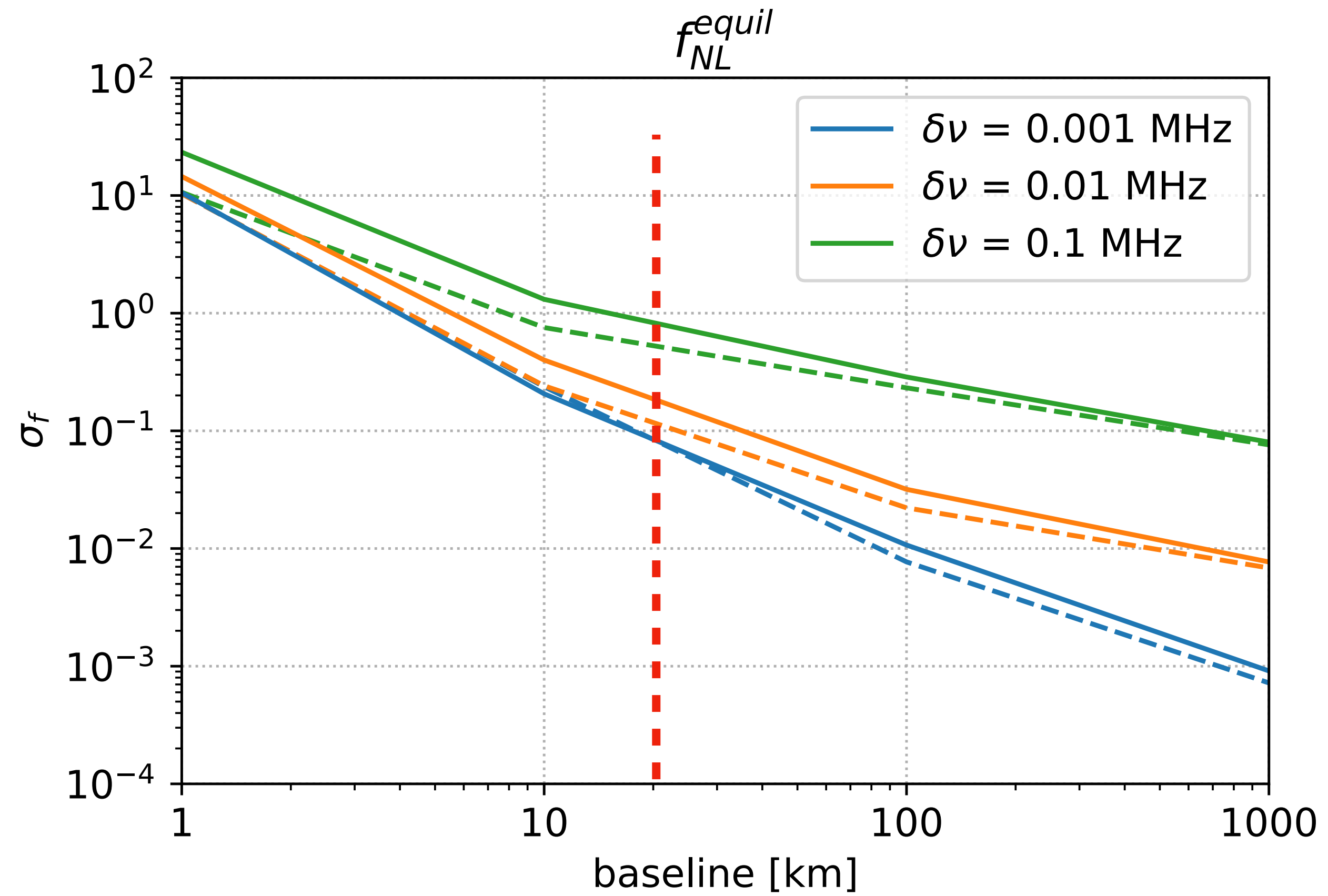
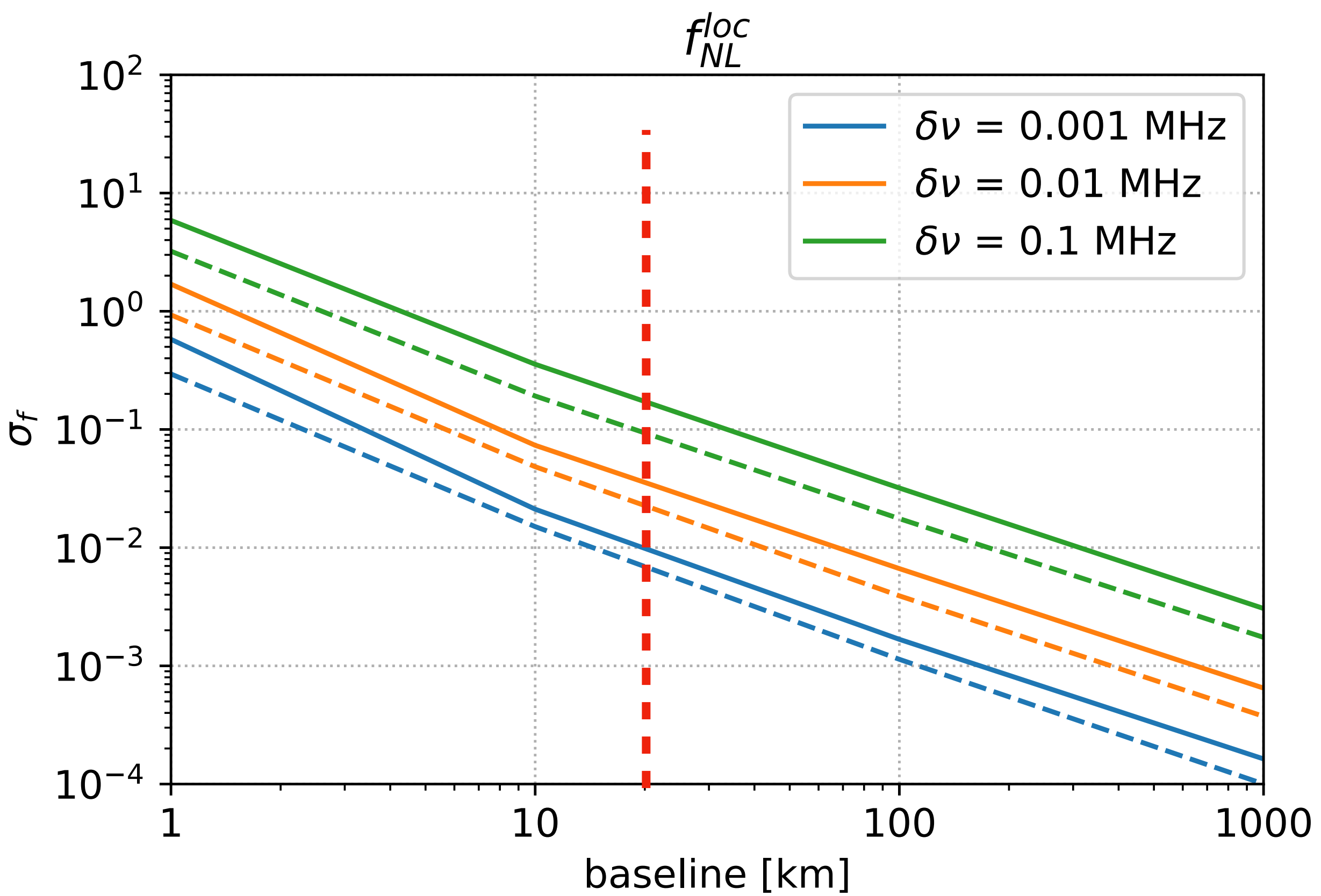
Joseph Silk^{1,2,3, *}

2021:

2024:

J. Burns: “FarView timeline is the 2030s. We are looking at several prospects for deploying a pilot array on the Moon near the end of the decade”



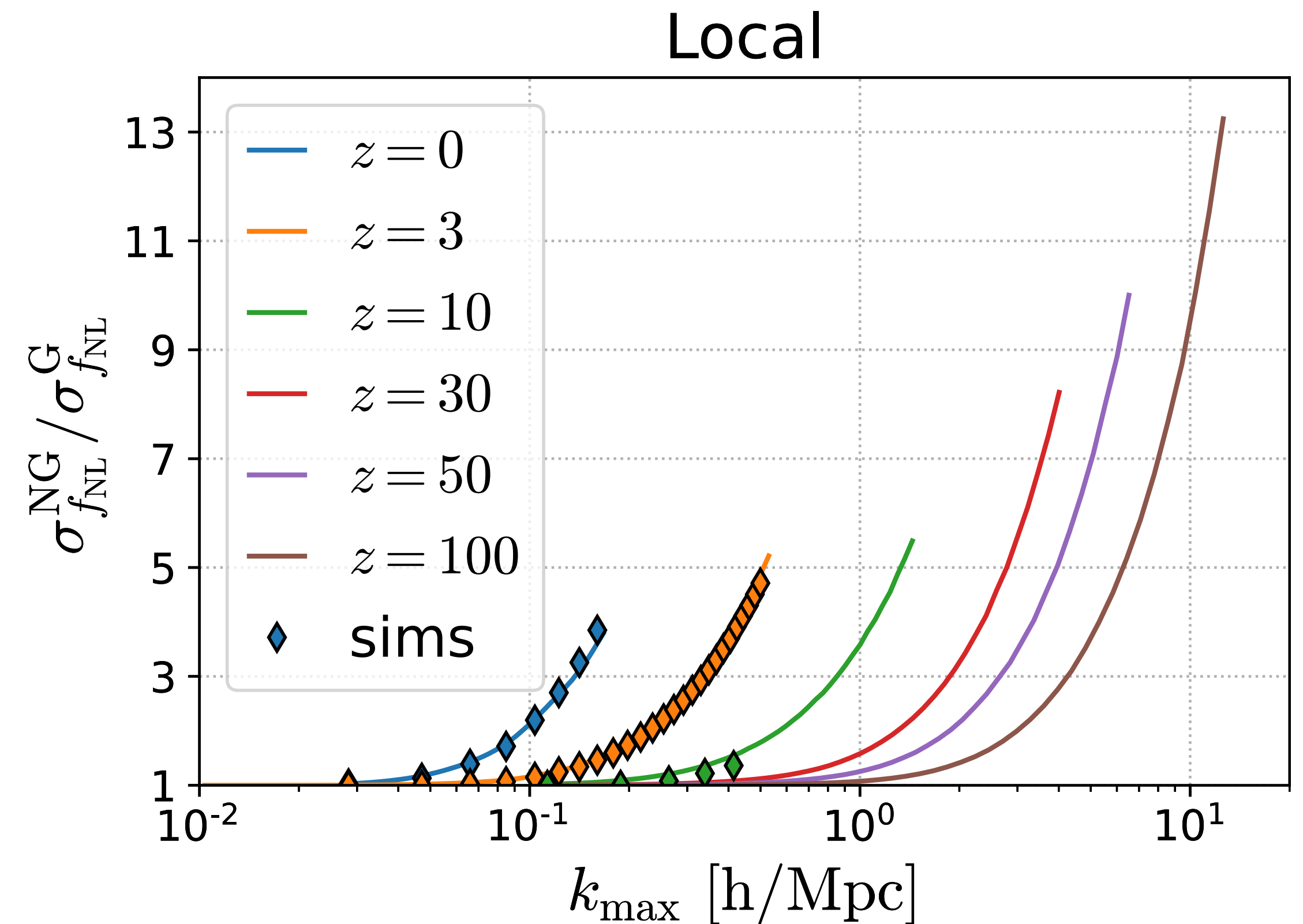
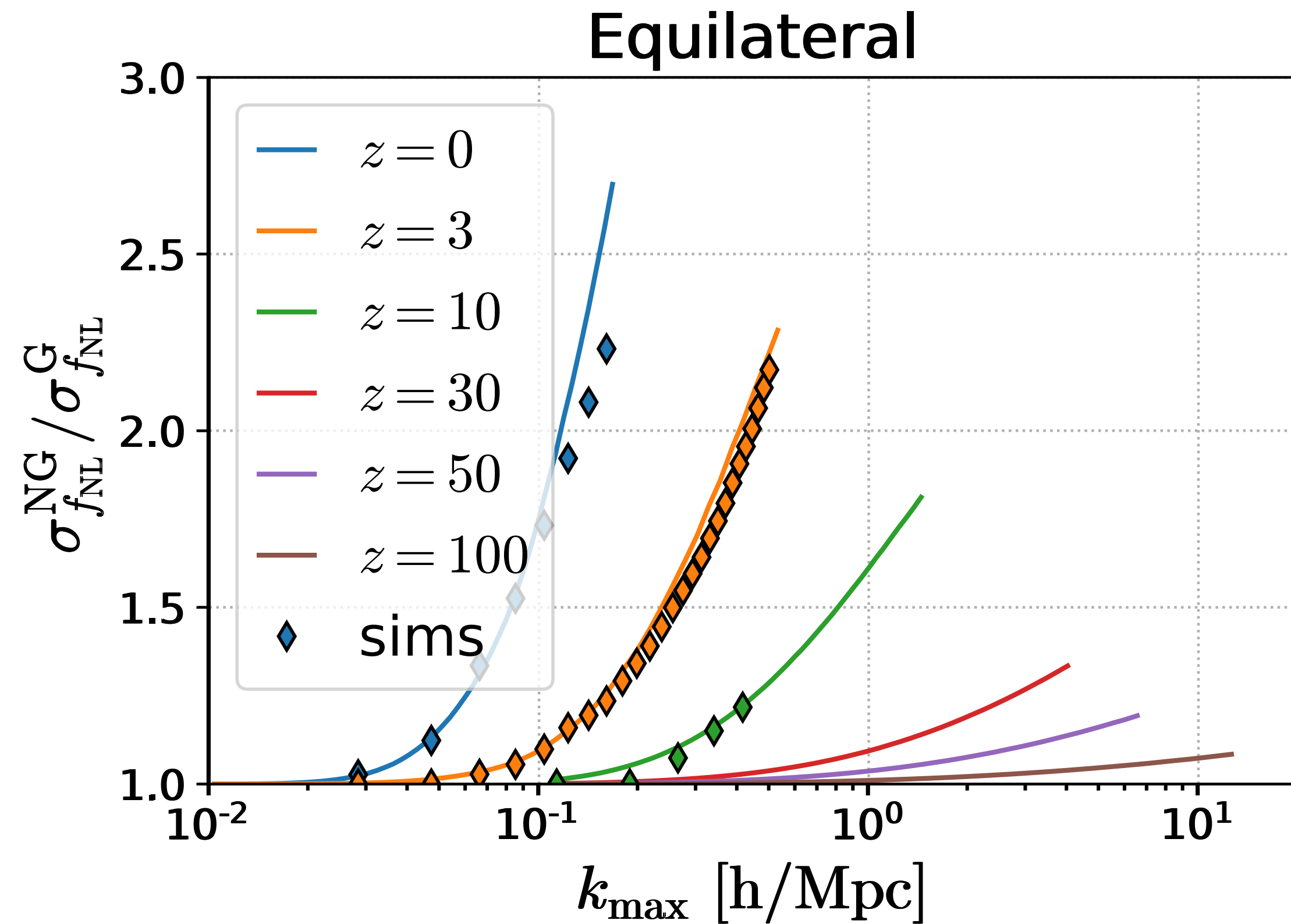


Farview: 10.000 dipoles, 400 km²

Flöss, de Wild, Meerburg, Koopmans, 2021
(See also Munoz et al 2015 and Meerburg et al 2016)

Non-Gaussian Covariance

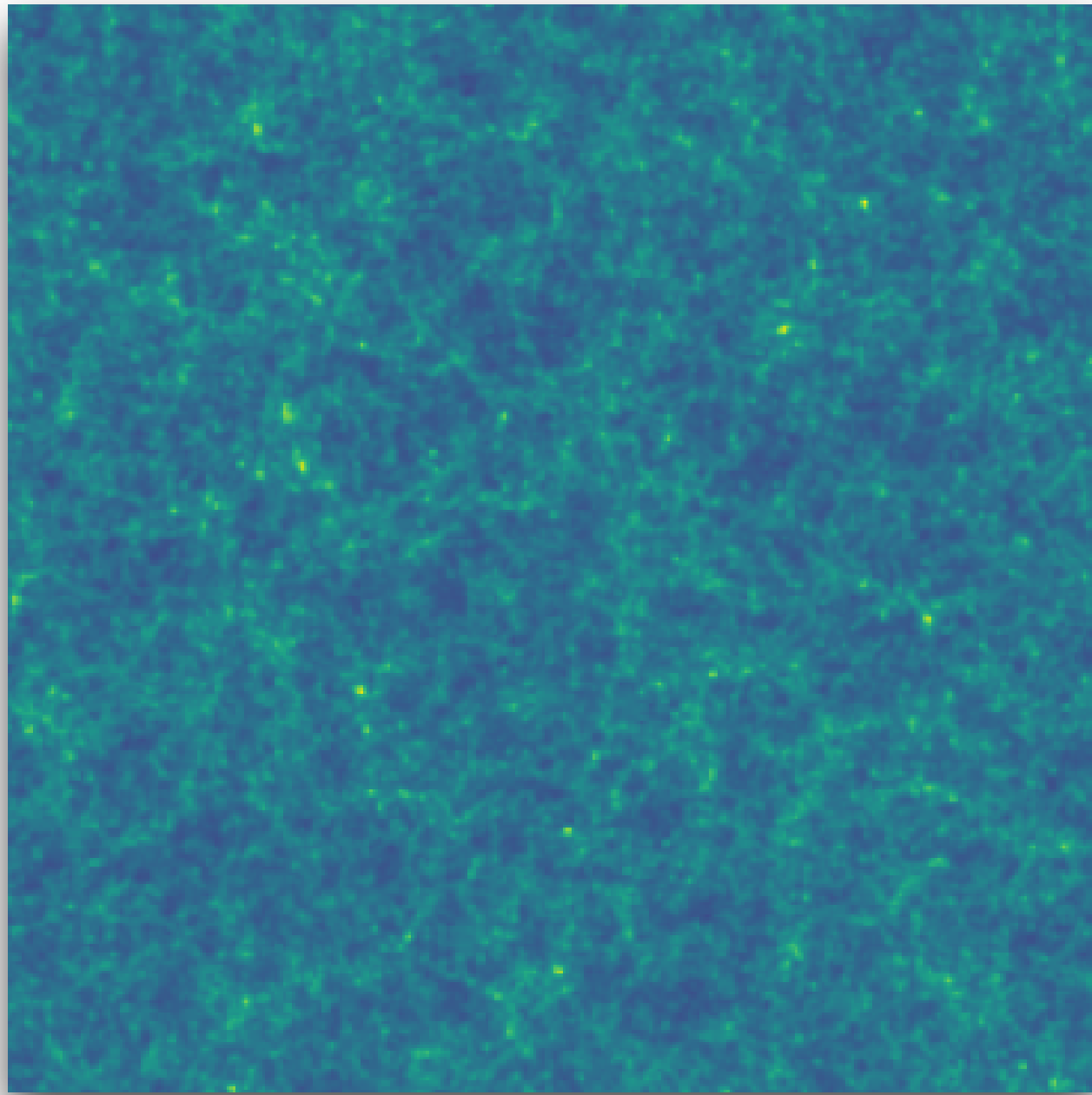
Flöss, Biagetti and Meerburg 2022



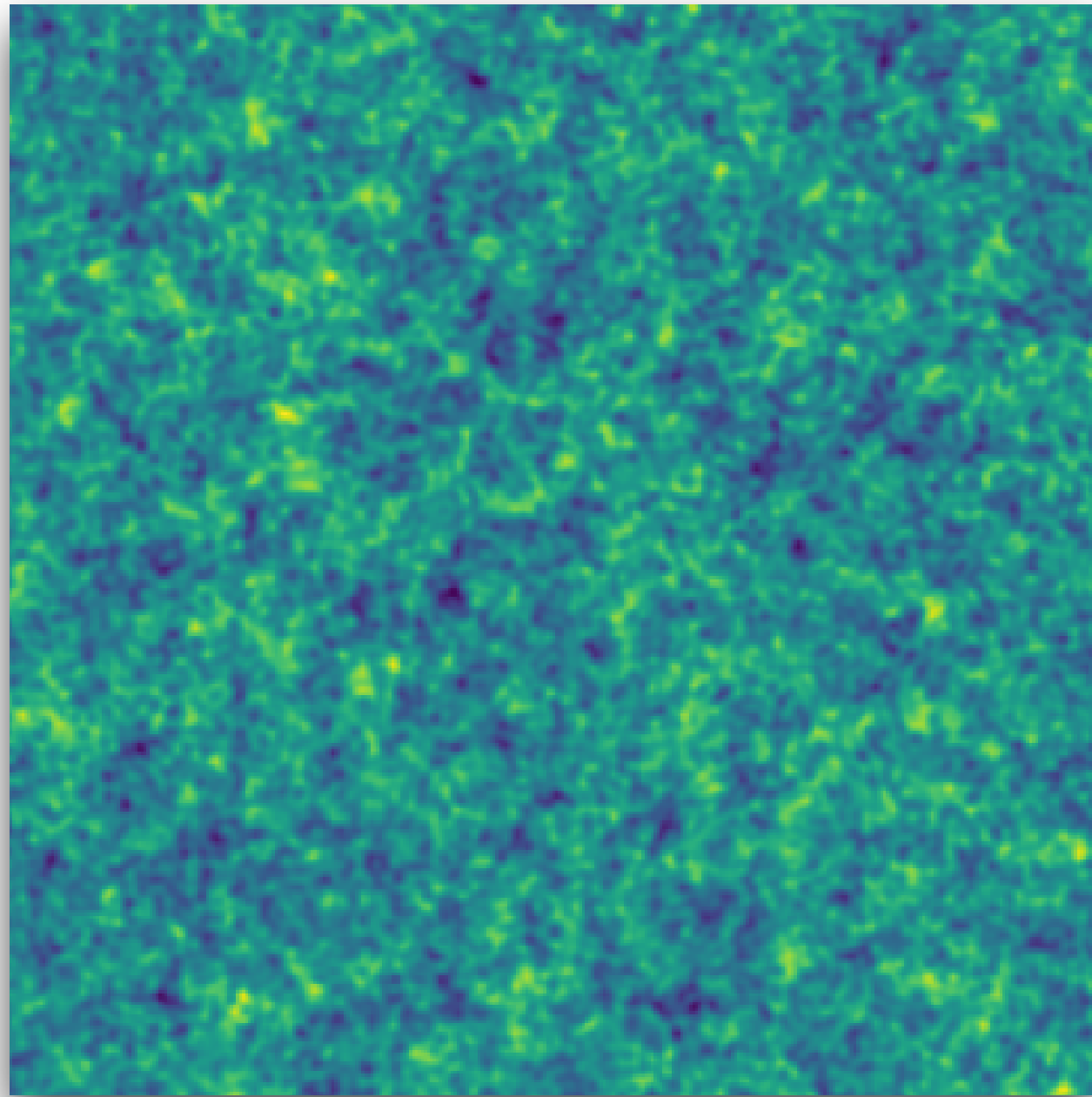
Figures: ratio of $\sigma(f_{\text{NL}})$ with and without non-Gaussian covariance for local and equilateral primordial bispectra at different redshifts

Undo the effect?

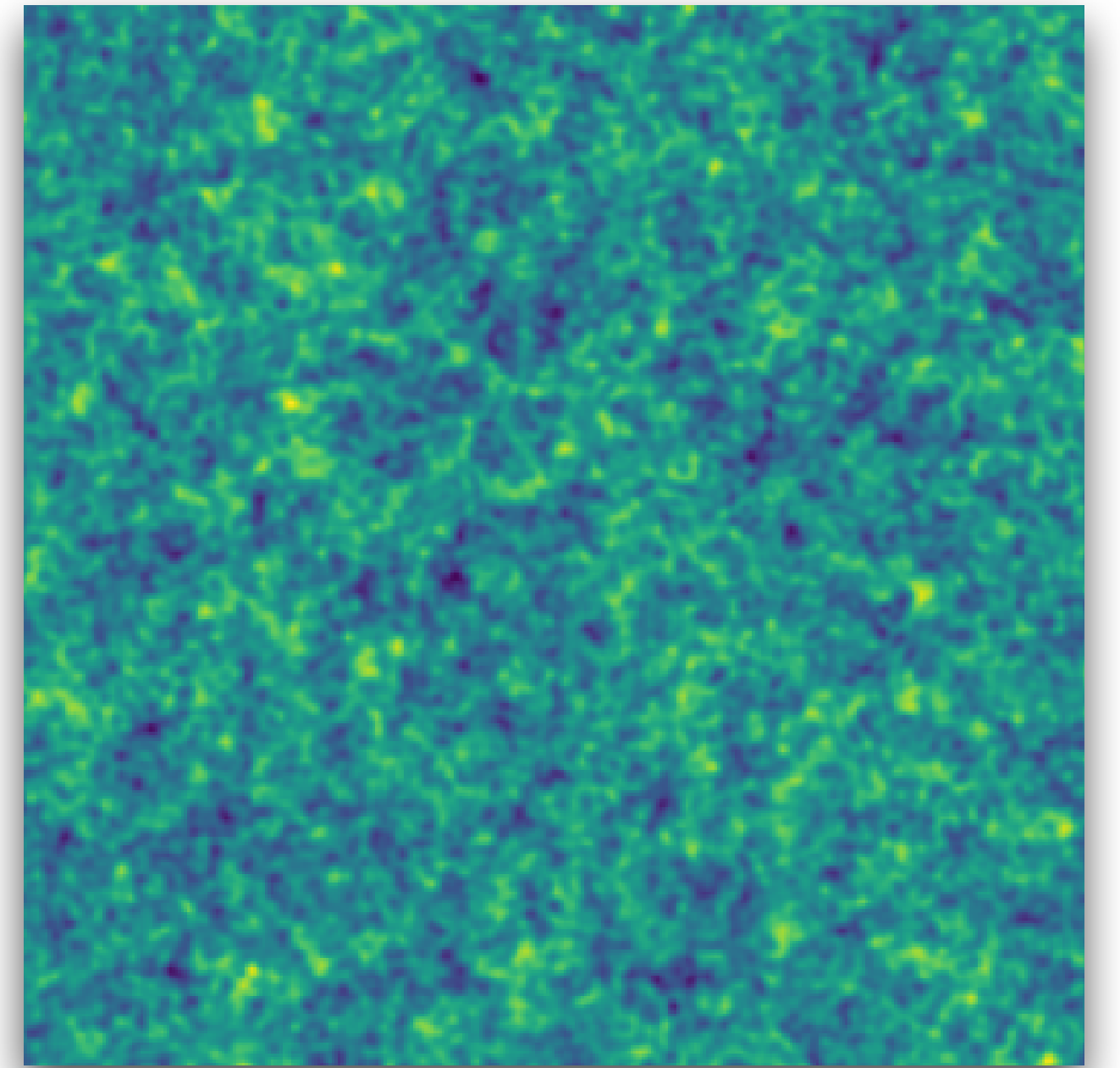
- NG covariance can significantly degrade constraints
- For CMB, de-lensing CMB removes lensing covariance
- De-gravitate?
- Analytical reconstruction can be done by estimating the large-scale modes from small-scale power (see e.g. Darwish et al. 2021)
- Use machine learning instead



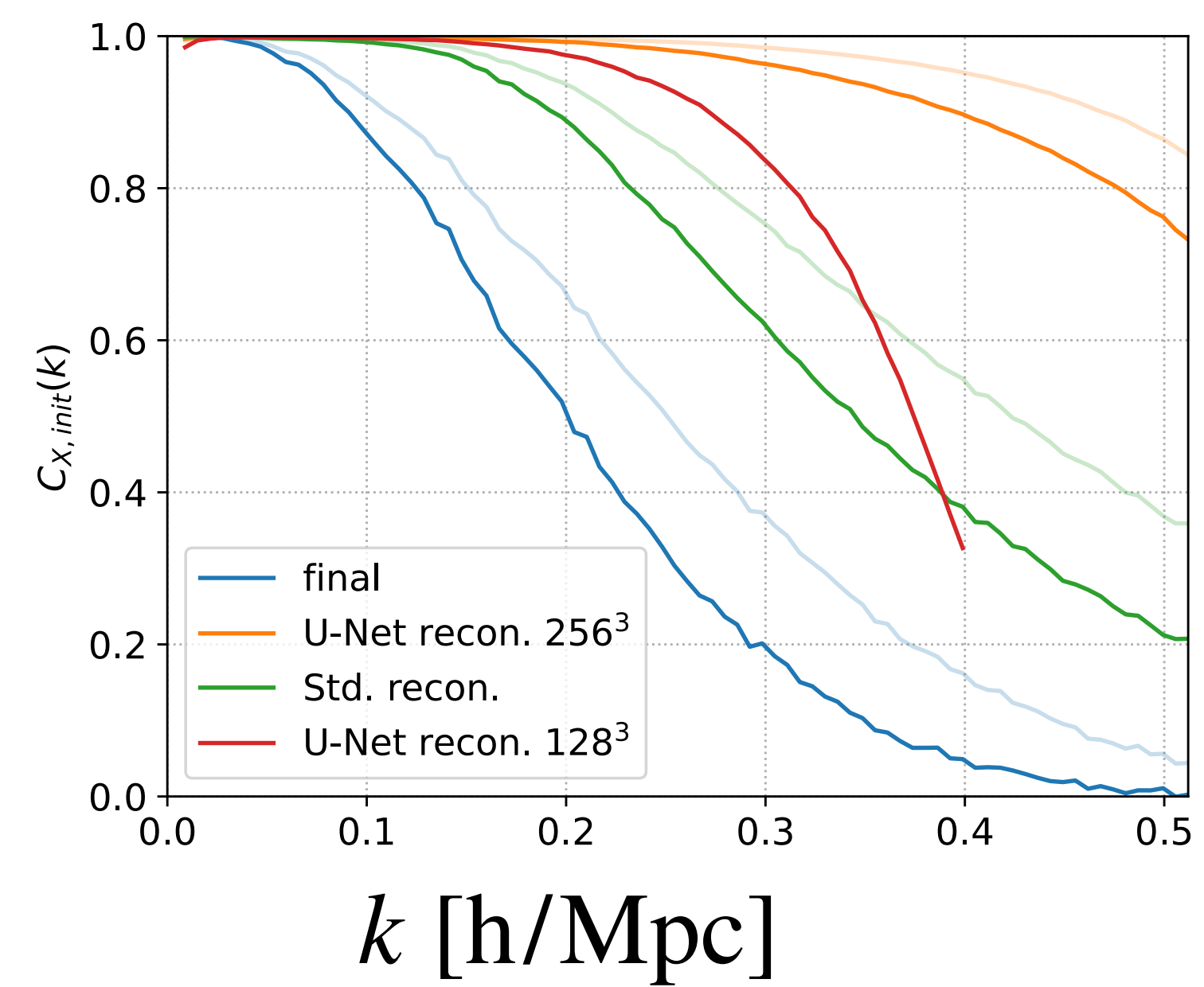
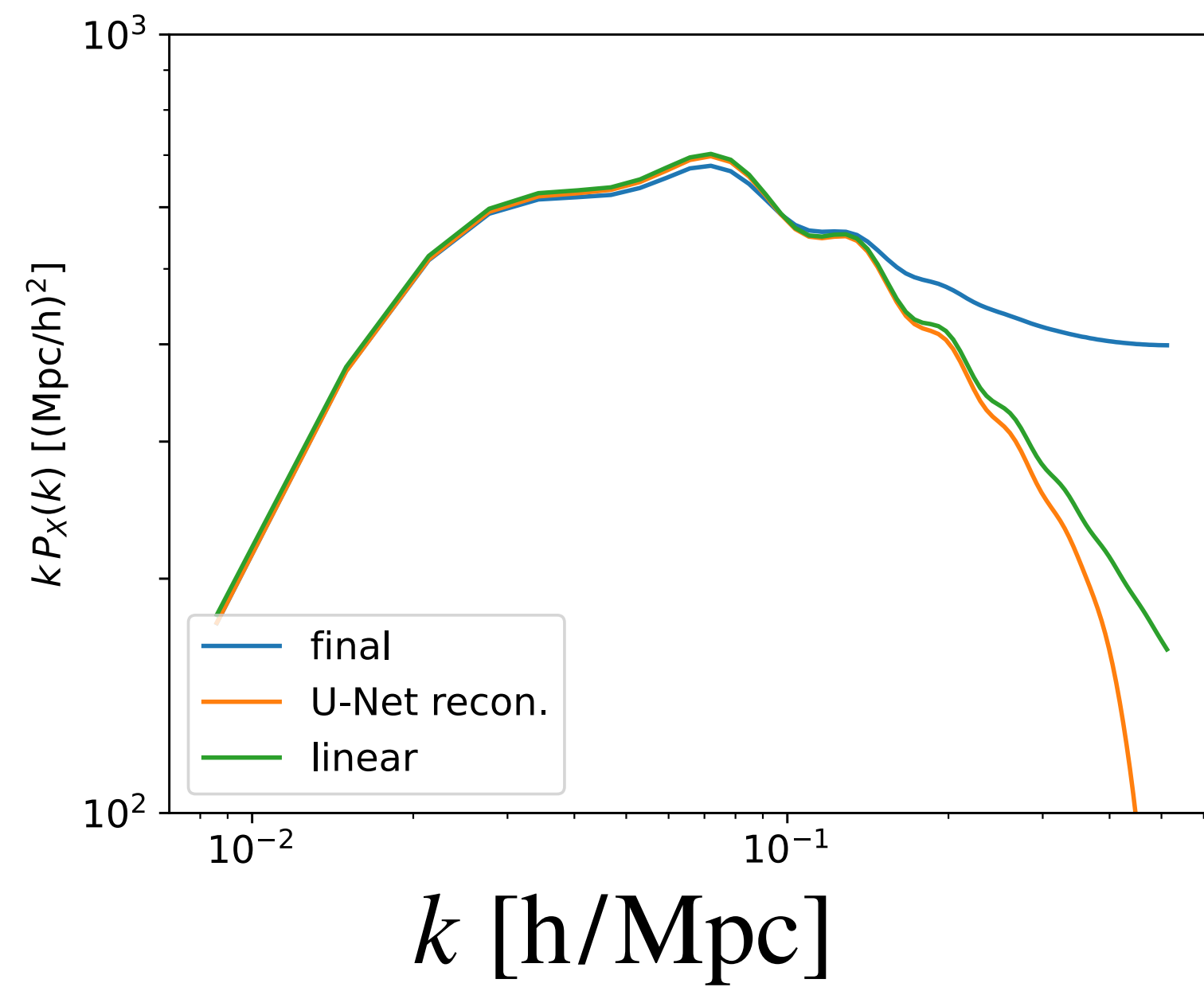
$z=0$



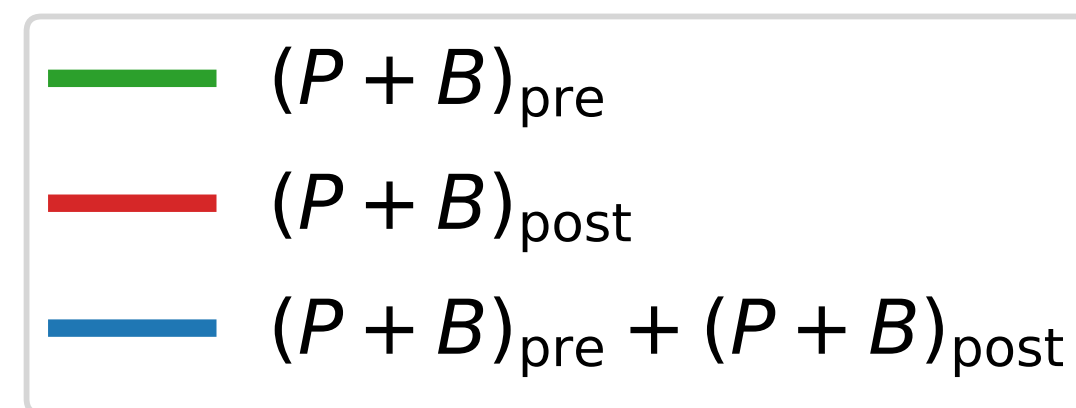
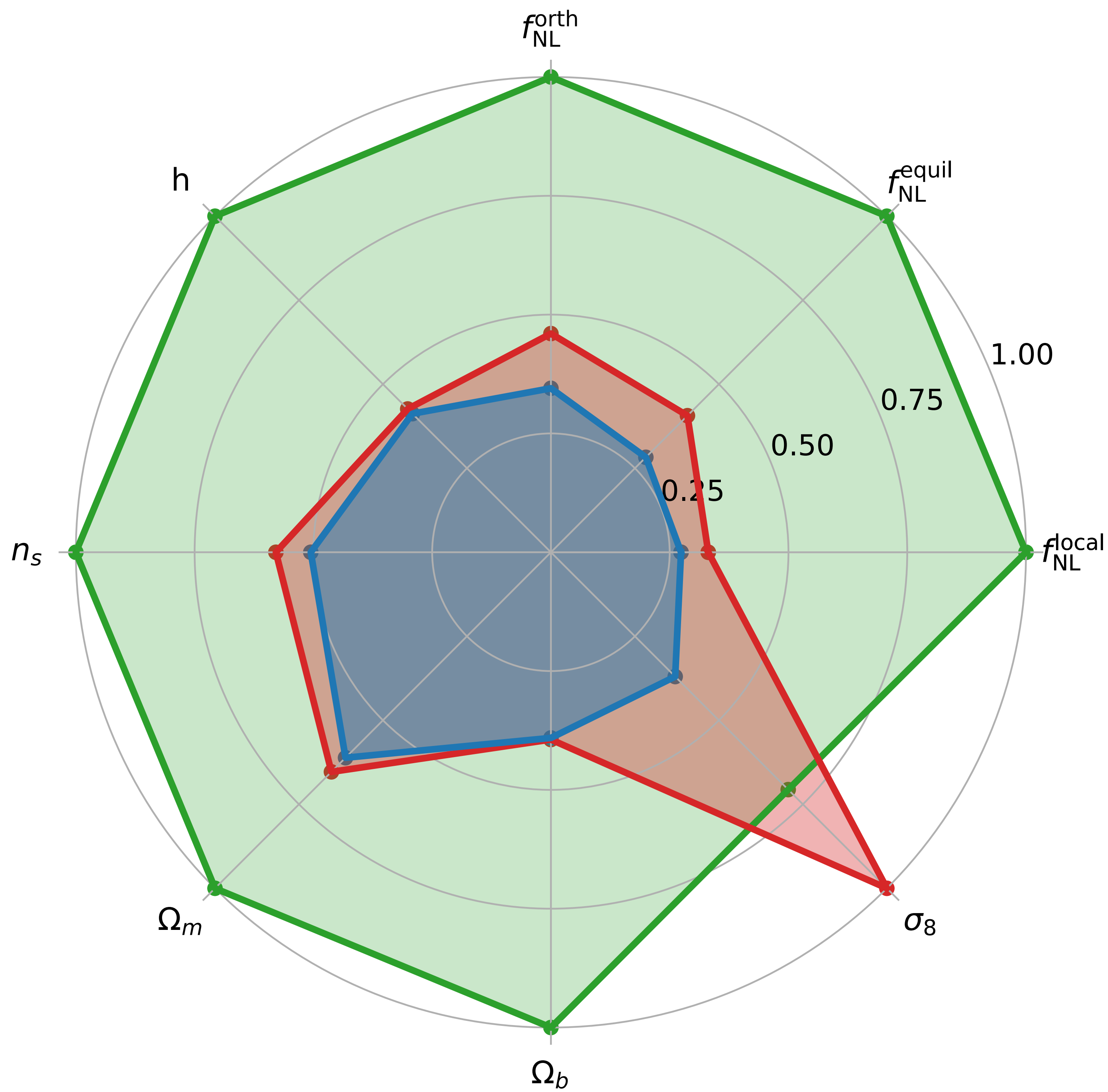
$z=127$



Reconstruction



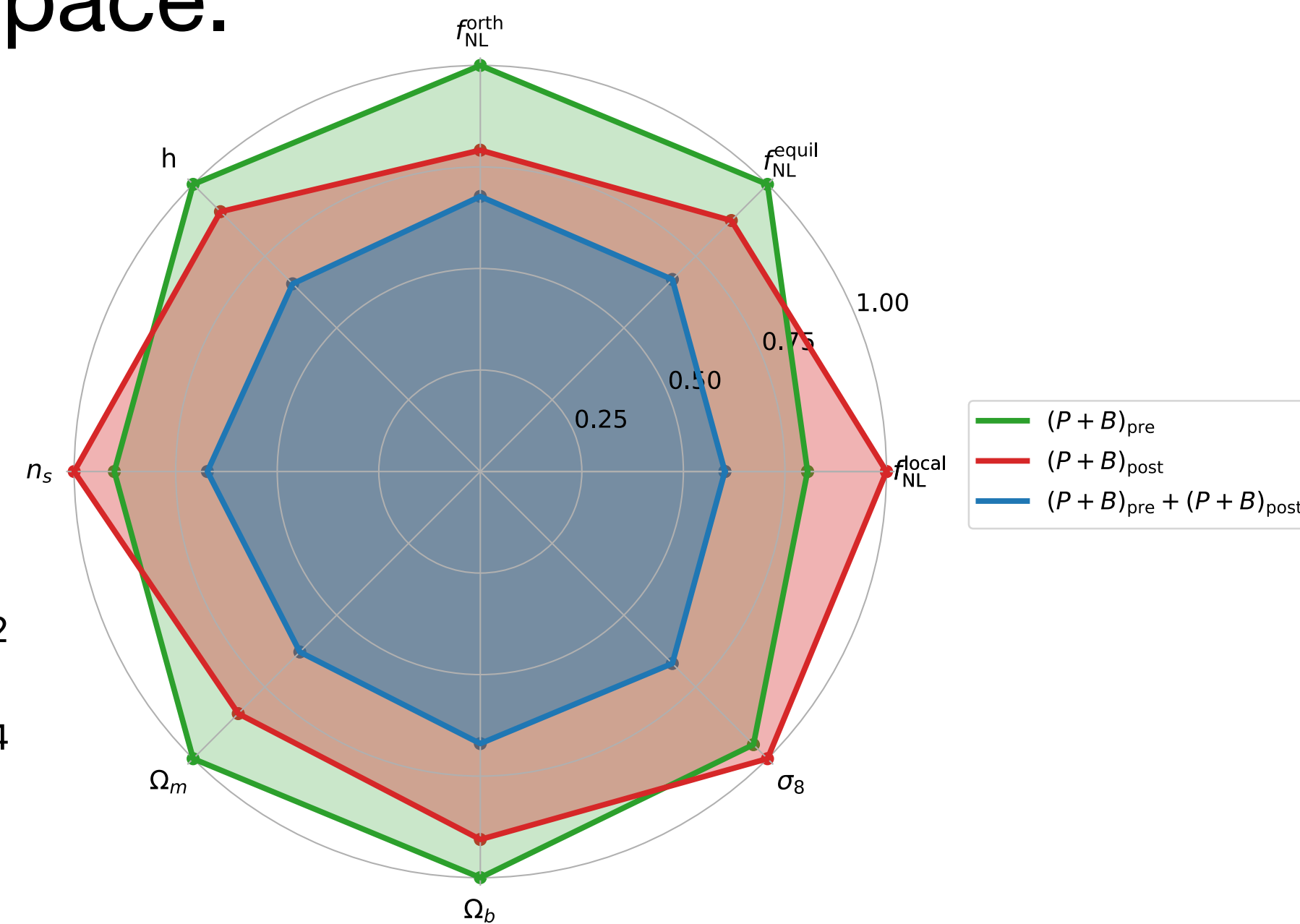
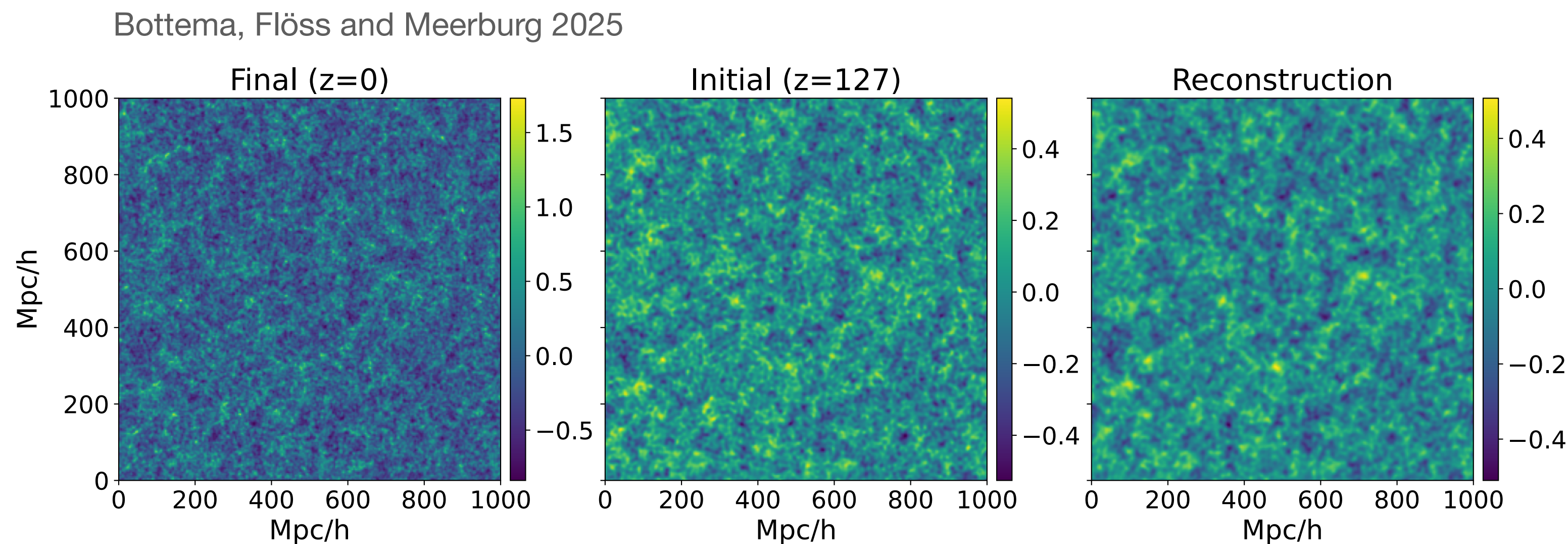
Flöss and Meerburg
2023

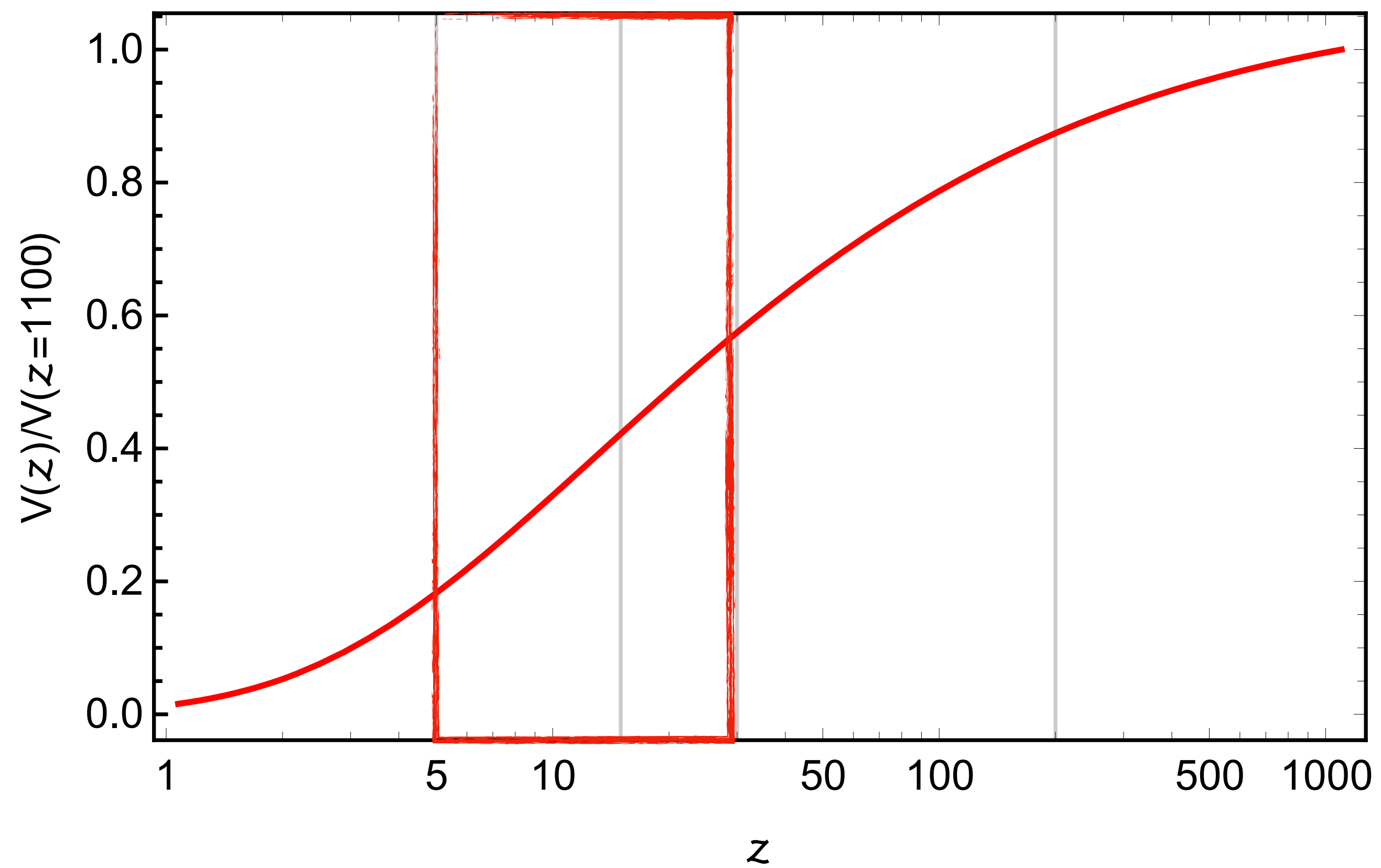
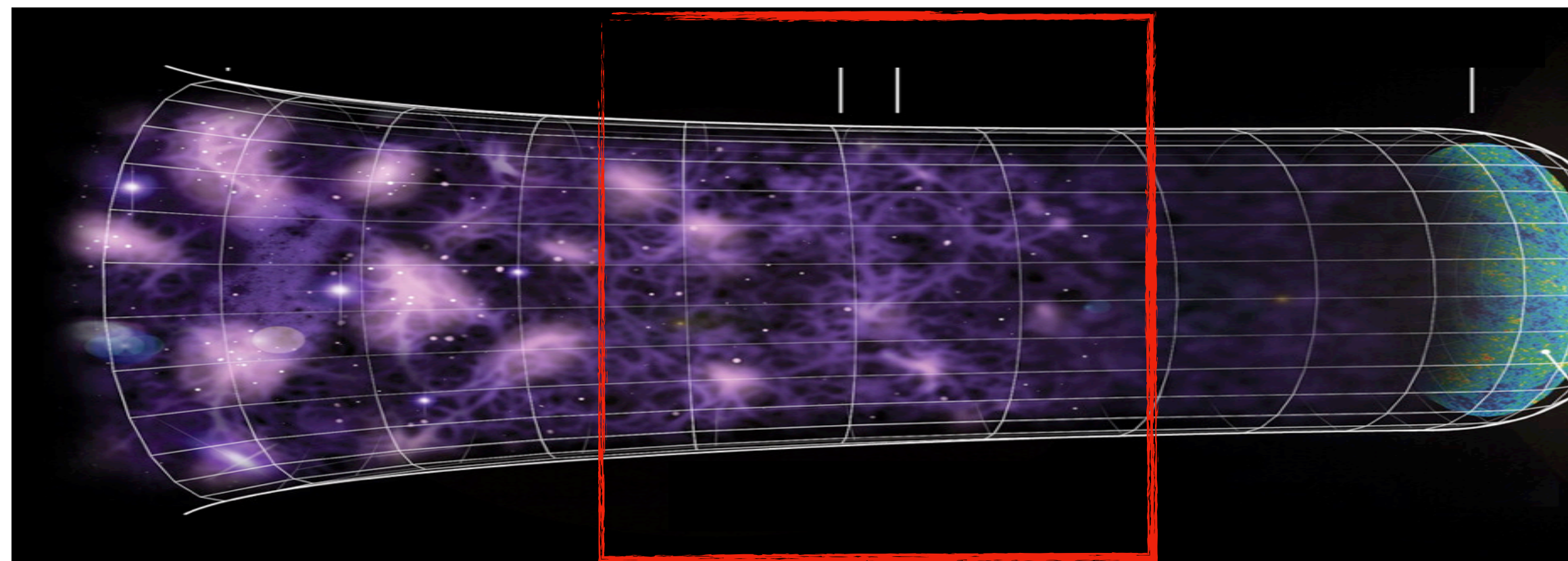


Flöss and
Meerburg 2023

Reconstruction take-away

- Non-linearities moves information into higher N-point functions. NN bring it back
- Improved parameter constraints, especially on primordial non-Gaussianity
- Not observed field. Observing galaxies in redshift space.



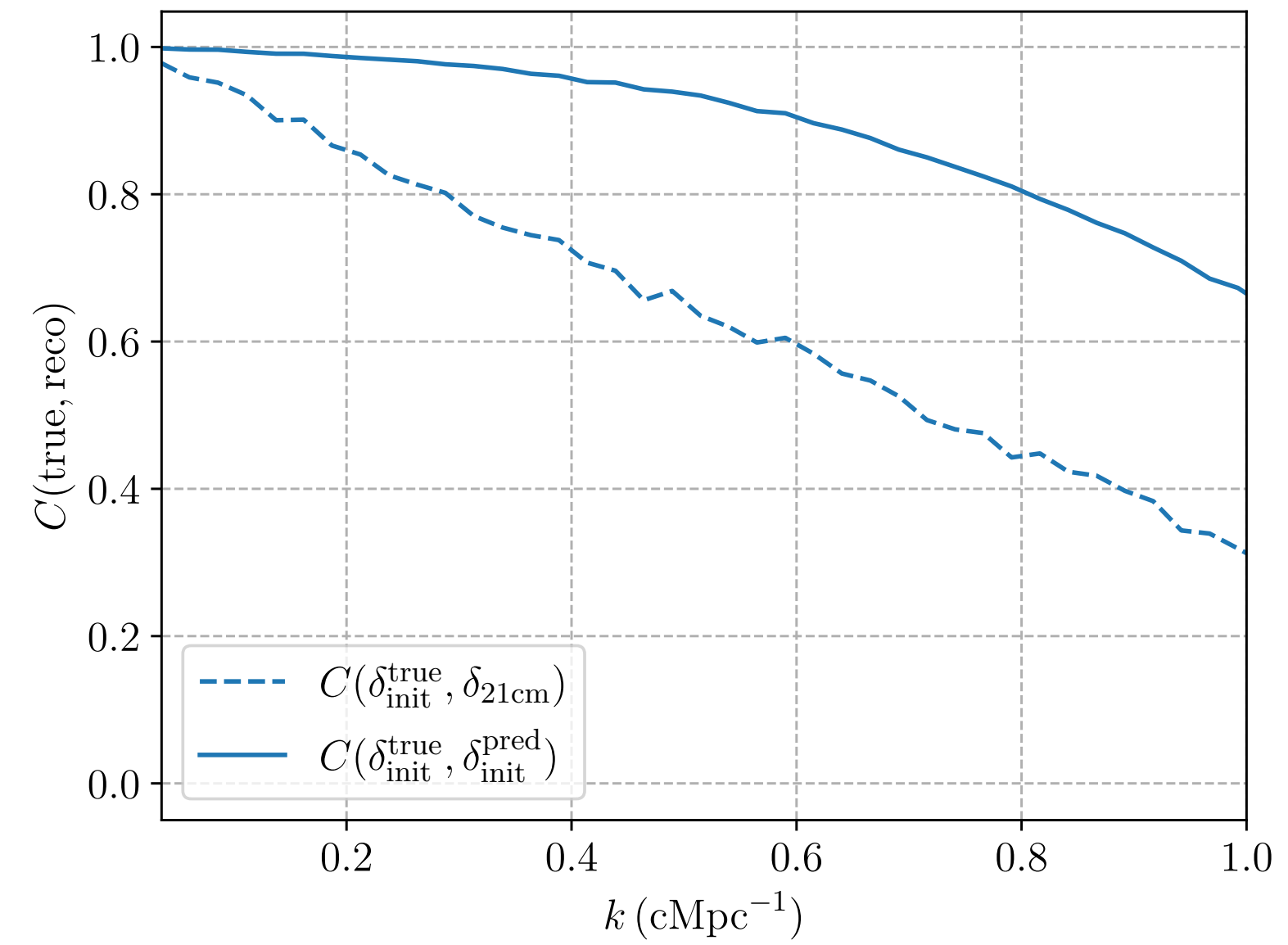
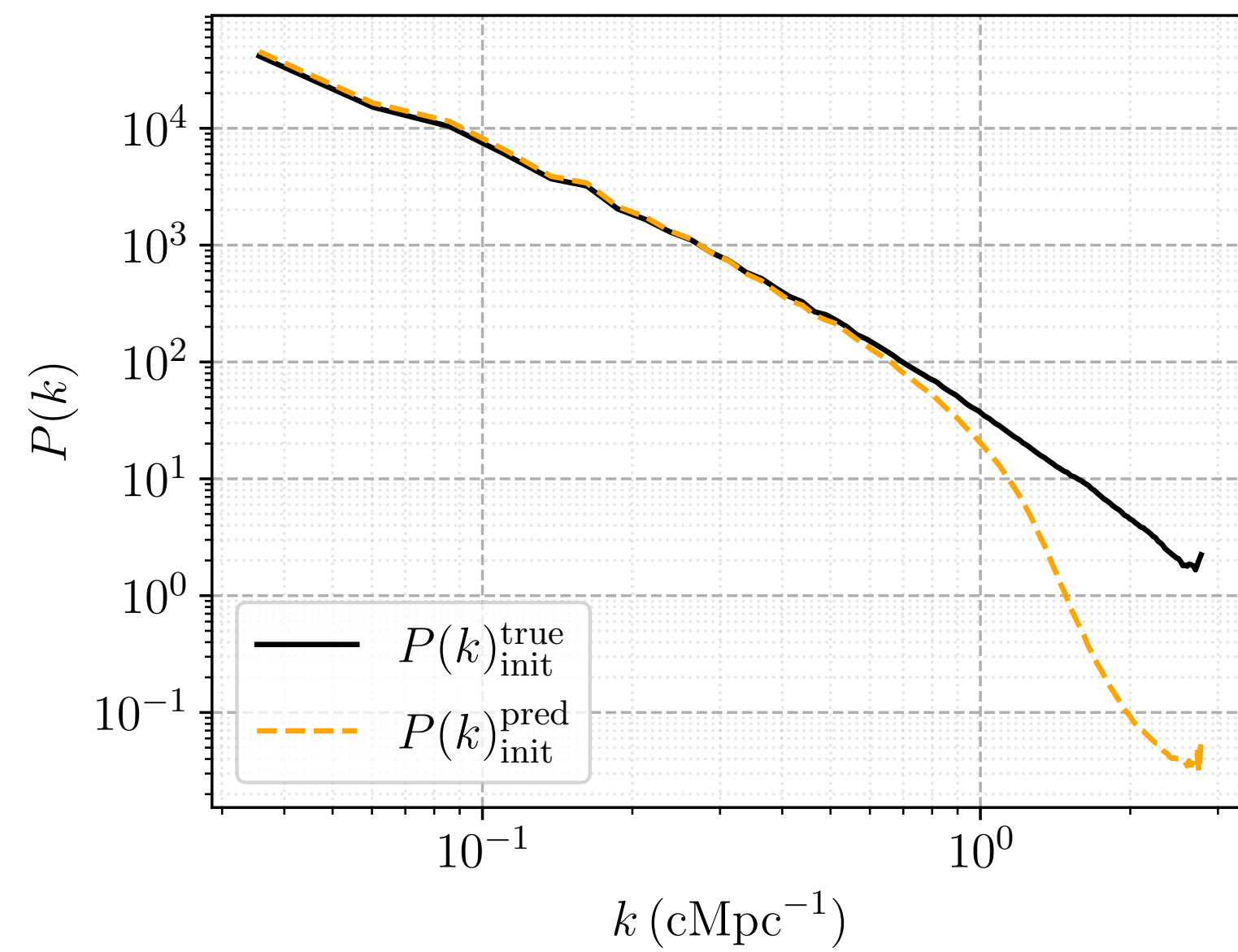
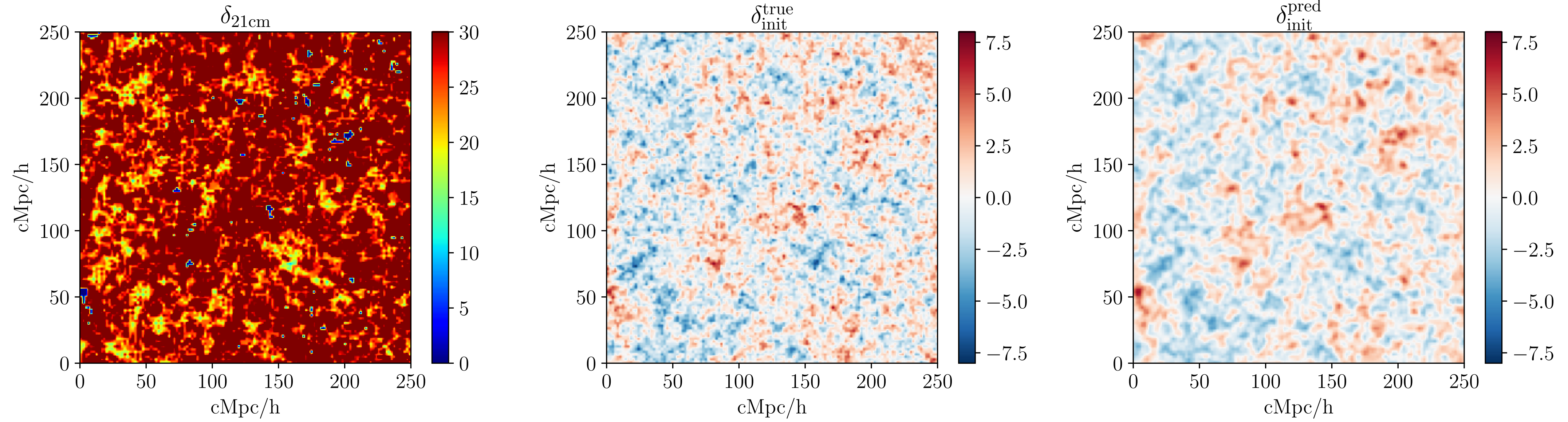


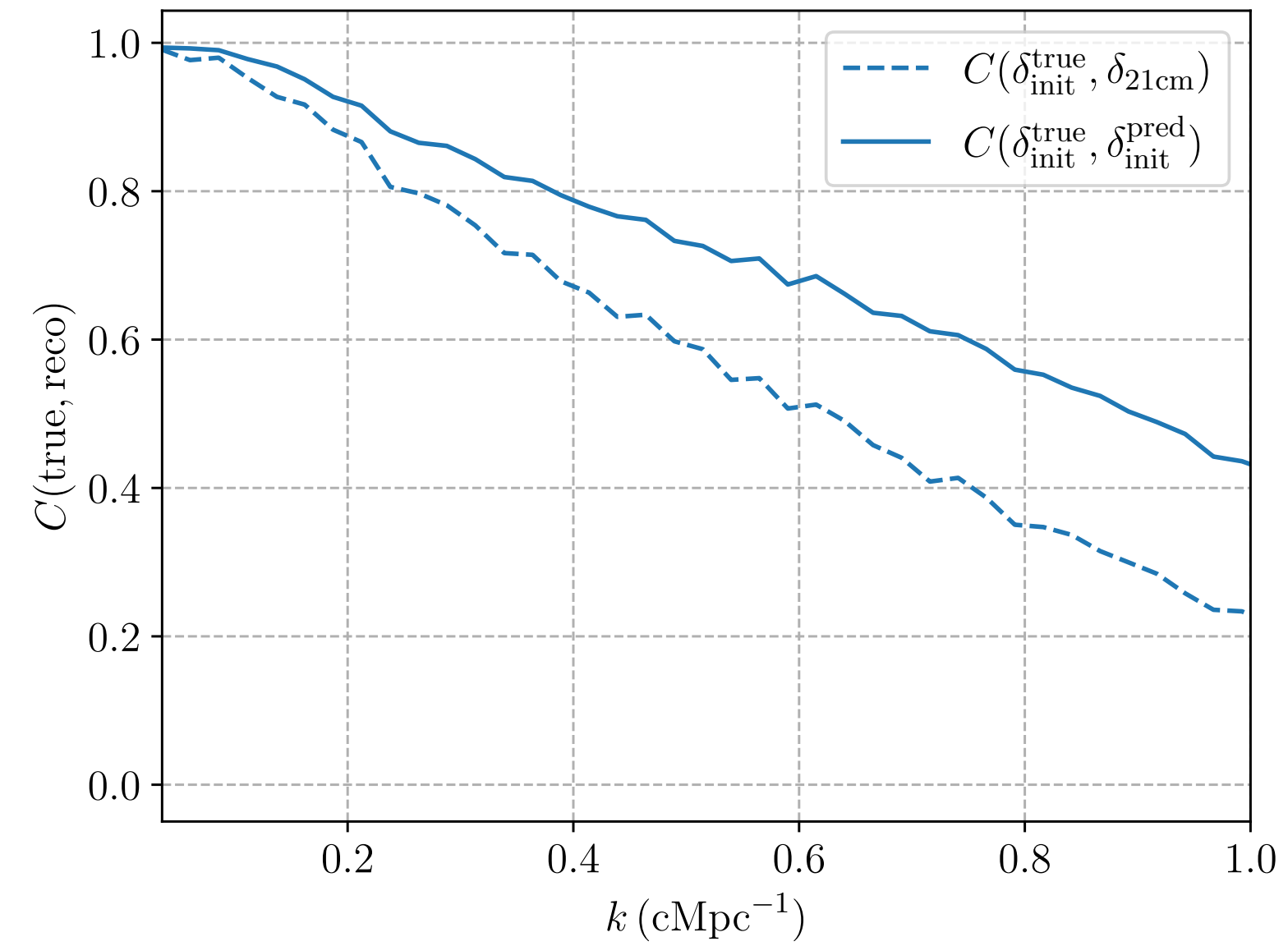
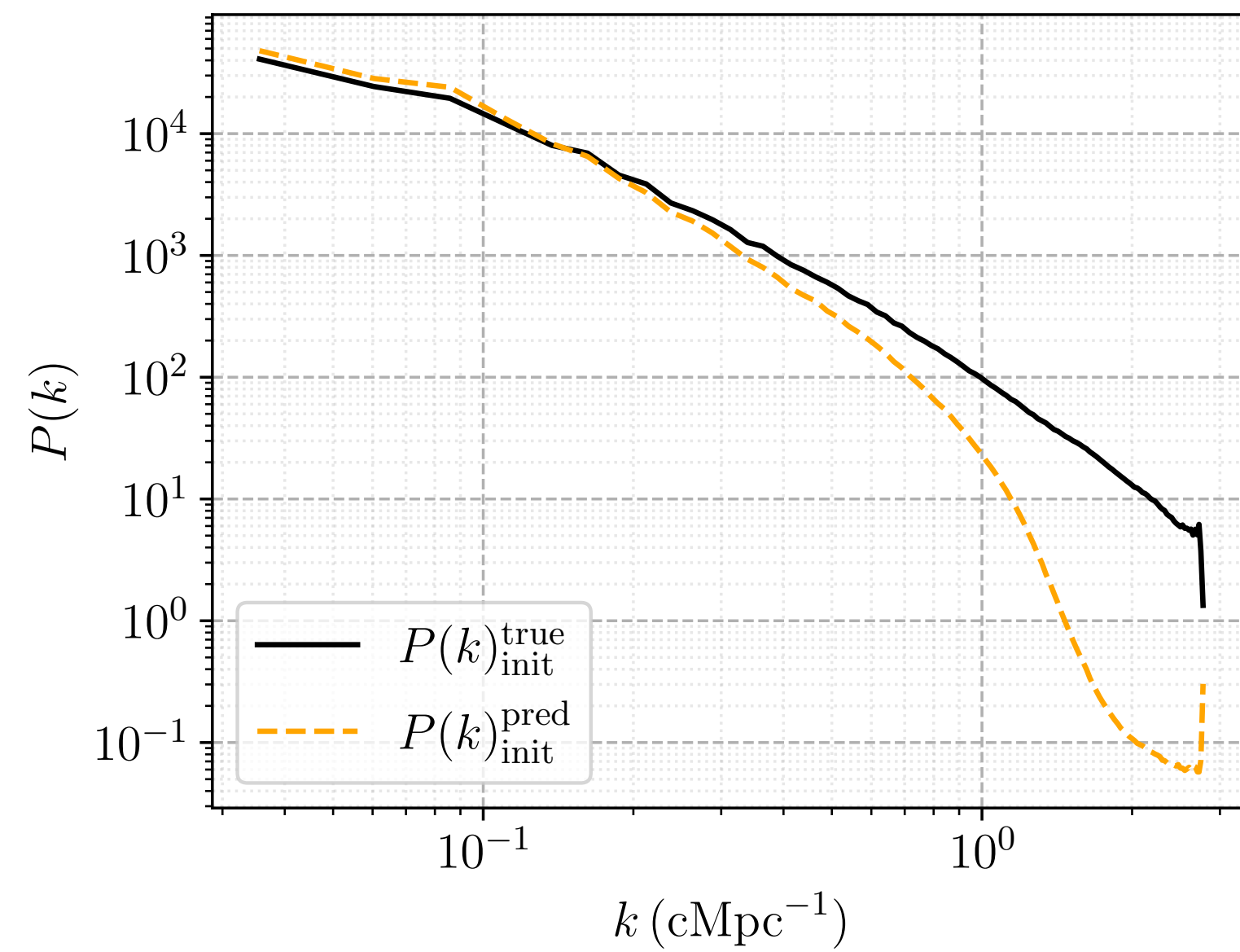
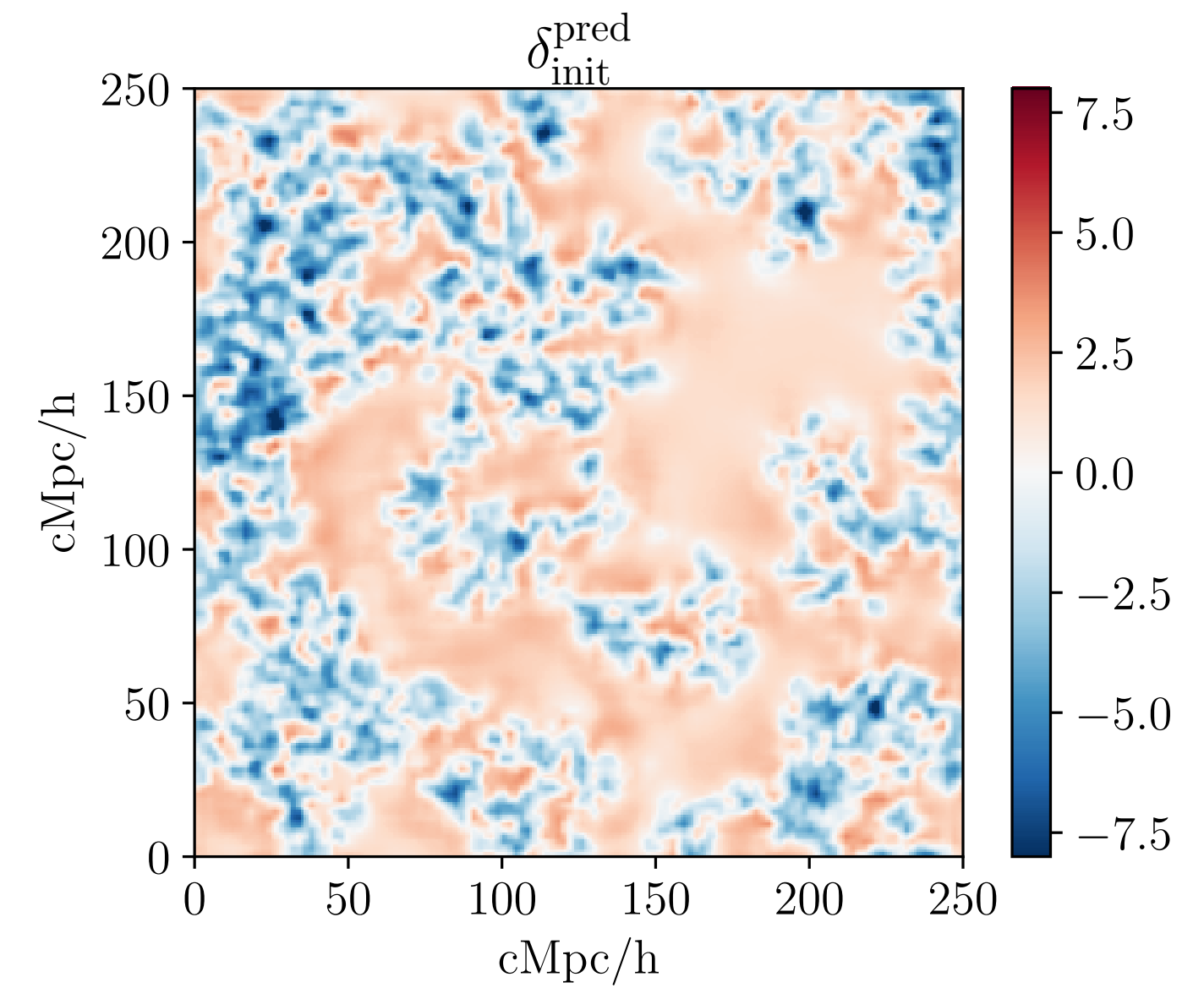
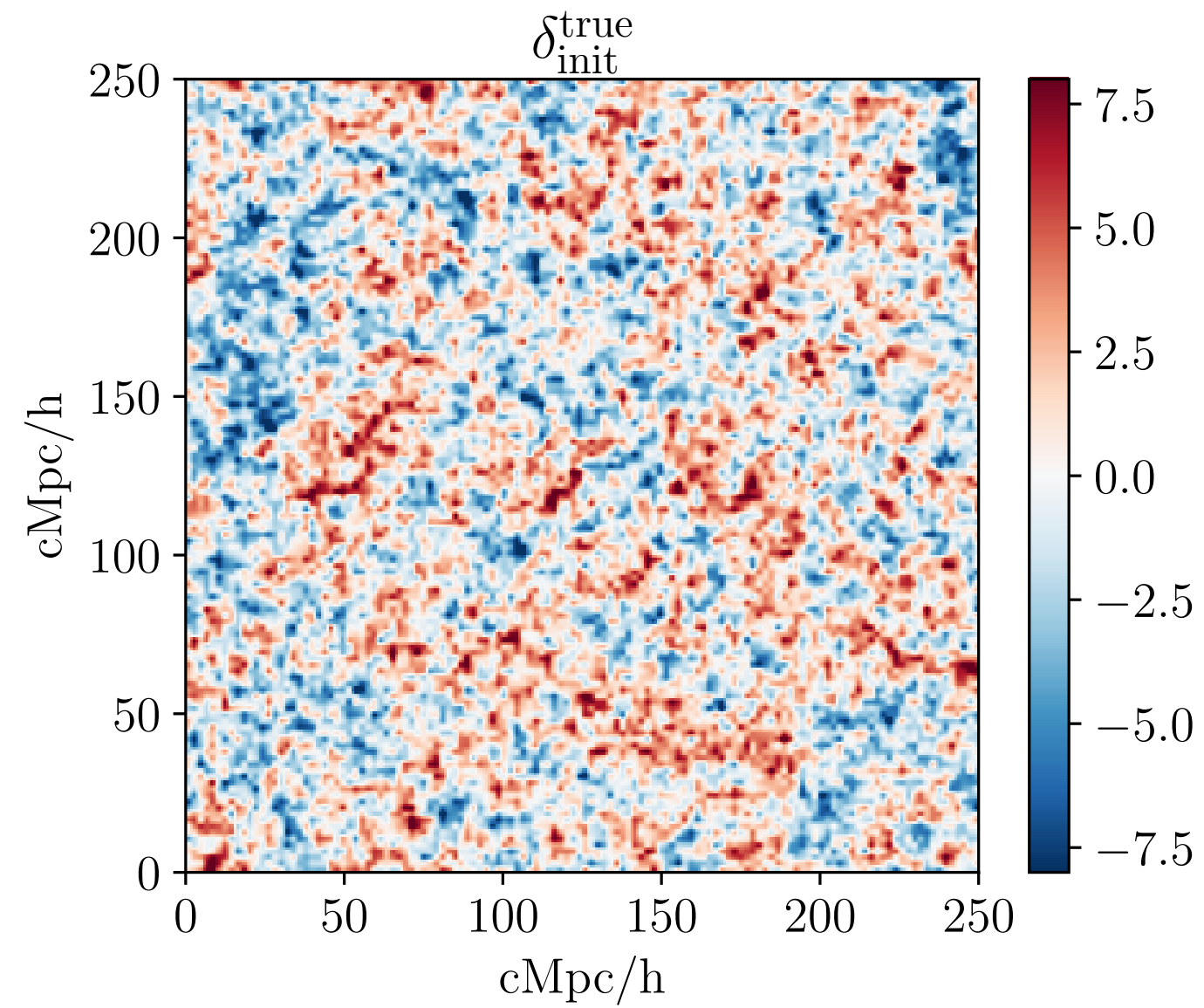
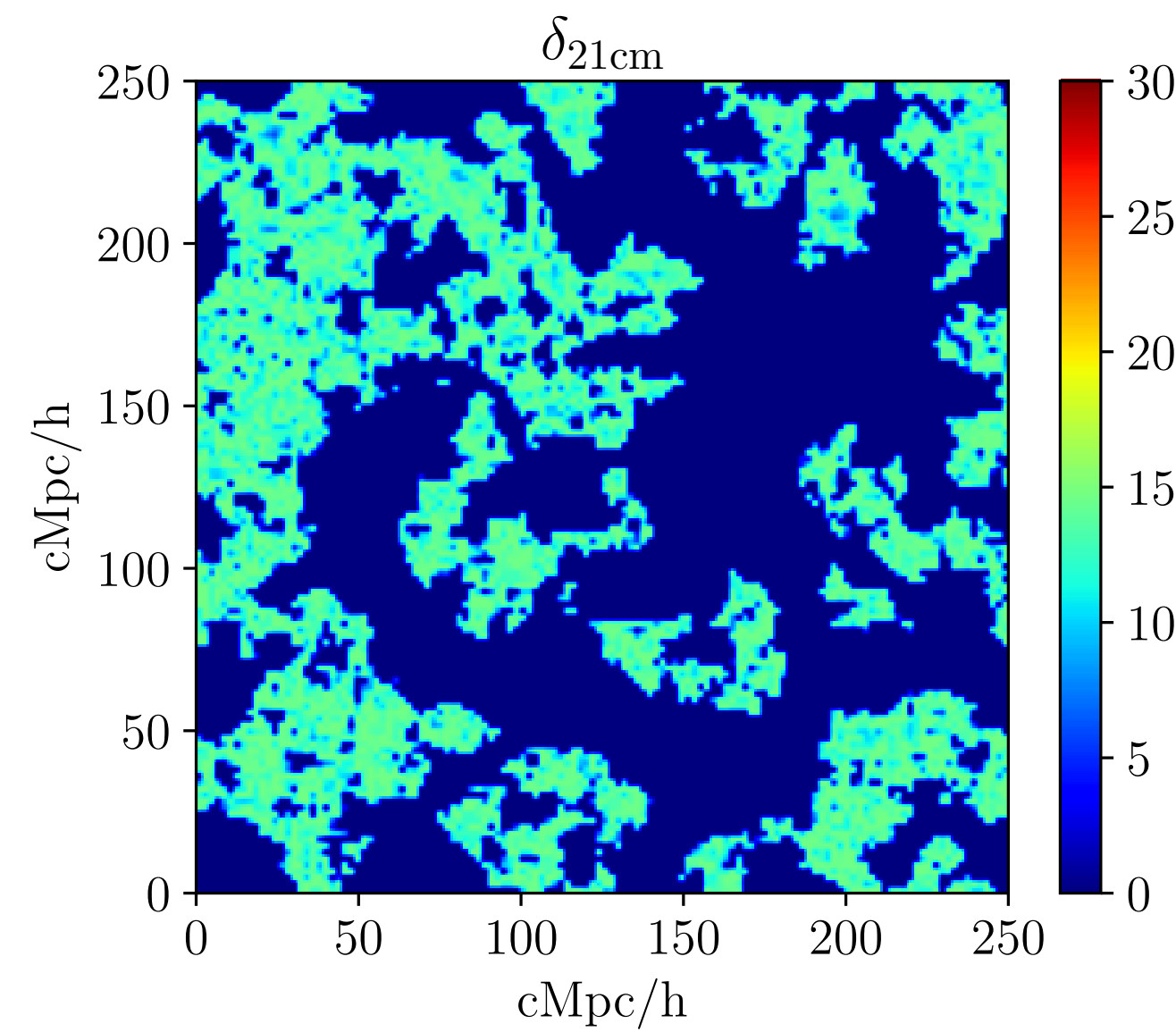
What about CD and EoR

- Lots of volume—> many modes
- Useful modes?
- For astrophysics, yes. Very non-Gaussian!
- Hard to model, rely on semi-numerical sims
- What about cosmology?
- Studies show minimal constraining power from power spectrum
- Can ML help here as well?
- Maybe, work in progress, for another time (or questions)

Conclusions

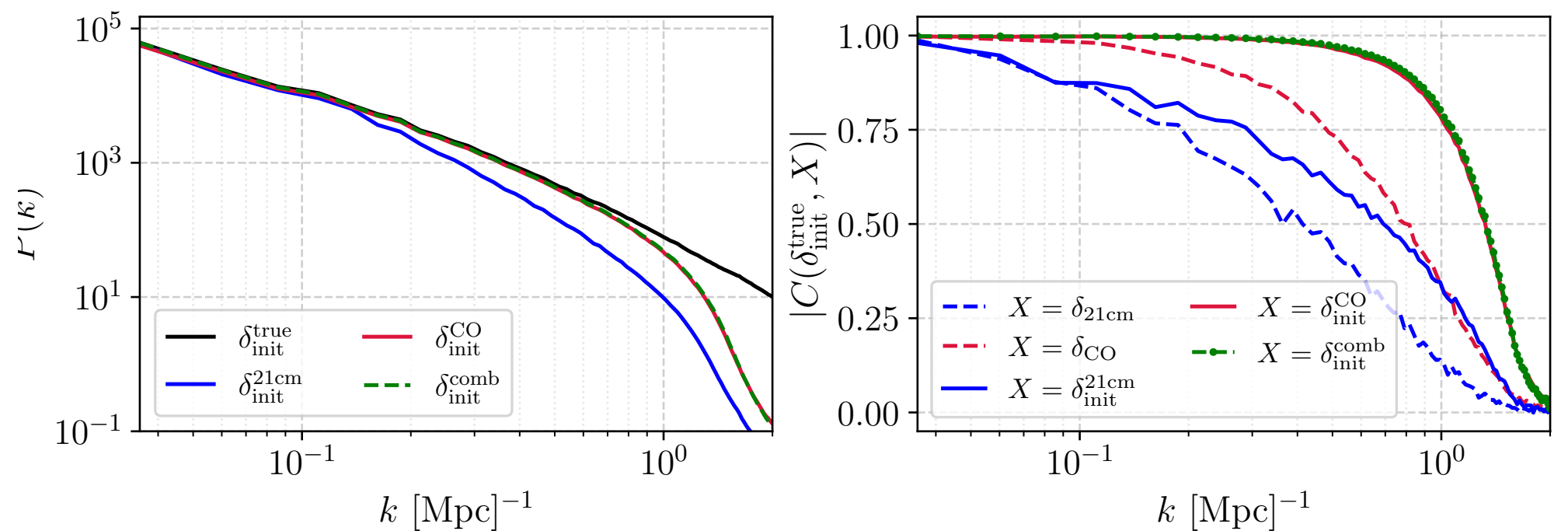
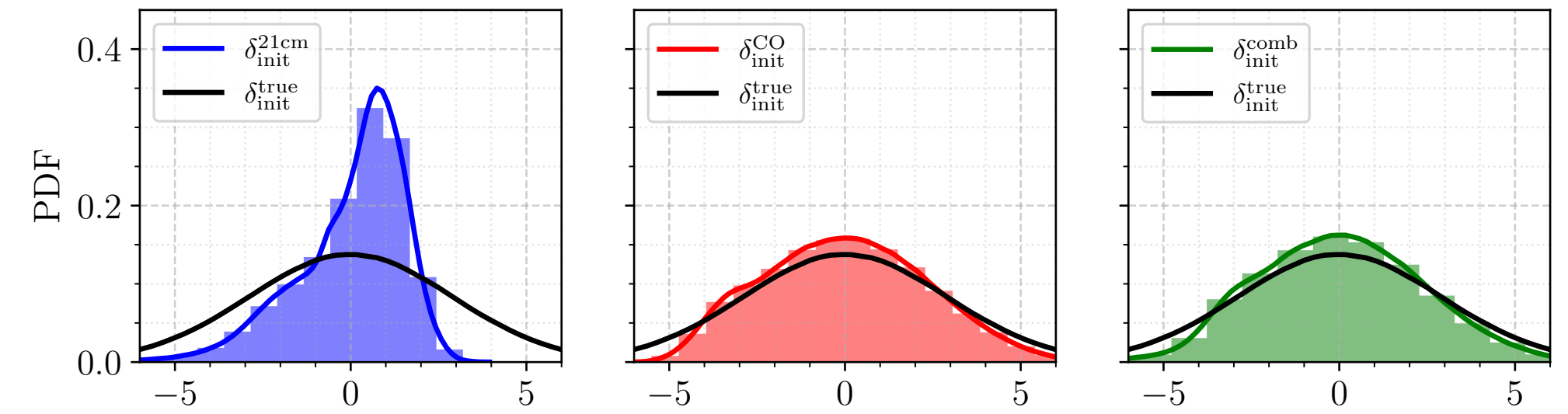
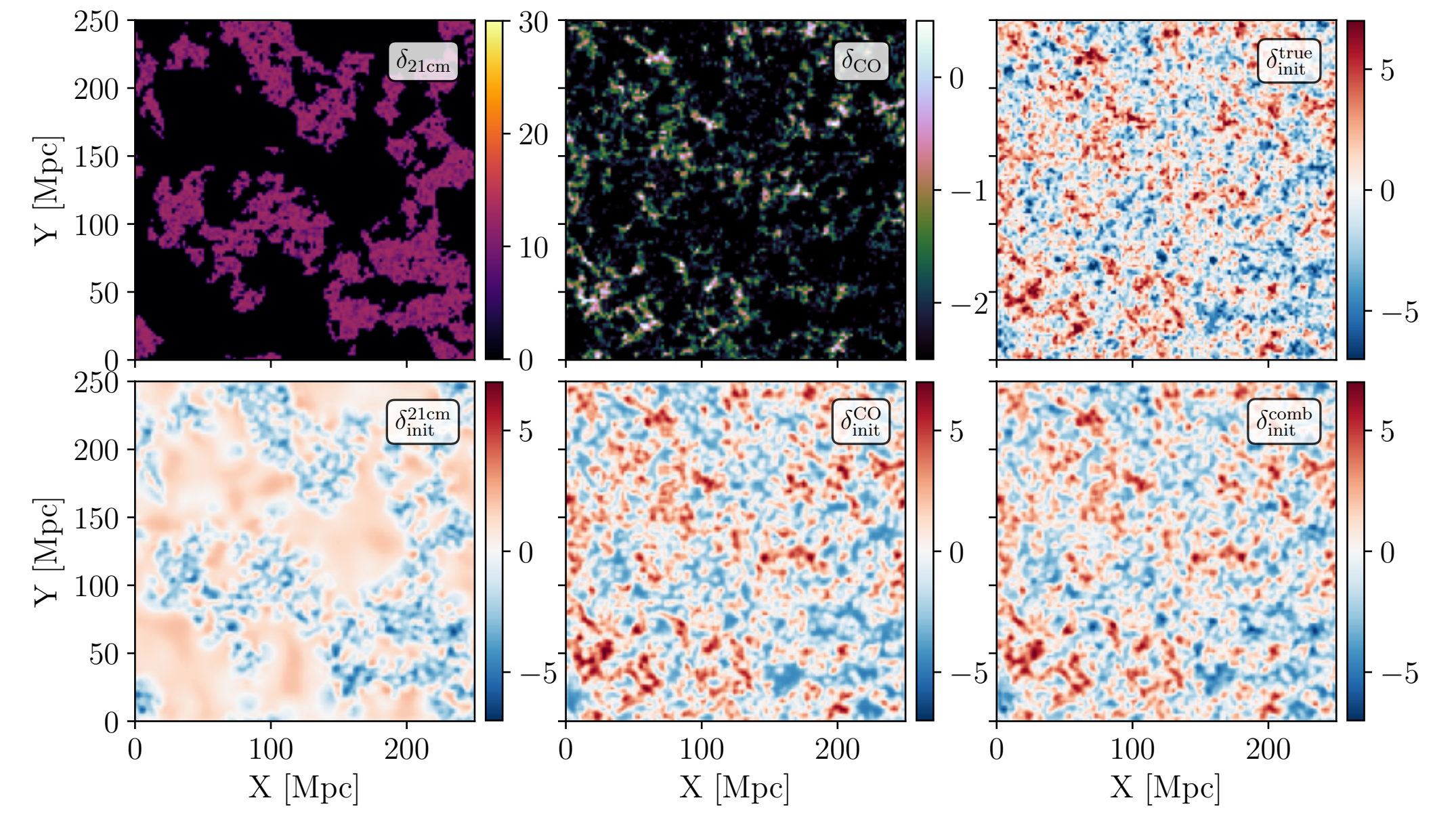
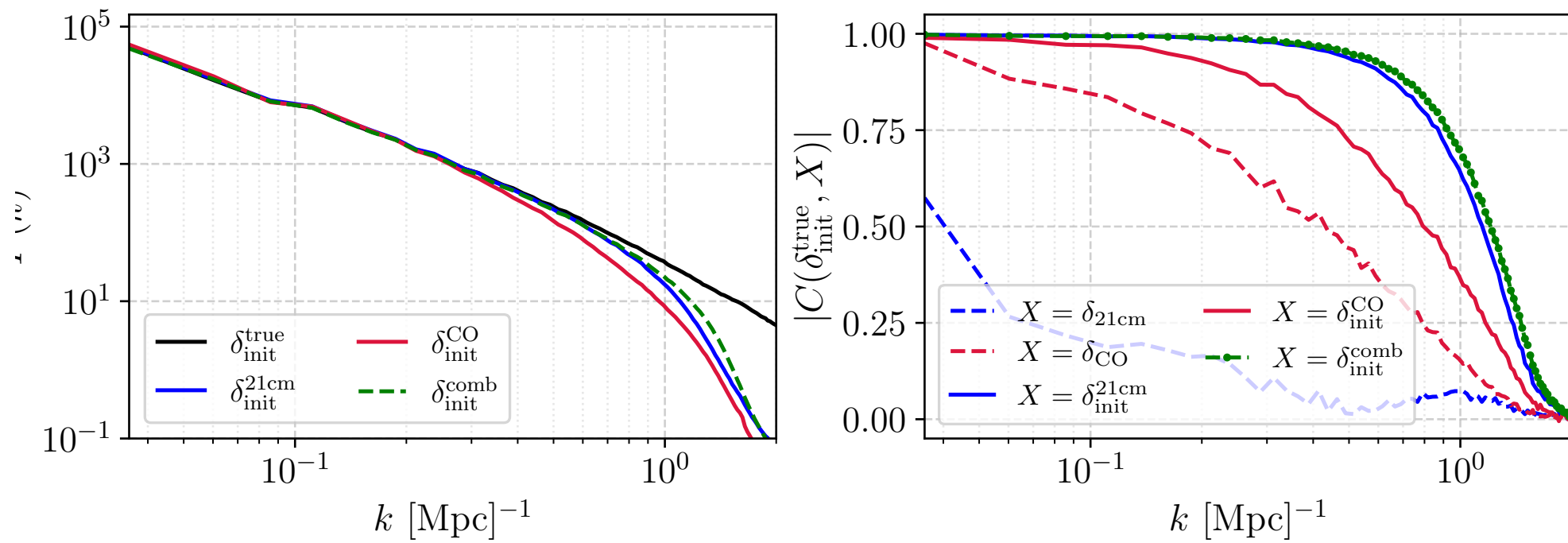
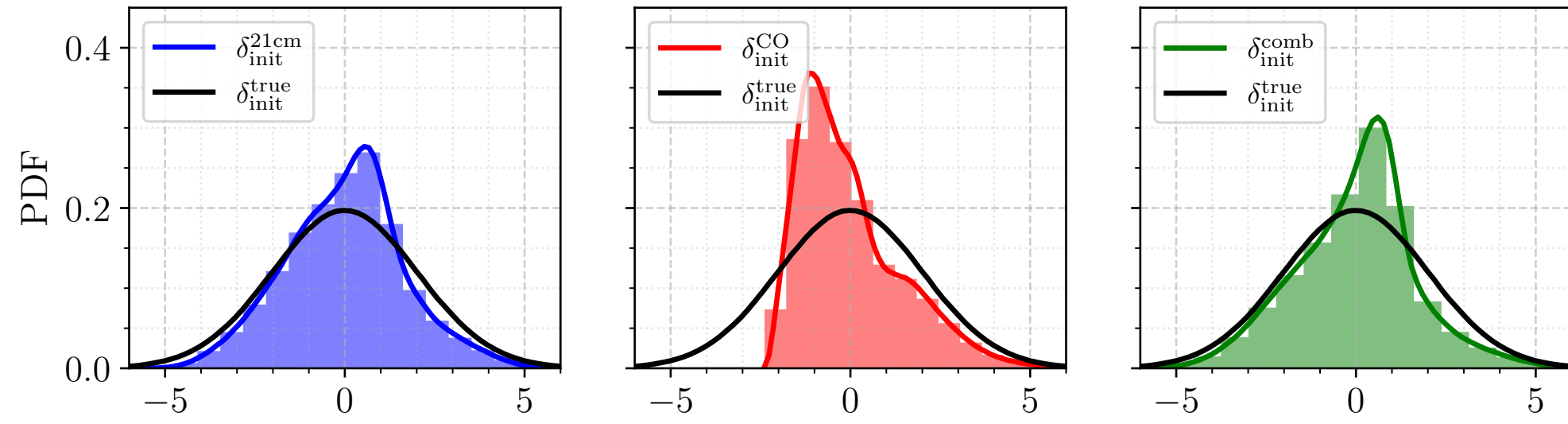
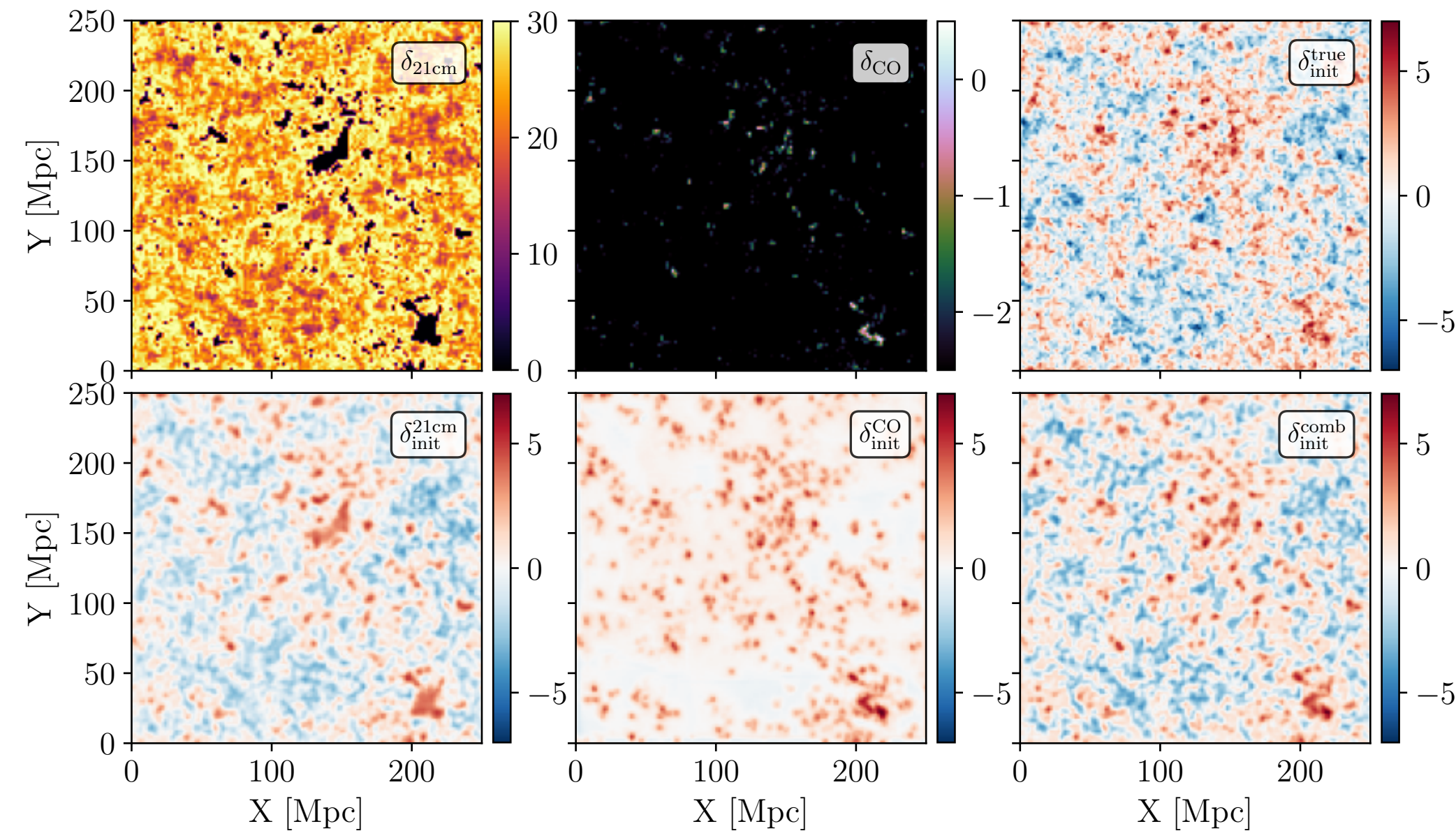
- Non-Gaussianities probe physics of inflation and early universe
- Data from Simons Observatory will either improve over current Planck bounds or make a detection!
- After Simons, eventually CMB will run out of ‘juice’
- Other cosmological observables:
 - Large scale structure very non-linear: ‘scrambles’ modes
 - High redshift 21 cm more linear, but swamped in foregrounds
- 21 cm cosmology + ML could unlock next breakthroughs
- A detection of primordial non-Gaussianities would be game-changer
- Null results still immensely valuable for model builders



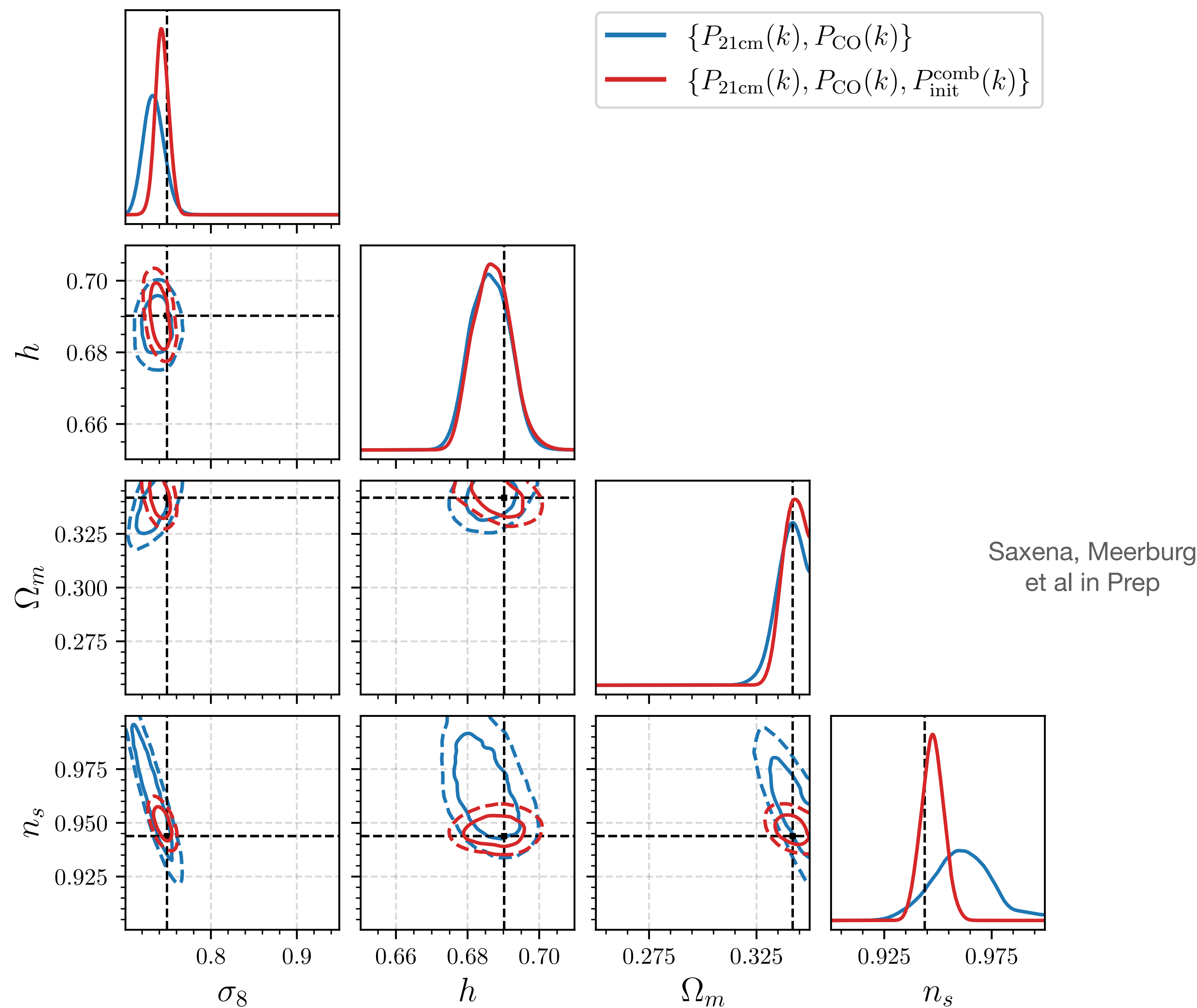


Reconstruction with the 21cm + CO line from the EoR

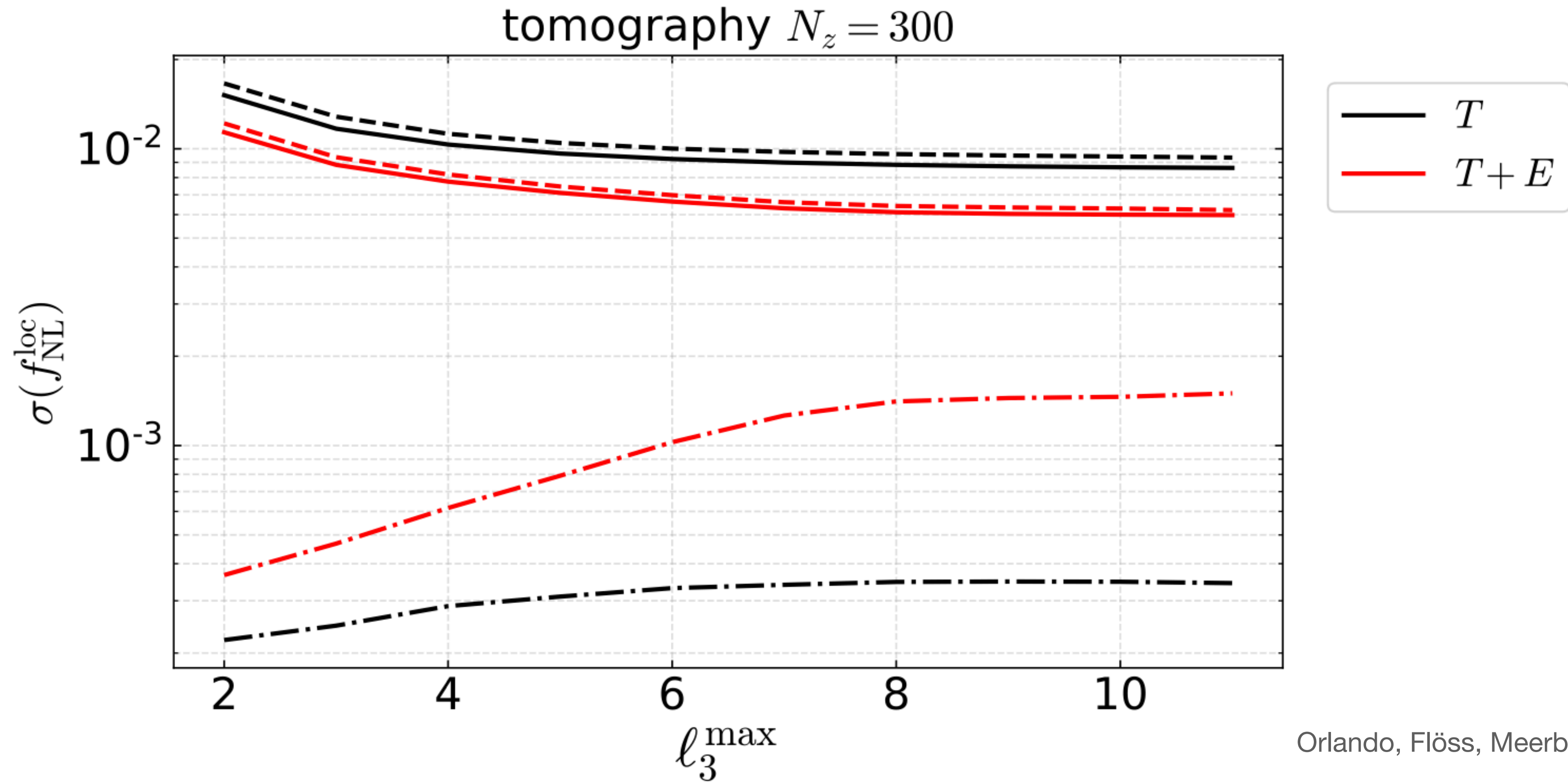
Saxena, Meerburg
et al in Prep



Constraining Cosmological Parameters

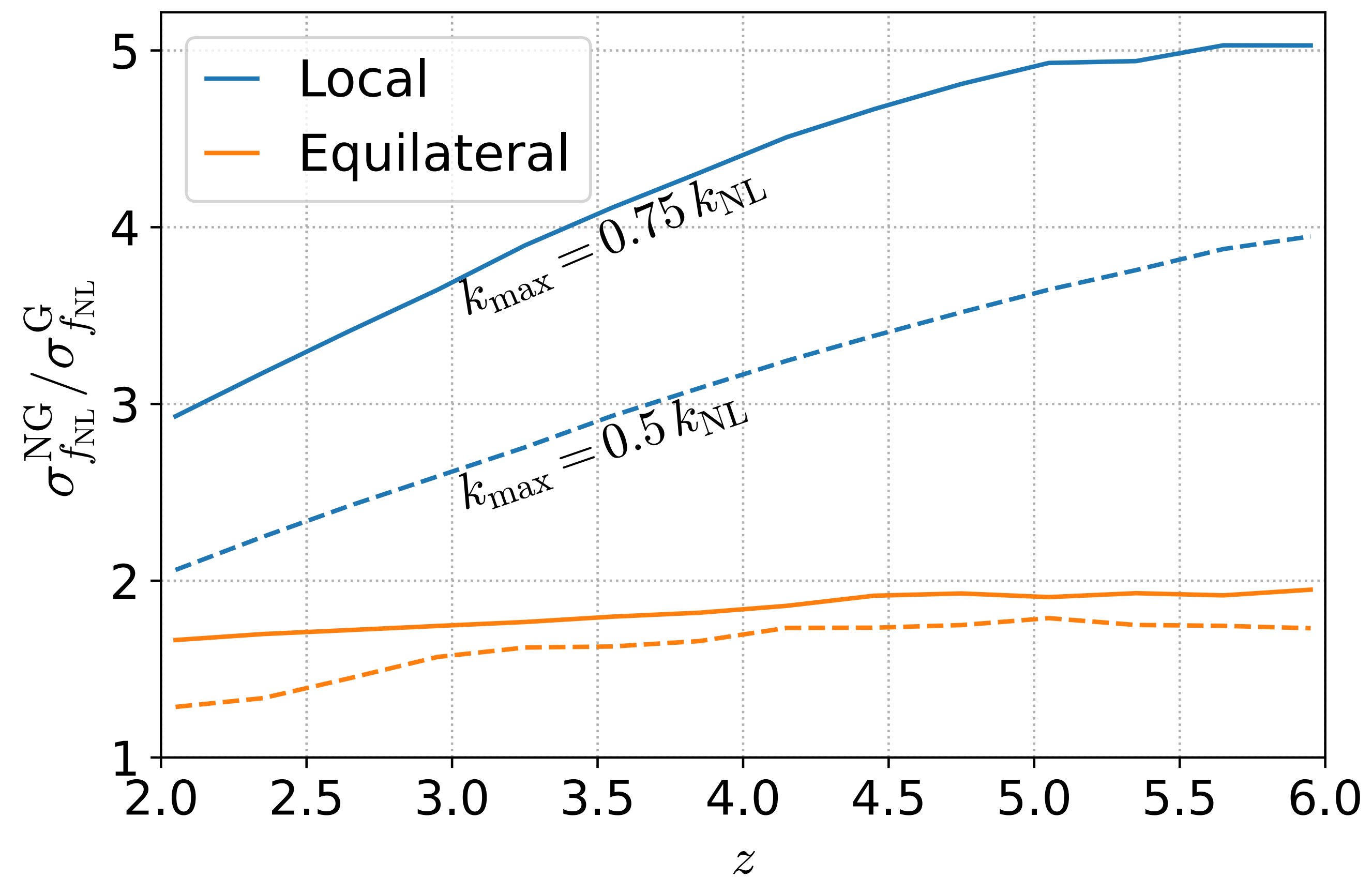
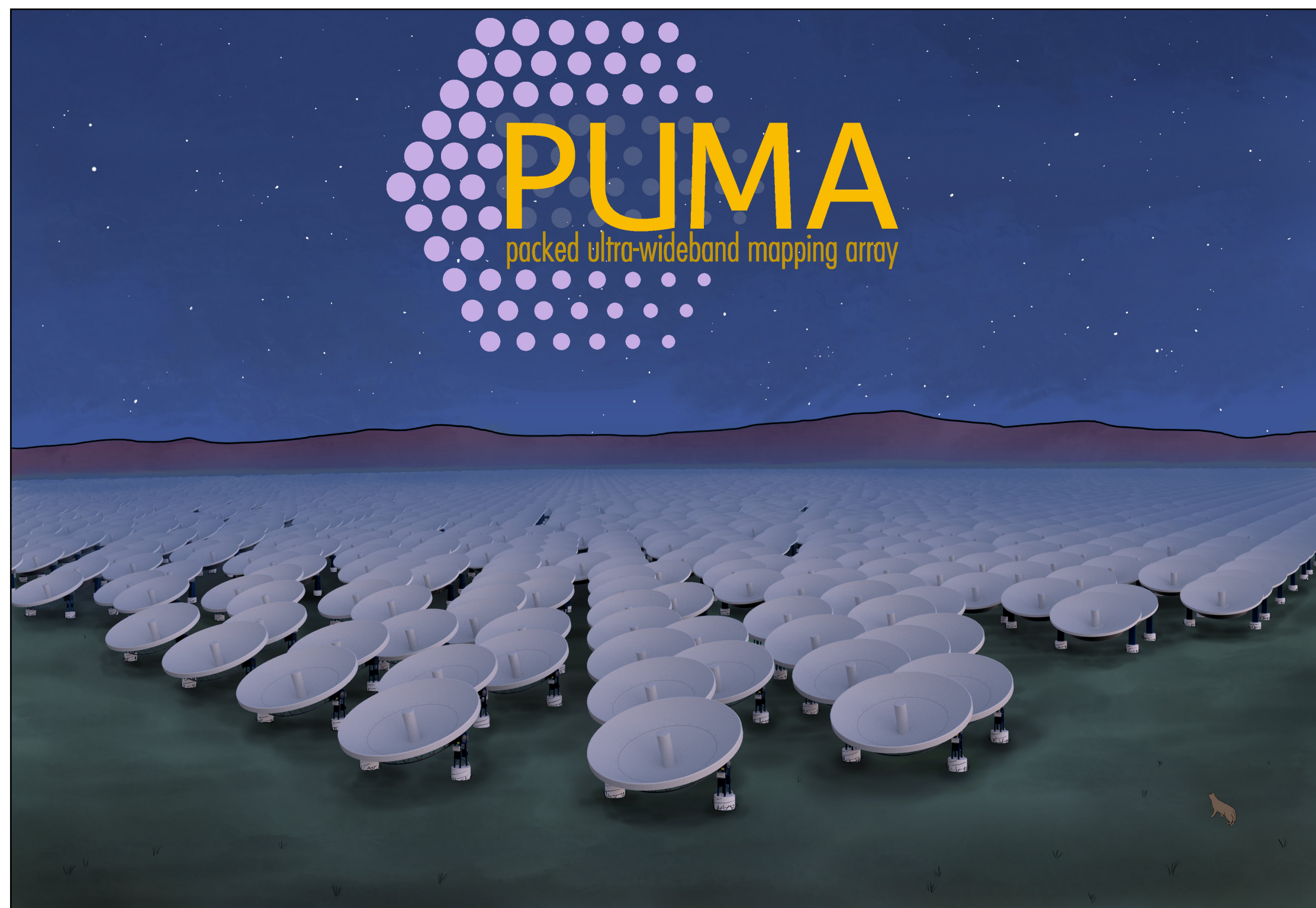


21cm X CMB?



Orlando, Flöss, Meerburg, Silk, 2023

Figure: $\sigma(f_{\text{NL}})$ using CMB x 21cm. $\ell_{\text{max}}^{\text{CMB}} = 10$ and $\ell_{\text{max}}^{21} = 10^5$. Includes secondaries. From estimates should be less affected by non-Gaussian covariance. Redshift range $30 \leq z \leq 200$



Flöss, Biagetti and Meerburg 2022