UNIVERSITY OF CAMBRIDGE

ACTPOL

SIMONS OBSERVATORY

TESTING FUNDAMENTAL PHYSICS WITH HIGH RESOLUTION CMB LENSING MASS MAPS

Frank J. Qu

DAMTP

Advised by Blake D. Sherwin

Tuesday 8th of November

BCCP/COSMOLOGY SEMINAR

OUTLINE

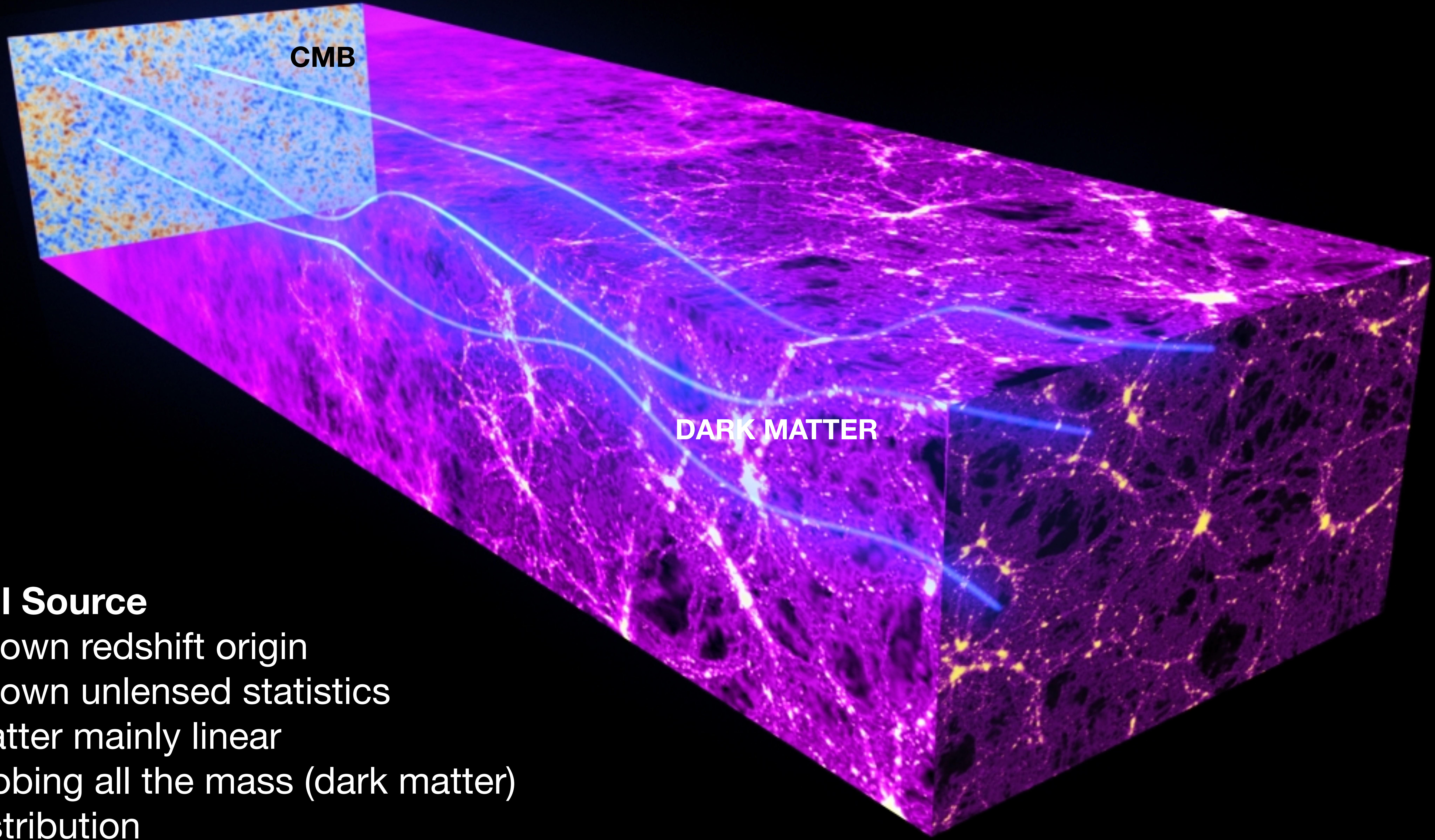
Progress on new CMB lensing measurements with AdvACT DR6 and implications on structure growth

- CMB lensing introduction
- High precision lensing measurement with AdvACT
- Towards a robust lensing measurement. Null test suite
- Challenges with ground based CMB.
  - Systematic modelling: Instrument noise
  - Foregrounds

Tracking structure growth across redshifts with high redshift only lensing maps

- Constructing a high redshift lensing map
- Tomographic measurement of amplitude of structure

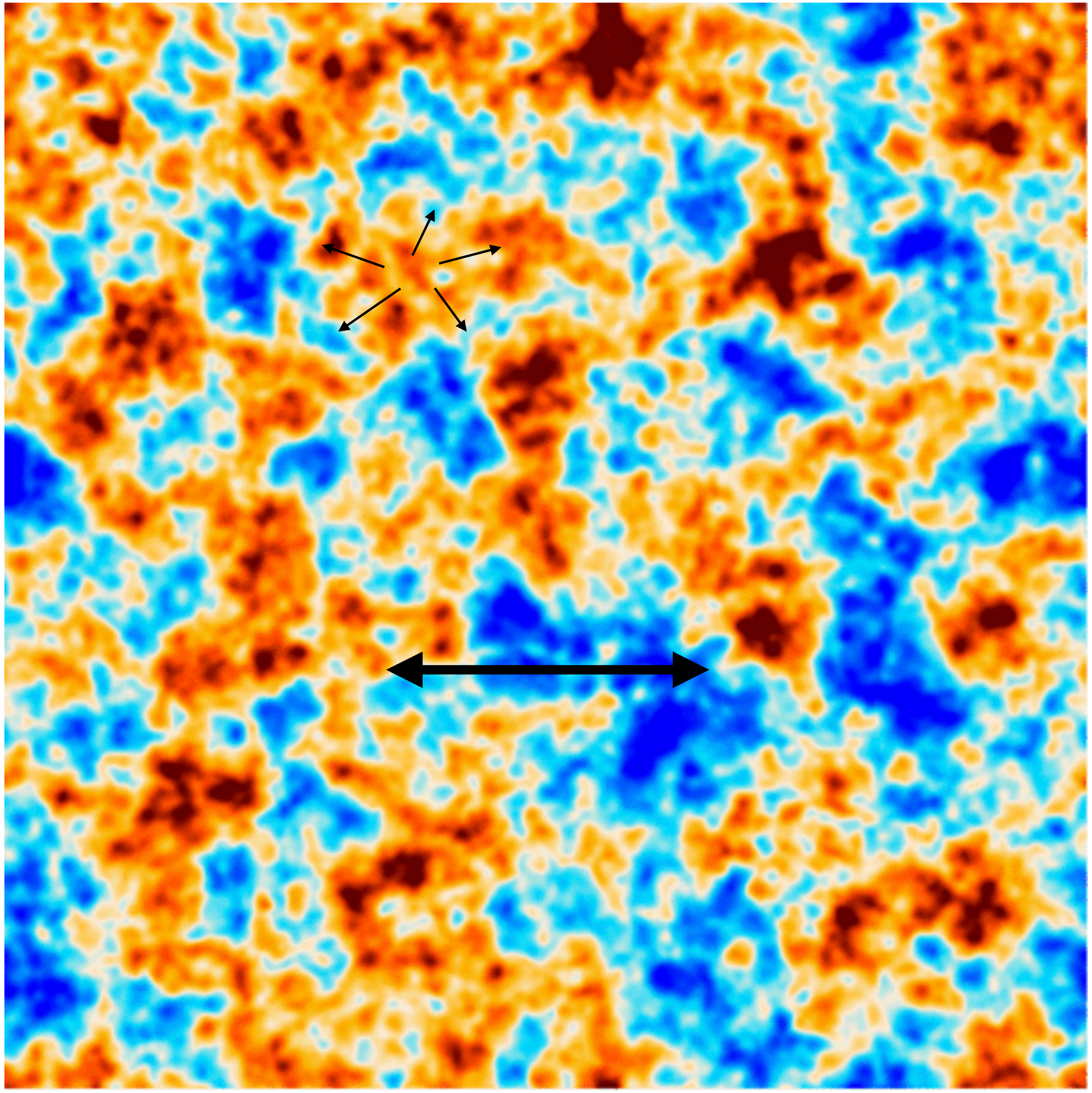
BACKLIGHTING THE UNIVERSE WITH THE CMB



Ideal Source
- Known redshift origin
- Known unlensed statistics
- Matter mainly linear
- Probing all the mass (dark matter) distribution

Image: ESA/Planck

EFFECT OF CMB LENSING



$$T^{\text{lensed}} = T^0(\hat{\boldsymbol{n}} + \nabla\phi)$$

Small-scale arc minute deflections described by deflection field $\nabla\phi$

Coherent over large degree-scales

Lensing convergence $$\kappa = -\frac{1}{2}\nabla^2\phi$$

LENSING RECONSTRUCTION VIA THE QUADRATIC ESTIMATOR

REAL SPACE

- **Unlensed CMB** translationally invariant.
- **Lensing** breaks the isotropy of the unlensed CMB statistics

FOURIER/ HARMONIC SPACE

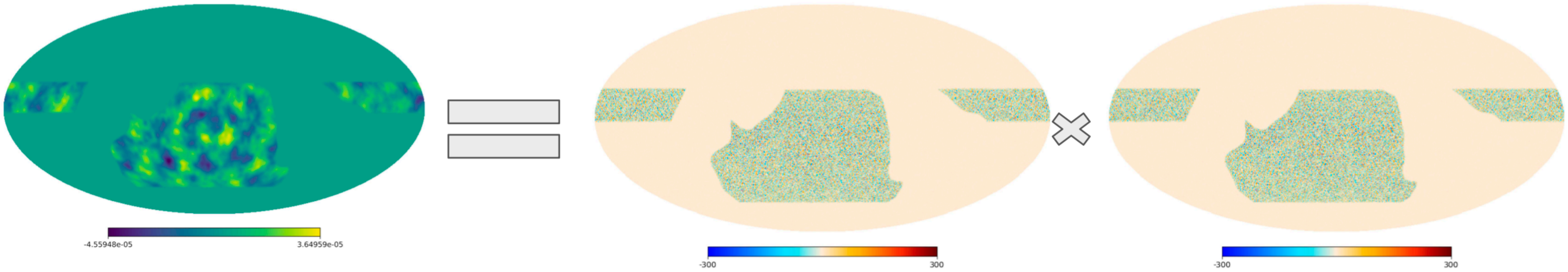
$$\langle T^0(\boldsymbol{\ell})T^{0*}(\boldsymbol{\ell}-\boldsymbol{L})\rangle_{\mathrm{CMB}} = 0$$

Mode coupling

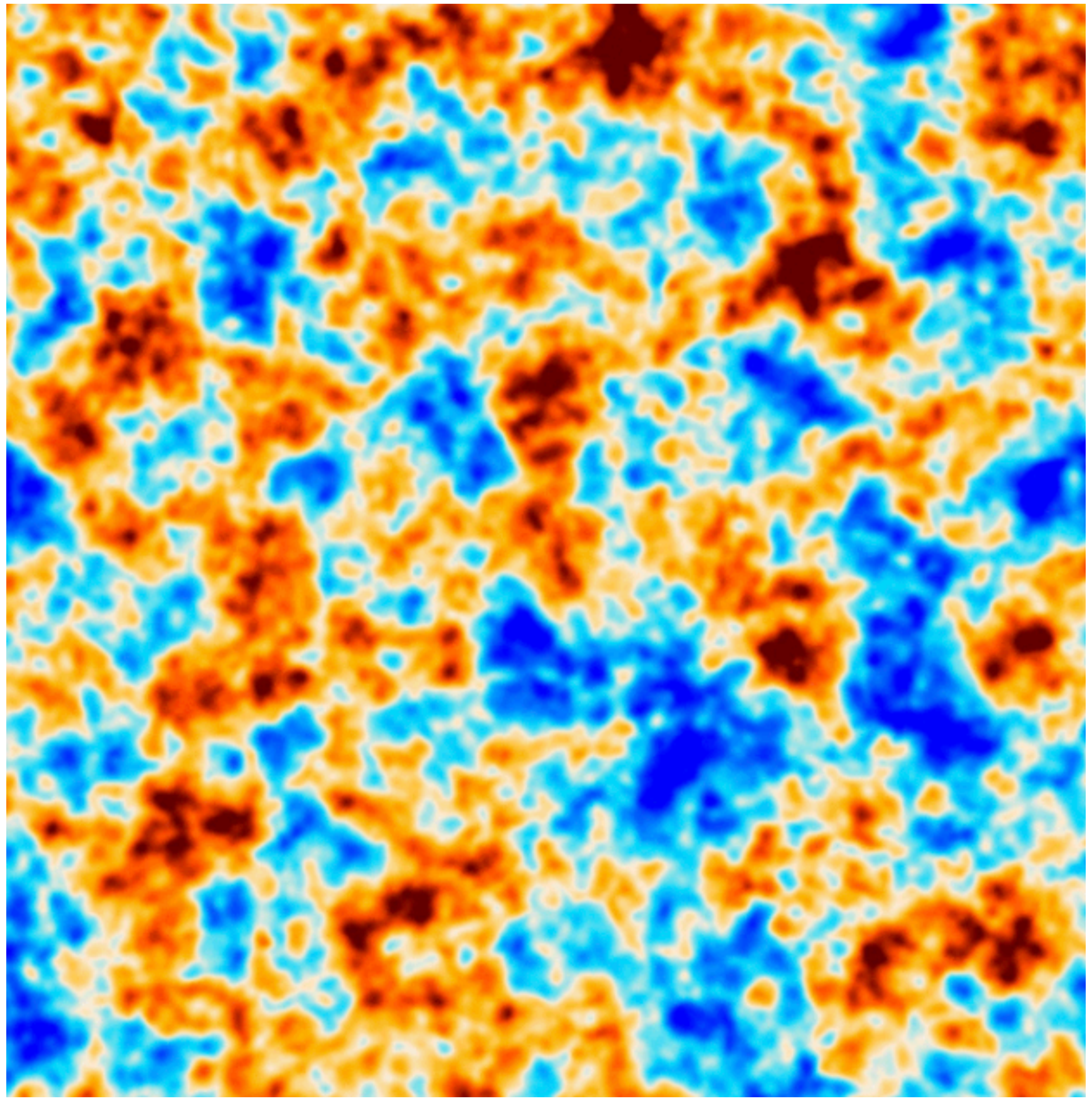
$$\langle T(\boldsymbol{\ell})T^*(\boldsymbol{\ell}-\boldsymbol{L})\rangle_{\mathrm{CMB}} \sim \phi(\boldsymbol{L})$$

Mode by mode reconstruction of lensing from quadratic CMB combinations

$$\hat{\phi}(\boldsymbol{L}) \sim \int d^2\boldsymbol{\ell}\, T(\boldsymbol{\ell})T^*(\boldsymbol{\ell}-\boldsymbol{L})$$



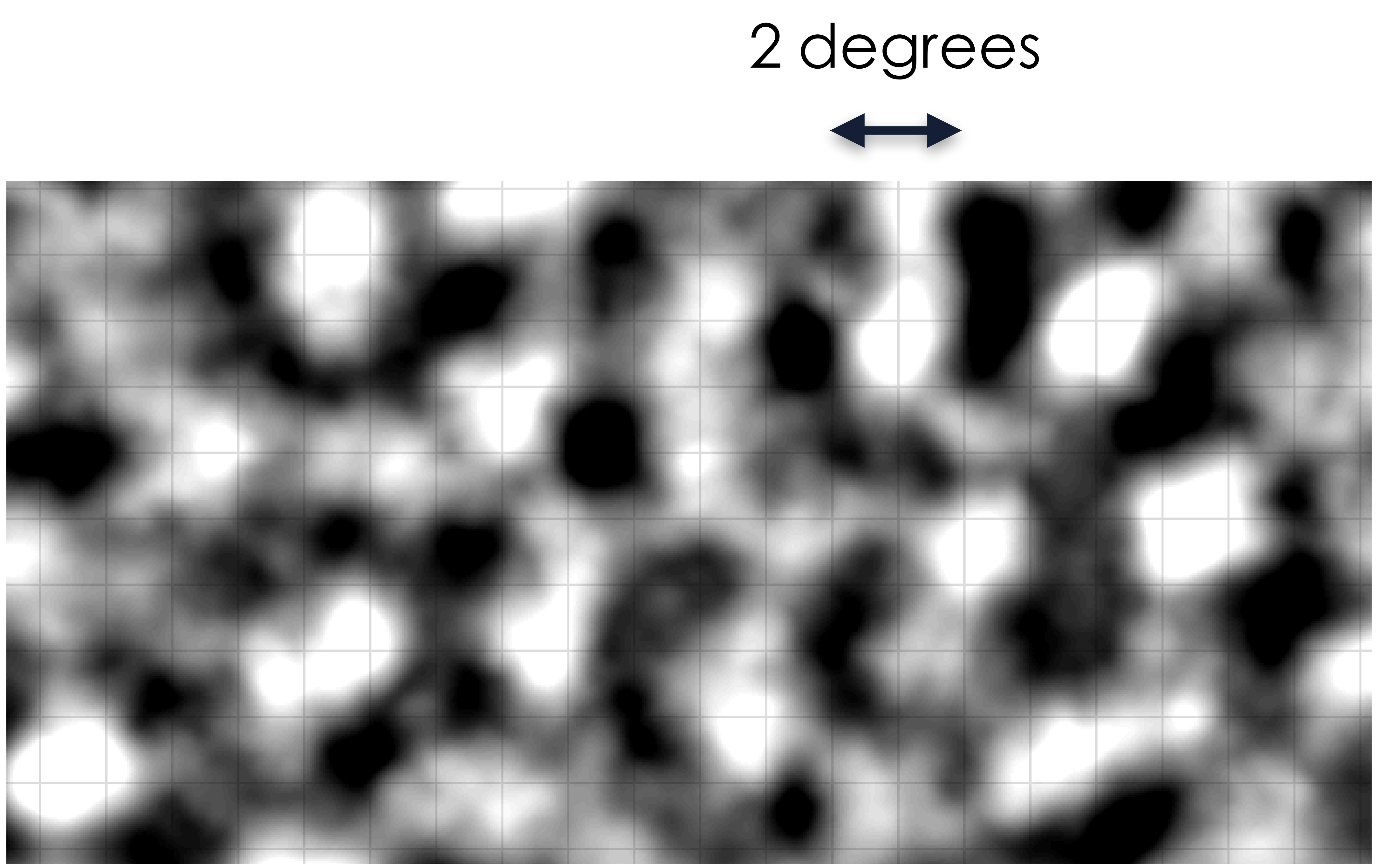
LENSING RECONSTRUCTION VIA THE QUADRATIC ESTIMATOR



Typically use $600 < \ell < 3000$

$$\hat{\phi}(\boldsymbol{L}) \sim \int d^2\boldsymbol{\ell}\, T(\boldsymbol{\ell}) T^*(\boldsymbol{\ell} - \boldsymbol{L})$$

Use **small scale** CMB modes to reconstruct **large scale** lenses

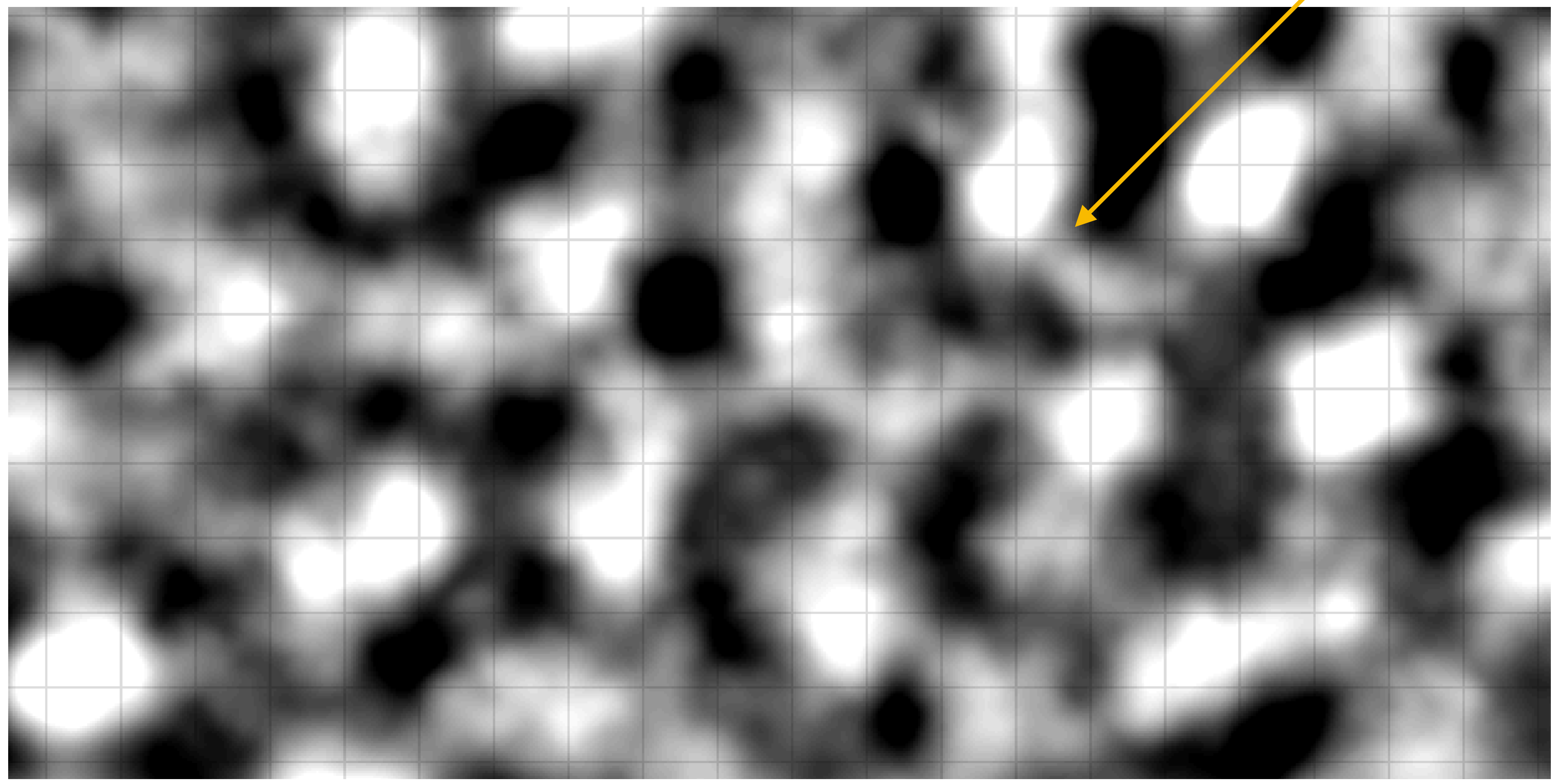


Reconstructed CMB Lensing Matter Distribution

Benefit from **high resolution** CMB measurements

KEY STATISTICS: LENSING POWER SPECTRUM

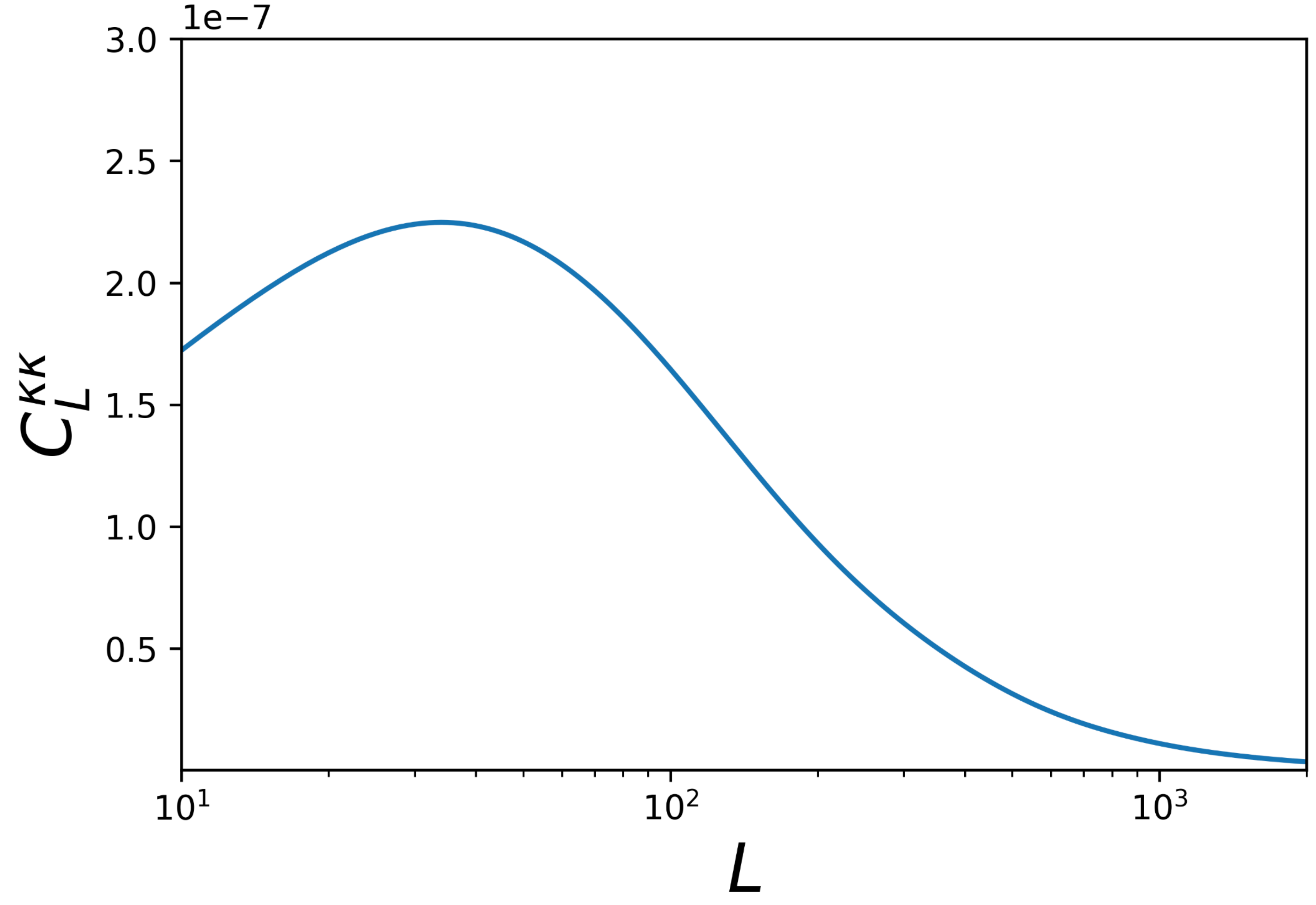
Bright regions = High Density



Reconstructed mass map

$$\hat{C}_L^{\phi\phi} \sim \langle \hat{\phi}_{LM} \hat{\phi}^*_{LM} \rangle$$

y-axis: How much lensing there is



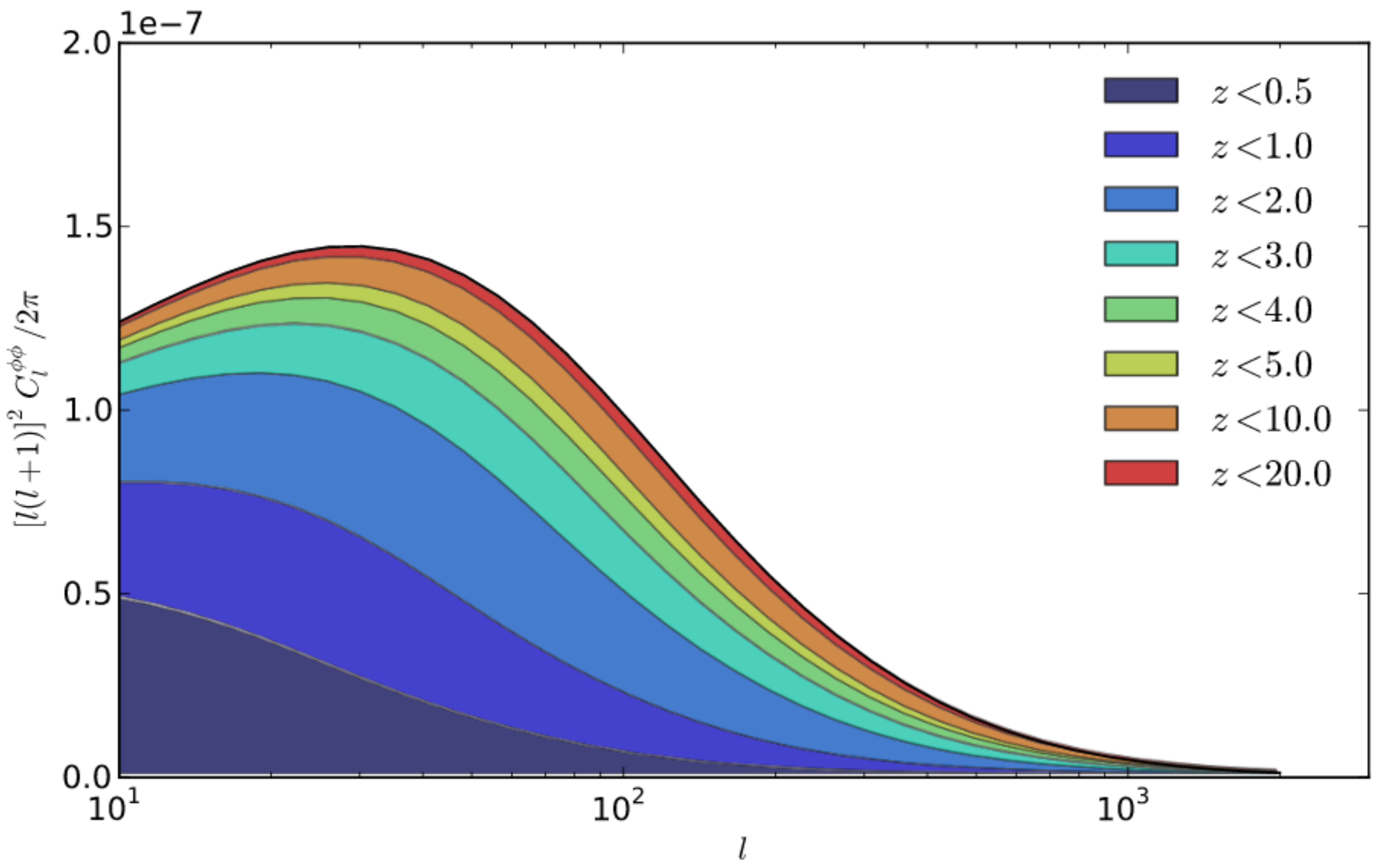
x-axis: For a lens of angular size $\sim \frac{1}{L}$

WHAT DOES CMB LENSING TELL US?

- Lensing probes the projected mass distribution to high redshifts.
- The lensing power spectrum hence probes the projected matter power spectrum

$$C_L^{\kappa\kappa} \sim \int_0^{z_\star} dz [W^\kappa(z)]^2 P_{\delta\delta}\left(k = \frac{L+\frac{1}{2}}{\chi(z)}, z\right)$$

Projection kernel — Matter power spectrum

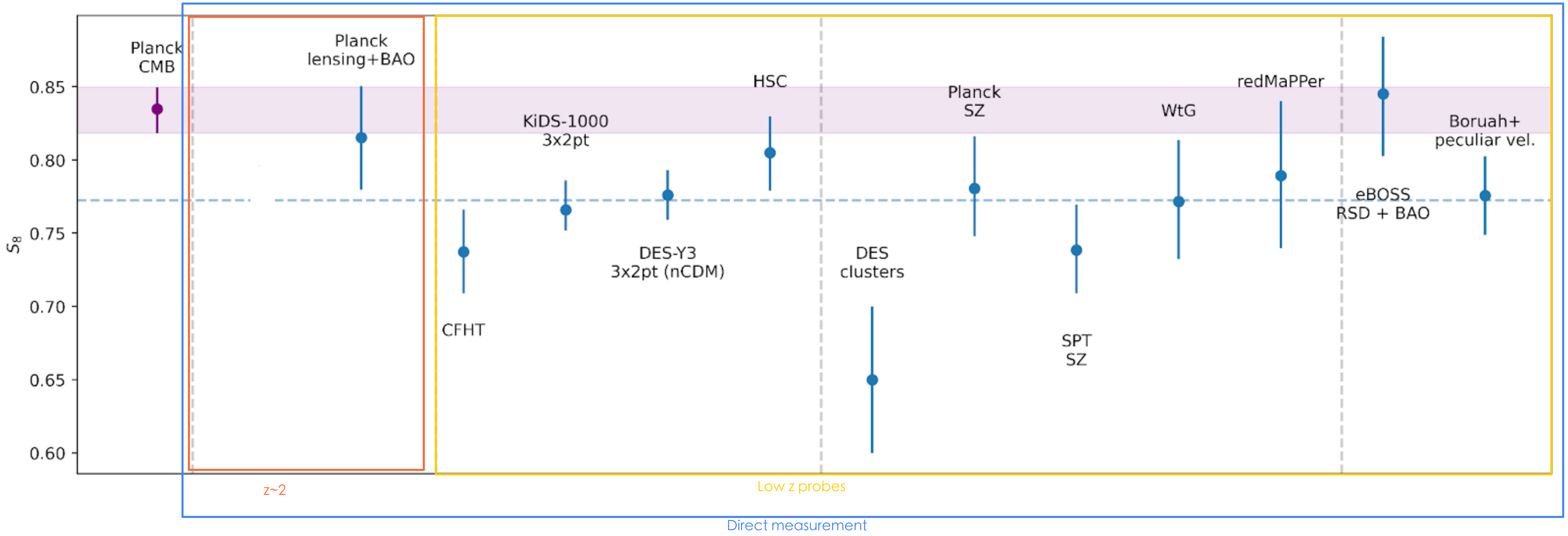


- CMB Lensing therefore sensitive to:
  - Neutrino mass sum via power spectrum suppression
  - Combination of **clumpiness** (amplitude of clustering on scales of 8Mpc/h) and the **total amount of matter**

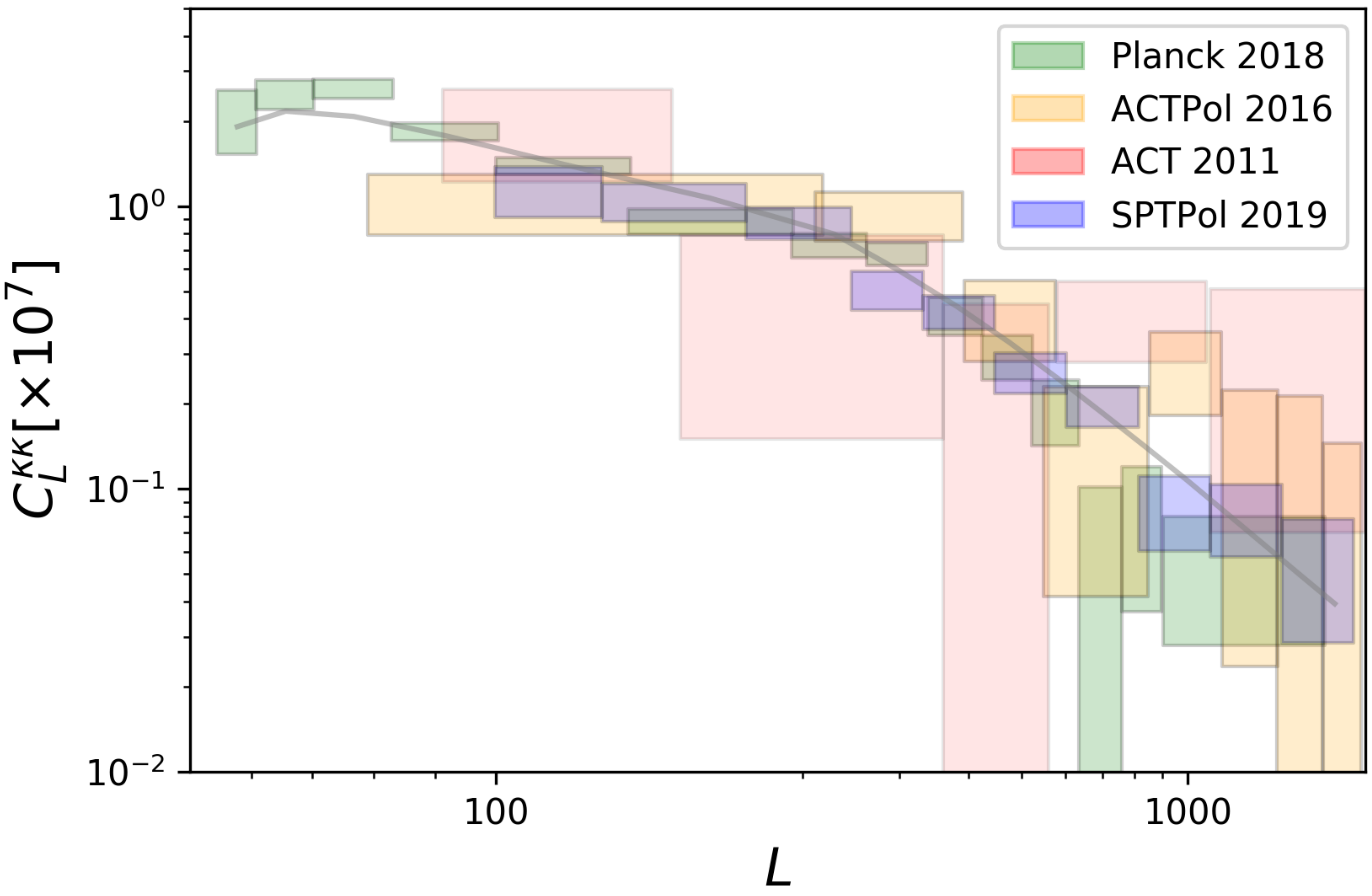
$$\sigma_8 \Omega_m^{0.25}$$

MOTIVATION: WEIGH IN CLAIMS ON S8 TENSION

- Discrepancy of 2-3 σ appearing in the amplitude of structure between low z probes and extrapolation result from CMB.
- **Probes involving galaxies** are very powerful, but also challenging: Photo-zs, blending, baryonic effects, intrinsic alignments…
- Useful to test this further with a direct probe like **CMB lensing. Independent of galaxies and Planck**
  - Completely different systematics.
  - Clean probe. *caveat of extragalactic foregrounds



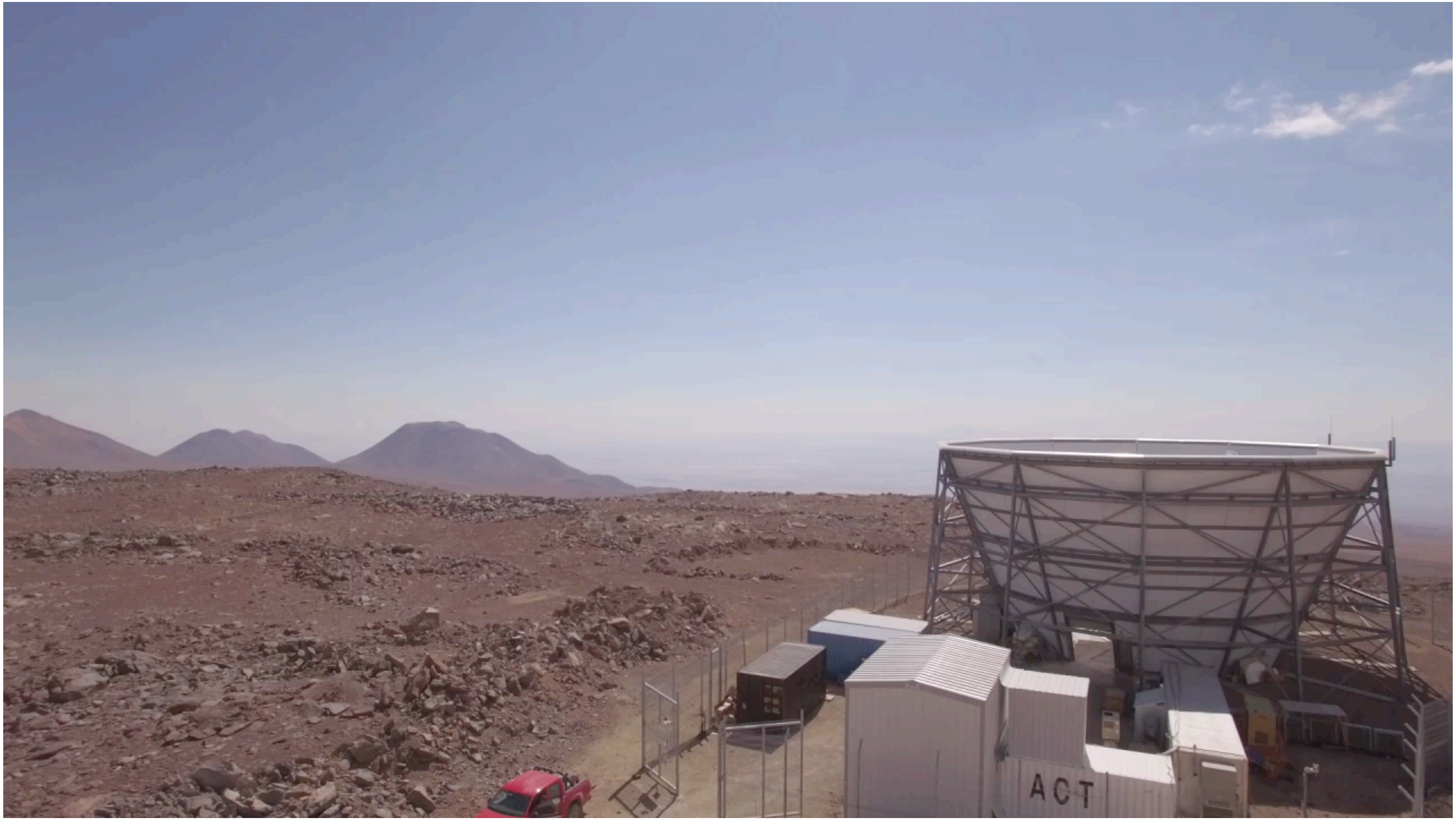
CMB LENSING POWER SPECTRA: TOWARDS PRECISION COSMOLOGY



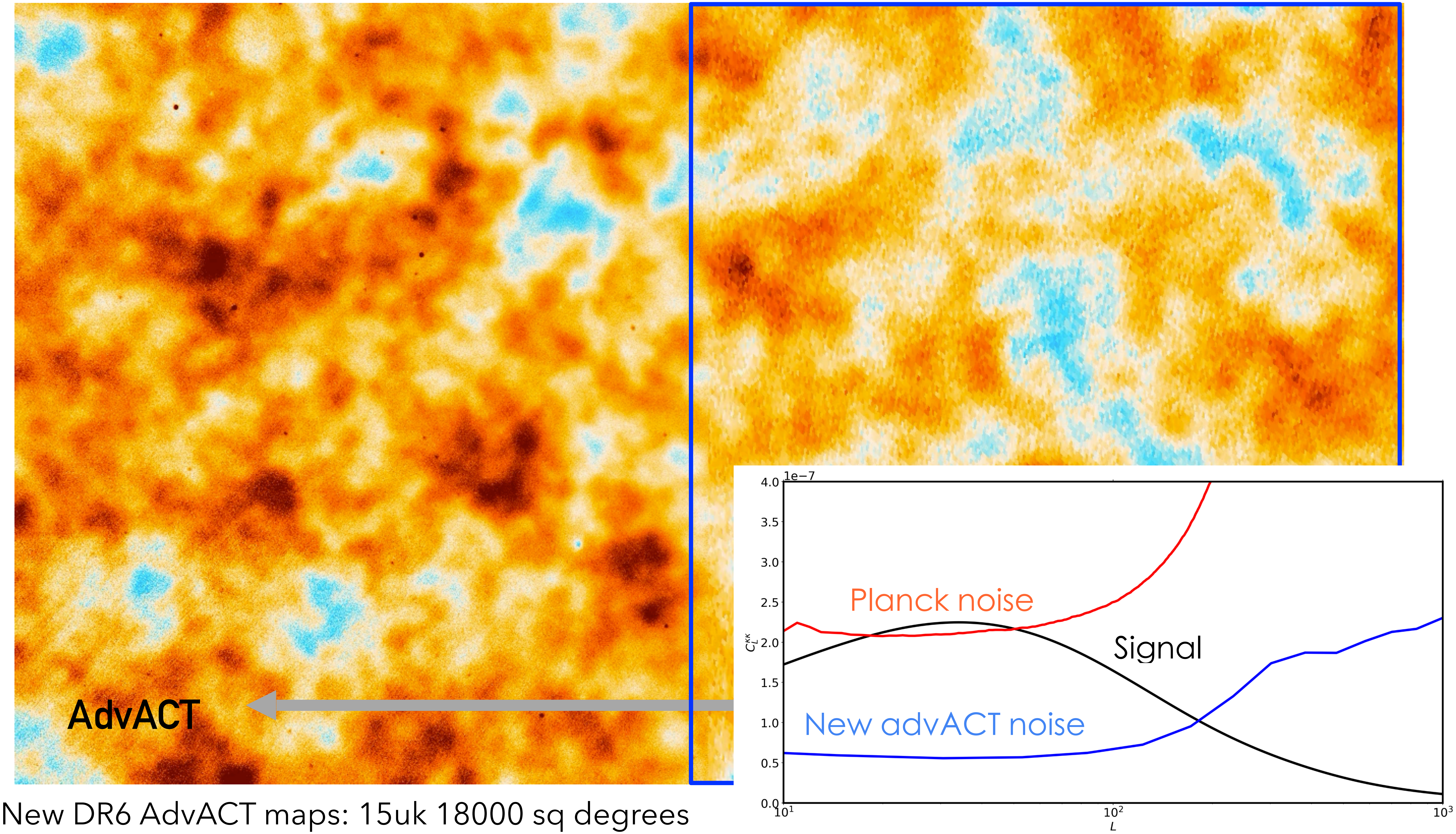
Very fast progress- But we are only unleashing the full potential of lensing **now** with new ground based experiments like **AdvACT**

ATACAMA COSMOLOGY TELESCOPE

Arcminute resolution CMB telescope, located in the Chilean Atacama desert

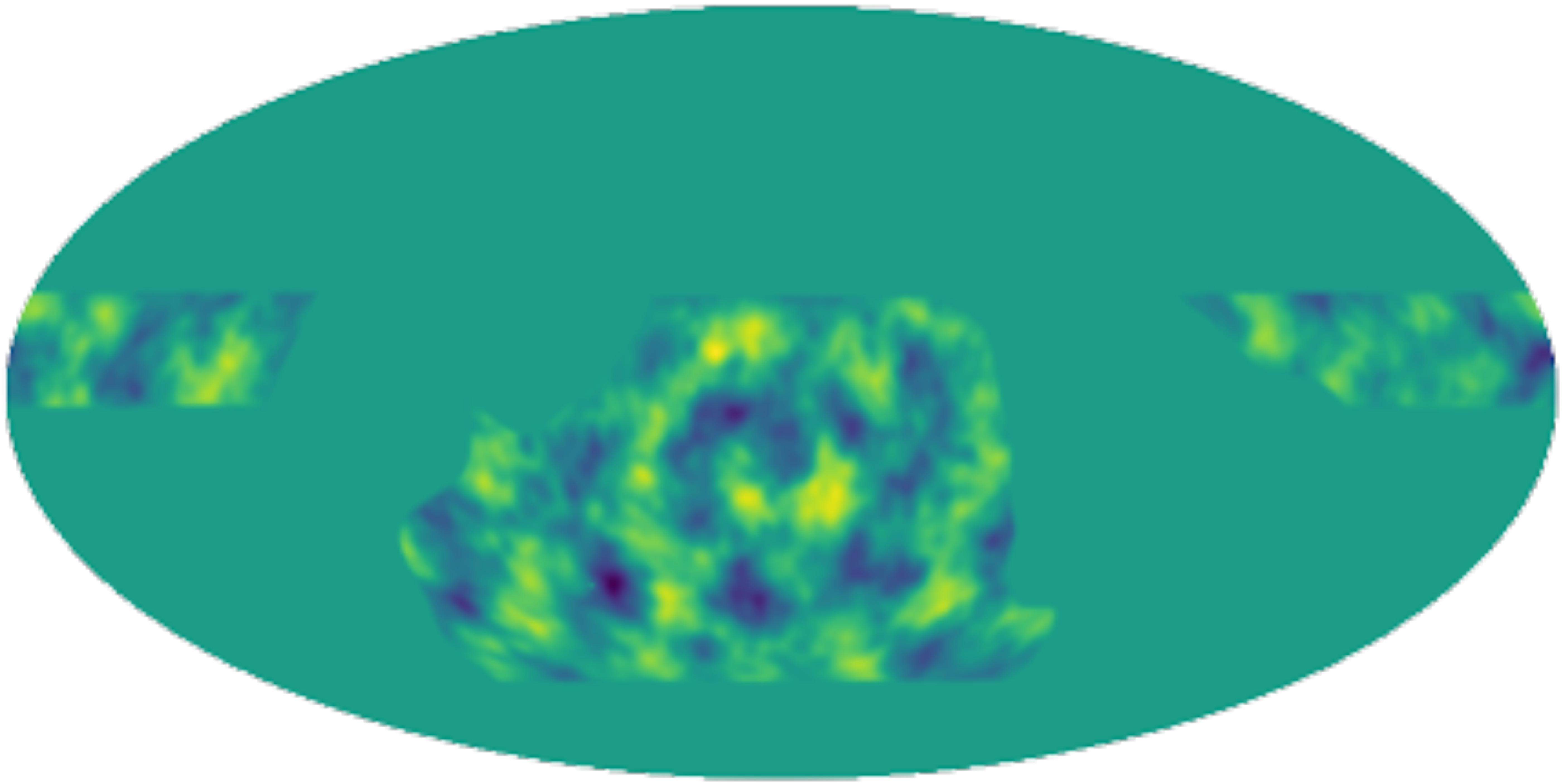


HIGH RESOLUTION CMB LENSING MEASUREMENTS FROM ADVACT



New DR6 AdvACT maps: 15uk 18000 sq degrees

HIGH RESOLUTION CMB LENSING MEASUREMENTS FROM ADVACT



PRELIMINARY AdvACT lensing Map

Signal dominated reconstruction enables seeing dark matter by eye!
Dusty forming galaxy emissions CIB contours highly correlated with reconstructed lensing field.

Demo

MEASURING THE LENSING POWER SPECTRUM

- NULL TEST SUITE
- CHALLENGES OF HIGH RESOLUTION GROUND BASED MEASUREMENTS AND SOLUTIONS

ROBUST LENSING MEASUREMENT WITH COMPREHENSIVE NULL TEST SUITE

More than 200 null tests for robust lensing measurement

Foreground tests
- Polarization vs temperature consistency
- Frequency consistency in map and spectrum.
- Shear estimator
- Galactic foreground/ sky area tests

Signal Isotropy tests

Cross linking tests
Patch based tests
North vs South

Curl deflection tests

Scale tests
- k-space filtering
- min-max multipole variation
  - 300<ell<3000
  - 500<ell<3000
  - 600<ell<3000
  - 600<ell<2500
  - 1500<ell<3000

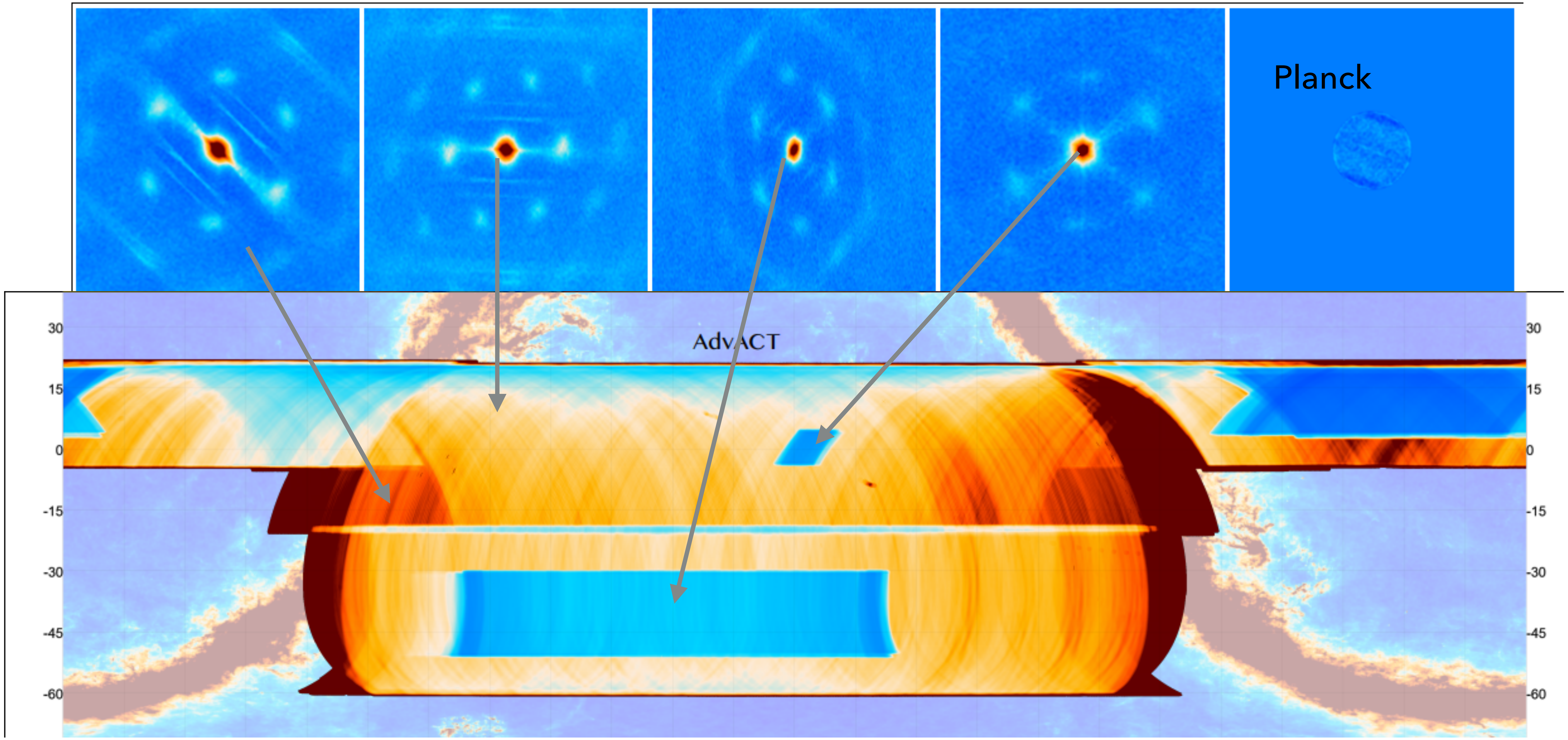
Instrument related tests

Noise only tests
Array difference tests
PWV tests
Season difference tests

KEY FOR PASSING
- Cross correlation based estimator. (Immune to instrumental noise)
- Two different methods for foreground mitigation
  - Profile hardening
  - Frequency cleaning

CHALLENGE:

GROUND BASED NOISE IS VERY COMPLICATED TO MODEL



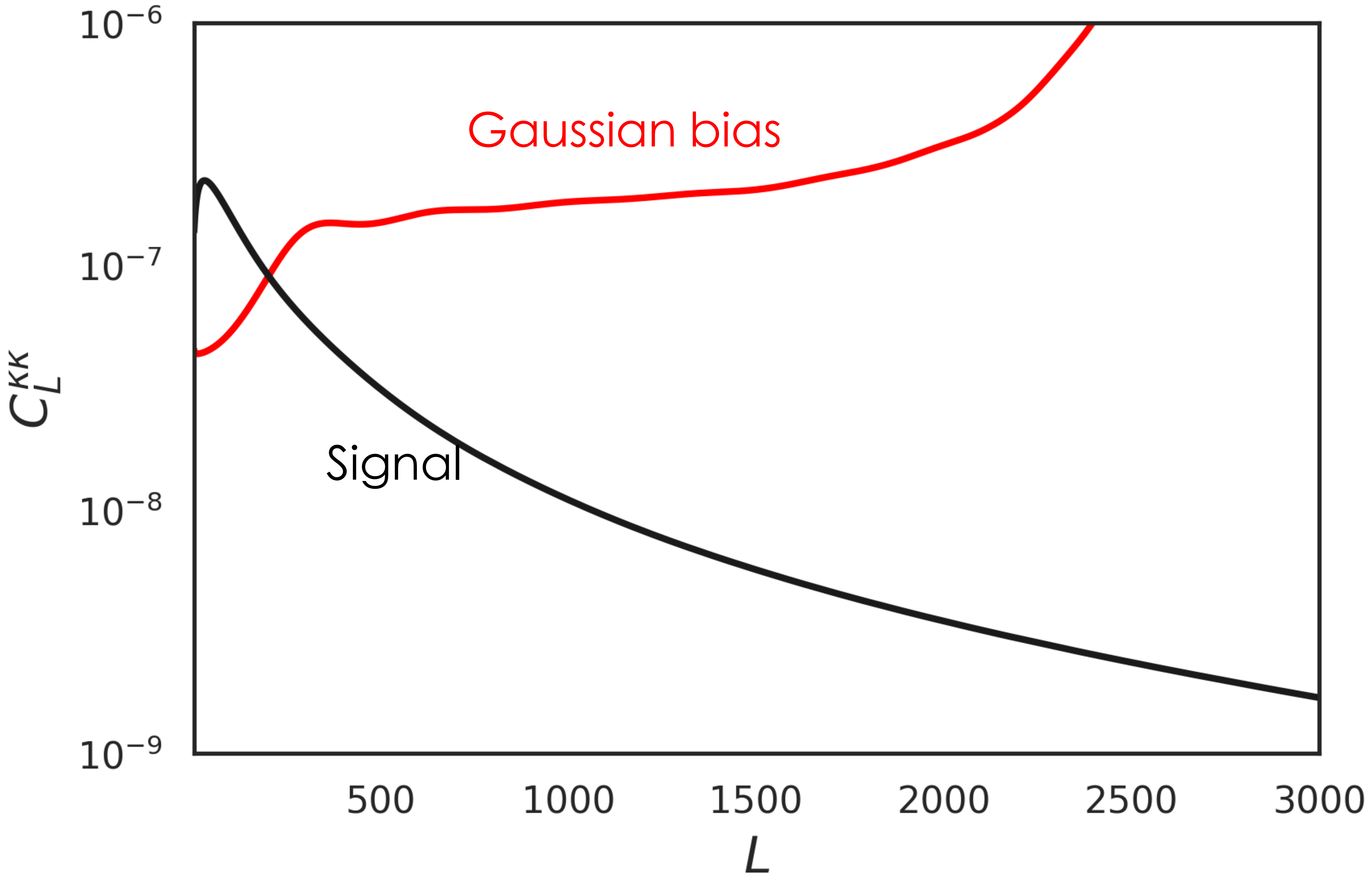
Naess et Al 2020

Challenge: Noise modelling. Why do we need accurate noise sims?

$$C_L^{\phi\phi} \sim \langle \phi(\mathbf{L})\phi^*(\mathbf{L})\rangle - \text{Gaussian bias} \longrightarrow \langle TTTT\rangle - \langle TT\rangle\langle TT\rangle$$

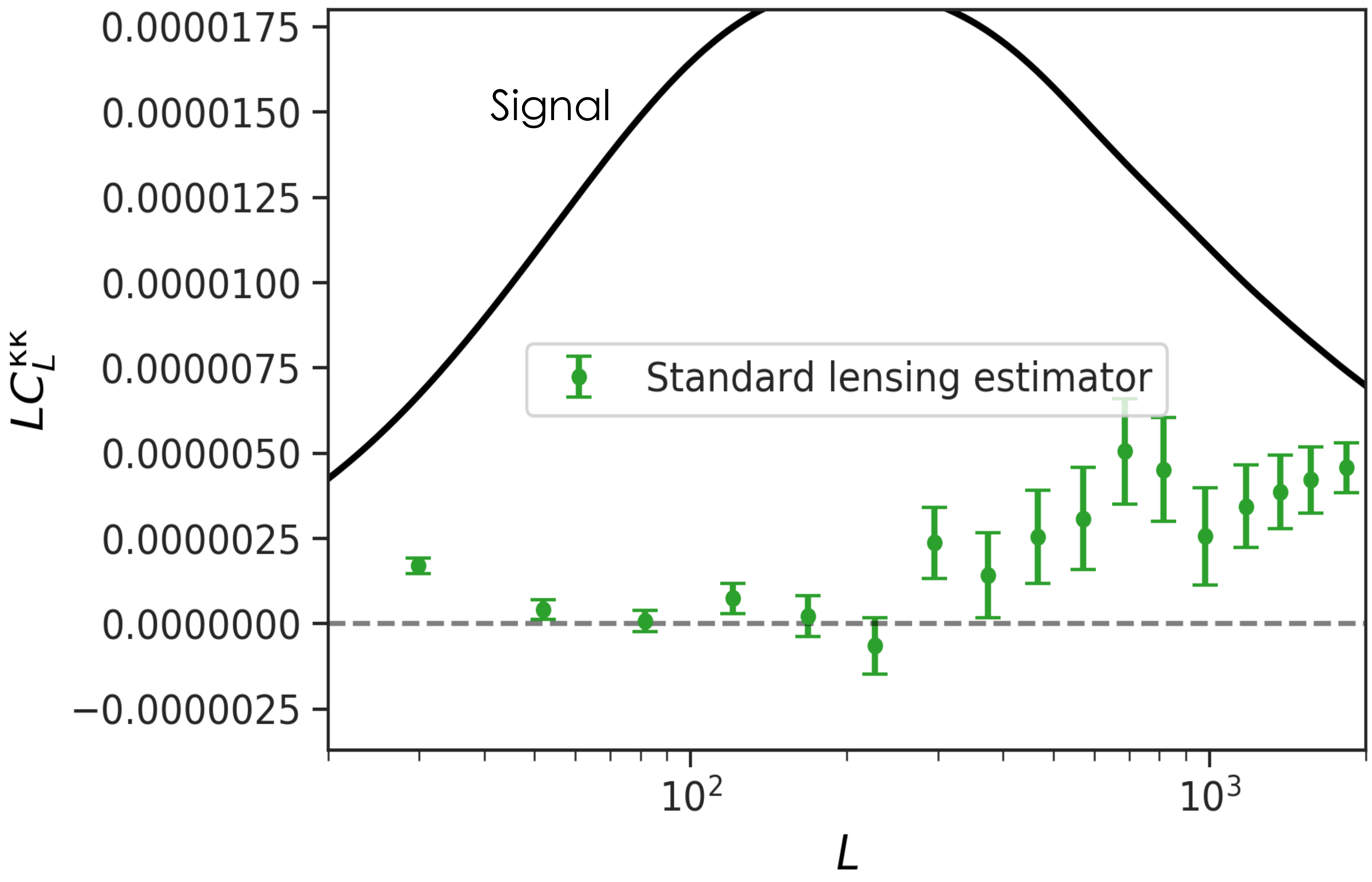
Schematically

Gaussian contractions give large bias



- Lensing power spectrum measures a 4 point function. Large bias arises from chance correlations from CMB signal and instrumental noise.
- Method to subtracting this uses combination of data and simulations. Arguably robust…

Challenge: Noise modelling, Noise only null test failure



- Take difference of splits to remove the CMB signal and obtain noise only maps.
- Run these noise only maps in the lensing pipeline. Including the subtraction of the gaussian bias using the data/sim method.

Expectation

Result should be consistent with zero.

Reality

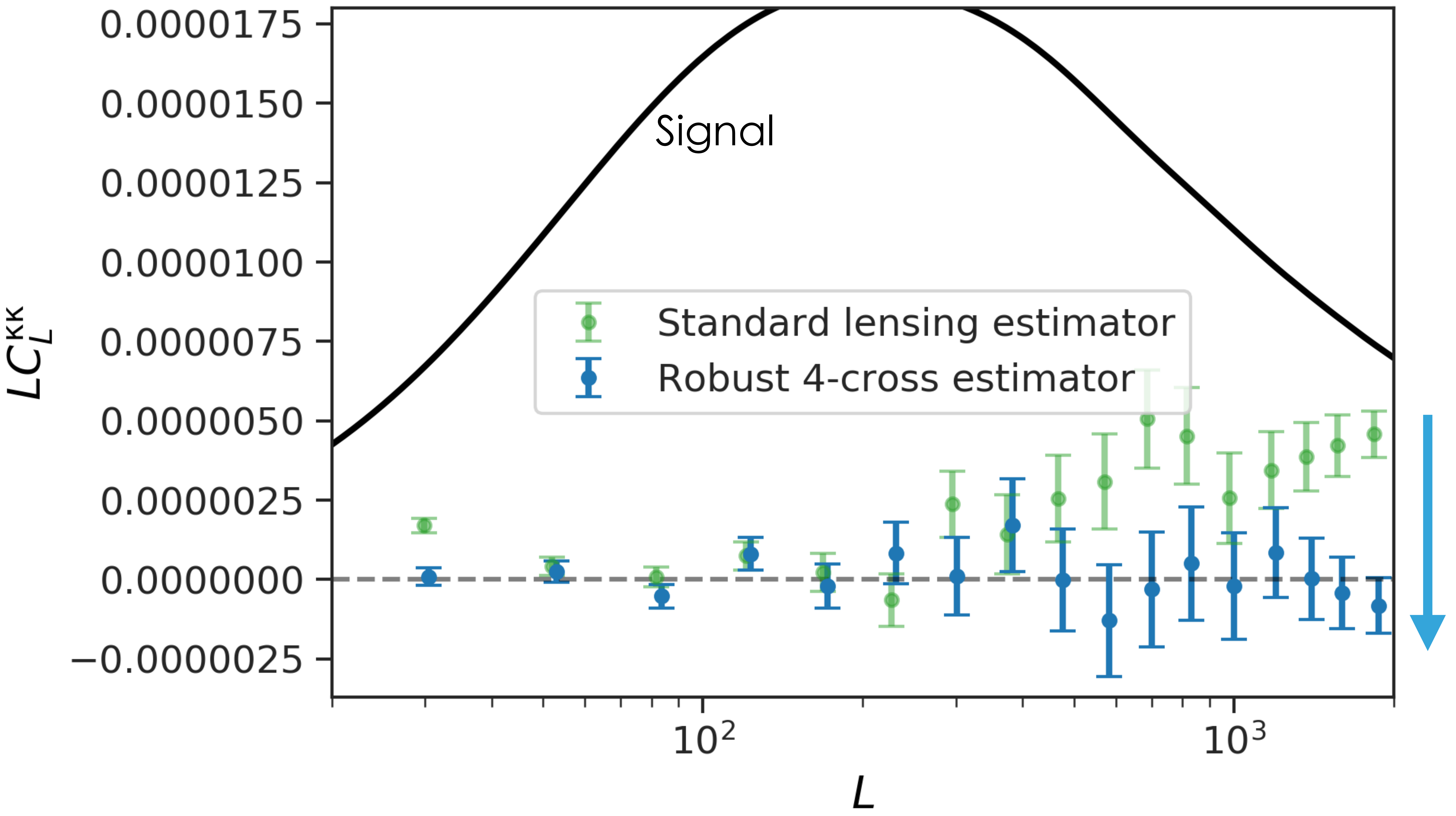
U shape failure

Solution: Cross correlation based estimator

- Divide data into splits with independent noise. Estimator immune to noise mis-simulations.
- Non trivial combination of splits makes computational cost $\mathcal{O}(\text{splits}^2)$ instead of naive $\mathcal{O}(\text{splits}^4)$

$$C_L^{\phi\phi,\text{cross}} \sim \langle T_1 T_2 T_3 T_4 \rangle$$

maps with independent noise

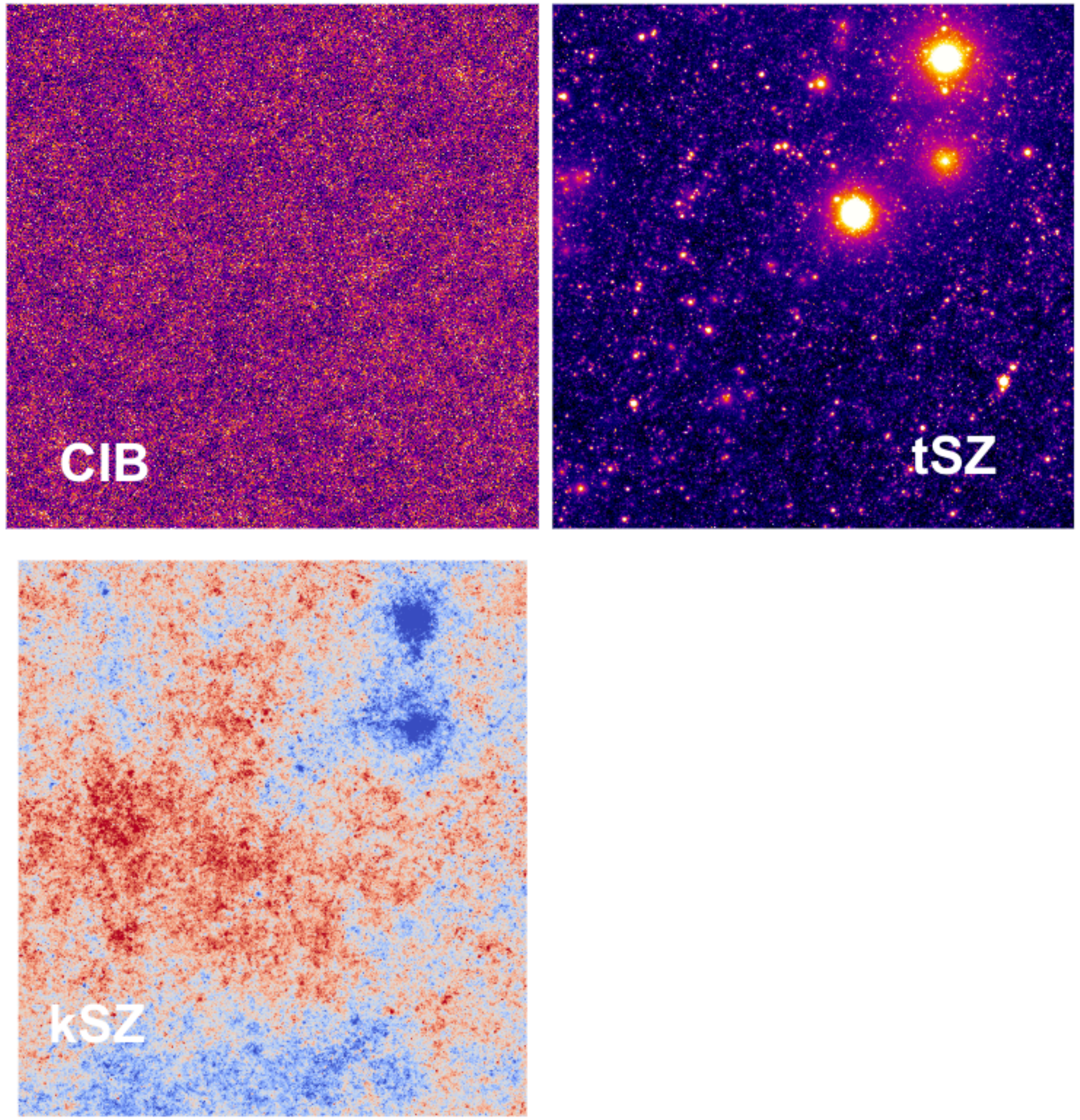


- Take difference of splits to remove the CMB signal and obtain noise only maps.
- Run these noise only maps in the lensing pipeline. Including the subtraction of the gaussian bias using the data/sim method.

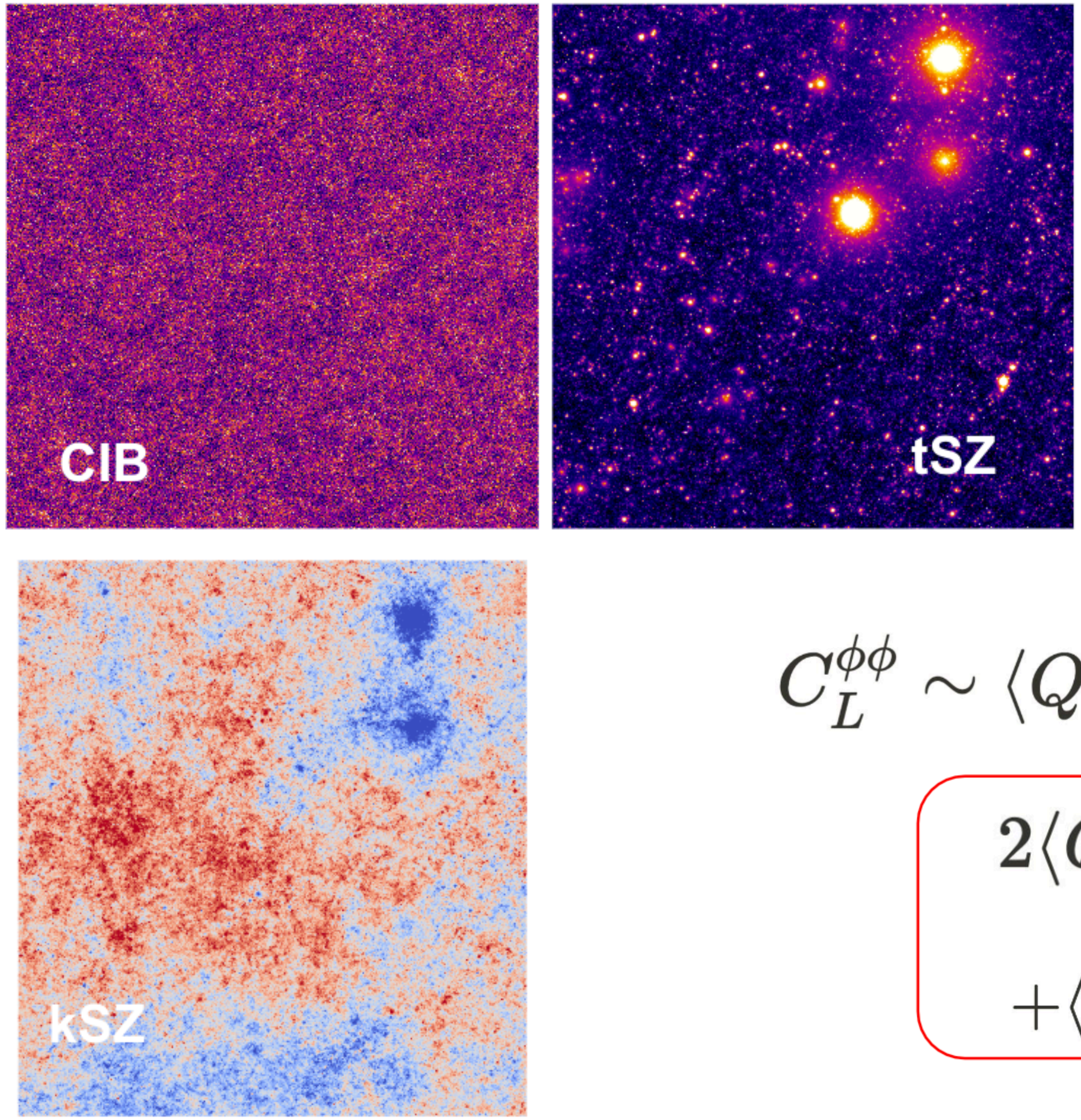
Pass the null test with robust cross estimator!

CHALLENGE II:

CONTAMINATION FROM EXTRA-GALACTIC FOREGROUNDS



Challenge I: Biases From Extragalactic foregrounds



- CMB maps contains from radio point sources, cosmic infrared background (CIB), thermal and kinetic SZ effects.

$$T = T + f$$

$$C_L^{\phi\phi} \sim \langle Q[T_{\mathrm{CMB}}, T_{\mathrm{CMB}}] Q[T_{\mathrm{CMB}}, T_{\mathrm{CMB}}] \rangle +$$

$$2\langle Q[T_{\mathrm{CMB}}, T_{\mathrm{CMB}}] Q[f, f] \rangle + 4\langle Q[T_{\mathrm{CMB}}, f] Q[T_{\mathrm{CMB}}, f] \rangle$$

$$+\langle Q[f, f] Q[f, f] \rangle$$

Foreground induced biases

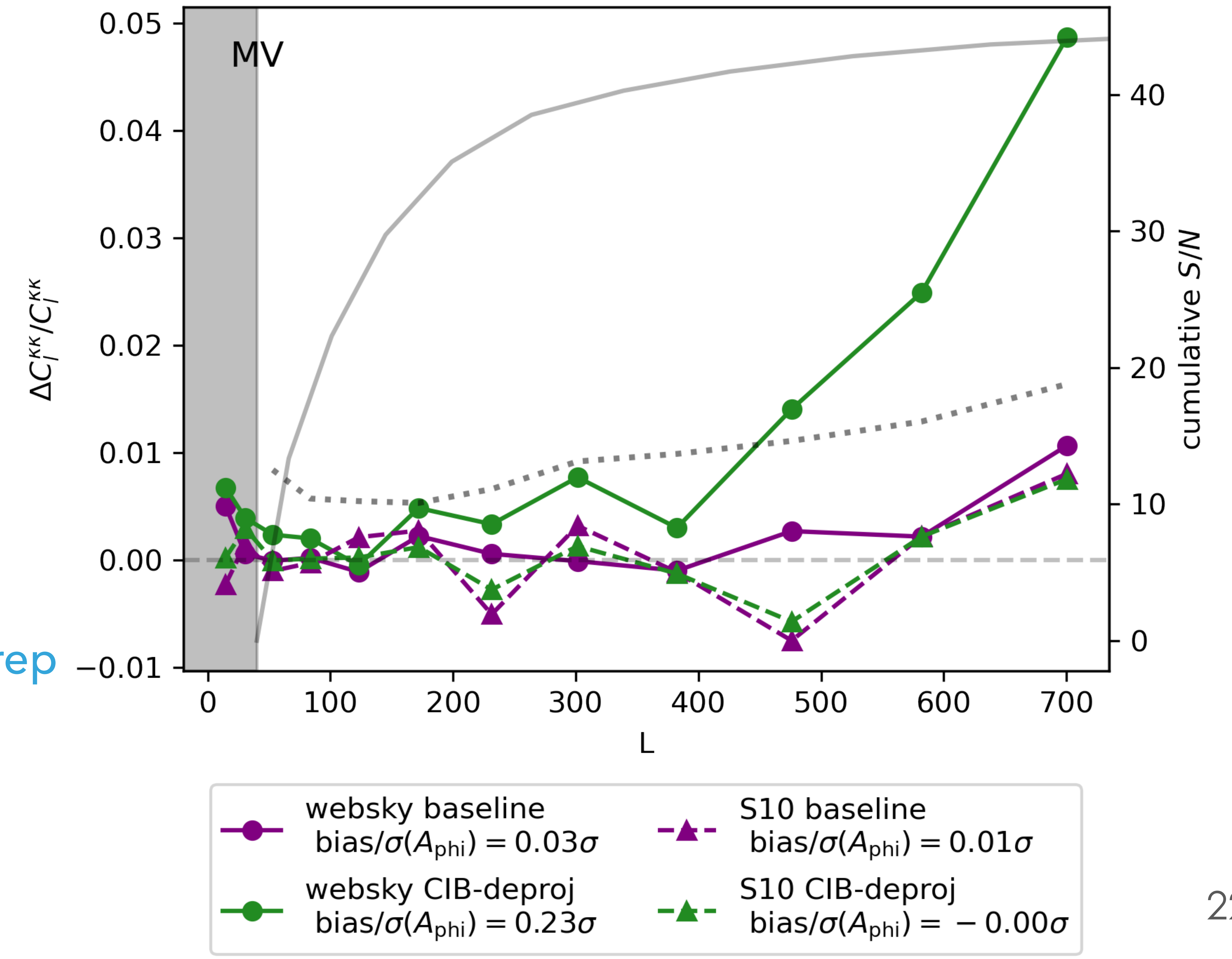
Foreground mitigation pipeline (Simulate bias estimates)

Implement curvedsky foreground mitigation methods → Test methods with simulations → Compare simulation results with data based null tests to reduce reliance to particular set of simulations.

AdvACT Lensing: Repertoire of mitigation methods

- **Geometric methods**
  - Profile hardening
  - Shear
- **Multifrequency**
  - CIB deprojection + Profile hardening

Macrann,Sherwin,Qu++ in prep



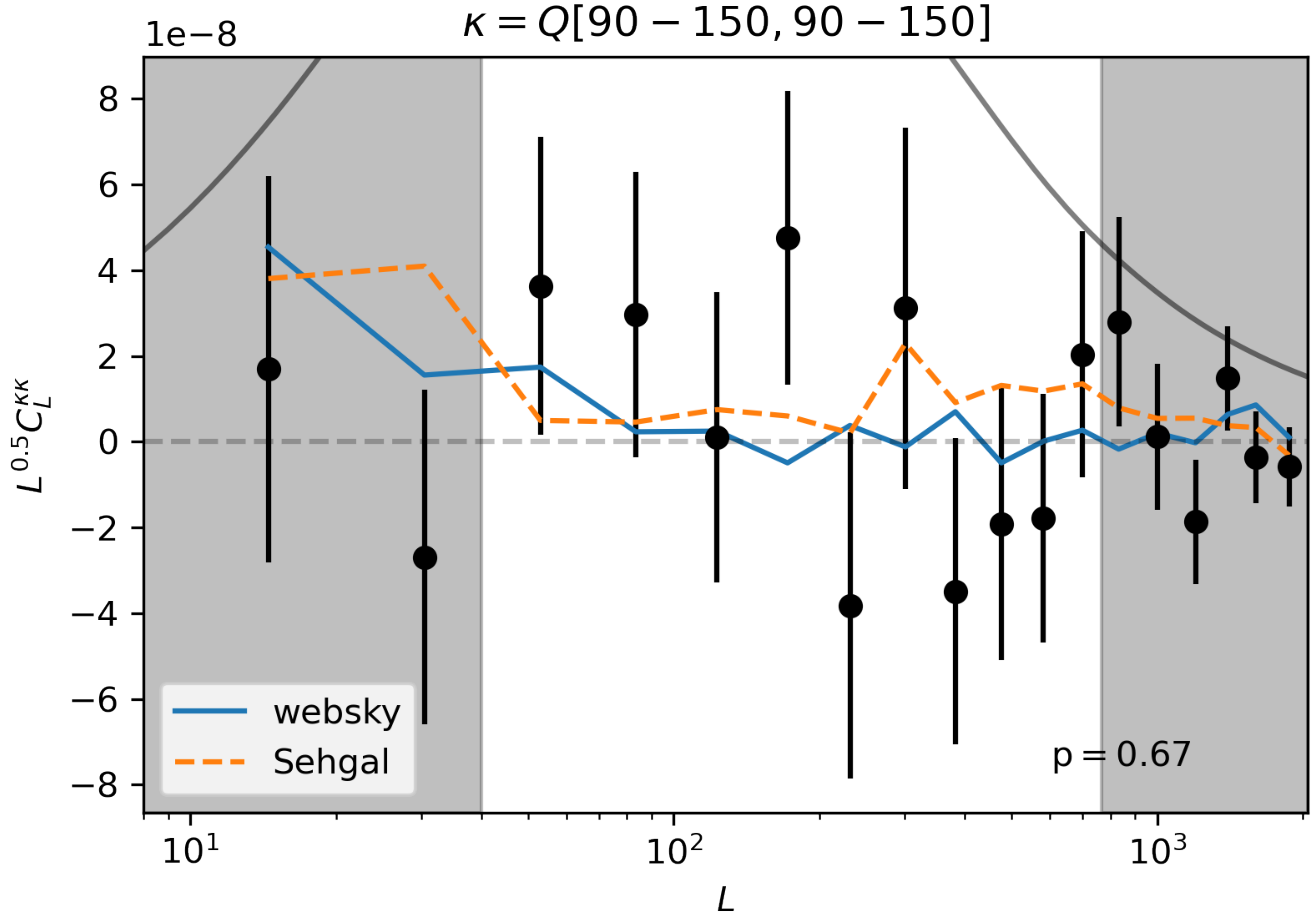
- **Simulated biases negligible in both methods (2 different sims)**

BASELINE MITIGATION TECHNIQUE: PROFILE HARDENING

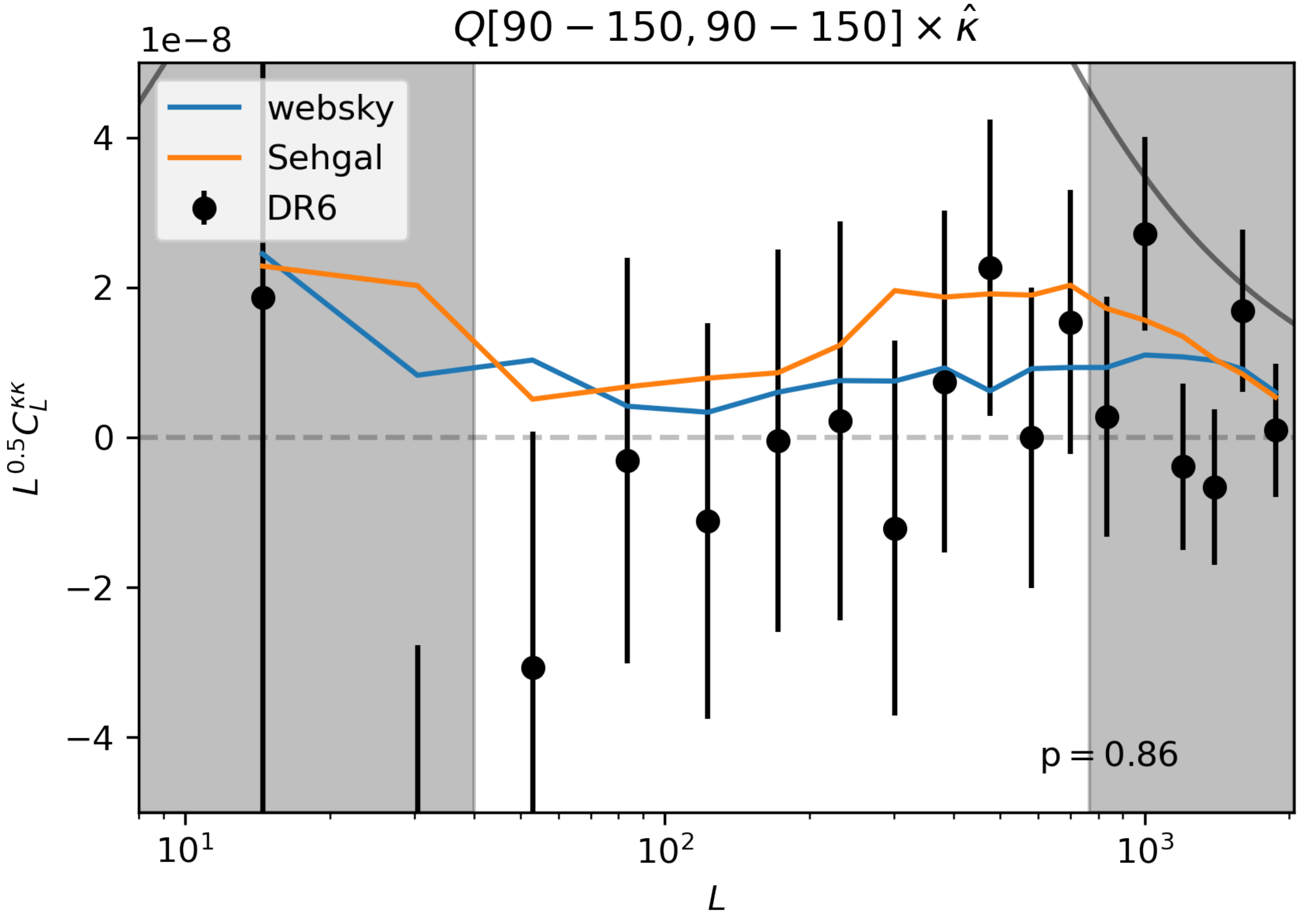
Namikawa+ 2013 Osborne+2013 Sailer+2020 Sailer+2022

Construct estimators that are insensitive to mode couplings generated by a particular field (tSZ clusters/CIB/point sources)

Null tests leveraging the 90 and 150 GHz frequencies to isolate the different foreground biases



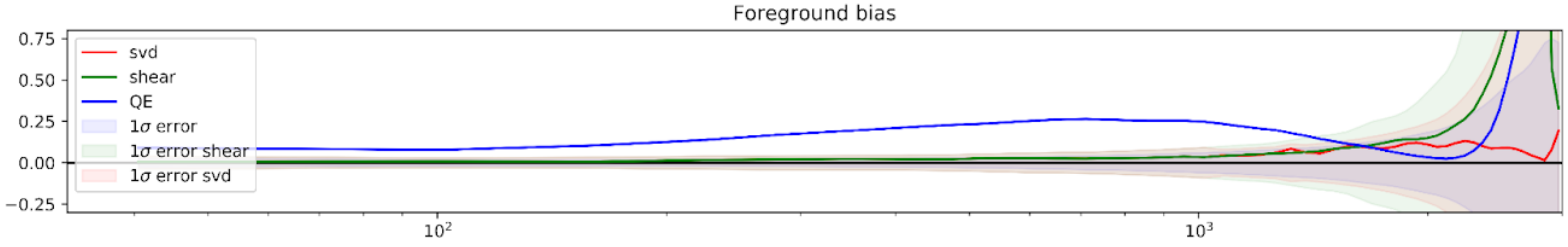
Testing the foreground trispectrum



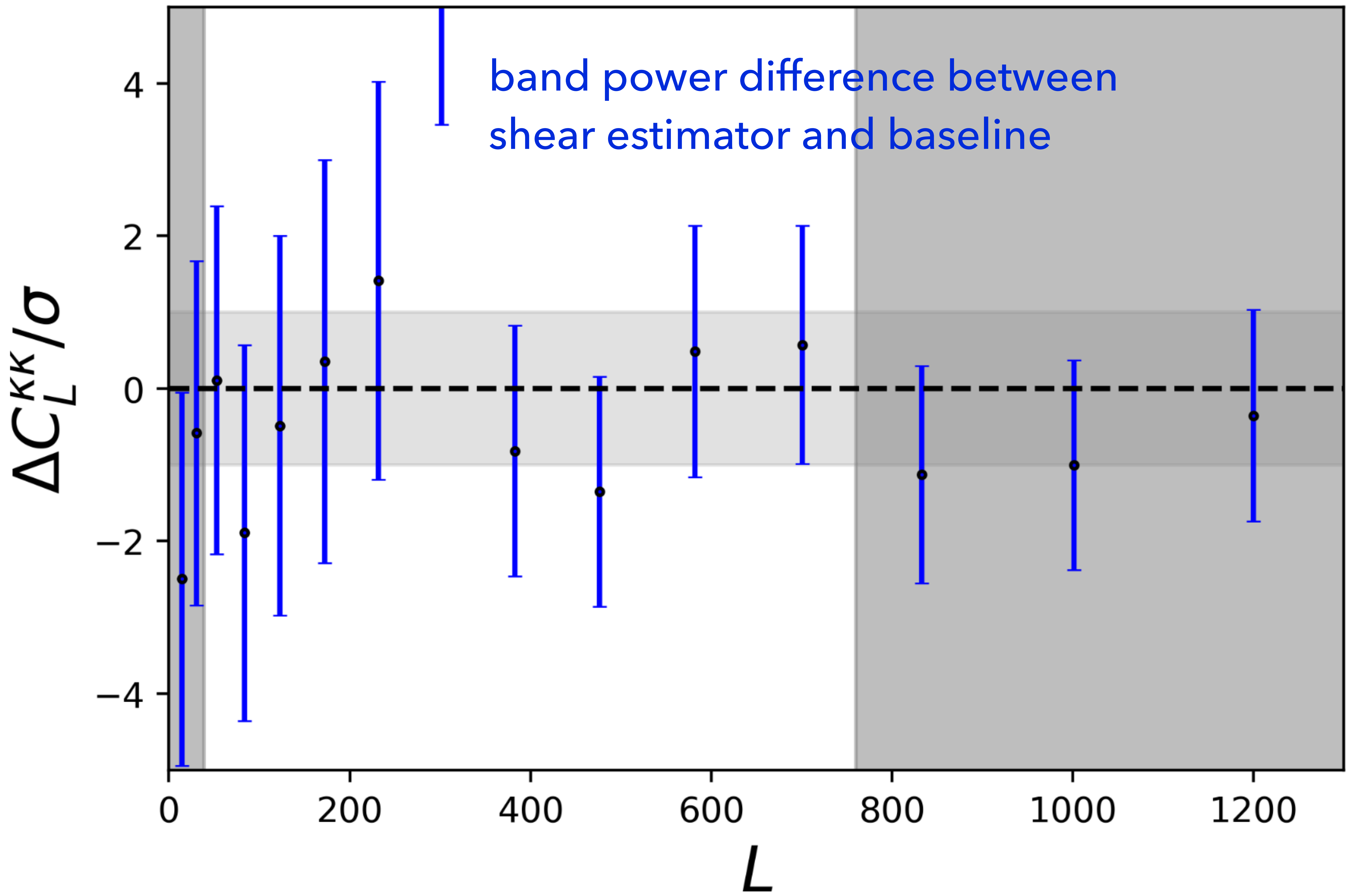
Testing the primary bispectrum

FULL SKY SHEAR ESTIMATOR

See Schaan+Ferraro 2019 , Qu, Challinor, Sherwin 2022



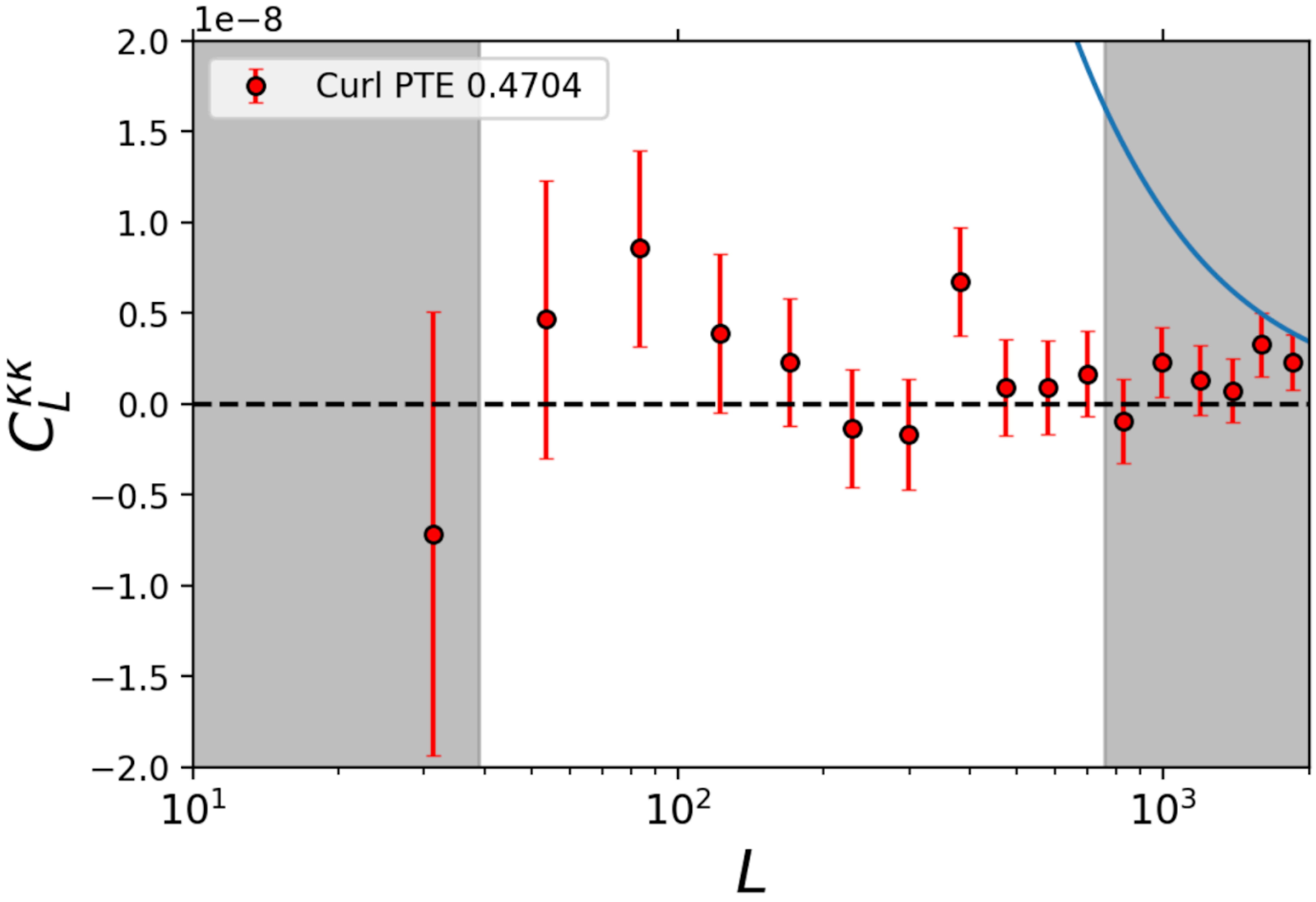
- Multipole expansion of the standard lensing estimator.
- Discarding the monopole motivated by symmetry of foregrounds leads to smaller biases.



- **First** application of shear estimator on data.
- Important role for SO as a foreground mitigation strategy Darwish + 2021 Sailer+ 2021
- Important role in mitigating extragalactic foreground biases in delensing applications Baleato+Ferraro 2022

+bandpower consistency with CIB deprojection

OTHER NULL TESTS HIGHLIGHT

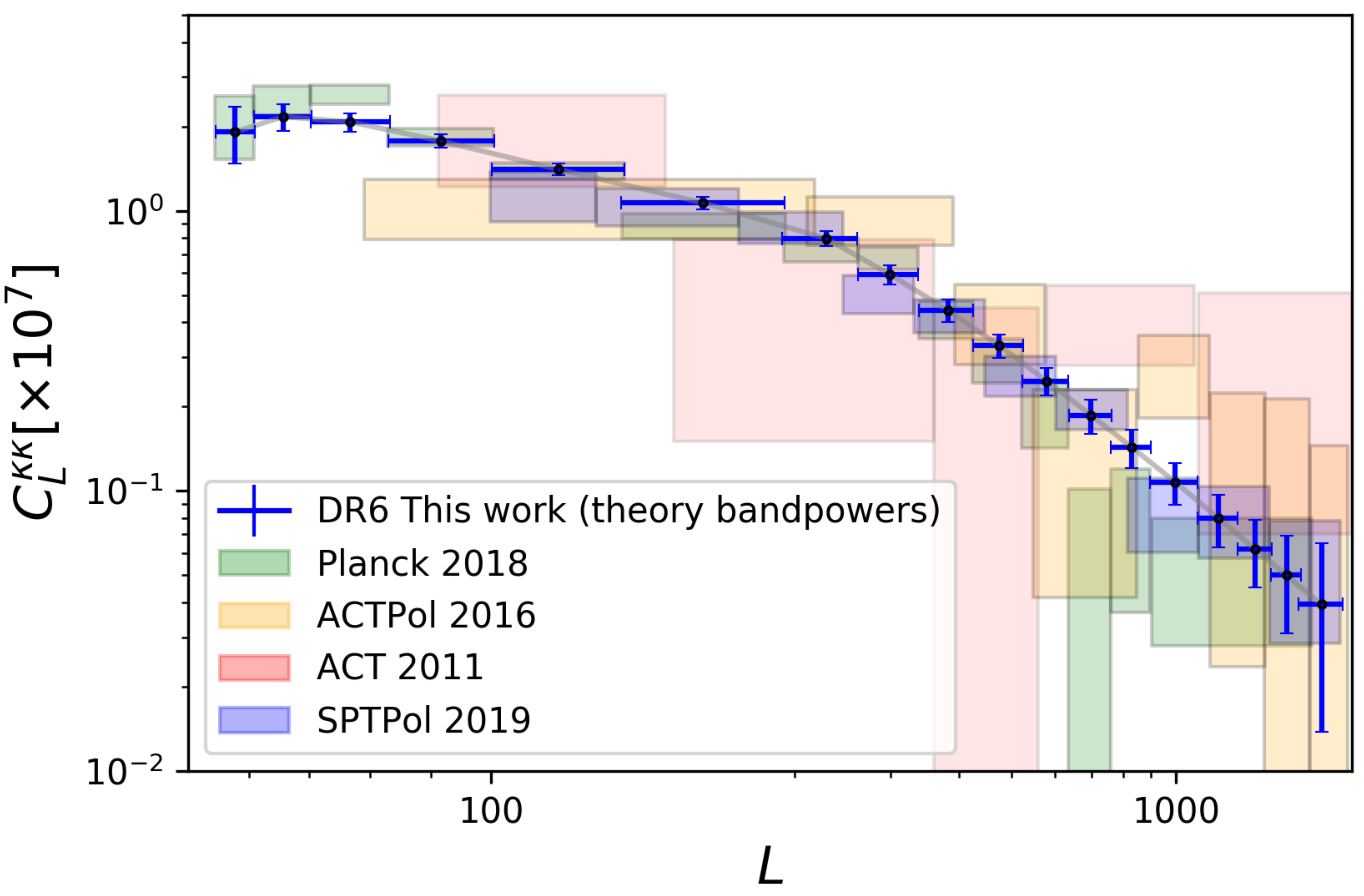


No evidence of curl modes detected in the lensing field.

Constrast with $\sim 3\sigma$ failure observed in Planck 2018

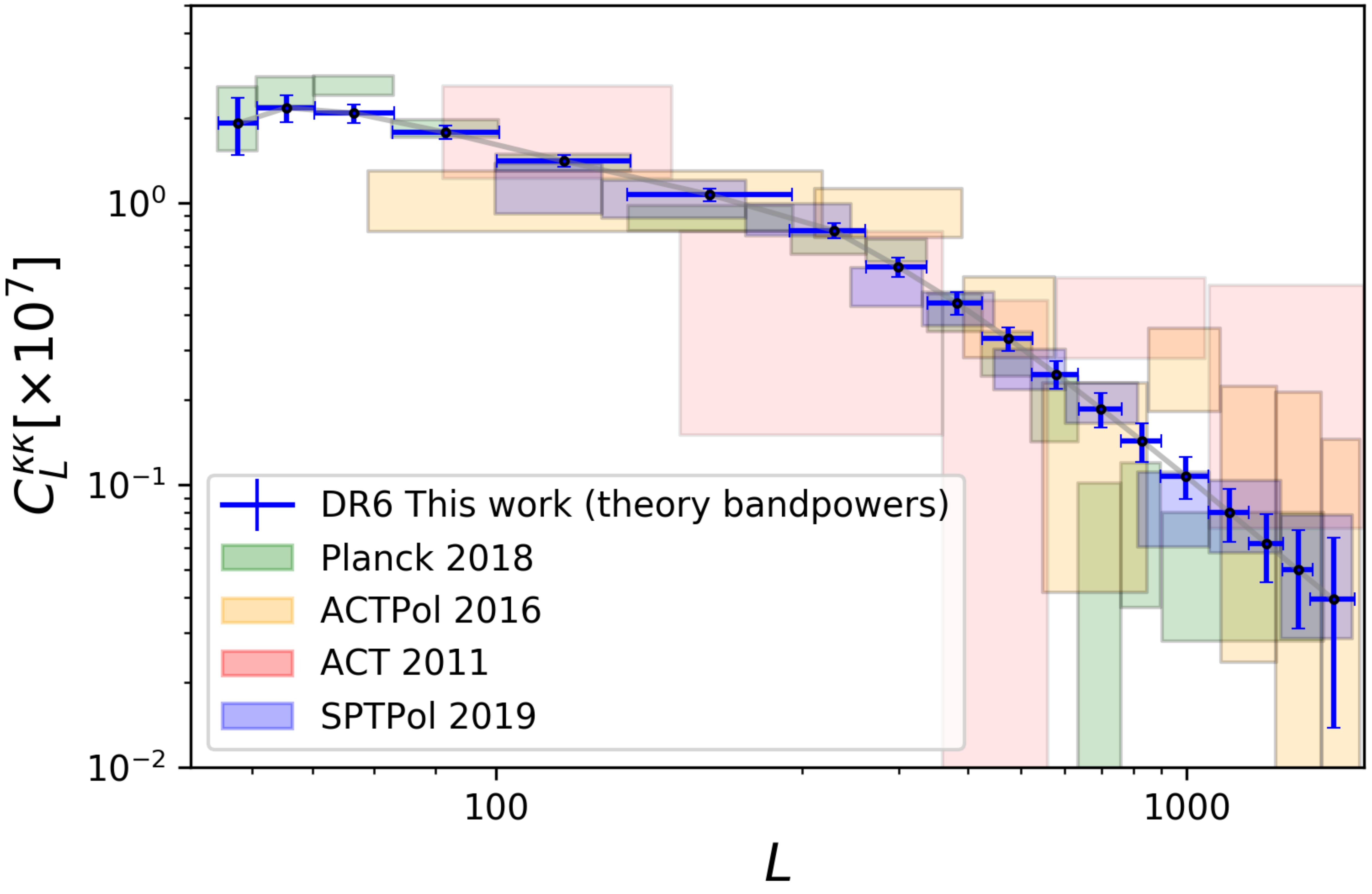
PRECISION COSMOLOGY WITH THE DR6 LENSING POWER SPECTRUM

2% MEASUREMENT OF LENSING POWER SPECTRUM



- SNR 42-44 using the actual error bars.
- Using CMB maps covering 30% of the sky.

2% MEASUREMENT OF LENSING POWER SPECTRUM



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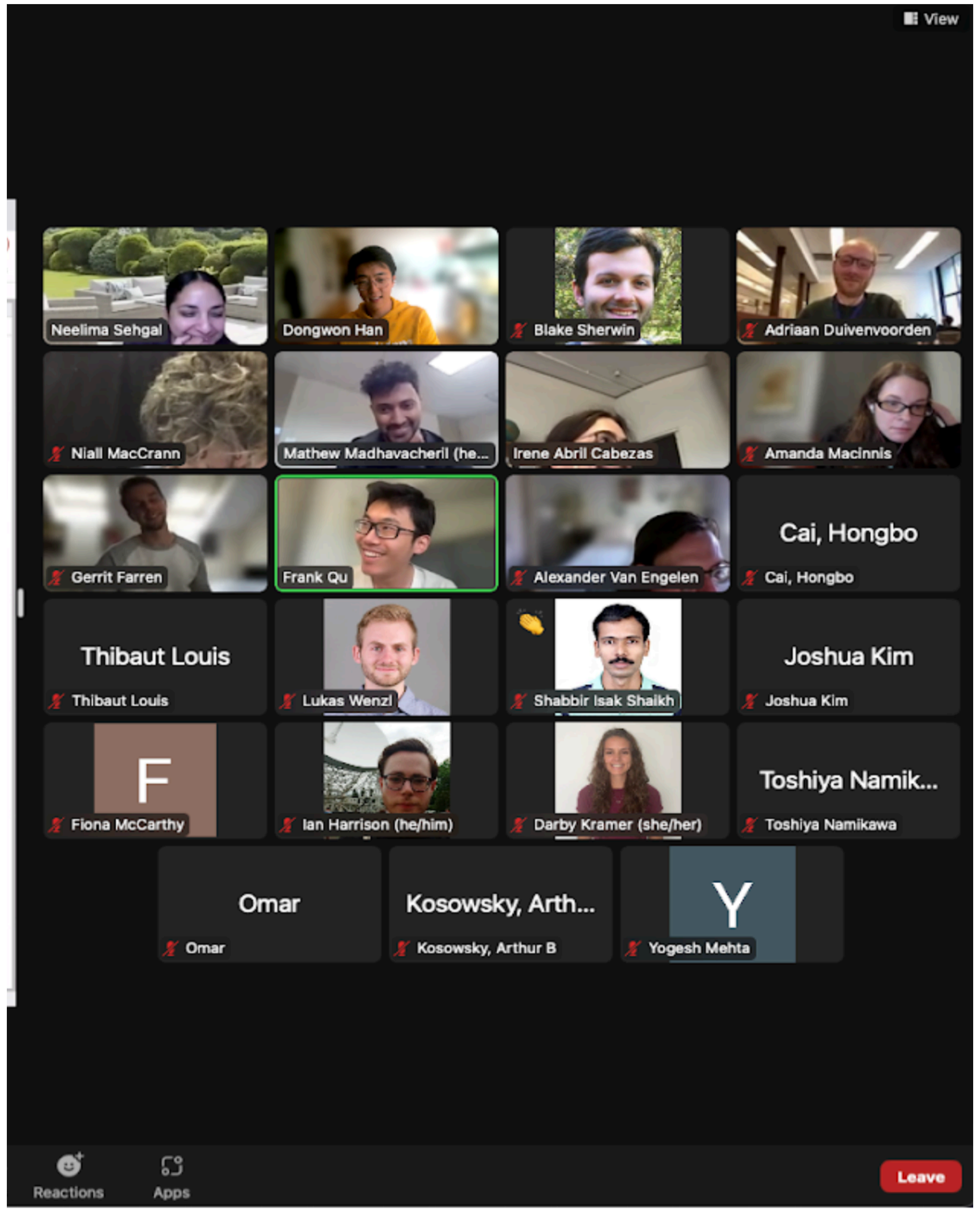


We have recently unblinded!

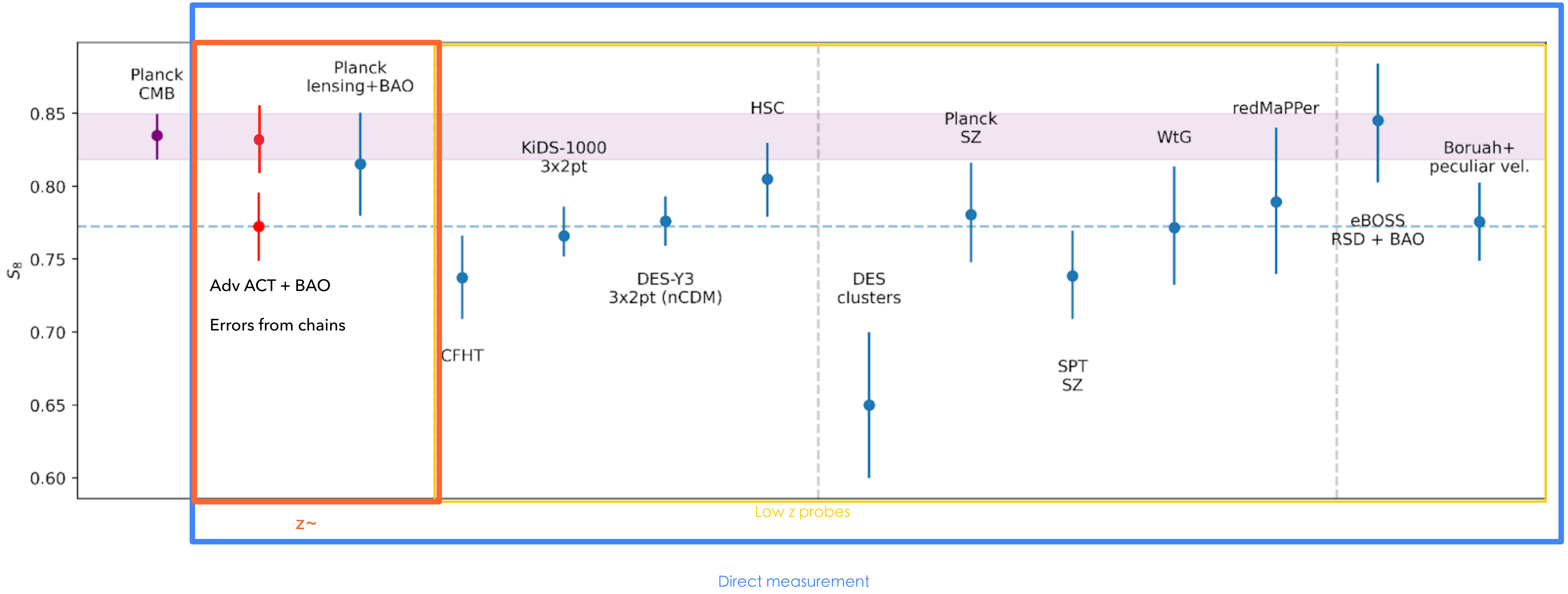
EXCITING APPLICATIONS: POTENTIAL CLARIFICATION OF S_8 TENSION

- $S_8 = \sigma_8\left(\frac{\Omega_m}{0.3}\right)^{0.25}$ to ± 0.021 CMB lensing only constraints
- ACT+BAO σ_8 to ± 0.014

Constraints from frozen unblinded bandpowers with desired level of performance

- ACT+Planck to ± 0.017 (Only if ACT compatible with Planck)

Compare with DES Y3 3×2pt $S_8 = 0.776^{+0.017}_{-0.017}$

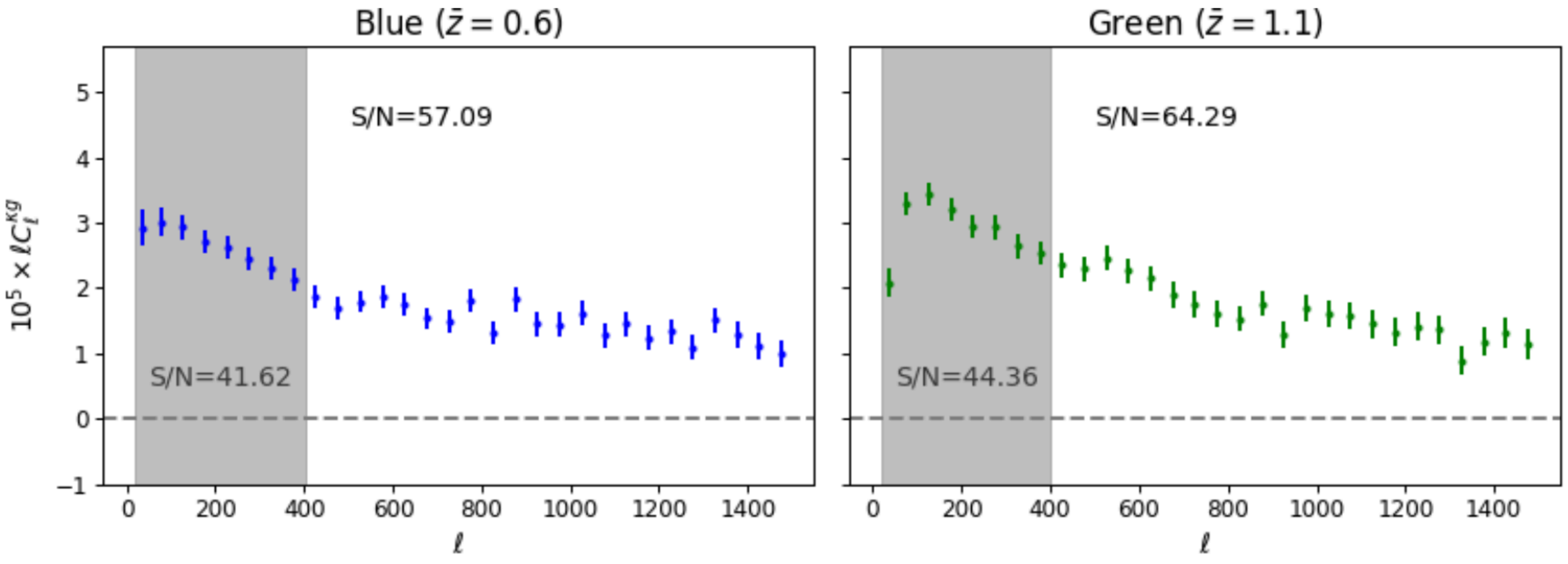


- + new tight constraints on the neutrino mass sum of $70\mathrm{meV}$ with BOSS BAO/ 40meV with DESI BAO. Compared with 60meV normal hierarchy

ENABLING EXCITING CROSS CORRELATIONS WITH LSS

Lensing tomography: Probing structure growth at low redshifts.

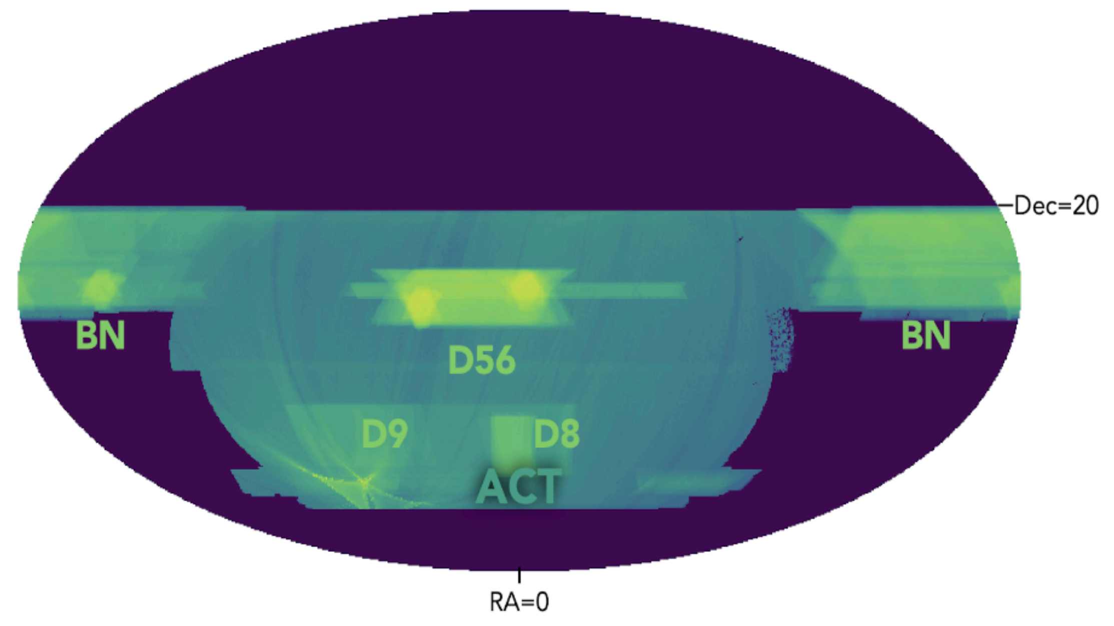
E.g., AdvACTxUnWISE lensing cross-correlation data

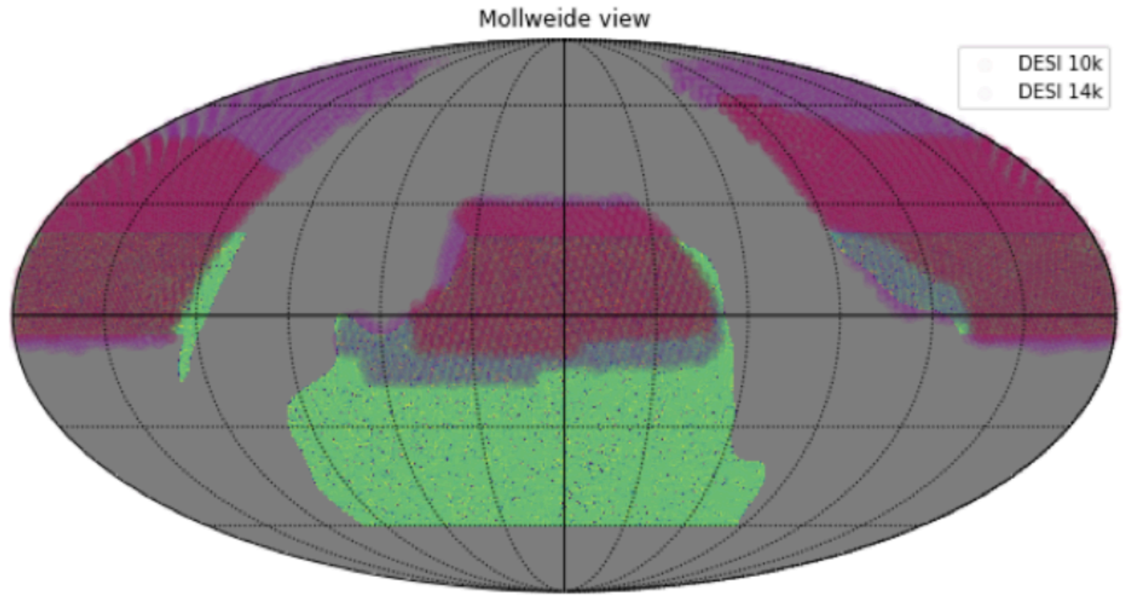


[Farren et Al (including Qu), in prep]

Many exciting cross correlation projects with DESI !

>10 projects and more with upcoming DESI x ACT MOU

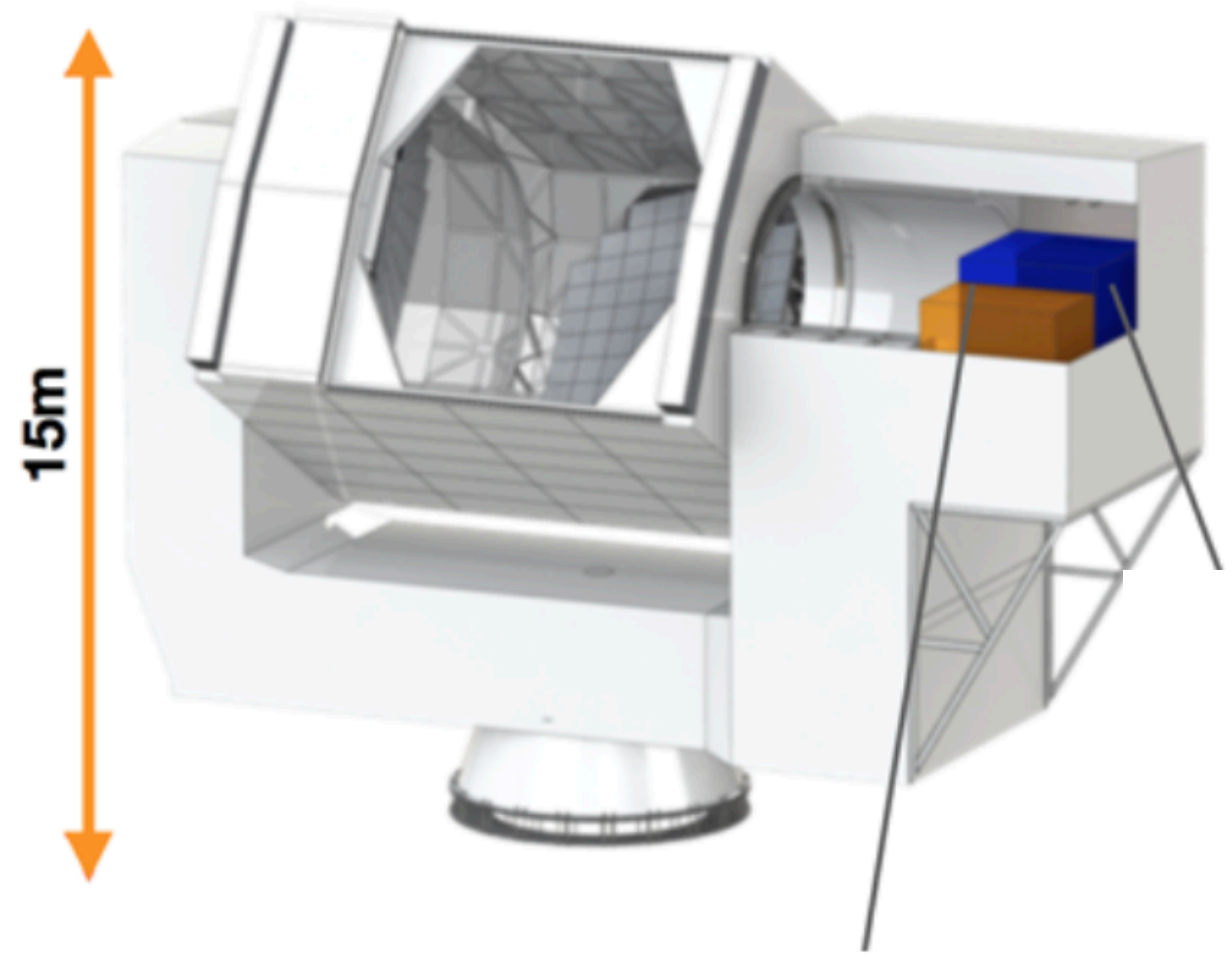




THE FUTURE: SIMONS OBSERVATORY AND CMB STAGE-IV

High-Precision Lensing Power Spectra

Co-lead development of the SO lensing pipeline ready for SO analysis.

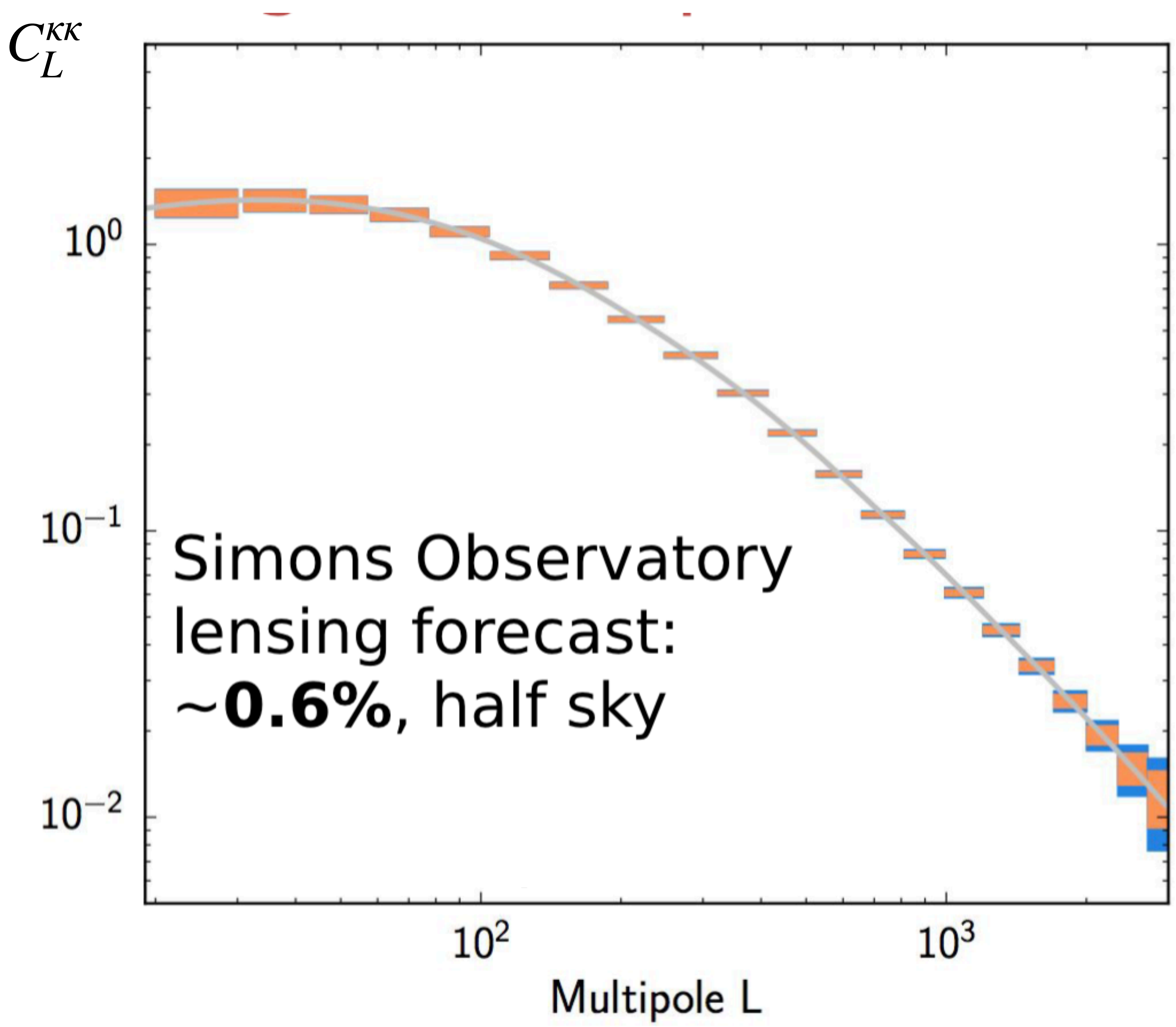


SO Large Aperture Telescope

- Observation from 2023-2028
- $f_{sky} \approx 30\,\%$
- Noise 2-3 times < ACT

$\sigma(\sum m_\nu) \approx 20 - 30\mathrm{meV}$ (Simons Obs. / CMB-S4)

c.f. limit, >60meV

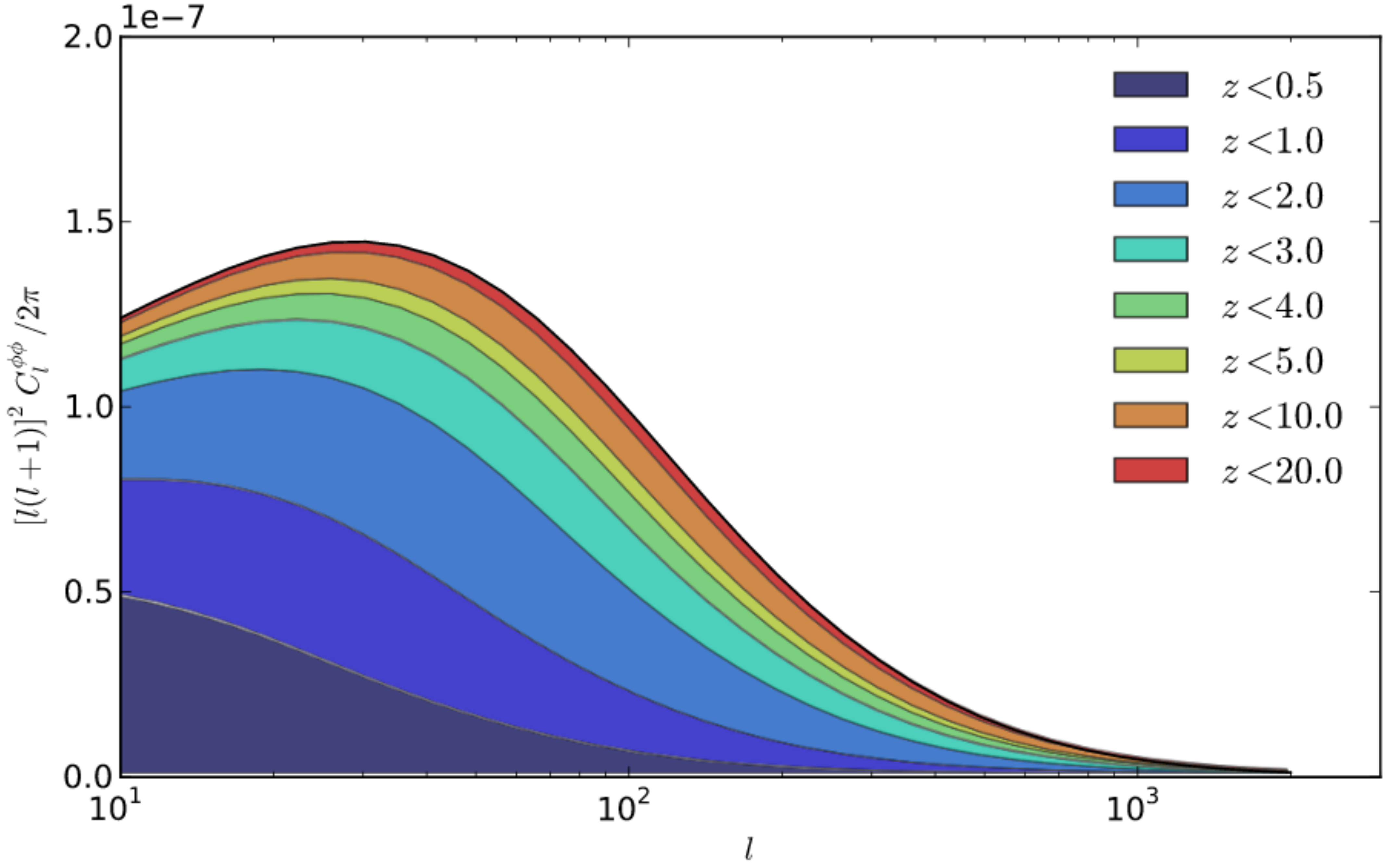


CMB LENSING: FORECASTING OPPORTUNITIES AT HIGH-Z

Qu++2022

MOTIVATION

- Lensing maps probe matter density, projected over a wide redshift range peaking at z~2. Unique z>5 reach!
- If we can remove the low -z contribution we can have a new window to the high redshift universe!



Credits: Duncan Hanson

HOW CAN WE ACCESS THE HIGH REDSHIFT INFO FROM LENSING

- **Delensing inspired approach.** Cleaning the lensing map with suitably scaled galaxy tracers. (This work)
- Cross correlation based methods. Analysing all cross and auto spectra

OBTAINING A HIGH Z LENSING MAP: METHODOLOGY

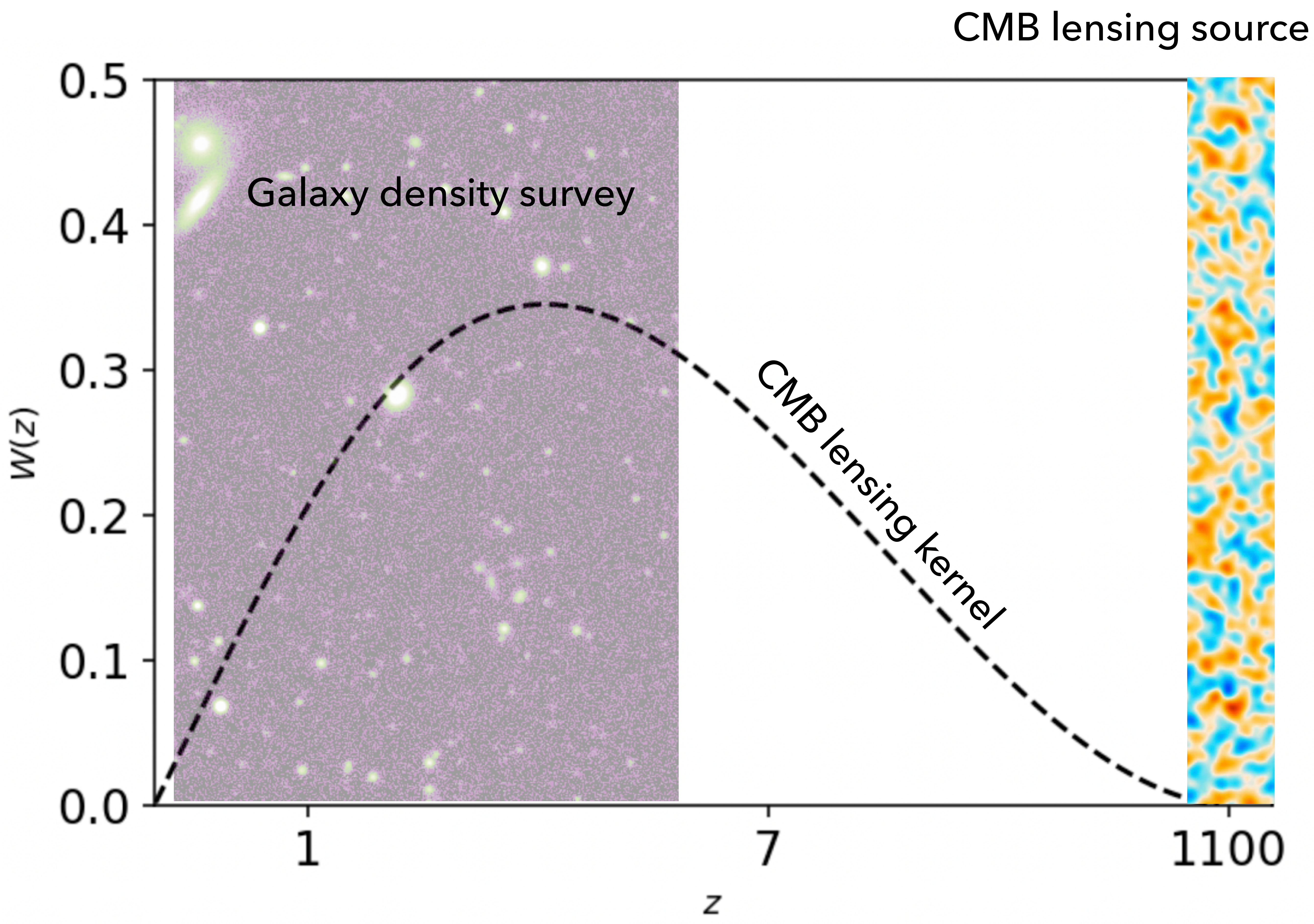
- Galaxy surveys will span a broad redshift range.
- Idea: Remove low z content of lensing with scaled galaxy density maps.
- Minimisation problem:

$$\hat{\kappa}^{clean}_{\mathbf{L}} = \hat{\kappa}_{\mathbf{L}} - c(\mathbf{L})\hat{X}_{\mathbf{L}}$$

Filter Galaxy tracer

- Filter obtained by minimisation power spectrum of $\hat{\kappa}^{clean}_{\mathbf{L}}$

$$c(L) = \frac{C_L^{\kappa X}}{C_L^{XX}}$$



TOWARDS HIGH Z LENSING MAP: CONSTRUCTING THE GALAXY TRACER FIELD $\hat{X}_{\mathbf{L}}$

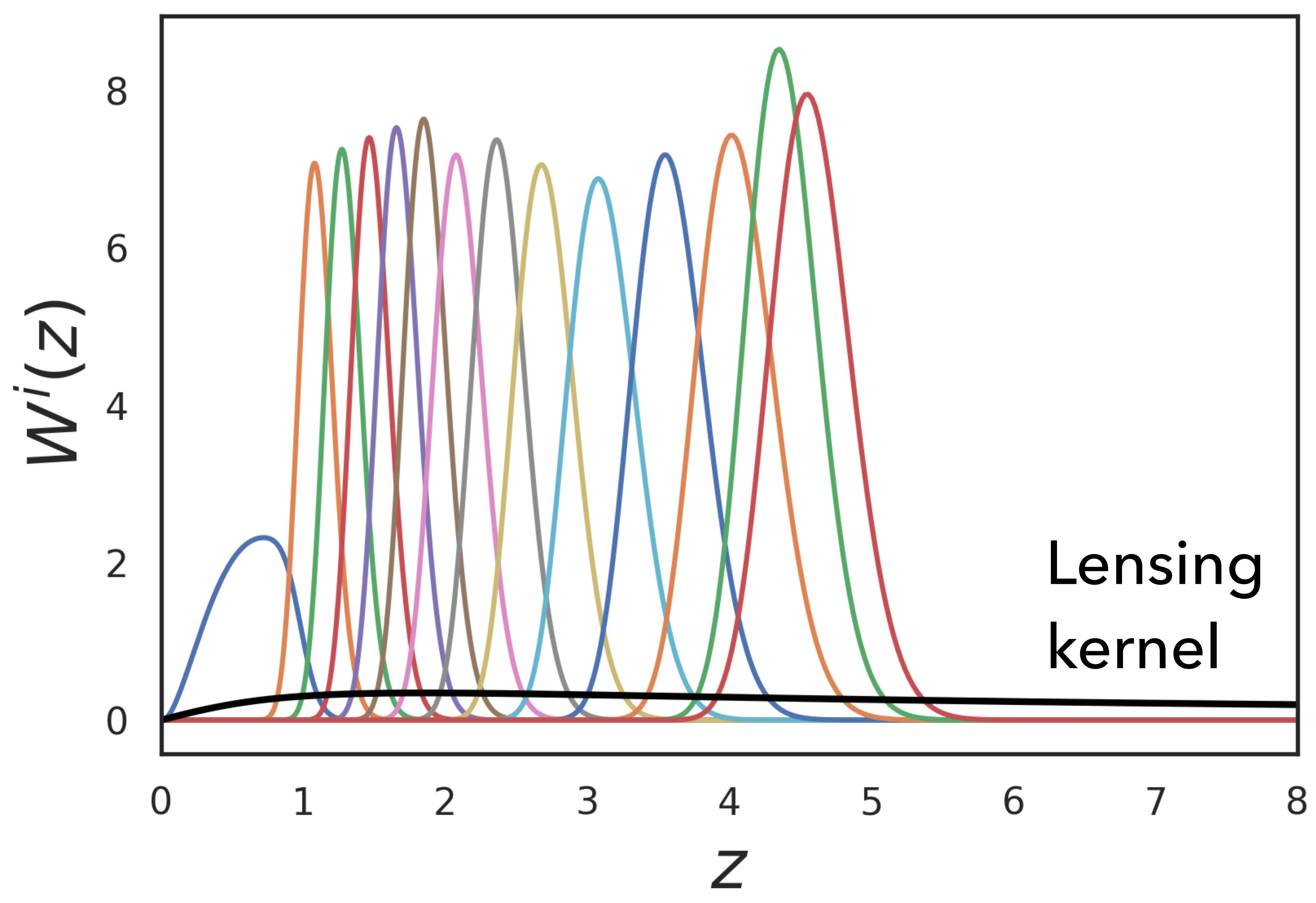
- Construct $\hat{X}_{\mathbf{L}}$ by combining LSS tracers $\hat{g}_i$ in narrow redshift bins.
- Tracers weighted appropriately to maximise correlation with the lensing field.
- Weights $c_{i,L}$ can be obtained empirically from measured auto and cross spectra.

$$\hat{X}_{\mathbf{L}} = \sum_i c_{i,L} \hat{g}_{i,\mathbf{L}}$$

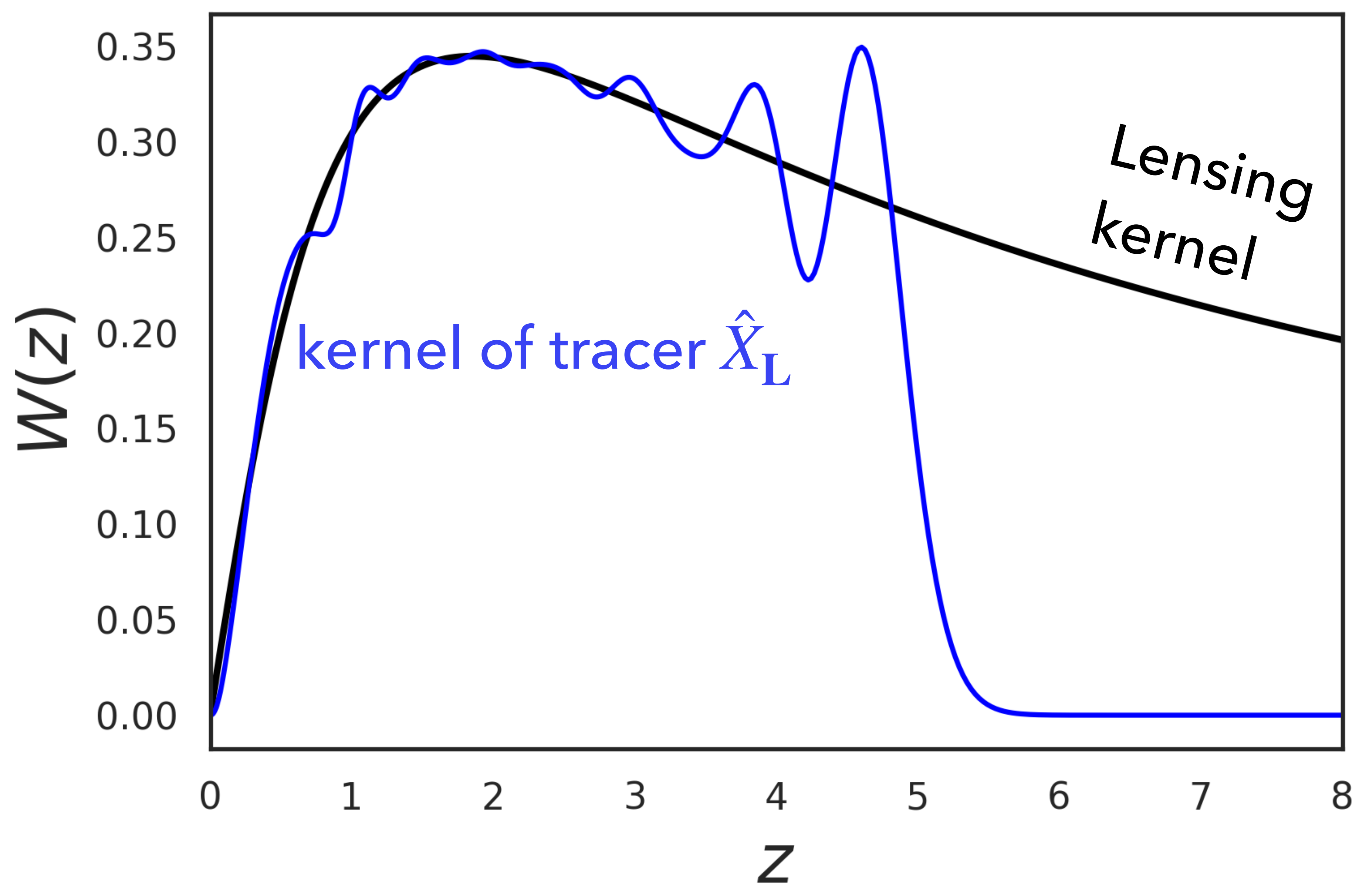
Scaling weights

$$c_{i,L} = \sum_j (\mathrm{Cov}^{gg}_L)^{-1}_{ij} C^{\kappa g_j}_L .$$

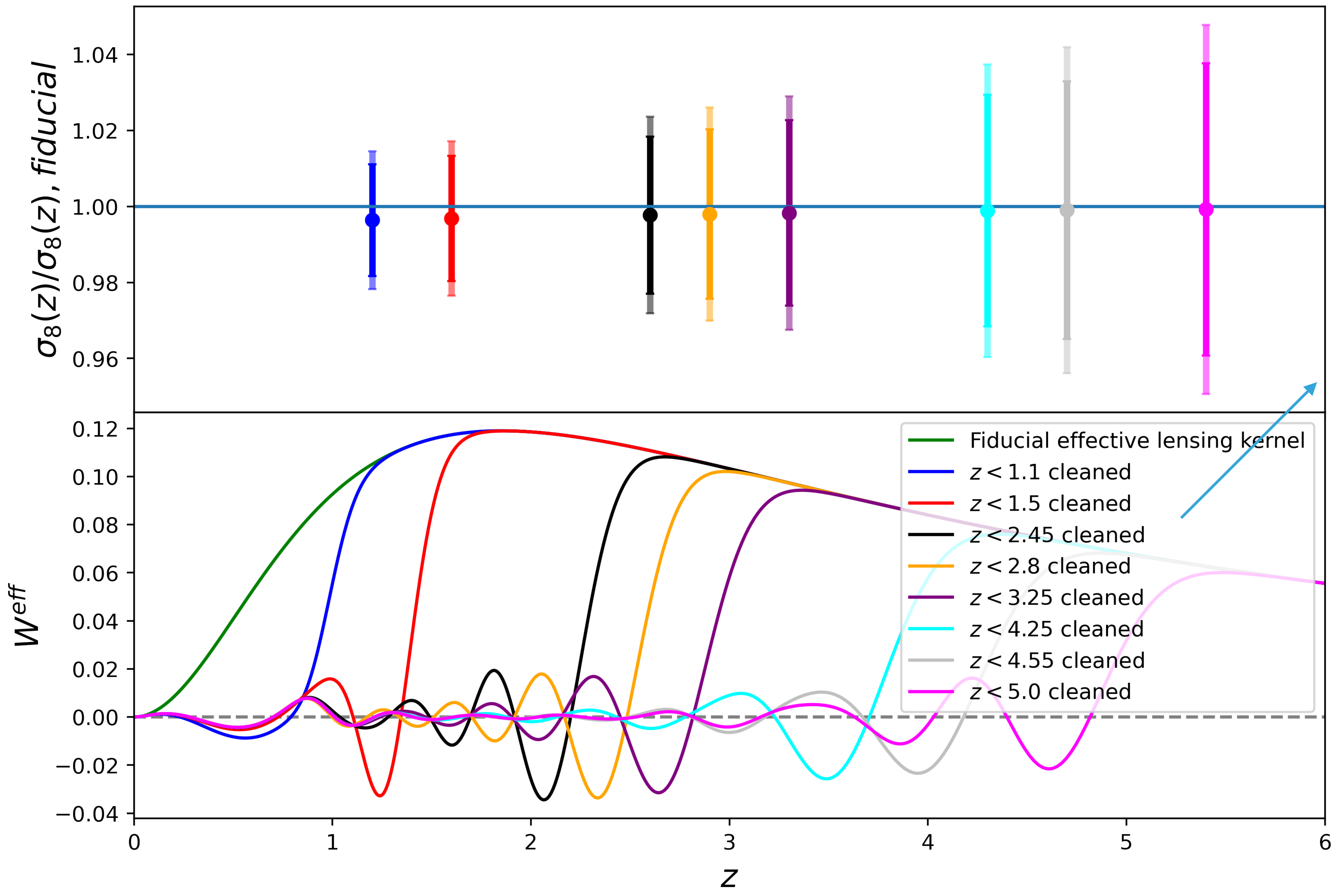
EXAMPLE WITH LSST SURVEY



Find weights by calculating all the auto and cross correlations



MEASURING HIGH Z AMPLITUDE OF STRUCTURE



Original lensing power spectrum sensitive to all redshifts up to recombination

- $$C_L^{\kappa\kappa} \sim \int_0^{z_\star} dz [W^\kappa(z)]^2 P_{\delta\delta}\left(k = \frac{L+\frac{1}{2}}{\chi(z)}, z\right)$$

Apply cleaning

$$C_L^{\kappa\kappa} \sim \int_{z_{clean}}^{z_\star} dz [W^\kappa(z)]^2 P_{\delta\delta}\left(k = \frac{L+\frac{1}{2}}{\chi(z)}, z\right)$$

- Low z cleaned maps have projection kernel close to 0 at low z. Hence effectively probing high z S_8
- **4% measurement** of S_8 at $z = 5$ with CMB S4 and LSST
- + Neutrino mass measurements robust to biases from Dark energy models.

SUMMARY

- AdvACT DR6 datasets will provide the highest precision ground based CMB lensing power spectra to date . **We are unblinded.** The measurement is robust against systematics and can provide interesting insights regarding S_8 and $\sum M_\nu$

- Methodology of obtaining a high redshift only lensing map. Many interesting applications! Tomographic S_8 measurements, neutrino mass sum measurement without bias, sharpening cross correlation measurements.

Stay tuned for later this year

•***Qu***, *Sherwin,Madhavacheril et al ACT in prep (expected 2022): Lensing power spectra and lensing only S8*
•*Madhavacheril,* ***Qu***, *Sherwin et al ACT in prep (expected 2022): Lensing map and cosmology*
•*MacCrann, Sherwin,* ***Qu*** *et al ACT in prep (expected 2022): Foreground bias mitigation*
•*Atkins,Duivenvoorden,Coulton,****Qu*** *et al ACT (expected 2022): Map-Based Noise Simulations for AdvACT DR6*