NEW CMB LENSING MASS MAPS FROM ADVACT AND THEIR IMPLICATIONS FOR STRUCTURE GROWTH

FRANK J. QU (DAMTP CAMBRIDGE 4th year graduate student)

COSMO 2022 RIO JAINERO

25 AUGUST 2022

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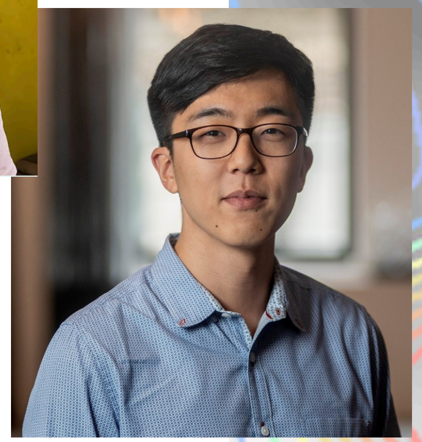
Blake Sherwin (Cambridge)

Mat Madhavacheril (Perimeter Institute)

Niall Maccrann (Cambridge)



Dongwon Han (Cambridge)

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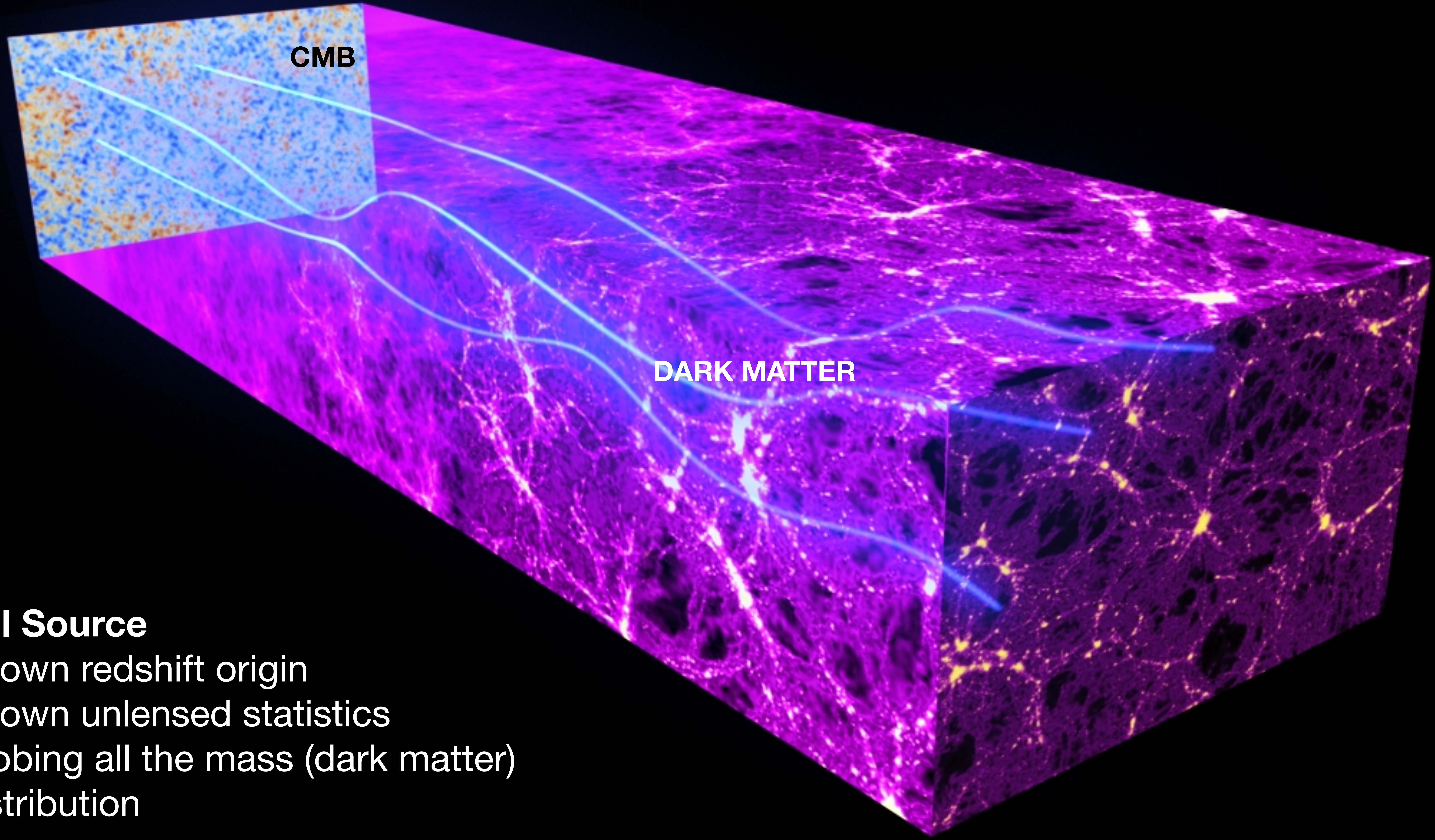
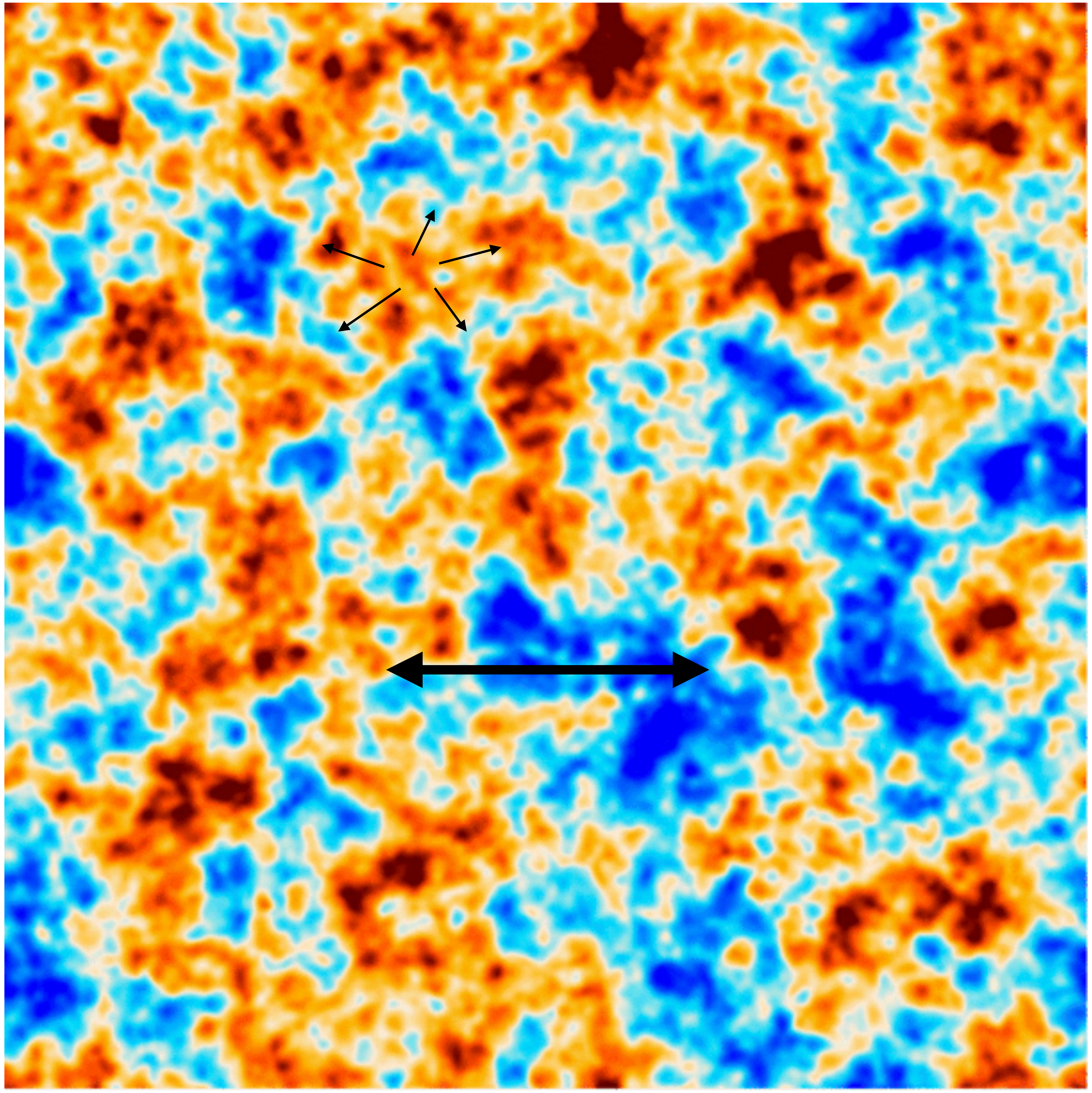
BACKLIGHTING THE UNIVERSE WITH THE CMB



Ideal Source

- Known redshift origin
- Known unlensed statistics
- Probing all the mass (dark matter) distribution

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 fields

FOURIER/ HARMONIC SPACE

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

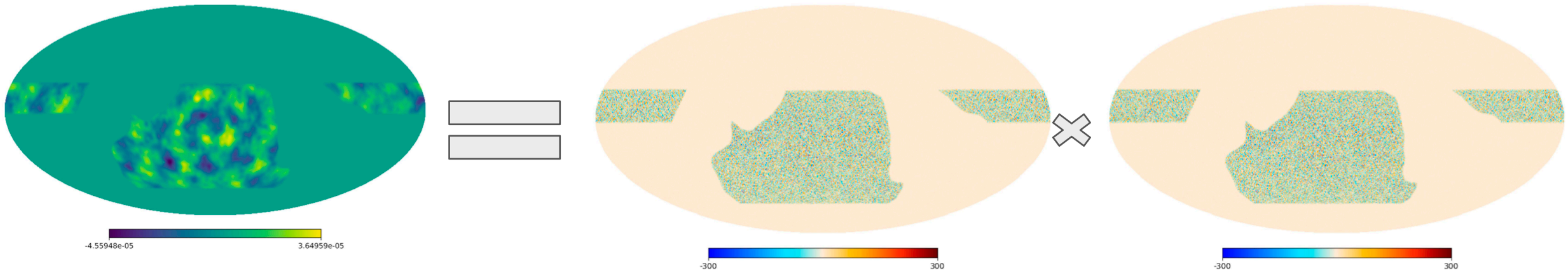
Mode coupling

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

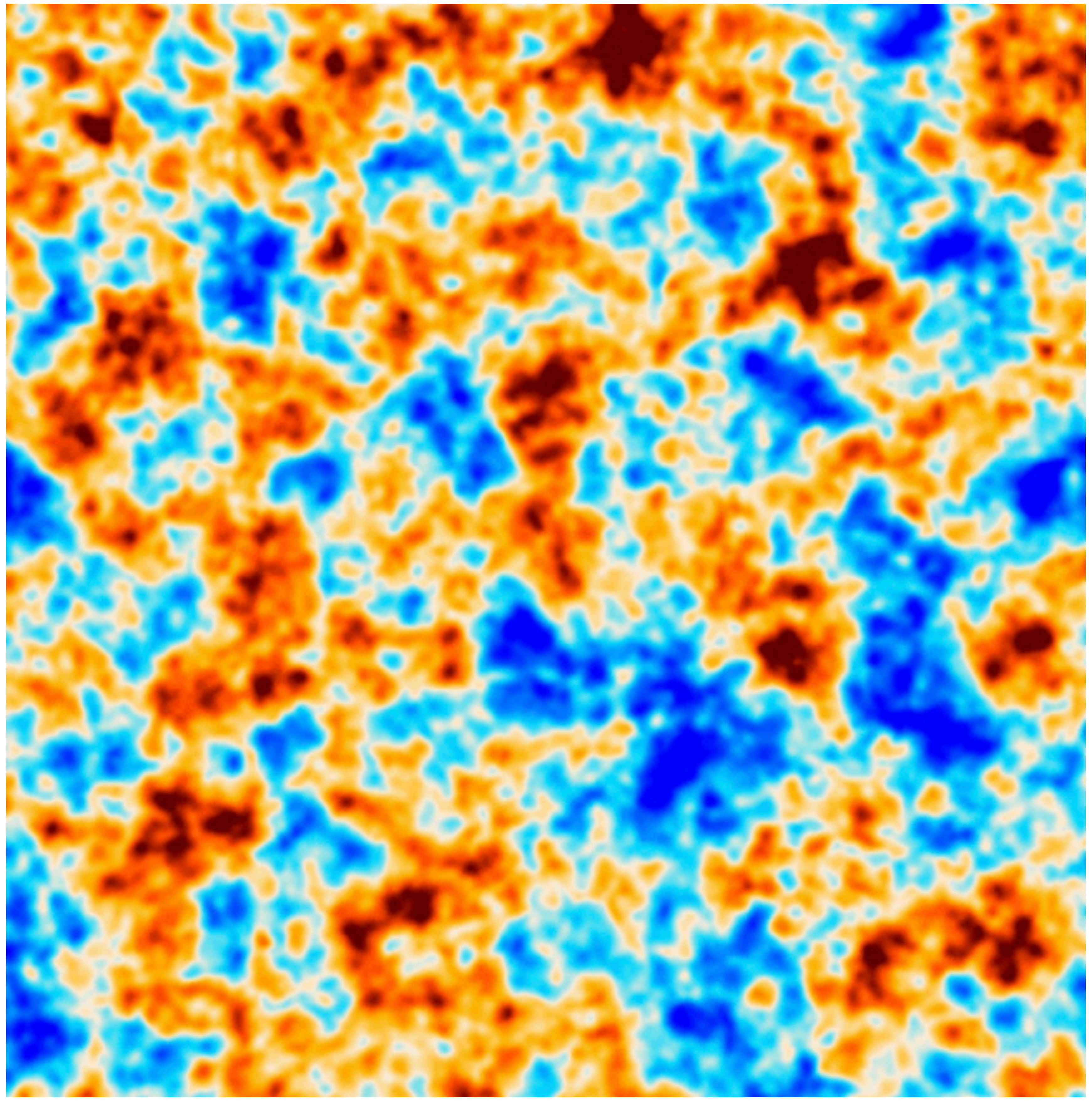
Mode by mode reconstruction of lensing from quadratic CMB combinations

See also Louis Legrand talk

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



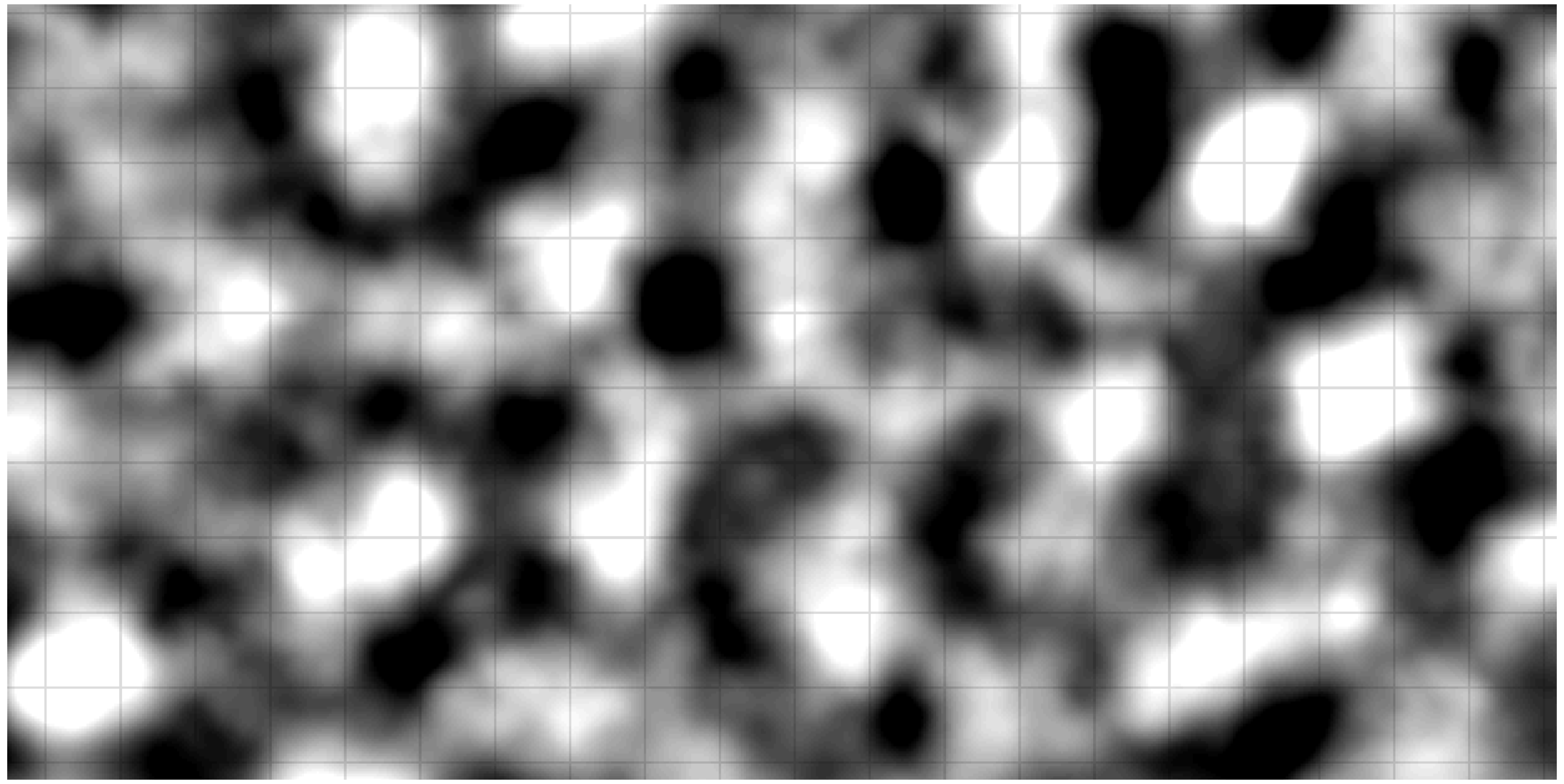
LENSING RECONSTRUCTION VIA THE QUADRATIC ESTIMATOR



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

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

2 degrees



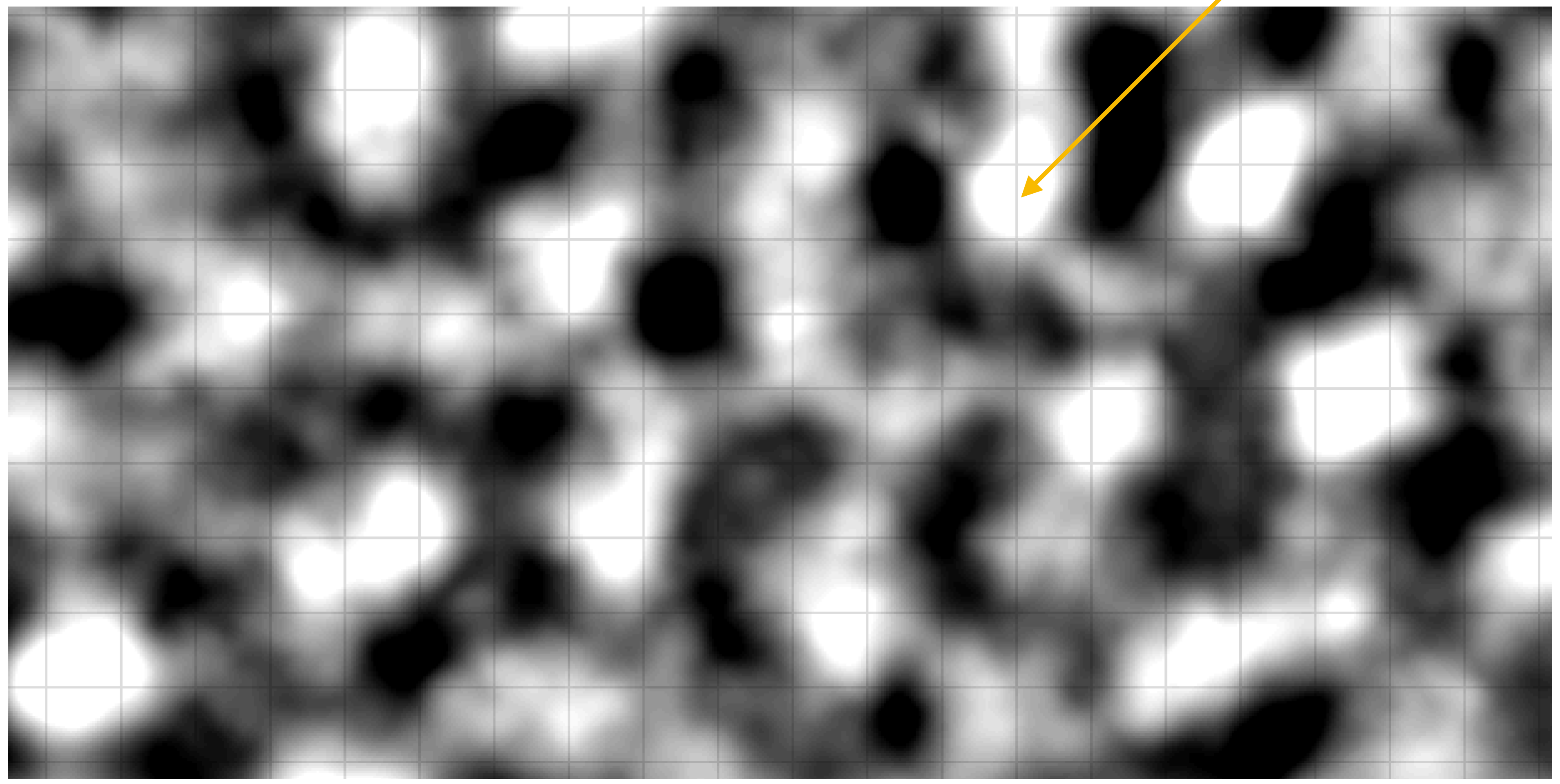
Reconstructed CMB Lensing Matter Distribution

Typically use $600 < \ell < 3000$

Benefit from **high resolution** CMB measurements

KEY STATISTICS: LENSING POWER SPECTRUM

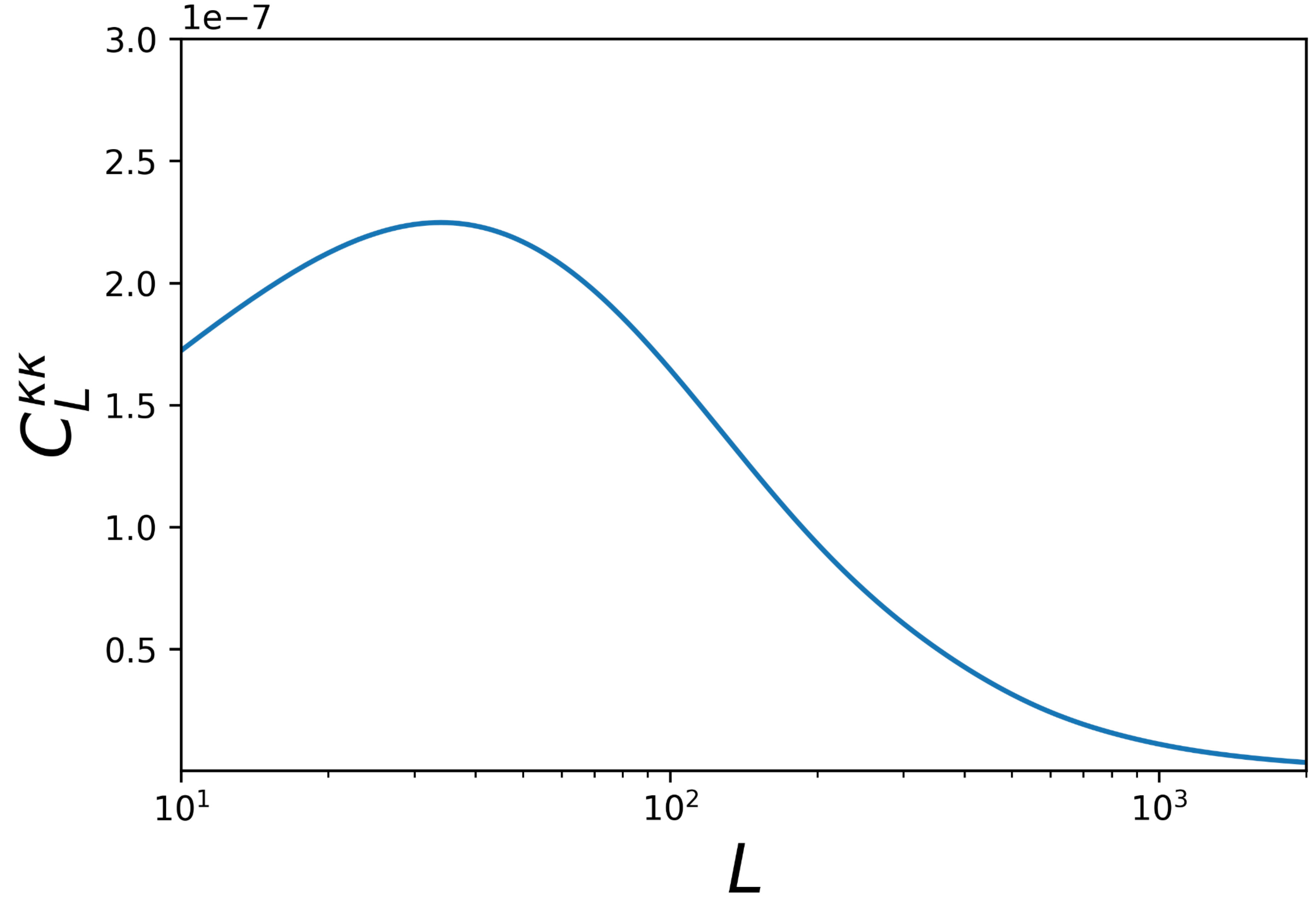
Bright regions = High Density



Reconstructed CMB Lensing Matter

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

y-axis: How much lensing there is



x-axis: For a lens of angular size

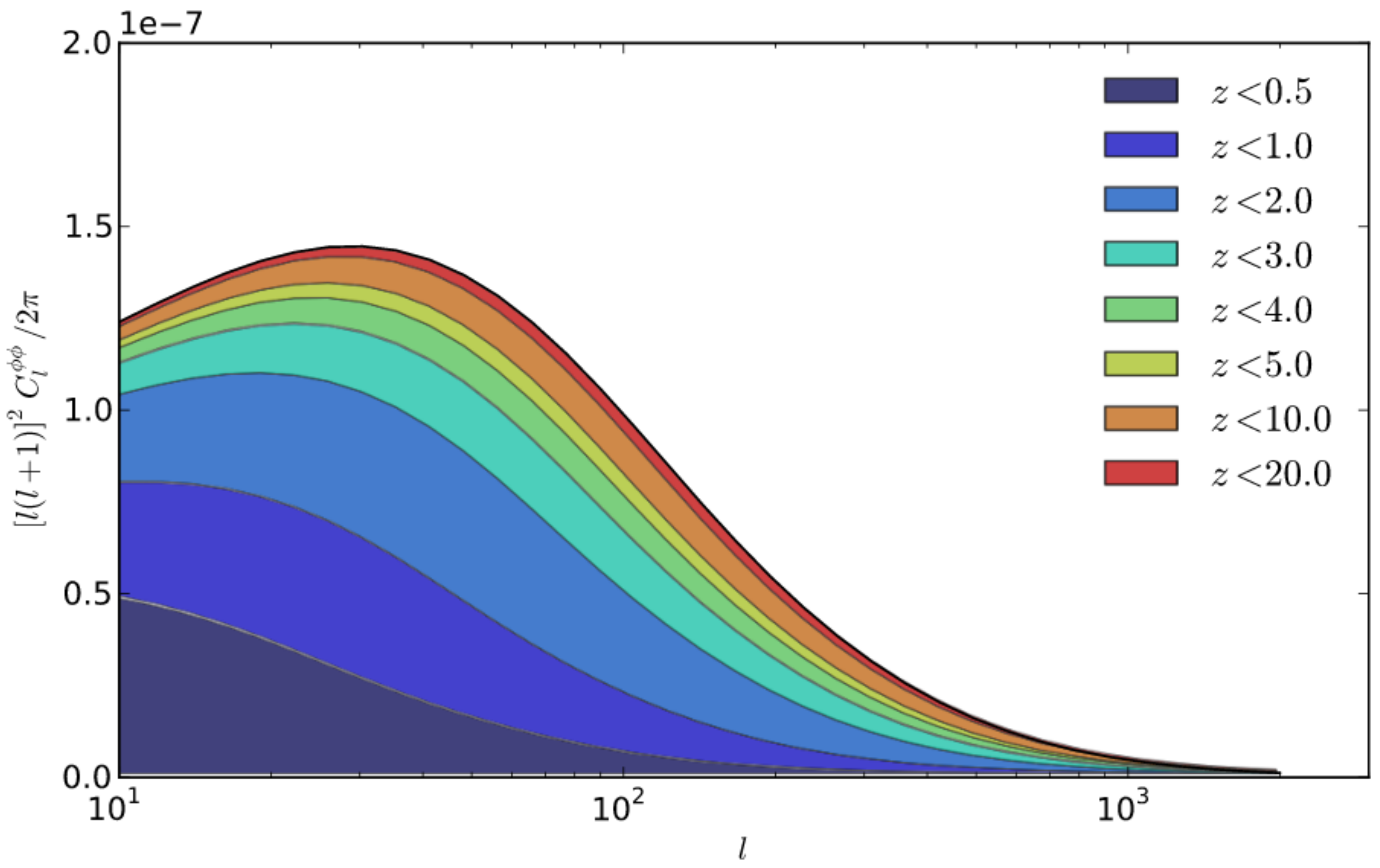
WHAT DOES CMB LENSING TELL US?

- 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

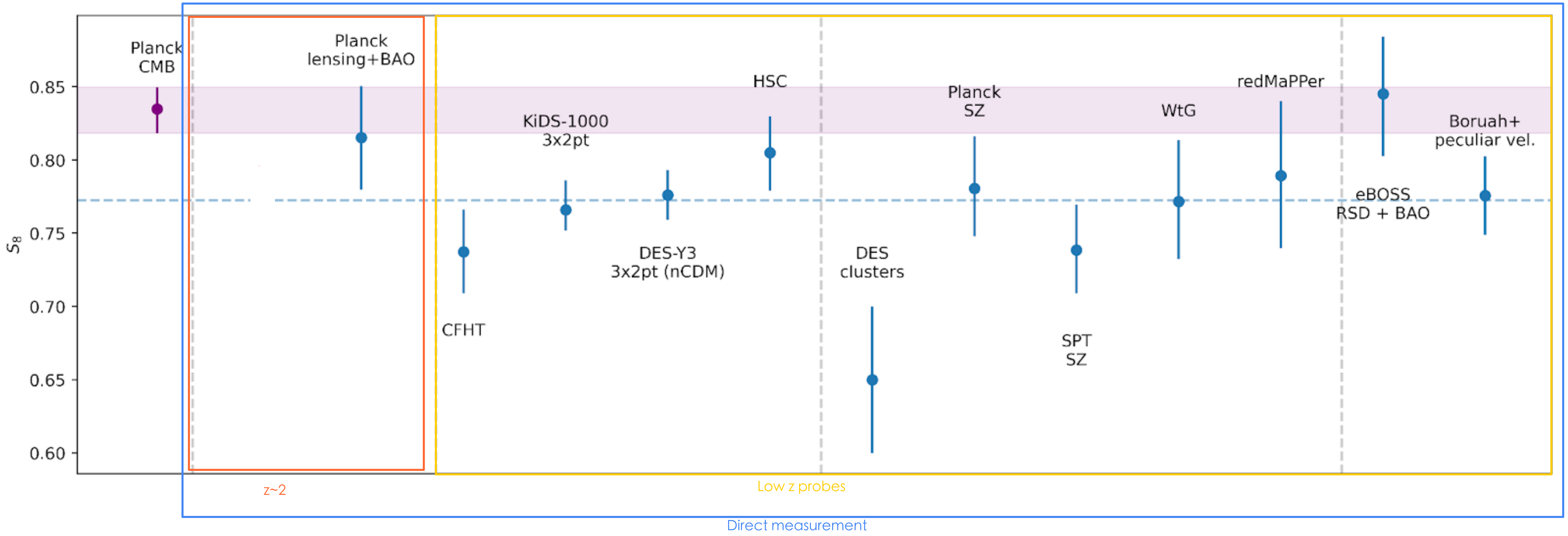


- CMB Lensing therefore sensitive to:
  - Neutrino mass sum via power spectrum suppression
  - Combination of **clumpiness** (amplitude of clustering on scales of 8Mpc/h) and the **total amount of matter**

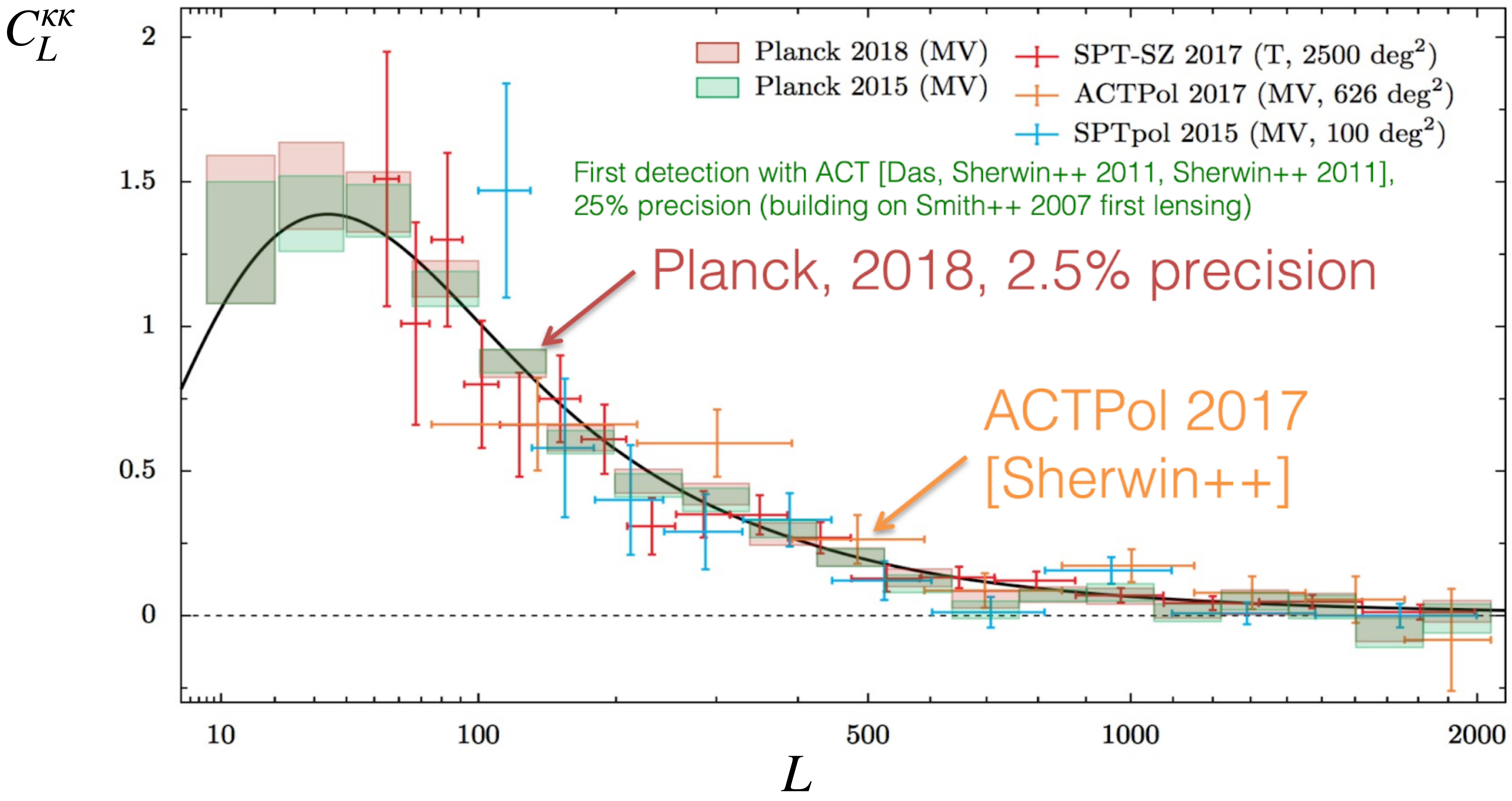
$$\sigma_8 \Omega_m^{0.25}$$

MOTIVATION: WEIGHT 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.**
  - Completely different systematics.
  - Clean probe. *caveat of extragalactic foregrounds



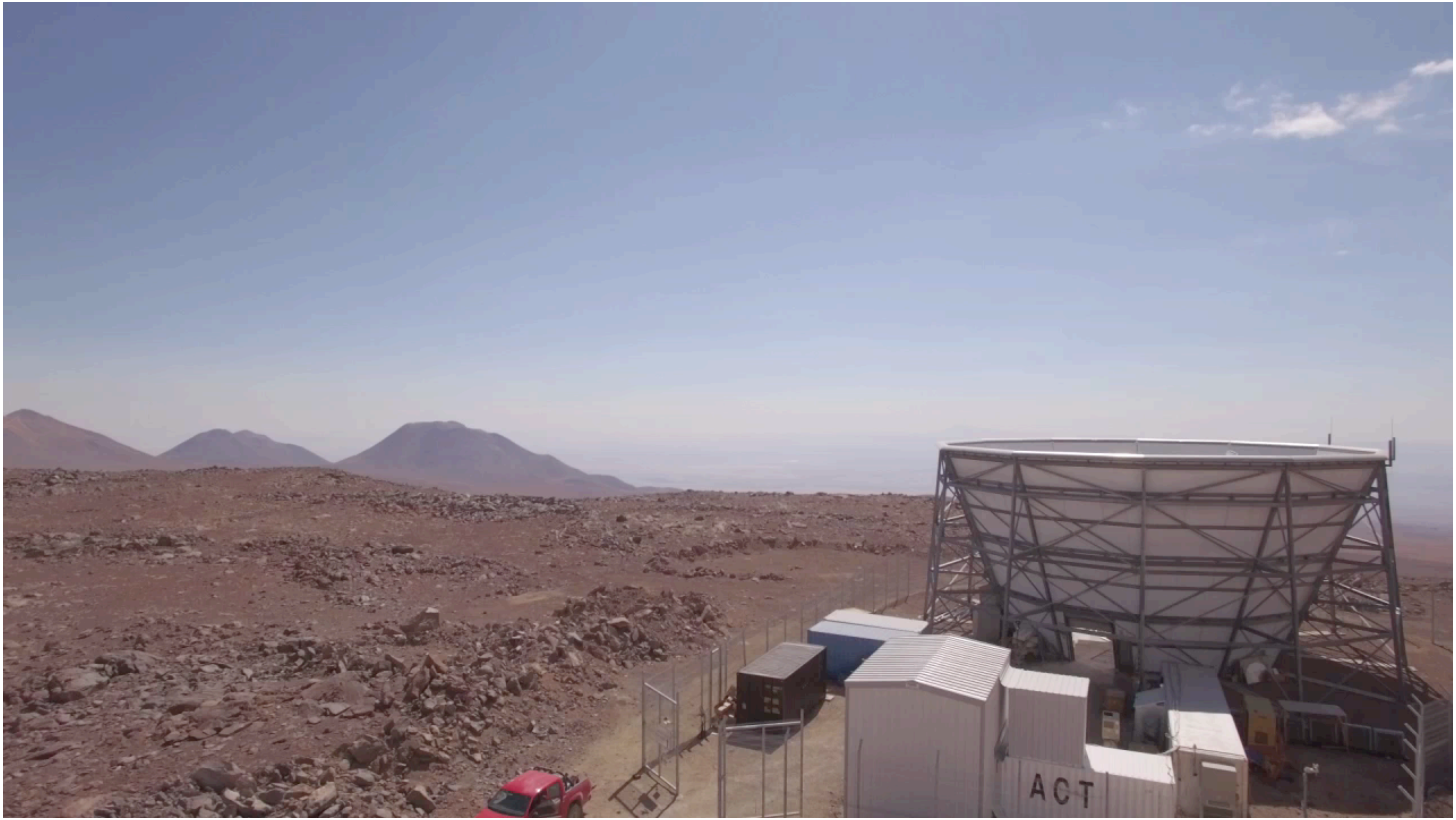
CMB LENSING POWER SPECTRA: TOWARDS PRECISION COSMOLOGY



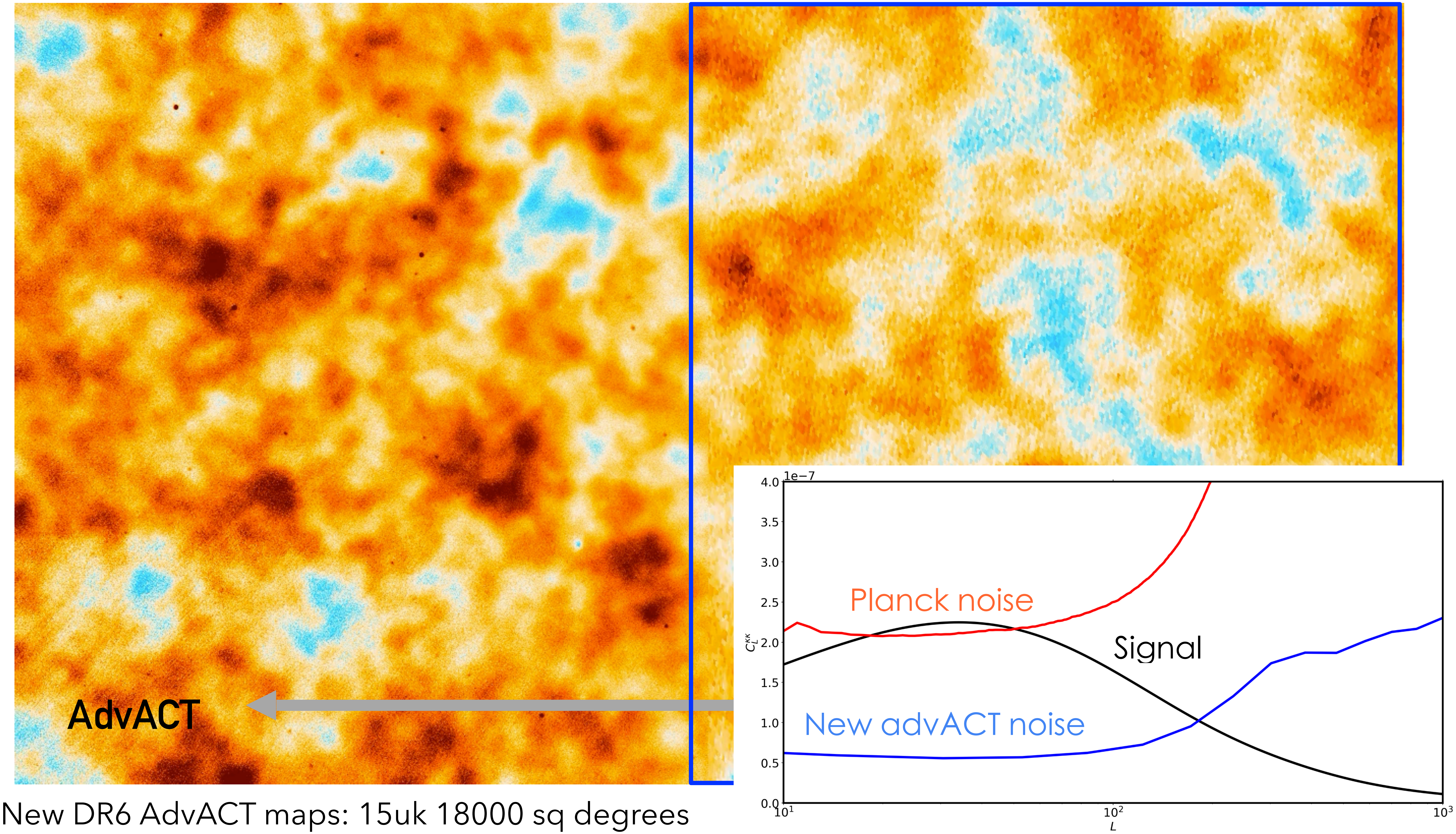
Very fast progress- But we are only unleashing the full potential of lensing **now**!

ATACAMA COSMOLOGY TELESCOPE

Arcminute resolution CMB telescope, located in the Chilean Atacama desert



HIGH RESOLUTION CMB LENSING MEASUREMENTS FROM ADVACT

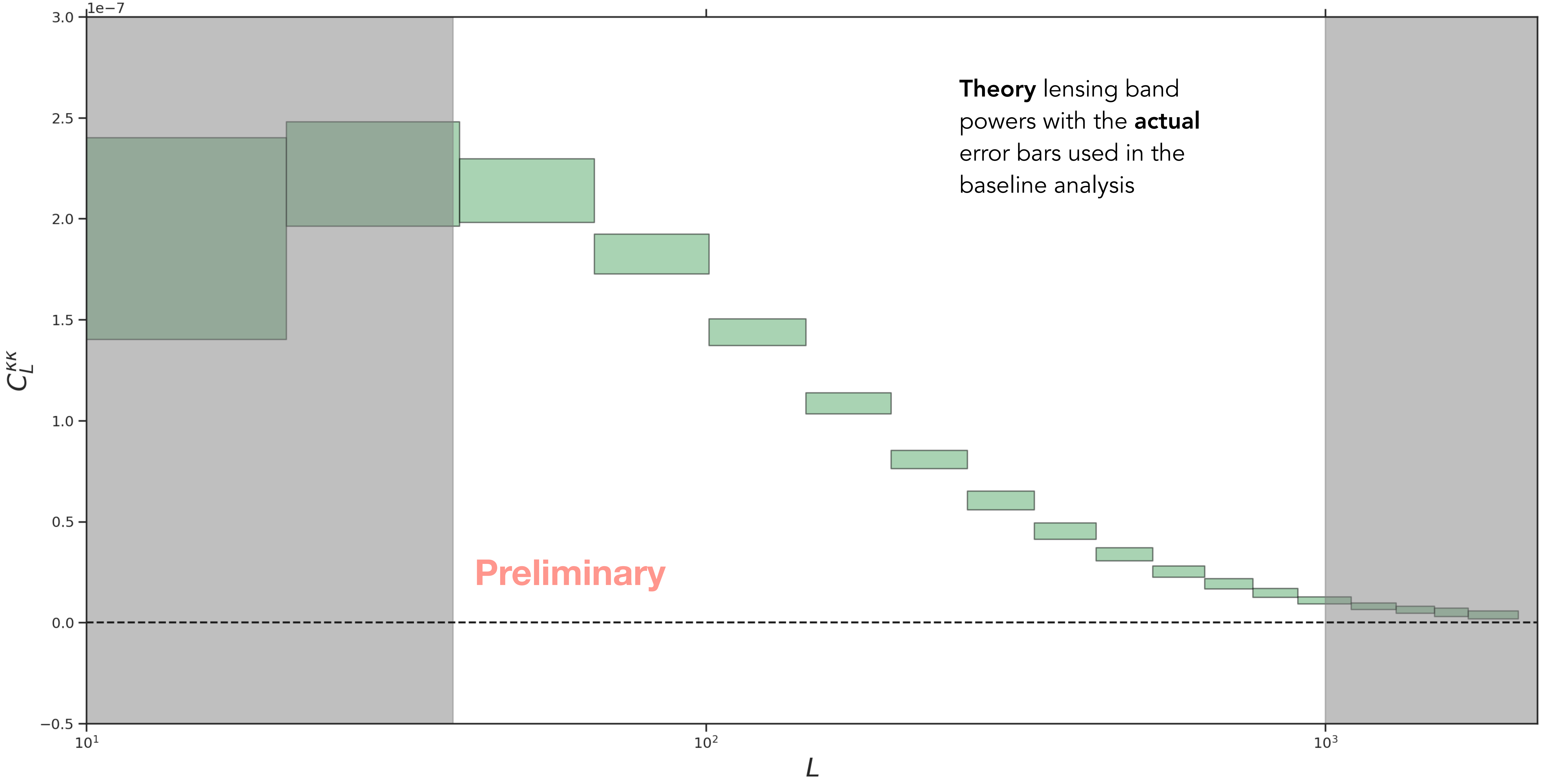


New DR6 AdvACT maps: 15uk 18000 sq degrees

NEW ADVACT STATE OF THE ART CMB LENSING MAPS!

AdvACT 10.000 square degrees total

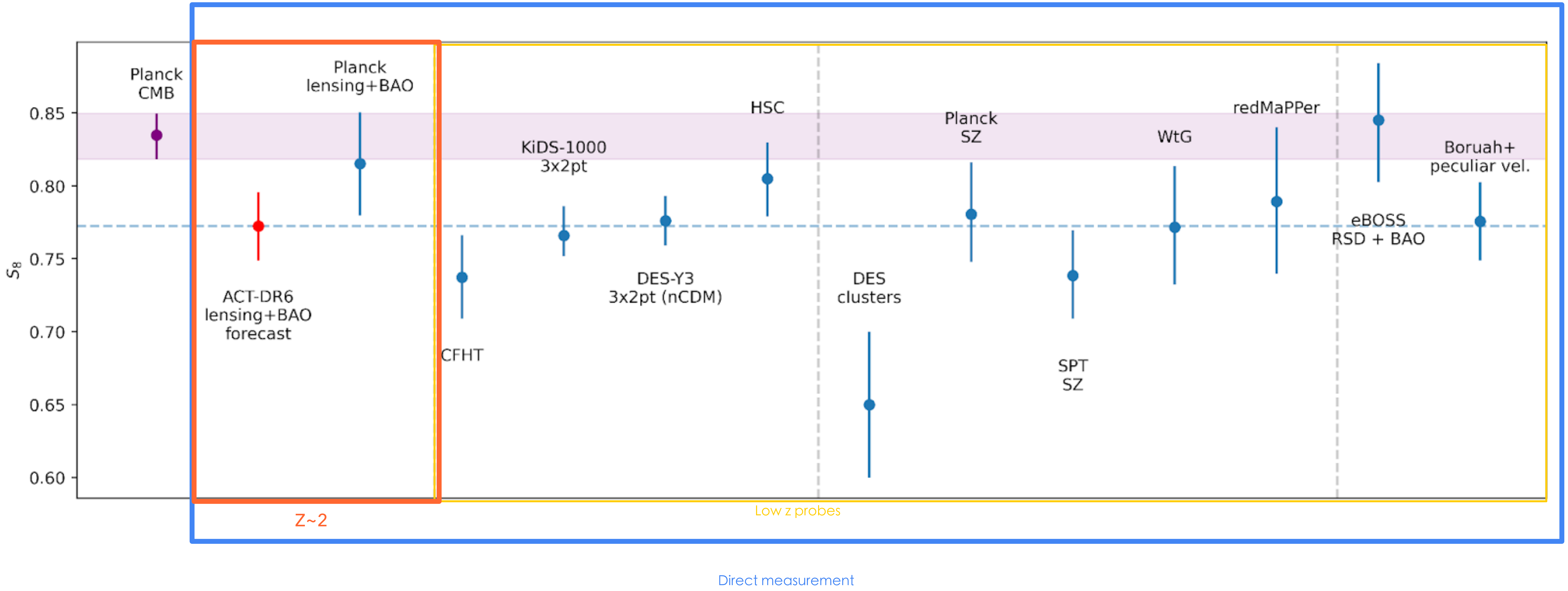
2% MEASUREMENT OF LENSING POWER SPECTRUM



- SNR 50 using the actual error bars.
- Using CMB maps covering 30% of the sky.

ADVACT MEASUREMENTS WILL ENABLE POTENTIAL CLARIFICATION OF S_8 TENSION

- $S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3} \right)^{0.25}$ to ± 0.017 CMB lensing only constraints



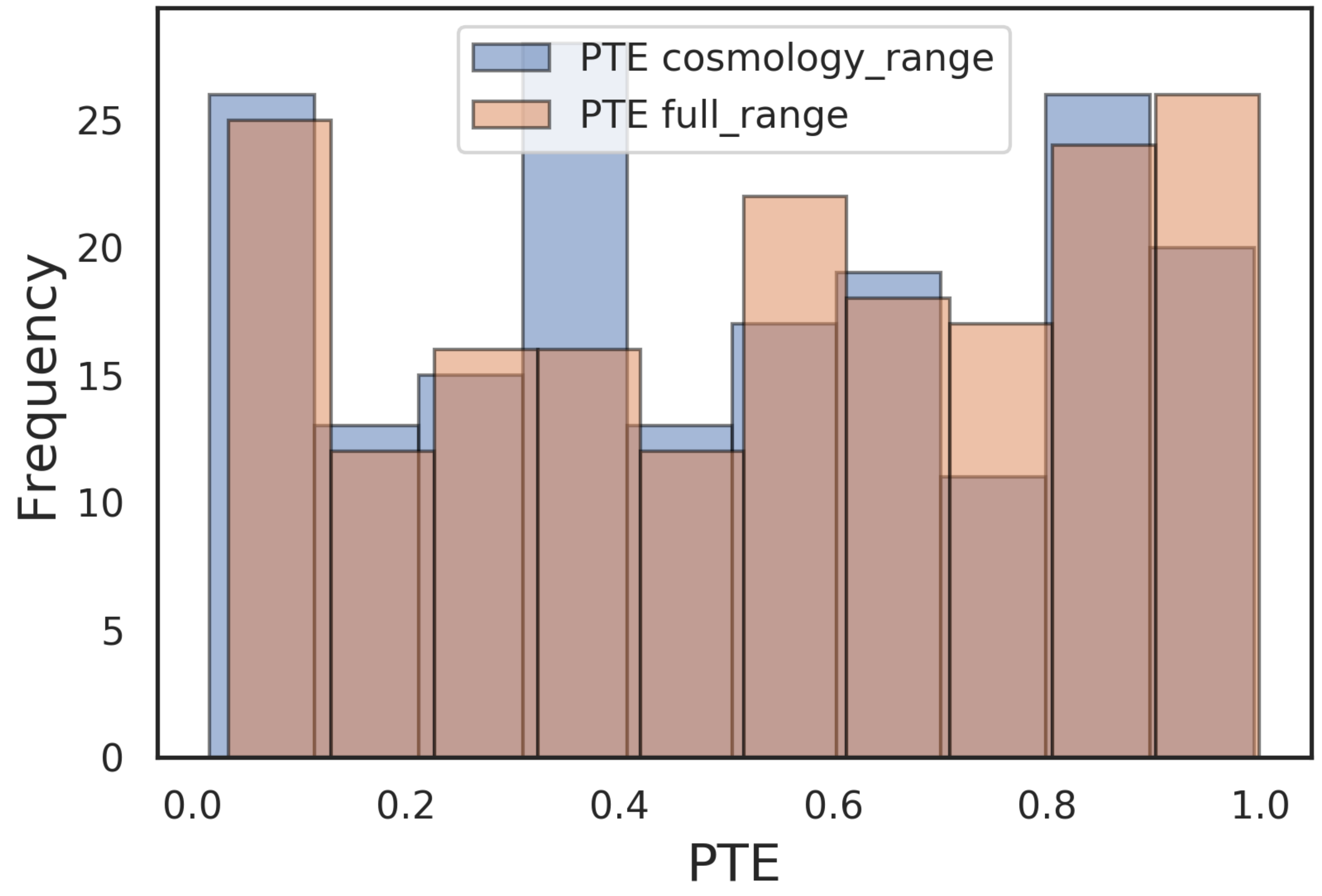
ROBUST LENSING MEASUREMENT

Great SNR comes with great responsibility

Over 200 null tests targeting for specific systematics:

- Systematics due to noise mis-simulation and bias subtraction
- Instrumental systematics (Calibration, beam and masking)
- Foregrounds (Galactic and extragalactic)

Null test summary



- Cosmology range Lmin=40 Lmax=1000
- Full range Lmin=8 Lmax=2048
- 198 null tests in total
- No <0.01 failure observed in either cosmology range or full range

COMPREHENSIVE NULL TEST SUITE

VERY ROBUST SINCE MANY DIFFERENT WAYS TO CHECK RESULTS

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

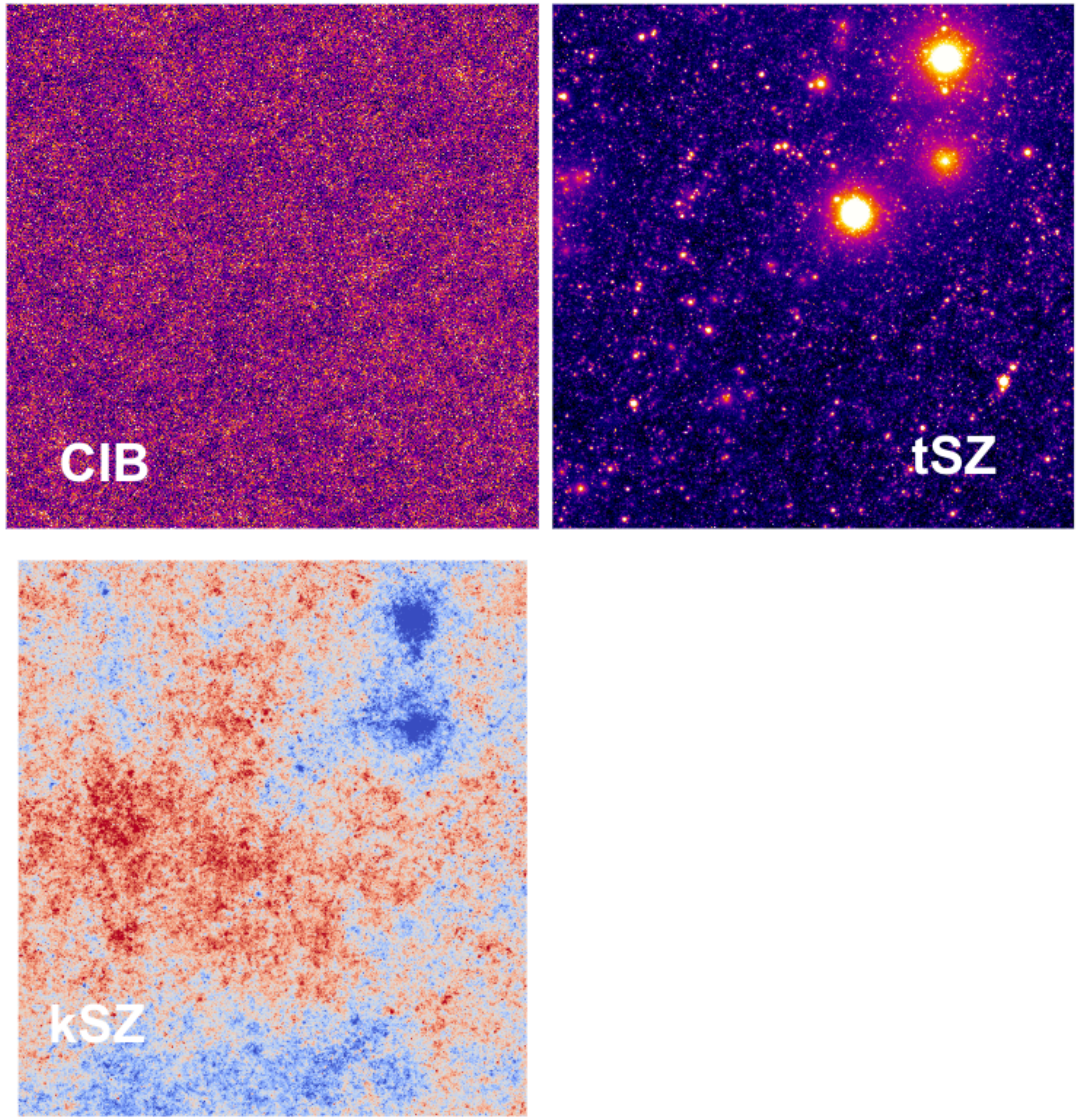
PWV tests

Season difference tests

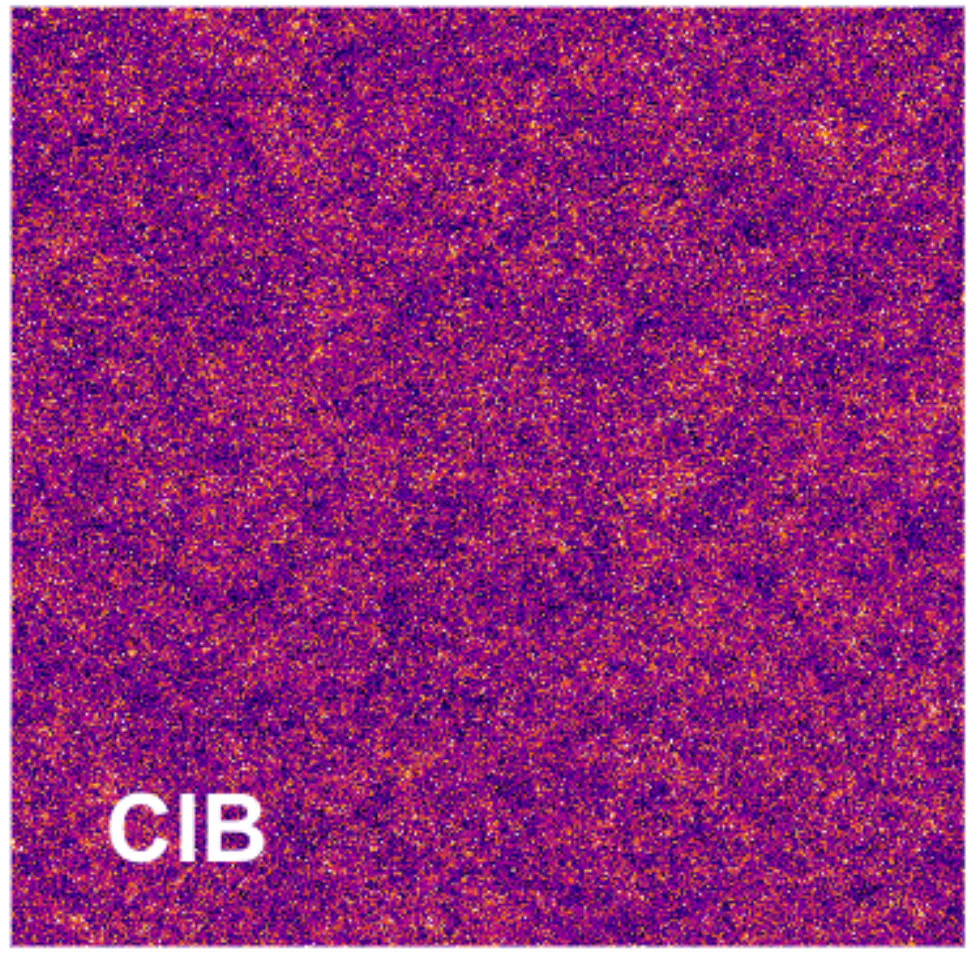
KEYS FOR PASSING
- Two different methods for foreground mitigation
  - Profile hardening
  - Frequency cleaning
- Cross correlation based estimator. (Immune to instrument noise)

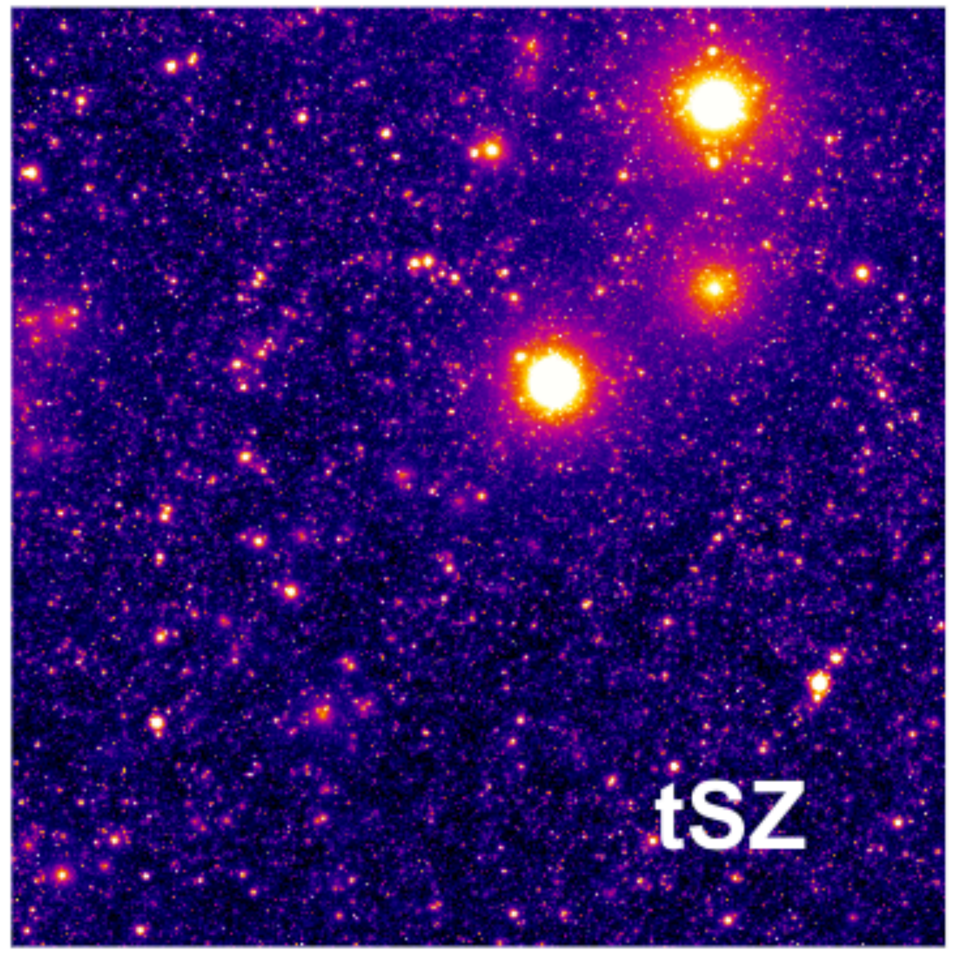
CHALLENGE I:

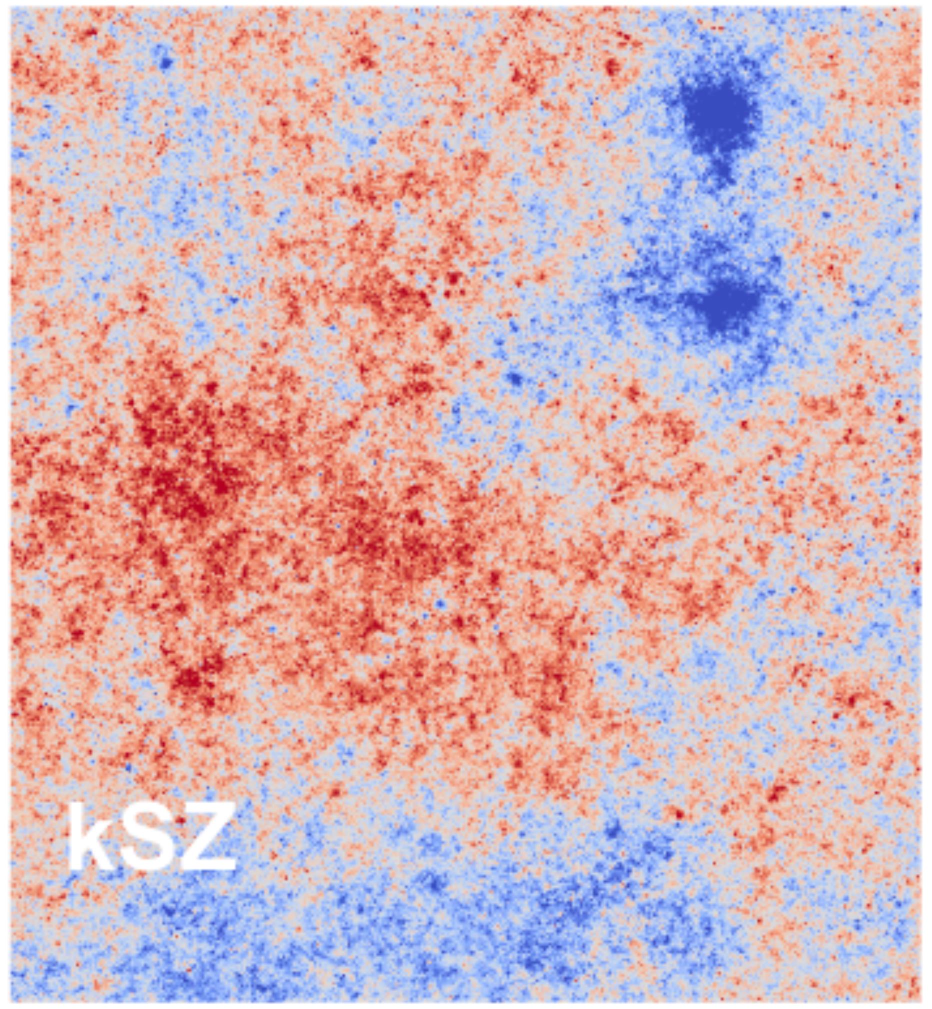
CONTAMINATION FROM EXTRA-GALACTIC FOREGROUNDS



Challenge I: Biases From Extragalactic foregrounds







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

$$T = T + f$$

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

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

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

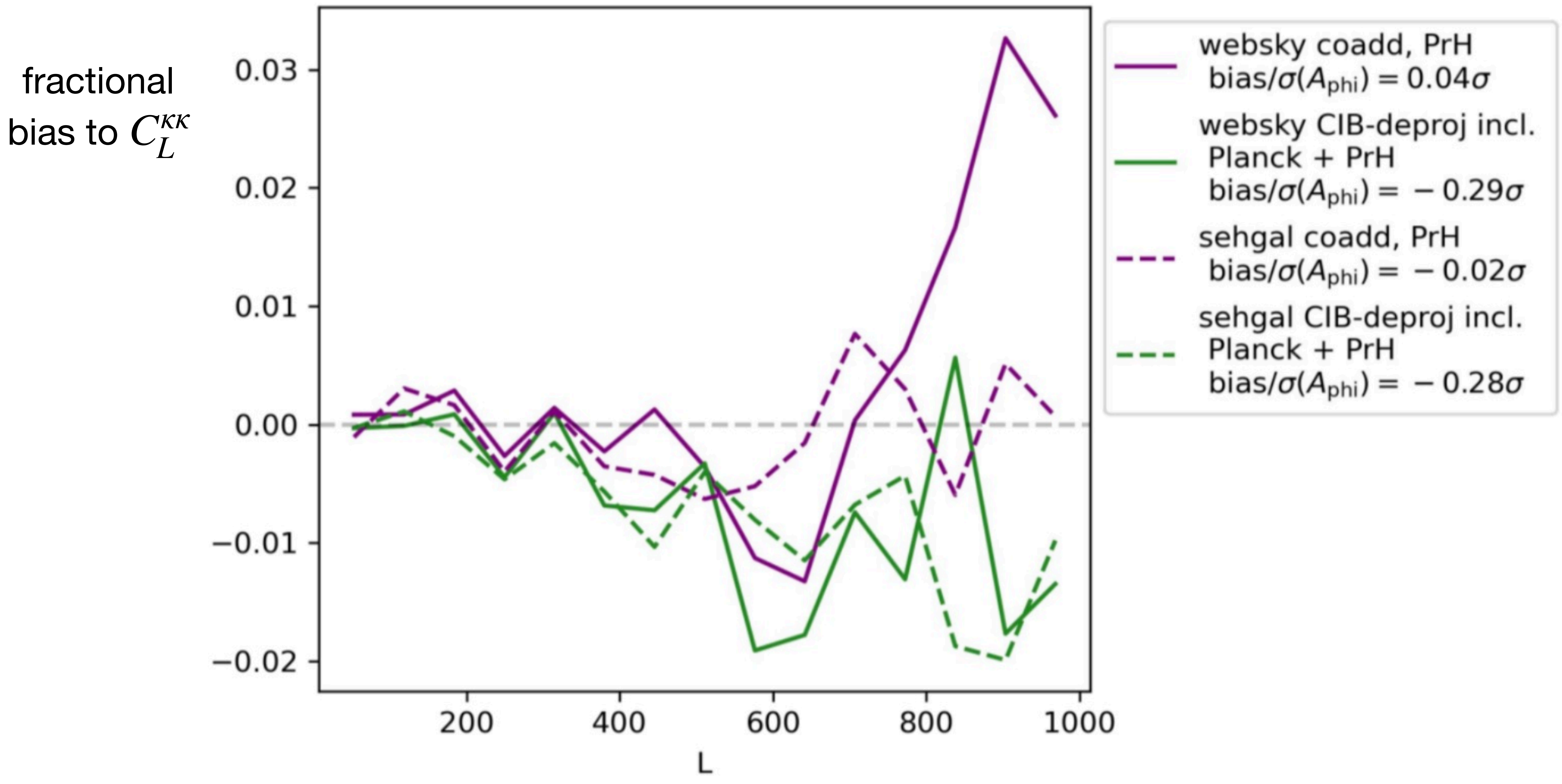
Foreground induced biases

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: Two primary mitigation methods

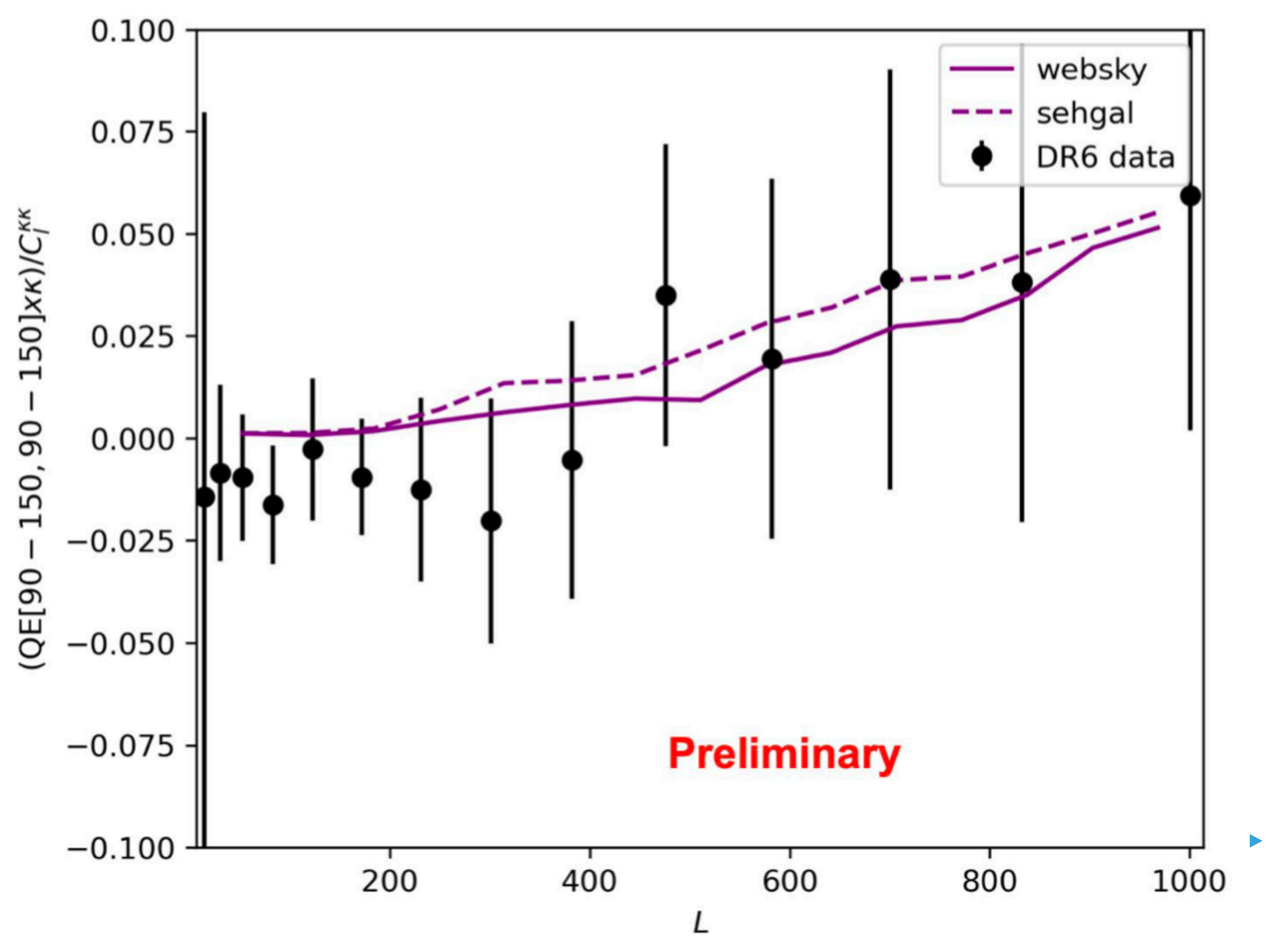
- **Geometric methods**
  - Profile hardening
  - Shear [**Qu**,Challinor,Sherwin in prep]
- **Multifrequency**
  - CIB deprojection + Profile hardening



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

Foreground mitigation pipeline: Cross-check results from independent menthods/frequencies

- Cross-check lensing spectrum between methods
  - Geometric: Profile hardening
  - Shear [**Qu**,Challinor,Sherwin in prep]
  - Multifrequency: CIB deprojection +above
- Check lensing consistency in 90 and 150 Ghz maps

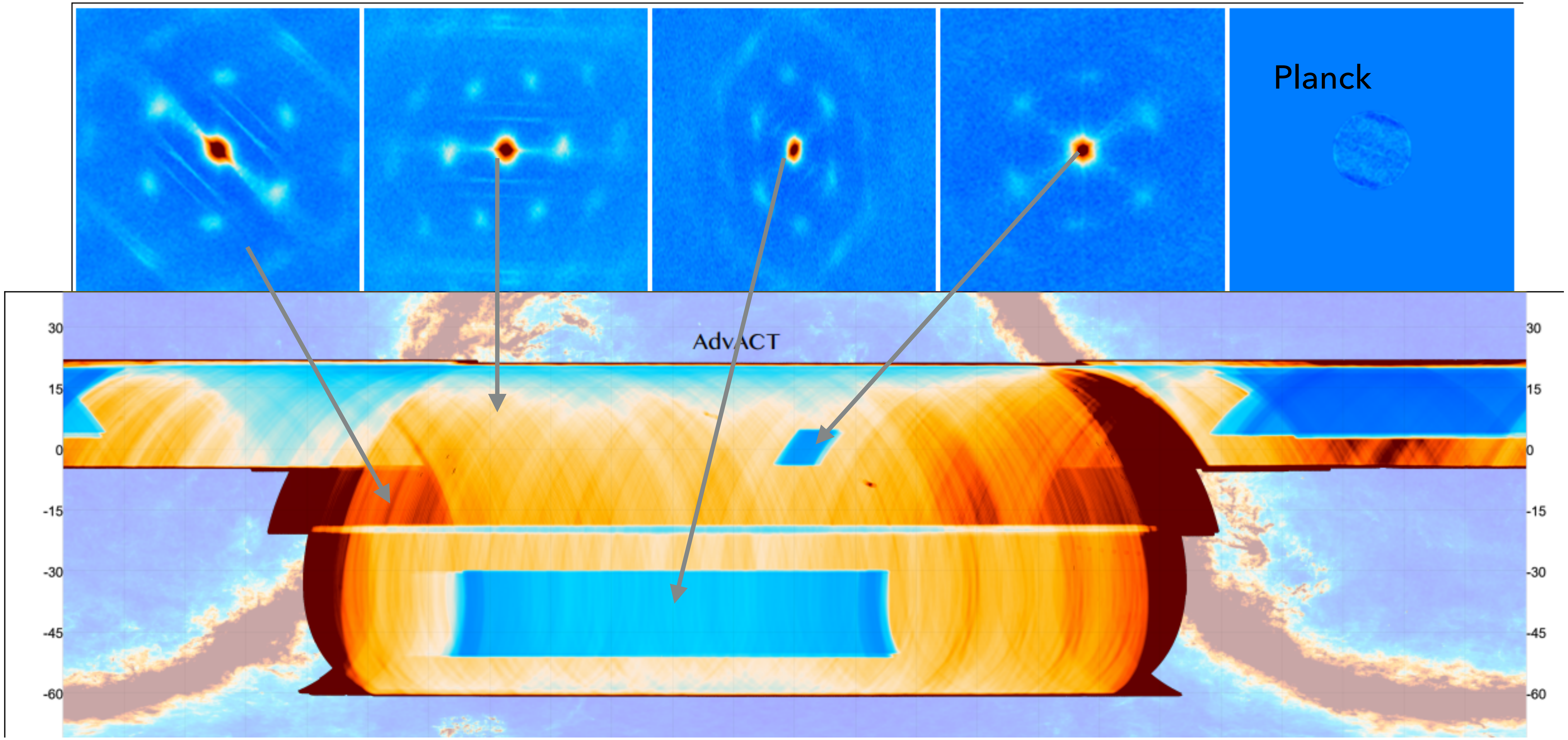


- **Consistent lensing power spectrum for all mitigation methods.**
- **Frequencies are fully consistent and the data bias estimates are small.**

- [MacCrann,Sherwin,**Qu**,++ in prep]

CHALLENGE II:

GROUND BASED NOISE IS VERY COMPLICATED TO MODEL

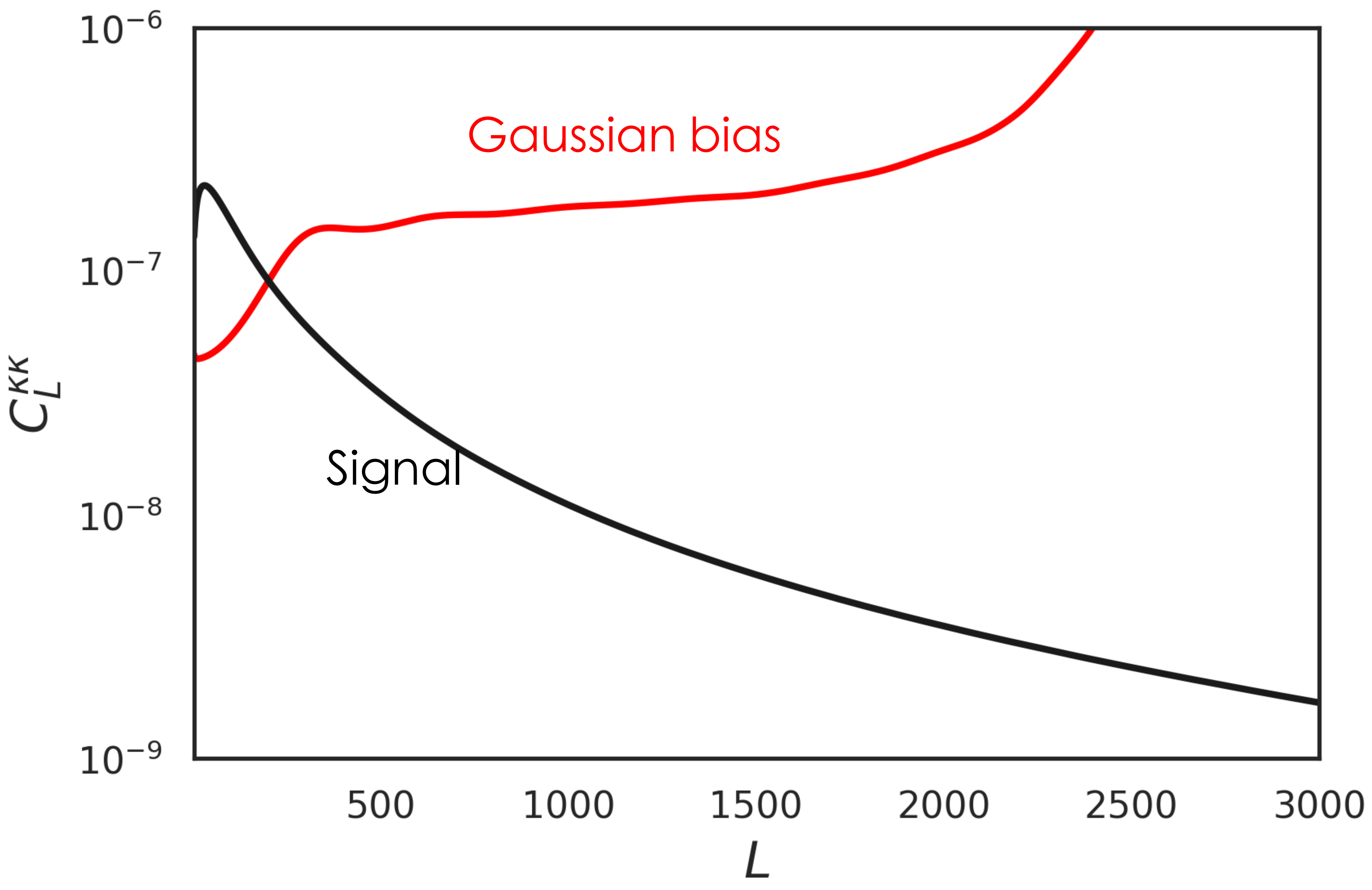


Naess et Al 2020

Challenge II: Noise modelling. Why do we need accurate noise

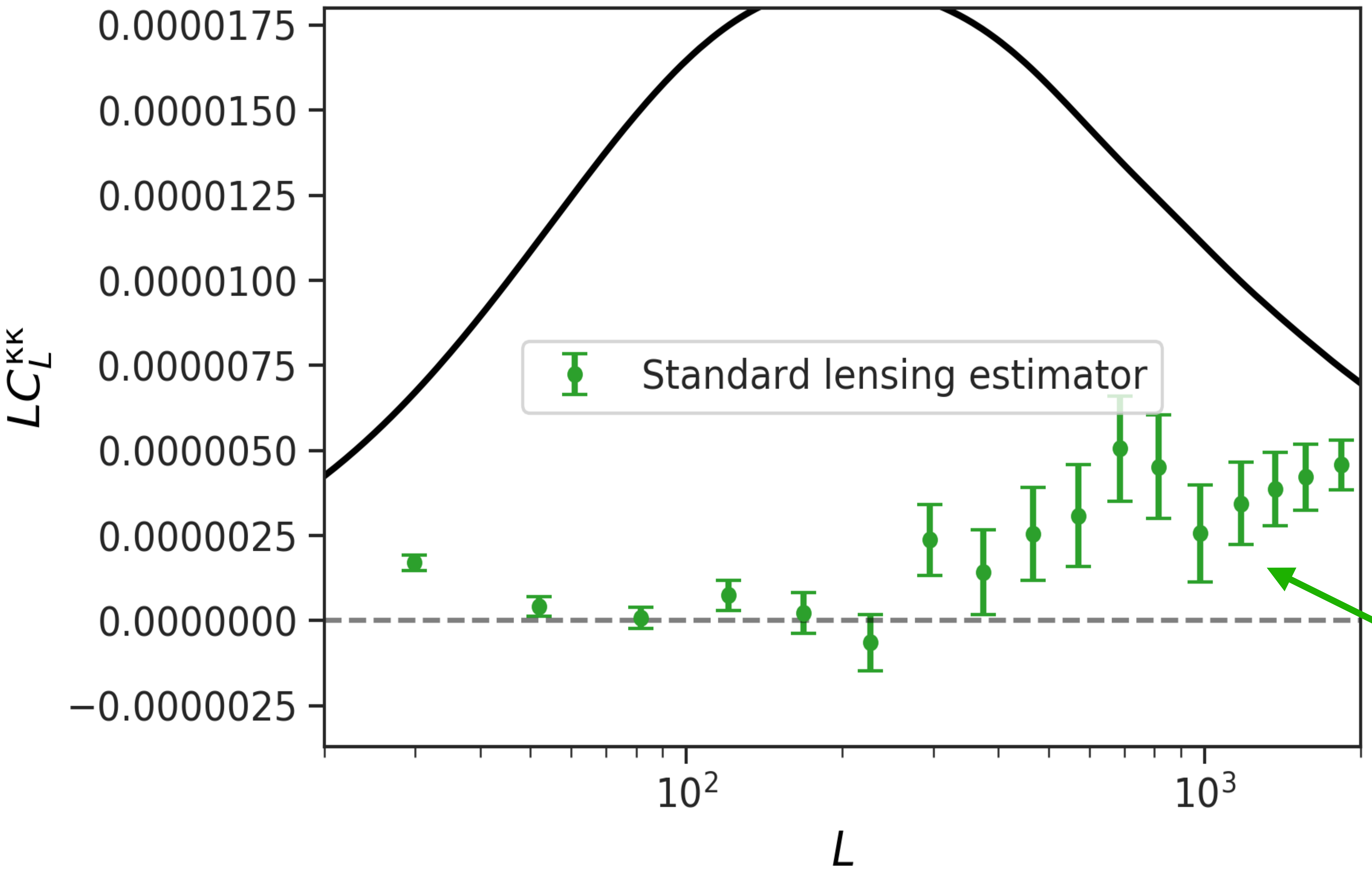
$$C_L^{\phi\phi} \sim \langle \phi(\mathbf{L}) \phi^*(\mathbf{L}) \rangle - \text{Gaussian bias} \xrightarrow{\text{Schematically}} \langle TTTT \rangle - \langle TT \rangle \langle TT \rangle$$

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 II: Noise modelling, Noise only null test failure



Null test

- Prepare noise-only maps.
- Run the lensing pipeline (including bias removal) on these noise-only maps.

Expectation

Result should be consistent with zero.

Reality

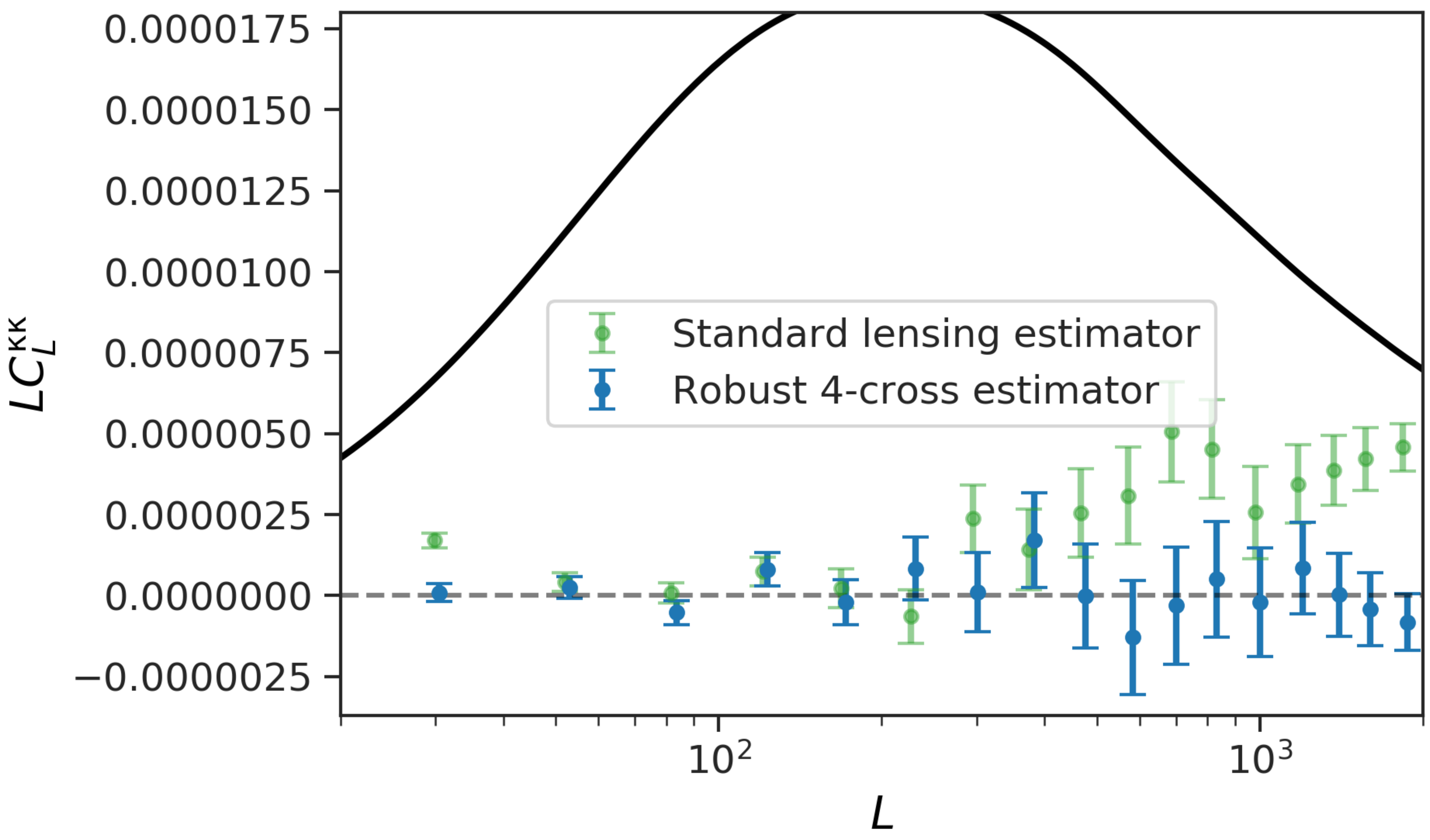
U shape failure :(

Solution: Cross correlation based estimator

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

maps with independent noise

- Divide data into **'splits'** which have independent noise
- Non trivial combination of splits makes computational cost $\mathcal{O}(\mathrm{splits}^2)$ instead of naive $\mathcal{O}(\mathrm{splits}^4)$ Mat M, Blake Sherwin+ arXiv:2011.02475v1



Null test

- Prepare noise-only maps.
- Run the lensing pipeline (including bias removal) on these noise-only maps.

Pass the null test with robust cross estimator!

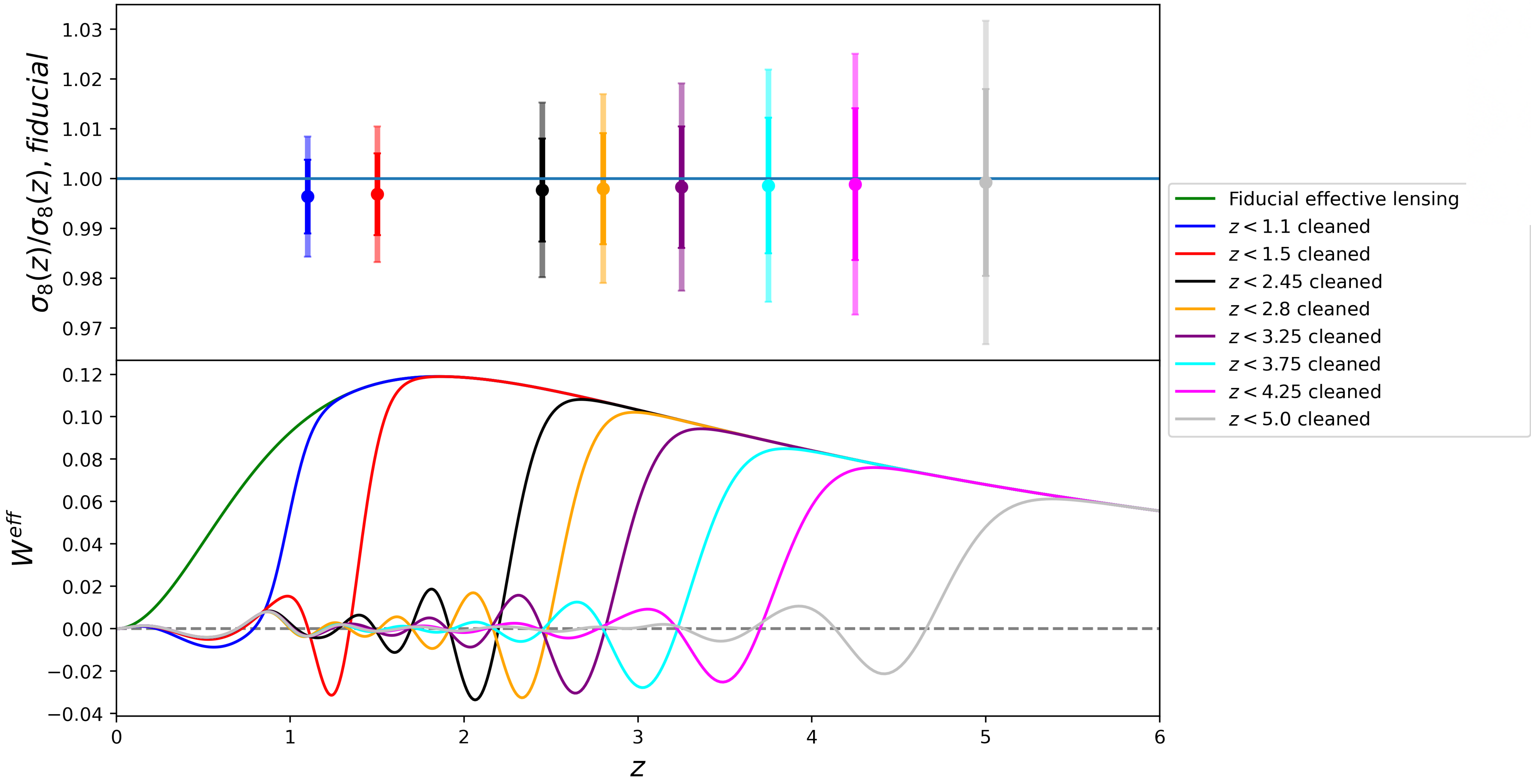
NOVEL PROBE OF HIGH Z UNIVERSE

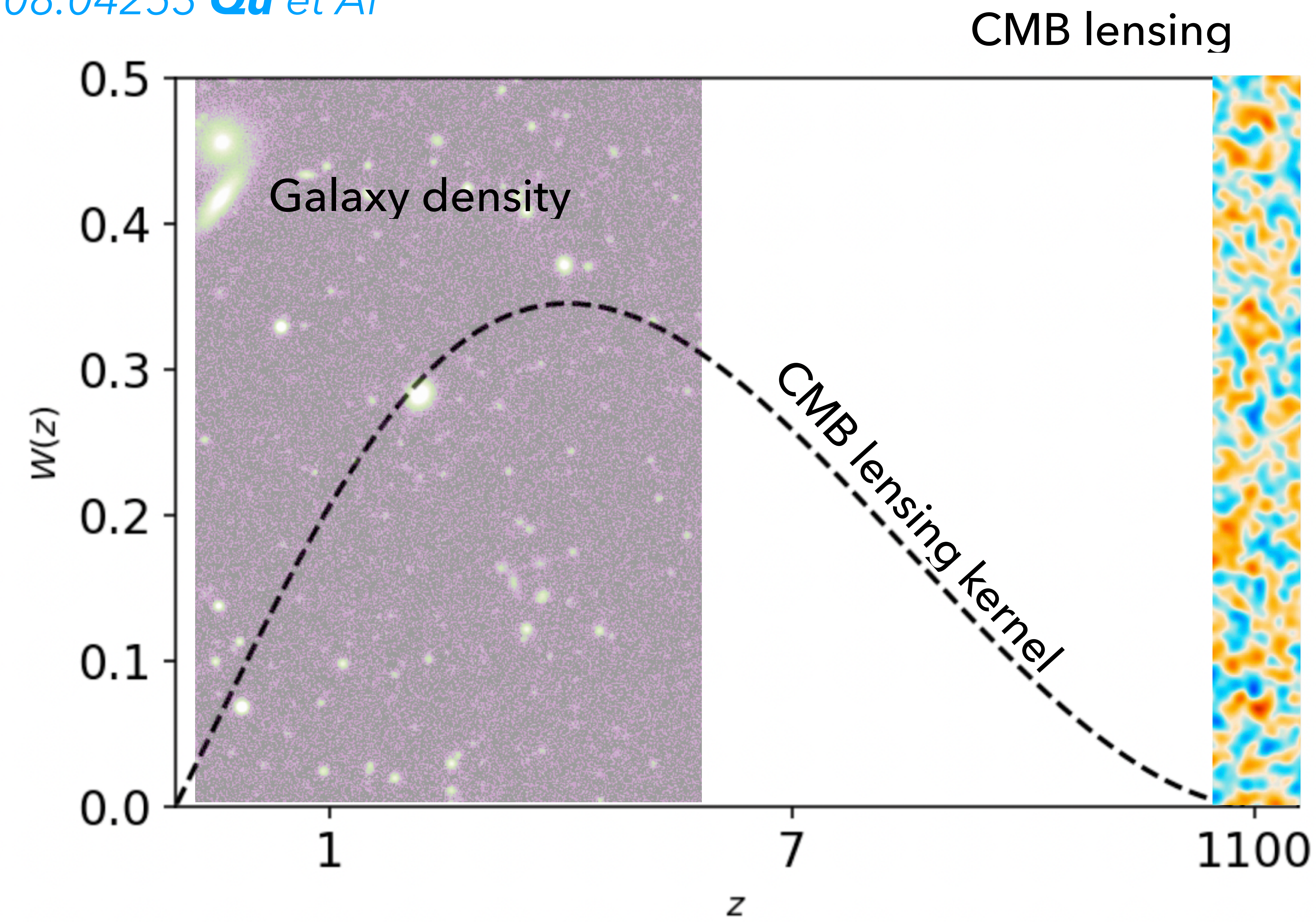
arXiv:2208.04253 ***Qu*** *et Al*

- CMB lensing kernel overlaps with many other mass tracers.
- Can use the galaxy tracers to **null** the low redshift contributions of the CMB lensing kernel

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

Galaxy tracer





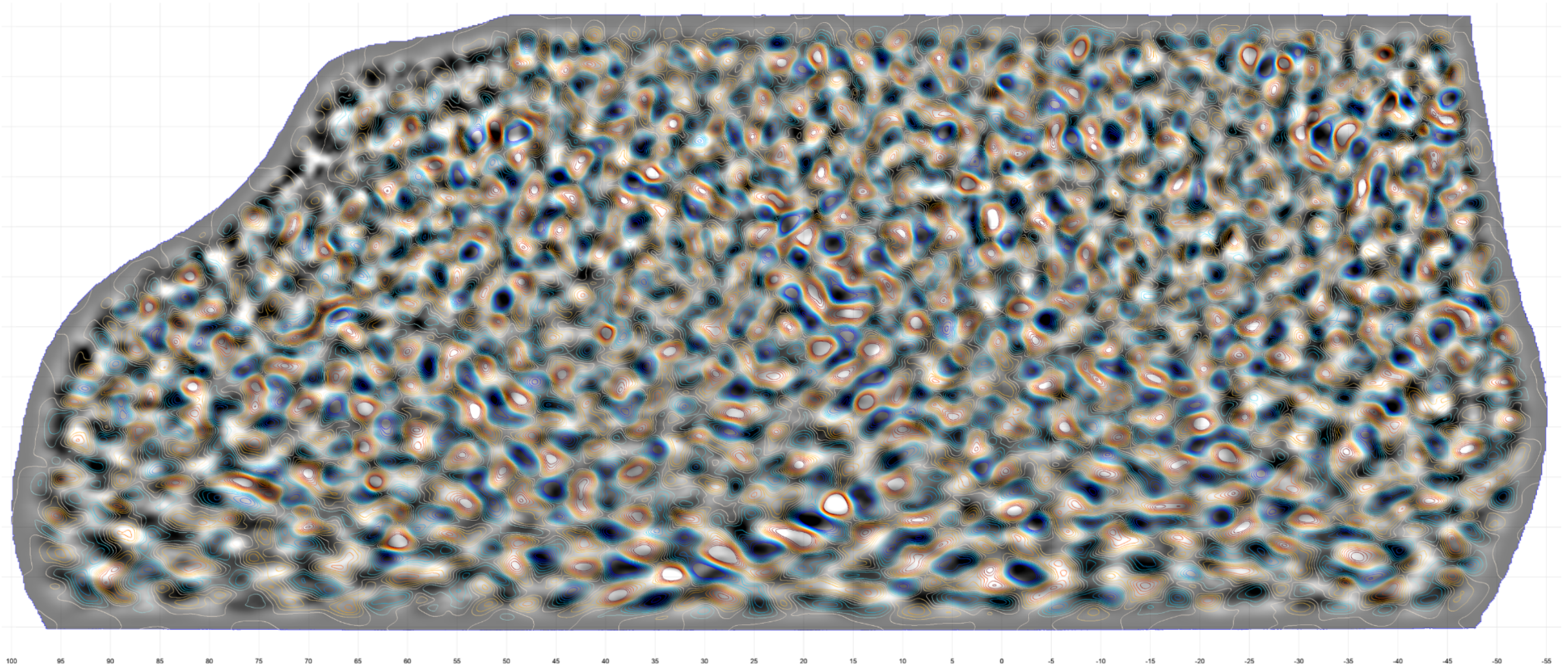
- Exciting prospects of measuring amplitude of structures at high redshifts

4% measurement of S_8 at z=5.
CMB-S4+LSST cleaning

- + nearly model independent neutrino mass sum measurements

SUMMARY

- Working towards the highest precision CMB lensing power spectrum
- Tested rigorously with large null and systematic suite.
- Expect state of the art S_8 and $\sum m_\nu$ constraints with very different systematics to weak lensing. + High resolution maps for cross-correlation/delensing science.
- **Novel probe** of high z Universe. *arXiv:2208.04253*
  ***Qu**,Sherwin,Darwish,Namikawa,Madhavacheril*



Stay tuned for this autumn!

- ***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*
- ***Qu,** Challinor,Sherwin. Full sky shear only estimator. (expected 2022)*
- *Atkins,Duivenvoorden,Coulton,**Qu** et al ACT (expected 2022): Map-Based Noise Simulations for DR6*

OBRIGADO!