CMB LENSING WITH THE ATACAMA COSMOLOGY TELESCOPE: A NEW WINDOW TO FUNDAMENTAL PHYSICS

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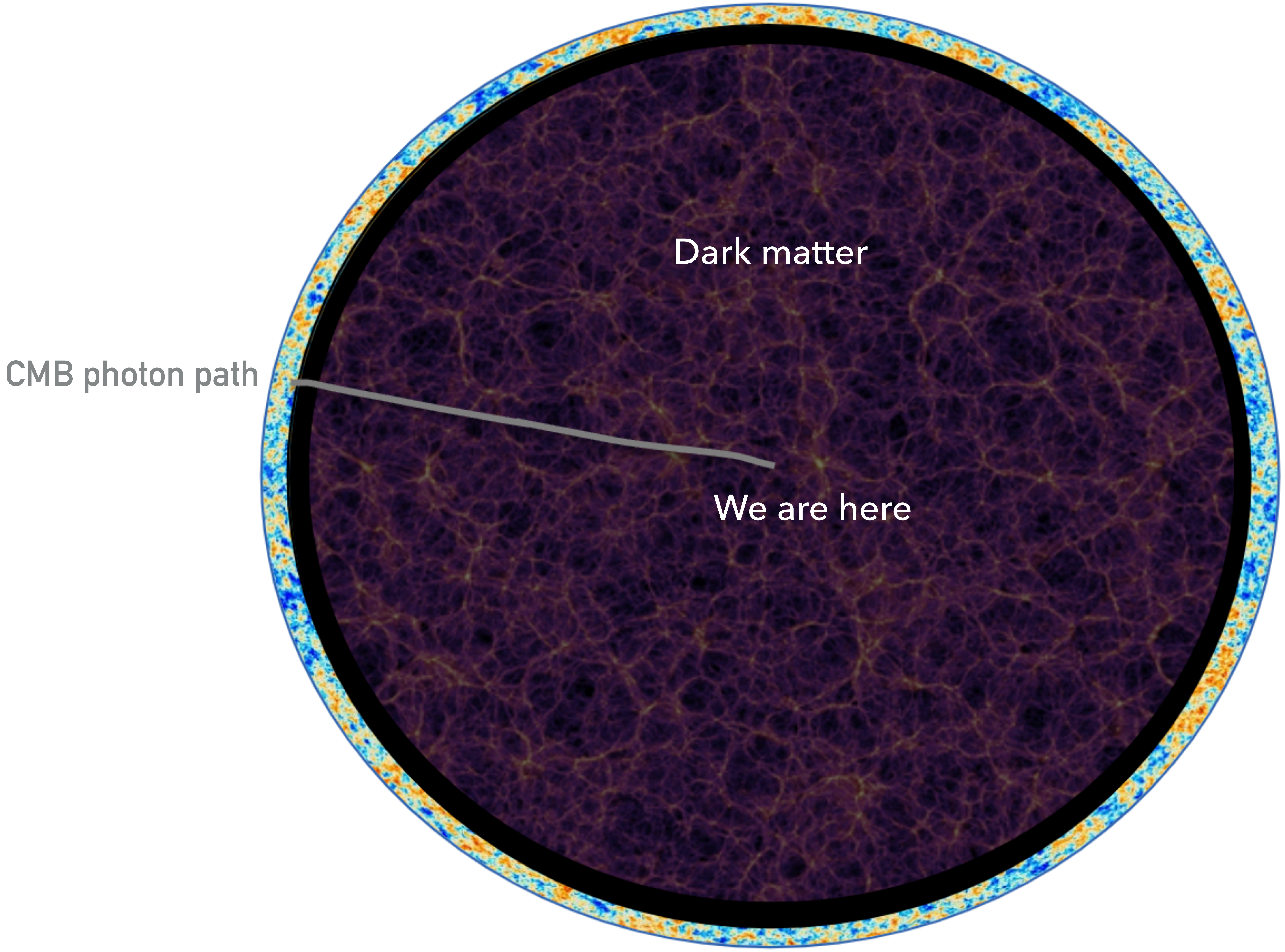
+ ACT collaboration

Frank J. Qu Tuesday 7th of August 2023

Rencontres du Vietnam

THE CMB AS A SOURCE OF GRAVITATIONAL LENSING



Ideal Source for lensing

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

BACKLIGHTING THE UNIVERSE WITH THE CMB

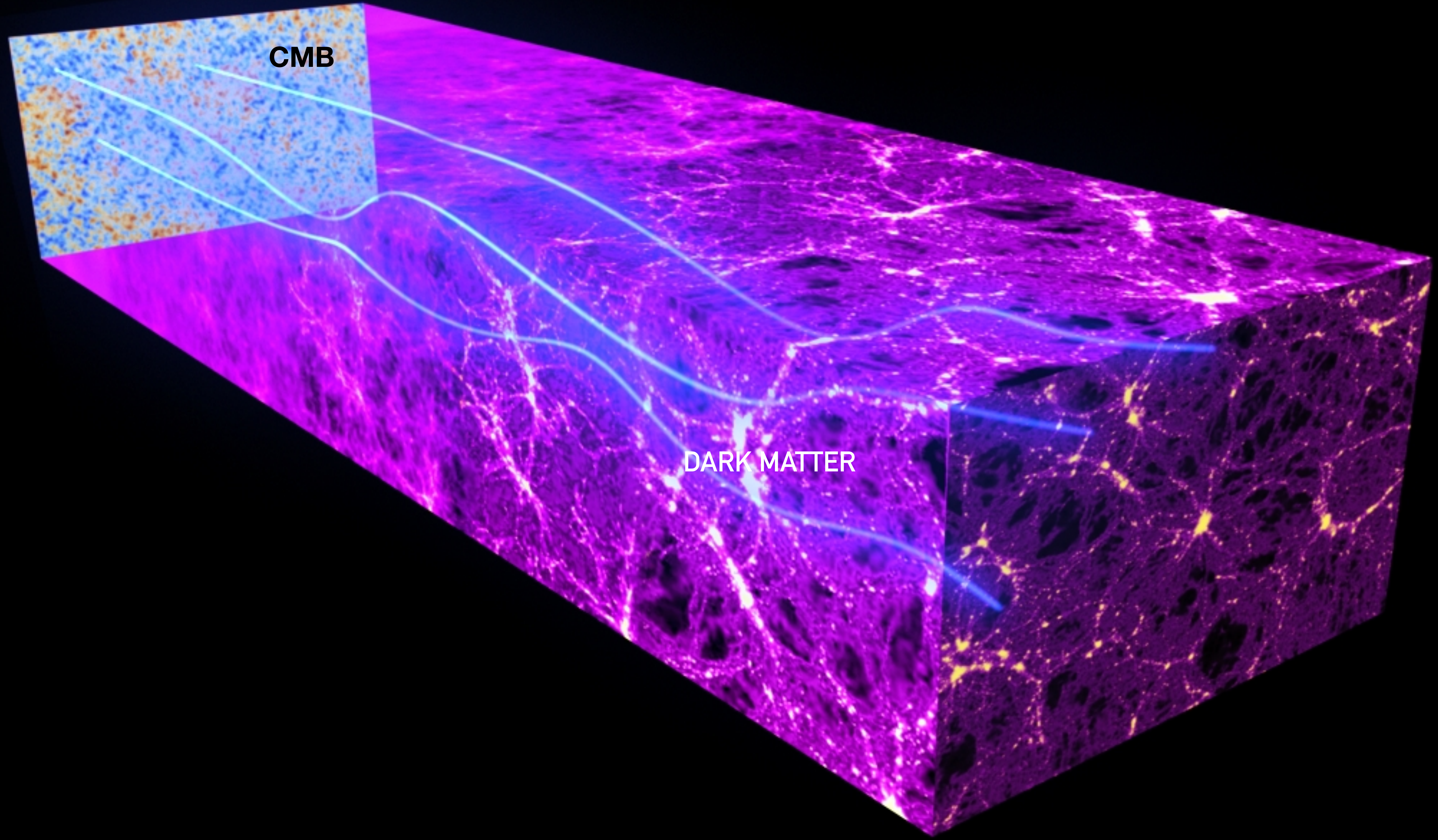
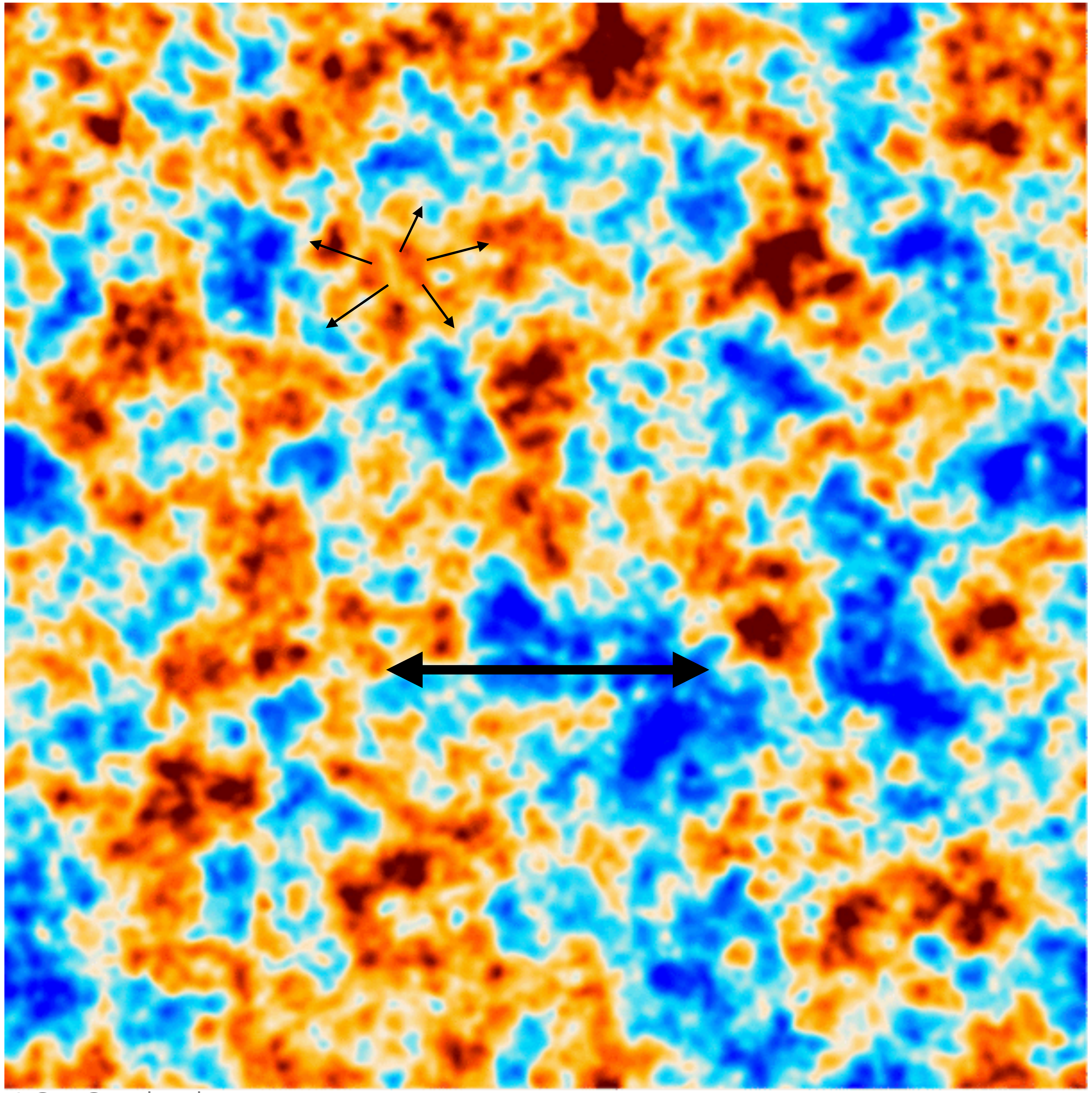


Image: ESA/Planck

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 (QE)

REAL SPACE

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

FOURIER/ HARMONIC SPACE

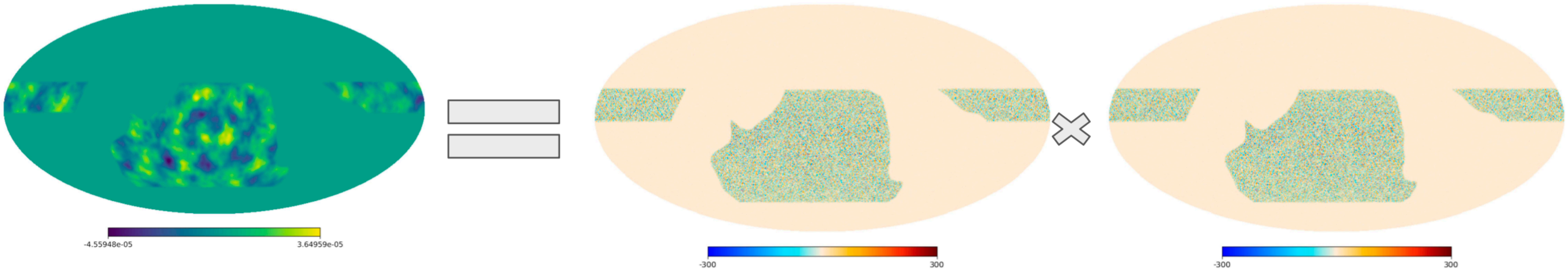
$$\langle T^0(\boldsymbol{\ell})T^{0*}(\boldsymbol{\ell}-\mathbf{L})\rangle_{\text{CMB}} = 0$$

Mode coupling

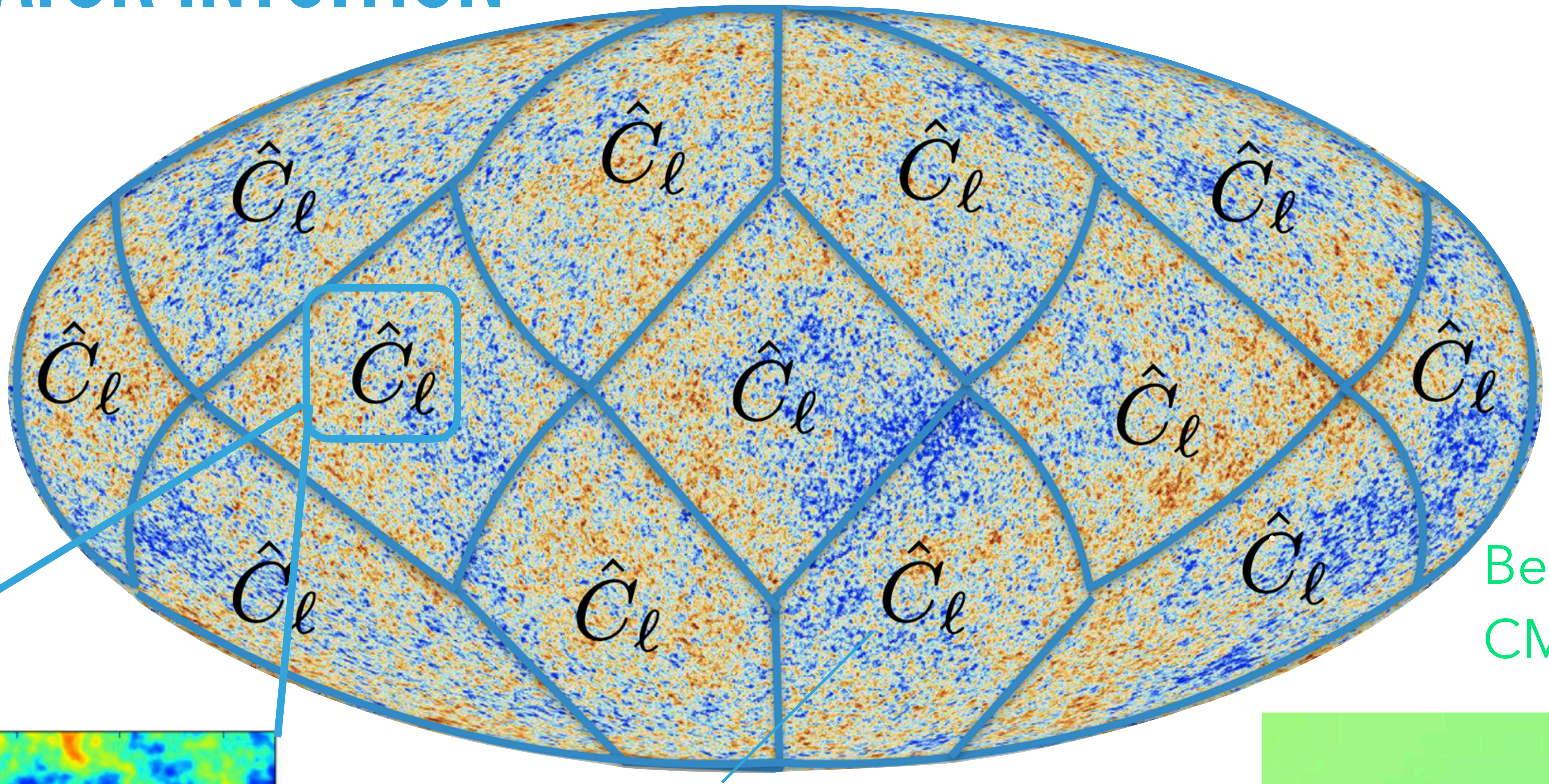
$$\langle T(\boldsymbol{\ell})T^*(\boldsymbol{\ell}-\mathbf{L})\rangle_{\text{CMB}} \sim \phi(\mathbf{L})$$

Mode by mode reconstruction of lensing from quadratic CMB combinations

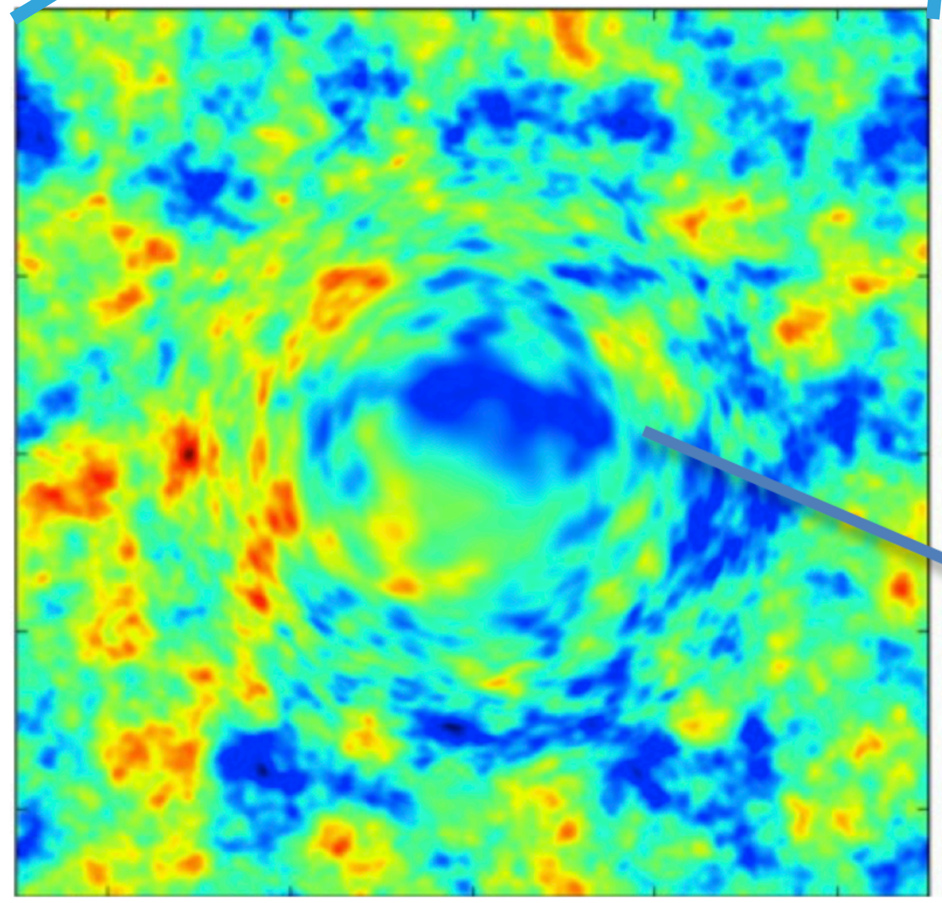
$$\hat{\phi}(\mathbf{L}) \sim \int d^2\boldsymbol{\ell}\, T(\boldsymbol{\ell})T^*(\boldsymbol{\ell}-\mathbf{L}) \sim QE(T_{CMB}, T_{CMB})$$



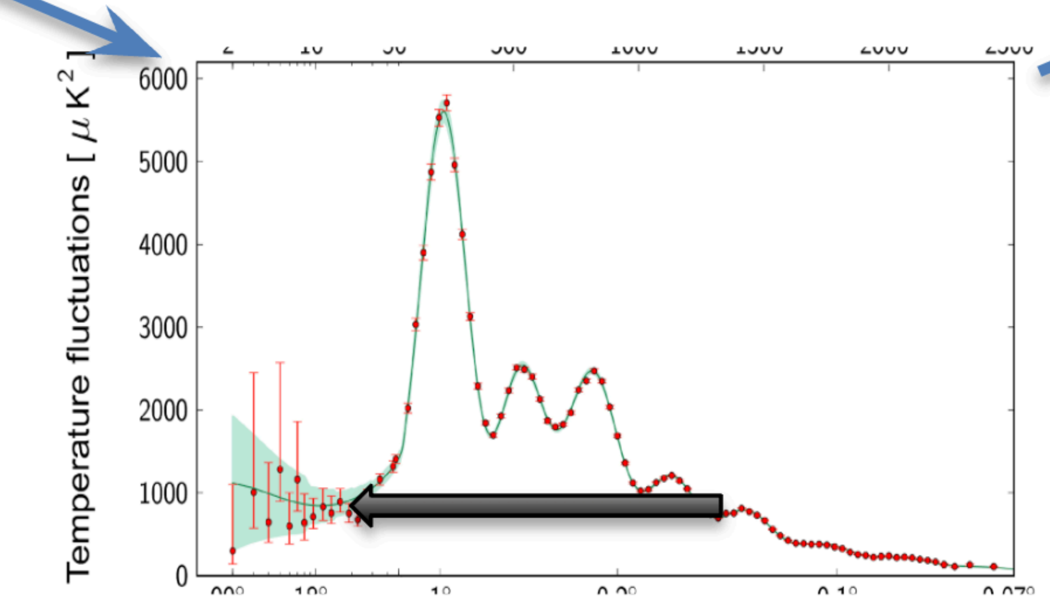
QUADRATIC ESTIMATOR INTUITION



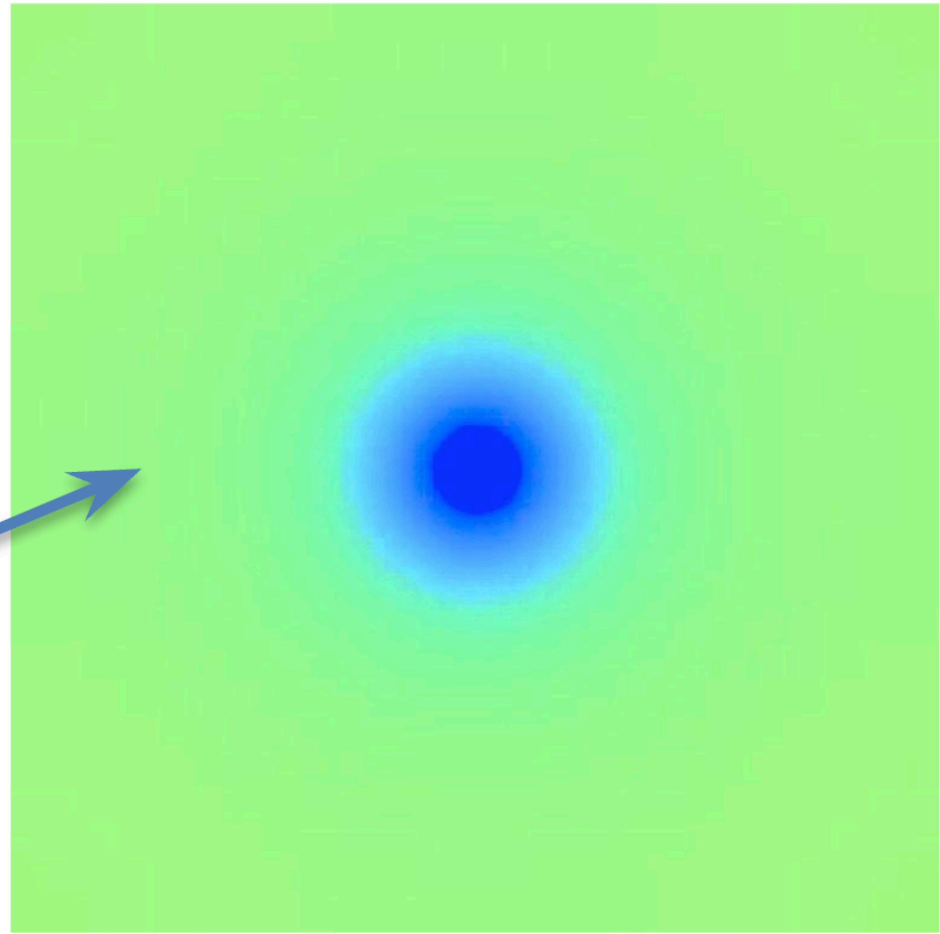
Benefit from **high resolution** CMB measurements



CMB



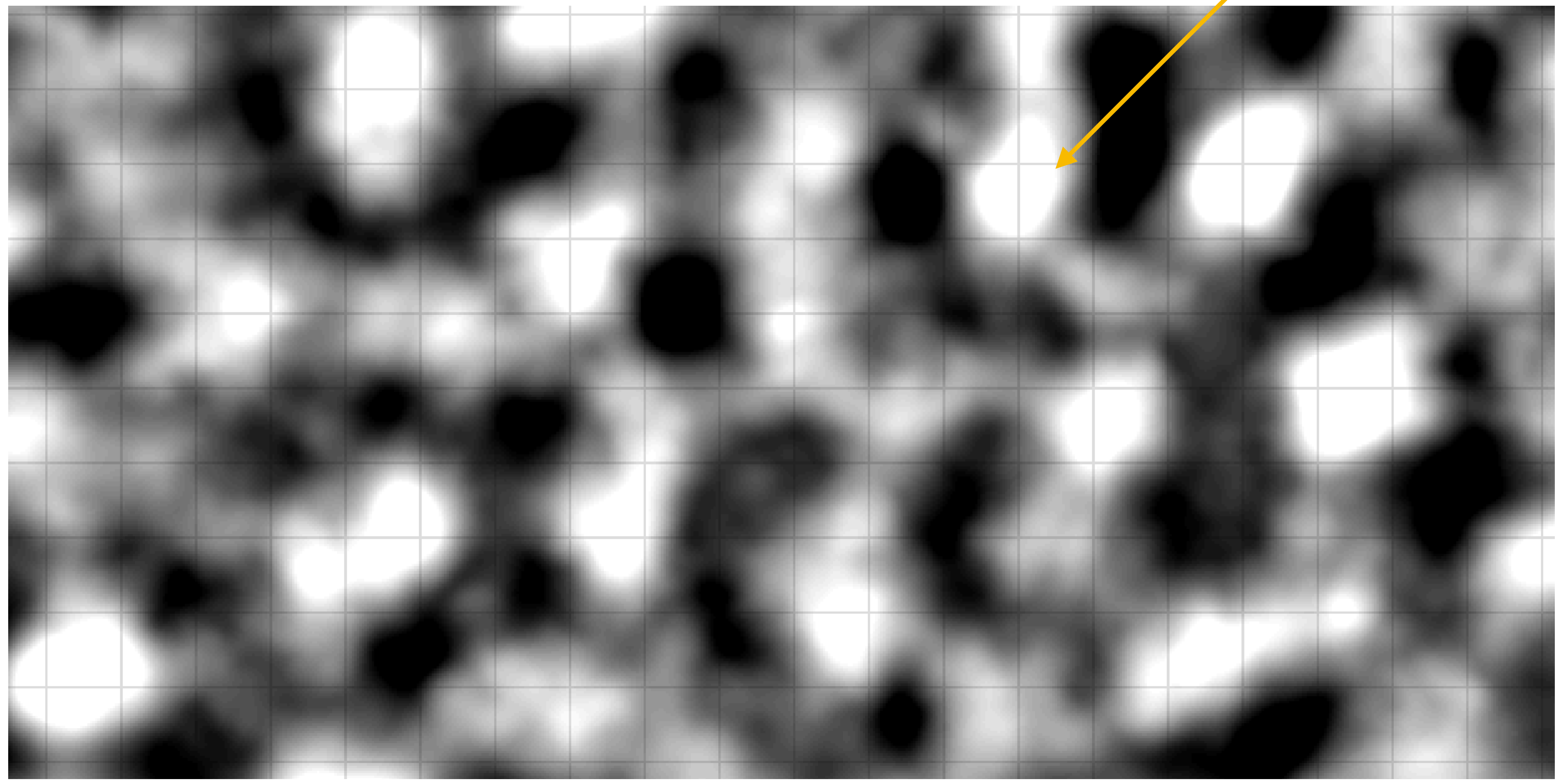
Shift to larger angular scales



Lensing inferred from the local stretching/shearing of the local CMB power spectrum

KEY STATISTICS: LENSING POWER SPECTRUM

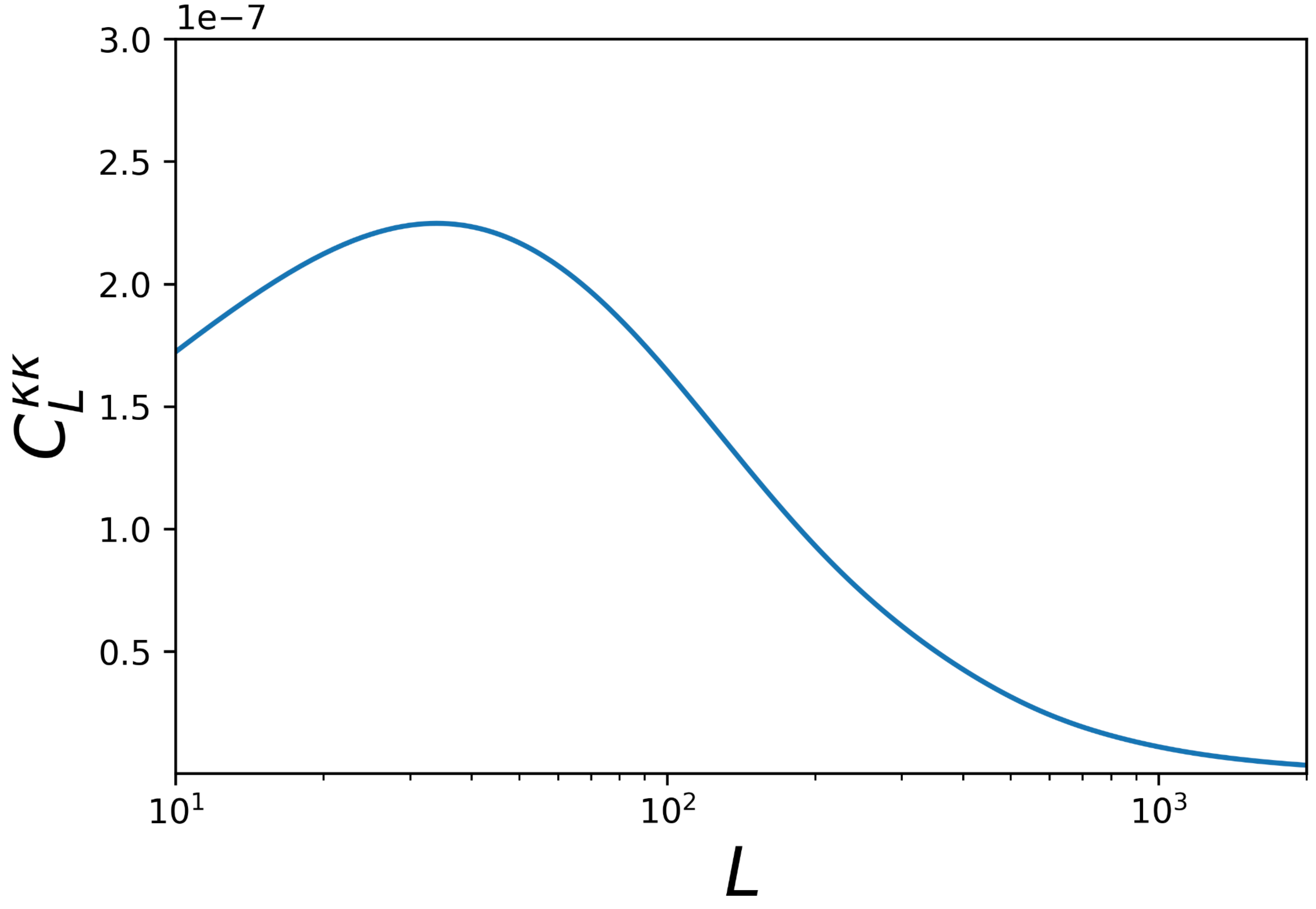
Bright regions = High Density



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 $\sim \frac{1}{L}$

MOTIVATION: WHY IS CMB LENSING INTERESTING?

- Lensing probes the projected mass distribution to high redshifts.
- Hence the lensing power spectrum is the projected matter power spectrum

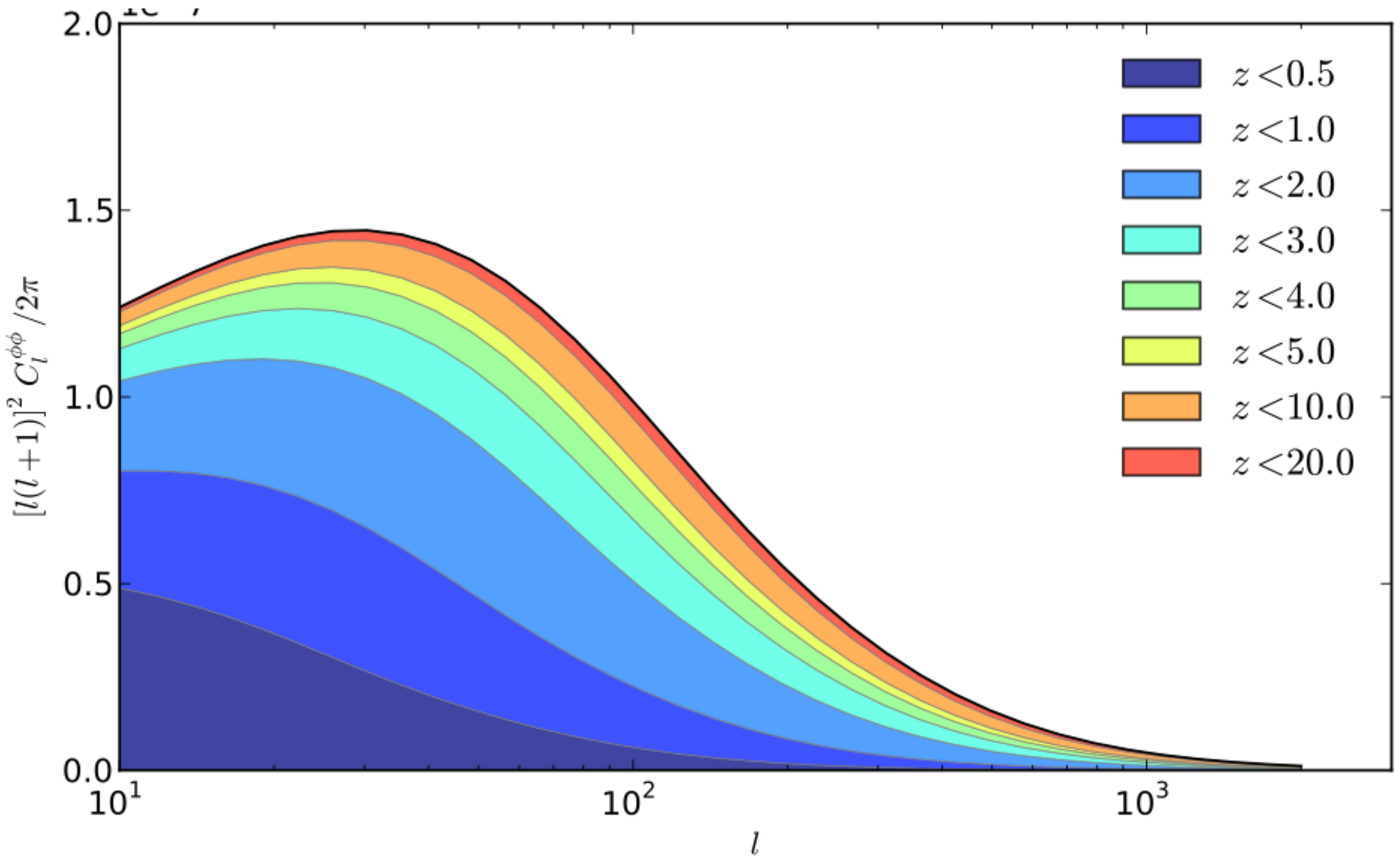
$$L^4 C_L^{\phi\phi}/4 = \int_0^{1100} dz (\tilde{W}^{\kappa}(z))^2 P(k = L/\chi, z)$$

lensing power spec. — redshift kernel — matter power spectrum

$$\kappa(\hat{\mathbf{n}}) \sim \int_0^{z_\star} dz\, W^{\kappa}(z)\, \delta(\hat{\mathbf{n}}, z)$$

Fractional mass overdensity

Projection kernel

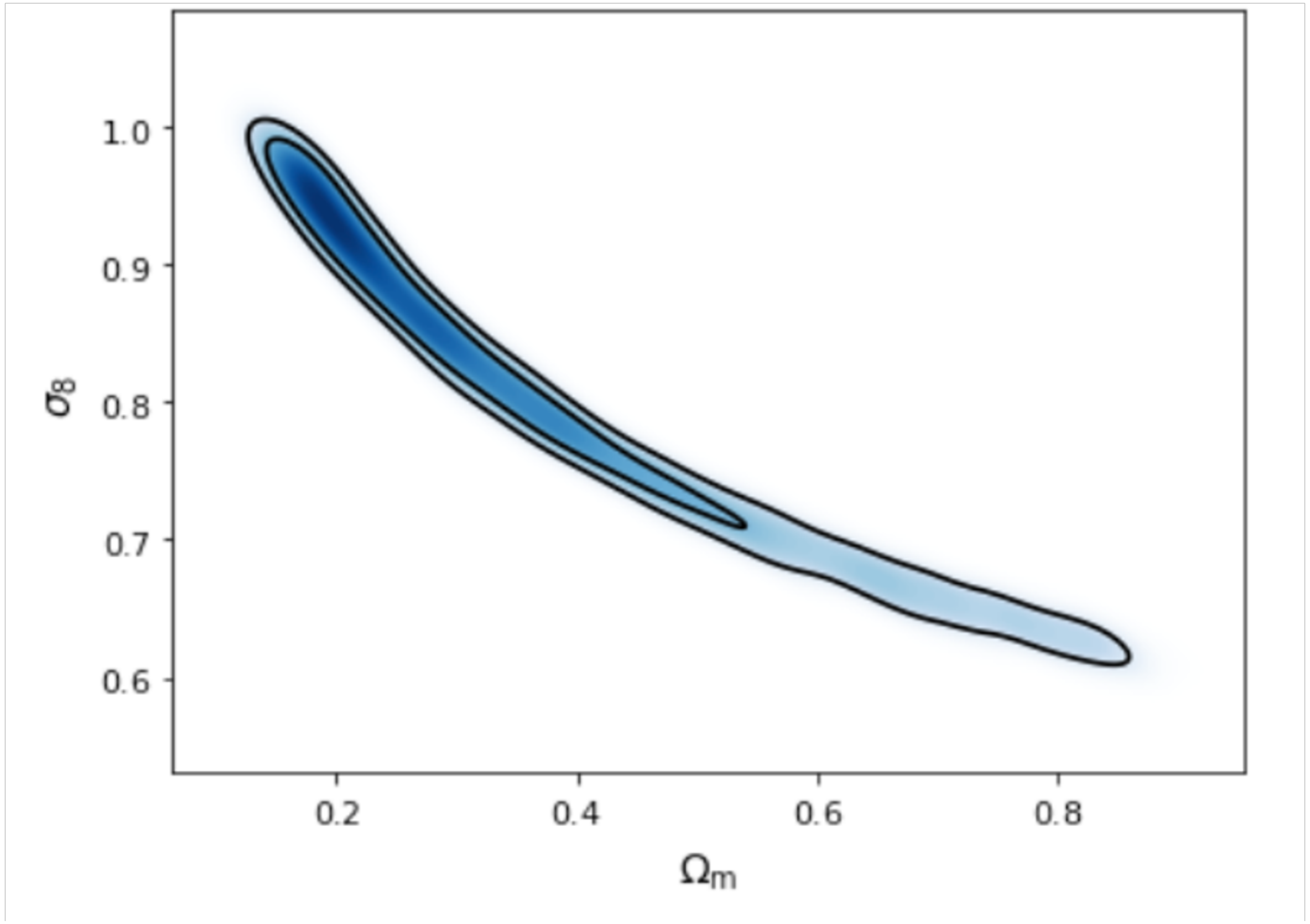


Redshift origin of the signal: mean at z~2, peak at z~1, broad support over extended redshifts z=0.5~6

COSMOLOGICAL PARAMETER DEPENDENCE

- Combination of clumpiness (amplitude of clustering on scales of 8Mpc/h) and the total amount of matter

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



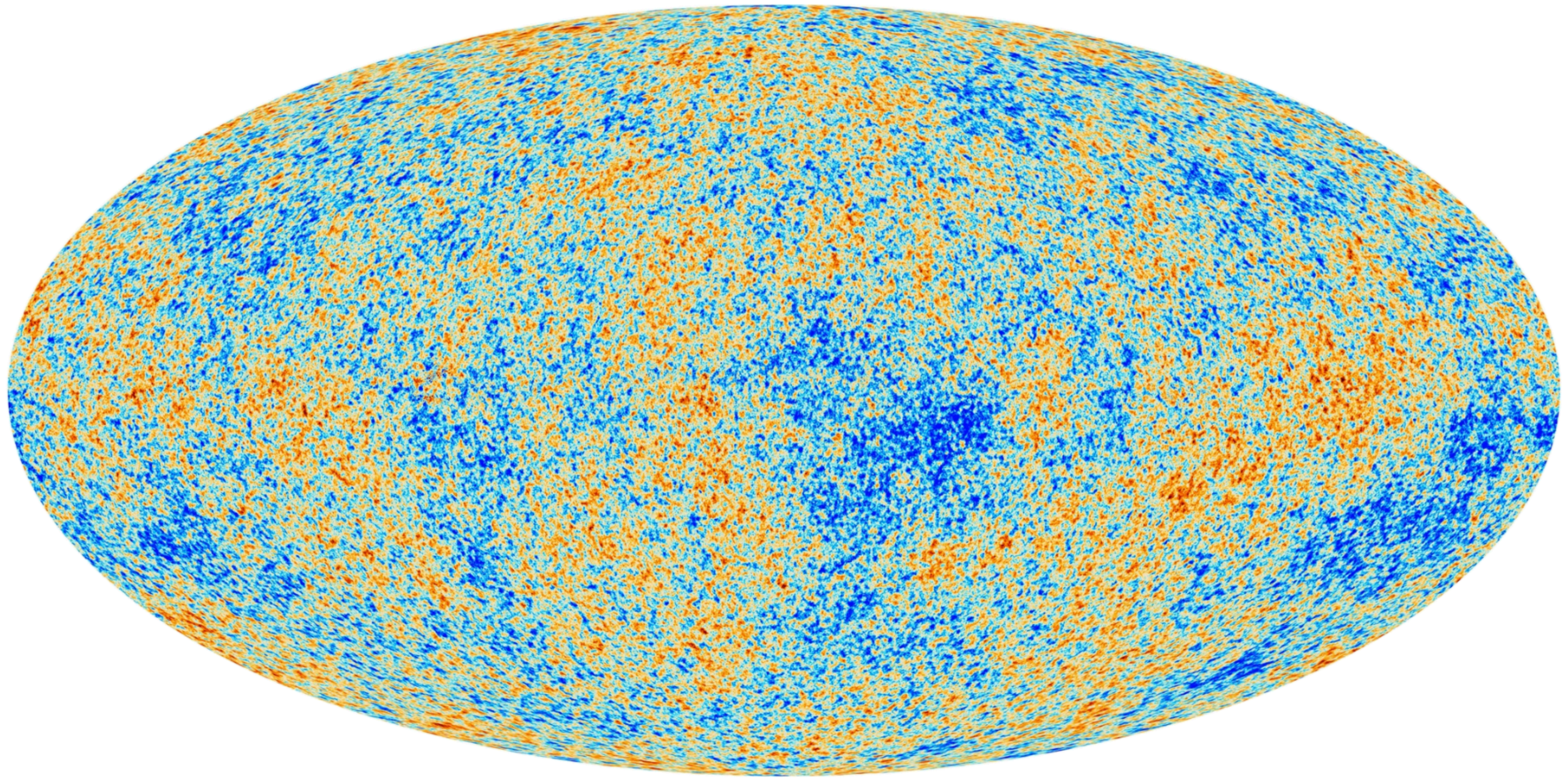
- Neutrino mass sum via power spectrum suppression

MOTIVATION: LENSING MASS MAPS AS TESTS OF STRUCTURE GROWTH

- CMB lensing provide a powerful test of the Standard Cosmological model.
- Do observations match predictions of standard structure growth (dark matter, dark energy and GR)?

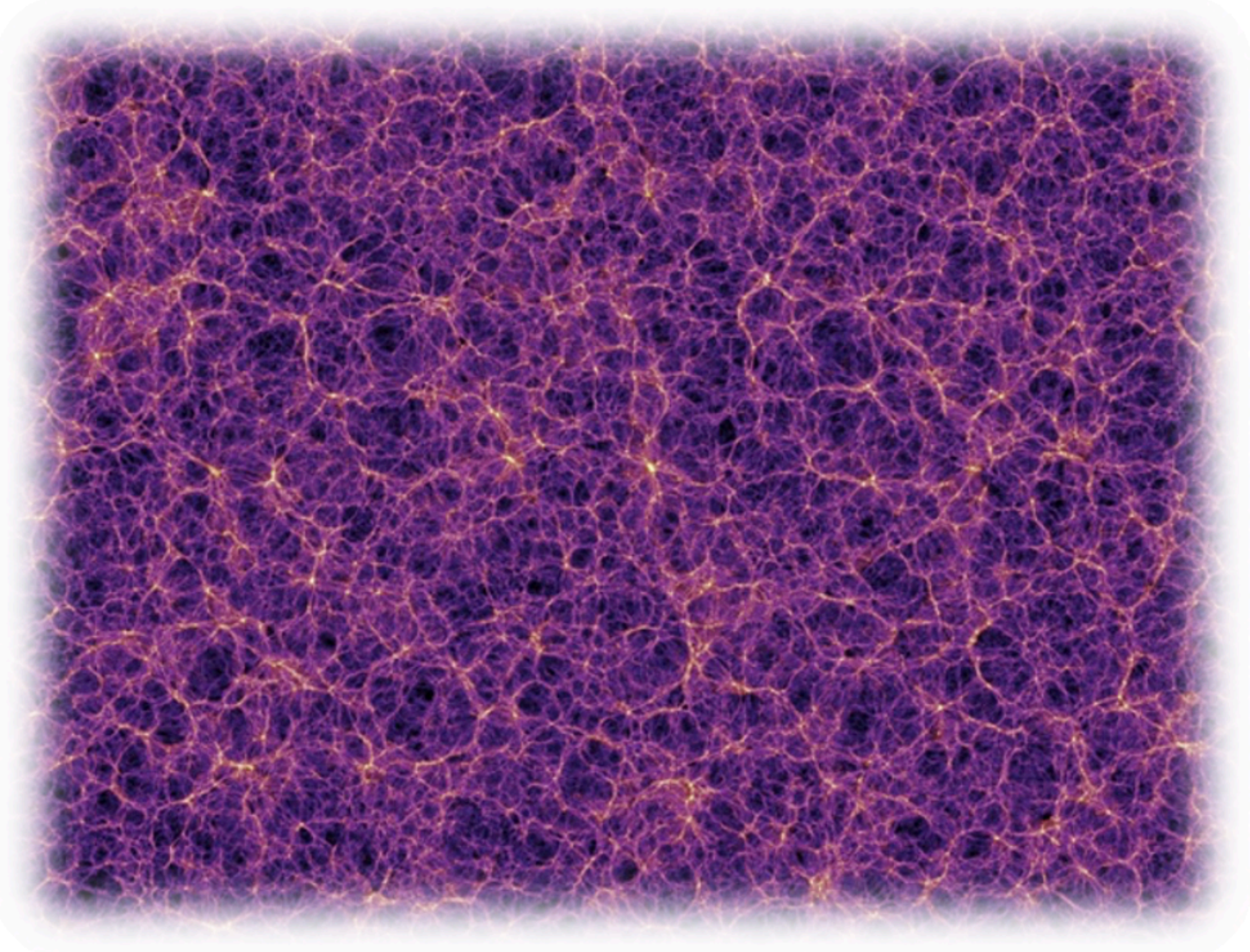
Predict size of structure formation at late times

- Parametrize structure size today with σ_8, RMS of matter density fluctuations smoothed on scales of $8\mathrm{Mpc/h}$



Fit standard cosmological model to the CMB at early times.

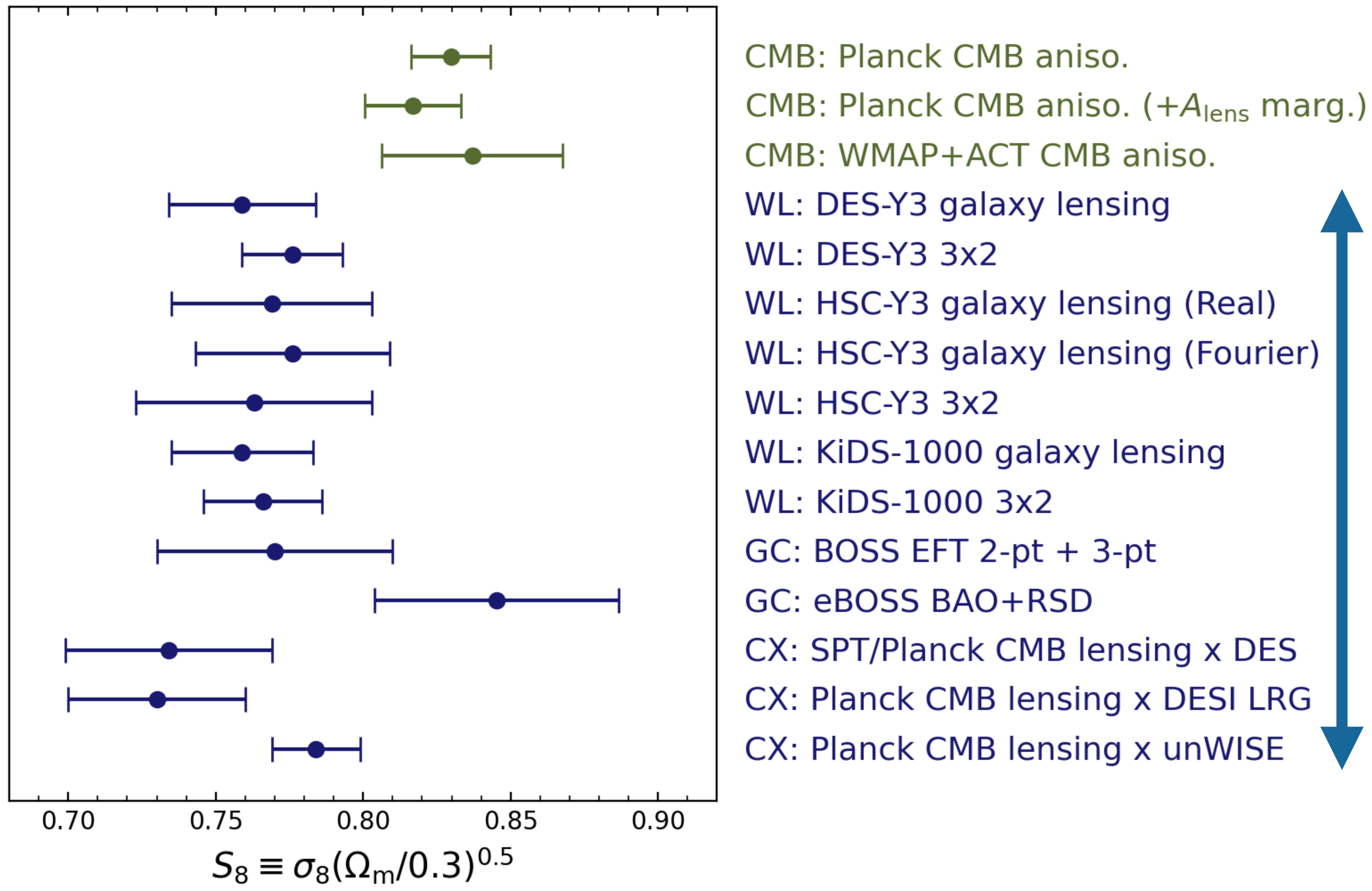
$t = 0.0004\mathrm{Gyr}$



Compare with observations

$t > 1\mathrm{Gyr}$

MOTIVATION : LENSING MASS MAPS AS TESTS OF STRUCTURE GROWTH 'S_8 TENSION'

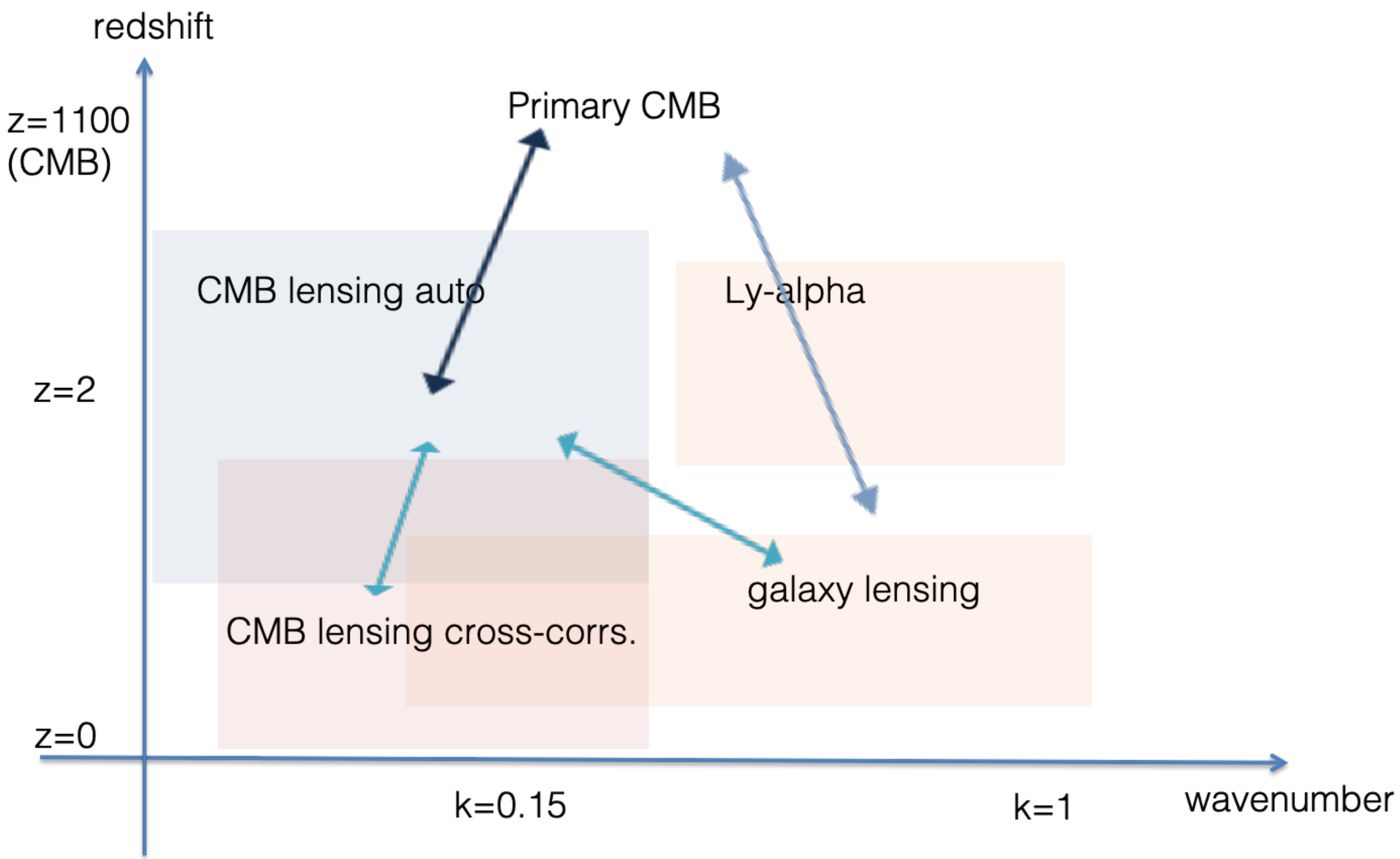


Direct low z measurements from galaxy surveys: 2-3 sigma low in several channels

- We will present ~2% measurements of $\sigma_8\Omega_m^{0.25}$, S_8 and σ_8

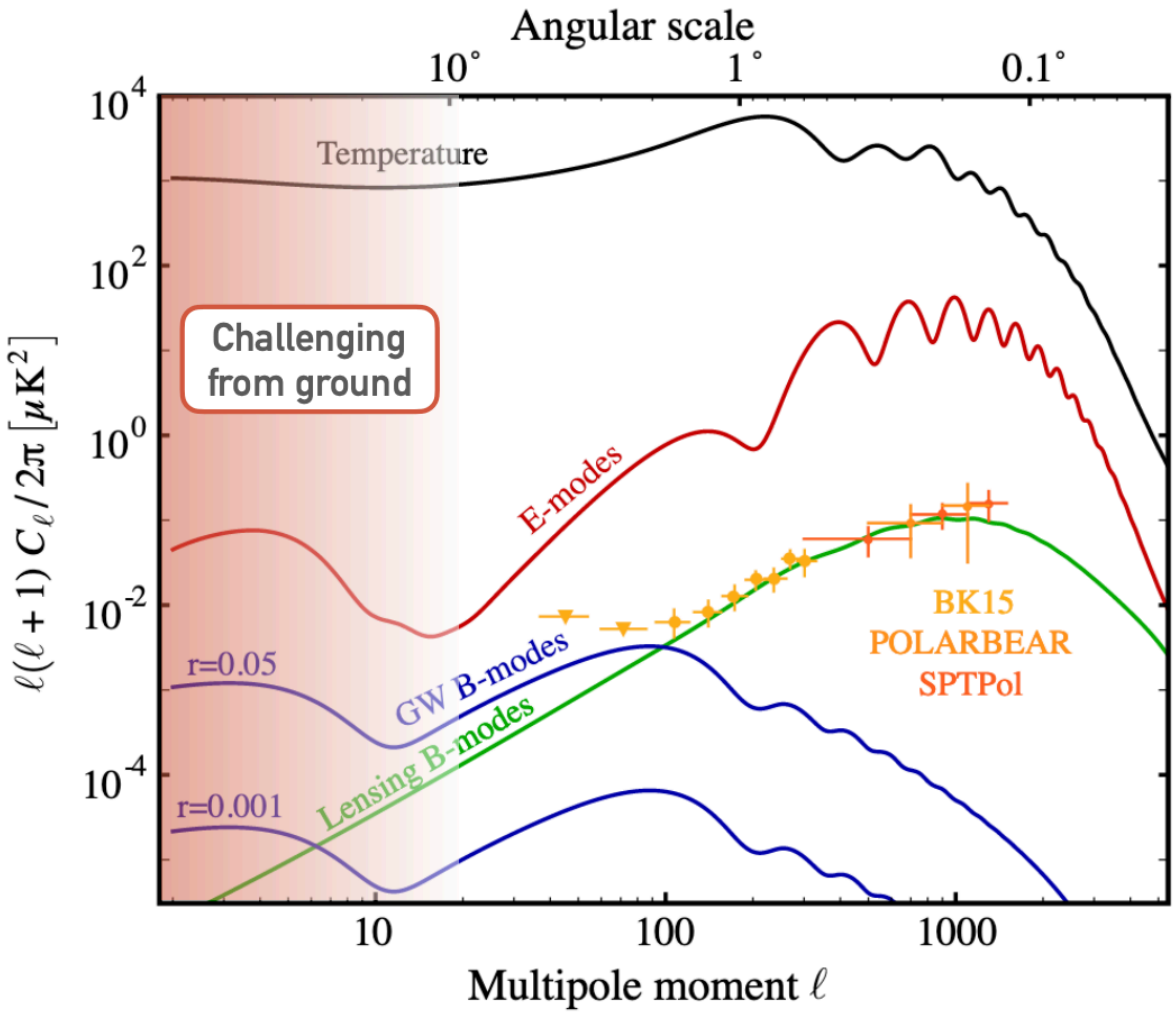
HOW CAN CMB LENSING CLARIFY THE S_8 TENSION?

- Can give insight into systematics and test z/k dependence of any new physics



MOTIVATION: REVEALING INFLATIONARY SIGNAL BY DELENSING

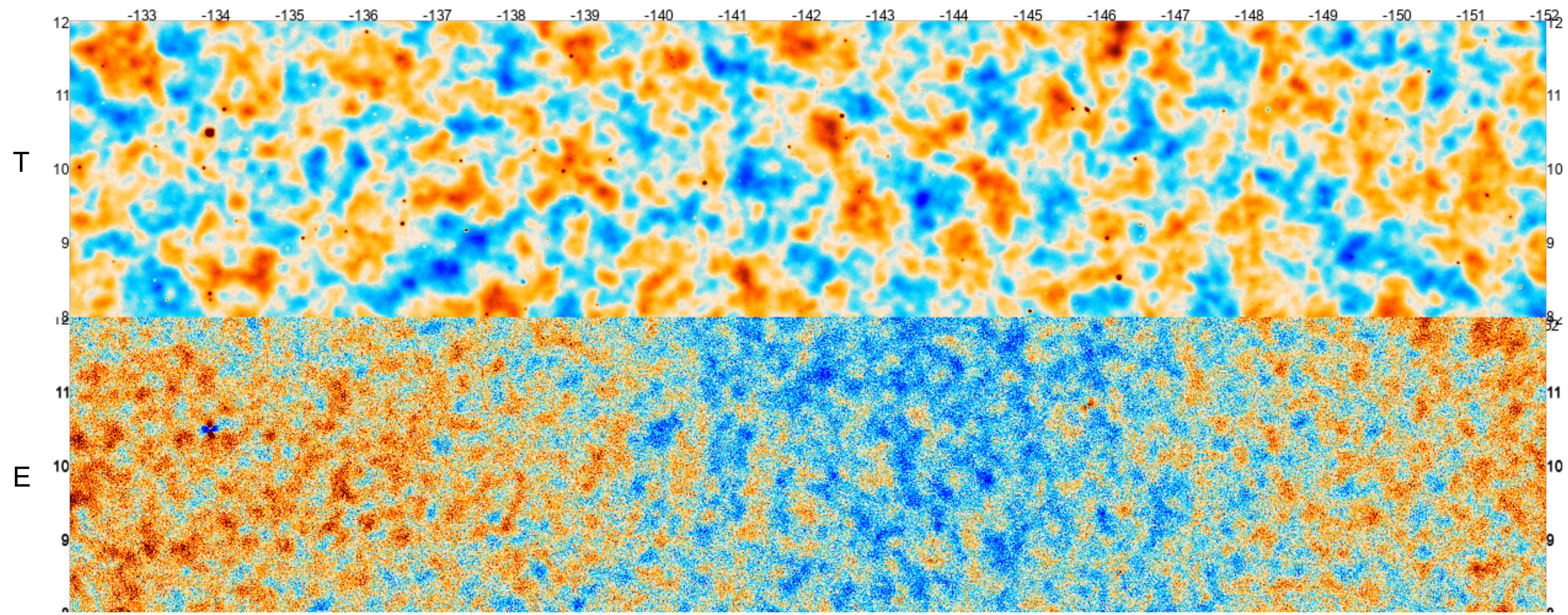
John Kovac's talk



- Lensing converts E modes into B modes.
- Acting as a source of noise for the detection of the primordial B modes.

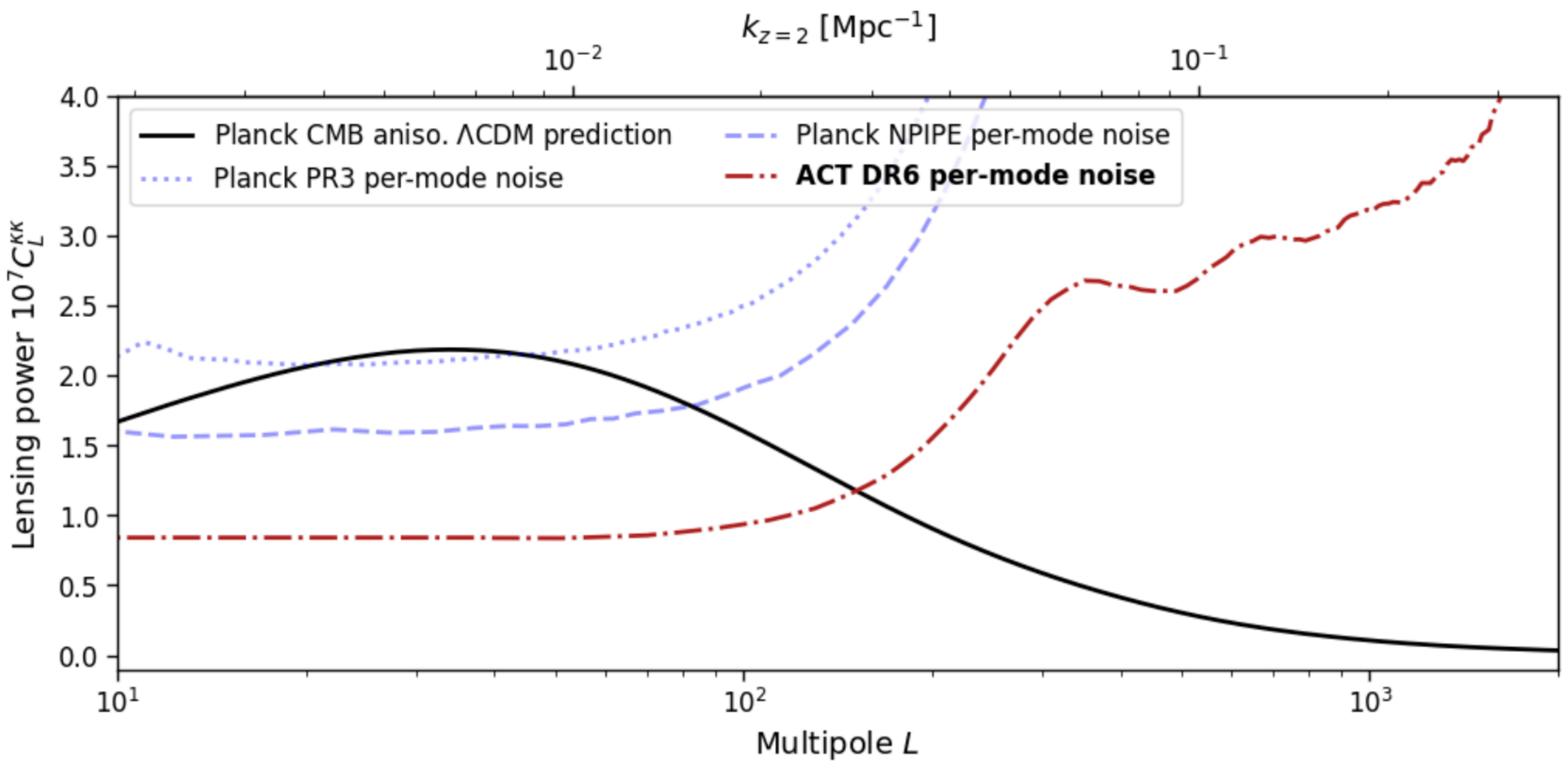
Credit: CMB-S4

ACT DR6 CMB MAPS

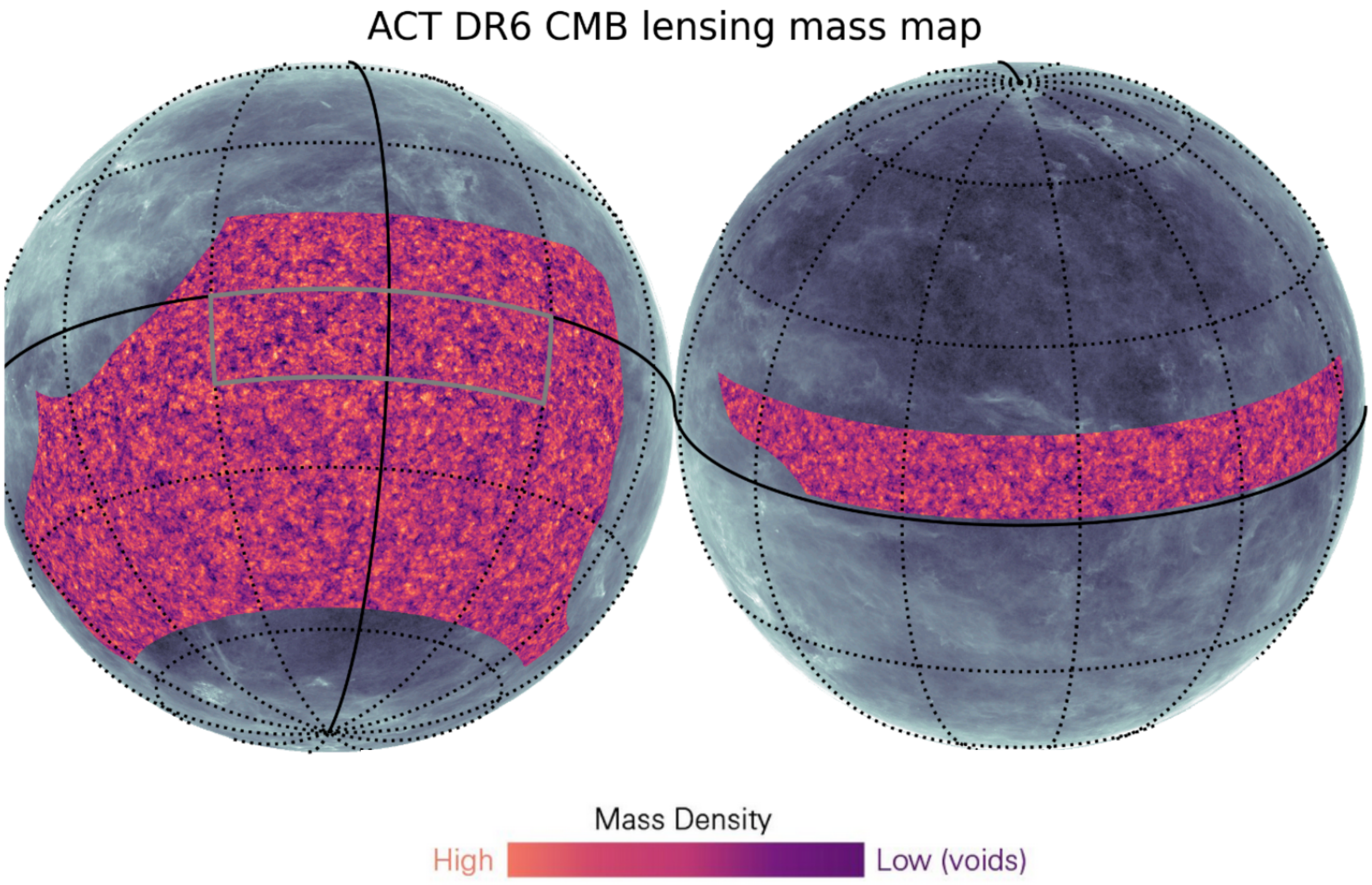


New DR6 AdvACT maps: 15uk 18000 sq degrees

Lensing performance scales with number of high-S/N modes.



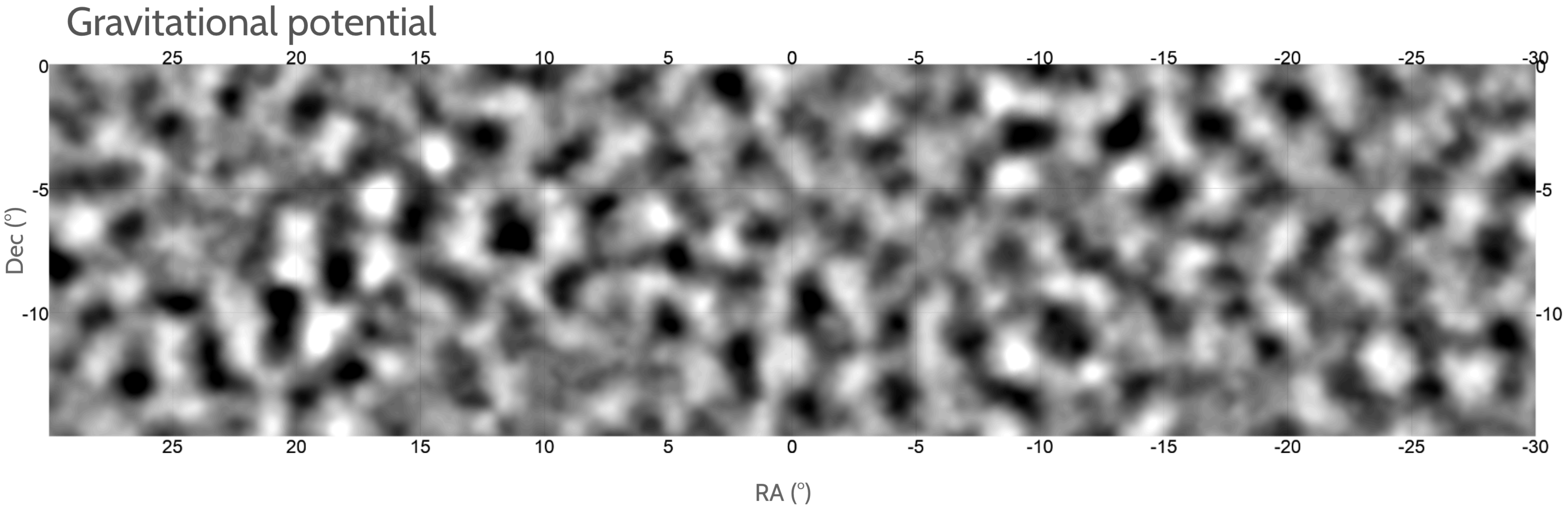
HIGH RESOLUTION CMB LENSING MEASUREMENTS FROM ADVACT



Gravitational Lensing Convergence

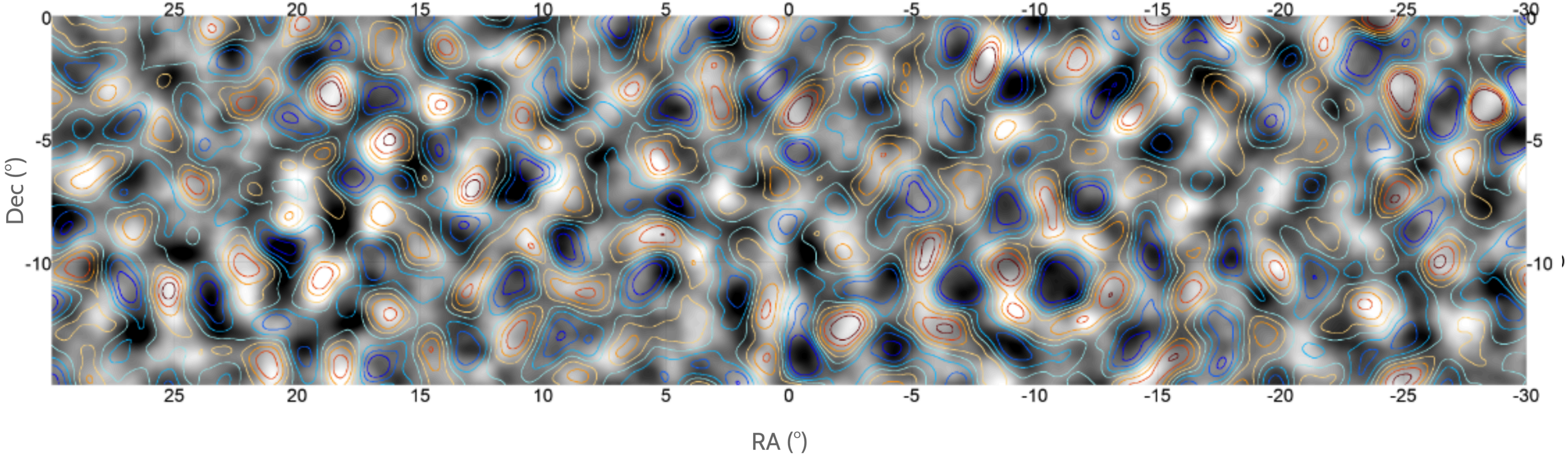
- Signal dominated lensing maps covering a quarter of the sky.
- These are high fidelity-> enabling seeing the dark matter by eye!

ZOOM IN OF 900 SQ. DEG OF THE 9400 SQ. DEG. MASS MAP



ZOOM IN OF 900 SQ. DEG OF THE 9400 SQ. DEG. MASS MAP

Gravitational potential + CIB (contours)



Correlation with dusty galaxies seen by eye

TOWARDS A ROBUST LENSING ANALYSIS

- **Blinded analysis with 200 null tests.**

MAIN CHALLENGES

- Noise bias subtraction for ground based CMB measurements.
- **Extragalactic foregrounds**

BLINDED ANALYSIS FRAMEWORK WITH EXTENSIVE NULL TEST SUITE

- DR6 lensing analysis follows blinded analysis procedure.
- DR6 dataset allows rigorous check for consistency and presence of systematics.

200 null tests broadly divided into the following categories:

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

CHALLENGE:

CONTAMINATION FROM EXTRA-GALACTIC FOREGROUNDS

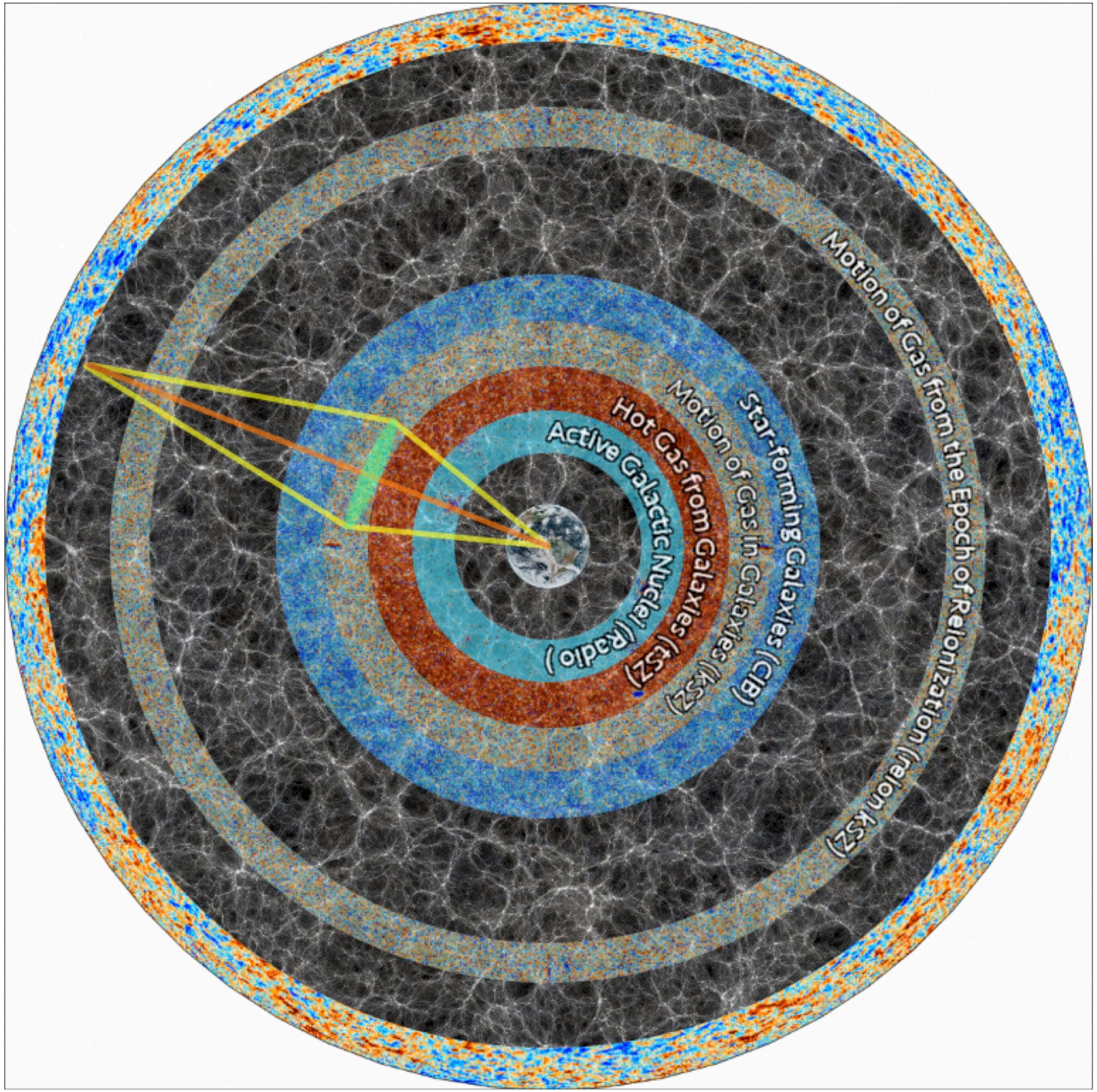
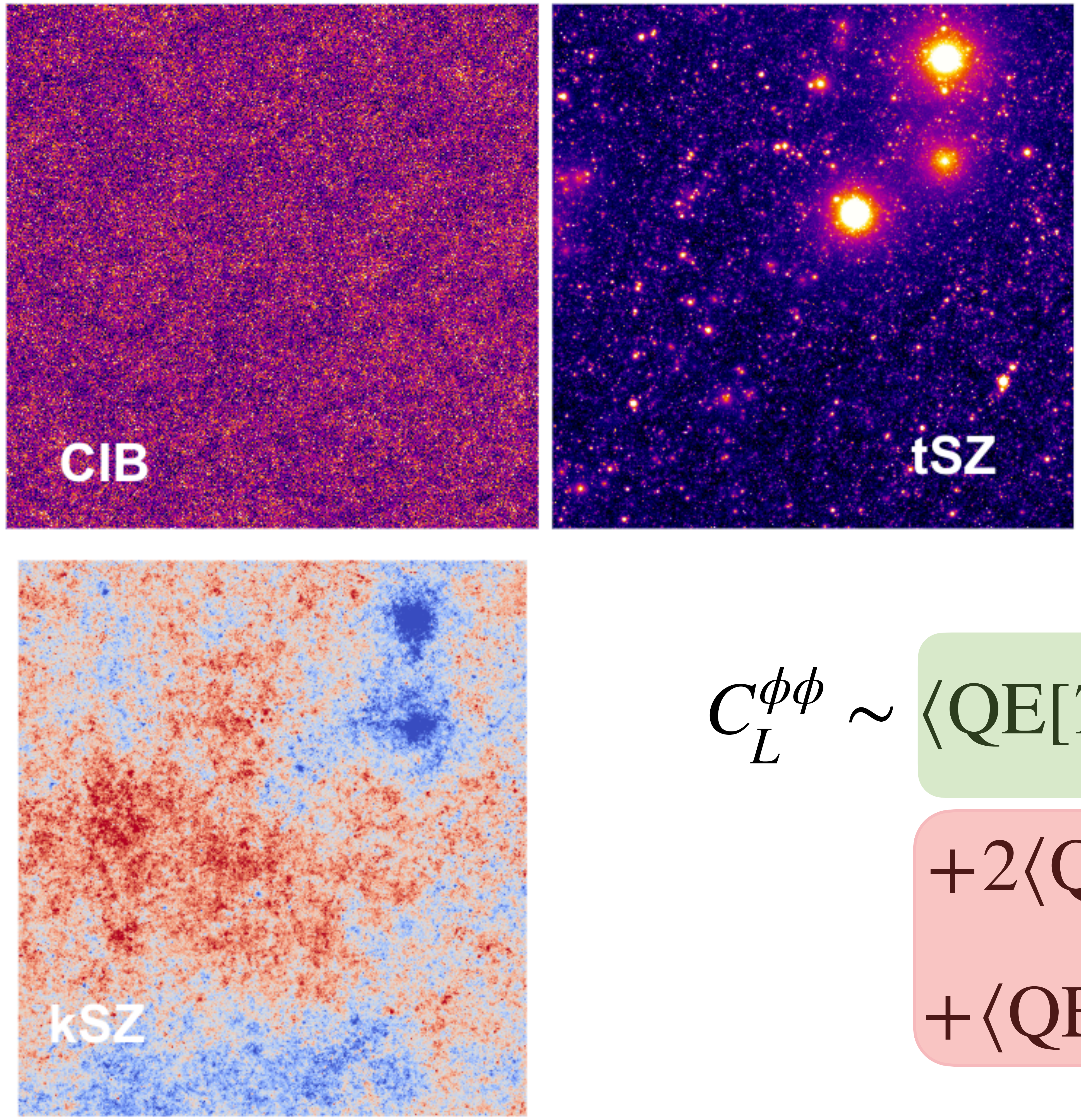


image credit: Dongwon Han

Challenge: Biases From Extragalactic foregrounds



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

$$T = T_{\mathrm{CMB}} + f$$

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

Lensing signal

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

$$+\langle \mathrm{QE}[f,f]\mathrm{QE}[f,f] \rangle$$

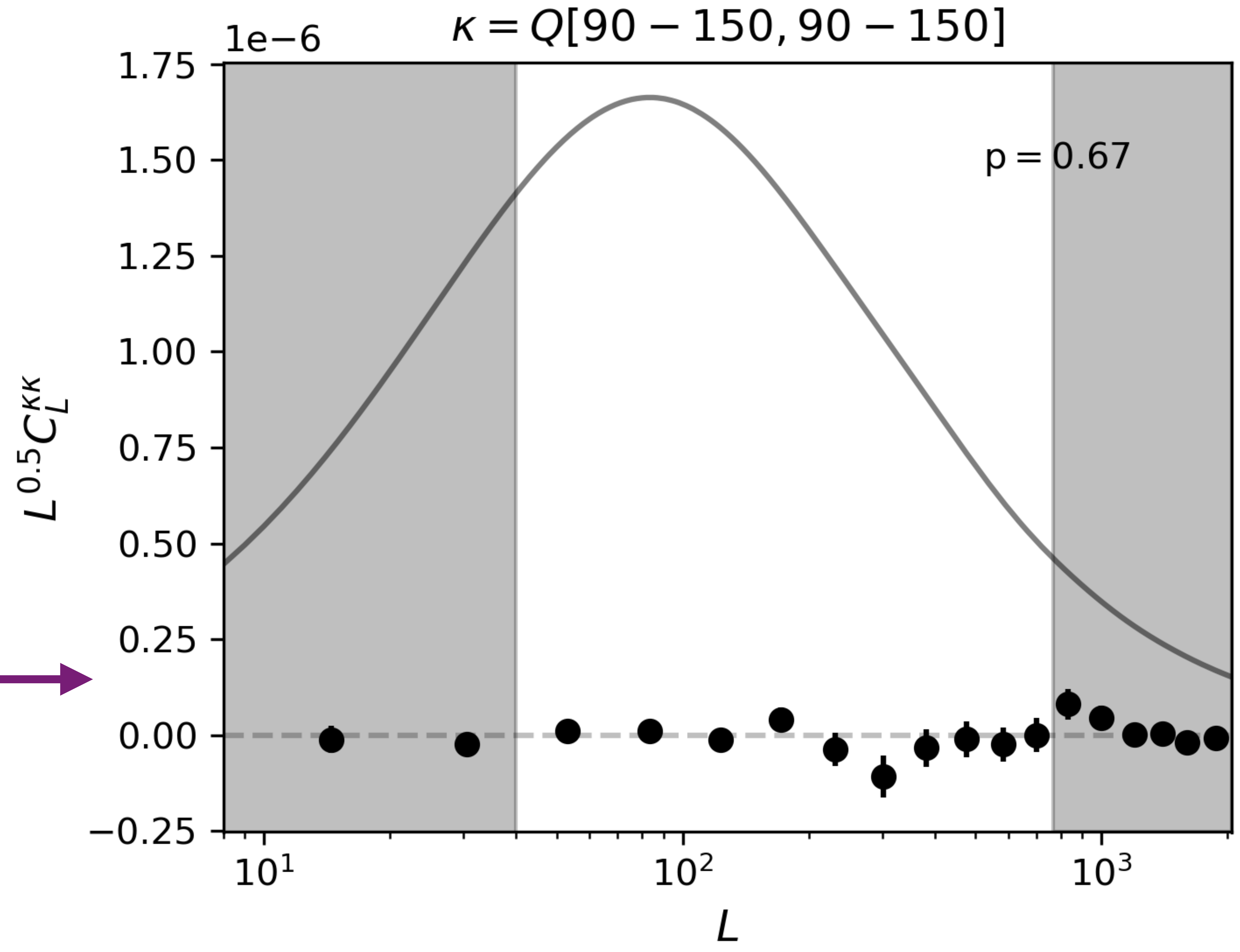
Foreground induced biases

Control on galactic foregrounds: Three pronged approach

1. Simulation tests using two independent sims. (Websky and Seghal)

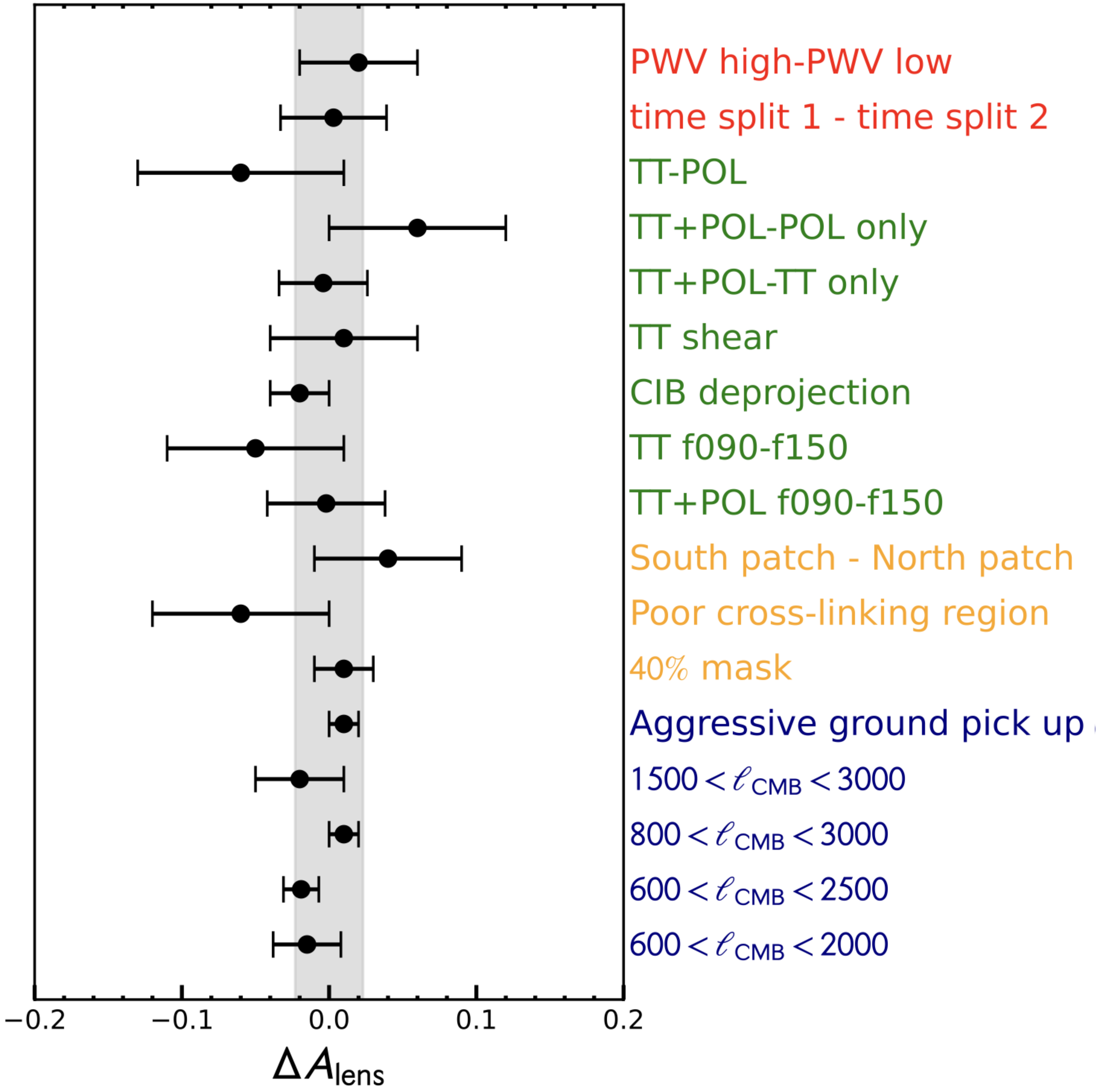
2. Consistency of results from **profile hardening** and other foreground mitigation methods. (CIB-deprojection, shear)

3. Data driven null tests - **no evidence for biases.**



NULL TESTS NOW PASSES! STABILITY OF THE LENSING SPECTRUM

Consistent amplitude of lensing spectrum $A_{\rm lens}$ ……



Difference in Amplitude of lensing

at different times

in polarization

w. different foreground cleaning

at different frequencies

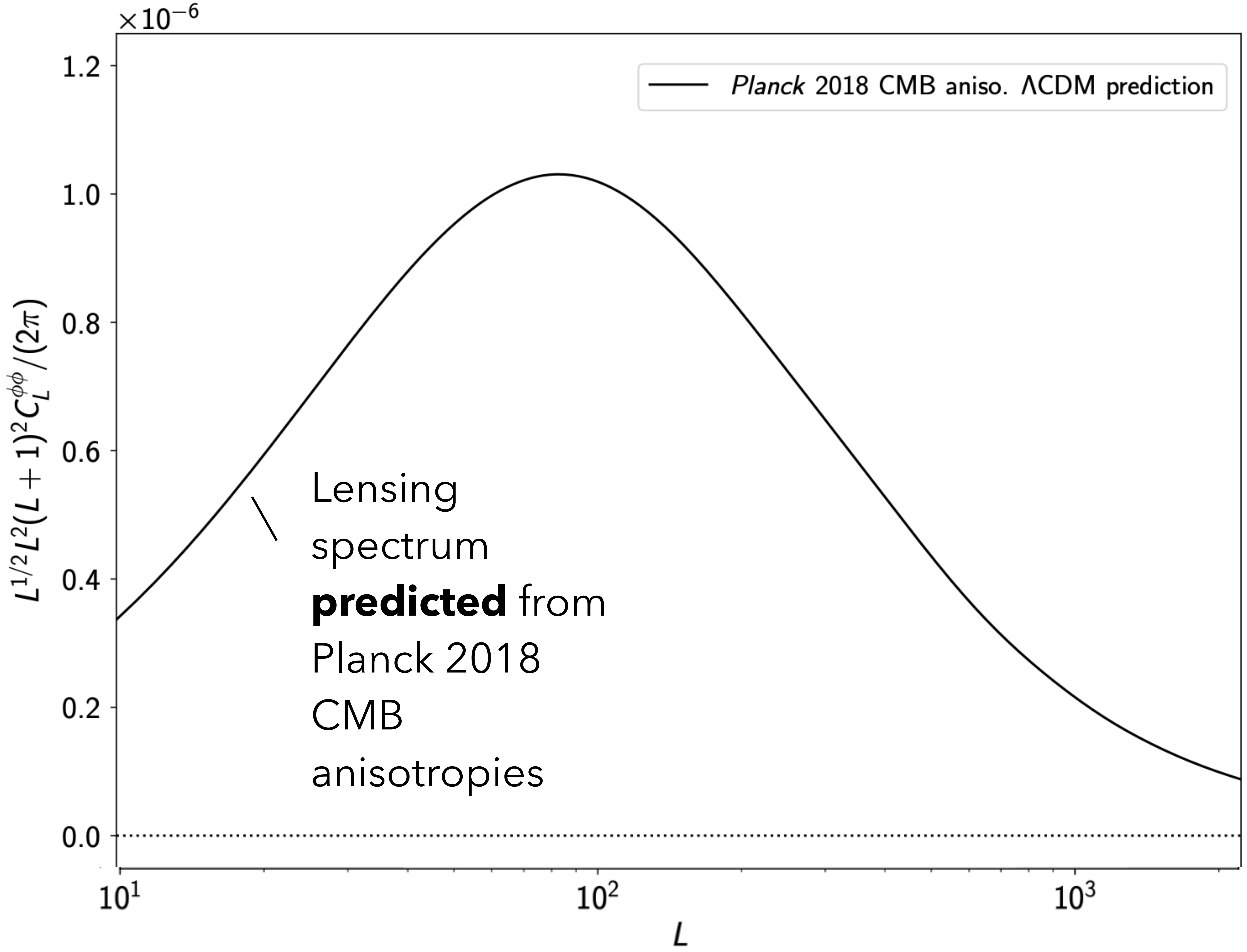
in different parts of sky

on different scales

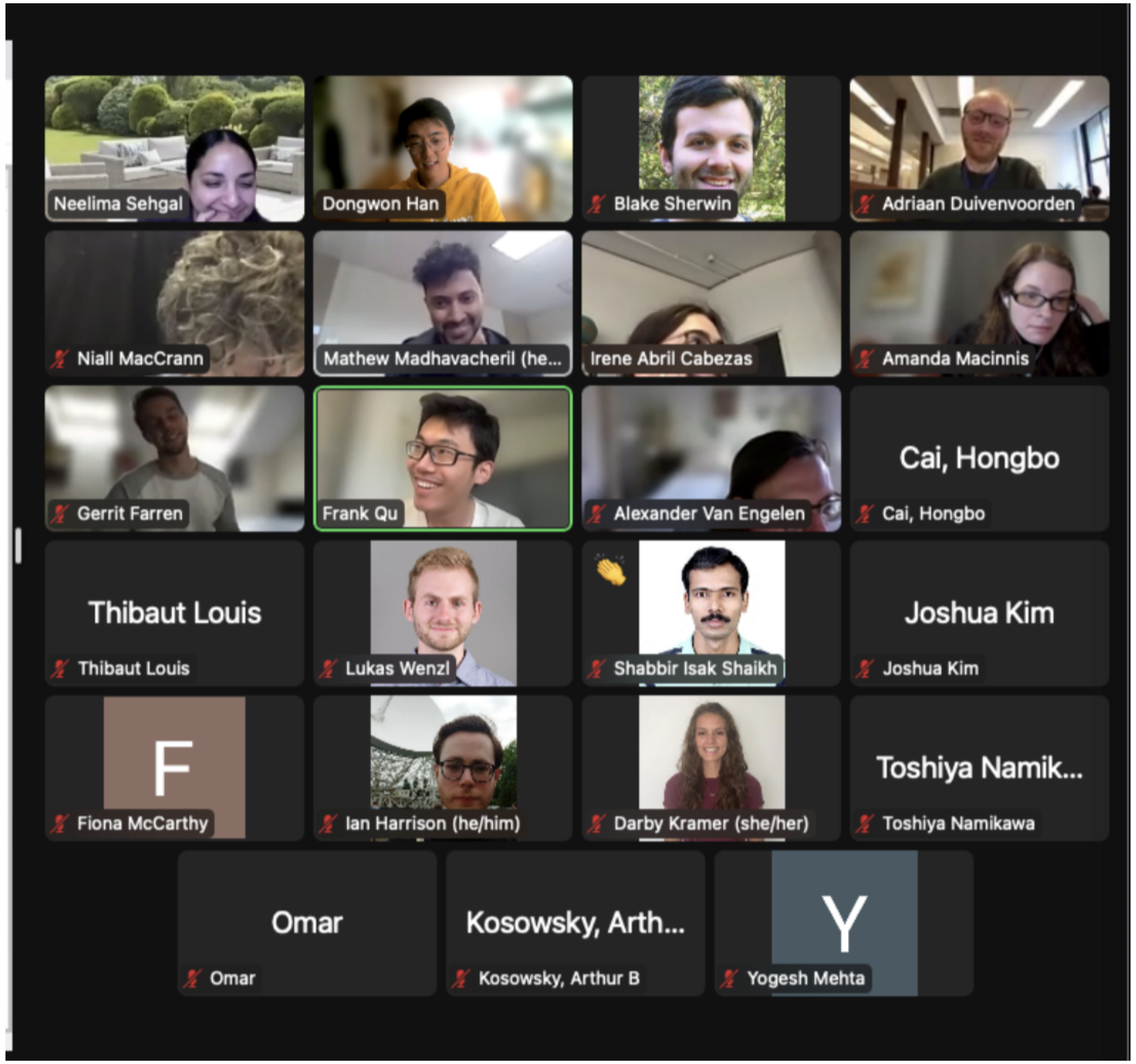
+… many more tests!

CMB LENSING POWER SPECTRUM: RESULTS AND IMPLICATIONS

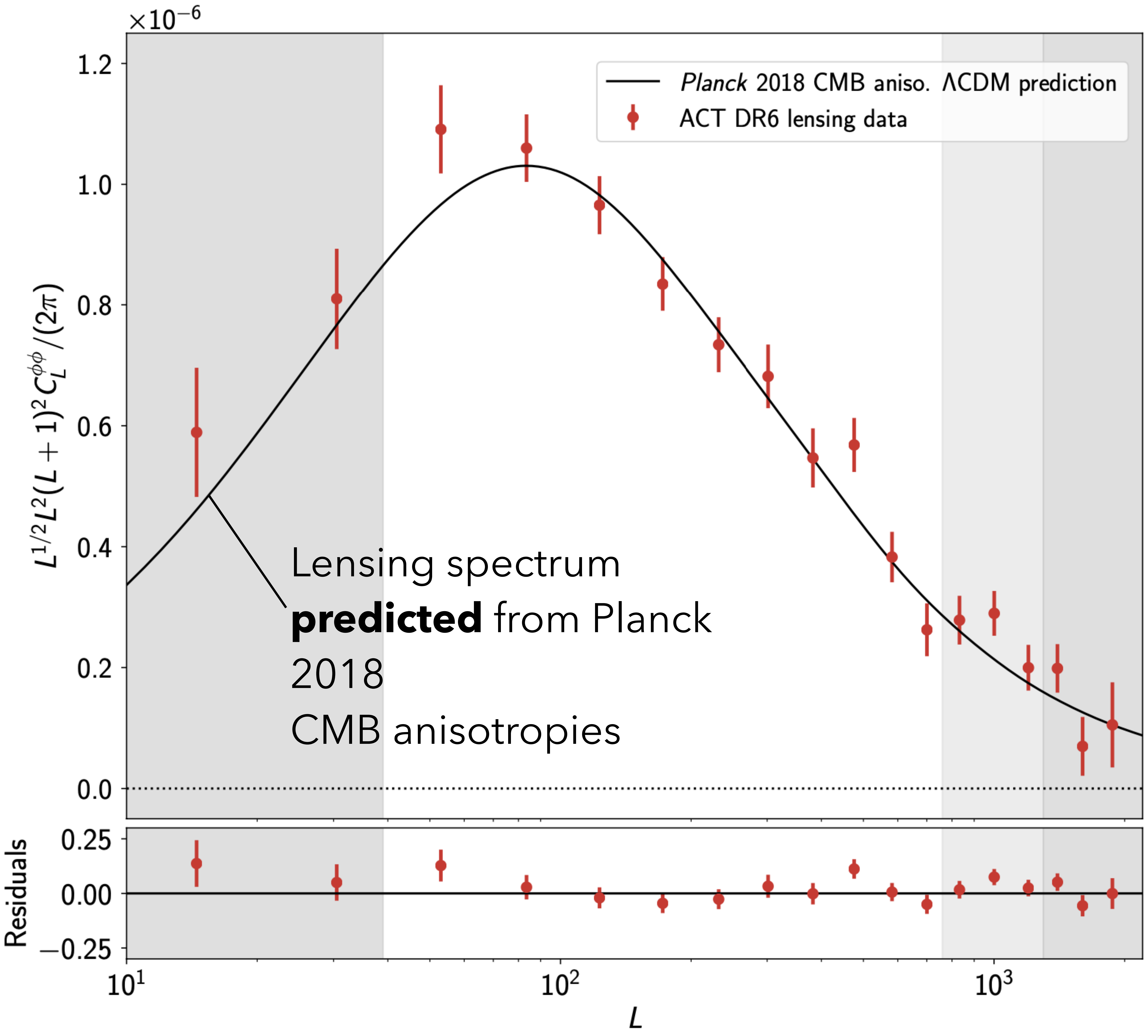
PLANCK CMB ANISOTROPY PREDICTION



Lensing spectrum **predicted** from Planck 2018 CMB anisotropies



UNBLINDED RESULTS: ACT DR6 LENSING POWER SPECTRUM



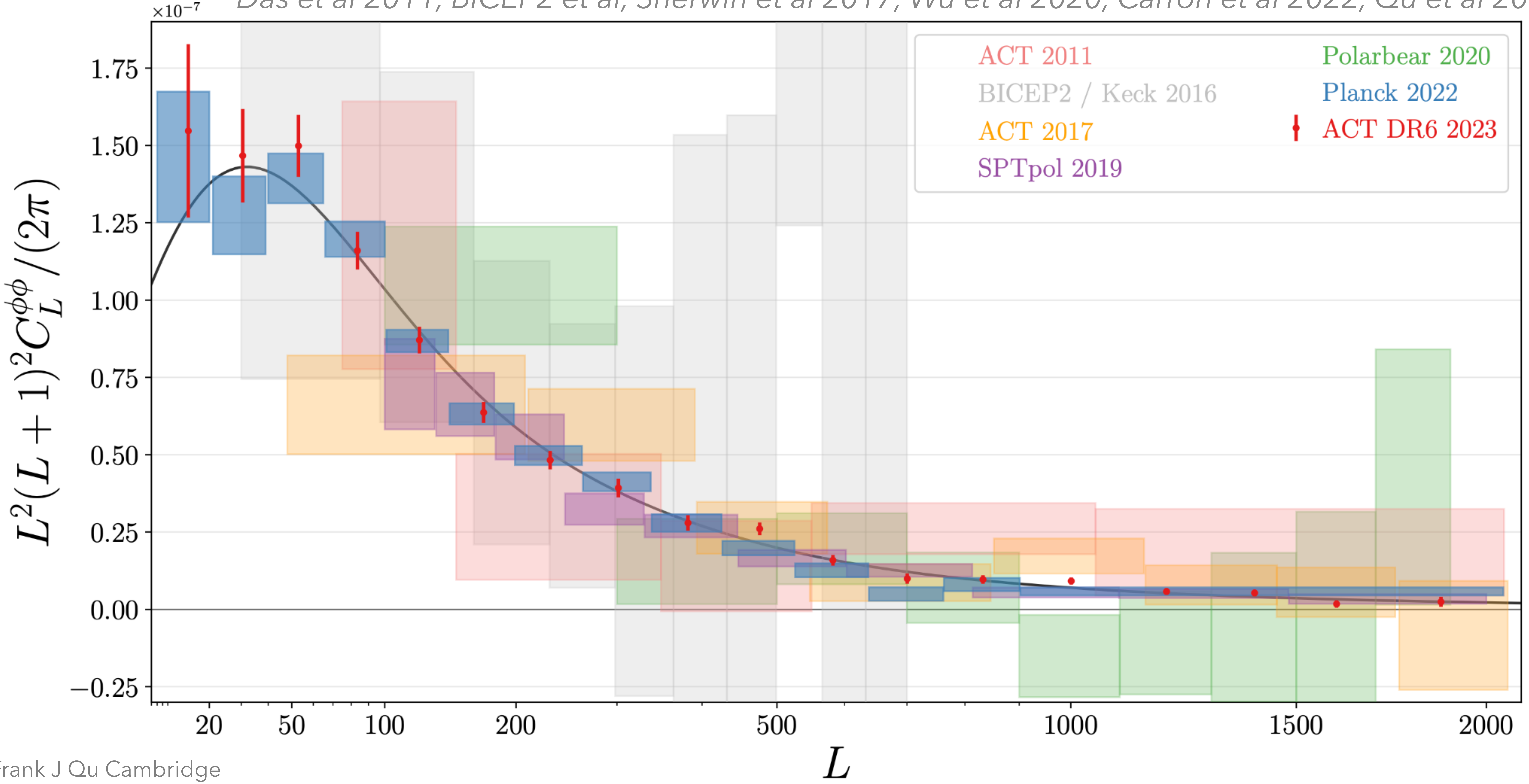
- Excellent agreement of our measurement (with no free parameters) with the LCDM theory predictions based on *Planck* 2018 CMB power spectra. A PTE of 0.17
- Amplitude of lensing (relative to theory amplitude) determined to 2.3%

$$A_{\rm lens} = 1.013 \pm 0.023$$

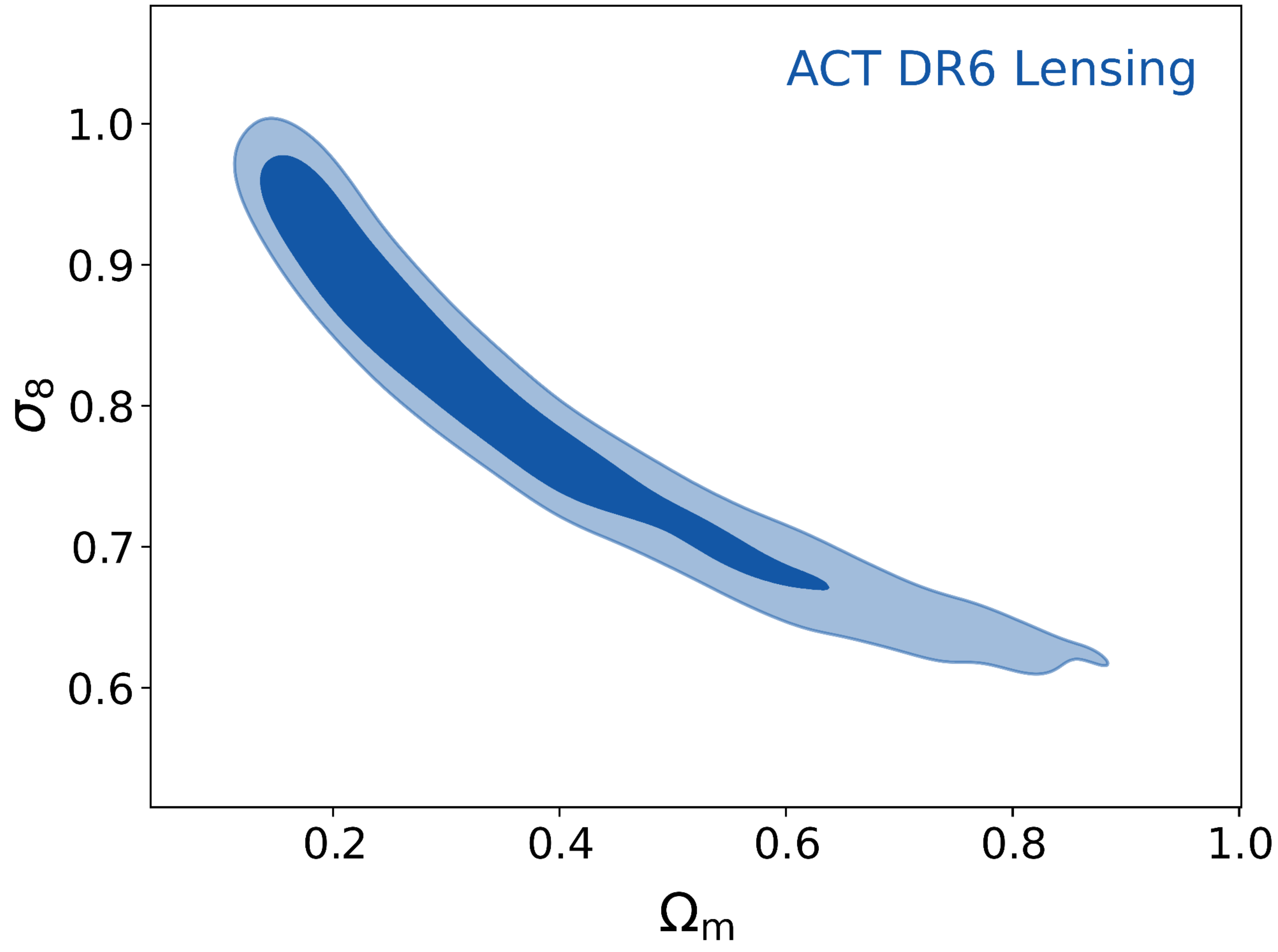
- SNR of 43

PUTTING OUR MEASUREMENT IN CONTEXT

Das et al 2011, BICEP2 et al, Sherwin et al 2017, Wu et al 2020, Carron et al 2022, Qu et al 2023



COSMOLOGY FROM DR6 CMB LENSING

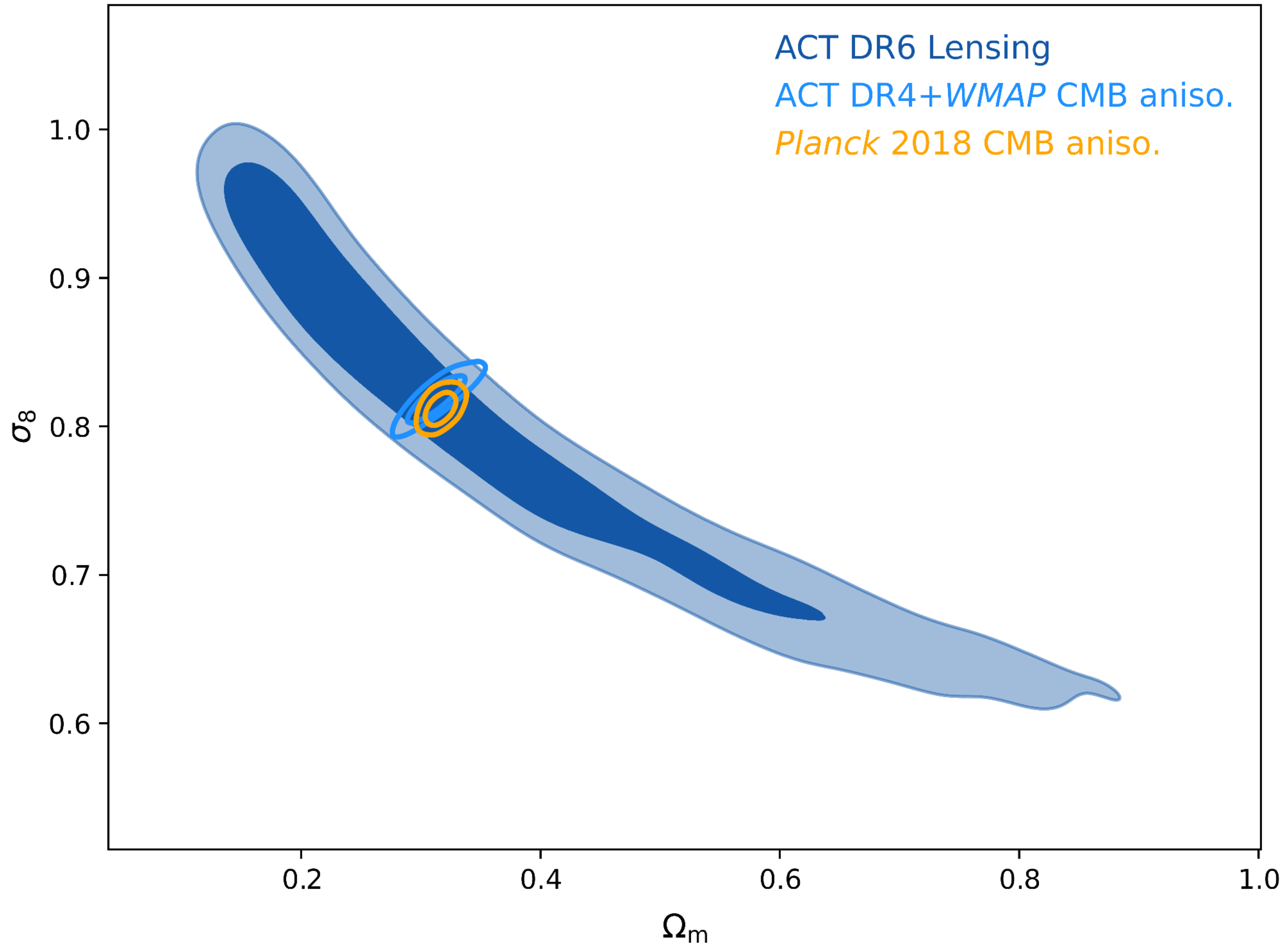


$$S_8^{\mathrm{CMBL}} \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.25}$$

$$S_8^{\mathrm{CMBL}} = 0.818 \pm 0.022$$

2.7 % measurement

EXCELLENT AGREEMENT WITH PREDICTION FROM CMB POWER SPECTRA–OUR LENSING IS NOT LOW



$$S_8^{\rm CMBL} \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.25}$$

$$S_8^{\rm CMBL} = 0.818 \pm 0.022$$

Early time CMB predictions

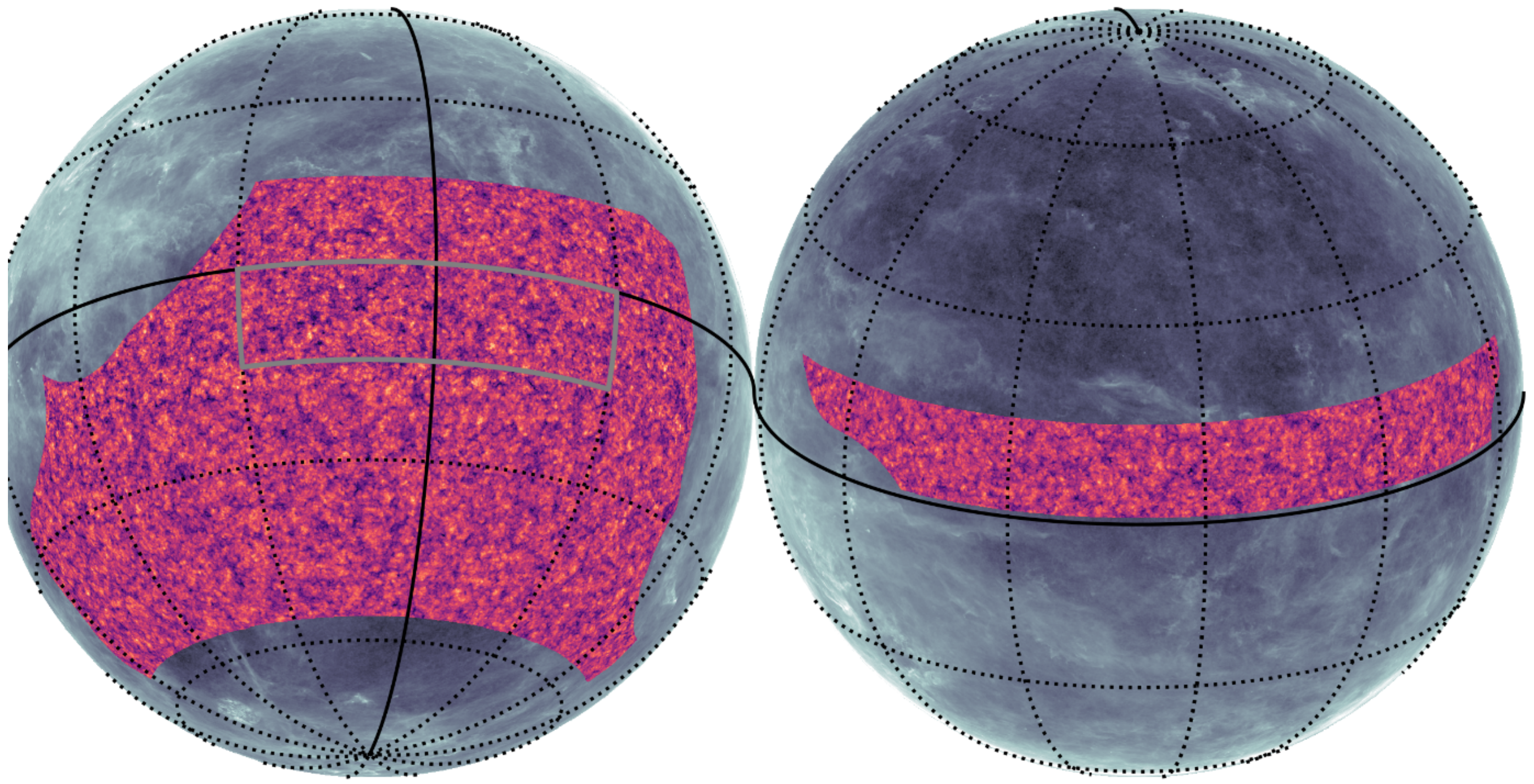
ACT DR4 + *WMAP* CMB aniso.

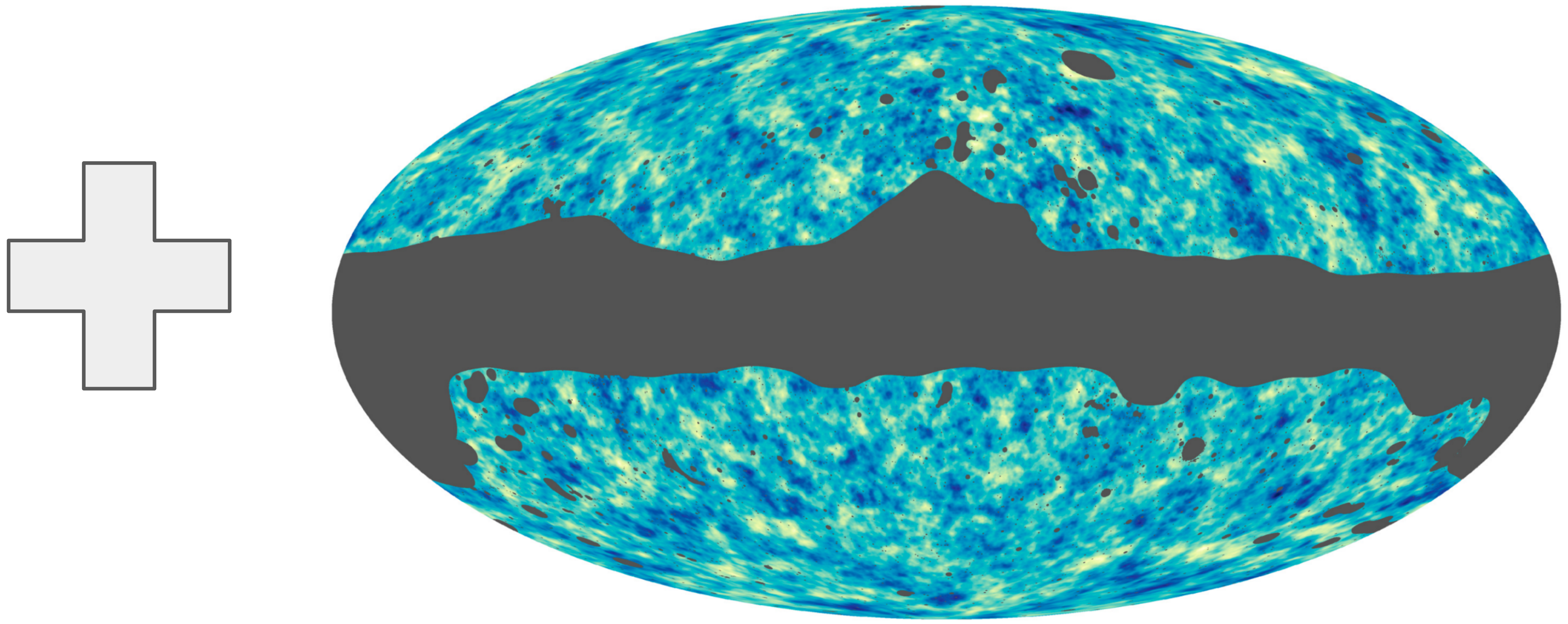
$$S_8^{\rm CMBL} = 0.828 \pm 0.020$$

Planck 2018 CMB aniso.

$$S_8^{\rm CMBL} = 0.823 \pm 0.011$$

ACT+PLANCK COMBINATION: TOWARDS THE MOST PRECISE CMB LENSING MEASUREMENT TO DATE

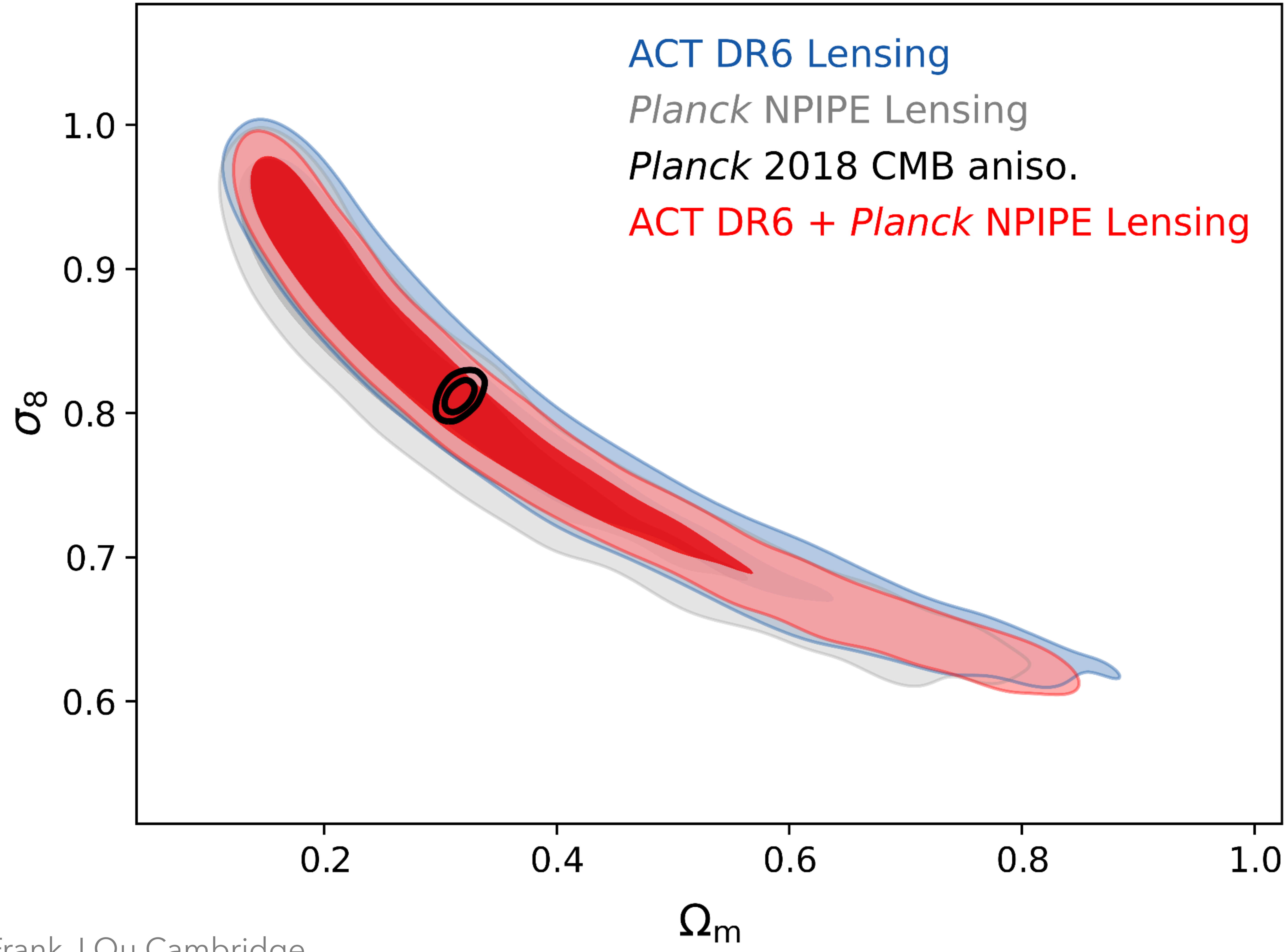




Planck lensing map

- ACT lensing and *Planck* lensing maps have significantly independent information.
  - different noise and instrument related systematics.
  - different sky overlap.
  - different angular scales.

CONSTRAINT FROM ACT LENSING AND PLANCK NPIPE LENSING JOINT LIKELIHOOD

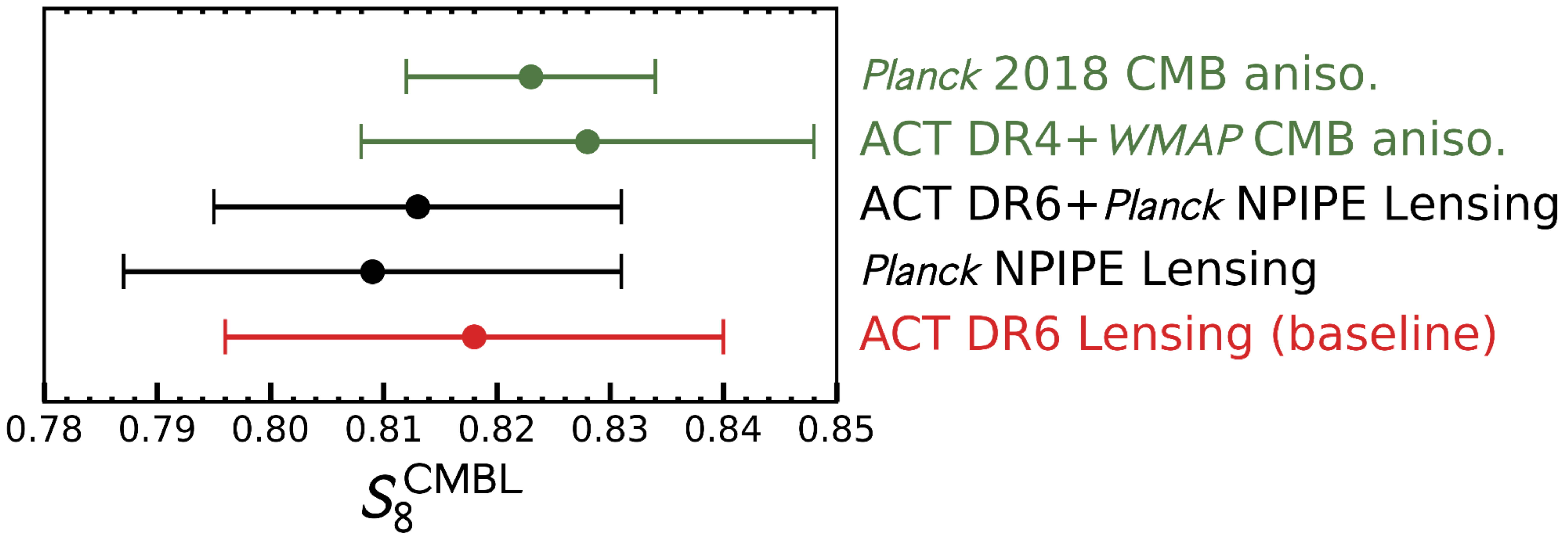


ACT+NPIPE constraint:

$$S_8^{\mathrm{CMBL}} = 0.813 \pm 0.018$$

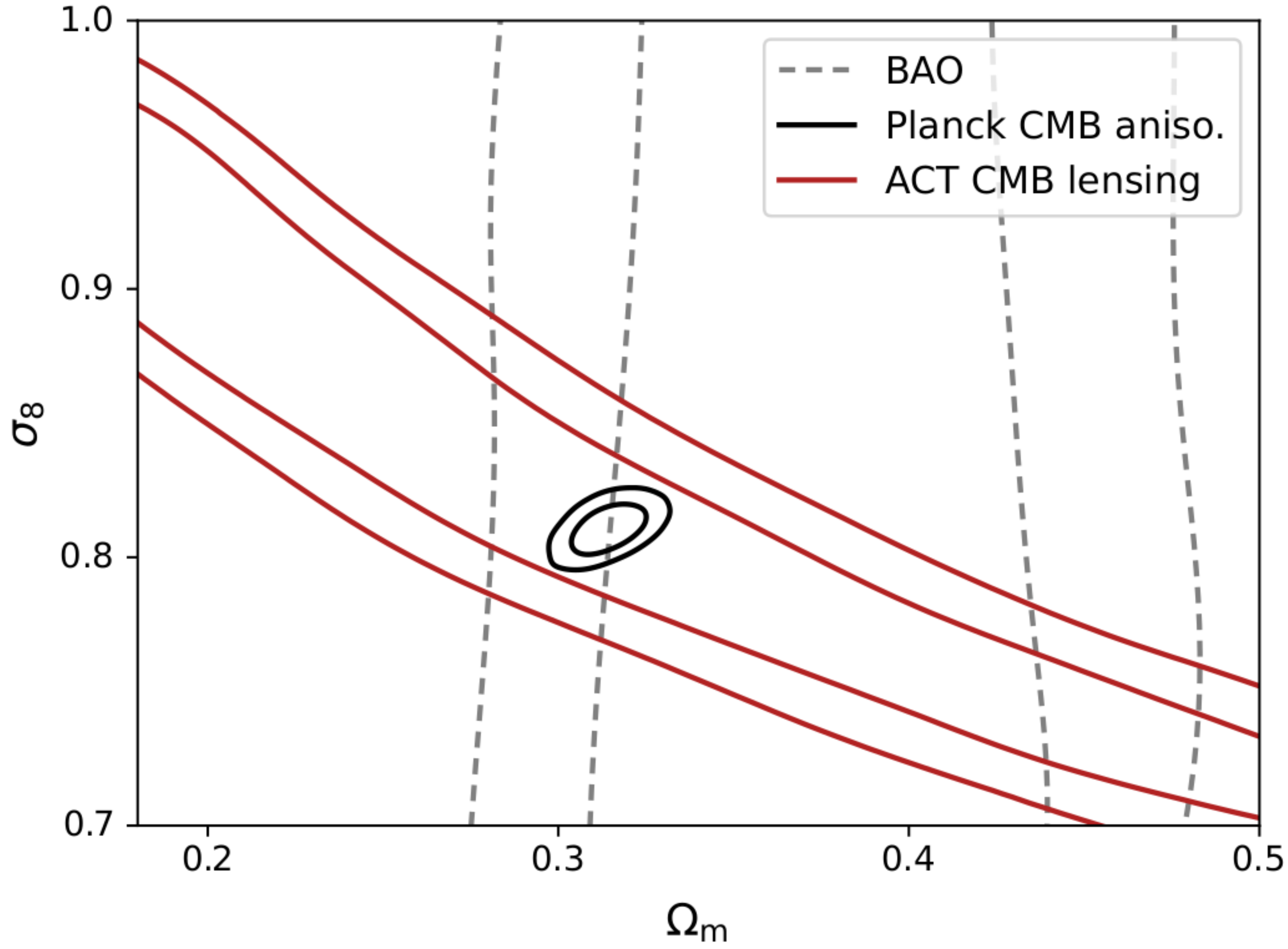
2.2% constraint from single weak lensing observable alone

DR6 CMB LENSING SPECTRUM + PLANCK COMBINATION: IMPLICATIONS



- A success for LCDM: fit Planck CMB at z~1100, predict structure to low-z, predict lensing signal arising over a wide range of z and trispectrum in ACT – agrees to 2%. Signal is not low!
- Agreement with Planck lensing + CMB – no evidence for Planck systematics
- Disfavours new physics explanations that change structure growth at high z (z>1) and low k.

DR6 CMB LENSING + BAO

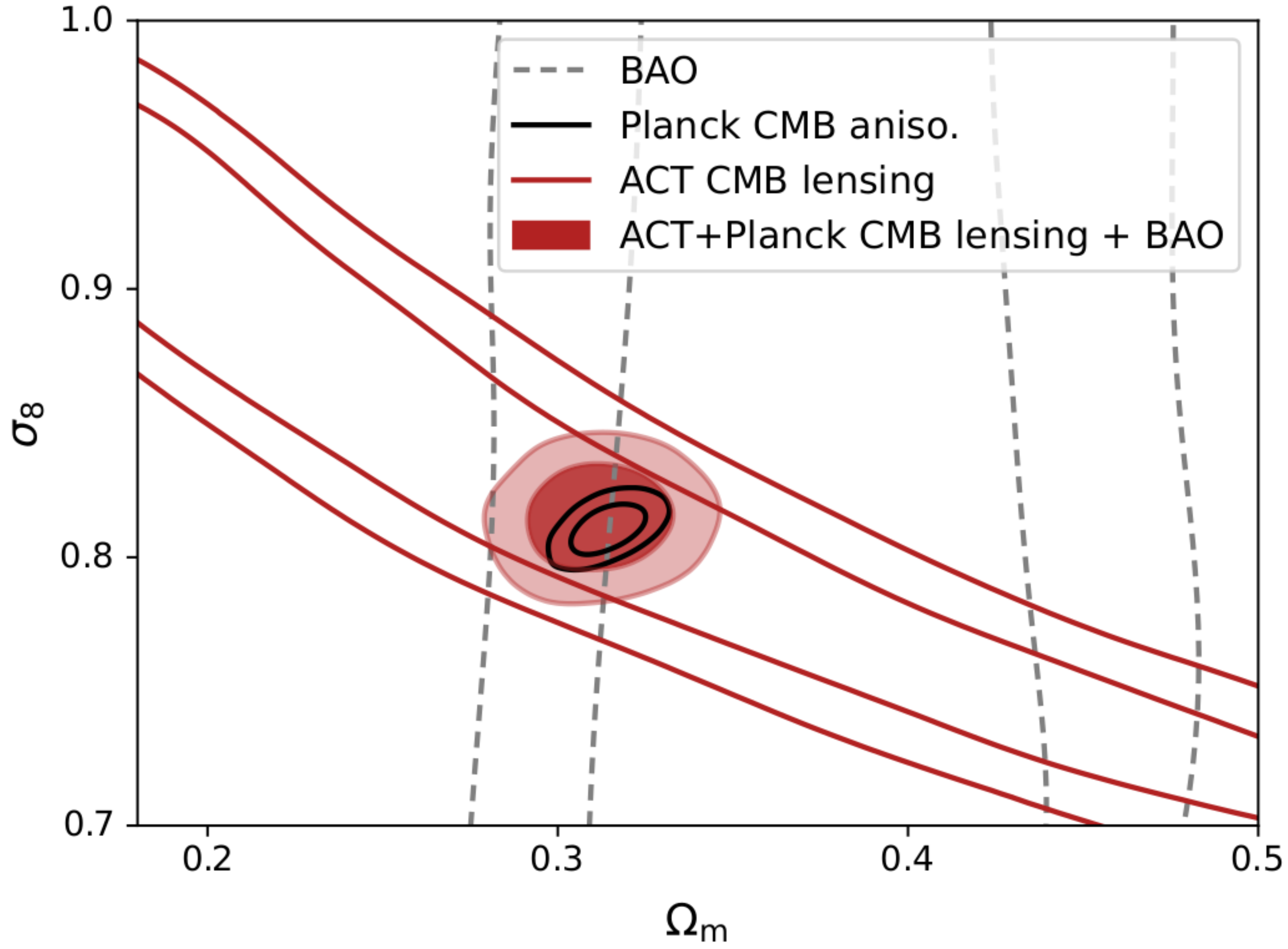


CMB lensing alone measures $\sigma_8\,\Omega_m^{0.25}$

Combination with BAO* isolates σ_8

*BAO data set includes 6df, SDSS MGS, BOSS and eBOSS LRGs

DR6 + PLANCK CMB LENSING + BAO



CMB lensing alone measures $\sigma_8 \Omega_m^{0.25}$

Combination with BAO isolates σ_8

$$\sigma_8 = 0.812 \pm 0.013$$

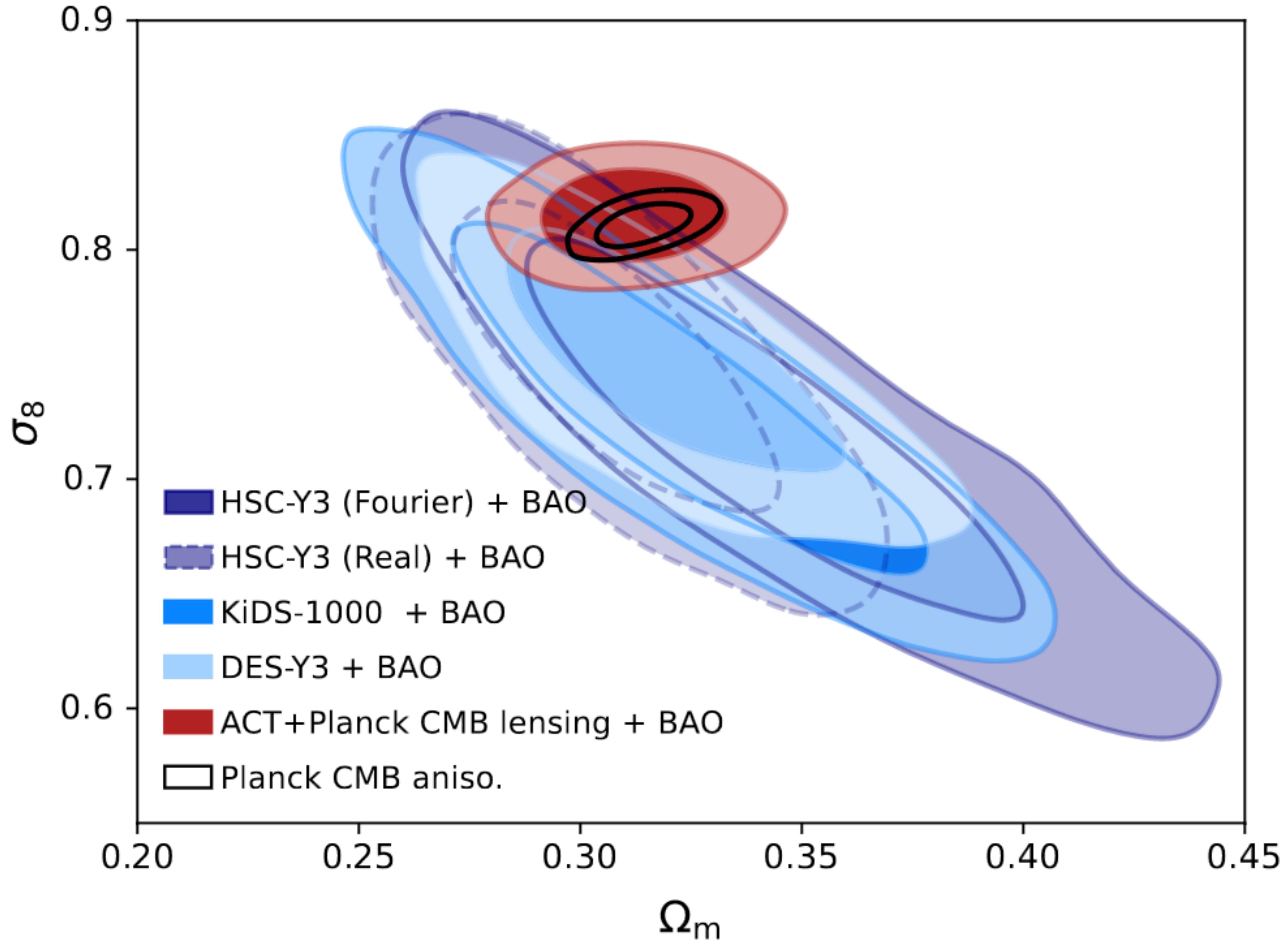
1.6% measurement for ACT+Planck lensing combination

COMPARISON WITH OTHER WEAK LENSING PROBES

Check out Sunao Sugiyama's talk about HSC results

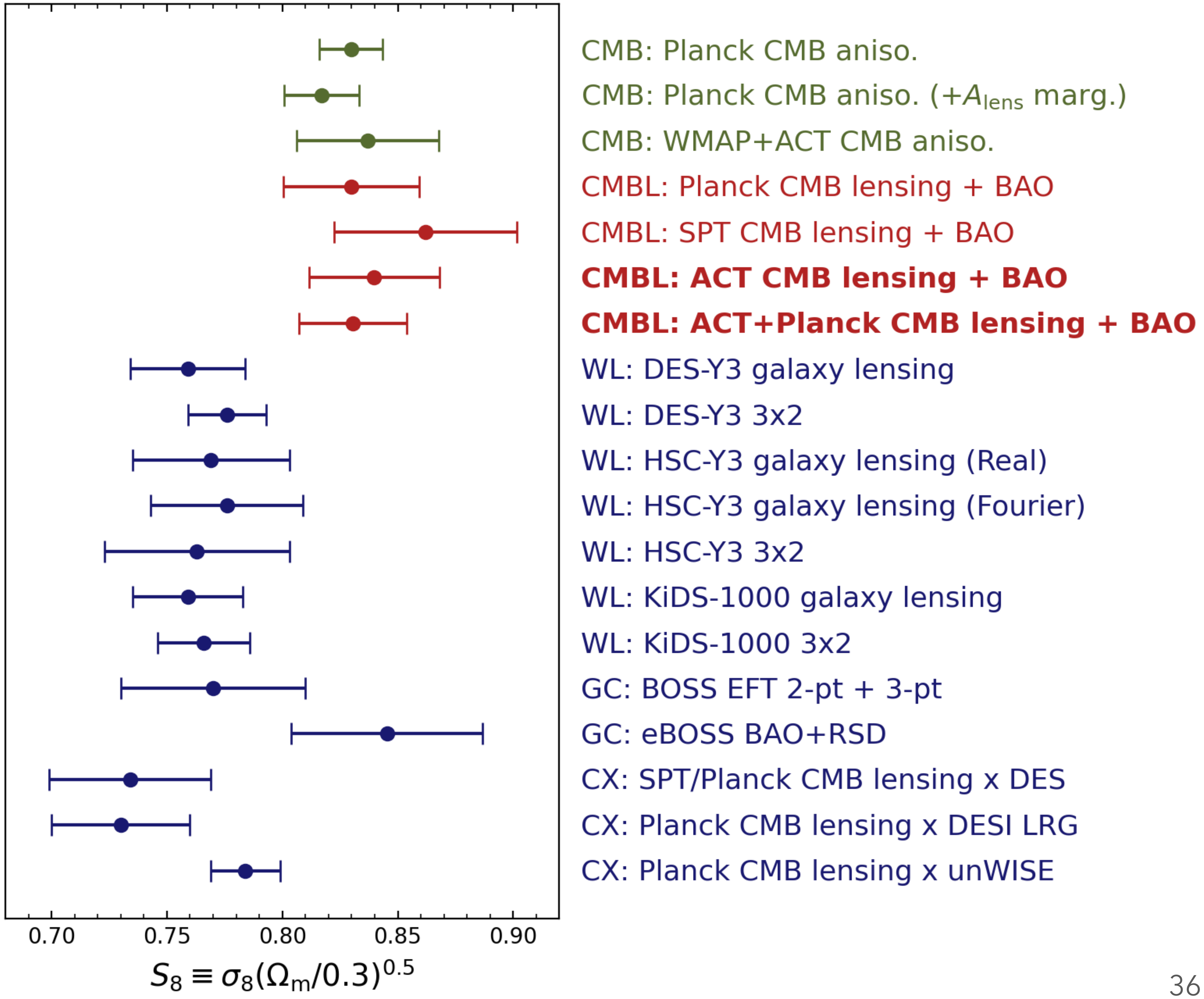
Shown against various **cosmic shear** measurements with consistent priors and BAO

Wider range of scales probed by CMB lensing allows tight constraint compared to cosmic shear



OUTLOOK FOR S_8

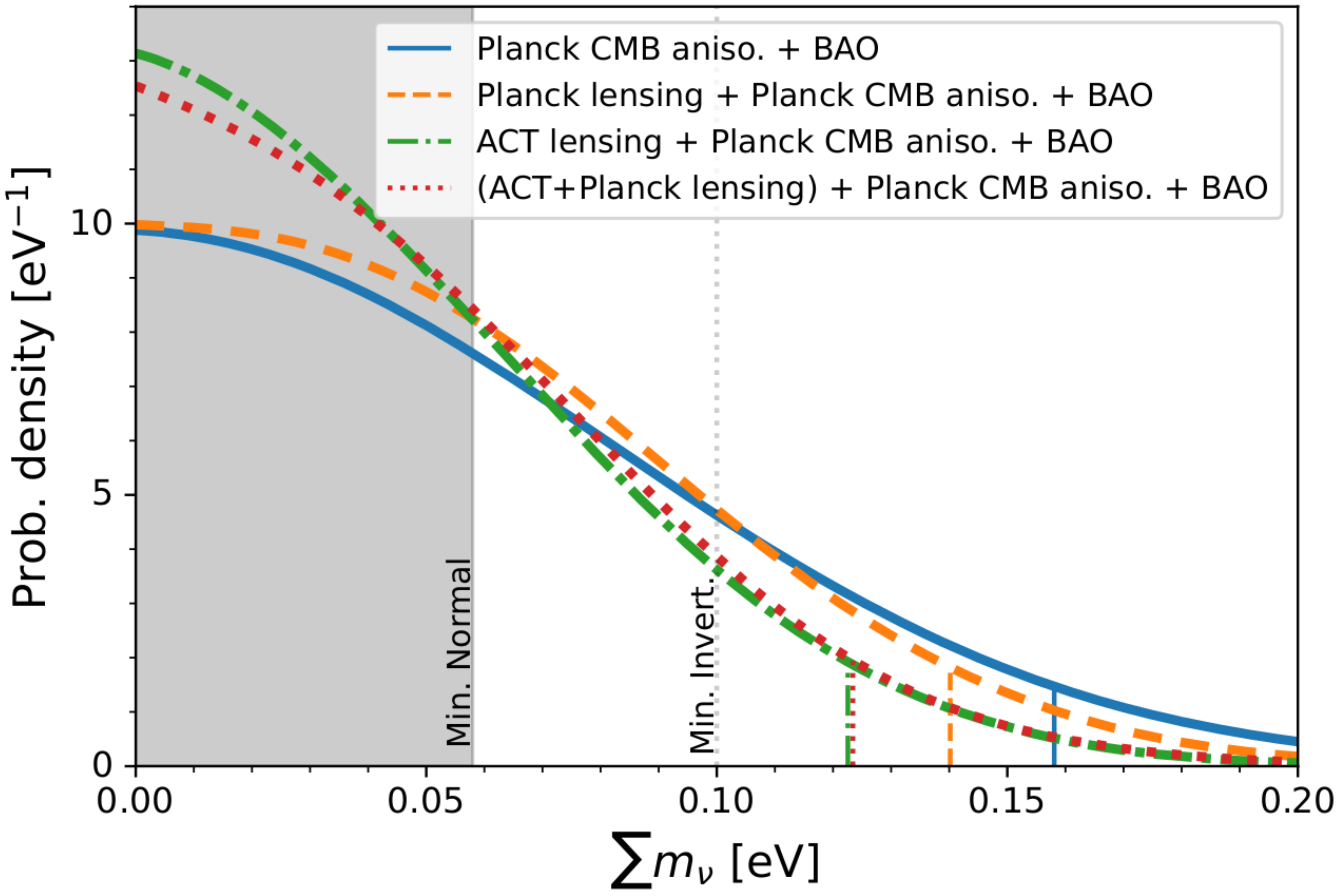
- CMBLens from z=0.5-5 and **linear scales** is consistent with early universe prediction
- Probes of z<~0.5 and **smaller scales** generally fall lower
- **New outlook:** Motivates not just CMB vs. LSS comparisons, but intermediate-z/linear-scales vs. low-z/non-linear scale



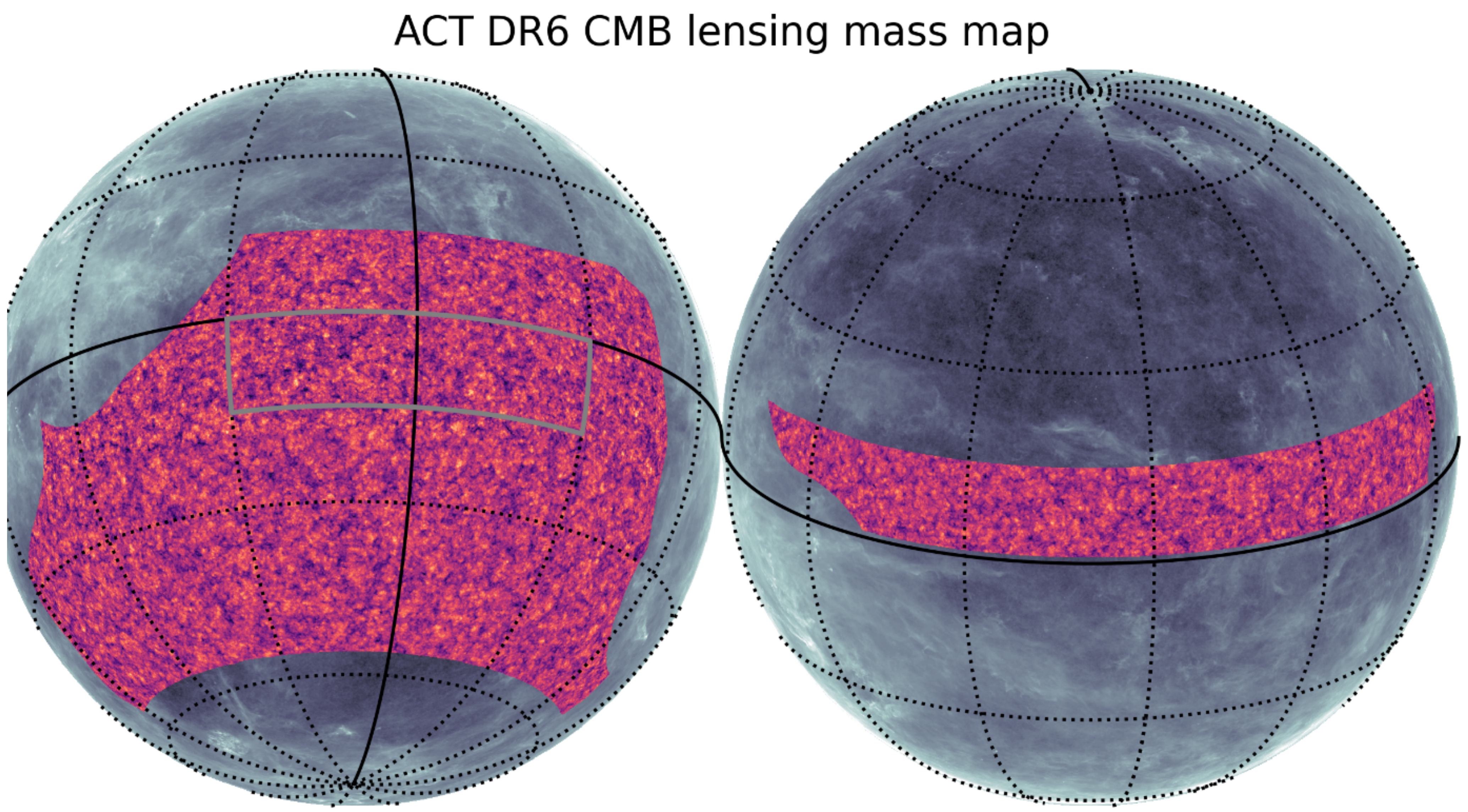
CONSTRAINING NEUTRINO MASSES

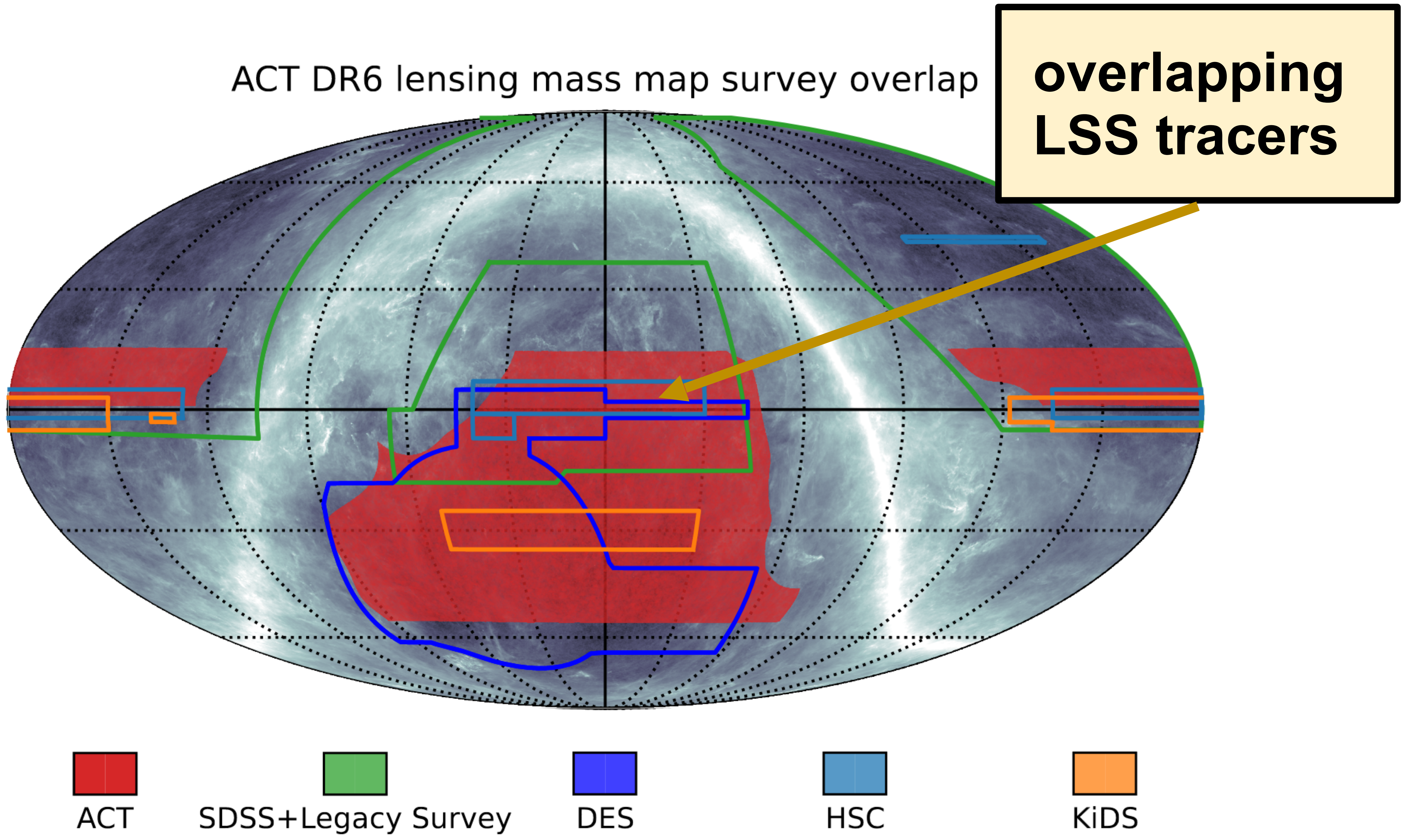
See Yvonne Wong's and Pailine Vielzeuf's talks

- We combine with CMB anisotropies which predict low-redshift clustering amplitude
- Translate observed low-redshift clustering amplitude to suppression caused by massive neutrinos
- **m<0.12 eV 95% c.l.**
  Compare to:
  (m<0.14 eV; Planck lensing)
  (m<0.16 eV; no lensing, only CMB+BAO)



FUTURE DIRECTIONS: DR6 ACT LENSING X LSS



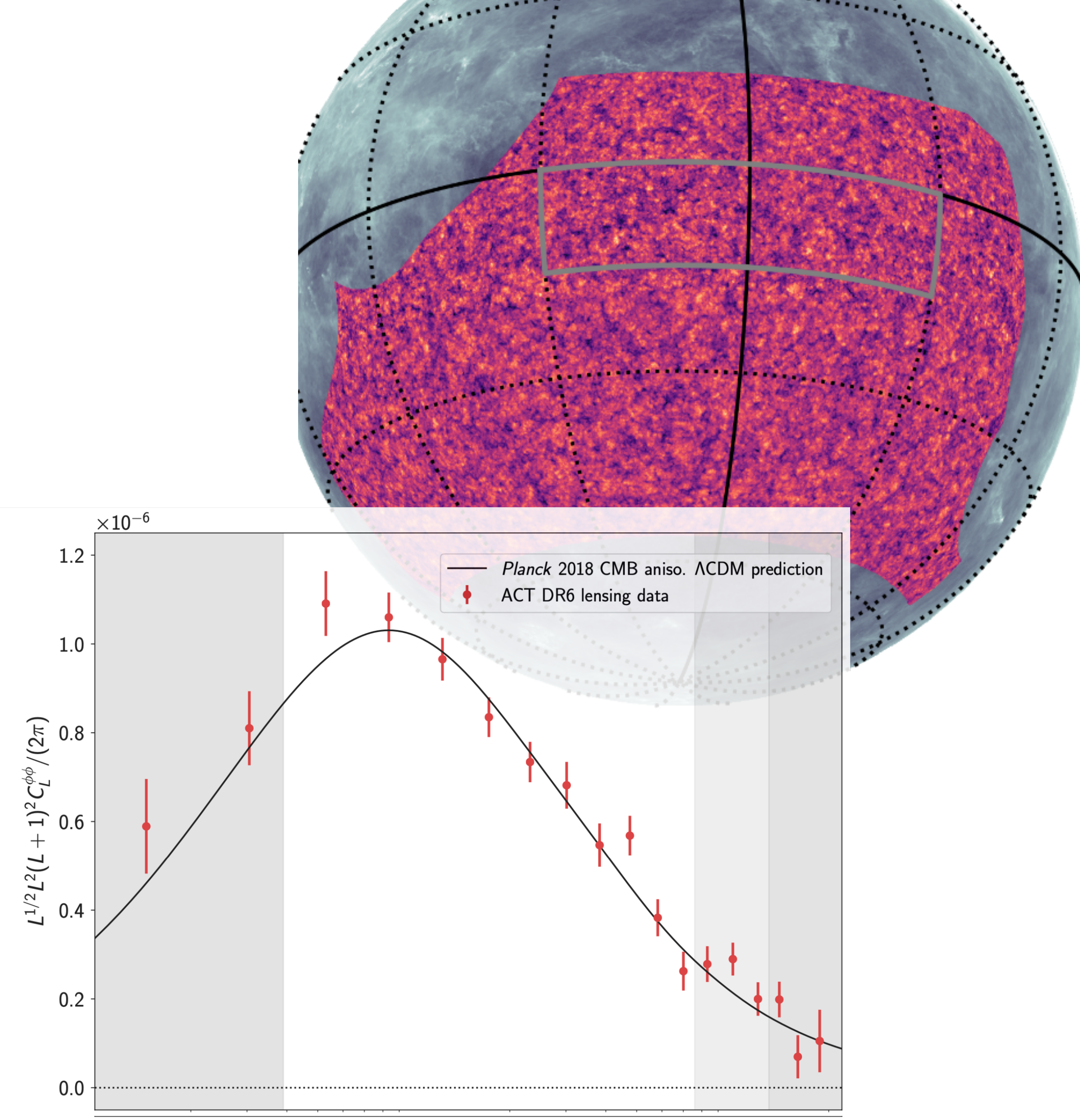


ACT DR6 lensing map will be released upon publication of the 3 papers, likelihood available here:

(NASA LAMBDA: https://lambda.gsfc.nasa.gov/product/act/actadv_prod_table.html)

SUMMARY

- CMB lensing power spectrum with high precision, SNR~43; tested extensively
- High-fidelity lensing map over ¼ sky
- Excellent agreement with Planck or ACT CMB power spectrum predictions. No evidence for low value



THANK YOU FOR YOUR ATTENTION

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Papers available on arxiv

Qu, Sherwin, Madhavacheril, Han, Crowley et al 2304.05202
A Measurement of the DR6 CMB Lensing Power Spectrum and its Implications for Structure Growth
Madhavacheril, Qu, Sherwin, MacCrann, Li et al 2304.05203
DR6 Gravitational Lensing Map and Cosmological Parameters
MacCrann, Sherwin, Qu, Namikawa, Madhavacheril et al 2304.05196
Mitigating the impact of extragalactic foregrounds for the DR6 CMB lensing analysis

THE ACT COLLABORATION

160 Collaborators at 45 institutions