COSMOLOGY FROM HIGH-PRECISION CMB LENSING MEASUREMENTS WITH THE ATACAMA COSMOLOGY TELESCOPE

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in collaboration with

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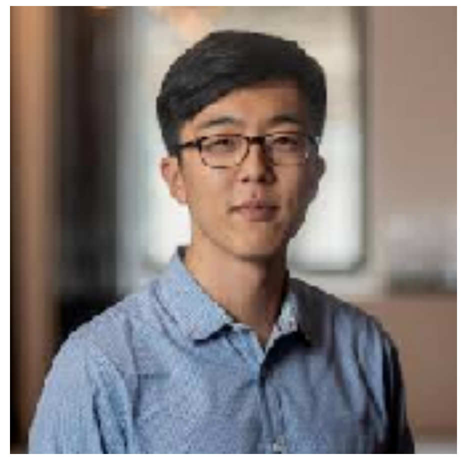


Dongwon Han (University of Cambridge)

+ ACT collaboration

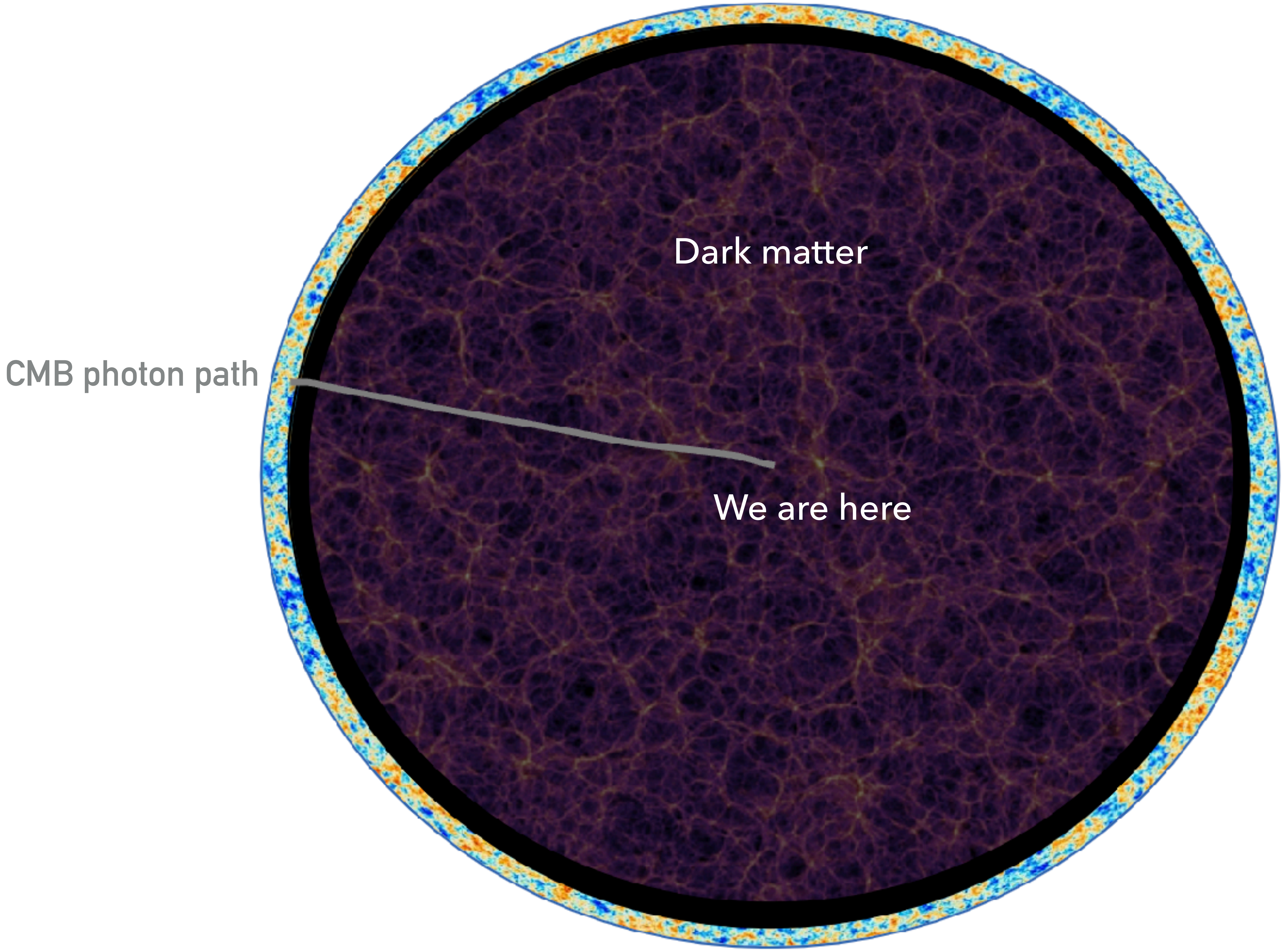
Frank J. Qu Thursday 18th of May 2023

RPM talk

THE ACT COLLABORATION

160 Collaborators at 45 institutions

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

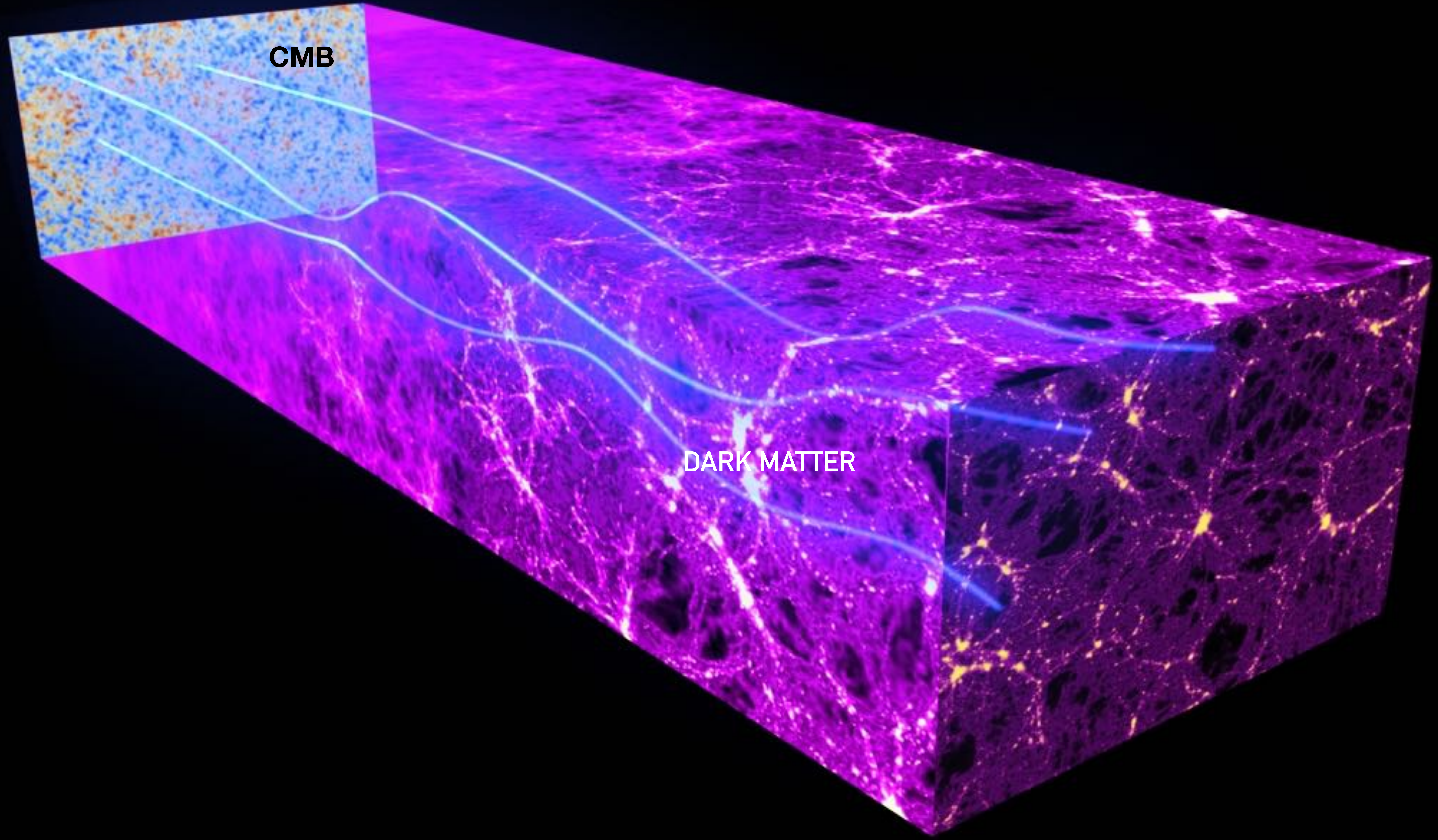
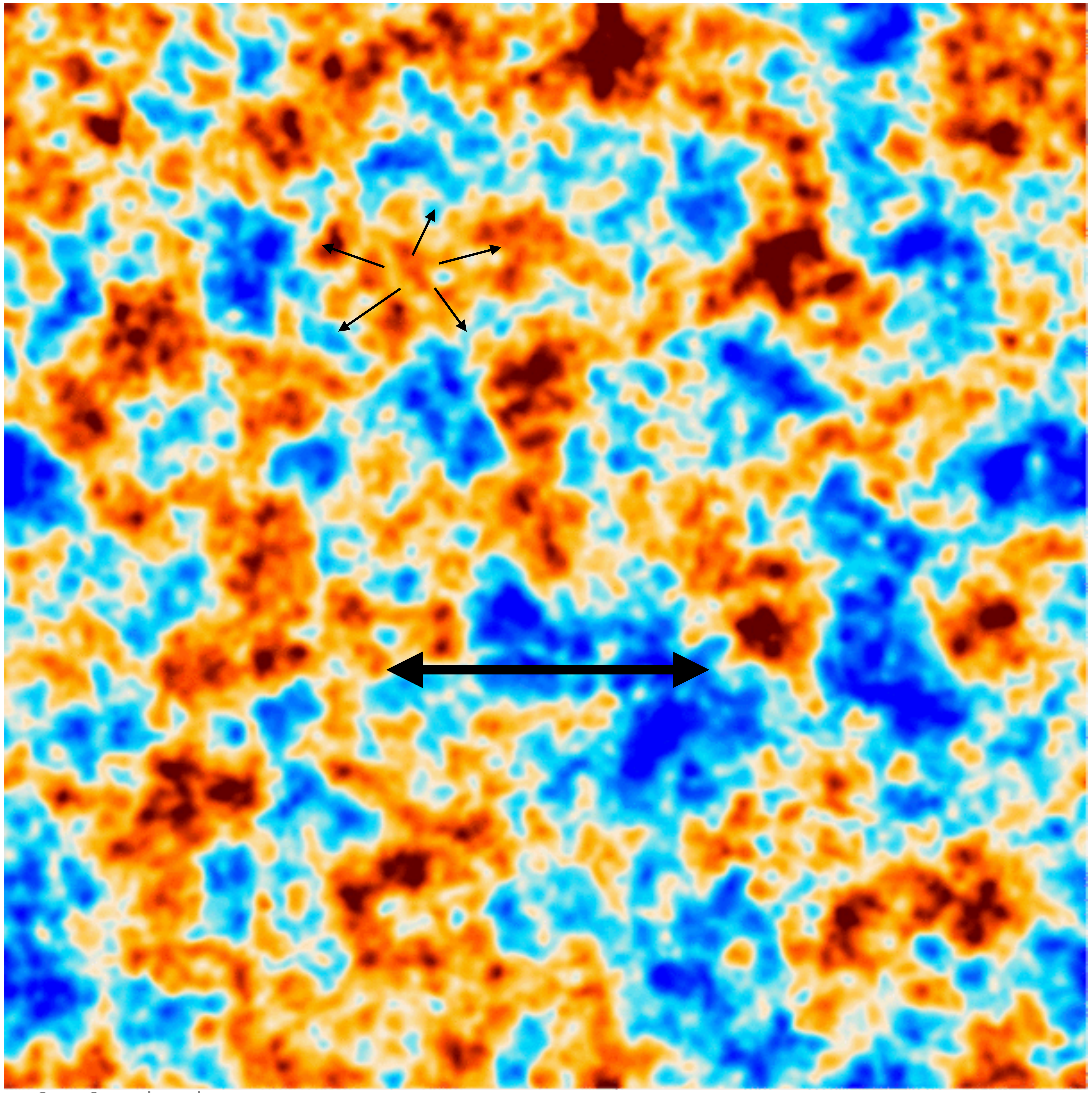


Image: ESA/Planck

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

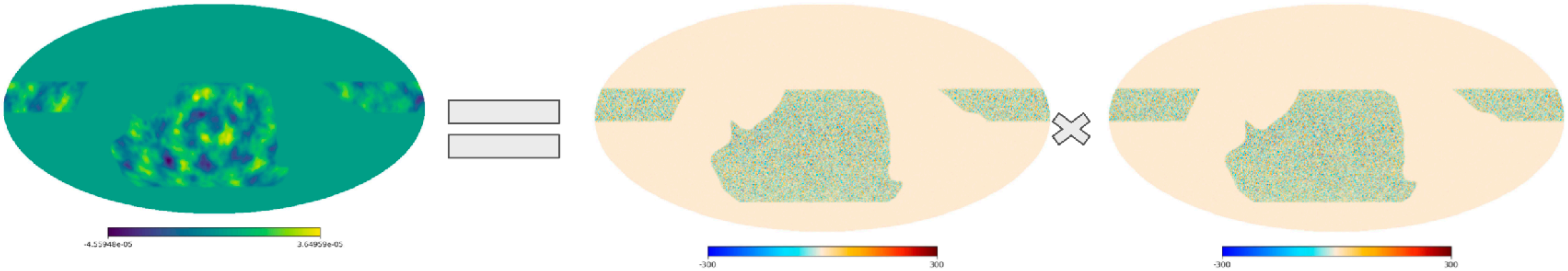
$$\langle T^0(\boldsymbol{\ell})T^{0*}(\boldsymbol{\ell}-\boldsymbol{L})\rangle_{\text{CMB}} = 0$$

Mode coupling

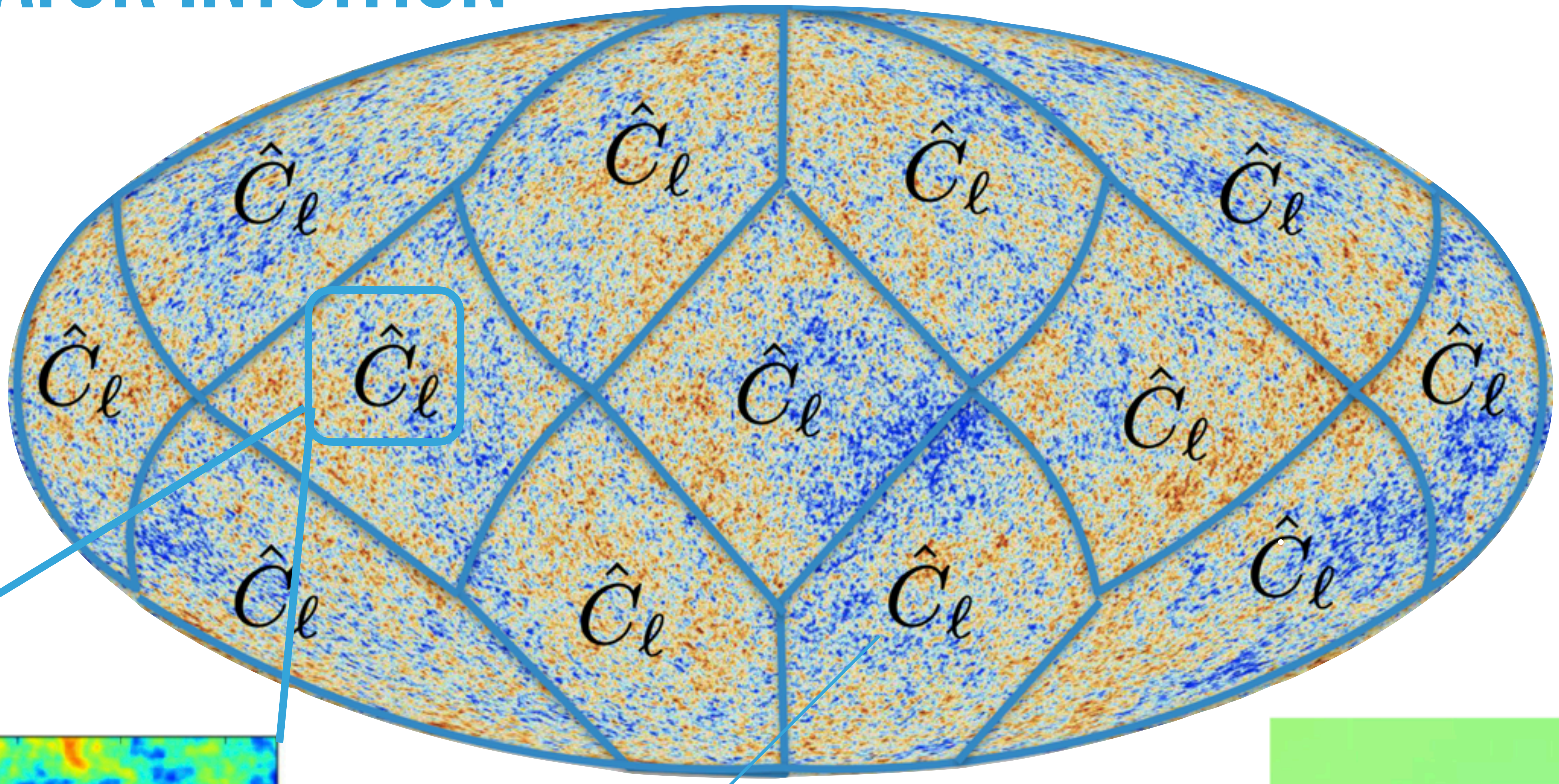
$$\langle T(\boldsymbol{\ell})T^*(\boldsymbol{\ell}-\boldsymbol{L})\rangle_{\text{CMB}} \sim \phi(\boldsymbol{L})$$

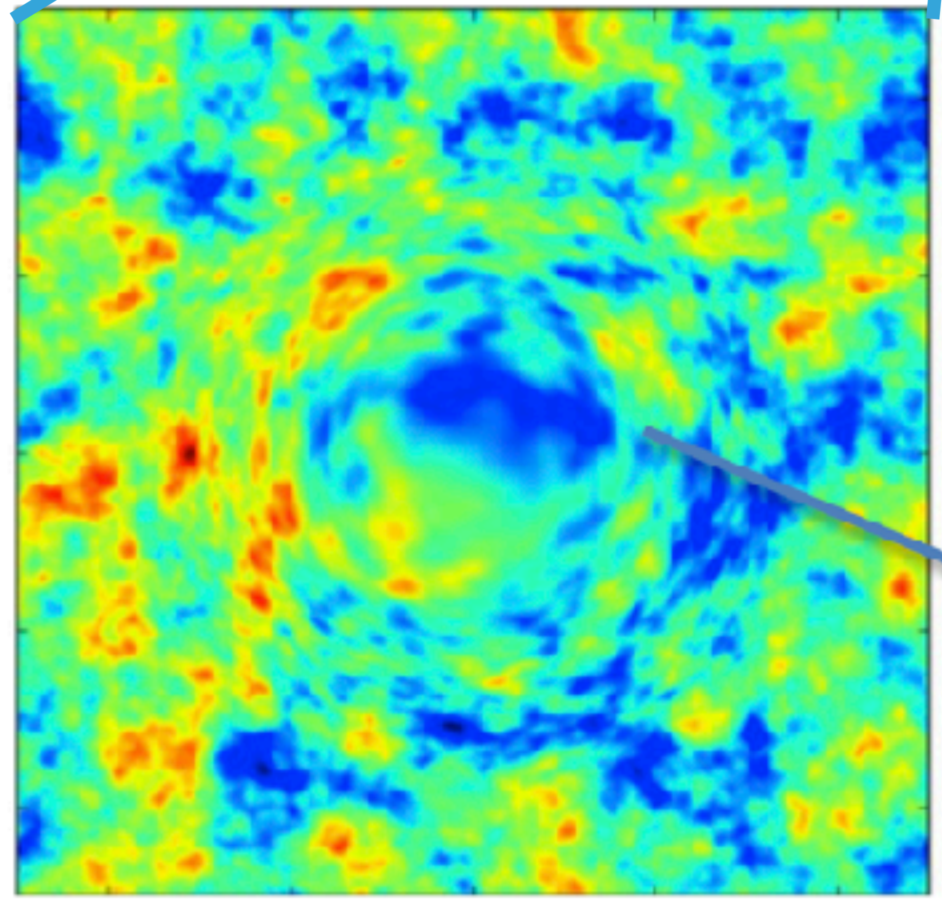
Mode by mode reconstruction of lensing from quadratic CMB combinations

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

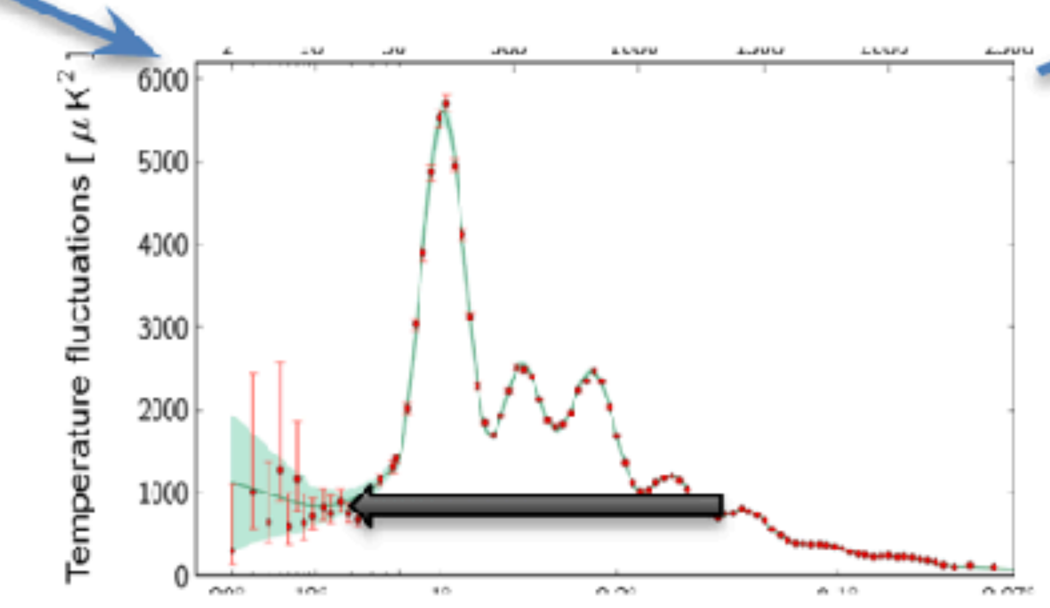


QUADRATIC ESTIMATOR INTUITION

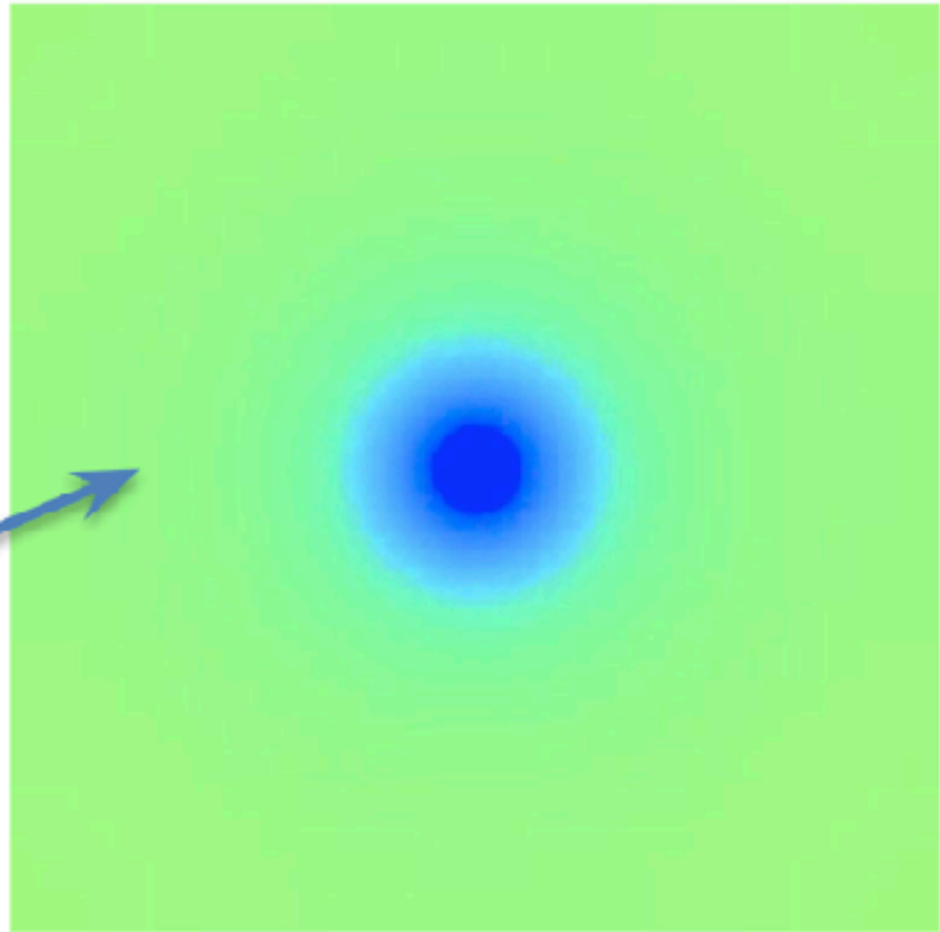




CMB

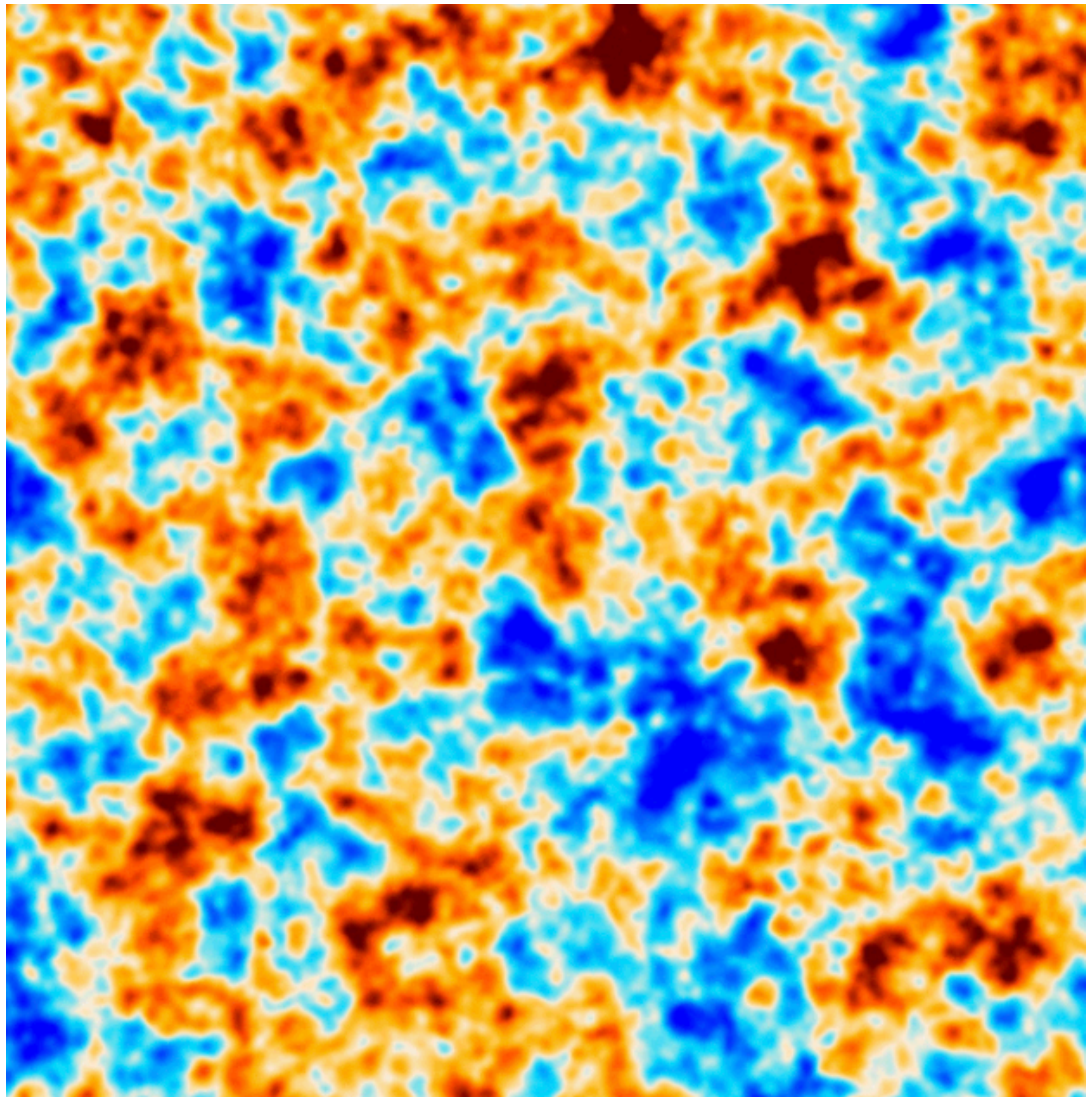


Shift to larger angular scales



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

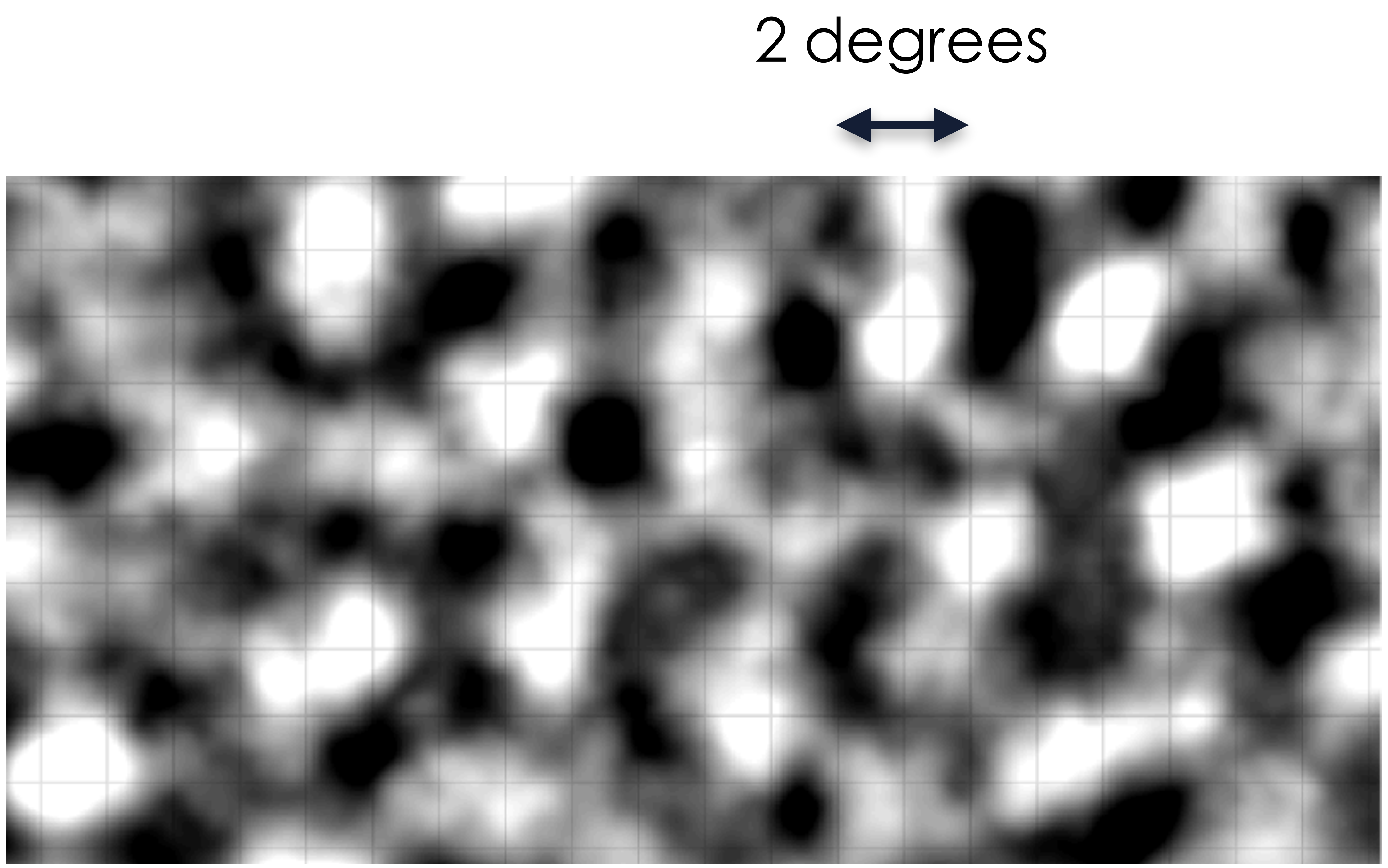
LENSING RECONSTRUCTION VIA THE QUADRATIC ESTIMATOR



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

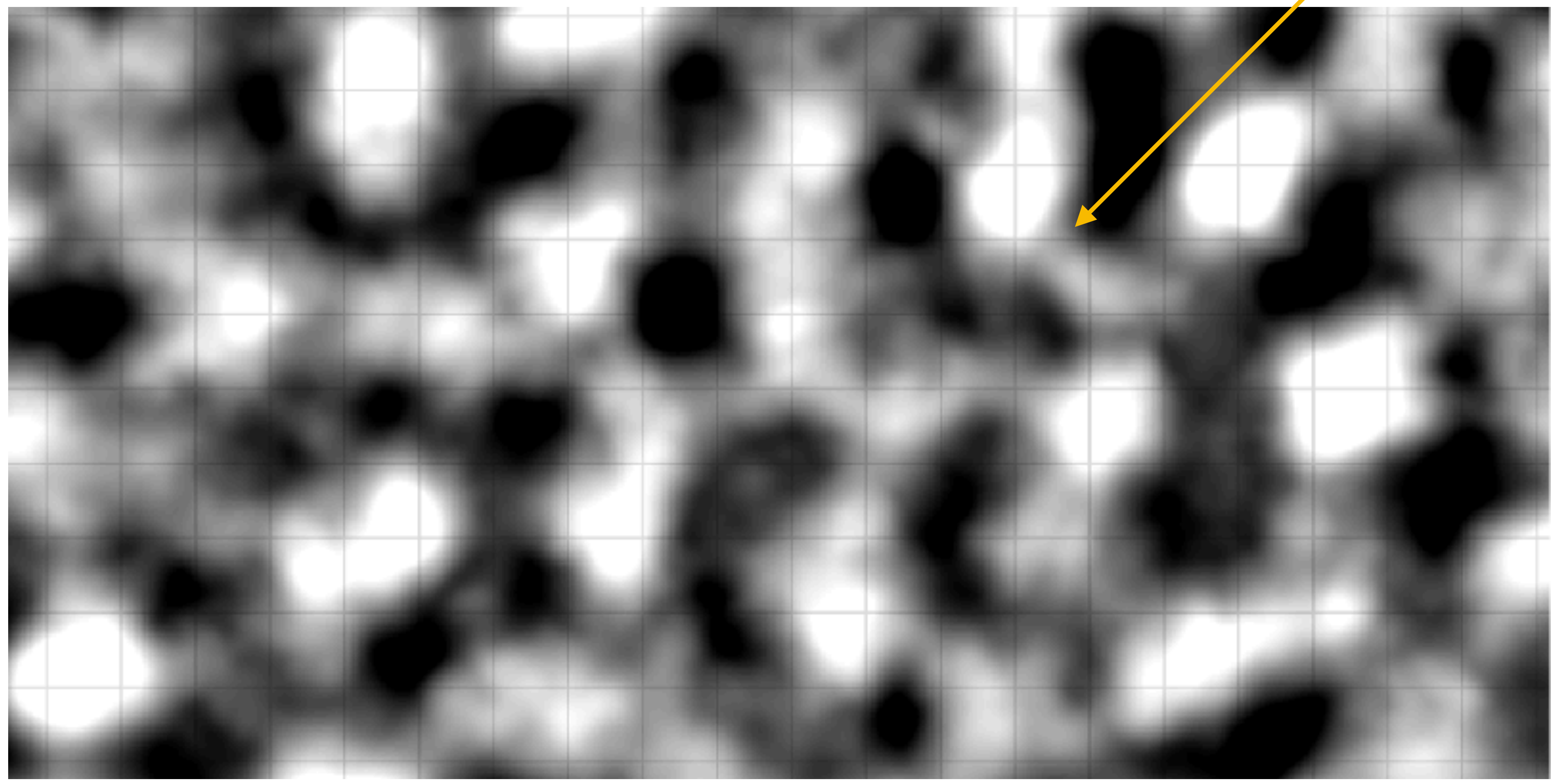


Reconstructed CMB Lensing Matter Distribution

Benefit from **high resolution** CMB measurements

KEY STATISTICS: LENSING POWER SPECTRUM

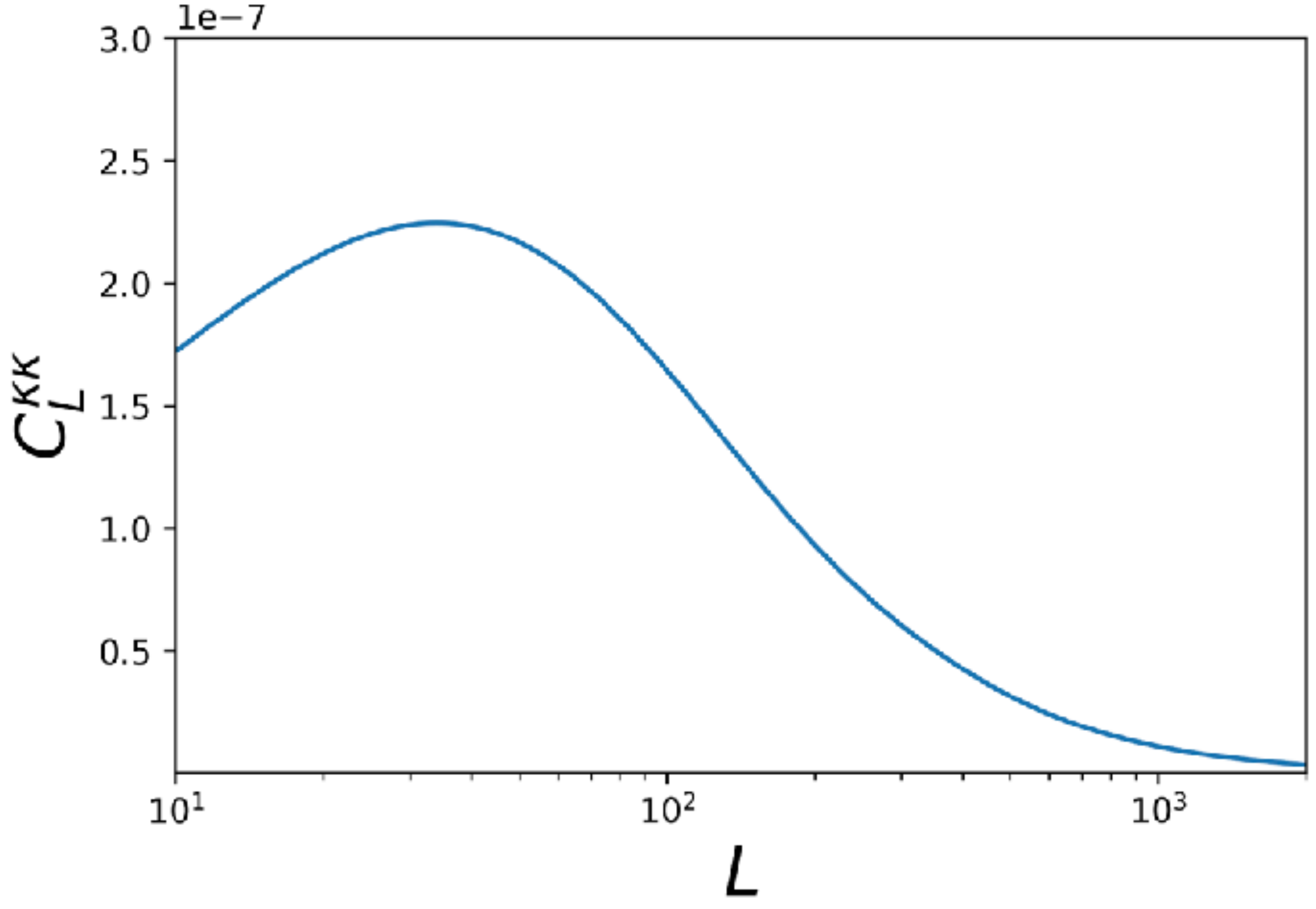
Bright regions = High Density



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

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

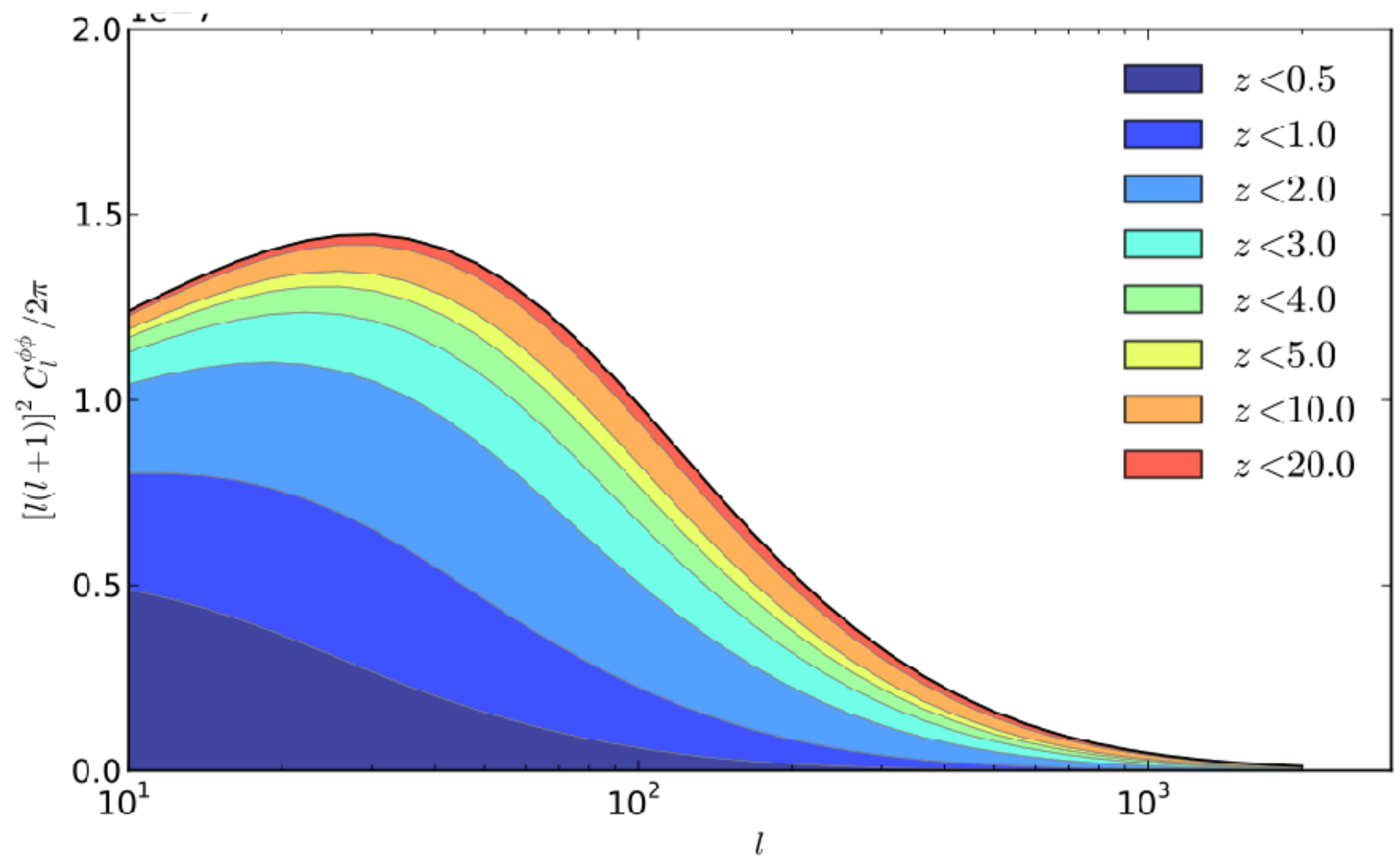
$$L^4 C_L^{\phi\phi}/4 = \int_0^{1100} dz (\tilde{W}^\kappa(z))^2 P(k = L/\chi, z)$$

lensing power spec. — redshift kernel — matter power spectrum

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

Projection kernel

Fractional mass overdensity

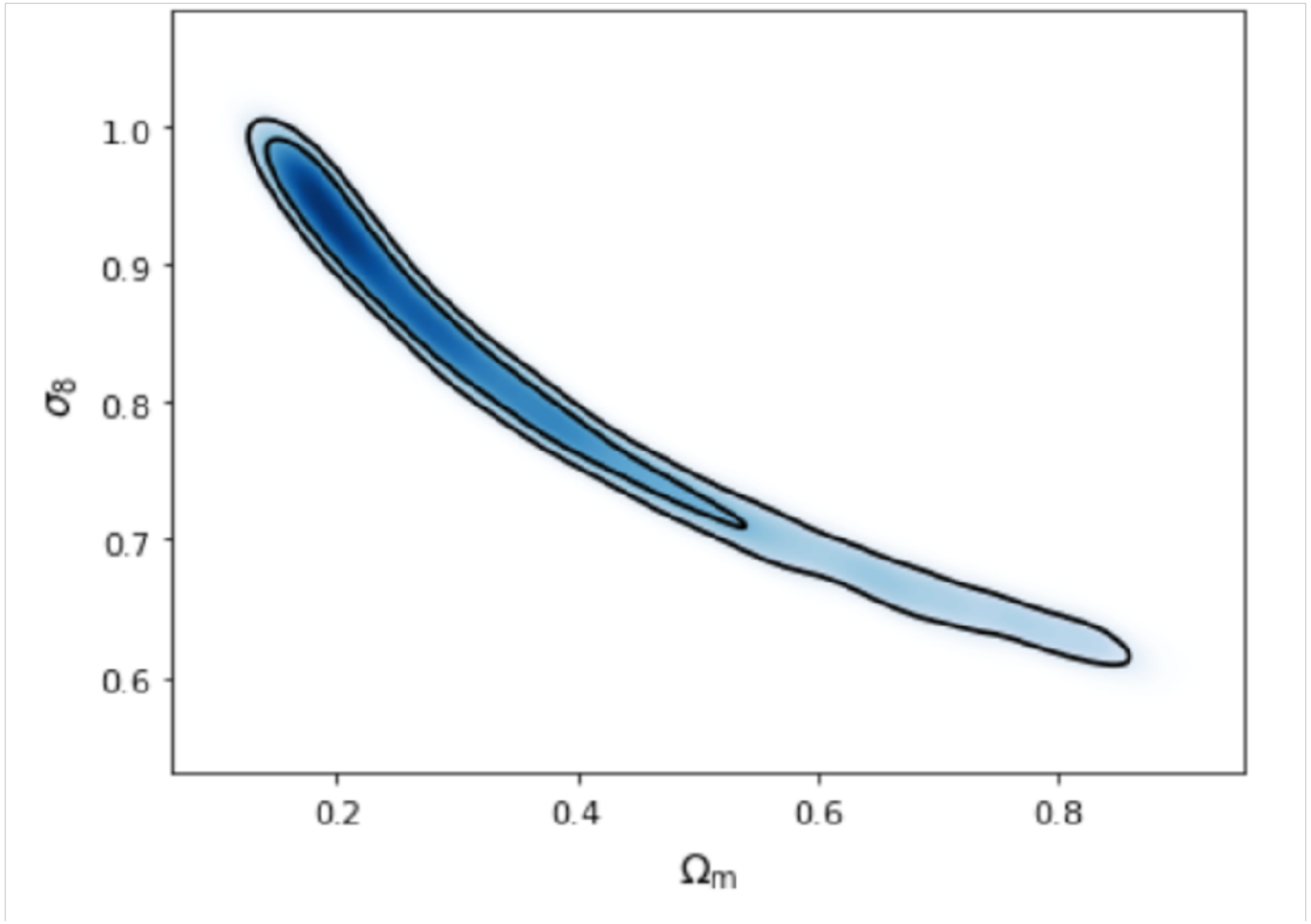


Redshift origin of the signal: mean at z~2, peak at z~1, broad support over extended redshifts z=0.5~6

COSMOLOGICAL PARAMETER DEPENDENCE

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

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

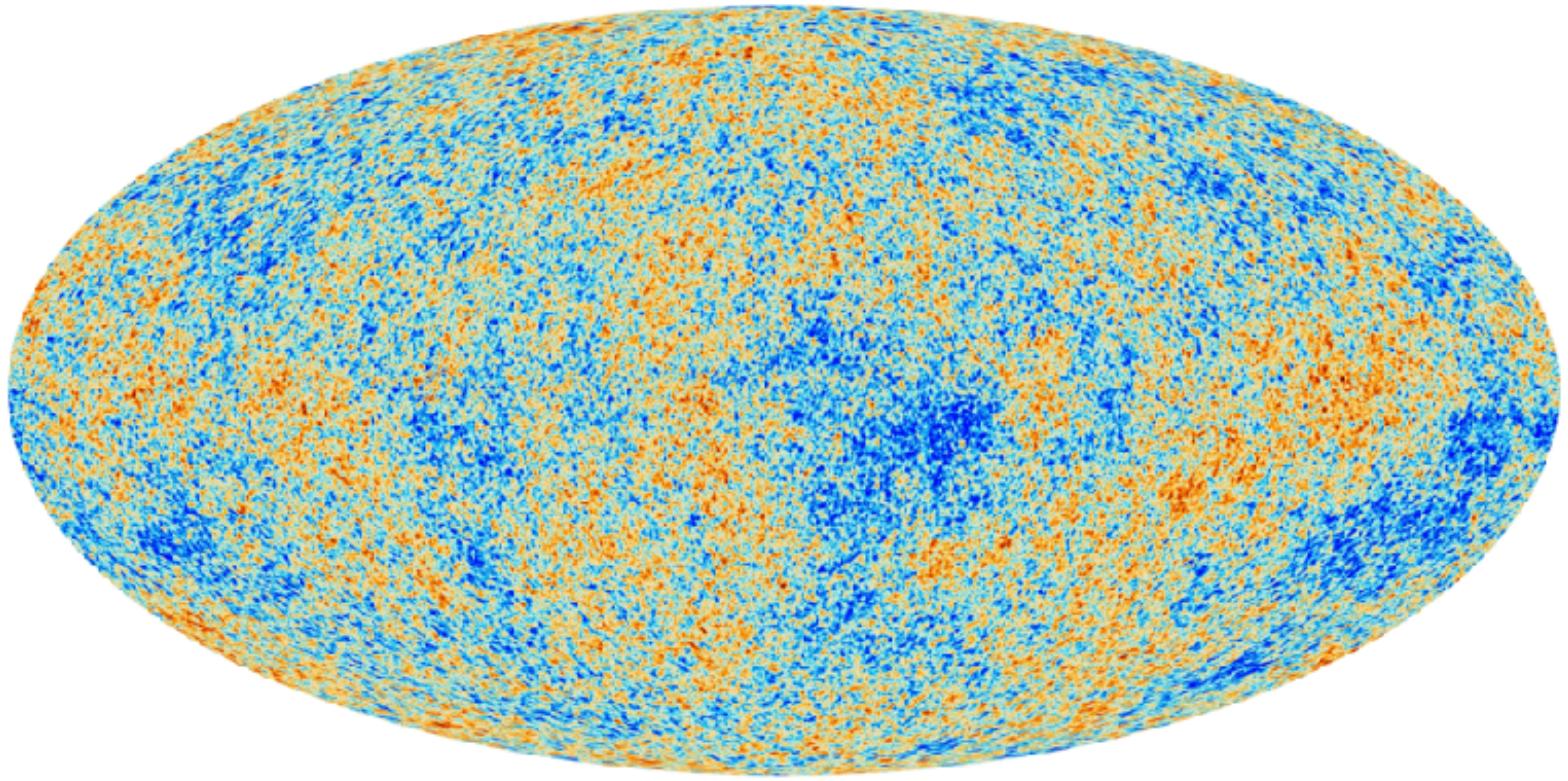


MOTIVATION: LENSING MASS MAPS AS TESTS OF STRUCTURE GROWTH

- 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)?

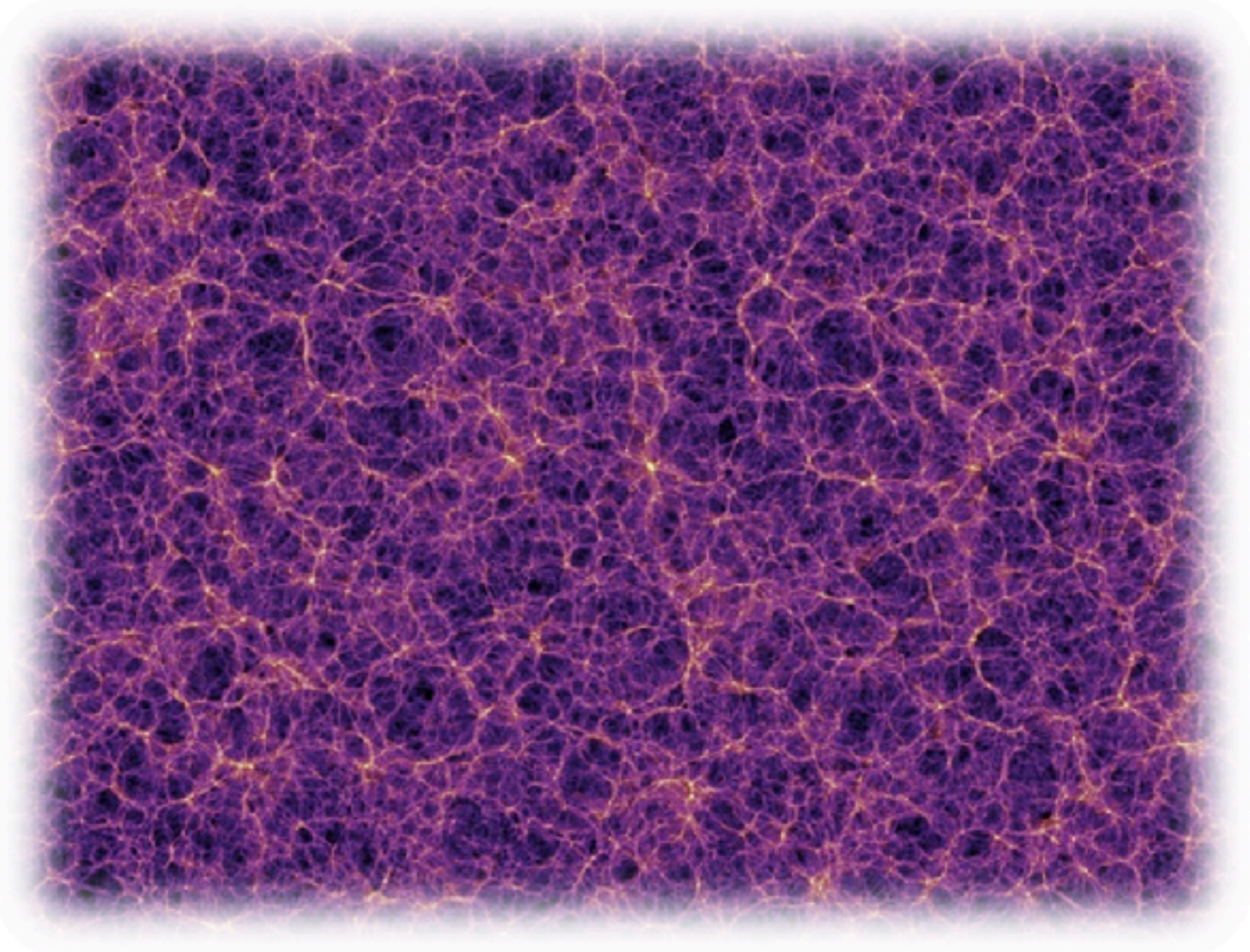
Predict size of structure formation at late times

- 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.

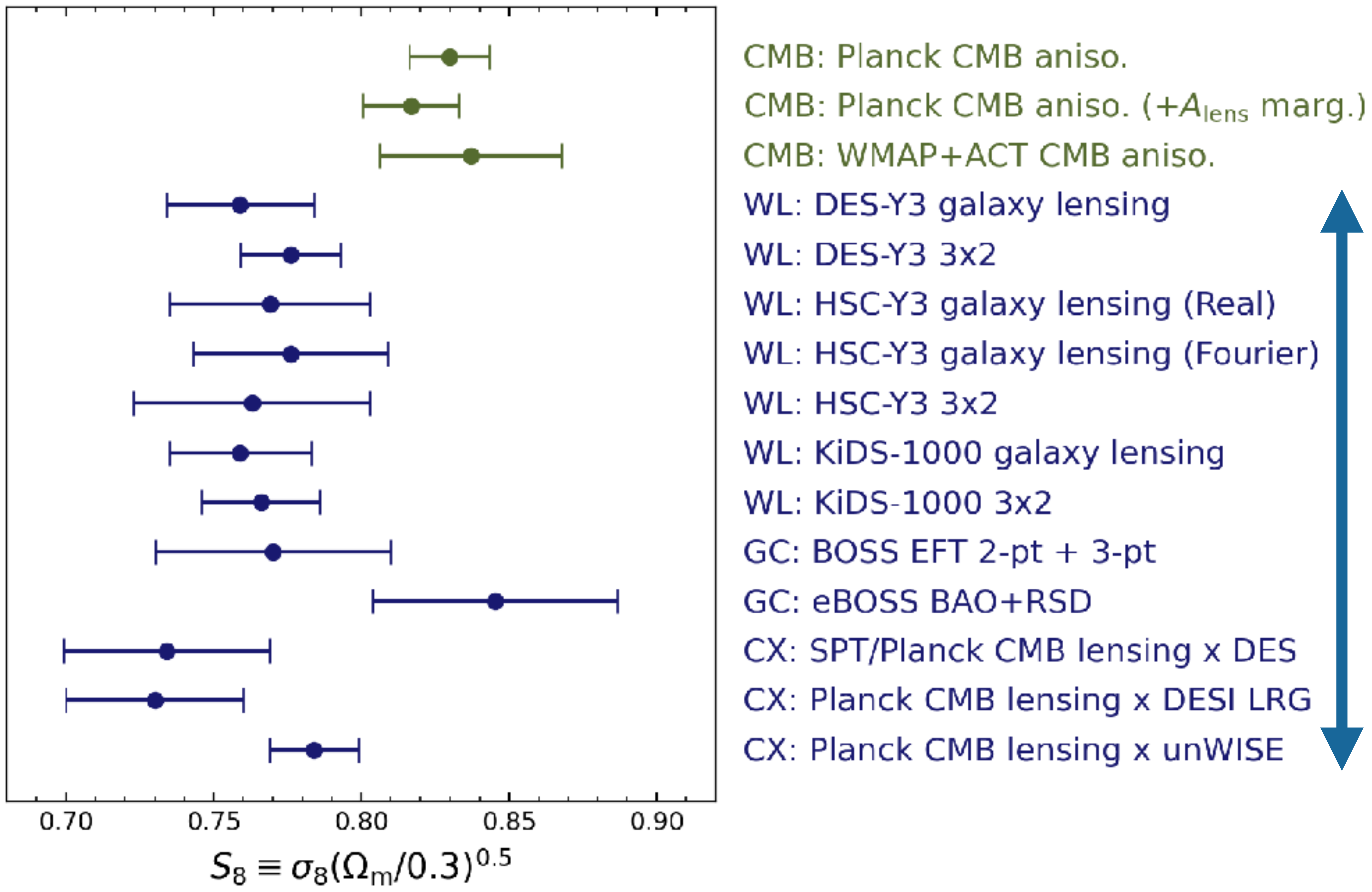
$t = 0.0004\mathrm{Gyr}$



Compare with observations

$t > 1\mathrm{Gyr}$

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

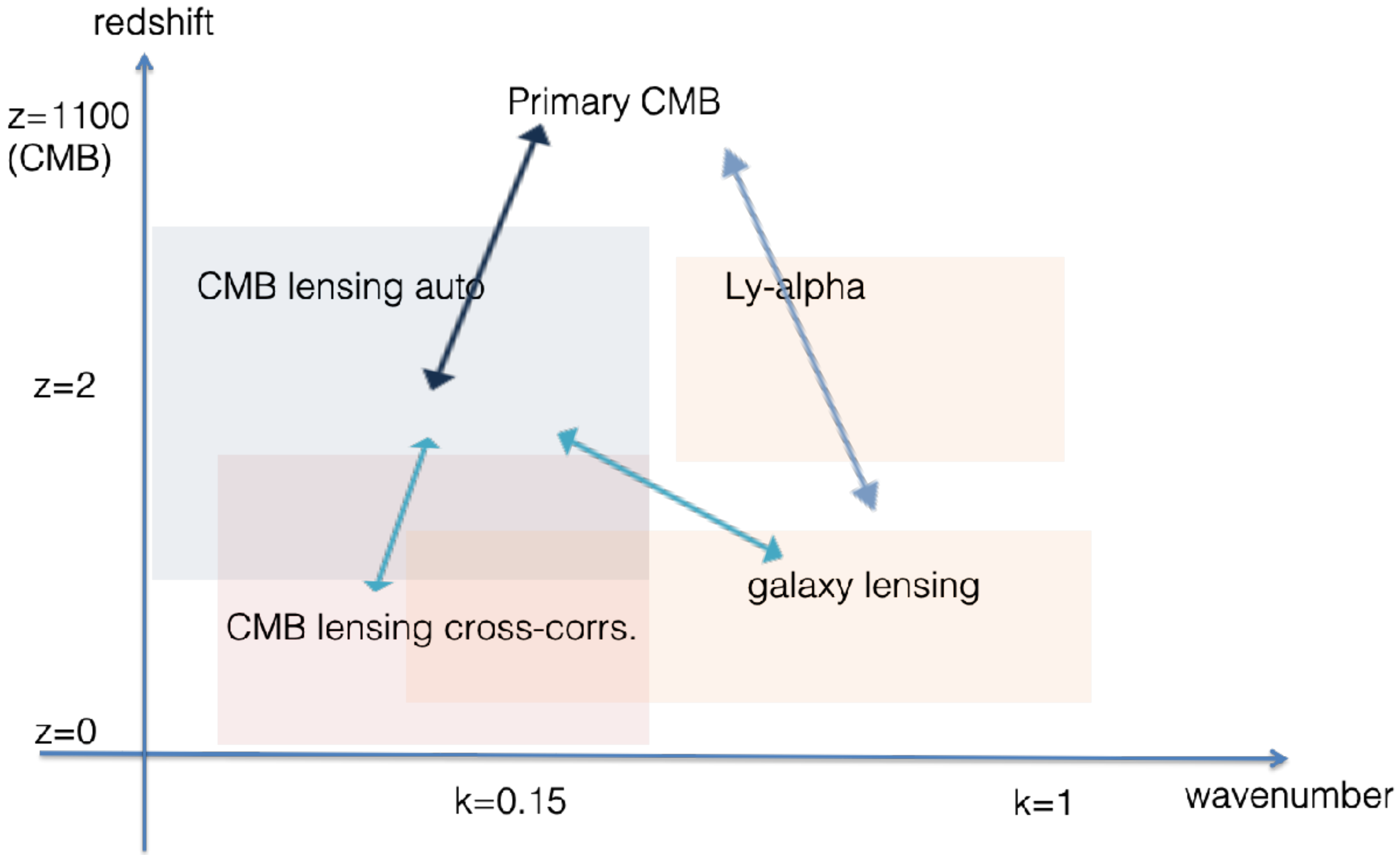


Direct low z measurements from galaxy surveys: 2-3 sigma low in several channels

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?

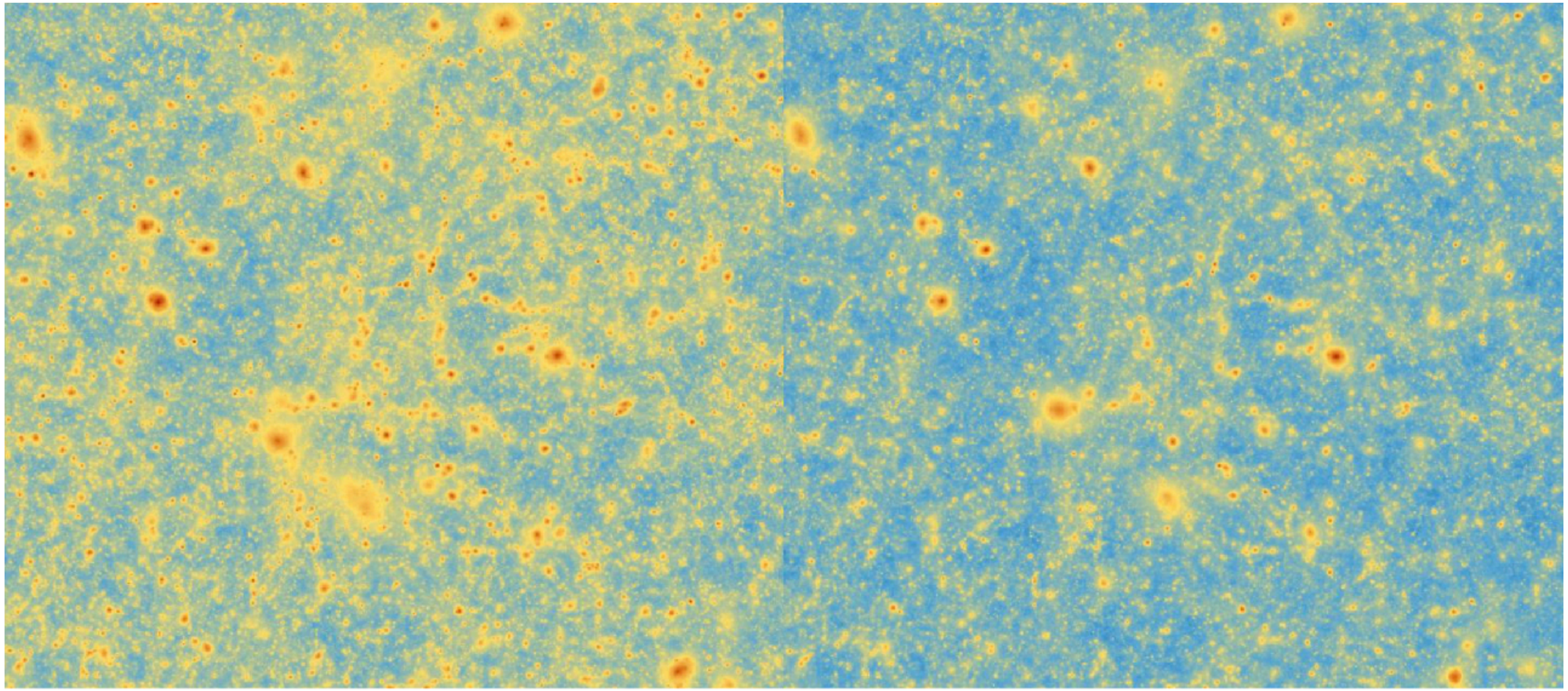
- Can give insight into systematics and test z/k dependence of any new physics



MOTIVATION 2 : MEASURING NEUTRINO MASS SUM

- Neutrinos affect structure growth: the more massive the neutrinos, the more the small scale growth are suppressed.

Large-scale mass distribution



McCarthy

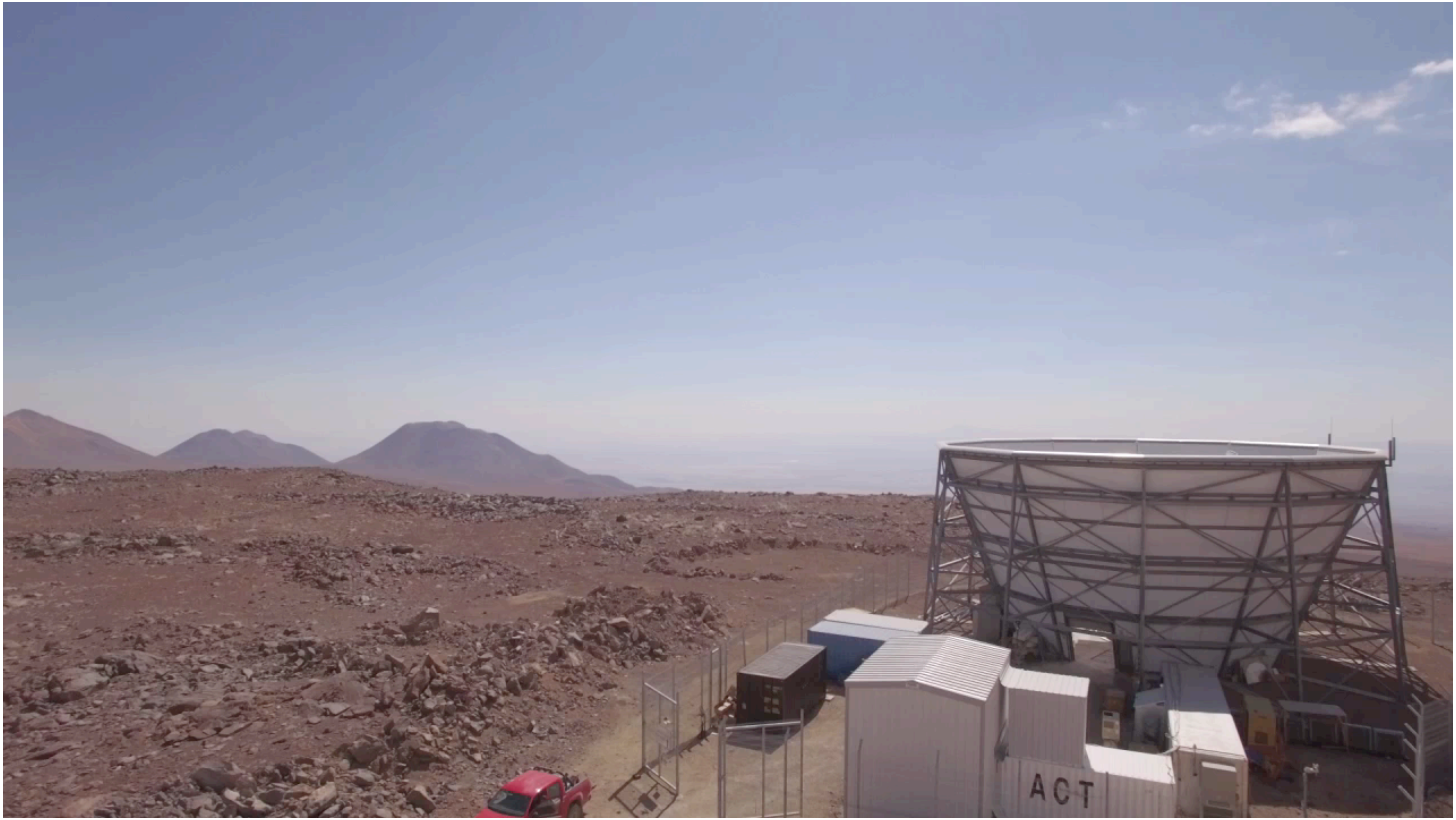
Massless neutrino

Massive neutrino

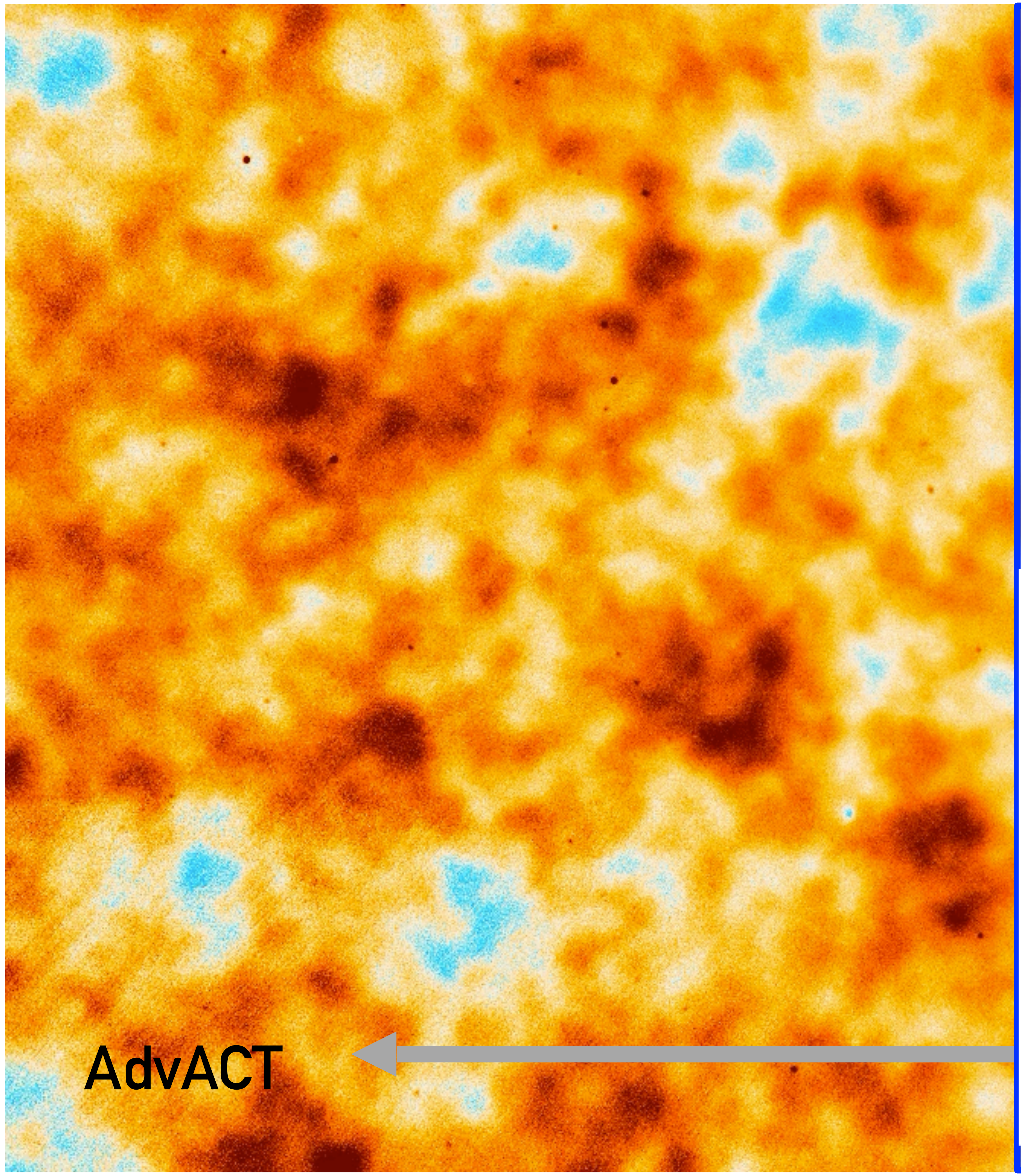
Probes approaching the $60\mathrm{meV}$ lower limit using AdvACT, SPTPOL, SO, S4

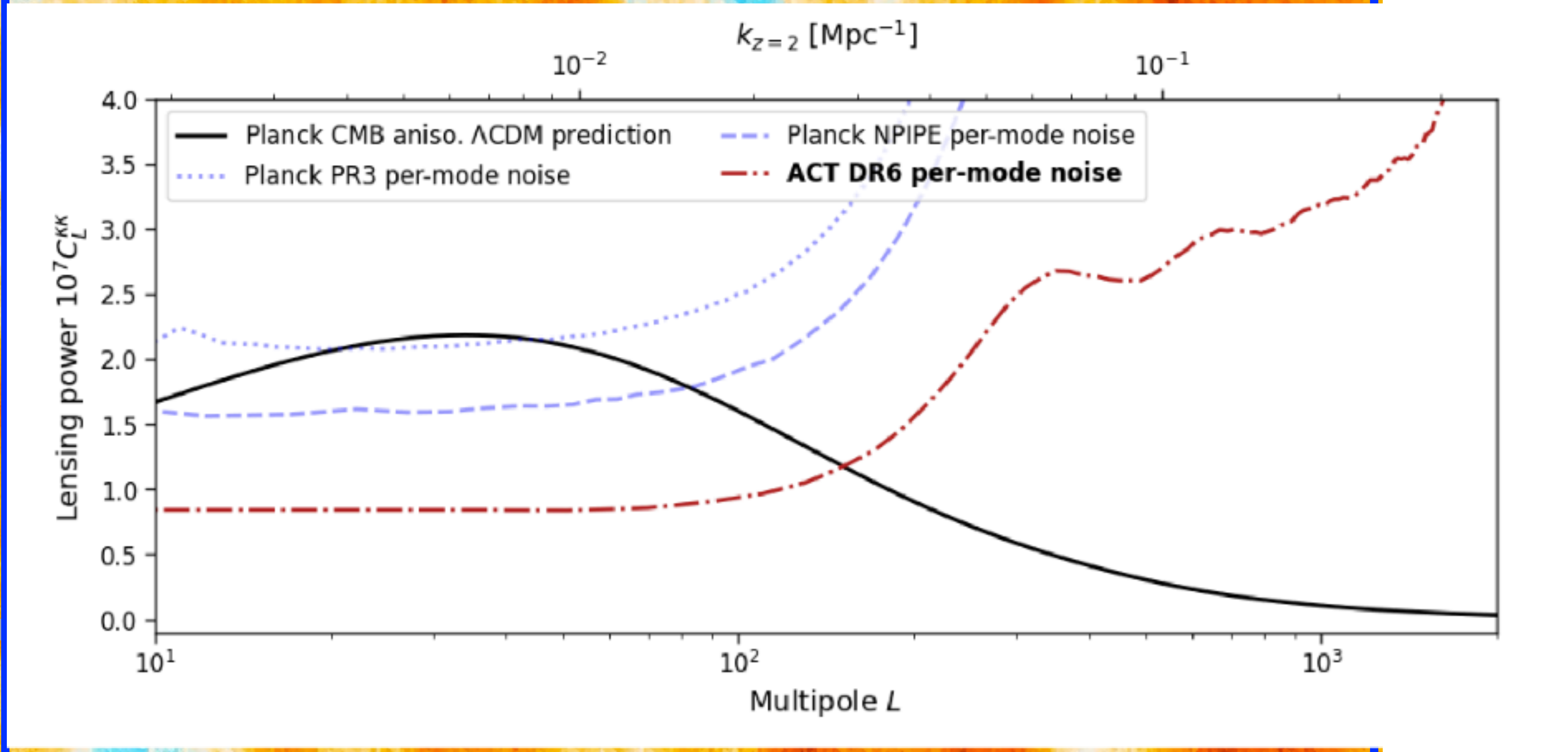
ATACAMA COSMOLOGY TELESCOPE

Arcminute resolution CMB telescope, located in the Chilean Atacama desert



HIGH RESOLUTION CMB LENSING MEASUREMENTS FROM ADVACT

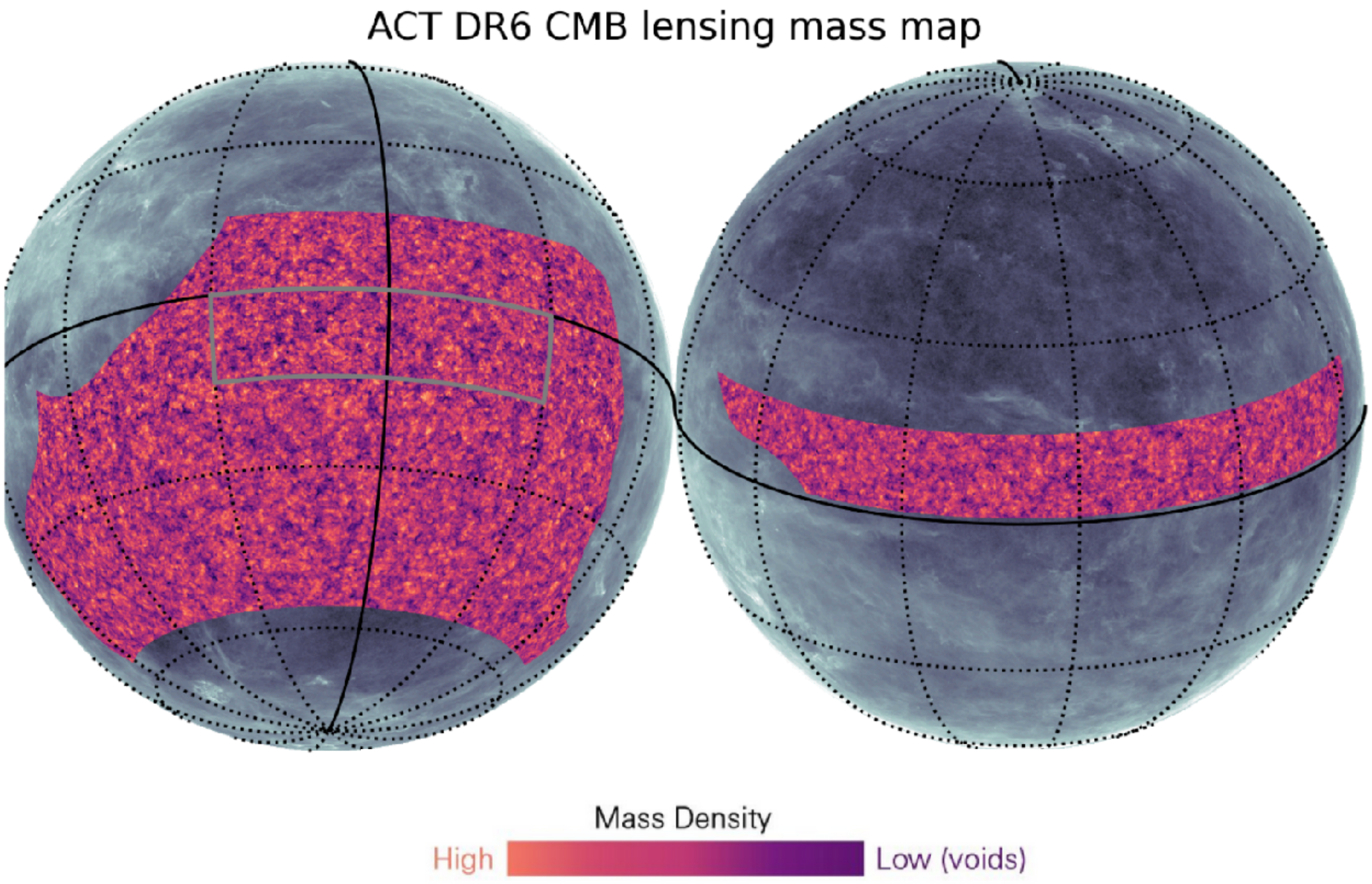




New DR6 AdvACT maps: 15uk 18000 sq degrees

Credits: Sigurd Naess

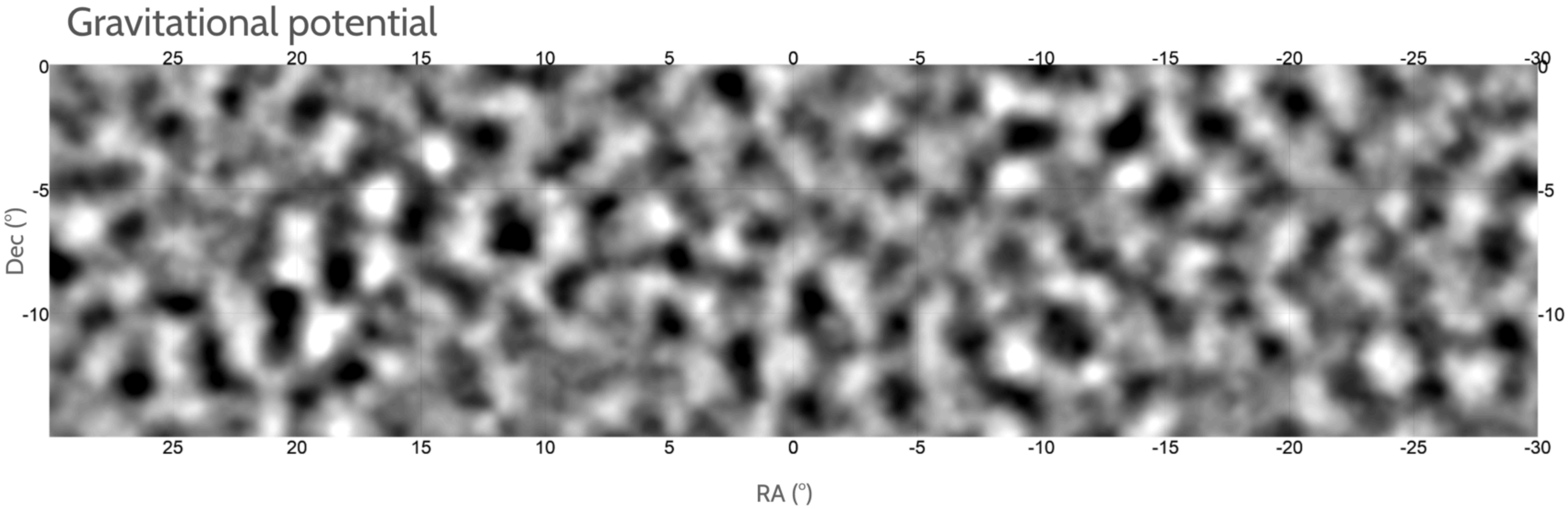
HIGH RESOLUTION CMB LENSING MEASUREMENTS FROM ADVACT



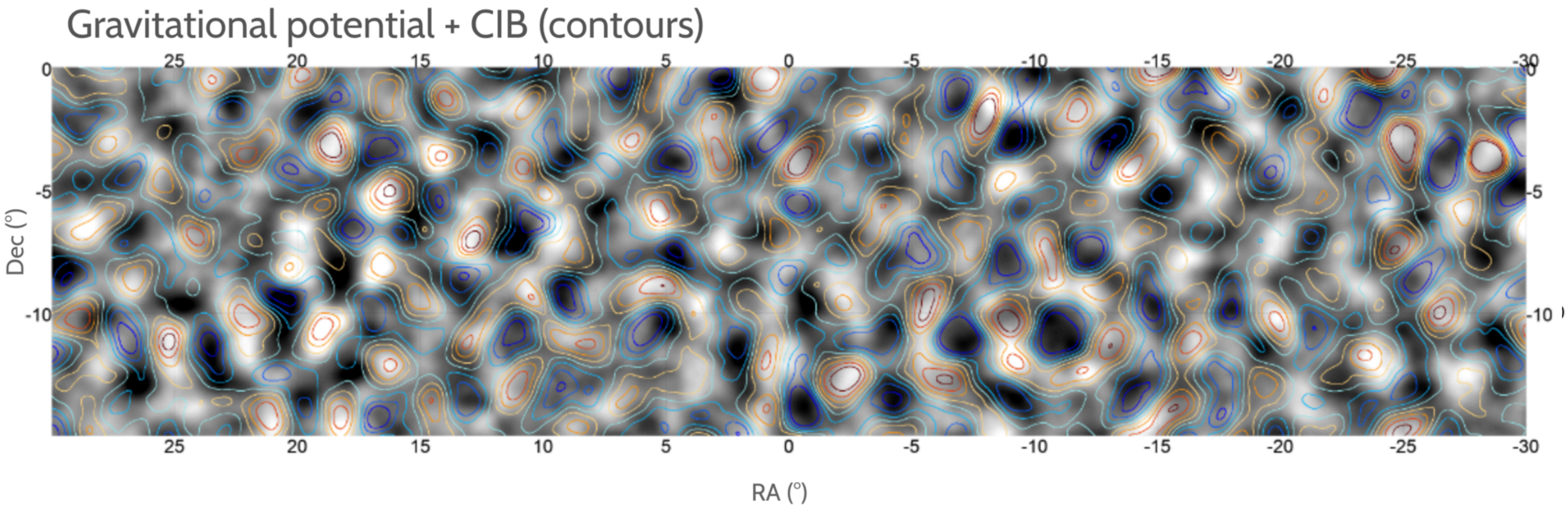
Gravitational Lensing Convergence

- 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

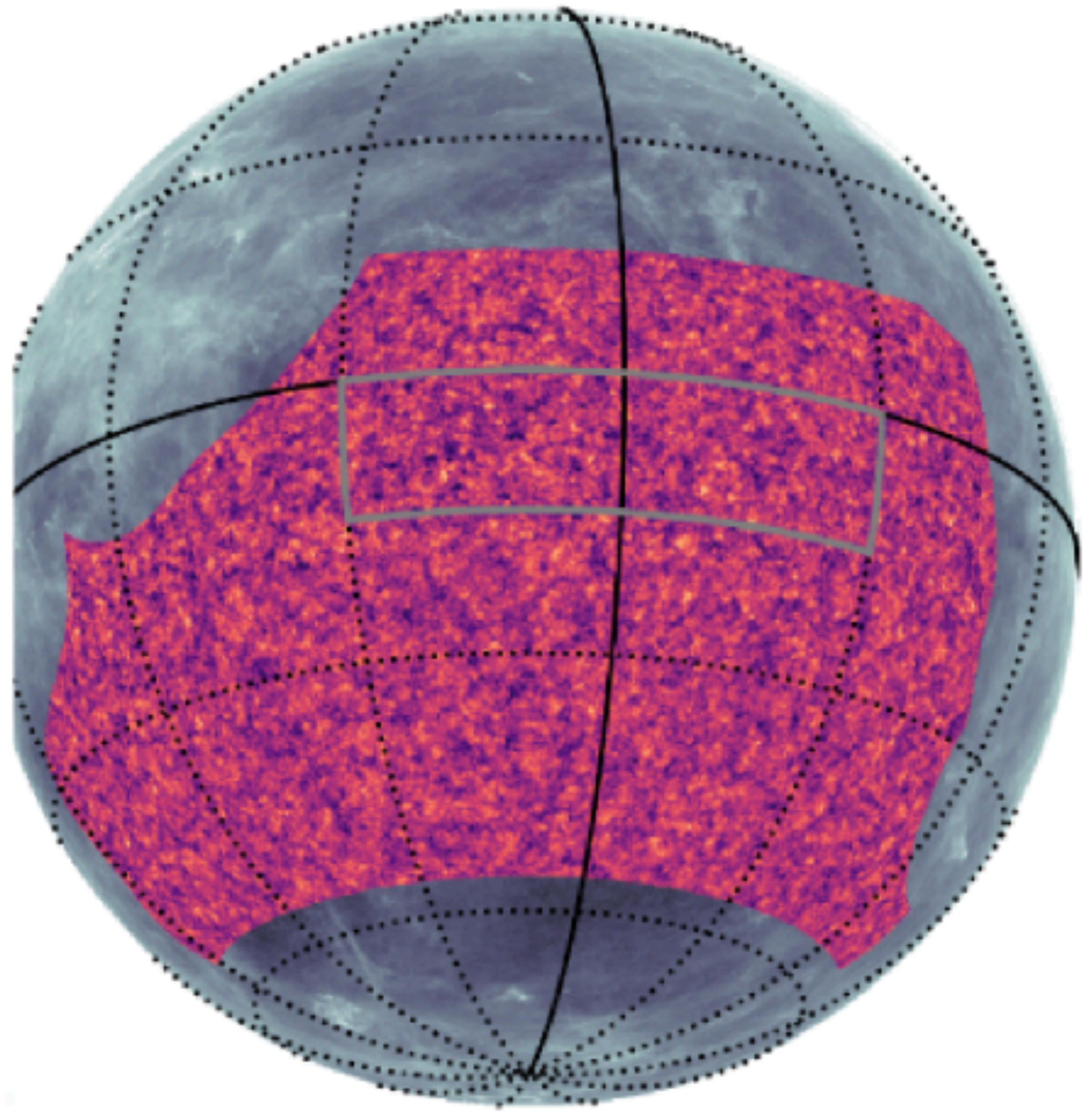


ZOOM IN OF 900 SQ. DEG OF THE 9400 SQ. DEG. MASS MAP

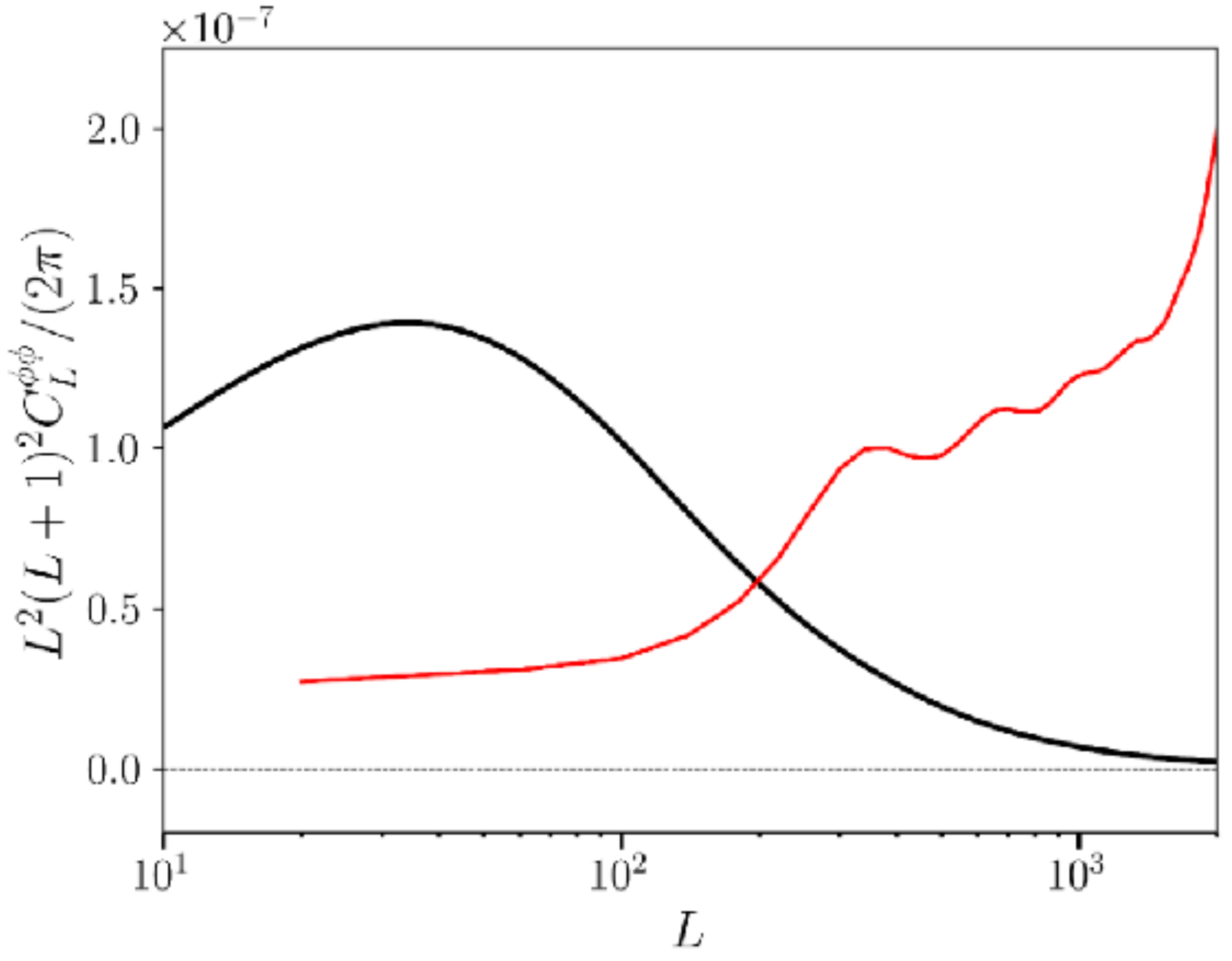


Correlation with dusty galaxies seen by eye

MEASURING THE CMB LENSING POWER SPECTRUM (NEW LENSING PIPELINE)



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



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

Schematically

Gaussian contractions give large bias

Our lensing spectrum pipeline subtracts **noise biases** from naive power spectrum

BLINDED ANALYSIS FRAMEWORK WITH EXTENSIVE NULL TEST SUITE

- DR6 lensing analysis follows blinded analysis procedure. (No comparison with theory/ other data, parameter runs)
- 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

SYSTEMATIC CHALLENGES FOR OUR MEASUREMENT

Generally, CMB lensing quite robust: known redshift and source, near-linear matter with baryonic effects currently negligible.

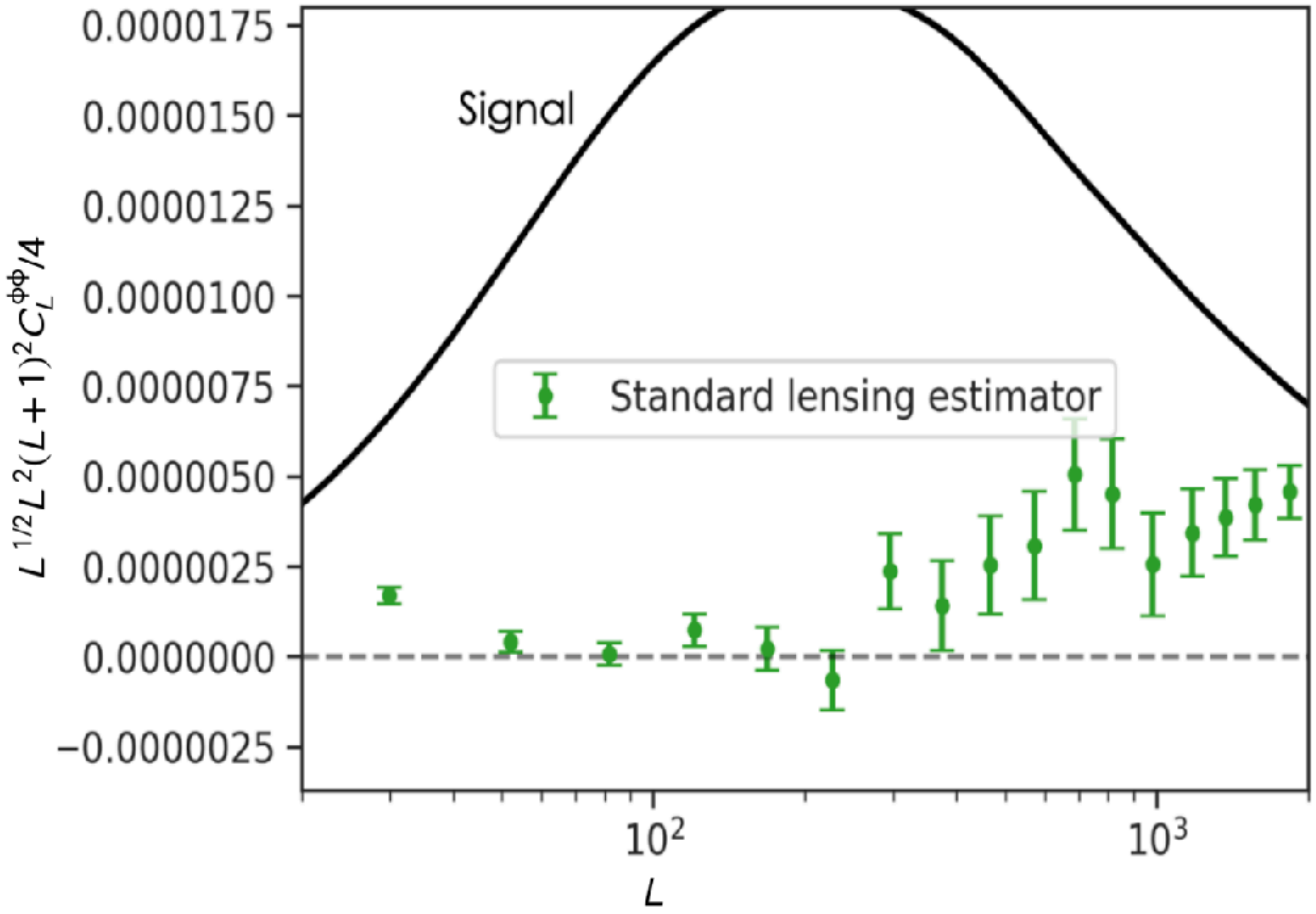
Key challenges:

- **Accuracy of ground-based noise bias subtraction**
- **Foregrounds! Mainly extragalactic**

Today's focus

Also investigated instrument-related systematics with simulations and data – crucial work led by DW. Negligible effects found (earlier simulations also show subdominant levels at our SNR).

CHALLENGE I: NOISE BIAS SUBTRACTION



- Run data **noise only** maps through lensing power spectrum pipeline.

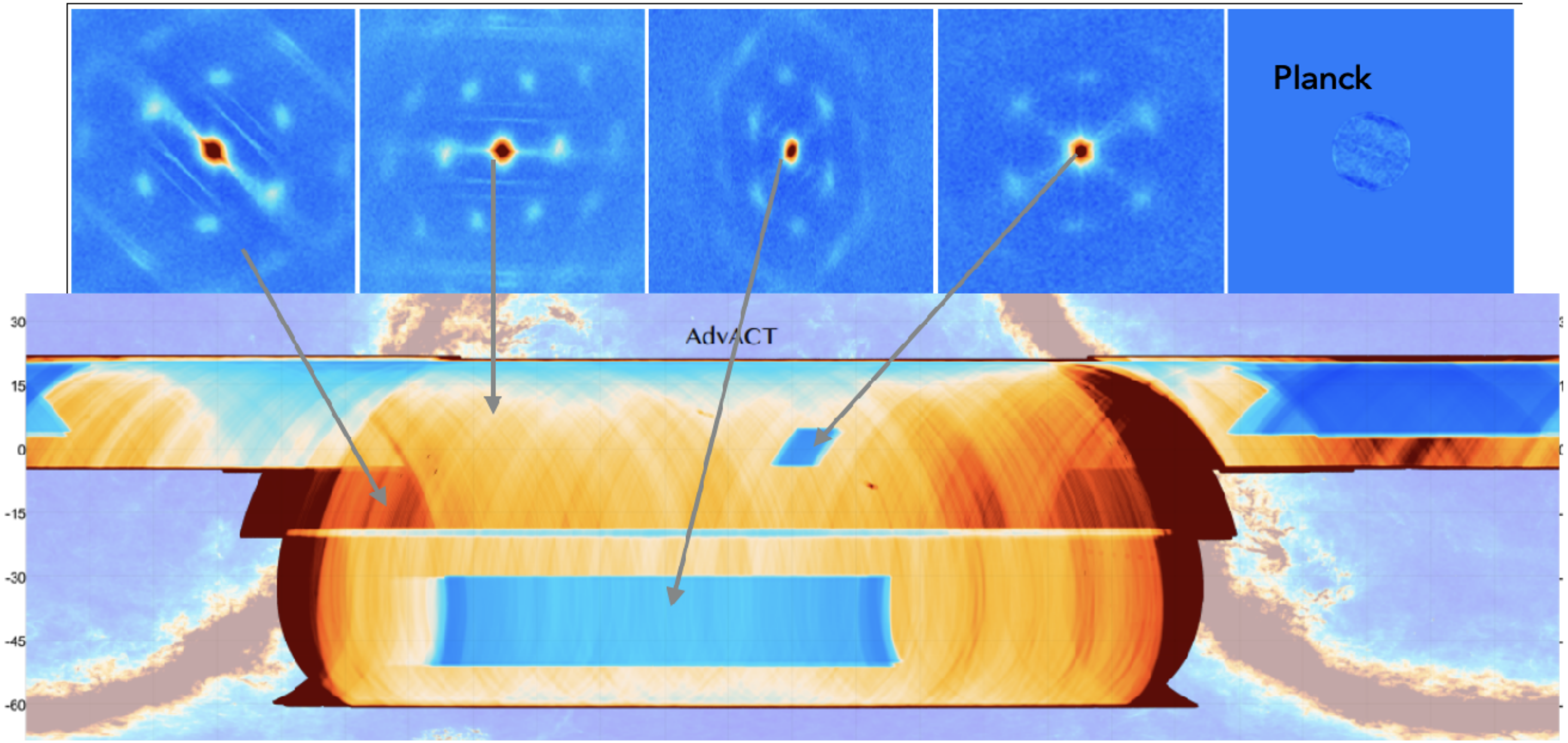
Expectation

Result should be consistent with zero.

Reality

U shape failure

CHALLENGE I: NOISE BIAS SUBTRACTION



Noise complexities for ground based surveys difficult to model.

- atmospheric noise
- spatial inhomogeneities from scan strategy

Lot of noise simulation improvements

See Atkins et al 2023

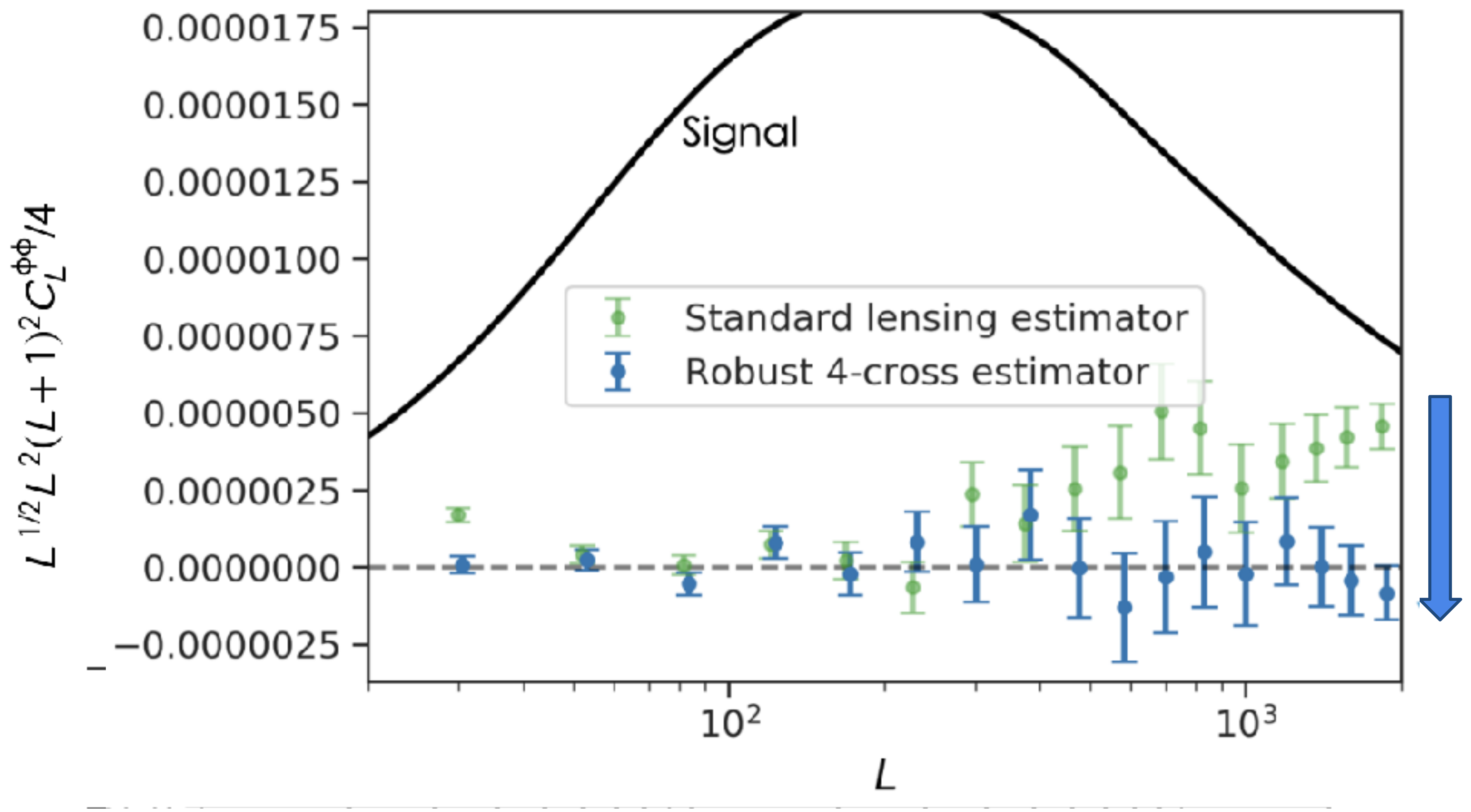

SOLUTION: CROSS CORRELATION BASED ESTIMATOR

- Use 4 CMB maps with independent noise. Immune to noise modelling

Madhavacheril, Smith, Sherwin, Naess et al 2020, JCAP

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

maps with independent noise



- Run data noise only maps through lensing power spectrum pipeline

now pass the null test with robust cross estimator

CHALLENGE II:

CONTAMINATION FROM EXTRA-GALACTIC FOREGROUNDS

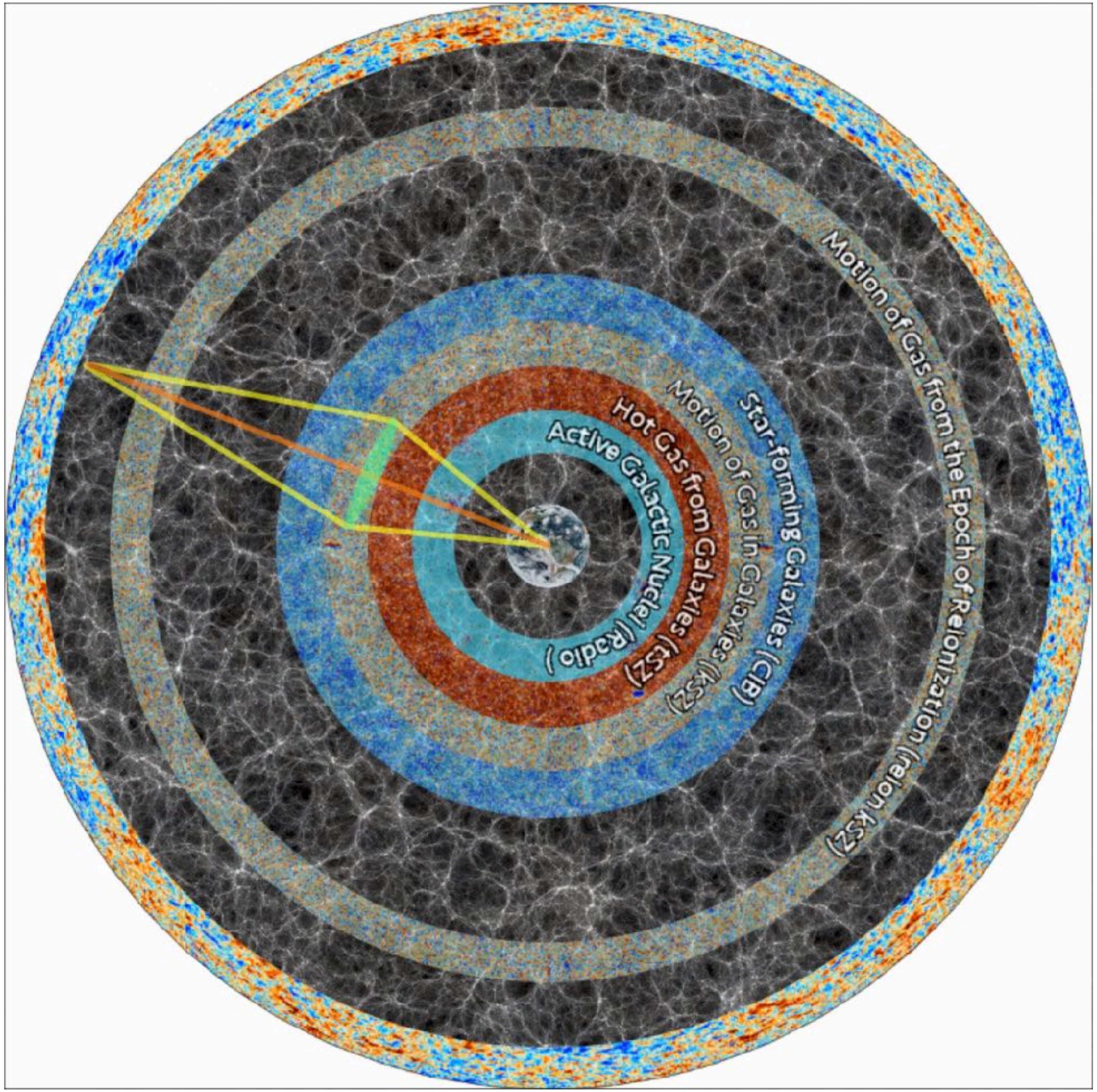
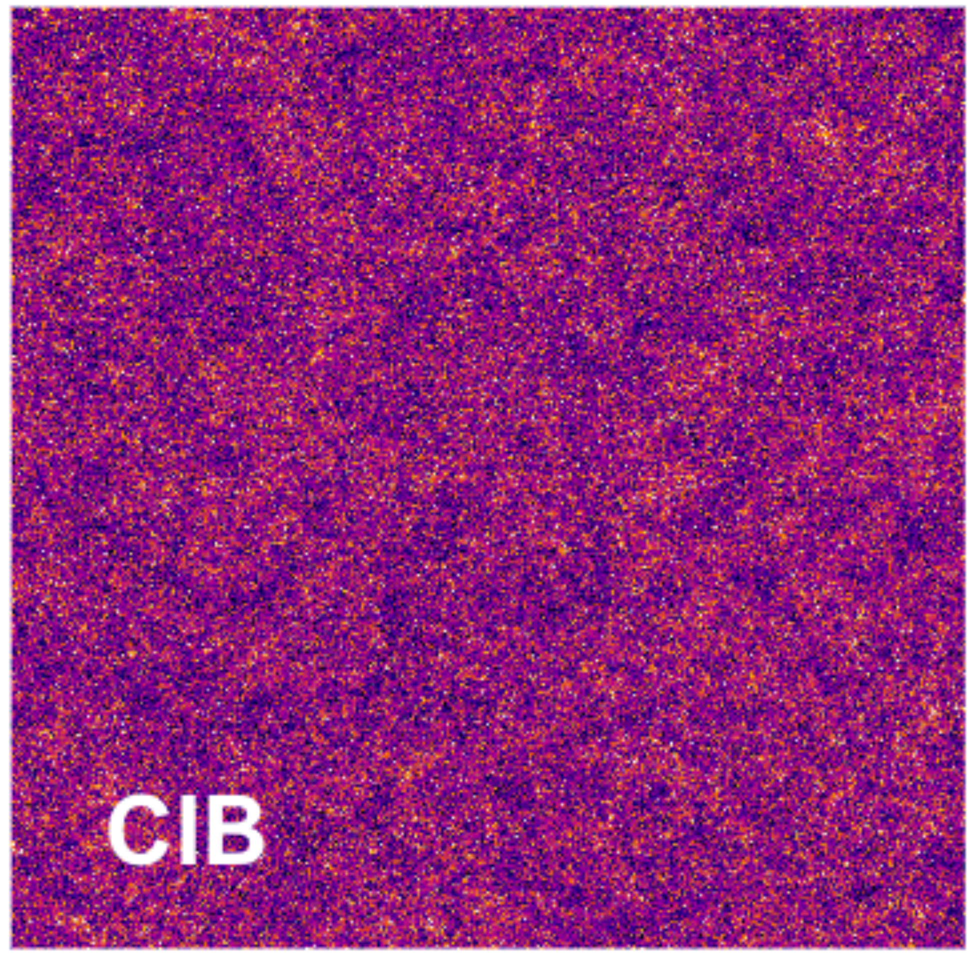
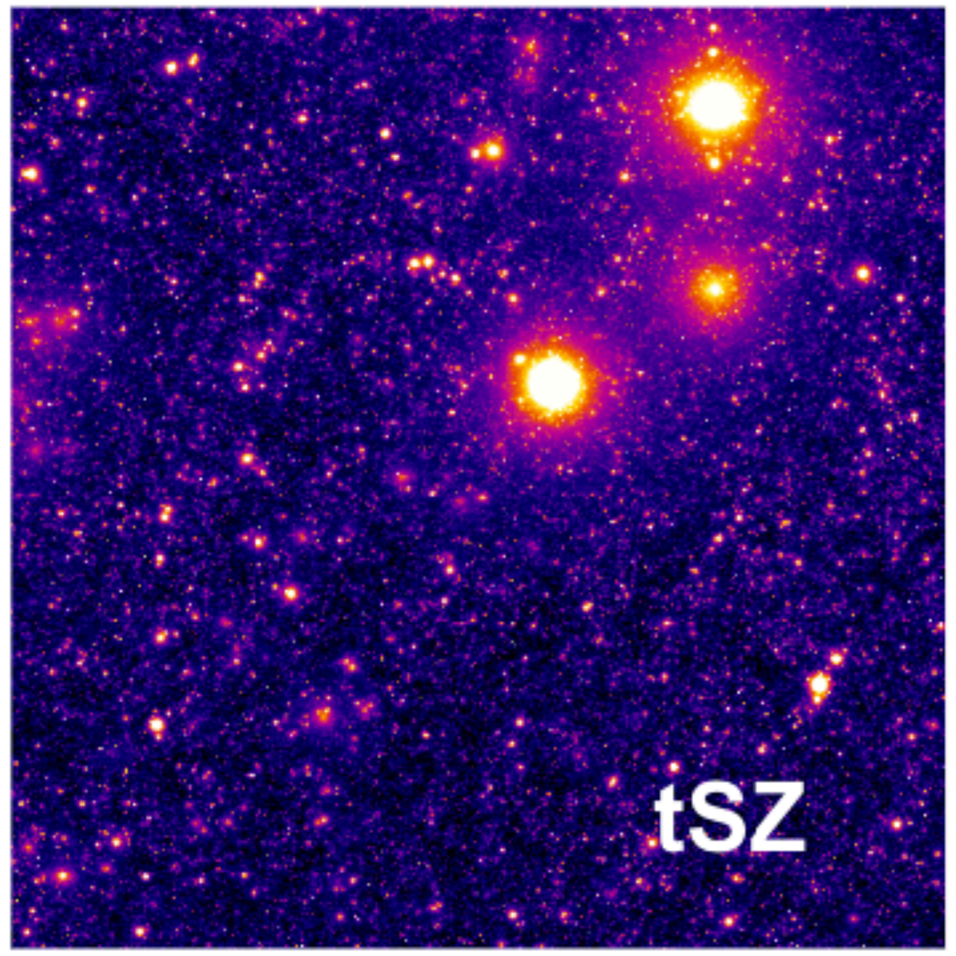
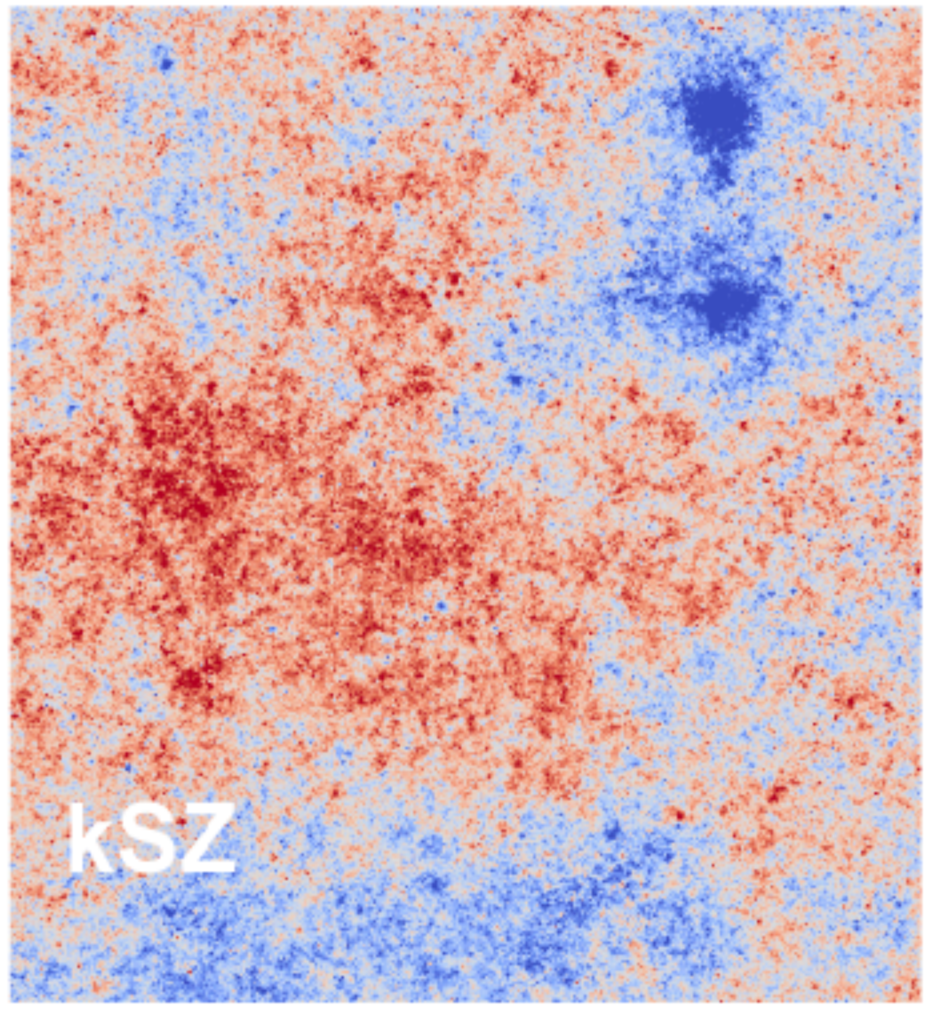


image credit: Dongwon Han

Challenge II: 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

Foreground mitigation pipeline (Simulate bias estimates)

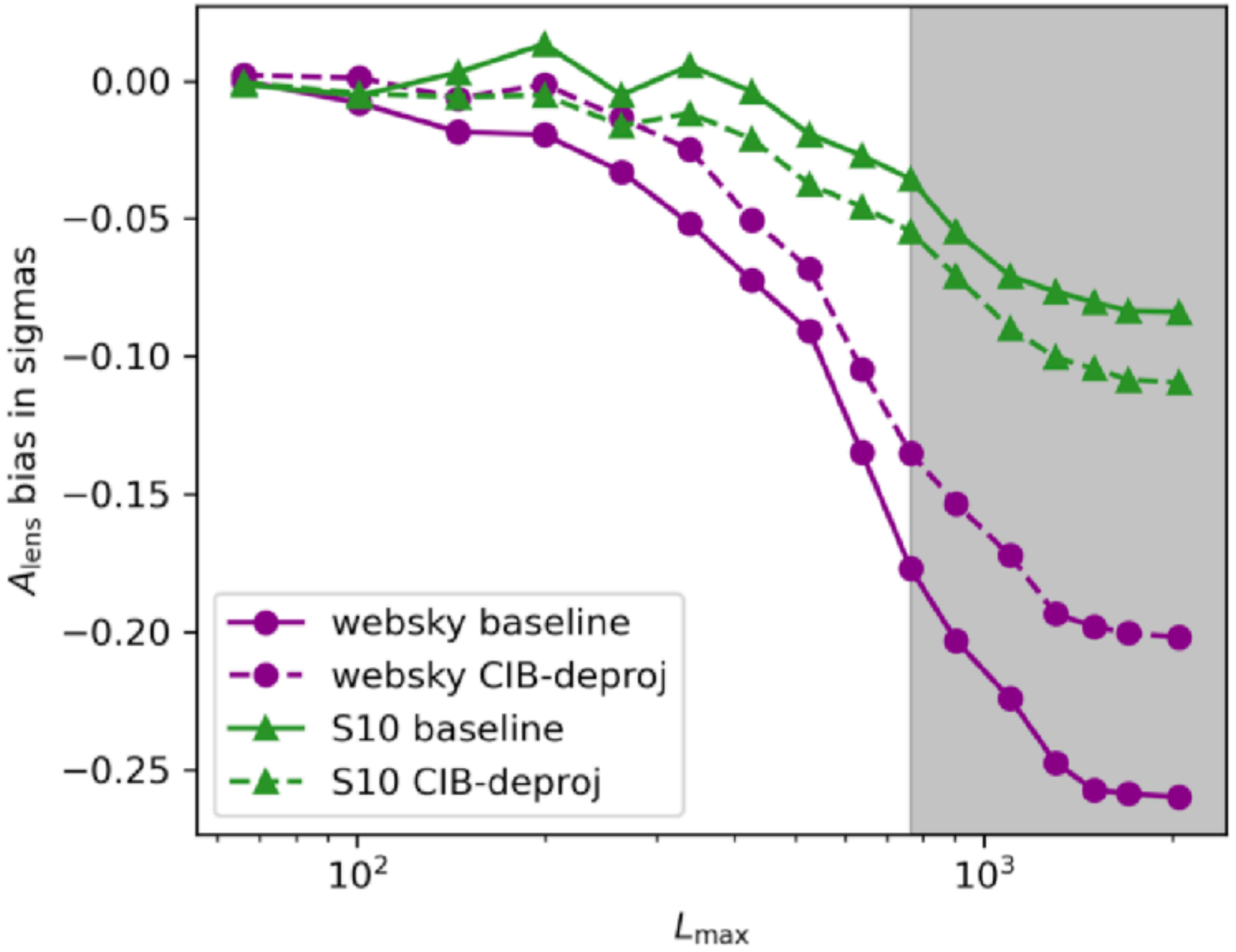
Implement curvedsky foreground mitigation methods → Test methods with simulations → Compare simulation results with data based null tests to reduce reliance to particular set of simulations.

AdvACT Lensing: Repertoire of mitigation methods

- **Geometric methods**
  - Profile hardening — Namikawa+ 2013 Osborne+2013 Sailer+2020 Sailer+2022
  - Shear — Schaan+Ferraro 2019, Qu+2022
- **Multifrequency**
  - CIB deprojection + Profile hardening

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

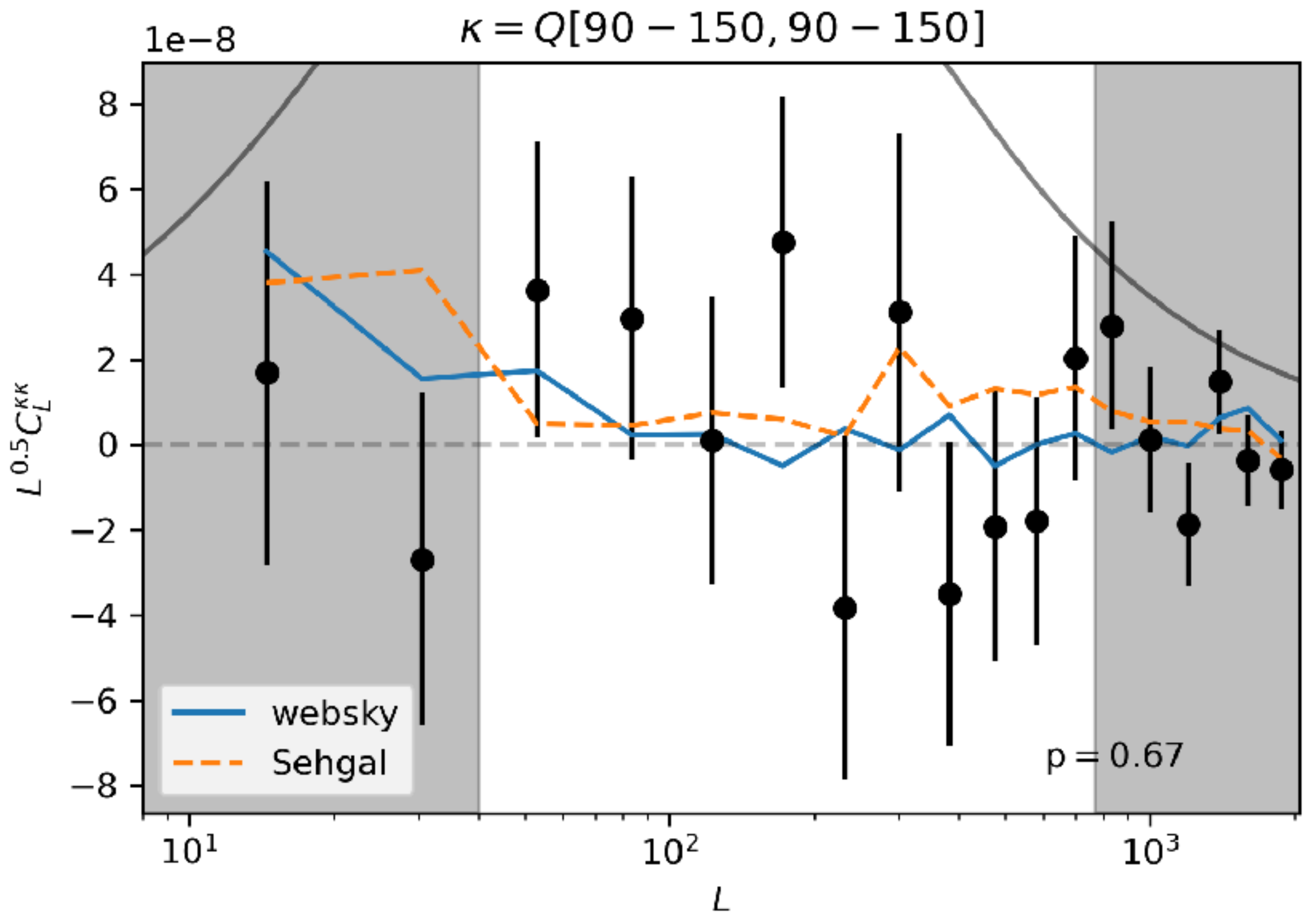
Gives foreground bias < 0.2 x statistical uncertainty



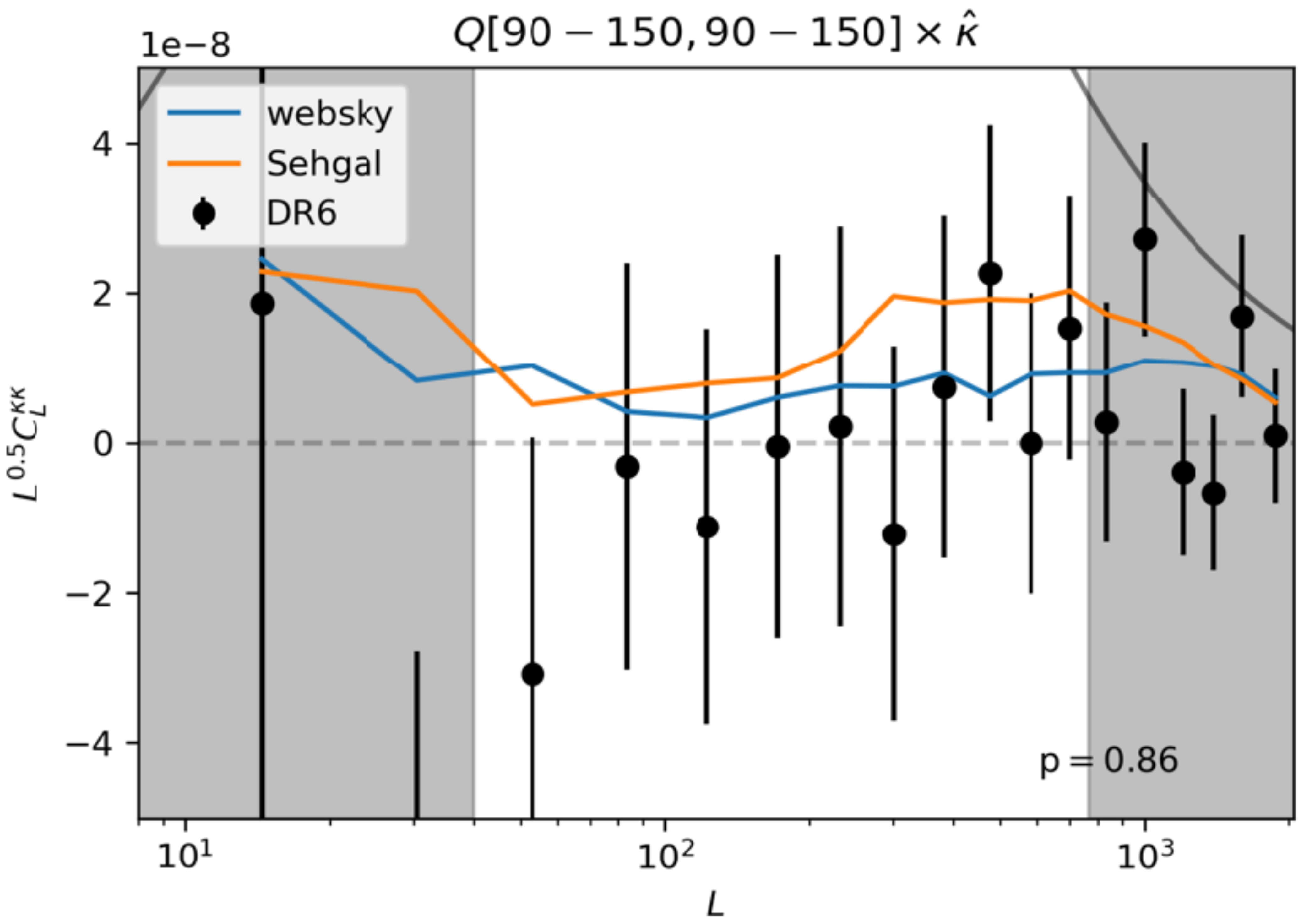
BASELINE MITIGATION TECHNIQUE: PROFILE HARDENING

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

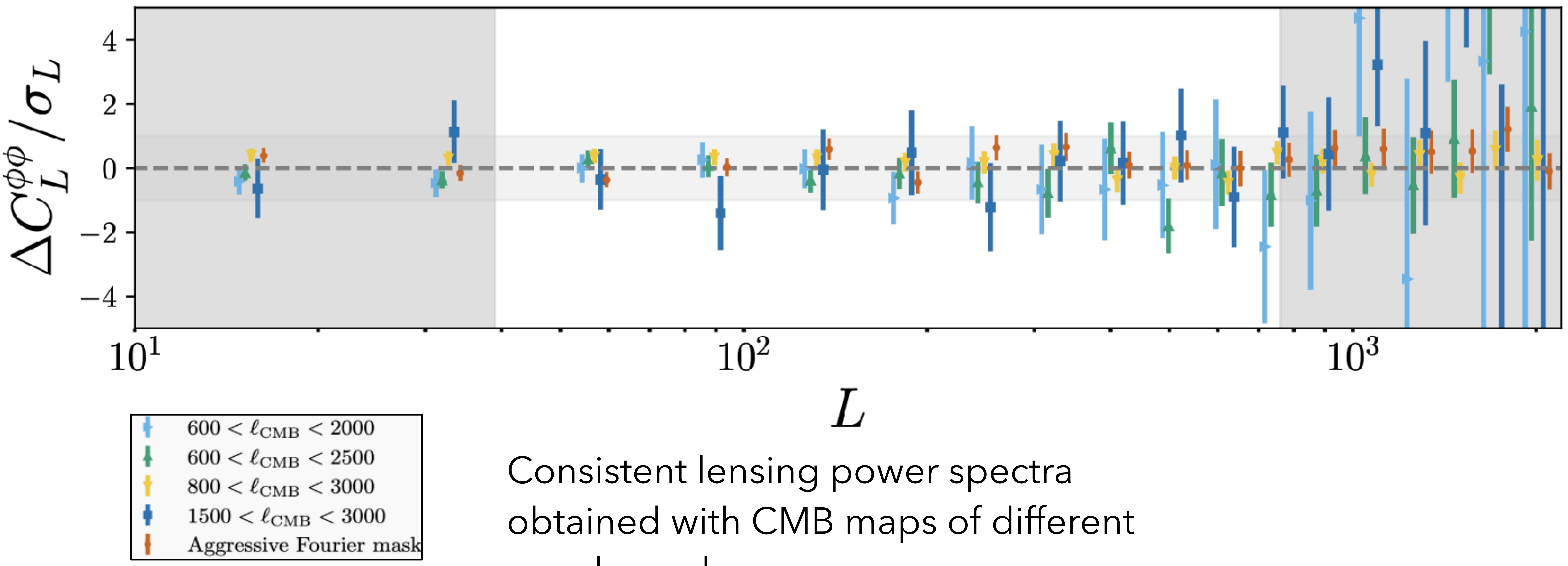


Testing the foreground trispectrum



Testing the primary bispectrum

NULL TESTS NOW PASSES! ONE EXAMPLE:

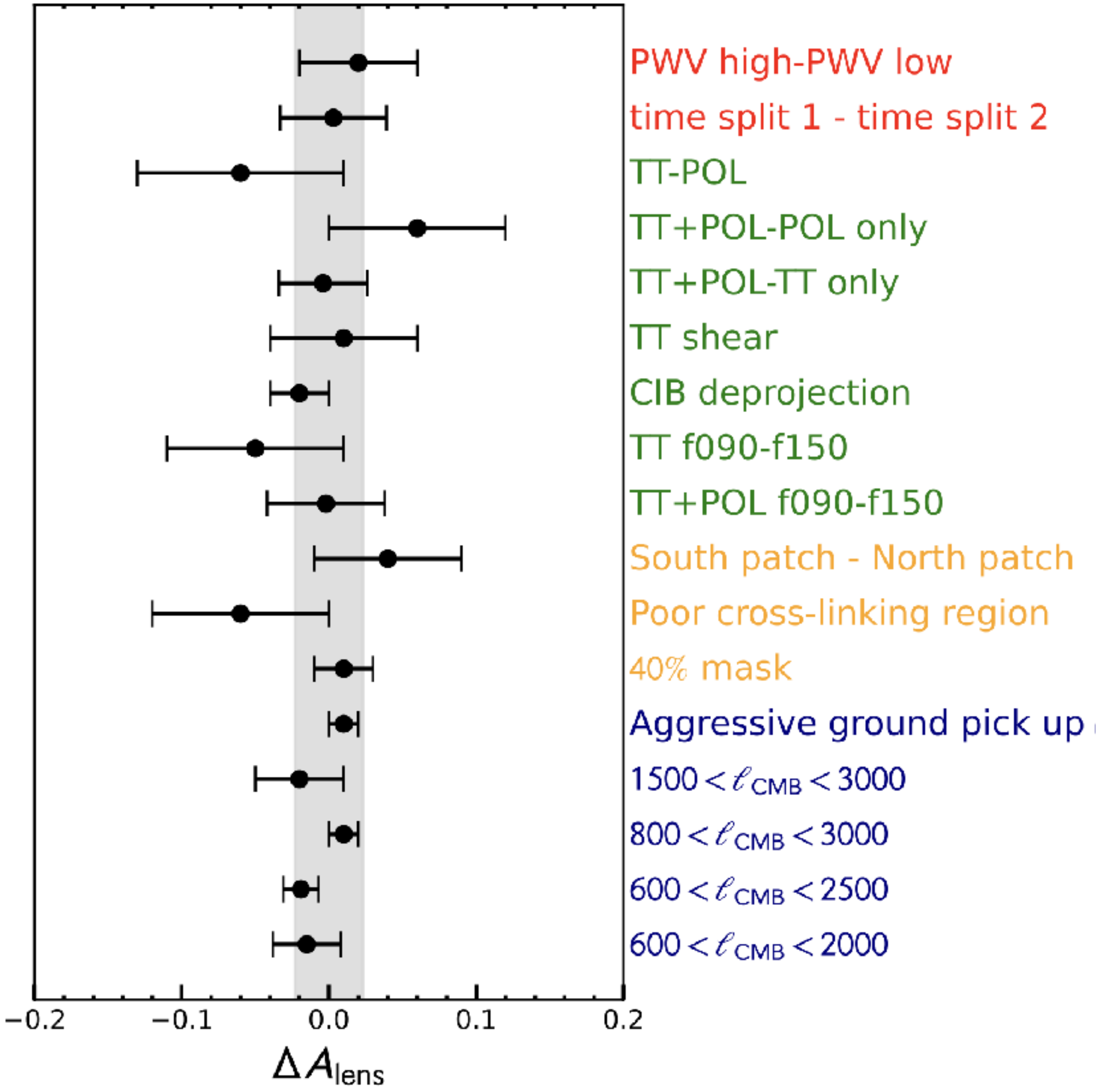


Consistent lensing power spectra obtained with CMB maps of different angular scales.

- **Consistent** lensing spectra obtained across scales, regions, frequencies, polarization combinations, instrument arrays, time,...

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

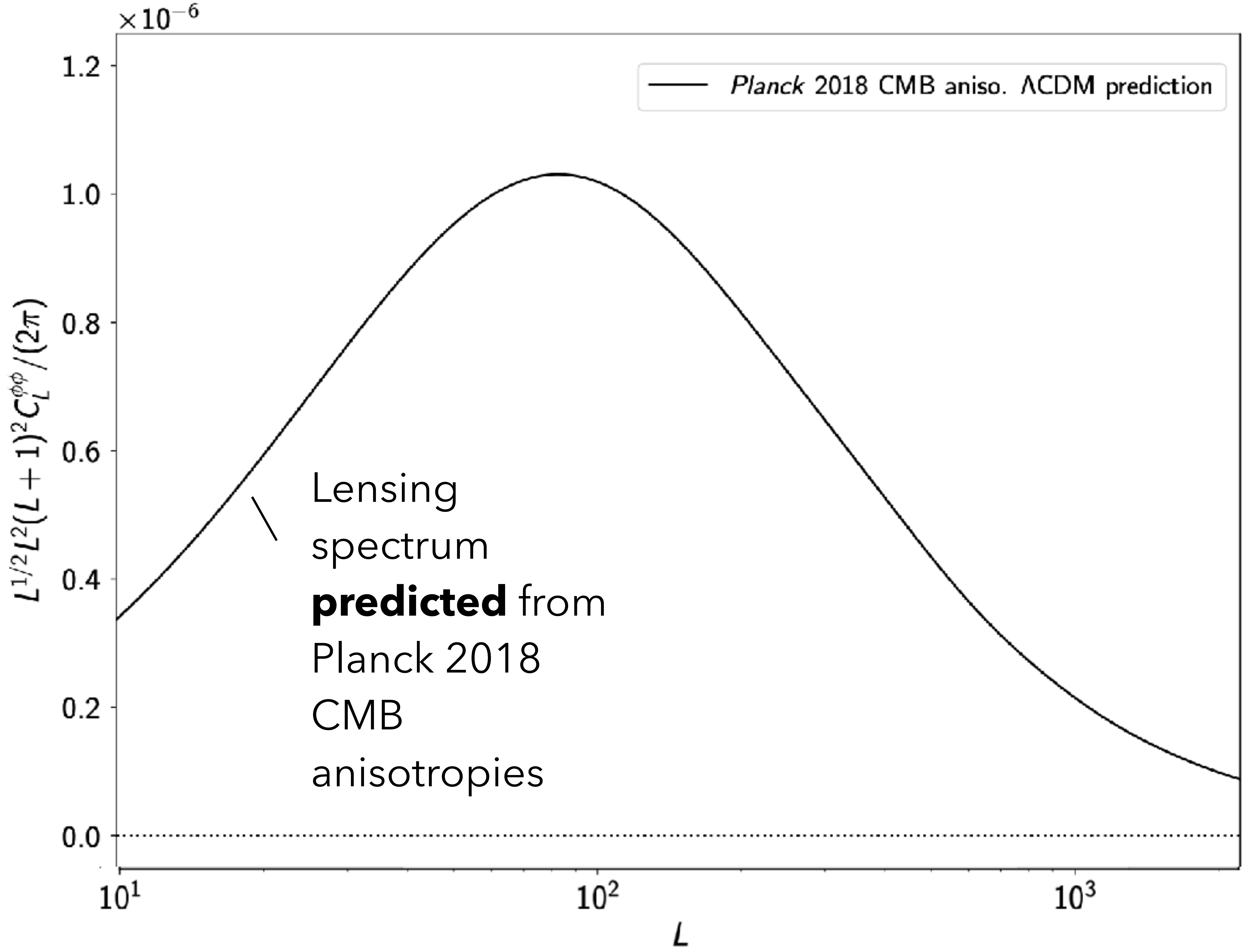
in different parts of sky

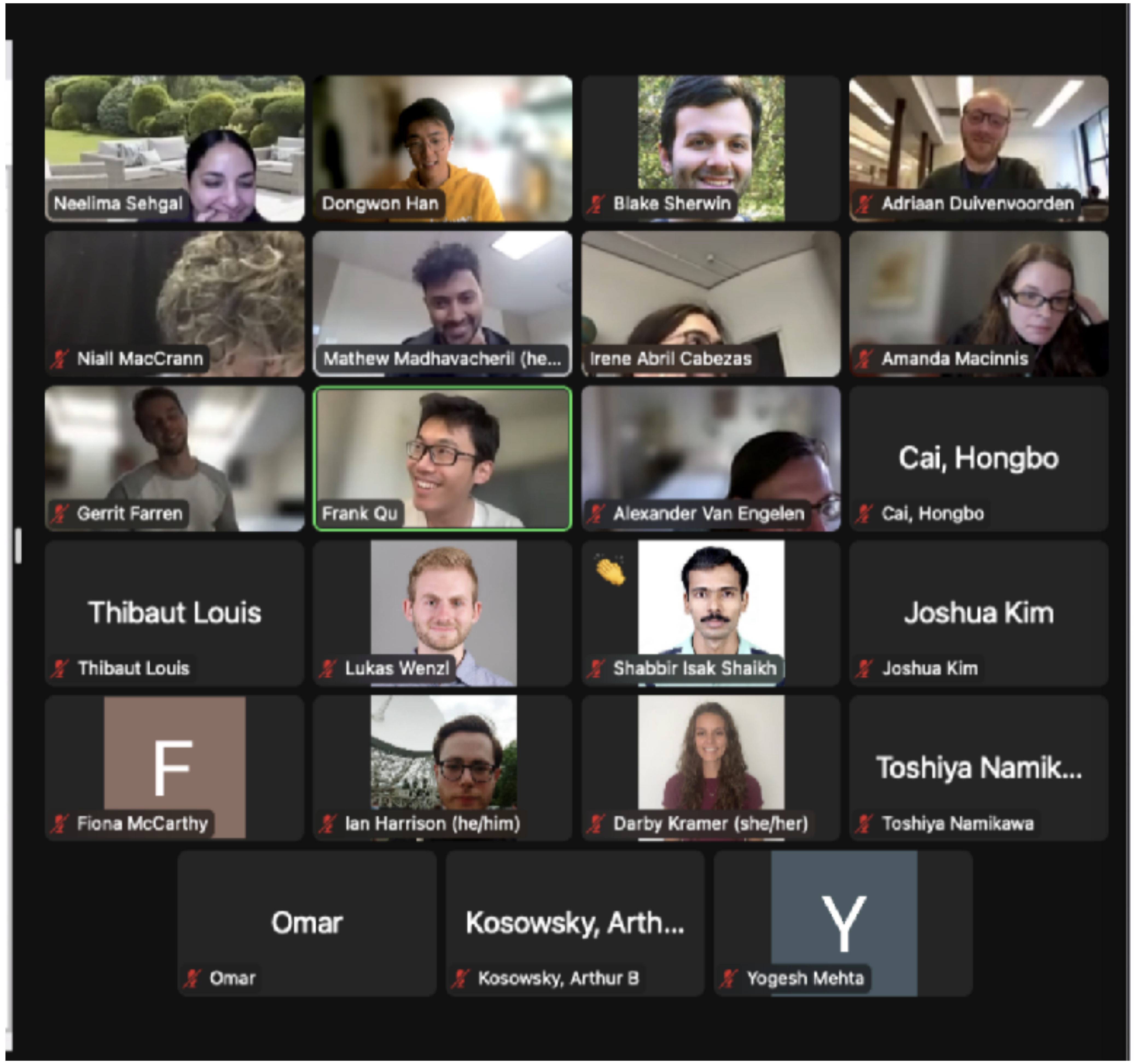
on different scales

+… many more tests!

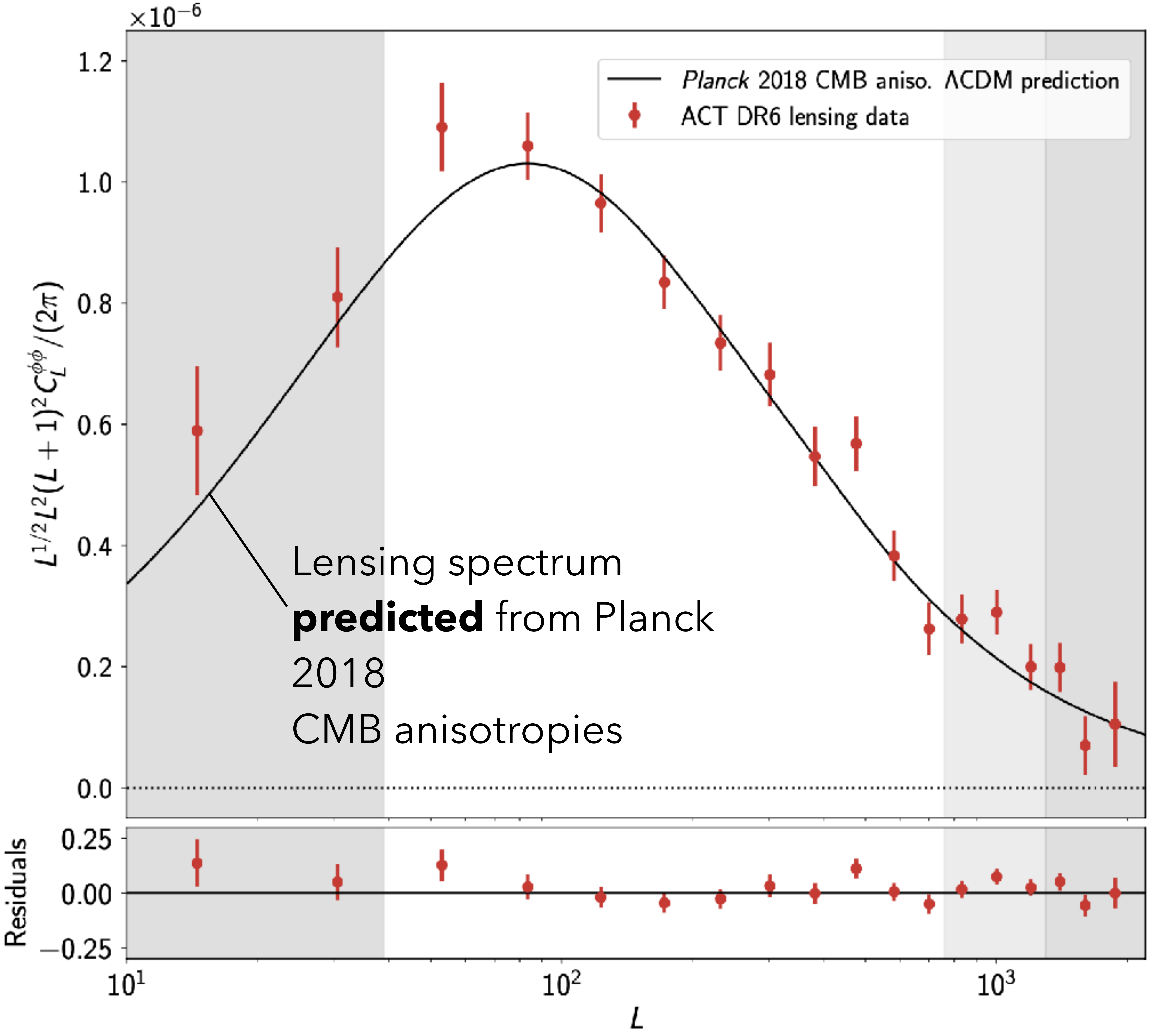
CMB LENSING POWER SPECTRUM: RESULTS AND IMPLICATIONS

PLANCK CMB ANISOTRPY PREDICTION





UNBLINDED RESULTS: ACT DR6 LENSING POWER SPECTRUM



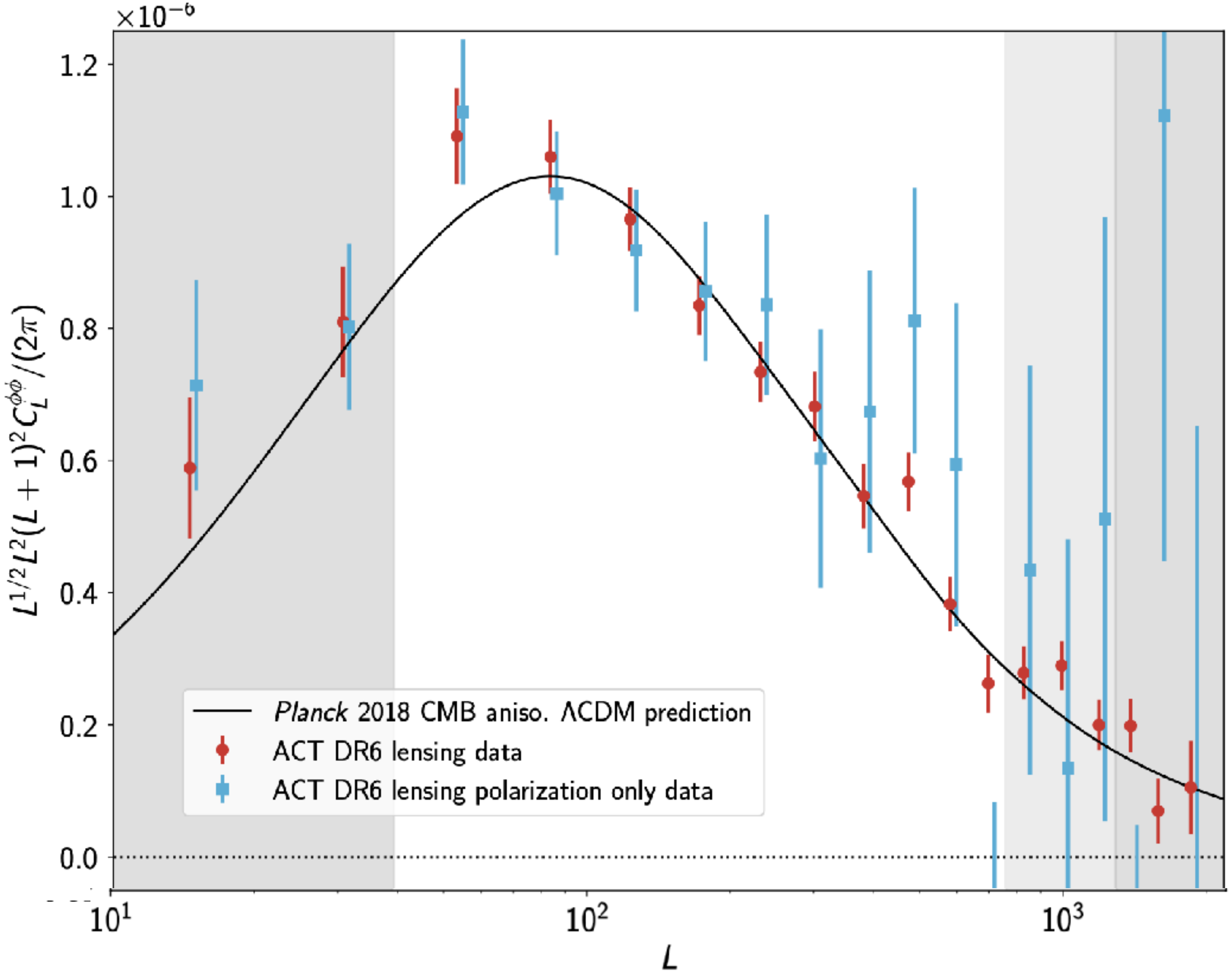
- Excellent agreement of our measurement (with no free parameters) with the LCDM theory predictions based on *Planck* 2018 CMB power spectra. A PTE of 0.17

- Amplitude of lensing (relative to theory amplitude) determined to 2.3%

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

- SNR of 43

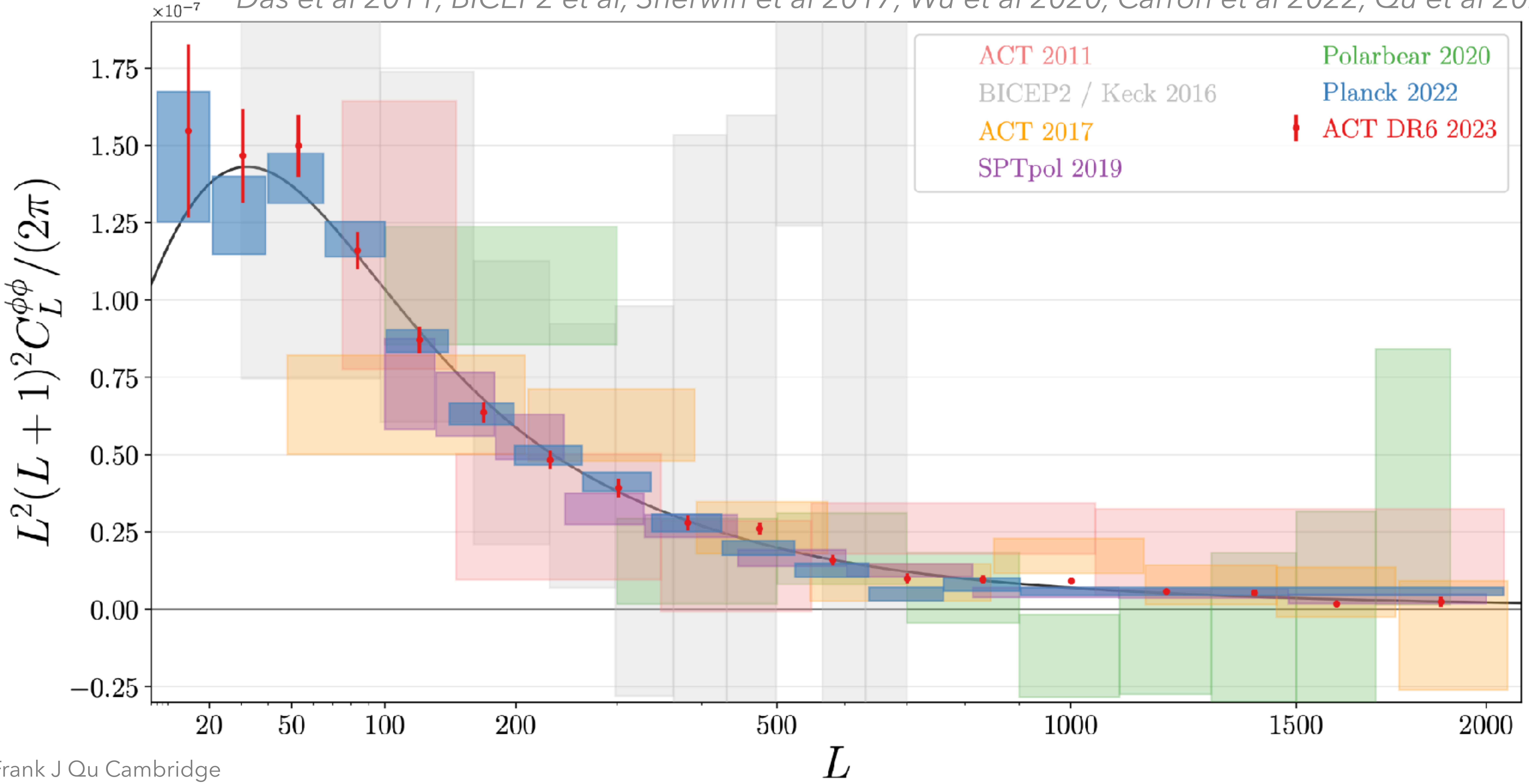
UNBLINDED RESULTS: ACT DR6 LENSING POWER SPECTRUM



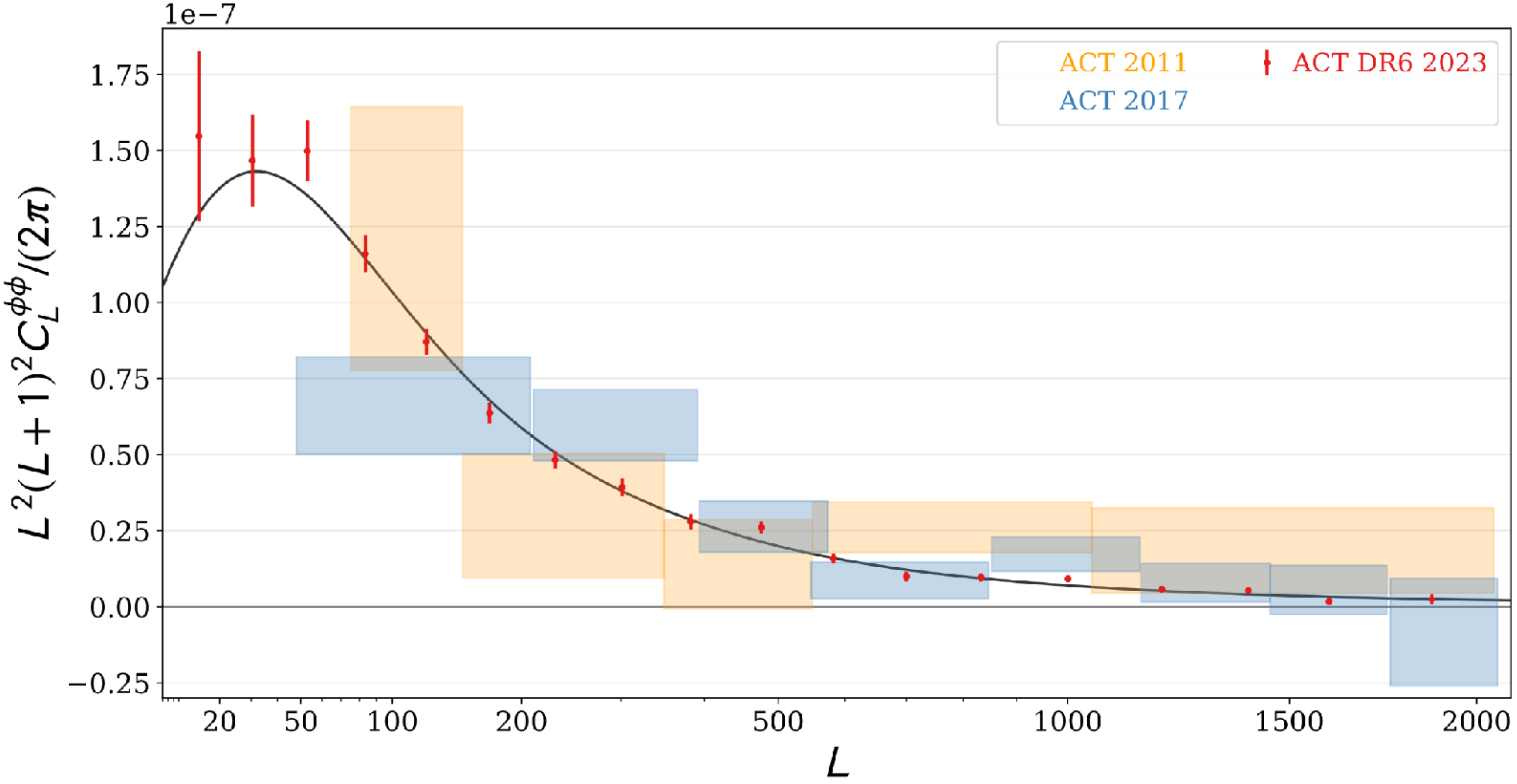
- Signal-to-noise ratio in baseline range ~43 competitive with all other weak lensing probes and Planck
- SNR - 20 using polarization data only (consistent)

PUTTING OUR MEASUREMENT IN CONTEXT

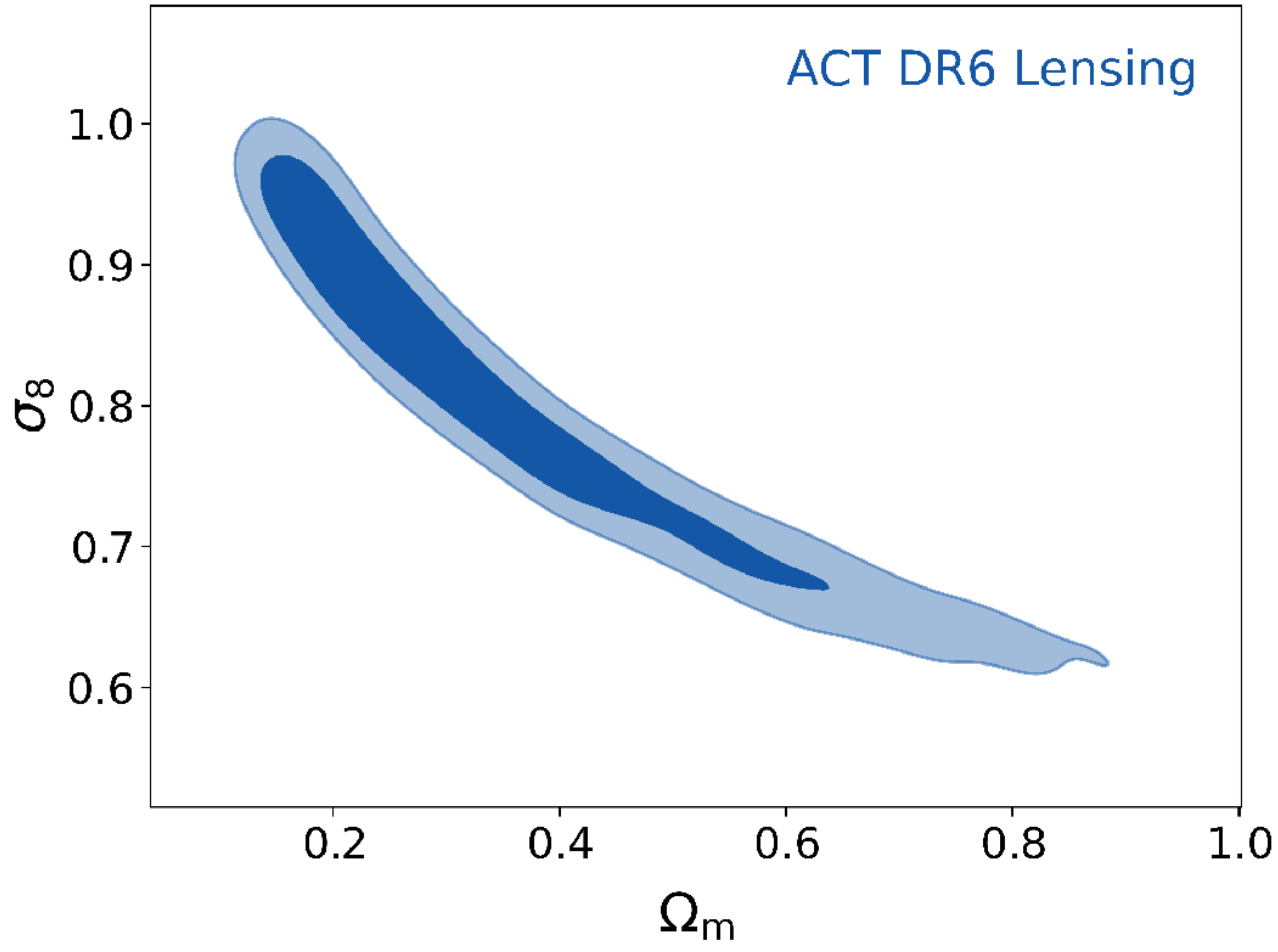
Das et al 2011, BICEP2 et al, Sherwin et al 2017, Wu et al 2020, Carron et al 2022, Qu et al 2023



RAPID PROGRESS OVER THE LAST DECADE WITH ACT AND OTHER EXPERIMENTS



COSMOLOGY FROM DR6 CMB LENSING

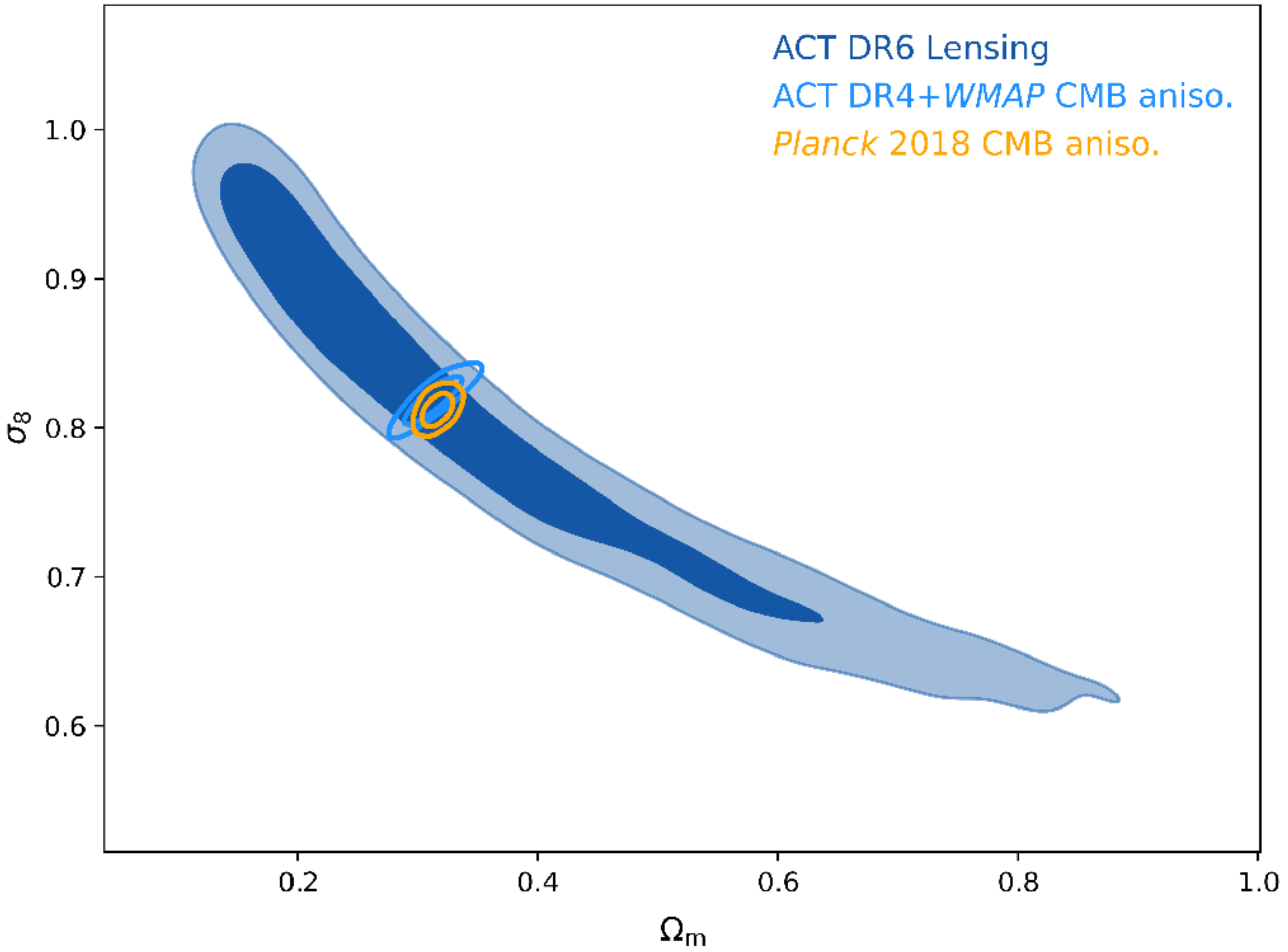


$$S_8^{\mathrm{CMBL}} \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.25}$$

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

2.7 % measurement

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



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

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

Early time CMB predictions

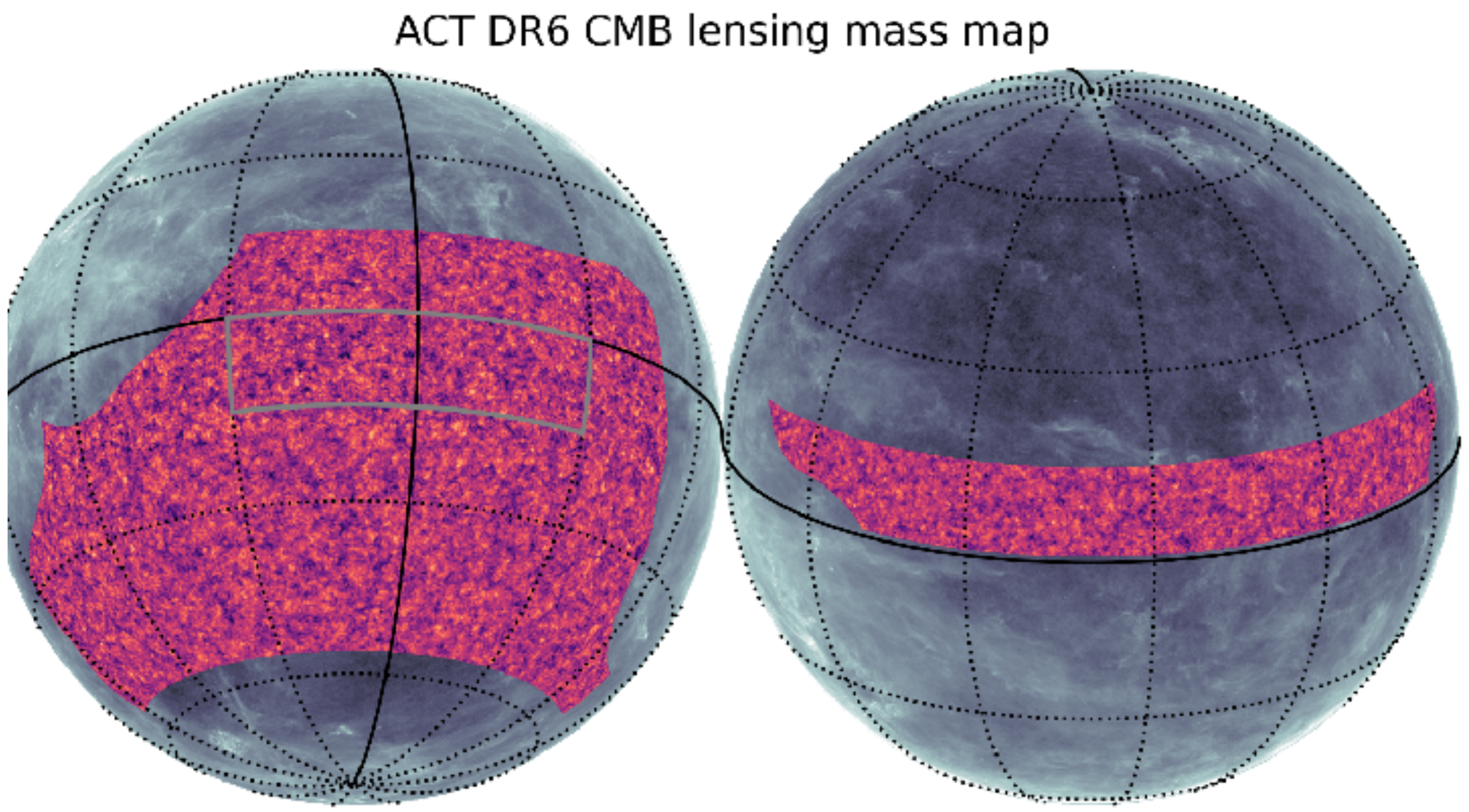
ACT DR4 + *WMAP* CMB aniso.

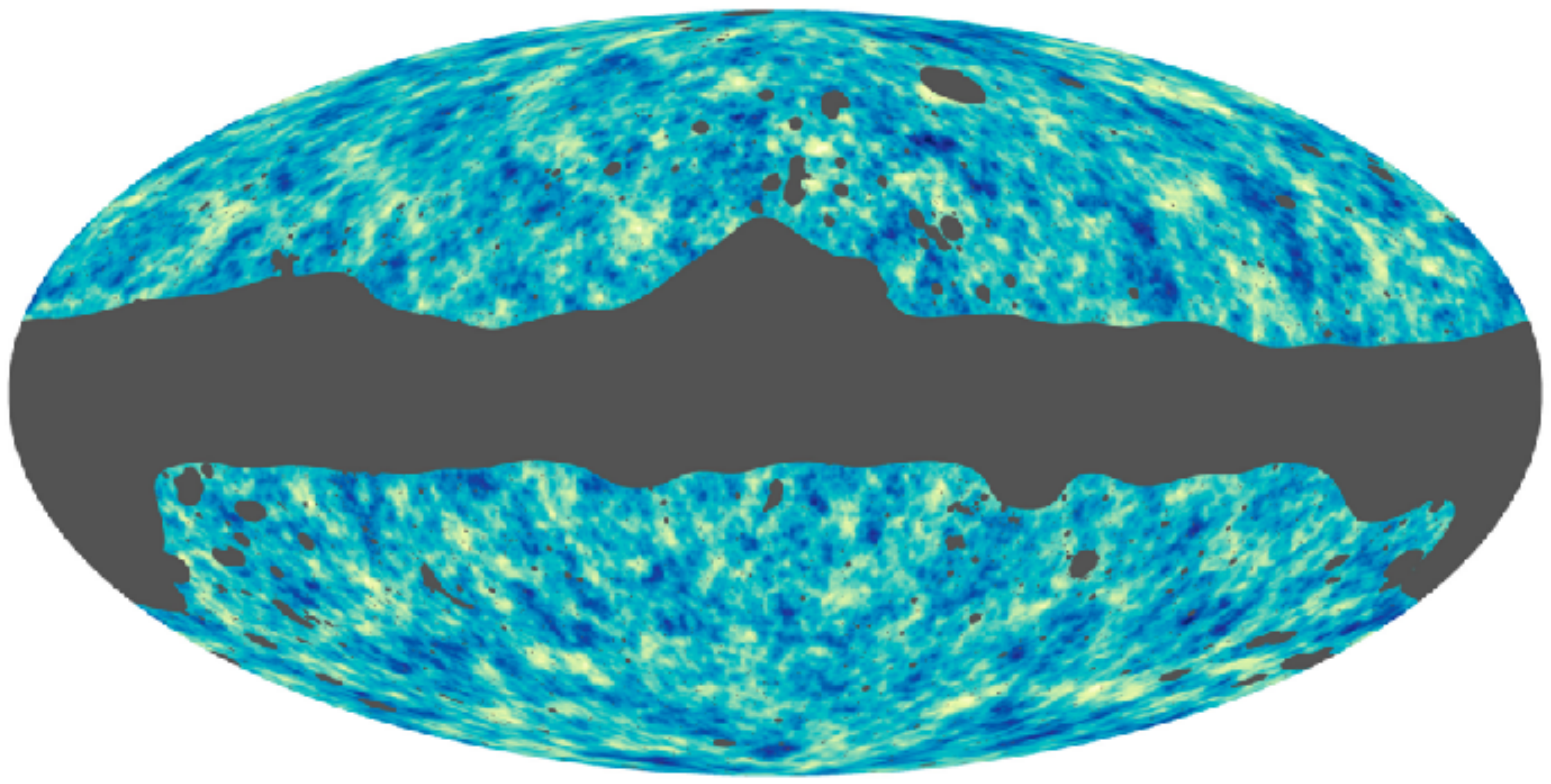
$$S_8^{\mathrm{CMBL}} = 0.828 \pm 0.020$$

Planck 2018 CMB aniso.

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

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

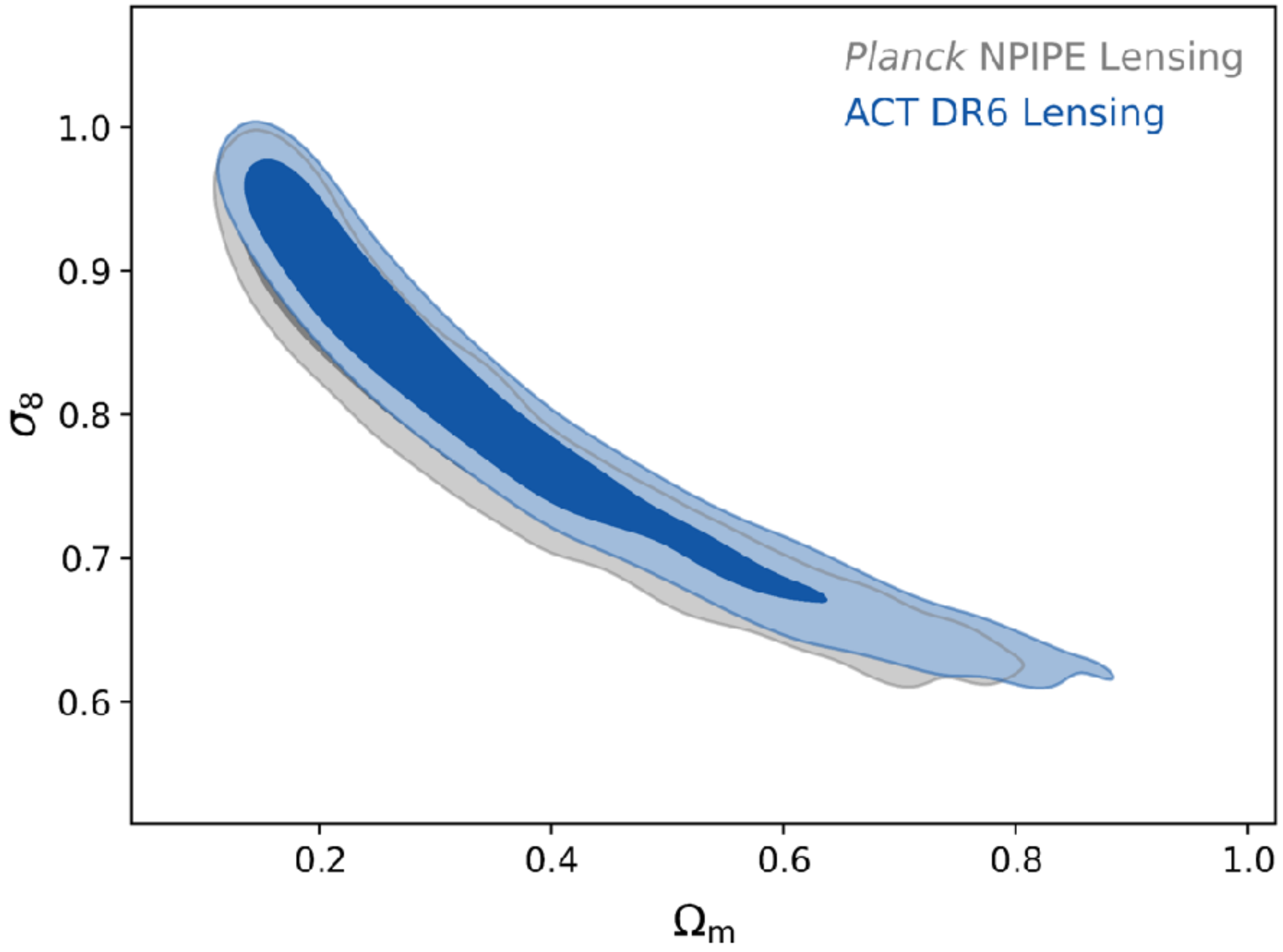




Planck lensing map

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

COMPARING ACT AND PLANCK NPIPE LENSING CONSTRAINTS



ACT DR6

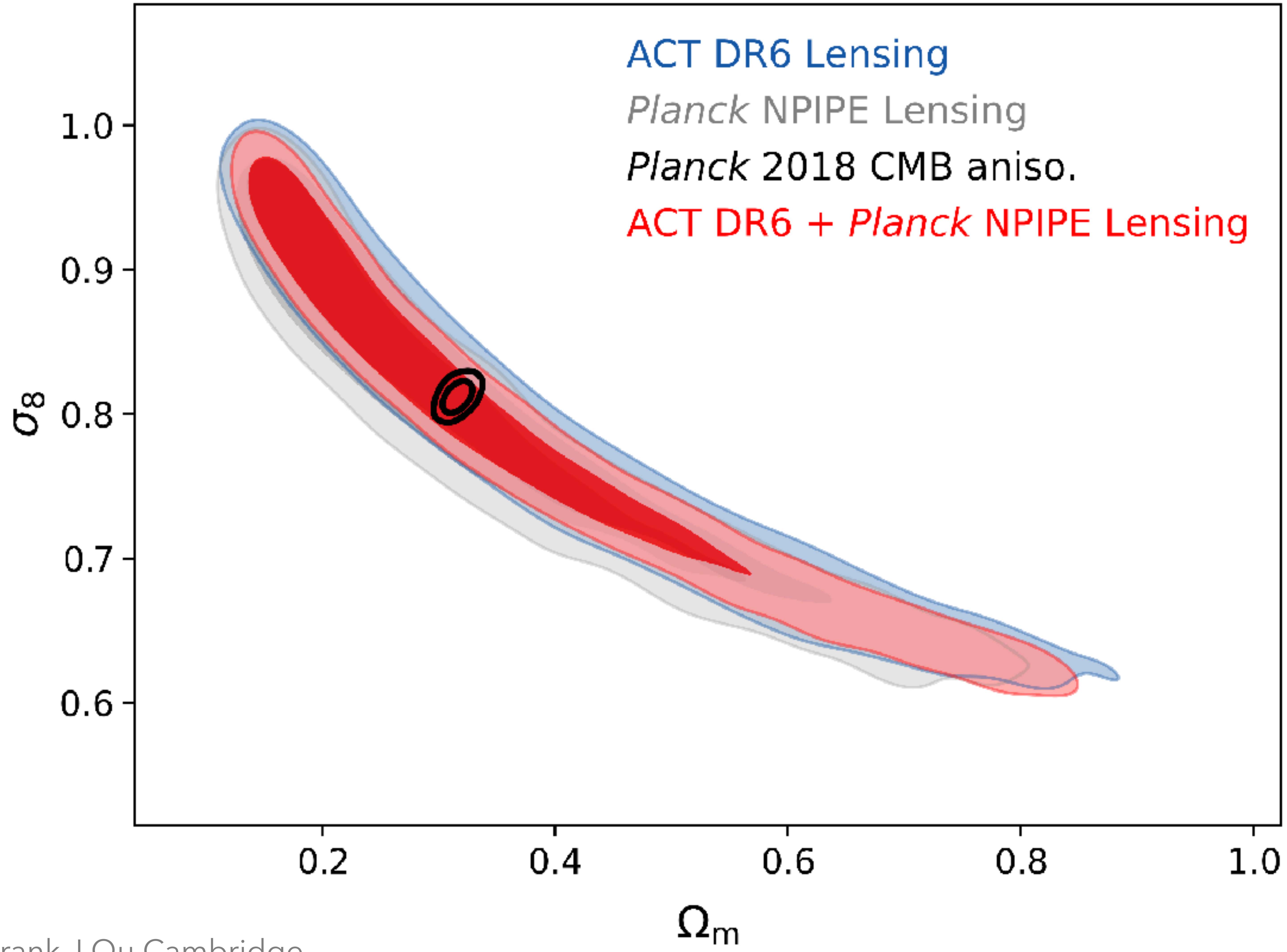
$$S_8^{\mathrm{CMBL}} = 0.818 \pm 0.022$$

Planck reanalysis

$$S_8^{\mathrm{CMBL}} = 0.802 \pm 0.024$$

- As expected, they are very consistent. Can combine!
- Since partial overlap in scales in area, must compute covariance.
- Use simulated ACT and Planck analyses of same sky to get covariance and joint likelihood

CONSTRAINT FROM ACT LENSING AND PLANCK NPIPE LENSING JOINT LIKELIHOOD

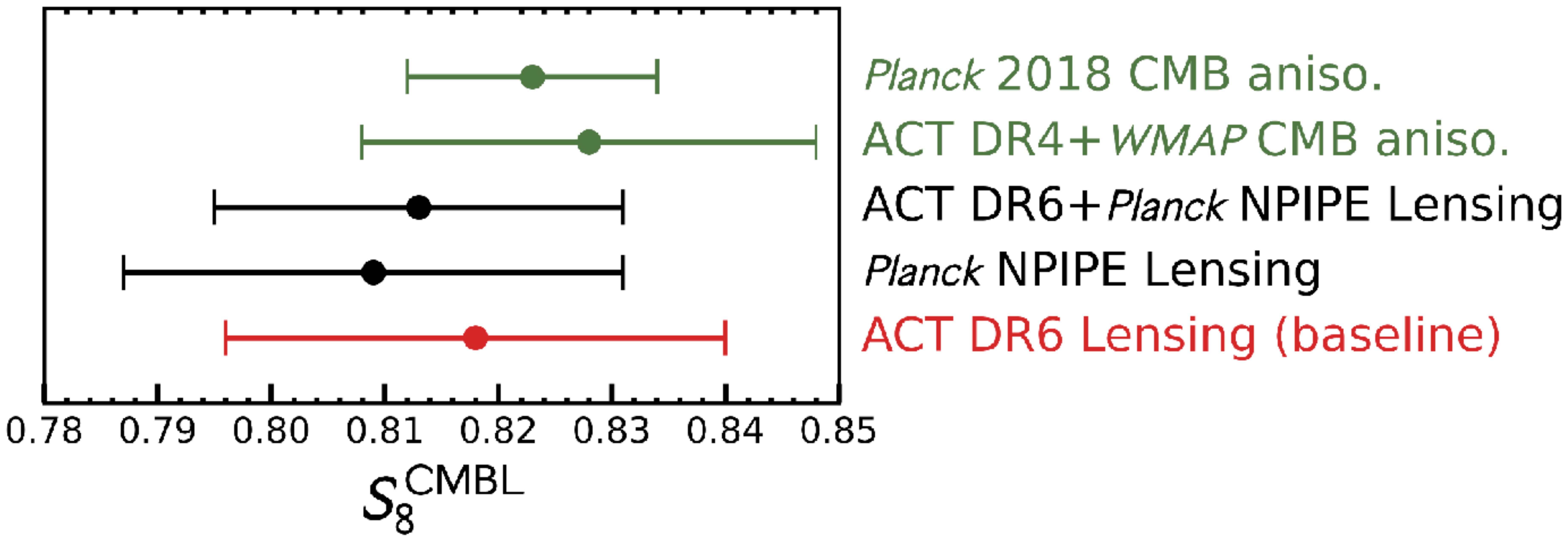


ACT+NPIPE constraint:

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

2.2% constraint from single weak lensing observable alone

DR6 CMB LENSING SPECTRUM + PLANCK COMBINATION: IMPLICATIONS

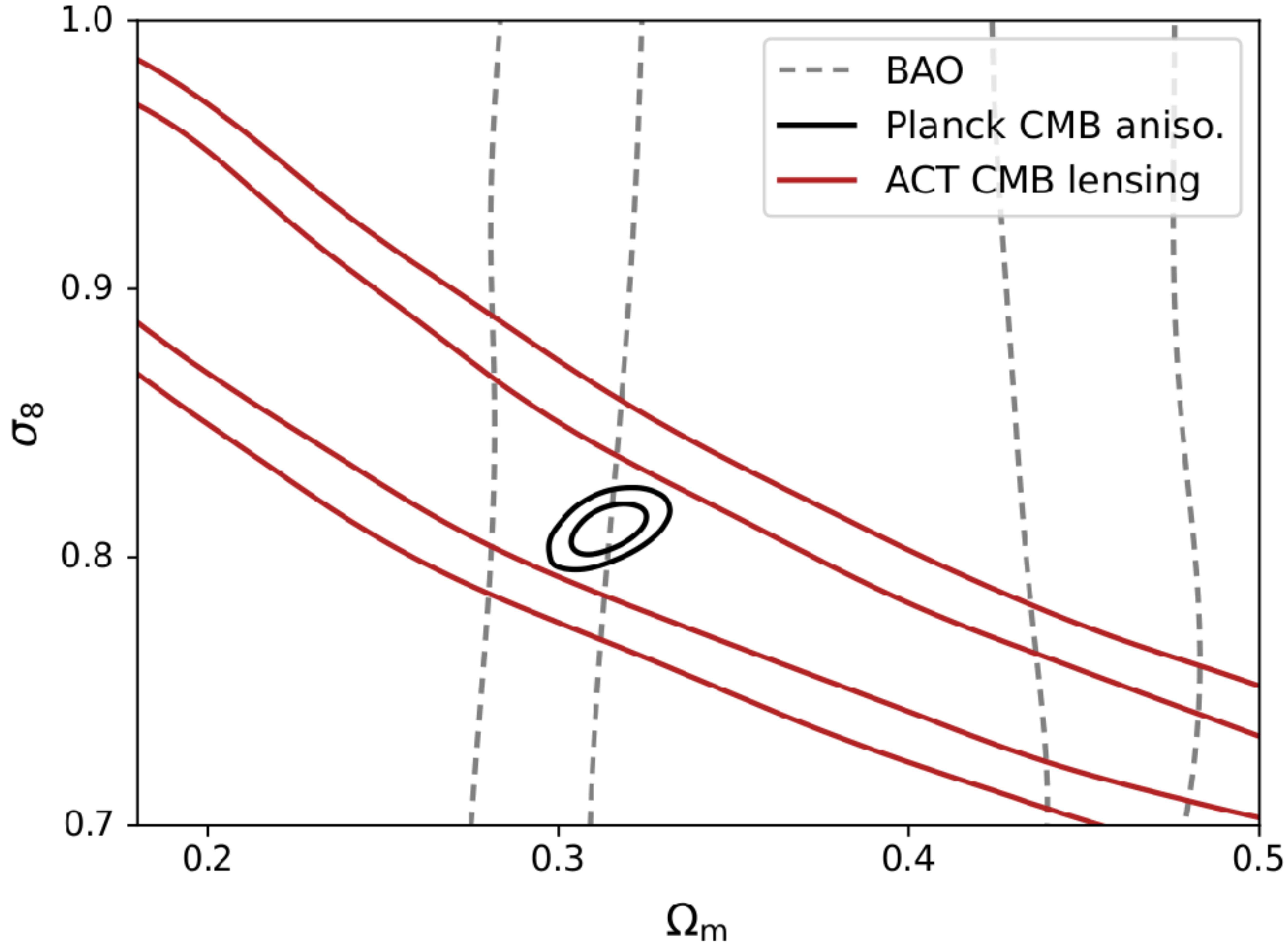


- A success for LCDM: fit Planck CMB at z~1100, predict structure to low-z, predict lensing signal arising over a wide range of z and trispectrum in ACT – agrees to 2%. Signal is not low!

- 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

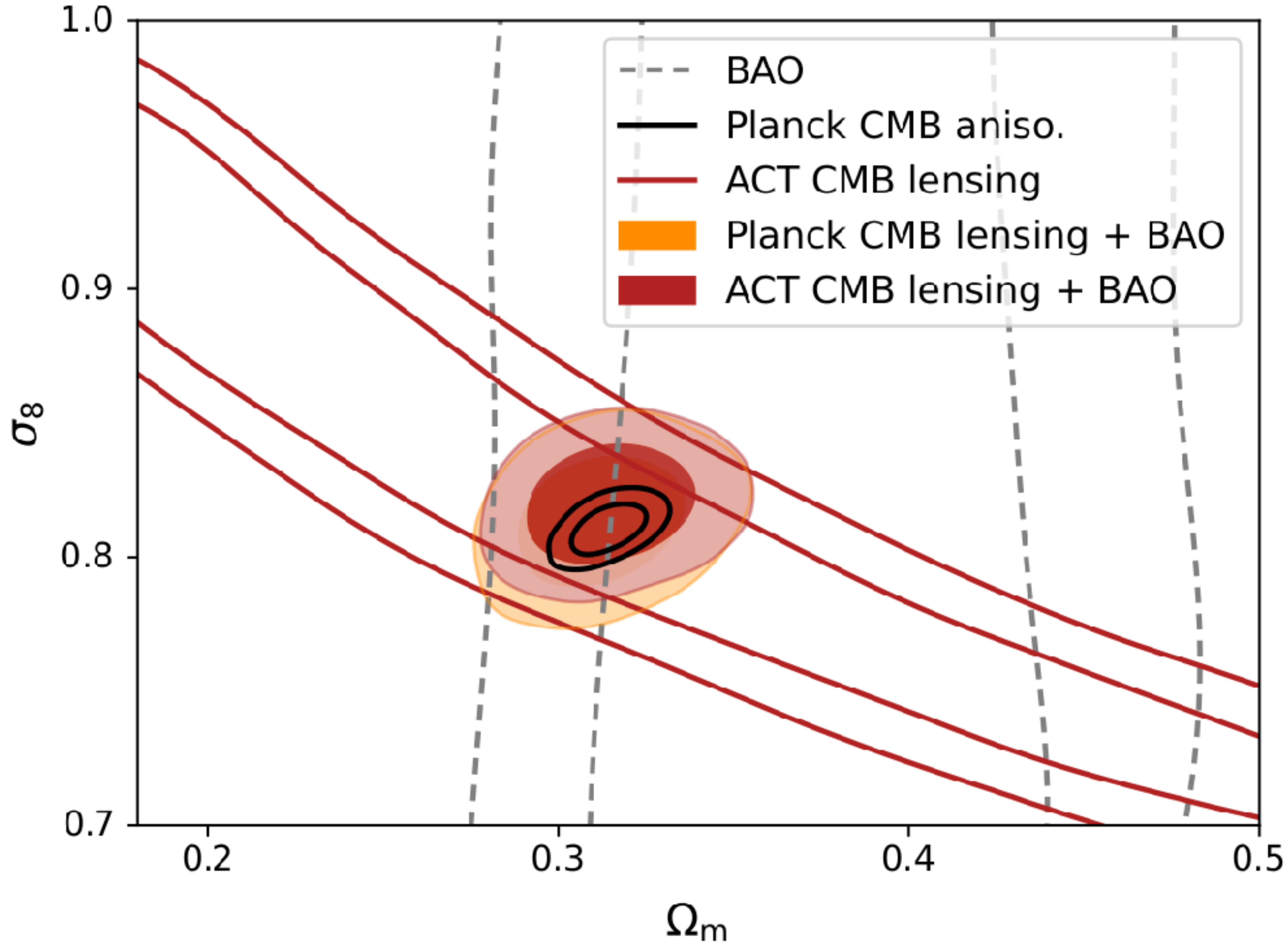


CMB lensing alone measures $\sigma_8 \, \Omega_m^{0.25}$

Combination with BAO* isolates σ_8

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

DR6 CMB LENSING + BAO



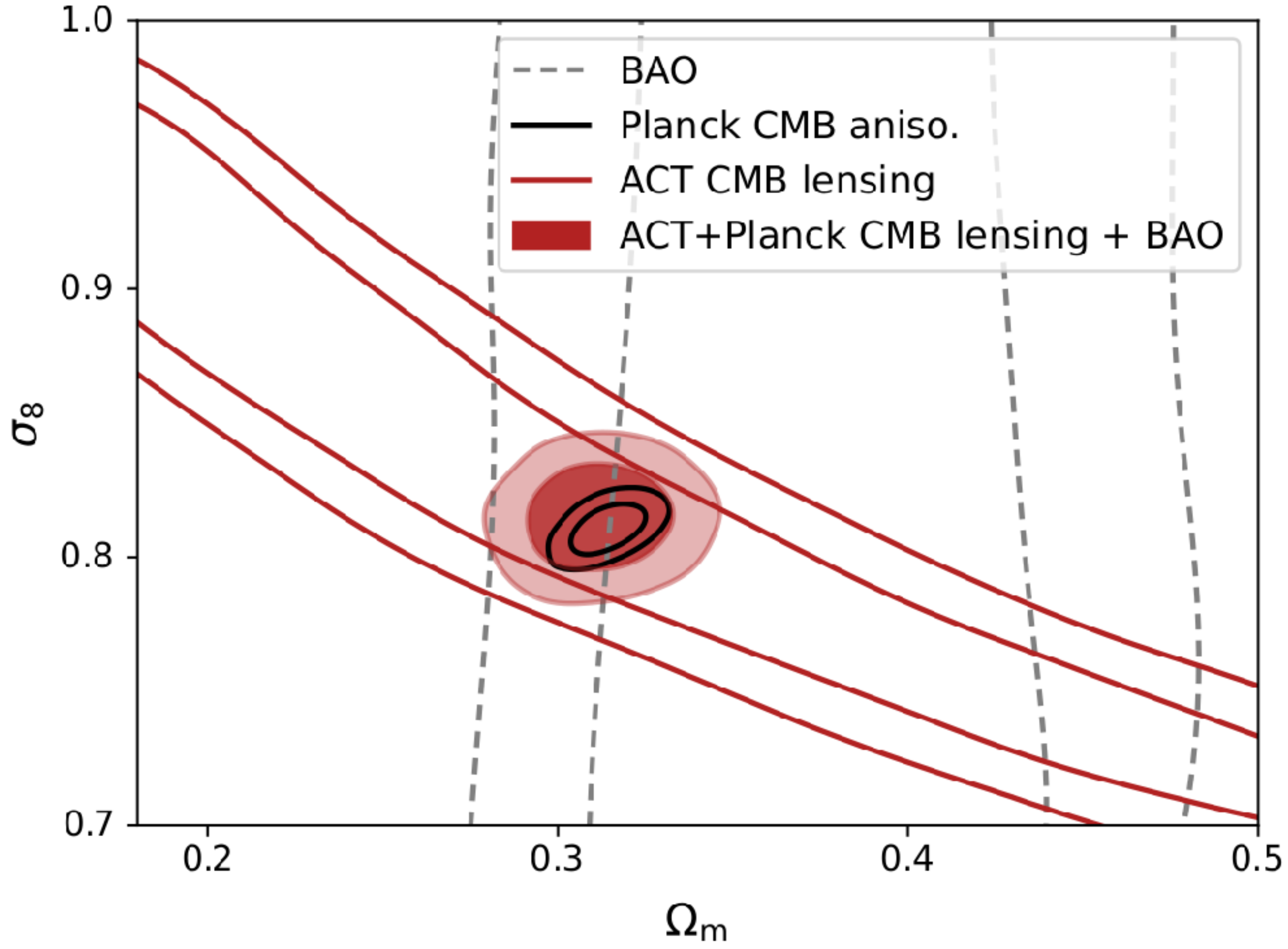
CMB lensing alone measures $\sigma_8 \, \Omega_m^{0.25}$

Combination with BAO isolates σ_8

$$\sigma_8 = 0.819 \pm 0.015$$

1.8% measurement

DR6 + PLANCK CMB LENSING + BAO



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

Combination with BAO isolates σ_8

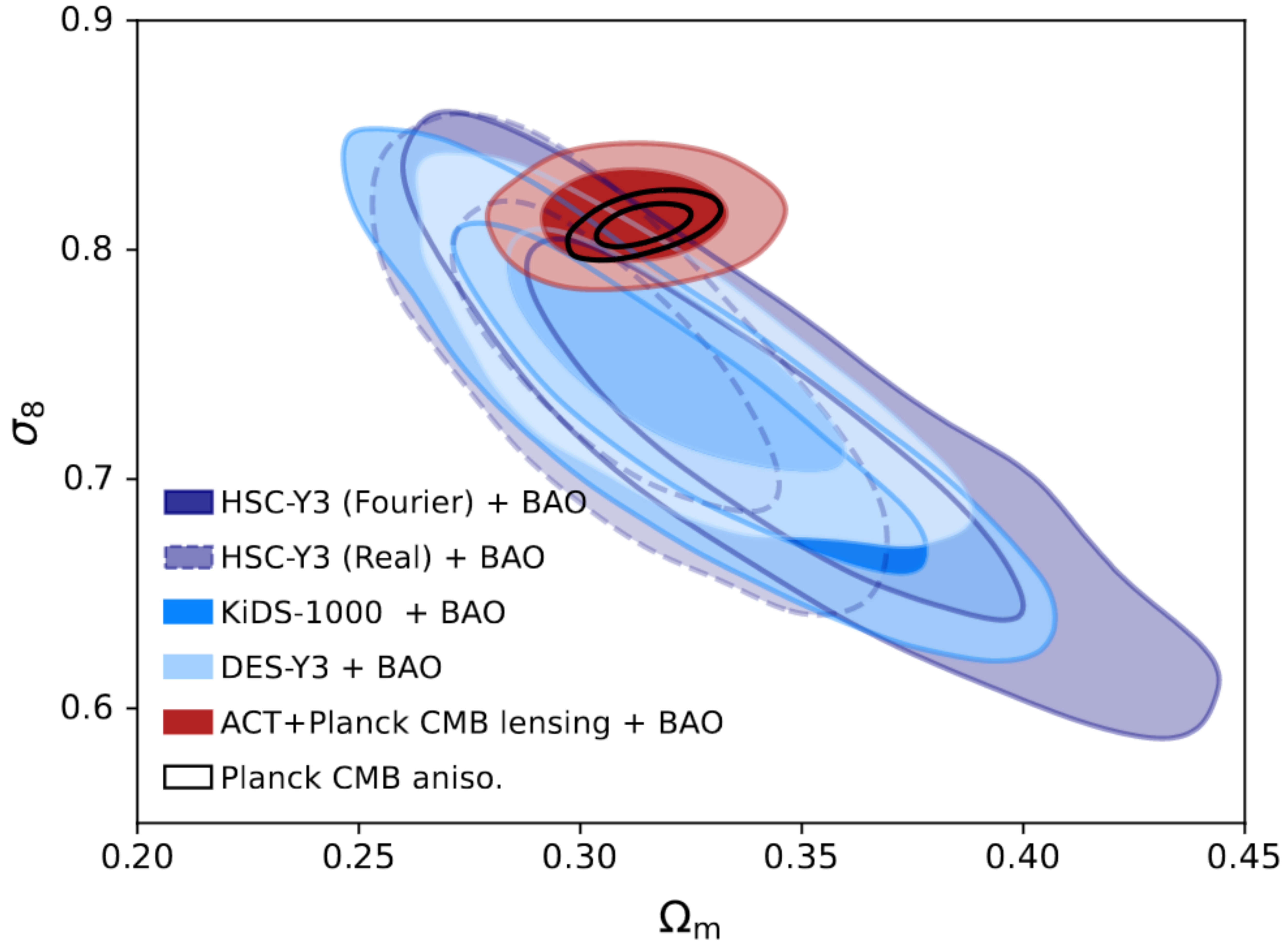
$$\sigma_8 = 0.812 \pm 0.013$$

1.6% measurement for ACT+Planck lensing combination

COMPARISON WITH OTHER WEAK LENSING PROBES

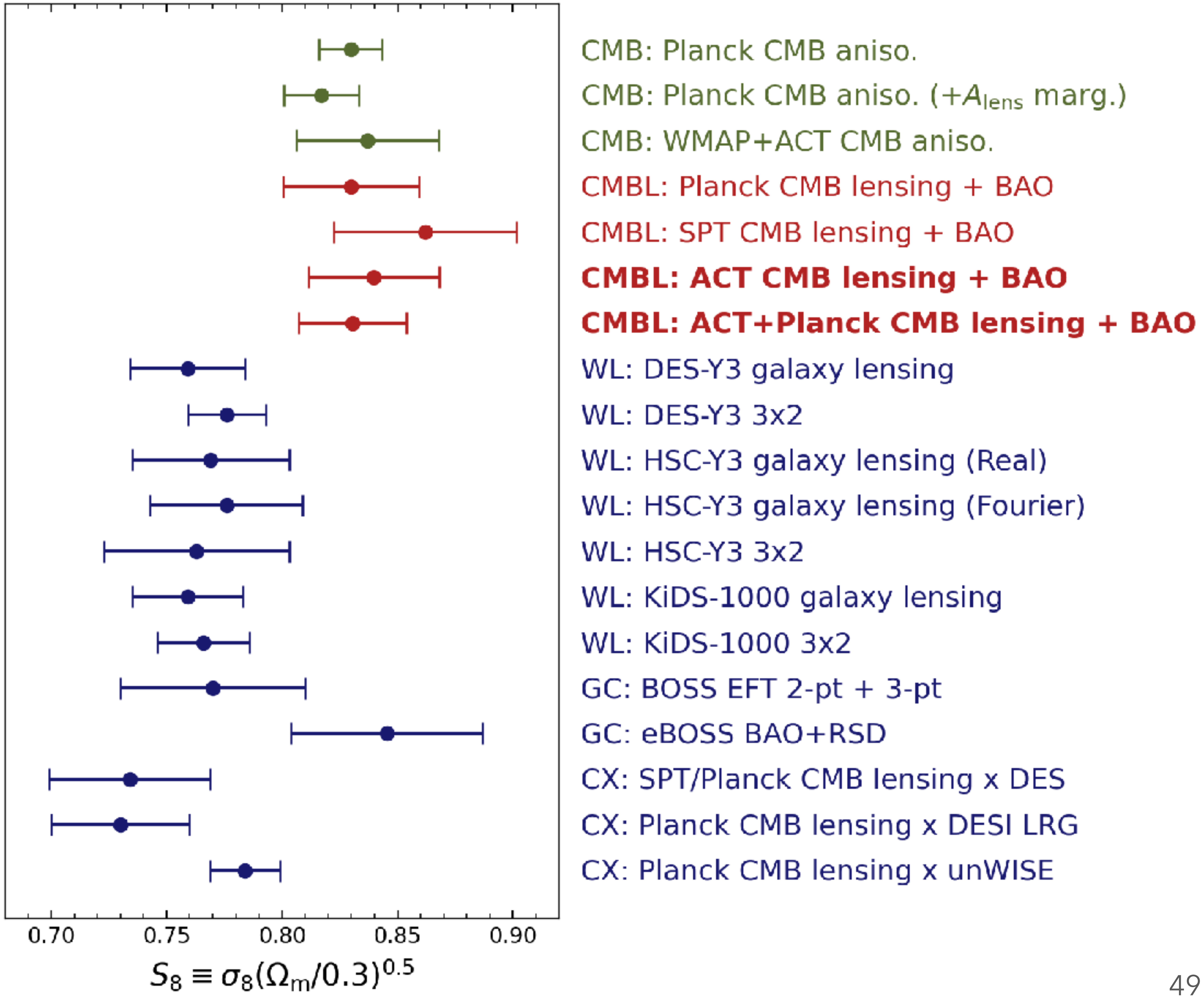
Shown against various **cosmic shear** measurements with consistent priors and BAO

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



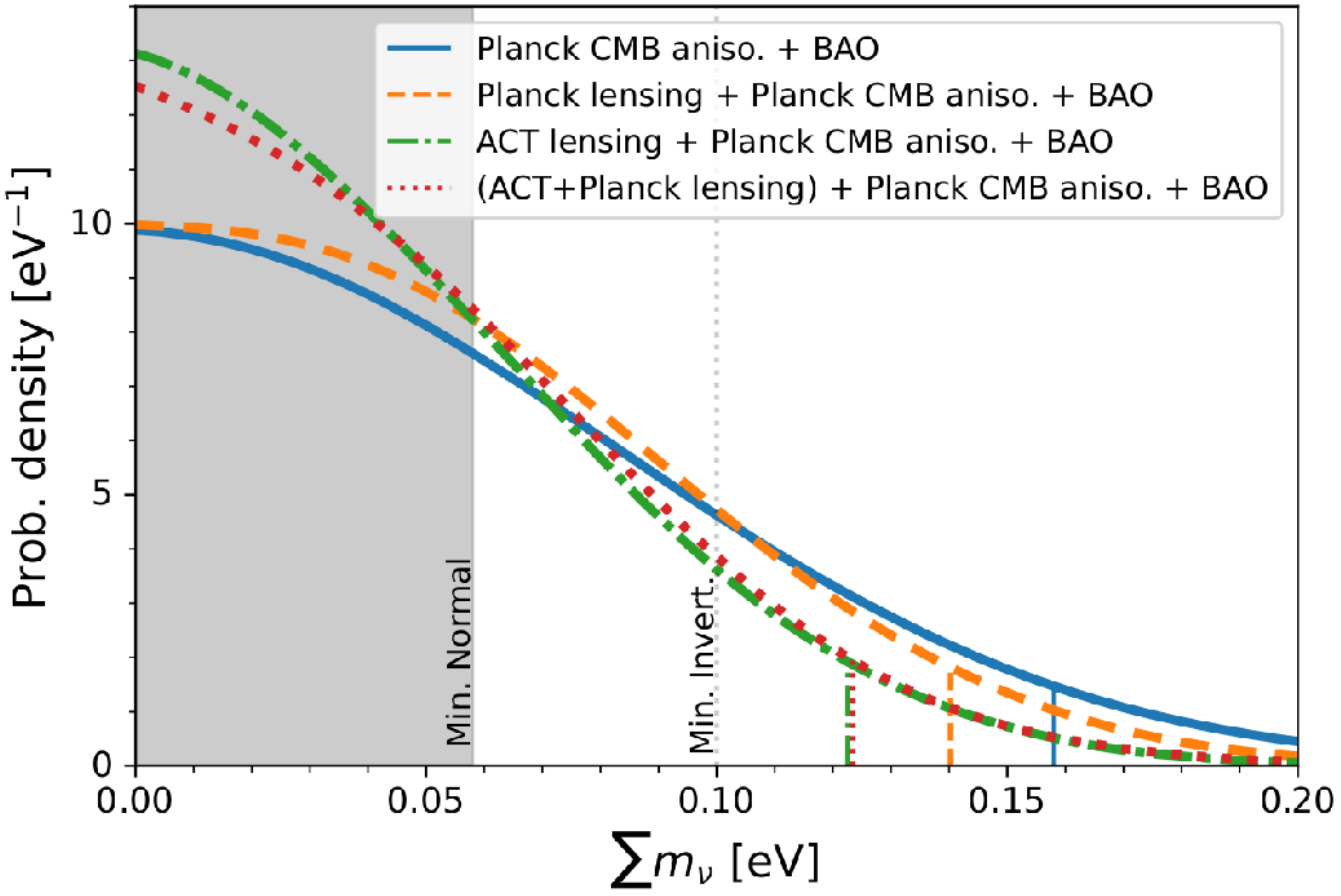
OUTLOOK FOR S_8

- 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

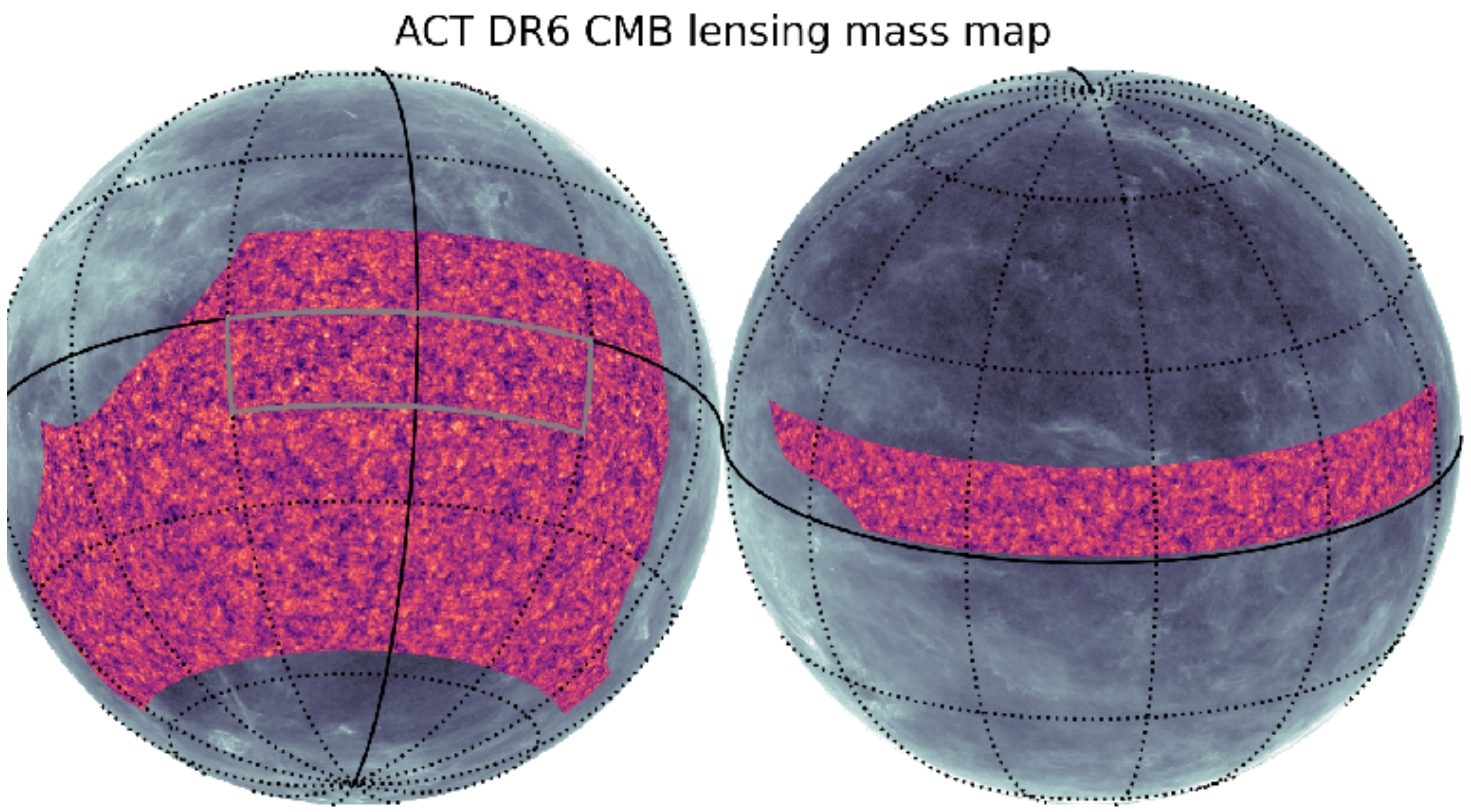


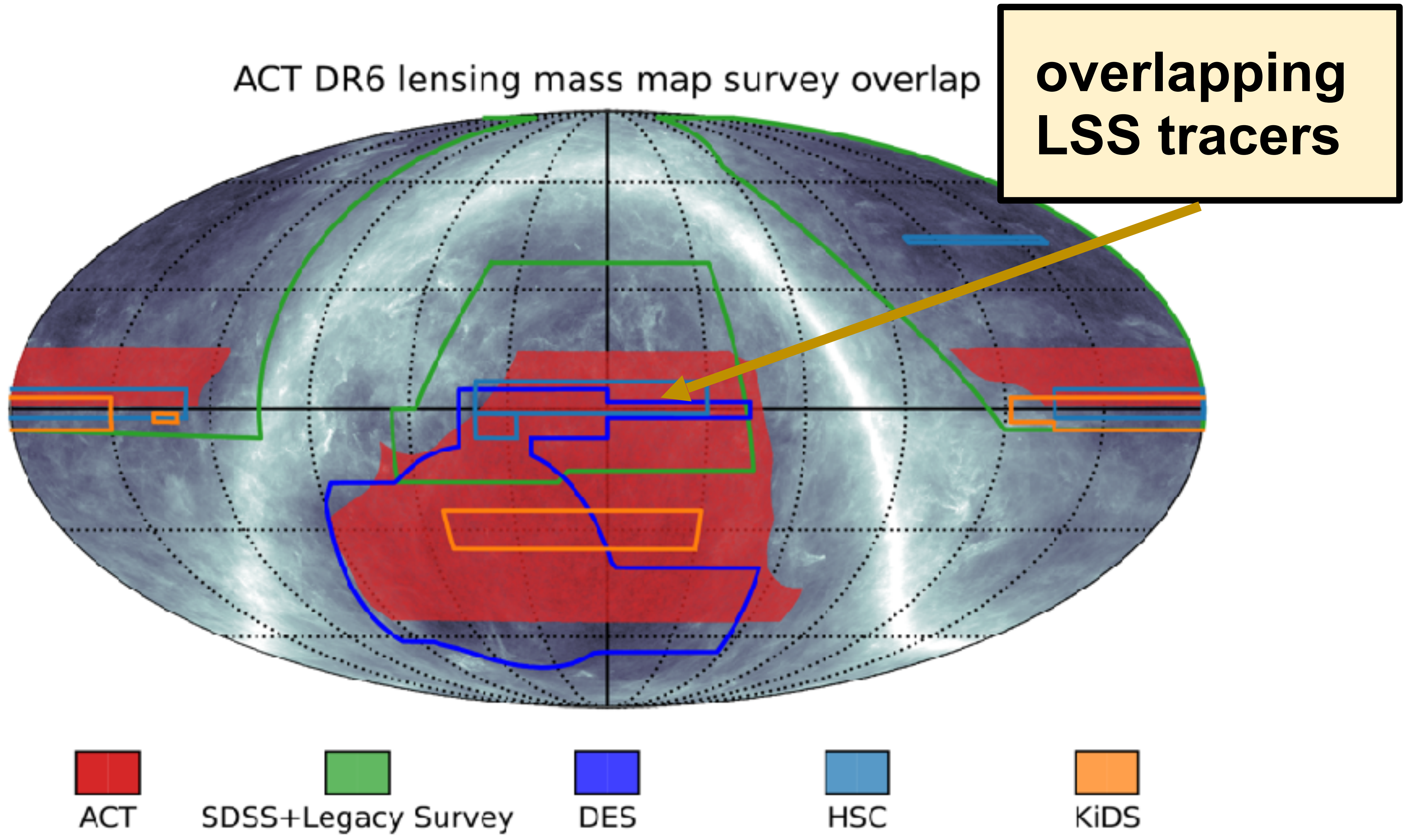
CONSTRAINING NEUTRINO MASSES

- 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



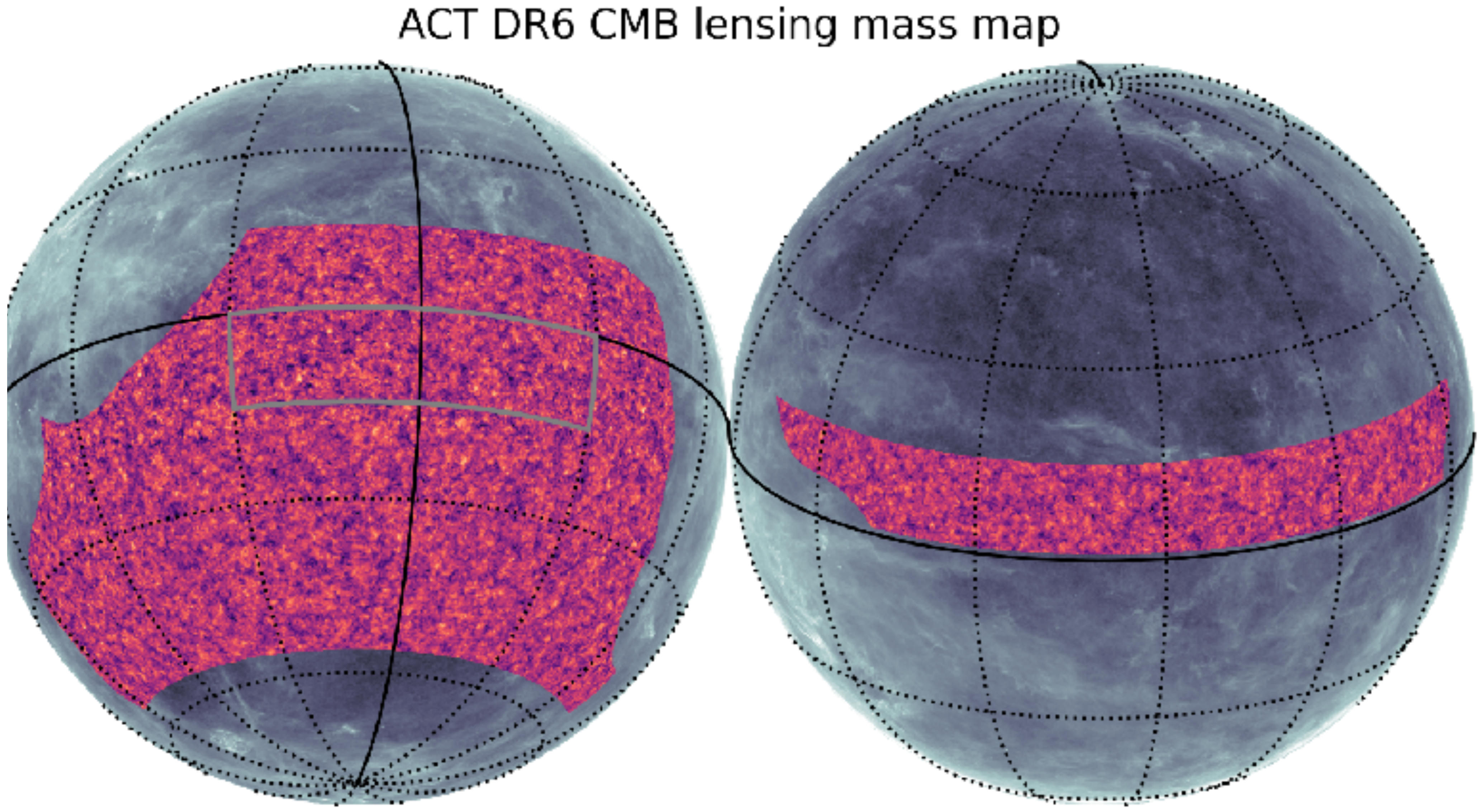


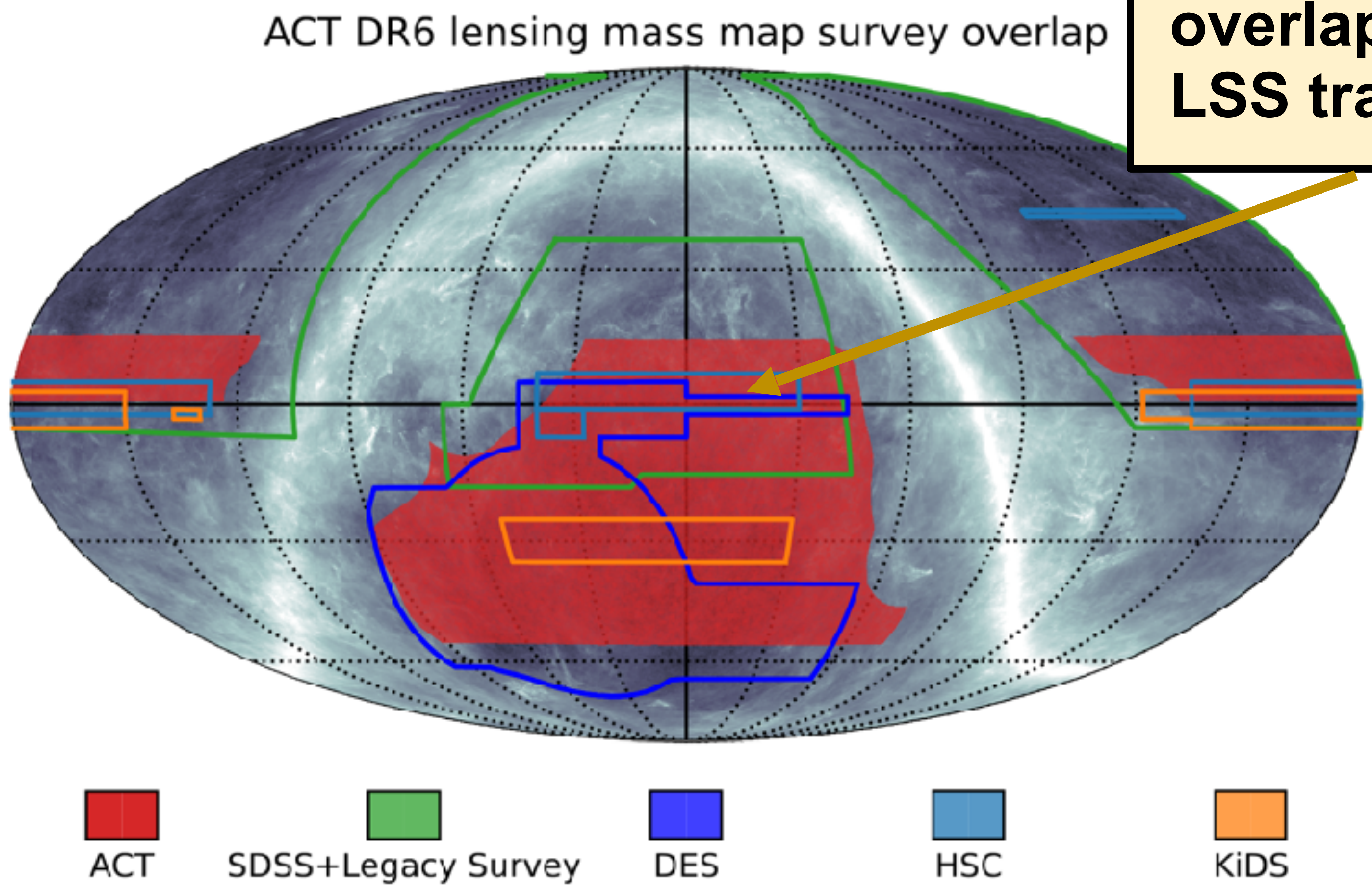
3D tomographic information of the matter distribution!

1. **Probe of structure growth vs. redshift: ACT x unWISE, Farren et al. (in prep), ACT x DES, Marques et al. (in prep), Shaikh et al (in prep), Darwish et al. (in prep), Kim et al. (in prep)… + > 10 ongoing projects with DESI**
2. **Tests of gravity: ACT x SDSS, Wenzl et al. (in prep)…**
3. **Astrophysics at high-z: ACT x Planck CIB, Mehta et al (in prep)…**

   ….

FUTURE DIRECTIONS: DR6 ACT LENSING X LSS



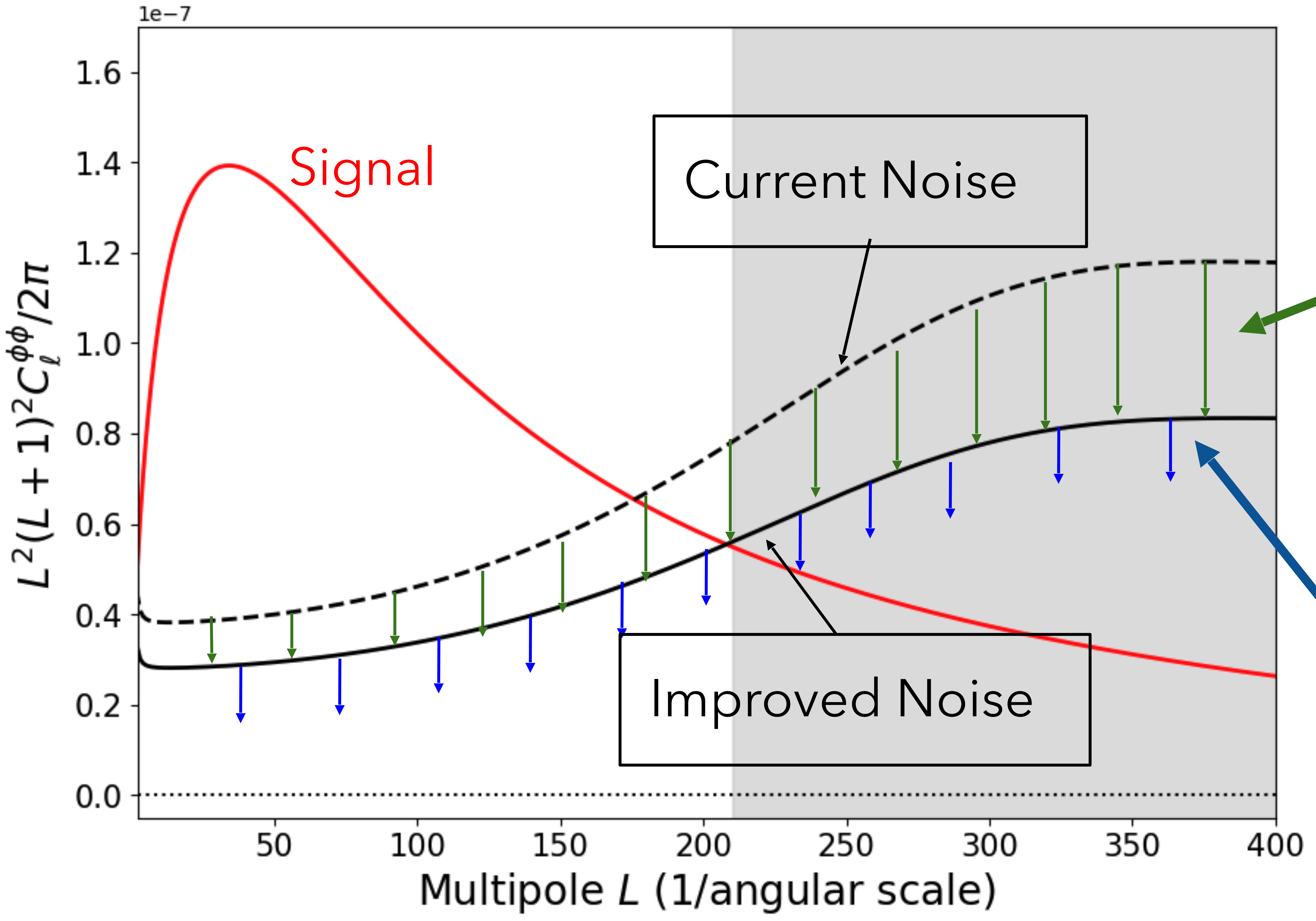


overlapping LSS tracers

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)

FUTURE DIRECTIONS: FURTHER IMPROVEMENTS ON MASS MAPPING



Expected Improvements for the next set of analyses

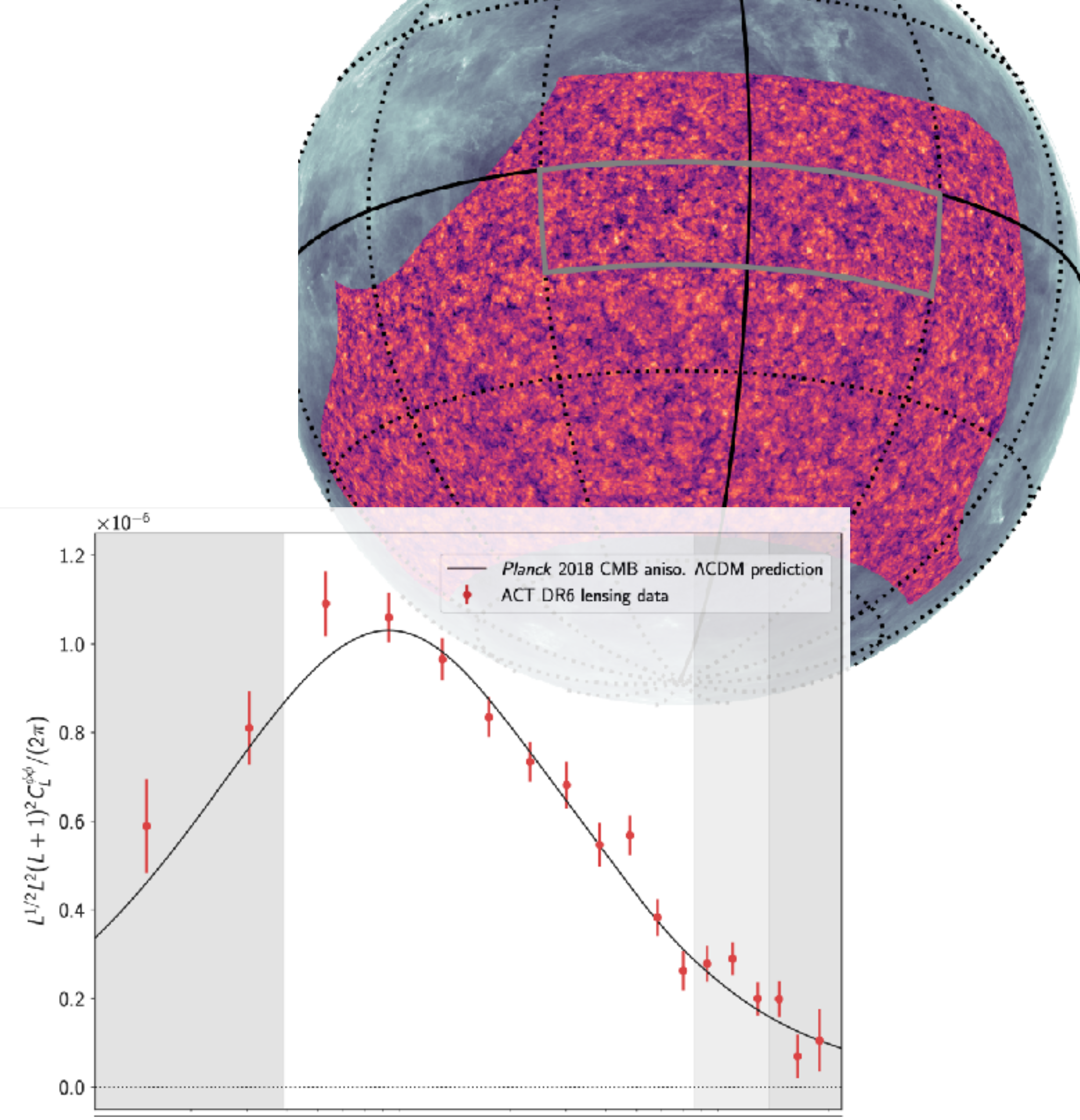
- **Inclusion of the daytime data: ~ 1.7x amount of the data**
- **Additional Seasons (Season 2021-2022)**

- **Optimal Filtering (10-15% improvement)**
- **Increase the number of splits used for the cross-estimator (~10% improvement)**
- **Improve sky-cuts (~10% improvement)**
- **Map-level combination with Planck**

More great lensing science from the ACT collaboration in the near future!

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

jq247@cam.ac.uk

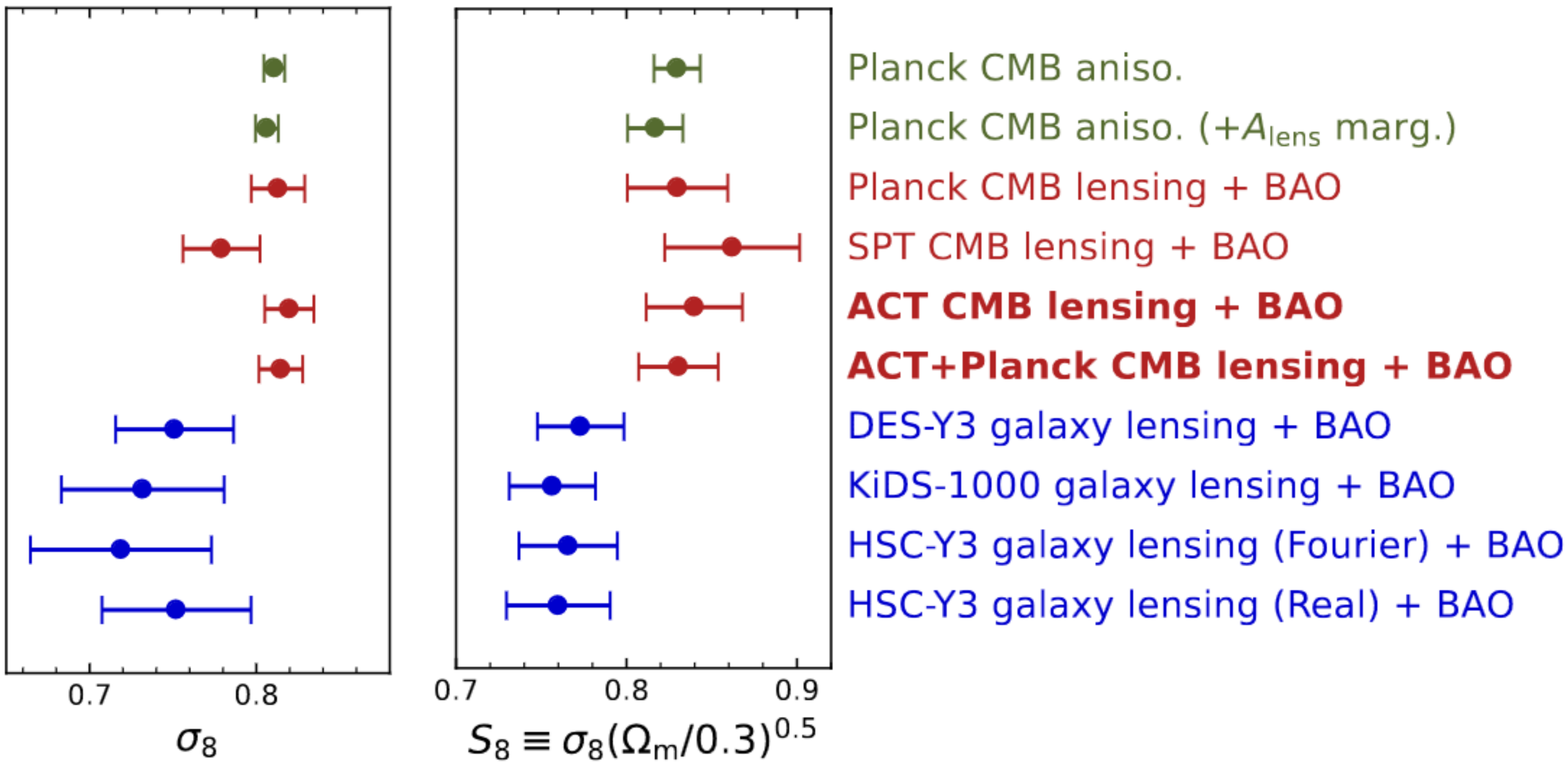
Papers available on arxiv

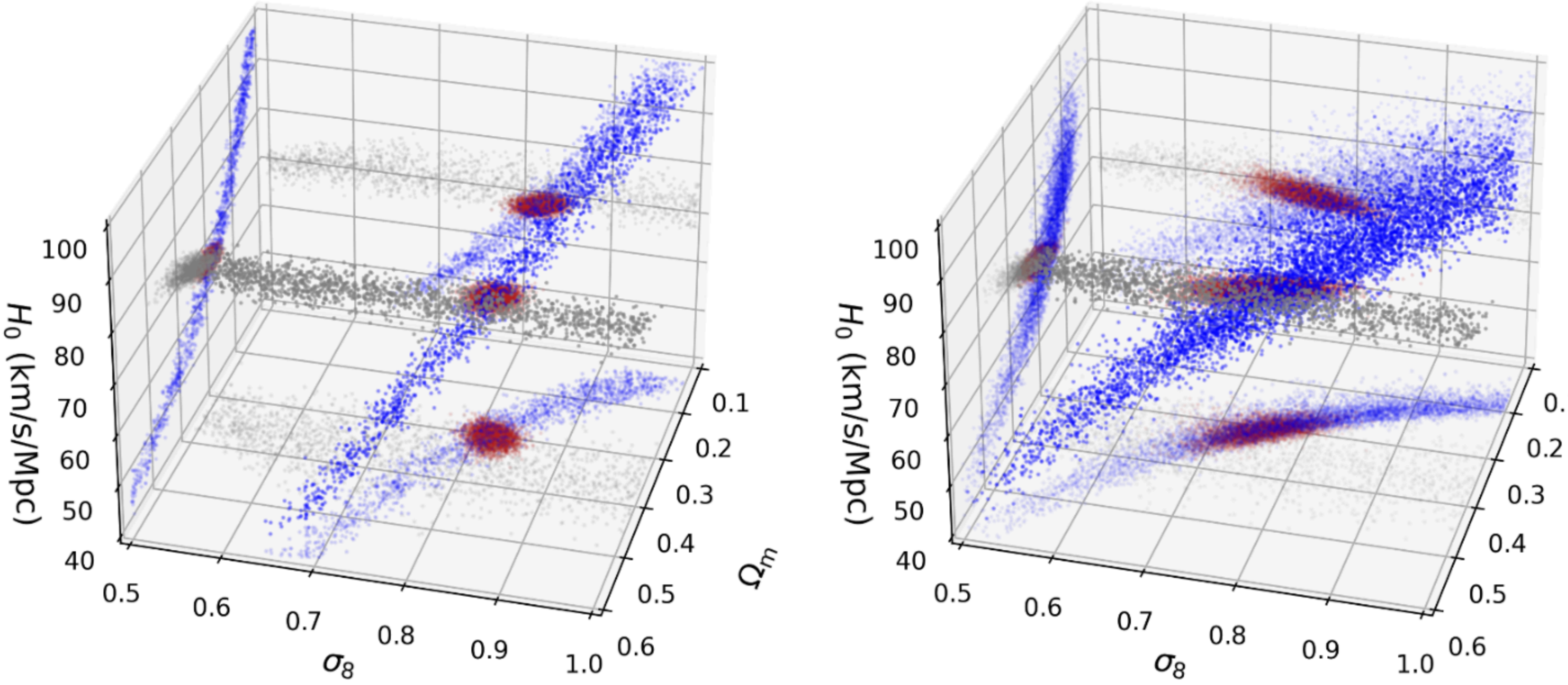
Qu, Sherwin, Madhavacheril, Han, Crowley et al 2304.05202
A Measurement of the DR6 CMB Lensing Power Spectrum and its Implications for Structure Growth
Madhavacheril, Qu, Sherwin, MacCrann, Li et al 2304.05203
DR6 Gravitational Lensing Map and Cosmological Parameters
MacCrann, Sherwin, Qu, Namikawa,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

EXTRA SLIDES

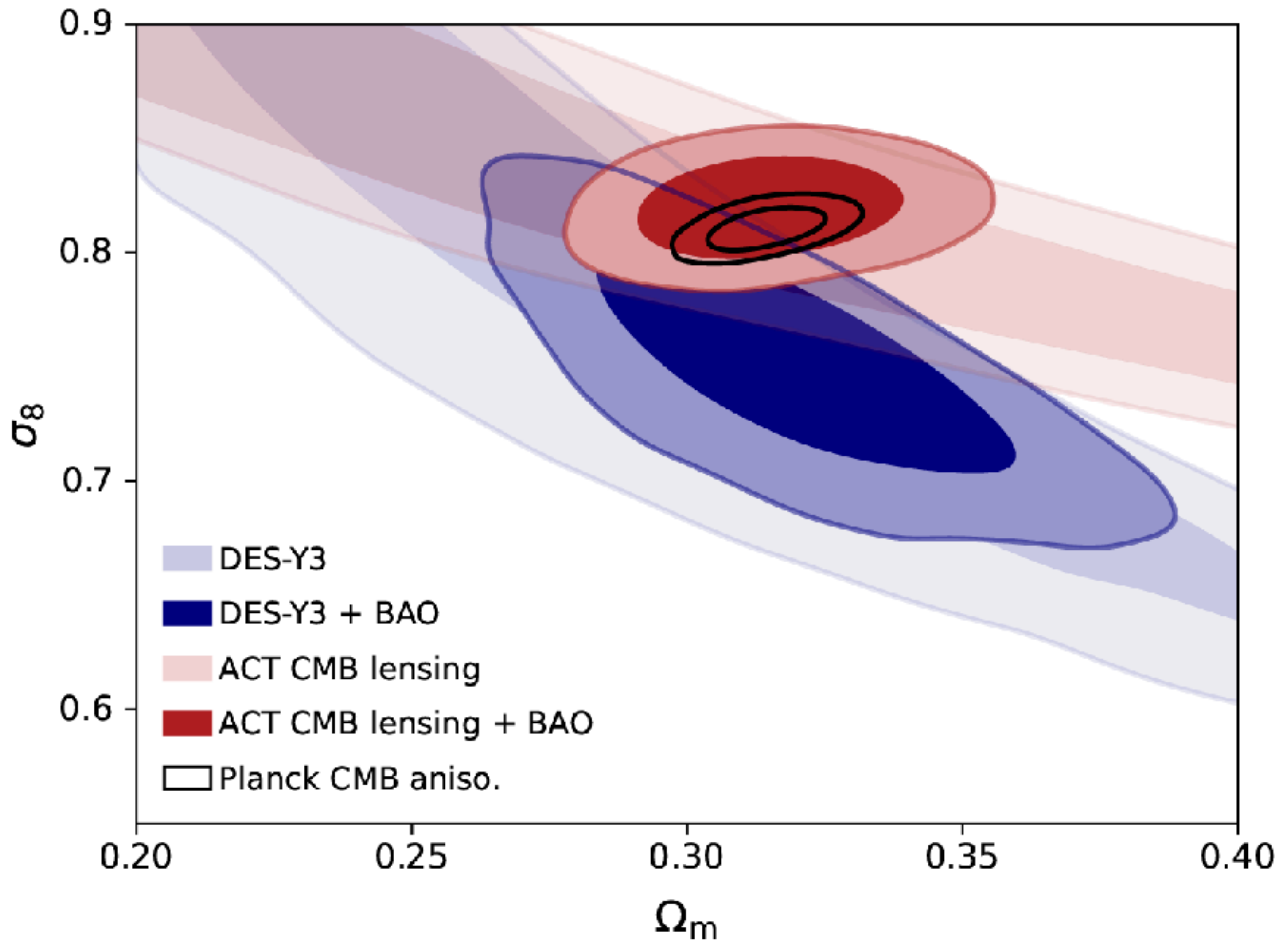
COSMIC SHEAR 1.7 TO 2.1 SIGMA LOWER THAN CMB LENSING

- Quantify tension in S_8 space, where both CMB lensing and cosmic shear have good constraining power
- But σ_8 constrained significantly better by CMB lensing

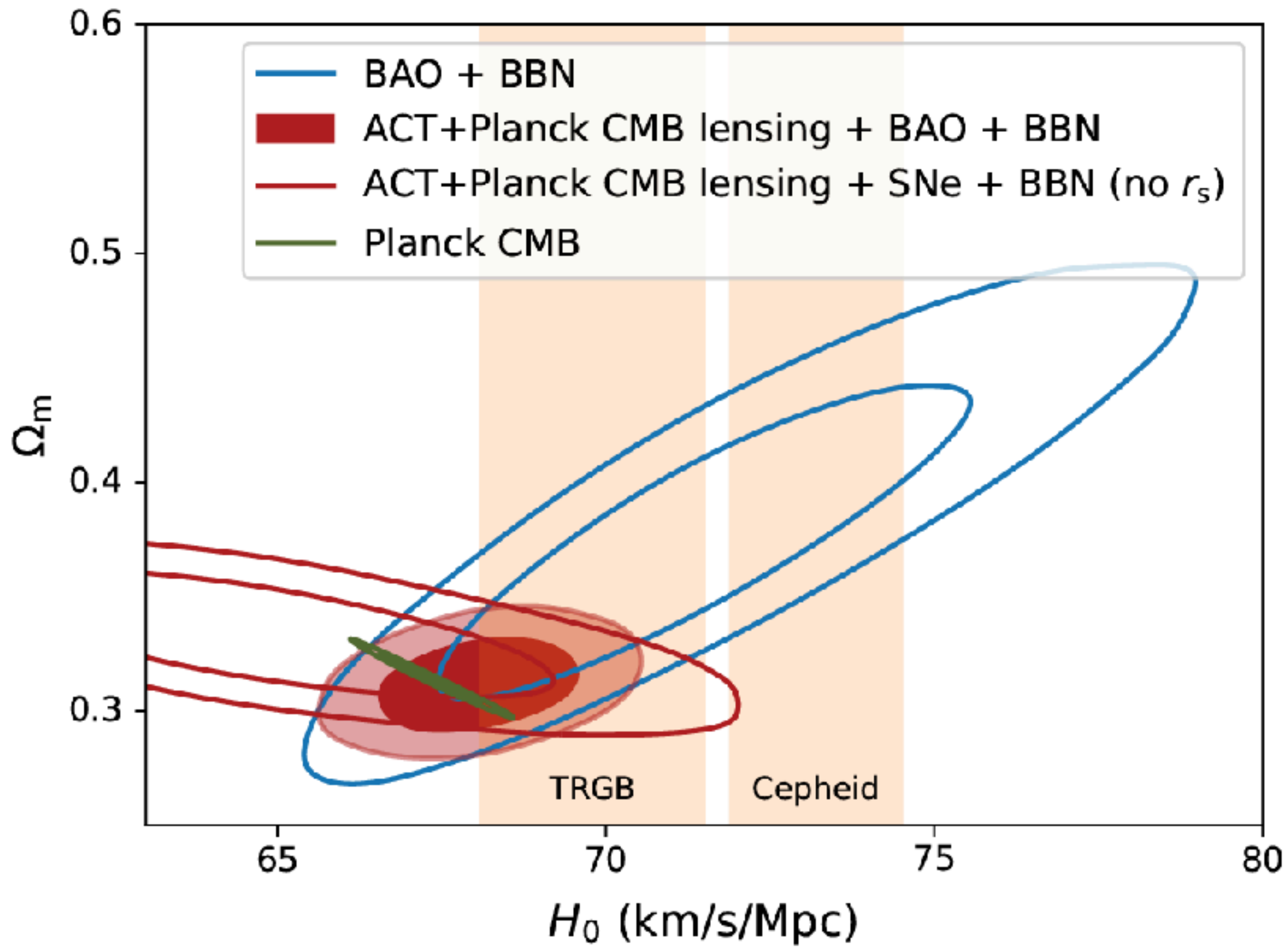




H_0 (km/s/Mpc)
100
90
80
70
60
50
40
0.5
0.6
0.7
0.8
0.9
1.0
σ_8
0.1
0.2
0.3
0.4
0.5
0.6
Ω_m
H_0 (km/s/Mpc)
100
90
80
70
60
50
40
0.5
0.6
0.7
0.8
0.9
1.0
σ_8
0.1
0.2
0.3
0.4
0.5
0.6
Ω_m

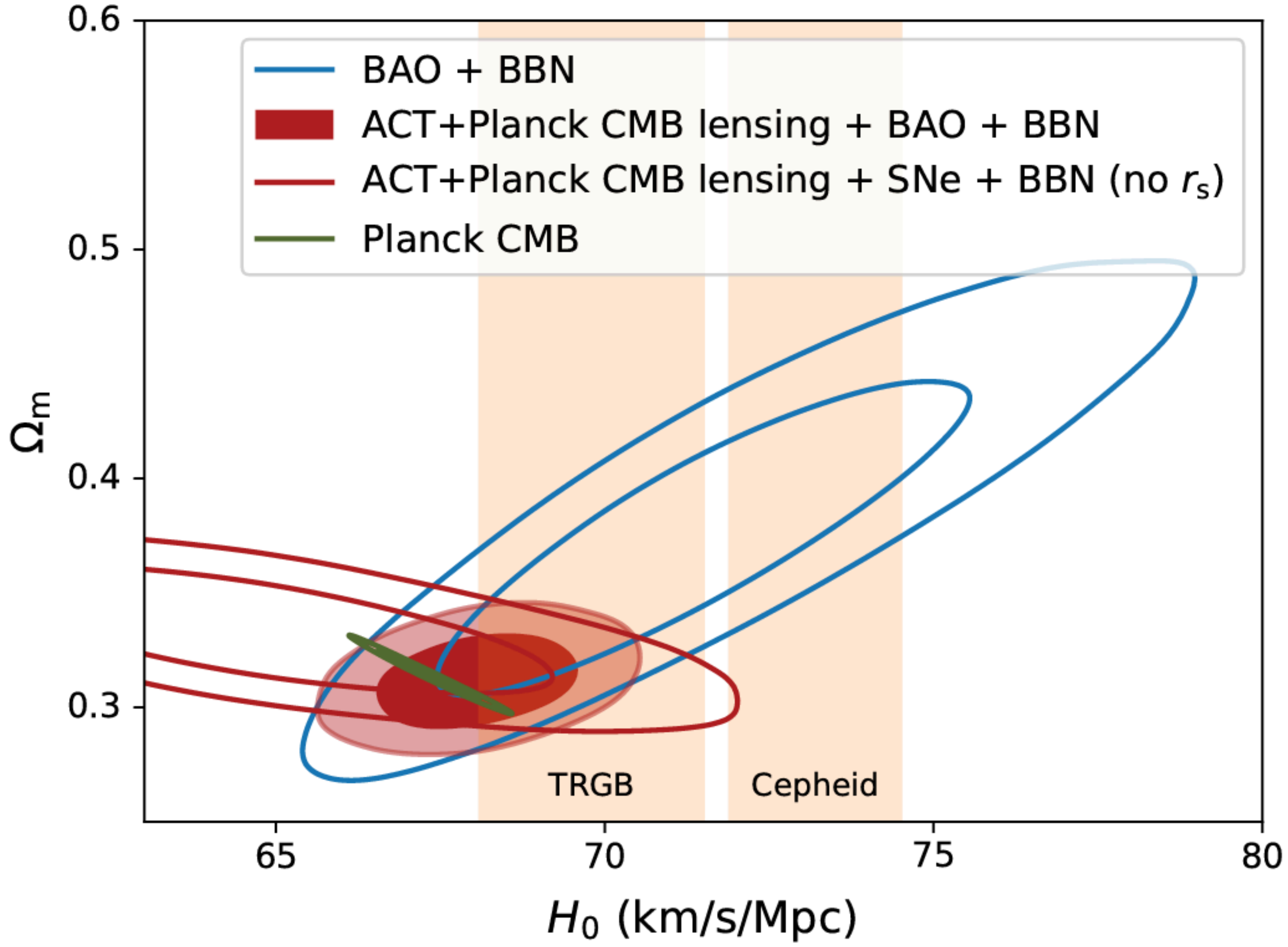


0.9
0.8
0.7
0.6
σ_8
0.20
0.25
0.30
0.35
0.40
Ω_m
DES-Y3
DES-Y3 + BAO
ACT CMB lensing
ACT CMB lensing + BAO
Planck CMB aniso.



0.6
0.5
0.4
0.3
Ω_m
65
70
75
80
H_0 (km/s/Mpc)
BAO + BBN
ACT+Planck CMB lensing + BAO + BBN
ACT+Planck CMB lensing + SNe + BBN (no r_s)
Planck CMB
TRGB
Cepheid

HUBBLE CONSTANT FROM LENSING



DR6 lensing+ BAO

$H_0 = 68.3 \pm 1.1 \text{kms}^{-1}\text{Mpc}^{-1}$

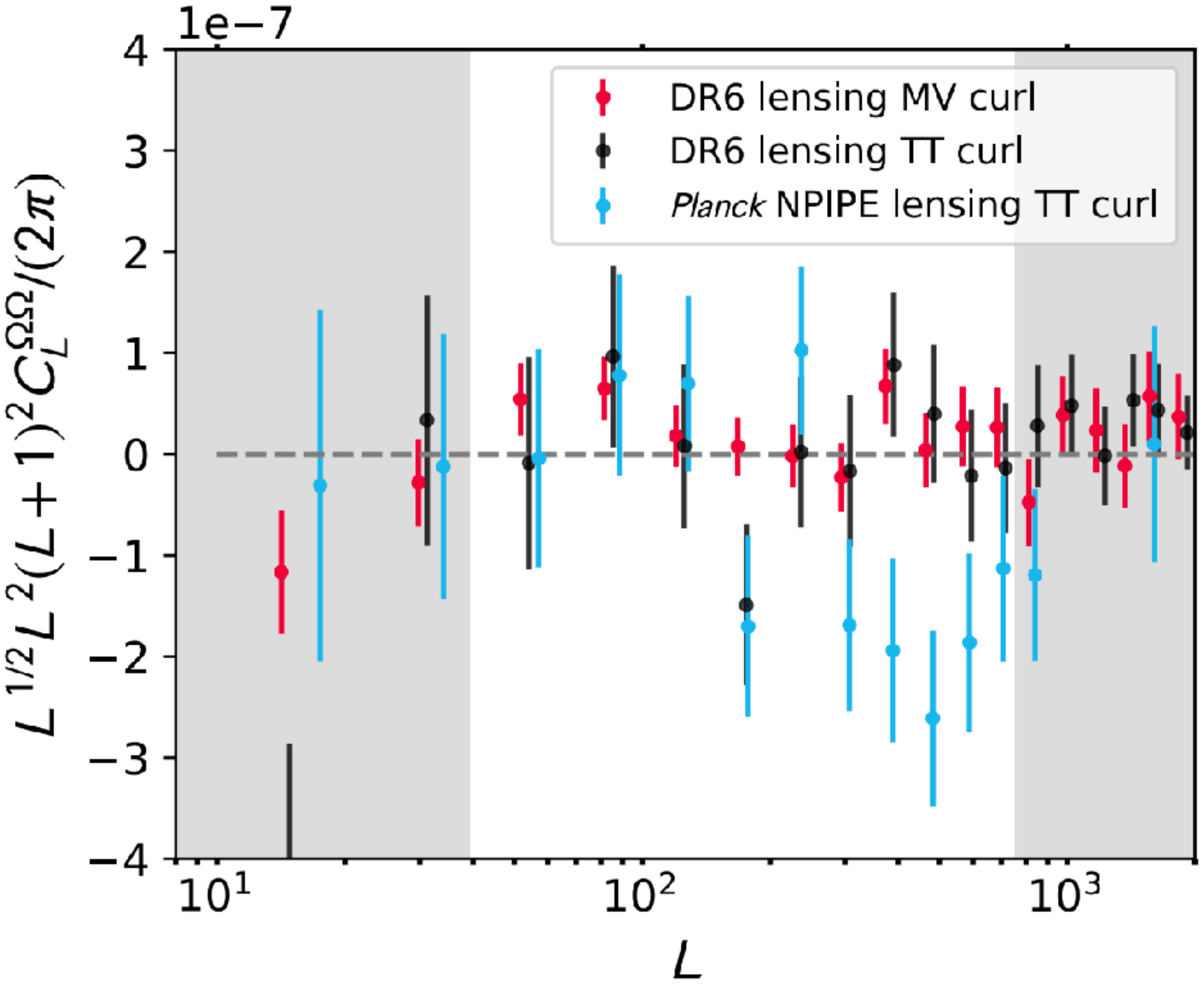
DR6+Planck CMB lensing+BAO

$H_0 = 68.1 \pm 1.0 \text{kms}^{-1}\text{Mpc}^{-1}$

Sound horizon independent constraint

$H_0 = 64.9 \pm 2.8 \text{kms}^{-1}\text{Mpc}^{-1}$

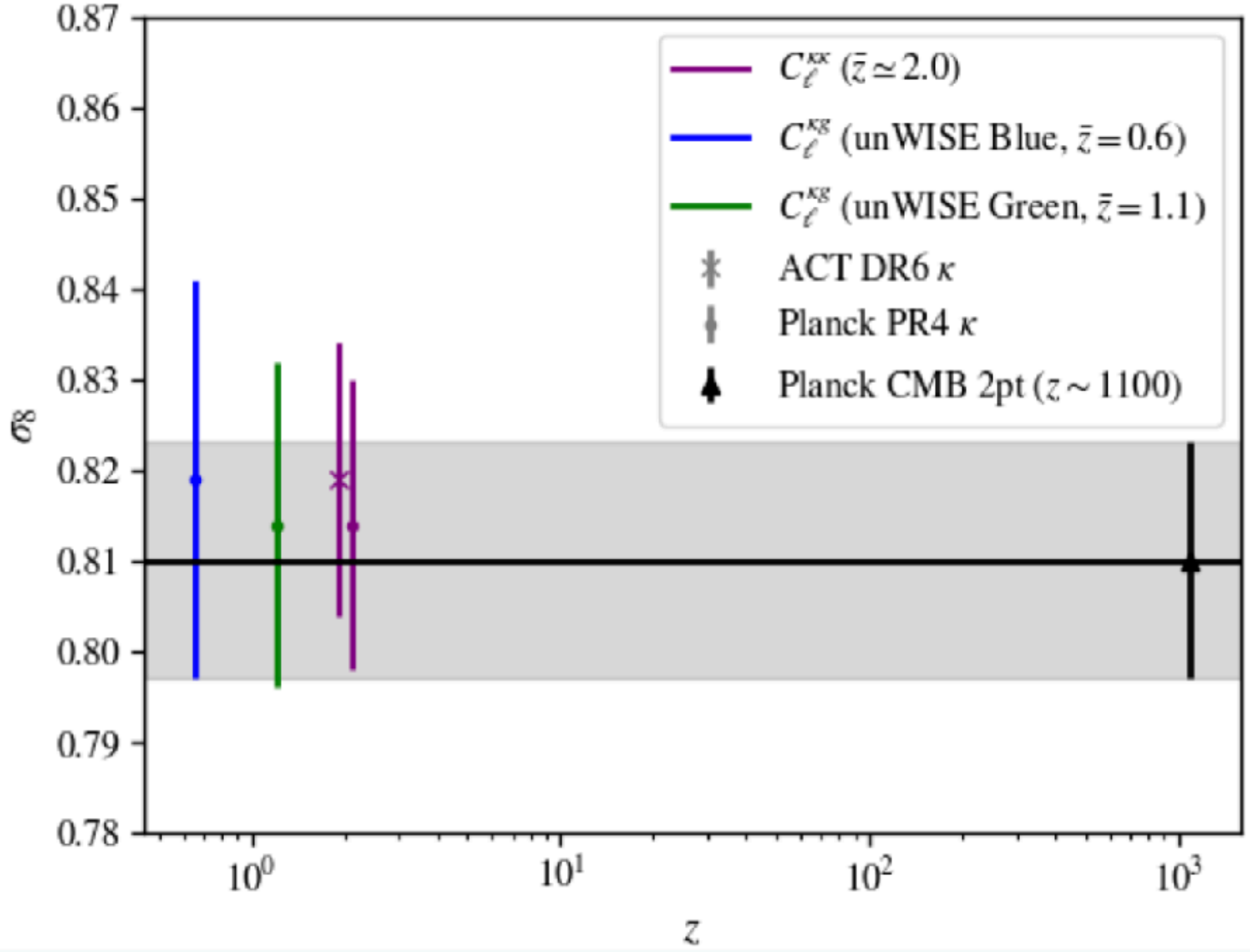
CURL MODES



1e−7
4
3
2
1
0
−1
−2
−3
−4
$L^{1/2}L^2(L+1)^2C_L^{\Omega\Omega}/(2\pi)$
10^1
10^2
10^3
L
DR6 lensing MV curl
DR6 lensing TT curl
Planck NPIPE lensing TT curl

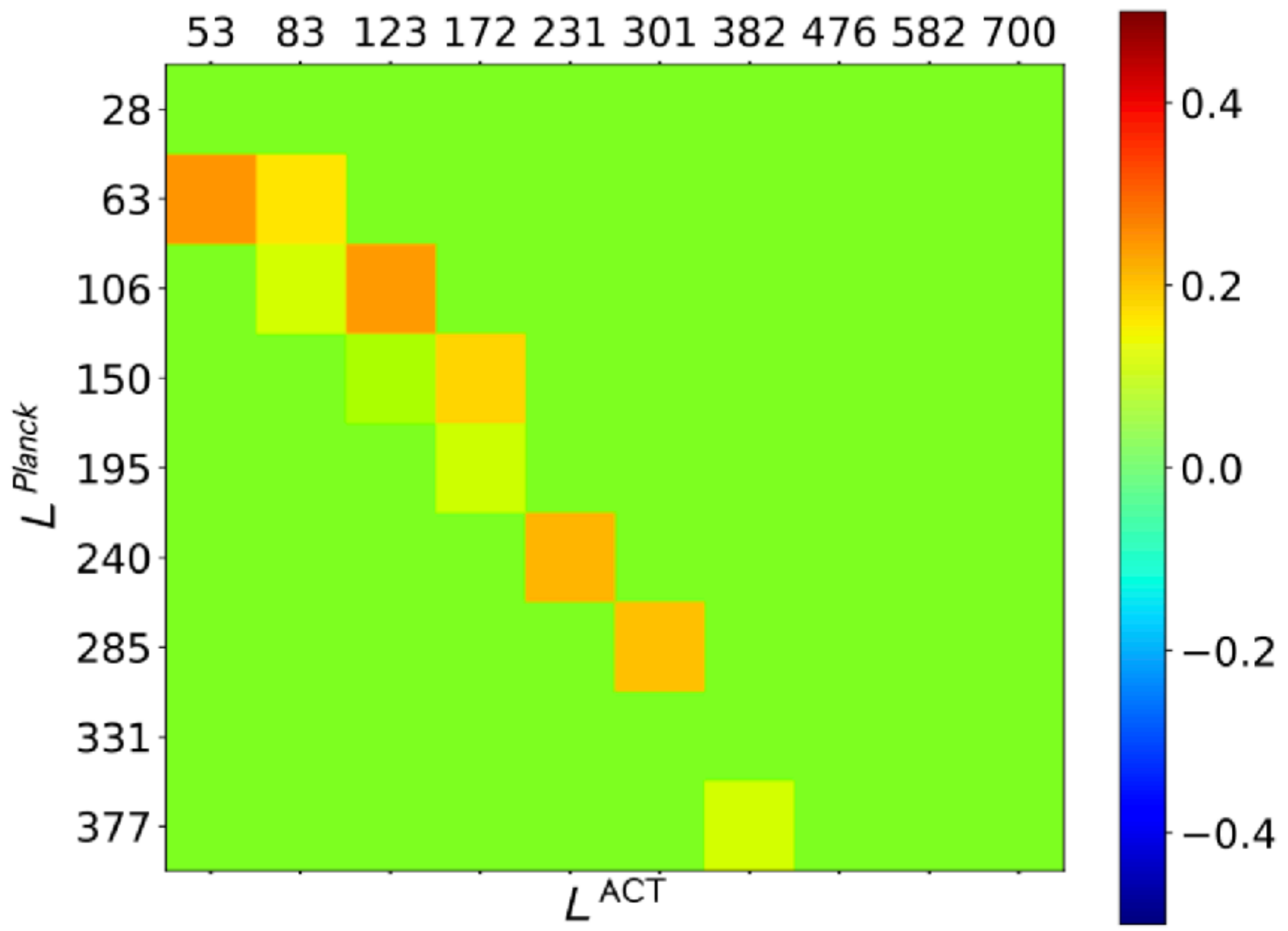
CROSS CORRELATIONS

$\sigma_8(z)$



cc Farren

Offdiagonal covmat ACT+Planck



Baryonic effects - suppression negligible where our SNR arises (L<500)