Fundamental Physics from the Microwave Sky

Results from ACT and Prospects for Simons Observatory

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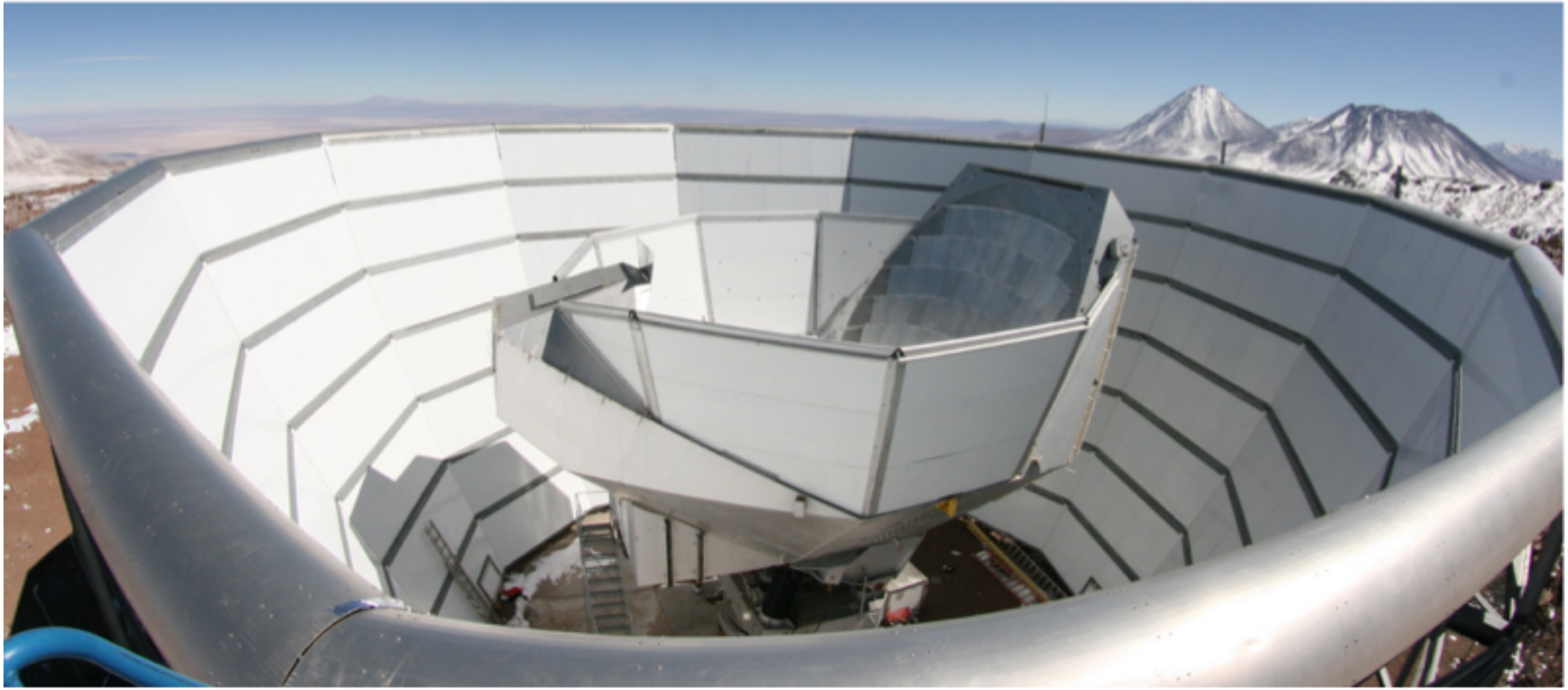
The Atacama Cosmology Telescope

Atacama Cosmology Telescope
2008-2022

The Atacama Cosmology Telescope

- >5x Planck resolution. ACT&SPT only high-res CMB telescopes
- Near equator at -23° lat. Access to most of the sky
- 5200 m altitude in Atacama desert
- Typical PWV 1.2 mm (about 3x south pole, 9x ridge A)
- Observed 2007-2022



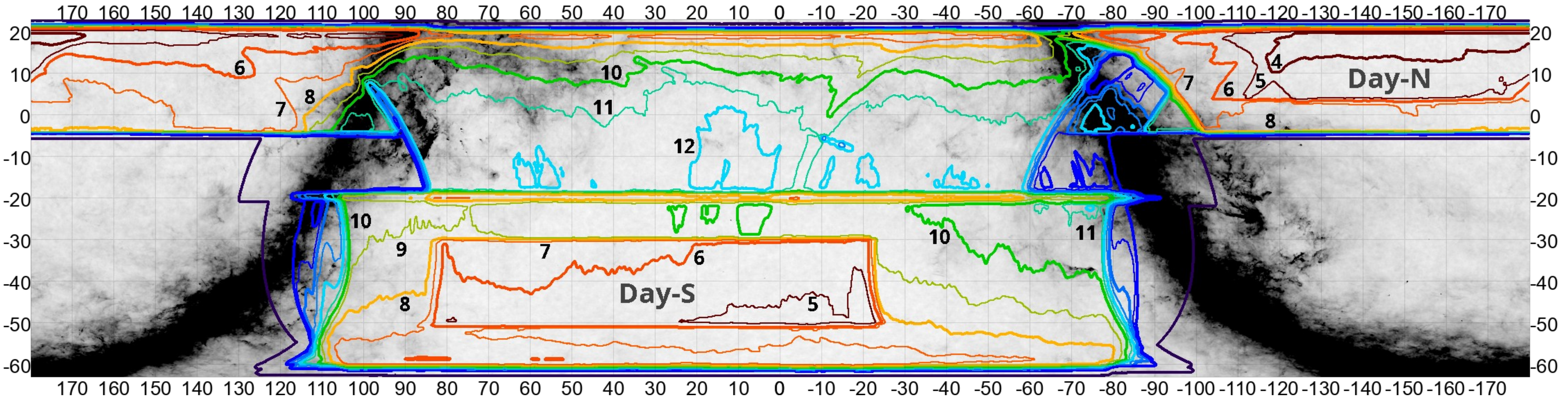
The ACT Collaboration

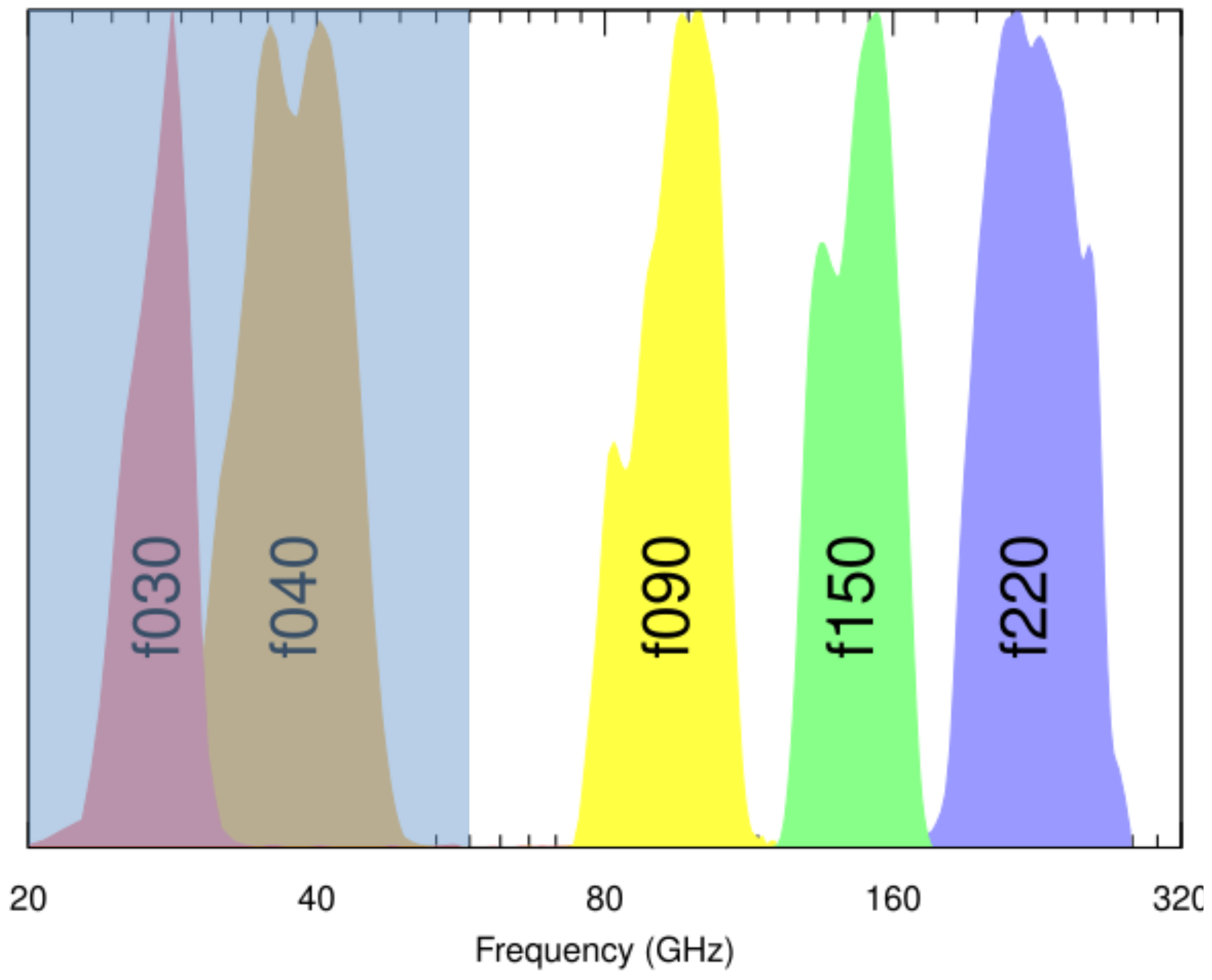
160 collaborators at 45 institutions

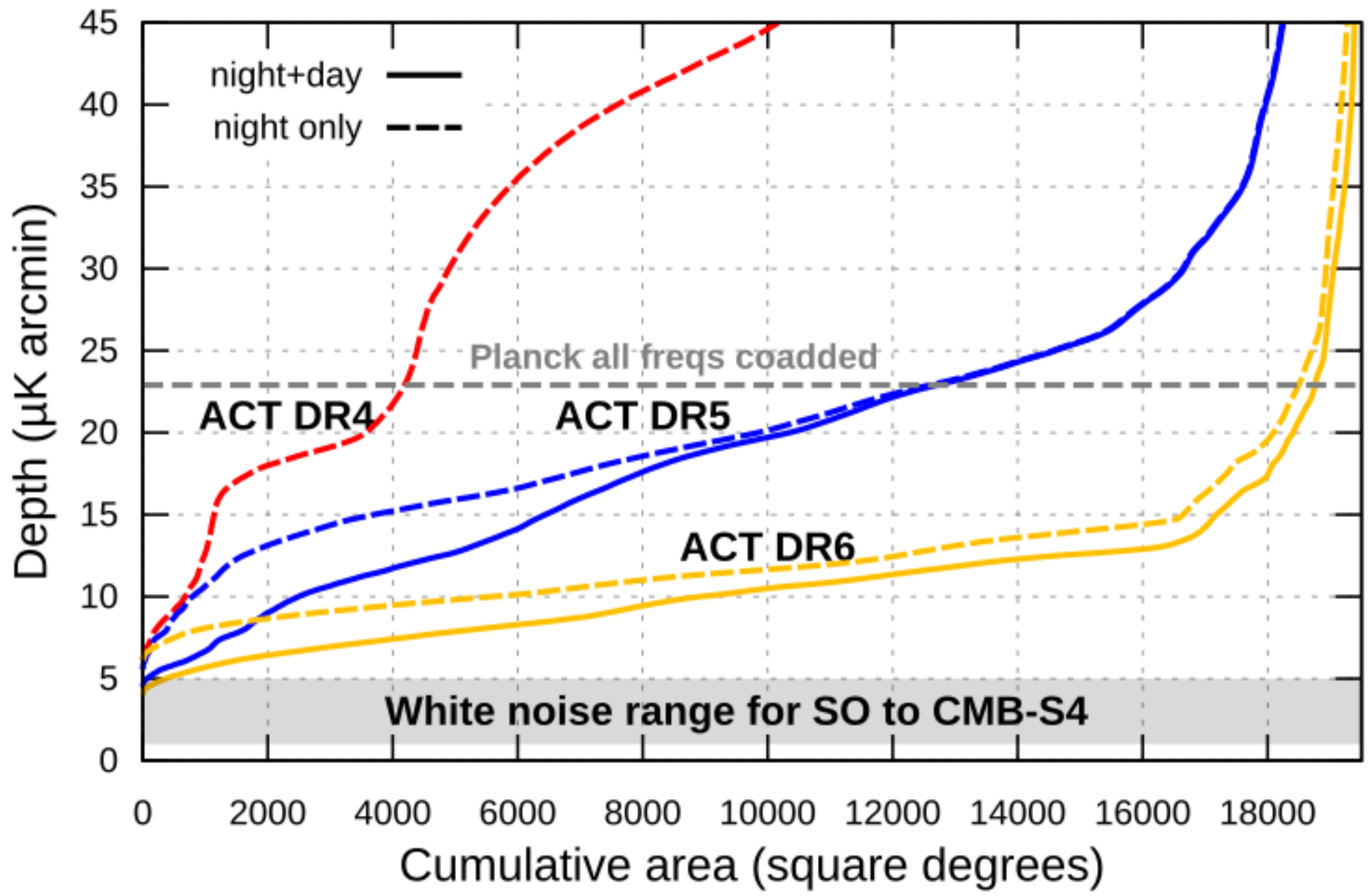
PI: Suzanne Staggs (Princeton University)

Current Maps and Power Spectra

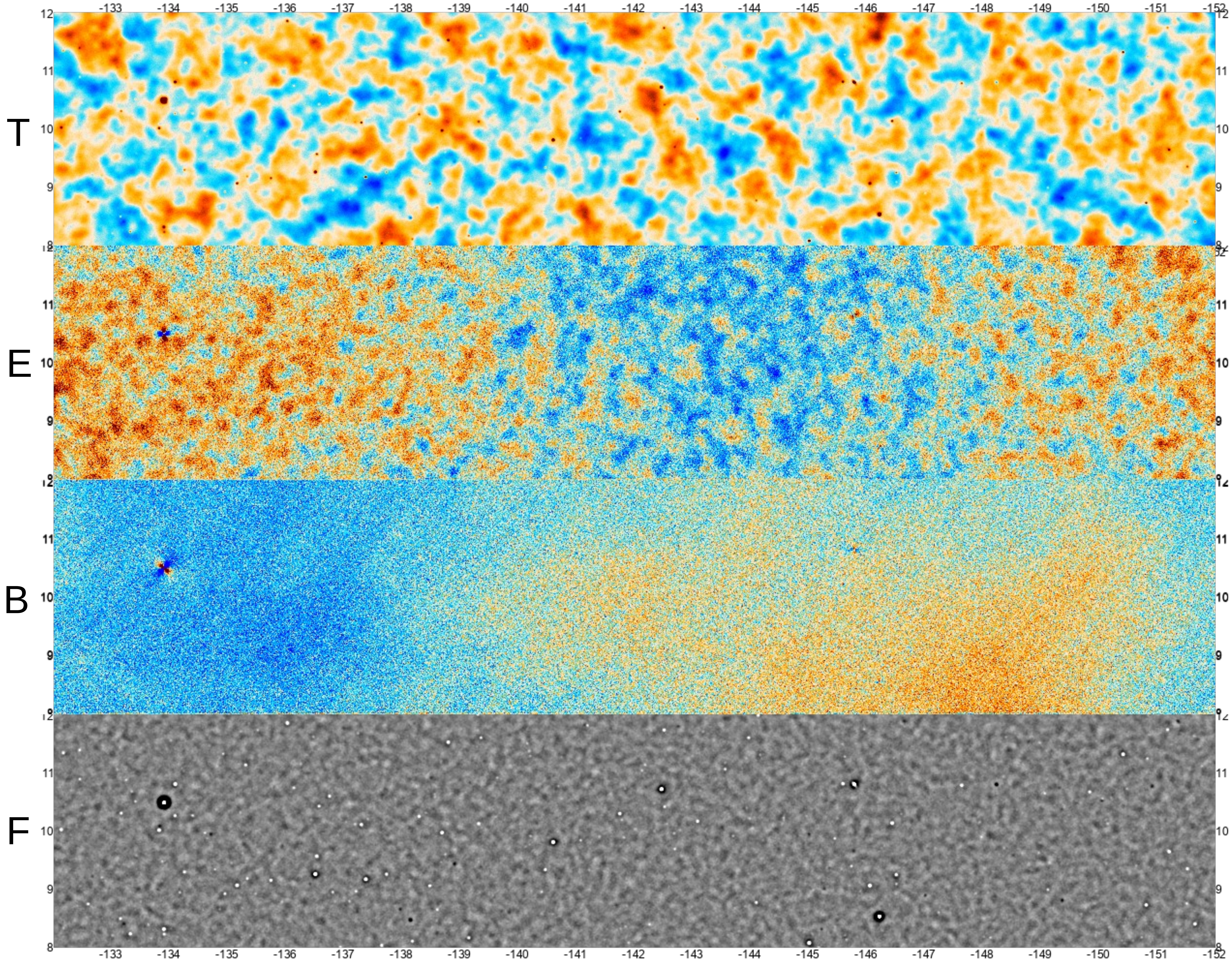
Advanced ACT survey



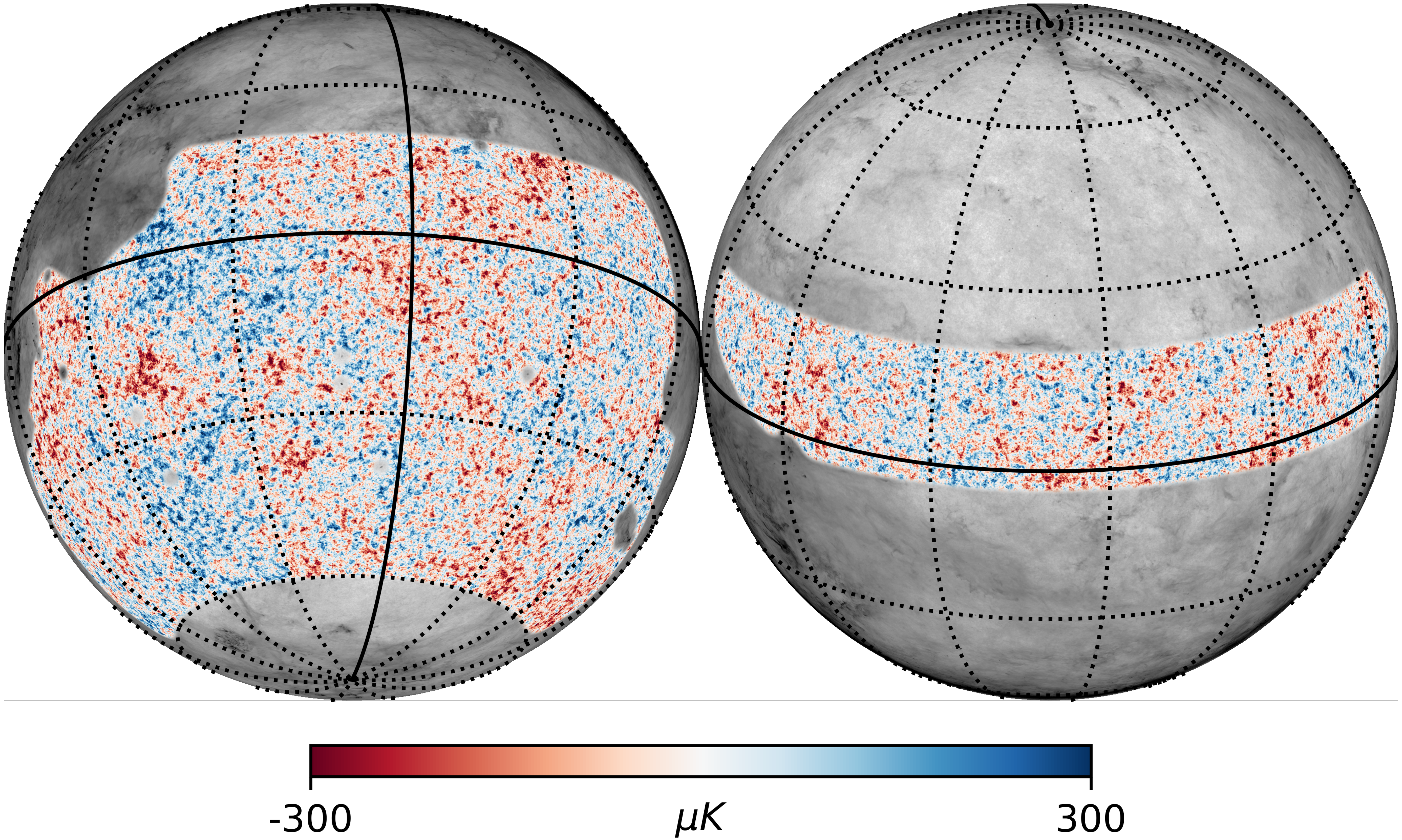




- Observed 2017-2022 in 5 bands
- Combined sensitivity of 6.1 μK√s (mostly in f090 and f150)
- ACT DR6 coming soonish
- Deeper than Planck over 19000°²
- Median depth of 10 μK arcmin
- 10x as much statistical power as DR4 (prev. cosmology release)

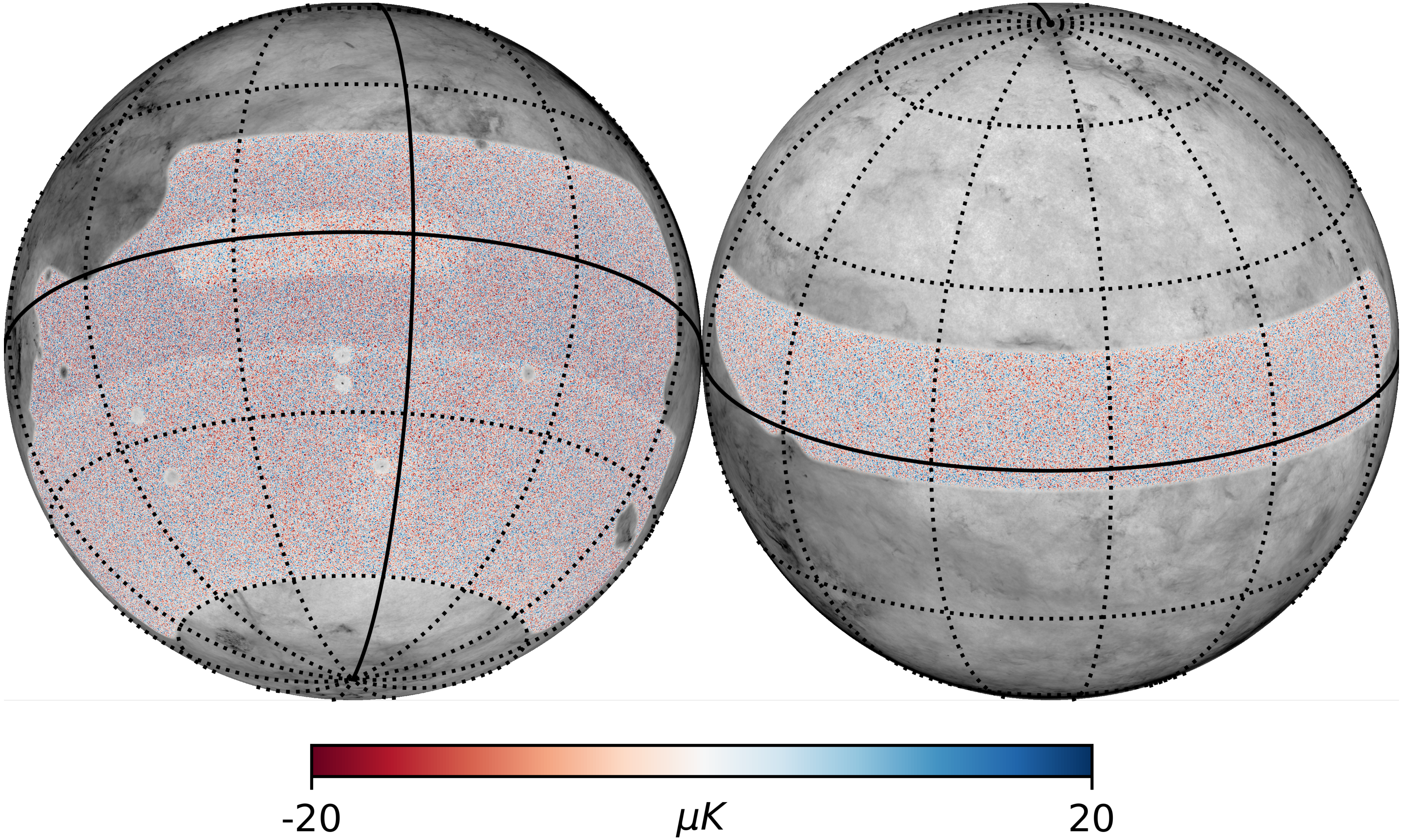


DR6 map example (from 4-5 μK arcmin region)



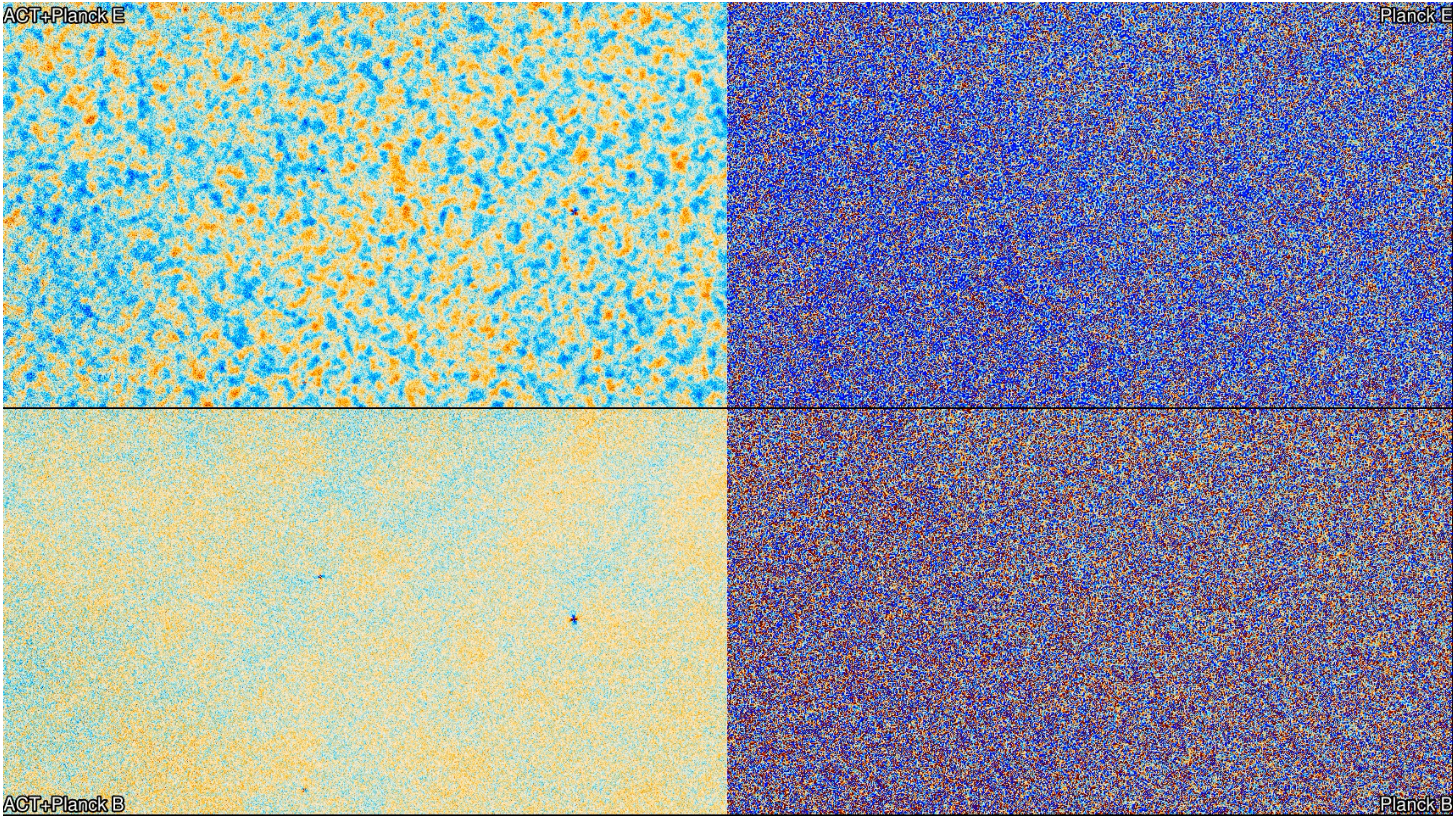
(a) ACT & *Planck* NILC CMB temperature and kinetic Sunyaev-Zel'dovich anisotropy map.

Coulton et al. 2023



(b) ACT & *Planck* NILC CMB E-mode anisotropy map.

Coulton et al. 2023

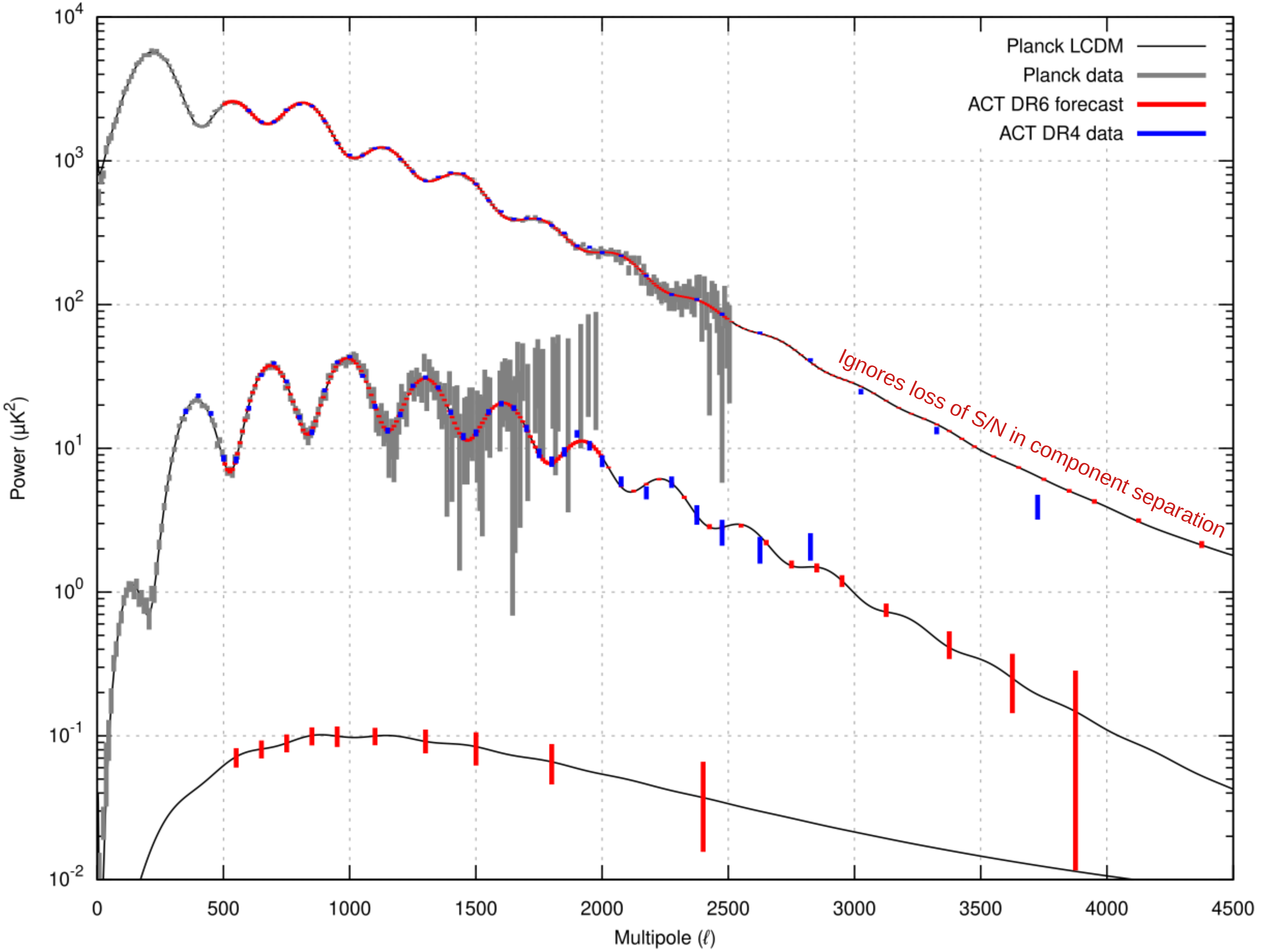


ACT+Planck E,B vs. Planck E,B

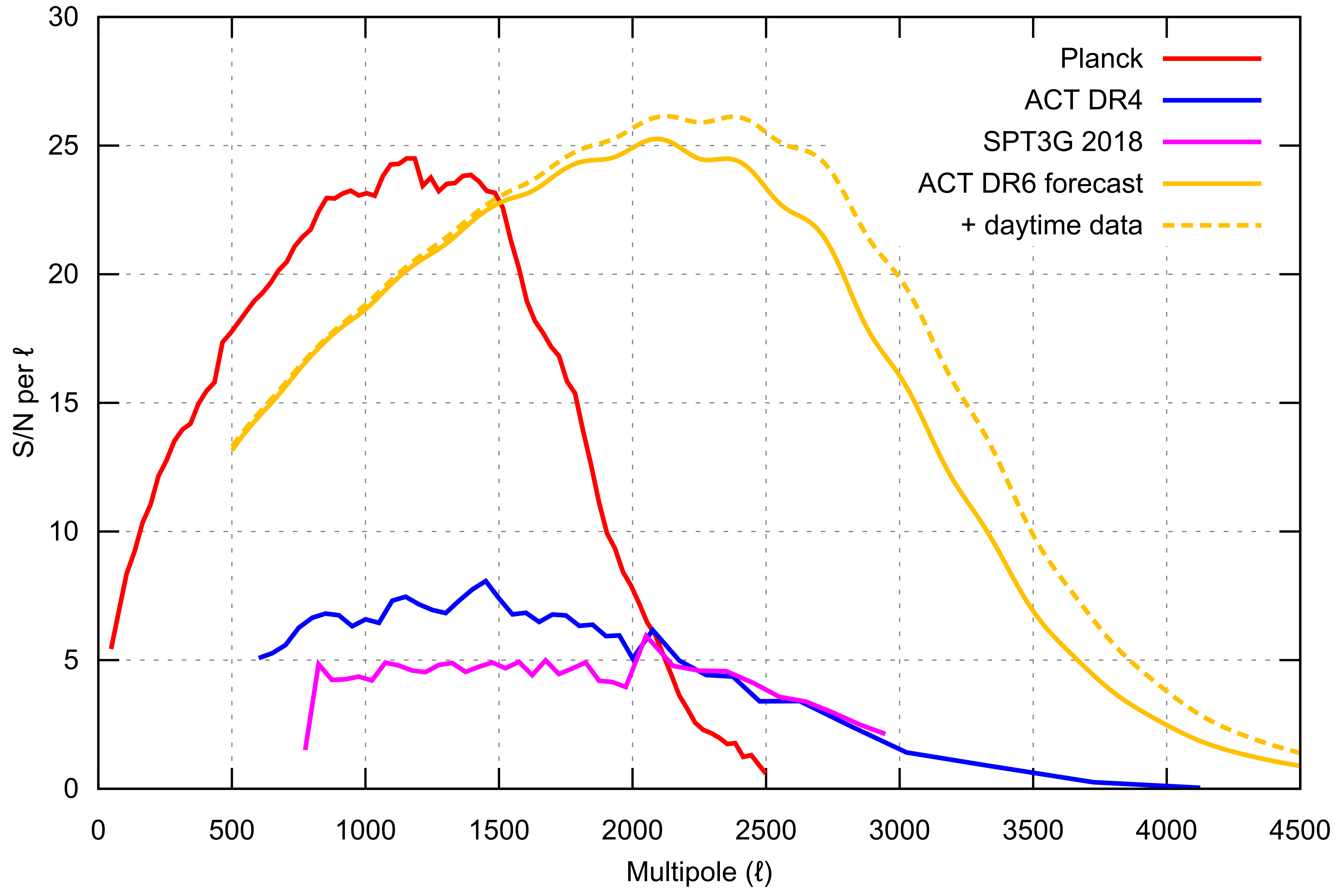
Visualization by S. Naess

CMB power spectrum forecast

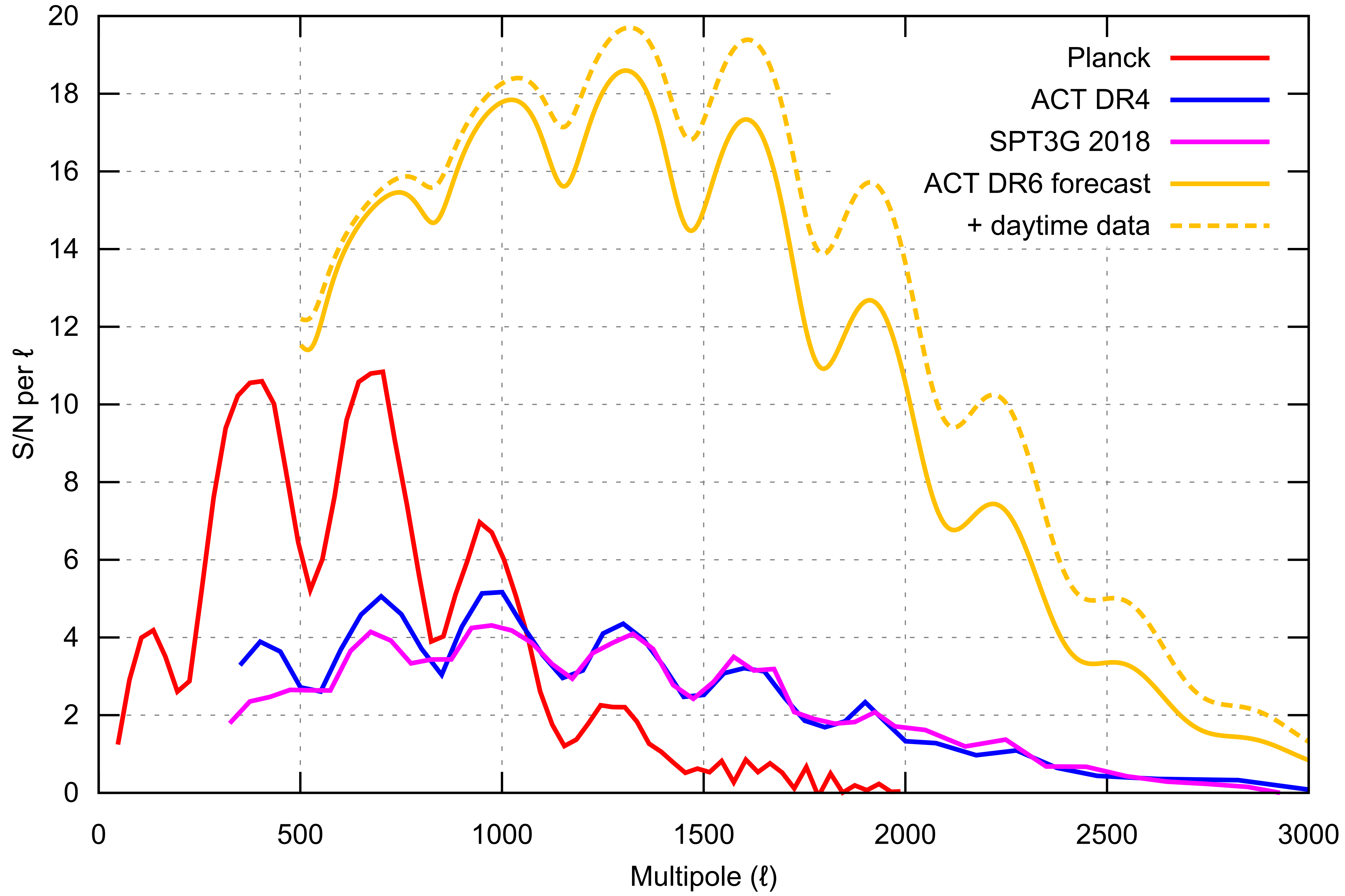
- Data not quite ready yet :(But we have a preliminary forecast
- Same bin size for Planck and DR6
- Larger bins for DR4
- Hard to see the error bars!



S/N per l mode



TT



EE

ACT DR6: forecast in yellow (coming soon!)

Forecast from Knox (1993) approximation
courtesy S. Naess

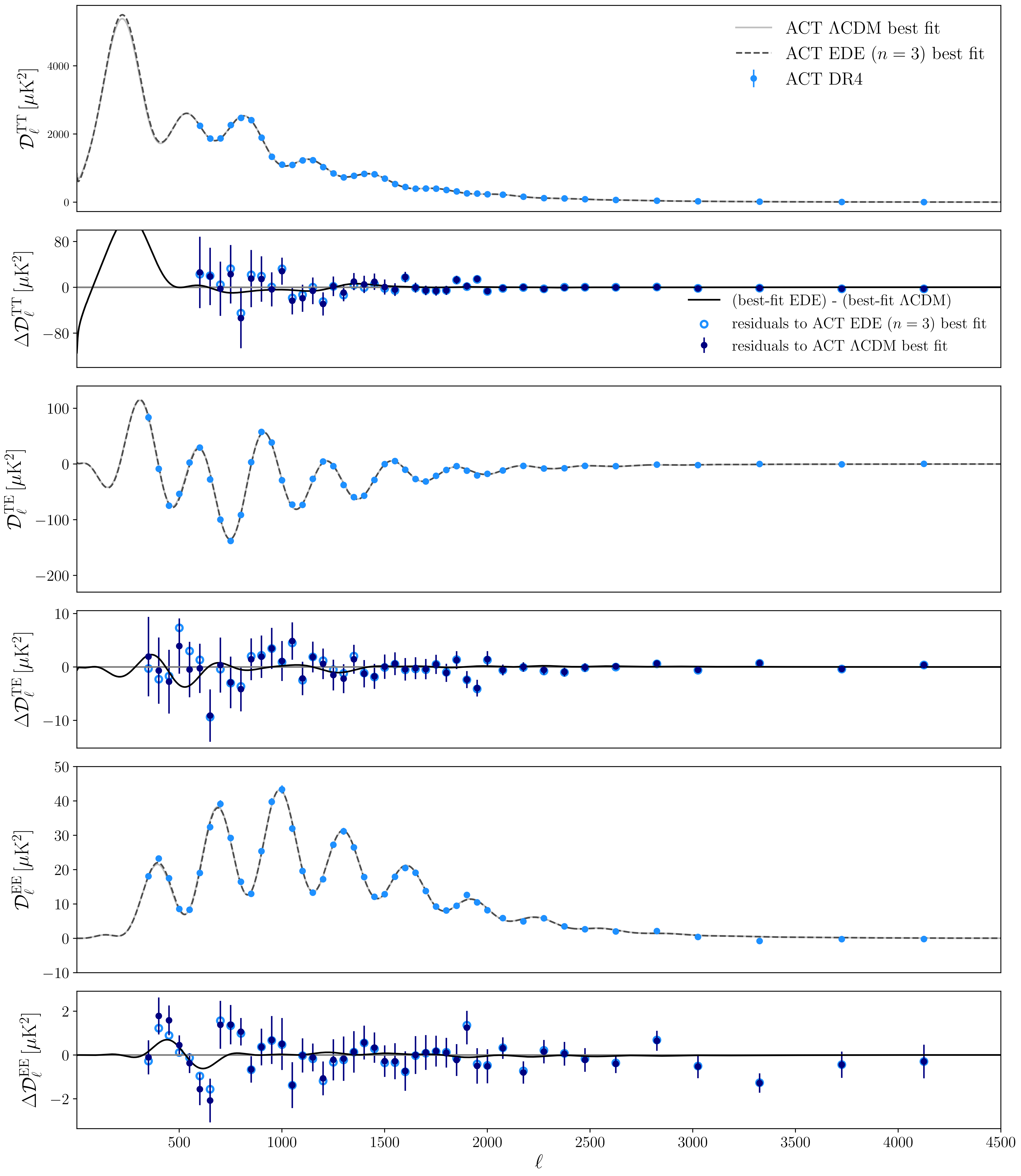
Forecast for cosmological parameters

(Hopefully the real measurements will be out soon!)

	DR4 + WMAP	Planck	DR6 + Planck
$\sigma(H_0)$	1.1	0.5	**0.4**
$\sigma(n_s)$	0.006	0.004	**0.003**
$\sigma(N_{\rm eff})$	0.3	0.2	**0.1**

Preliminary Forecast

2x improvement in sensitivity to new light relic particles ($N_{\rm eff}$)



ACT DR4 power spectra (2018)

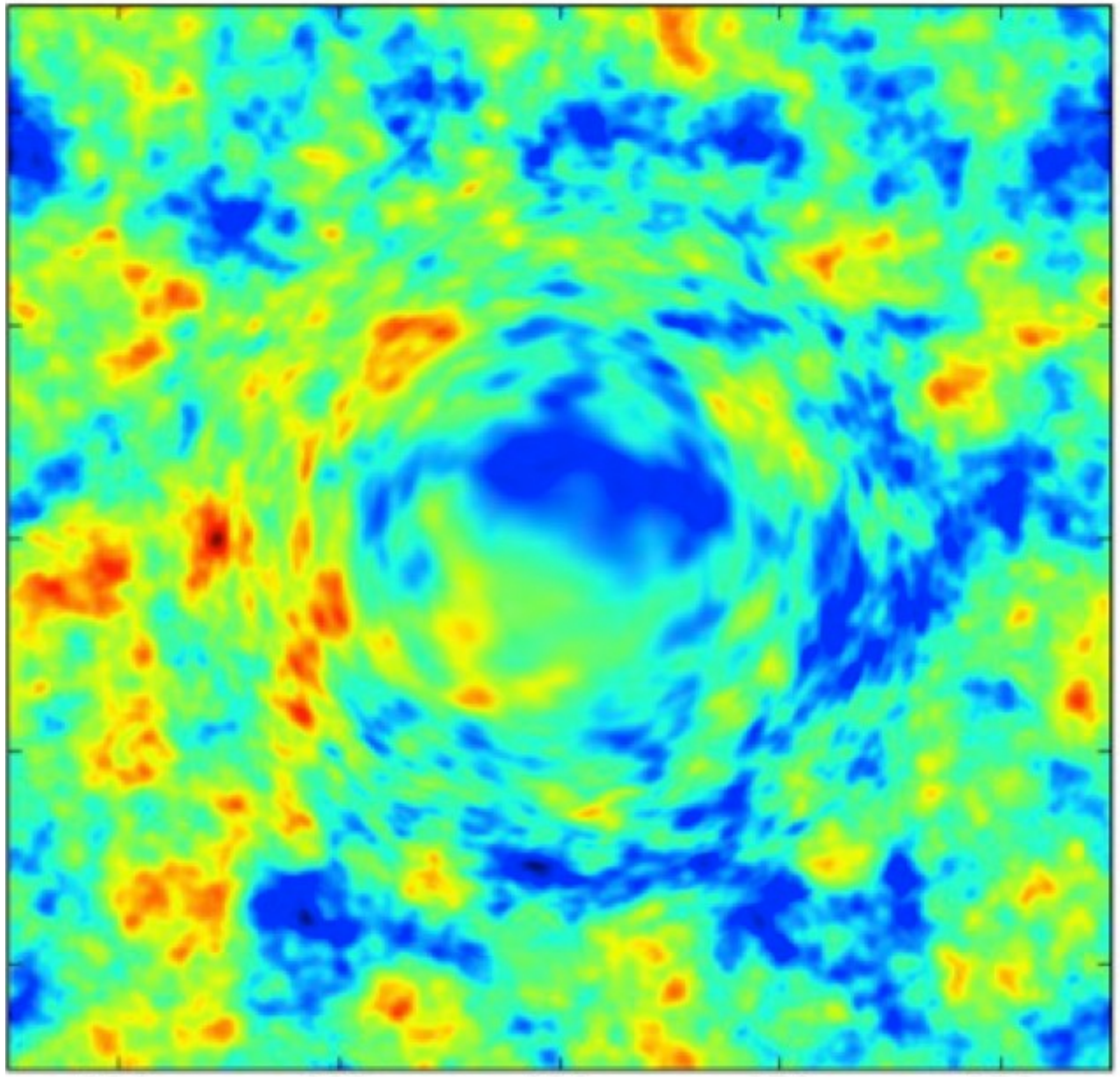
Does 400 < l < 700 EE show early dark energy (?!?)

Not seen in Planck

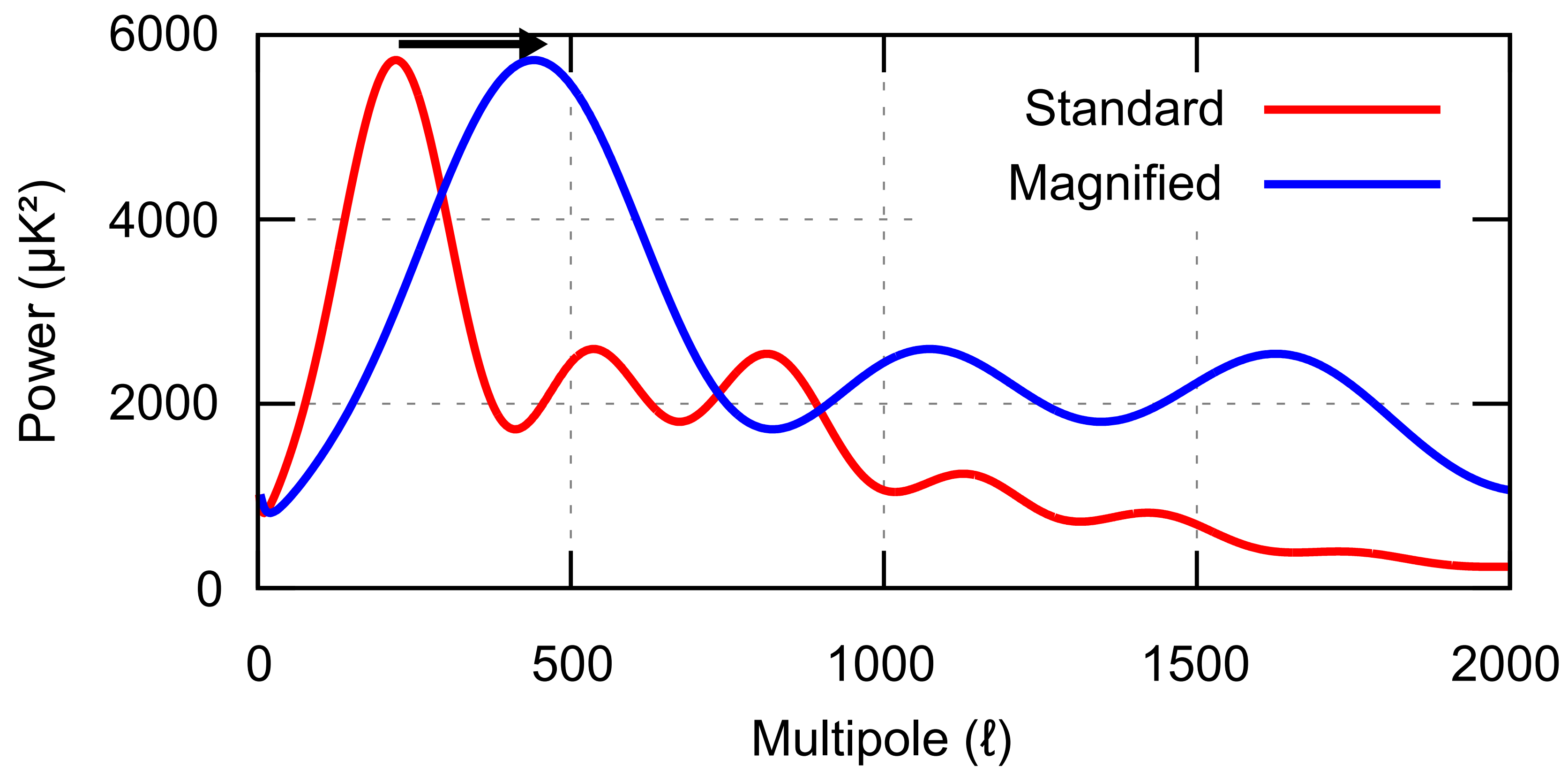
ACT DR6 will have more EE weight than Planck

Hill et al. 2022

Gravitational Lensing



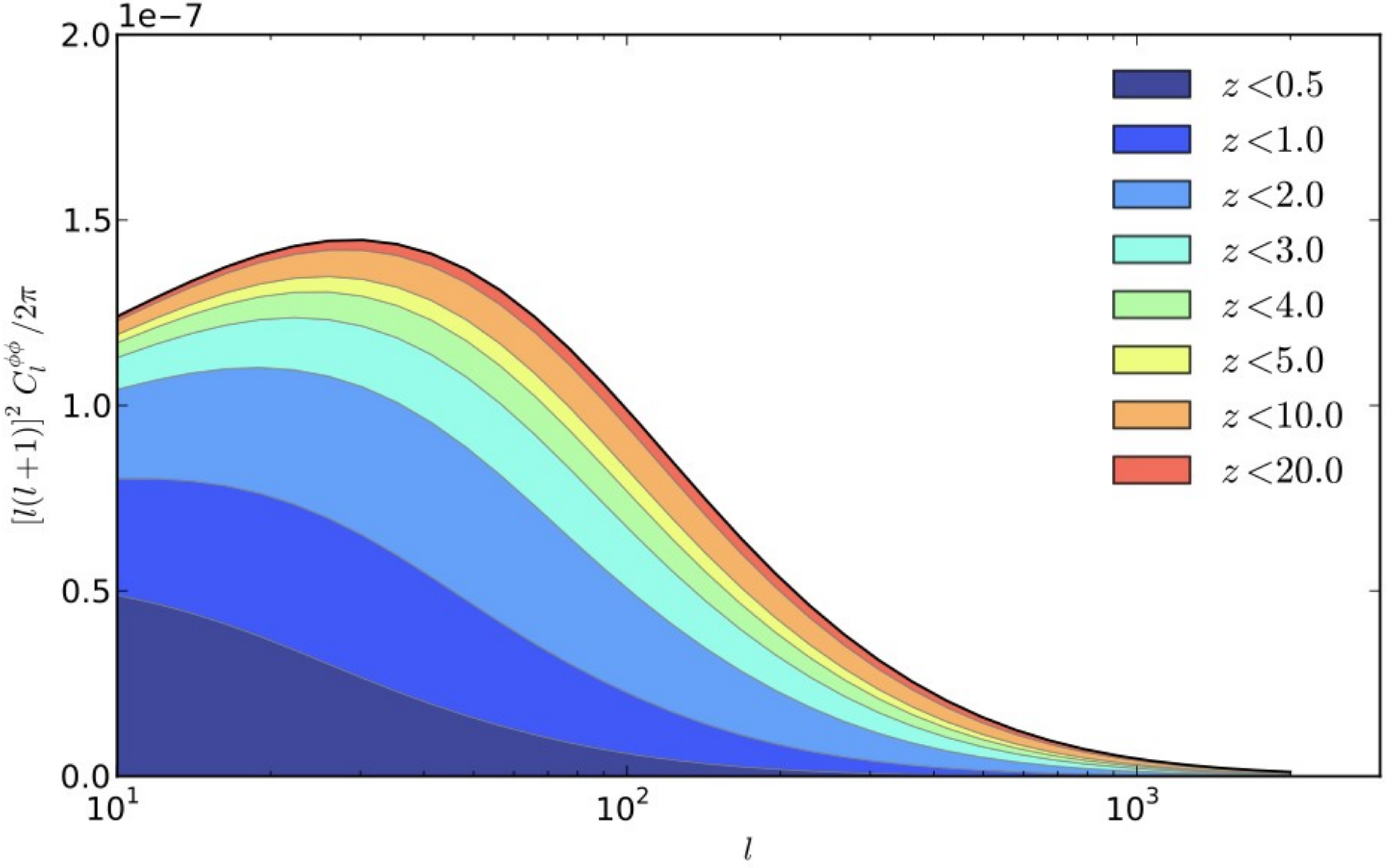
- Exaggerated example of lensing of CMB by a point mass
- More mass ⇒ more magnification
- Can recover mass distribution by comparing power spectra in different areas of the map



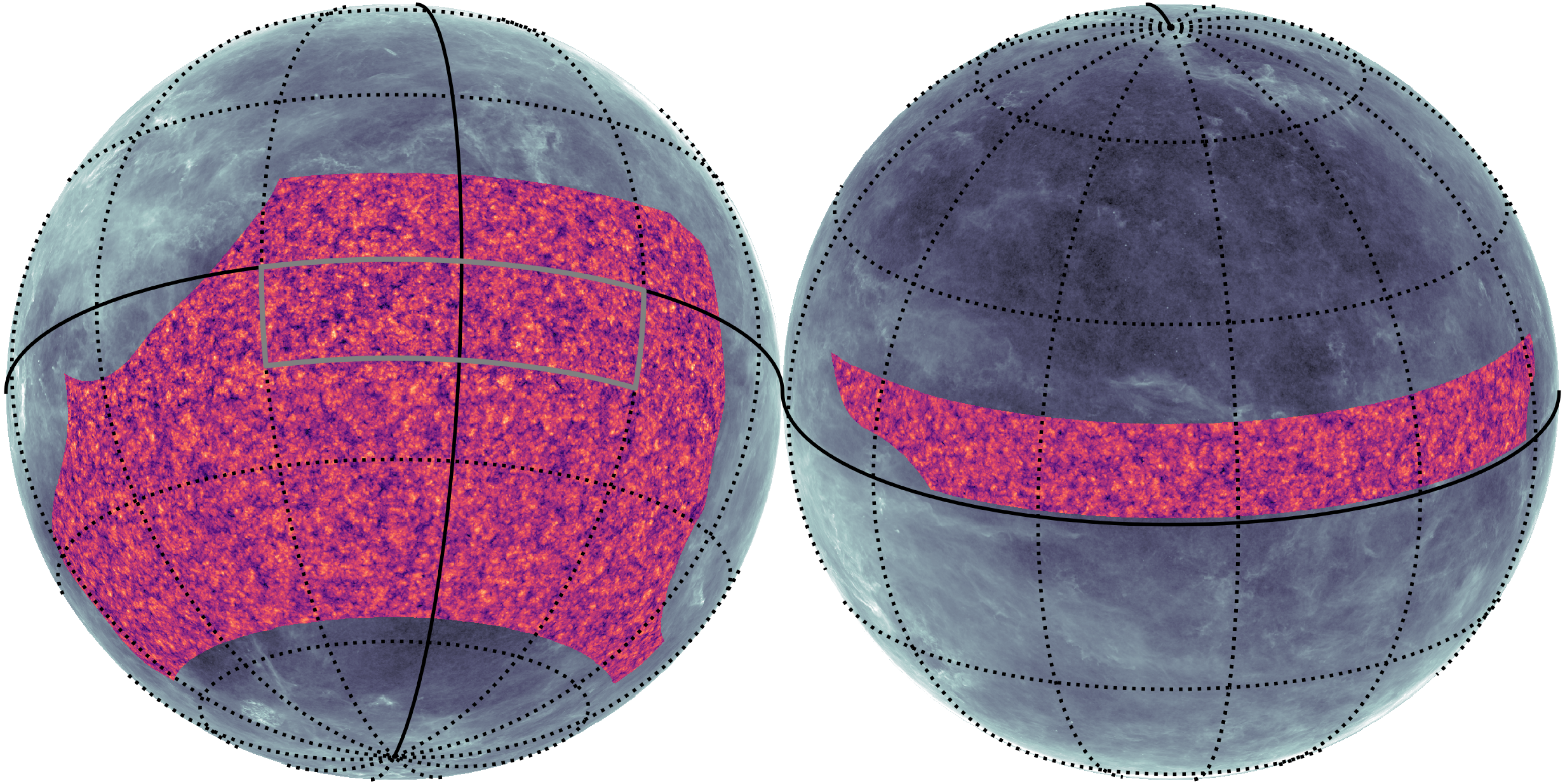
- In practice a fancier algorithm is used, but principle is the same

What does CMB lensing tell us?

Sensitive to integral of matter power spectrum over all redshifts
Probes higher redshifts than galaxy surveys, but lower than the CMB

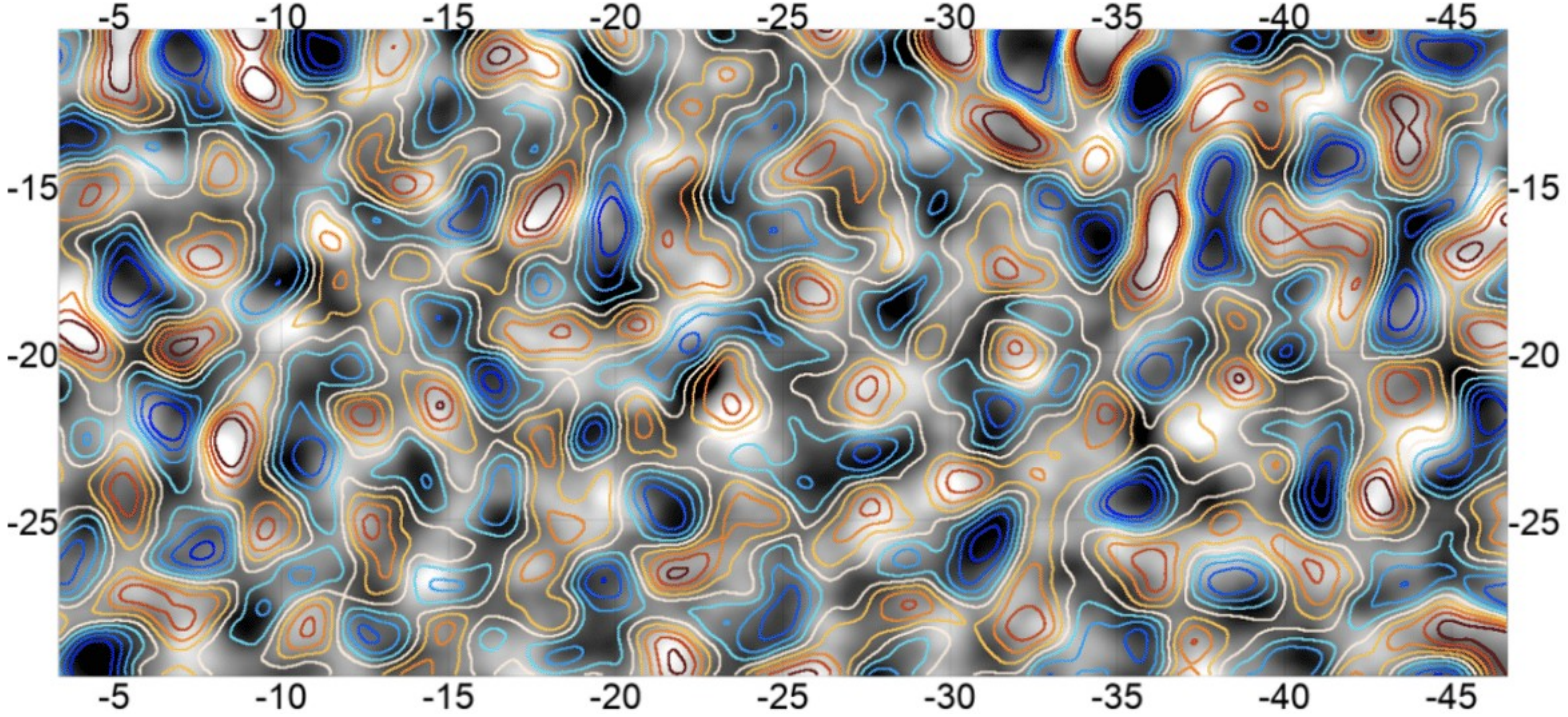


ACT DR6 CMB lensing mass map



Madhavacheril et al. 2023

Great consistency with CIB!

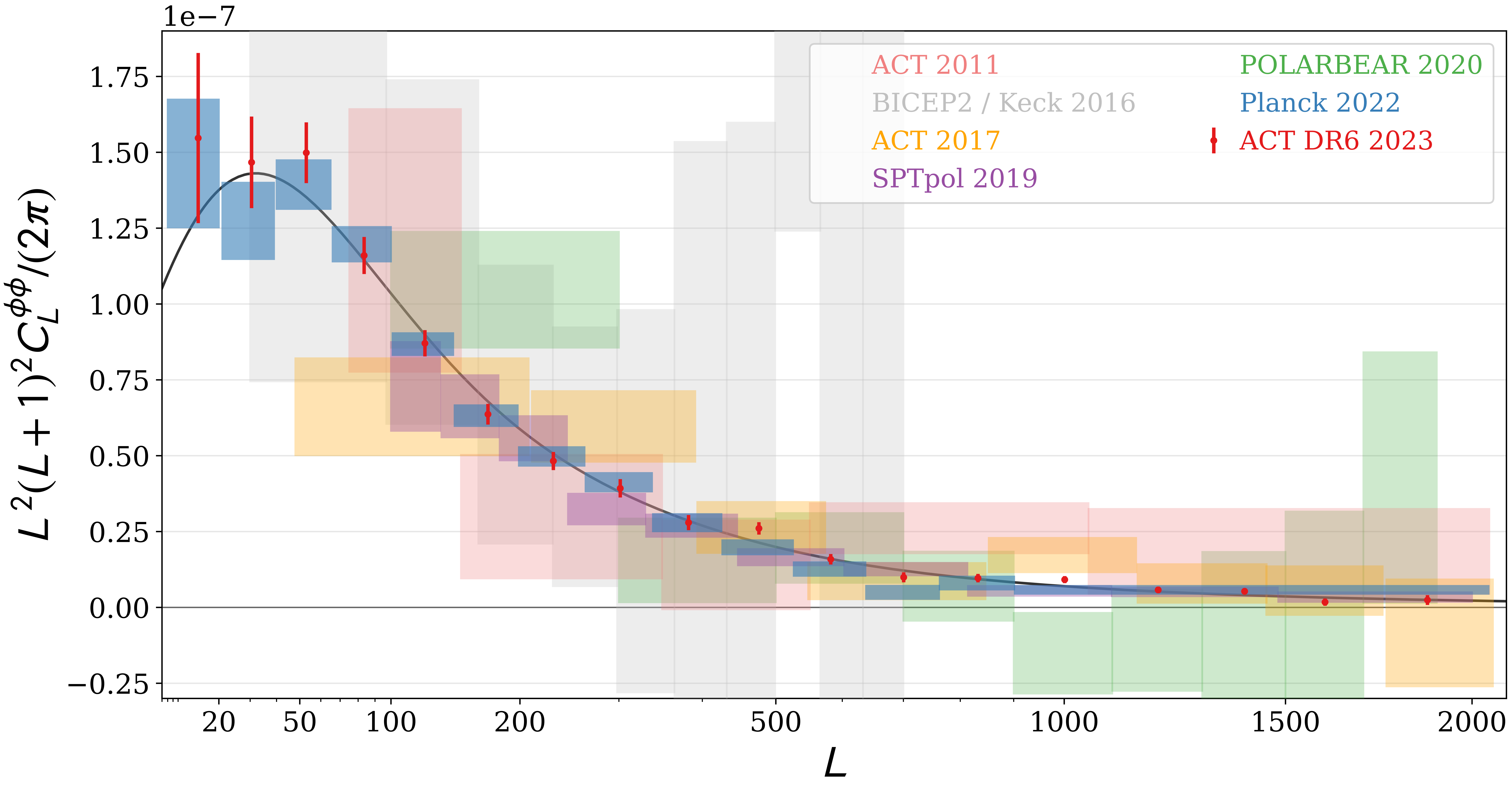


Background: ACT lensing map

Contours: Planck Cosmic Infrared Background (CIB) map

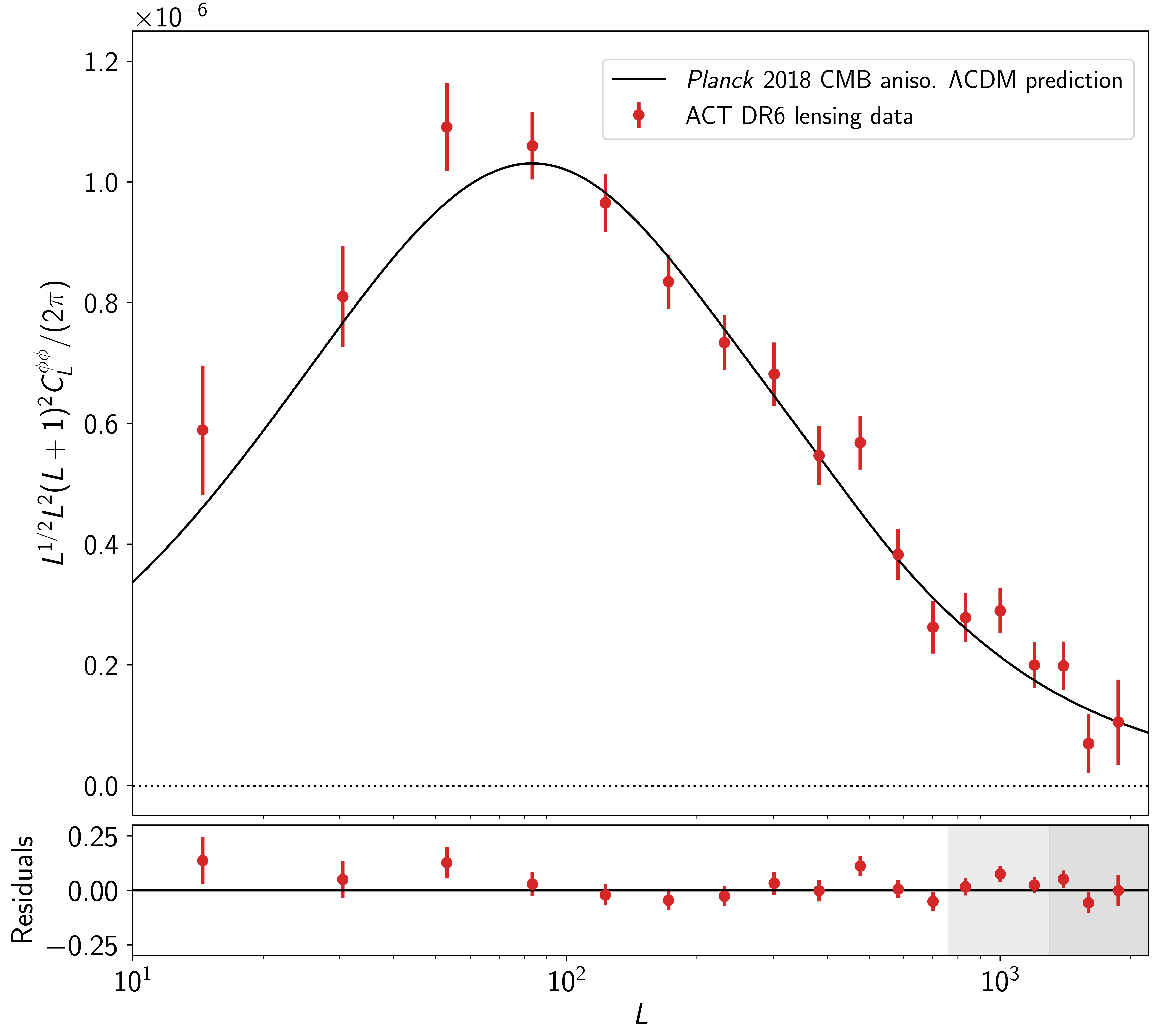
High correlation because both are sensitive broad redshift range around z = 2

Madhavacheril et al. 2023

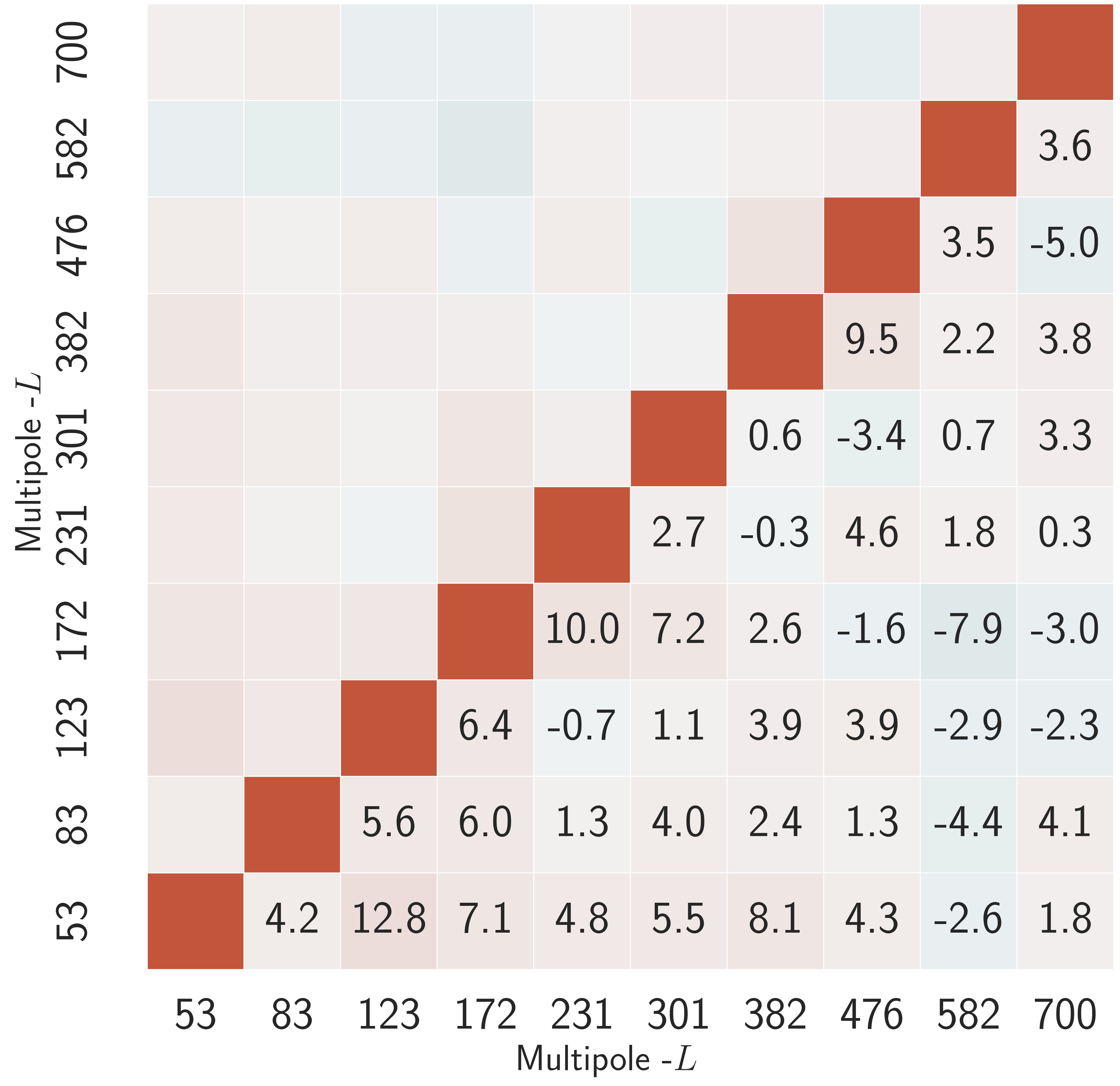


12 years of CMB lensing progress

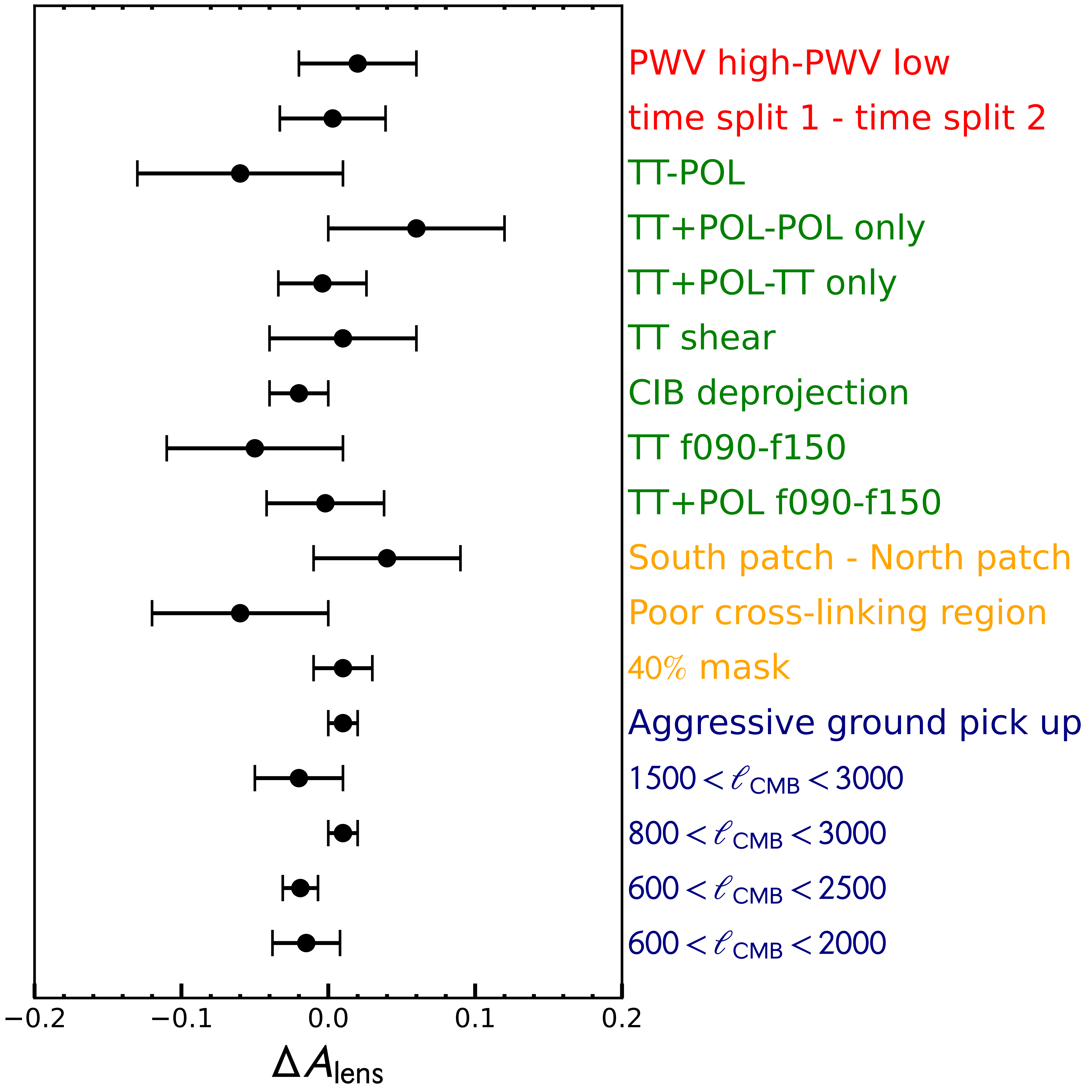
Qu et al. 2023



ACT lensing is highly consistent with predicted lensing signal from Planck best-fit cosmology

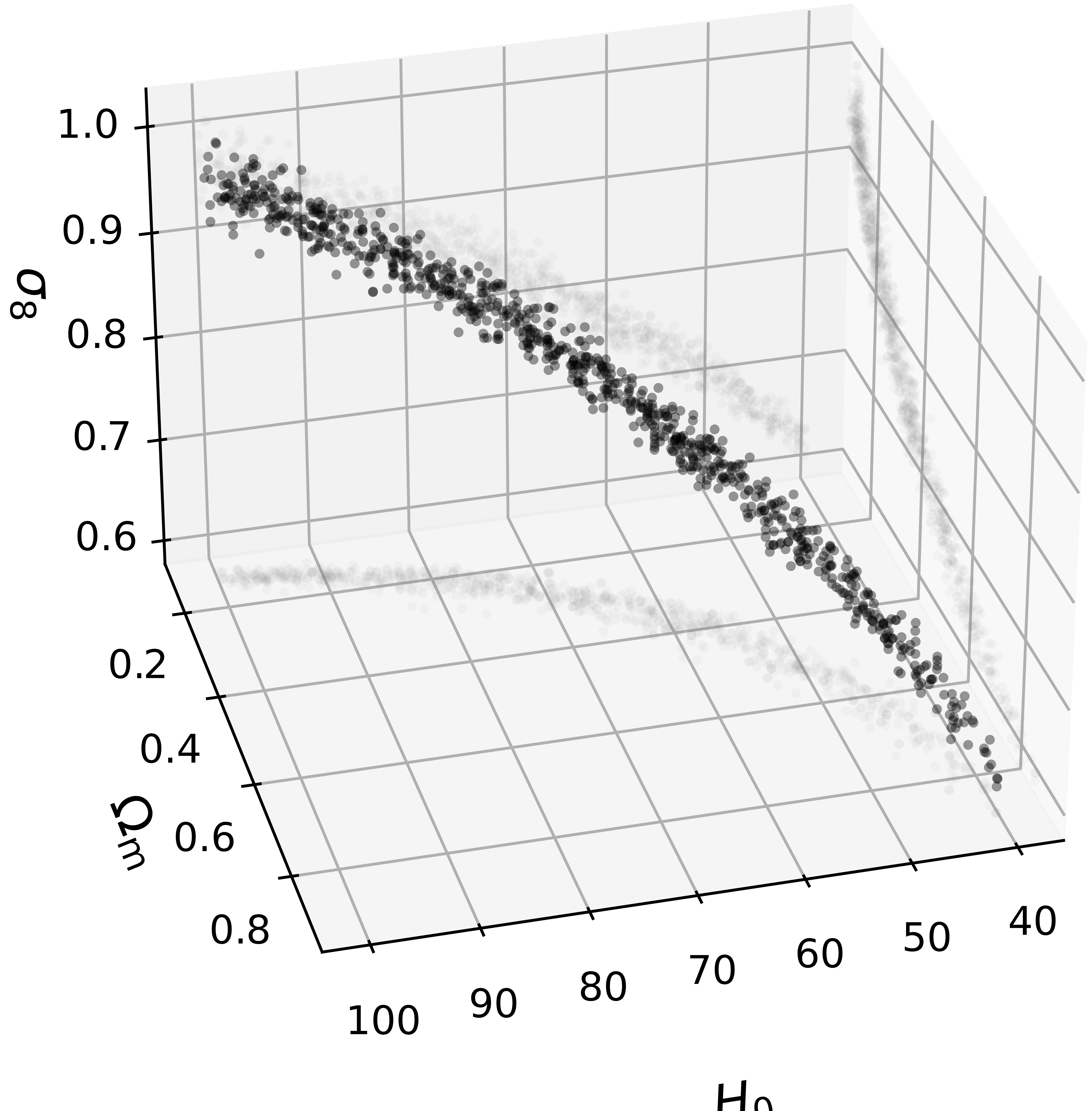


Qu et al. 2023



Passing over 100 null tests for lensing power spectra

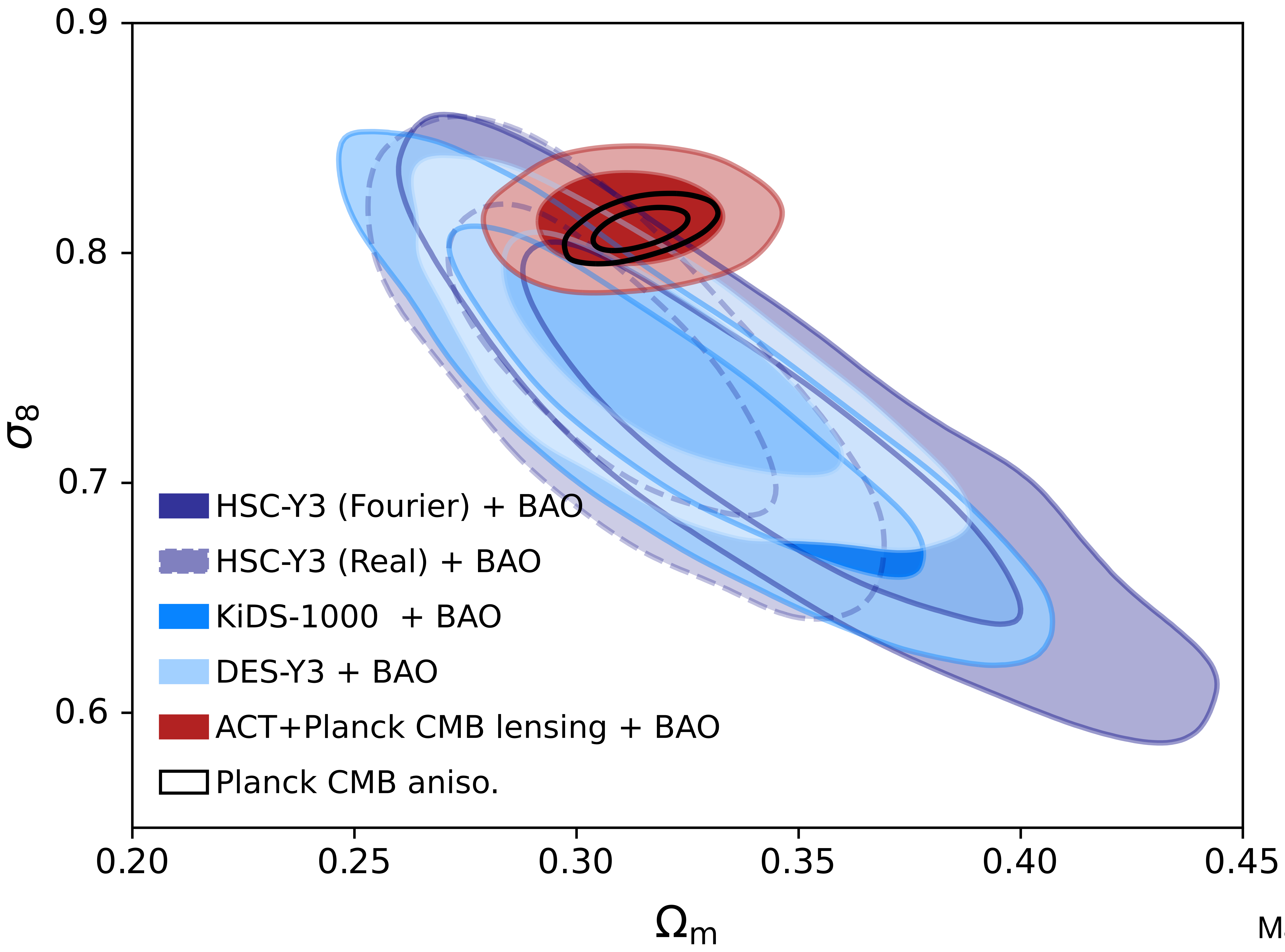
Qu et al. 2023



Lensing-only constraint is along a line in space of sigma-8, Omega_m, and H_0

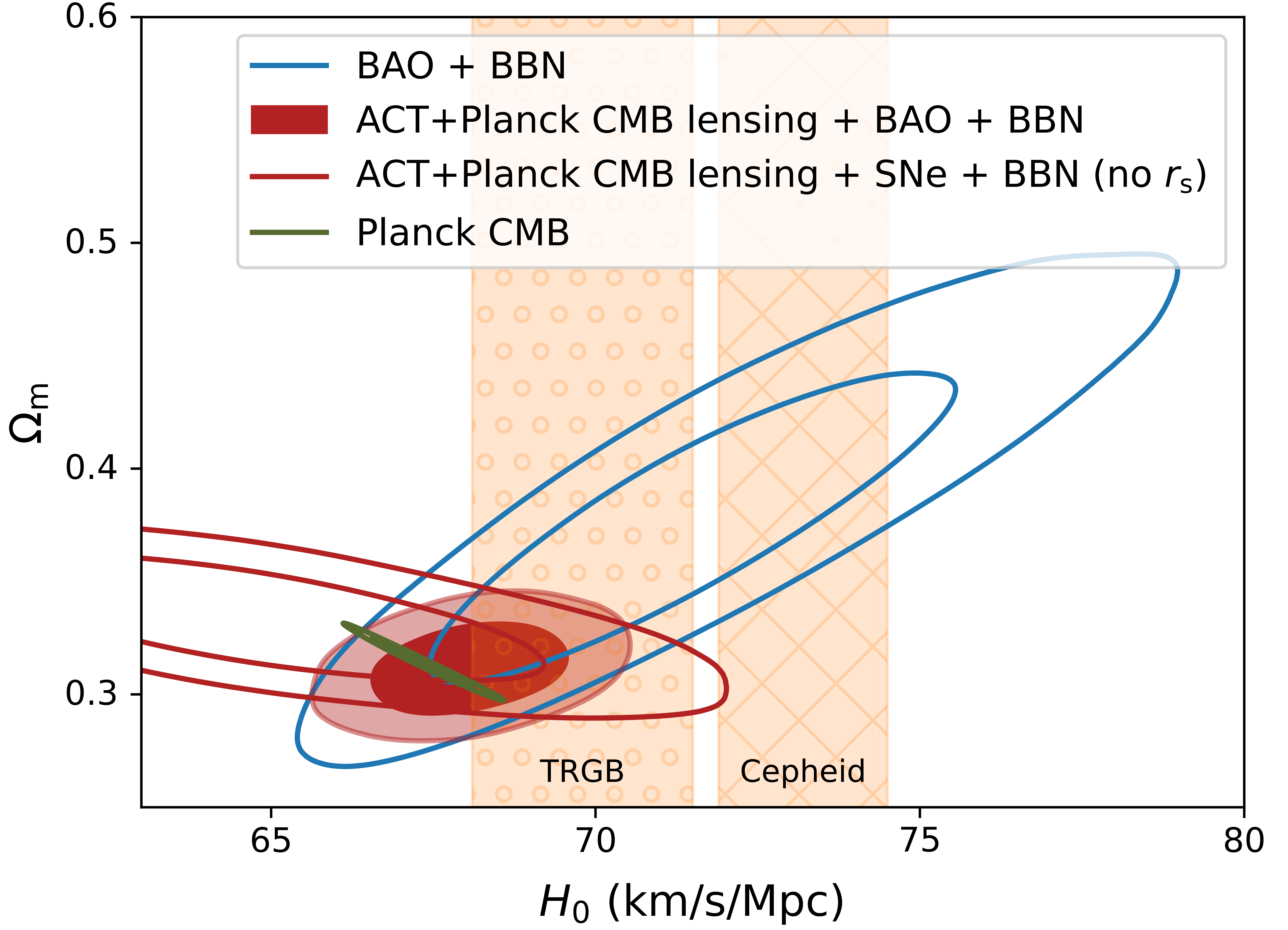
$$\sigma_8 \Omega_m^{0.25} = 0.606 \pm 0.016.$$

Qu et al. 2023

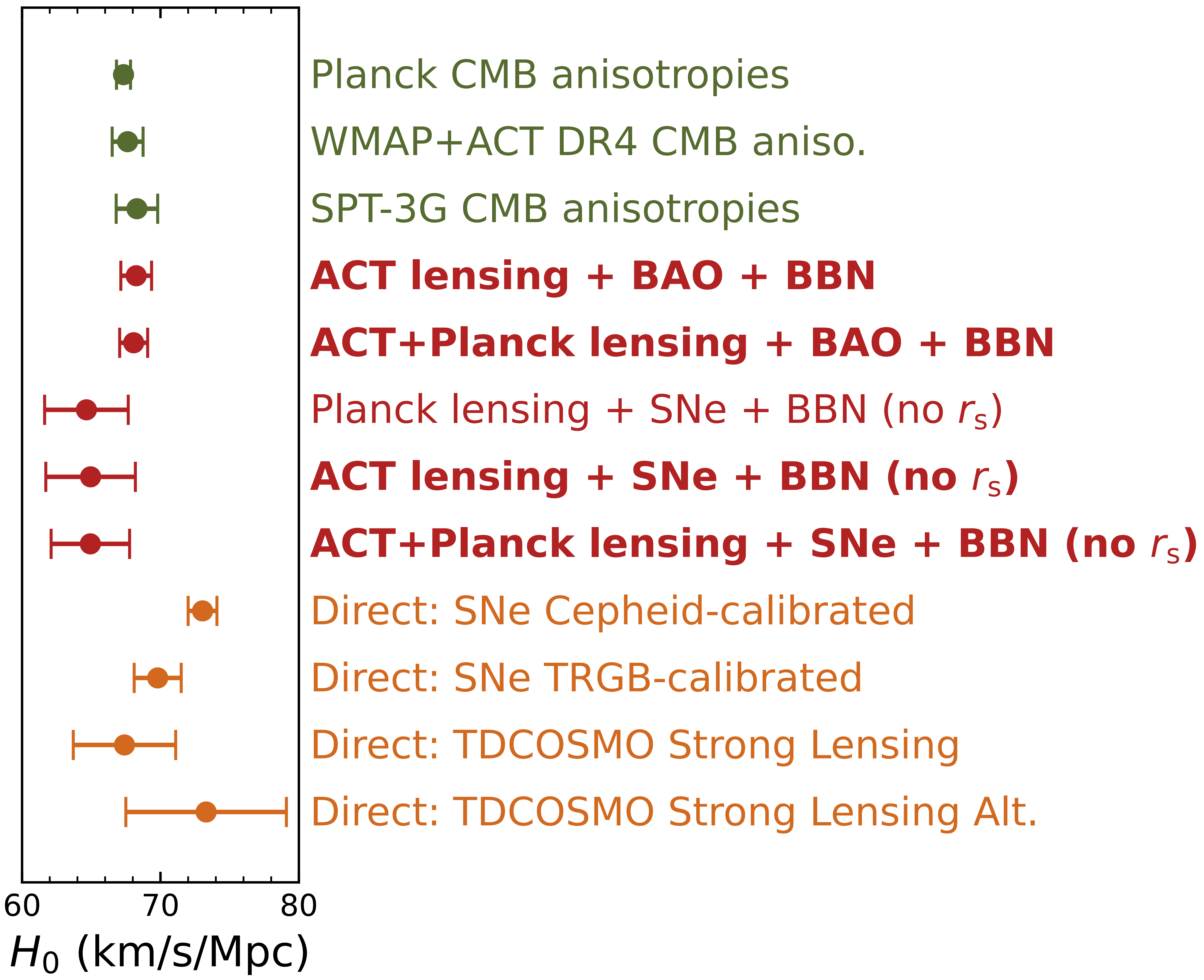


CMB lensing + BAO gives sigma-8 consistent with Planck cosmology, higher than optical weak lensing values

Madhavacheril et al. 2023

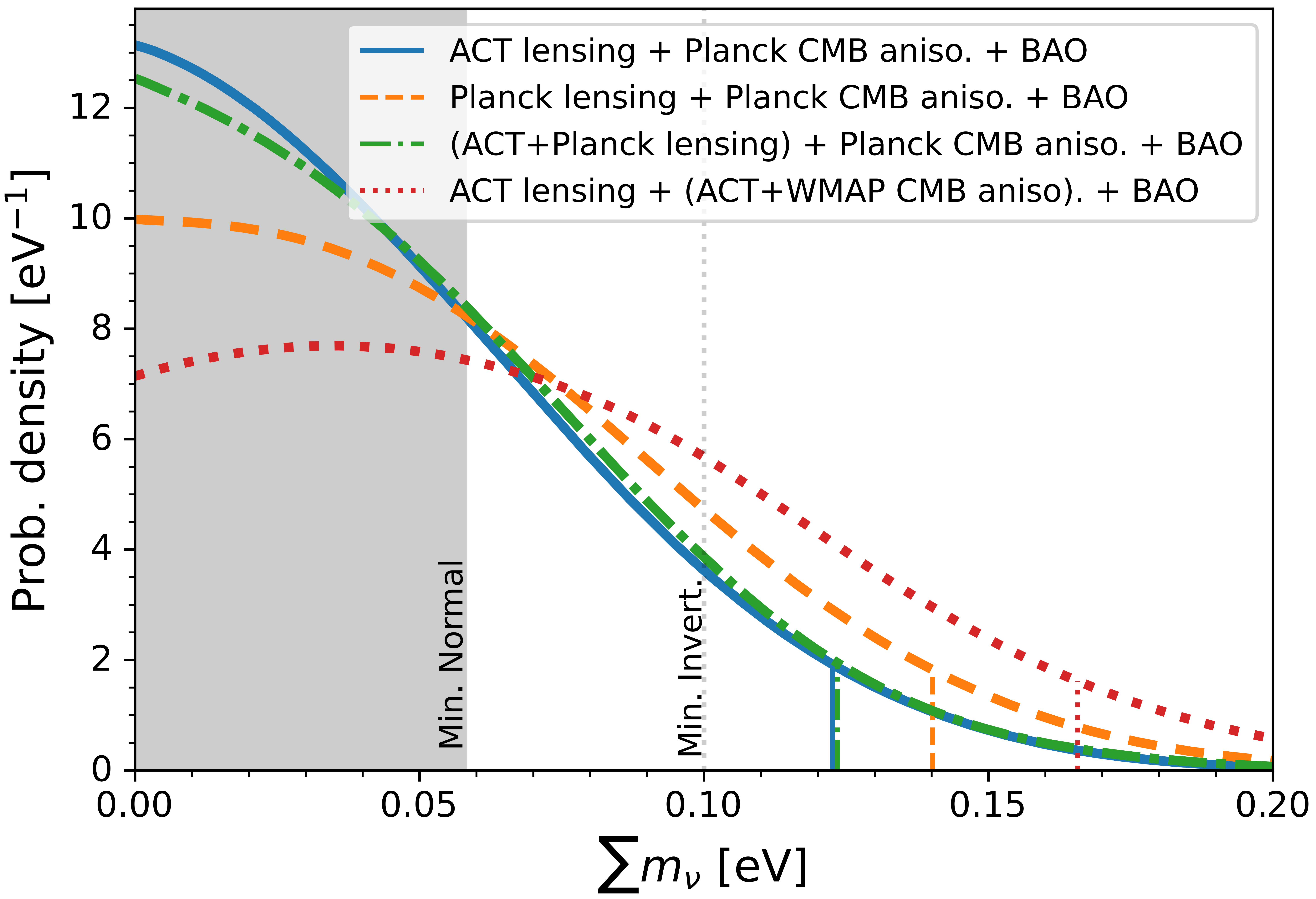


Madhavacheril et al. 2023



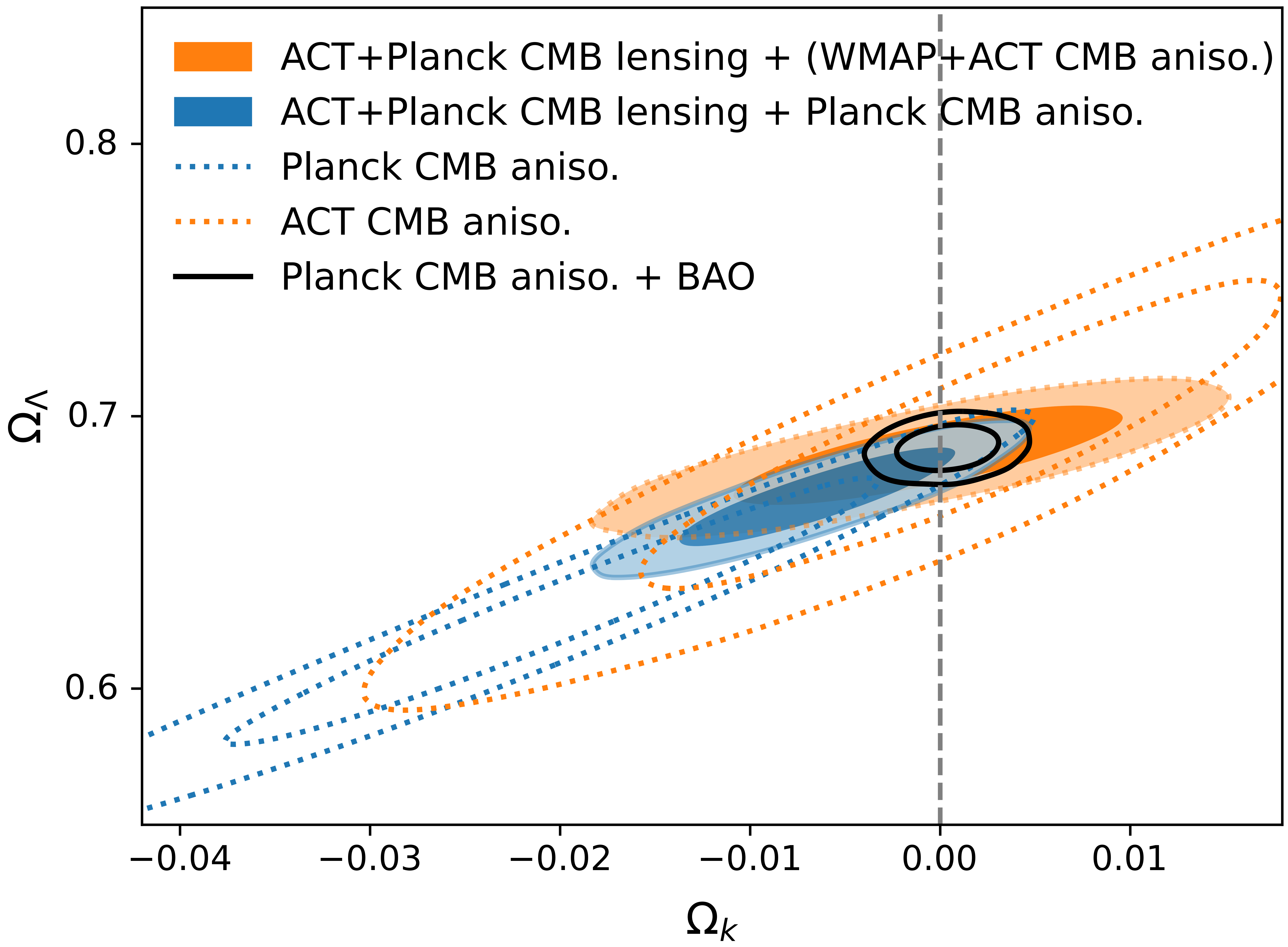
CMB primary constrains Hubble constant

Madhavacheril et al. 2023



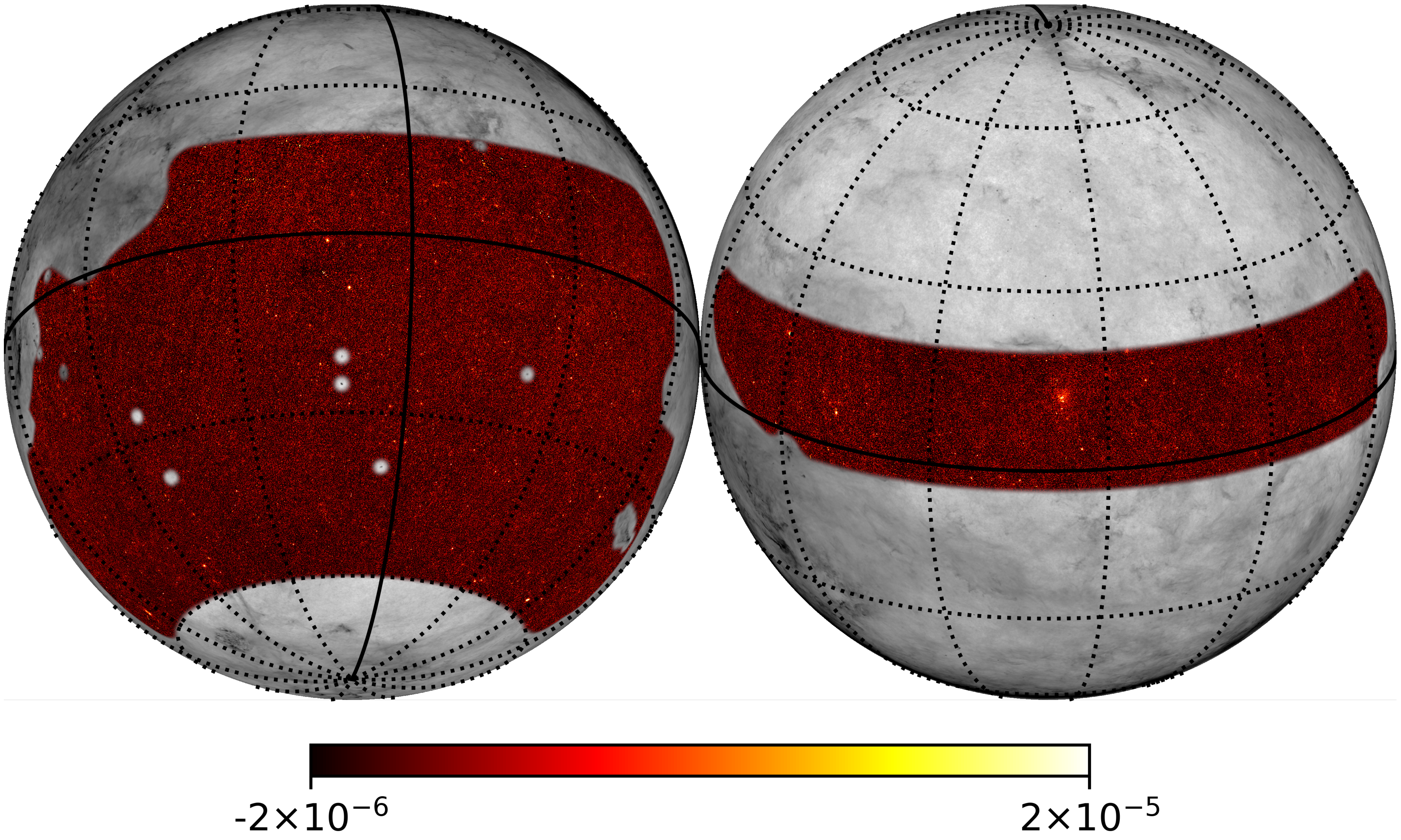
CMB lensing constrains neutrino masses

Madhavacheril et al. 2023



CMB lensing + CMB primary constrains geometry

Galaxy Clusters

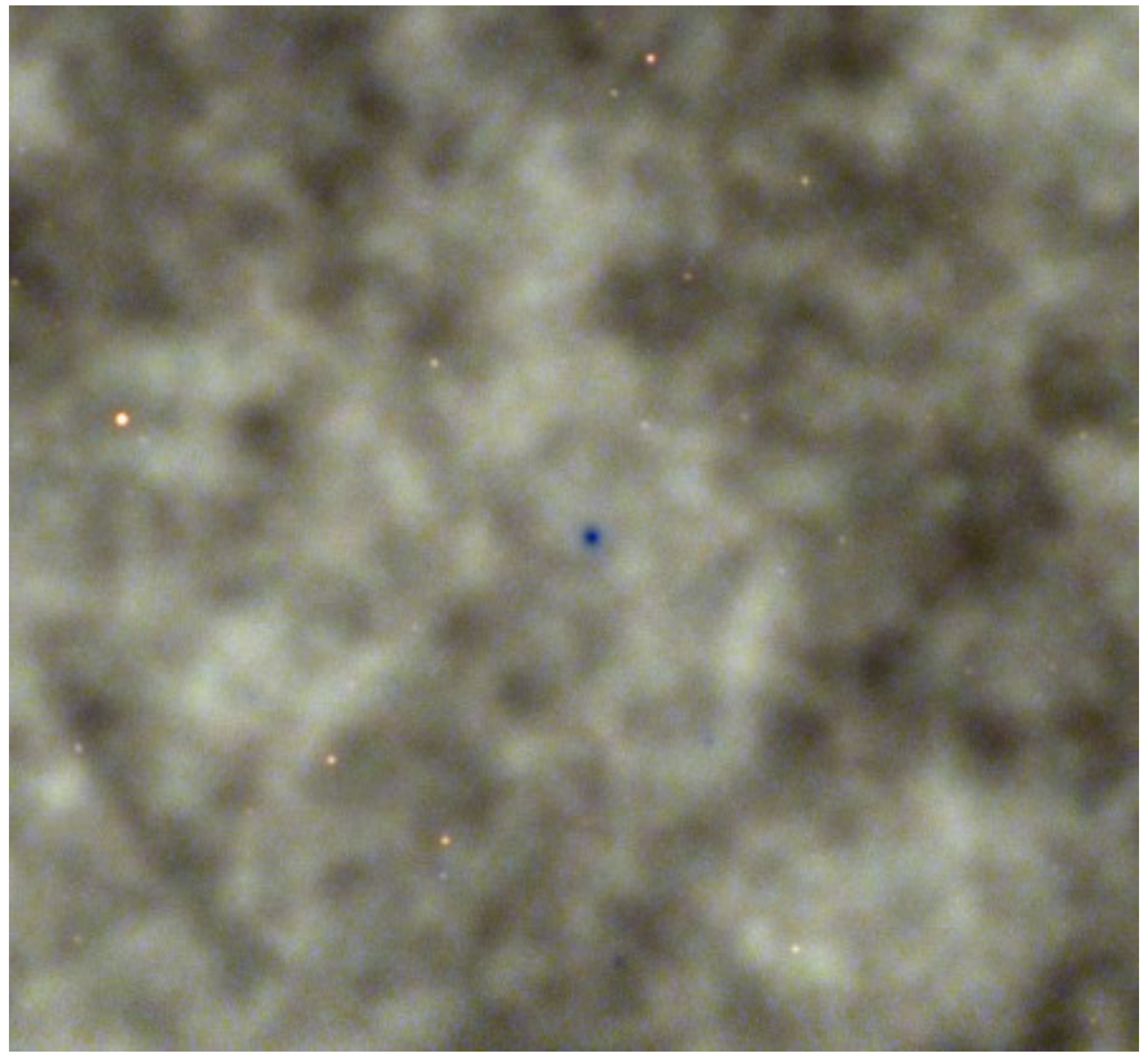


(a) ACT & *Planck* NILC Compton-y map.

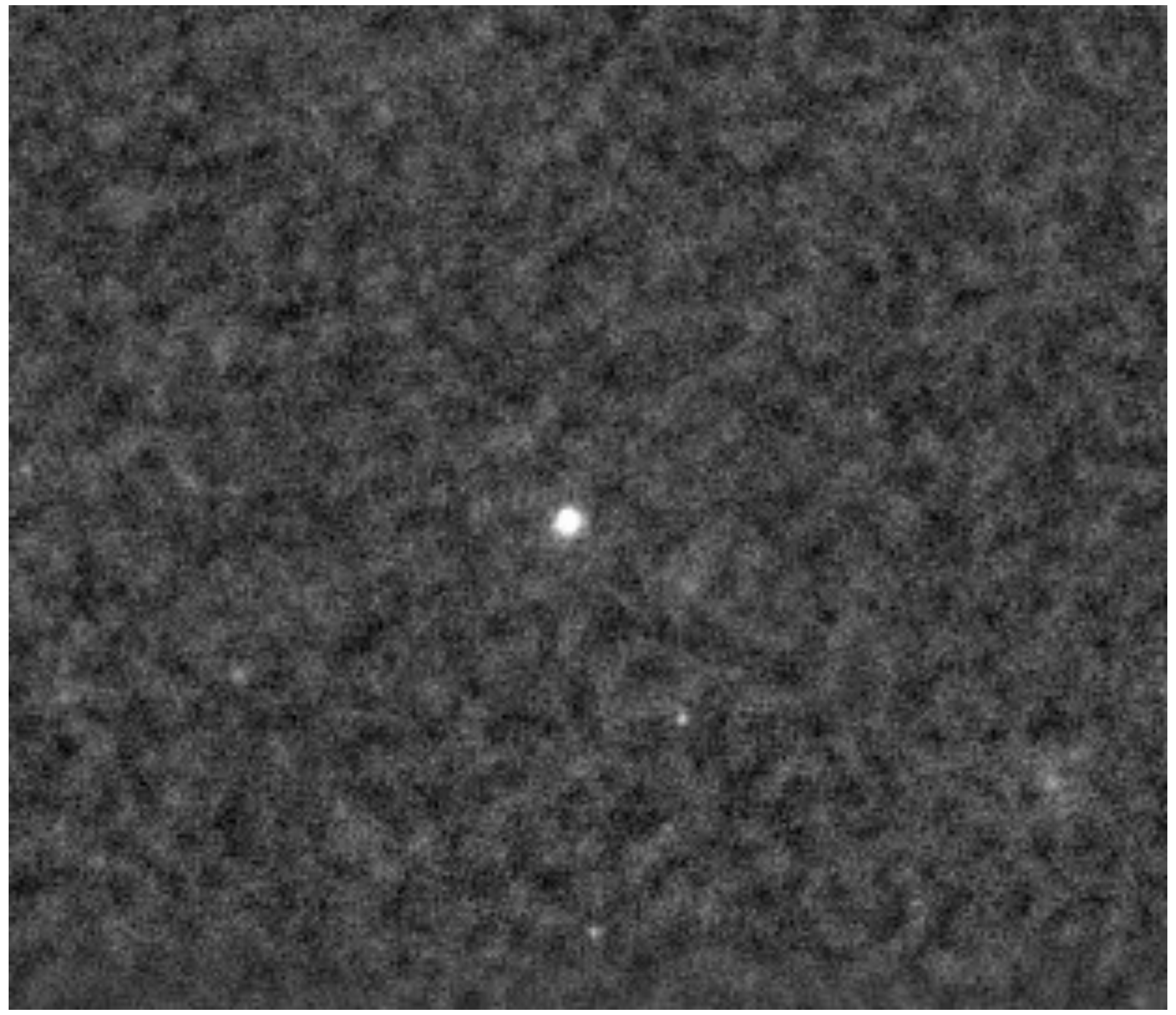
Coulton et al. 2023

Galaxy clusters appear as dark spots in CMB map below 230 GHz

Intensity map
R:f090,G:f150,B:f220



Compton y map

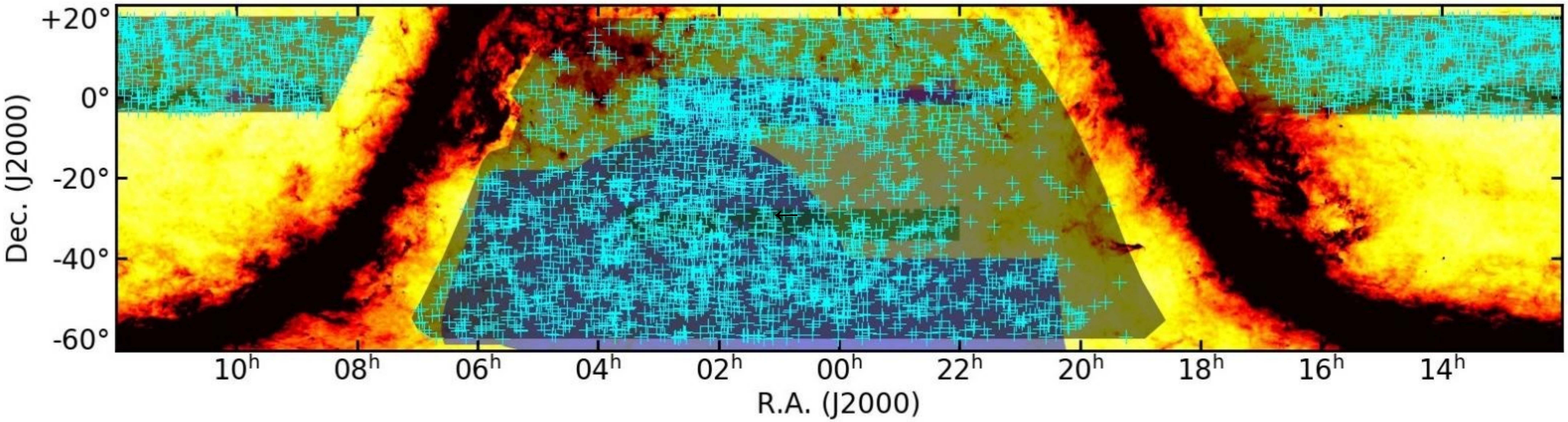


DES optical image
(zoom)

Detect by looking for negative point sources in the CMB map
(or positive point sources in the y map)

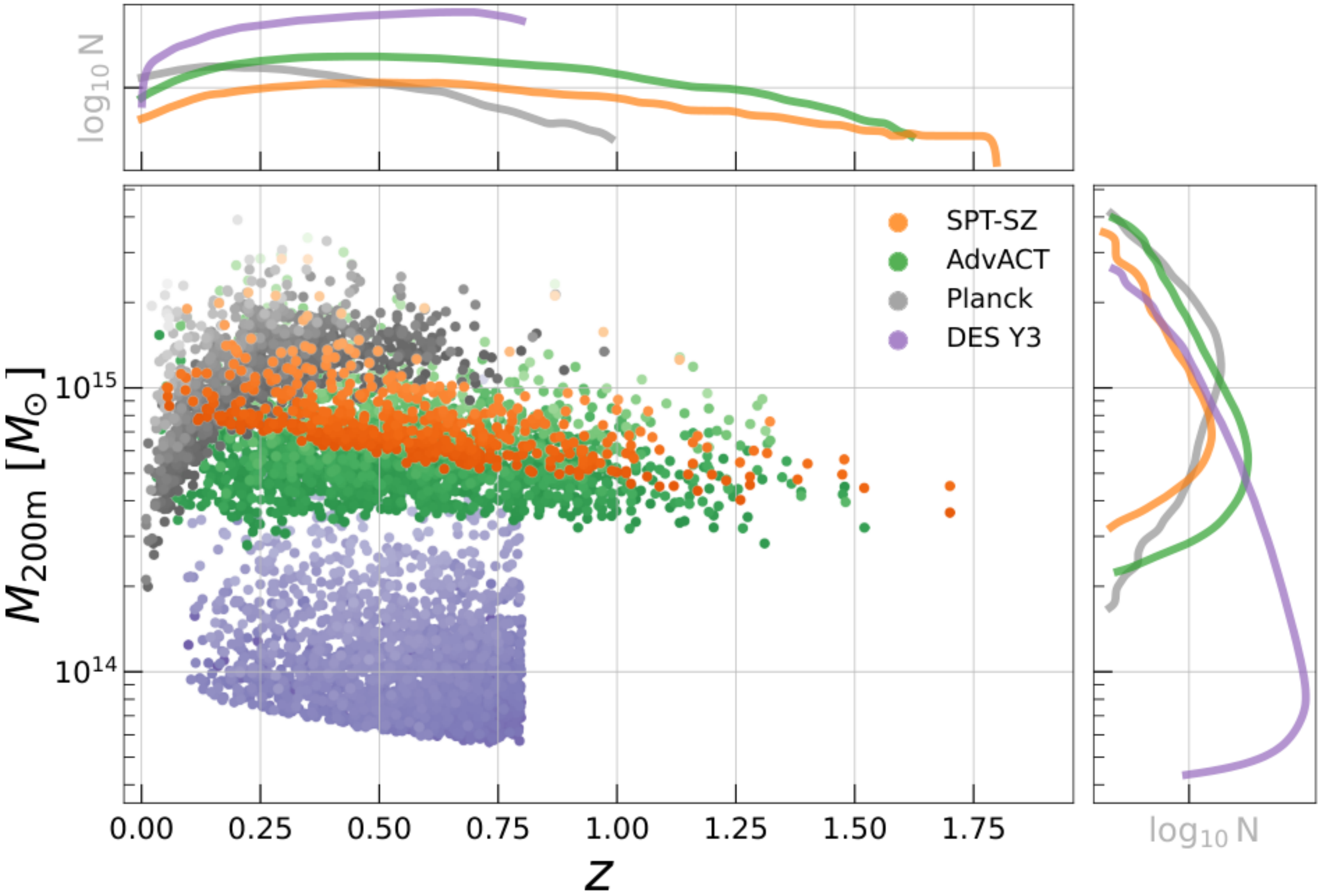
Cluster catalog

DR5 SZ cluster catalog from Hilton et al. (2021) (>4000 confirmed SNR>4 clusters)

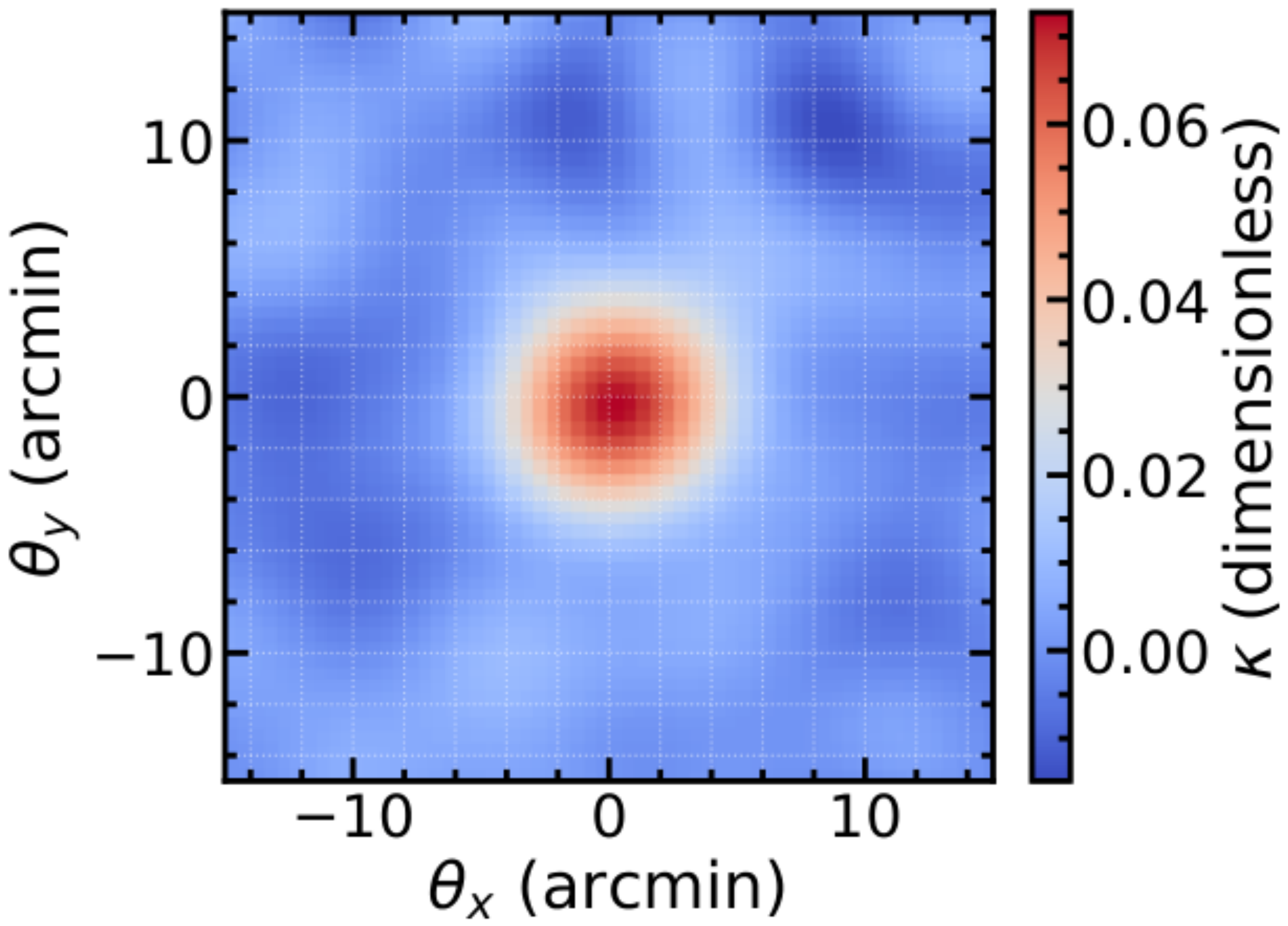


Preliminary number for DR6 catalog: 6800 SNR>4 clusters!
Comparison: Planck has 1203 confirmed clusters

tSZ gives almost redshift-independent selection function
Very different from optical surveys like DES!

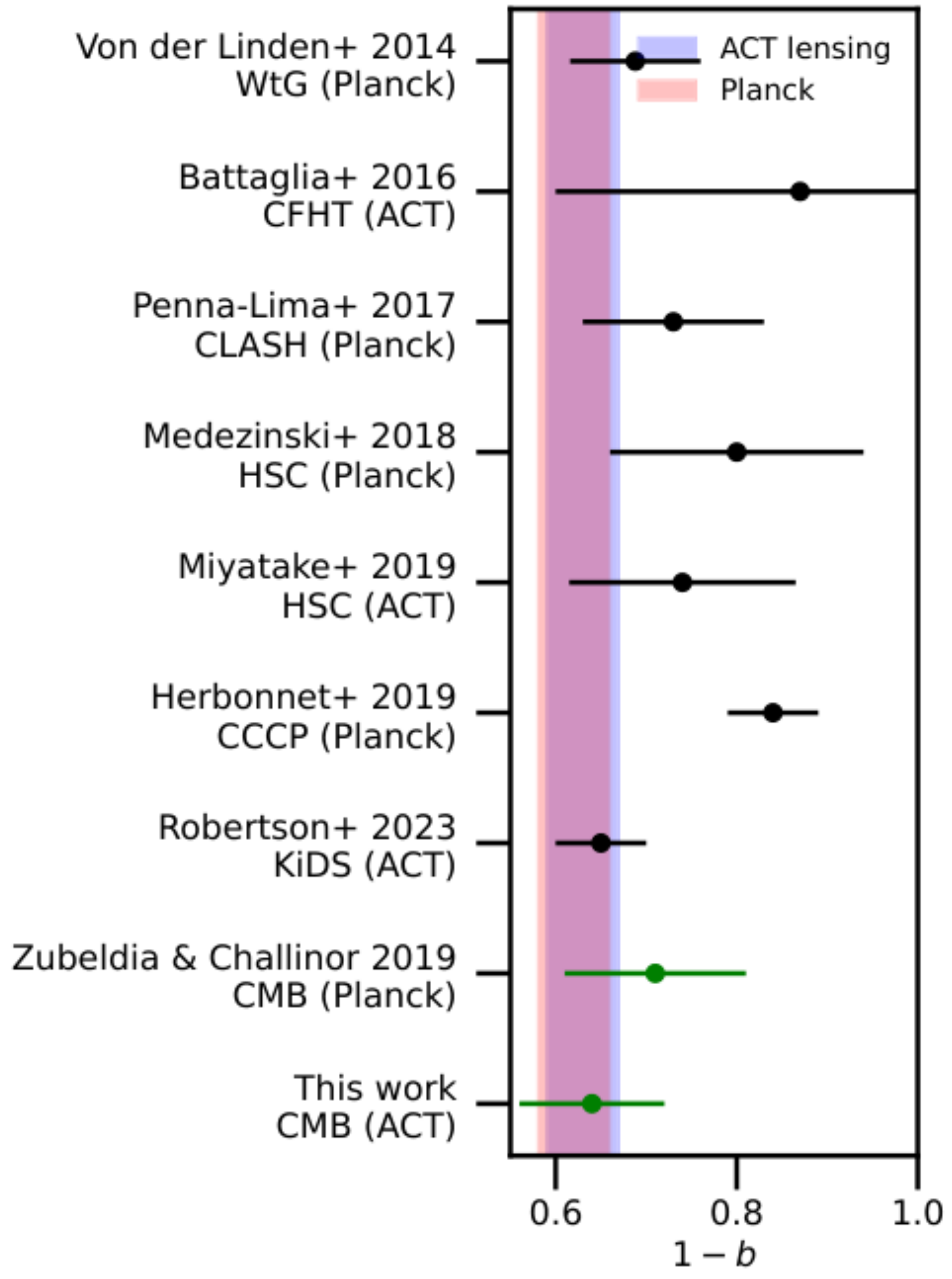


Need to calibrate tSZ-mass relationship to do cosmology with clusters. Solution: Cluster lensing!



Stack of lensing maps from 3958 clusters. 15σ detection!

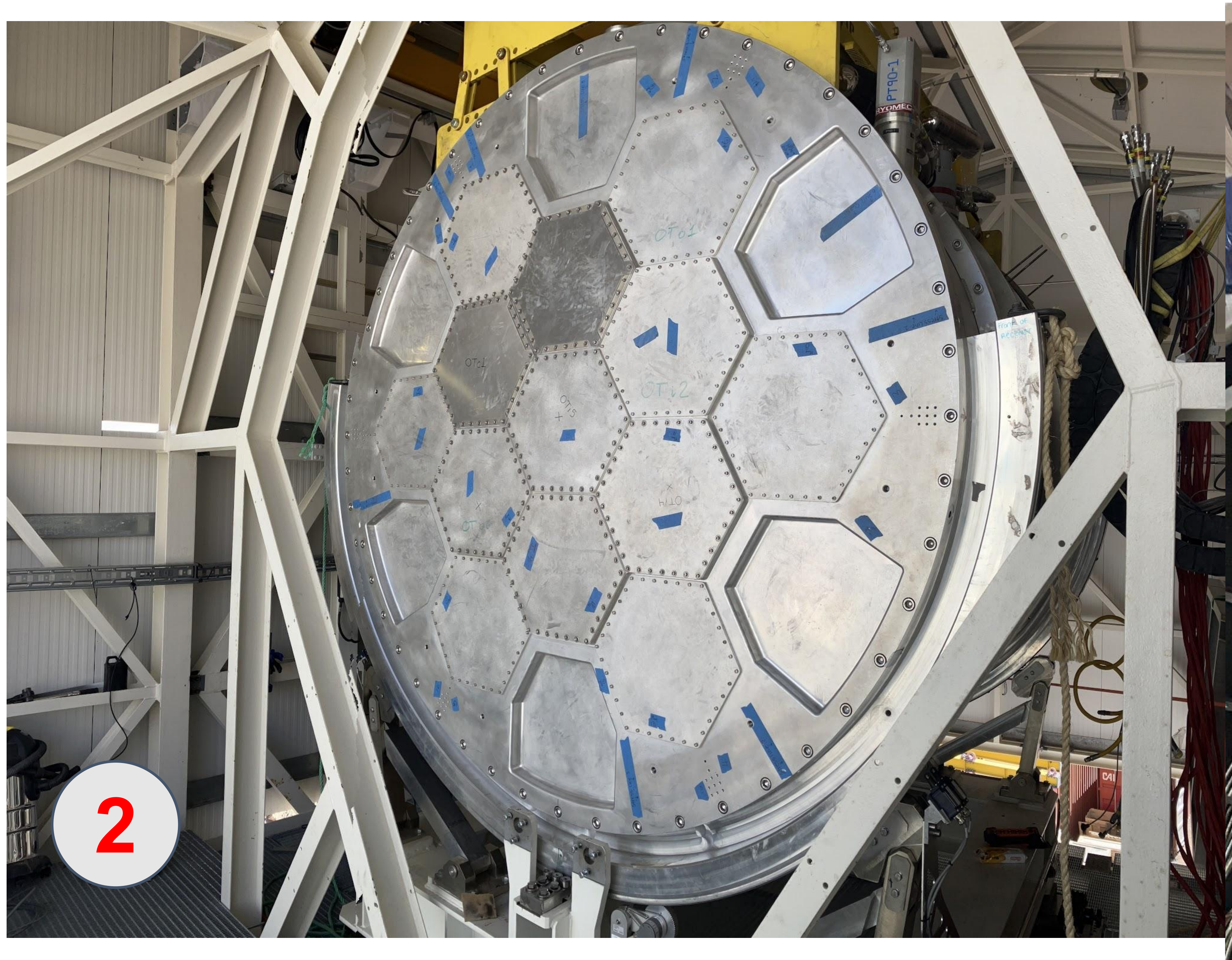
Preliminary! Eunsong Lee at al. (in prep)

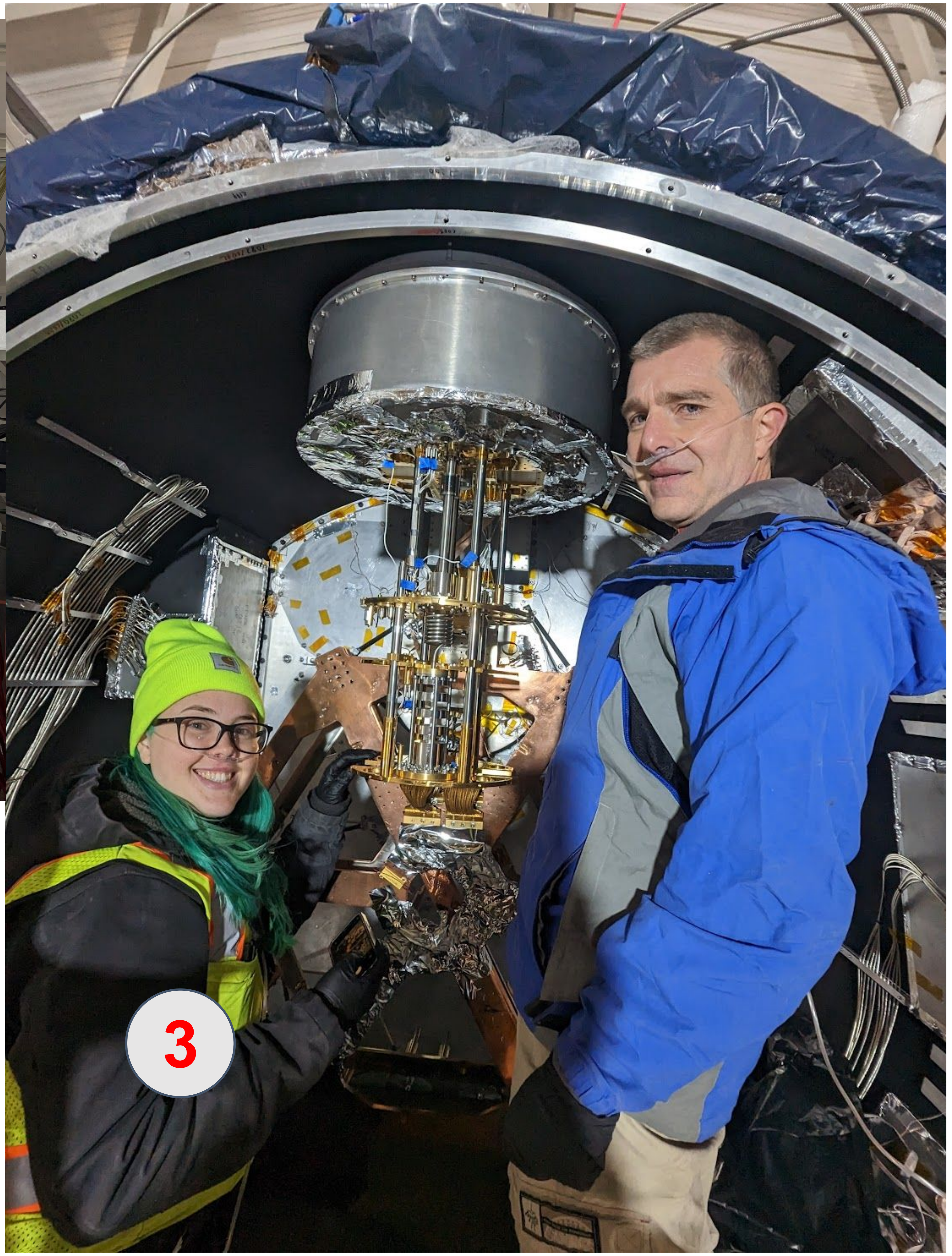


Simons Observatory

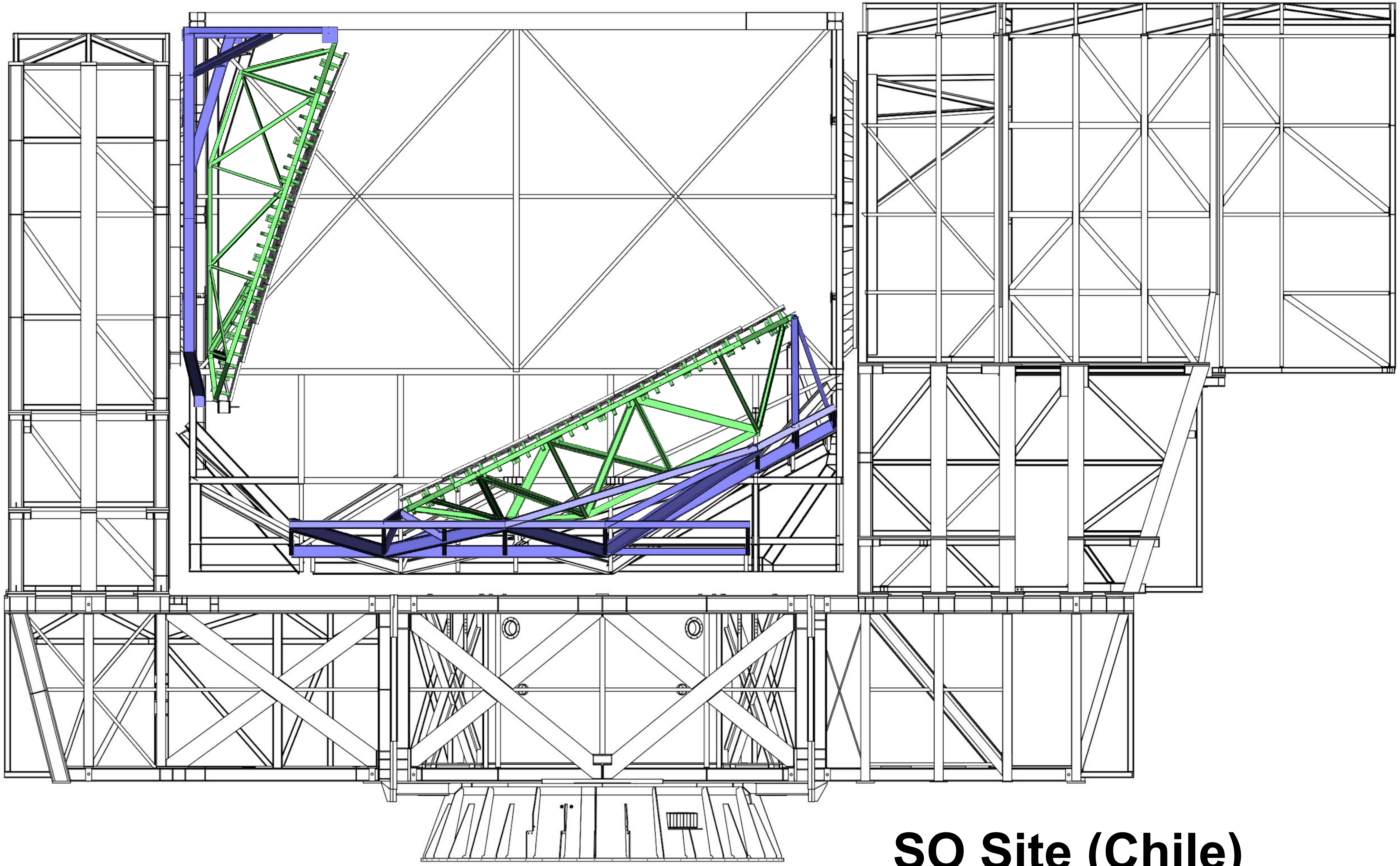
Simons Observatory site, Cerro Toco, 2023

Simons Observatory Large Aperture Telescope mechanical structure on site, 2023

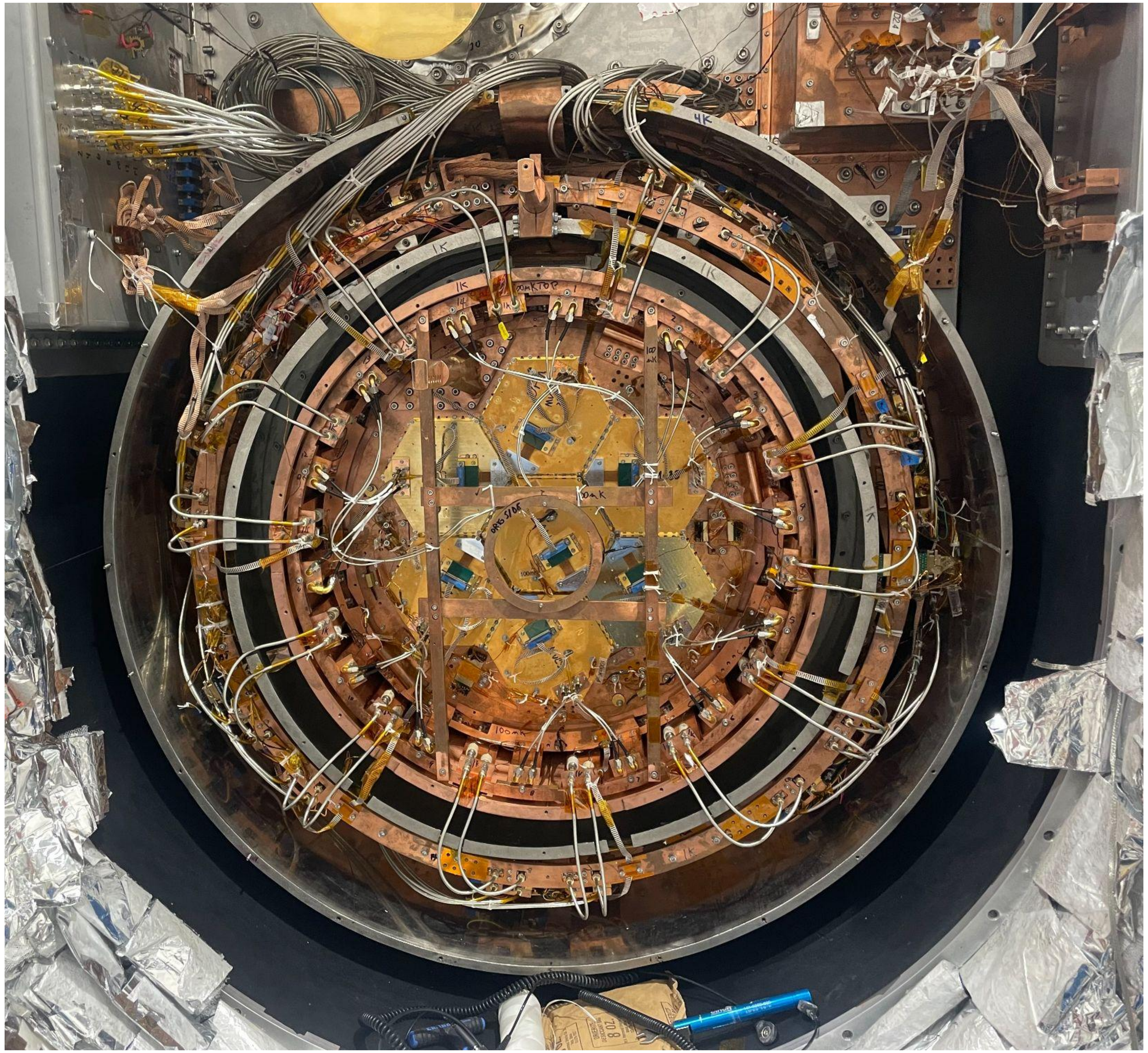




1. Lifting the LATR into the receiver cabin (IS1)
2. LATR receiver installed on the co-rotator in IS1
3. Replacing the Dilution Refrigerator INSIDE the LAT



SO Site (Chile)



SO Small-Aperture Telescope focal plane (at site, Nov. 2023)

Simons Observatory

Large Aperture Telescope: 6-meter primary mirror

Each optics tube contains 3 detector arrays
6 optics tubes in 2024
Space for 13 optics tubes
Up to 65,000 total bolometer detectors (ACT: around 4000 detectors)

Small Aperture Telescopes: 1-meter primary lens

Each telescope contains 7 detector arrays
3 telescopes in 2024
Plans for 6: 2 UK, 1 Japan
Rotating half-wave plates for polarization modulation

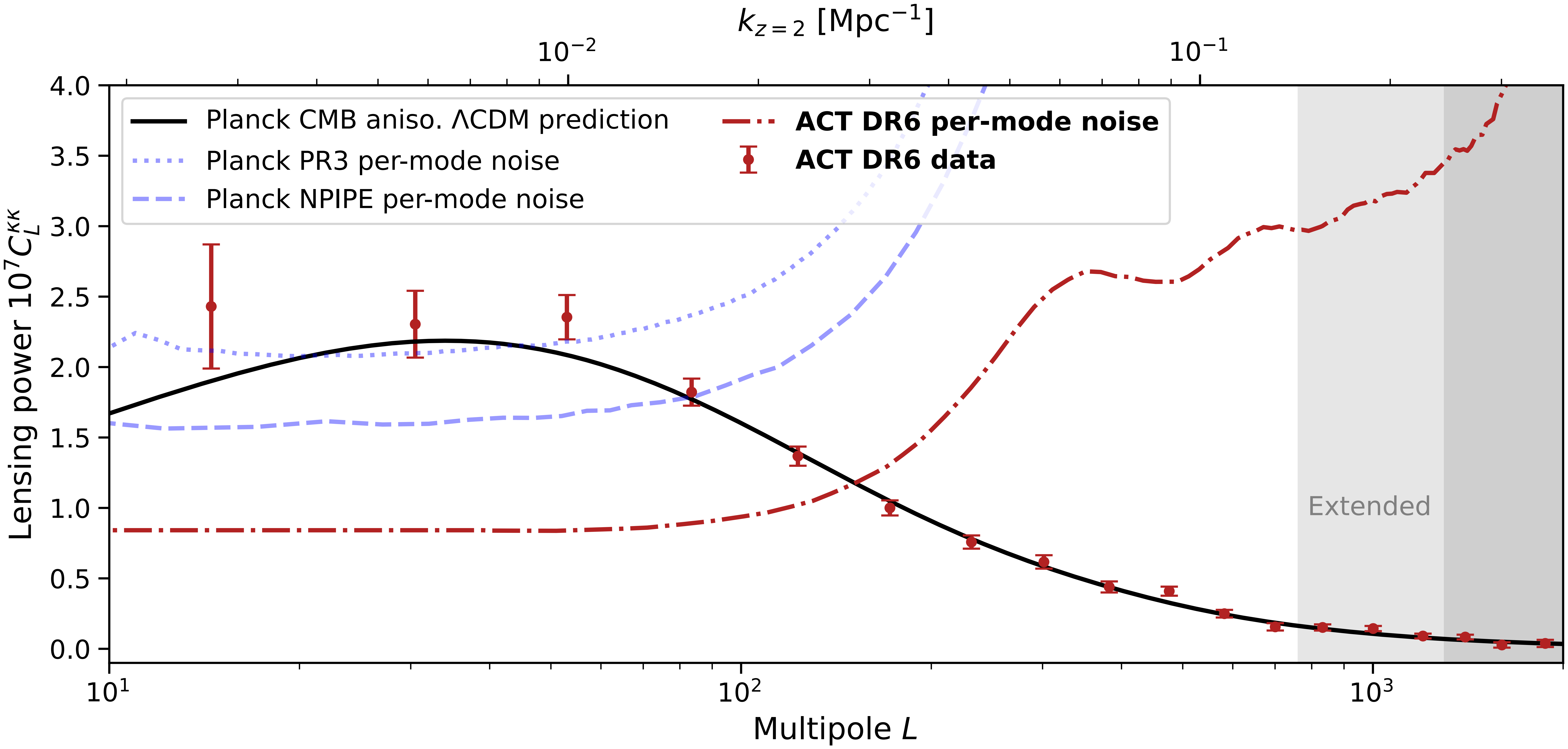
SO LAT aims to make maps over 1/3 of the sky with arcminute resolution, blackbody sensitivity 5 muK arcmin, 6 frequency bands (ACT: 11 muK arcmin)

SO SATs aim to establish tensor amplitude $r < 0.003$ at 95% CL. Will compete with BICEP3. Litebird satellite: aims for $r < 0.001$ after 2030

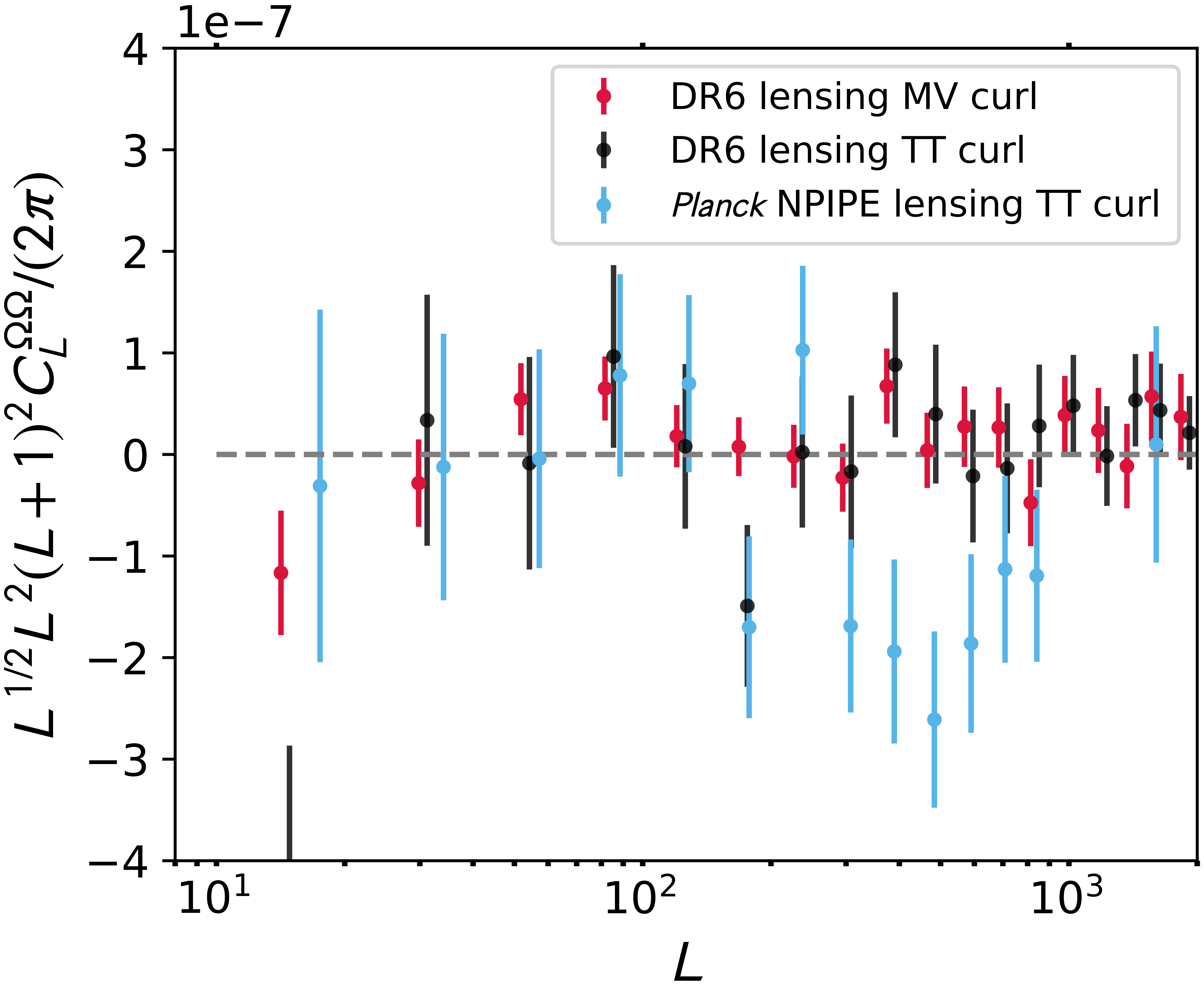
Ade et al. JCAP 02, 056 (2019) for science projections
Hensley et al. ApJ 929, 166 (2022) for galactic science

CMB-S4 is a main recommendation of the US P5 report last week: likely to be a major DOE-funded project over the next decade

S4 will be roughly SO x 3. Aims for 1 muK-arcmin sensitivity maps, r limits at 0.001

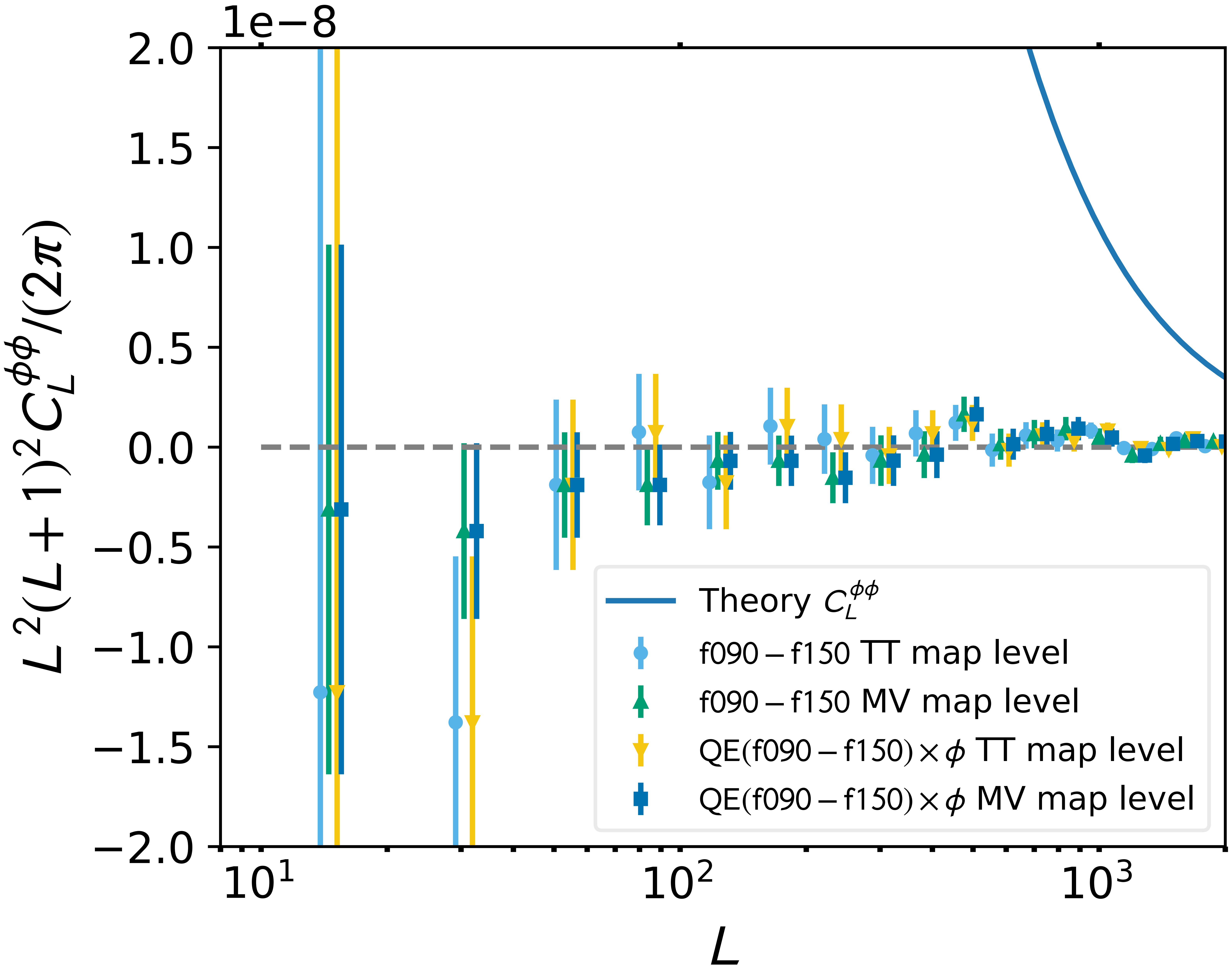


$k_{z=2}$ [Mpc^{-1}]
10^{-2}
10^{-1}
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Lensing power $10^7 C_L^{\kappa\kappa}$
Planck CMB aniso. ΛCDM prediction
Planck PR3 per-mode noise
Planck NPIPE per-mode noise
ACT DR6 per-mode noise
ACT DR6 data
Extended
10^1
10^2
10^3
Multipole L



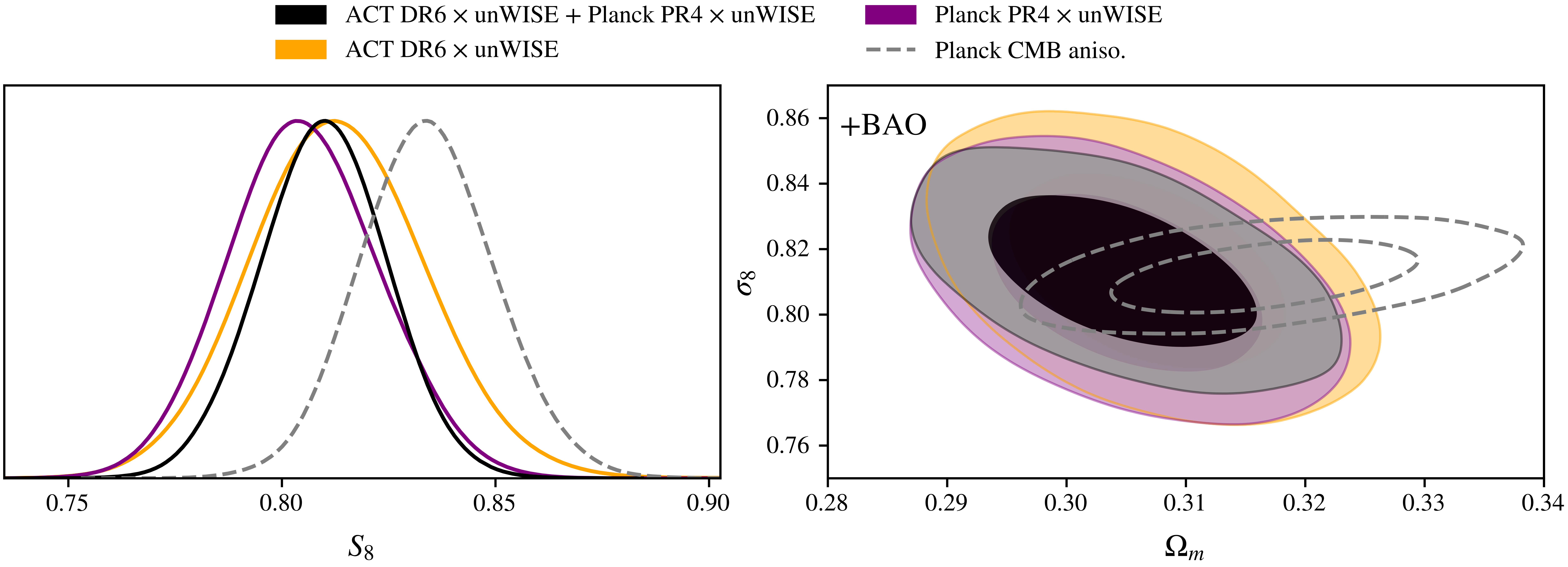
ACT lensing curl consistent with zero

Qu et al. 2023



ACT lensing frequency nulls consistent with zero

Qu et al. 2023

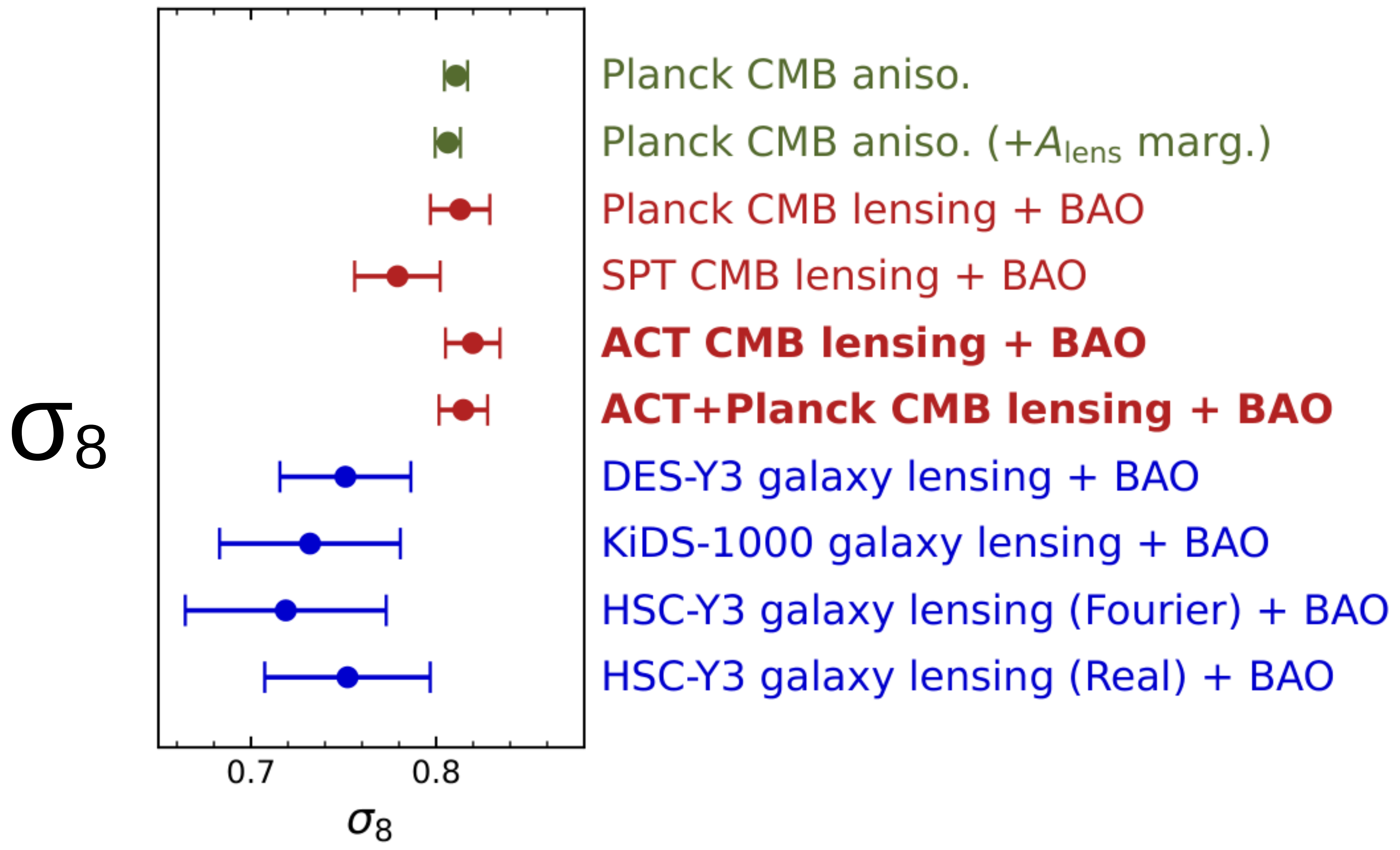


Ferren et al. 2023

Both ACT and Planck CMB lensing agree with CMB anisotropies

ACT lensing (z~2): $\sigma_8 = 0.819 \pm 0.015$
ACT+Planck lensing (z~2): $\sigma_8 = 0.815 \pm 0.013$
Planck CMB aniso (z≈1000): $\sigma_8 = 0.811 \pm 0.006$

No sign of the low σ_8 (or equivalently S_8) seen in galaxy lensing! Problem with non-linear scales?



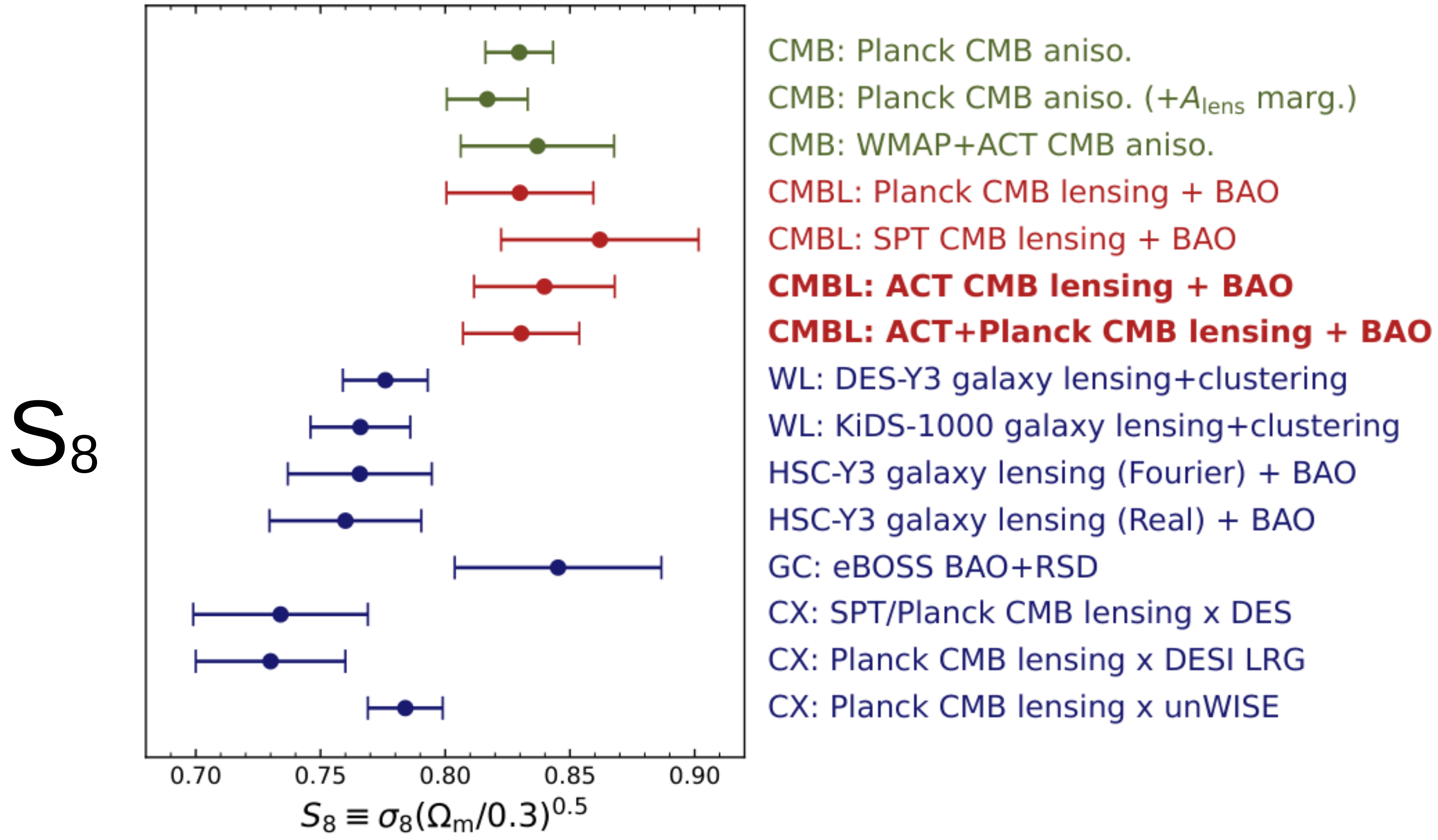


Table 2. Marginalized constraints on cosmological parameters in a consistent analysis of various weak lensing data-sets shown alongside CMB anisotropy (two-point) constraints. Throughout this work, we report the mean of the marginalized posterior and the 68% confidence limit, unless otherwise mentioned.

Data	σ_8	S_8	Ω_m	H_0 ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)
Planck CMB aniso. (PR4 TT+TE+EE) + `SRoll2` low-ℓ EE	0.811 ± 0.006	0.830 ± 0.014	0.314 ± 0.007	67.3 ± 0.5
Planck CMB aniso. (+A_lens marg.)	0.806 ± 0.007	0.817 ± 0.016	0.308 ± 0.008	67.8 ± 0.6
ACT CMB Lensing + BAO	0.820 ± 0.015	0.840 ± 0.028	0.315 ± 0.016	68.2 ± 1.1
ACT+*Planck* Lensing + BAO	0.815 ± 0.013	0.830 ± 0.023	0.312 ± 0.014	68.1 ± 1.0
ACT+*Planck* Lensing (extended) + BAO	0.820 ± 0.013	0.841 ± 0.022	0.316 ± 0.013	68.3 ± 1.0
KiDS-1000 galaxy lensing + BAO	0.732 ± 0.049	0.757 ± 0.025	0.323 ± 0.034	68.9 ± 2.0
DES-Y3 galaxy lensing + BAO	0.751 ± 0.035	0.773 ± 0.025	0.319 ± 0.025	68.7 ± 1.5
HSC-Y3 galaxy lensing (Fourier) + BAO	0.719 ± 0.054	0.766 ± 0.029	0.344 ± 0.038	70.2 ± 2.3
HSC-Y3 galaxy lensing (Real) + BAO	0.752 ± 0.045	0.760 ± 0.030	0.308 ± 0.024	68.0 ± 1.5

Madhavacheril et al. 2023