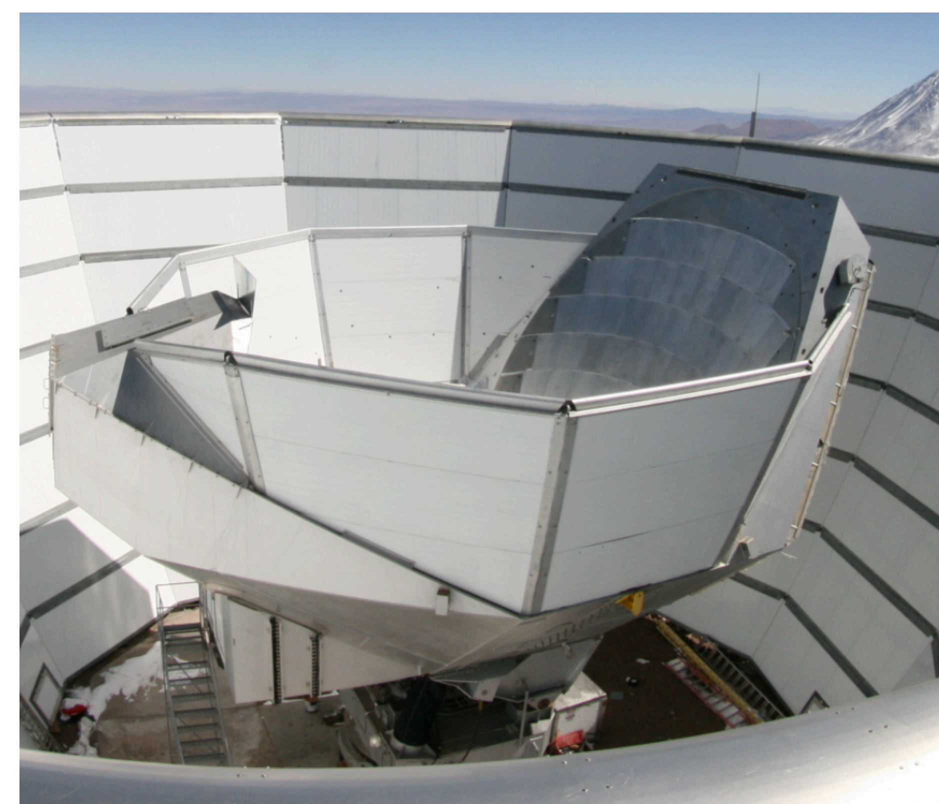
FINAL ACT (2007-2022)

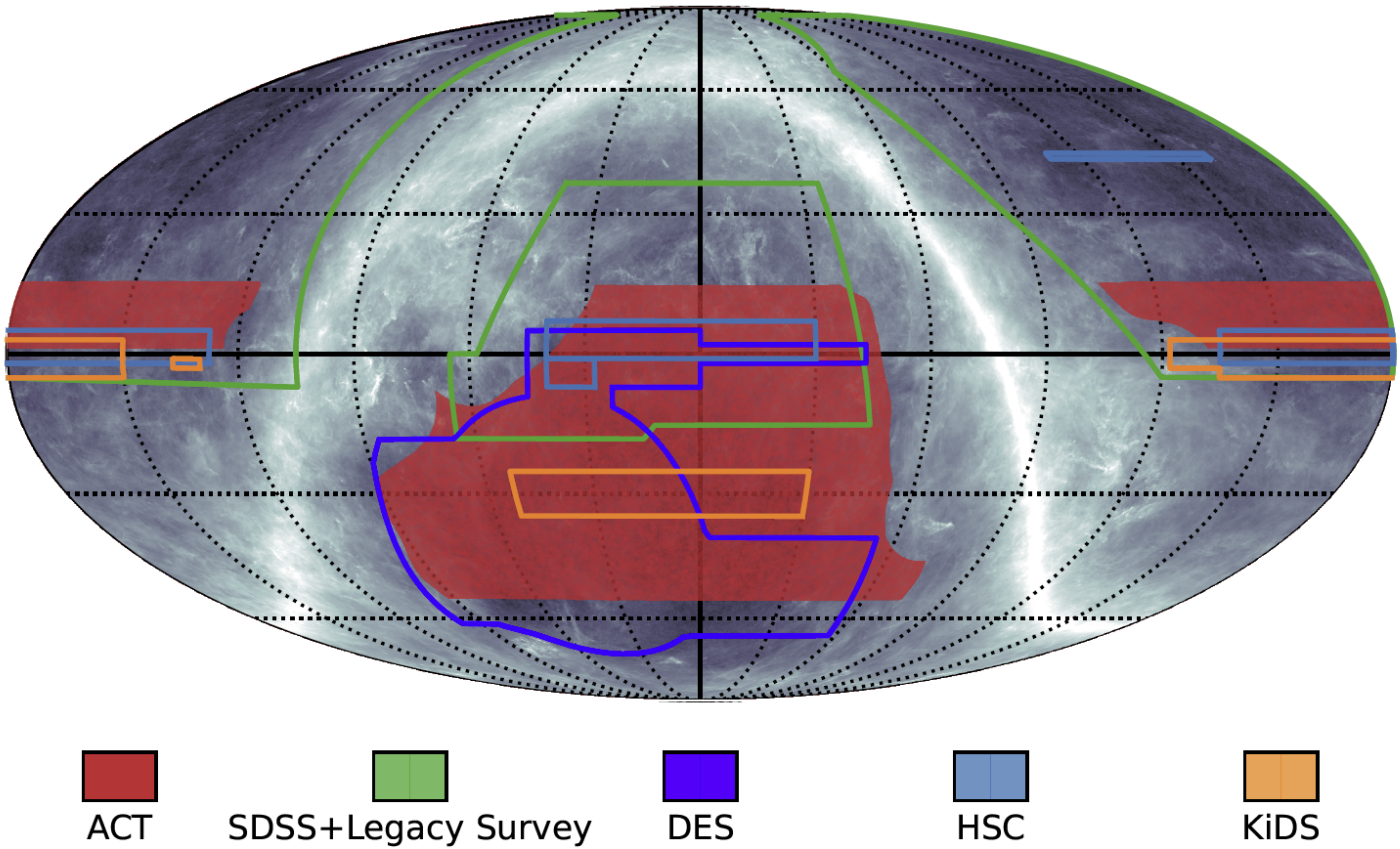
Thibaut Louis

6 meter telescope (4x Planck angular resolution)
Located in the Atacama desert (Chile).
Observing in 5 frequencies bands :
-> 30, 40, 90, 150, 220 GHz
With 6000 detectors (transition edges sensor)

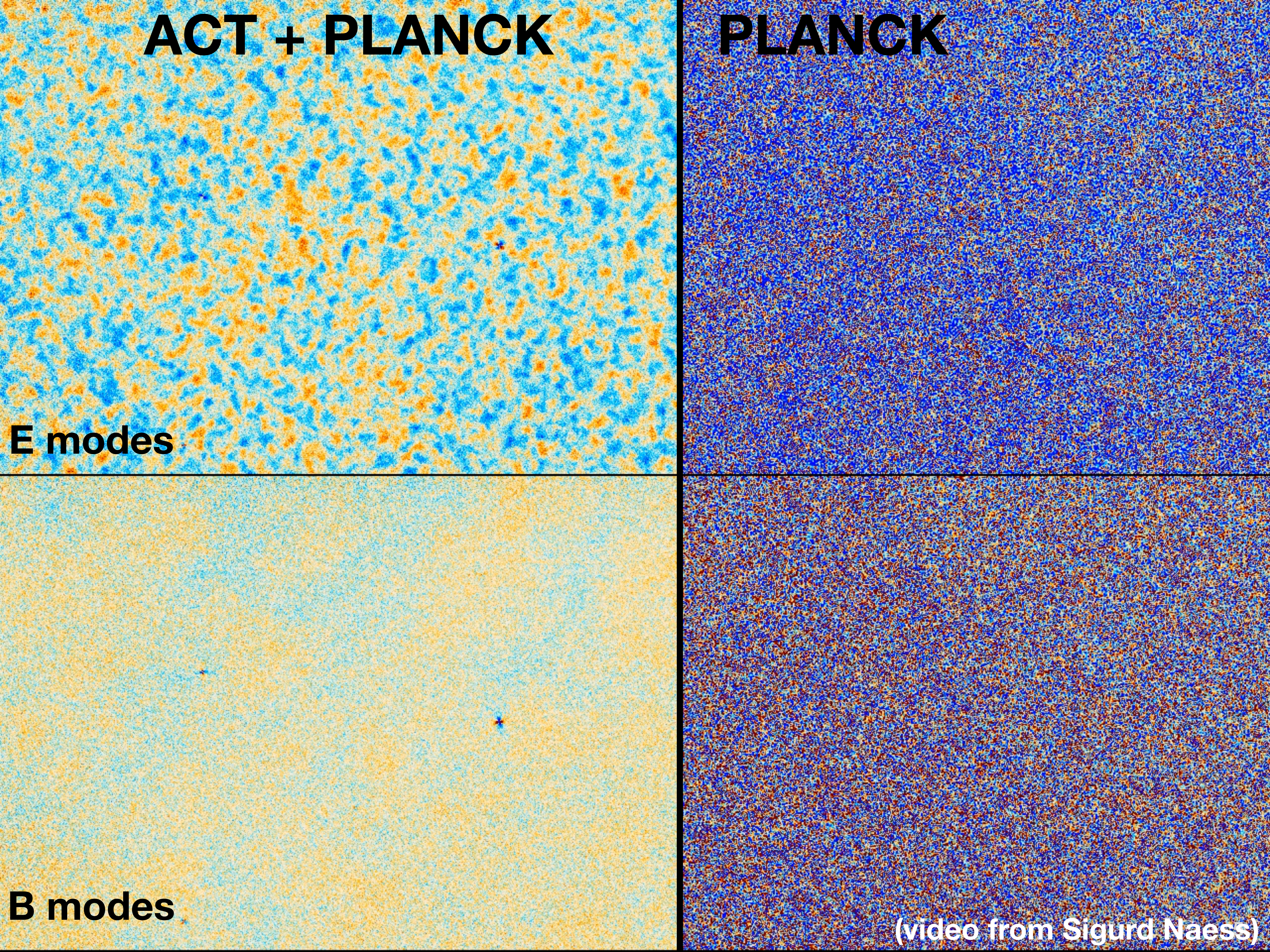


<u>Next data release: ACT DR6 (2024)</u>

ACT survey: approx. 40% of the sky

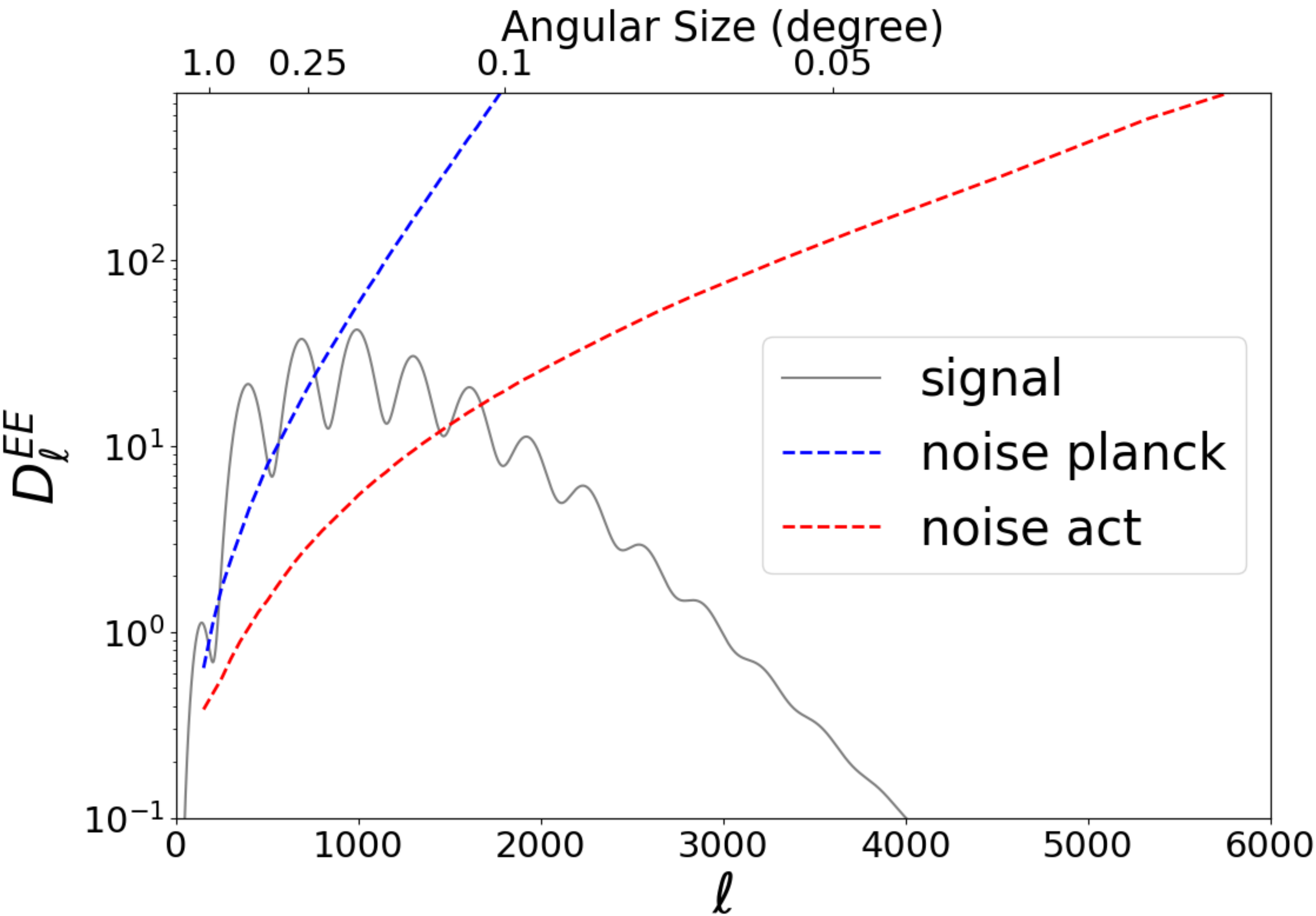


ACT polarisation field



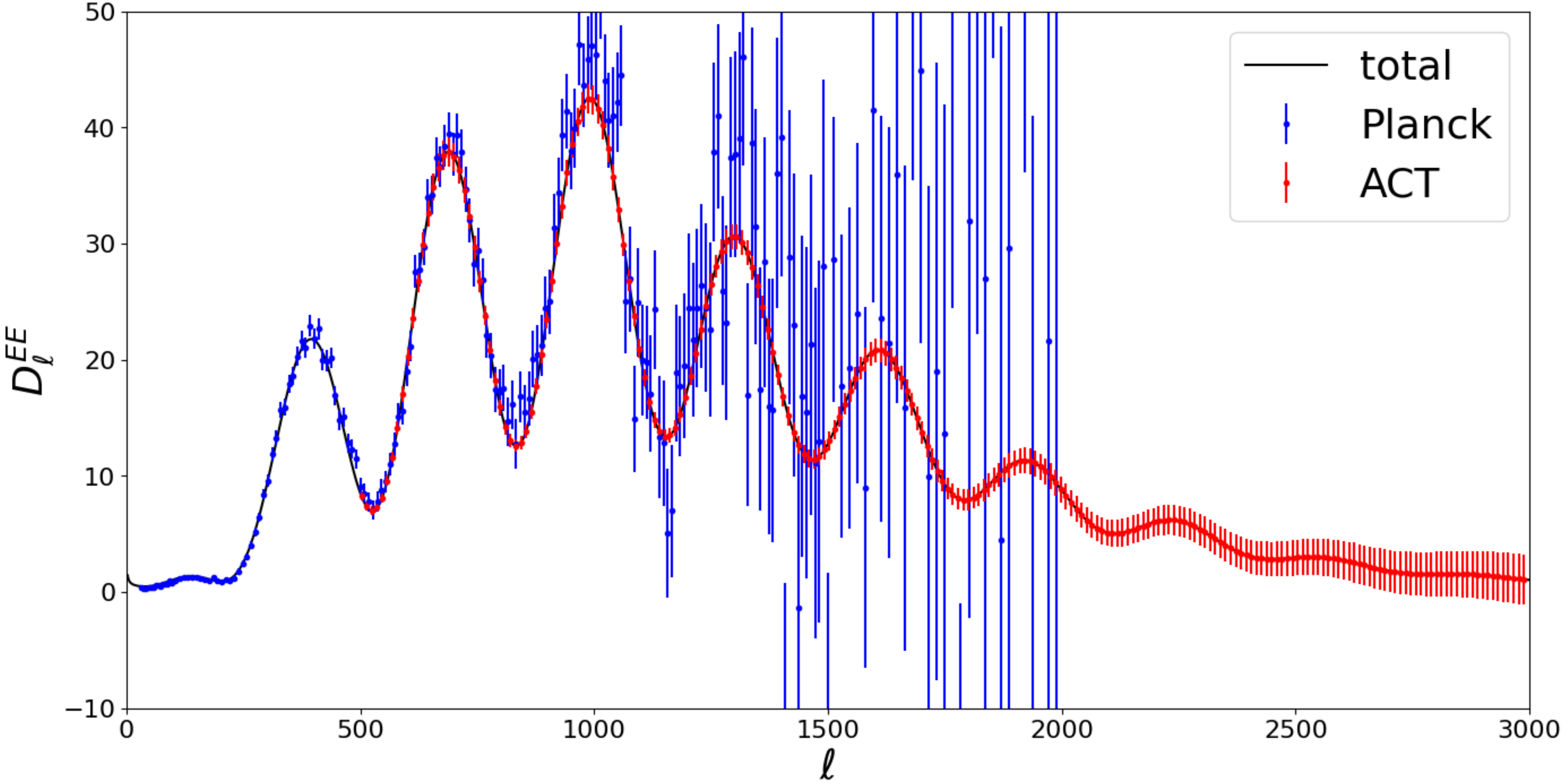
ACT + PLANCK
PLANCK
E modes
B modes
(video from Sigurd Naess)

Signal to noise: ACT vs Planck



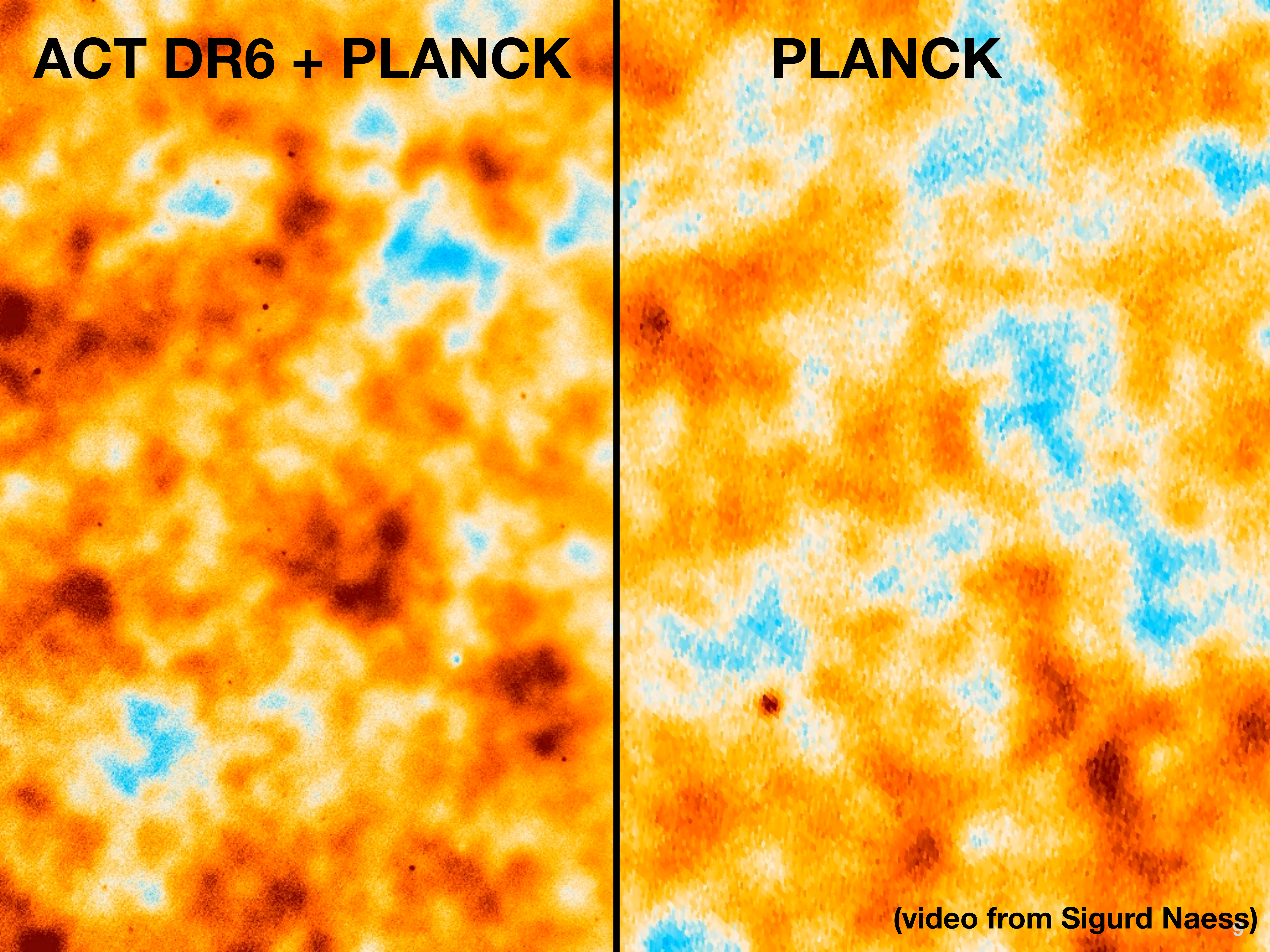
DR6 data errors

150 GHz

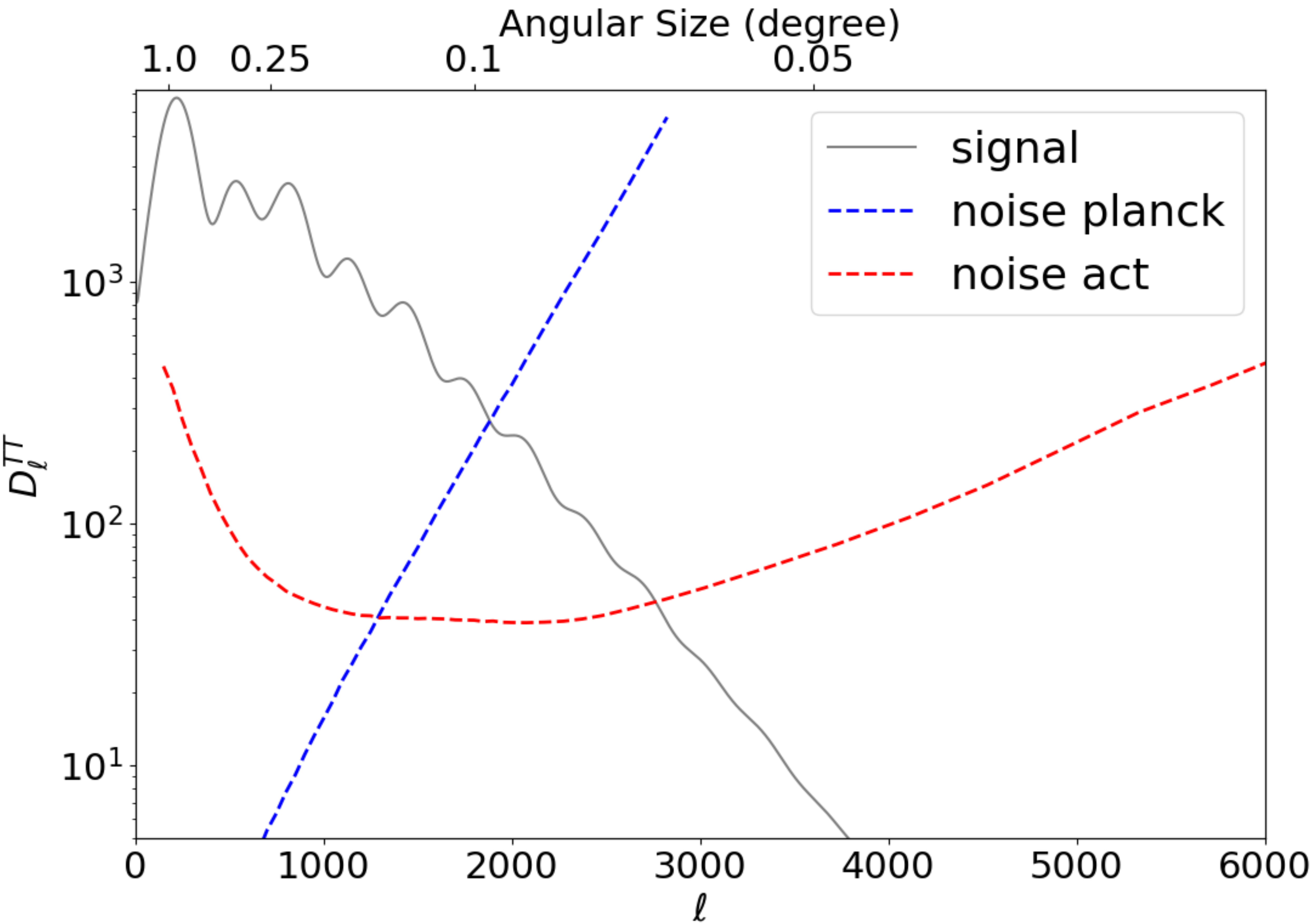


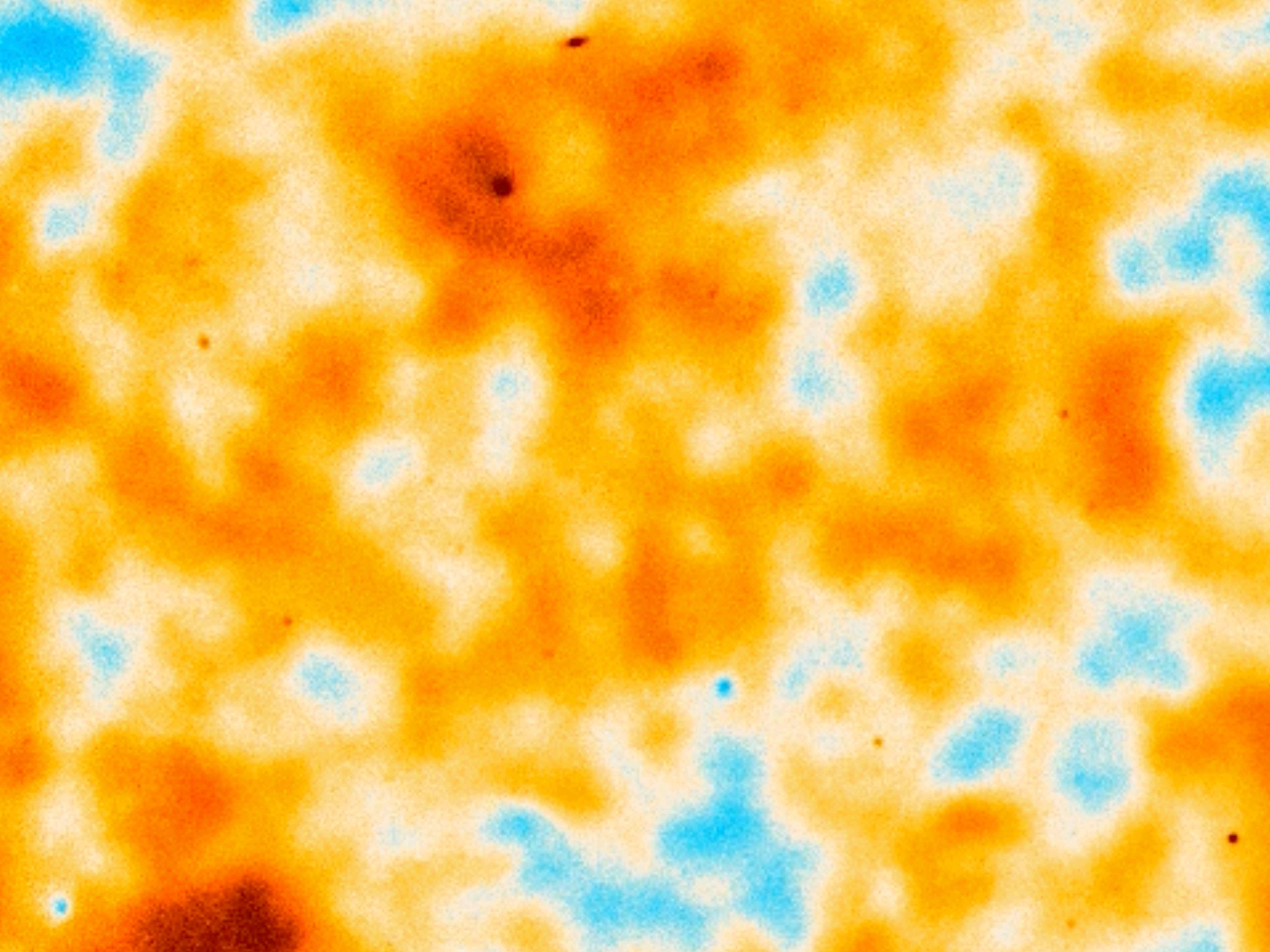
The Atacama Cosmology Telescope: DR6 Power spectra, Likelihood, and constrains on LCDM
Louis, La Posta, Li, et al (expected 2024)

ACT Temperature anisotropies field

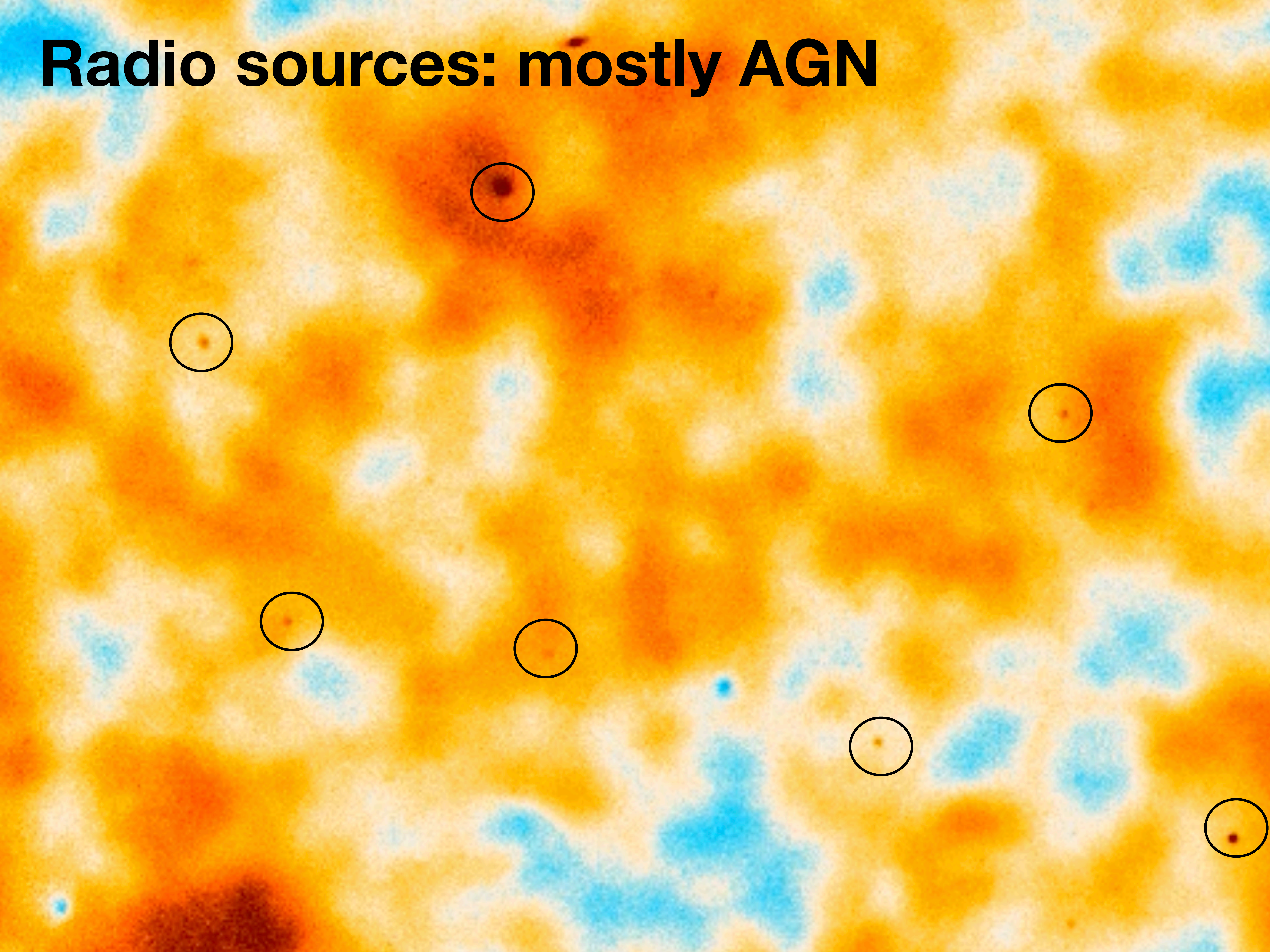

ACT DR6 + PLANCK
PLANCK
(video from Sigurd Naess)

Signal to noise: ACT vs Planck



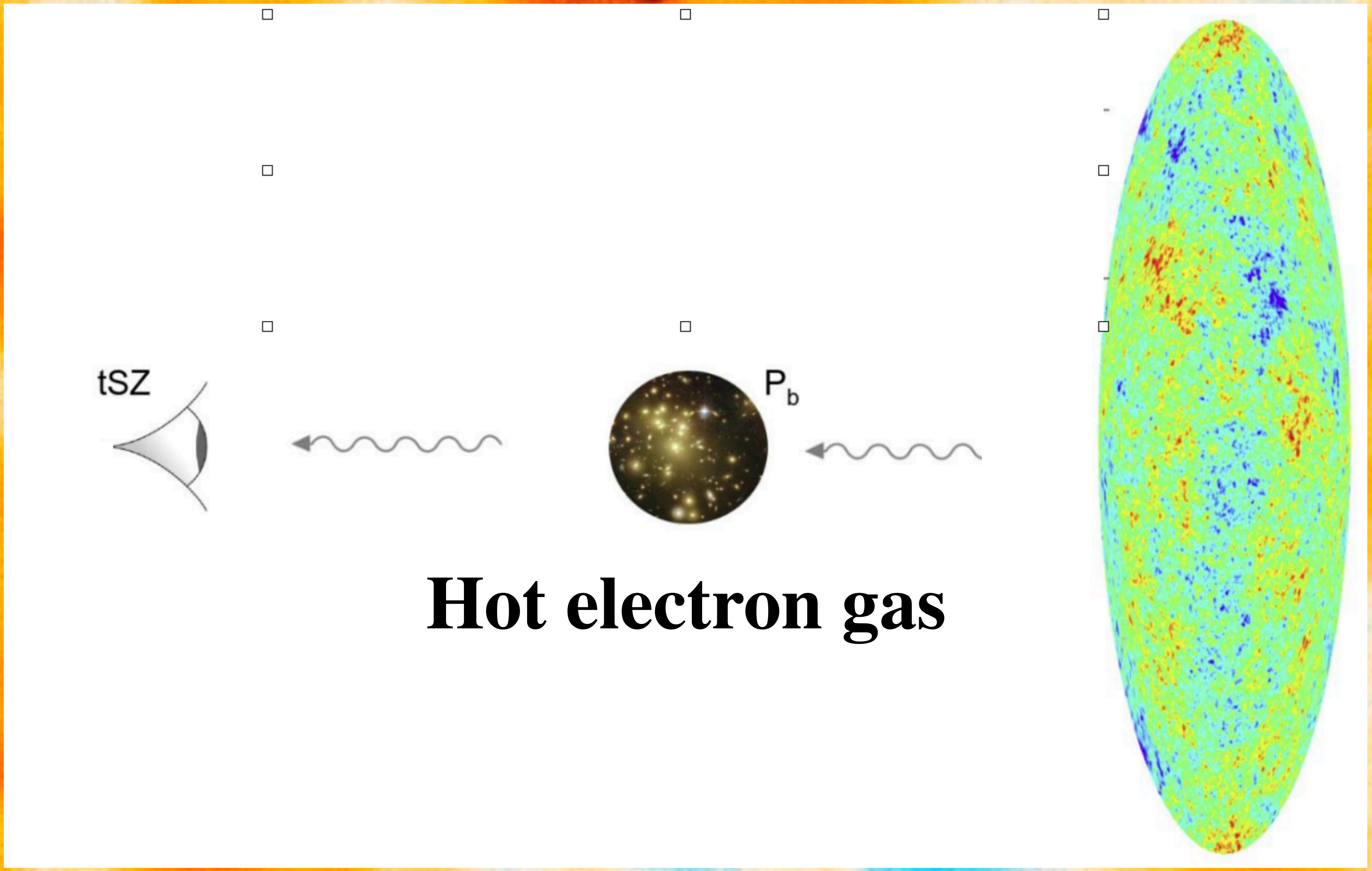


Radio sources: mostly AGN

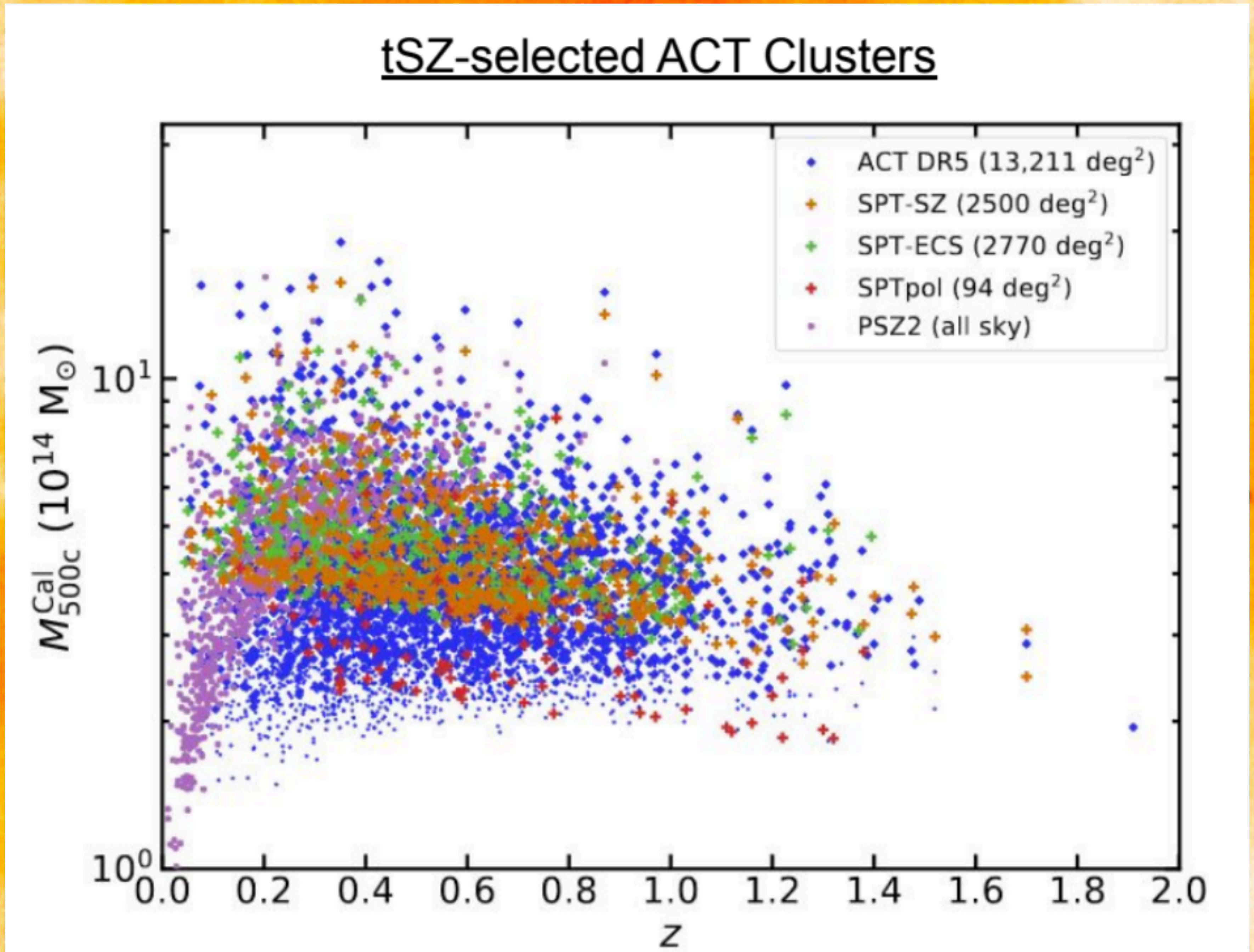


Galaxy clusters

thermal Sunyaev-Zel'dovich effect



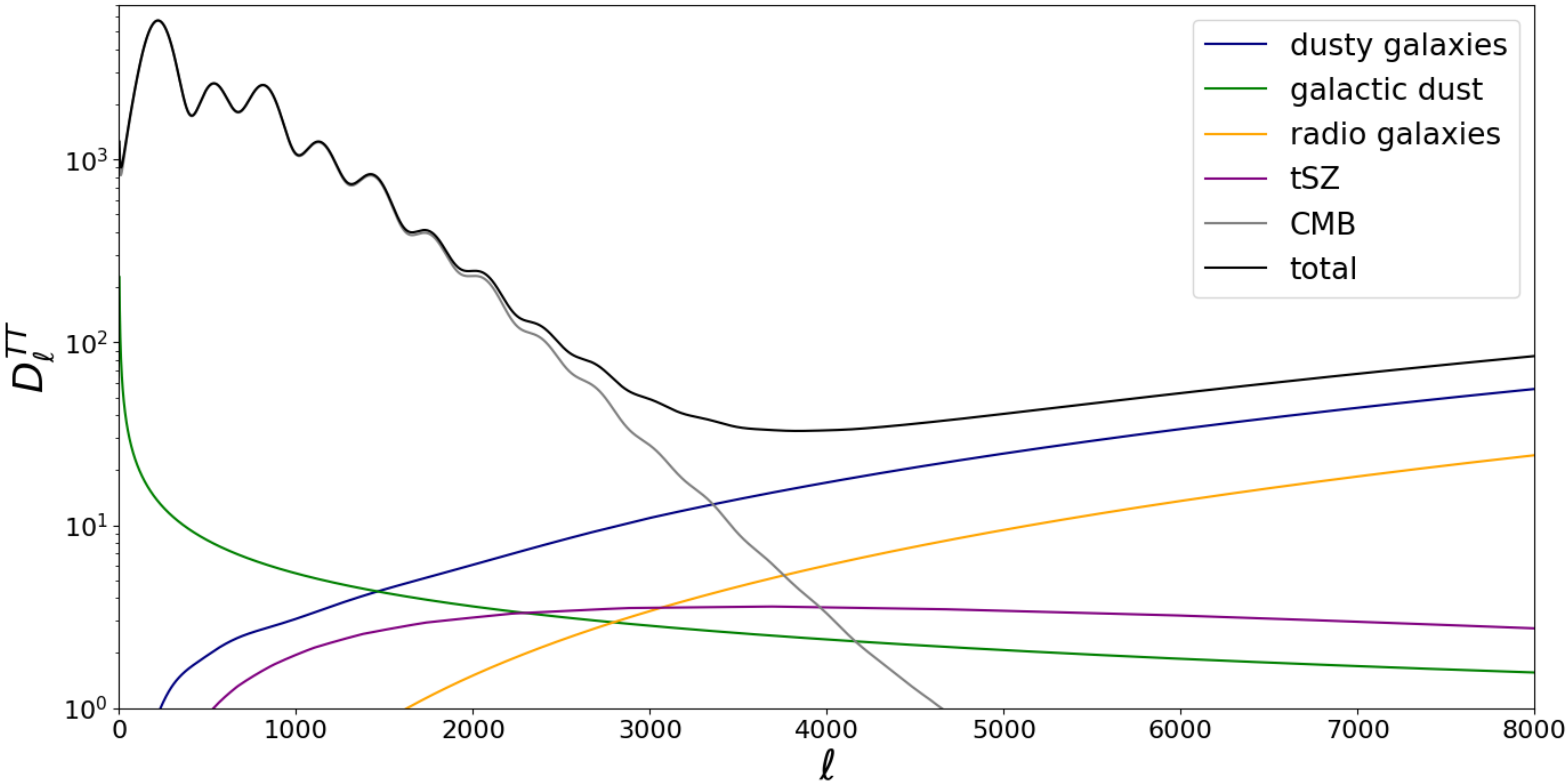
Galaxy clusters



Hilton et al 2021

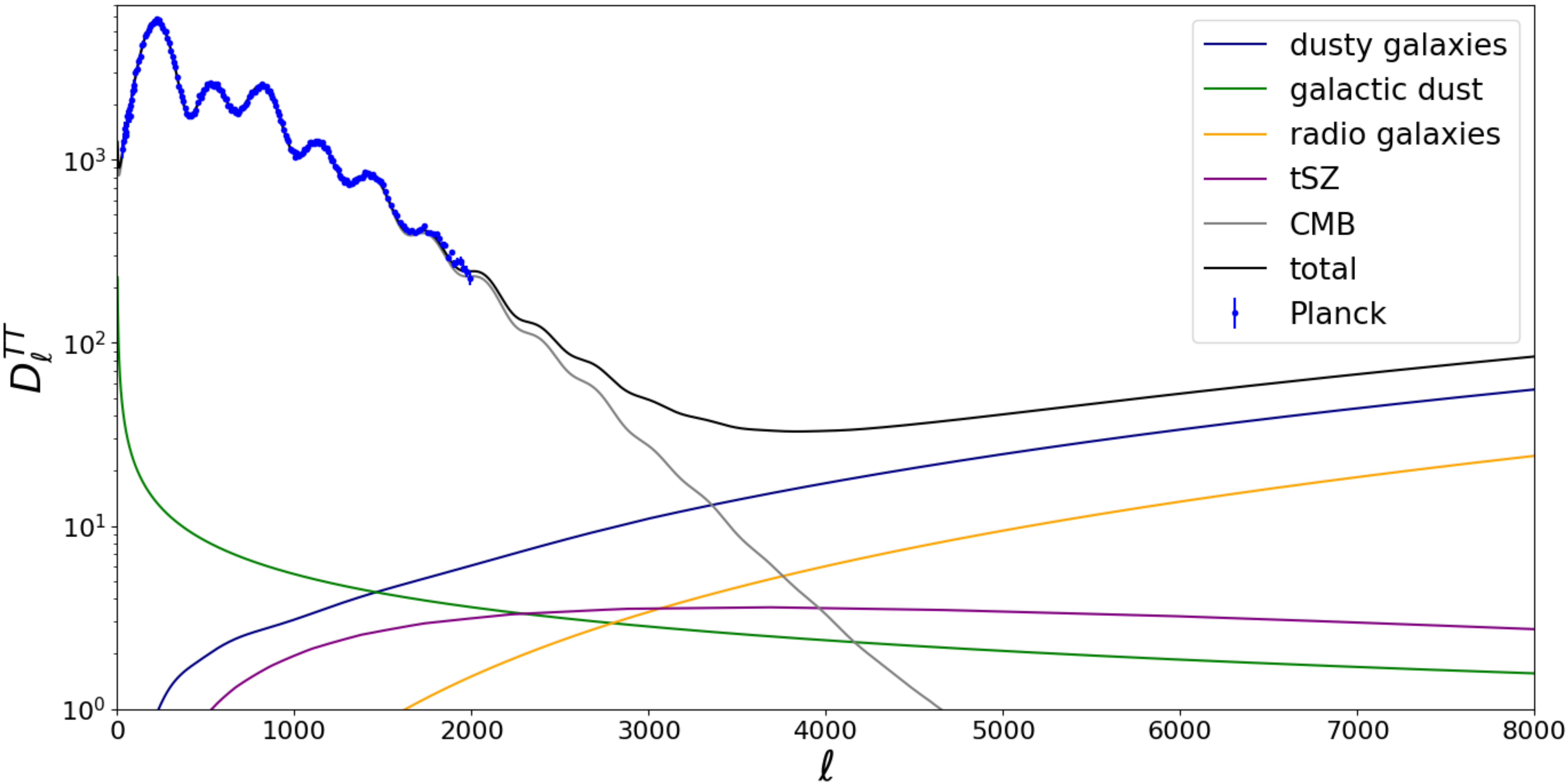
ACT has published around 4000 galaxy clusters, expect 7000 with the final data release

150 GHz



dusty galaxies
galactic dust
radio galaxies
tSZ
CMB
total
D_ℓ^{TT}
10^3
10^2
10^1
10^0
0
1000
2000
3000
4000
5000
6000
7000
8000
ℓ

150 GHz



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galactic dust
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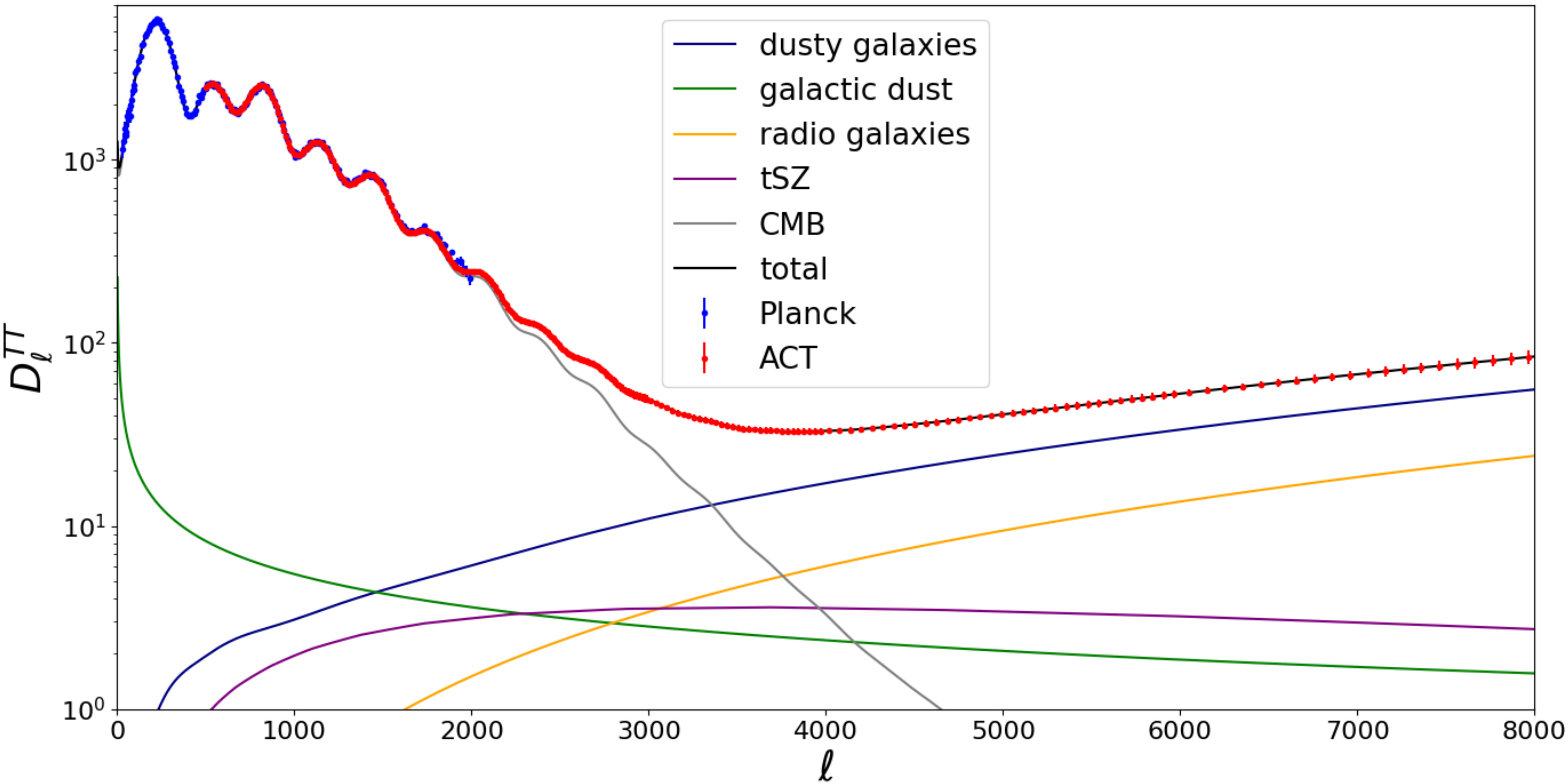
DR6 data errors

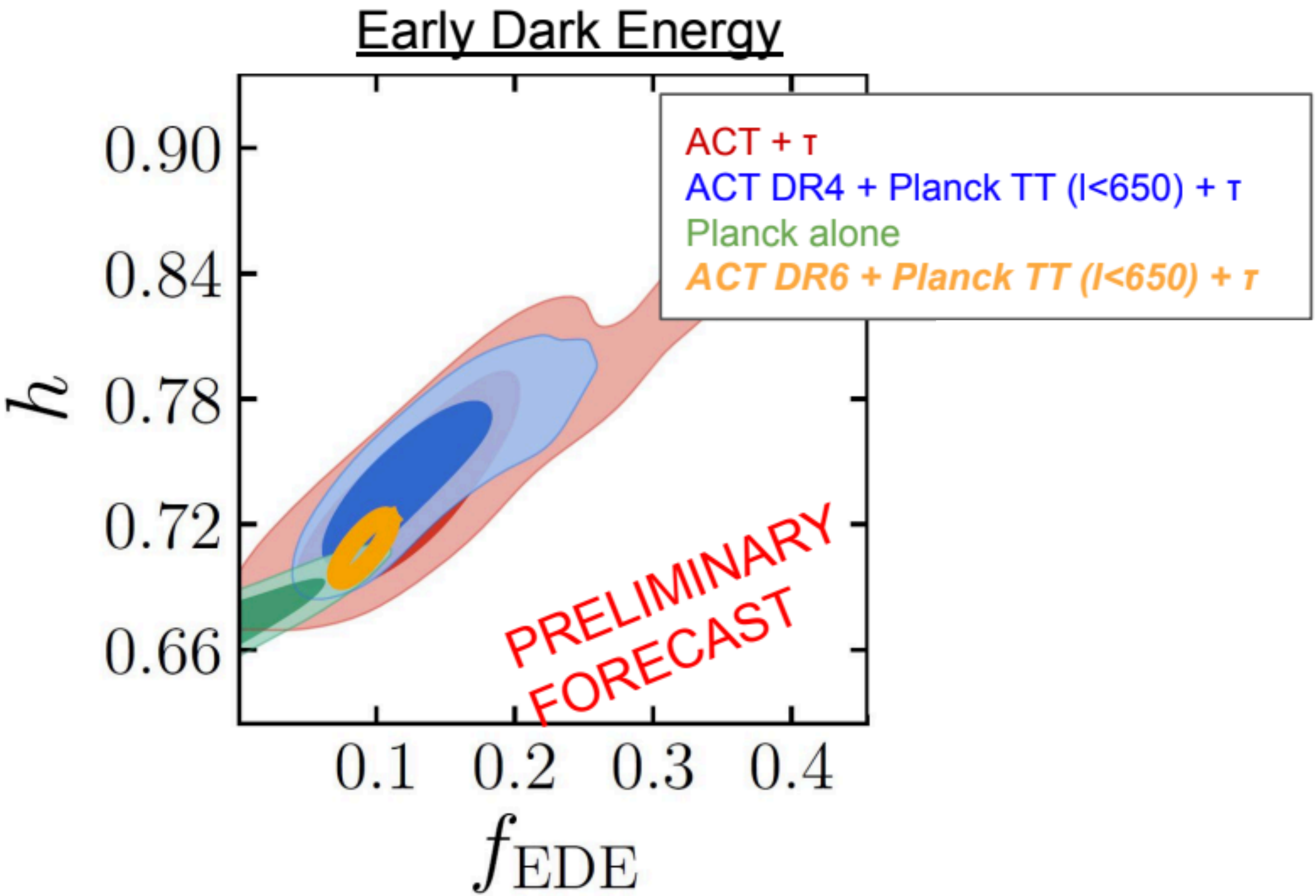
150 GHz



The Atacama Cosmology Telescope: DR6 Power spectra, Likelihood, and constrains on LCDM
Louis, La Posta, Li, et al (expected 2024)

Strong tests on LCDM

Discriminate f_{EDE} ~ 0.1 model from ΛCDM at ~10-20σ



ACT DR6 lensing result

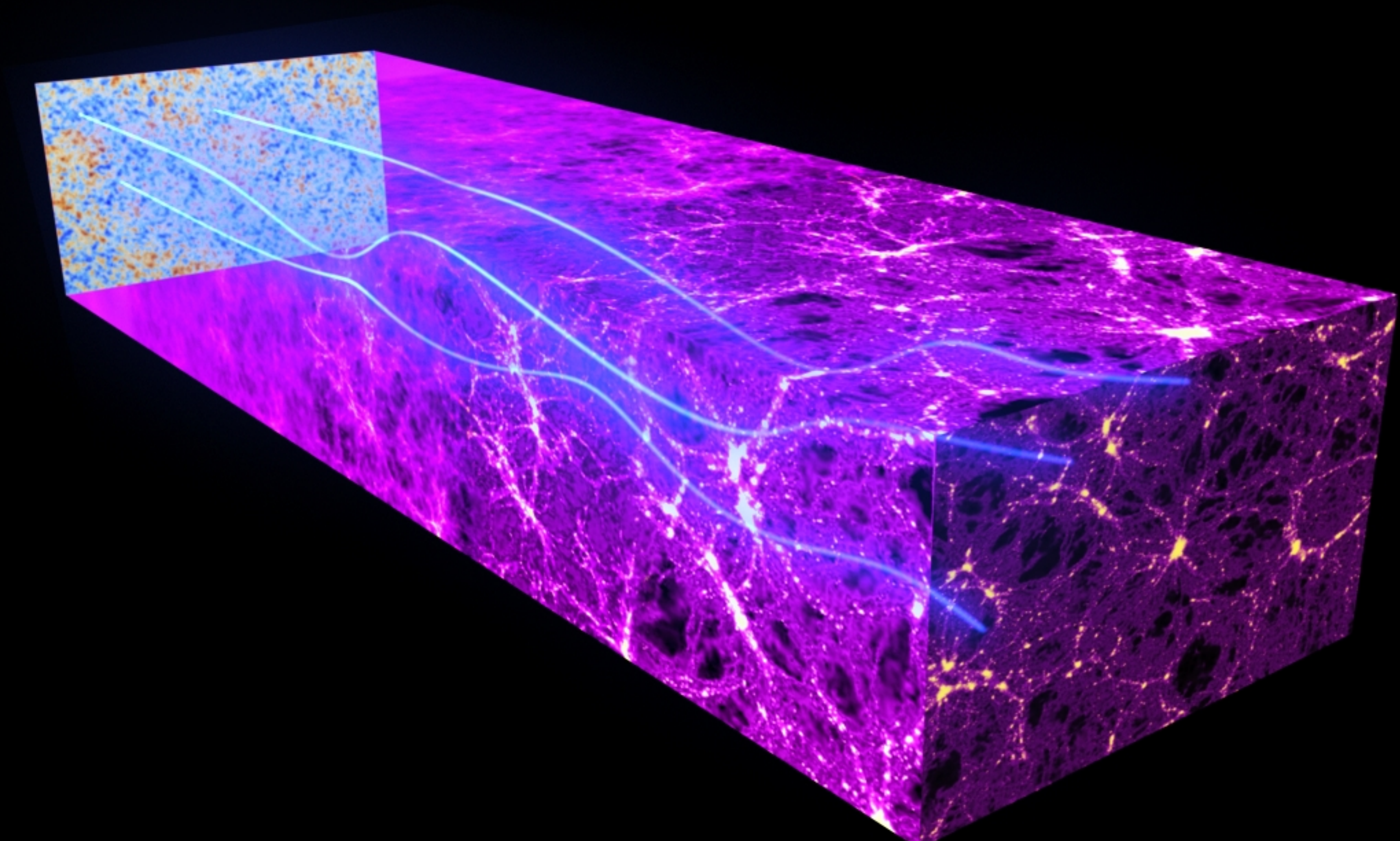
The Atacama Cosmology Telescope: A Measurement of the DR6 CMB Lensing Power Spectrum and its Implications for Structure Growth: Qu et al. (April 2023)

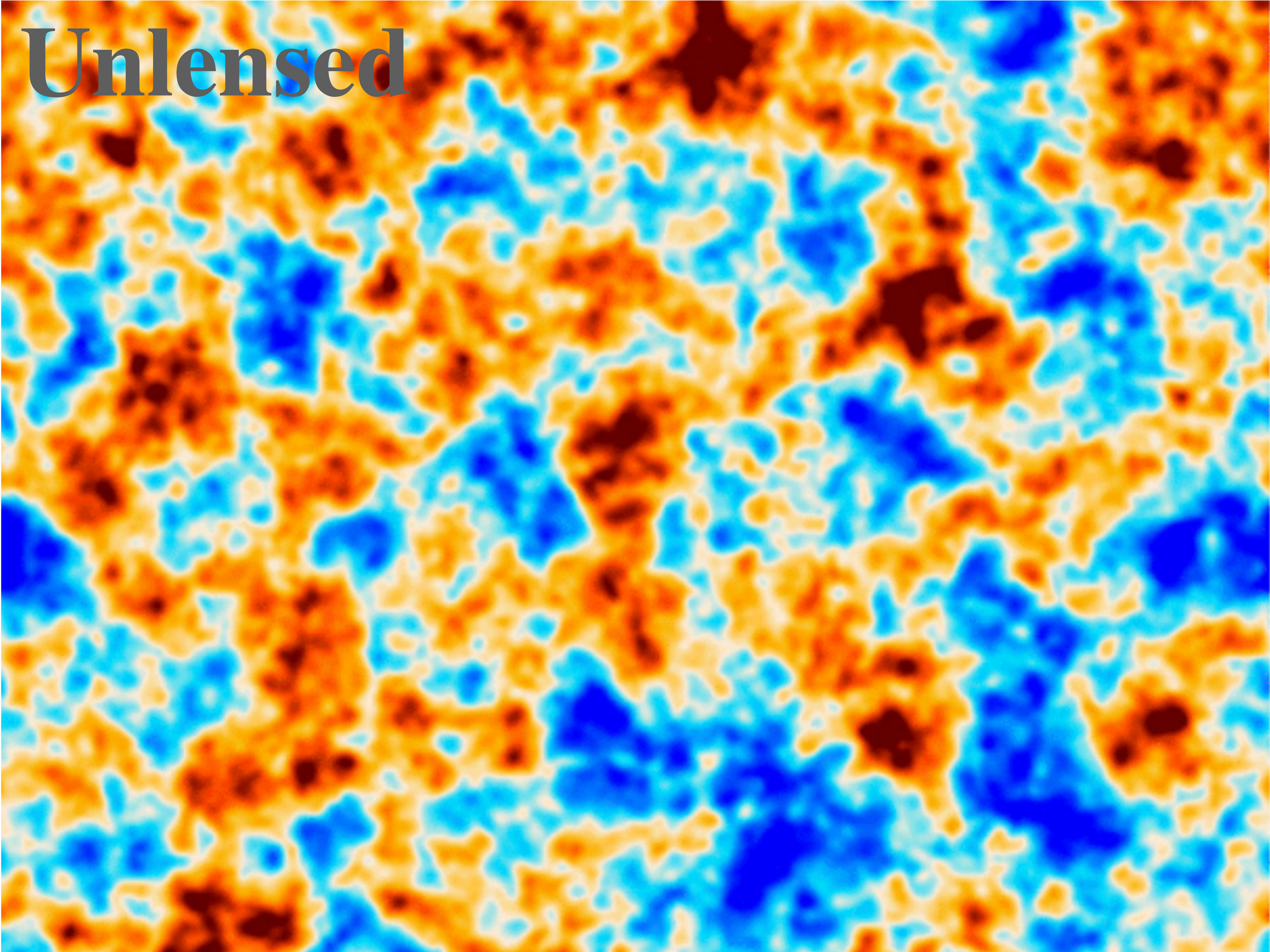
The Atacama Cosmology Telescope: DR6 Gravitational Lensing Map and Cosmological Parameters: Madhavacheril et al. (April 2023)

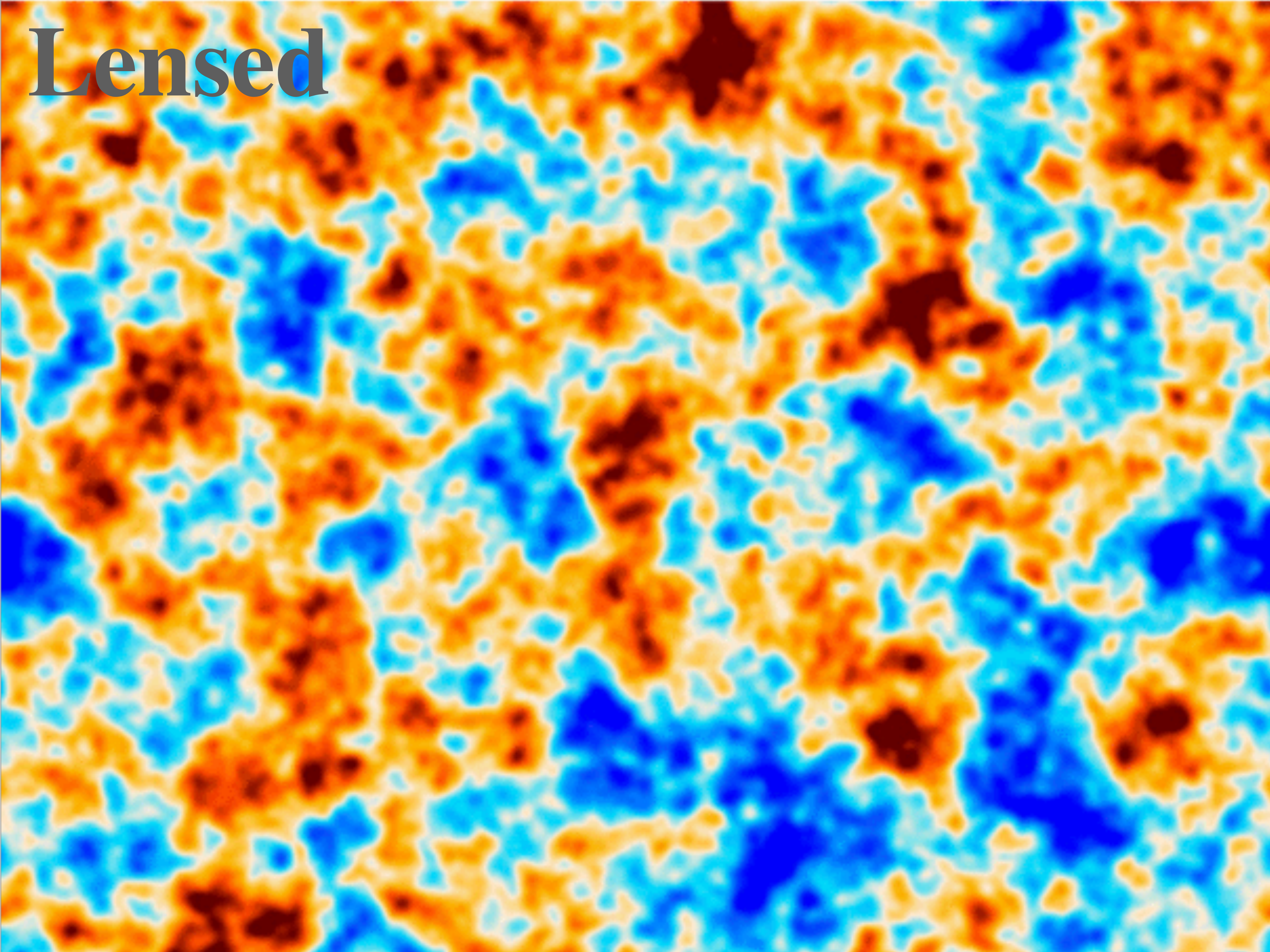
The Atacama Cosmology Telescope: Mitigating the impact of extragalactic foregrounds for the DR6 CMB lensing analysis: MacCrann et al. (April 2023)

The Atacama Cosmology Telescope: Cosmology from cross-correlations of unWISE galaxies and ACT DR6 CMB lensing: Farren et al (Sept. 2023)

Image ESA: Planck




Unlensed


Lensed

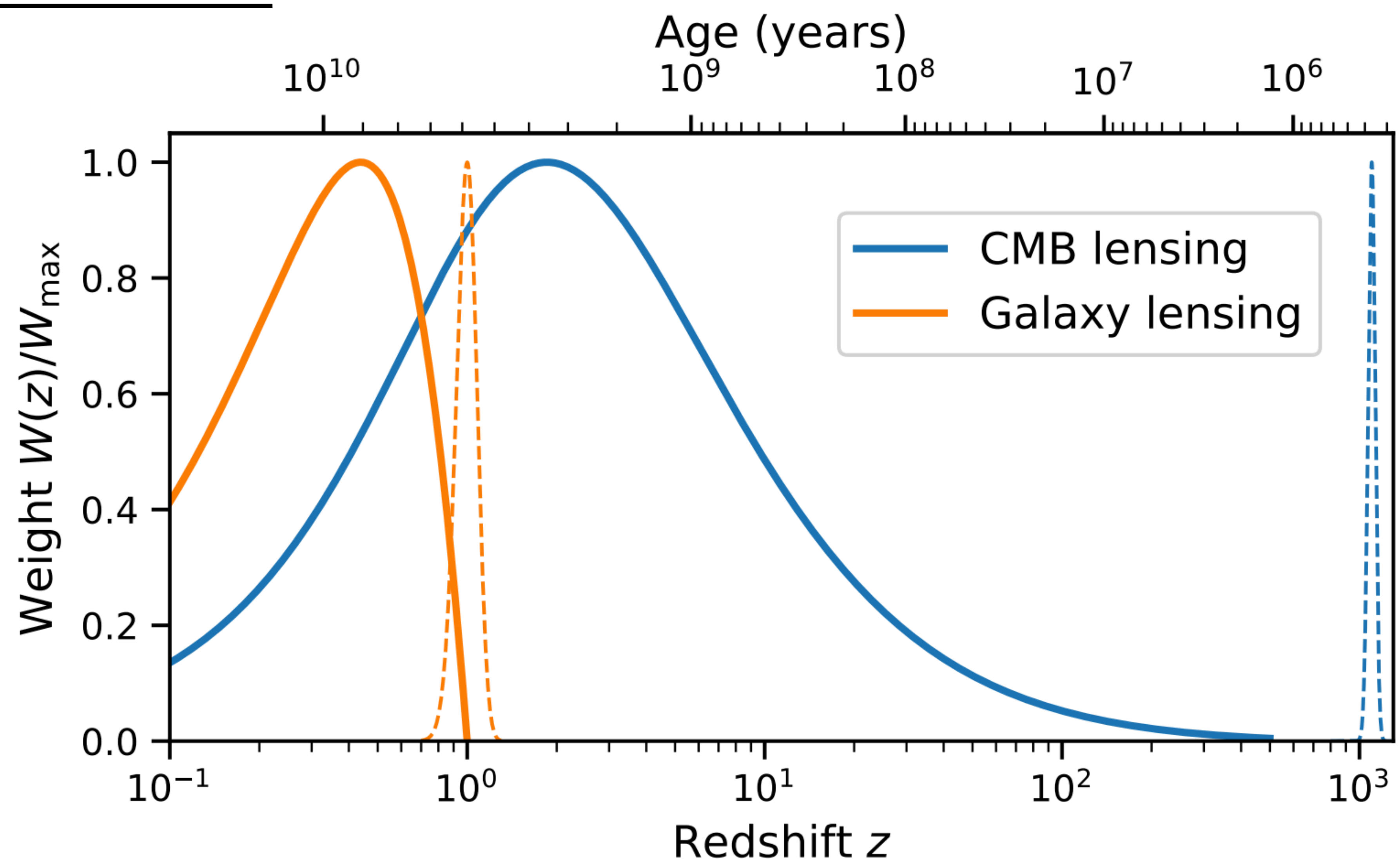
What does CMB lensing tells us ?

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

lensing power spec. — redshift kernel — matter power spectrum

- Lensing power spectrum is a projected matter power spectrum

Redshift kernel



How do we measure this effect ?

We assume that the cosmological principle is correct

The key assumption here is that, in an isotropic universe, the angular covariance matrix describing the CMB statistical properties is only a function of the angular separation of the different line of sights

$$\xi^{TT}(\hat{n}_1, \hat{n}_2) = \langle T(\hat{n}_1)T(\hat{n}_2)\rangle = \xi(\hat{n}_1.\hat{n}_2) = \xi(\cos\theta)$$

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If this is true, then it implies that in harmonics space

The different $a^T_{\ell m}$ are uncorrelated

$$\langle a^T_{\ell m} a^{T,*}_{\ell' m'}\rangle = C_\ell \delta_{\ell,\ell'} \delta_{m,m'}$$

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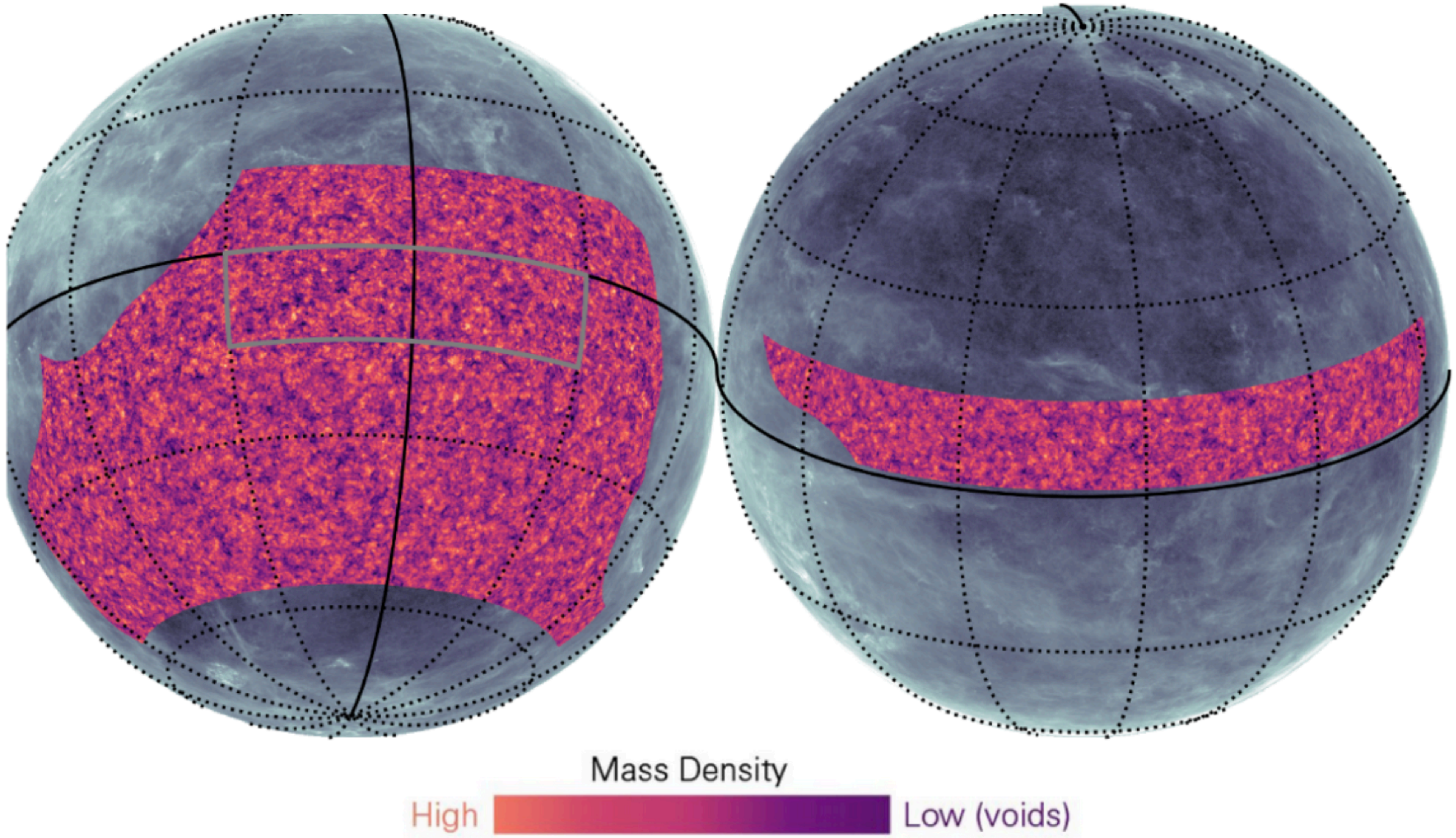
Lensing break the isotropy, part of the sky are magnified while other are not. The way we reconstruct the lensing field is by measuring the correlation between different $a^T_{\ell m}$

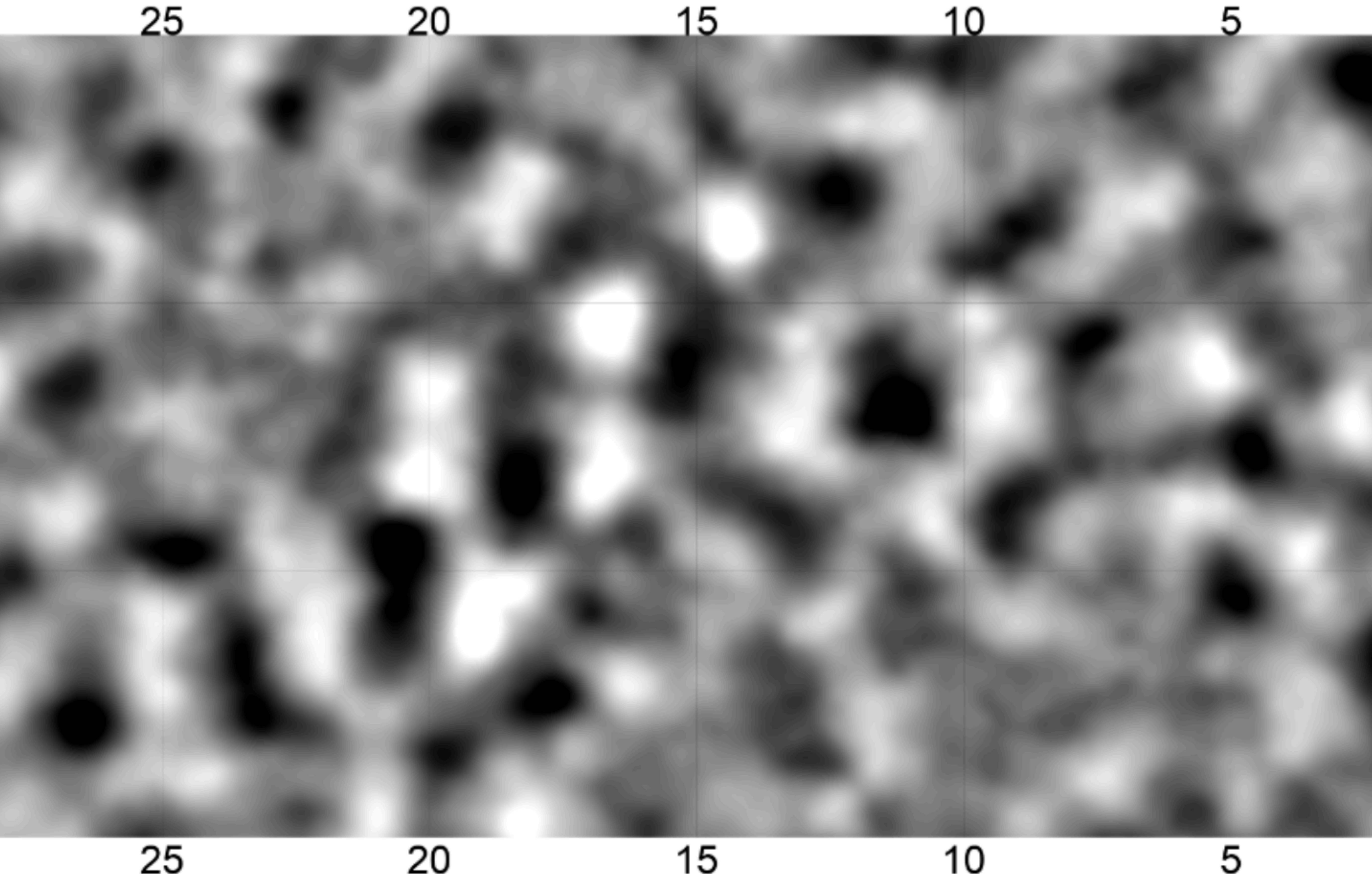
ACT DR6 lensing map



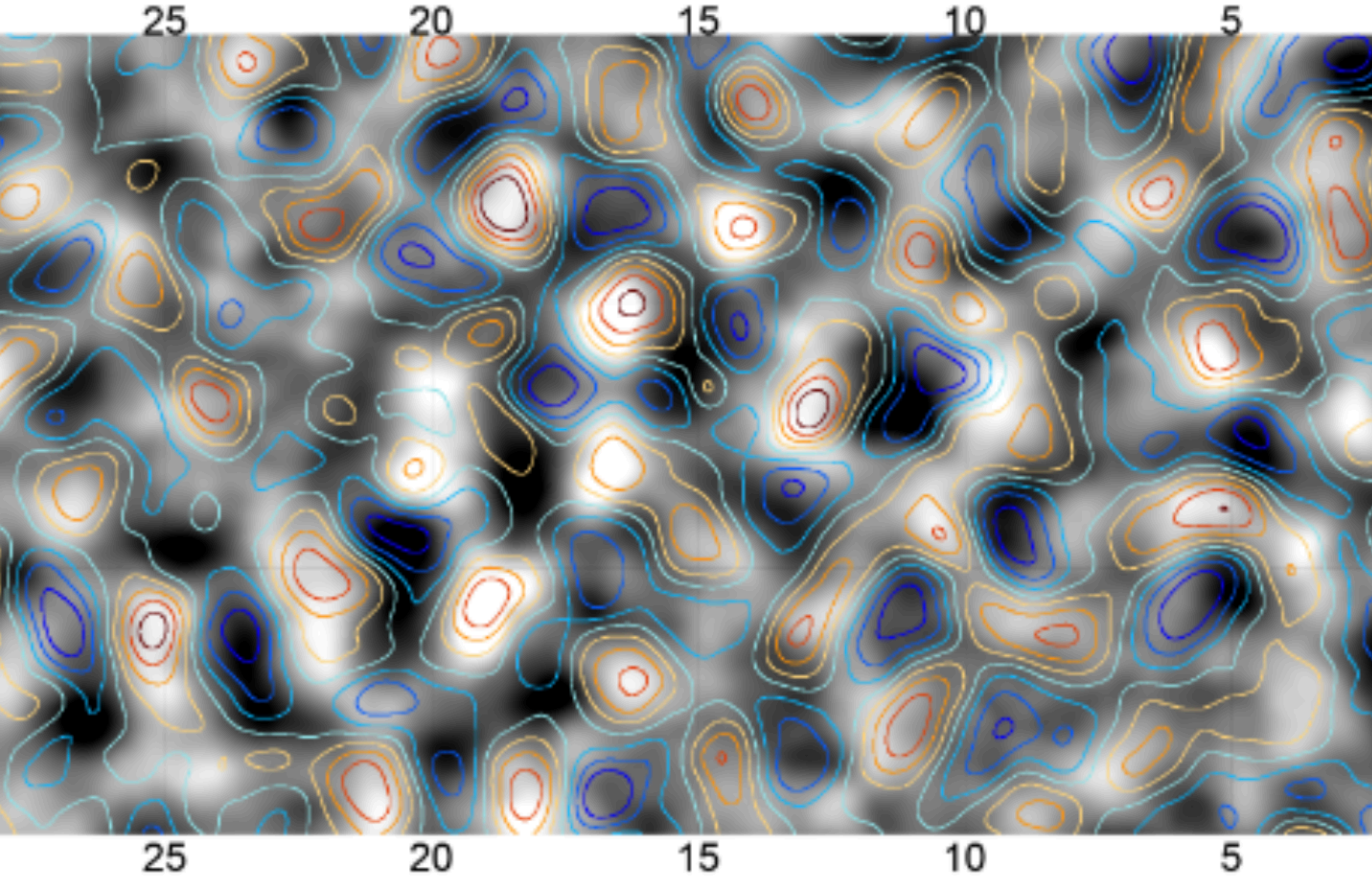
- Covers a quarter of the sky
- You can see the projected dark matter distribution
- Few degree-scale structure corresponding to the P(k) peak at z=1-2

The Atacama Cosmology Telescope: DR6 Gravitational Lensing Map and Cosmological Parameters: Madhavacheril et al. (April 2023)

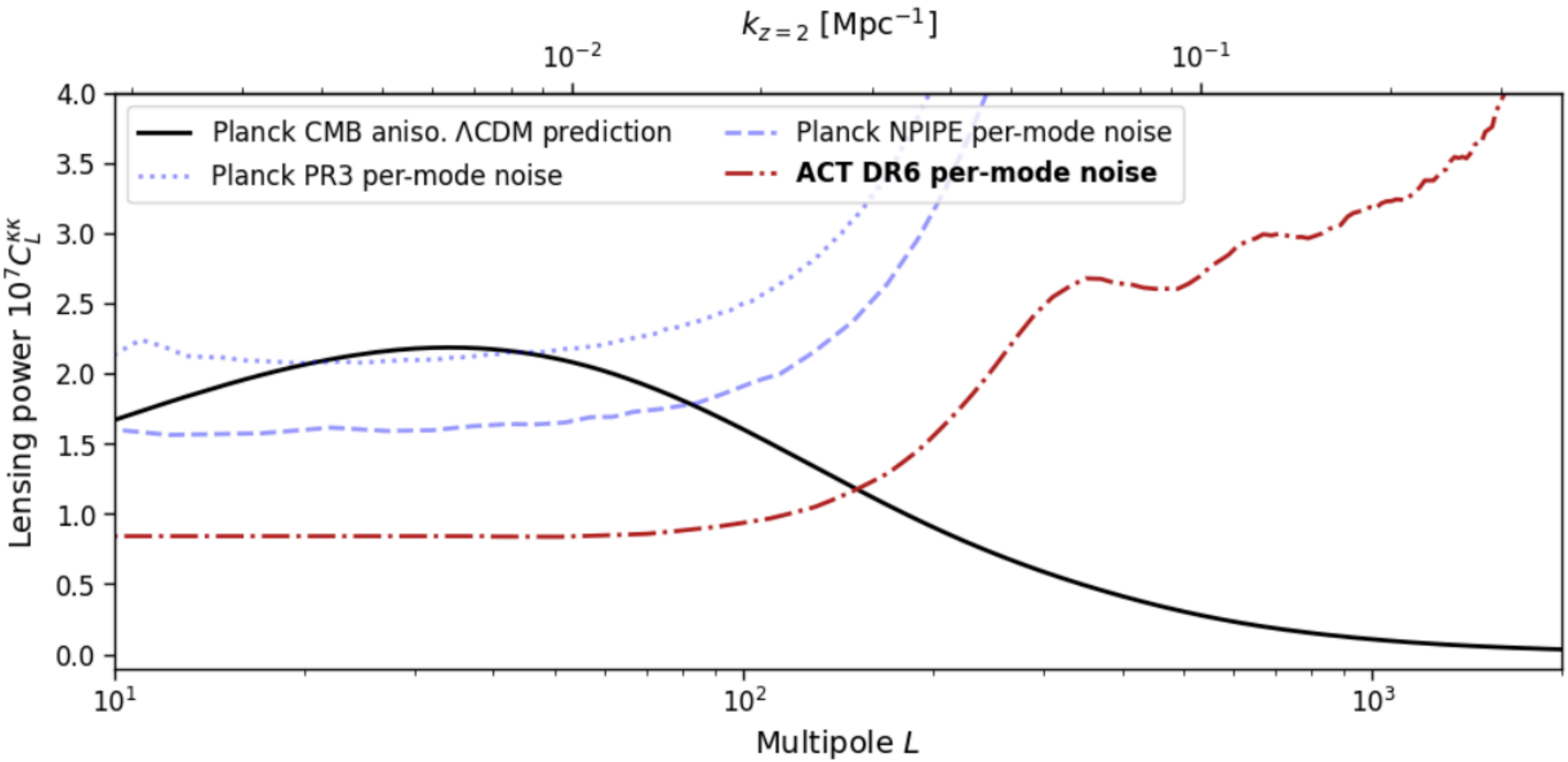
ZOOM IN: ACT DR6 Gravitational potential map



ZOOM IN: ACT DR6 Gravitational potential map + Planck CIB



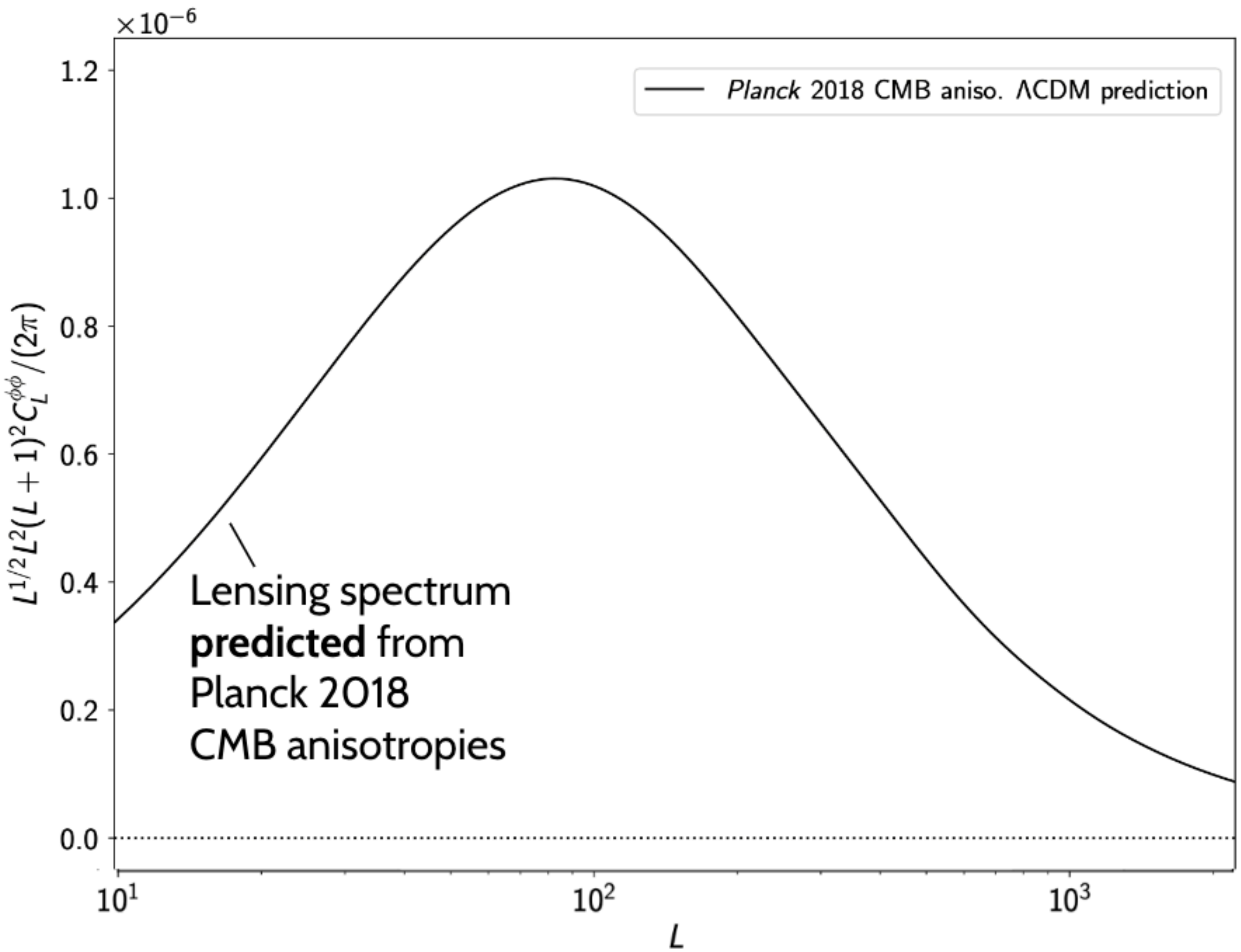
ZOOM IN: ACT DR6 Gravitational potential map + Planck CIB

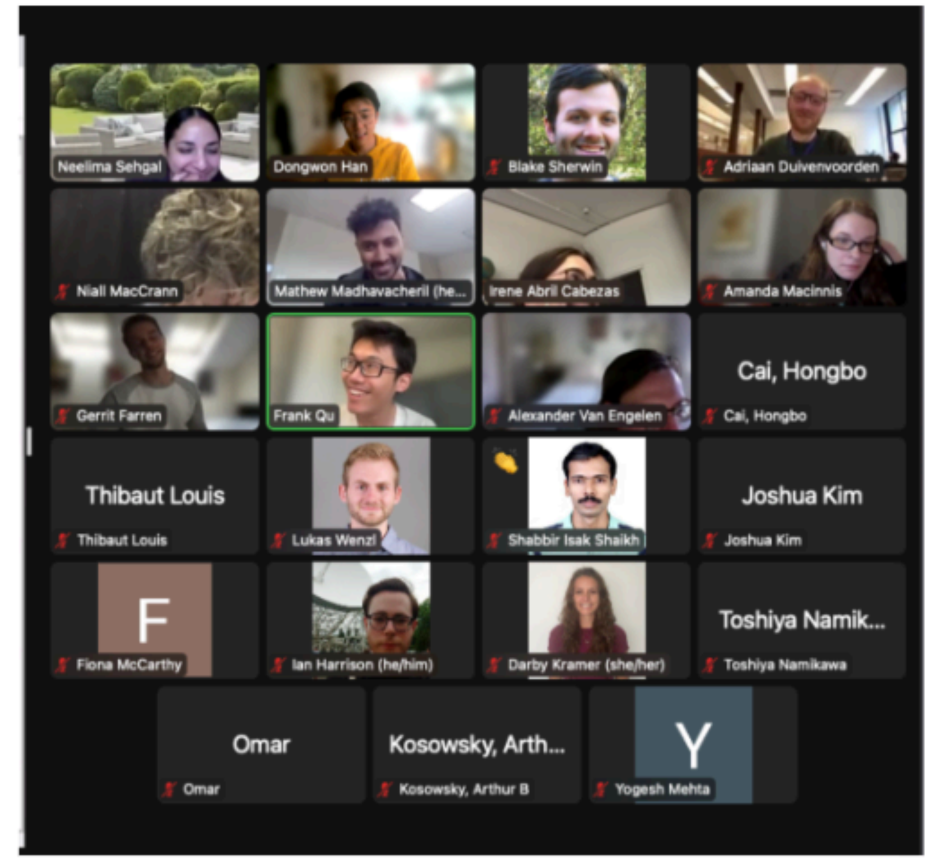


2x SNR per mode compared to *Planck*.

Reconstruction on mostly linear scales.

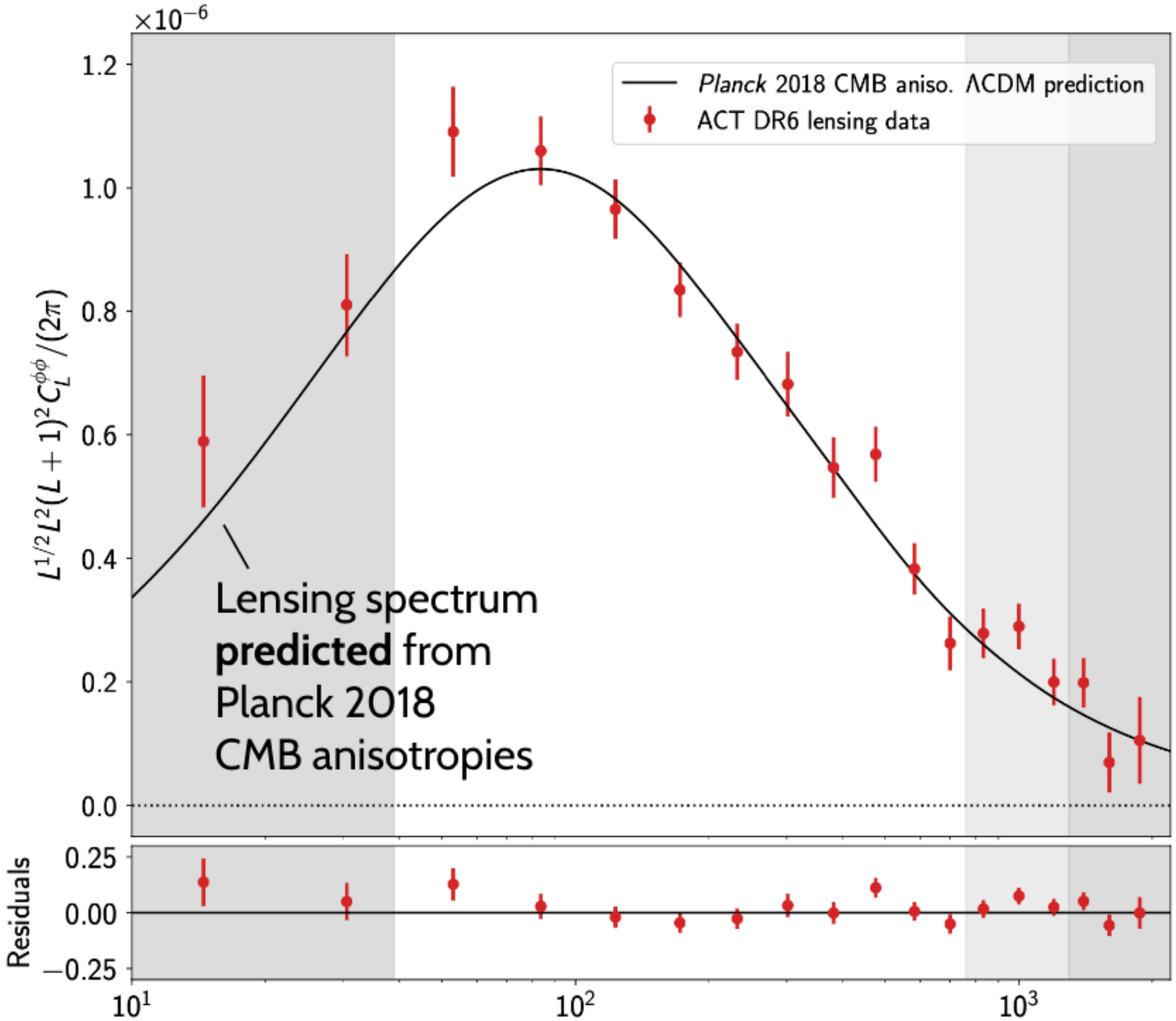
CMB lensing power spectrum





The Atacama Cosmology Telescope: A Measurement of the DR6 CMB Lensing Power Spectrum and its Implications for Structure Growth: Qu et al. (April 2023)

CMB lensing power spectrum



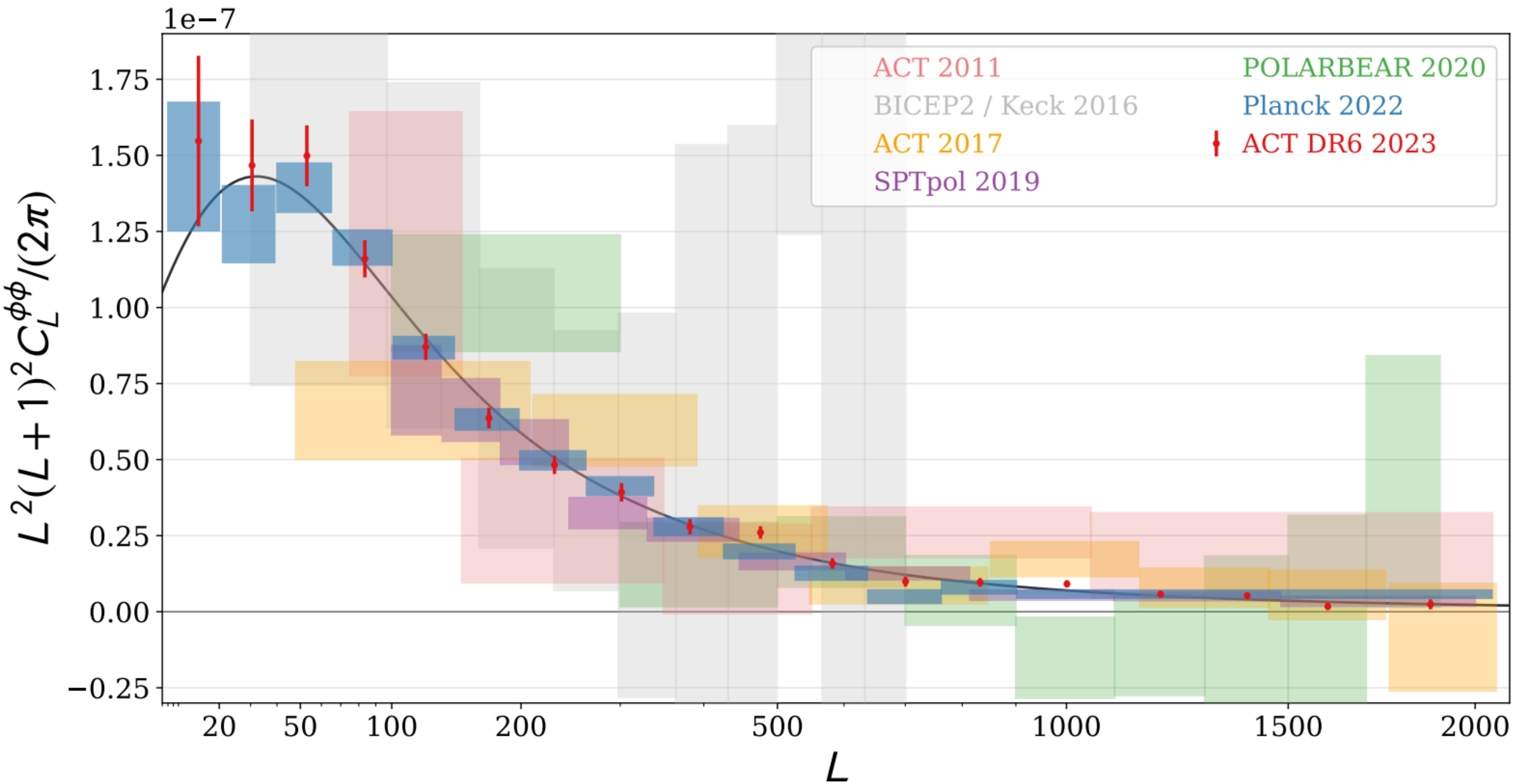
- Excellent agreement of our measurement (with no free parameters) with the LCDM theory predictions based on *Planck* 2018 CMB power spectra. A PTE of 0.17
- Amplitude of lensing (relative to theory amplitude) determined to 2.3%

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

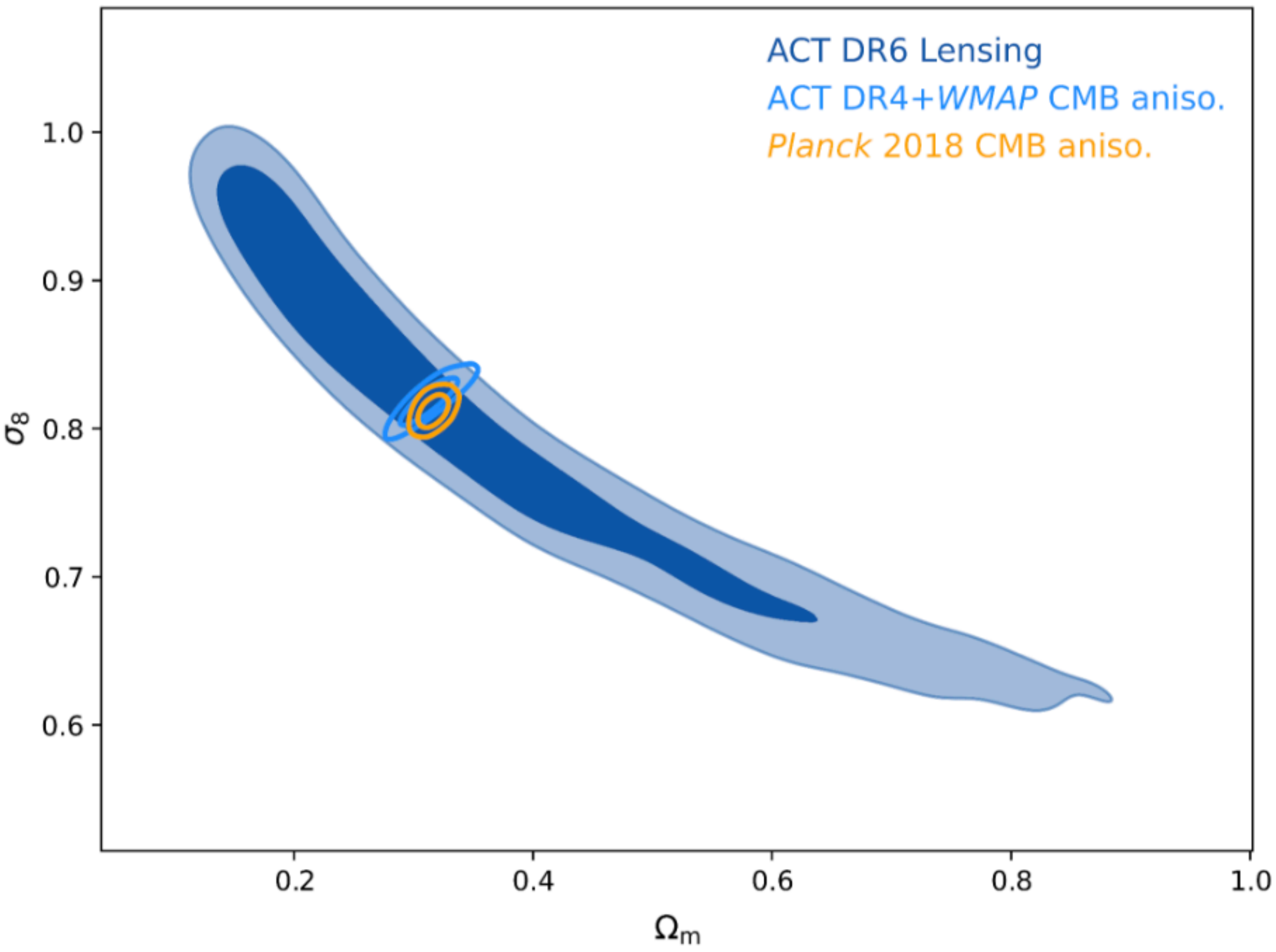
- SNR of 43

The Atacama Cosmology Telescope: A Measurement of the DR6 CMB Lensing Power Spectrum and its Implications for Structure Growth: Qu et al. (April 2023)

CMB lensing power spectra



Cosmological constraint



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

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

Early time CMB predictions

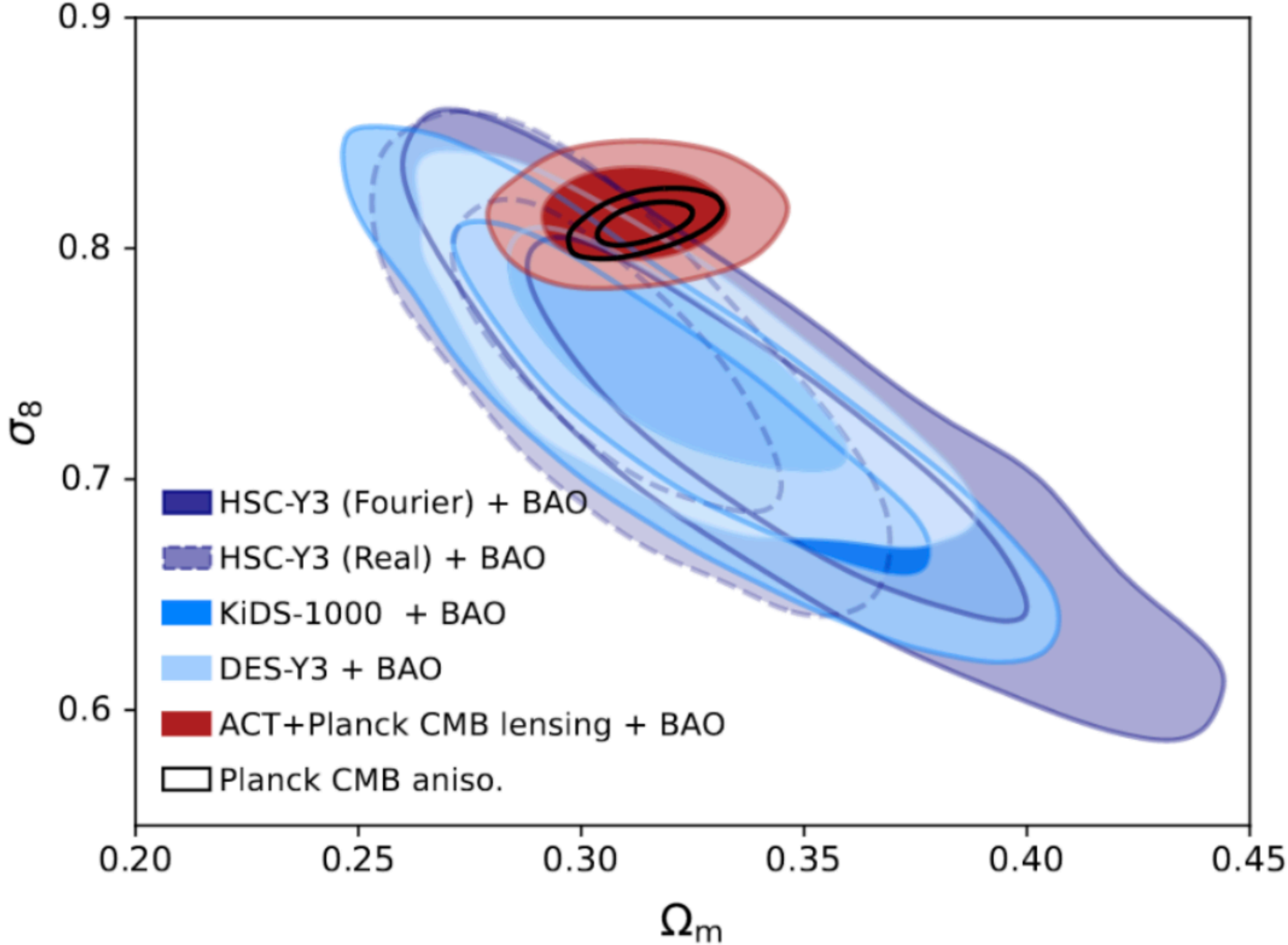
ACT DR4 + *WMAP* CMB aniso.

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

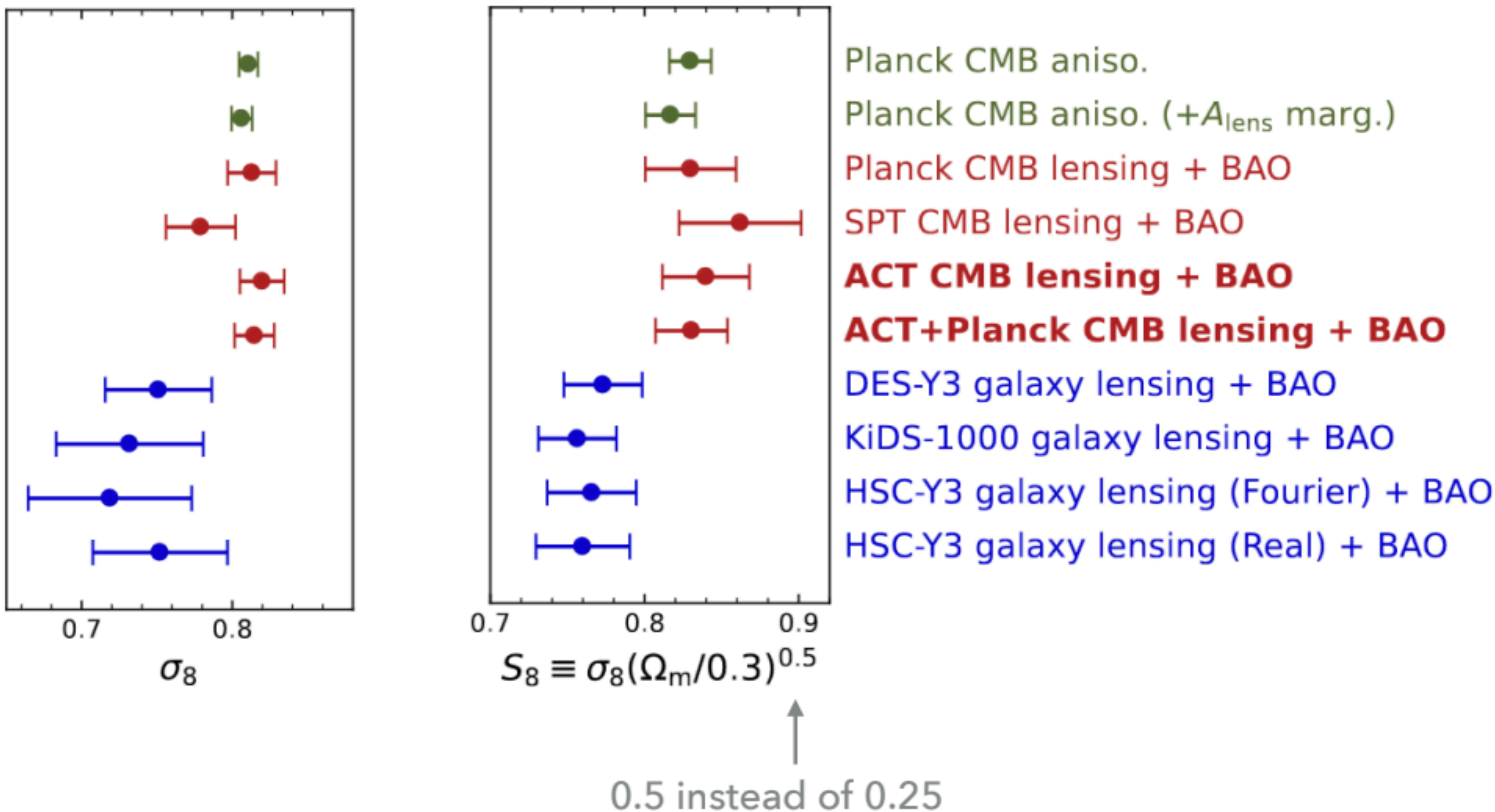
Planck 2018 CMB aniso.

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

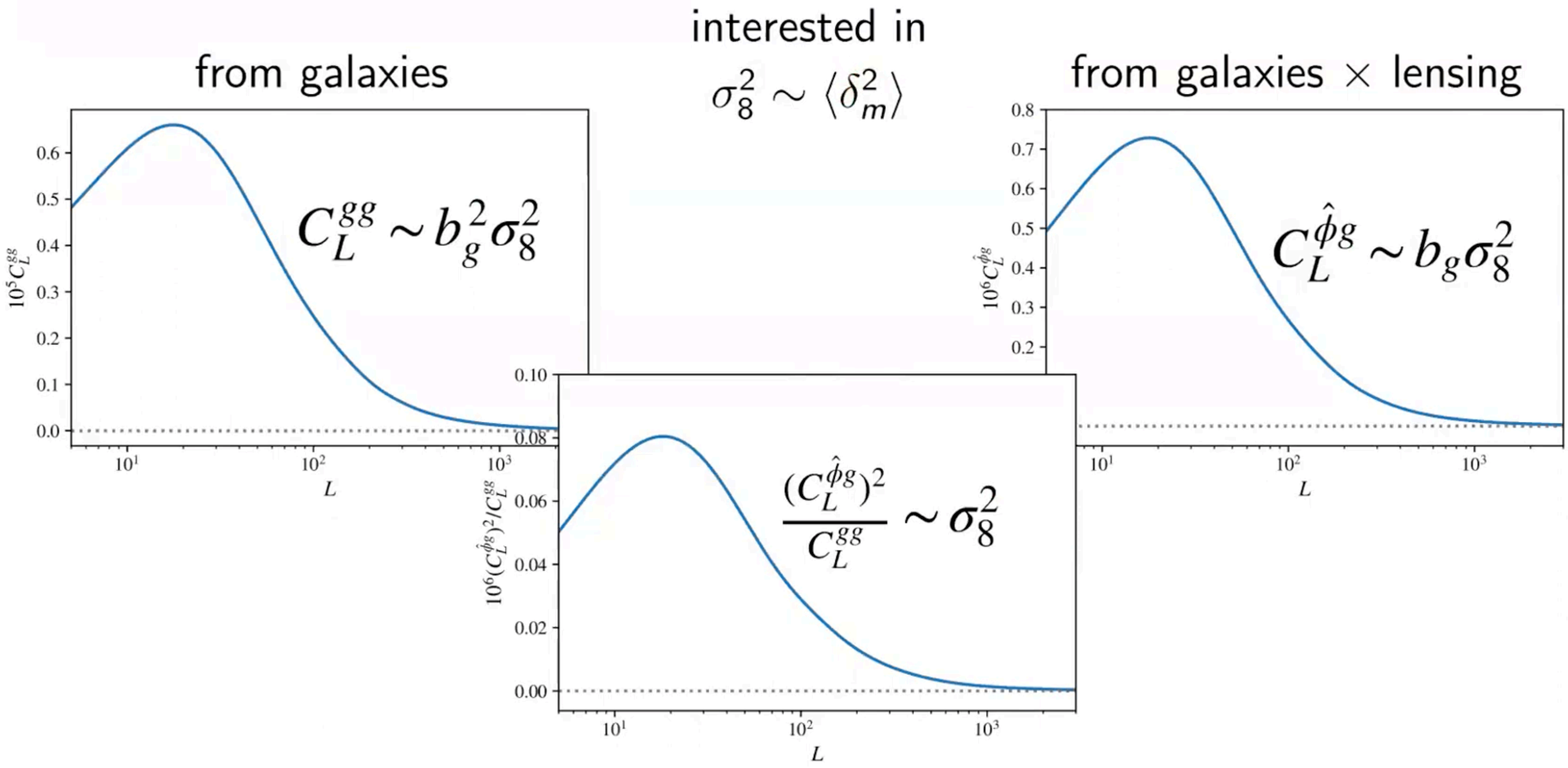
ACT lensing is not low !!



ACT lensing is not low !!



Now and next: cross correlations



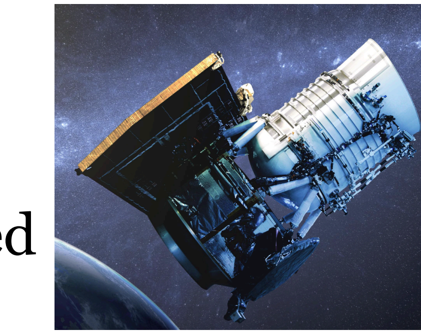
The Atacama Cosmology Telescope: Cosmology from cross-correlations of unWISE galaxies and ACT DR6 CMB lensing: Farren et al (Sept. 2023)

in preparation:

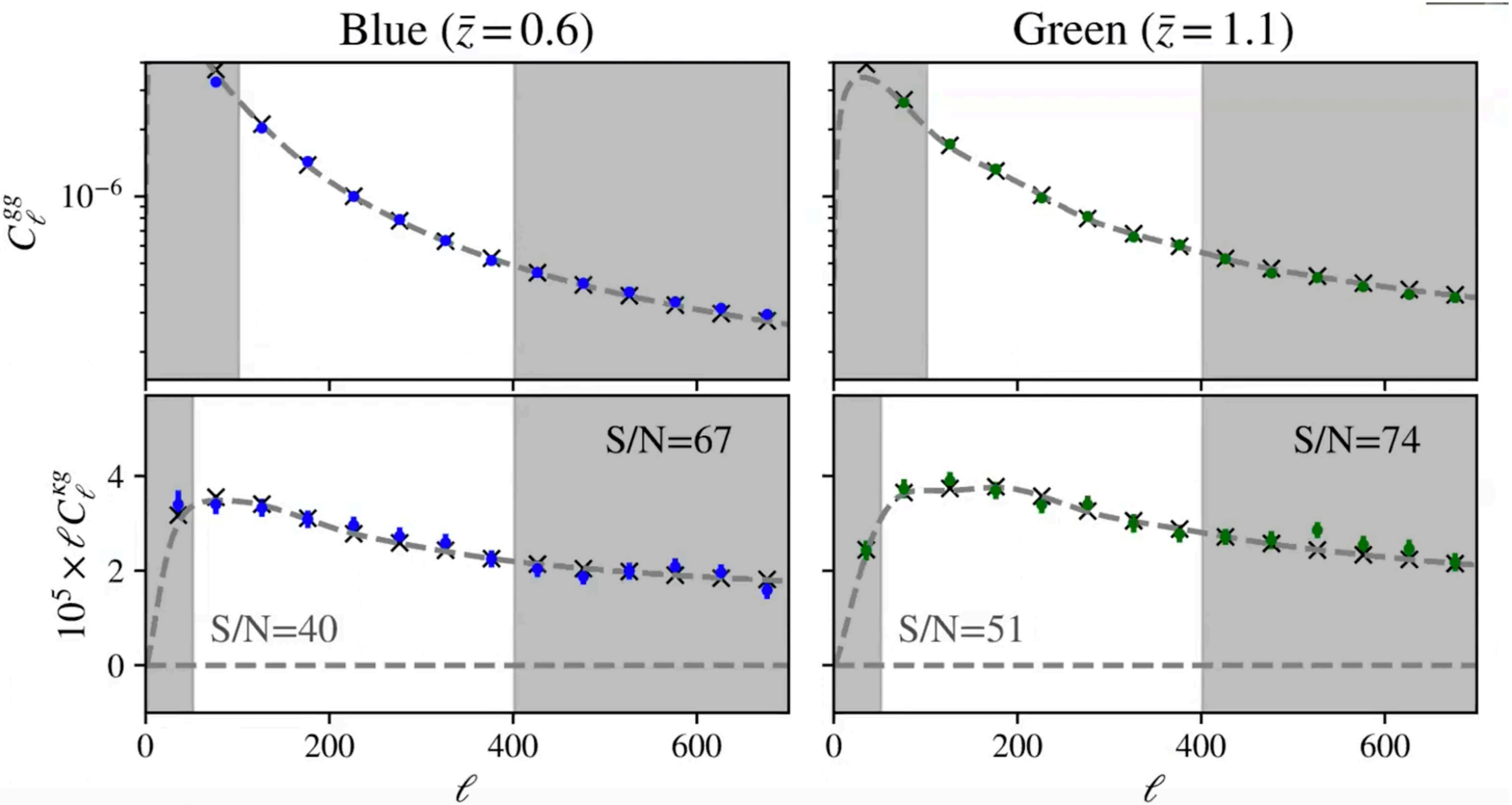
DESI LRGs:	Kim & Sailer *et al.*
	Hang *et al.*
SDSS BOSS:	Wenzl *et al.*
DES-Y3:	Darwish *et al.*
	Shaikh & Harrison *et al.*
	Pitocco *et al.*
	Kim *et al.*
Planck CIB:	Mheta *et al.*

...

Now and next: cross correlations



Wide-field Infrared Survey Explorer



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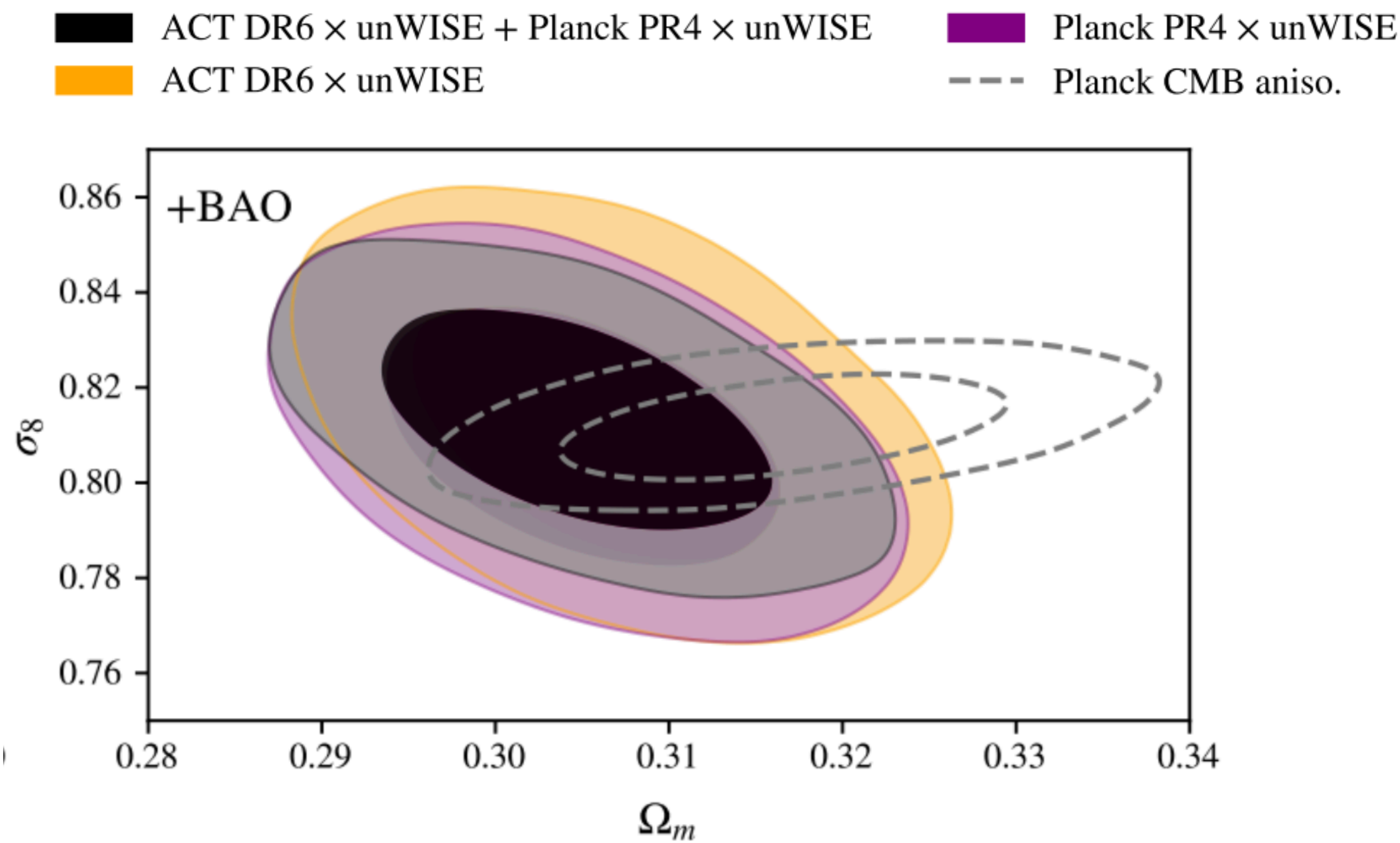
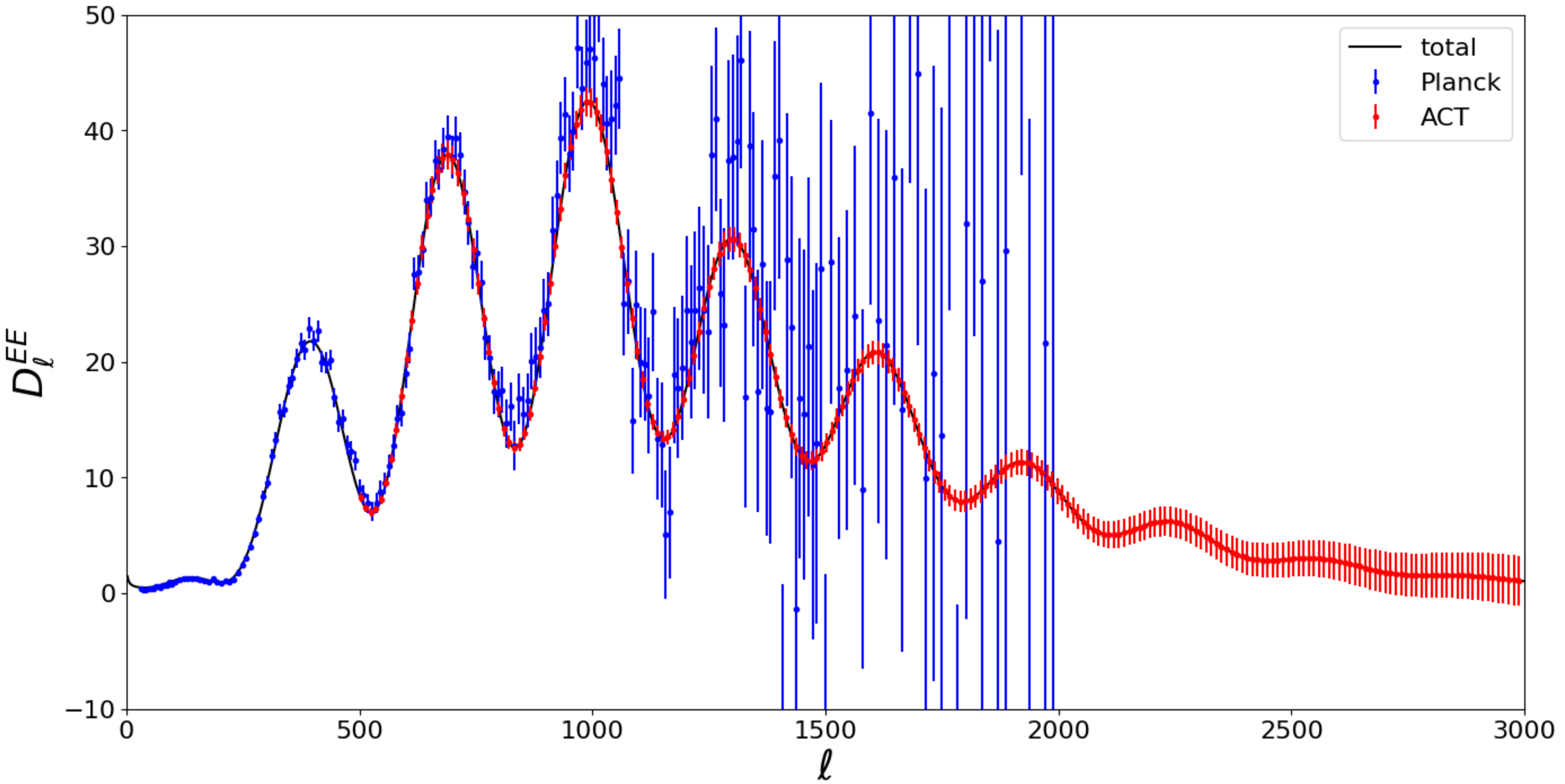
Now and next: cross correlations



The Atacama Cosmology Telescope: Cosmology from cross-correlations of unWISE galaxies and ACT DR6 CMB lensing: Farren et al (Sept. 2023)

Conclusion:

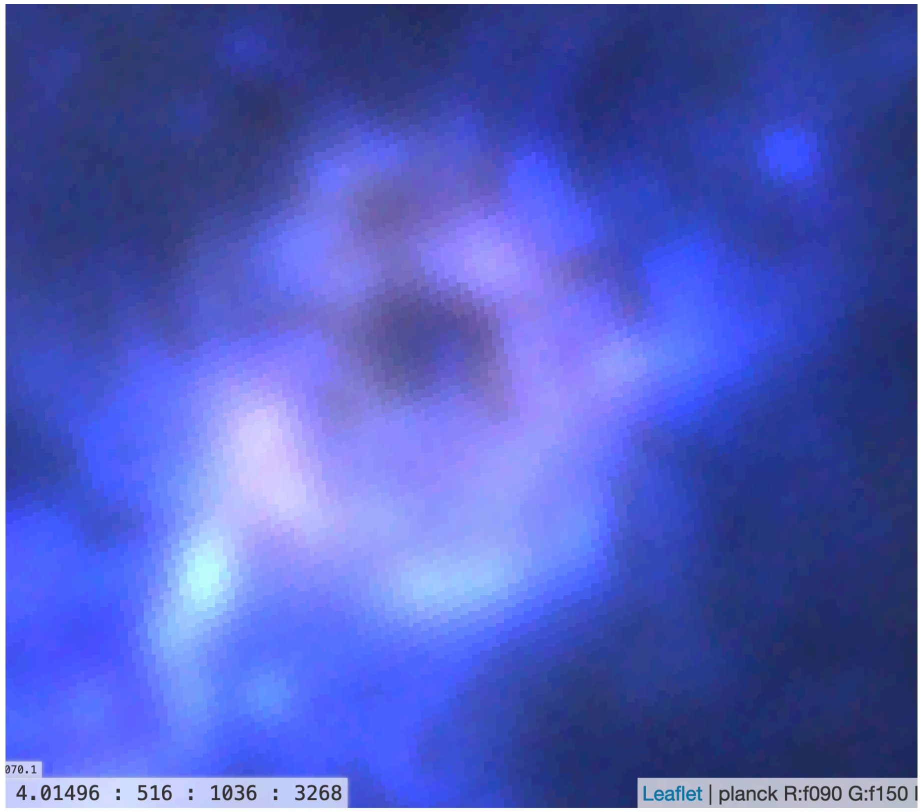
- ACT DR6 lensing papers are out, lensing maps are going to be public on Lambda soon
- ACT lensing is not low
- Lot of cross correlation papers coming
- ACT power spectra/likelihood and parameters are coming !



The Atacama Cosmology Telescope: DR6 Power spectra, Likelihood, and constrains on LCDM
Louis, La Posta, Li, et al (expected 2024)

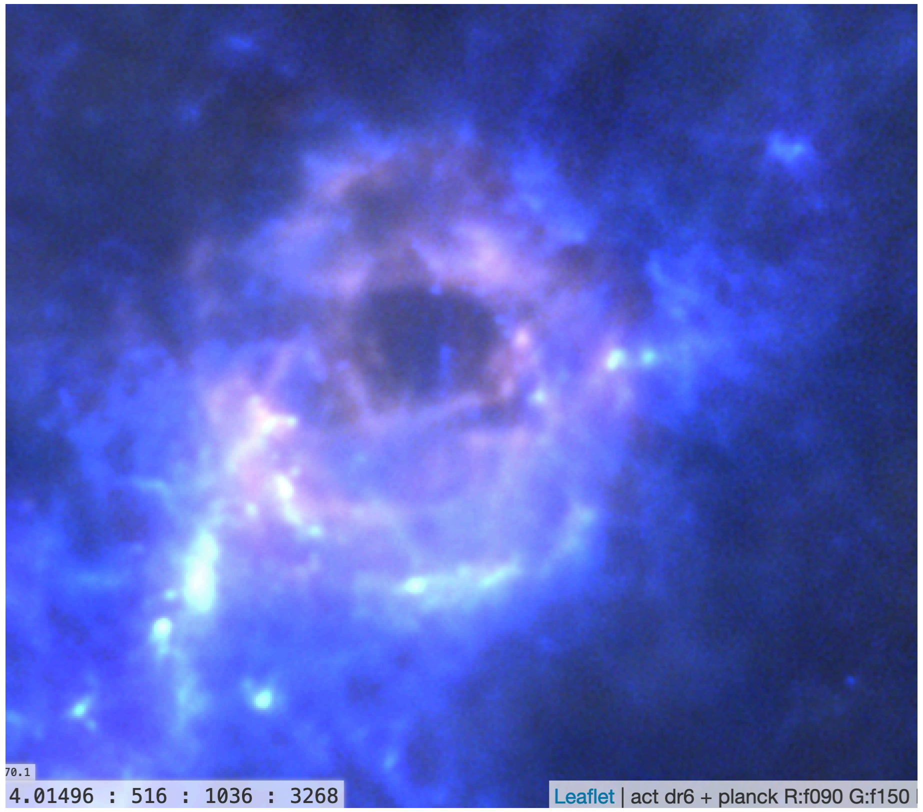
Rosette Nebula

Planck



WISE

ACT + Planck

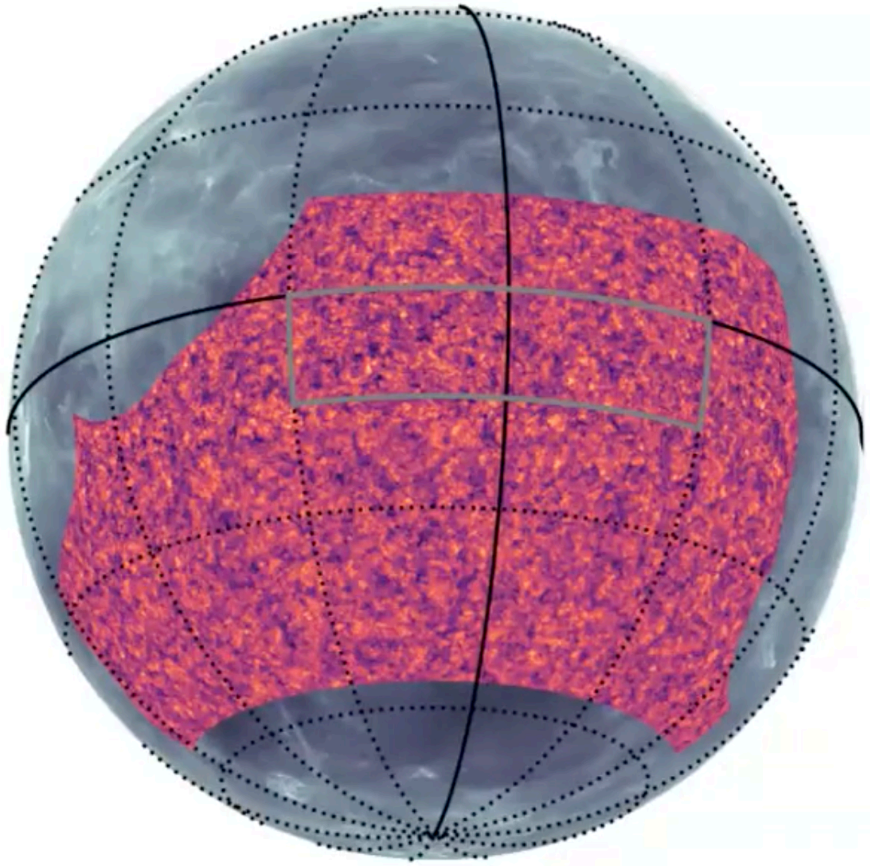


BACK UP

Now and next: cross correlations

Wide-field Infrared Survey Explorer

CMB Lensing reconstruction



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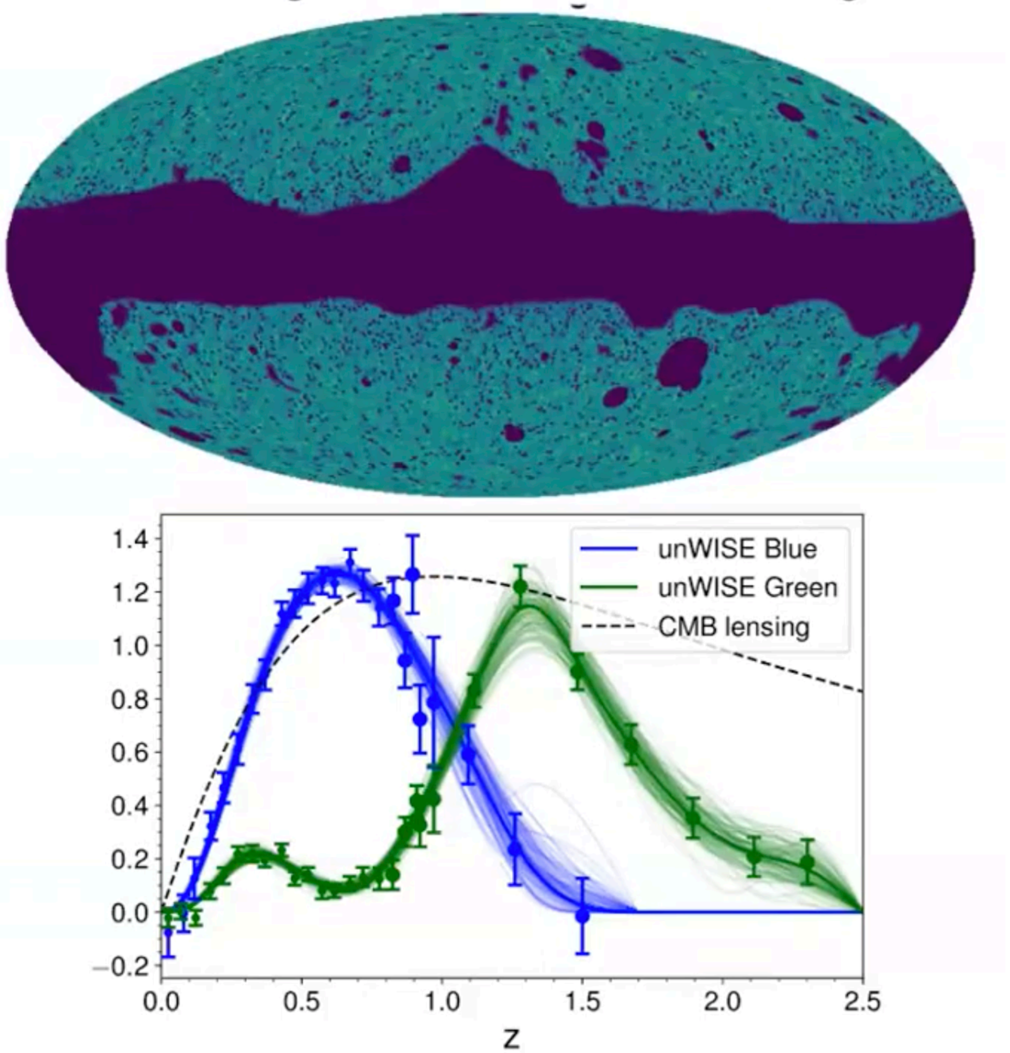
Galaxy number density



The Atacama Cosmology Telescope: Cosmology from cross-correlations of unWISE galaxies and ACT DR6 CMB lensing: Farren et al (Sept. 2023)

BAO likelihoods

3.1. *BAO likelihoods*

Weak lensing measurements depend primarily on the amplitude of matter fluctuations σ_8, the matter density $\Omega_{\rm m}$, and the Hubble constant H_0. In order to reduce degeneracies of our σ_8 constraint with the latter parameters and allow for more powerful comparisons of lensing probes with different degeneracy directions, we include information from the 6dF and SDSS surveys. The data we include measures the BAO signature in the clustering of galaxies with samples spanning redshifts up to $z \simeq 1$, including 6dFGS (Beutler et al. 2011), SDSS DR7 Main Galaxy Sample (MGS; Ross et al. 2015), BOSS DR12 luminous red galaxies (LRGs; Alam et al. 2017), and eBOSS DR16 LRGs (Alam et al. 2021). We do not use the higher-redshift Emission Line Galaxy (ELG; Comparat et al. 2016), Lyman-α (du Mas des Bourboux et al. 2020), and quasar samples (Hou et al. 2021), though we hope to include these in future analyses. We only include the BAO information from these surveys (which provides constraints in the $\Omega_{\rm m}$–H_0 plane) and do not include the structure growth information in the redshift-space distortion (RSD) component of galaxy clustering. We make this choice so as to isolate information on structure formation purely from lensing alone.

$$
\begin{aligned}
\xi^{TT}(\hat{n}_1,\hat{n}_2) &= \langle T(\hat{n}_1)T(\hat{n}_2)\rangle = \xi(\hat{n}_1.\hat{n}_2) = \xi(\cos\theta) \\
\langle a^T_{\ell m} a^{T,*}_{\ell' m'}\rangle &= \langle \int d\hat{n} T(\hat{n}) Y^*_{\ell m}(\hat{n}) \int d\hat{n}' T(\hat{n'}) Y_{\ell' m'}(\hat{n'})\rangle \\
\langle a^T_{\ell m} a^{T,*}_{\ell' m'}\rangle &= \int d\hat{n} d\hat{n}' \langle T(\hat{n}) T(\hat{n}')\rangle Y^*_{\ell m}(\hat{n}) Y_{\ell' m'}(\hat{n}') \\
&= \int d\hat{n} d\hat{n}' \xi(\hat{n}.\hat{n}') Y^*_{\ell m}(\hat{n}) Y_{\ell' m'}(\hat{n}')
\end{aligned}
$$

We can expand a function of $\cos\theta$ in Legendre polynomials, and expand the legendre polynomial in spherical harmonics

$$
\begin{aligned}
\xi(\hat{n}.\hat{n}') &= \sum_{\ell_0=0}^{\infty} \frac{2\ell_0+1}{4\pi} C_{\ell_0} P_{\ell_0}(\hat{n}.\hat{n}')) \\
&= \sum_{\ell_0=0}^{\infty} C_{\ell_0} \sum_{m=-\ell_0}^{\ell_0} Y_{\ell_0 m_0}(\hat{n}) Y^*_{\ell_0 m_0}(\hat{n}')
\end{aligned}
$$

$$
\begin{aligned}
\langle a^T_{\ell m} a^{T,*}_{\ell' m'}\rangle &= \int d\hat{n} d\hat{n}' \sum_{\ell_0=0}^{\infty} C_{\ell_0} \sum_{m=-\ell_0}^{\ell_0} Y_{\ell_0 m_0}(\hat{n}) Y^*_{\ell_0 m_0}(\hat{n}') Y^*_{\ell m}(\hat{n}) Y_{\ell' m'}(\hat{n}') \\
&= \sum_{\ell_0=0}^{\infty} C_{\ell_0} \sum_{m=-\ell_0}^{\ell_0} \int d\hat{n} Y_{\ell_0 m_0}(\hat{n}) Y^*_{\ell m}(\hat{n}) \int d\hat{n'} Y^*_{\ell_0 m_0}(\hat{n}') Y_{\ell' m'}(\hat{n}') \\
&= \sum_{\ell_0=0}^{\infty} C_{\ell_0} \sum_{m=-\ell_0}^{\ell_0} \delta_{\ell_0,\ell}\delta_{m_0,m}\delta_{\ell_0,\ell'}\delta_{m_0,m'} = C_\ell \delta_{\ell,\ell'}\delta_{m,m'}
\end{aligned}
$$

Where we use the orthonormality of spherical harmonics

$$
\int d\hat{n} Y_{\ell_0 m_0}(\hat{n}) Y^*_{\ell m}(\hat{n}) = \delta_{\ell_0,\ell}\delta_{m_0,m}
$$

$$
\langle a^T_{\ell m} a^{T,*}_{\ell' m'}\rangle = C_\ell \delta_{\ell,\ell'}\delta_{m,m'}
$$

Testing gravity with the E_G statistic

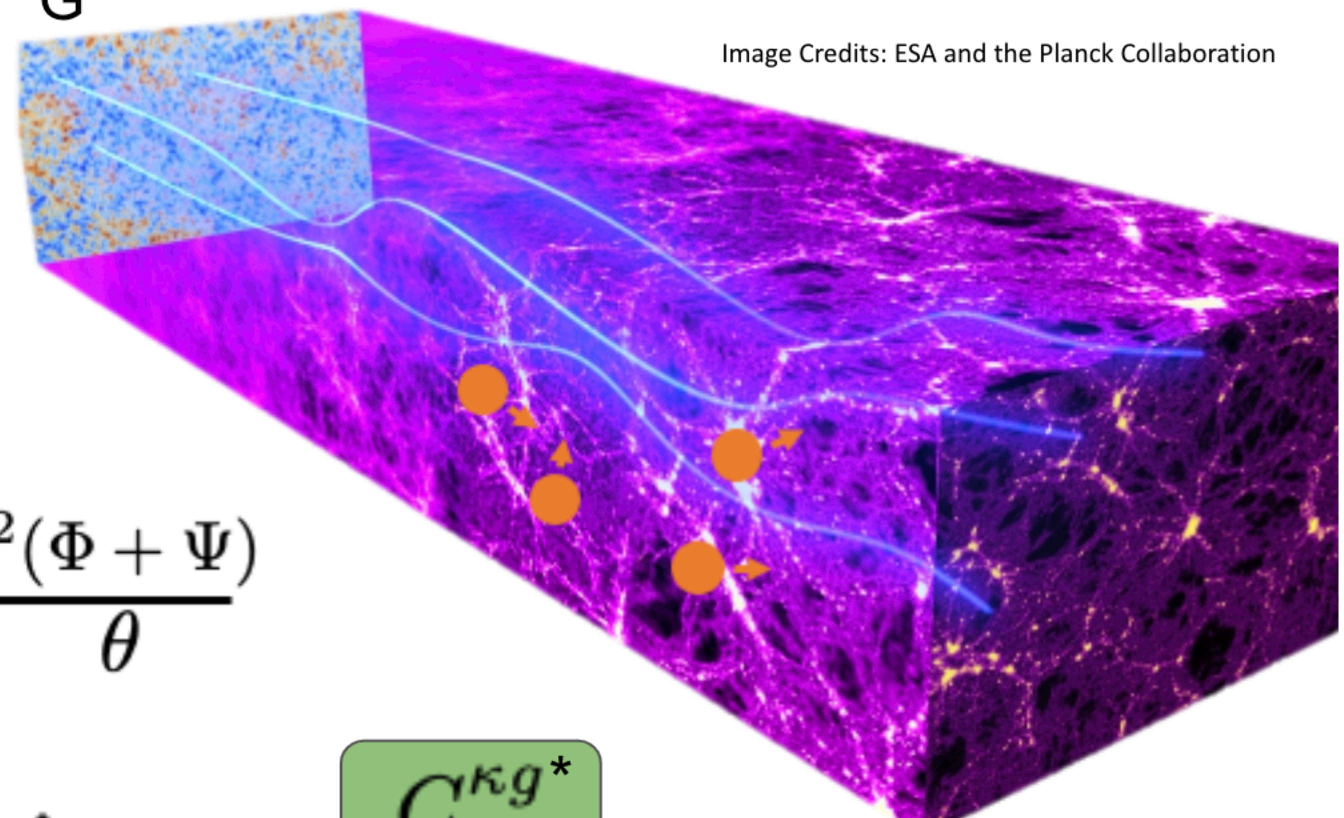


Image Credits: ESA and the Planck Collaboration

Often Modified Gravity can match expansion history but predicts deviations in Poisson equation

E_G tests this by comparing lensing and non-relativistic motions $\frac{\nabla^2(\Phi + \Psi)}{\theta}$

Can measure E_G from CMB lensing and spectroscopic galaxy survey

$$\hat{E}_G \approx \Gamma_G \frac{C_\ell^{\kappa g *}}{\beta C_\ell^{gg}}$$

New and improved estimator

$$E_G^{\mathrm{GR}}(z) = \frac{\Omega_{\mathrm{m},0}}{f(z)}$$