

Cosmology from the Cosmic Microwave Background

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LBNL, May 7 2026

*We are entering the next level of CMB data-gathering
Order of magnitude more detectors than Stage-3*

- Simons Observatory (SO) is here and gathering data*
- Berkeley/LBNL are a big part of SO*
- With support, SO can pursue P5/Astro2020 CMB science and deliver data*
- There is room for expansion in Chile, and complementarity with South Pole efforts.*
- There is a lot of science to do from SO & DESI together*

Cosmic questions

Did cosmic inflation imprint the initial conditions?

Is dark energy a vacuum energy or a scalar field, or something else?

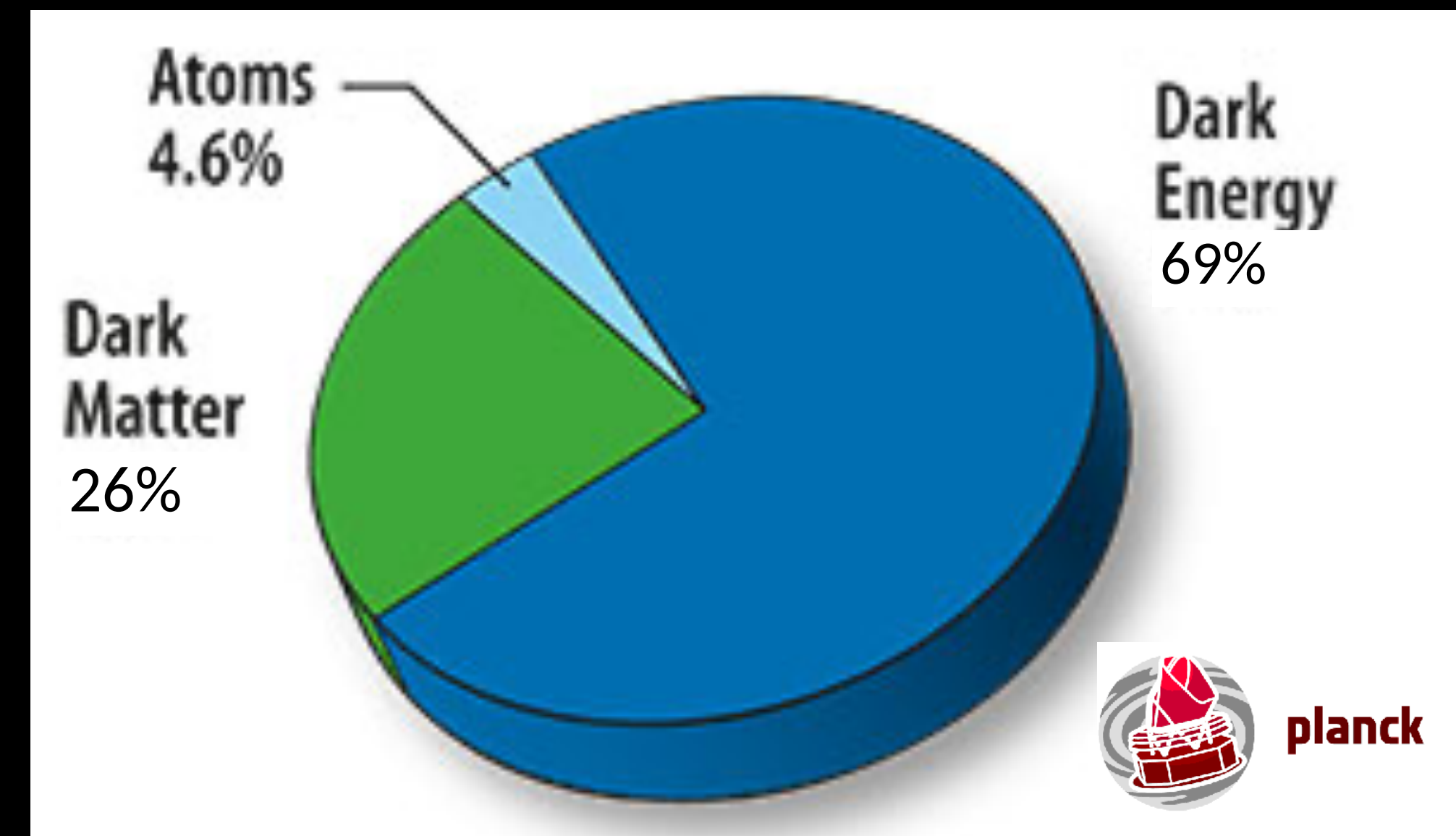
What is the cold dark matter, and do we understand the hot dark matter (neutrinos)?

Are we missing 'new' physics?

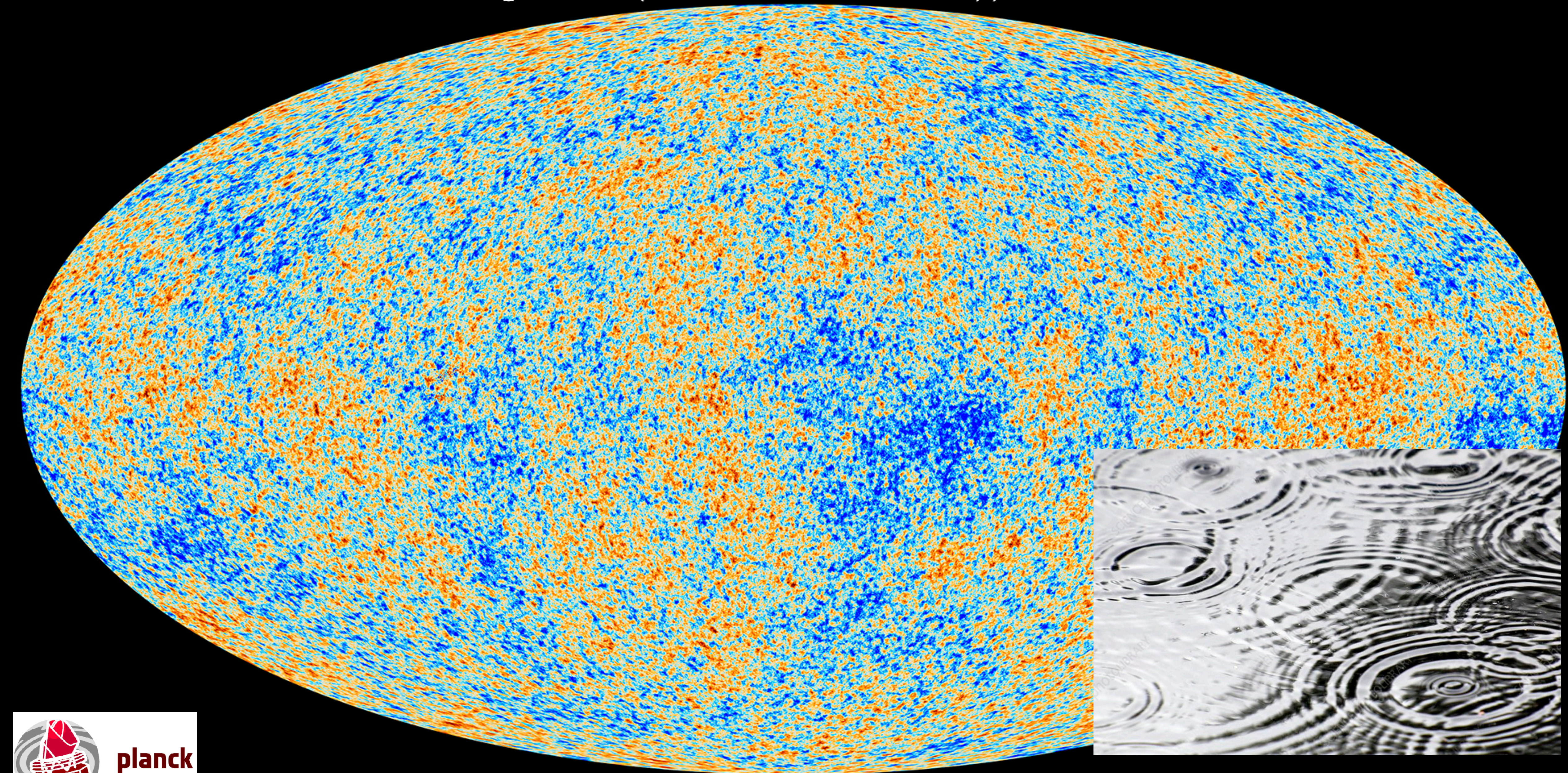
The best model for the universe continues to be ' Λ CDM', in place for 20+ years

Flat universe with 'regular' matter, cold dark matter (CDM) and cosmological constant (Λ), and simple initial conditions.

Physics follows General Relativity.

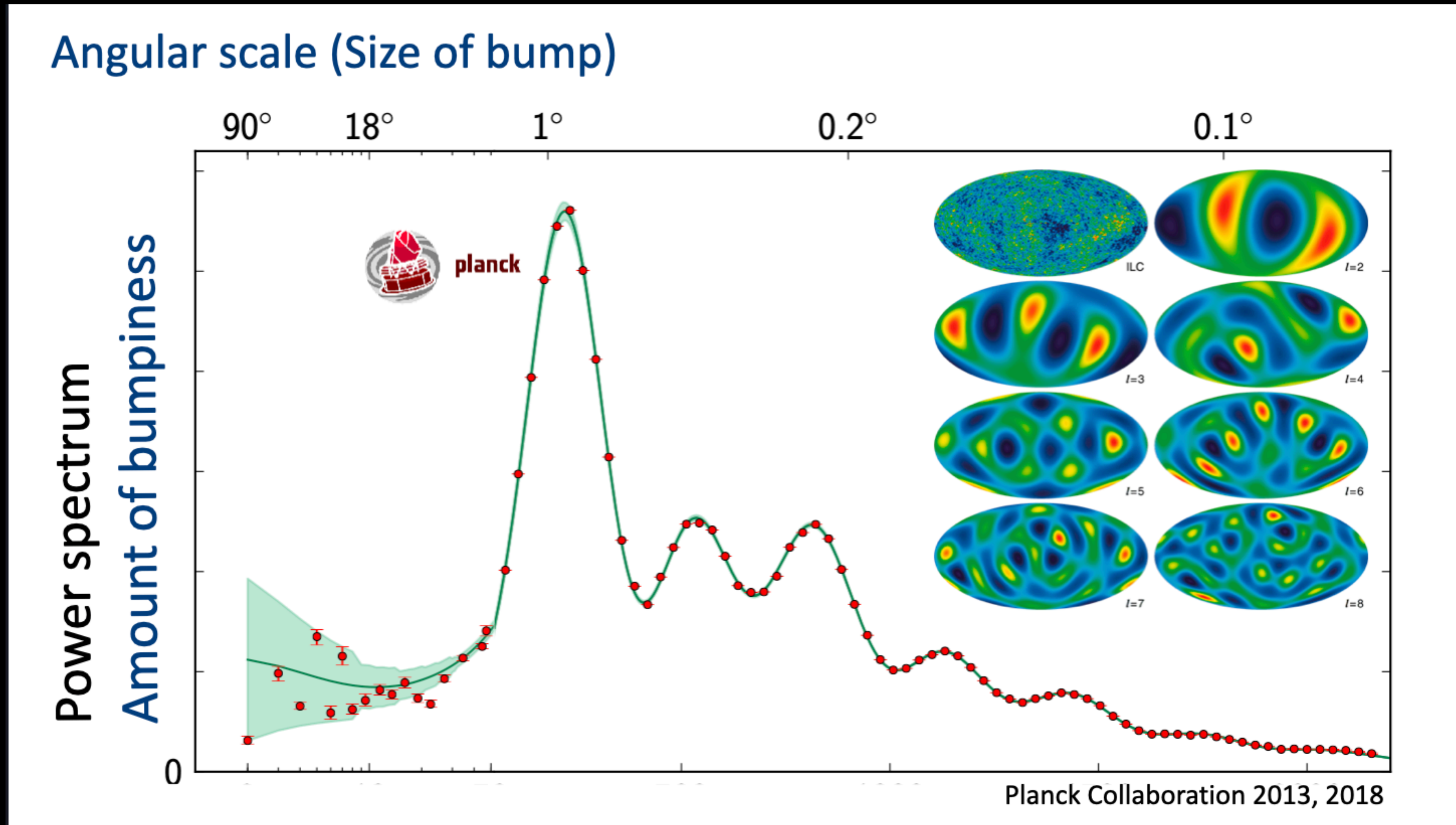


The Cosmic Microwave Background (variations in intensity)



Tracks density (and velocity) of photon-baryon plasma at recombination, $z=1100$, $t=380,000$ yrs. $\pm 300 \mu\text{K}$

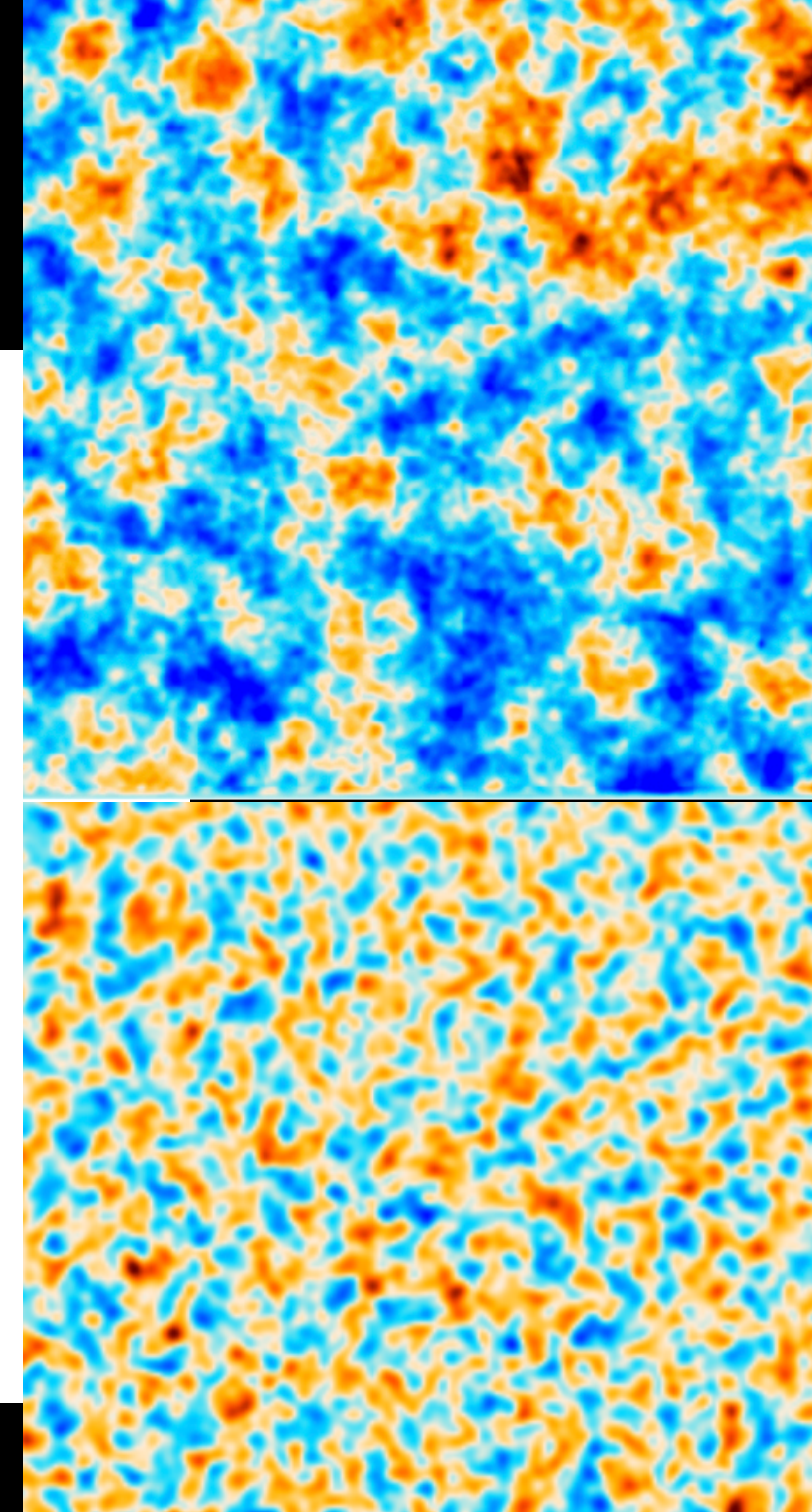
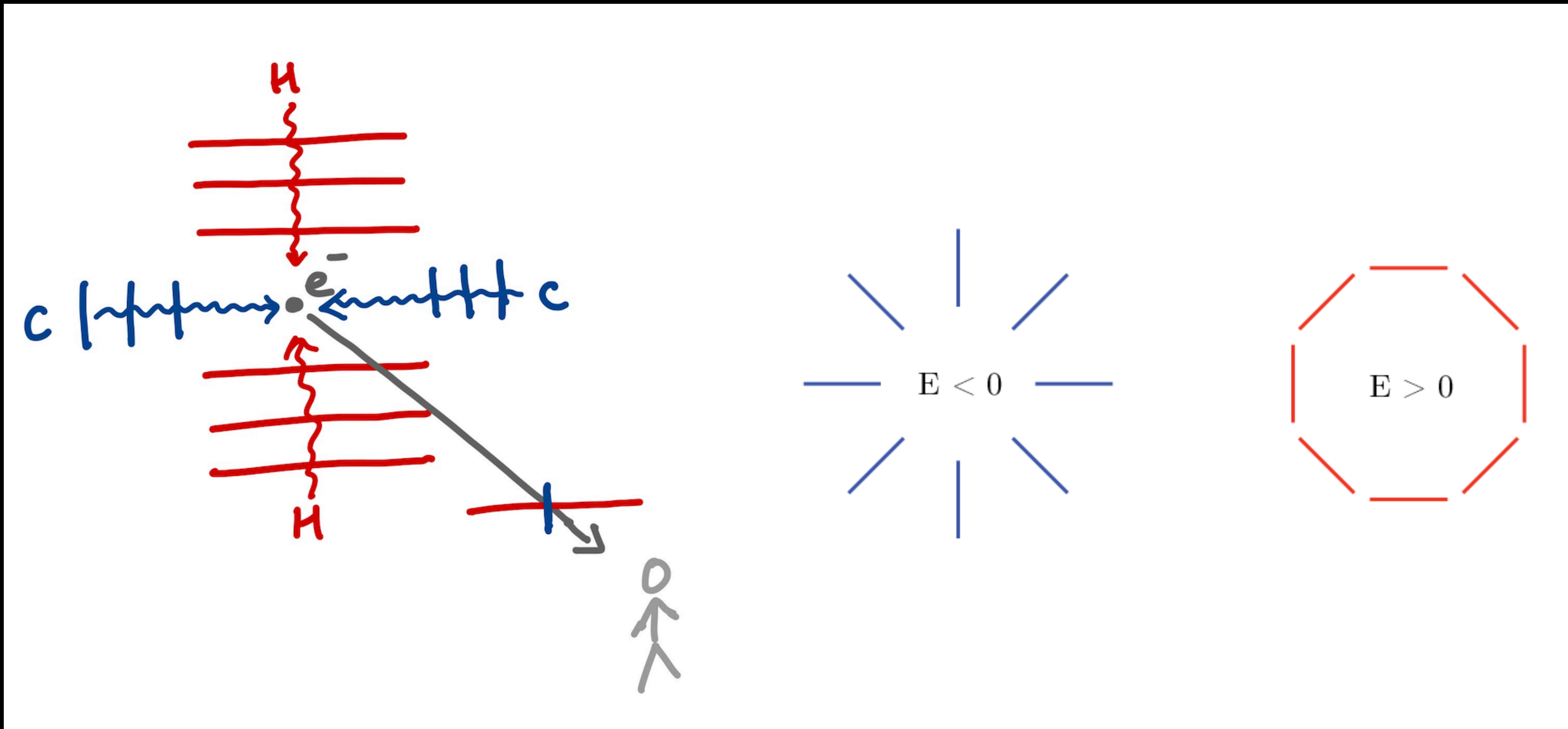
The CMB power spectrum: intensity



The power spectrum is the most-used statistic: we predict it theoretically, and modify ingredients and initial conditions until it fits data. Given us Λ CDM ingredients and 2 initial conditions.

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*} \right)^{n_s - 1}$$

The CMB is polarized



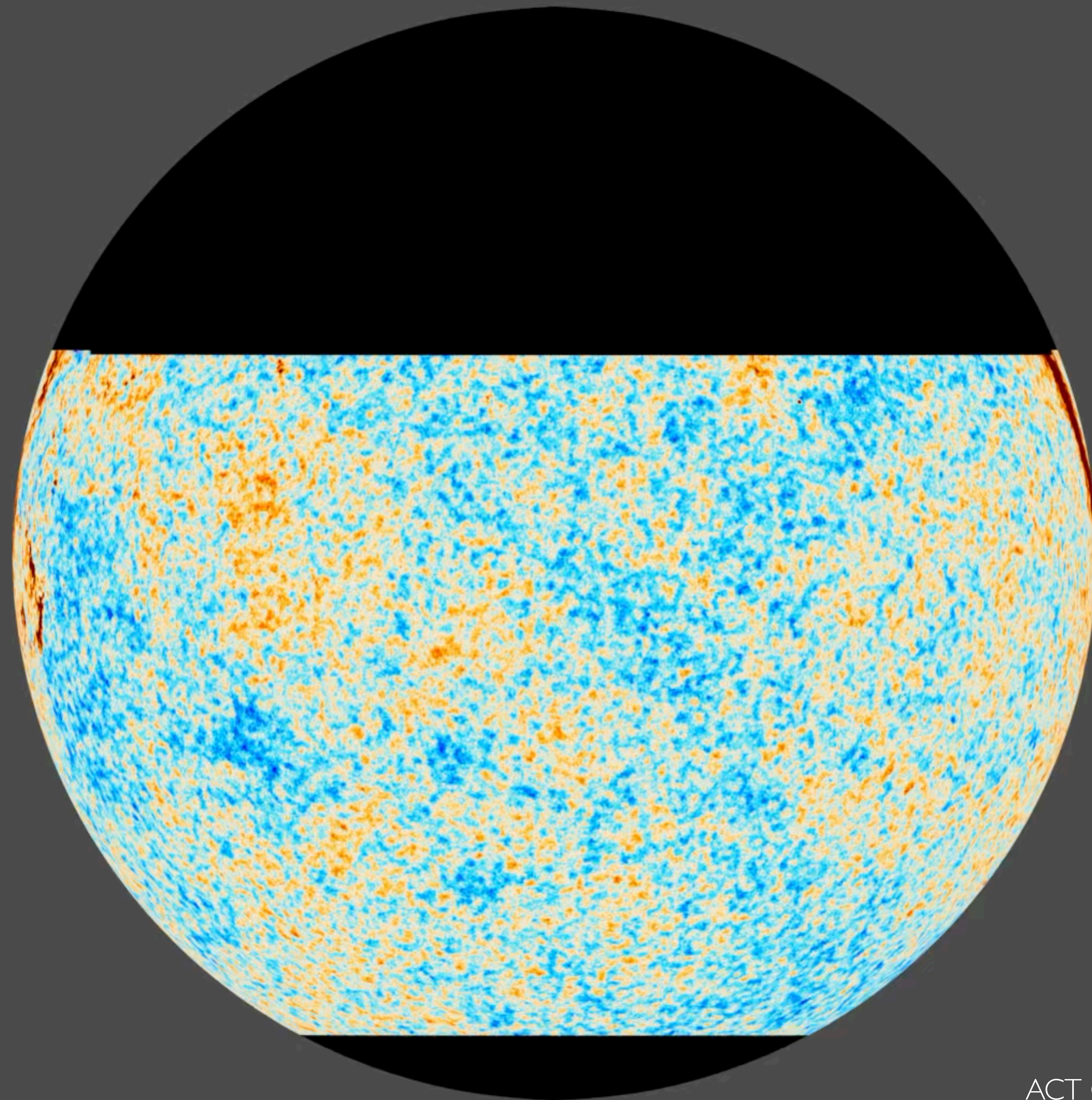
ACT Collaboration

'E-mode' polarization captures velocity of hydrogen-helium plasma at $t=380,000$ yrs
Second image of the 'same' physics

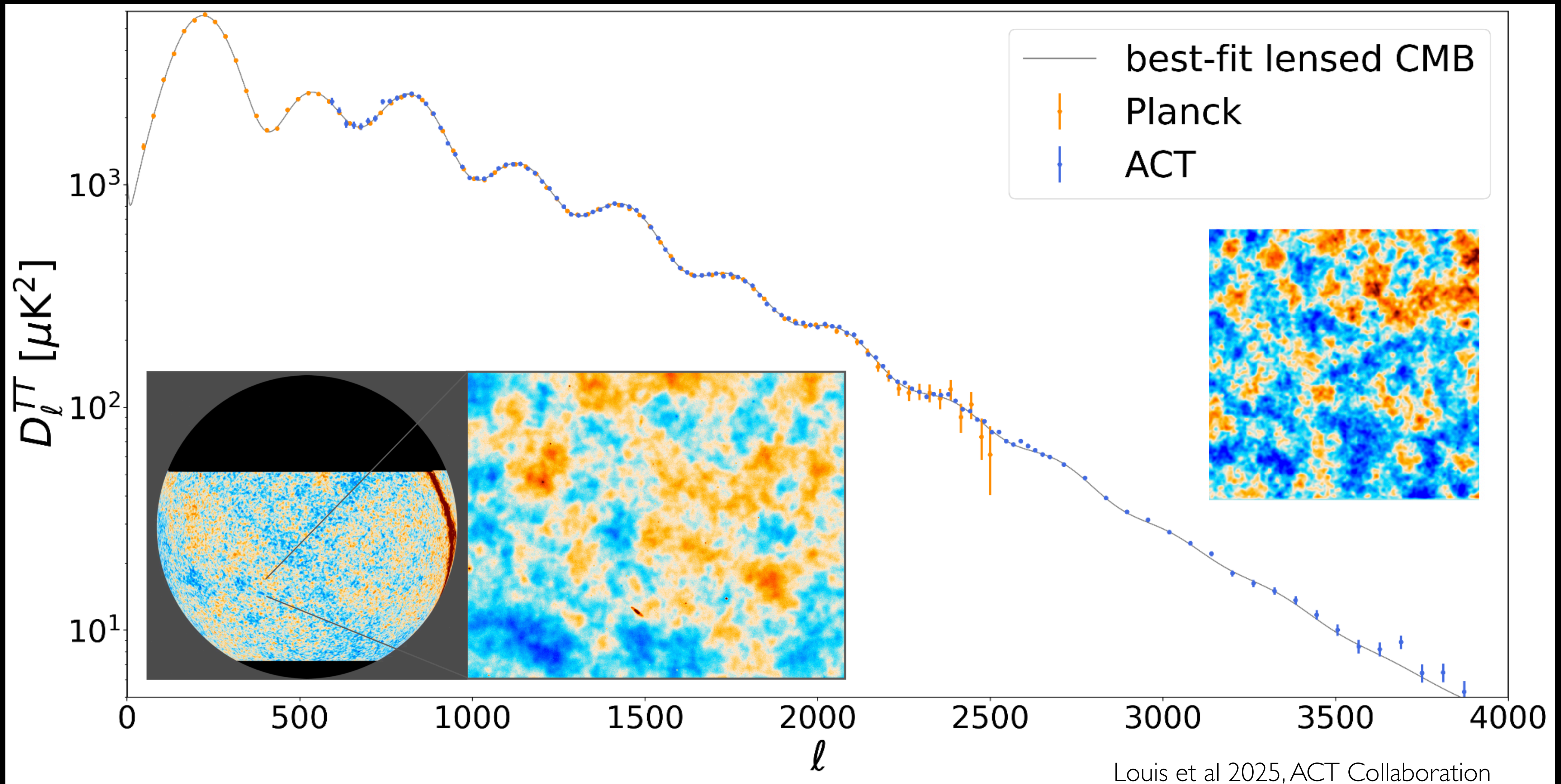


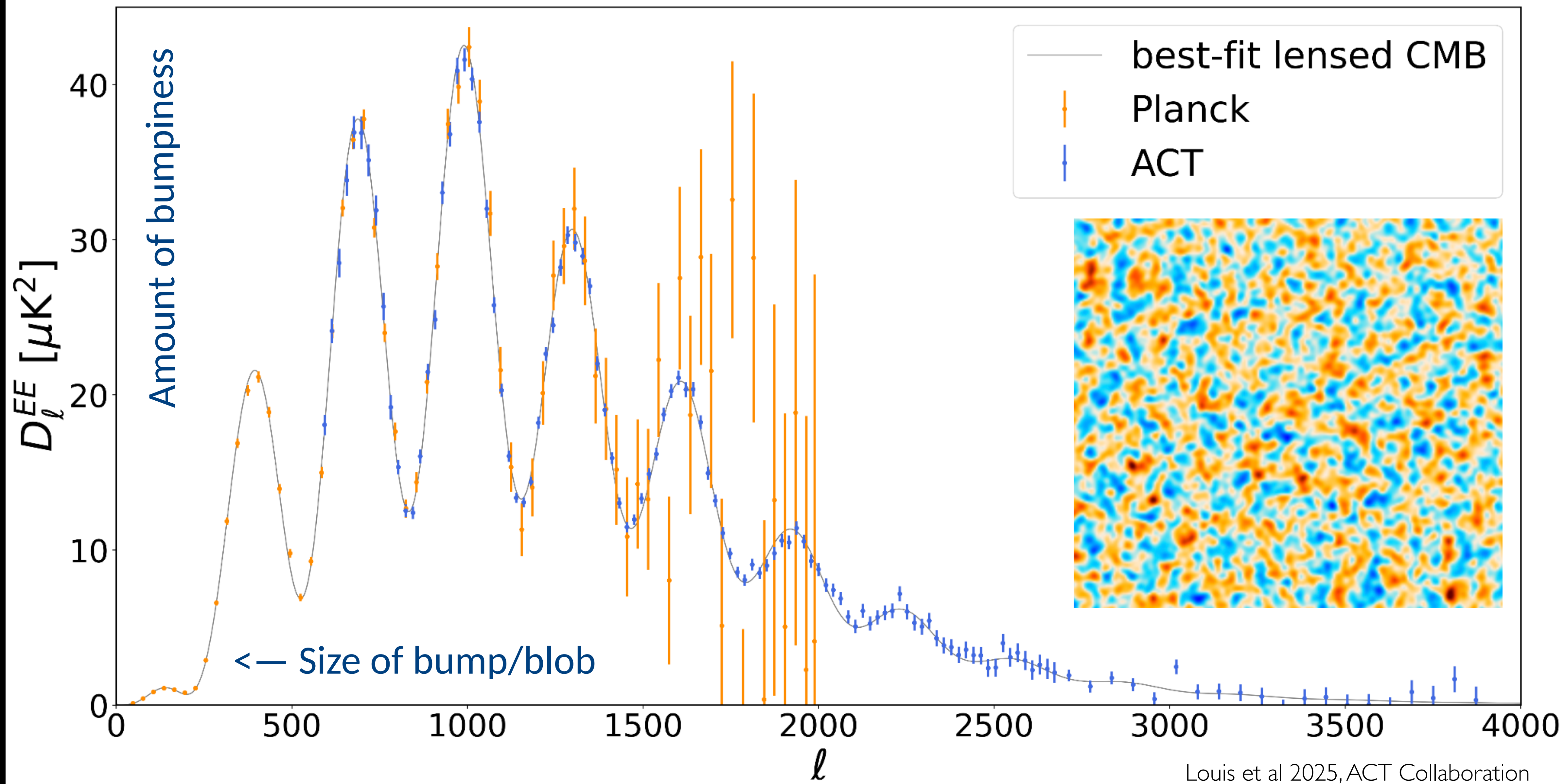
Credit: Debra Kellner

The Atacama Cosmology Telescope

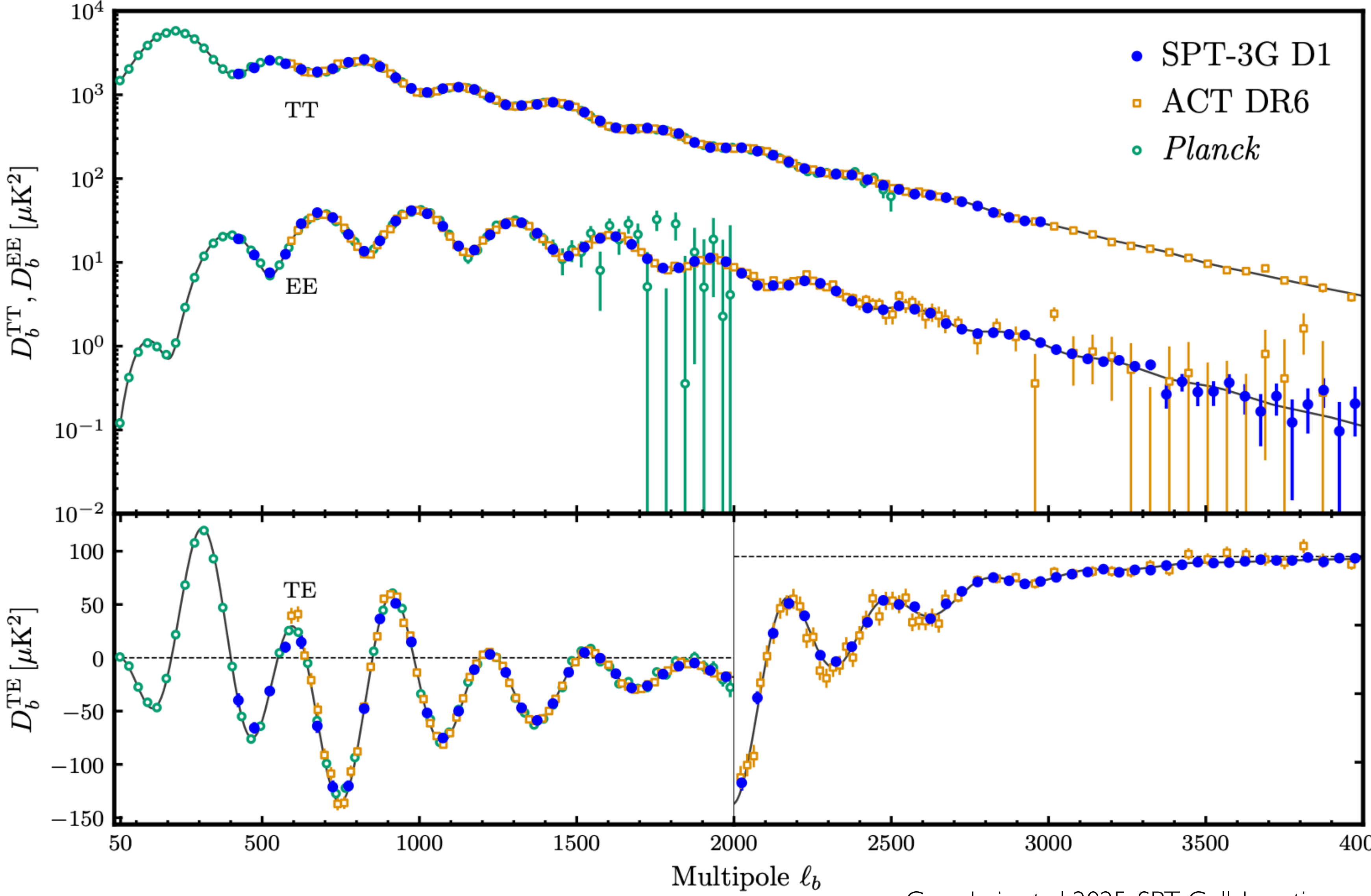
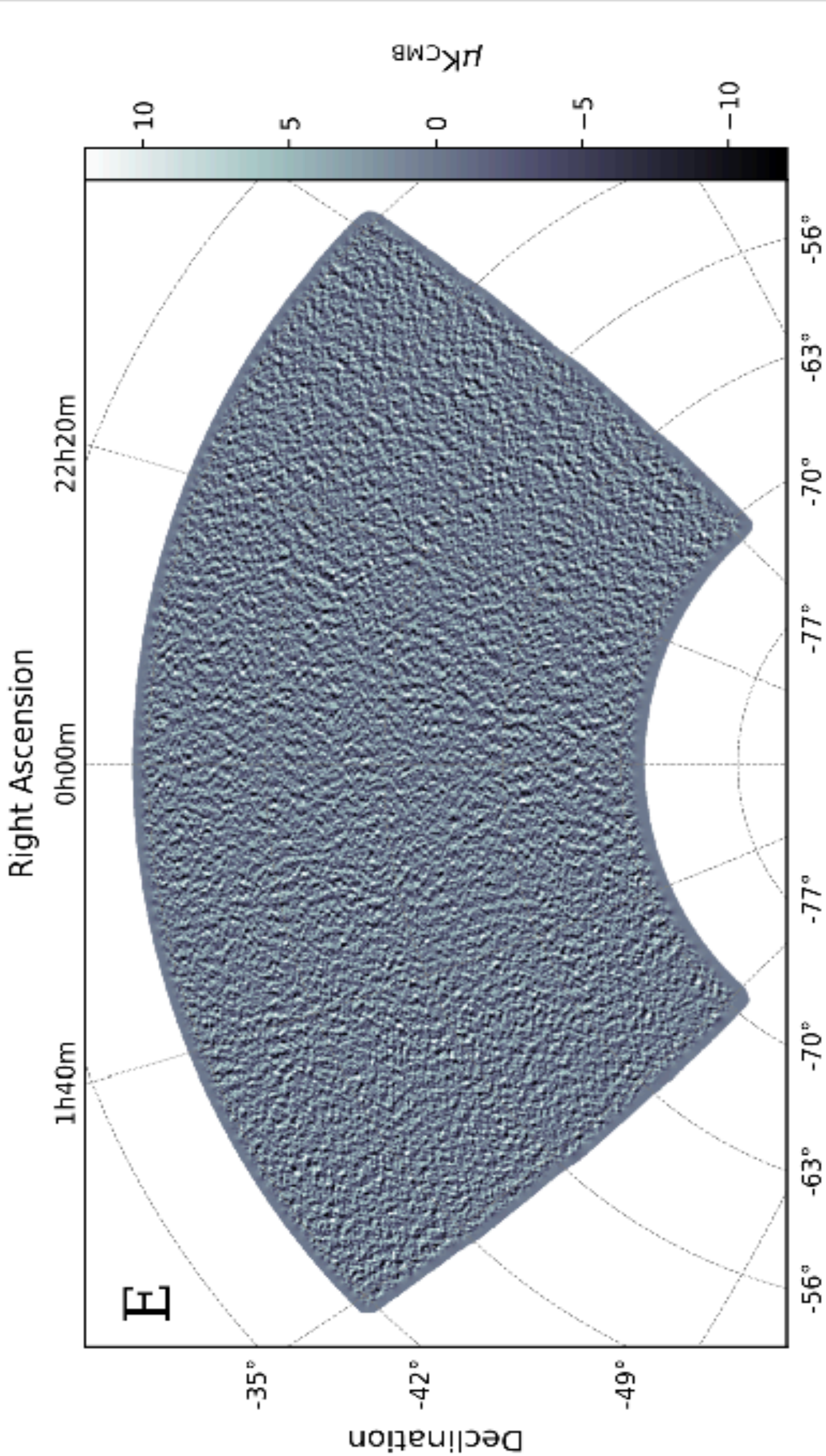


The CMB power spectrum: intensity





Deeper-look CMB: South Pole Telescope

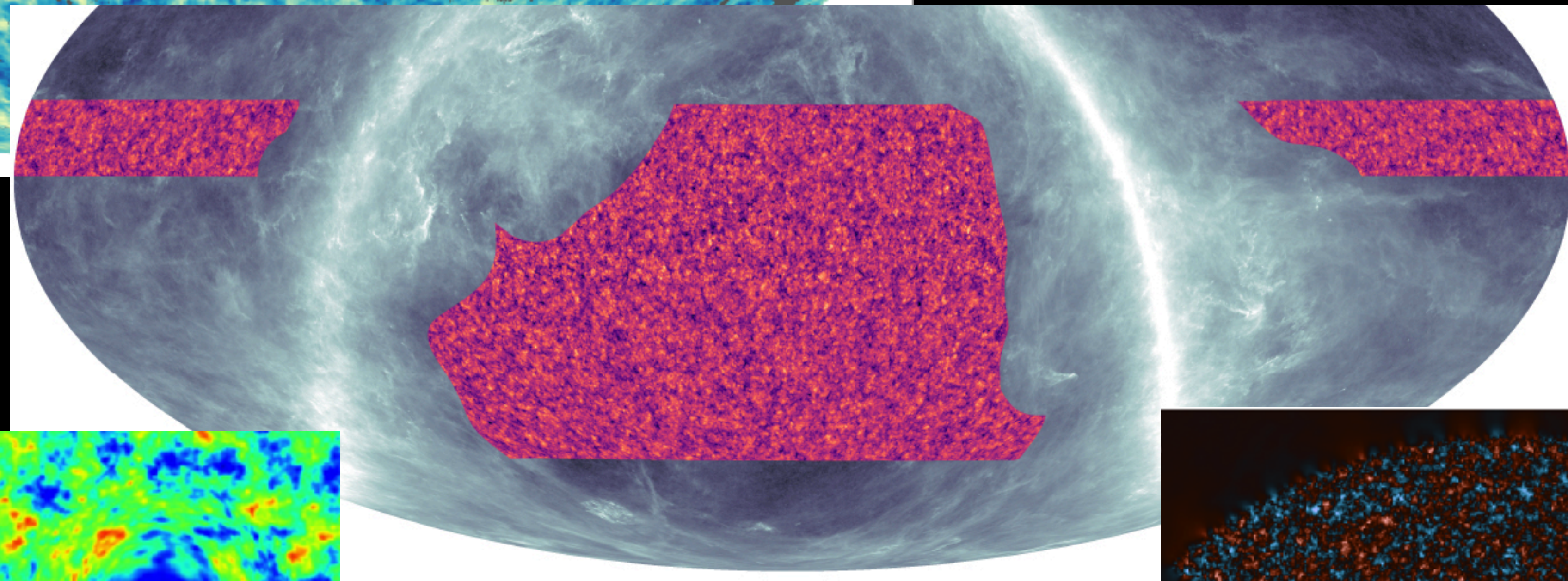
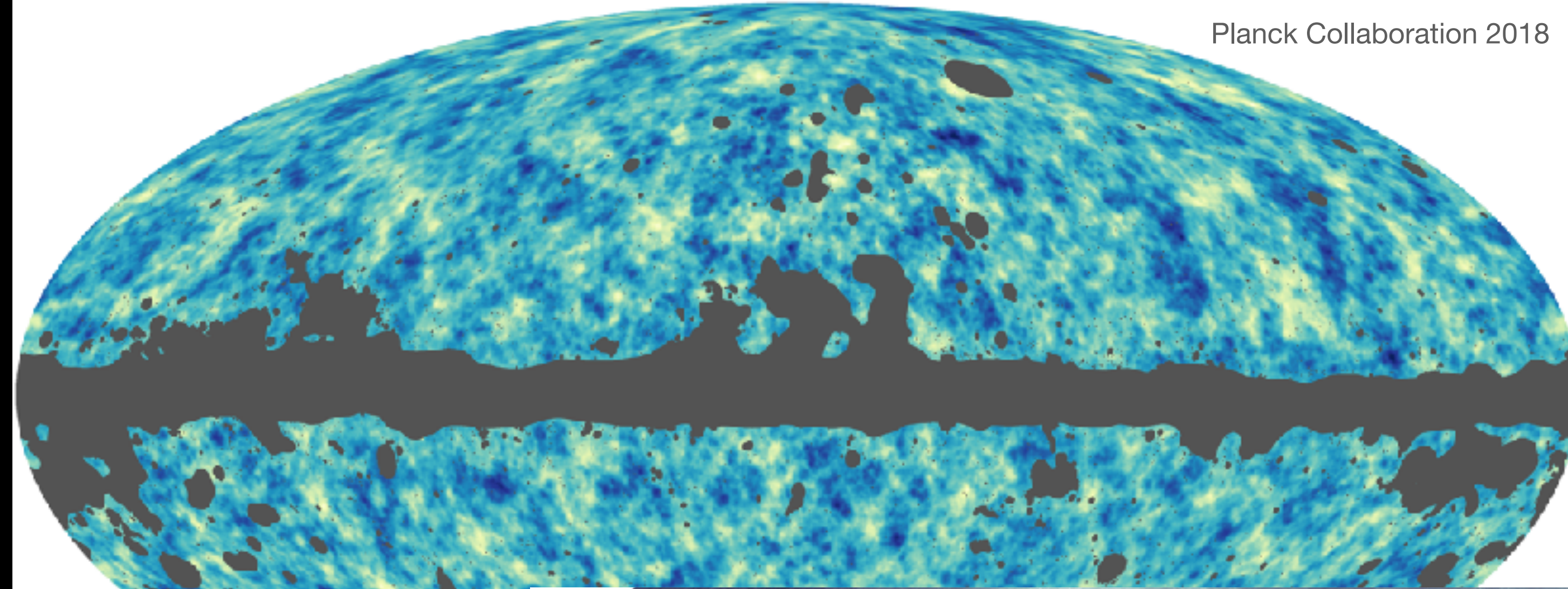


Planck Collaboration 2018

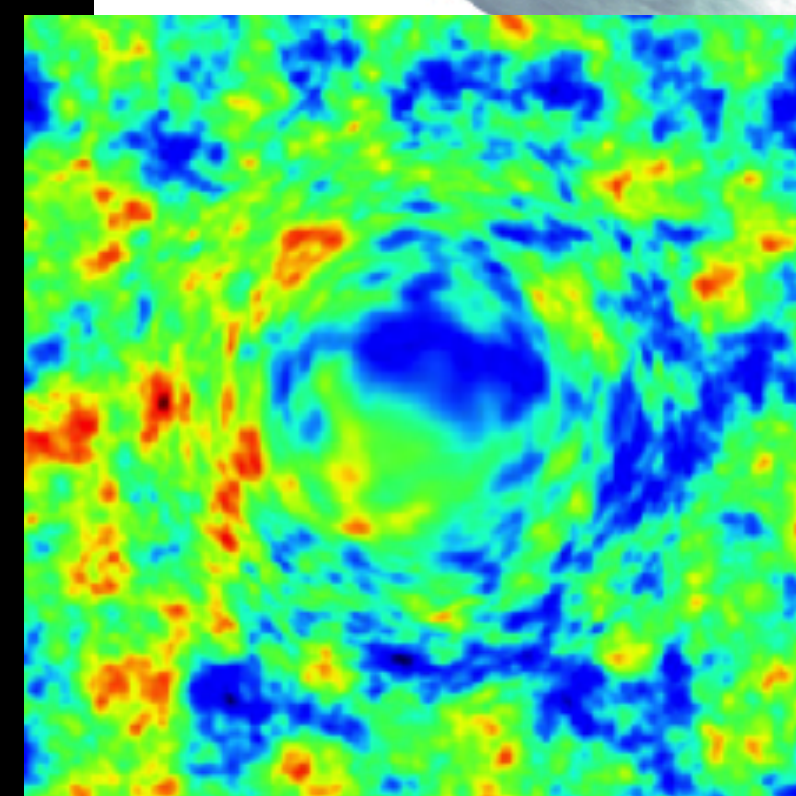
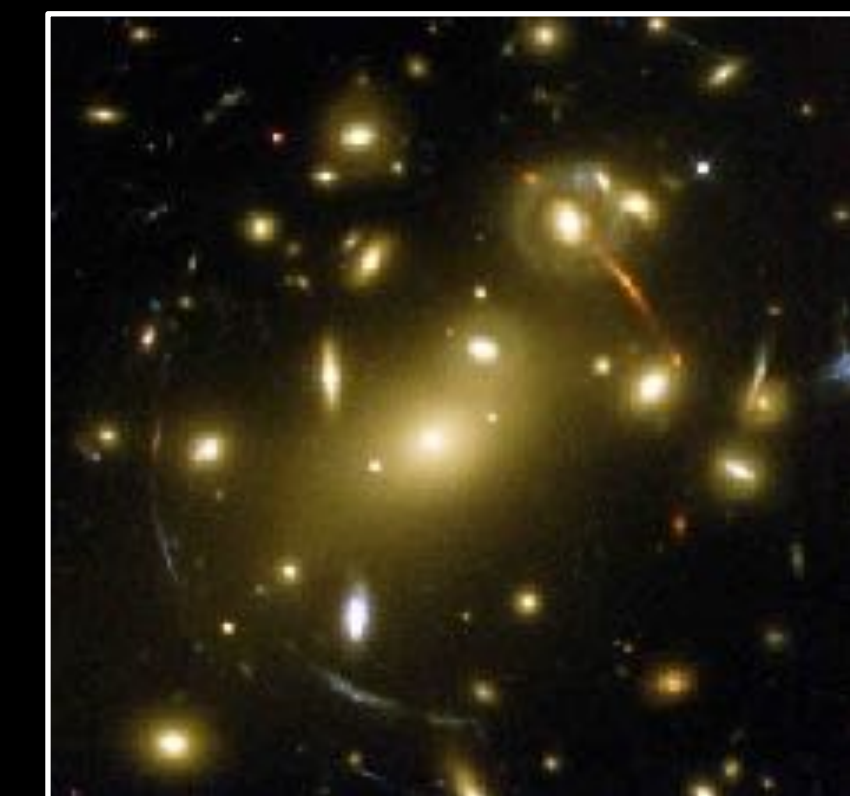
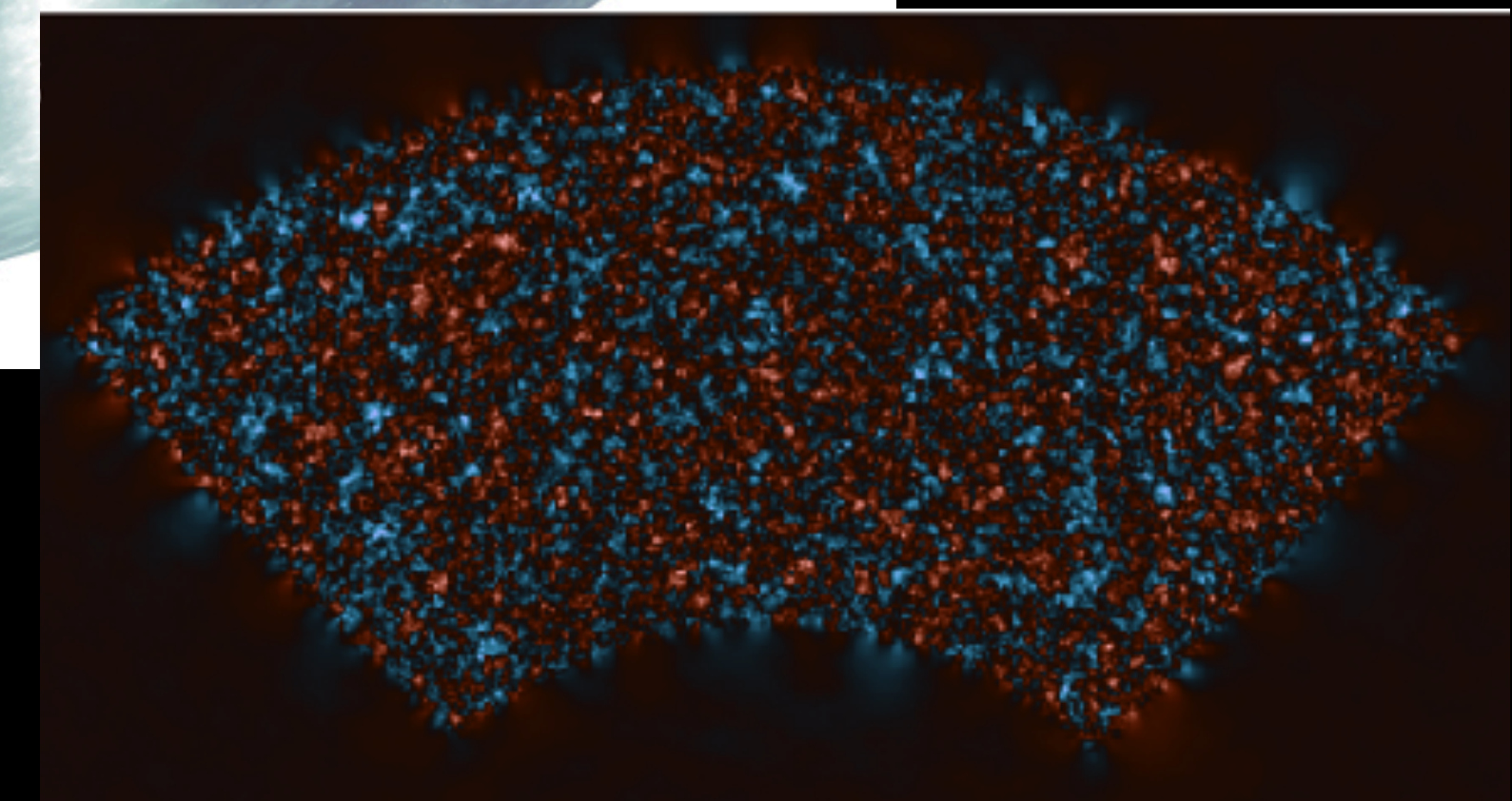
The CMB is also lensed on its journey

Reconstruct lensing map from coupling of primary CMB modes

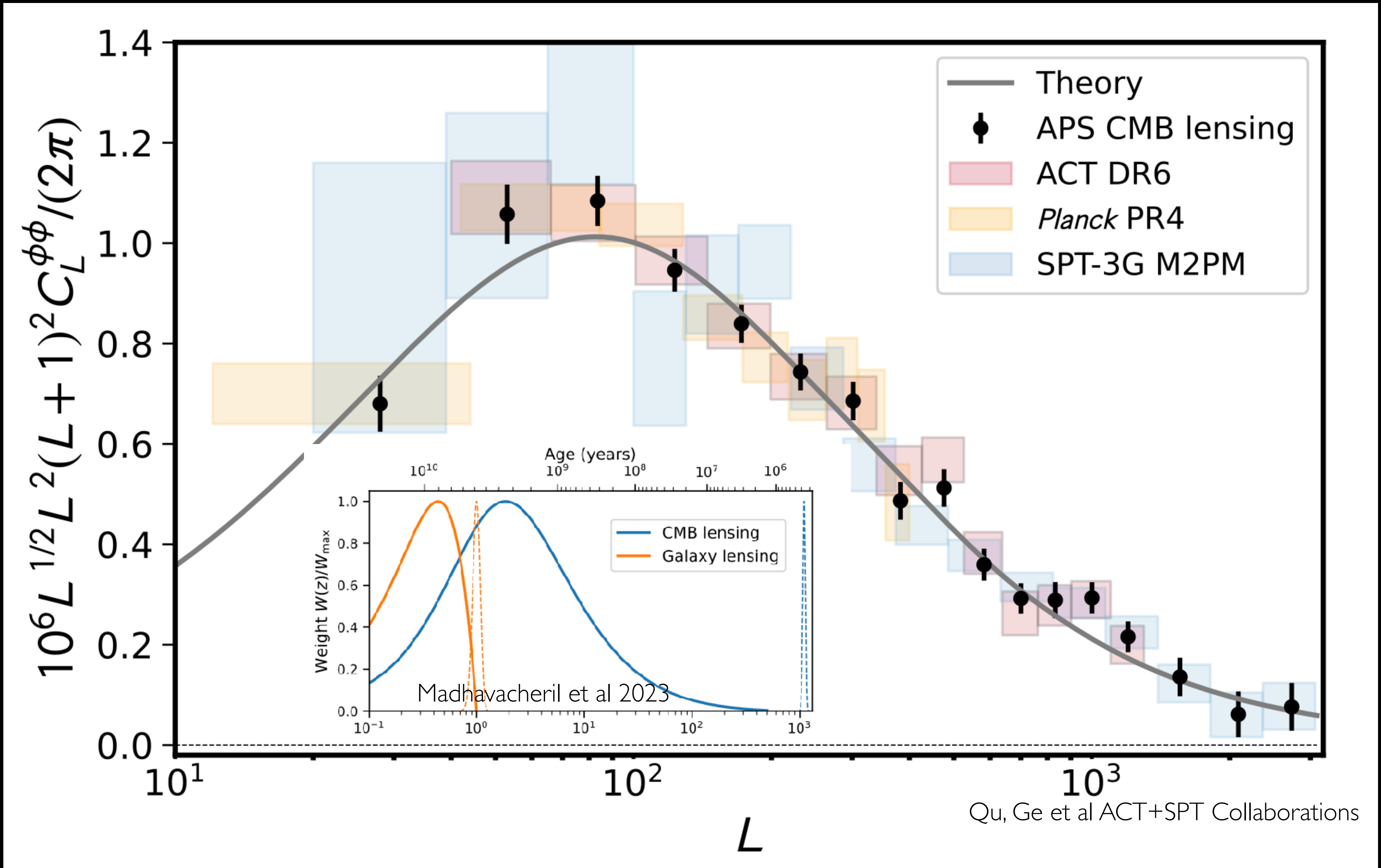
Madhavacheril et al, Qu et al,
ACT Collaboration 2023



Ge et al,
SPT Collaboration 2024

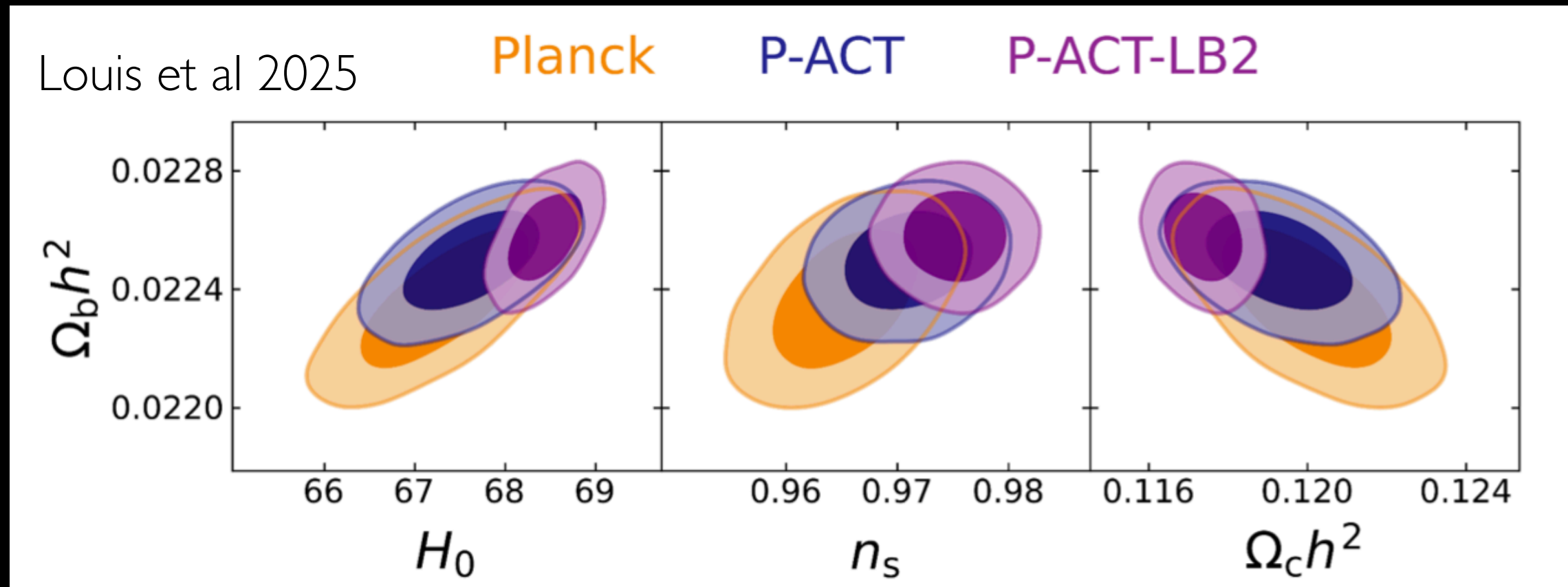


CMB lensing: Planck, ACT, SPT

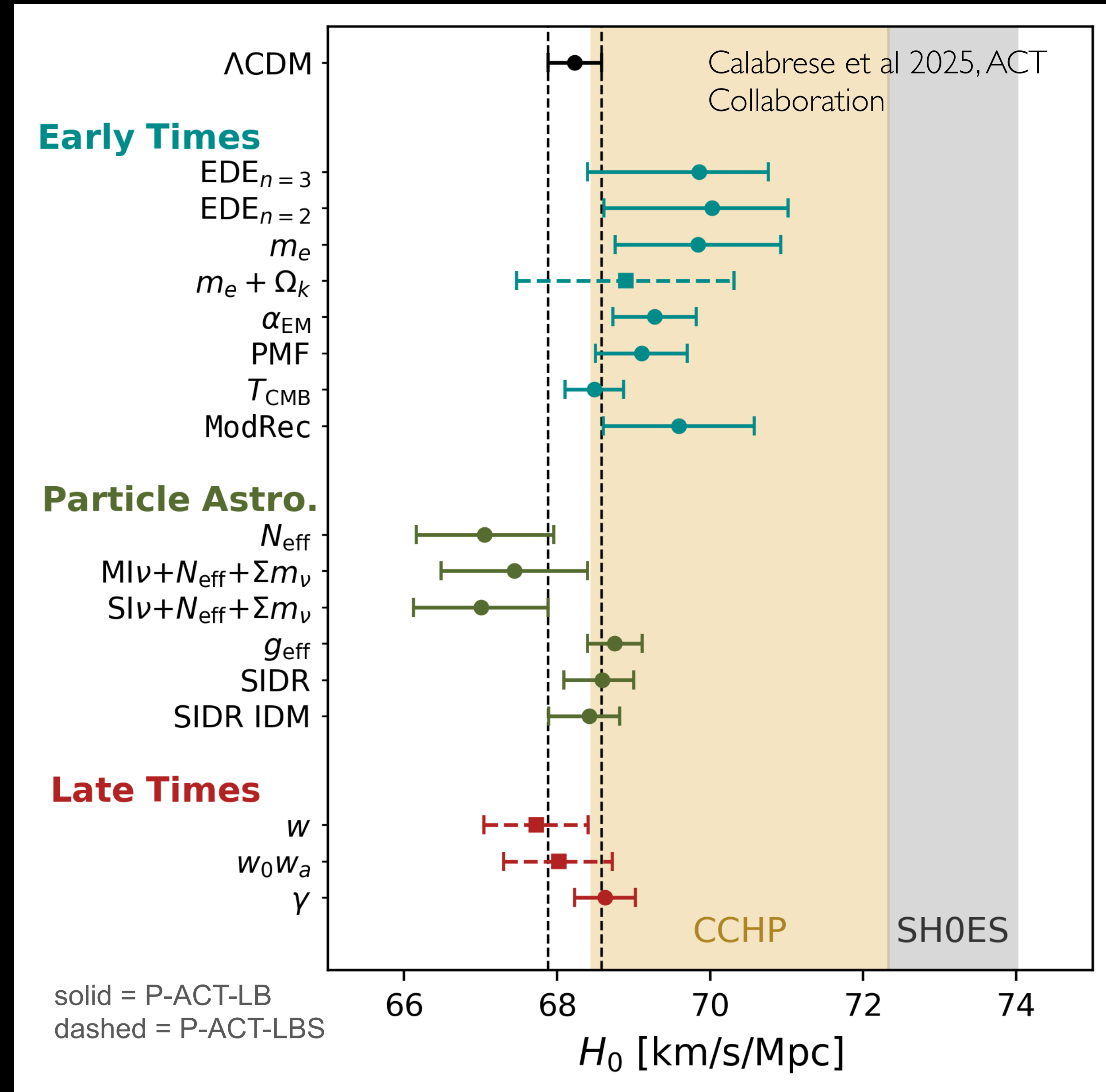


This is the lensing power is those reconstructed maps; the CMB TT/EE/TE power spectra are *also* lensed

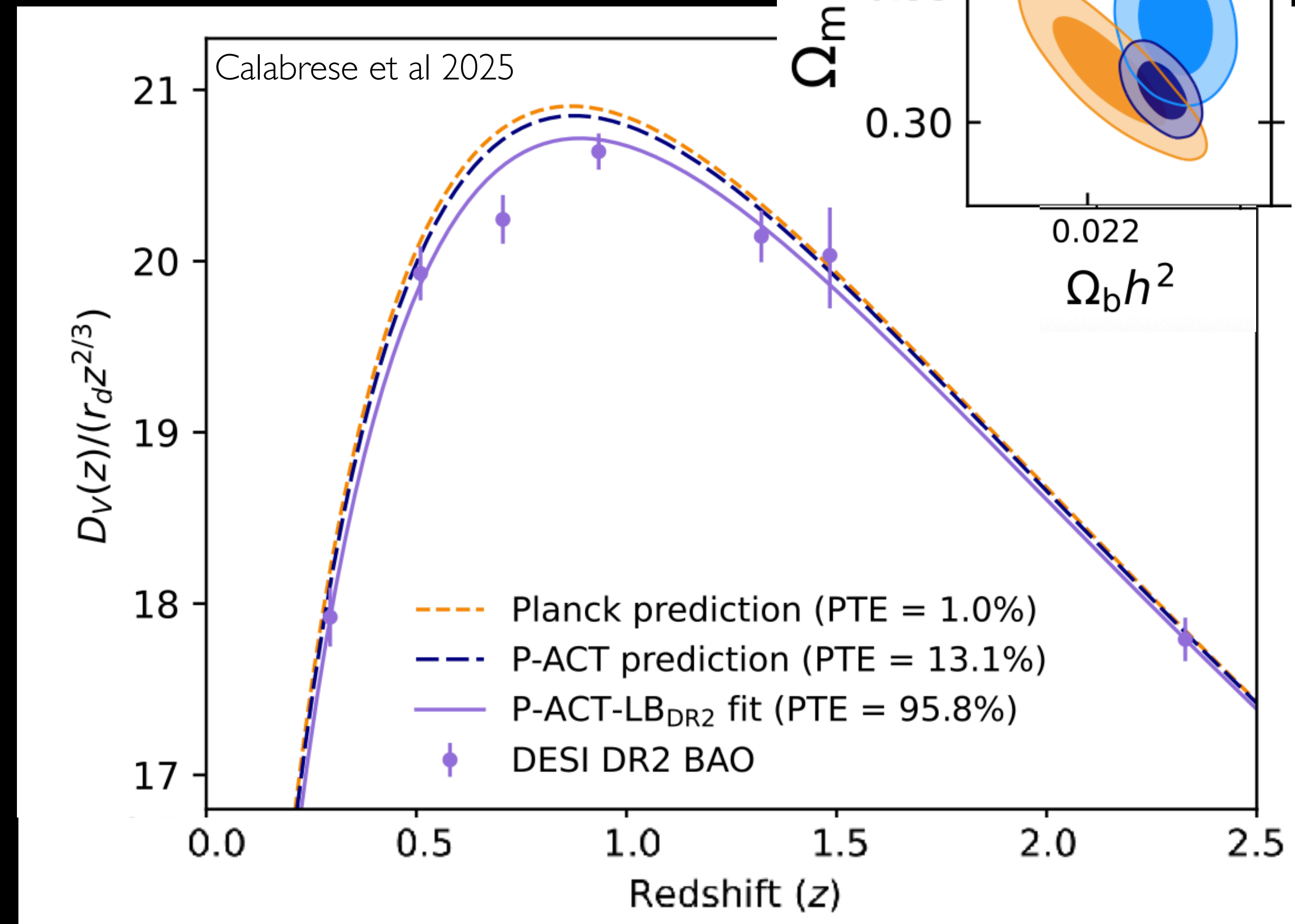
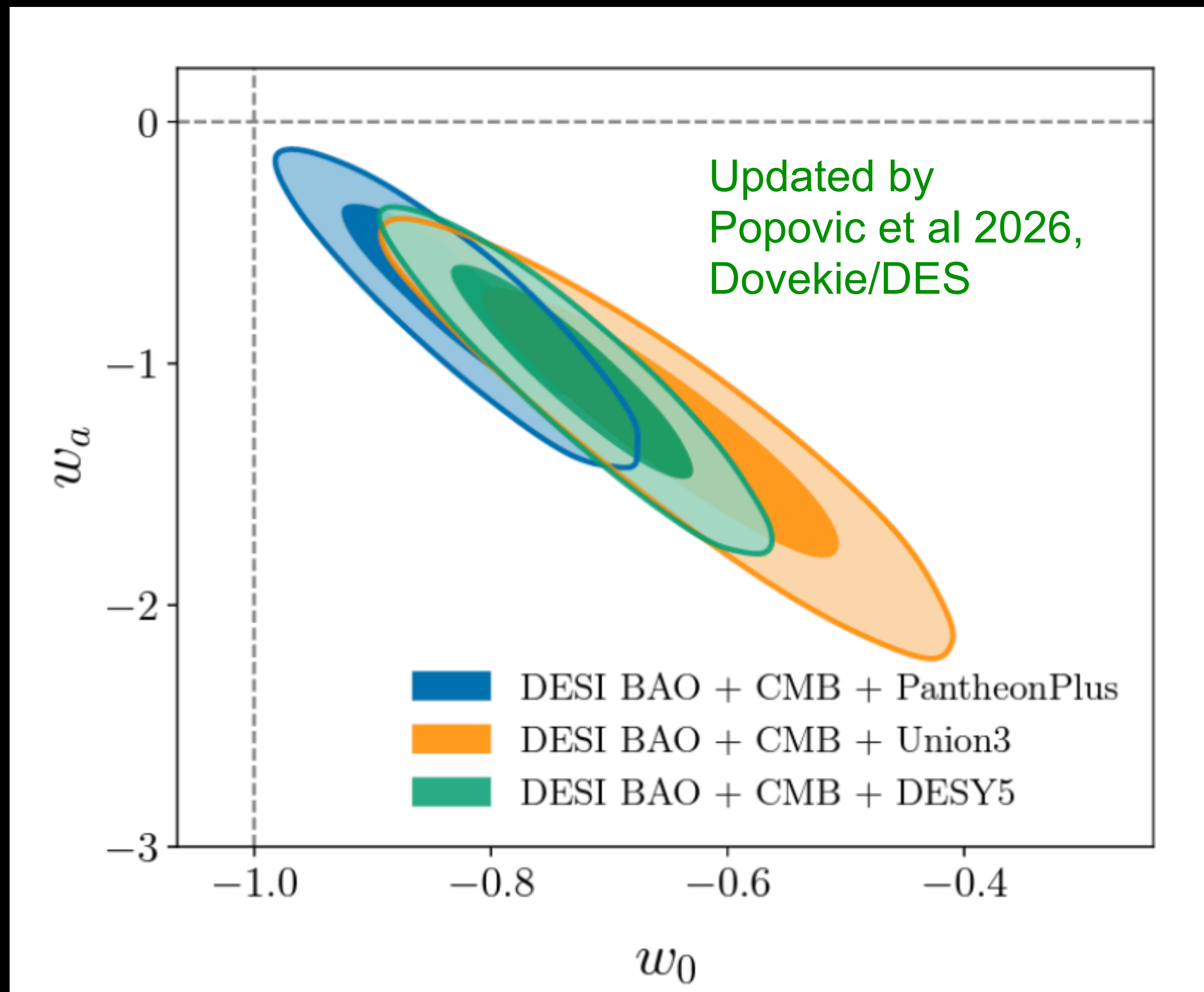
Robustness of Λ CDM and precise measure of H_0



Combining CMB with DESI BAO tightly constrains Λ CDM. Expansion rate $H_0 = 68.4 \pm 0.3$ km/s/Mpc (ACT collab) (or 68.2 ± 0.3 , DESI collaboration)



What about time-varying dark energy?



Preference for w_0 - w_a or curvature: CMB, BAO, SN don't all agree on matter fraction Ω_m

For P-ACT & DESI DR2: *time-varying dark energy not strongly preferred (1.6σ agreement within Λ CDM, or $\sim 2\sigma$ with Pantheon+)* because P-ACT prefers lower Ω_m than Planck or ACT.

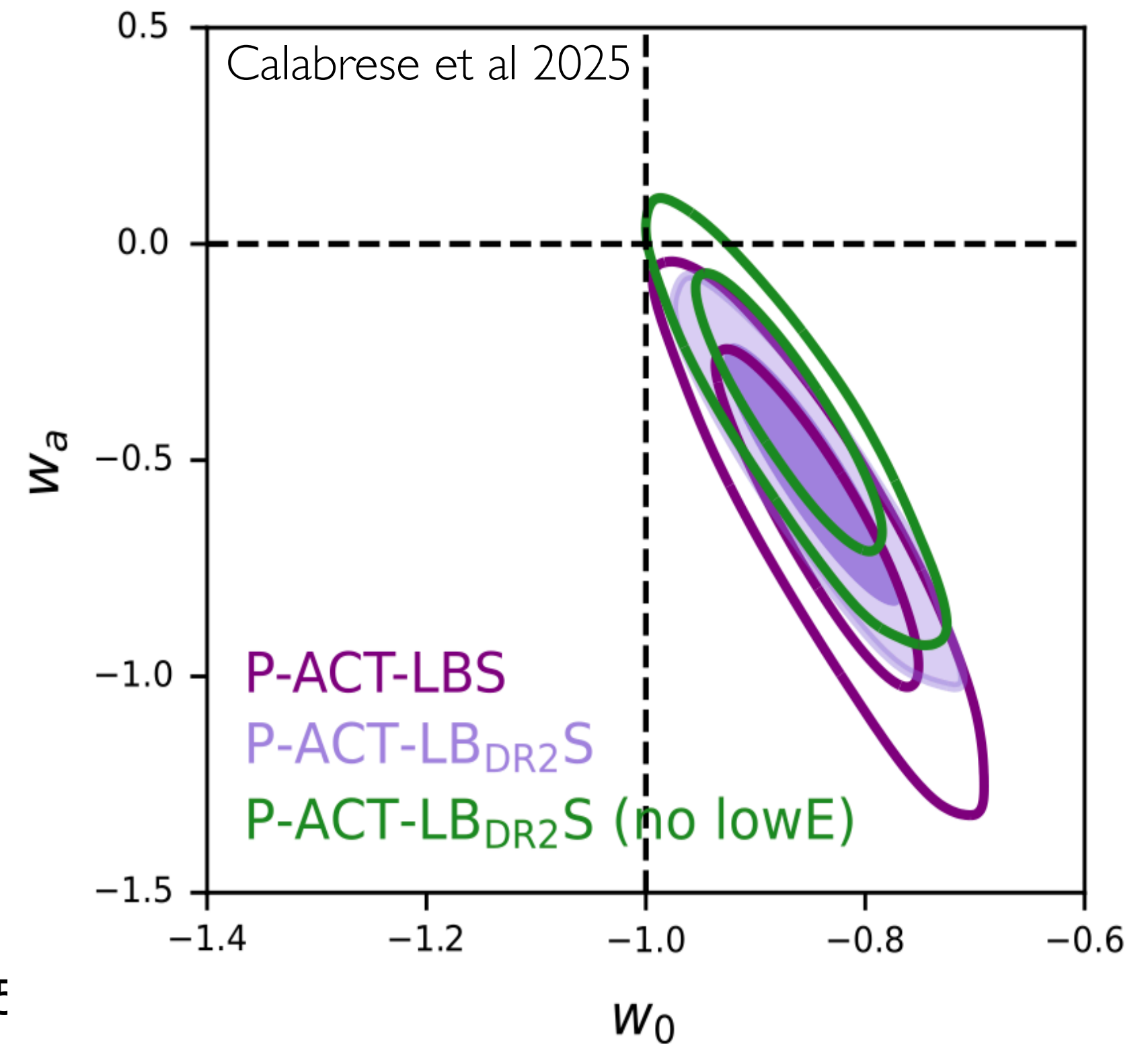
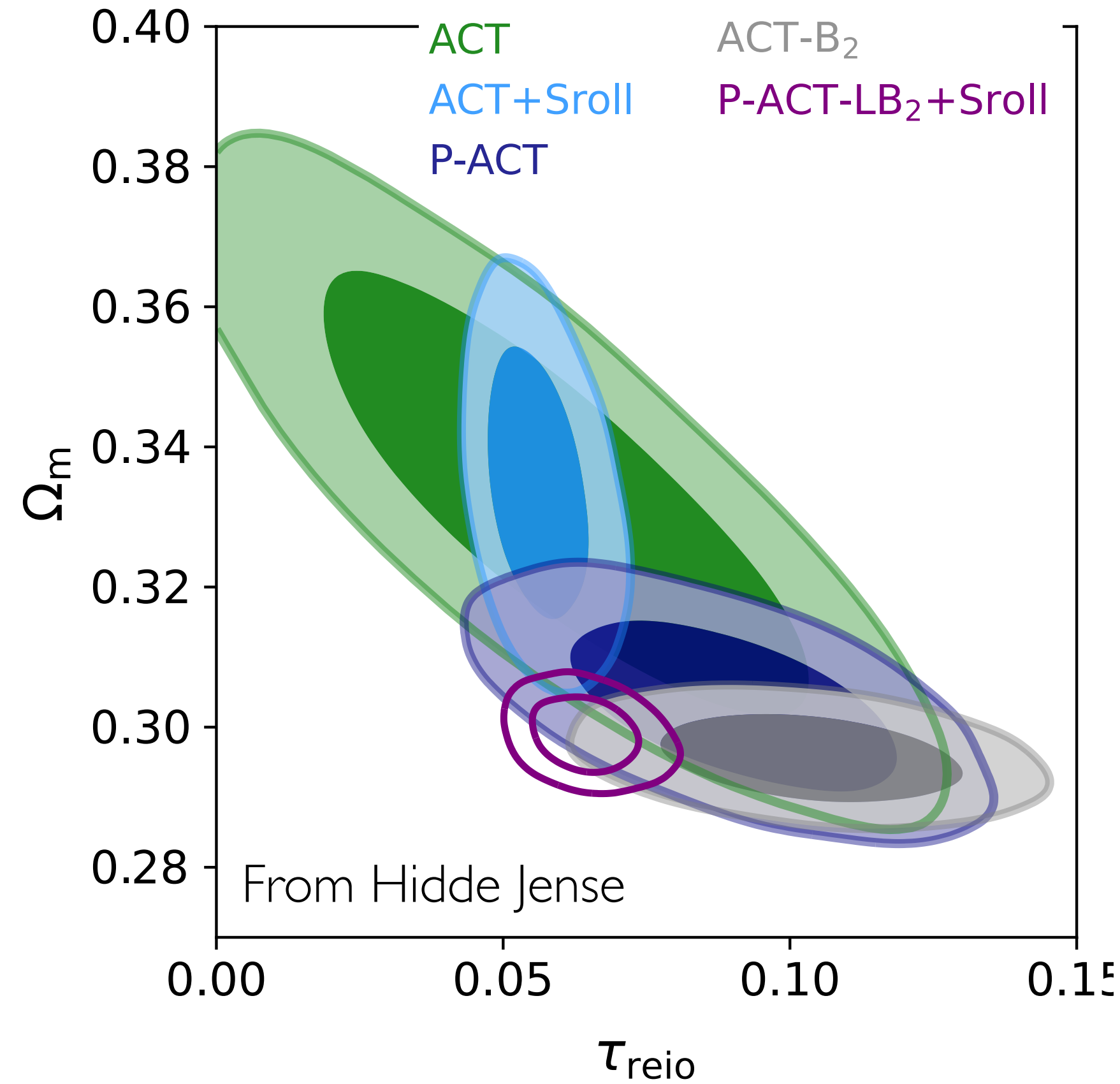
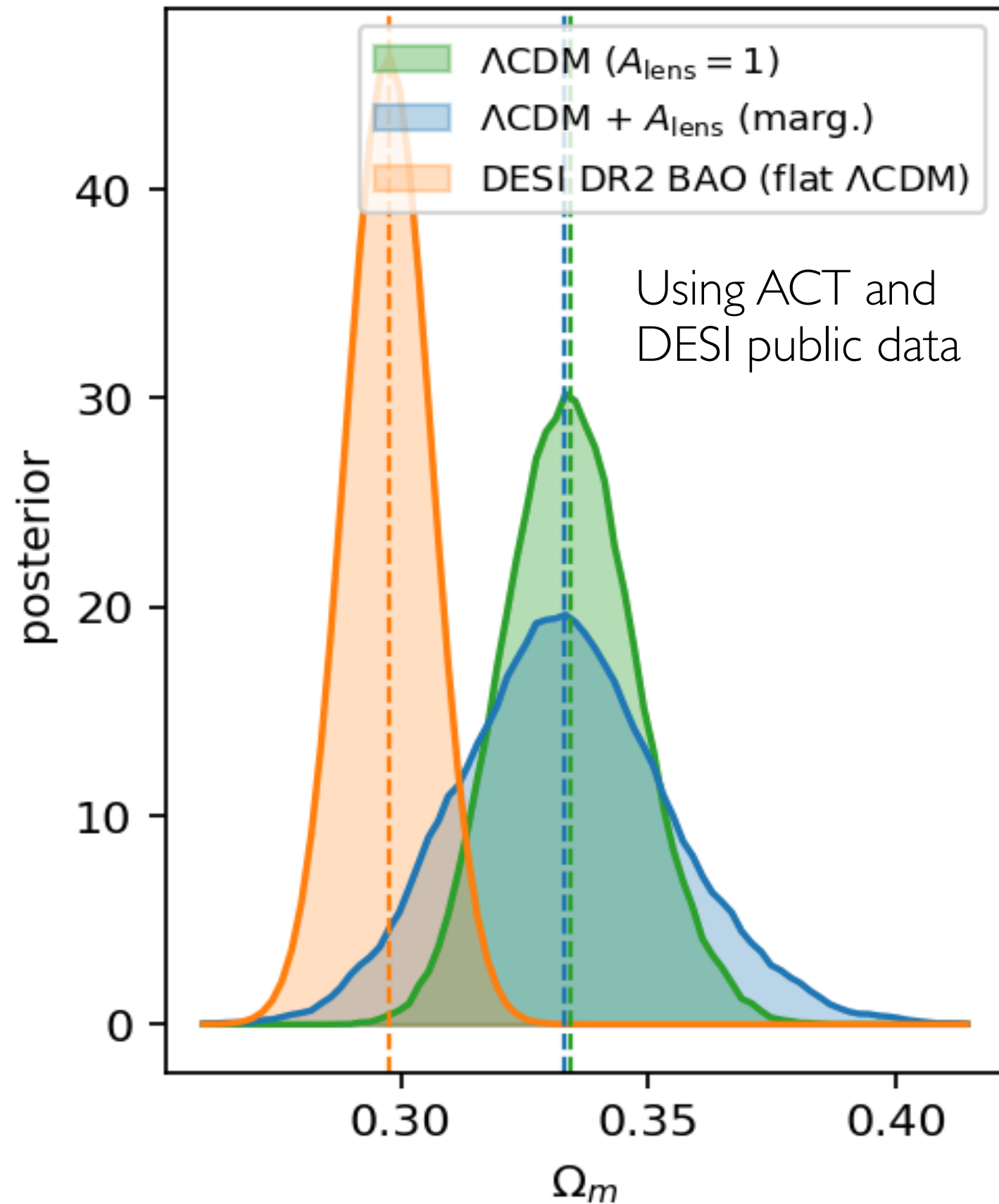
Higher τ \rightarrow higher primordial scalar amplitude to fit primary CMB
 \rightarrow lower Ω_m to fit CMB lensing
 (Allison et al 2015; Sailer et al 2025, Jhaveri et al 2025)

But $\sim 3\sigma$ tensions remains

ACT (or SPT, without Planck or WMAP but with τ prior) is $>2.8\sigma$ different to DESI-DR2 in Λ CDM

Tension is reduced when:

- adding the $l < 1000$ CMB data from Planck or WMAP
- when \sim 'removing' the lensing from the primary CMB
- when increasing the optical depth to reionization compared to Planck's result

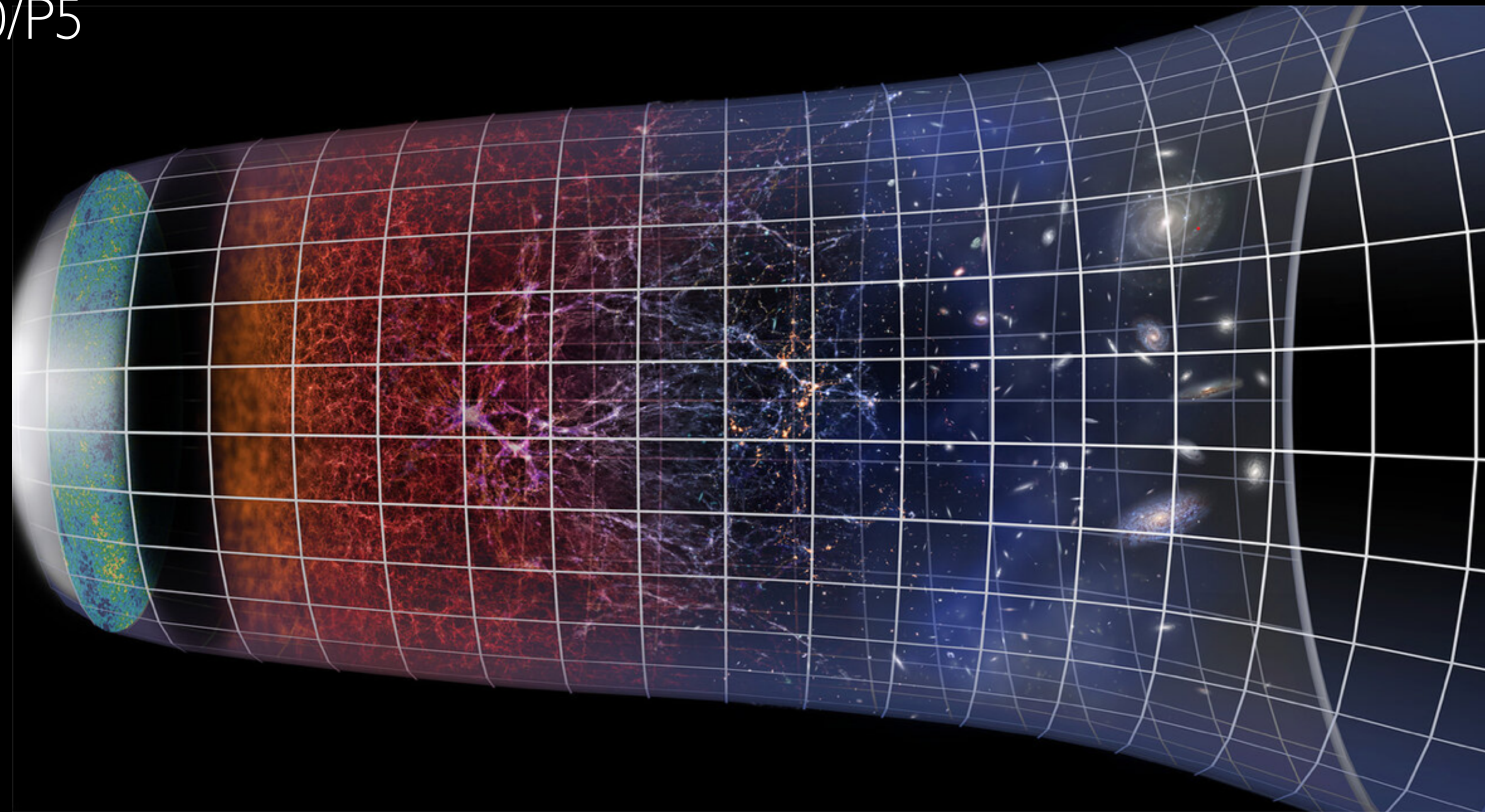






Simons Observatory ("SO")
Polarized mm-wave half-sky survey
Five times the resolution of Planck
Ten times (+) lower noise

SO covers all Astro2020/P5
CMB science



Primary CMB: physics of the early universe

Secondary CMB: matter mapping

Mm-wave sources: time domain astronomy

Public data and software

The Simons Observatory: Science Goals and Forecasts (2019)

The Simons Observatory: Science Goals and Forecasts for the enhanced Large Aperture Telescope (2025)

The Simons Observatory: Forecasted constraints on primordial gravitational waves (2026)

SATP1

06/11/2025 03:41:53 THU SATP2

06/11/2025 03:41:53 THU SATP3

06/11/2025 03:41:54 THU

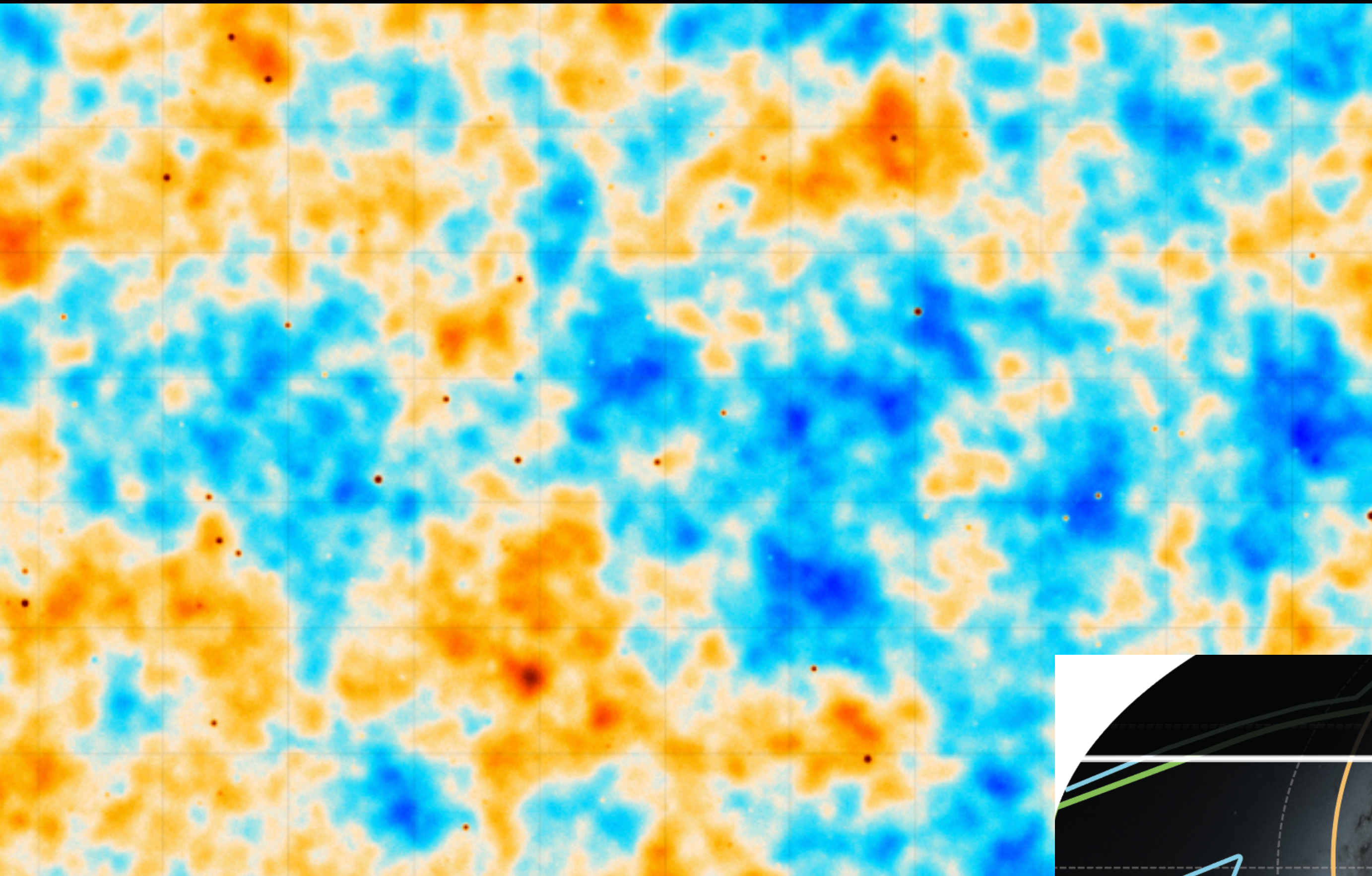


Highbay-side-lat

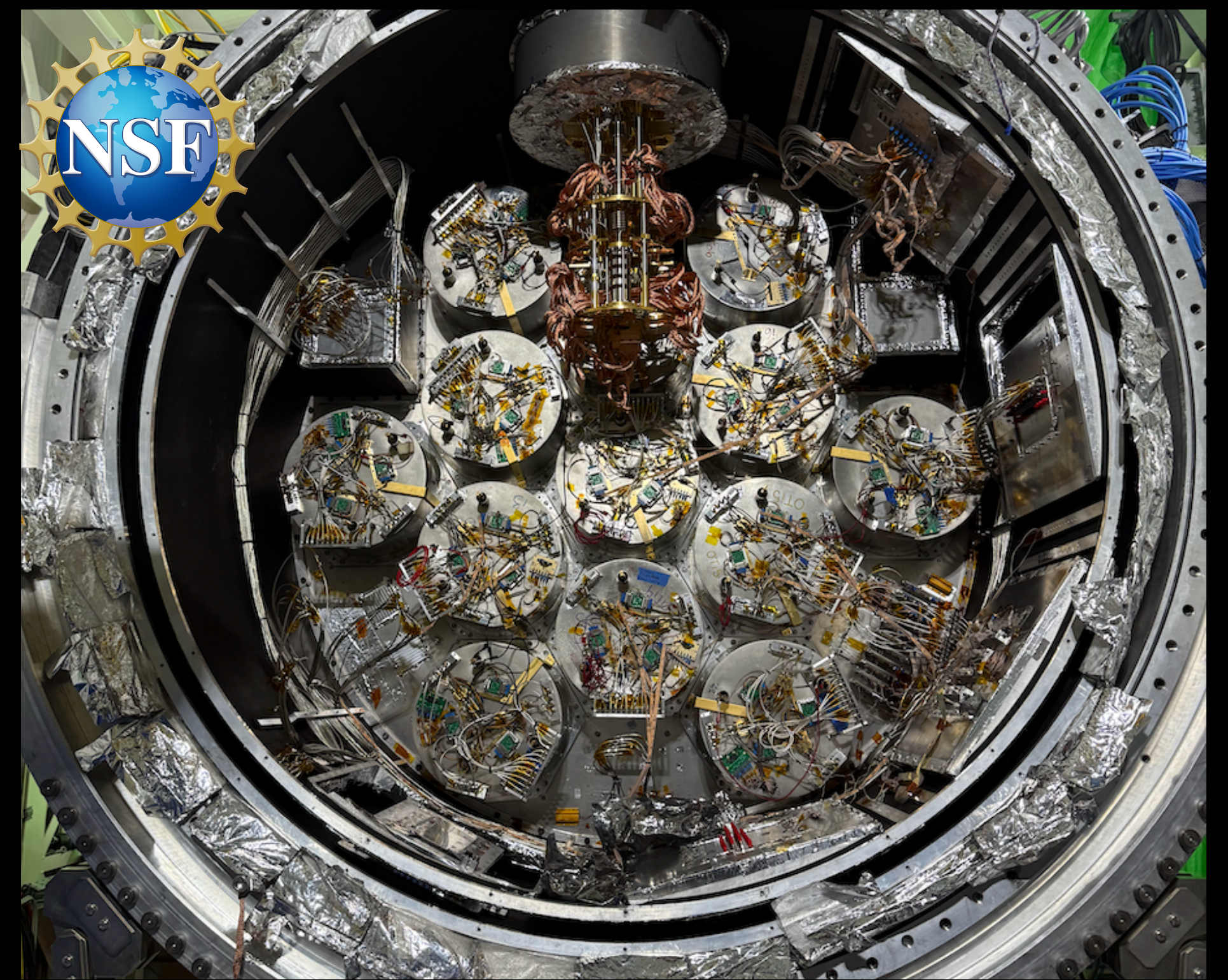
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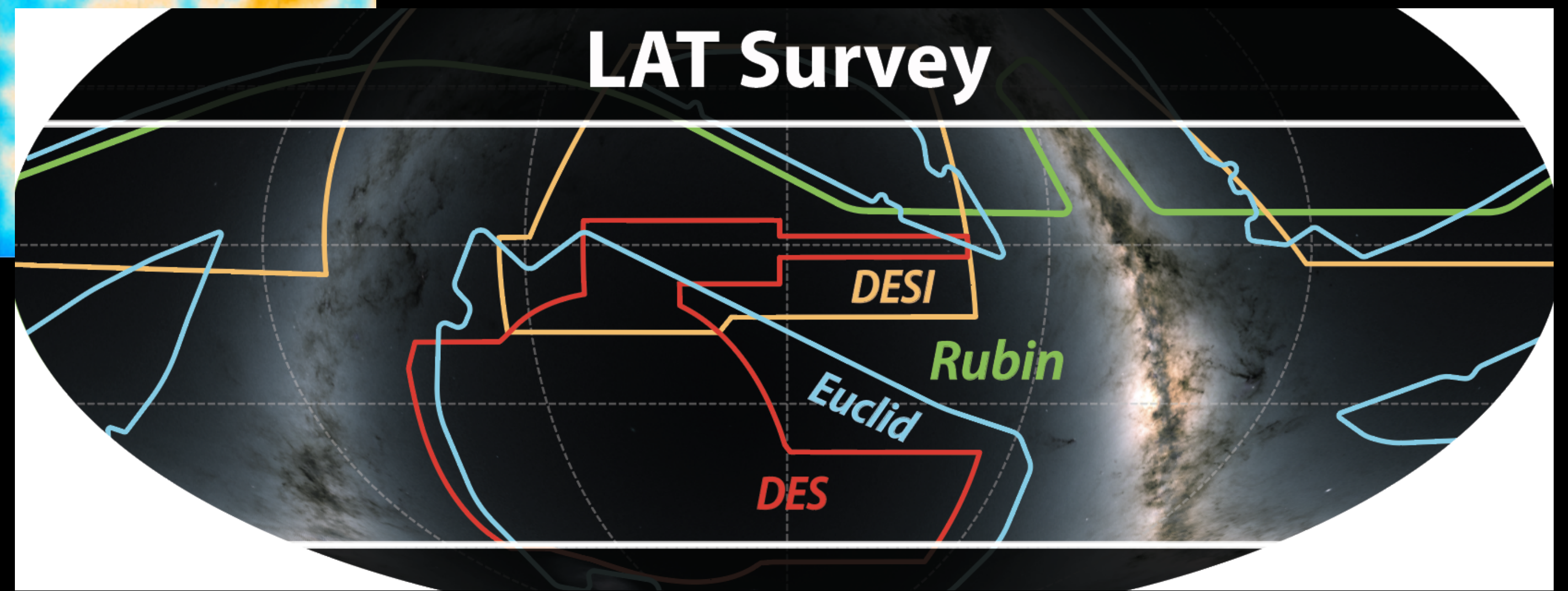
Large Aperture Telescope ($> \times 10$ ACTs)



Early data (180 hrs, 2025) at 90 GHz
SO Collaboration

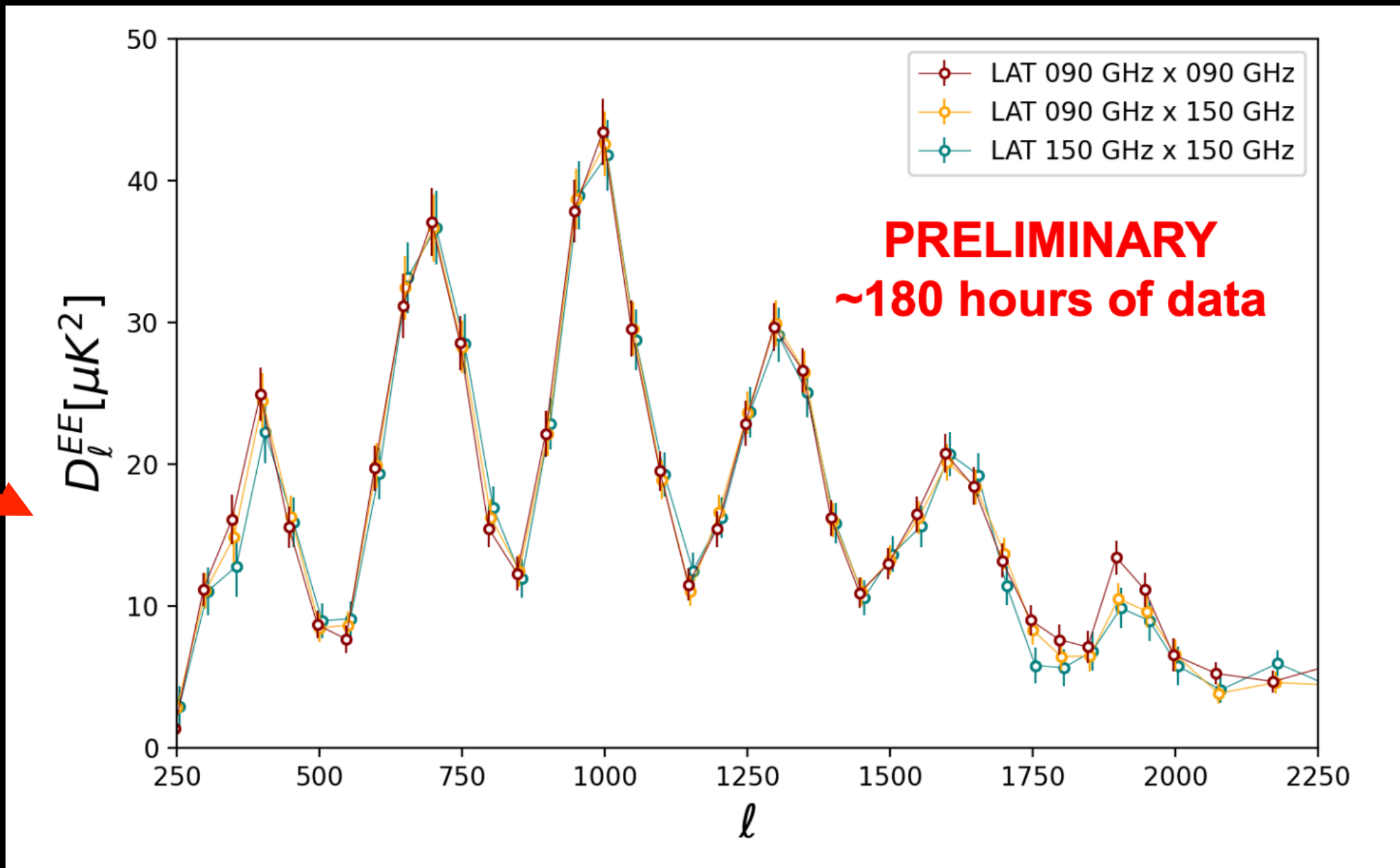
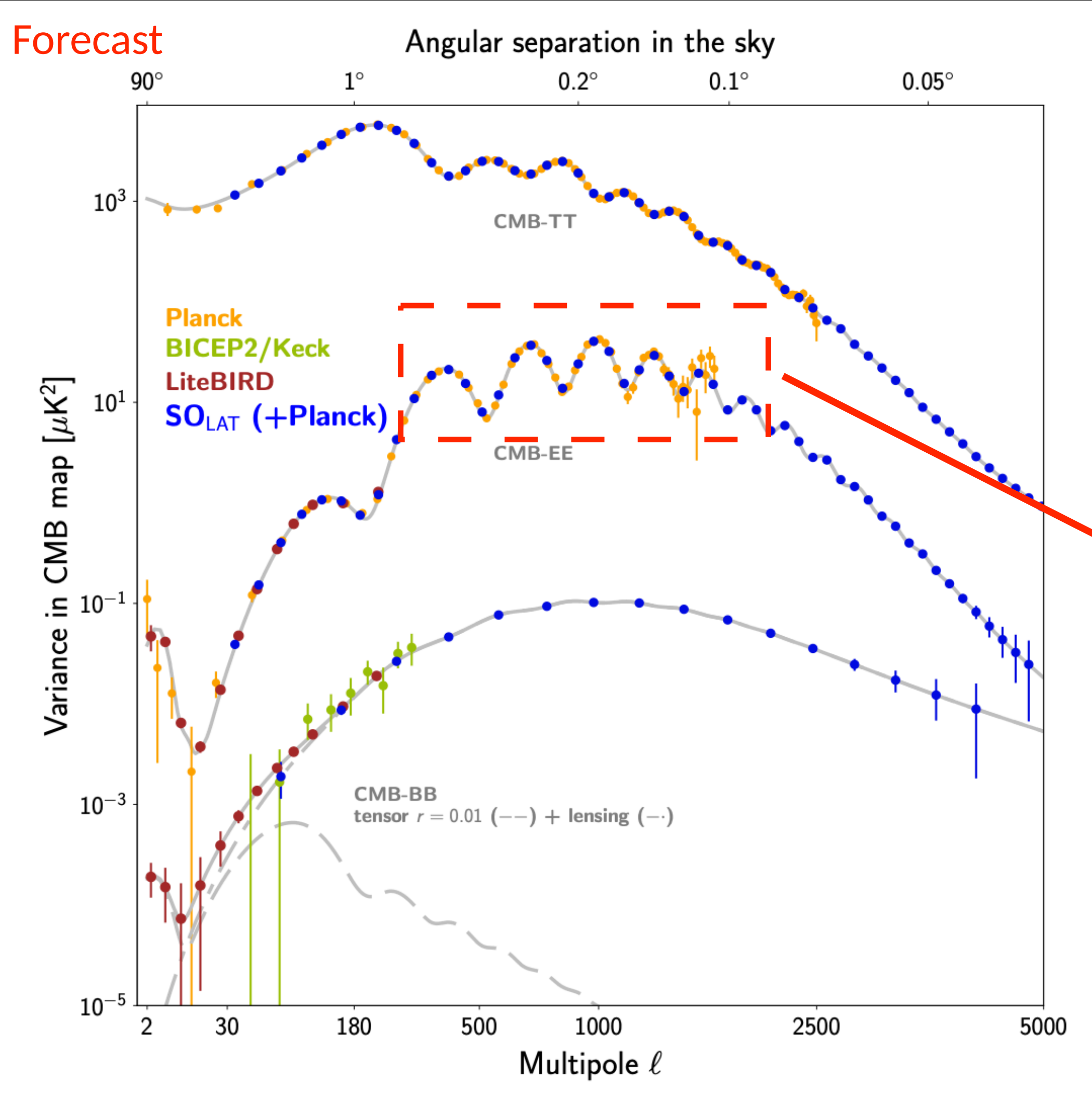


Recent upgrade: now 60,000 detectors with 6 wavelengths
Projected to reach $\sim 3 \mu\text{K-arcmin}$



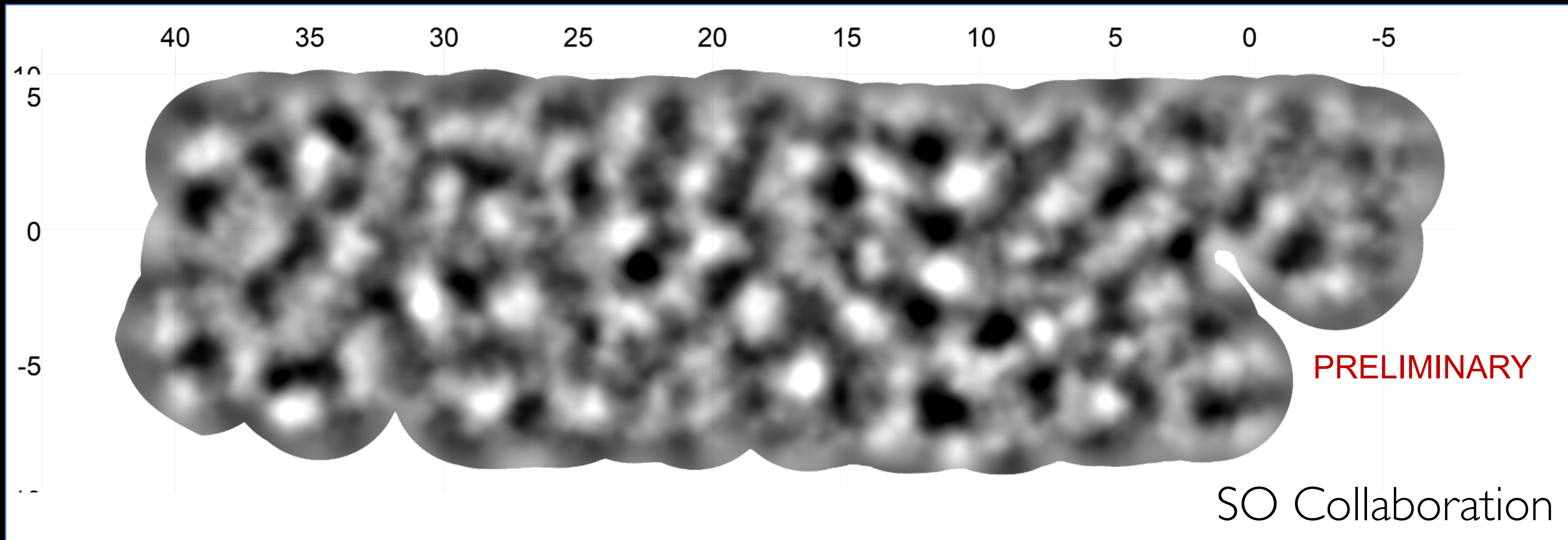
Improved CMB power spectrum: test inflation through n_s , assess dark energy

Three times lower noise than ACT (similar to SPT), half the sky



SO targets $\sigma(n_s)=0.002$ and $\sigma(N_{\text{eff}})=0.045$

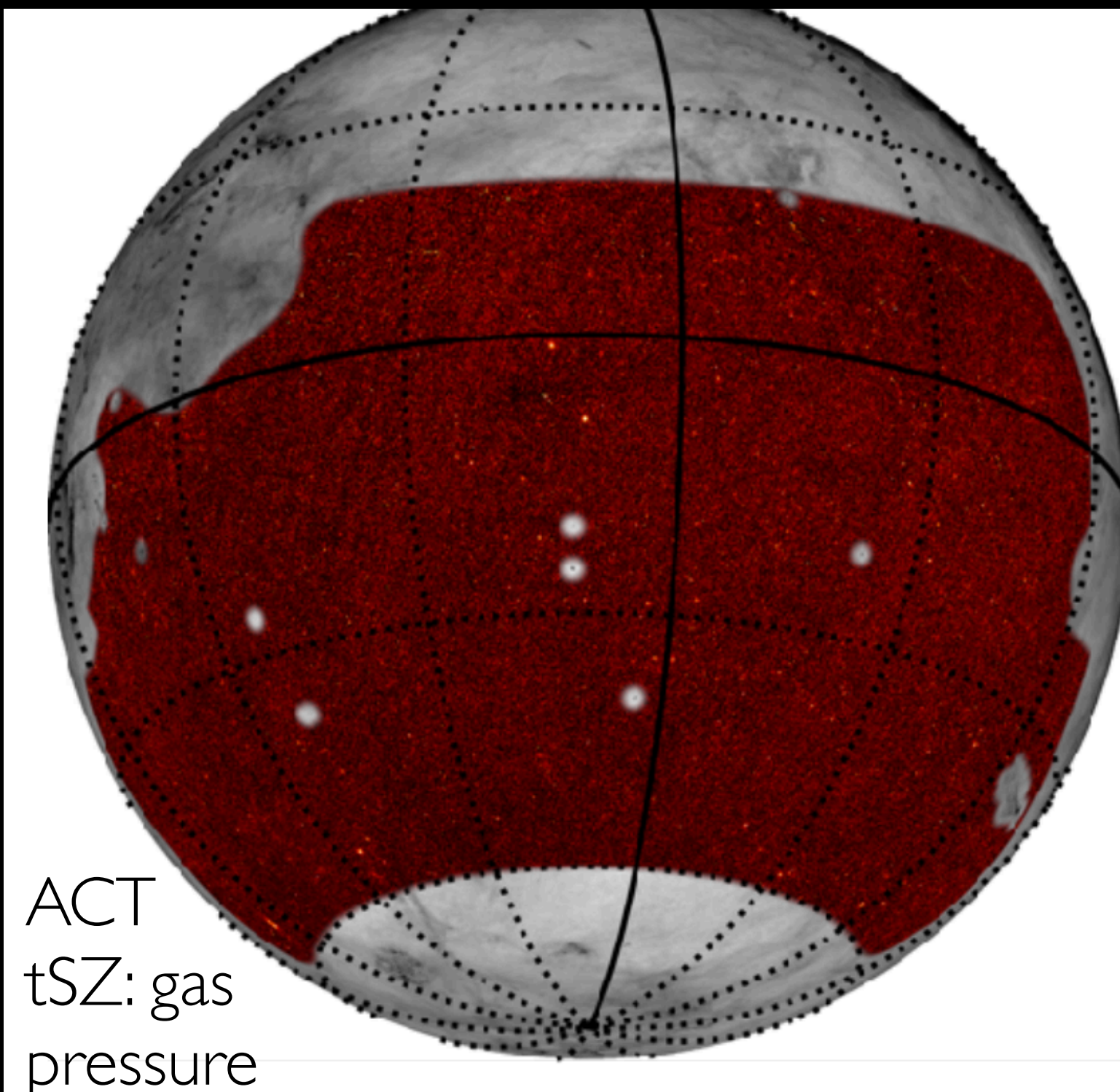
Improved CMB lensing and Sunyaev Zel'dovich: test inflation, weigh in on dark energy



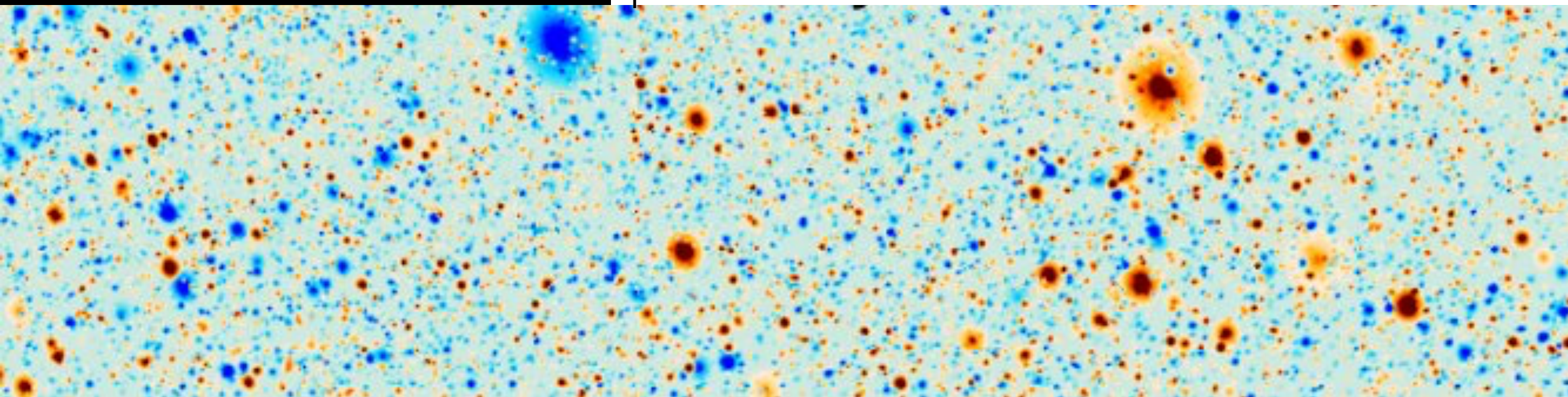
New SO lensing map from 180 hrs of observations, 4 optics tubes
SO targets $\sigma(f_{NL}) \sim 1$ through x-correlations

$$\Phi(\mathbf{x}) = \phi(\mathbf{x}) + f_{NL} (\phi^2(\mathbf{x}) - \langle \phi^2(\mathbf{x}) \rangle)$$

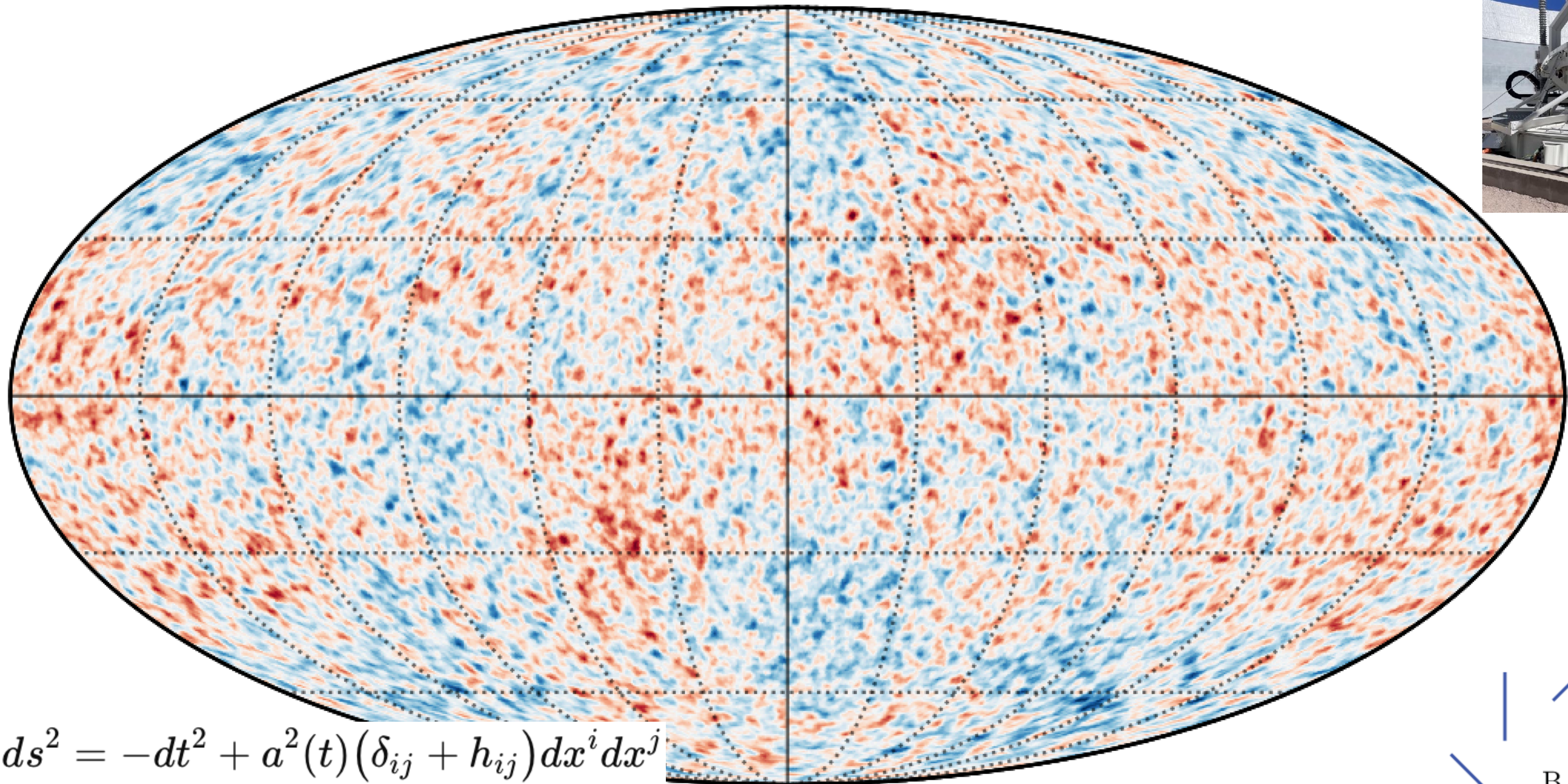
Measure the gas pressure and momentum and correlate with DESI, Rubin



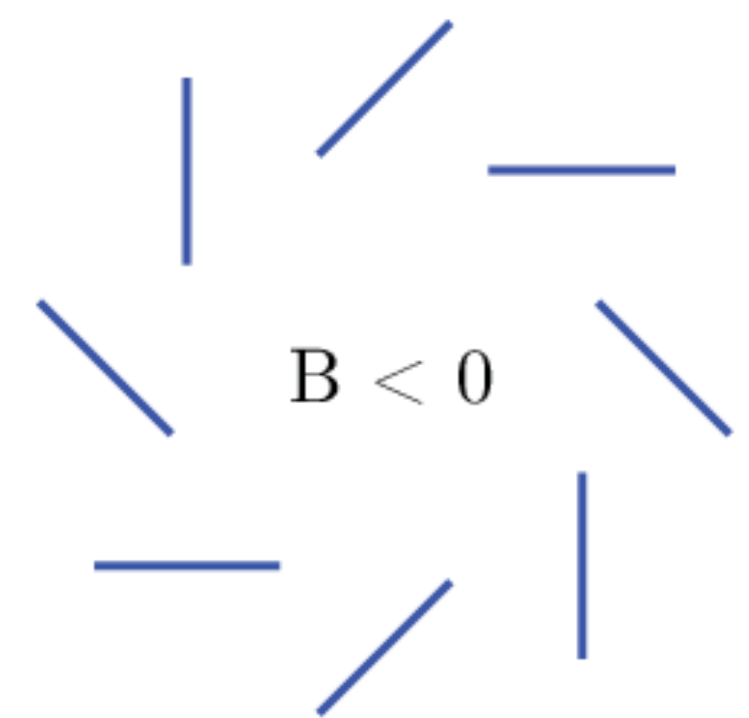
Simulated kSZ



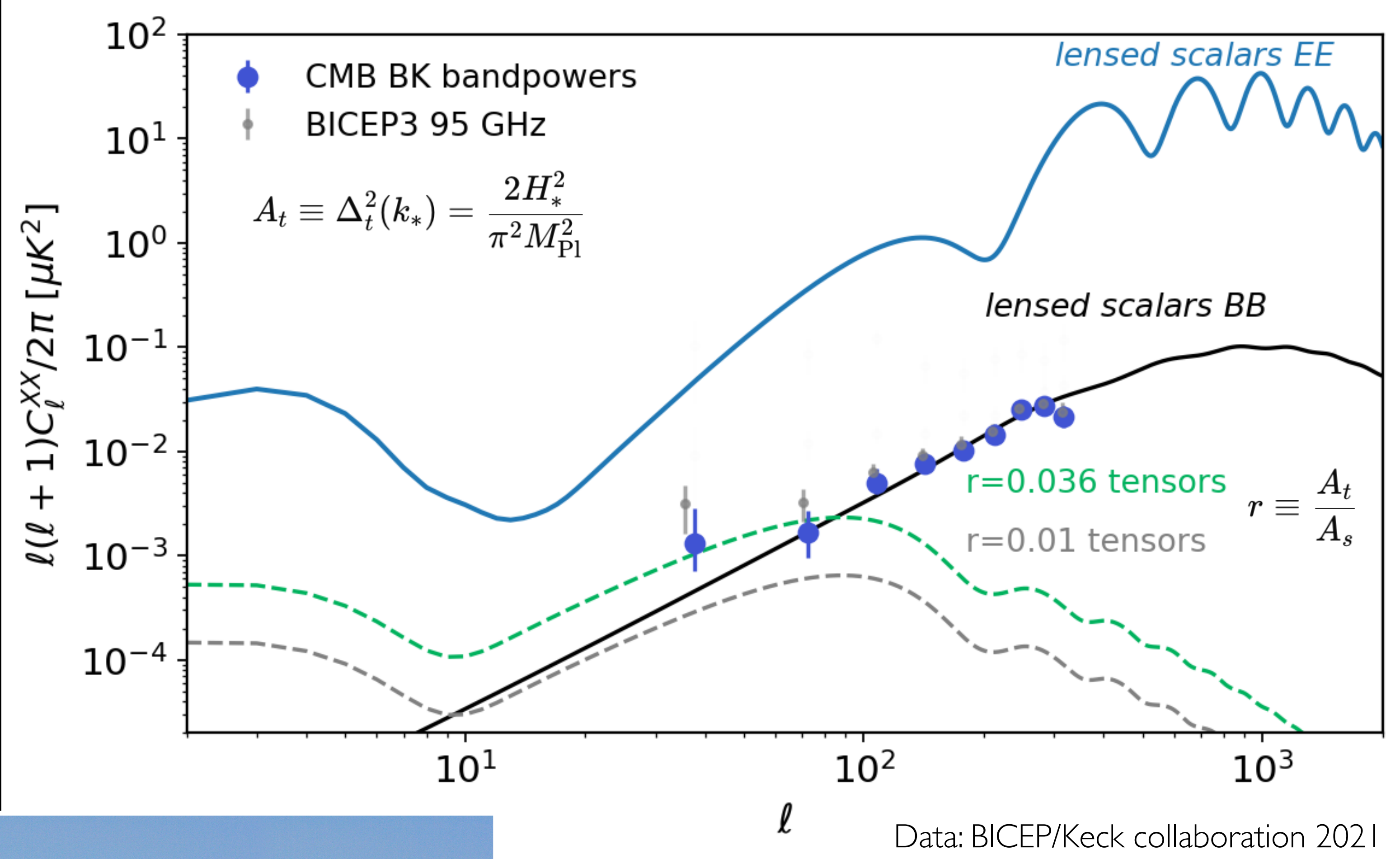
What about expansion at the beginning of universe?



Simulated map of B-modes from scale-invariant tensor fluctuations
Assuming period of inflation/acceleration, tensor amplitude tells you $H(a)$



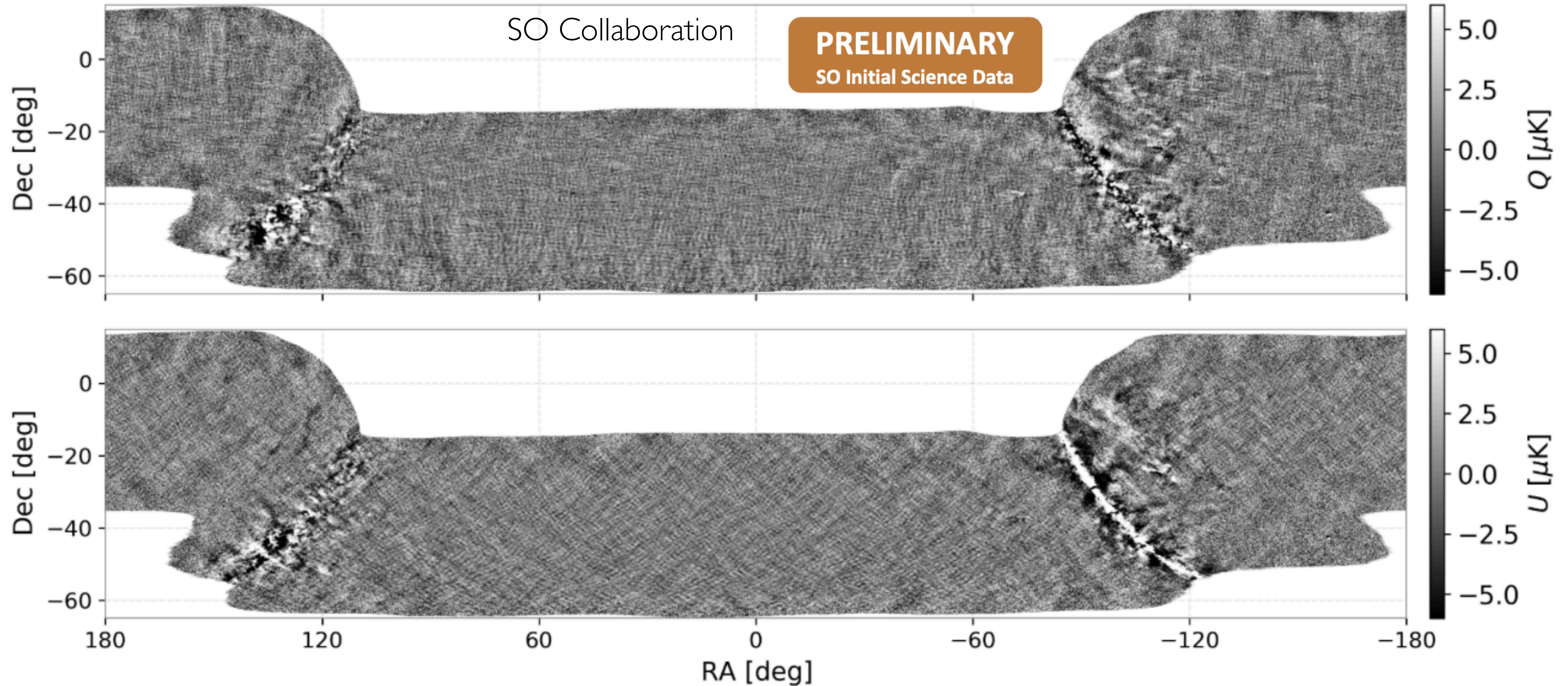
Measuring tensor perturbations



$$h_k'' + 2\frac{a'}{a}h_k' + k^2 h_k = 0$$



SO Small Aperture Telescopes (SATs)

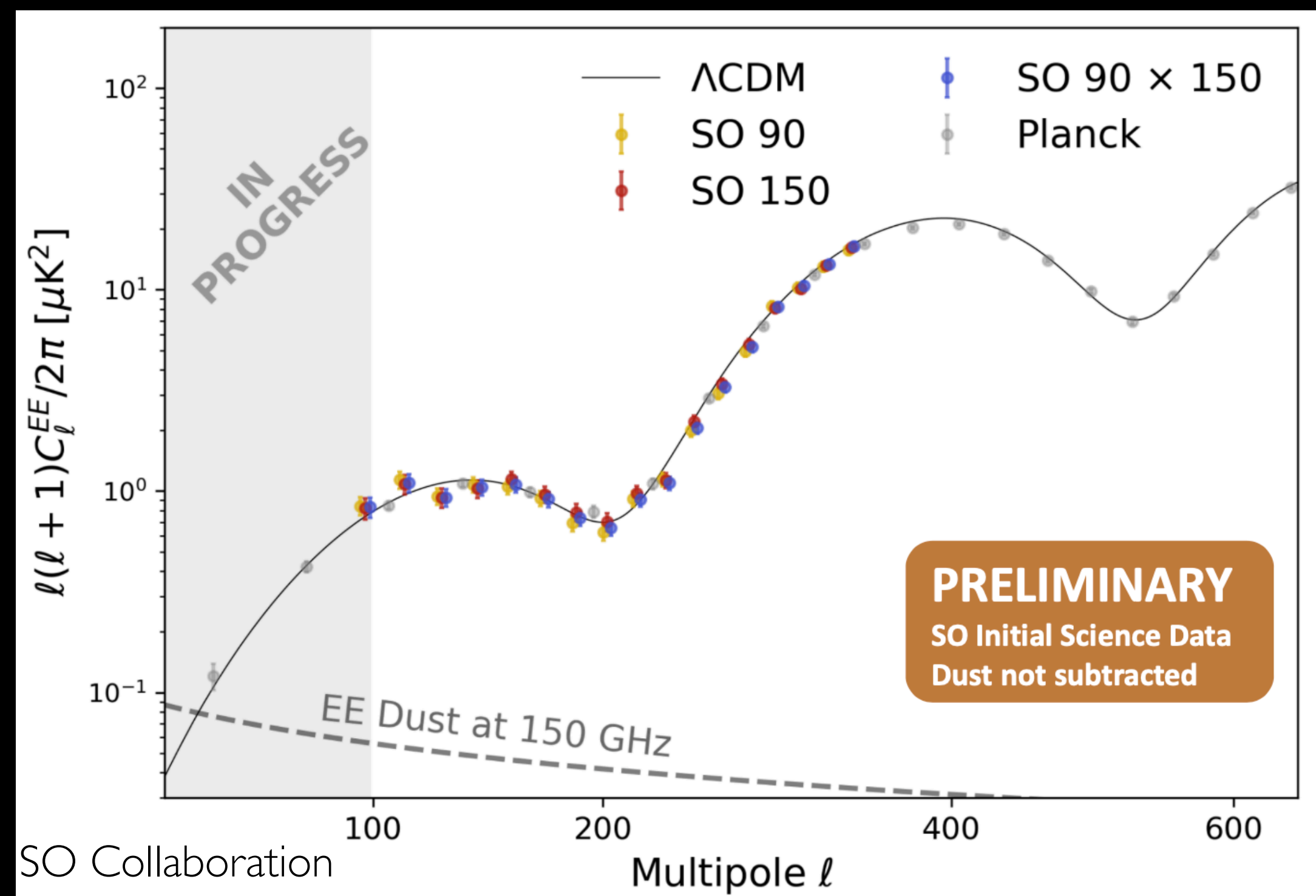
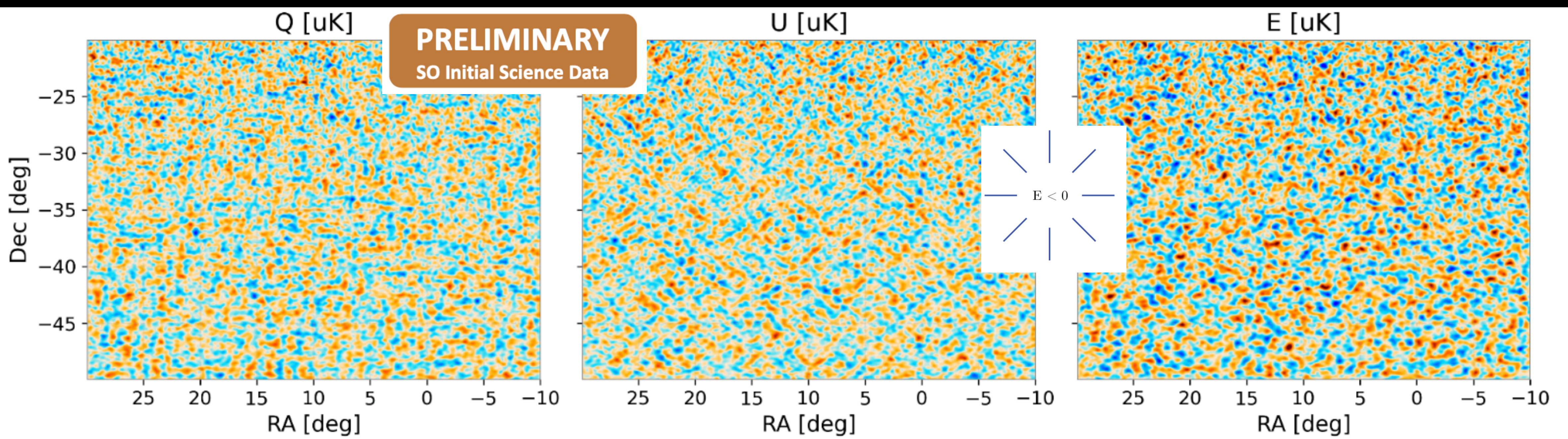


~30,000k superconducting detectors (~doubling soon with UK & Japan SATs)

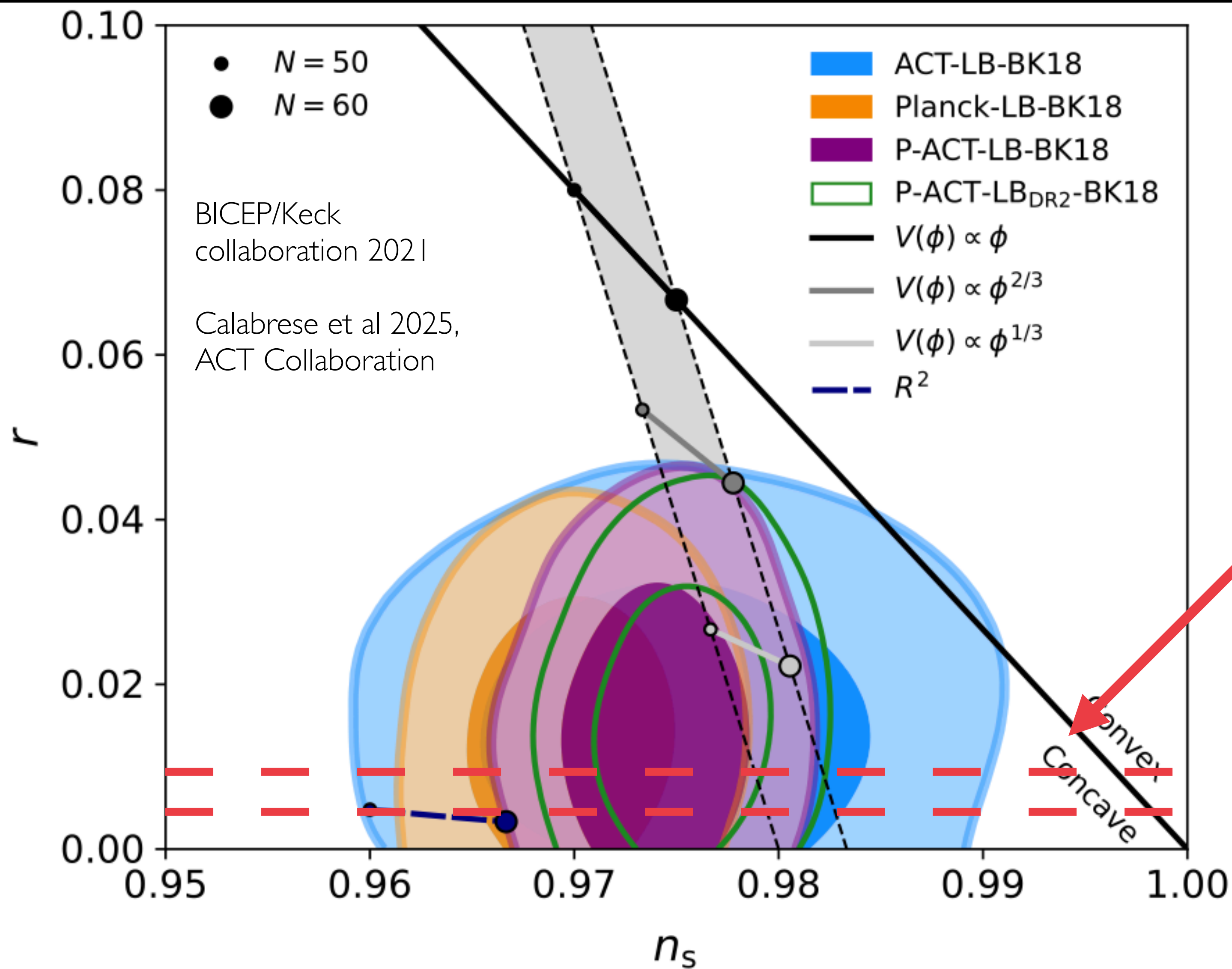
SO detectors are exceeding baseline specifications

A key enabling technology: rotating half-wave plates

Target depth is $\sim 1 \mu\text{K-arcmin}$ for $f_{\text{sky}} \sim 0.1$



Seeking a detection of the initial accelerated expansion



SO's goal detection levels:

$r=0.01$ in 4 yrs w 3 SATs ($\sigma \sim 0.002-3$)

$r=0.005$ in 10 yrs w 6 SATs ($\sigma \sim 0.001$)

Similar progress expected from South Pole using different instruments, site and sky coverage; this will be really exciting!

If we detect something, we will want to map out as much of that B-mode map as possible, and check it behaves as expected.



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- *There is a lot of science to do from SO & DESI together*

<https://arxiv.org/abs/1808.07445>
<https://arxiv.org/abs/2503.00636>
<https://arxiv.org/pdf/2512.15833>

We can still make progress on all the planned P5/A2020 science

Similar $\sigma(r)$ levels forecast for upgraded BICEP/Keck + SPT

Search for B-modes from the infant universe & inflation signatures

Study the dark universe

Matter mapping

	Current	SO 2025-2034	CMB-S4	Using Rubin, DESI, or <i>Euclid</i>
<i>Numbers show 1-σ</i>				
Primordial perturbations				
r ($A_L = 0.3$)	0.01	0.0012	0.0005	✓
n_s	0.003	0.002	0.002	-
$e^{-2\tau} \mathcal{P}(k = 0.2/\text{Mpc})$	1%	0.4%	✓	-
$f_{\text{NL}}^{\text{local}}$	5	1	~ 1	✓
Relativistic species				
N_{eff}	0.13	0.045	0.03	-
Neutrino mass				
m_ν (eV, $\sigma(\tau) = 0.01$)	0.06	0.03	0.03	✓
m_ν (eV, $\sigma(\tau) = 0.002$)		0.015	0.015	✓
Accelerated expansion				
$\sigma_8(z = 1 - 2)$	7%	1%	1%	✓

<https://arxiv.org/abs/1808.07445>

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