Photo: Aman Chokshi (December 2021)

A Polarized Look at the Hubble Constant Problem

Lloyd Knox
LBL Physics Division RPM
January 16, 2025

F. Ge et al., "*Cosmology From CMB Lensing and Delensed EE Power Spectra Using 2019-2020 SPT-3G Polarization Data*," arXiv:2411.06000, submitted to Phys. Rev. D

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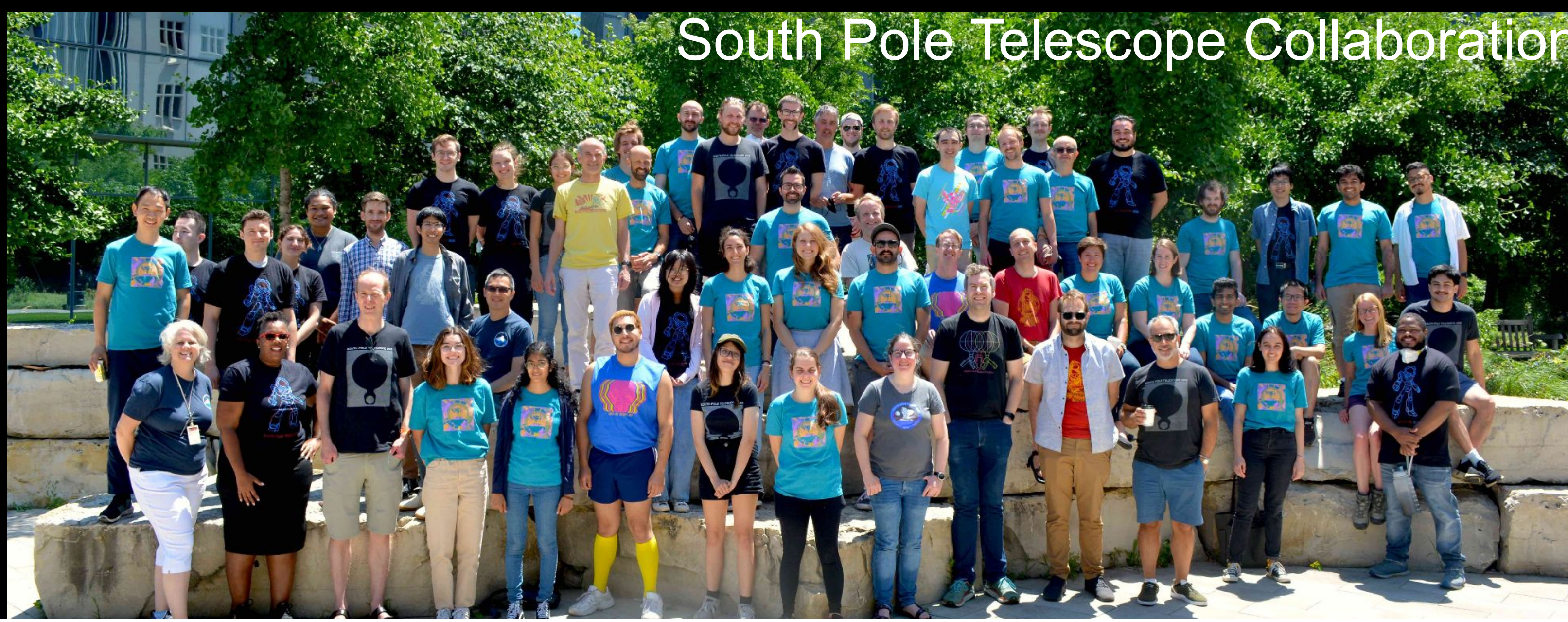
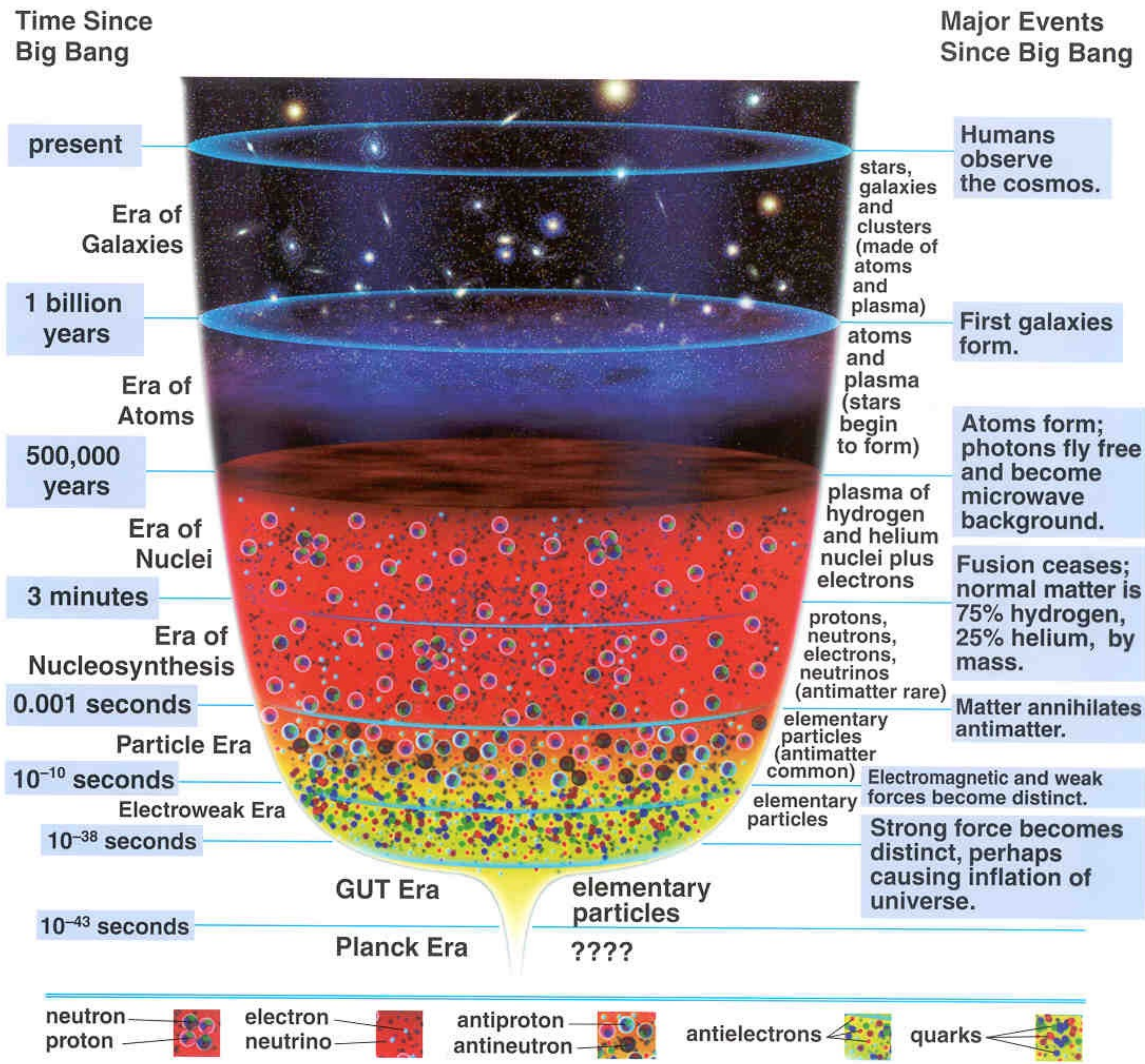
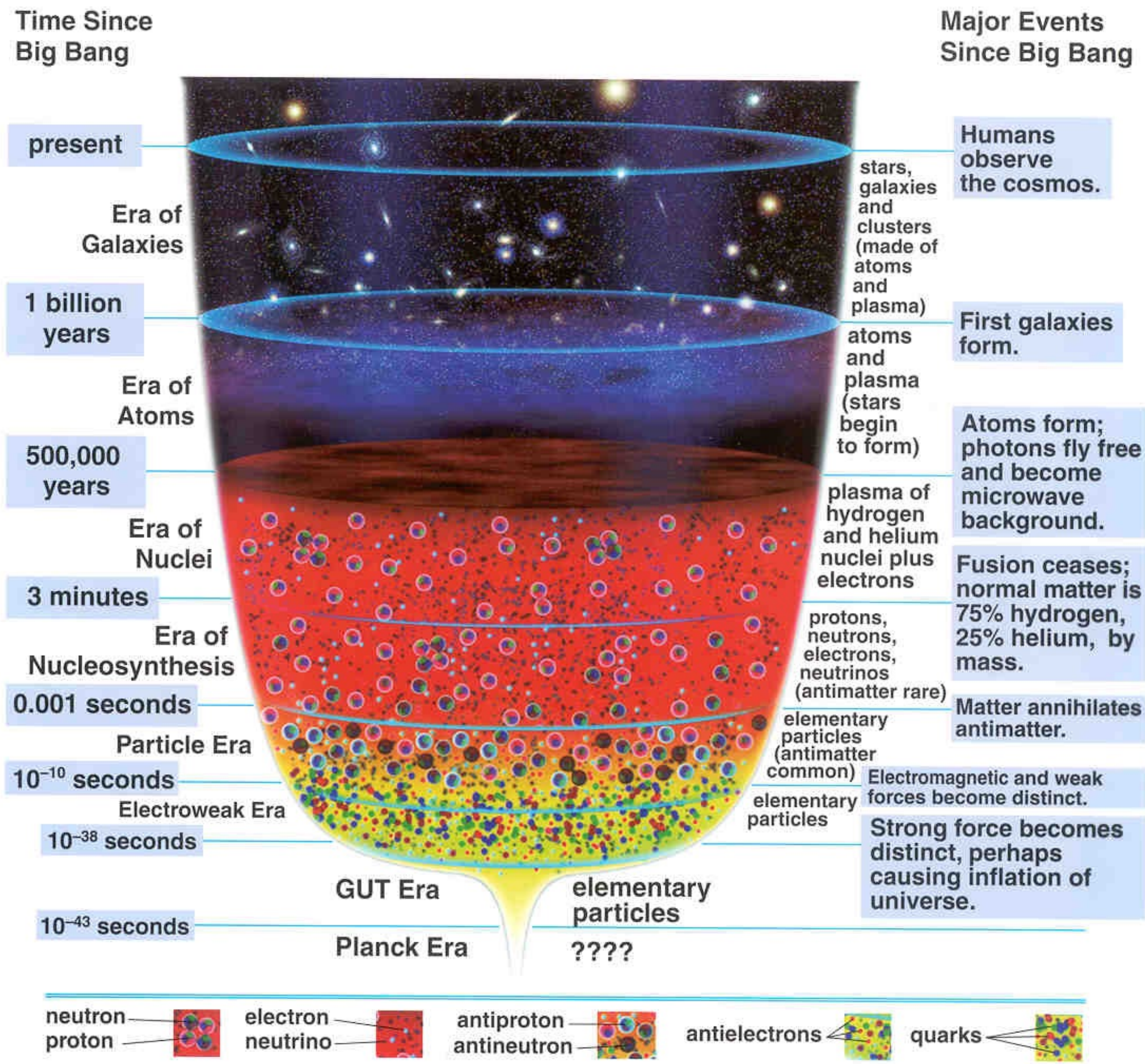




Credit: The Cosmic Perspective



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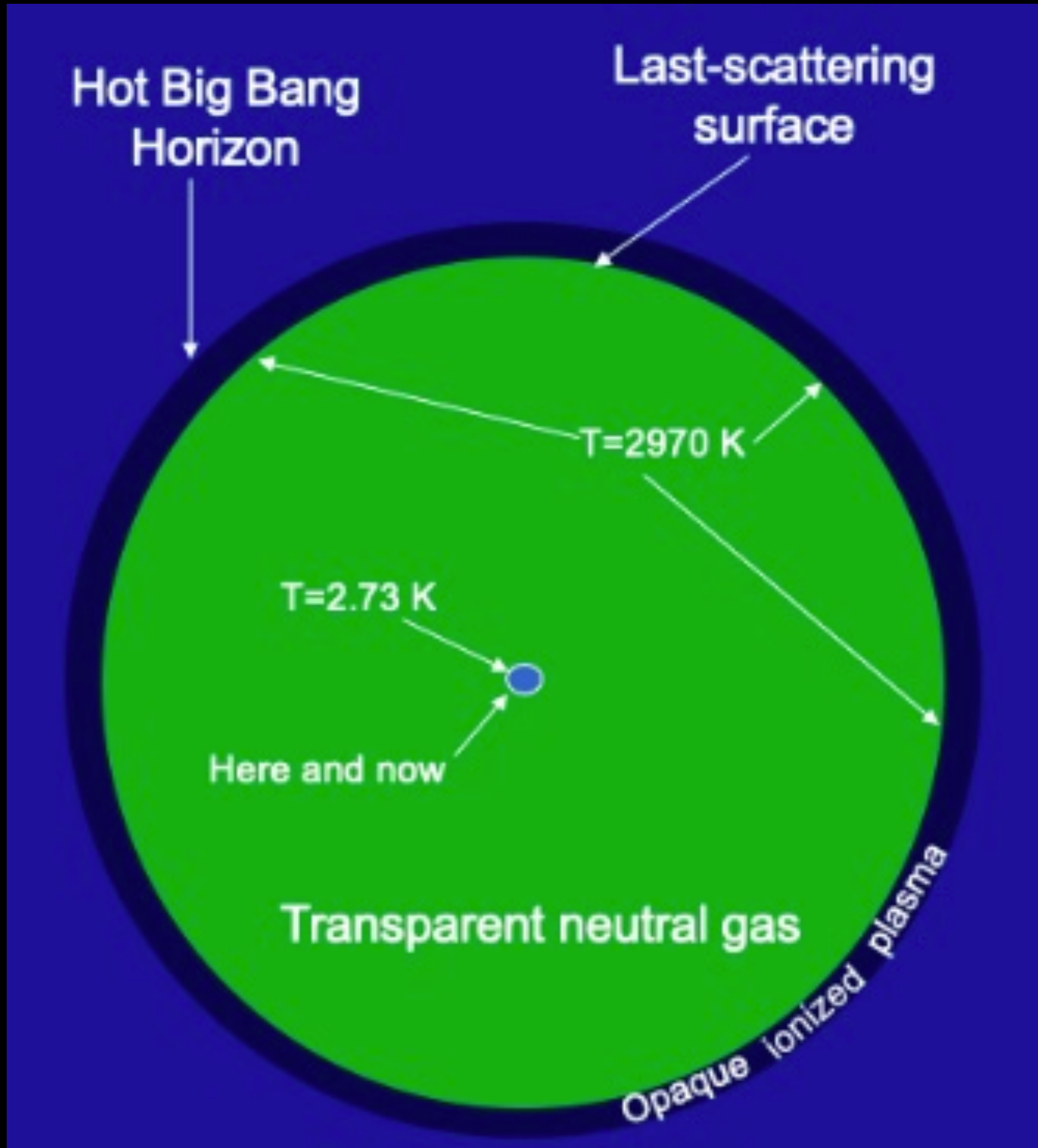
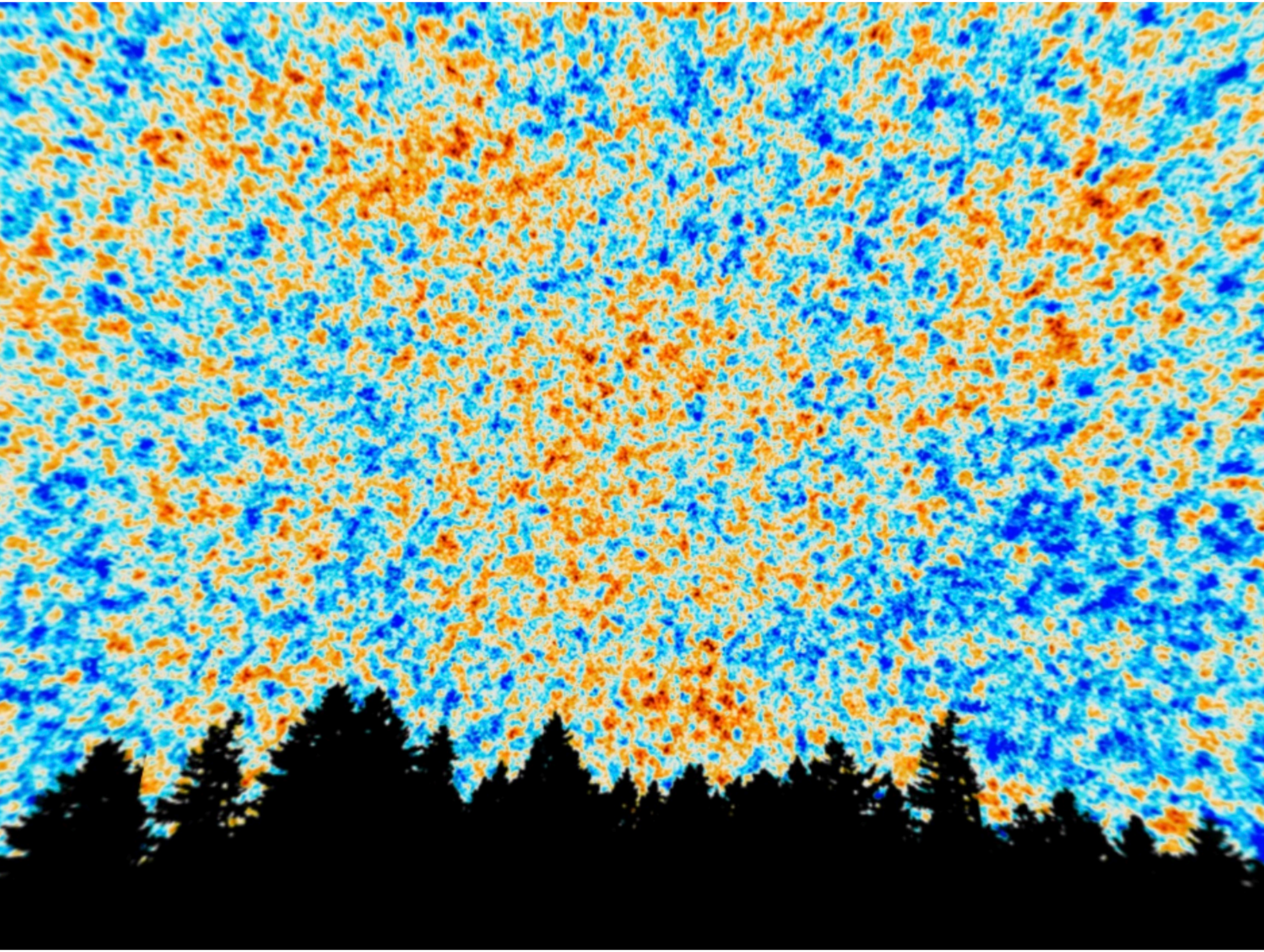


Our past light cone, projected on to the screen



Two Gifts of Nature

The Solar System	The Primordial Plasma
Unusually simple and regular natural system	Unusually simple natural system
Observable	Observable
Calculable (with Newton's theory)	Calculable
Phenomenologically rich	Phenomenologically rich
Highly successful theory (e.g. discovery of Neptune)	Highly successful theory (Lambda CDM)

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The Standard Cosmological Model, ΛCDM

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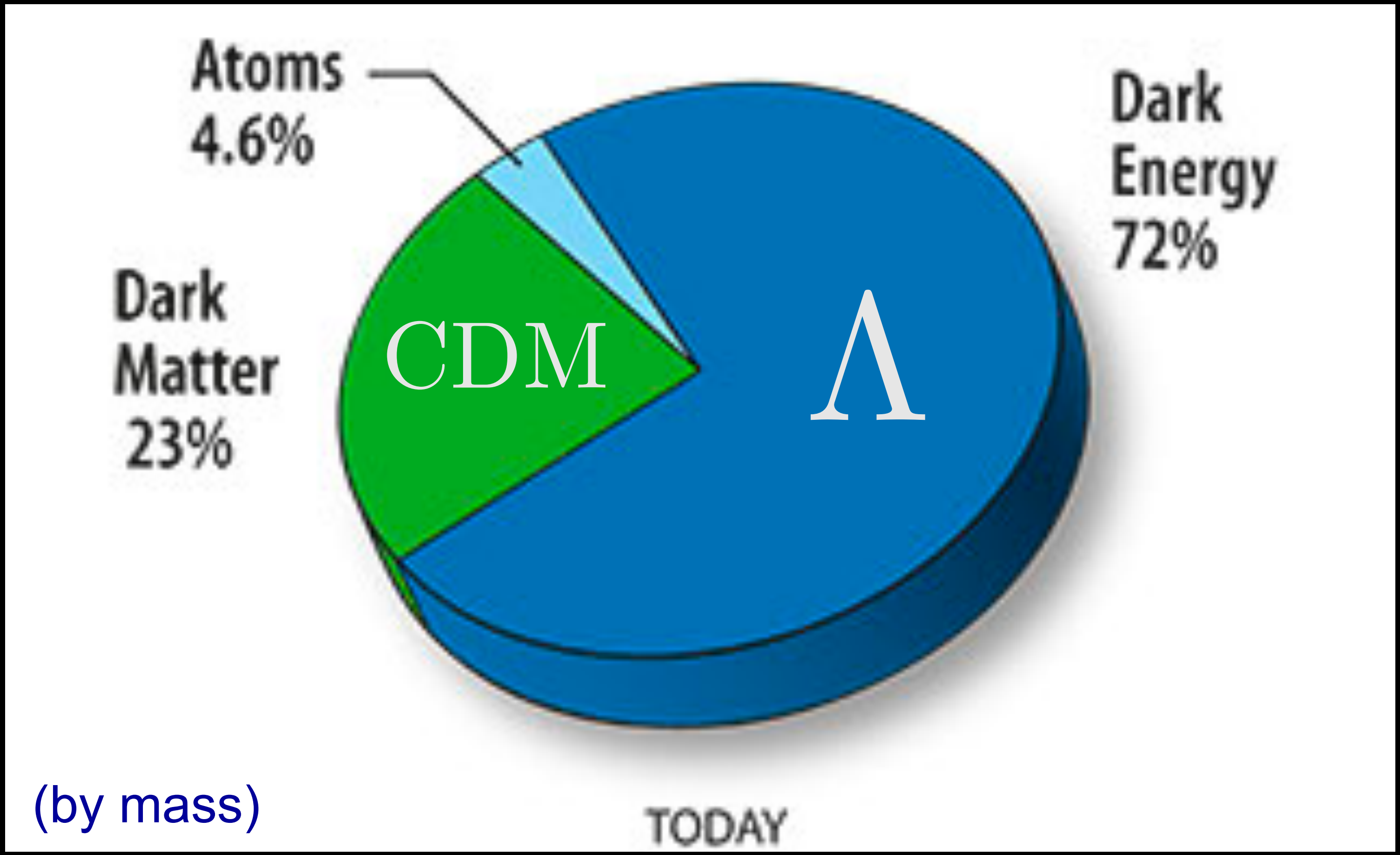
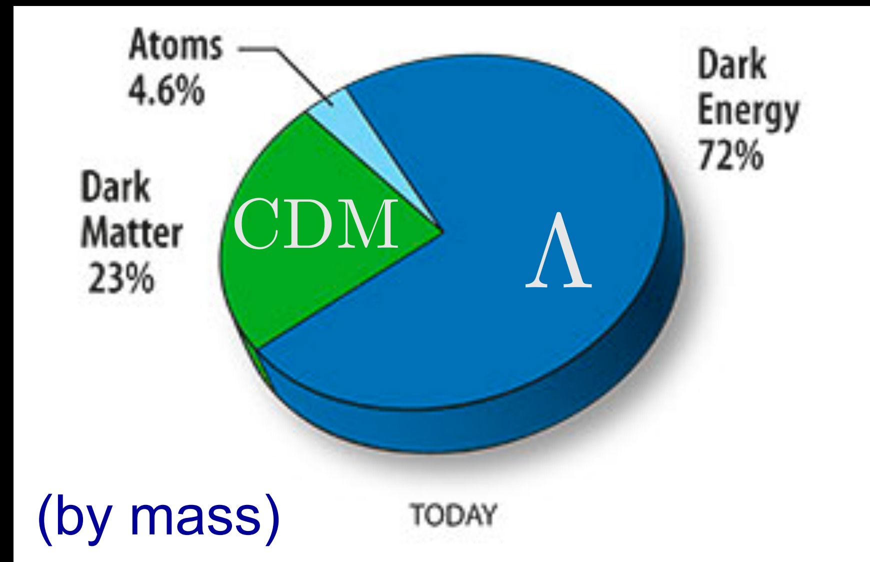


The Standard Cosmological Model, ΛCDM



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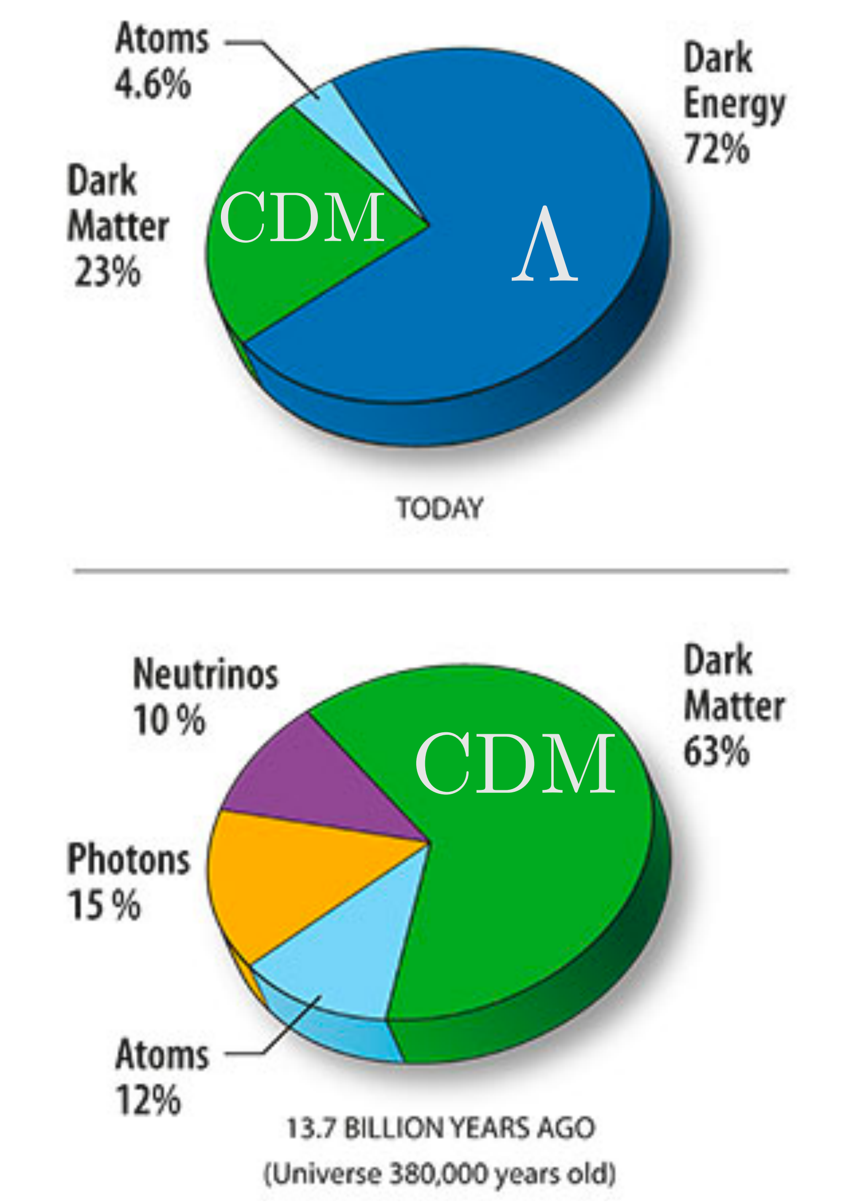
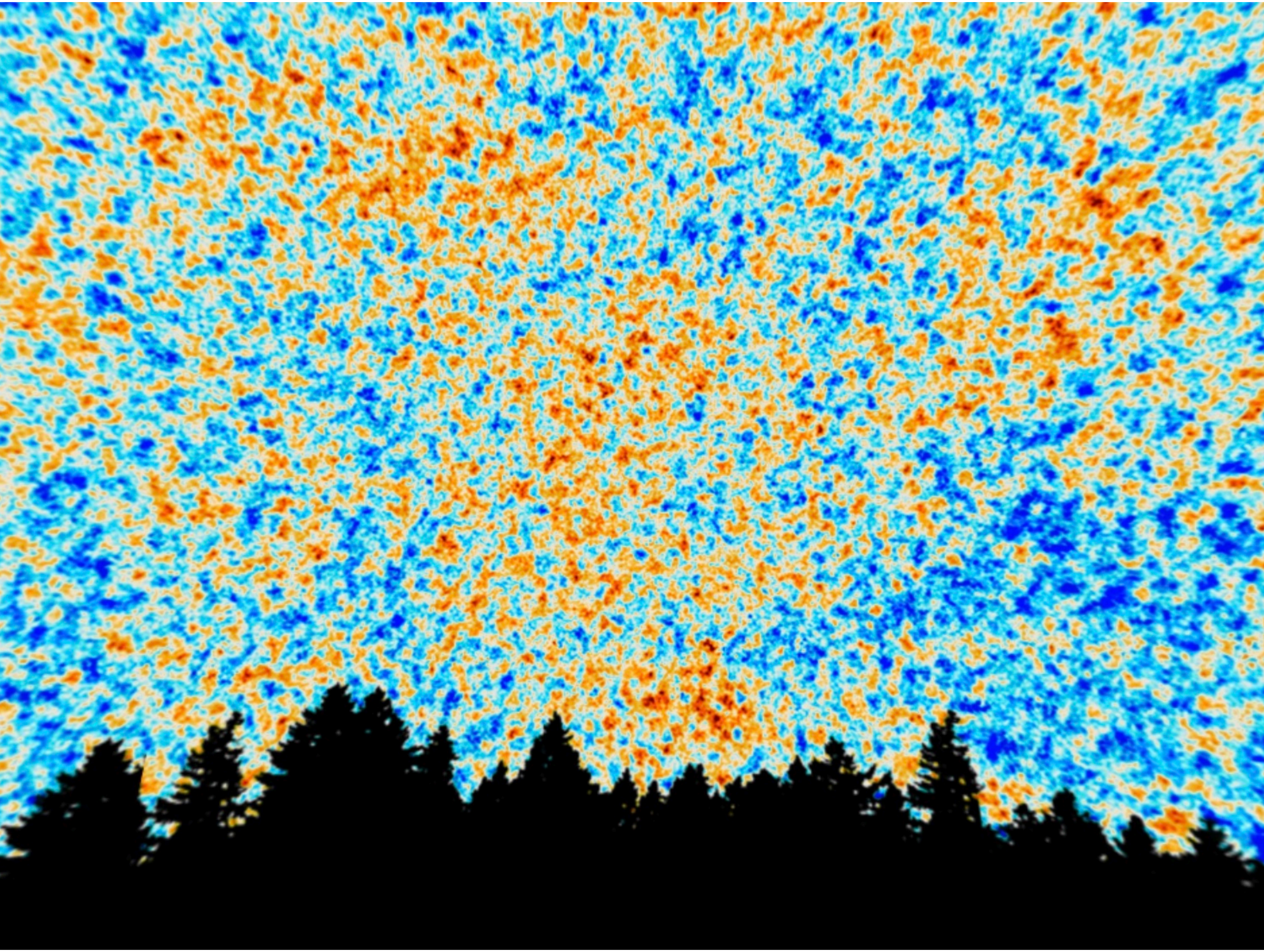
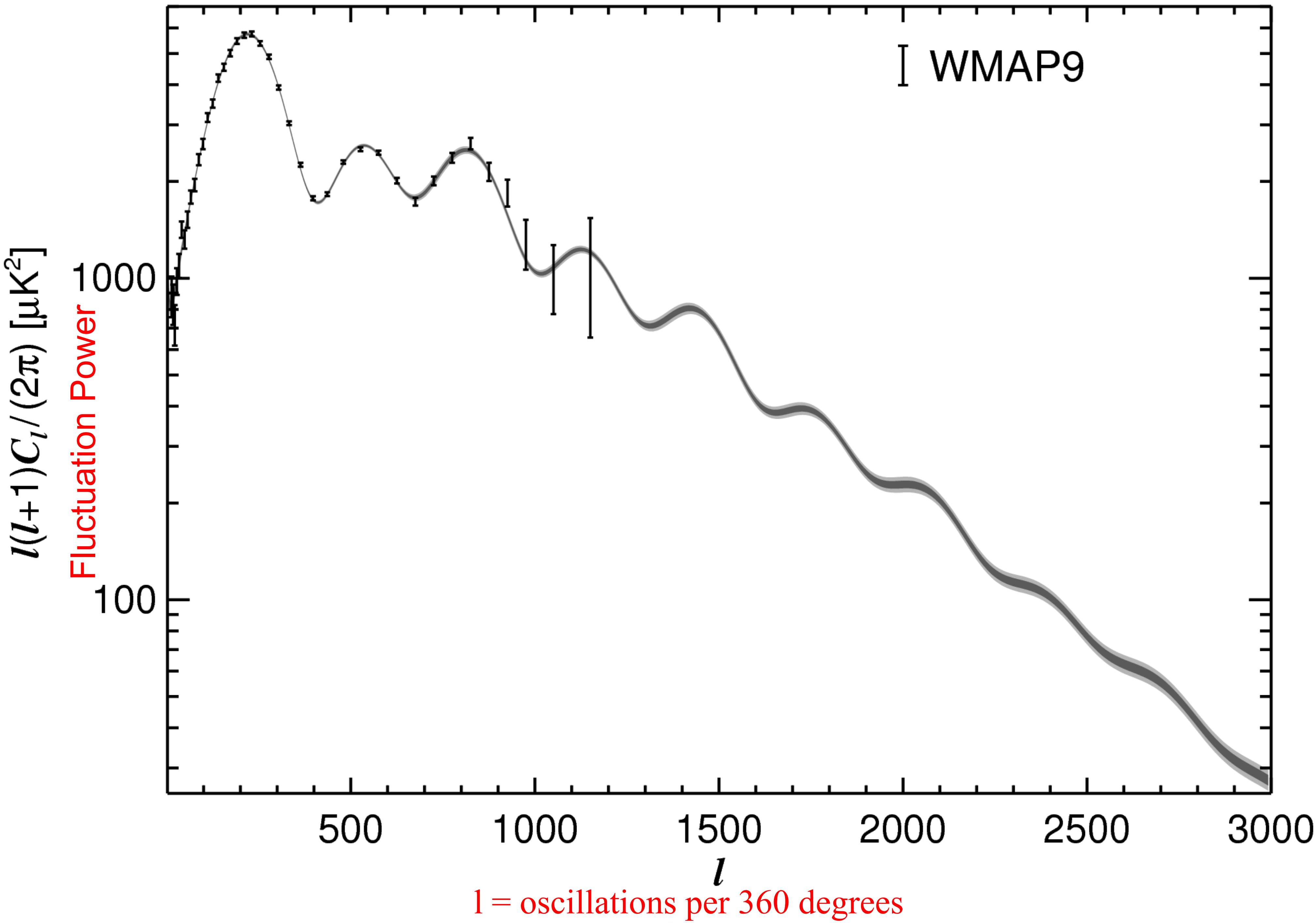
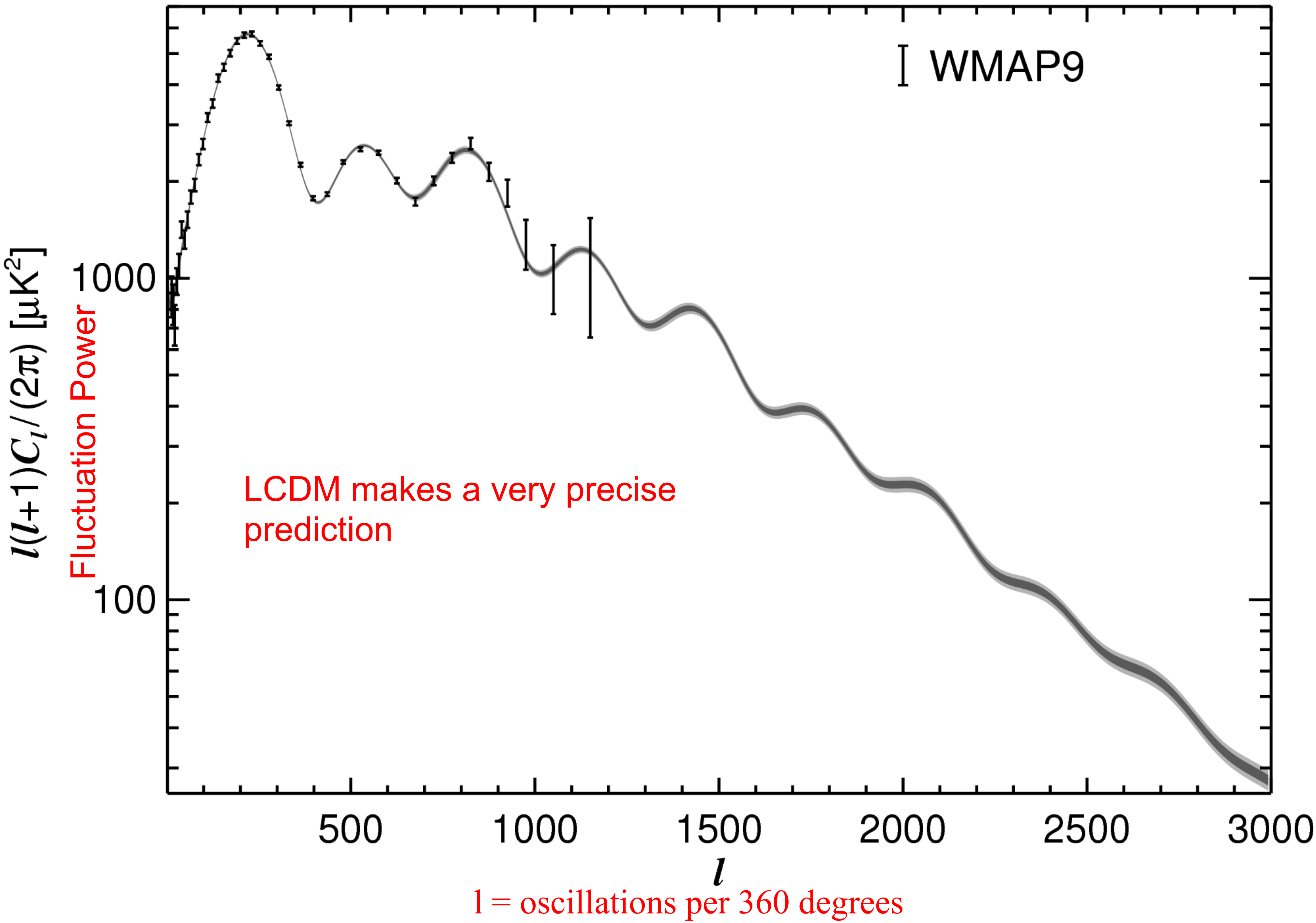
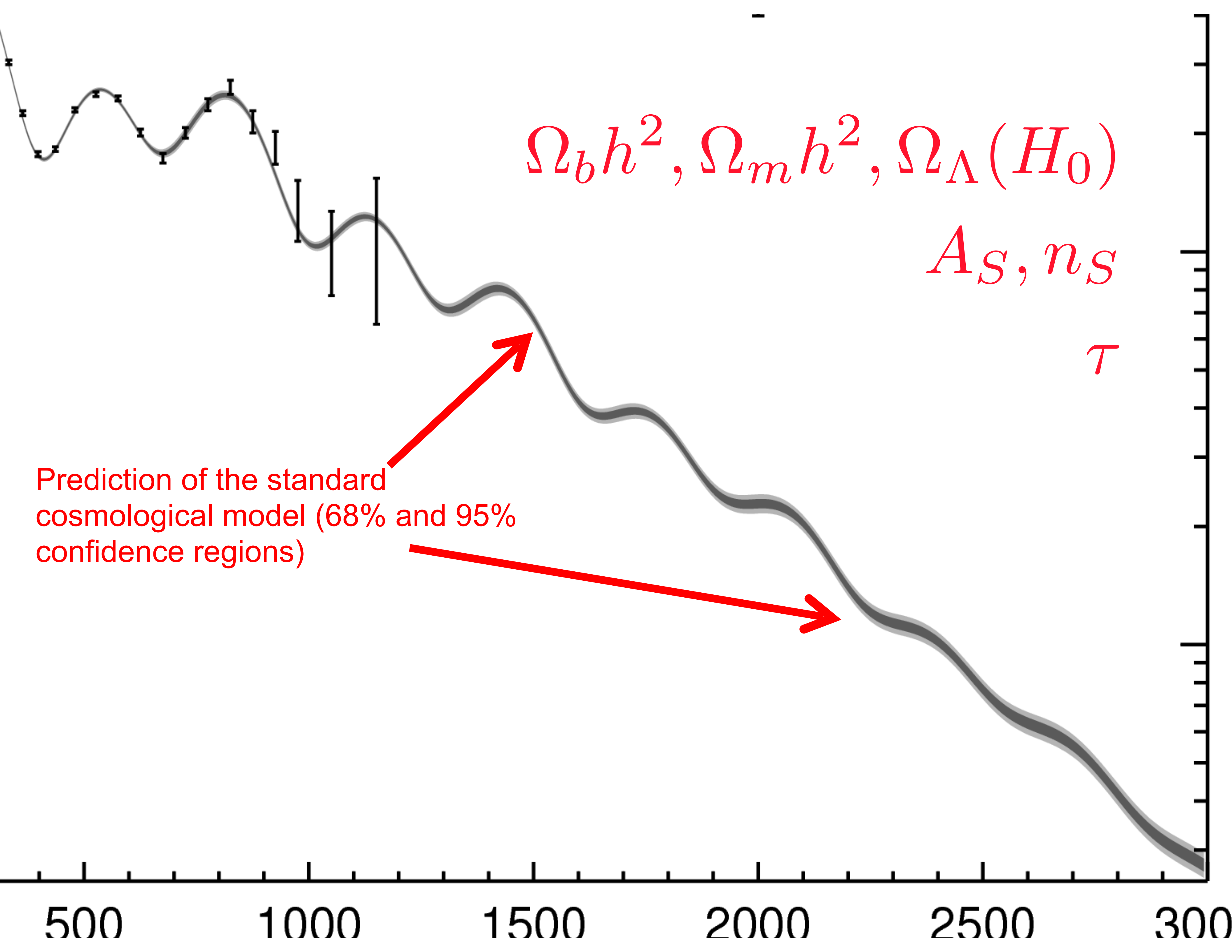


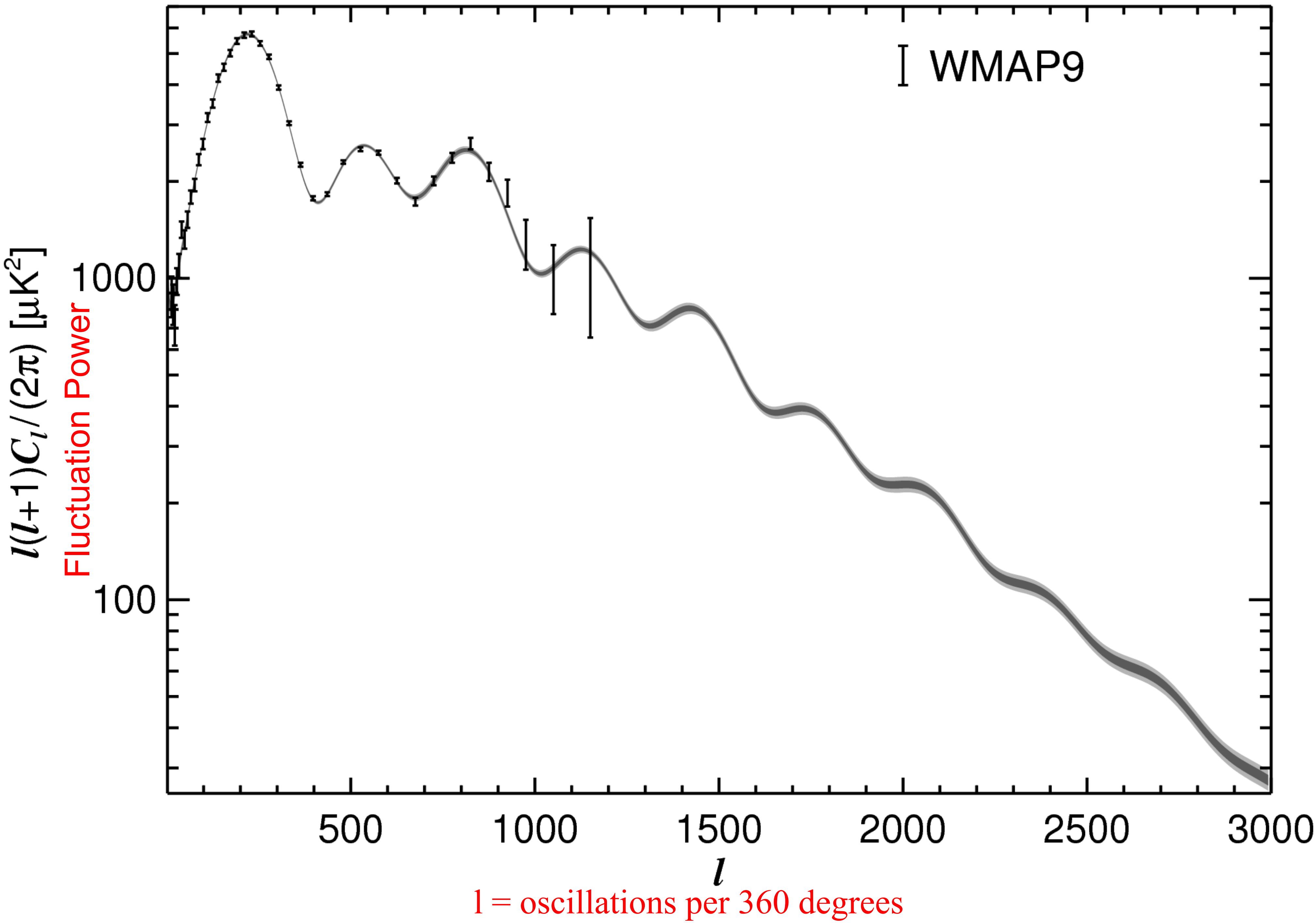



WMAP9
1000
100
500
1000
1500
2000
2500
3000
l
l(l+1)C_l/(2π) [μK^2]
Fluctuation Power
l = oscillations per 360 degrees


WMAP9
$l(l+1)C_l/(2\pi)$ [μK^2]
Fluctuation Power
1000
100
500
1000
1500
2000
2500
3000
l
LCDM makes a very precise prediction
l = oscillations per 360 degrees



$\Omega_b h^2, \Omega_m h^2, \Omega_\Lambda (H_0)$
A_S, n_S
τ
Prediction of the standard cosmological model (68% and 95% confidence regions)
500
1000
1500
2000
2500
300


WMAP9
1000
100
500
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$l(l+1)C_l/(2\pi)\ [\mu K^2]$
Fluctuation Power
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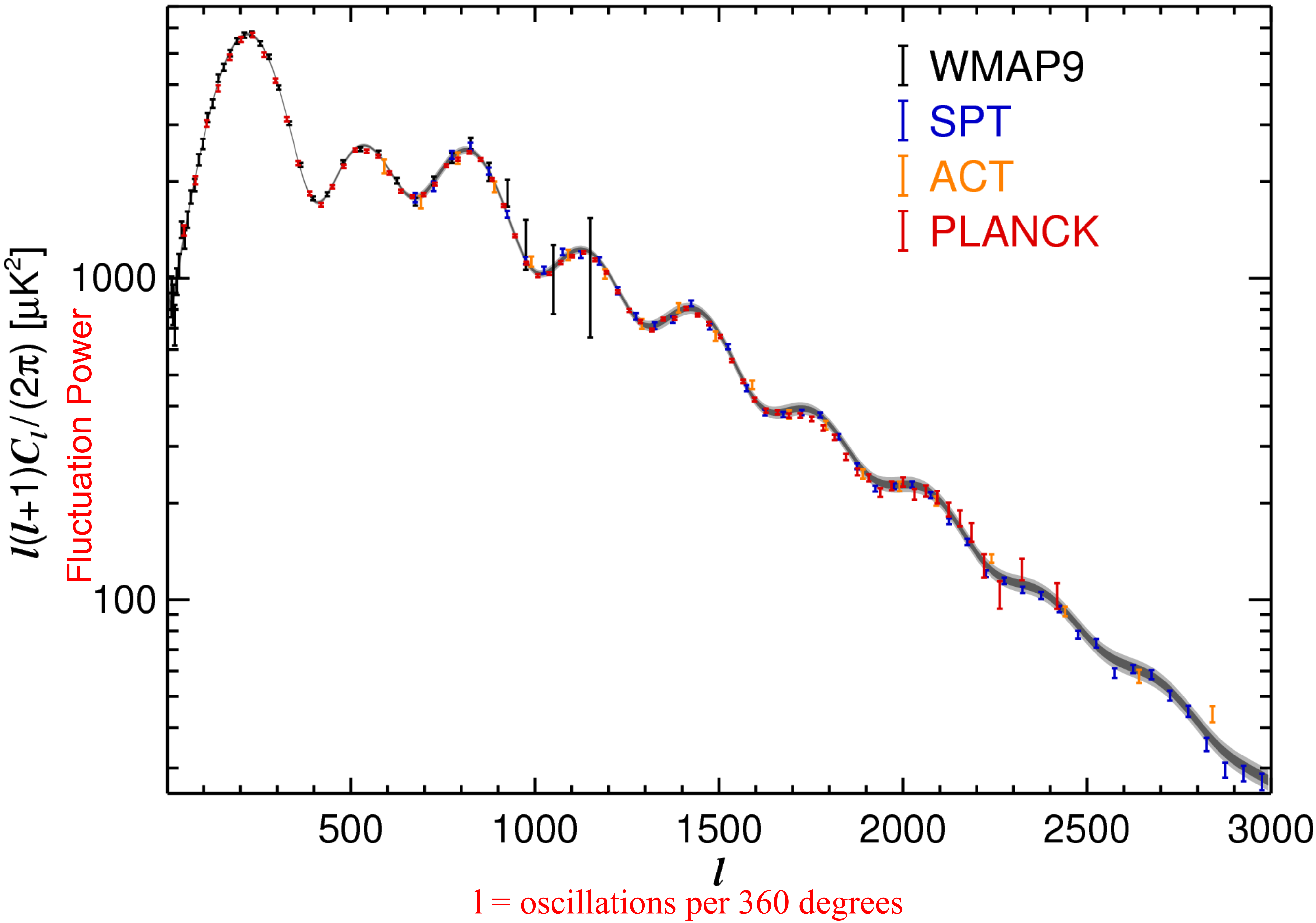
WMAP9
SPT
ACT
PLANCK
1000
100
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3000
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The Hubble Constant Problem

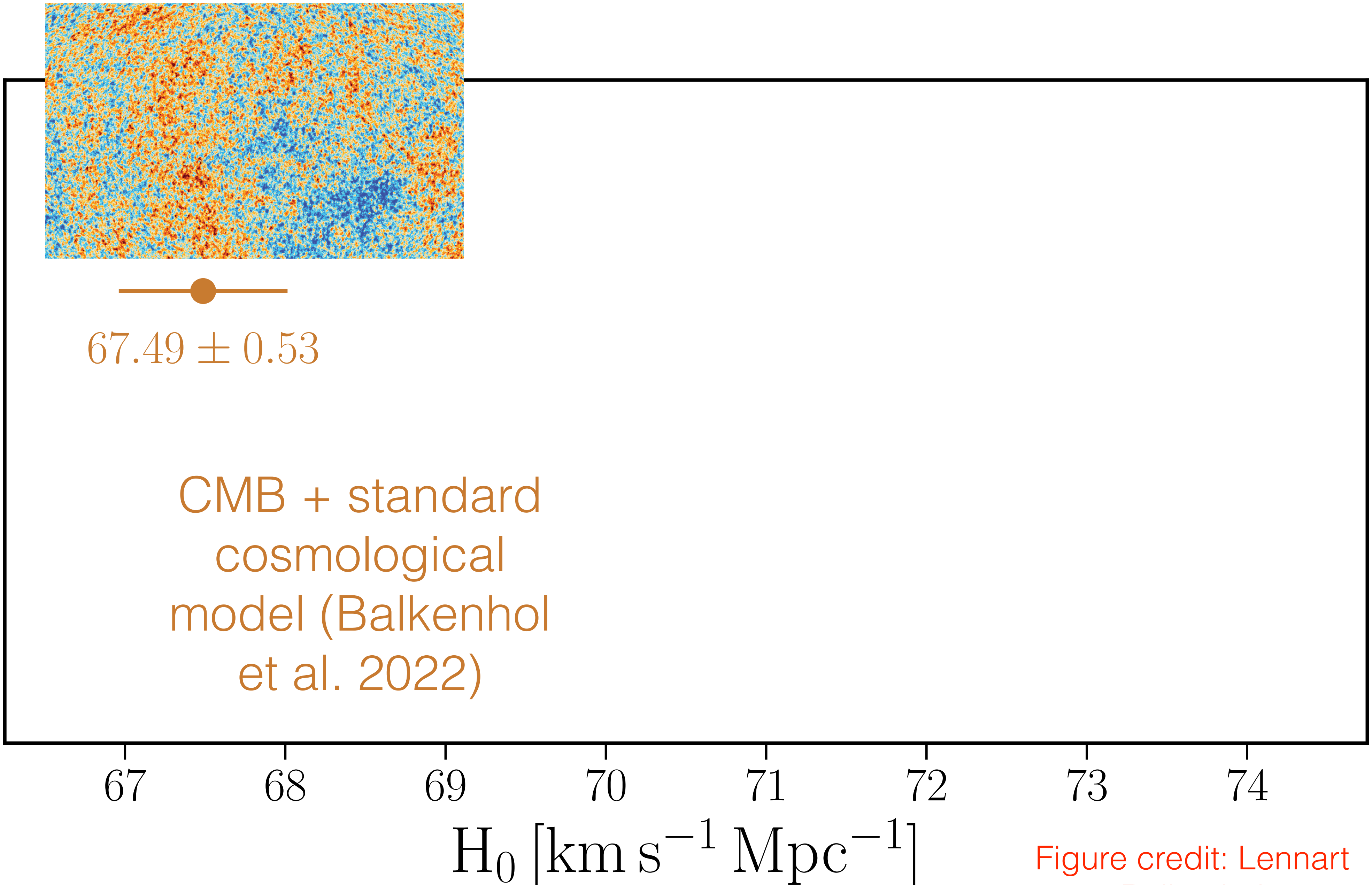


Figure credit: Lennart Balkenhol

The Hubble Constant Problem

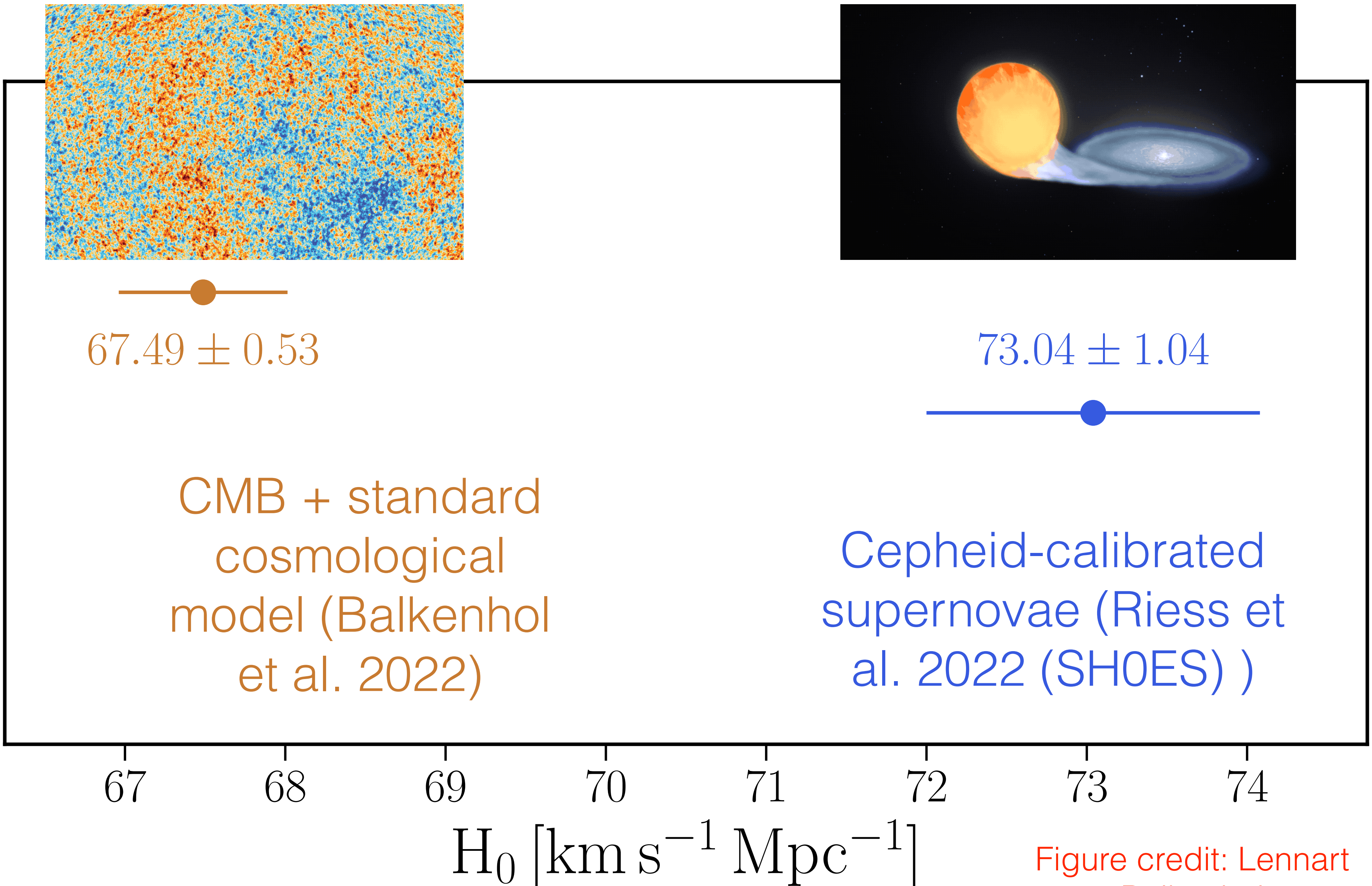


Figure credit: Lennart Balkenhol

The Hubble Constant Problem

Update: 73.17 ± 0.86 (Breuval et al. 2024 (SH0ES))

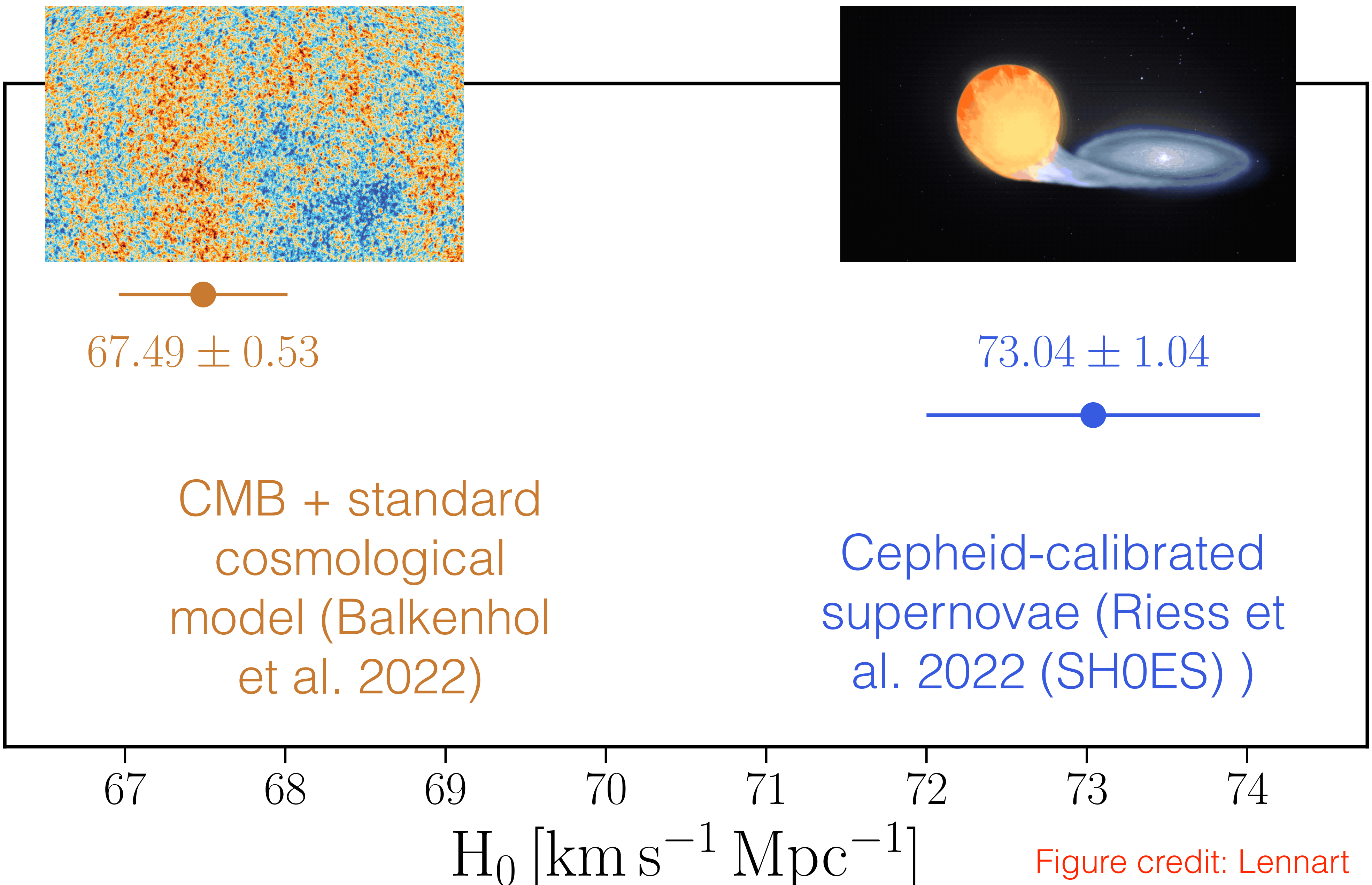
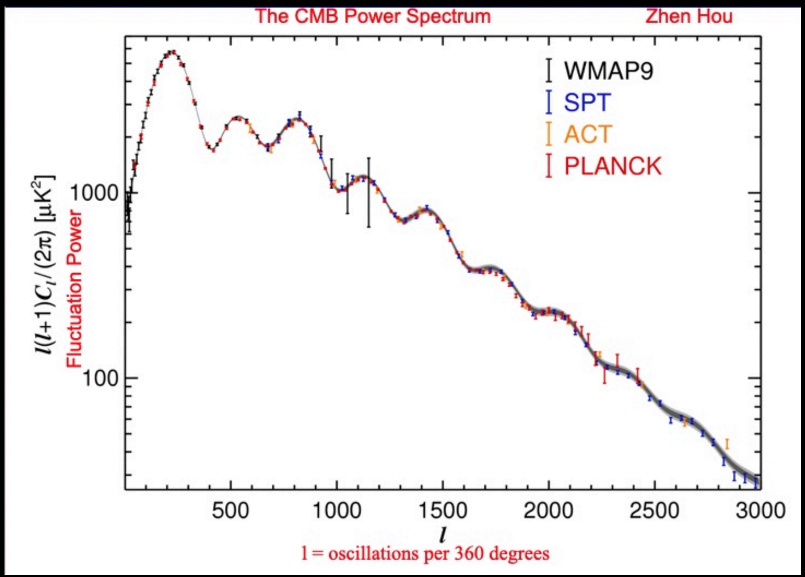


Figure credit: Lennart Balkenhol

So what's left to do with CMB anisotropies?



1) T at high resolution (high ell)
2) Polarization at all angular scales
3) Gravitational lensing (inferred from T and P maps)

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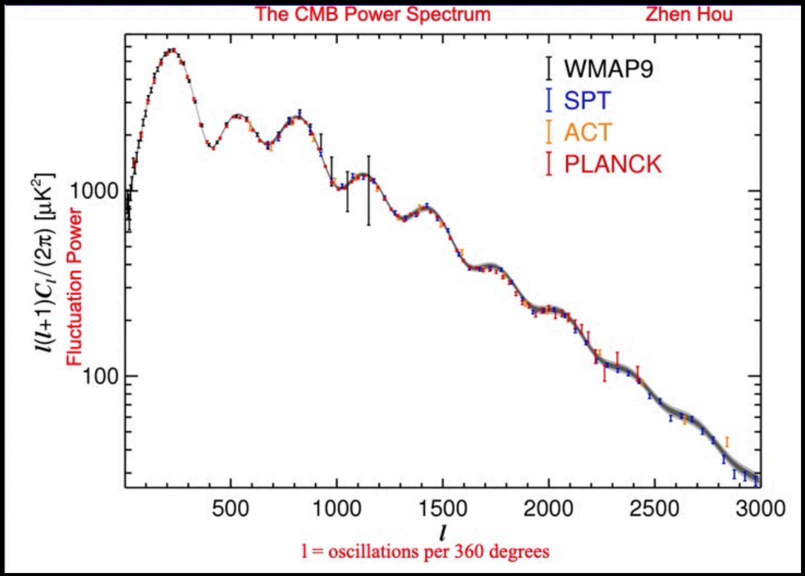

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Ge, F. + SPT Collaboration, "*Cosmology From CMB Lensing and Delensed EE Power Spectra Using 2019-2020 SPT-3G Polarization Data*," arXiv:2411.06000, submitted to Phys. Rev. D

Note: E is the "E-mode" of polarization — a curl-free polarization pattern

Generation of polarization

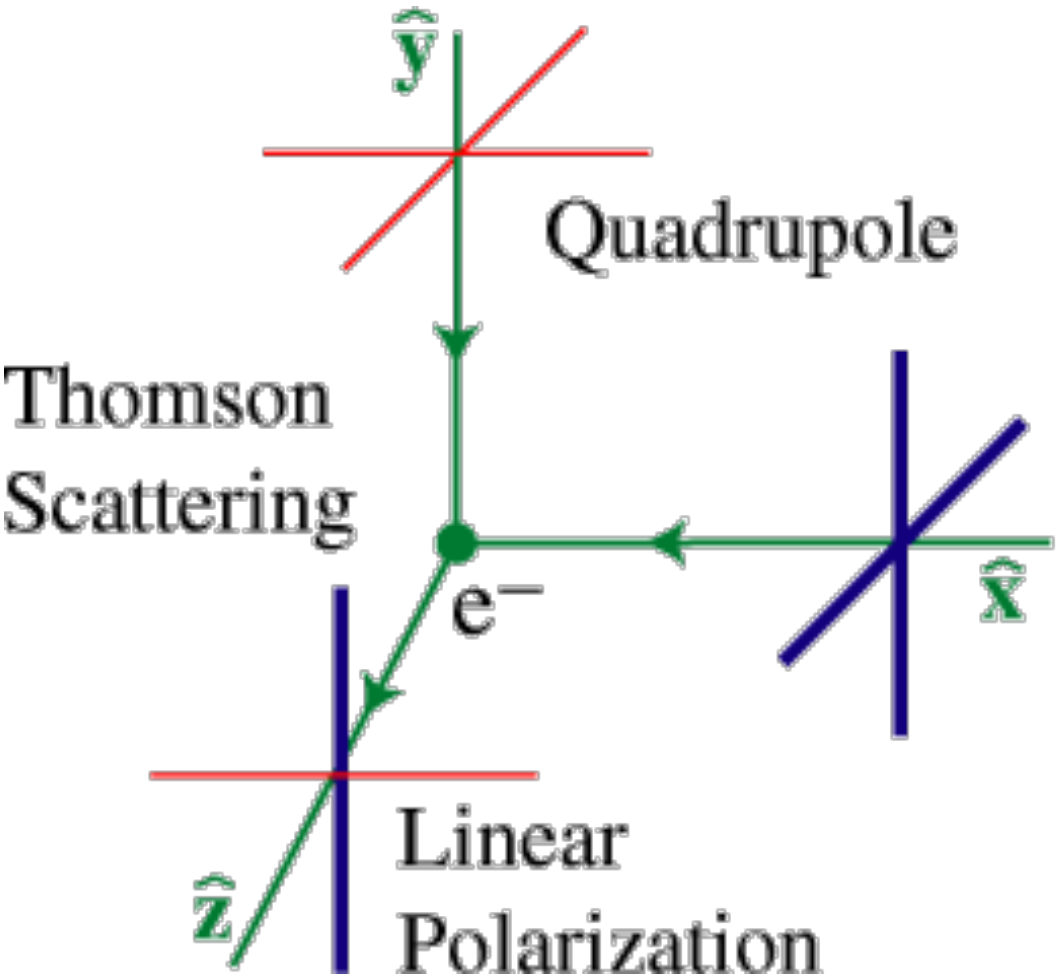
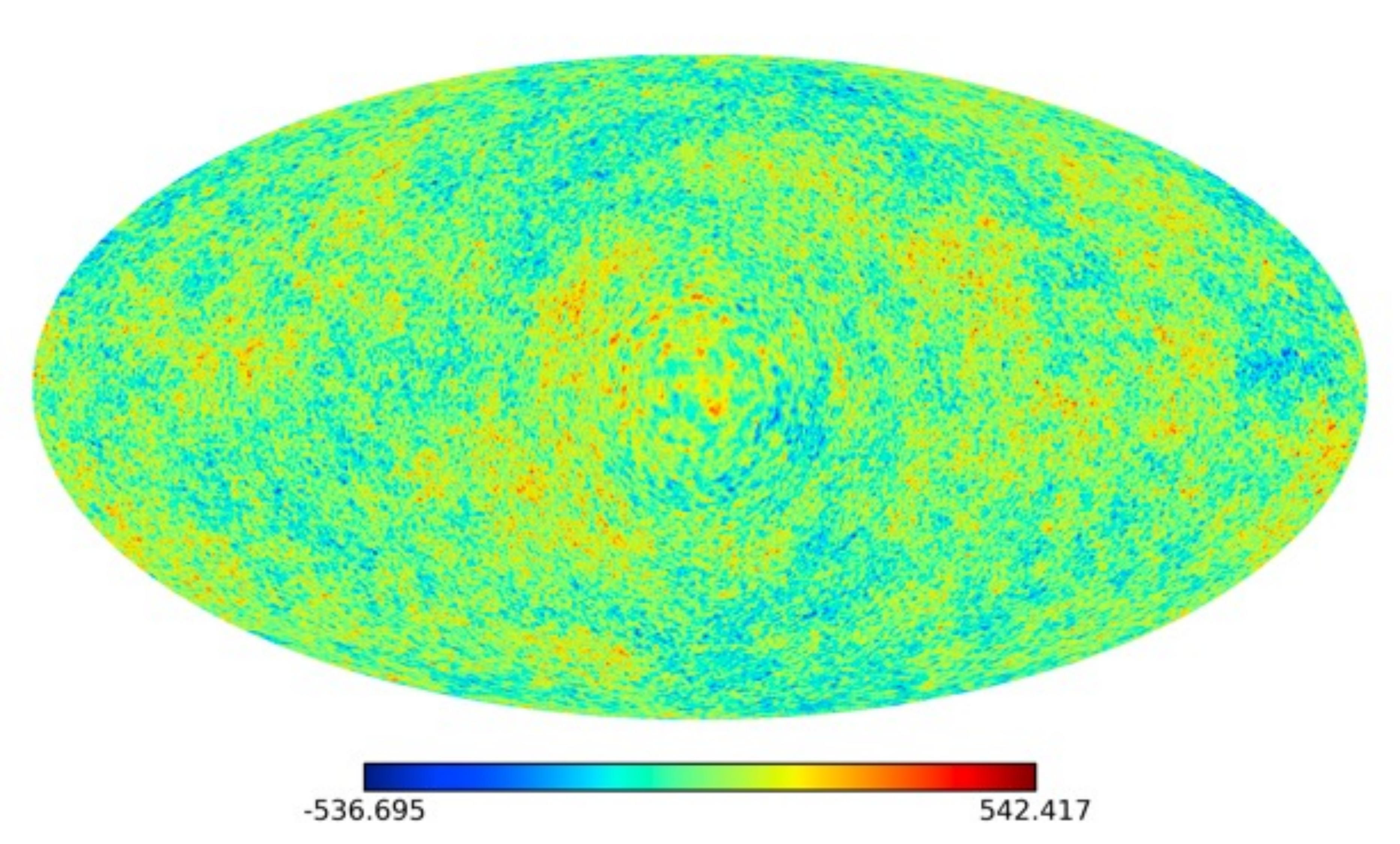


Image credit: Wayne Hu

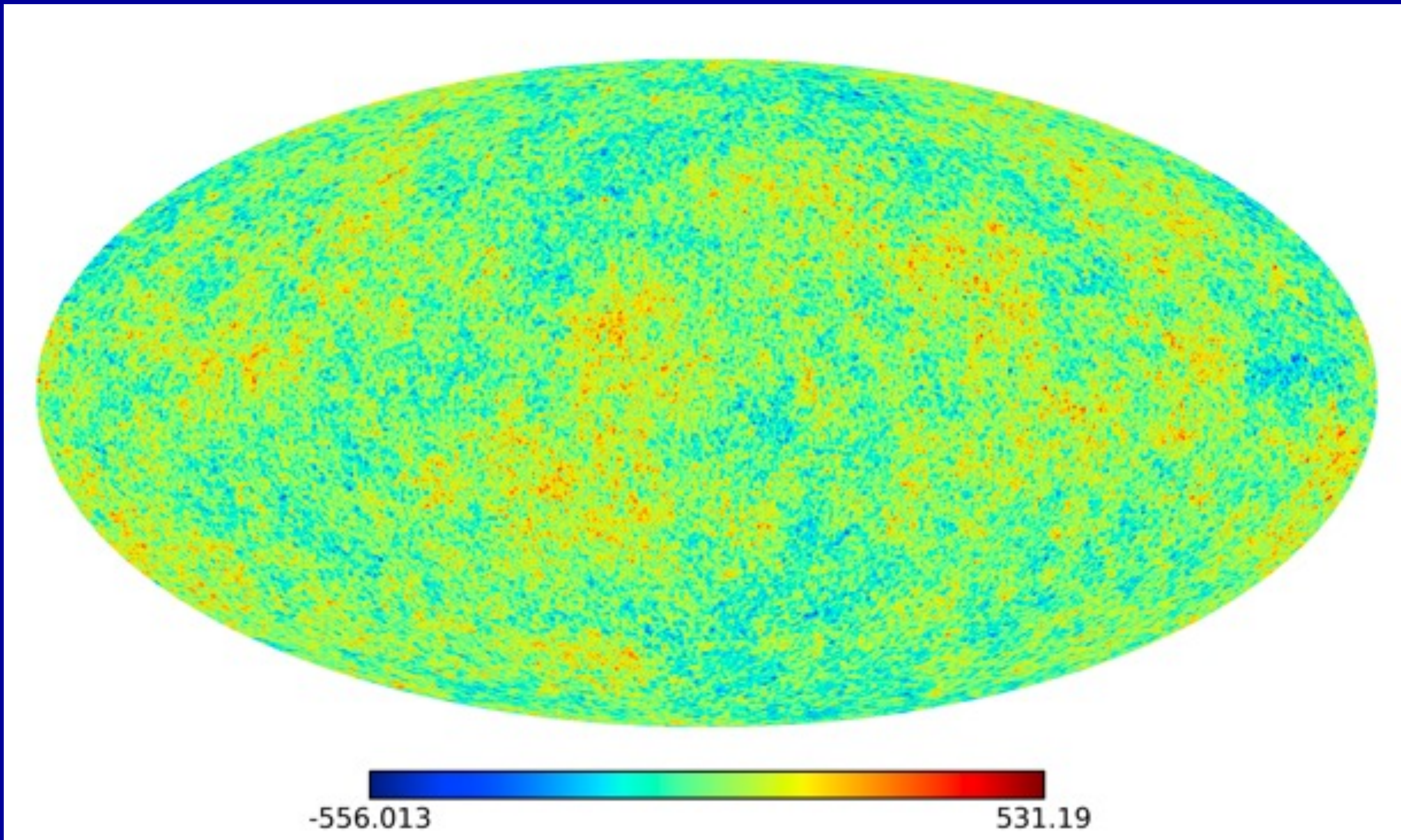
Gravitational Lensing

(Artificially Large Distortion)

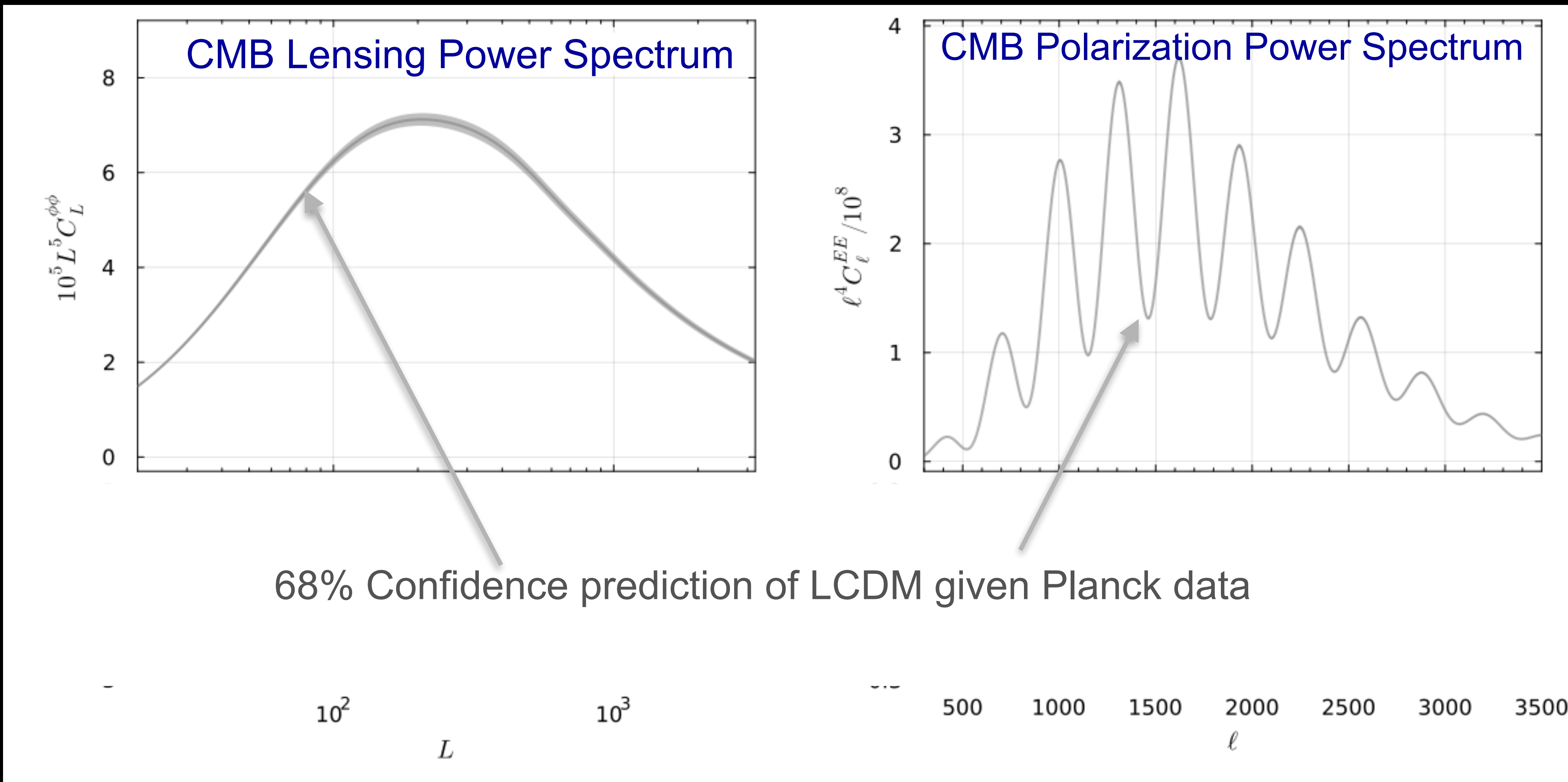
Gravitational Lensing



Gravitational Lensing



LCDM predictions given Planck data



The South Pole Telescope and the SPT-3G Camera

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Slide stolen from Yuuki Omori

2007 - 2011: **SPT-SZ**
960 detectors
95/150/220 GHz
Temperature only
2,500 sq.deg

2012 - 2016: **SPTpol**
1,600 detectors
95/150 GHz
Temperature + polarization
500 sq.deg

2017-2026: **SPT-3G**
16,000 detectors
95/150/220 GHz
Temperature + polarization
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SPT-3G Surveys

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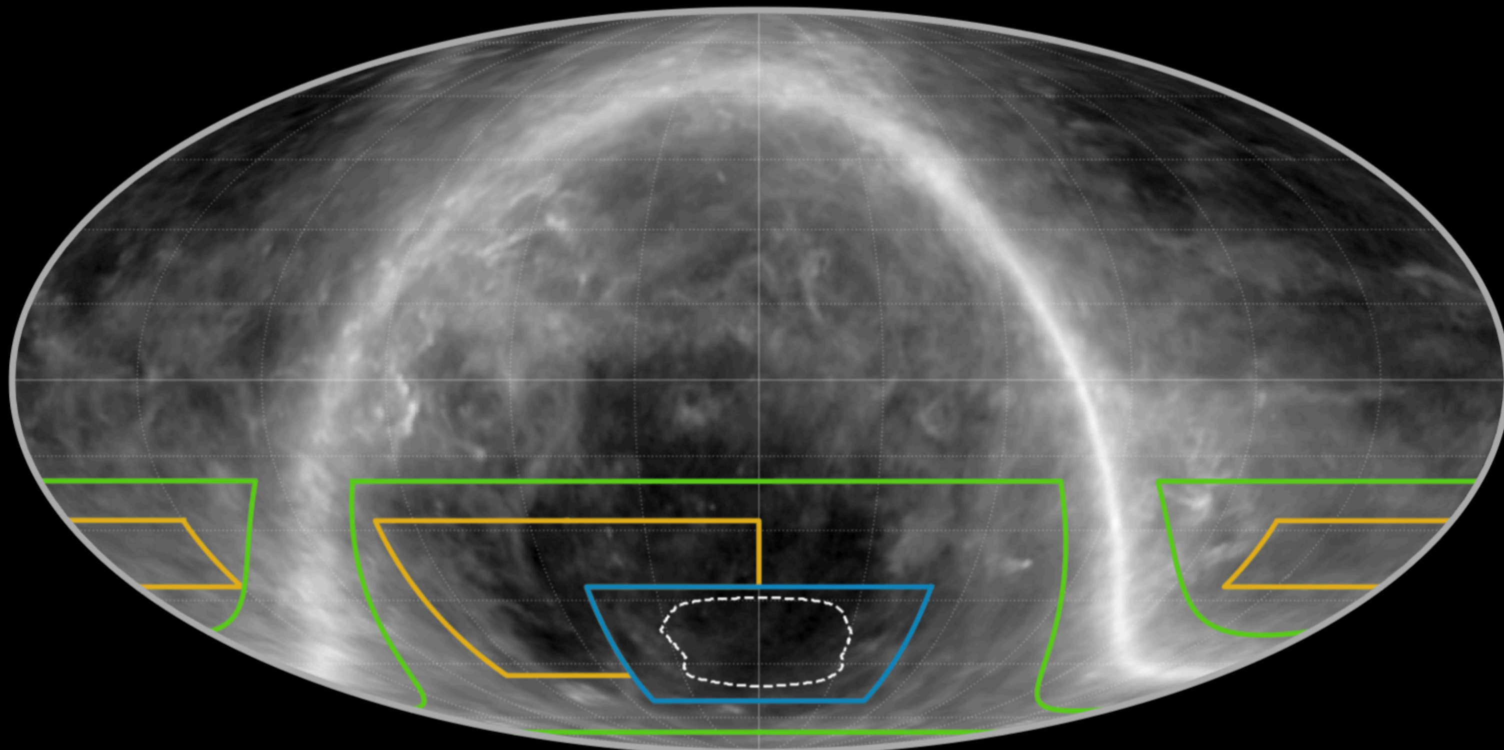
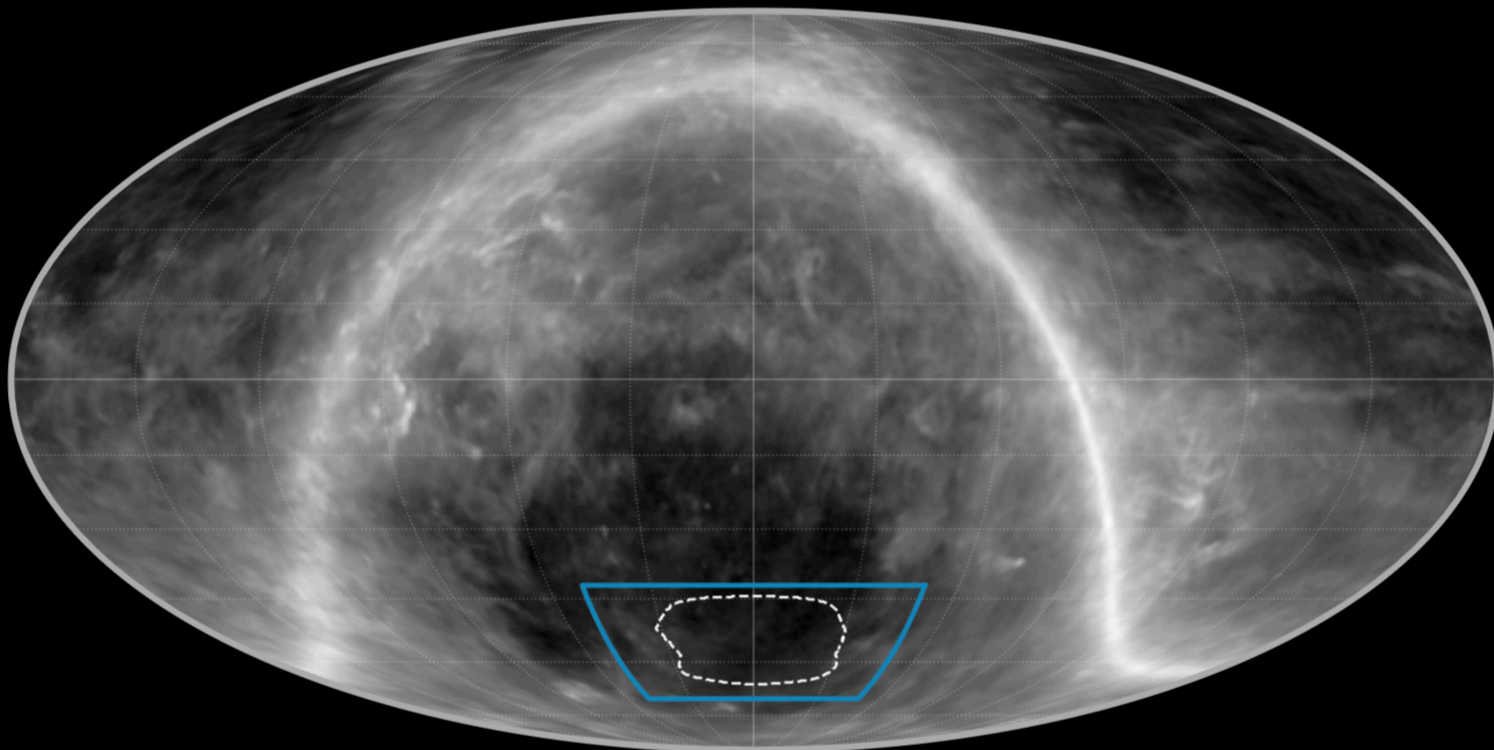


Survey	Area [deg^2]	Years observed	Noise level (T) [μK-arcmin] 95 GHz	150 GHz	220 GHz	Coadded
SPT-3G Main	1500	2019-2023, 2025-2026	2.5	2.1	7.6	1.6
SPT-3G Summer	2600	2019-2023	10	9.0	31	6.5
SPT-3G Wide	6000	2024	14	12	42	8.8

2019-2020 SPT-3G Results



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2019-2020 Main field maps have noise levels ~2.5x higher than in this table

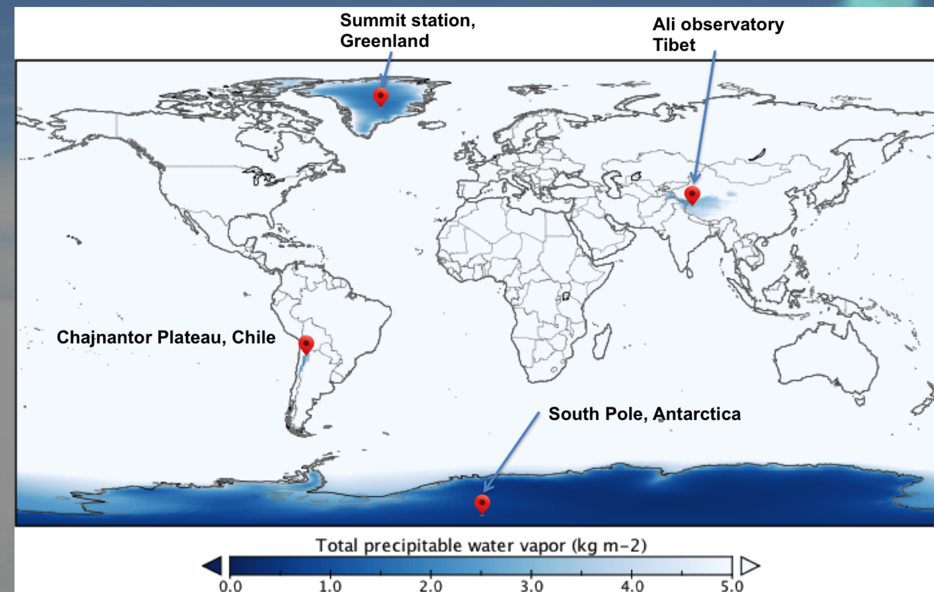
Challenges

- Risk of confirmation bias
- Tiny signal
- Sources of contamination
  - ~300K ground
  - emissive atmosphere
  - Astrophysical foregrounds
  - “Beam” uncertainty
  - Temperature to polarization leakage

Challenges + Mitigation Strategies

- Risk of confirmation bias → Blinded analysis
- Tiny signal → ~16K TES detectors + a 10m dish
- Sources of contamination
  - ~300K ground → Ground shield
  - emissive atmosphere → South Pole
  - Astrophysical foregrounds →
    1) Observe low MW-emission region
    2) 95, 150, 220 GHz
    3) Polarization only
  - "Beam" uncertainty → Measure response to Saturn and radio-bright galaxies (AGN)
  - Temperature to polarization leakage → Include in the model of the data

The South Pole is a unique window to the CMB… like being in space!



South Pole Environment

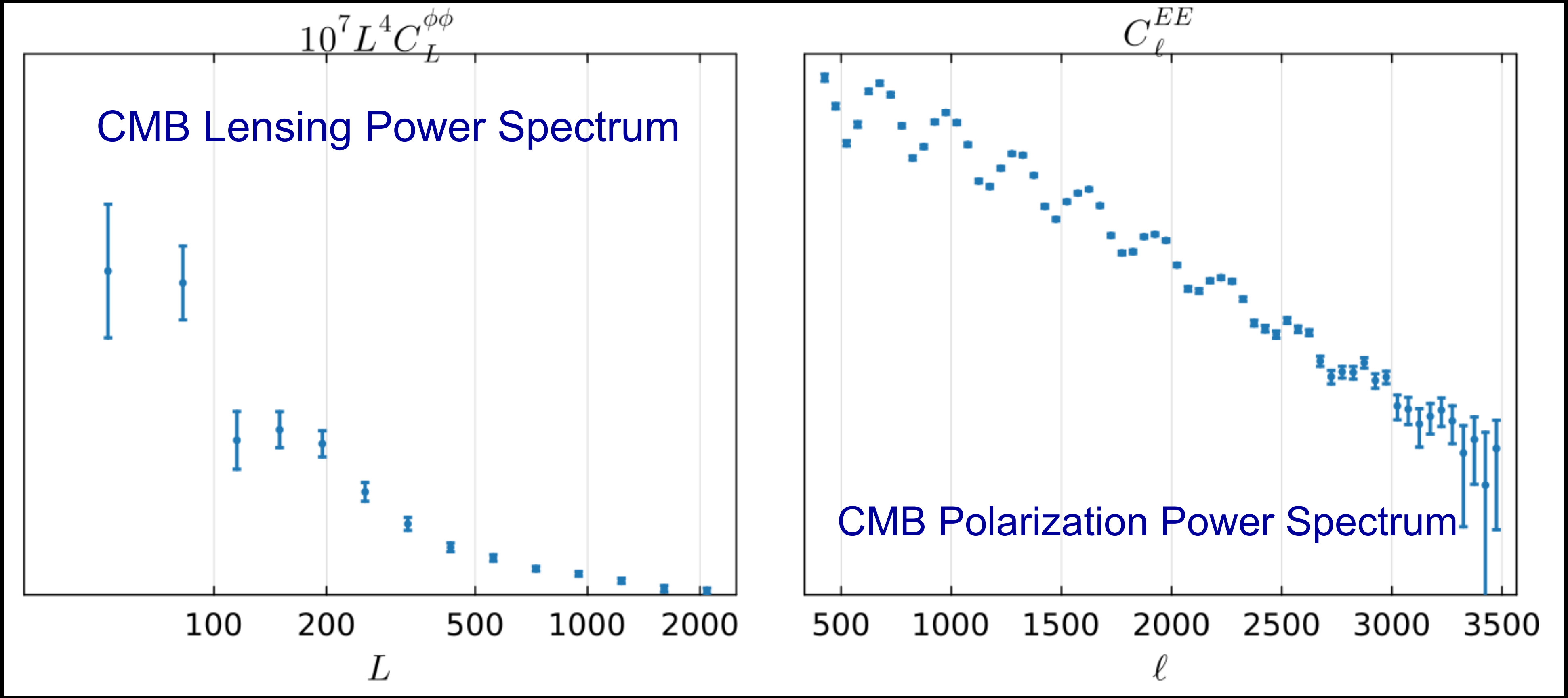
- **High Altitude (~10,000 ft) with unique Polar Vortex**
- **Driest desert on Earth with most stable atmosphere**
  - At Pole, the water vapor is 4x lower with a ~30-100x more stable atmosphere than the Chilean Atacama desert.
- **Relentless Observing**
  - 24/7 year-round access to Southern Sky, e.g., including the Black Hole at the Milky Way's center for the Event Horizon Telescope
- **Annual Access for rapid technology deployment**

Slide from B. Benson

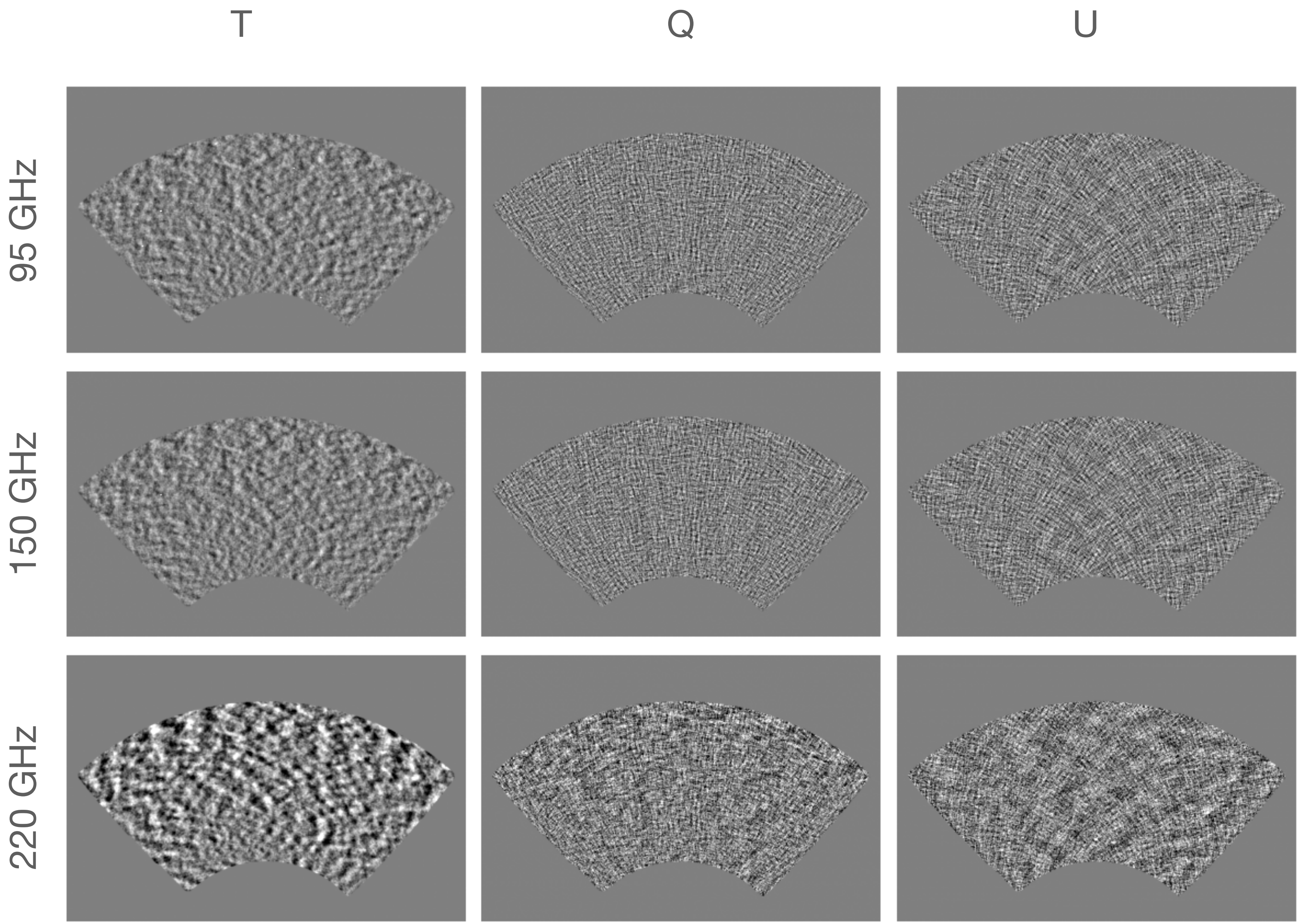
How did we blind ourselves?

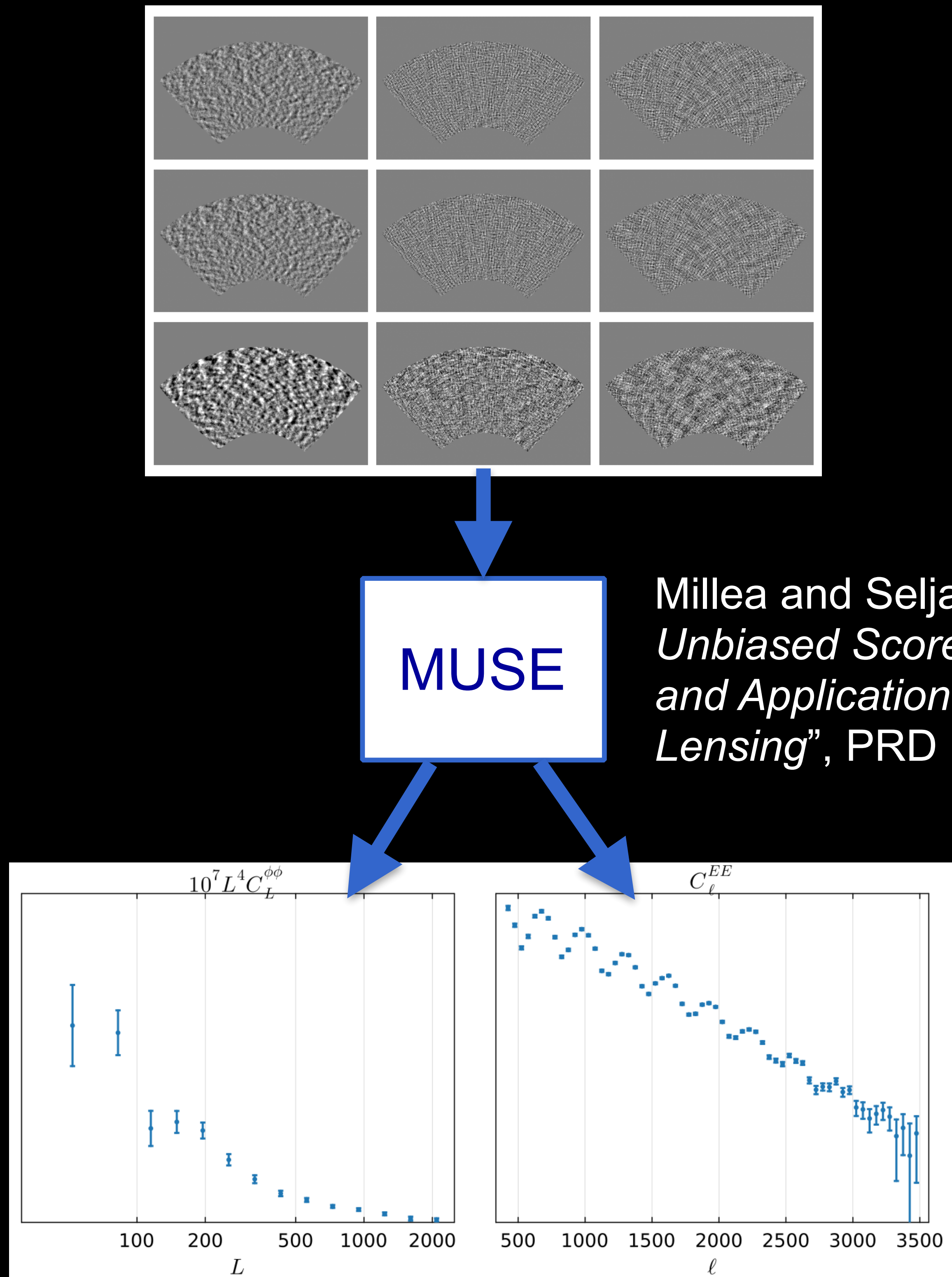
1) No comparing model power spectra to estimated power spectra
2) No looking at estimates of cosmological parameters

We did allow ourselves to see estimated spectra without y-axis labels:



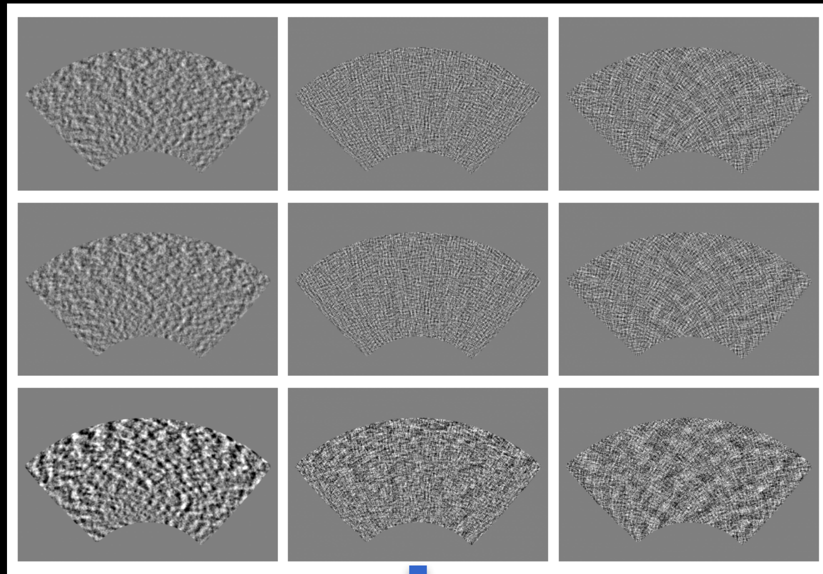
2019-2020 SPT-3G Maps





Millea and Seljak, "*Marginal Unbiased Score Expansion and Application to CMB Lensing*", PRD (2022)

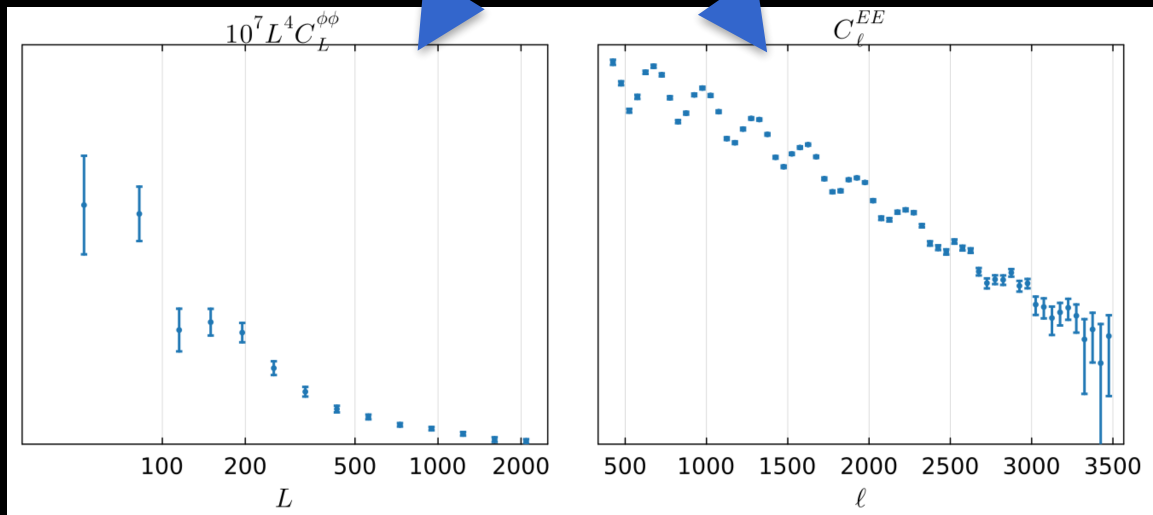
first use on real data



1) outperforms QE for lensing power reconstruction
2) Produces *unlensed* field power spectra
3) Convenient framework for incorporating instrumental effects

MUSE

Millea and Seljak, "*Marginal Unbiased Score Expansion and Application to CMB Lensing*", PRD (2022)



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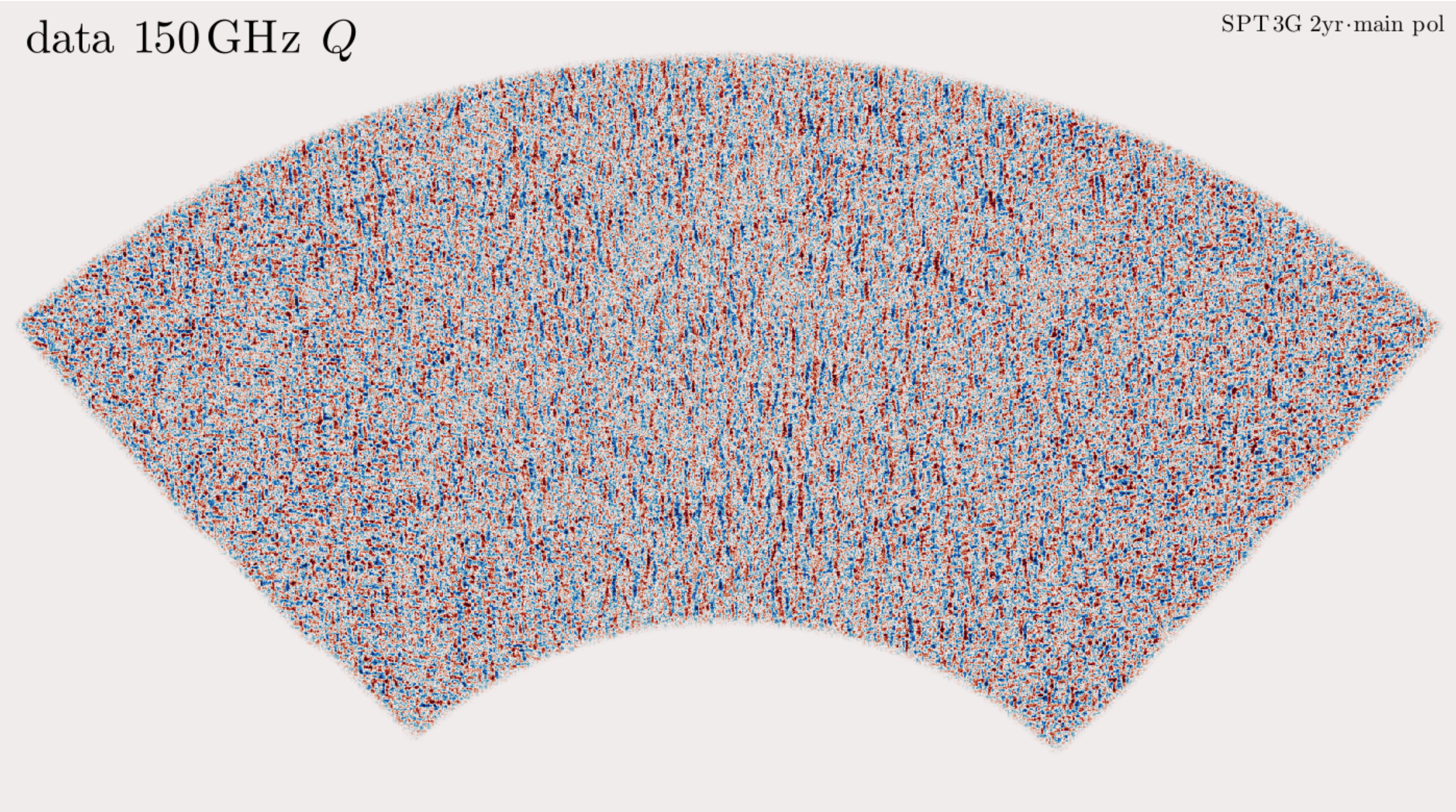
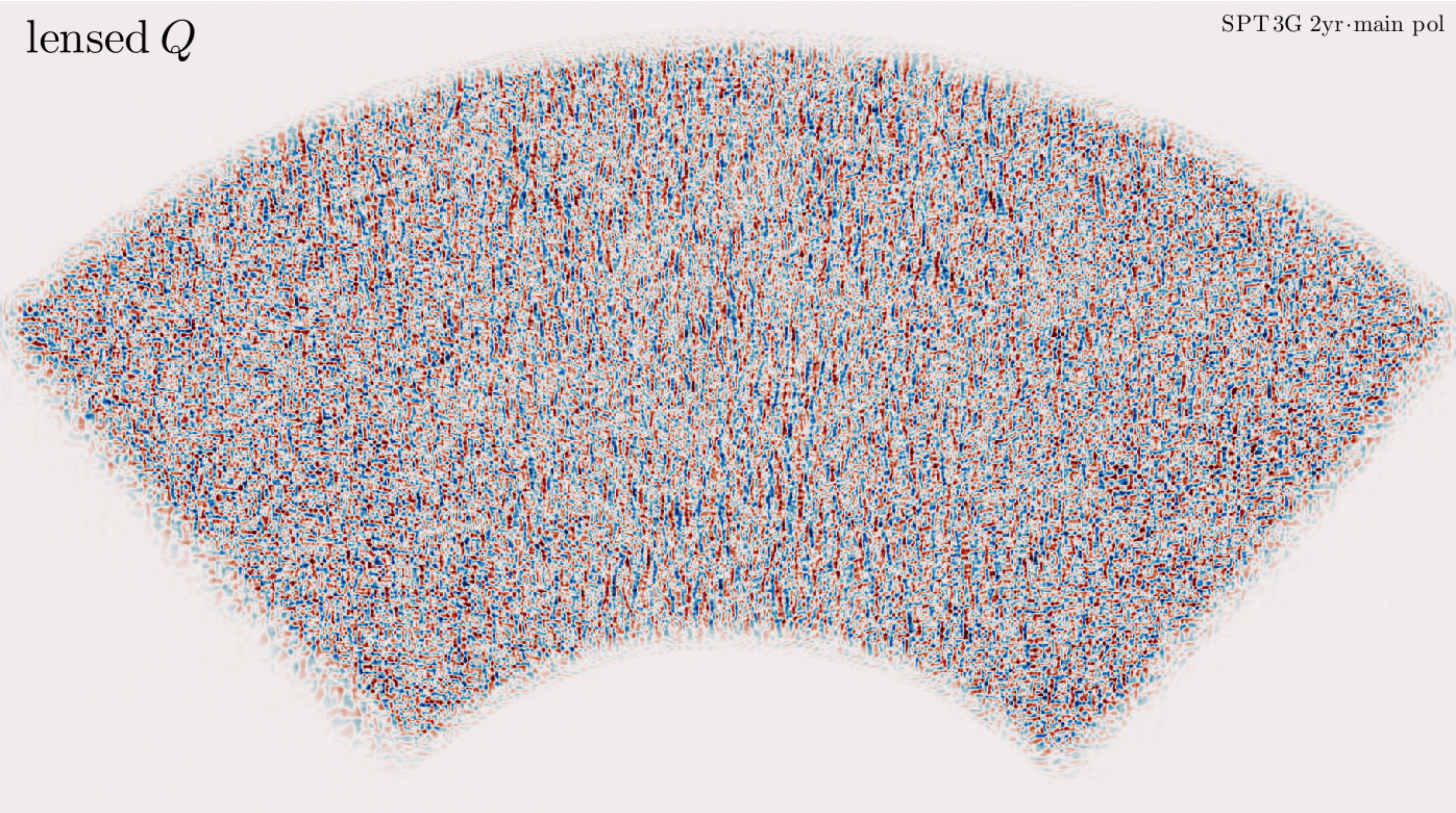
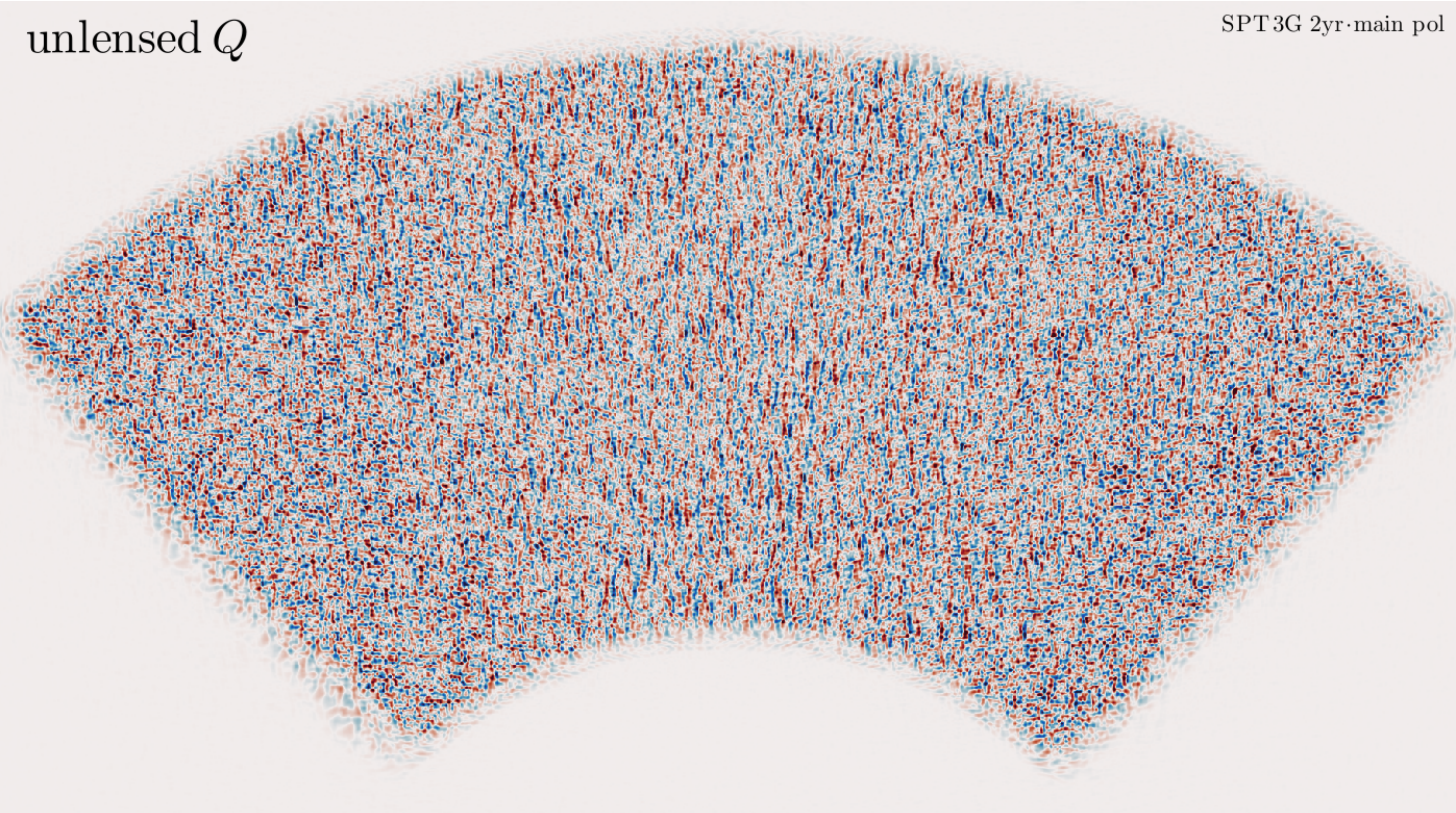
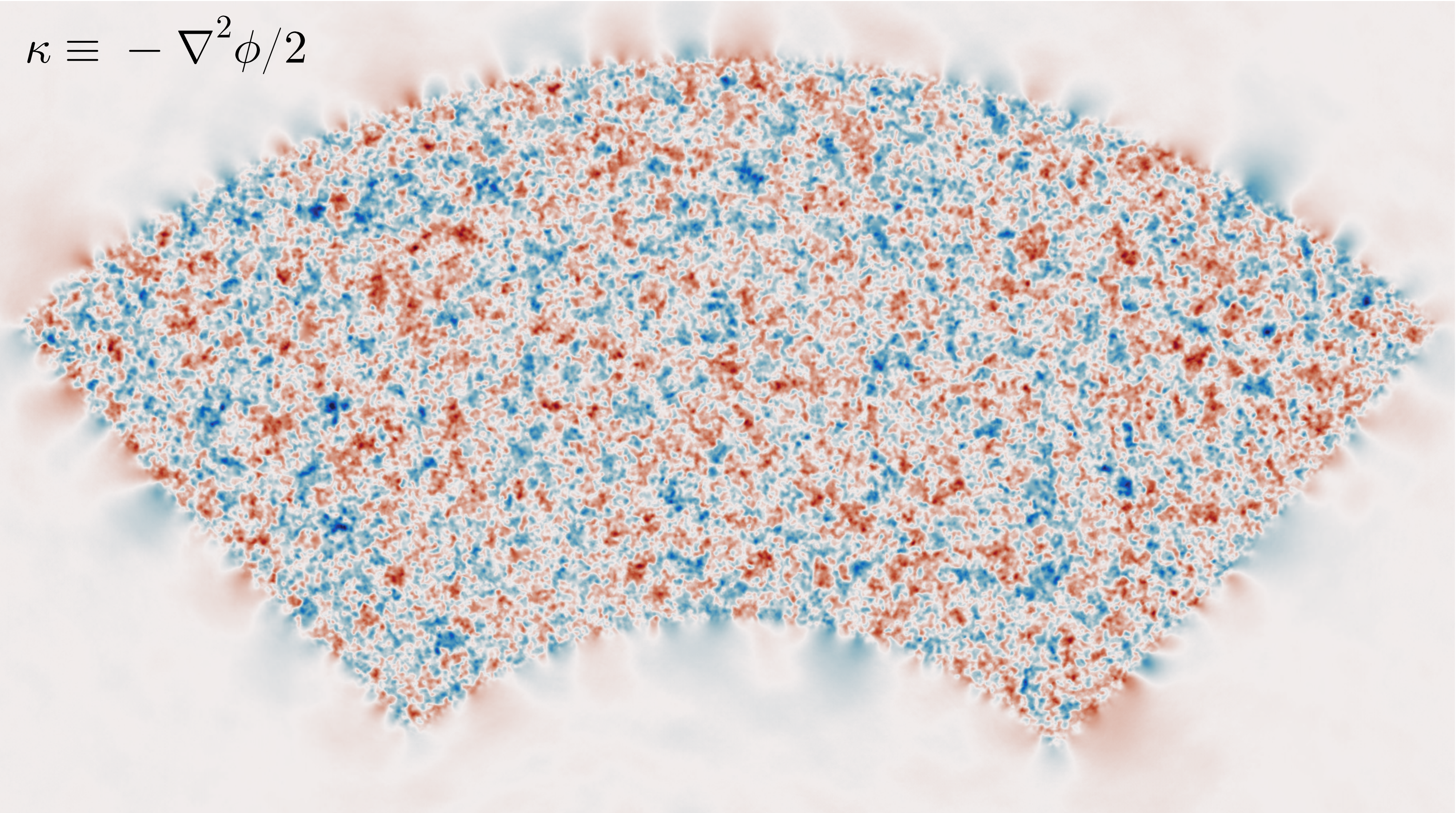
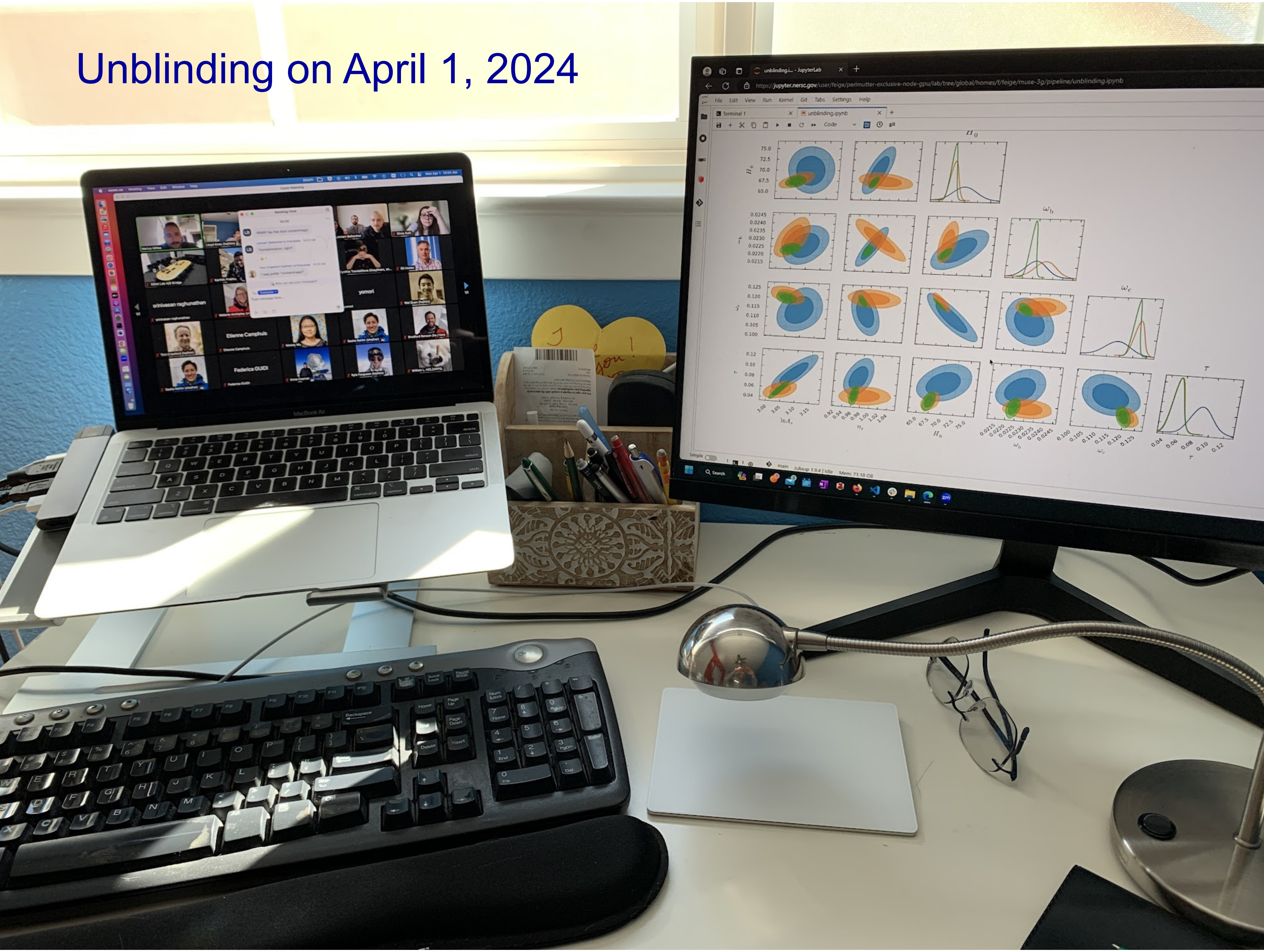

data 150 GHz Q
SPT3G 2yr·main pol


lensed Q
SPT3G 2yr·main pol

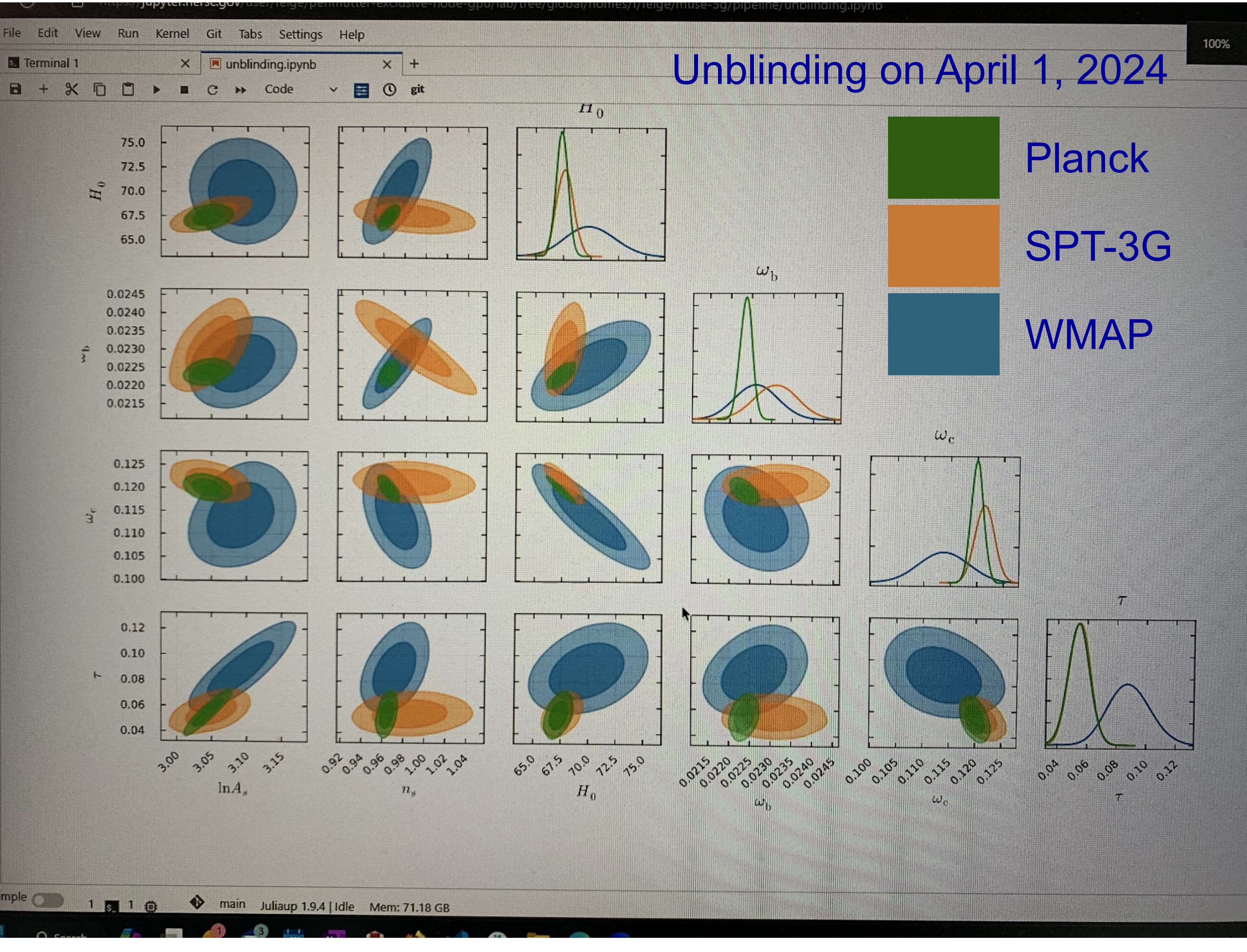

unlensed Q
SPT3G 2yr·main pol


$\kappa \equiv -\nabla^2\phi/2$

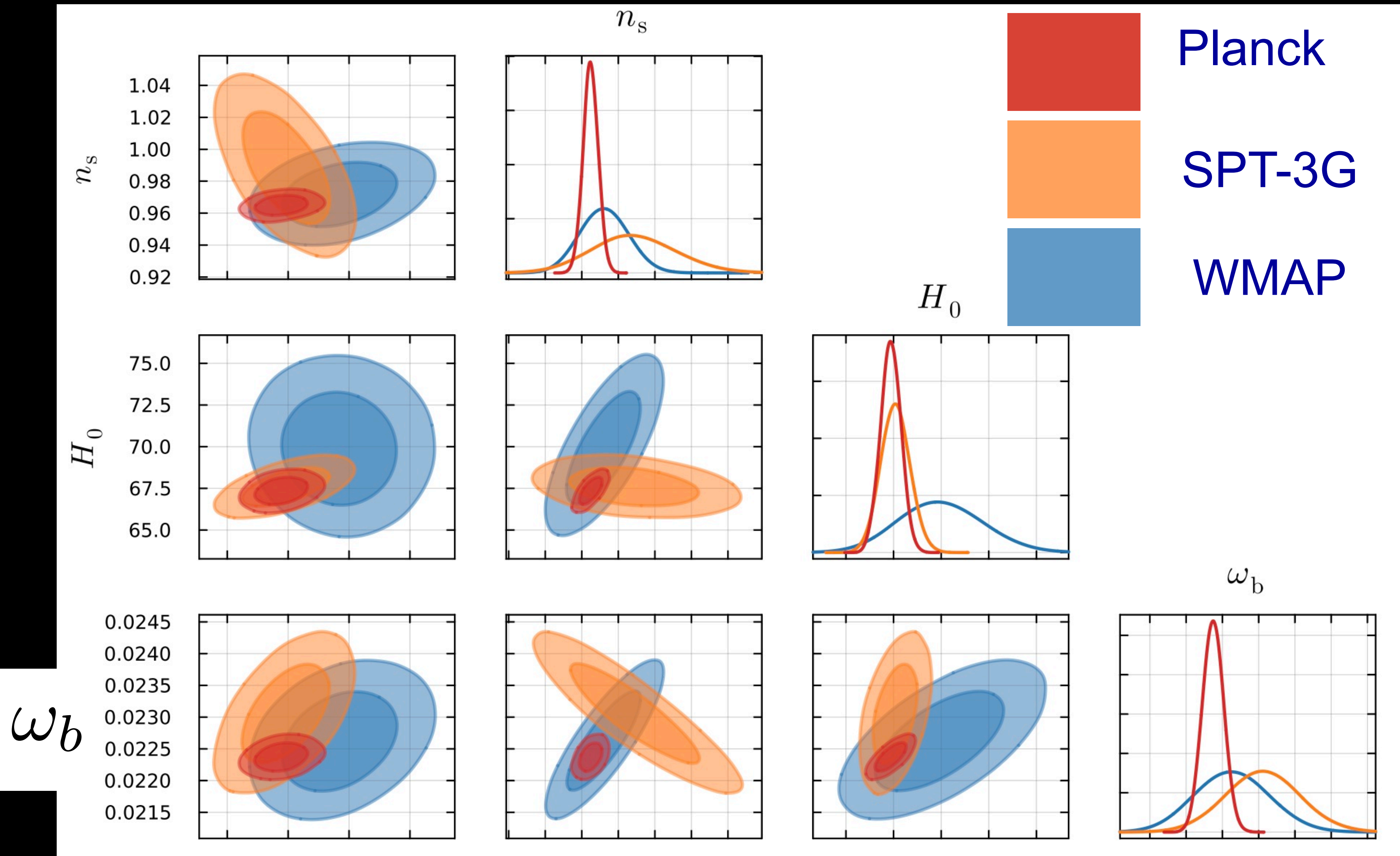
Unblinding on April 1, 2024



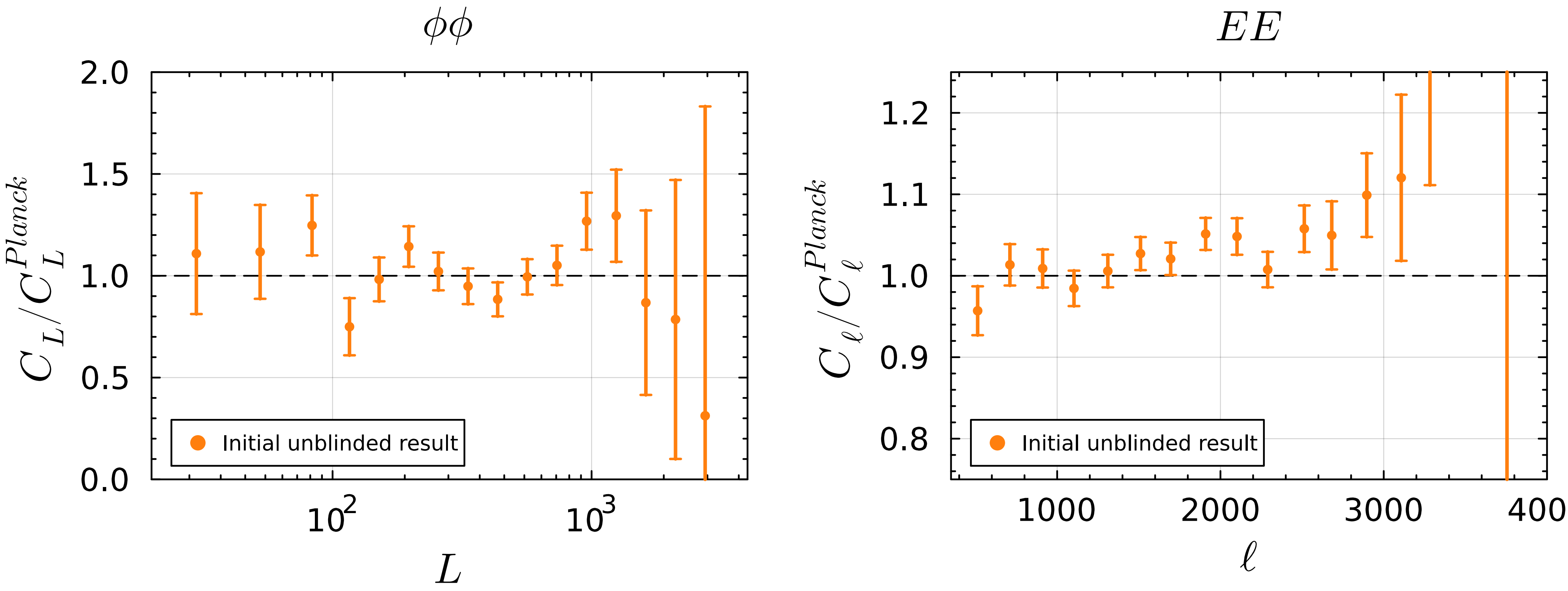
Unblinding on April 1, 2024



3.5 sigma discrepancy!



State of power spectra at unblinding, plotted with a best-fit-to-Planck model divided out



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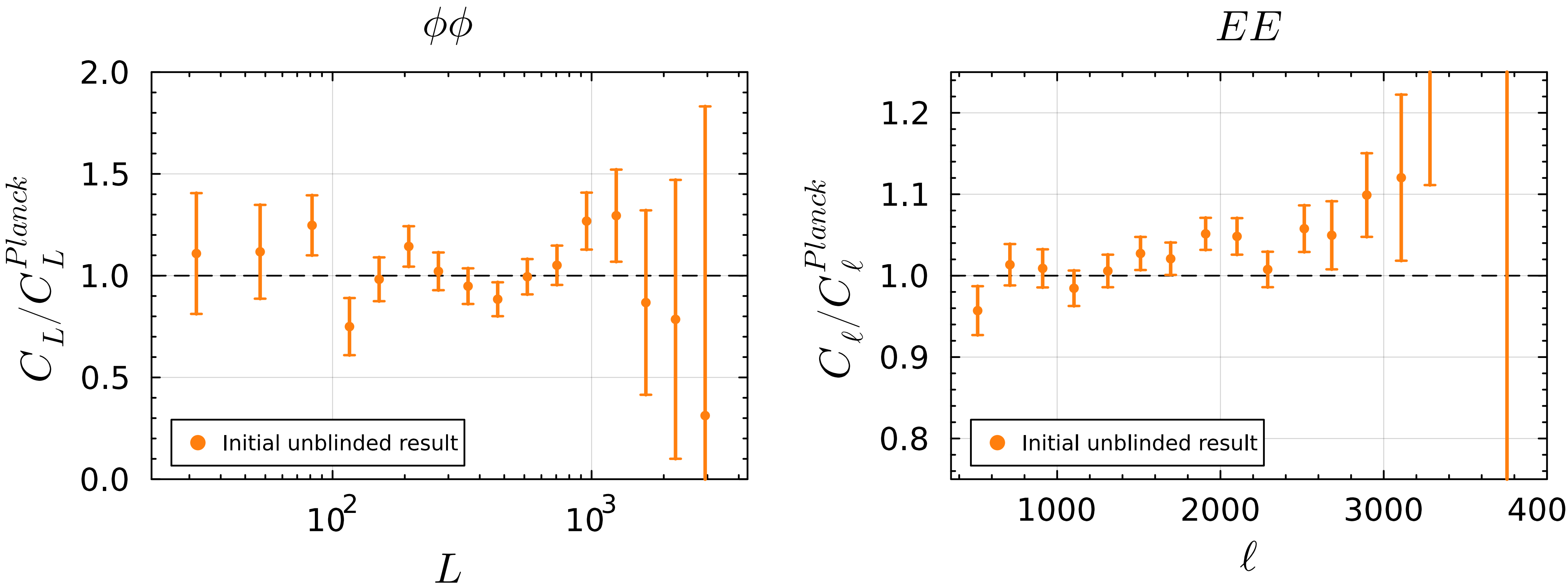
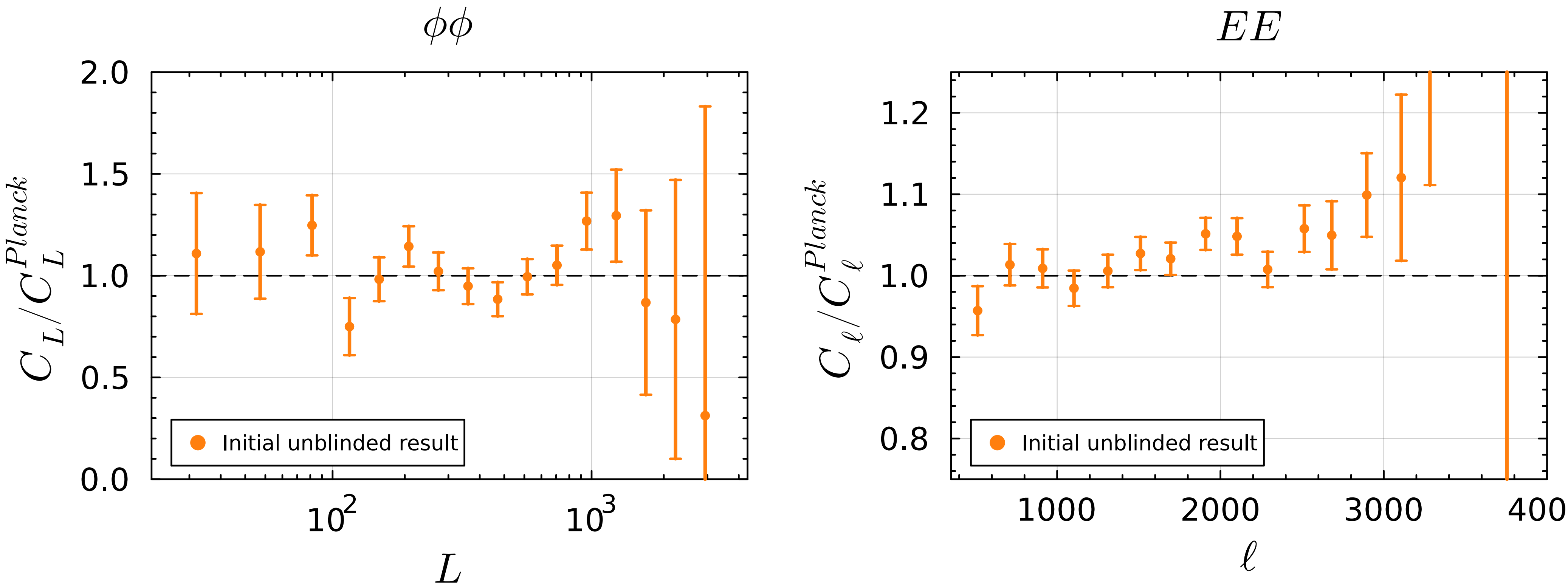


What do we believe about the instrument, that might not be so?

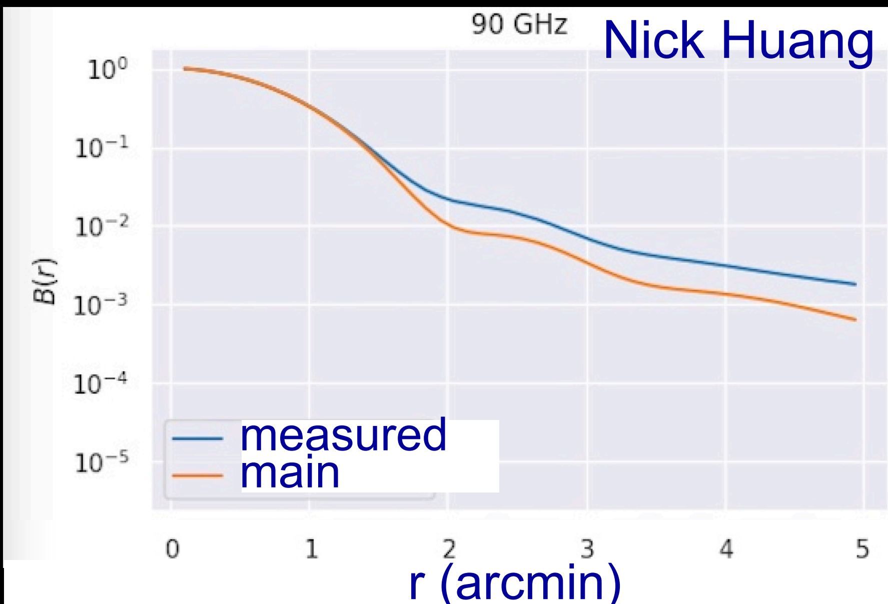
State of power spectra at unblinding, plotted with a best-fit-to-Planck model divided out

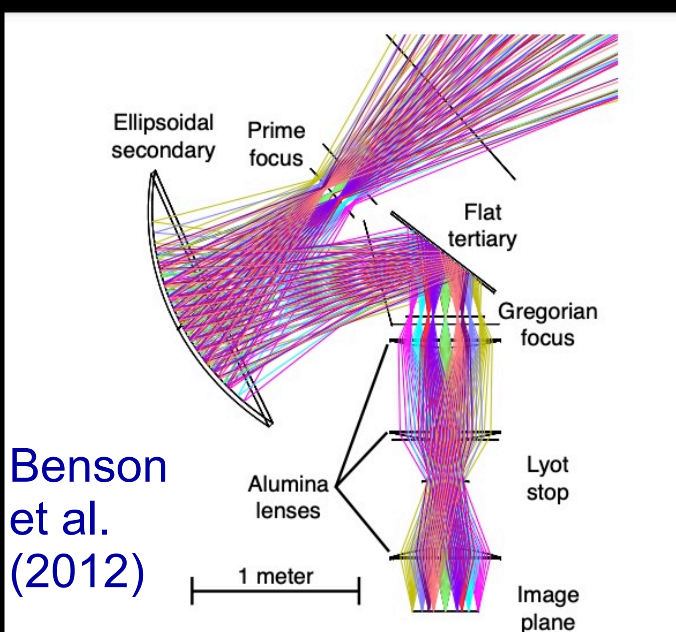


What do we believe about the instrument, that might not be so?

Is it a beam problem?

Polarized Beam Model





"main" is calculated with an idealized physical model of the optics. The effects included in the calculation preserve the polarization.

"measured" here is the measured response to a point source (Saturn + AGN). Differences with the main beam arise from additional scattering or reflection from, e.g., optical elements in the camera, or panel gaps in the primary mirror. These contributions do not necessarily preserve polarization.

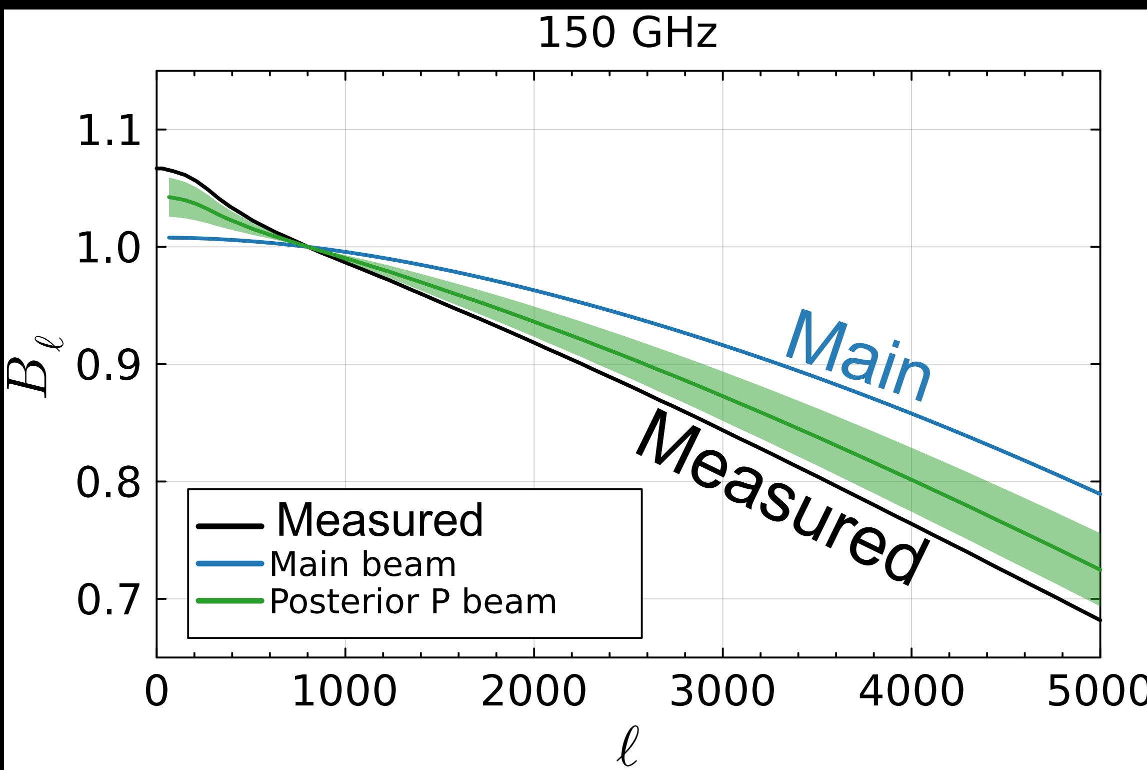
$$B^{\rm pol}(r) = B^{\rm main}(r) + \beta_{\rm pol}(B^{\rm measured}(r) - B^{\rm main}(r))$$

$$= {\rm main} + \beta_{\rm pol} \times {\rm sidelobe}$$

Polarized Beam Model

$$B_l^{\mathrm{polarized}} = B_l^{\mathrm{main}} + \beta_{\mathrm{pol}} \left(B_l^{\mathrm{measured}} - B_l^{\mathrm{main}} \right)$$

Sidelobe contribution



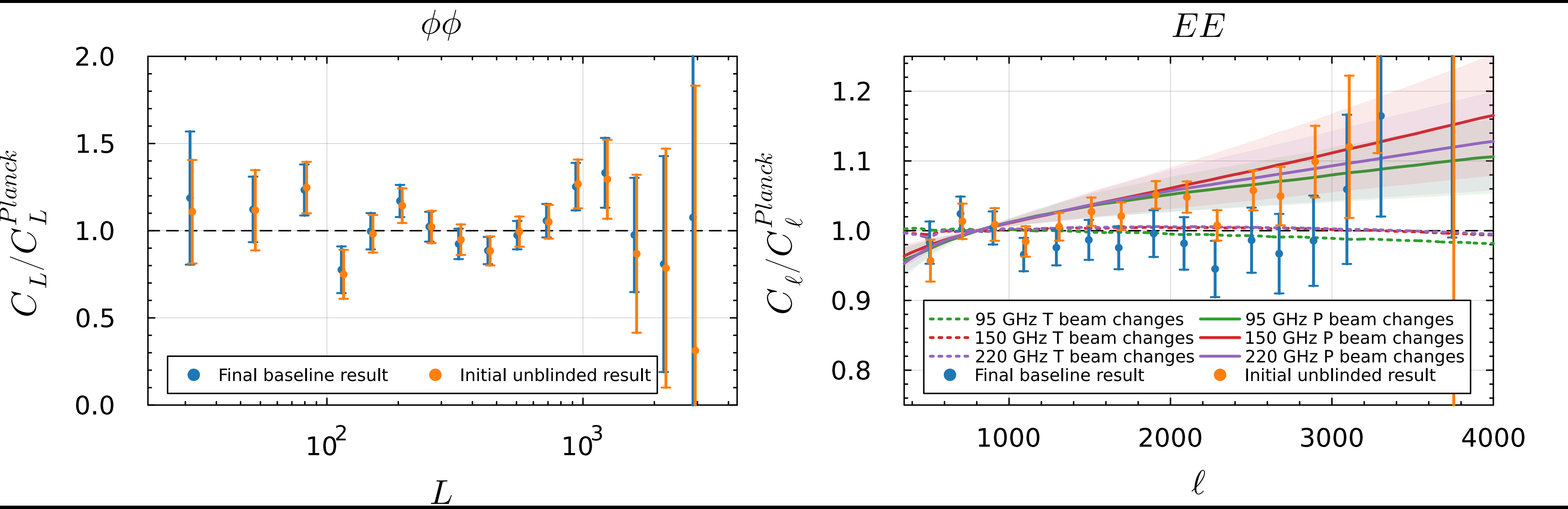
Prior: $\beta_{\mathrm{pol}} \in [0, 1]$

Posterior:

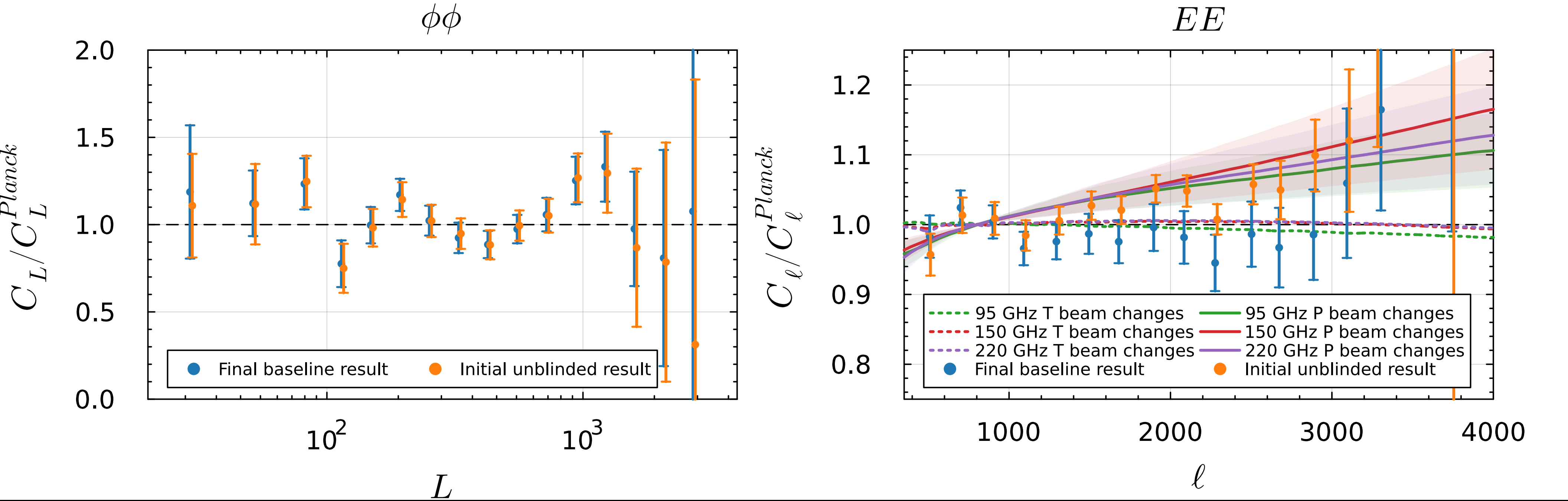
$$\beta_{\mathrm{pol}} = 0.60 \pm 0.28$$

The sidelobe at each frequency has a different shape ==> can simultaneously fit CMB power spectra and β_{pol} at each frequency

New bandpowers (blue points)

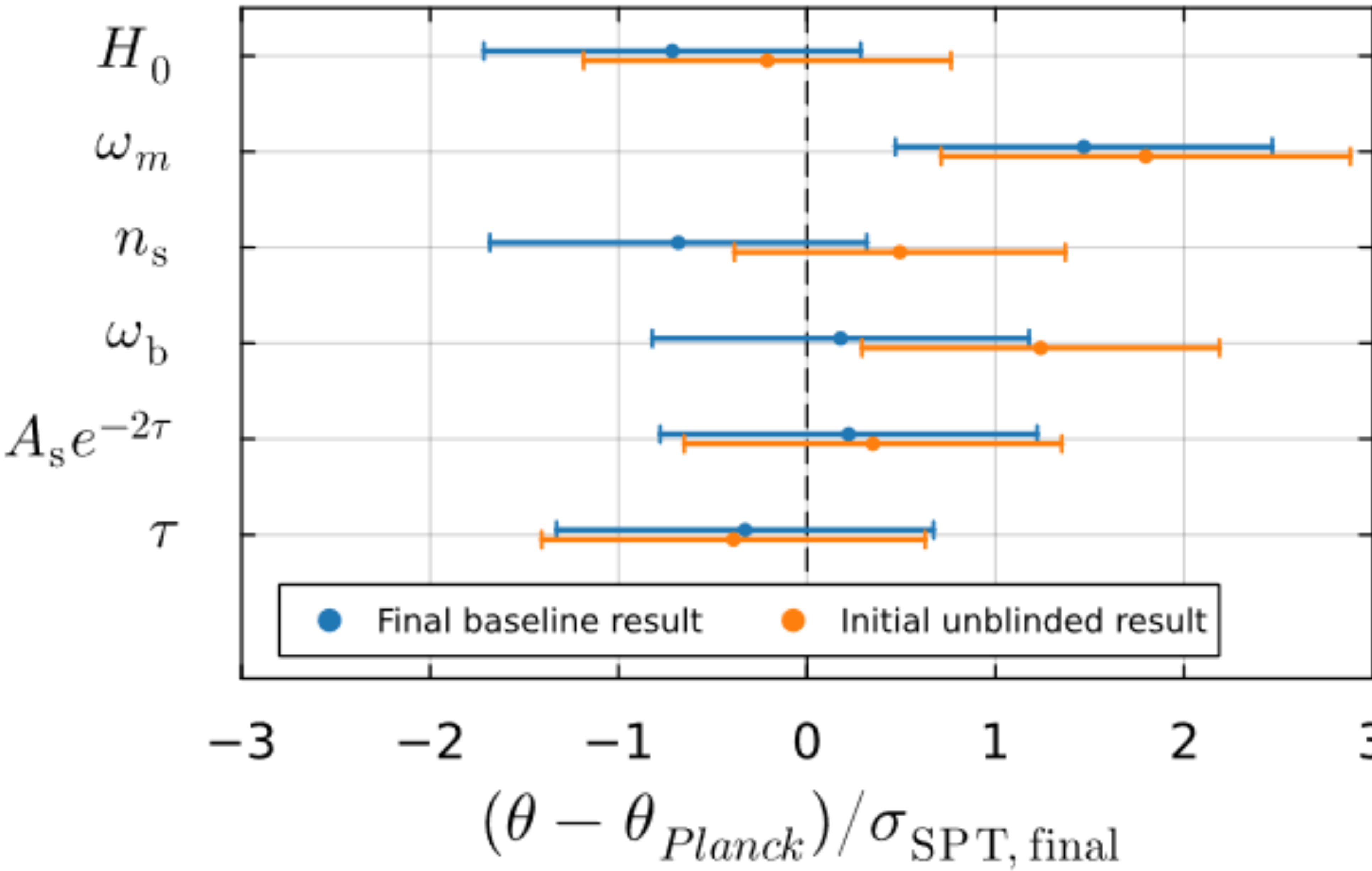


New bandpowers = final band powers



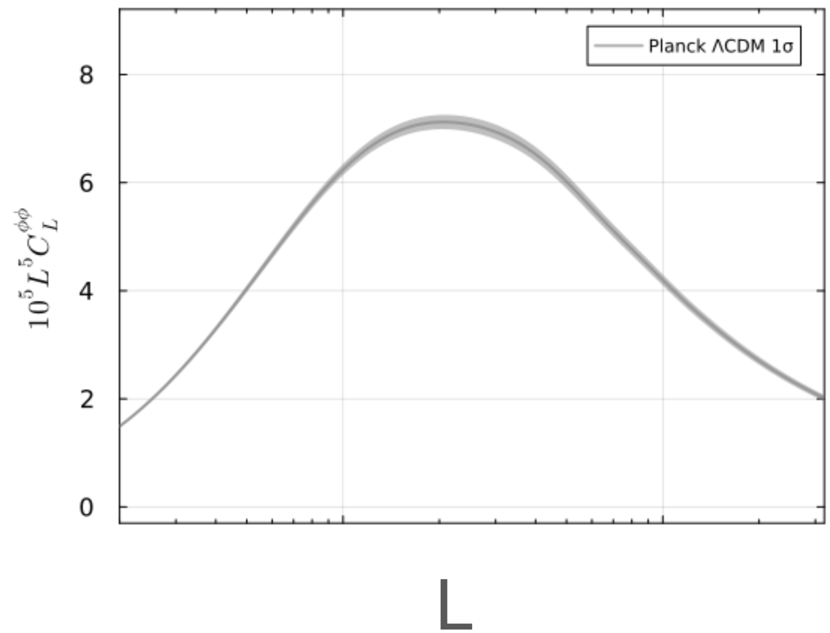
Bandpowers and cosmology robust to: 1) simplifying our model of the main beam and 2) allowing for each $\beta_{\rm pol}$ to depend on angular scale

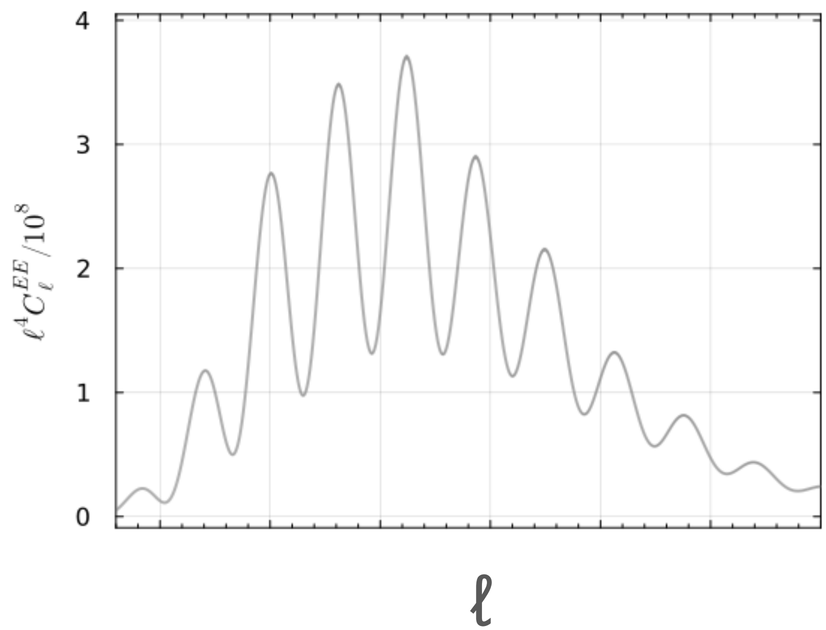
Initial unblinded to final parameter shifts



Results – bandpowers

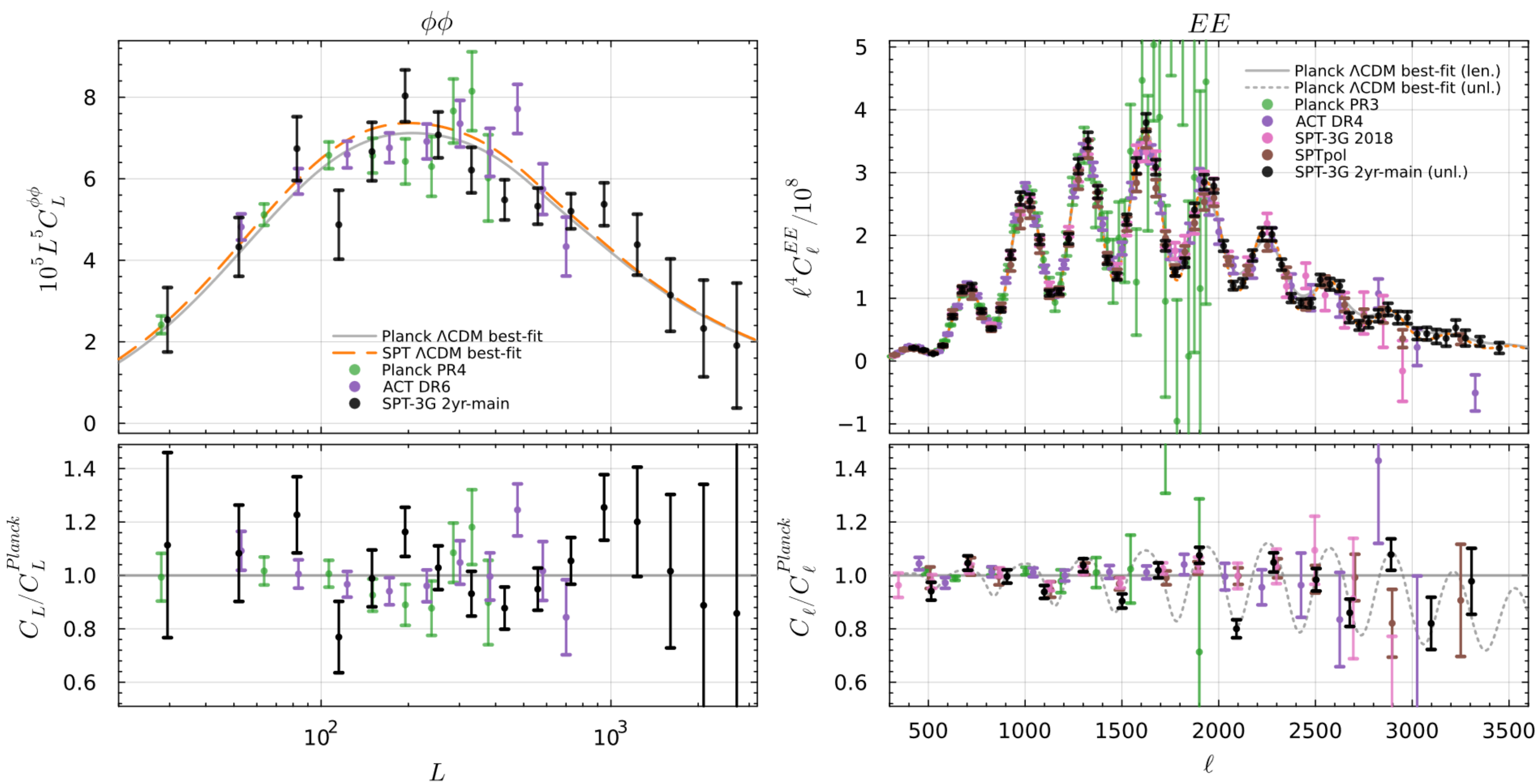
- LCDM model fits SPT data well and in agreement with Planck.





Results – bandpowers

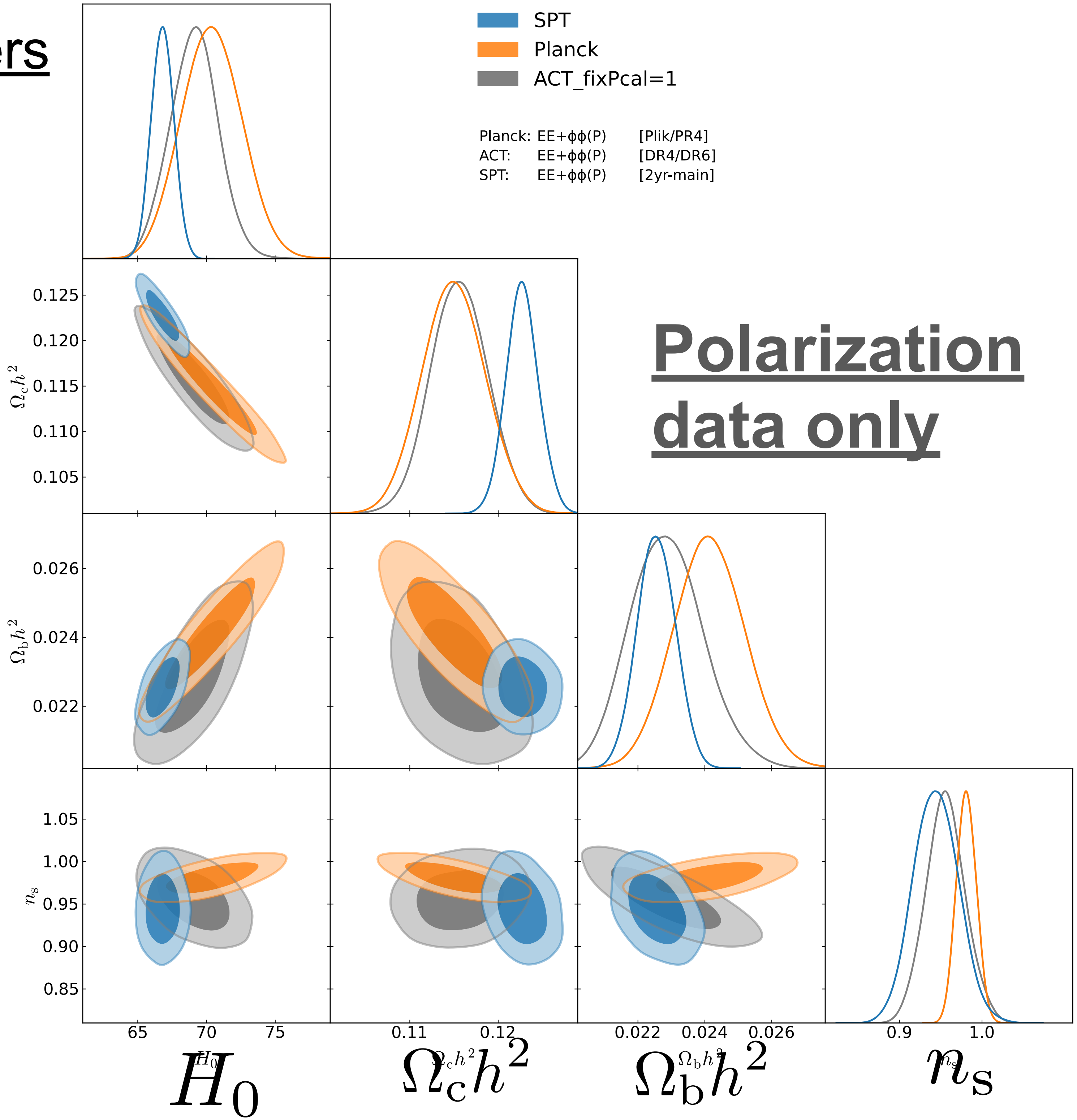
- This work has the tightest bandpower measurement of ϕϕ at L>350 and EE at ℓ>2000 to date.



LCDM parameters

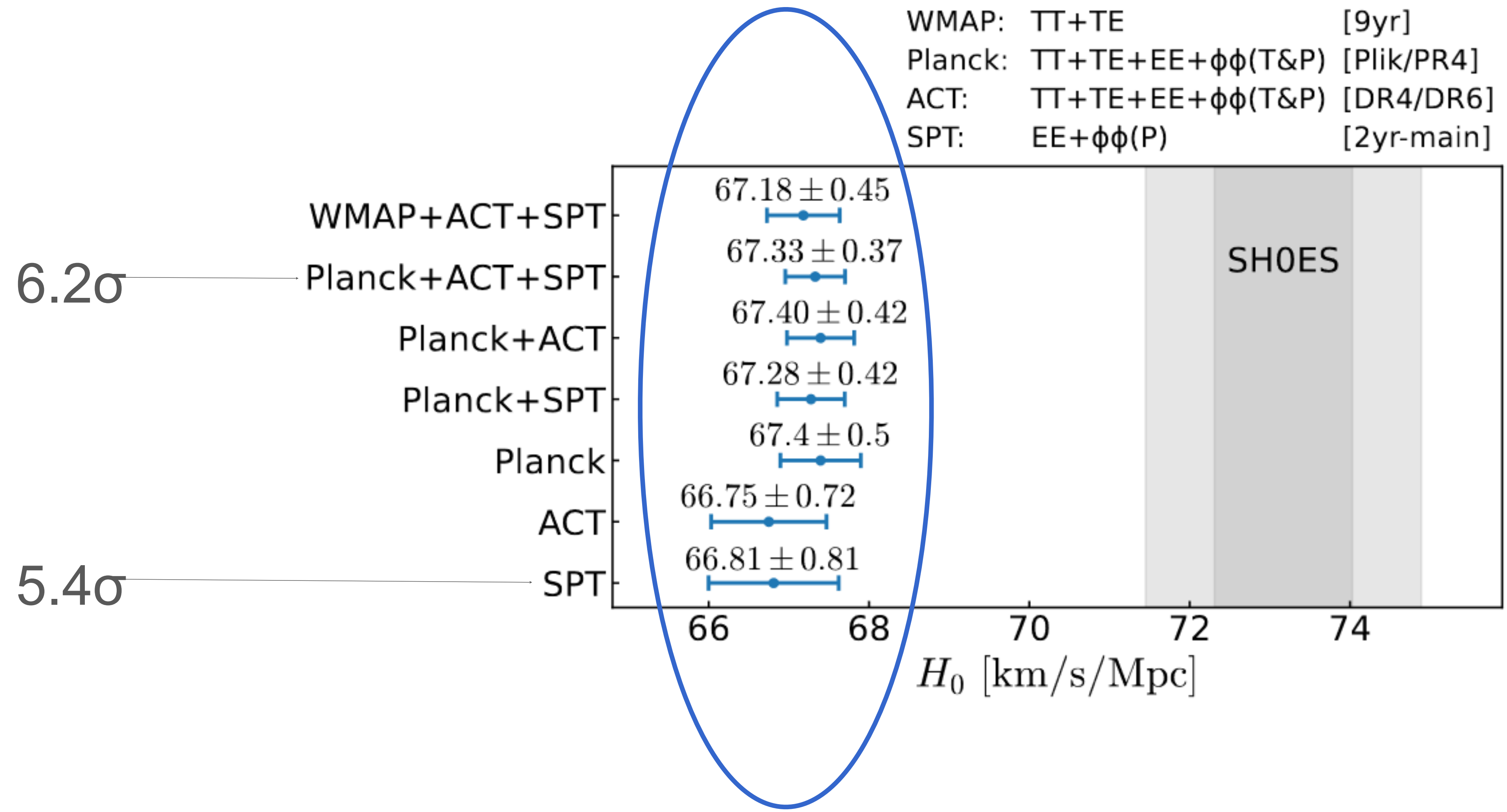
SPT-3G:
H_0=66.8+/-0.8 km/sec/Mpc

5.4σ difference with SH0ES.



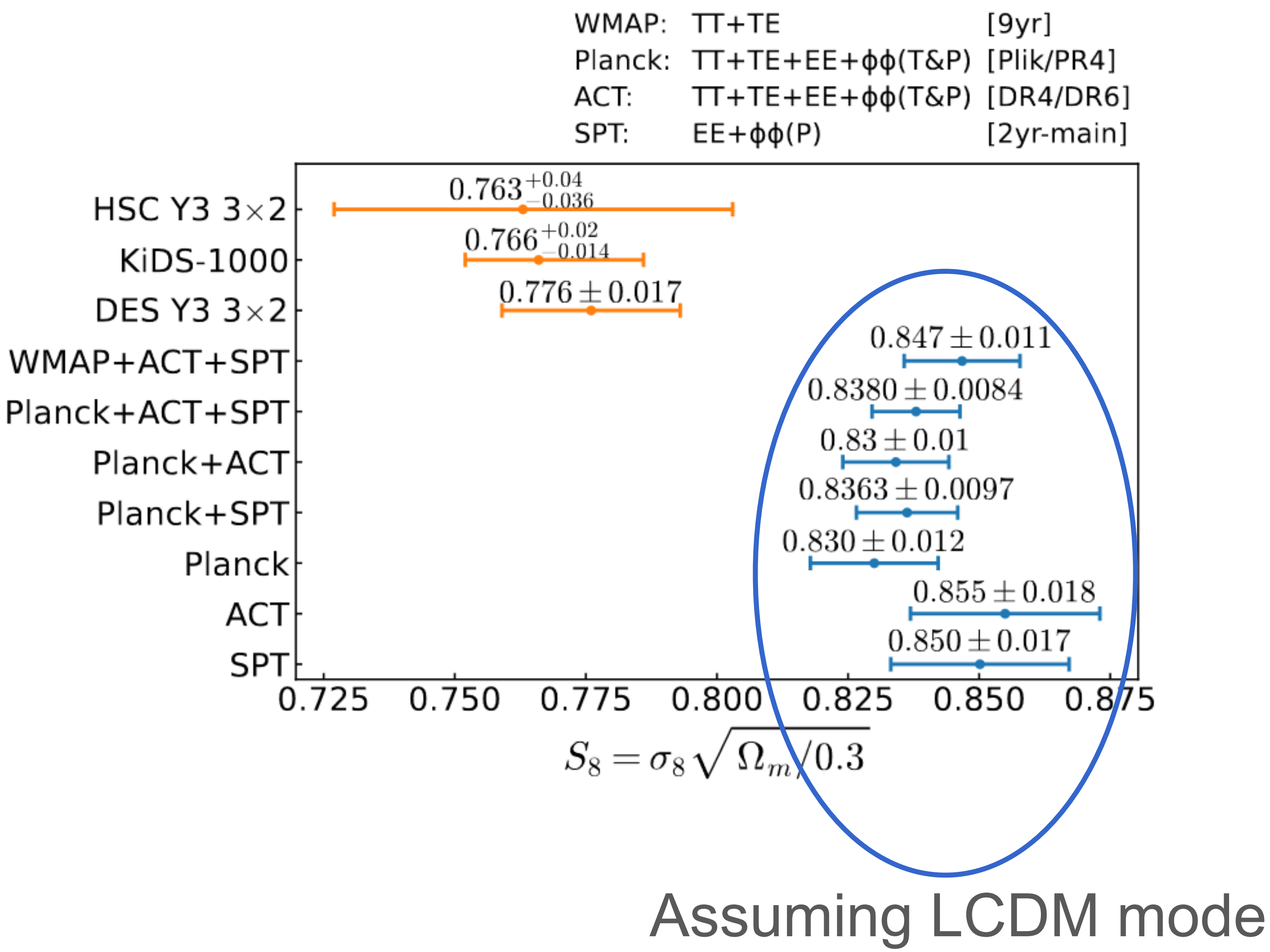
Polarization data only

Results – H_0



Assuming LCDM model

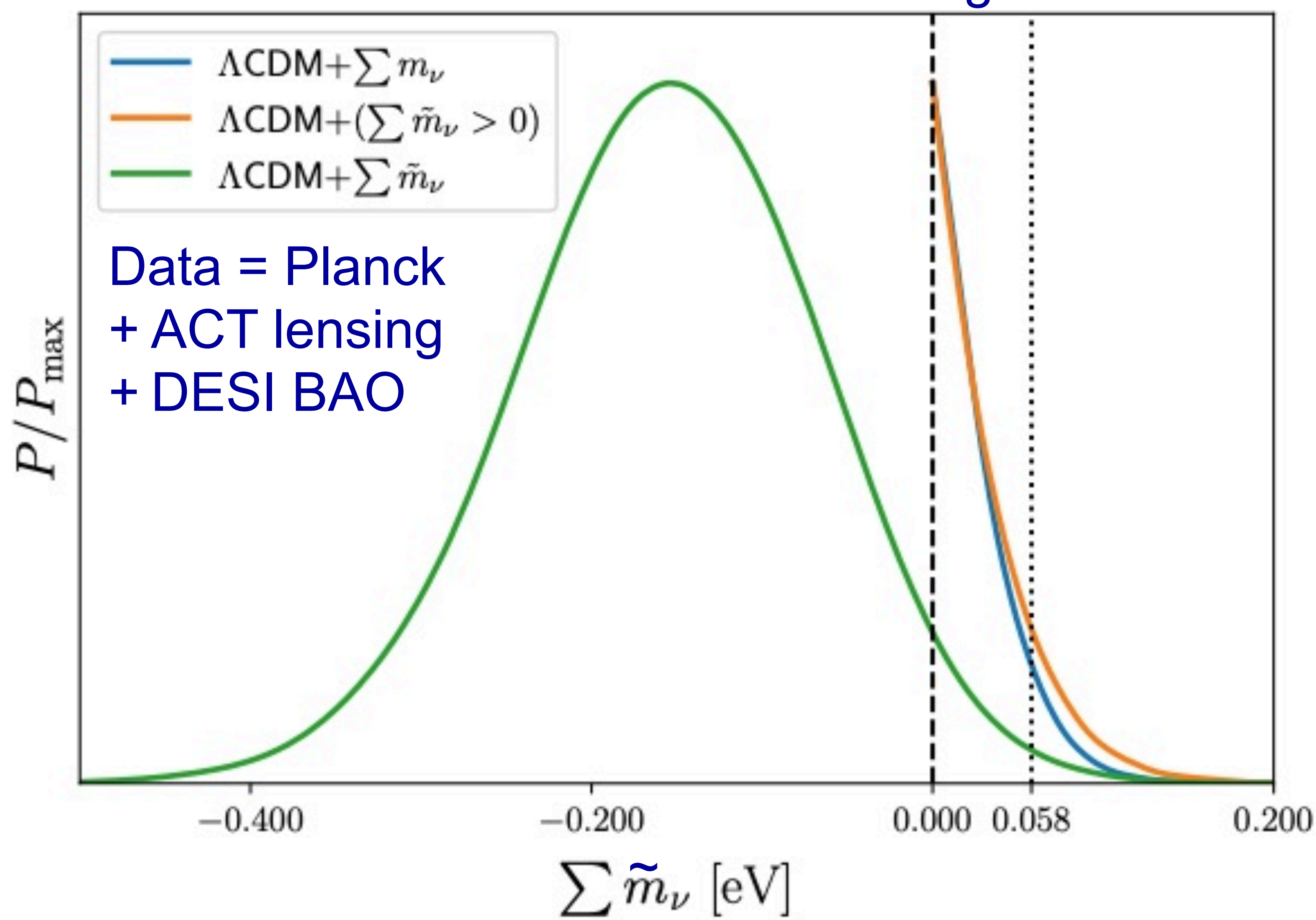
Results – S_8



WMAP: TT+TE [9yr]
Planck: TT+TE+EE+ϕϕ(T&P) [Plik/PR4]
ACT: TT+TE+EE+ϕϕ(T&P) [DR4/DR6]
SPT: EE+ϕϕ(P) [2yr-main]
HSC Y3 3×2
KiDS-1000
DES Y3 3×2
WMAP+ACT+SPT
Planck+ACT+SPT
Planck+ACT
Planck+SPT
Planck
ACT
SPT
$0.763^{+0.04}_{-0.036}$
$0.766^{+0.02}_{-0.014}$
0.776 ± 0.017
0.847 ± 0.011
0.8380 ± 0.0084
0.83 ± 0.01
0.8363 ± 0.0097
0.830 ± 0.012
0.855 ± 0.018
0.850 ± 0.017
0.725
0.750
0.775
0.800
0.825
0.850
0.875
$S_8 = \sigma_8\sqrt{\Omega_m/0.3}$
Assuming LCDM model

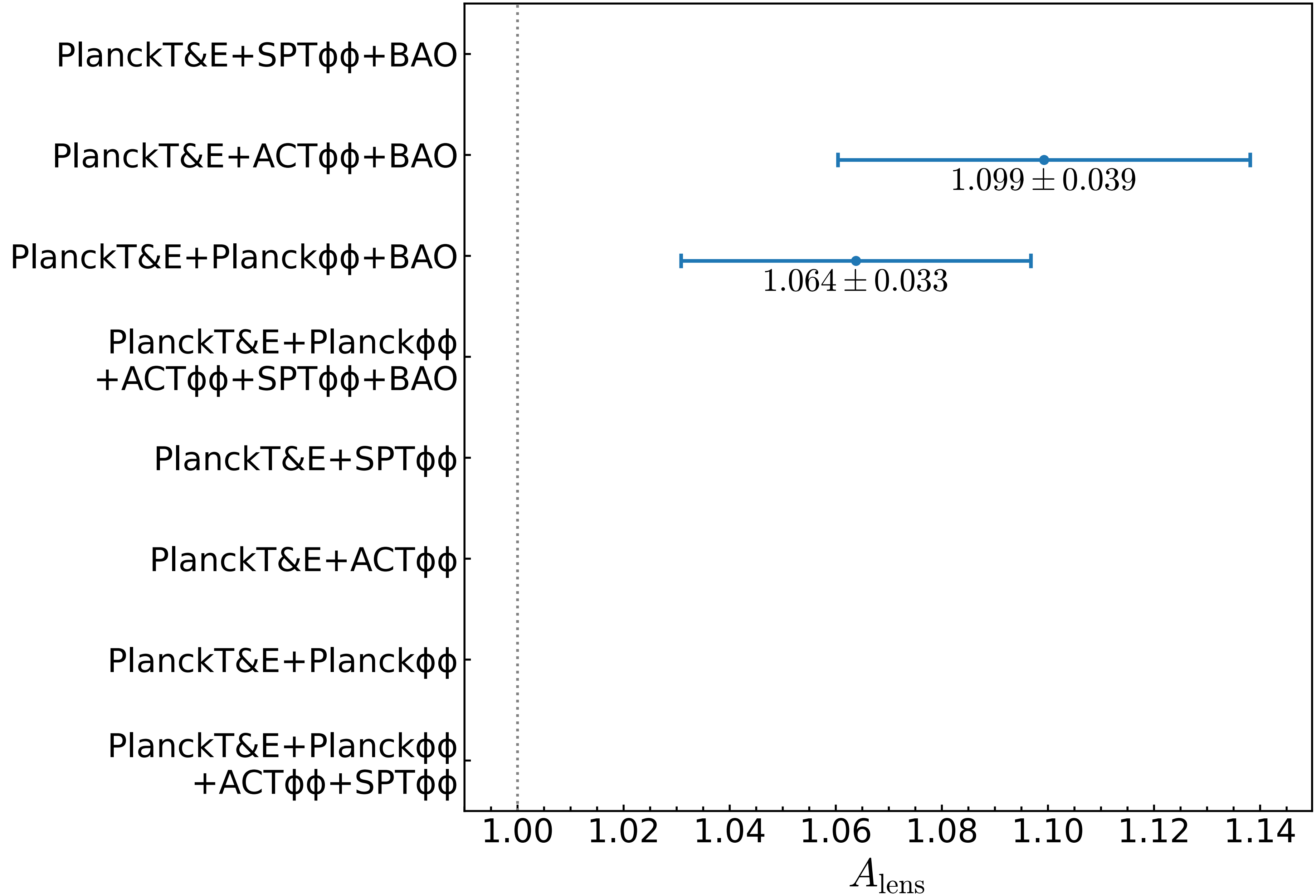
Results – excess lensing power

Craig et al. 2024



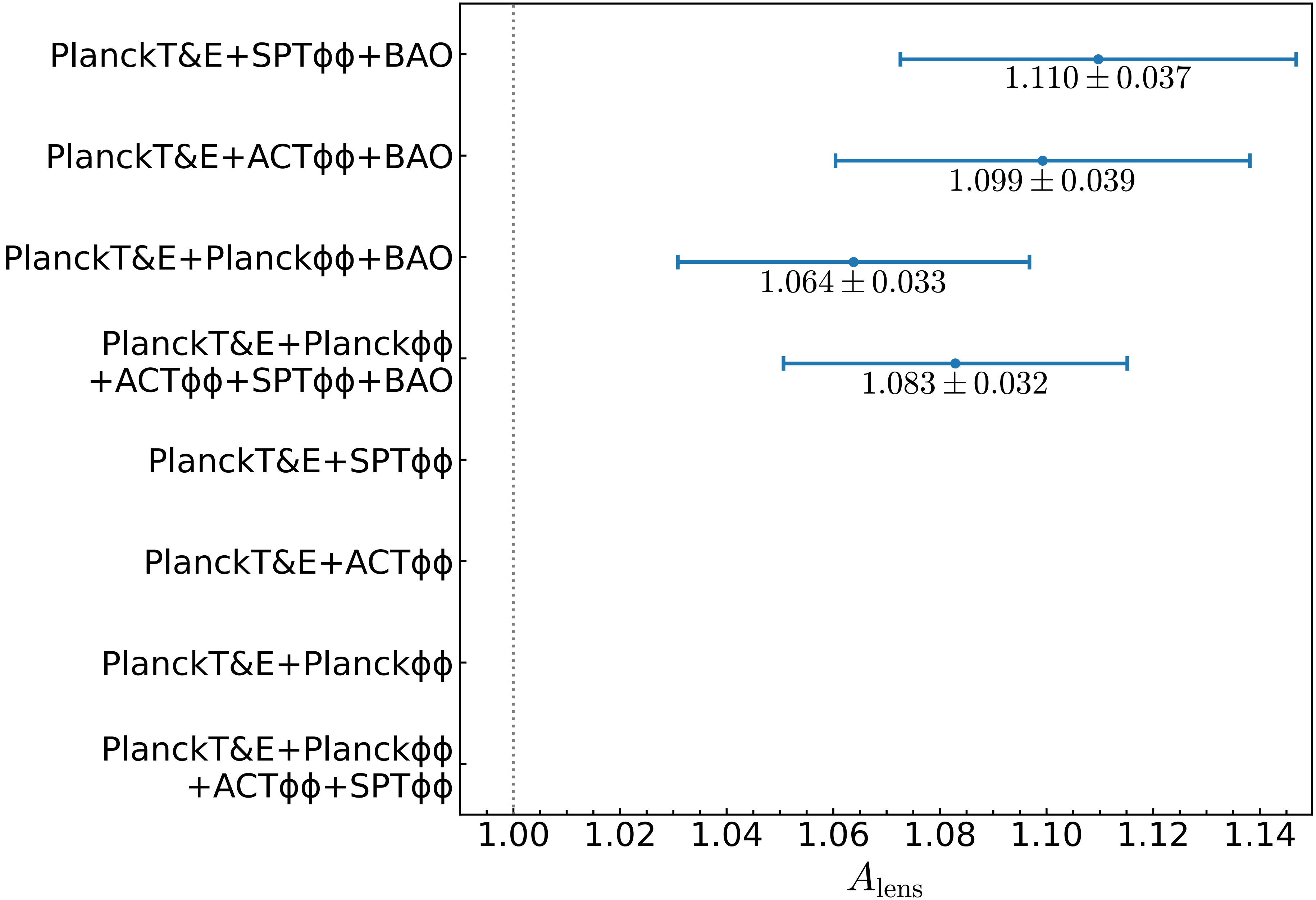
$\Lambda\mathrm{CDM} + A_{\mathrm{lens}}$

Results – excess lensing power



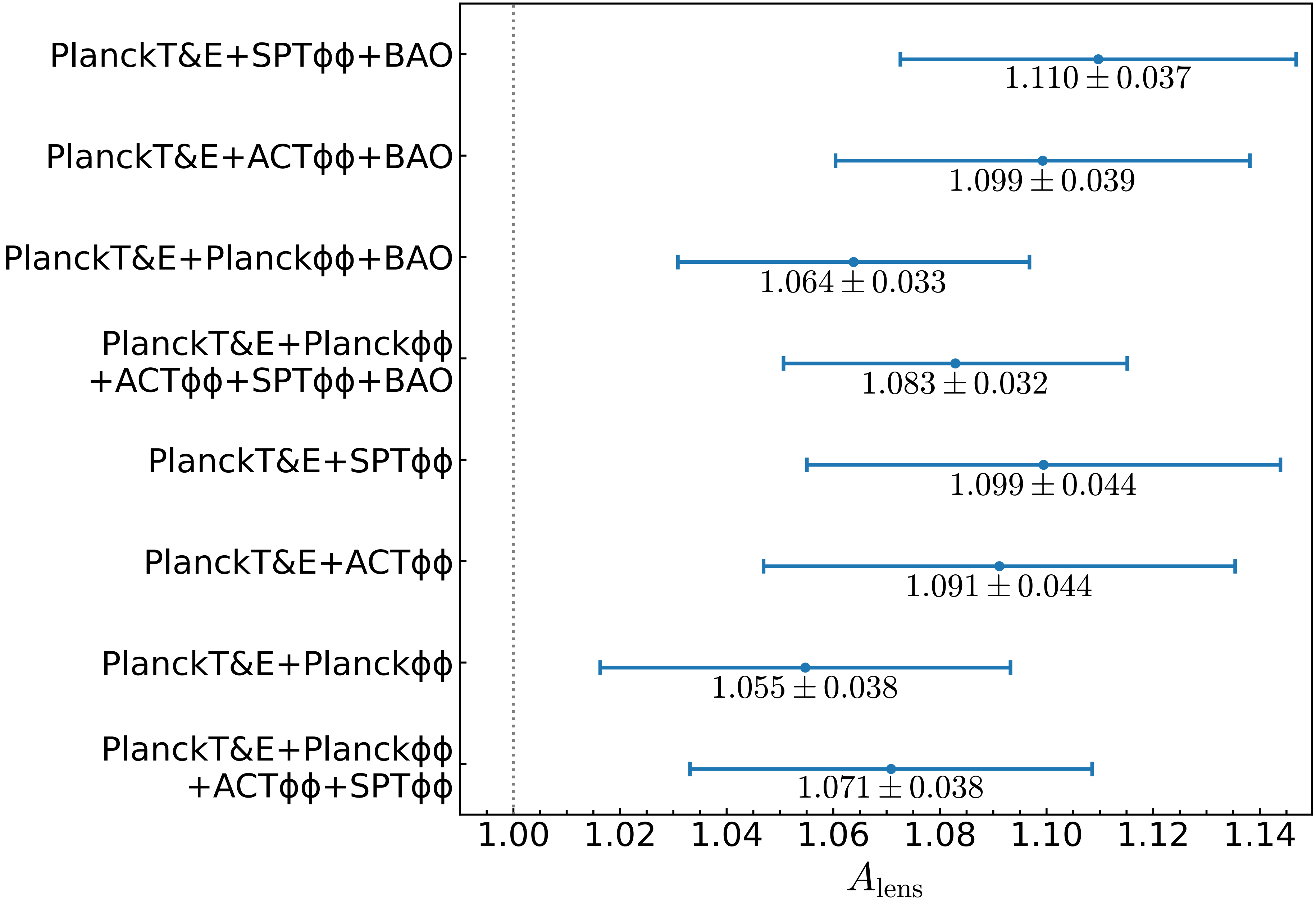
$\Lambda\text{CDM} + A_{\text{lens}}$

Results – excess lensing power



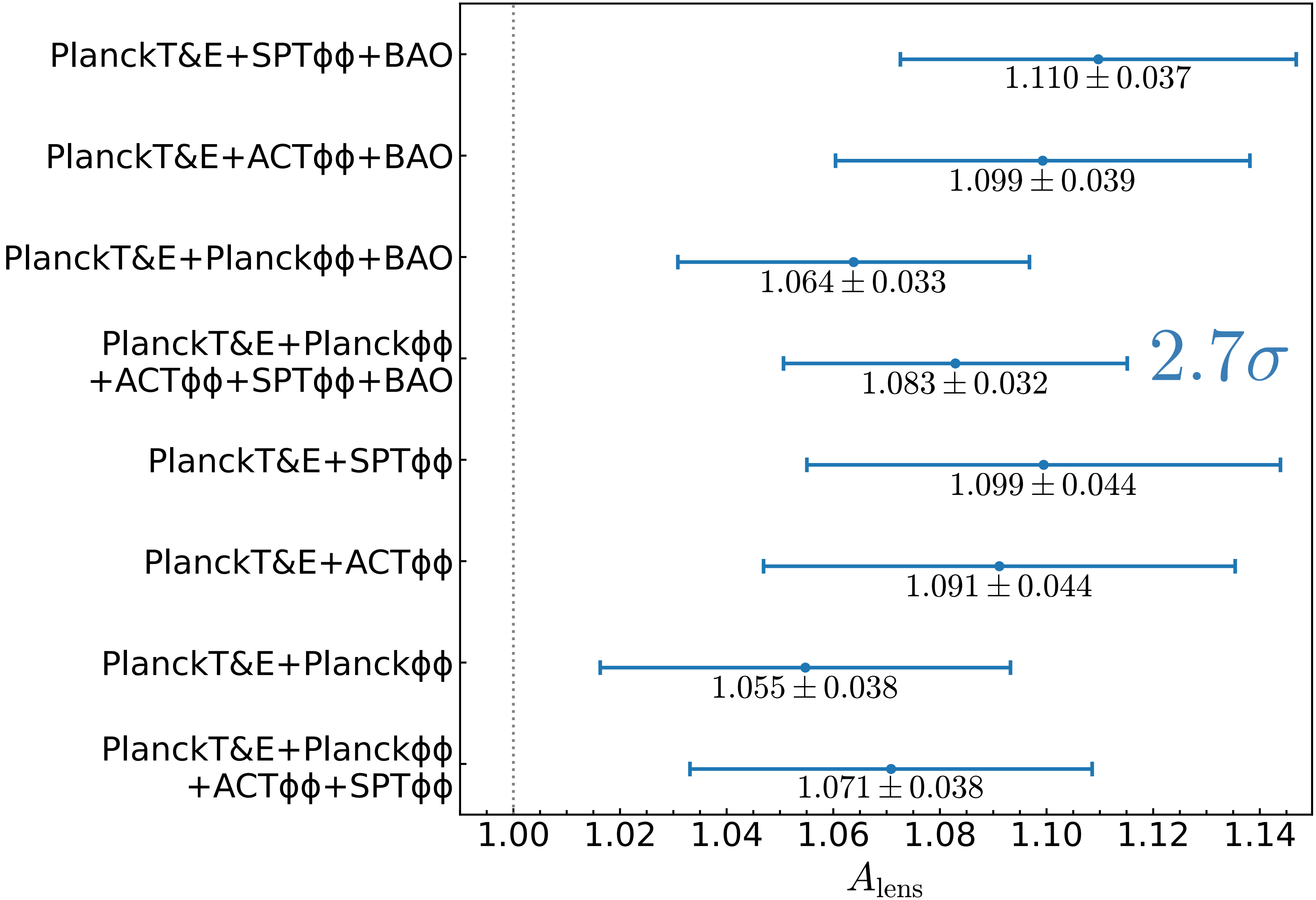
$\Lambda\text{CDM} + A_{\text{lens}}$

Results – excess lensing power



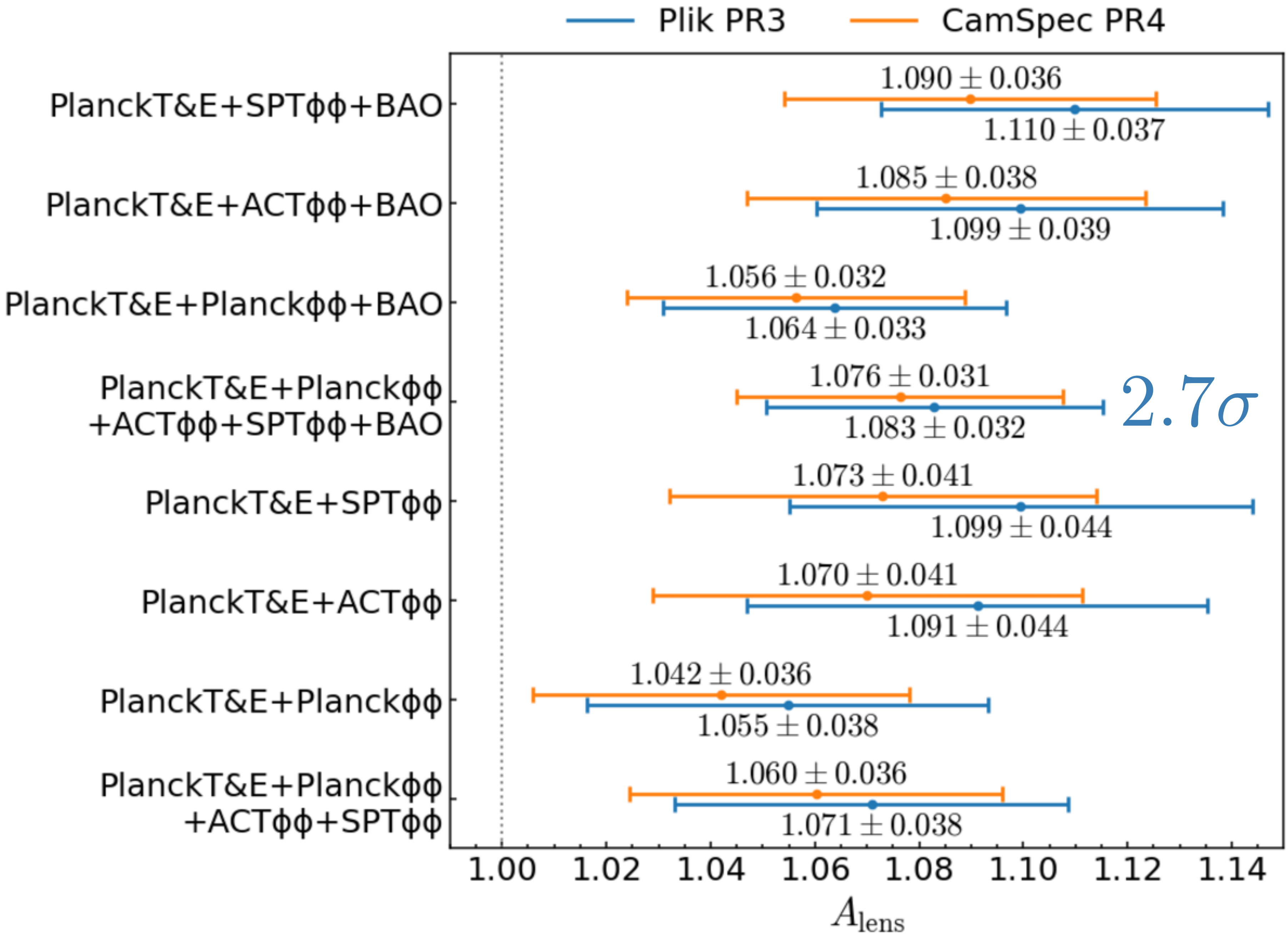
$\Lambda\mathrm{CDM} + A_{\mathrm{lens}}$

Results – excess lensing power



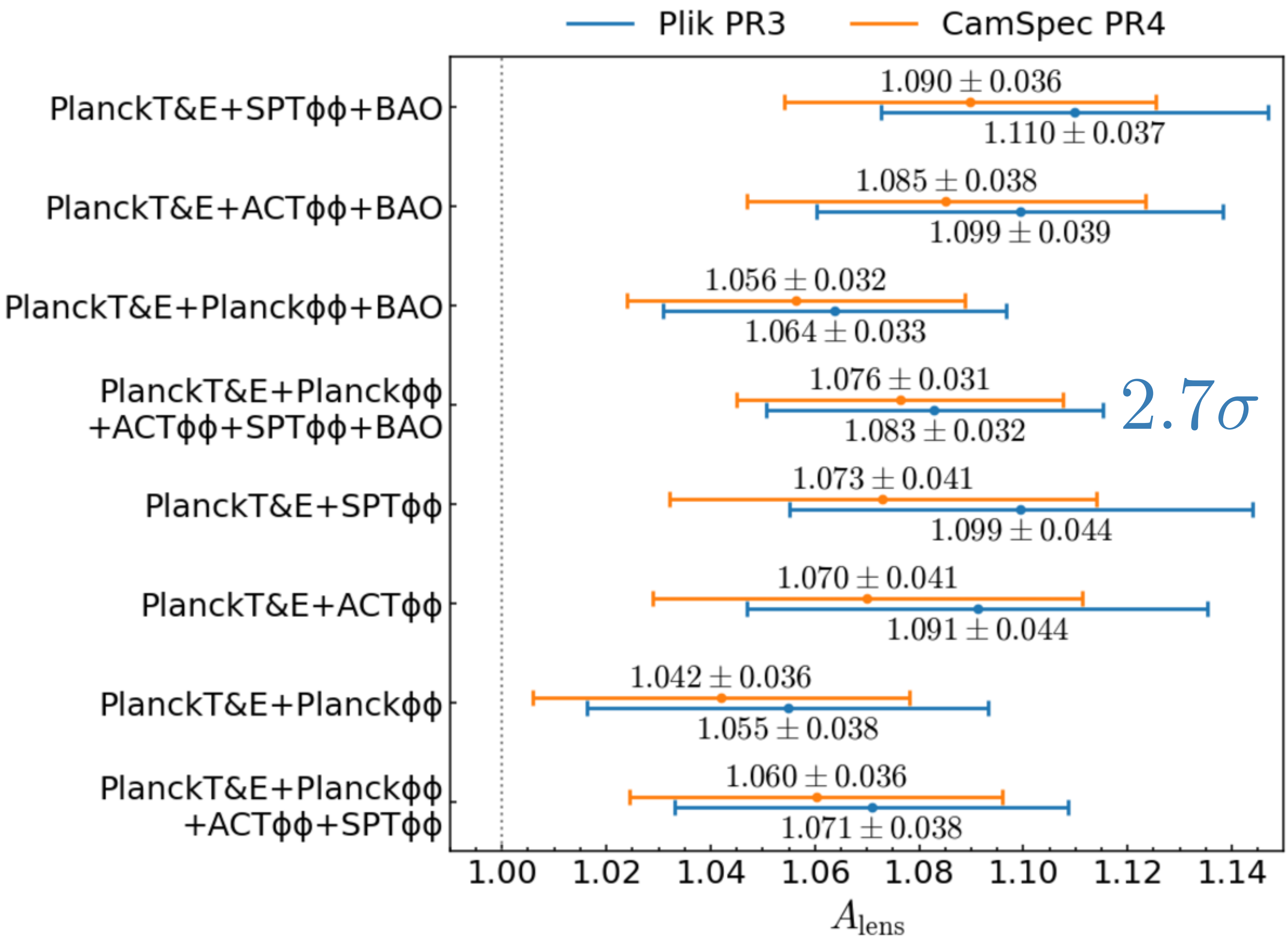
$\Lambda\mathrm{CDM} + A_{\mathrm{lens}}$

Results – excess lensing power



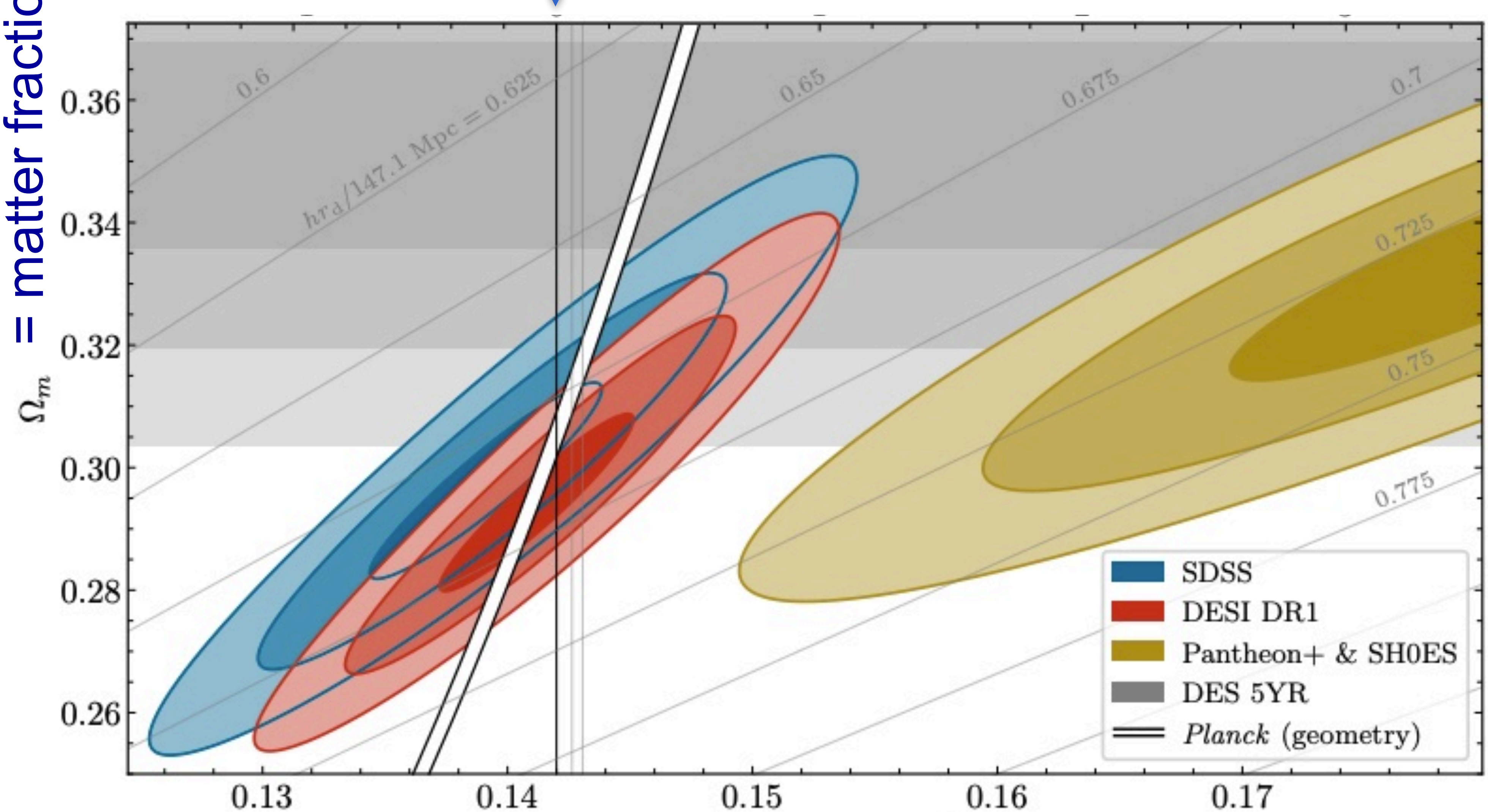
$\Lambda\text{CDM} + A_{\text{lens}}$

Results – excess lensing power



Adapted from Loverde & Weiner (2024)

baryon + cdm density today (best-fit to Planck)



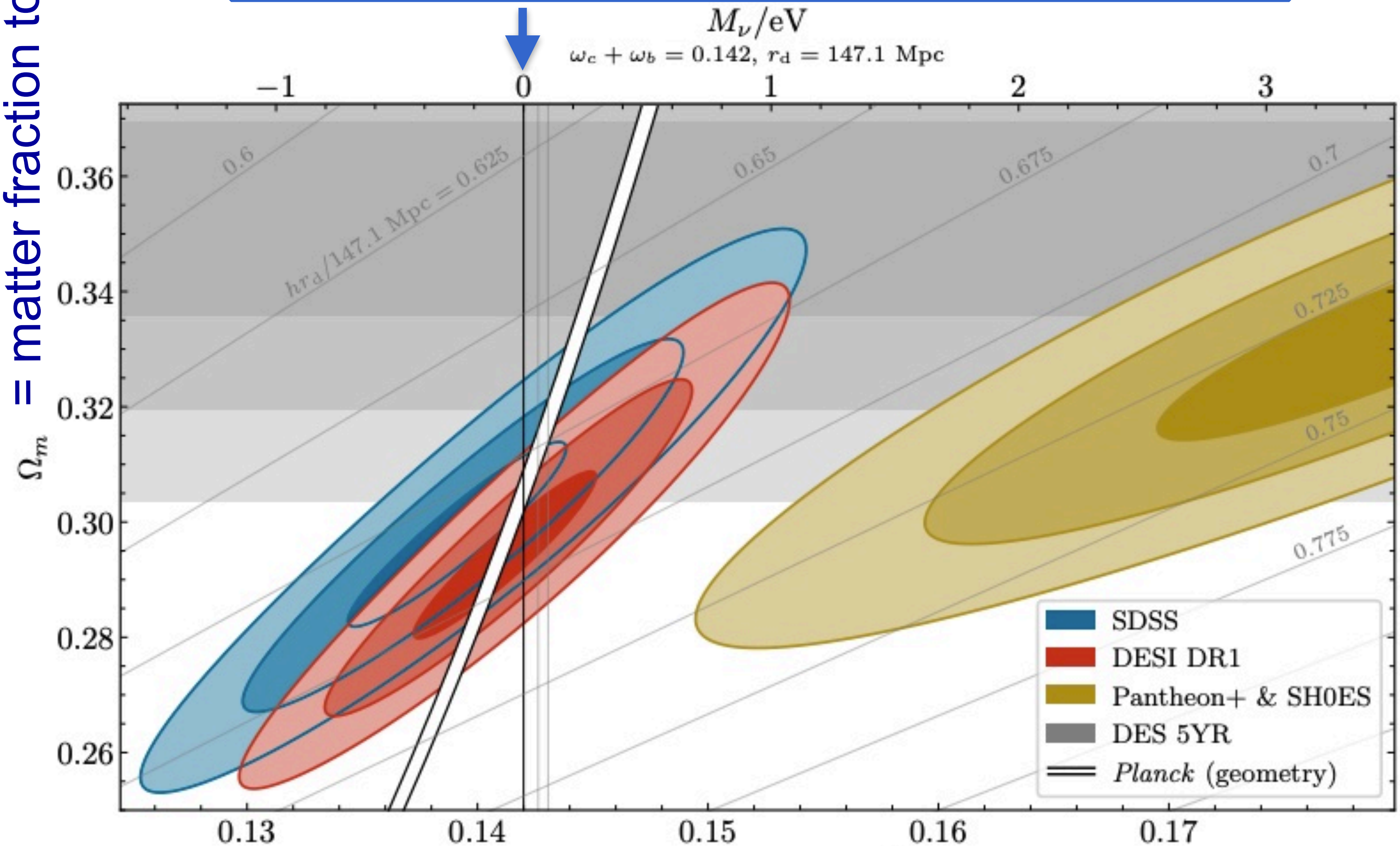
= matter fraction today

$\omega_{\rm m}$ = matter density today [$1.88 \times 10^{-29}{\rm g/cm}^3$]

(Including from non-relativistic neutrinos)

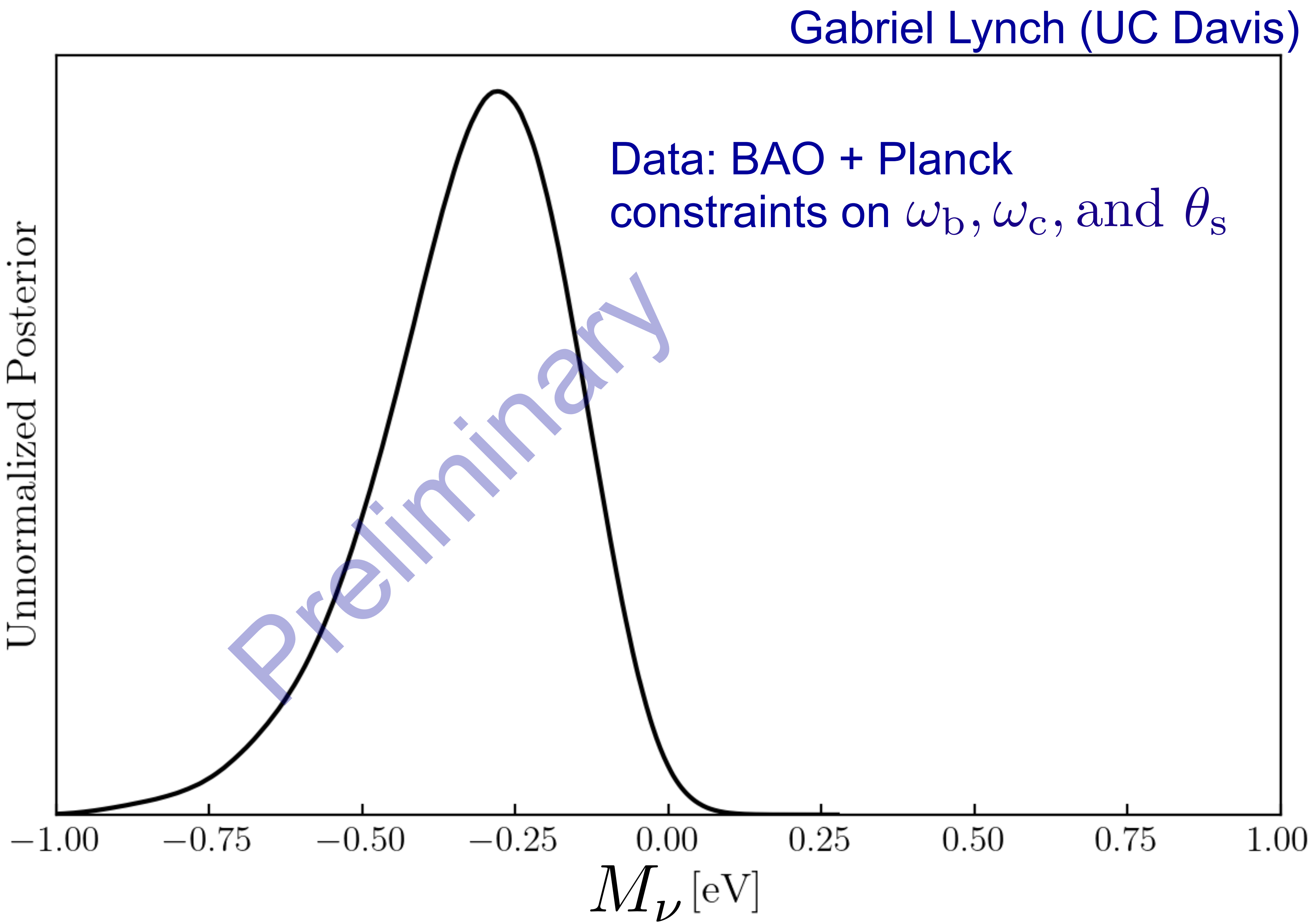
Adapted from Loverde & Weiner (2024)

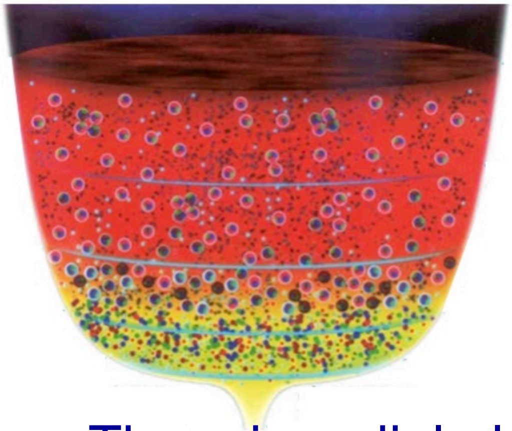
baryon + cdm density today (best-fit to Planck)



ω_m = matter density today [1.88×10^{-29}g/cm^3]

(Including from non-relativistic neutrinos)


Gabriel Lynch (UC Davis)
Data: BAO + Planck
constraints on $\omega_{\rm b}, \omega_{\rm c}$, and $\theta_{\rm s}$
Preliminary
Unnormalized Posterior
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
M_ν [eV]



Summary

- The primordial plasma is a beautiful gift of nature.
- Our measurements of CMB lensing and polarization are largely consistent with the highly-precise predictions of LCDM given Planck data.
- For polarization power this is only the case following a post-unblinding change to the analysis: an unjustified assumption about our polarized beams was dropped.
- From the SPT-3G CMB data alone we find, assuming LCDM, H_0 = 66.8 +/- 0.8 km/sec/Mpc, consistent with the Planck result of H_0 = 67.3 +/- 0.5 km/sec/Mpc and inconsistent at 5.4 sigma with SH0ES.
- Lensing power inference was robust to post-unblinding changes.
- Our lensing results support prior (weak) evidence for an excess of lensing power beyond LCDM expectations. Puzzling neutrino mass situation.
- There is much more to come from 3G. This was 2 years on 1500 sq. deg. We have 5 years on 10,000 sq. deg. “in the can.”

National Science Foundation

Michael and Ester Vaida

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