SPT-3G: Cosmology from CMB Lensing and Delensed EE Power Spectra with 2019 and 2020 Polarization Data

(2411.06000)

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(mm-Universe, 2025 Chicago, IL)

European Research Council
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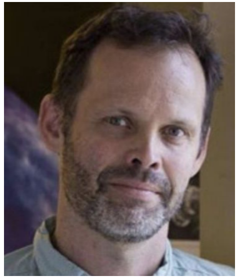
- Many thanks to the other key contributors to this project.

Marius
Millea
UC Davis



Lloyd
Knox
UC Davis

Etienne
Camphuis
IAP

Cail
Daley
IRFU/UIUC

Nicholas
Huang
UC Berkeley

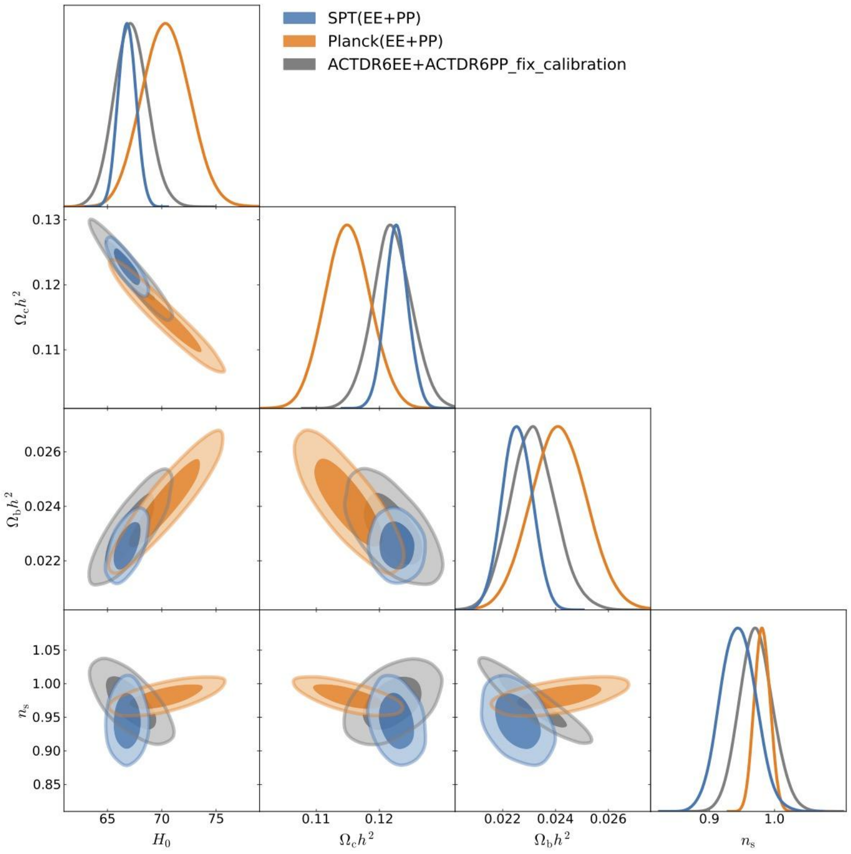
Yuuki
Omori
KICP

Wei
Quan
Argonne

Polarization only*

Highlights:

- We perform a joint estimate of CMB lensing bandpowers and unlensed EE bandpowers using MUSE†.
- With signals only from CMB polarization, we are able to achieve constraints on H0 and S8 comparable to Planck results.
- Assuming LCDM, SPT results are consistent with Planck and ACT.
- Our analysis observes weak preference of an excess lensing power relative to LCDM prediction.
- We also detect >3σ effects from non-linear evolution in CMB lensing.



† Likelihoods can be found at https://pole.uchicago.edu/public/data/ge25/index.html

*ACT lensing is from polarization-only signal and has no calibration uncertainty..

The South Pole Telescope (SPT)

3 bands: 95, 150, 220 GHz
Resolution: 1.6, 1.2, 1.0 armin

CMB-S4 depths on ~3.5% of the full sky

SPT-SZ (2007)
~1,000 detectors

SPT-pol (2012)
~1,500 detectors

SPT-3G (2017)
~16,000 detectors

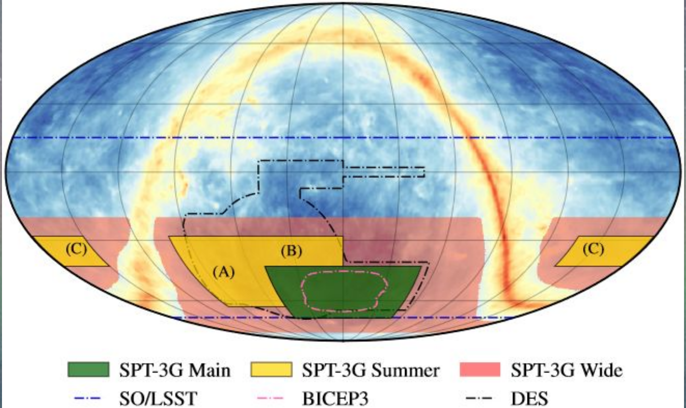


Photo: Aman Chokshi, SPT winterover

Marginal Unbiased Score Expansion (MUSE)(Millea & Seljak 2022)

- A Bayesian method jointly estimates
  - the CMB lensing potential bandpowers
  - unlensed EE bandpowers
  - systematic parameters.
- A map-level inference effectively uses all N-point statistics

$$\{A_b^{EE}, A_b^{\phi\phi}, \theta_{sys}\}$$

$$\mathcal{P}(\theta|d)$$

Observed CMB maps

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$\{A_b^{EE}, A_b^{\phi\phi}, \theta_{sys}\}$

Unlensed CMB polarization maps

$$\mathcal{P}(\theta|d) = \int df\ d\phi\ \mathcal{P}(f, \phi, \theta|d)$$

Observed CMB maps

Lensing potential (ϕ) map

Marginal Unbiased Score Expansion (MUSE)(Millea & Seljak 2022)

- MUSE equations to get bandpower estimate

$$s_i^{\mathrm{MAP}}(\hat{\theta}, d) = \left\langle s_i^{\mathrm{MAP}}\left(\hat{\theta}, d'\right)\right\rangle_{d' \sim \mathcal{P}(d'|\hat{\theta})}$$

$$s_i^{\mathrm{MAP}}(\theta, d) = \frac{d}{d\theta_i} \log \mathcal{P}(\hat{f}, \hat{\phi}, \theta | d)\Big|_{\theta}$$

$$\hat{f}, \hat{\phi} = \underset{f,\phi}{\mathrm{argmax}} \mathcal{P}(f, \phi, \theta | d)$$

$$d^{\nu,i} = \mathbb{M}_{\mathrm{fourier}} \cdot \mathbb{M}_{\mathrm{trough}} \cdot \mathbb{M}_{\mathrm{pix}} \cdot \big(\mathbb{PWF} \cdot \mathbb{TF}^{\nu} \cdot \mathbb{R}(\psi_{\mathrm{pol}}^{\nu}) \cdot A_{\mathrm{cal}}^{\nu,i} \cdot \mathbb{B}(\beta_n, \beta_{\mathrm{pol}}^{\nu}) \cdot \mathbb{G} \cdot \mathbb{P} \cdot \mathbb{L}(\phi) \cdot f \\ + \epsilon_{\mathrm{Q}}^{\nu,i} \cdot t_{\mathrm{Q}}^{\nu} + \epsilon_{\mathrm{U}}^{\nu,i} \cdot t_{\mathrm{U}}^{\nu} + n^{\nu}\big)$$

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$$\hat{f}, \hat{\phi} = \underset{f,\phi}{\mathrm{argmax}} \mathcal{P}(f, \phi, \theta | d)$$

Observed CMB Maps/
Mock CMB Maps

Simulated CMB Maps
via the simulation model

$$d^{\nu,i} = \mathbb{M}_{\mathrm{fourier}} \cdot \mathbb{M}_{\mathrm{trough}} \cdot \mathbb{M}_{\mathrm{pix}} \cdot \big(\mathbb{PWF} \cdot \mathbb{TF}^{\nu} \cdot \mathbb{R}(\psi^{\nu}_{\mathrm{pol}}) \cdot A^{\nu,i}_{\mathrm{cal}} \cdot \mathbb{B}(\beta_n, \beta^{\nu}_{\mathrm{pol}}) \cdot \mathbb{G} \cdot \mathbb{P} \cdot \mathbb{L}(\phi) \cdot f + \epsilon^{\nu,i}_{\mathrm{Q}} \cdot t^{\nu}_{\mathrm{Q}} + \epsilon^{\nu,i}_{\mathrm{U}} \cdot t^{\nu}_{\mathrm{U}} + n^{\nu}\big)$$

Marginal Unbiased Score Expansion (MUSE)(Millea & Seljak 2022)

- MUSE equations to get bandpower estimate

$$s_i^{\mathrm{MAP}}(\hat{\theta}, d) = \left\langle s_i^{\mathrm{MAP}}\left(\hat{\theta}, d'\right)\right\rangle_{\boxed{d' \sim \mathcal{P}\left(d' | \hat{\theta}\right)}}$$

$$s_i^{\mathrm{MAP}}(\theta, d) = \frac{d}{d\theta_i} \log \mathcal{P}(\hat{f}, \hat{\phi}, \theta | d)\Big|_{\theta}$$

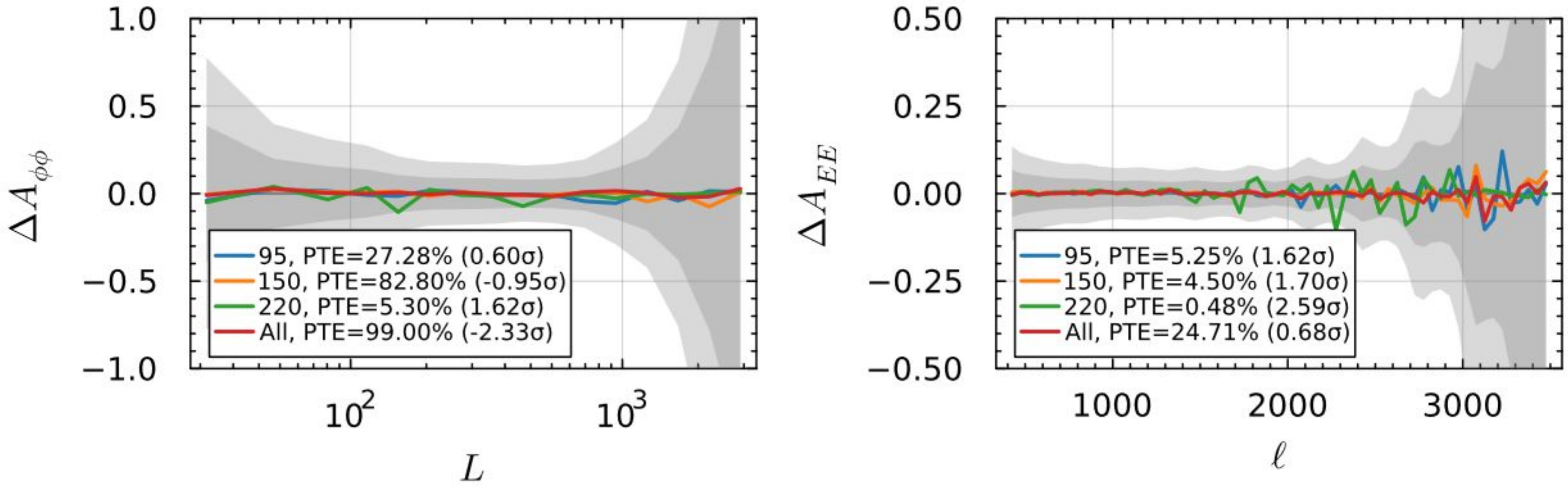
$$\hat{f}, \hat{\phi} = \underset{f,\phi}{\mathrm{argmax}}\, \mathcal{P}(f, \phi, \theta | d)$$

Accurate simulation model is the key to get unbiased bandpower estimates from MUSE.

$$d^{\nu,i} = \mathbb{M}_{\mathrm{fourier}} \cdot \mathbb{M}_{\mathrm{trough}} \cdot \mathbb{M}_{\mathrm{pix}} \cdot \big(\mathbb{PWF} \cdot \mathbb{TF}^{\nu} \cdot \mathbb{R}(\psi^{\nu}_{\mathrm{pol}}) \cdot A^{\nu,i}_{\mathrm{cal}} \cdot \mathbb{B}(\beta_n, \beta^{\nu}_{\mathrm{pol}}) \cdot \mathbb{G} \cdot \mathbb{P} \cdot \mathbb{L}(\phi) \cdot f + \epsilon^{\nu,i}_{\mathrm{Q}} \cdot t^{\nu}_{\mathrm{Q}} + \epsilon^{\nu,i}_{\mathrm{U}} \cdot t^{\nu}_{\mathrm{U}} + n^{\nu}\big)$$

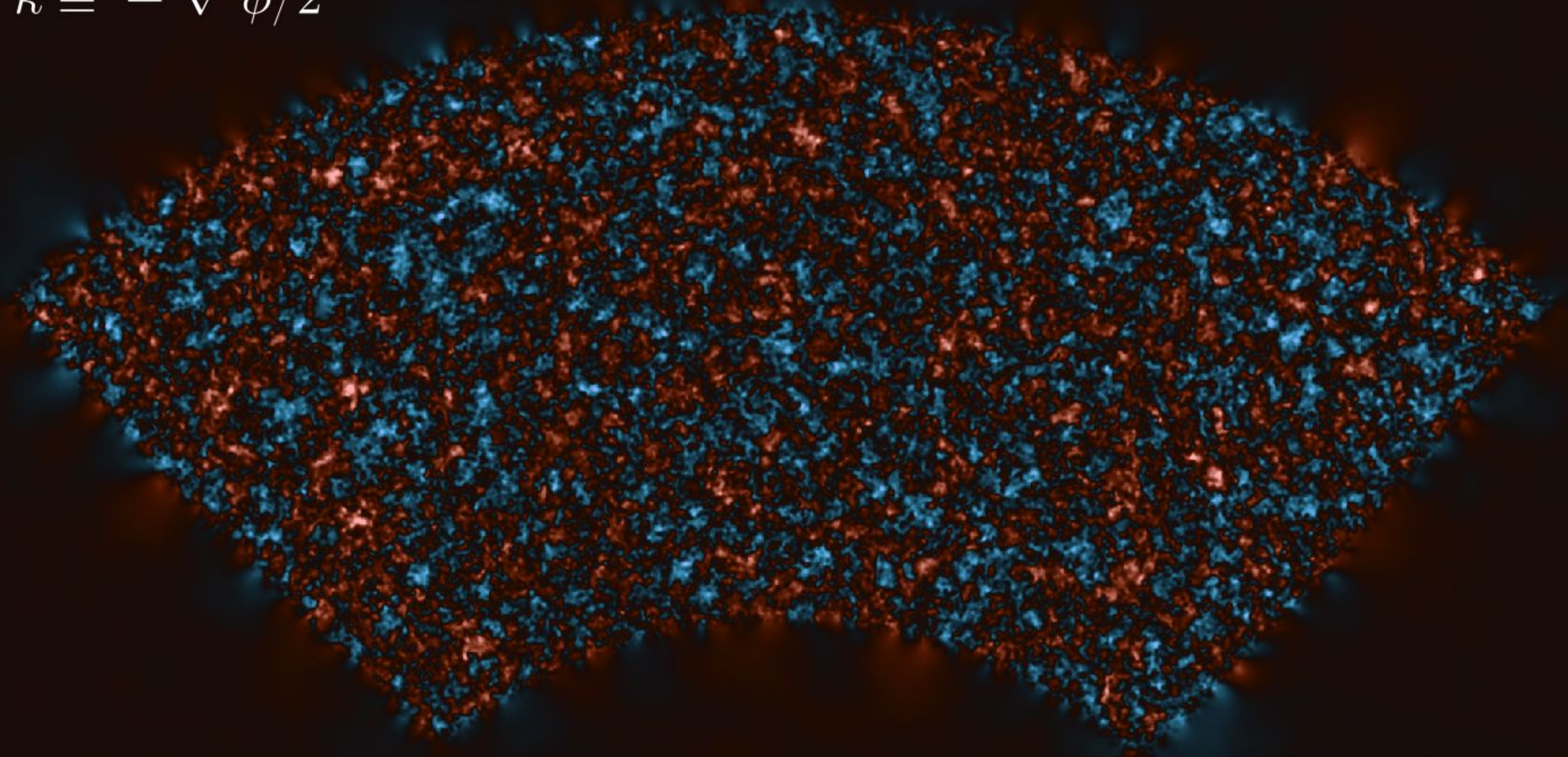
Validation Test – bandpowers on mocks

- No bias on the mean bandpowers estimated on a set of 100 mocks larger than 3σ.
- The scatter of mean bandpowers are within 10% of the statistical uncertainty.

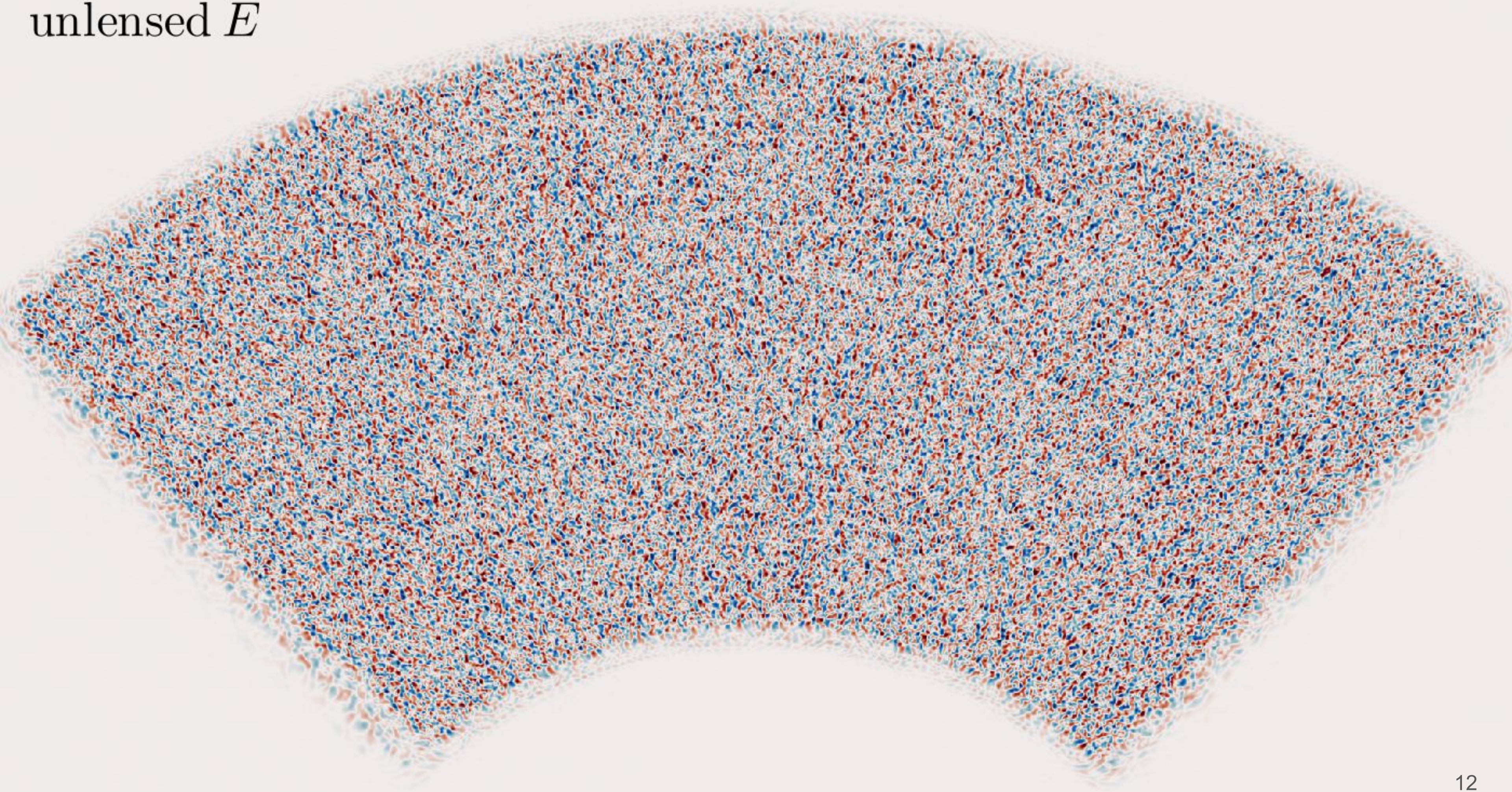


*All means joint analysis of 95+150+220 GHz.
*Colored lines show mean bandpowers over 100 mock sims.
*Gray bands show 1σ and 2σ error of 95+150+220 results.

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



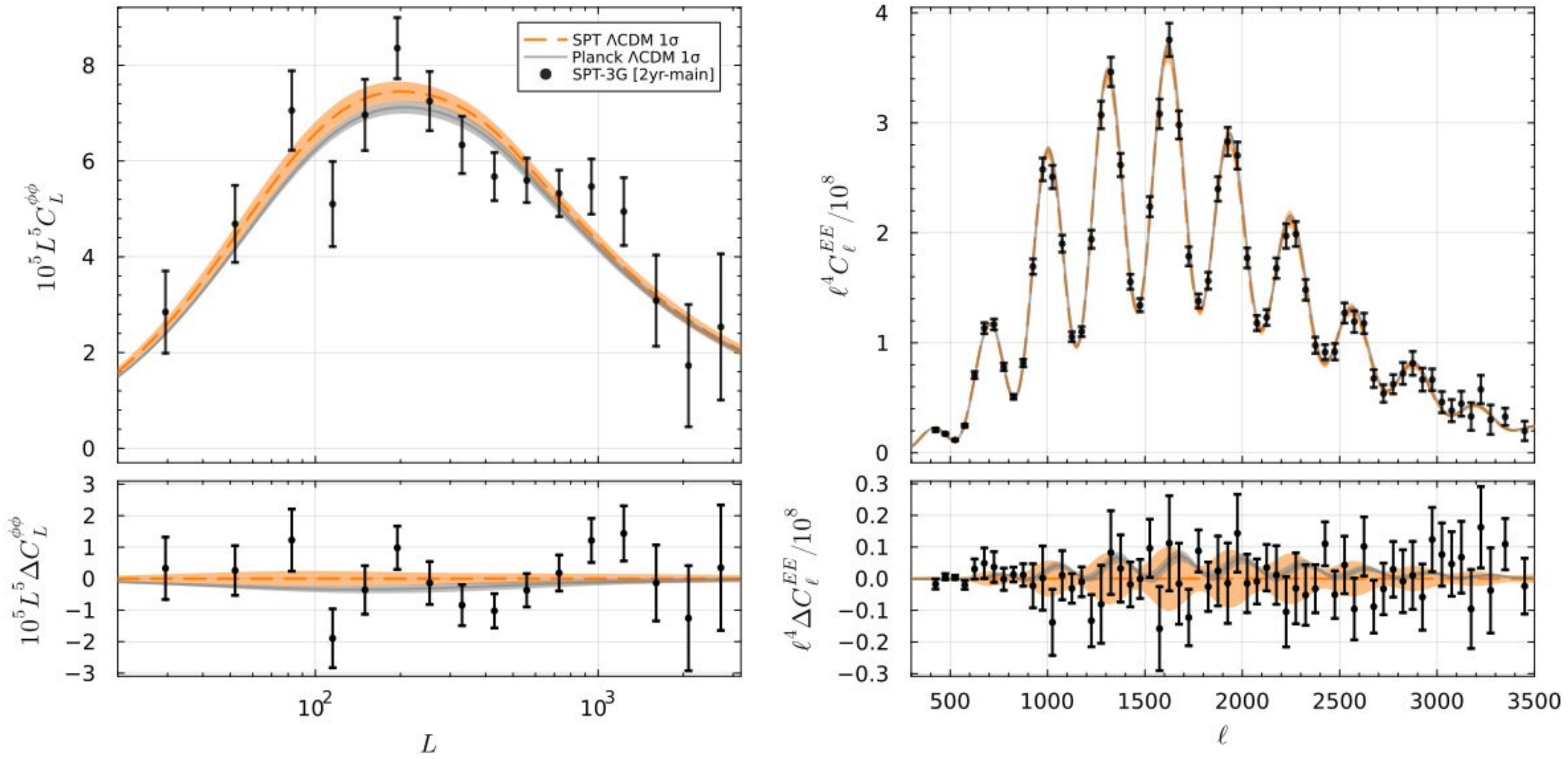
*reconstruction procedure imprints complex anisotropic filtering on these images unlensed E



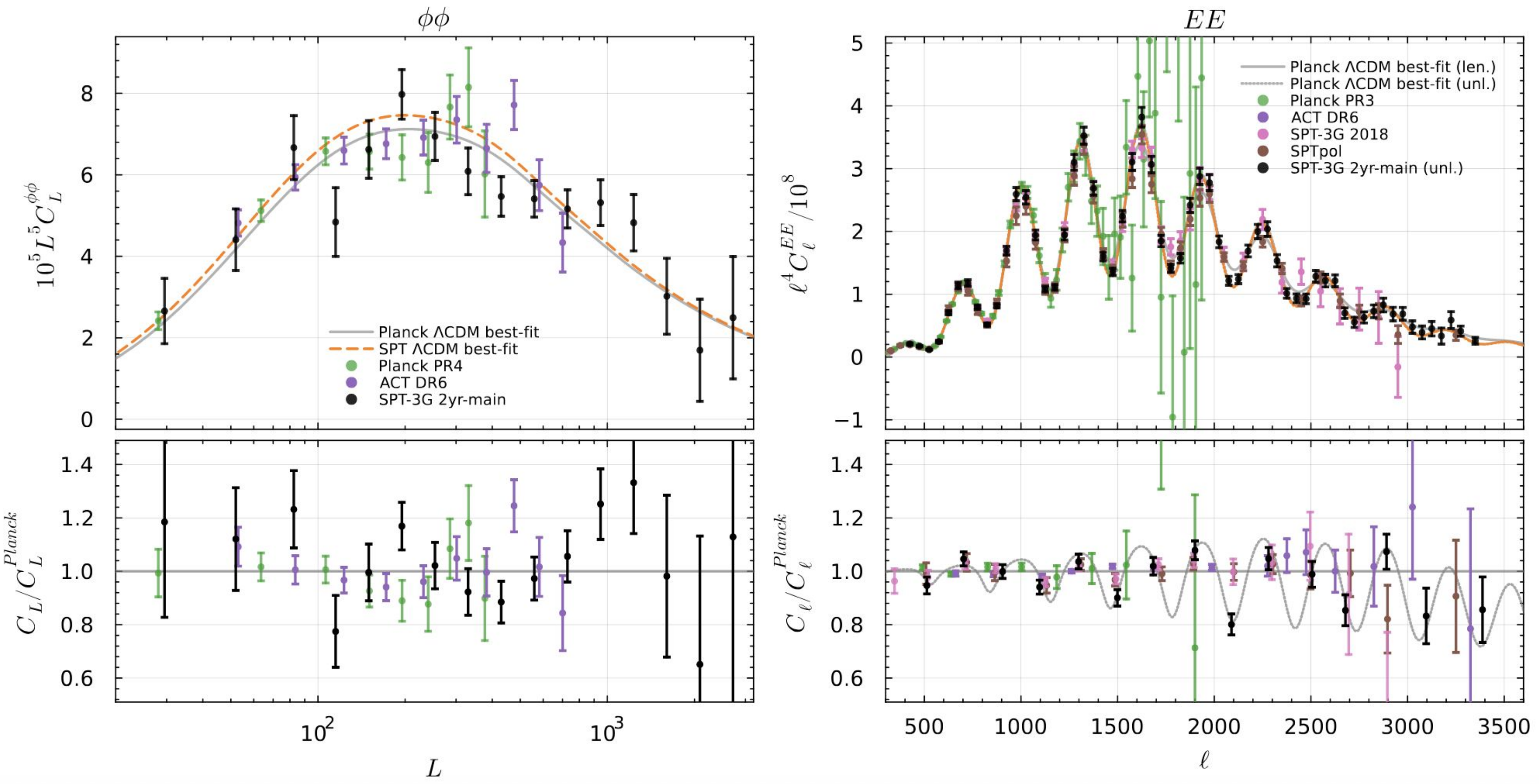
*reconstruction procedure imprints complex anisotropic filtering on these images

Results – bandpowers

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



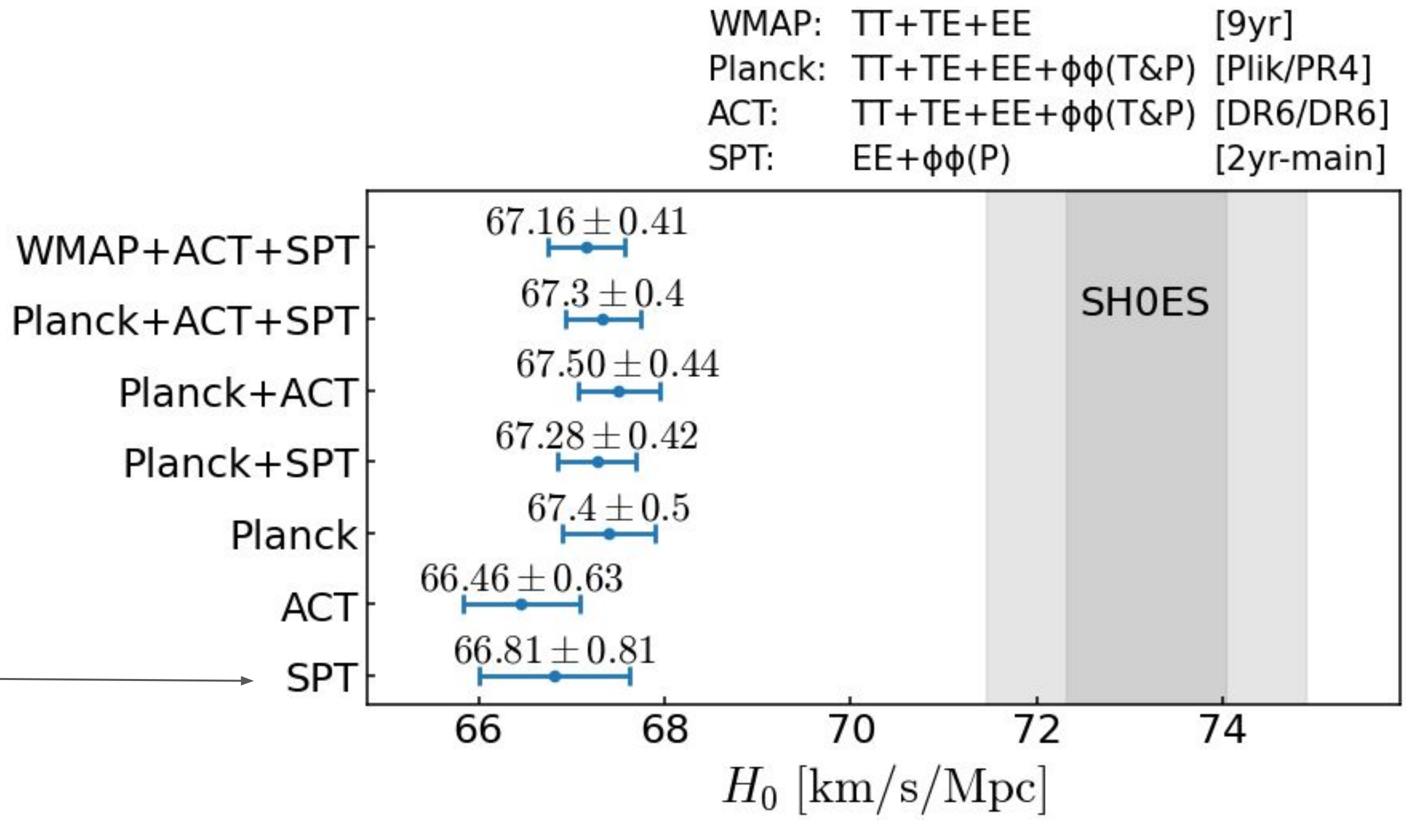
Results – bandpowers



Results – H0*

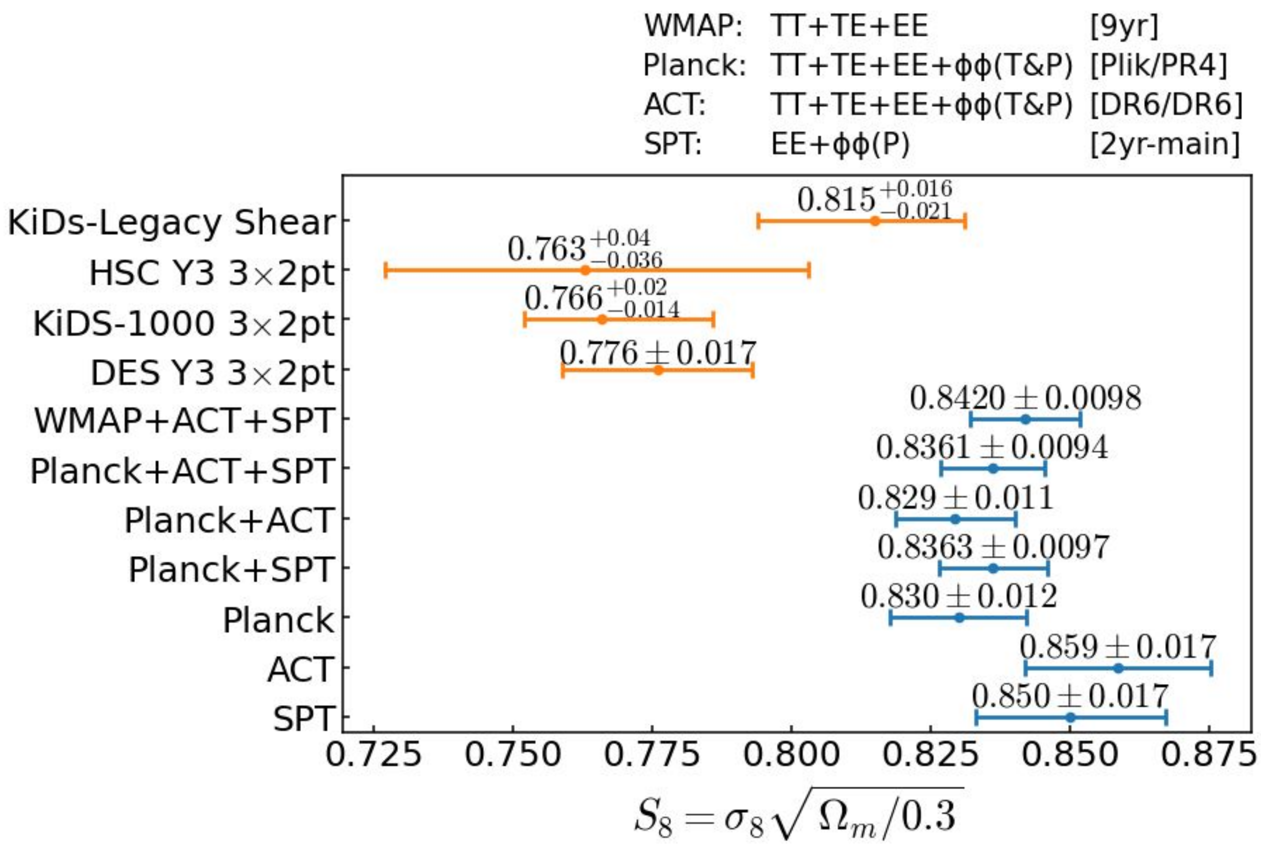
6.2σ

5.4σ



*Assuming LCDM model

Results – S8*

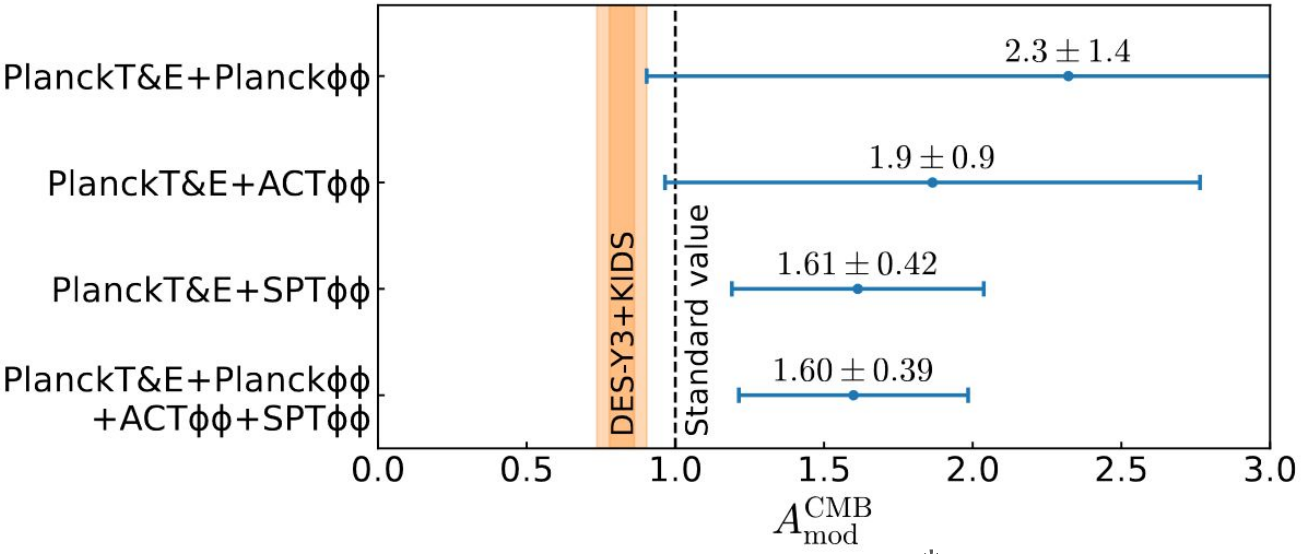


*Assuming LCDM model

Results – amplitude of nonlinear structure growth

$$C_L^{\phi\phi} = C_{L,\mathrm{lin}}^{\phi\phi} + A_{\mathrm{mod}}^{\mathrm{CMB}}(C_{L,\mathrm{nonlin}}^{\phi\phi} - C_{L,\mathrm{lin}}^{\phi\phi})$$

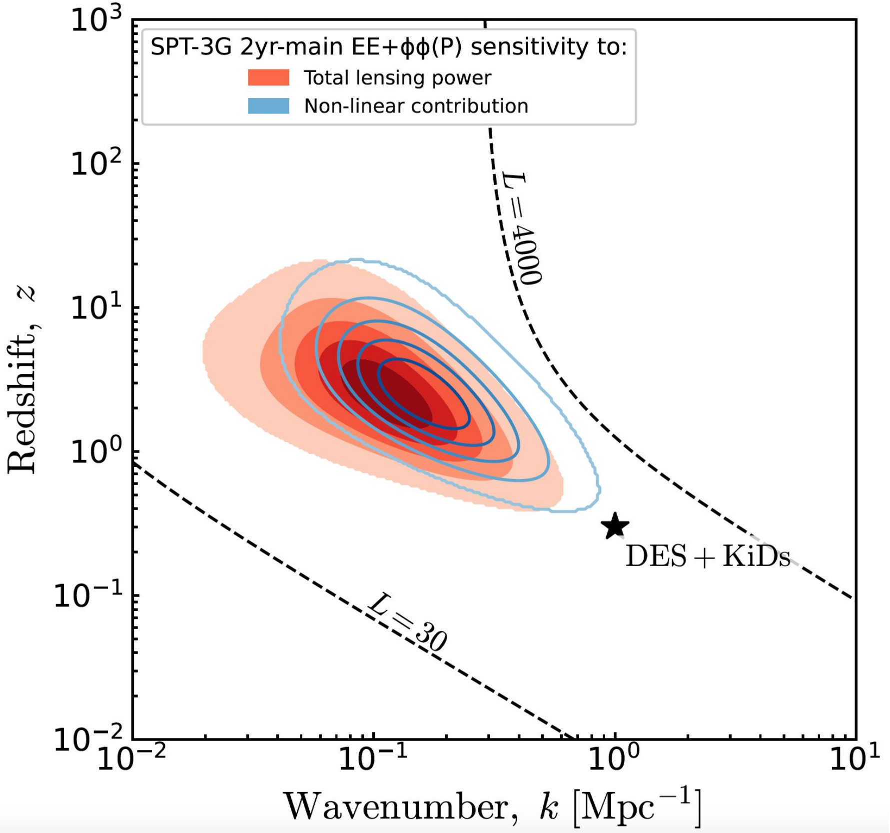
- Our results yields 3σ detection of non-linear structure growth in CMB lensing
- The A_mod from CMB lensing is consistent with 1 within 1.5σ.



*DES-Y3+KiDS is from [Preston et al 2023]

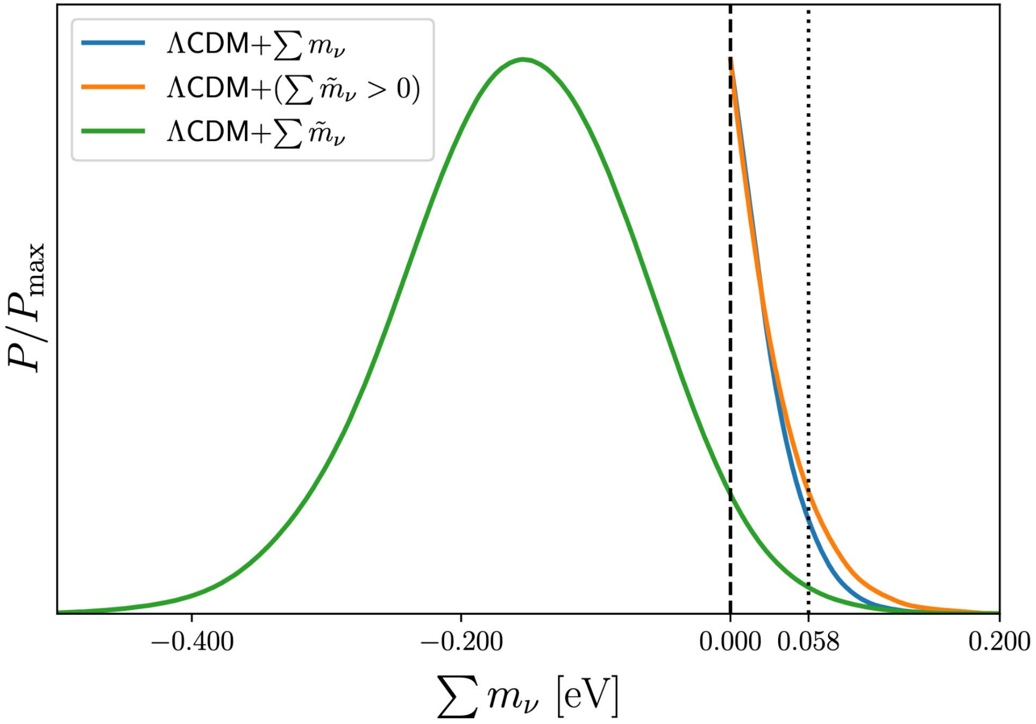
Results – amplitude of nonlinear structure growth

- If the solution to S8 tension is due to unknown physics of non-linear structure growth, our result suggests it to happen at a later time or at smaller scales.



Negative neutrino mass?

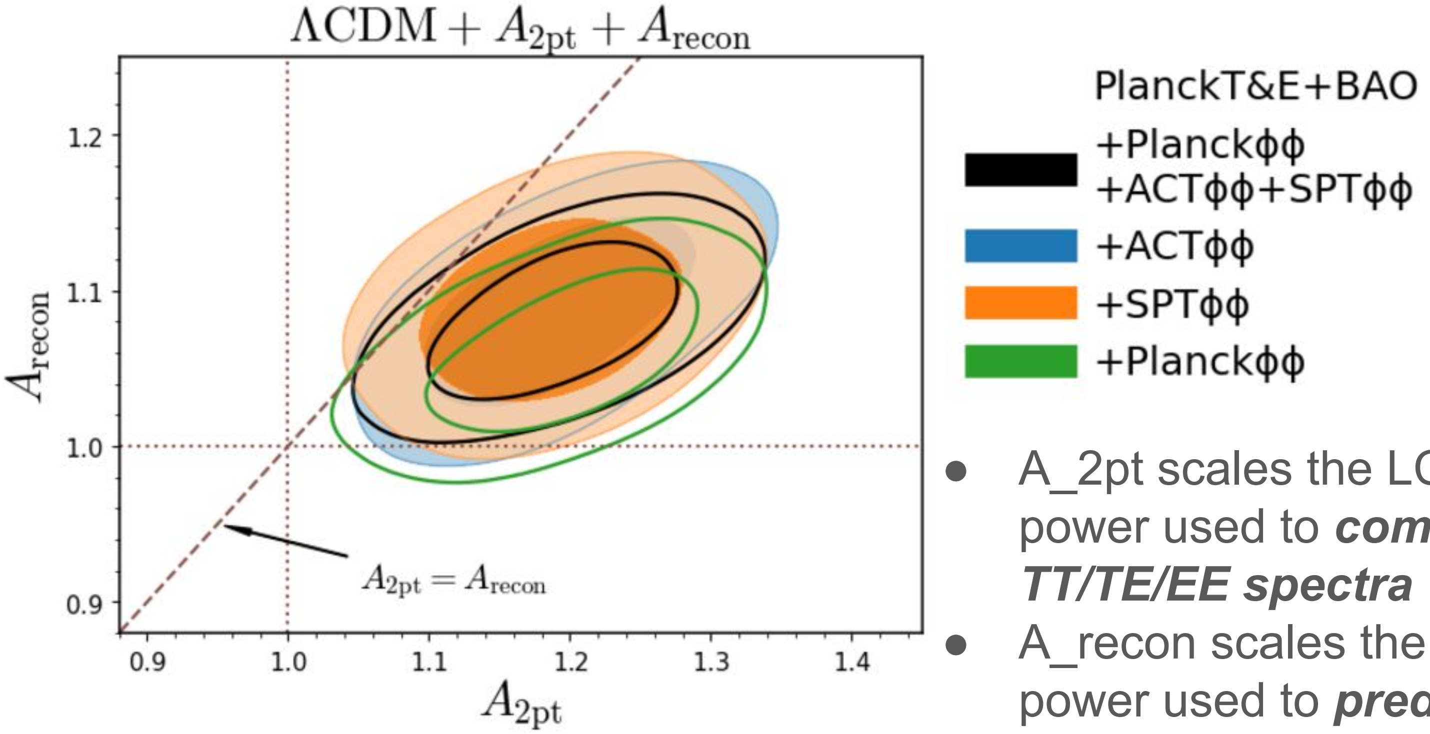
- Negative neutrino mass is found when the CMB lensing power spectrum is rescaled based on neutrino mass.



(Craig et al [2405.00836](2405.00836))

Results – excess lensing power

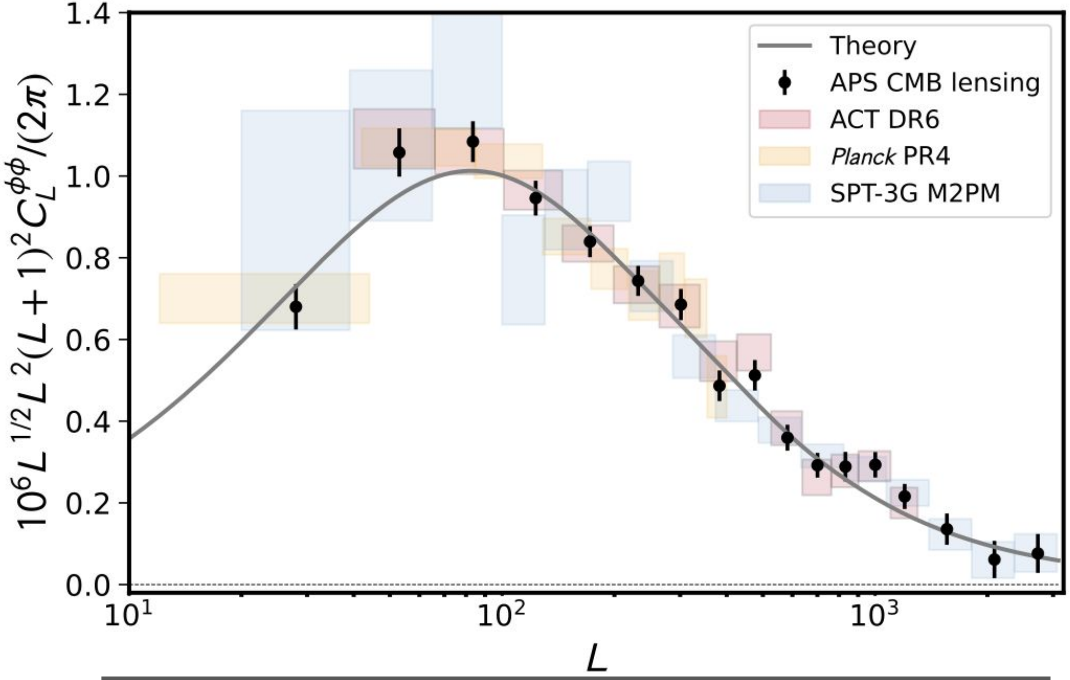
- SPT result shows the mild excess lensing power relative to LCDM prediction when using Planck Plik PR3 likelihood.



- A_2pt scales the LCDM lensing power used to ***compute lensed TT/TE/EE spectra***
- A_recon scales the LCDM lensing power used to ***predict reconstructed lensing power***

Joint ACT+Planck+SPT Lensing Analysis

- The joint lensing likelihood produces a measurement of the CMB lensing amplitude with a SNR at 61 sigma.



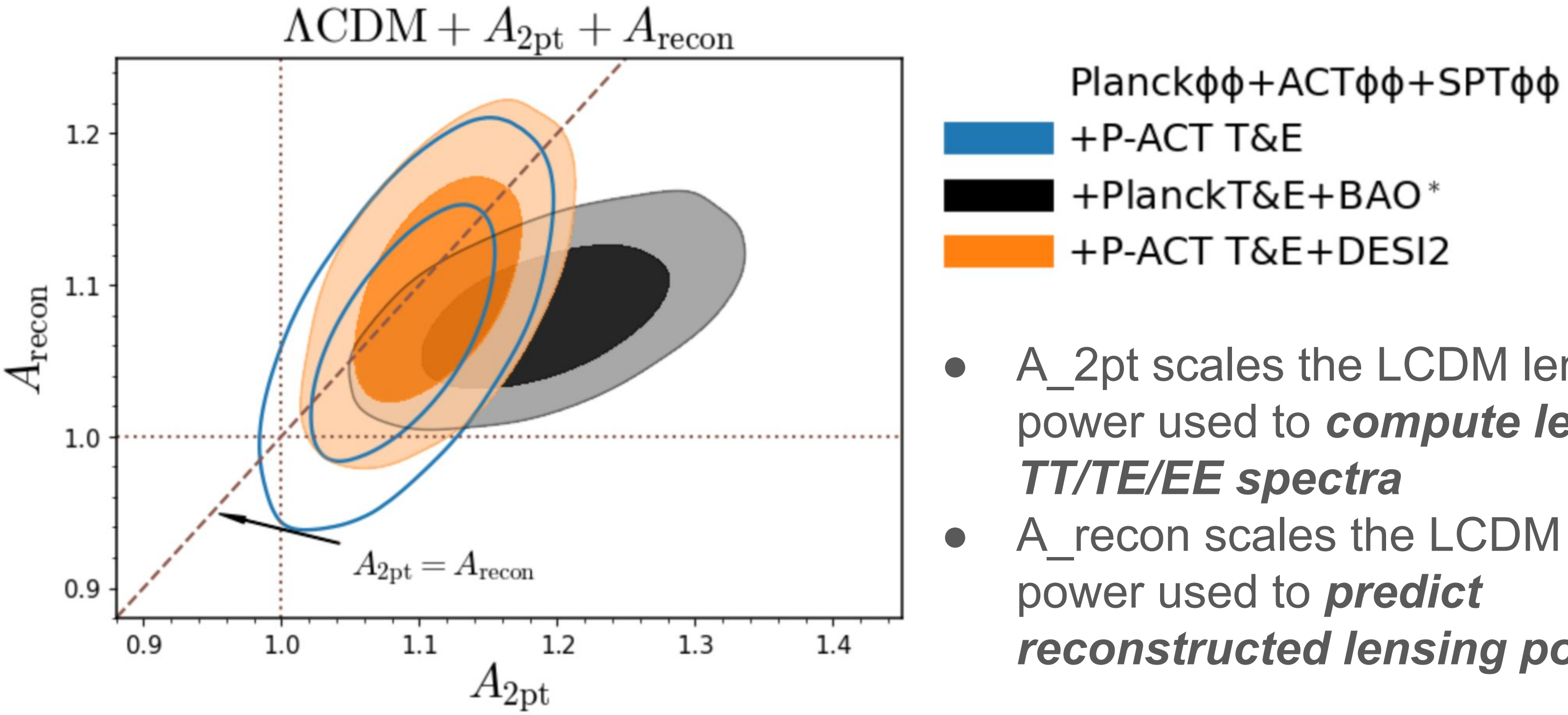
(2504.20038)

See also Frank's talk on Friday for more cosmological constraints with APS lensing.

Frank Qu
KIPAC

Results – excess lensing power

- Mild excess lensing power relative to LCDM prediction persists with updated primary CMB and BAO data.



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*BAO refers to data before DESI DR2.

Results – constraints on LCDM extensions

Ext. Parameter	WMAP+SPT	Planck	Planck+SPT	Planck+ACT+SPT	Planck+ACT+SPT+BAO
Ω_k	$-0.021^{+0.014}_{-0.011}$	-0.0070 ± 0.0056	-0.0098 ± 0.0052	$-0.0076^{+0.0053}_{-0.0047}$	0.0014 ± 0.0014
w_0	$-1.42^{+0.29}_{-0.47}$	$-1.48^{+0.20}_{-0.37}$	$-1.52^{+0.18}_{-0.35}$	$-1.52^{+0.19}_{-0.35}$	-1.075 ± 0.046
w_0	$-1.10^{+0.50}_{-0.69}$	$-1.18^{+0.46}_{-0.62}$	$-1.16^{+0.48}_{-0.60}$	$-1.18^{+0.48}_{-0.58}$	-0.65 ± 0.23
w_a	$-1.1^{+0.6}_{-1.9}$	$-1.06^{+0.61}_{-1.94}$	$-1.18^{+0.52}_{-1.82}$	$-1.21^{+0.57}_{-1.79}$	$-1.15^{+0.71}_{-0.59}$
$N_{\rm eff}$	2.95 ± 0.33	2.89 ± 0.18	2.85 ± 0.16	2.66 ± 0.14	2.86 ± 0.13
Σm_ν	$< 0.38\,\mathrm{eV}$	$< 0.31\,\mathrm{eV}$	$< 0.17\,\mathrm{eV}$	$< 0.20\,\mathrm{eV}$	$< 0.075\,\mathrm{eV}$
$N_{\rm eff}$	2.95 ± 0.32	2.89 ± 0.19	2.84 ± 0.17	2.67 ± 0.14	2.83 ± 0.13
Σm_ν	$< 0.38\,\mathrm{eV}$	$< 0.31\,\mathrm{eV}$	$< 0.17\,\mathrm{eV}$	$< 0.21\,\mathrm{eV}$	$< 0.061\,\mathrm{eV}$
$N_{\rm eff}$	2.79 ± 0.52	2.8 ± 0.3	2.77 ± 0.26	2.60 ± 0.23	2.89 ± 0.23
$Y_{\rm P}$	0.256 ± 0.028	0.248 ± 0.018	0.250 ± 0.016	0.246 ± 0.014	0.241 ± 0.015

*ACT refers to ACT DR4 T&E + ACT DR6 lensing.
*BAO refers to data before DESI DR2.

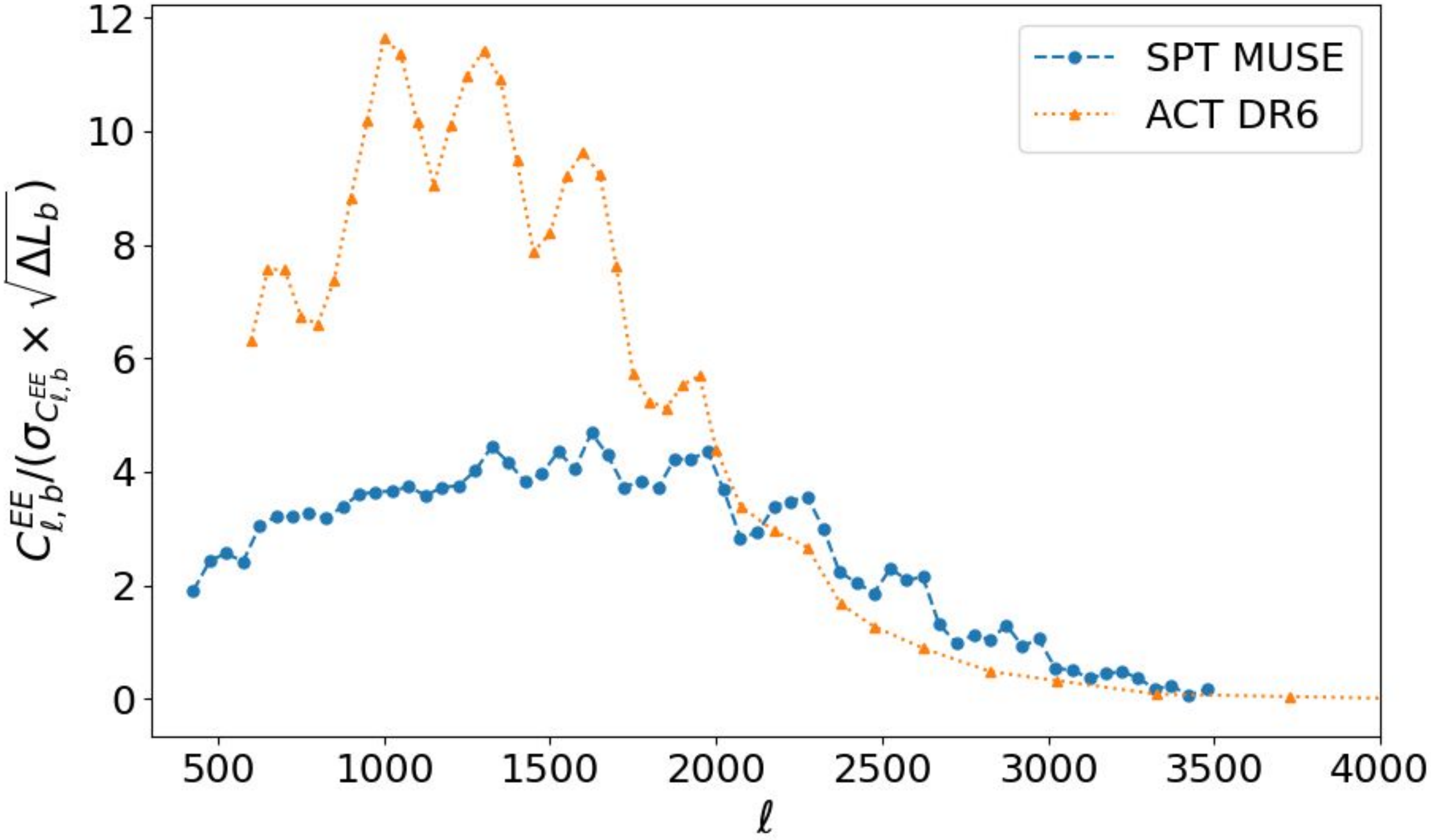
Summary

- Using MUSE method for optimal inference, this analysis yields the most precise measurement of ϕϕ at L>350 and EE at ℓ>2200 from SPT-3G polarization maps.
- The SPT results using polarization signal are comparable to Planck at H0 and S8.

$$H_0 = 66.81 \pm 0.81 \text{ km/s/Mpc} \qquad S_8 = 0.850 \pm 0.017$$

- Assuming LCDM, SPT results are consistent with Planck and ACT, passing a powerful test of the standard cosmological model.
- SPT results also shows the mild excess lensing power relative to LCDM prediction.
- We first see >3σ detection of non-linear structure growth in CMB lensing, and consistent with A_mod=1.
- For the LCDM extension models, we find no preference for significant deviations of the standard cosmology values using Planck, ACT and SPT data.
- Soon-to-come SPT likelihood release with 2019/20 Main TT/TE/EE results will provide powerful tests on LCDM model.

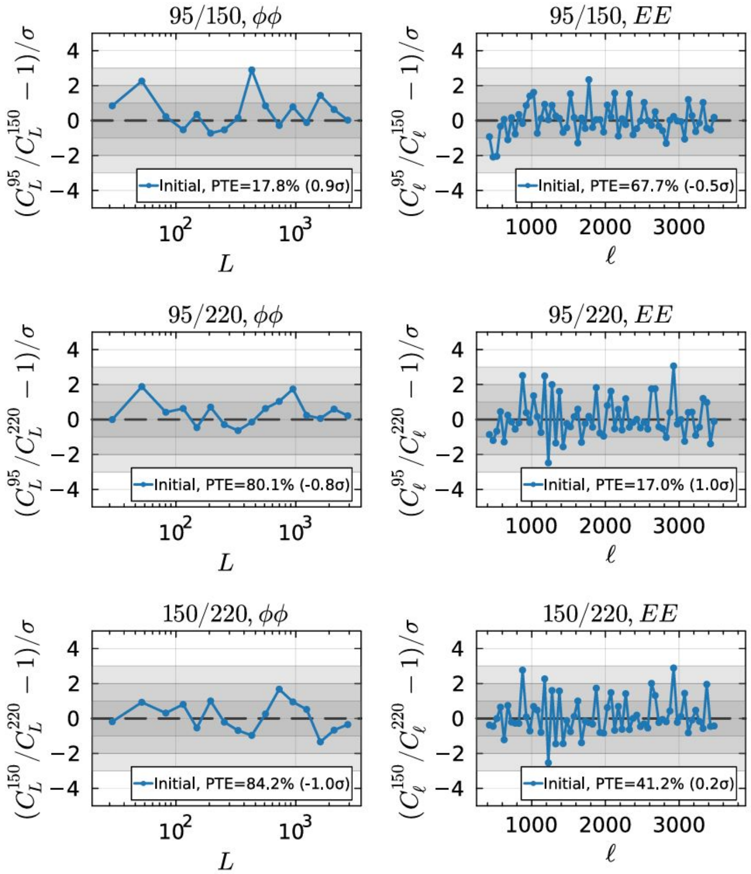
Backup Slides



SPT MUSE
ACT DR6
$C^{EE}_{\ell,b}/(\sigma_{C^{EE}_{\ell,b}} \times \sqrt{\Delta L_b})$
ℓ
0
2
4
6
8
10
12
500
1000
1500
2000
2500
3000
3500
4000

Validation Test – data test

- Good overall agreement between bandpowers from single frequency results.



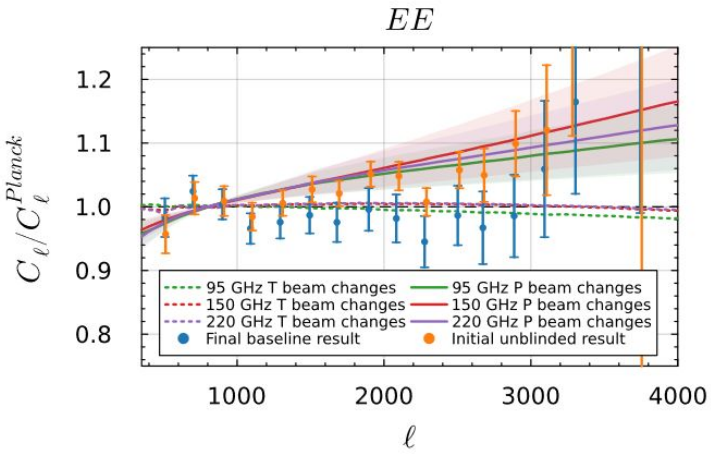
Post-Unblinding Changes

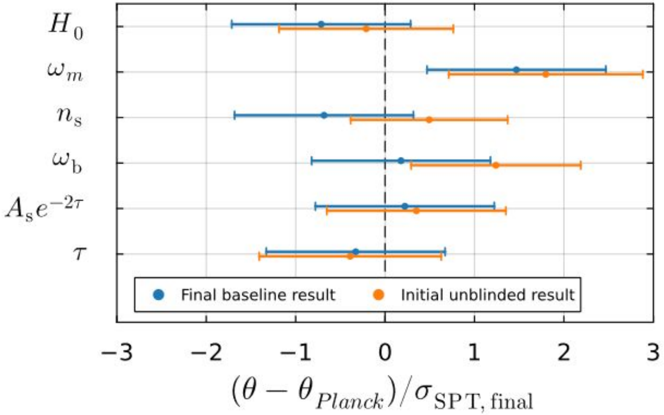
- Polarized Beam models
  - The sidelobes are only partially polarized.

$$\mathbb{B}_T^\nu(\beta_n) = \mathbb{B}_0^\nu + \beta_1 \mathbb{B}_1^\nu + \beta_2 \mathbb{B}_2^\nu + \ldots$$

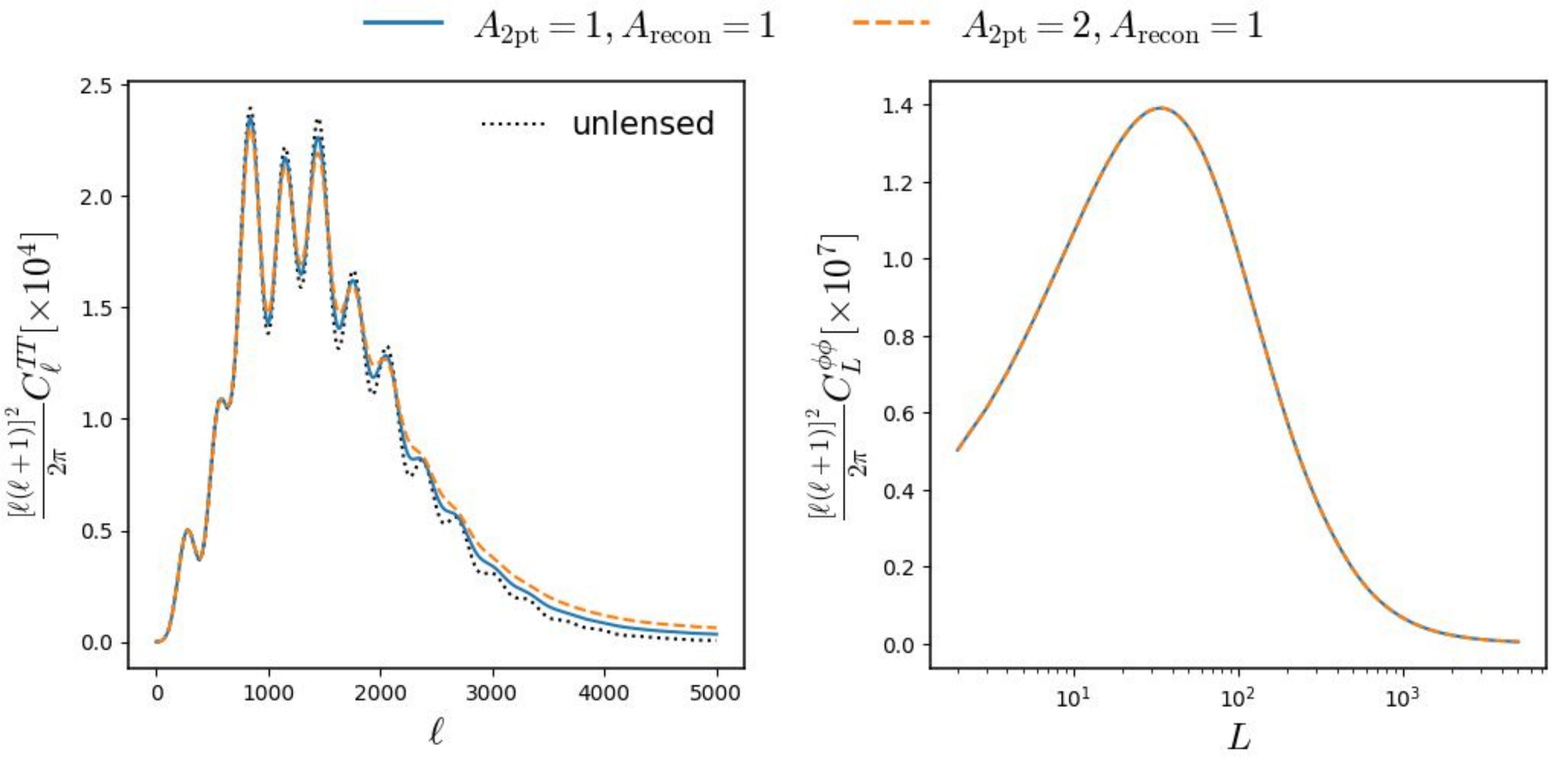
$$\mathbb{B}_P^\nu(\beta_n, \beta_{\mathrm{pol}}^\nu) = \mathbb{B}_{\mathrm{main}}^\nu + \beta_{\mathrm{pol}}^\nu \underbrace{\boxed{\left(\mathbb{B}_T^\nu(\beta_n) - \mathbb{B}_{\mathrm{main}}^\nu\right)}}_{\text{sidelobes}}$$

- The impact is mainly on inferred EE bandpowers and shifts in ωb and ns.





Excess lensing power



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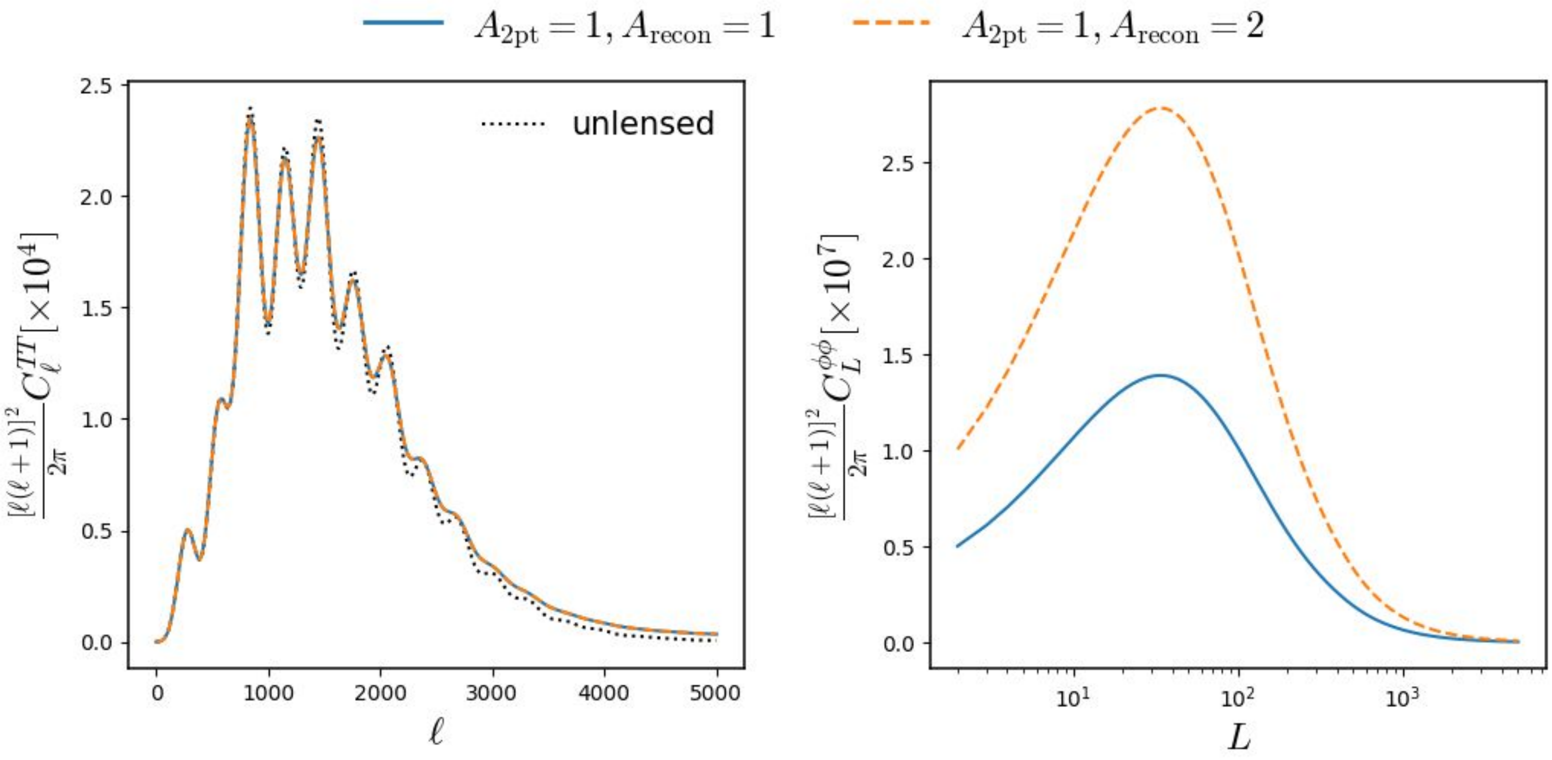

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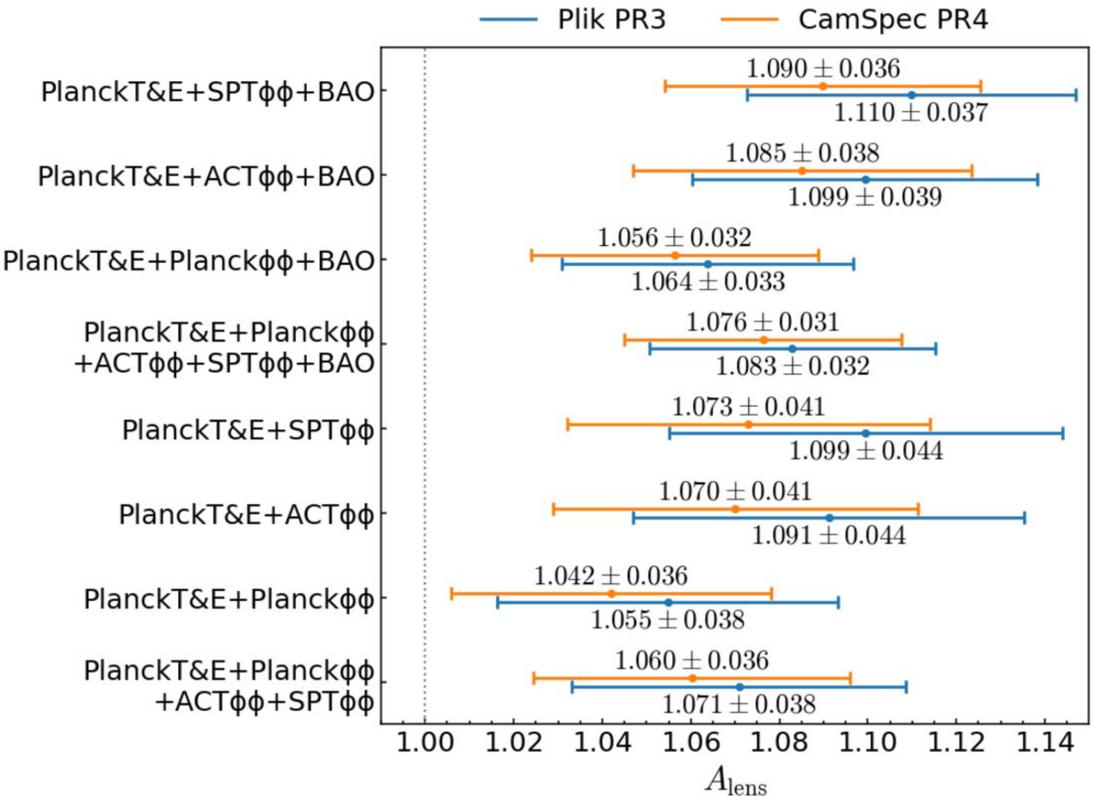
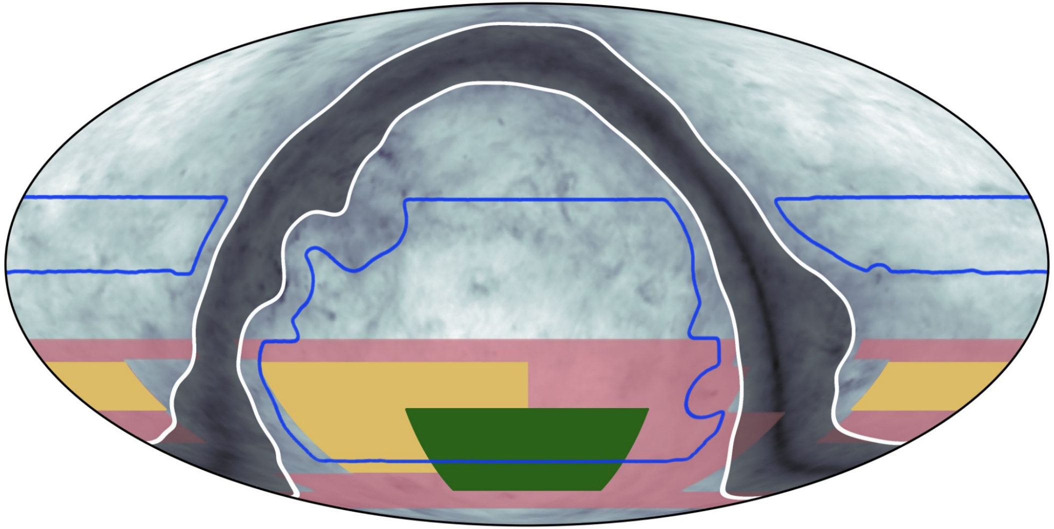
Results – excess lensing power



Other SPT-3G Surveys



Survey	Area [deg^2]	Year	Coadd Noise [muK-arcmin]
Main	1500	2019-2020	3.3
		2019-2023, 2025-2026	1.6
Summer	2600	2019-2023	6.5
Wide	6000	2019-2024	8.8