Cosmology from SPT-3G

Fei Ge, Marius Millea,

<u>Etienne Camphuis,</u> Cail Dailey, Wei Quan

with the SPT-3G collaboration

South Pole Telescope

10-meter diameter telescope located at the South Pole in optimal conditions for CMB observations

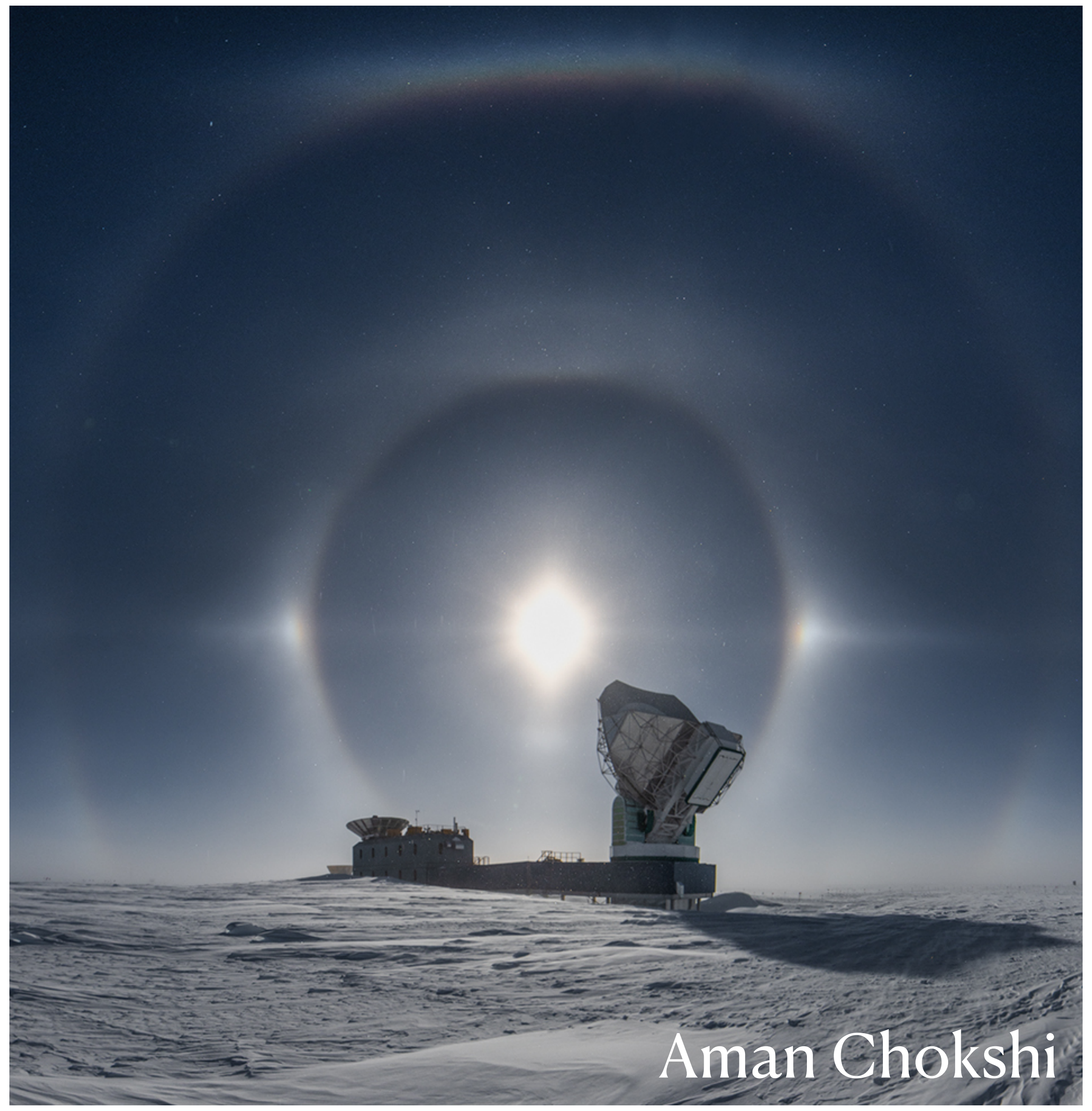
Science goals

- Delensing in the BICEP/Keck field
- **CMB Lensing**
- **Cosmological constraints from primary anisotropies**
- High-ell TT, tSZ kSZ, Low-ell BB, DES x SPT, axions, galaxy clusters, point sources, transients, asteroids, planet 9

High resolution: 1.6'/1.2'/1.0' at 95/150/220 GHz

Frequency	SPT-3G 19/20	
	TT	EE
95GHz	5.4	8.1
150GHz	4.6	6.6
220GHz	16	23

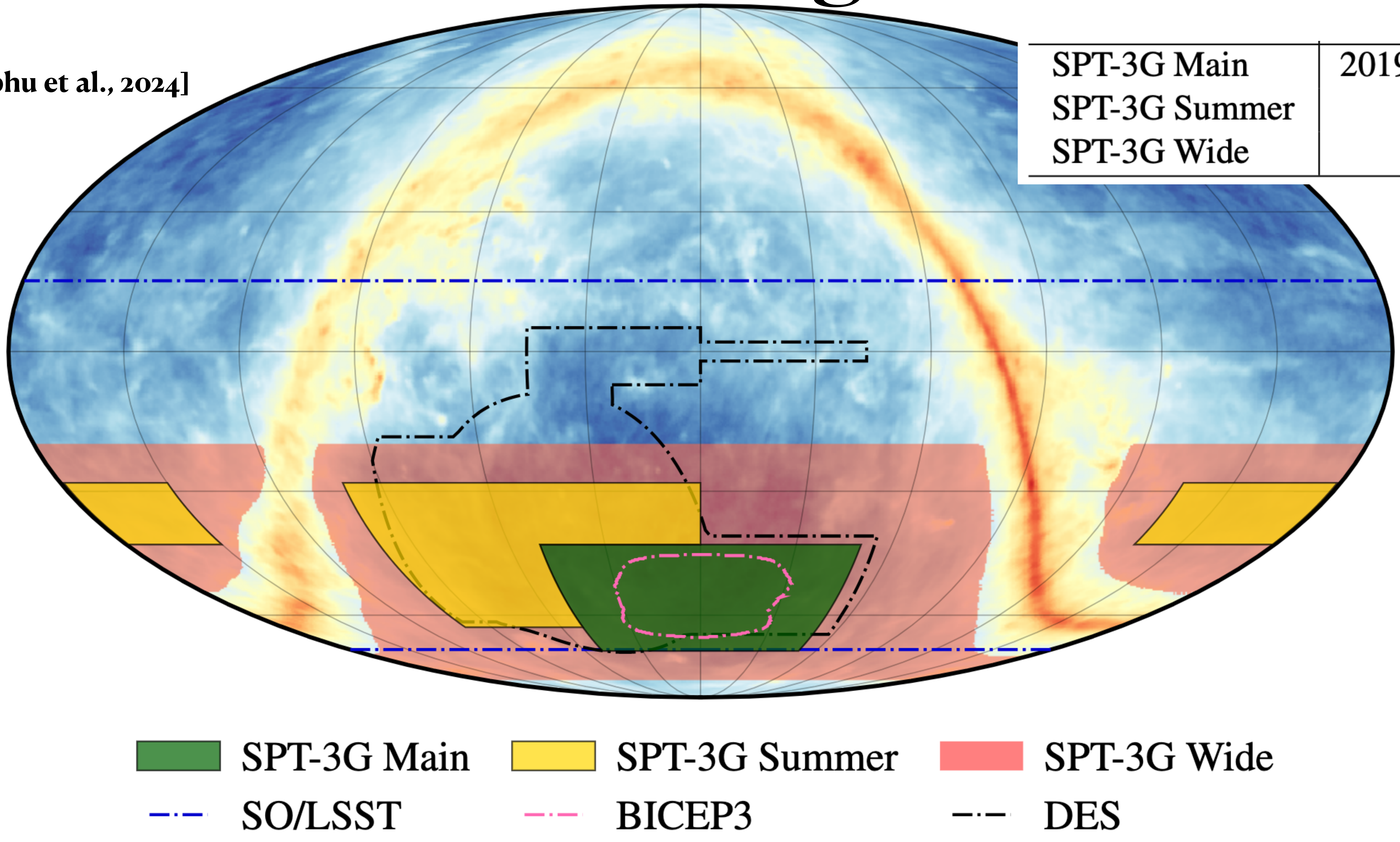
Noise levels in μK-arcmin for 2 years of data


Aman Chokshi

Fields - Total: ~10000 deg2 ➔ 25% of the sky

[Prabhu et al., 2024]

SPT-3G Main	2019-2023, 2025-2026
SPT-3G Summer	2019-2023
SPT-3G Wide	2024



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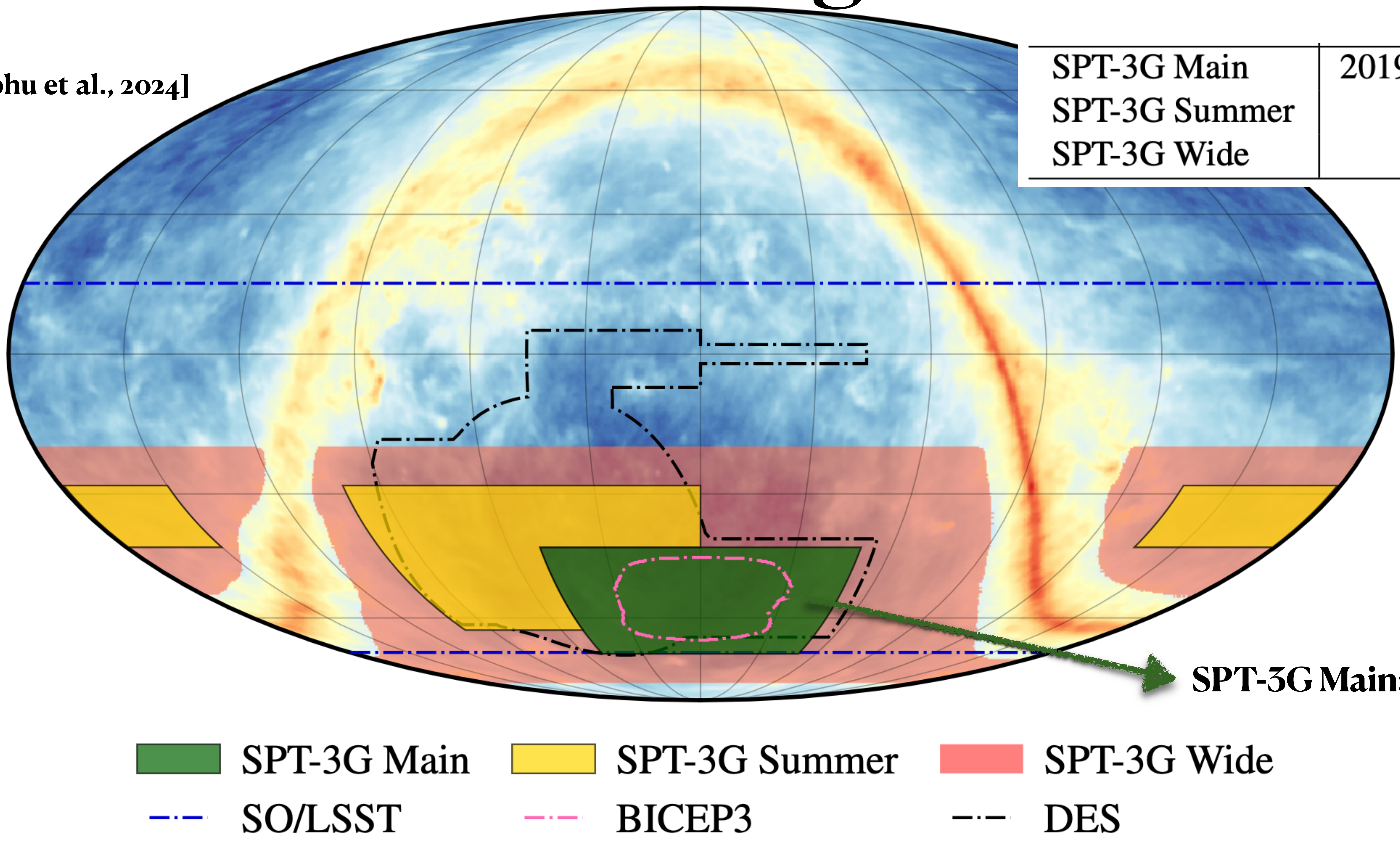
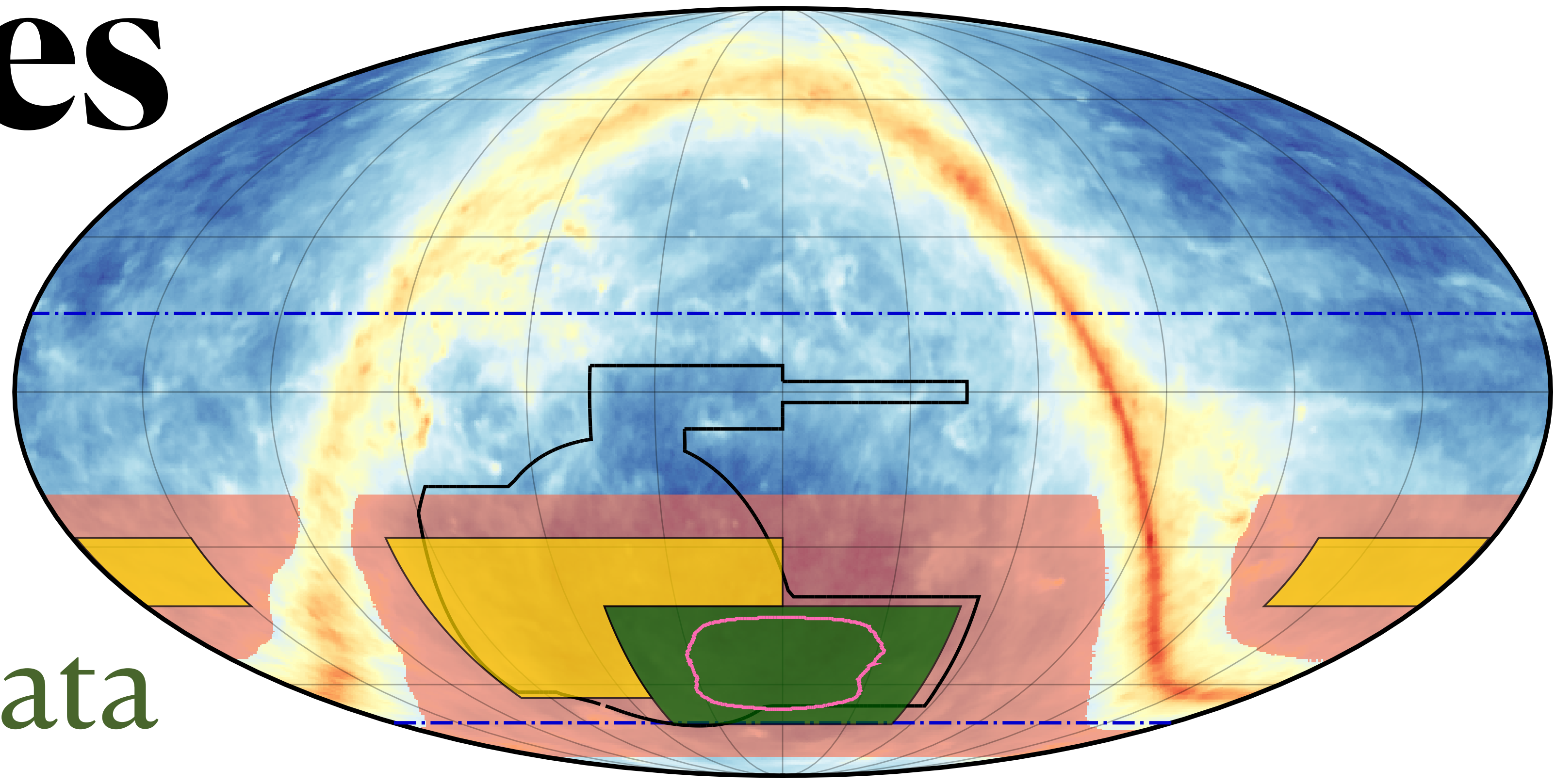


SPT-3G Main: 1500 deg2 → 4%

Outline - CMB analyses



- **Preprint is out!**
  - Cosmology from CMB lensing and delensed EE power spectra using 2019-2020 SPT-3G polarization data arXiv:2411.06000 [Fei Ge, Marius Millea, EC et al.]
- **Ongoing**:
  - Cosmology from TT/TE/EE power spectra using the main field (EC, W. Quan)
  - QE lensing (Y. Omori)
  - **Summer** field analysis (F. Guidi)
  - **Wide** field analysis (A. Vitrier, K. Dibert)

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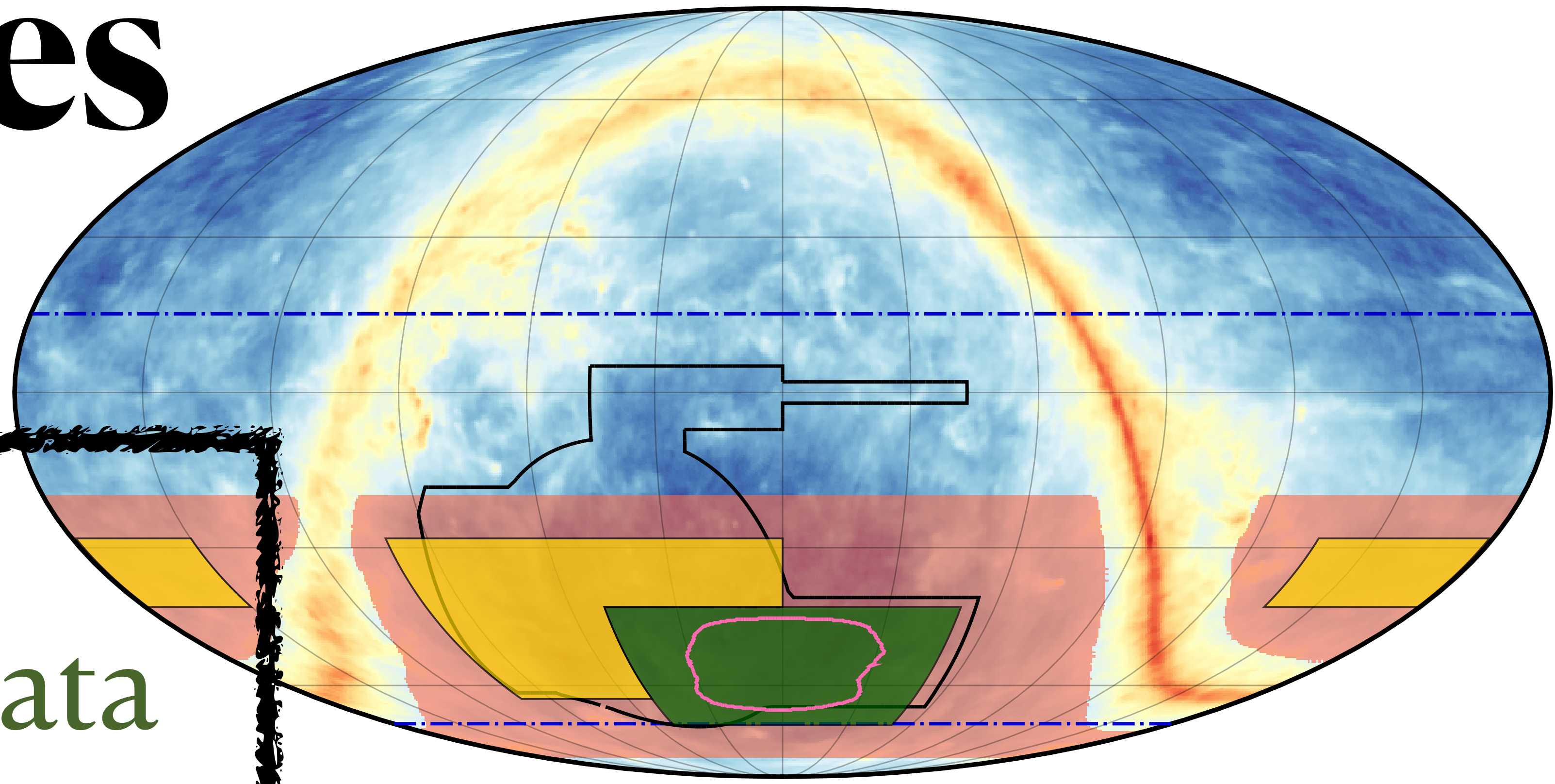

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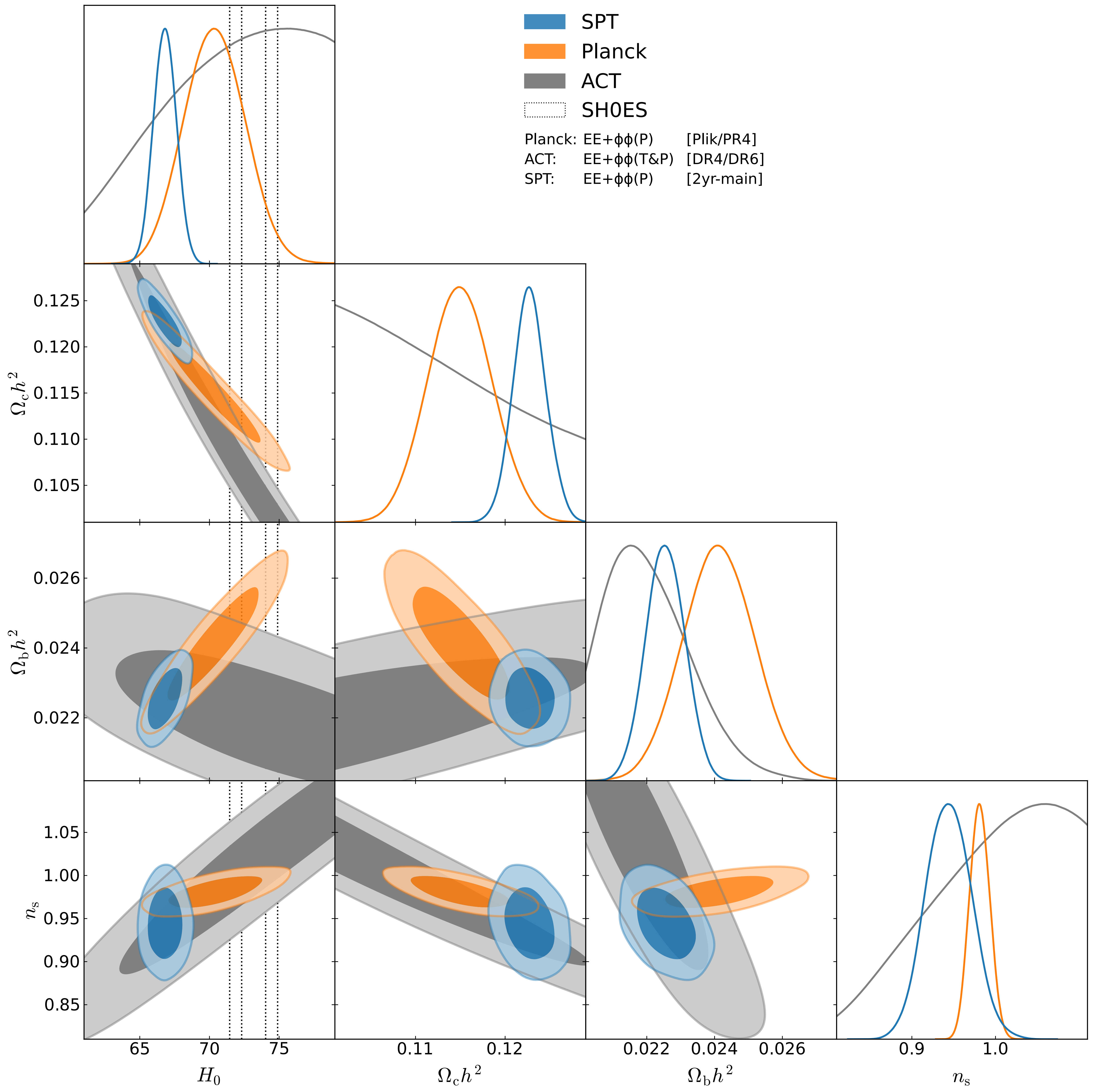
Highlights

- **The ϕϕ bandpowers at L>350 and EE bandpowers at ℓ>2000 are the most precisely measured to date.**
- With signals only from CMB polarization, we are able to achieve constraints on H_0 and S_8 comparable to Planck results, and are the tightest constraints from CMB polarization-only inference.
- Assuming LCDM, SPT results are consistent with Planck and ACT.
- Blind analysis, with a post-unblinding change
- We also detects >3σ effects from non-linear evolution in CMB lensing.

Experiments comparison from pol-only data



(1) Method

Marginal Unbiased Score Expansion (MUSE)

- (Millea & Seljak 2022)
- Goal: jointly reconstruct unlensed EE and $\phi\phi$ band powers, and **systematics parameters**
- A **bayesian map-level inference** effectively uses all N-point statistics

$$\mathscr{P}\left(f, \phi, \theta \,|\, d\right)$$

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SPT-3G CMB maps

Unlensed CMB polarization maps

Latent variables

Data

$$\mathcal{P}\left(f, \phi, \boxed{\theta} \,|\, d\right)$$

Lensing potential map

$$\left\{ C_b^{\mathrm{EE}}, C_b^{\phi\phi}, \theta_{\mathrm{sys}} \right\}$$

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Unlensed CMB polarization maps ← Latent variables

SPT-3G CMB maps ← Data

$$\mathscr{P}\left(f, \phi, \theta \,|\, d\right)$$

Lensing potential map

$$\theta = \left\{ C_b^{\mathrm{EE}}, C_b^{\phi\phi}, \theta_{\mathrm{sys}} \right\}$$

$$\mathscr{P}\left(\theta \,|\, d\right) = \int \mathrm{d}f\mathrm{d}\phi \, \mathscr{P}\left(f, \phi, \theta \,|\, d\right)$$

Marginalizing over the latent variables can be done using a large number of simulations of the data = MUSE approach (fully differentiable)

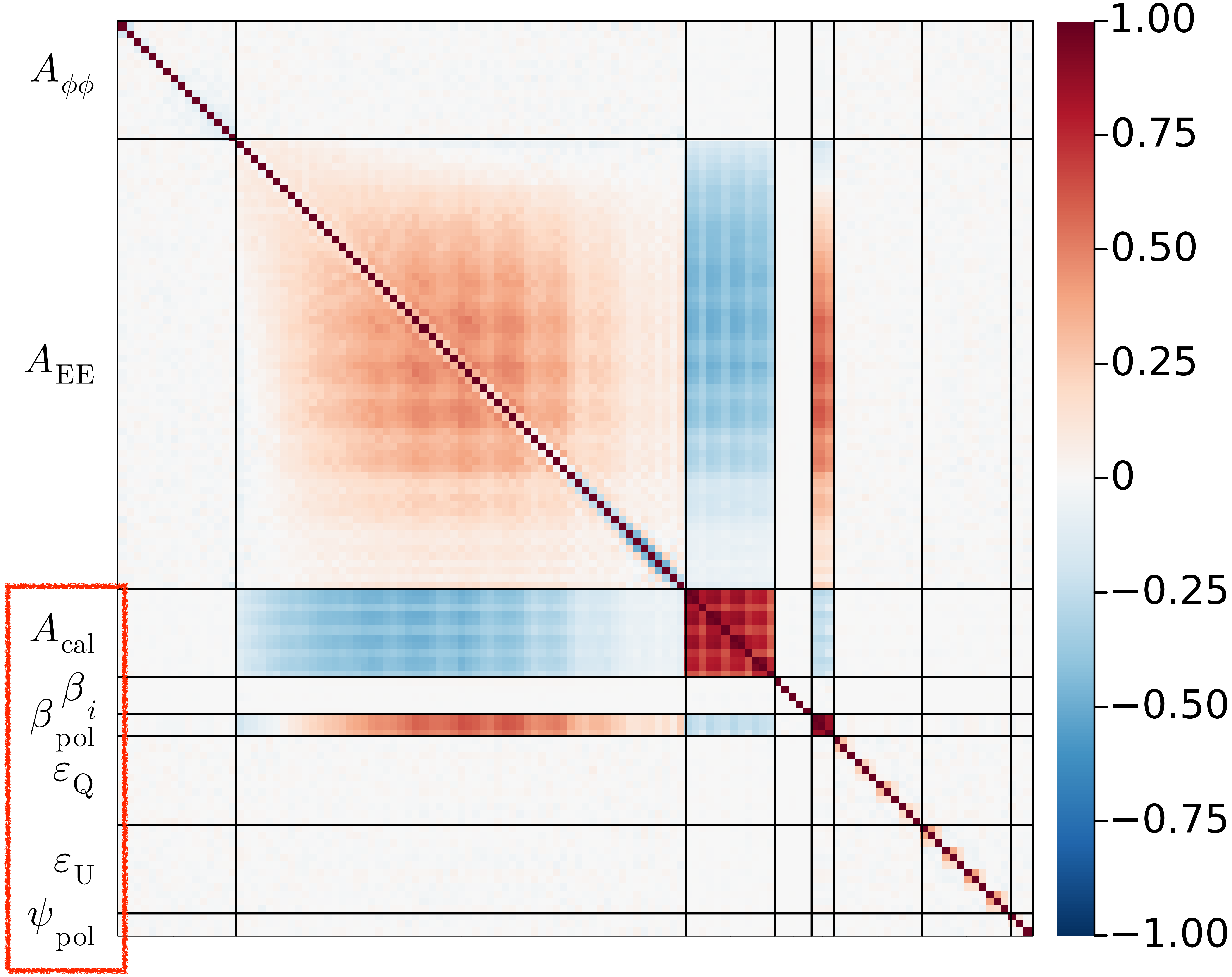
(1) Method

Marginal Unbiased Score Expansion (MUSE)

- **MUSE yields a multi-variate Gaussian approximation to the marginal posterior**
- Covariance is obtained with **differentiation and simulations**
- **Naturally includes systematic parameters**
- Cosmological parameters (γ) likelihood:

$$-2\log \mathscr{P}(\hat{\theta}\,|\,\gamma) = \left[\theta(\gamma) - \hat{\theta}\right]^{\dagger} \Sigma_{\mathrm{MUSE}}^{-1} \left[\theta(\gamma) - \hat{\theta}\right]$$

Correlation matrix of reconstructed bandpowers and systematic parameters

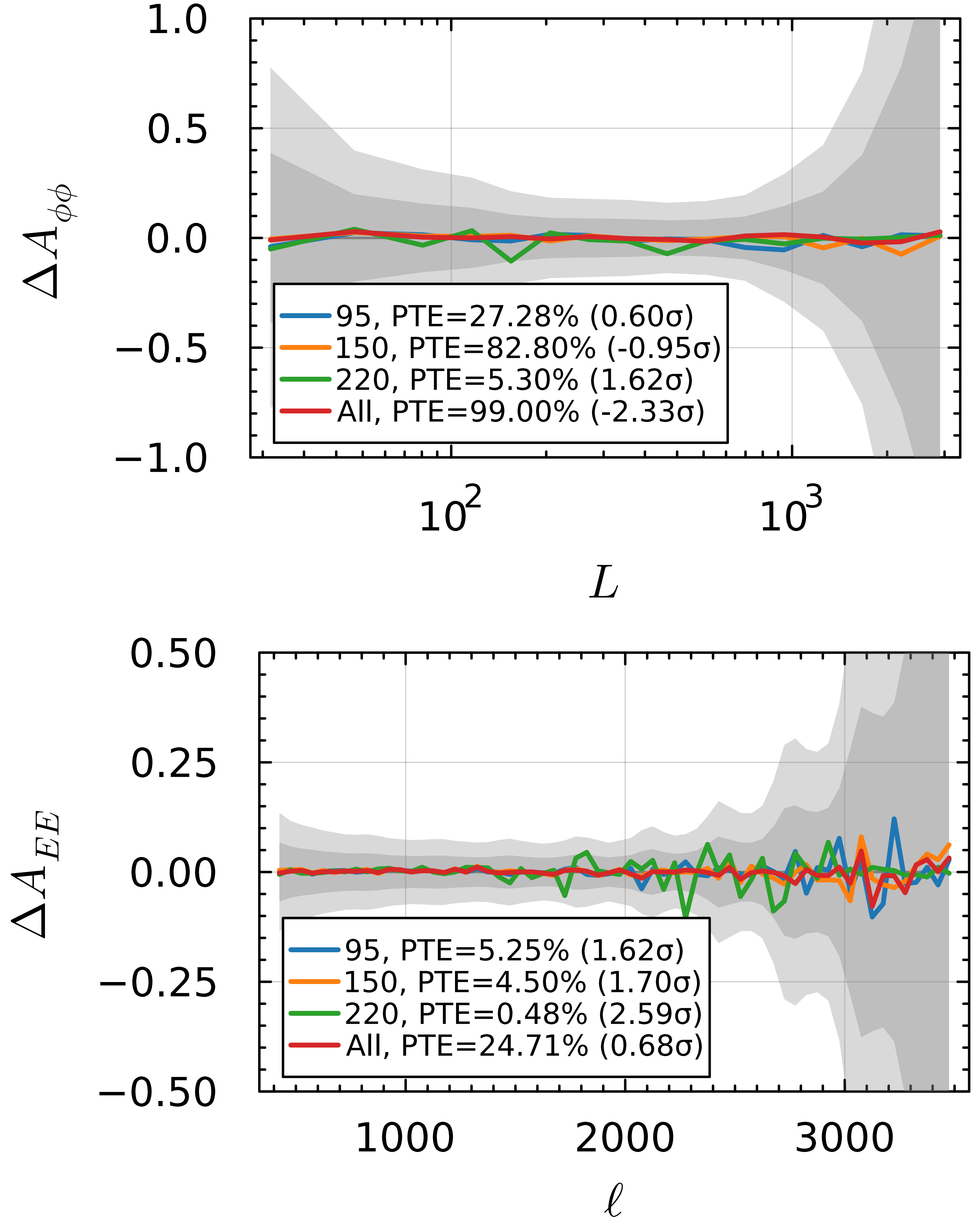


(2) Validation

(a) on mock observations

- 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.

Average bandpowers from 100 mocks

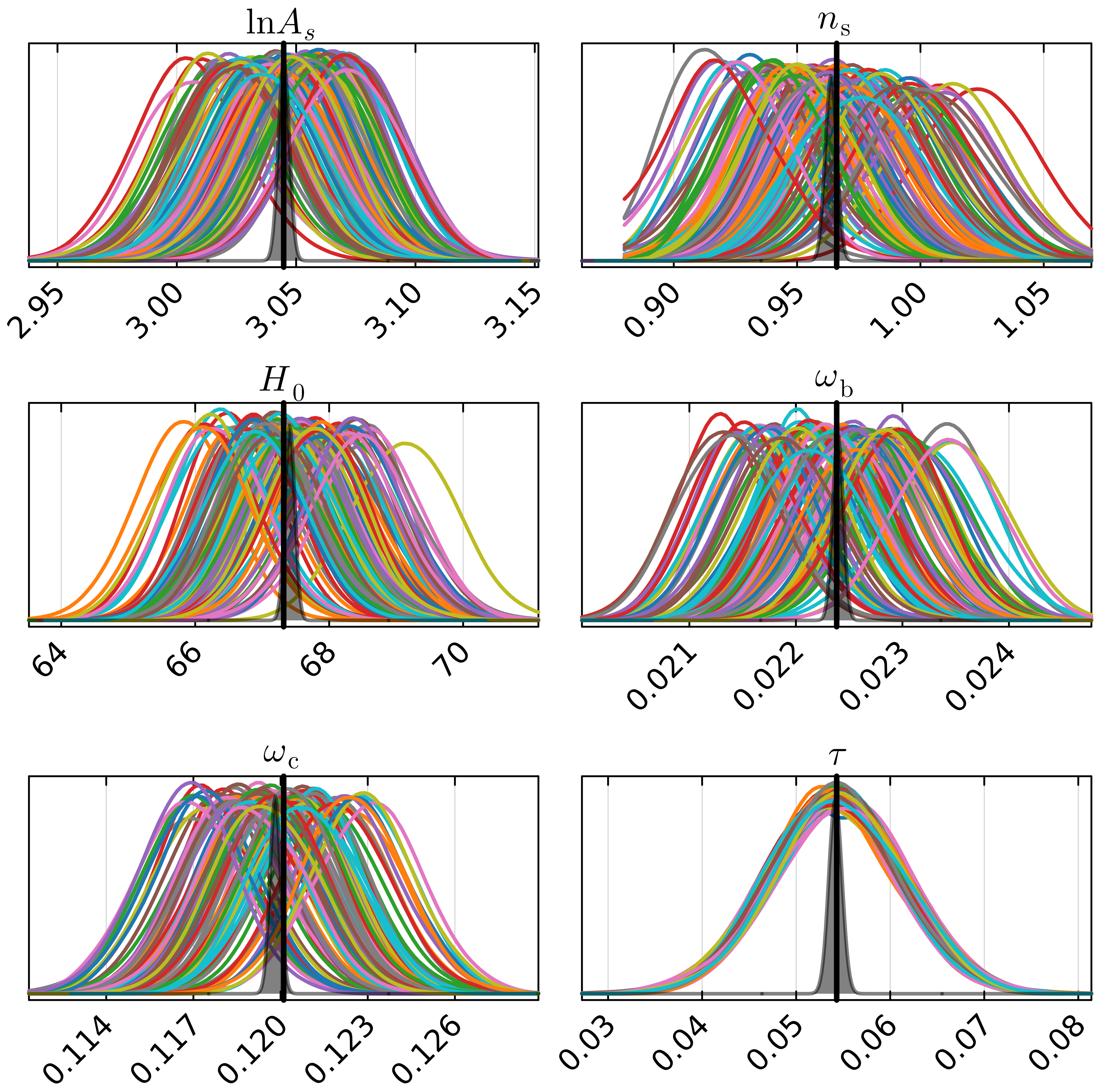


- All means joint analysis of 95+150+220 GHz.
- Colored lines show mean bandpowers over 100 mock sims.
- Gray bands show 1σ and 2σ error of 95+150+220 results.

(2) Validation

(a) on mock observations

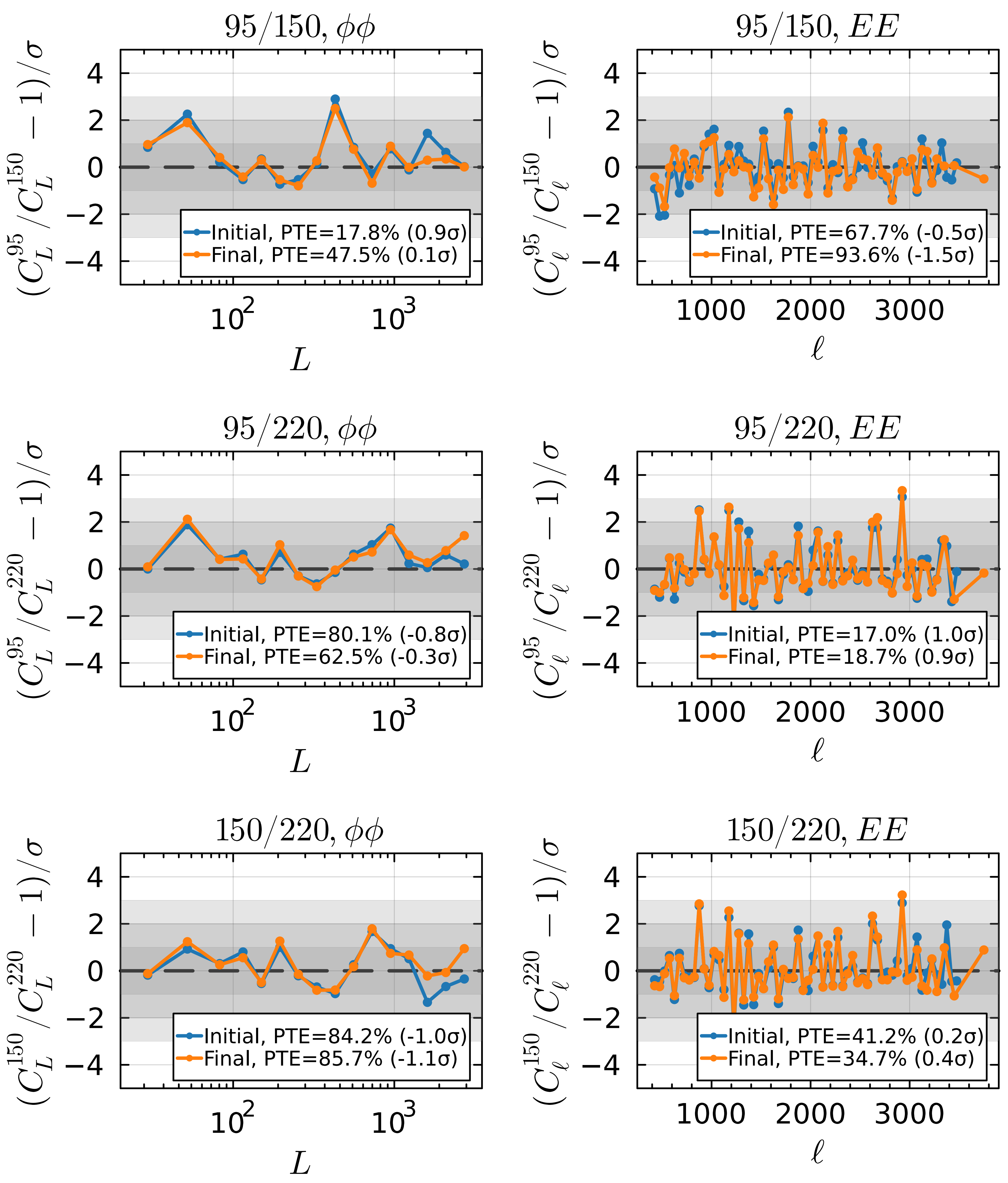
- The product of individual posteriors recover the input truth of the mocks using a set of 100 mocks.
- Pipeline bias to individual cosmological parameters has been bounded to $< 0.1\sigma$



(2) Validation

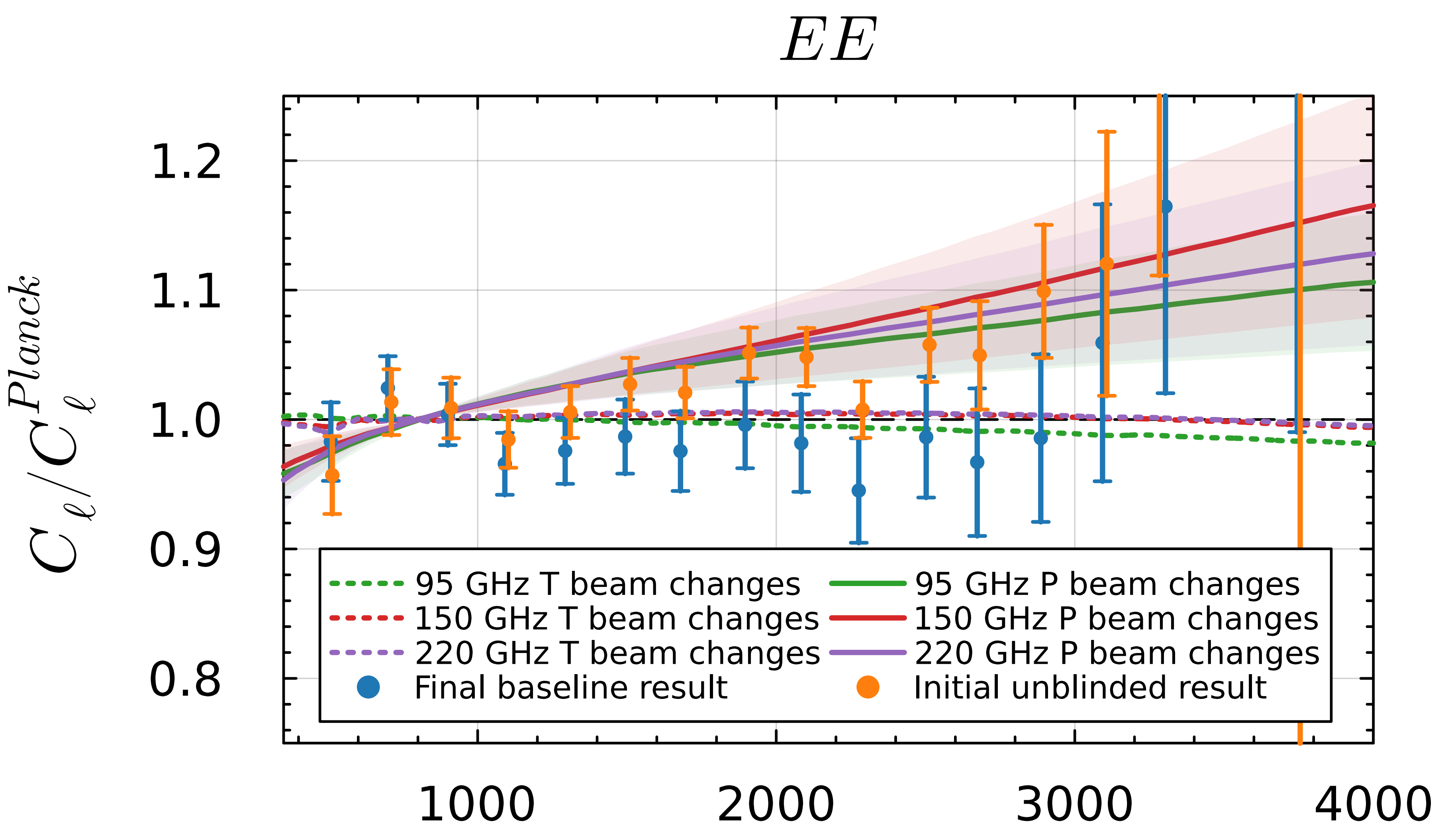
(b) on data

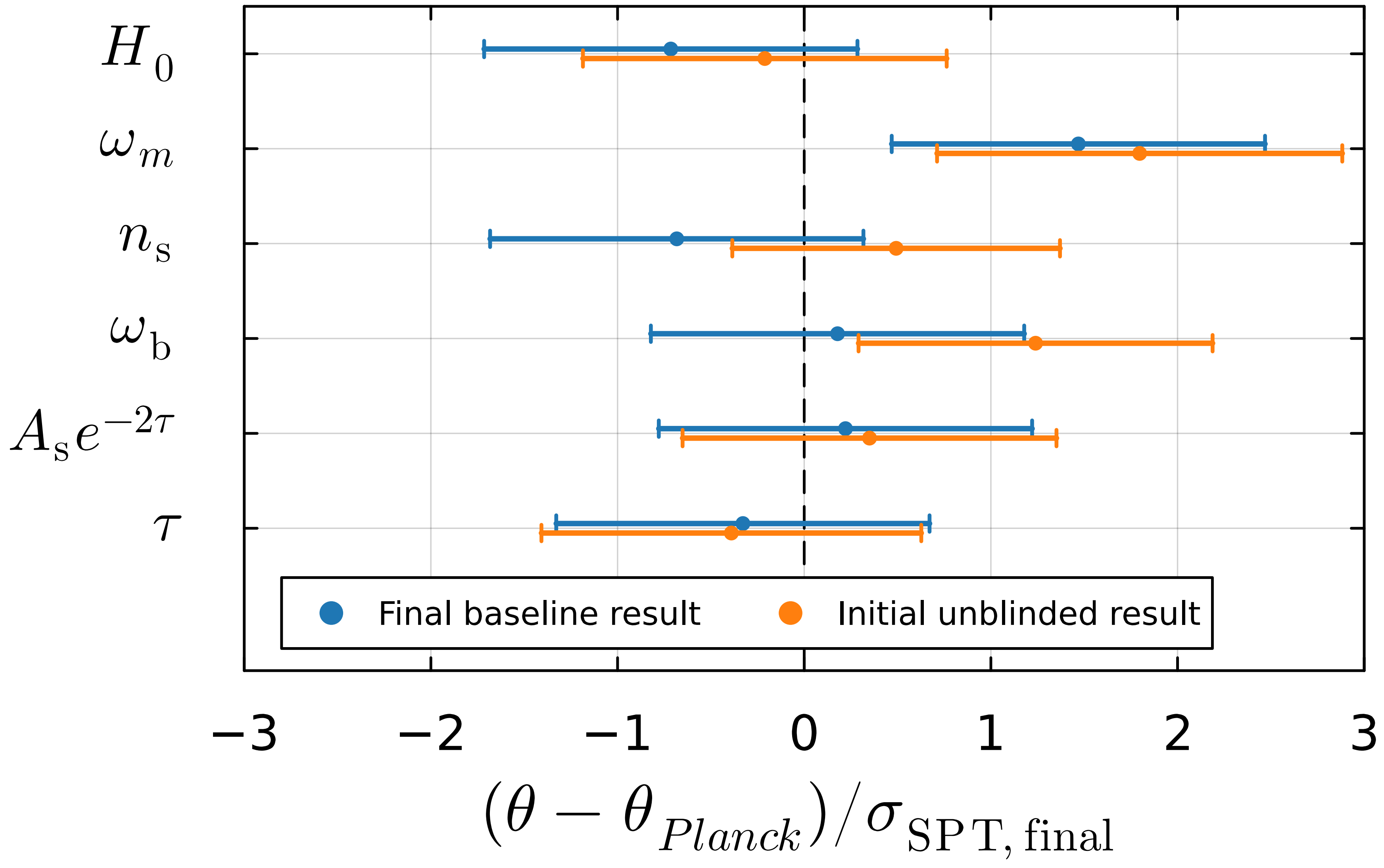
- We test data consistency by comparing band powers from single-frequency runs
- We find good agreement between frequency, before and after post-unblinding change
- Validation steps allow us to unblind cosmological parameters



(3) Post-unblinding

- After unblinding, we discovered an additional source of uncertainty coming from polarized beams
- Before:
  - $\mathbb{B}_P^\nu = \mathbb{B}_T^\nu$
- After:
  - $\mathbb{B}_P^\nu(\beta_{\rm pol}^\nu) = \mathbb{B}_{\rm main}^\nu + \beta_{\rm pol}^\nu \left(\mathbb{B}_T^\nu - \mathbb{B}_{\rm main}^\nu\right)$
- Affects:
  - Slope of unlensed EE band powers
  - $\{n_{\rm s}, \omega_{\rm b}\}$ plane





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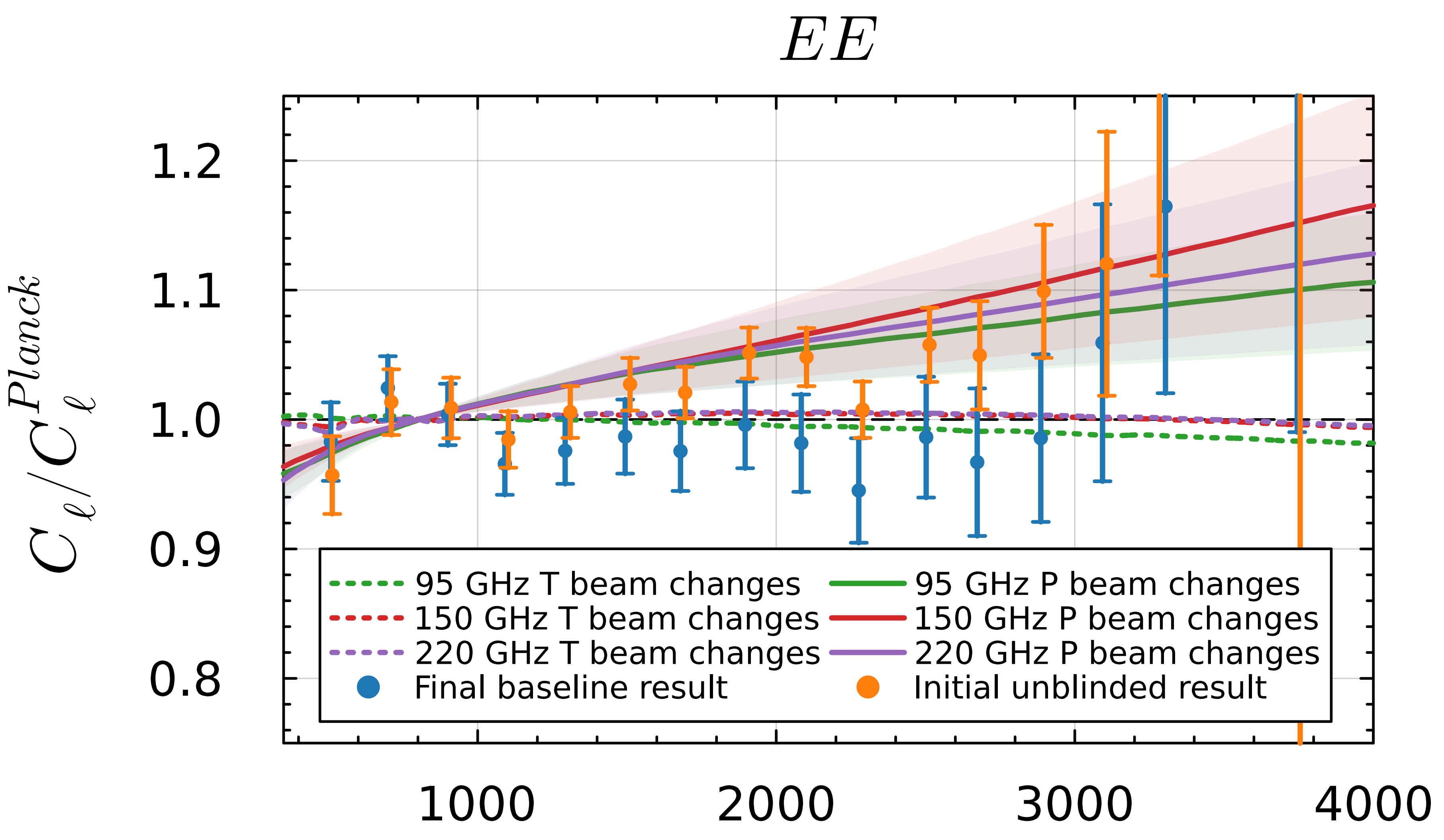
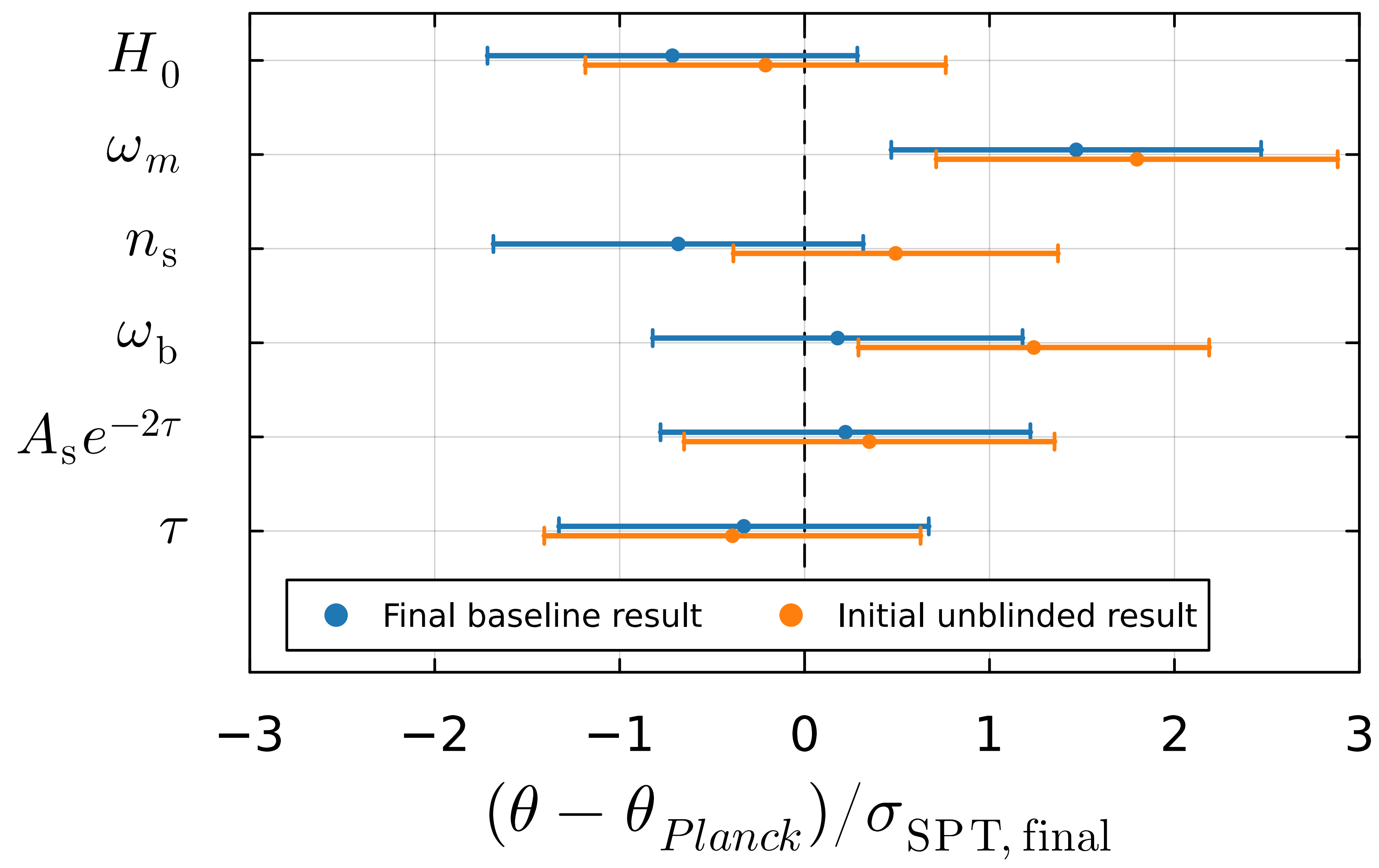
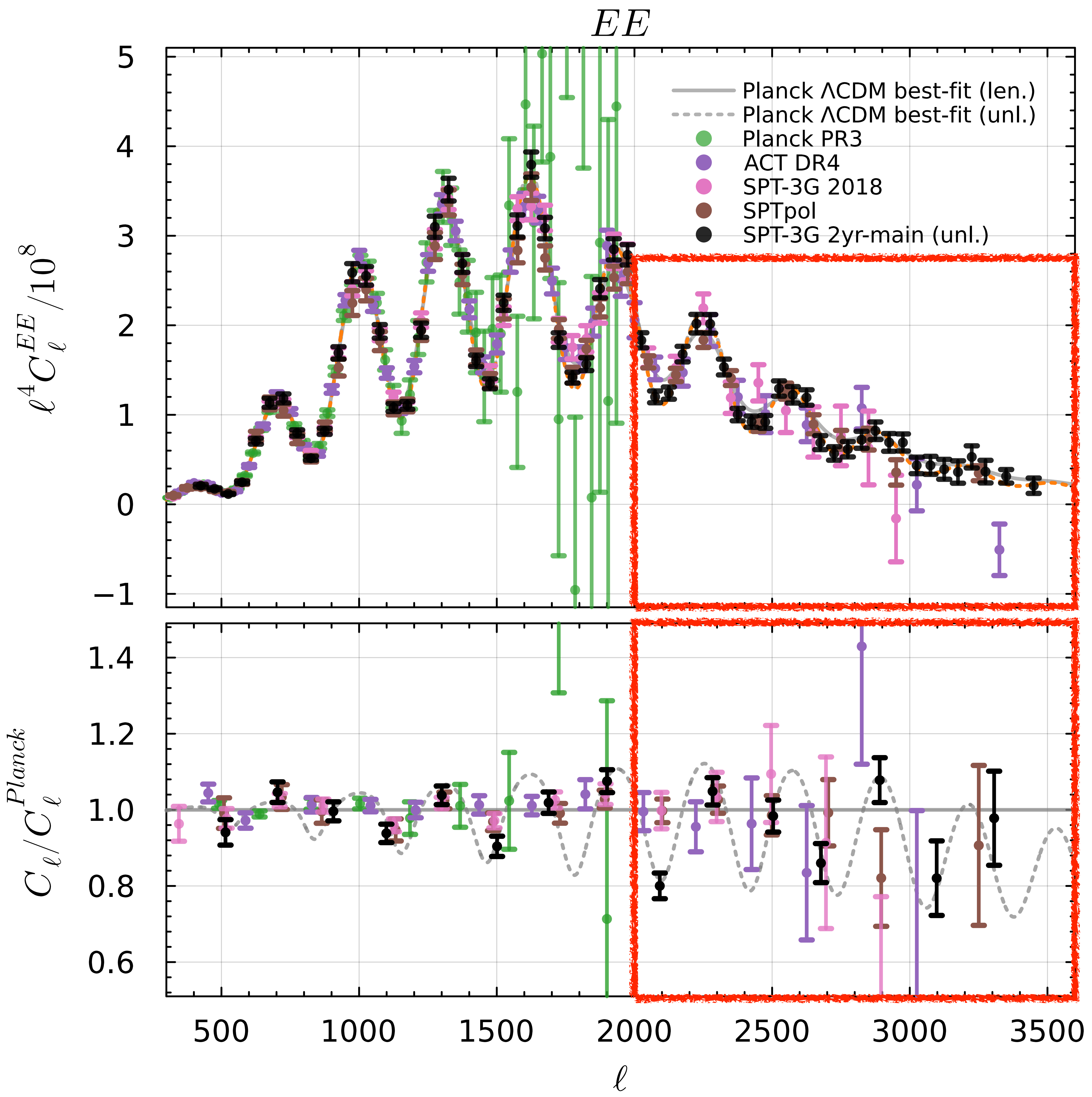
3 parameters

Fitted with uniform prior in [0,1]





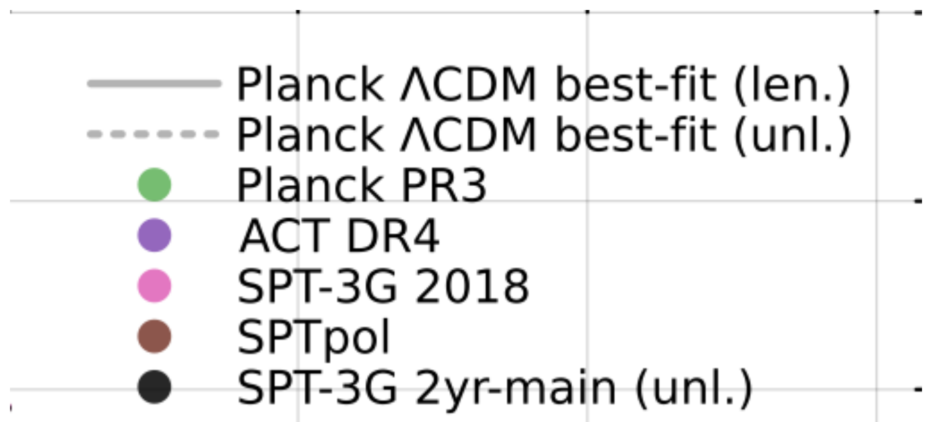


(4) Results: bandpowers

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

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

Unlensed EE band powers



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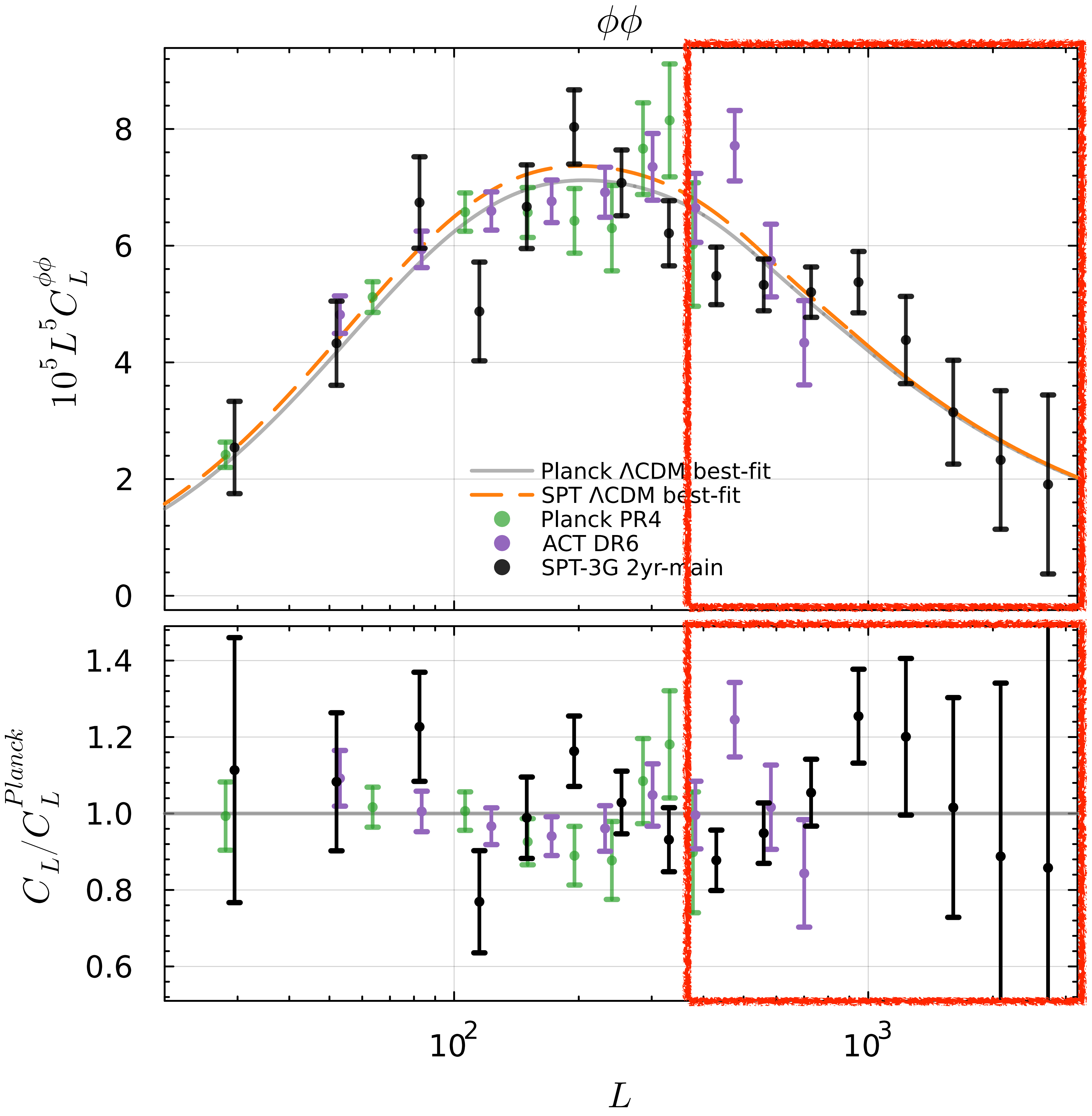
Lensing $\phi\phi$ band powers



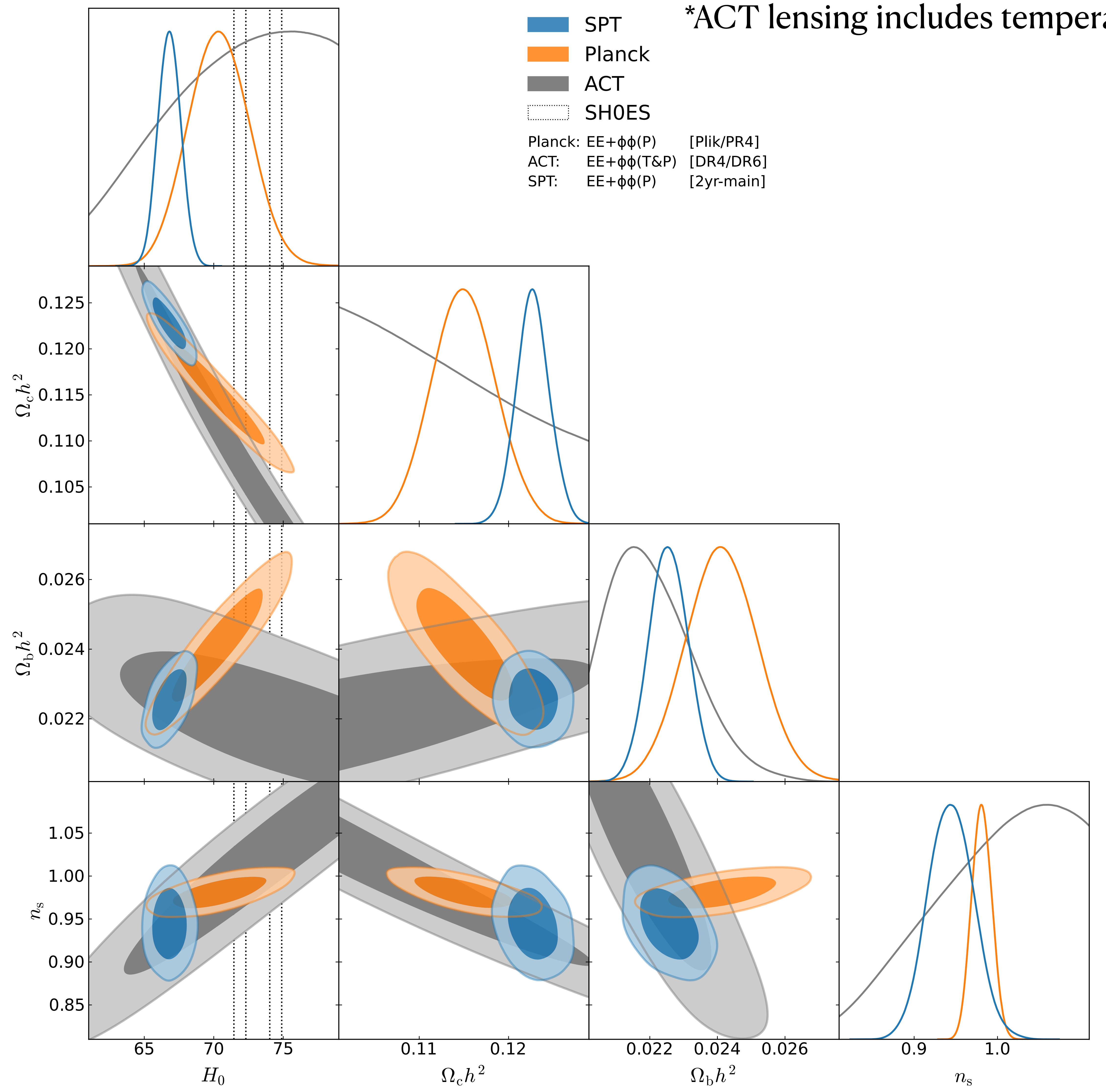
(4) Results: parameters

Pol-only

- The SPT polarization-only constraints are better than polarization data from other observations.
- From polarization only signal, SPT data also yields a low $H_0 = 66.81 \pm 0.81$ at 5.4σ tension with SHoES result.

Experiments comparison from pol-only data*

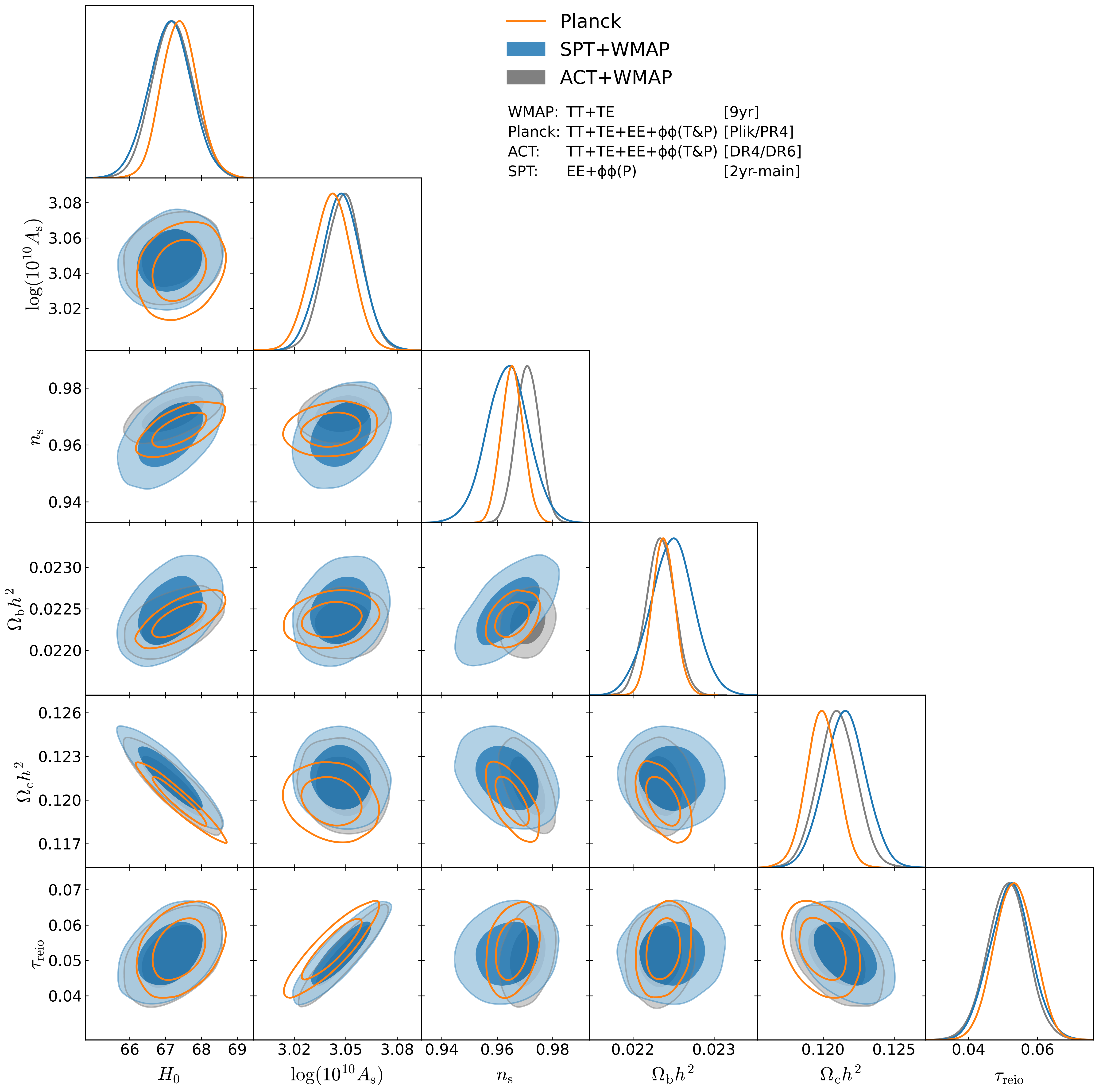
*ACT lensing includes temperature



(4) Results: parameters

Combined with WMAP

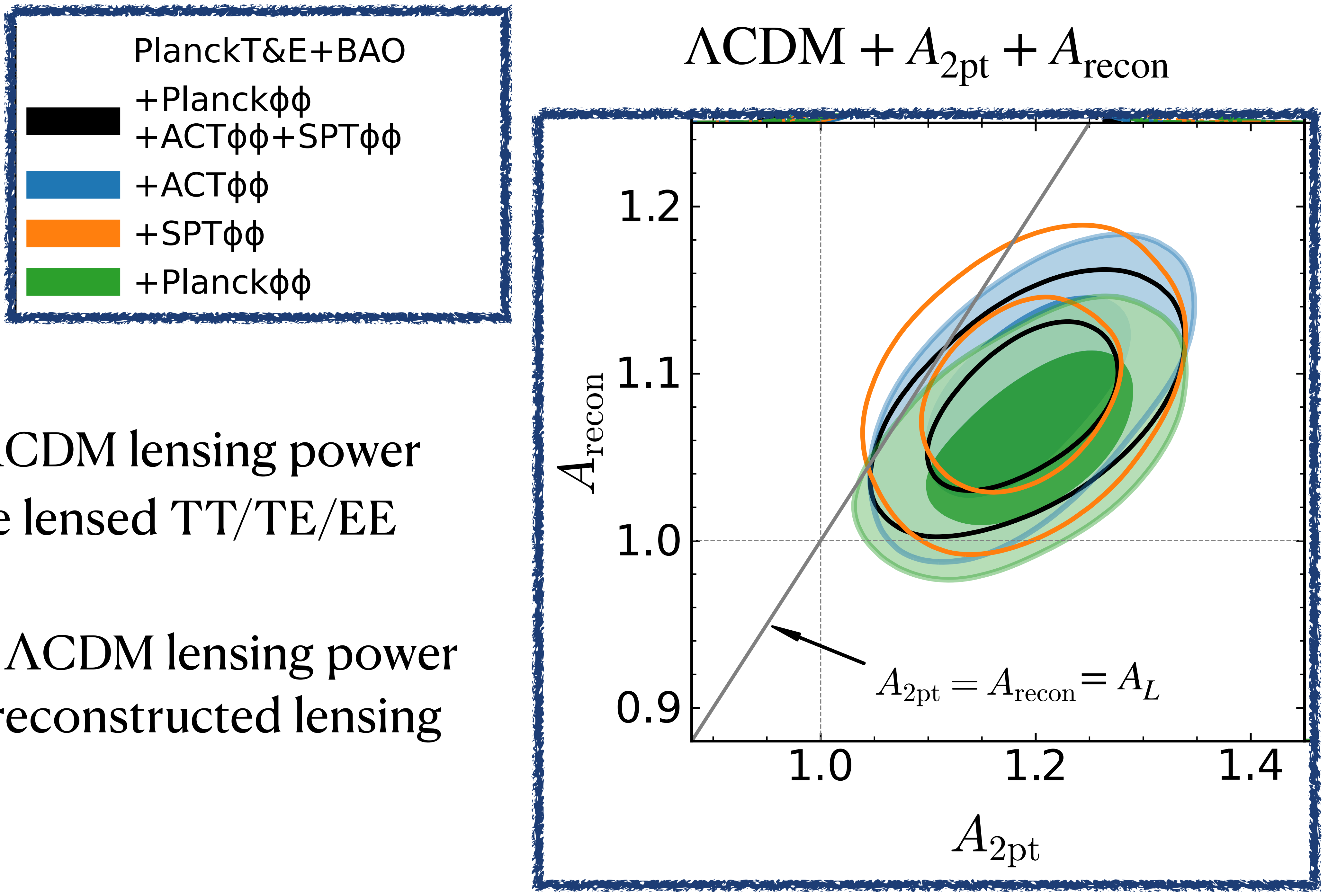
- We see that either ACT or SPT, when combined with WMAP for constraints on larger angular scales, achieve constraints on cosmological parameters with similar constraining power as the constraints from Planck.



(4) Results: Extensions

- SPT results also shows the mild excess lensing power with respect to *Planck* prediction
  See [Craig et al. 2024, Green&Meyers 2024]

- A_{2pt} scales the ΛCDM lensing power used to compute lensed TT/TE/EE spectra
- A_{recon} scales the ΛCDM lensing power used to predict reconstructed lensing power



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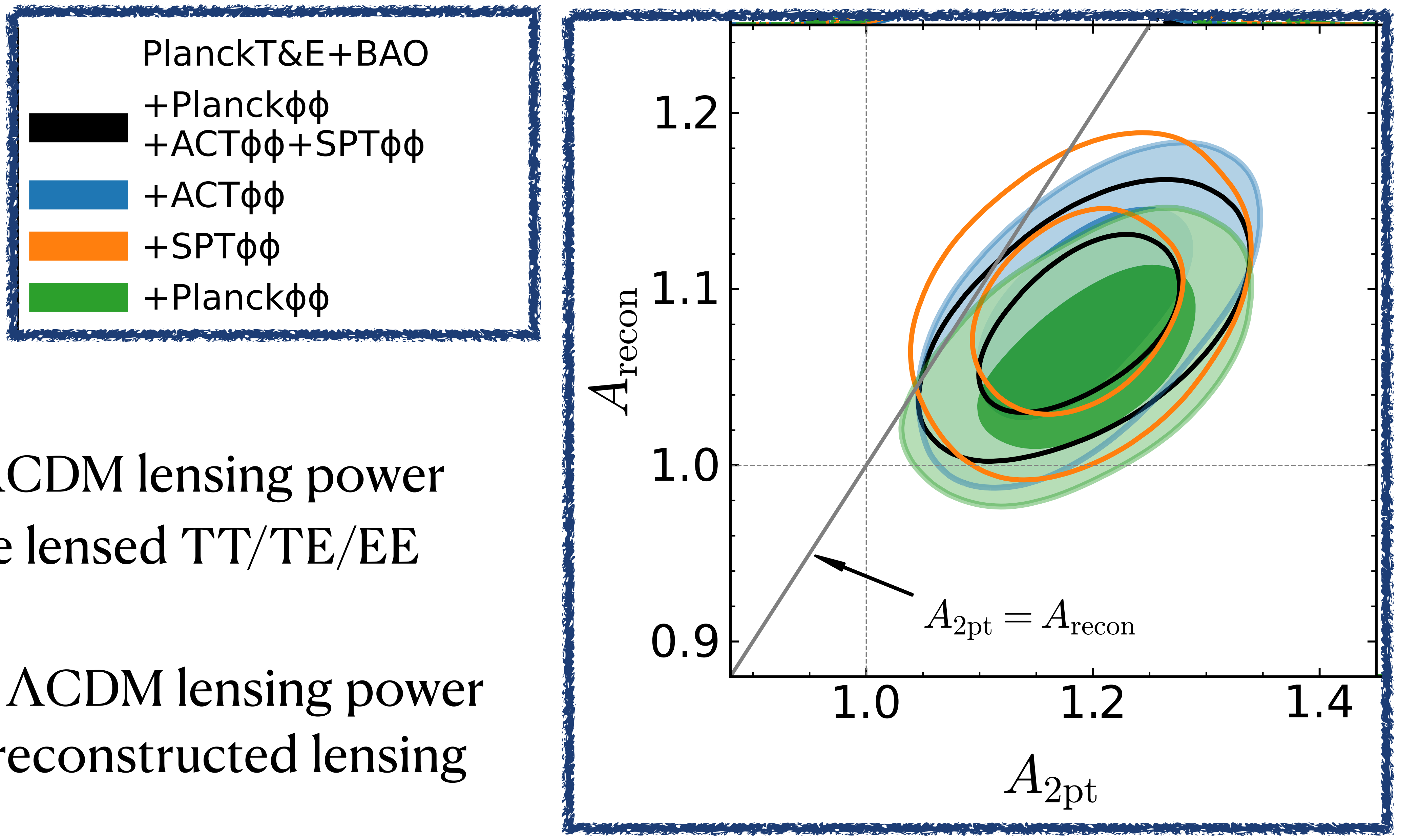
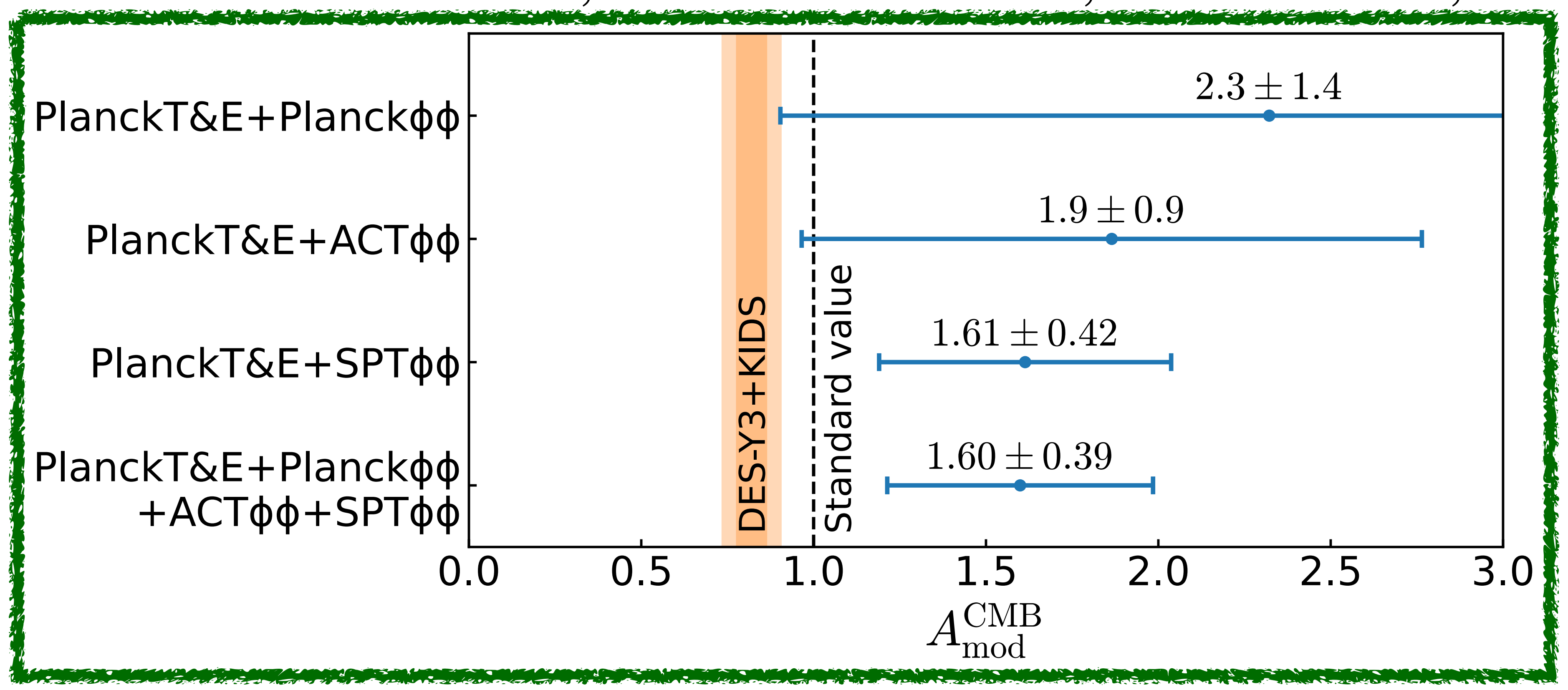


$$C_L^{\phi\phi} = C_{L,\rm lin}^{\phi\phi} + A_{\rm mod}^{\rm CMB}(C_{L,\rm nonlin}^{\phi\phi} - C_{L,\rm lin}^{\phi\phi})$$



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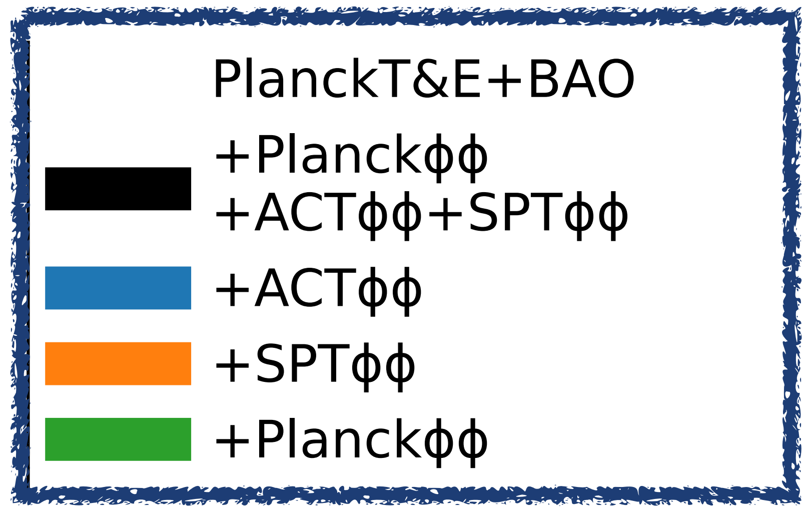
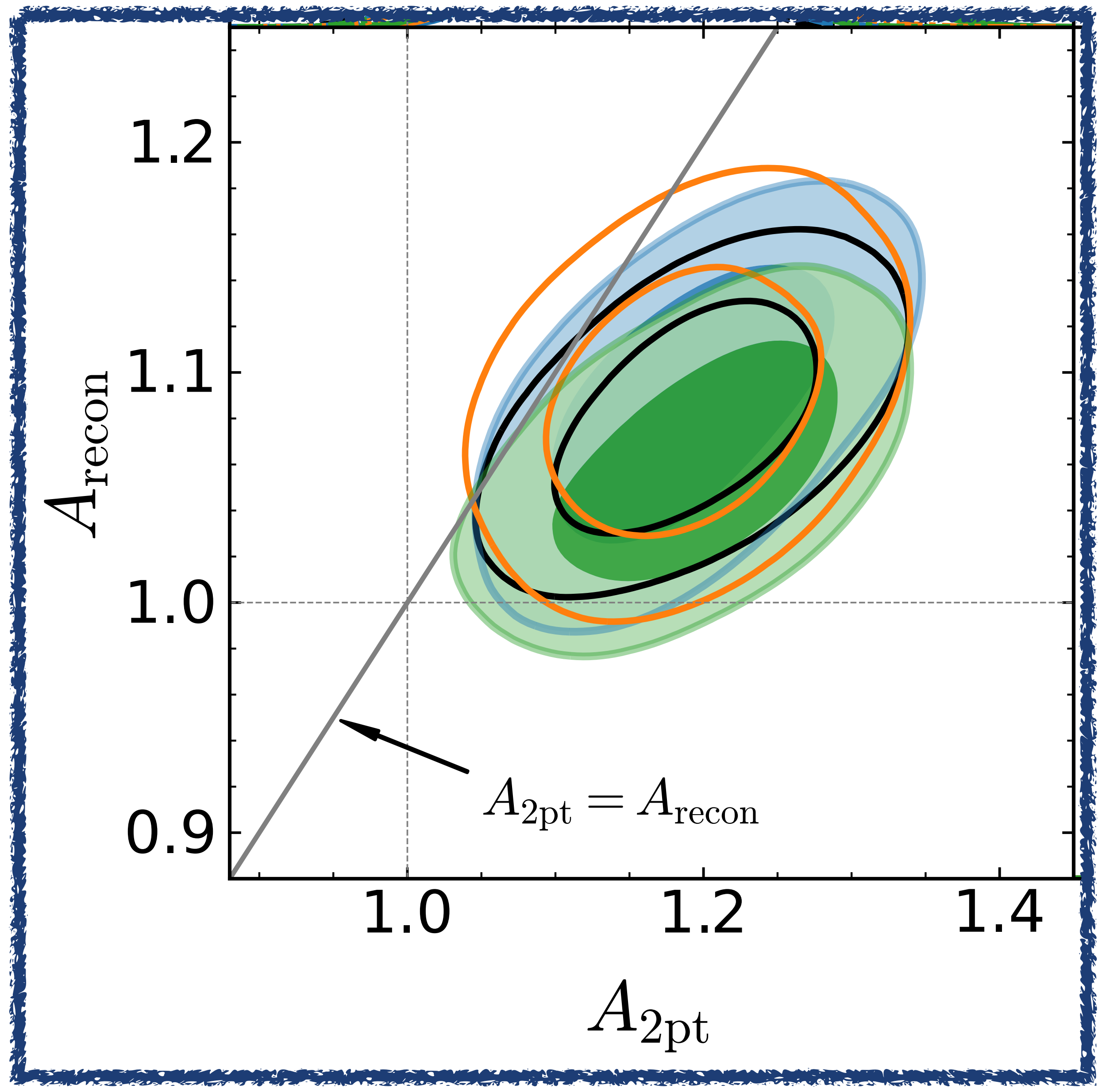
- SPT results also shows the mild excess lensing power with respect to *Planck* prediction
- We first see $> 3\sigma$ detection of non-linear structure growth in CMB lensing, and consistent with $A_{\rm mod} = 1$
- For the ΛCDM extension models, we find no preference for significant deviations of the standard cosmology values using Planck, ACT and SPT data.





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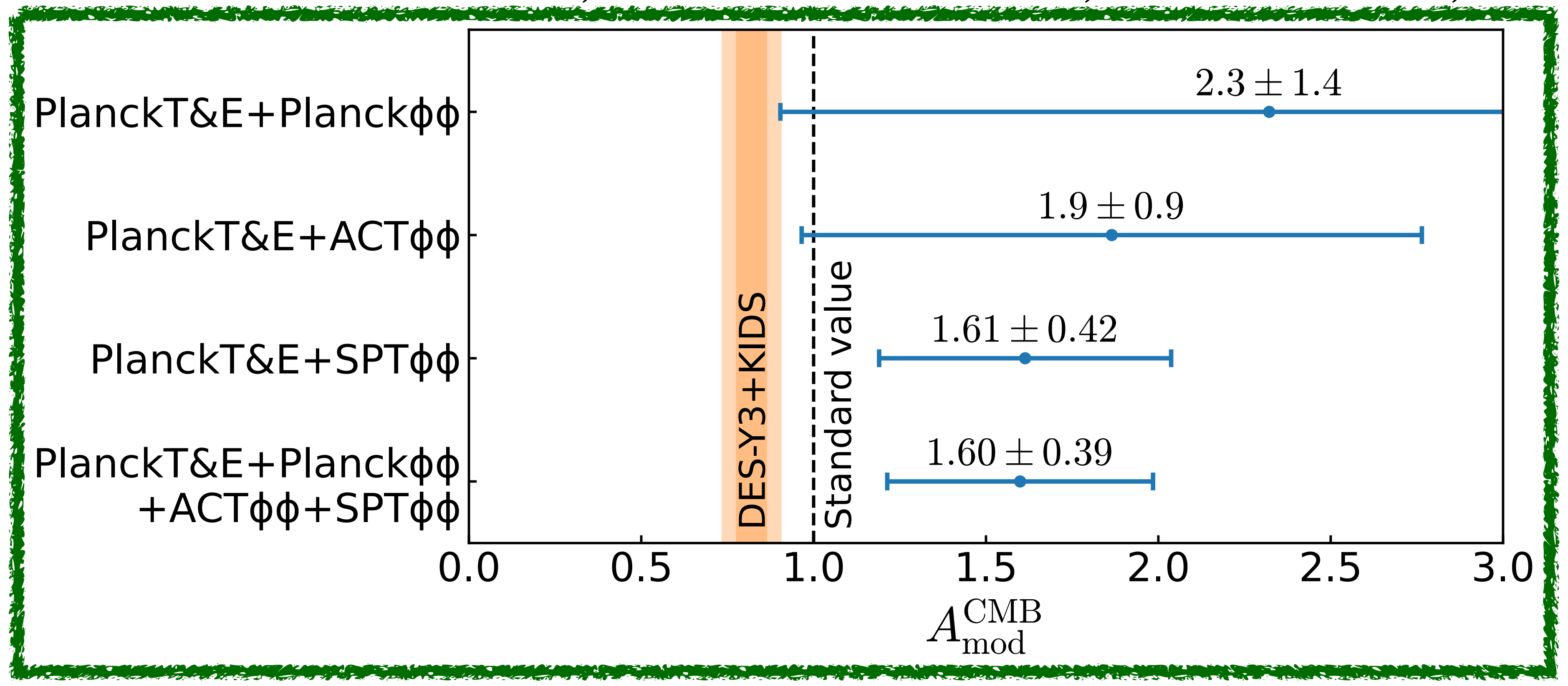


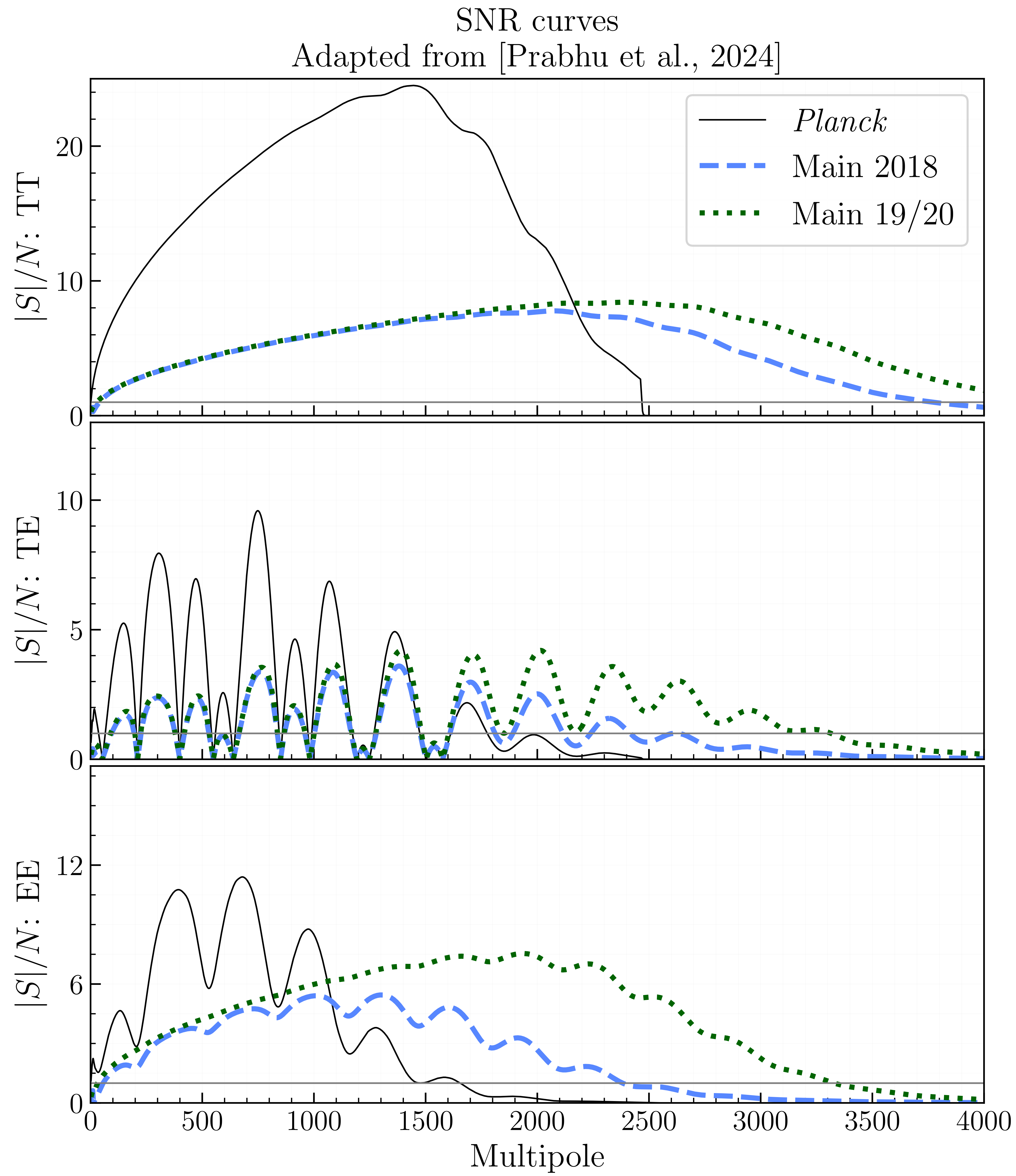
Cosmology from CMB TT/TE/EE using 2019-2020 SPT-3G data

Ongoing analysis

TT/TE/EE

SPT-3G/ 19/20

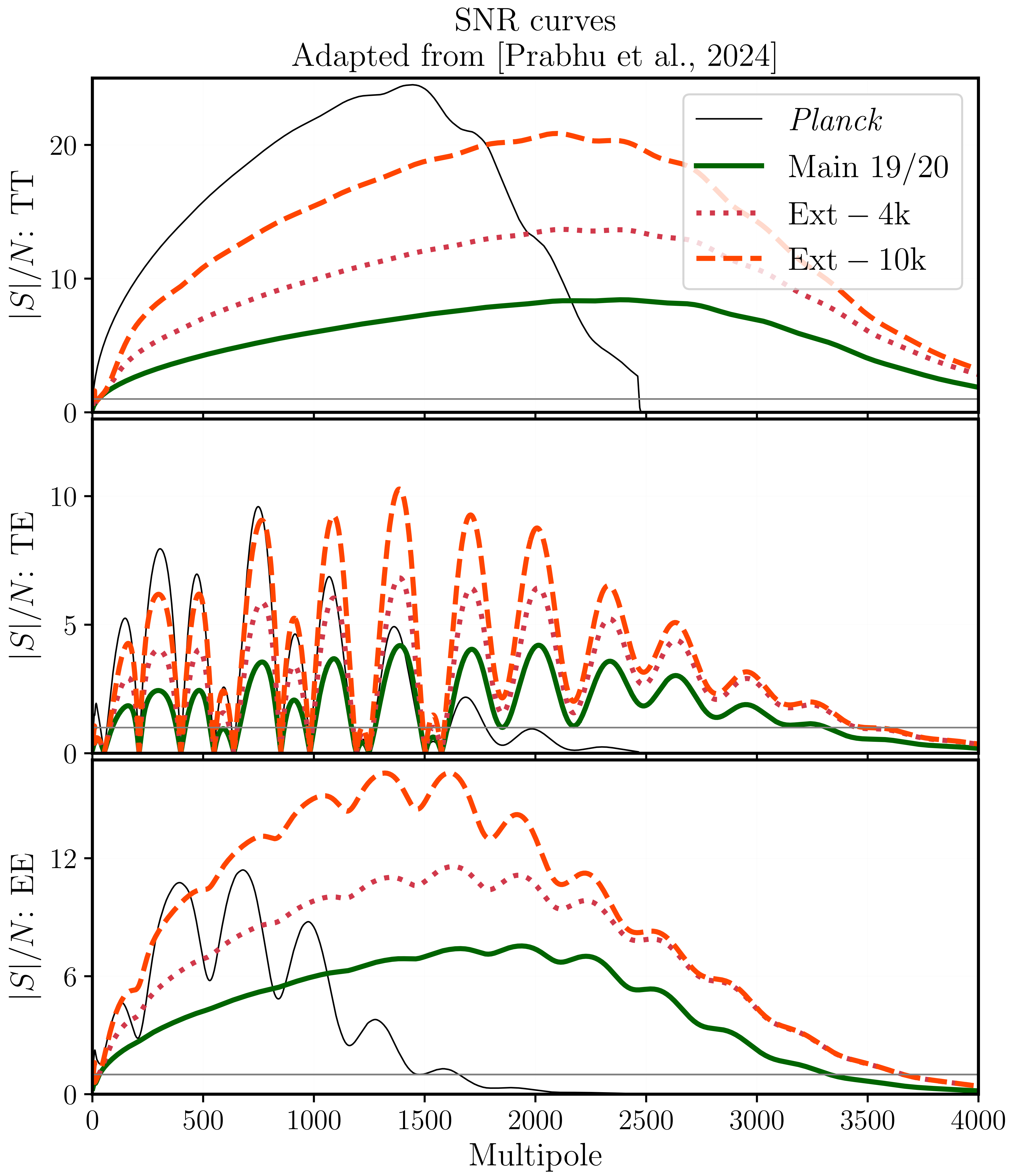
- TT/TE/EE power spectra SNR compared to *Planck* and SPT-3G
- SPT-3G 2018 results: [Balkenhol and SPT-3G collaboration, 2023]



TT/TE/EE

SPT-3G/ 19/20

- TT/TE/EE power spectra SNR compared to *Planck* and SPT-3G
- **Wide field will bring a lot more information**

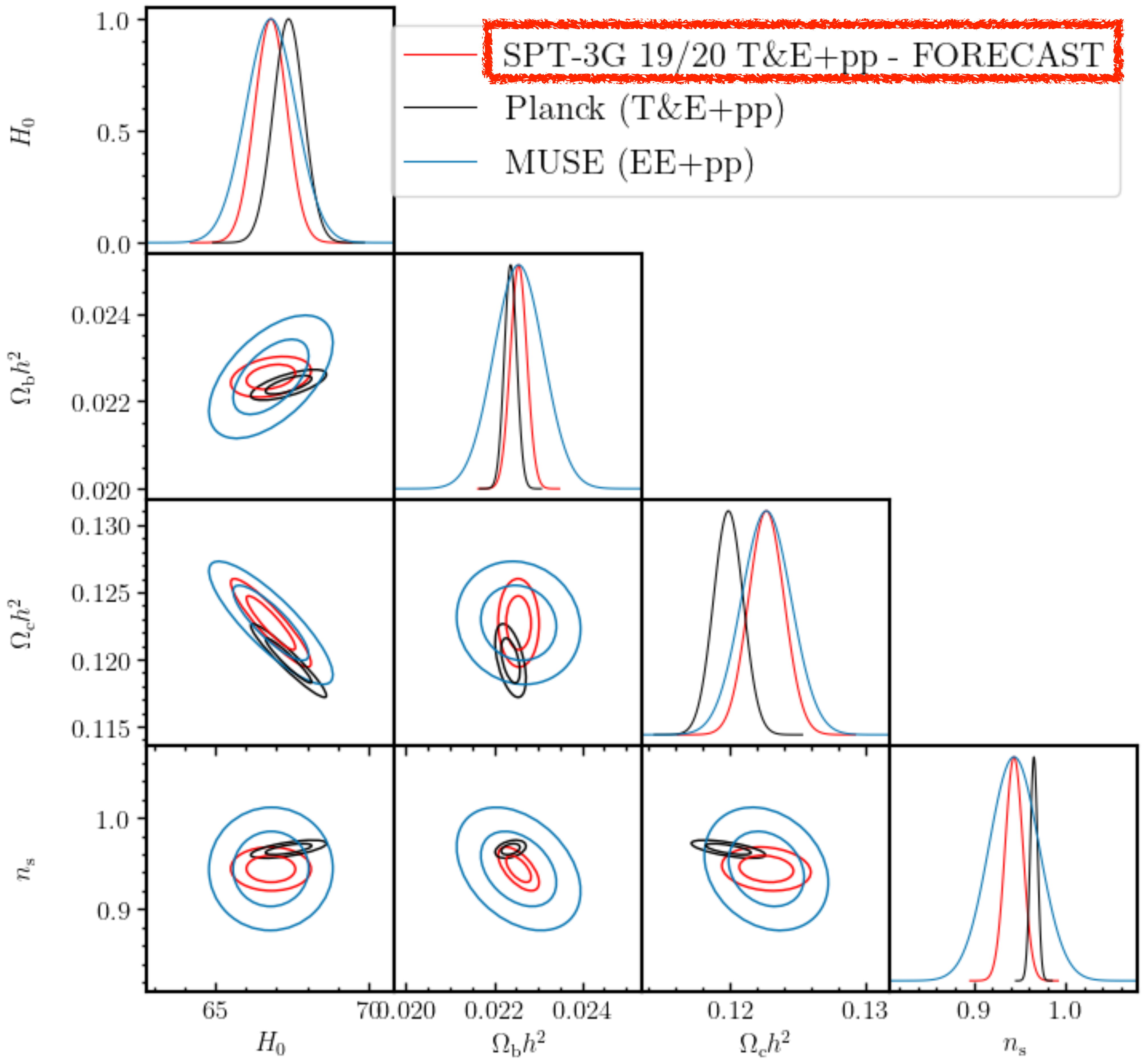


Conclusions

<u>Summary of results</u>

- **Using MUSE method** for optimal inference, we obtained the most precise measurement of $\phi\phi$ at $L > 350$ and EE at $\ell > 2000$ from SPT-3G **polarization** maps
- The SPT constraints using polarization signal are comparable to Planck at H_0 and S_8, confirming the existing tensions
- Assuming ΛCDM, SPT results are consistent with Planck and ACT, passing a powerful test of the standard cosmological model

Forecasts - SPT T&E + $\phi\phi$



SPT T&E+pp centered on MUSE EE+pp

Additional slides

(1) Method

Marginal Unbiased Score Expansion (MUSE)

Simulation model:

$$f \sim \mathcal{N}(0, \mathbb{C}_f^{\text{curv sky}}(A_b^{\text{EE}}))$$

$$\phi \sim \mathcal{N}(0, \mathbb{C}_\phi^{\text{curv sky}}(A_b^{\phi\phi}))$$

$$n^\nu \sim \{n^\nu_{\text{signflips}}\}$$

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

(1) Method

Marginal Unbiased Score Expansion (MUSE)

Posterior model:

$$f \sim \mathcal{N}(0, \mathbb{C}_f^{\text{flat sky}}(A_b^{\text{EE}}))$$

$$\phi \sim \mathcal{N}(0, \mathbb{C}_\phi^{\text{flat sky}}(A_b^{\phi\phi}))$$

$$\mu^{\nu,i} = \mathbb{M}_{\text{fourier}} \cdot \mathbb{M}_{\text{trough}} \cdot \mathbb{M}_{\text{pix}} \cdot \left(\mathbb{PWF} \cdot \mathbb{TF}^\nu \cdot \mathbb{R}(\psi_{\text{pol}}^\nu) \cdot A_{\text{cal}}^{\nu,i} \cdot \mathbb{B}(\beta_n, \beta_{\text{pol}}^\nu) \cdot \mathbb{L}(\phi) \cdot f + \epsilon_{\text{Q}}^{\nu,i} \cdot t_{\text{Q}}^\nu + \epsilon_{\text{U}}^{\nu,i} \cdot t_{\text{U}}^\nu\right)$$

$$d^\nu \sim \mathcal{N}(\mu^\nu, \mathbb{C}_n^\nu)$$

$$\Rightarrow -2\log\mathcal{P}(f, \phi, \theta \,|\, d) = f^\dagger \mathbb{C}_f^{-1} f + \phi^\dagger \mathbb{C}_\phi^{-1}\phi + \sum_\nu (d^\nu - \mu^\nu)^\dagger (\mathbb{C}_n^\nu)^{-1}(d^\nu - \mu^\nu) - 2\log\mathcal{P}(\phi)$$

where $-2\log\mathcal{P}(\phi) = \left\|\mathbb{M}_{\text{pix}}\nabla^2\phi\right\|^2/10^{-8}$

(1) Method

Marginal Unbiased Score Expansion (MUSE)

- (Millea & Seljak 2022)
- Marginal score evaluated at the maximum a posteriori (MAP)

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

$$\hat{z}(d,\theta) = \underset{z}{\arg\max}\, \mathscr{P}(z, \theta \,|\, d)$$

$$\mathscr{P}\left(\theta | d\right) = \int \mathrm{d}f \mathrm{d}\phi \mathscr{P}\left(f, \phi, \theta | d\right)$$

Solving this equation gives the marginal posterior mean

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

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

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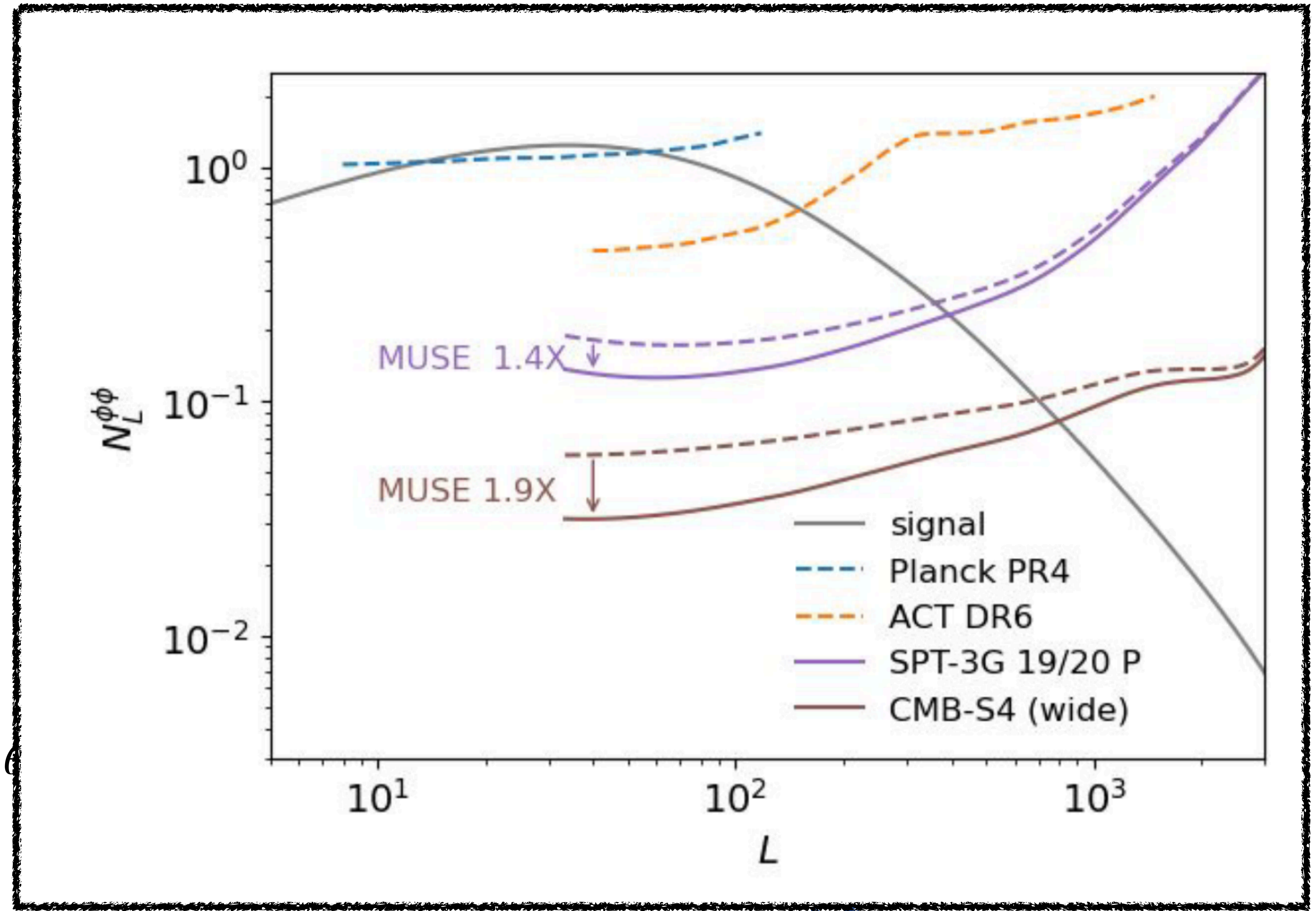

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$$\hat{z}(d,\theta) = \arg\max_{z} \mathcal{P}(z, \theta \,|\, d)$$

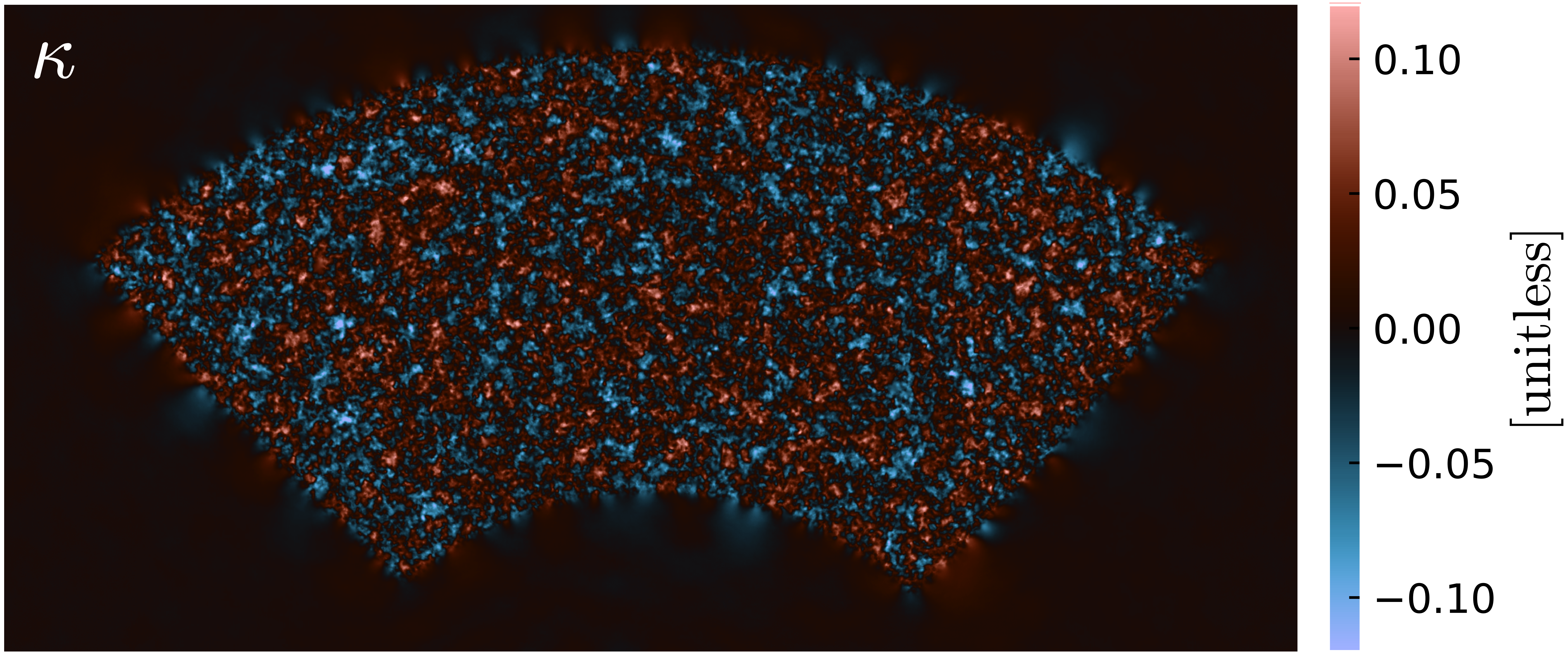
$$\Sigma_{\mathrm{MUSE}}^{-1} = H^{\dagger} J^{-1} H + \Sigma_{\mathrm{prior}}^{-1}$$

$$J_{ij} = \mathrm{cov}\Big(s_i^{\mathrm{MAP}}(\hat{\theta}, d), s_j^{\mathrm{MAP}}(\hat{\theta}, d)\Big)_{d \sim \mathcal{P}(d \,|\, \hat{\theta})}$$

$$H_{ij} = \frac{d}{d\theta_j}\left[\Big\langle s_i^{\mathrm{MAP}}(\hat{\theta}, d)\Big\rangle_{d \sim \mathcal{P}(d \,|\, \theta)}\right]\Bigg|_{\theta = \hat{\theta}}$$

$$-2 \log \mathcal{P}(\theta \,|\, d) \approx (\theta - \hat{\theta})^{\dagger} (\Sigma_{\mathrm{MUSE}})^{-1} (\theta - \hat{\theta}) + C$$

Maximum a posteriori (MAP) maps from 95+150+220 GHz data at the MUSE estimate of theory and systematics parameters, $\hat{\theta}$.
MAPs correspond to a filtering of the data which maximizes signal relative to noise (akin to a linear Wiener filter, but in the case of the MAP κ, a non linear filter).



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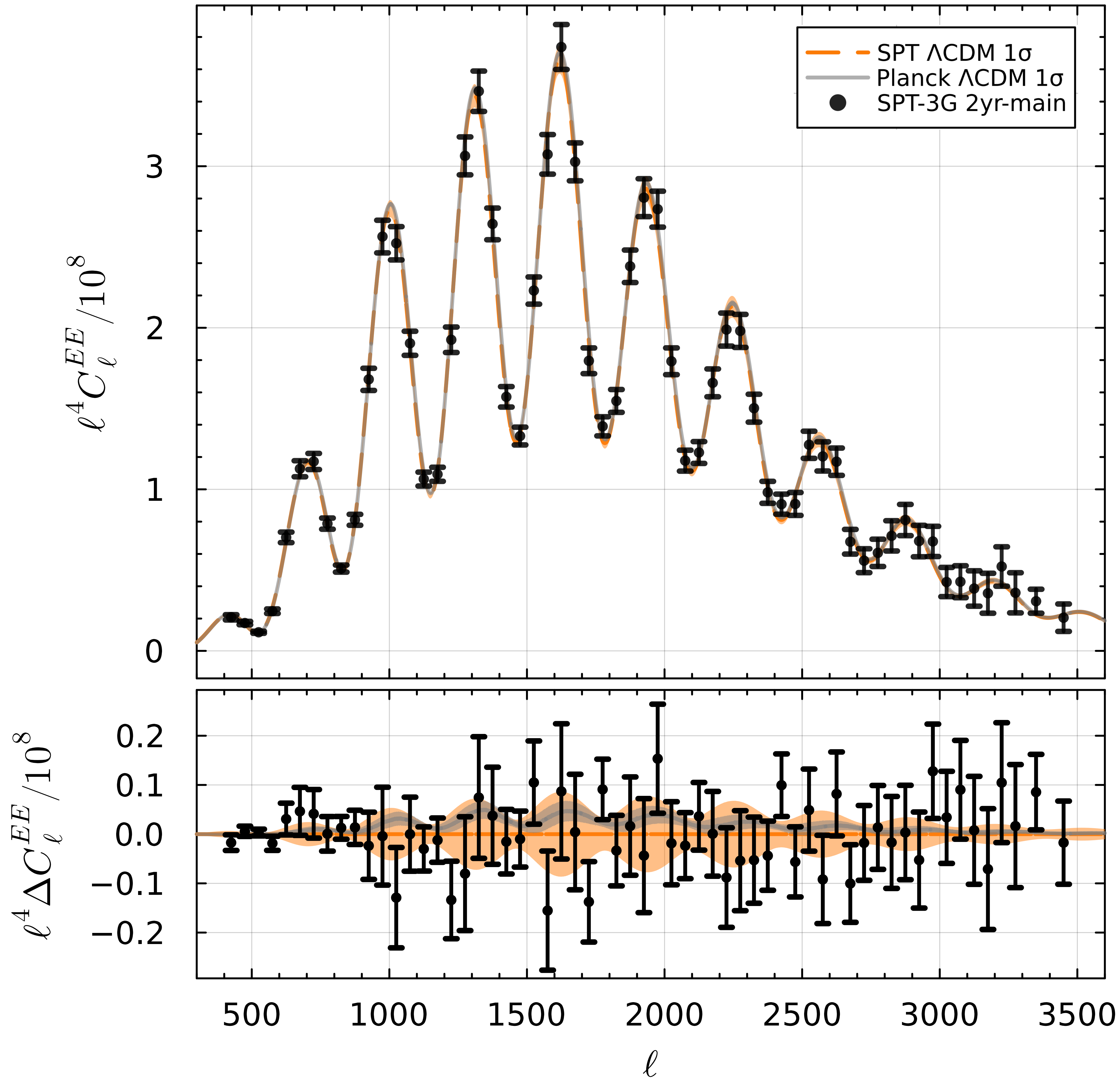
Unlensed EE band powers



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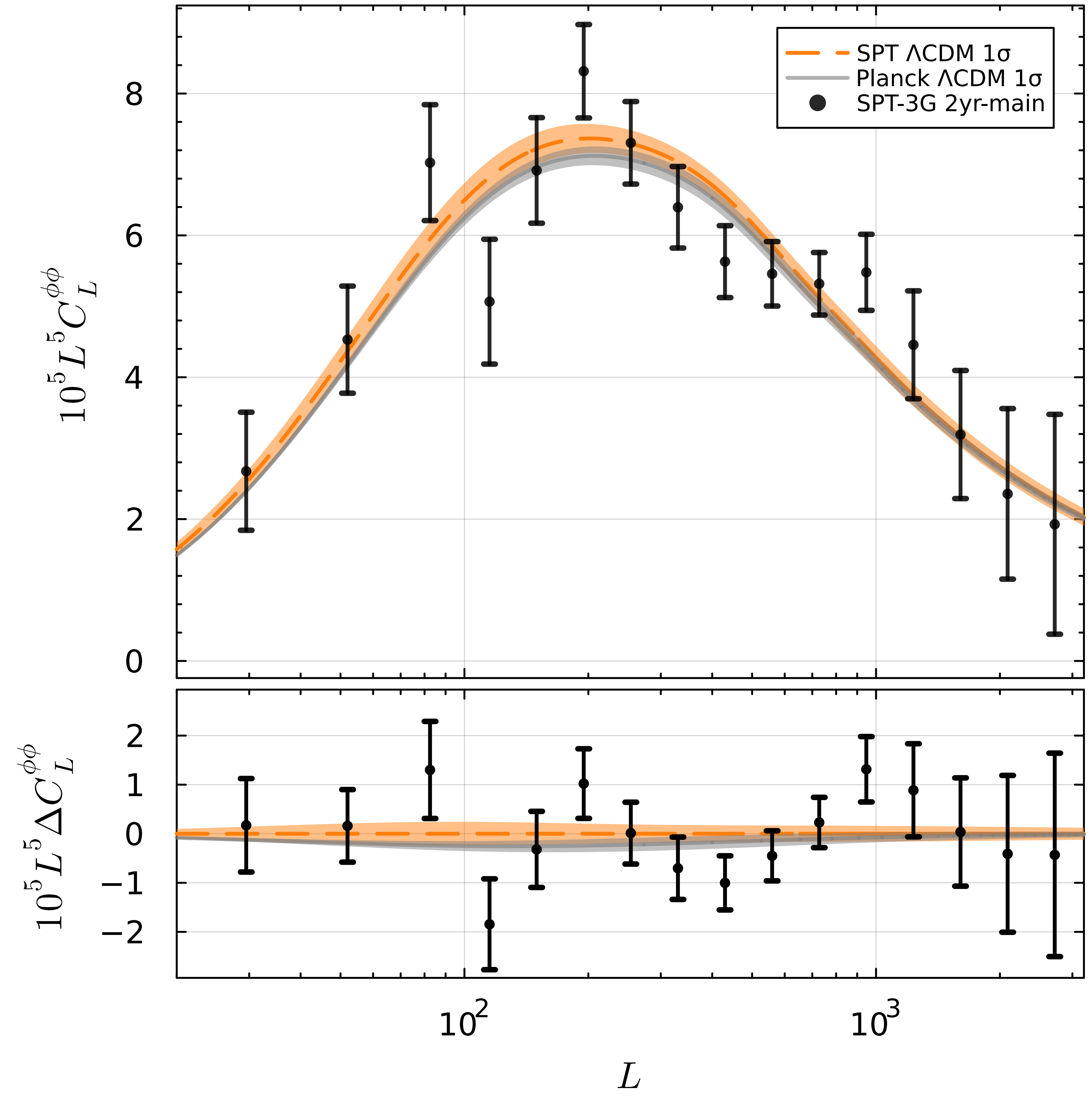
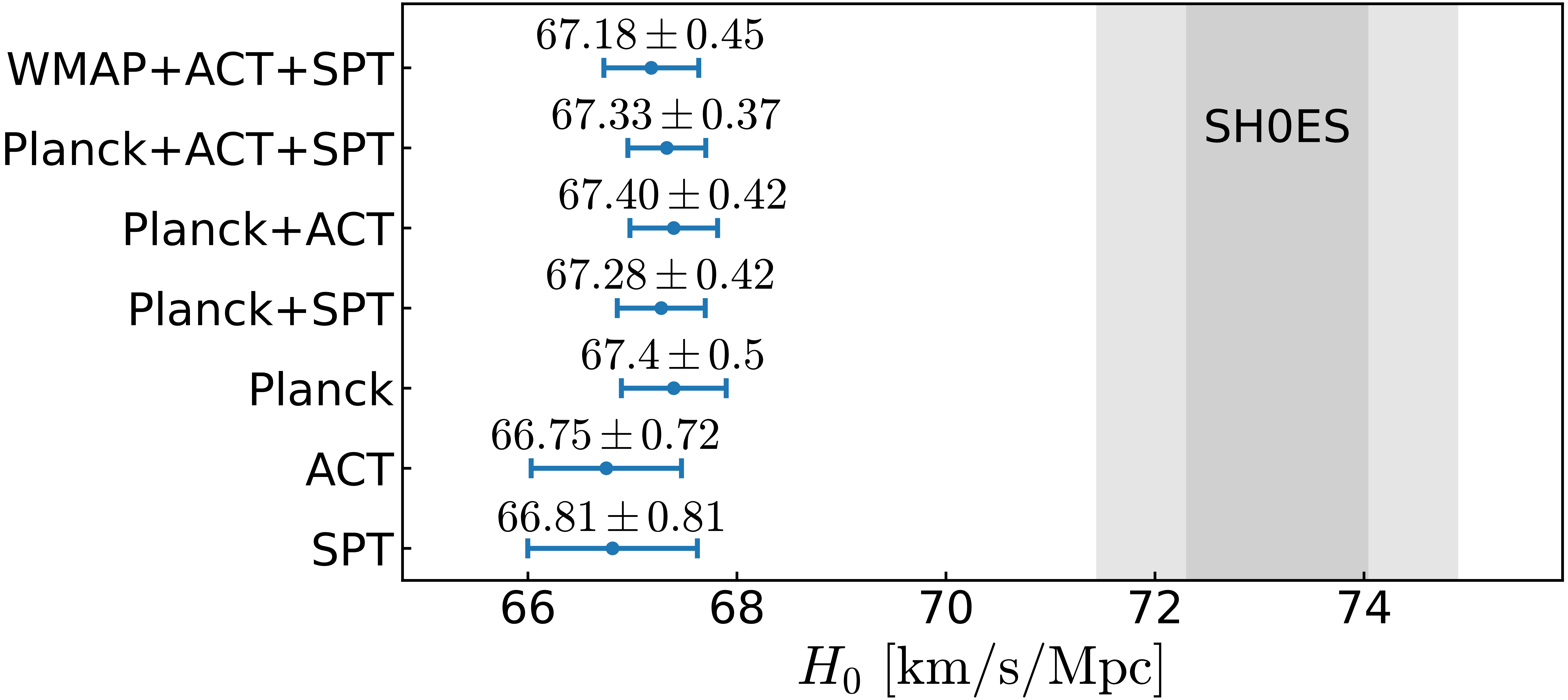
Lensing band powers



Results - H_0

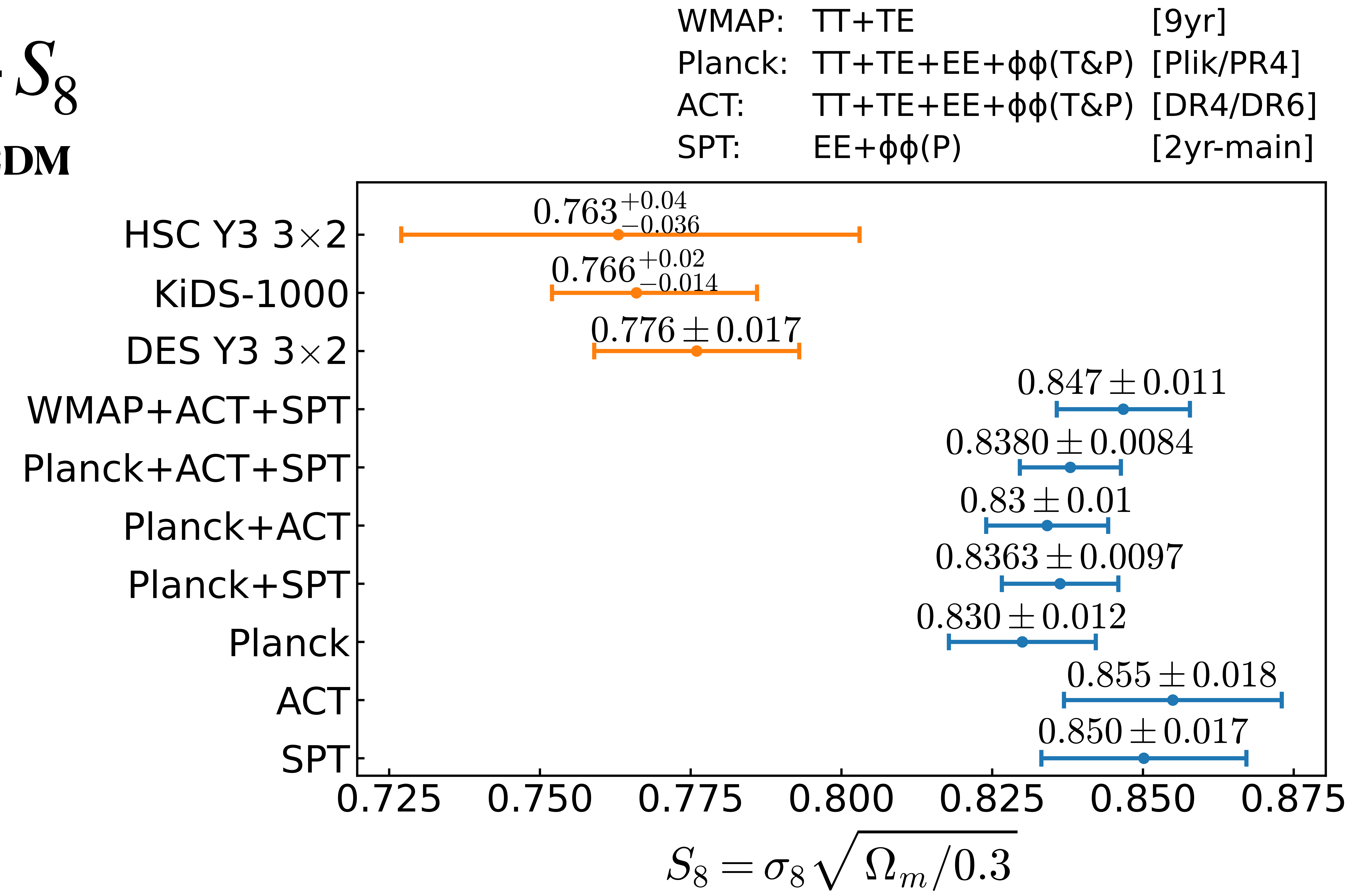
Assuming ΛCDM

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]



Results - S_8

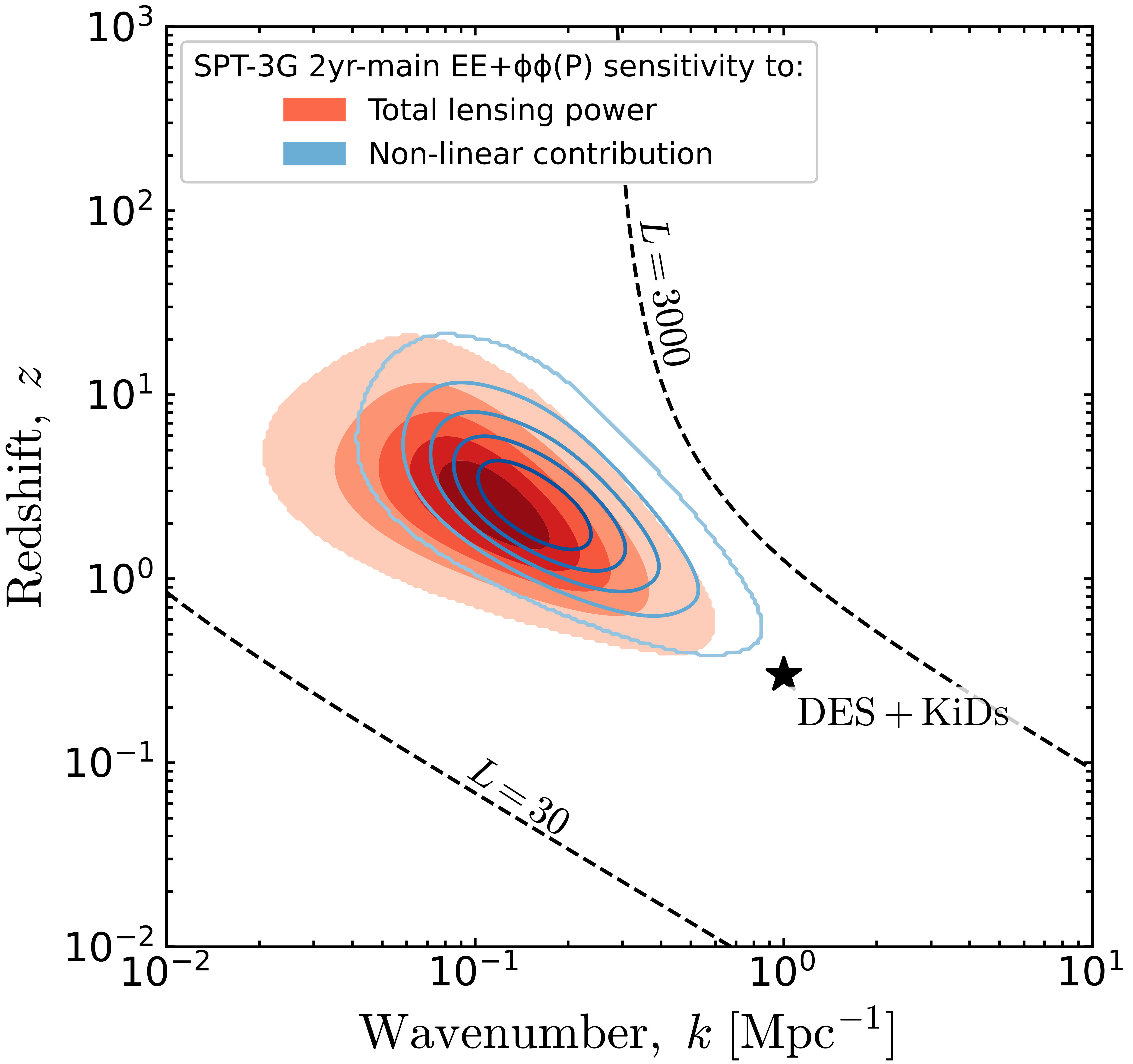
Assuming ΛCDM



Results

Amplitude of nonlinear structure growth

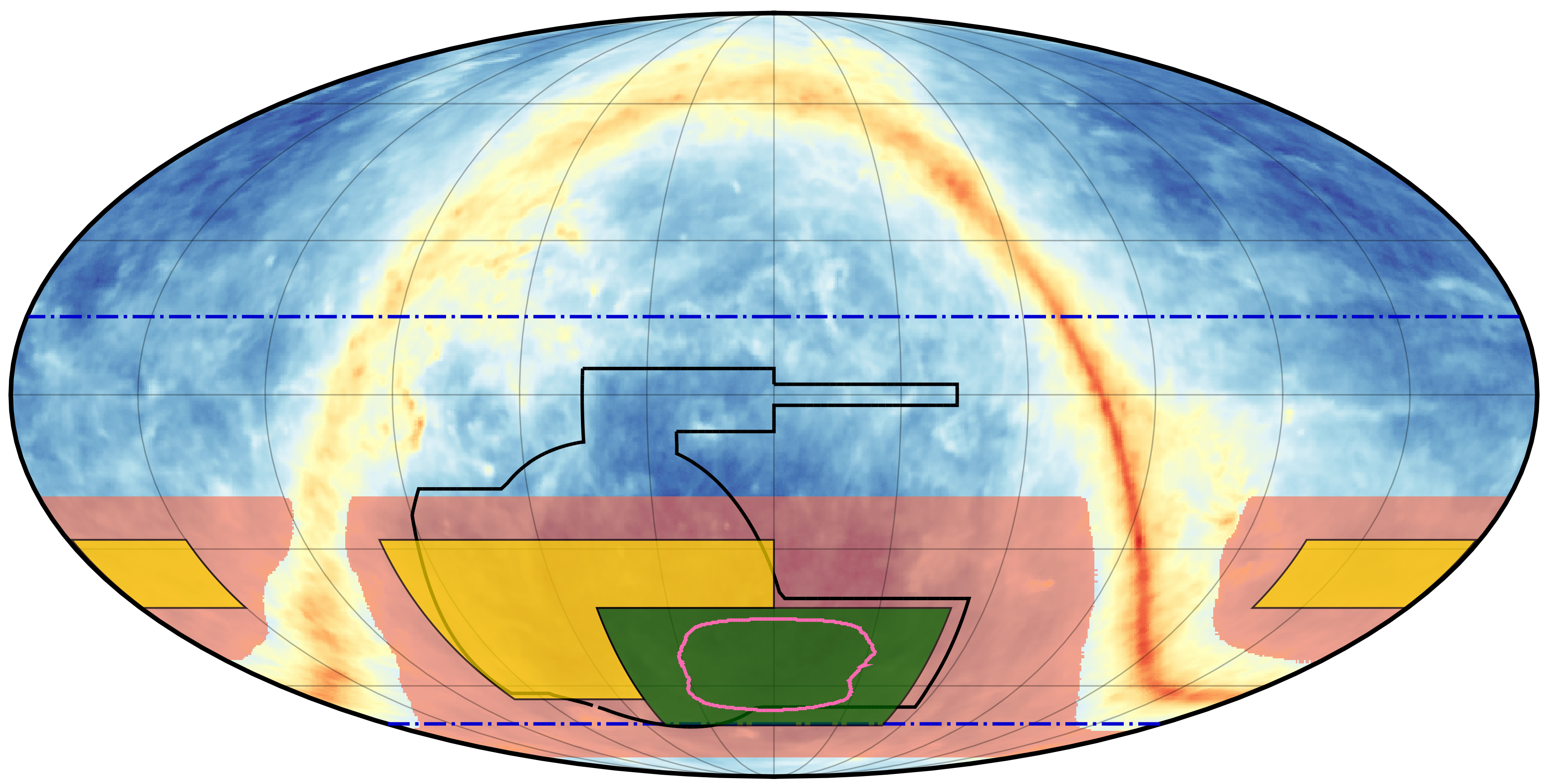
- If the solution to S8 tension is due to unknown physics of non-linear structure growth, our result suggests it to happen at a later time or at smaller scales.

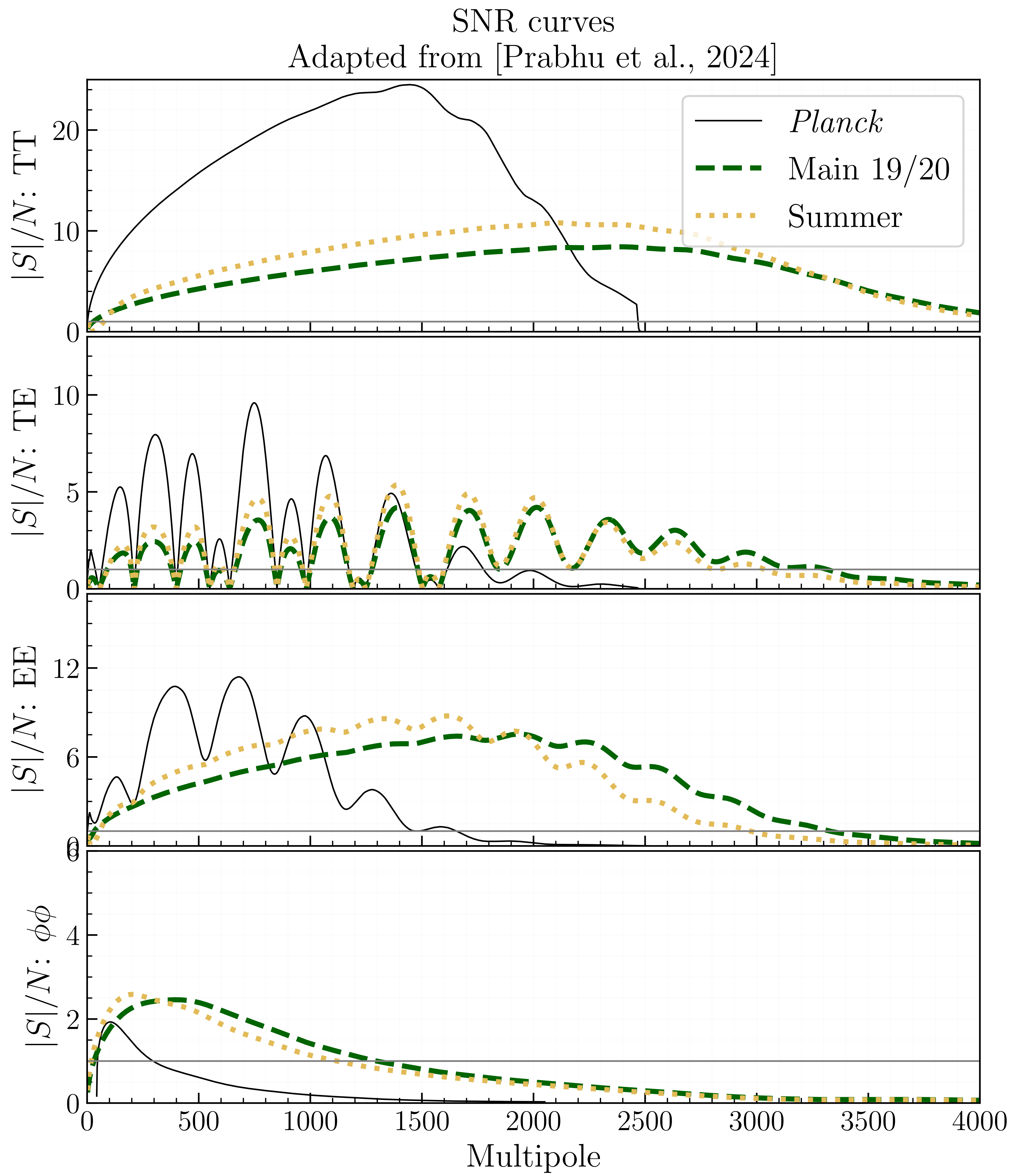


Summer fields

Led by F. Guidi

- Summer fields will add large scale information
- Particularly useful for ΛCDM extensions





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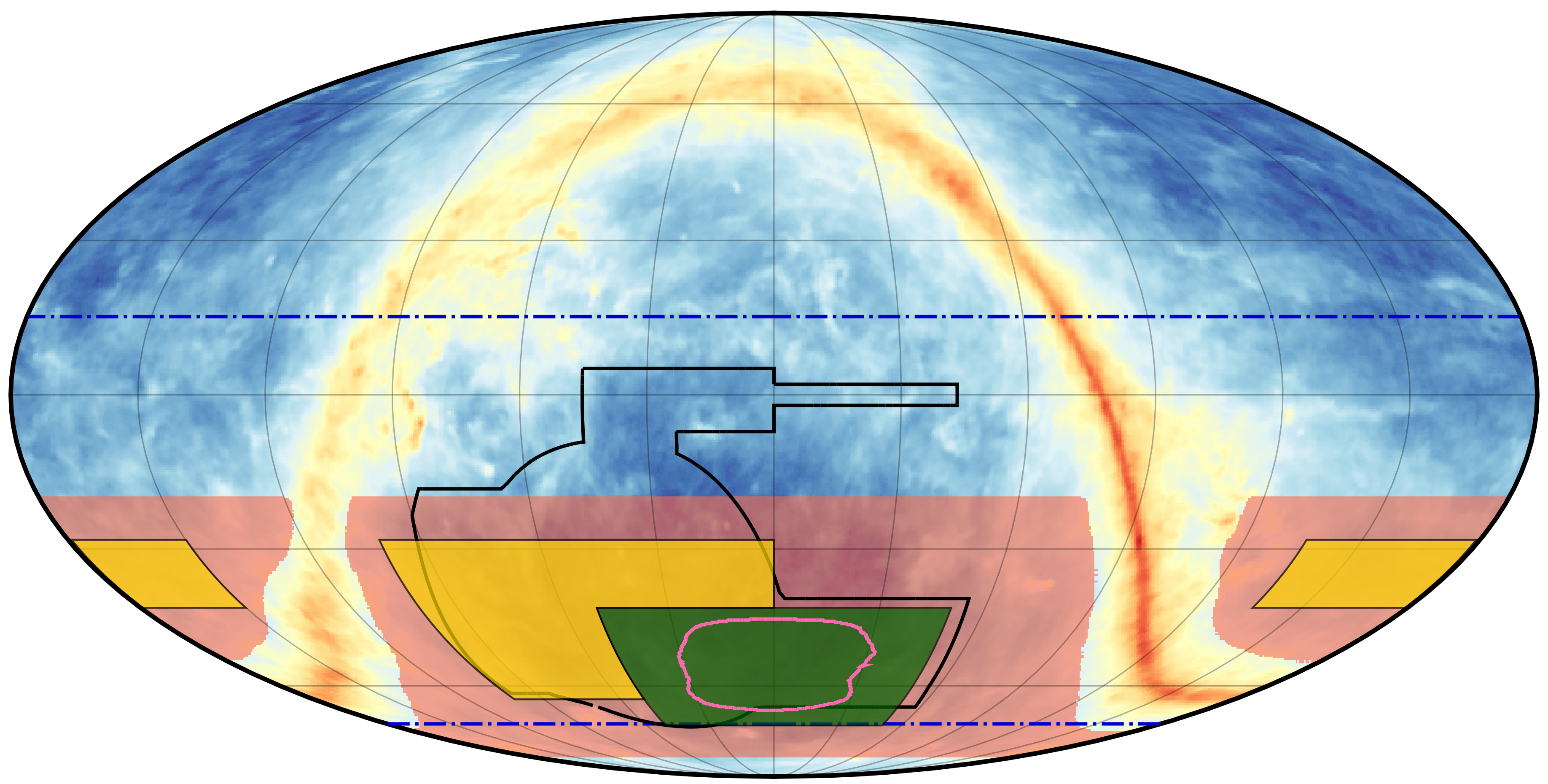

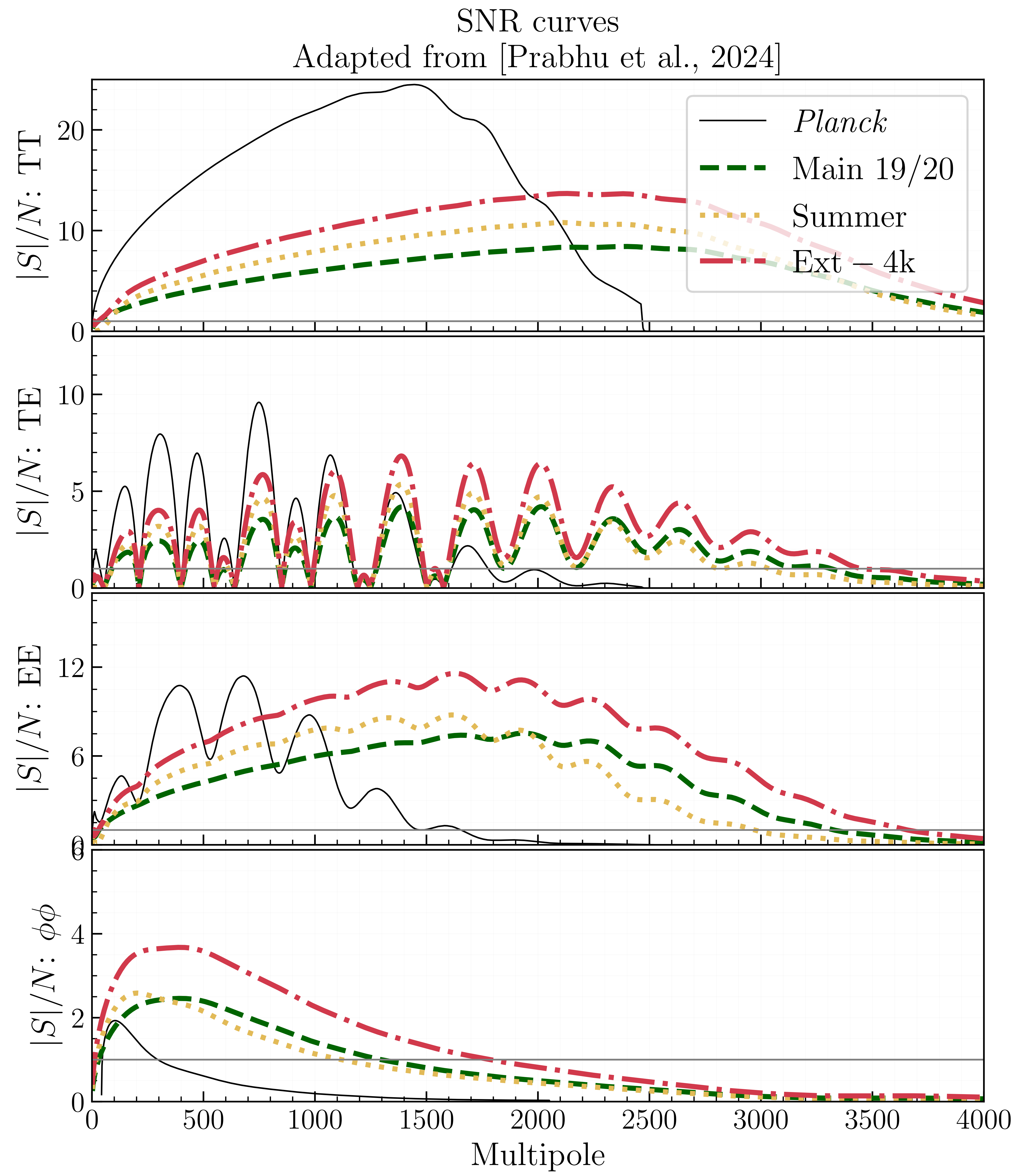

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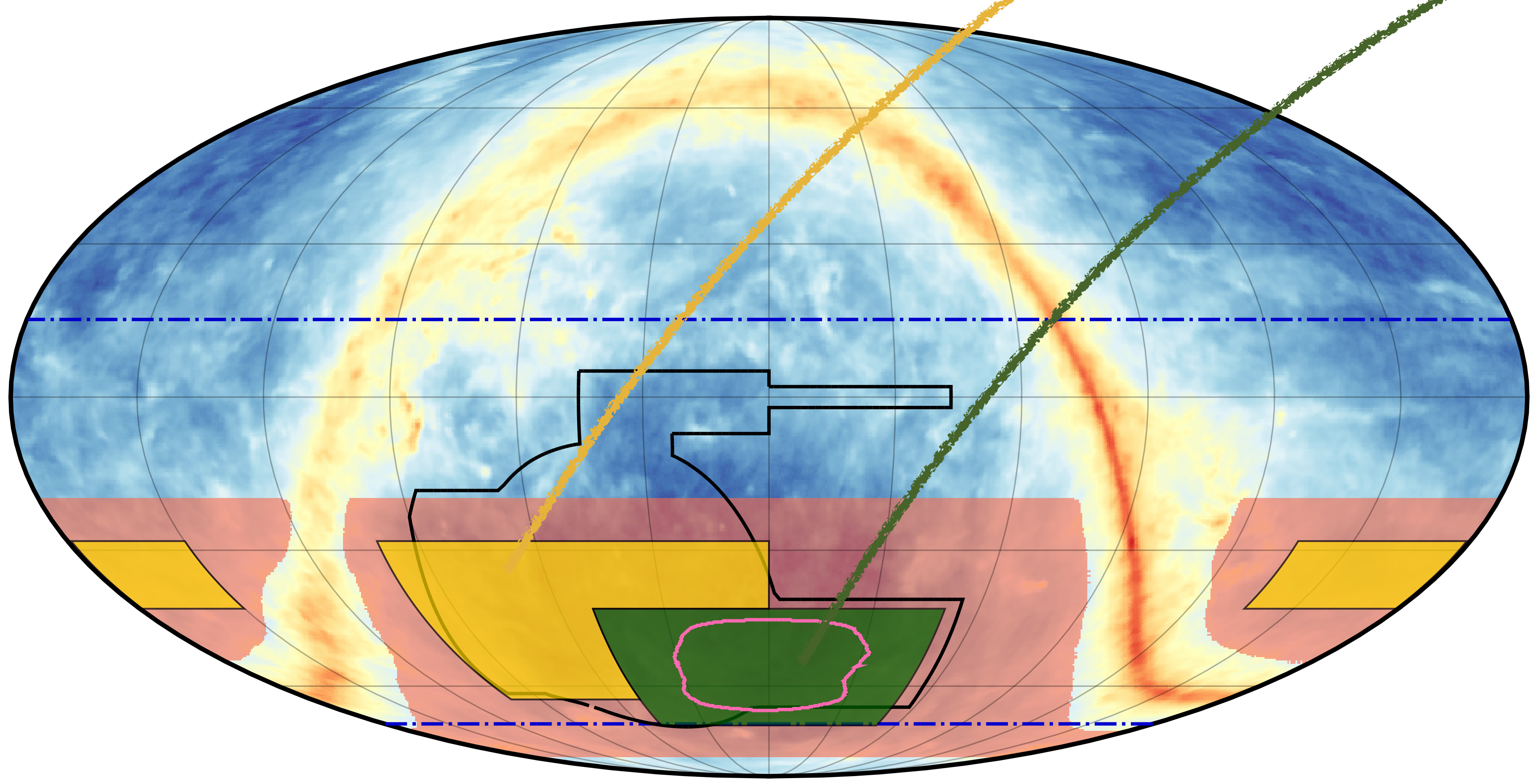
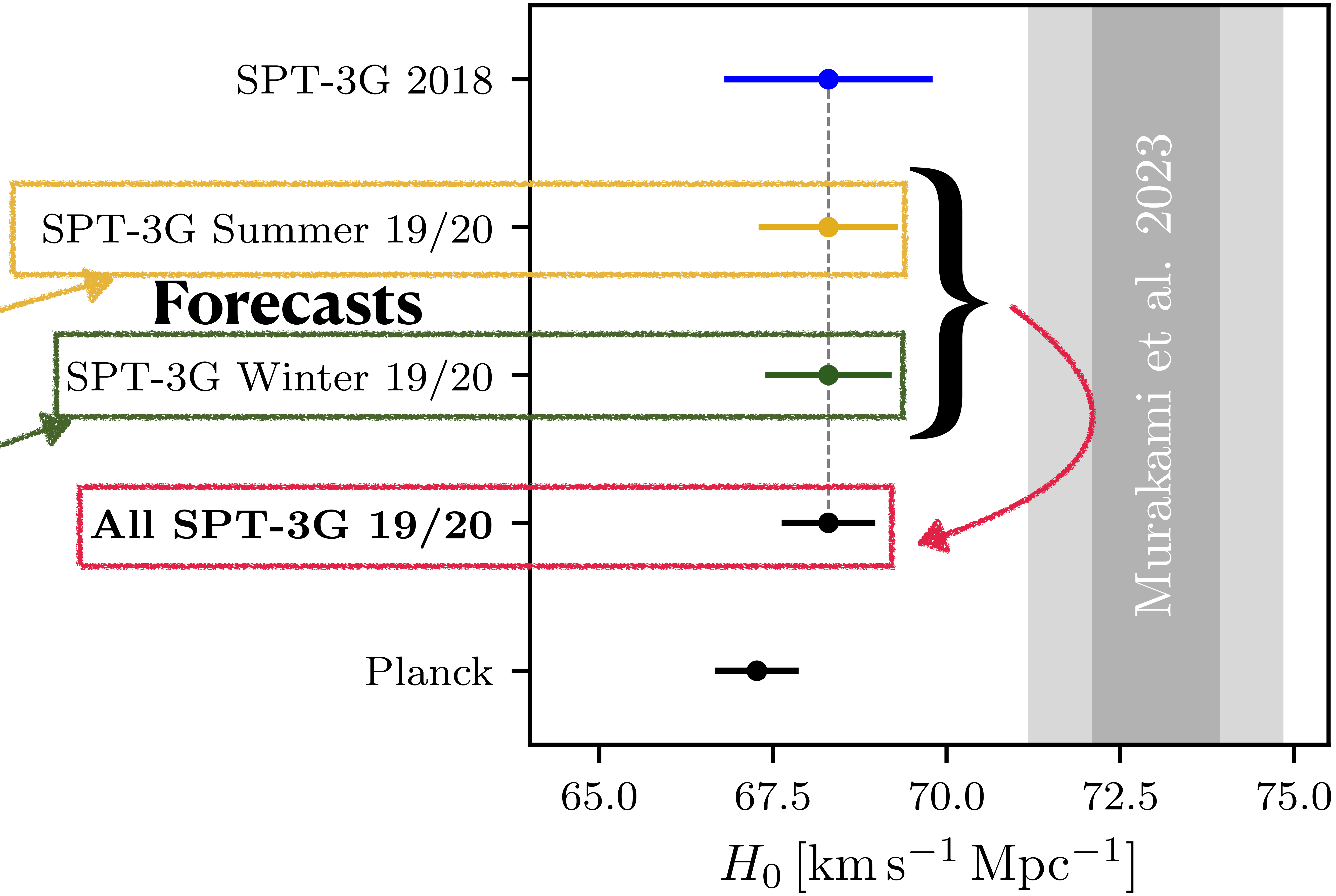
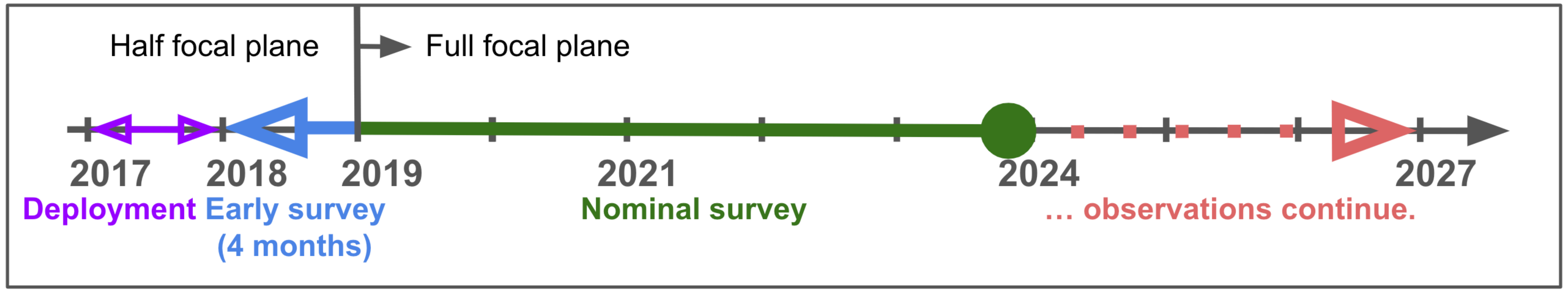


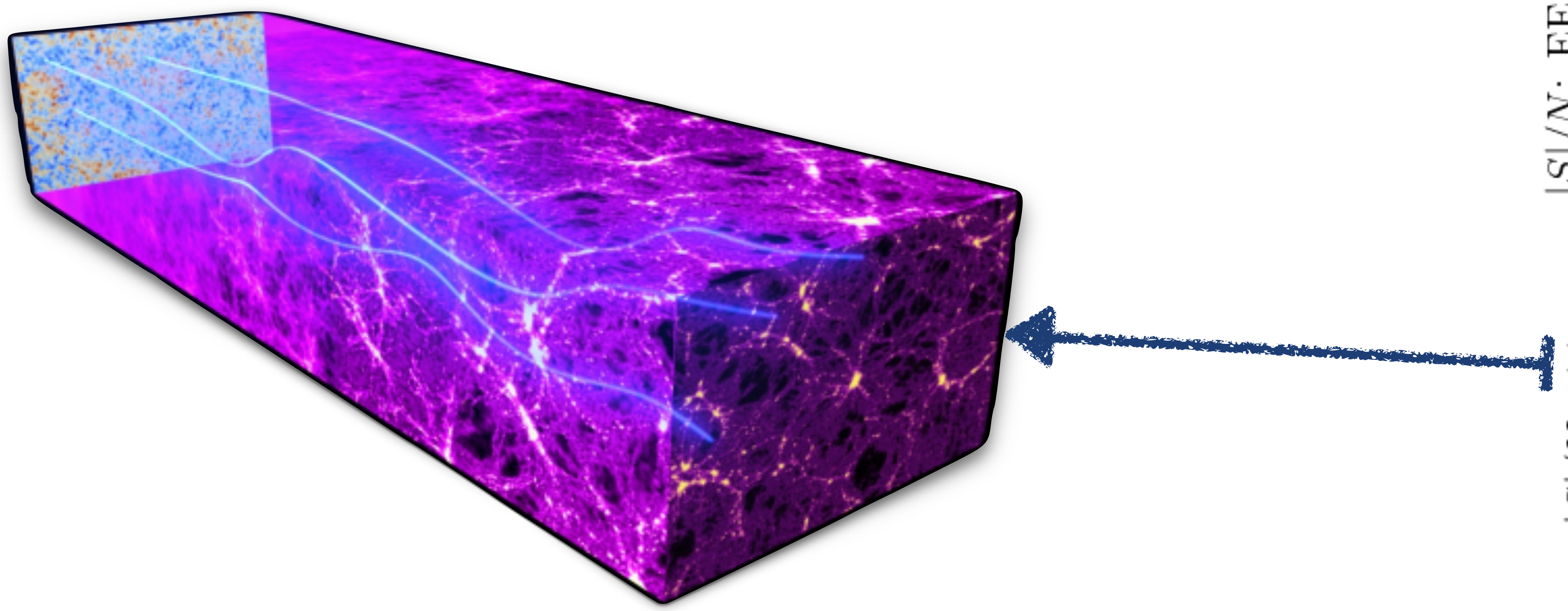


Adding in more data

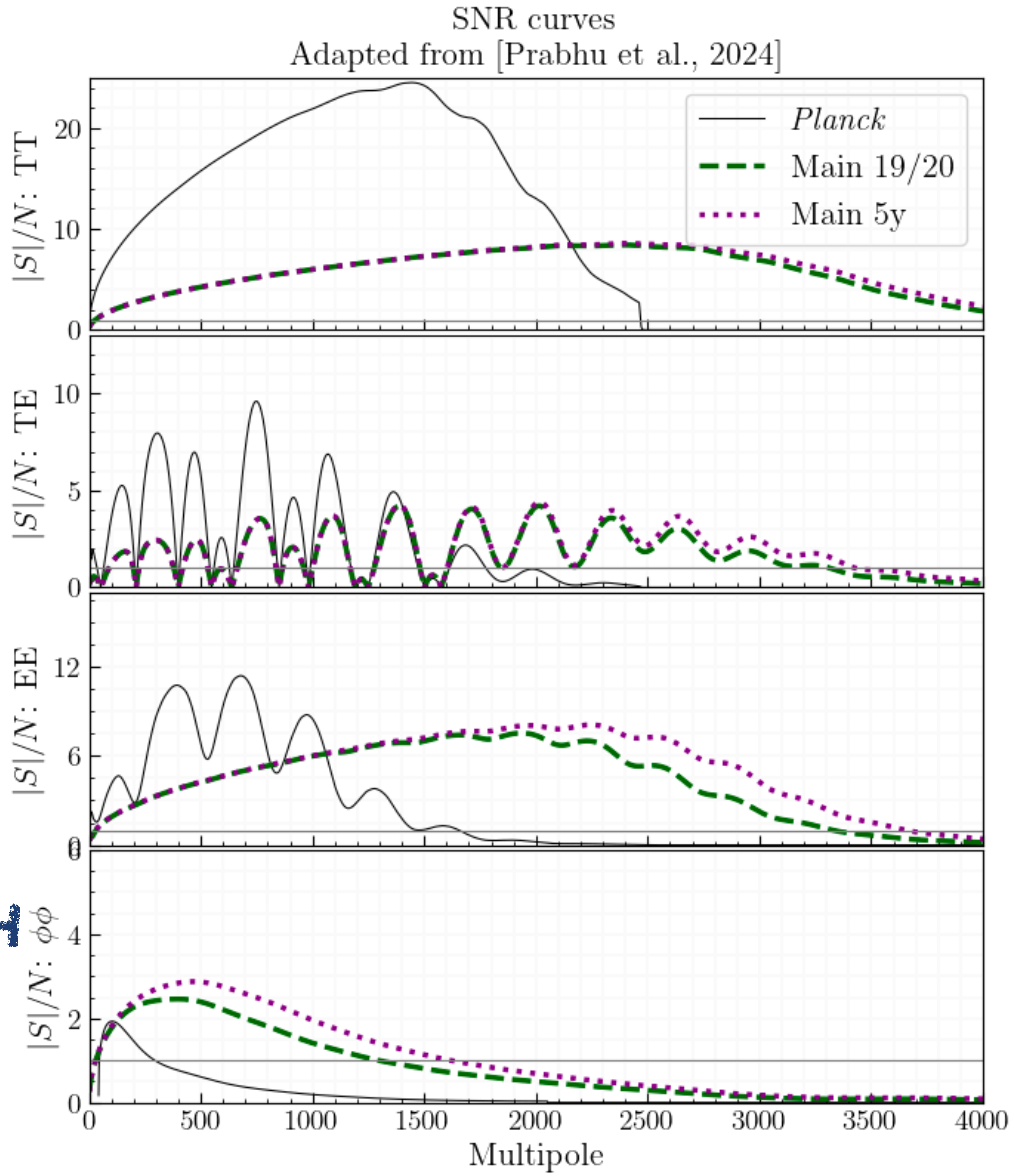
Full 5 years survey on the main field



CMB lensing



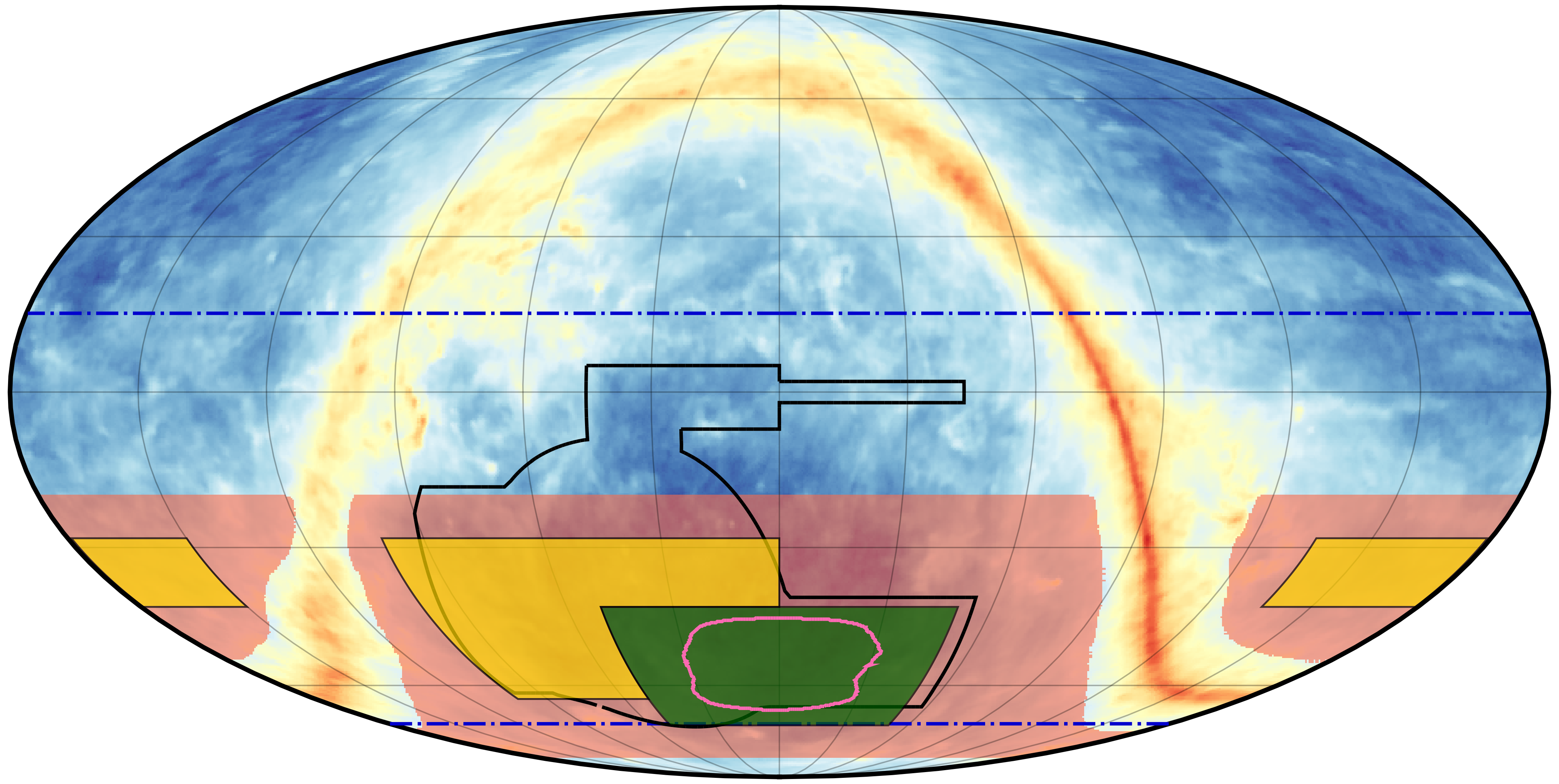
ESA

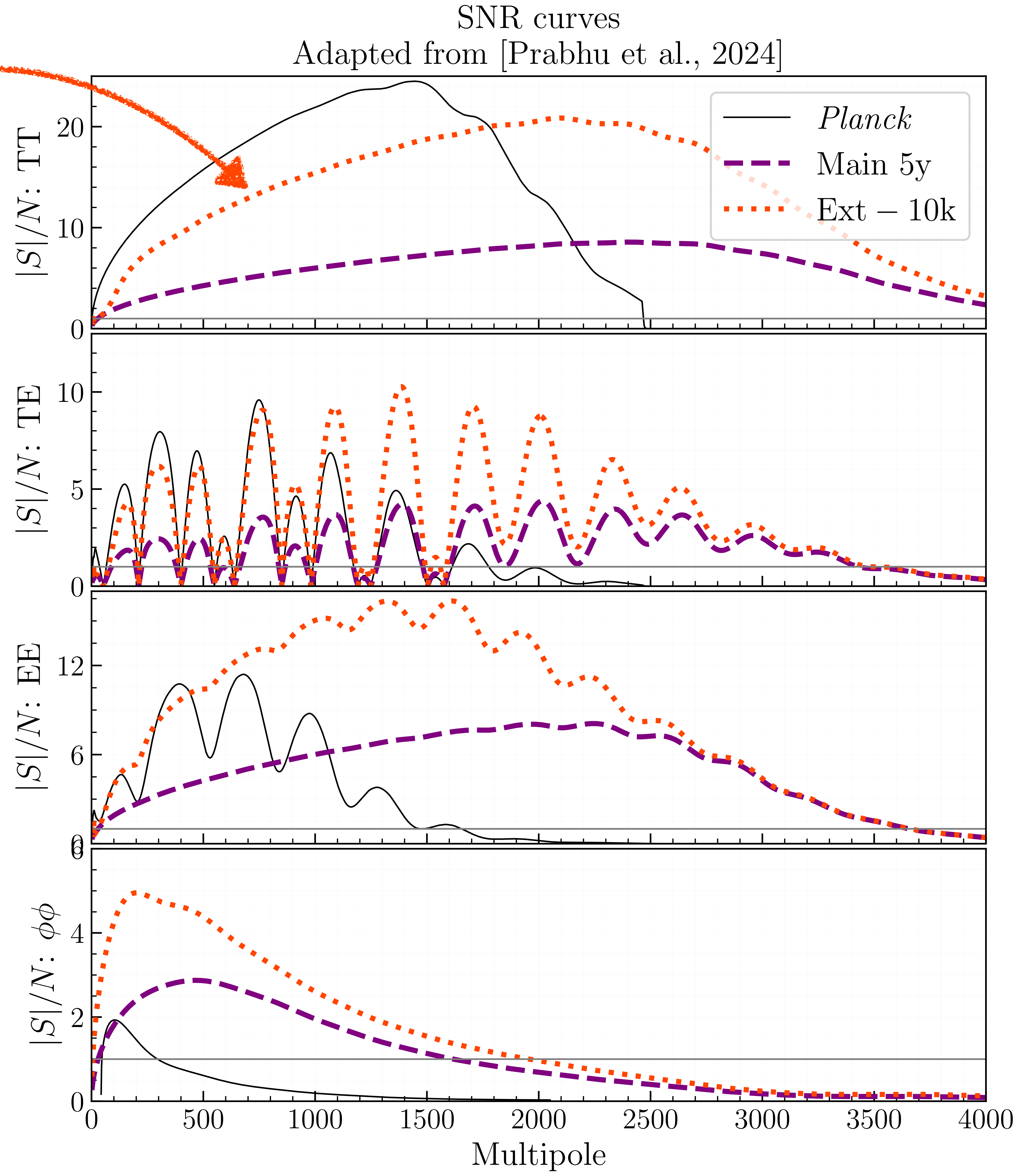


Full SPT-3G forecasts

[Prabhu et al., 2024]

Main (green) + **Summer (yellow)** + **Wide (red) ➔ Orange line**





Full SPT-3G forecasts

[Prabhu et al., 2024]

Main (green) + Summer (yellow) + Wide (red) ➔ Orange line