Optimal Cosmic Microwave Background Gravitational Lensing Reconstruction, Delensing, and Parameter Estimation with SPT-3G Polarization Data

Fei Ge (UC Davis)
With Marius Millea (UC Davis), Lloyd Knox (UC Davis) and SPT-3G Collaboration

Highlights

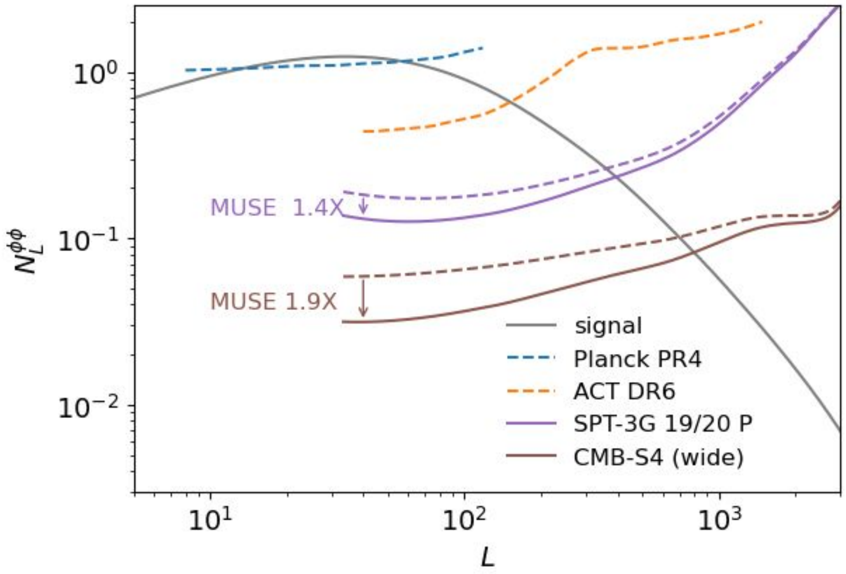
- We use the SPT-3G 2019/20 polarization maps to perform the first ever optimal CMB lensing potential bandpower reconstruction and delensed EE bandpower analysis.
- The analysis is achieved with the Bayesian inference method called MUSE.

(Millea & Seljak, 2022)

- The constraints on cosmological parameters with SPT-3G 2019/20 polarization data alone are comparable to Planck TTTEEE+lensing, notably $\sigma(H_0)$~0.7 km/s/Mpc and $\sigma(S8)$~0.017.
  - From *different* signals (SPT is weighted toward small scales, polarization, and lensing), so comparison to Planck parameters is a test of LCDM.
- Combining SPT-3G 2019/20 polarization data with Planck 2018 will improve the constraints on some LCDM extension models, notably ~ 2X smaller $\sigma(\Sigma m_\nu)$.

Introduction

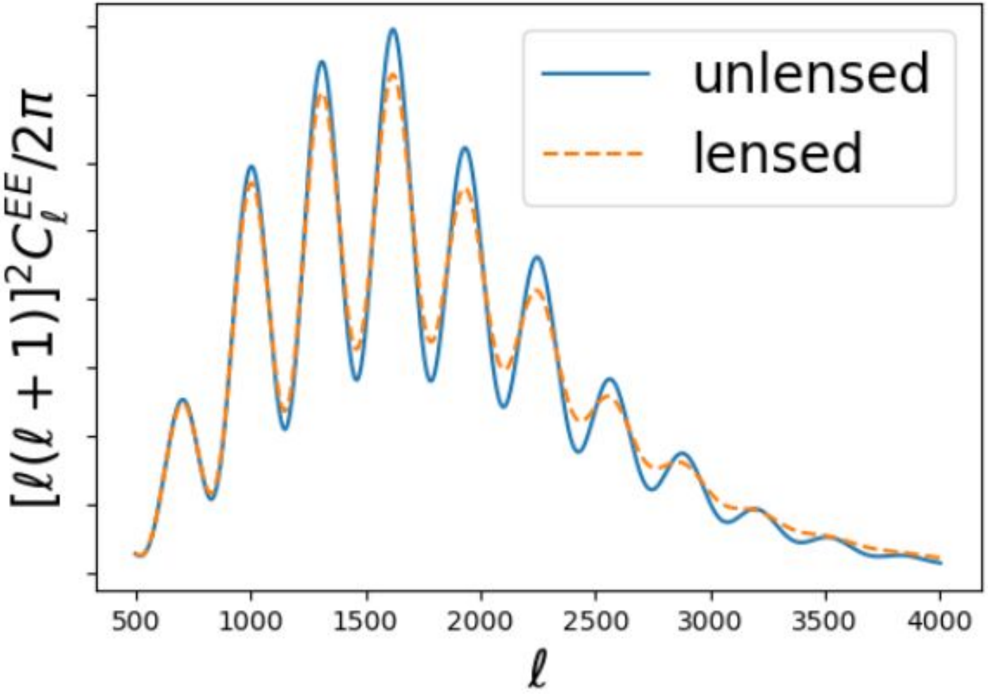
- Bayesian methods are optimal for CMB lensing reconstruction
  - Less lensing reconstruction noise for low instrumental noise observations
  - Improved CMB lensing reconstruction relative to QE as shown in a previous SPT analysis (Millea et al 2020)



Introduction

- De-lensed spectra have sharper features and less sample variance.

(See e.g. Hotinli et al 2021)



- Both Planck (Planck 2018 VII) and ACT (Han et al 2020) have done delensing on TT/EE spectra using a lensing potential map reconstructed by quadratic estimator.

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

- With MUSE, we implement map-level Bayesian inference, effectively using all N-points statistics to jointly reconstruct CMB lensing potential bandpowers and estimate unlensed CMB bandpowers

Unlensed CMB polarization maps

Lensing potential (ϕ) map

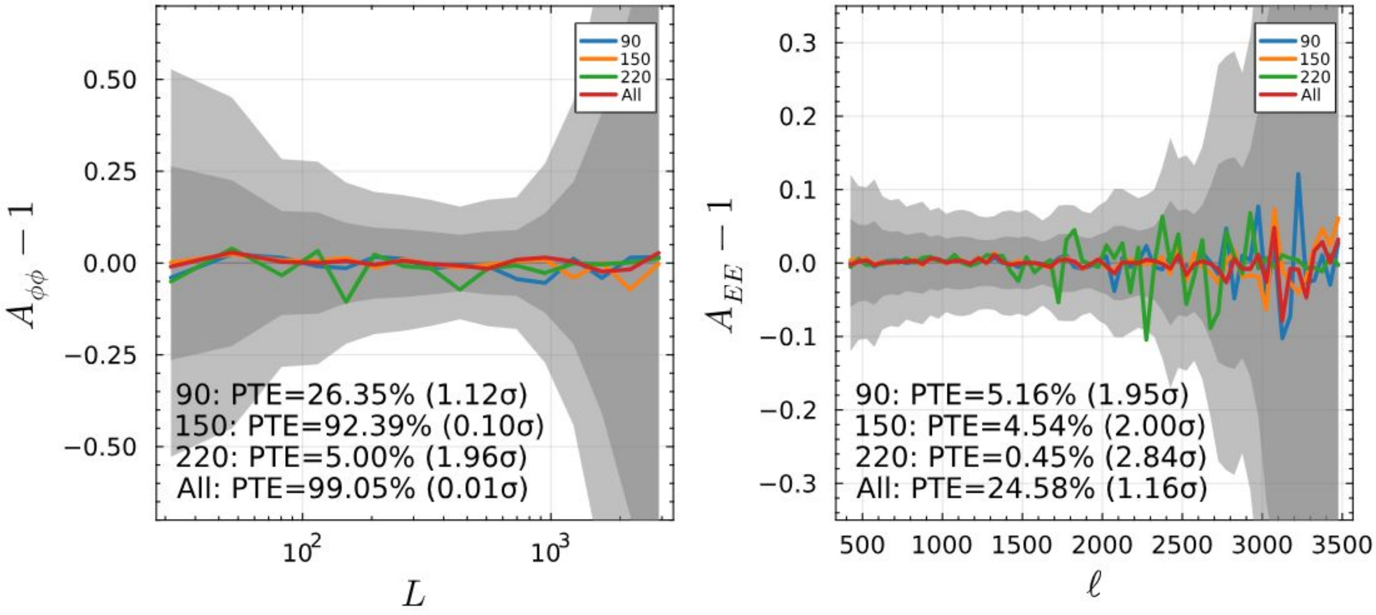
$$\mathcal{P}(f, \phi, \theta | d)$$

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

Observed CMB maps

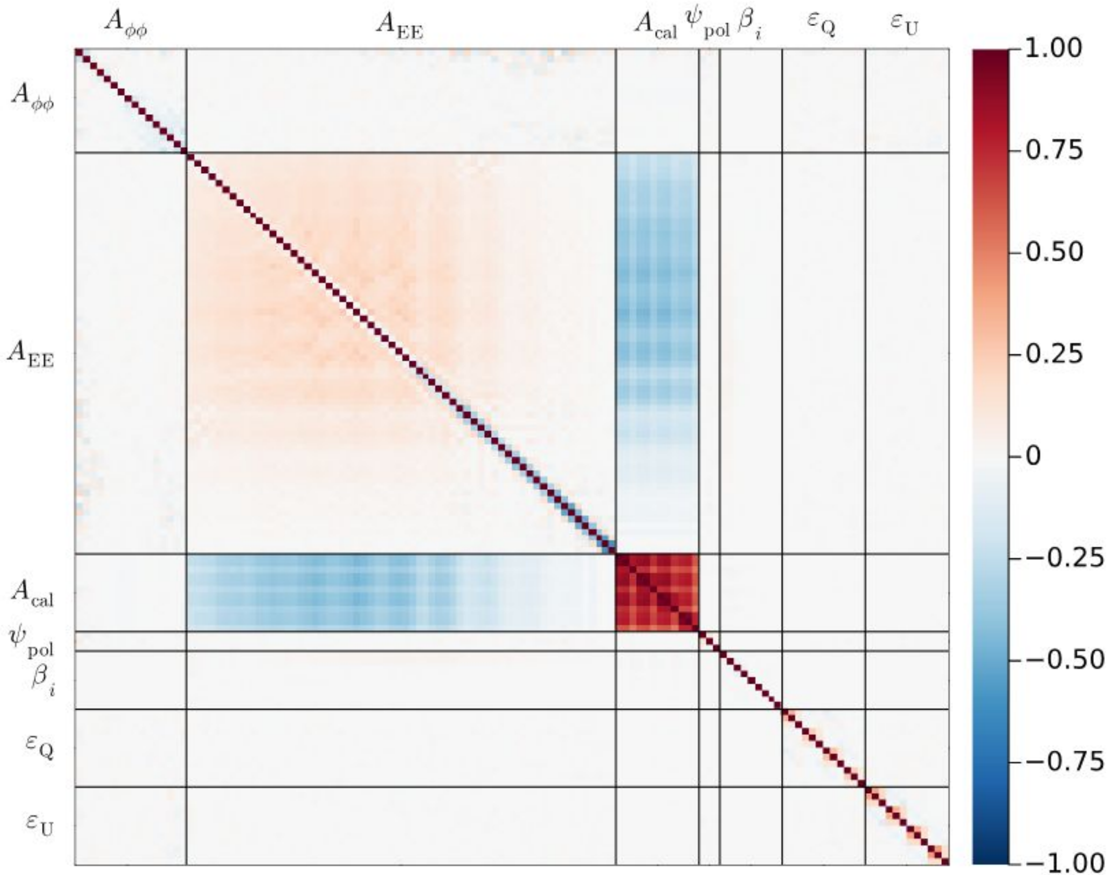
Pipeline test on mocks – Bandpowers

- No bandpower bias detected at >3σ with the precision of 100 simulations
- Any residual bias is limited to be ≲10% of the total uncertainty



- Lines are average over running MUSE on 100 mock observations + noise sign-flips
- Grey bands are MUSE 1 and 2-sigma error band from All-P
- PTEs are w.r.t. to the standard error on the mean, which is ~10X smaller than the gray band.

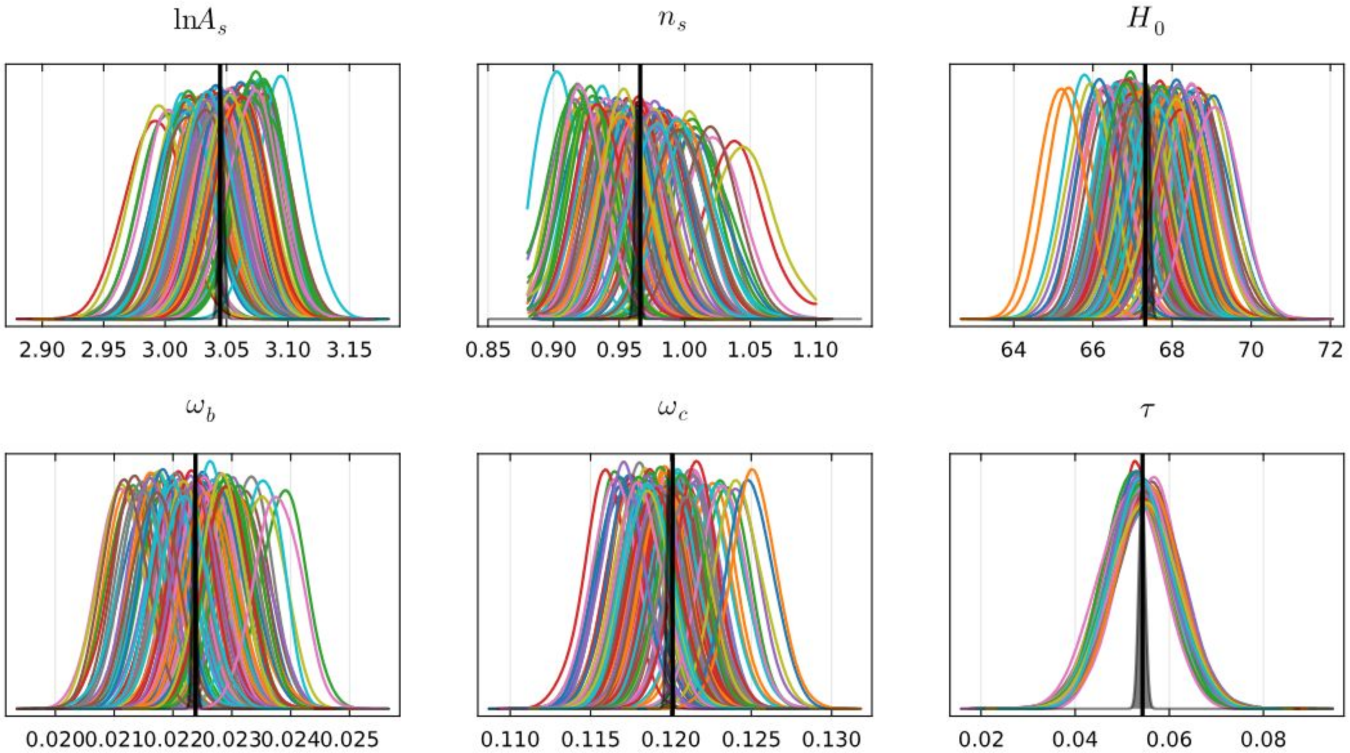
MUSE Correlation Matrix



With MUSE we can propagate uncertainties from the systematics to lensing potential bandpowers and delensed CMB bandpowers.

Pipeline test on mocks – cosmological parameters

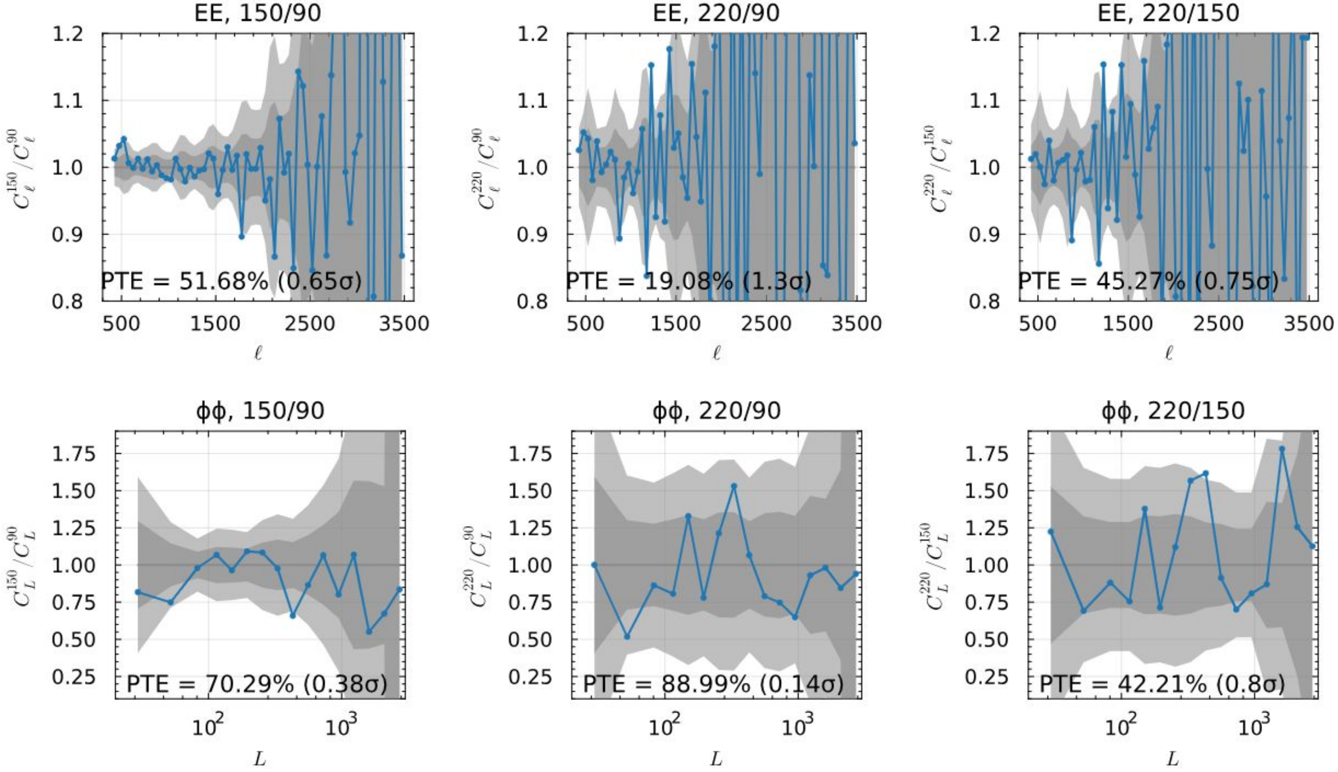
- No bias detected on the joint posterior from a set of 100 mock observations.



PTE w.r.t. SEM (5 parameters): 42%

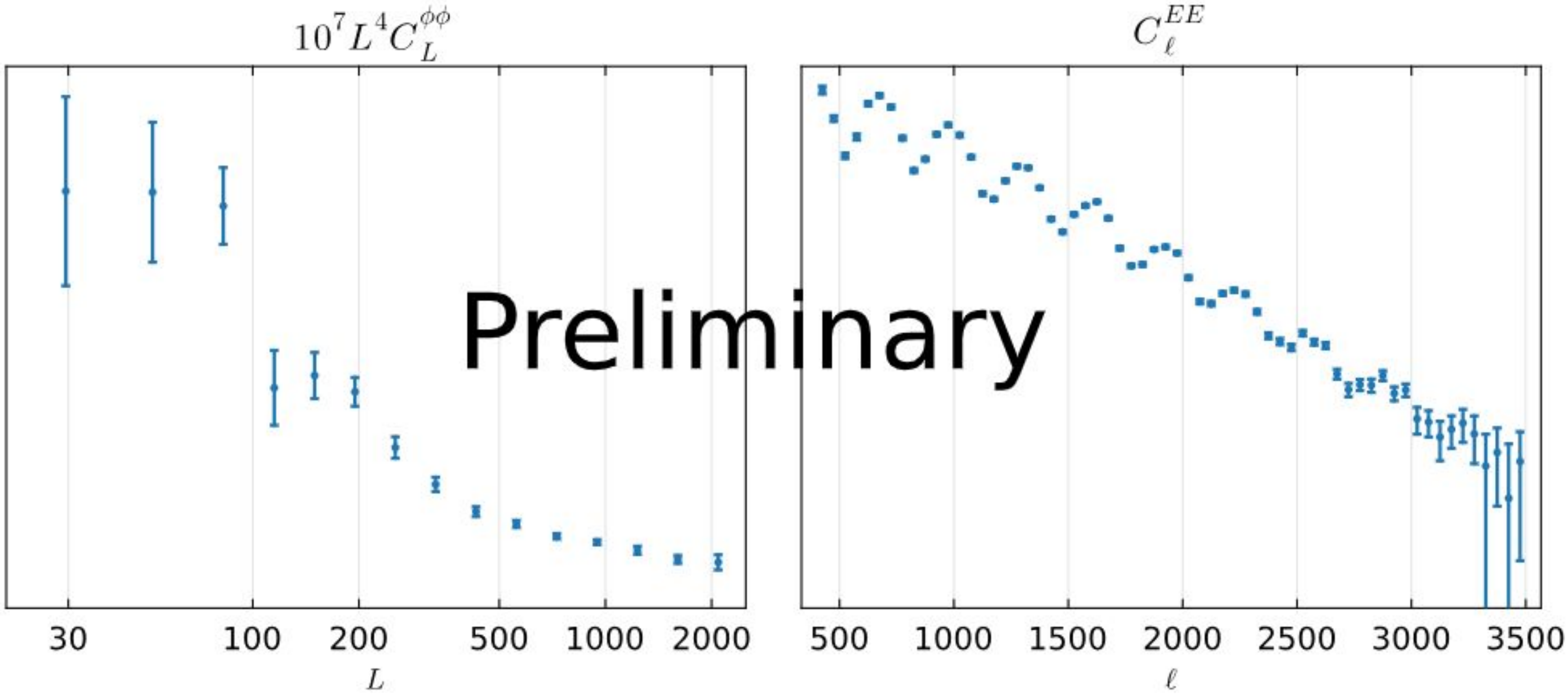
Pipeline test on data – inter-frequency agreement

- MUSE bandpower estimates from single-frequency maps have good overall agreement.
- The cosmological parameter constraints are consistent between 90/150 single-freq runs.

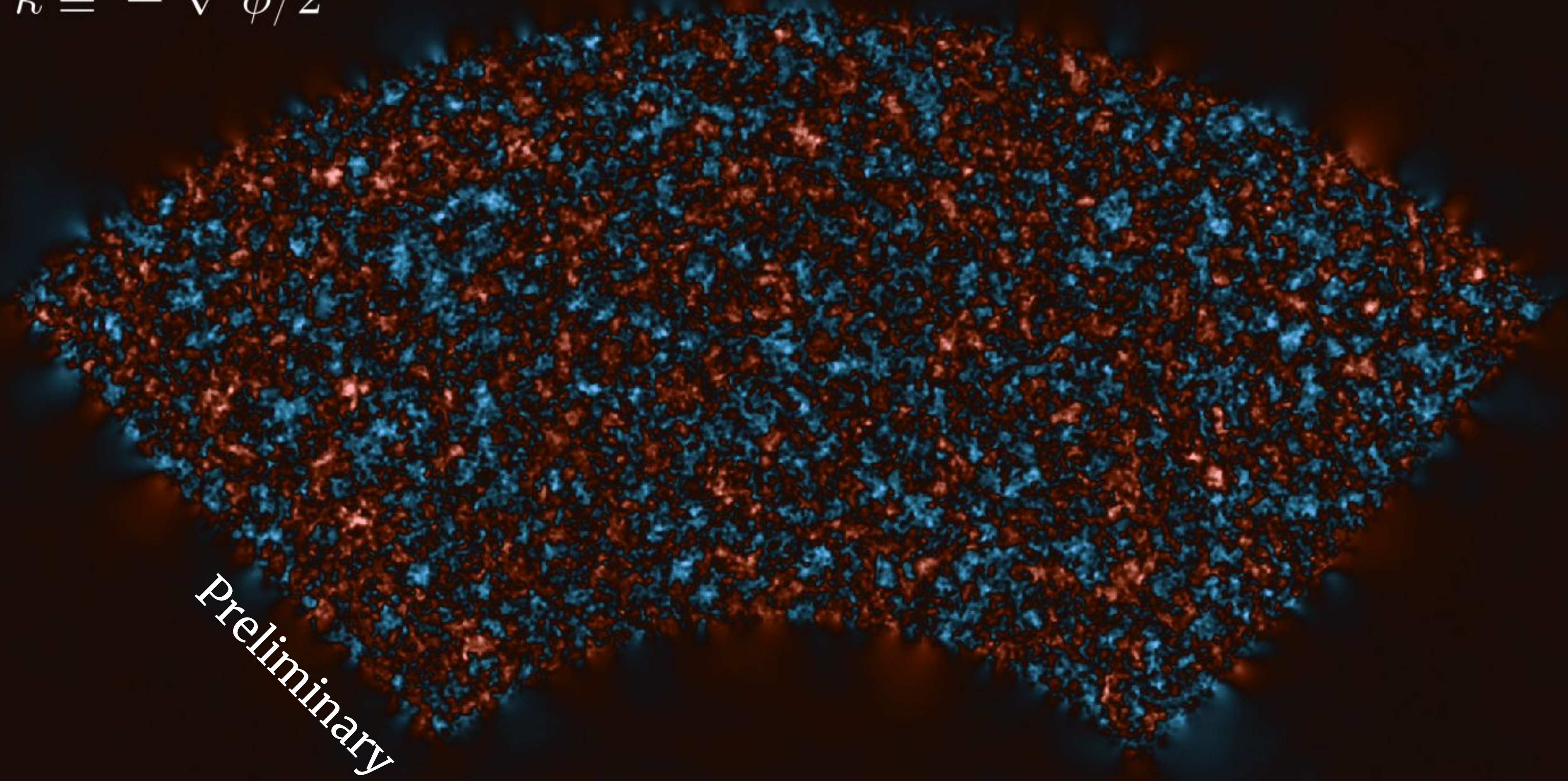


- Grey bands are the scatter of bandpower ratios measured from MUSE runs on mocks.
- PTE and significance are calculated using tridiagonal of the covariance matrix.

MUSE Estimation – 90+150+220 GHz Polarization Maps



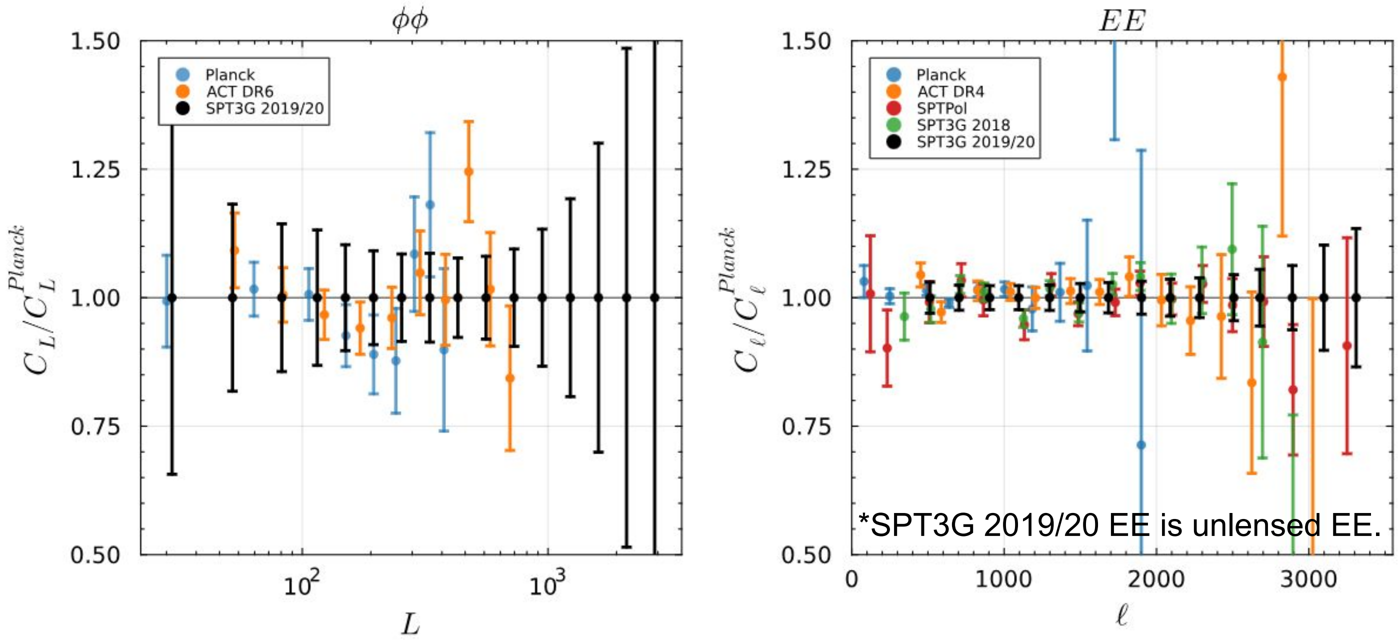
$$\kappa \equiv -\nabla^2\phi/2$$



*reconstruction procedure imprints complex anisotropic filtering on these images

SPT-3G EE+ϕϕ Bandpowers

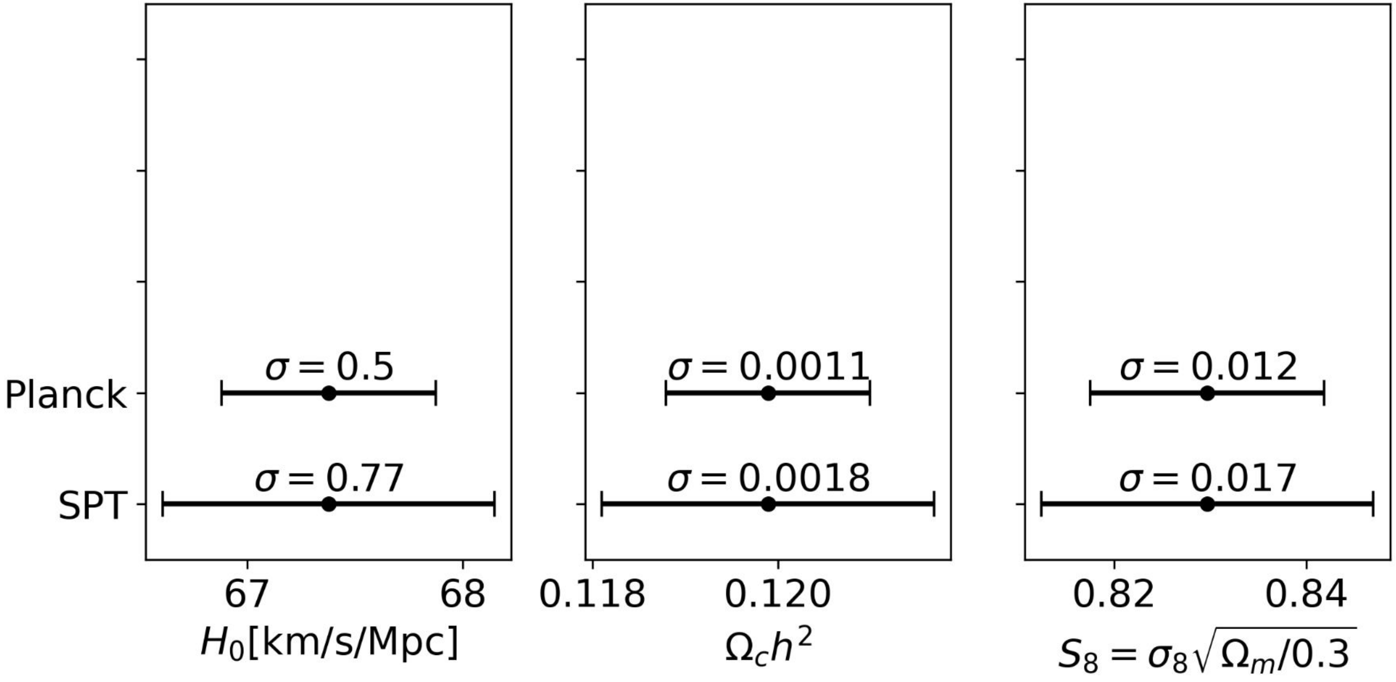
- Tighter measurements of the bandpowers at ϕϕ≳400 and EE≳2000
- New measured polarization signals at small angular scales



*All SPT3G 2019/20 bandpowers are re-centered at 1 with real errorbars estimated from data.

Cosmological Constraints – LCDM

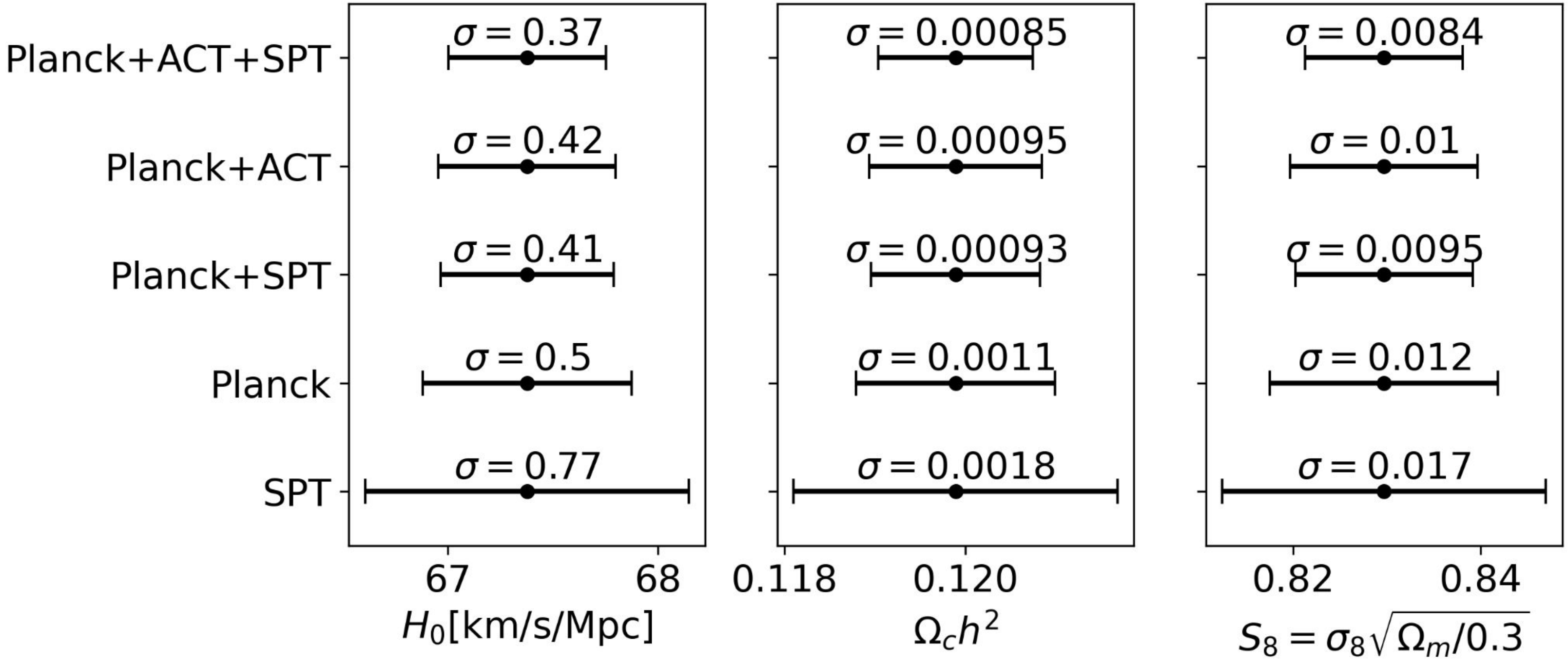
- Comparable constraints of SPT-3G 2019/20 polarization data to Planck 2018



*Error bars are estimated from data chains and recentered at Planck mean.

Cosmological Constraints – LCDM

- Further improve the constraints from joint SPT-3G and Planck analysis



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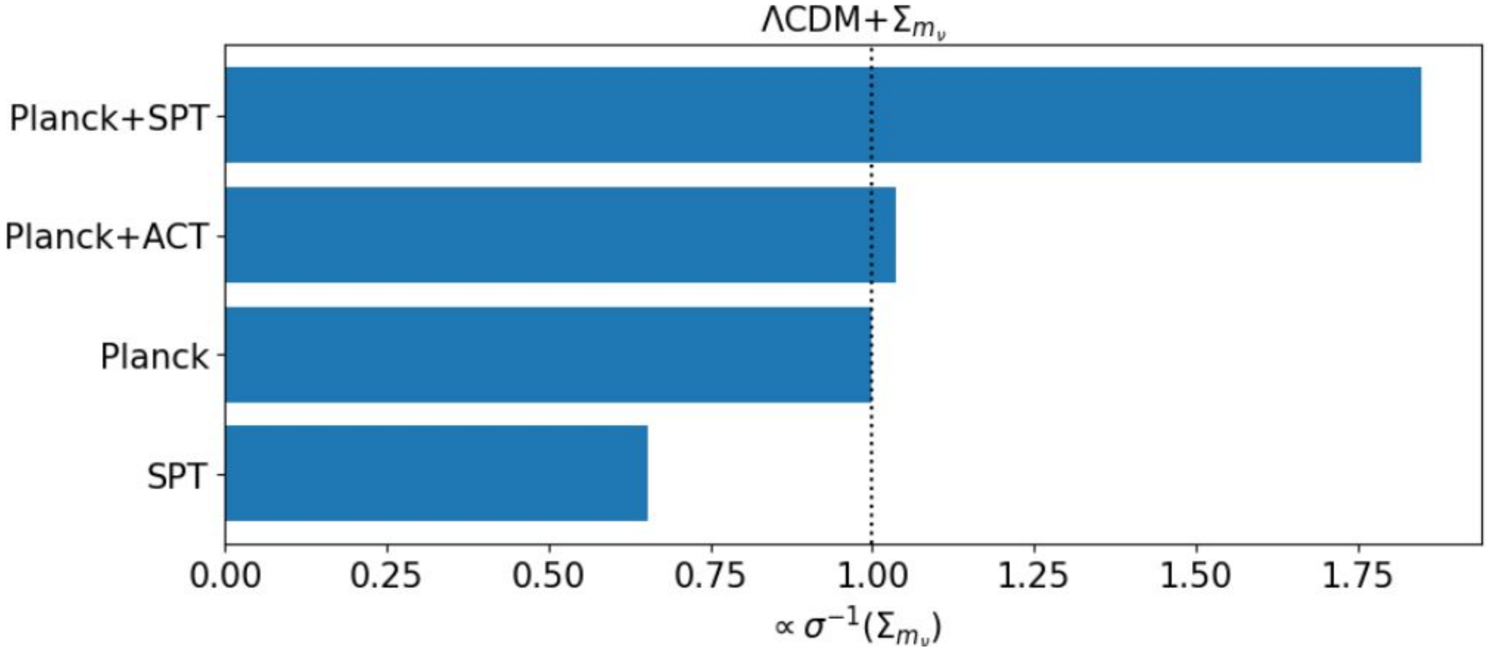
Cosmological Constraints – LCDM Extensions

- Further improve the constraints from joint SPT-3G and Planck analysis



*Larger bars represent tighter constraints.

*Error bars are estimated from real data chains mean.

Conclusion

- SPT-3G 2019/20 polarization data enables the deepest CMB lensing potential map ever made.

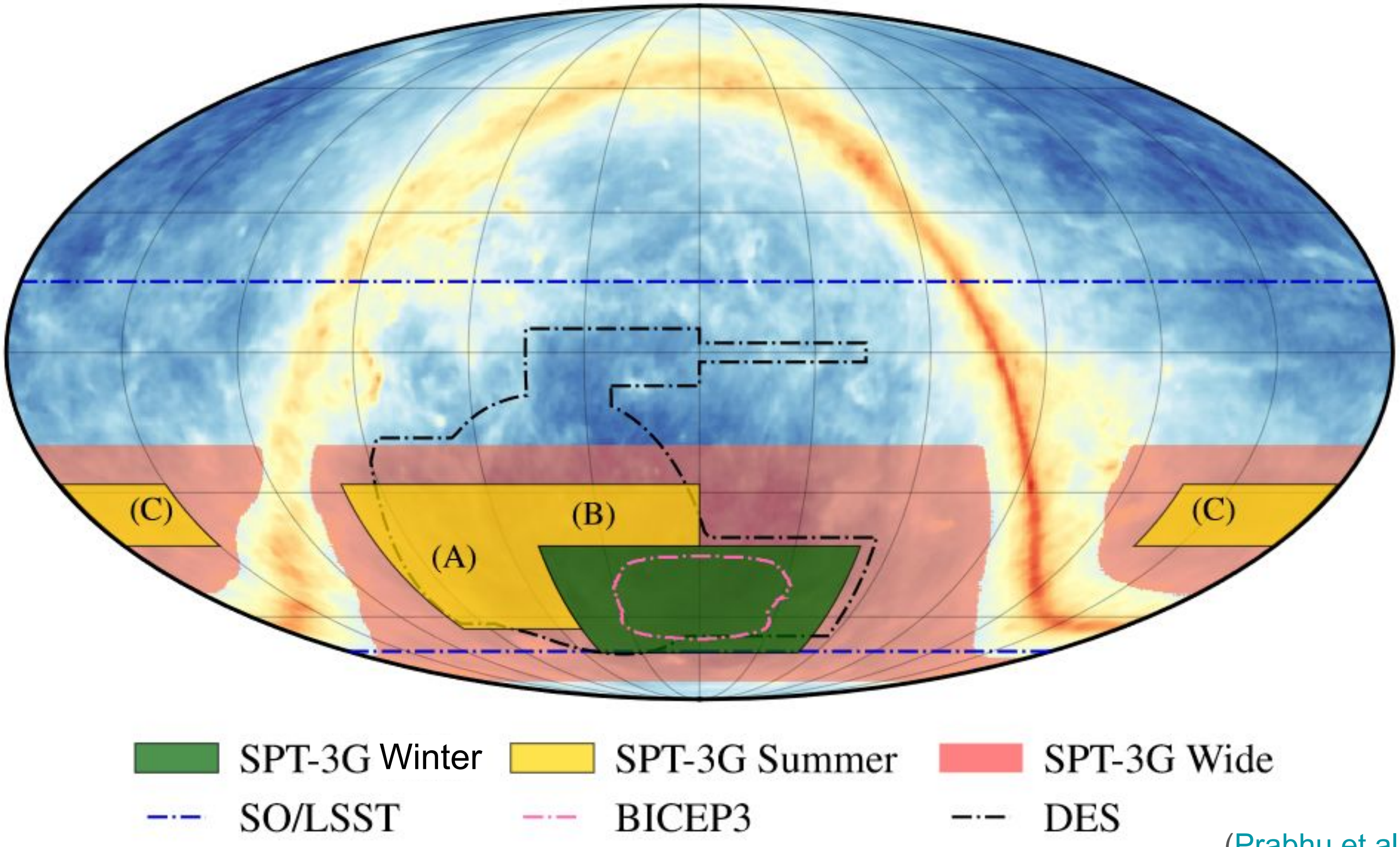
- With MUSE we can jointly estimate unbiased CMB lensing potential bandpowers and (unlensed) CMB EE bandpowers simultaneously, while marginalizing over sources of systematic error.
  - MUSE can be used for optimal lensing reconstruction for CMB-S4

- The SPT-3G 2019/20 polarization data will enable inference of LCDM parameters, some with similar precision as Planck, but from different signals.
  - SPT and Planck parameter comparisons will thus provide a powerful test of the LCDM model.

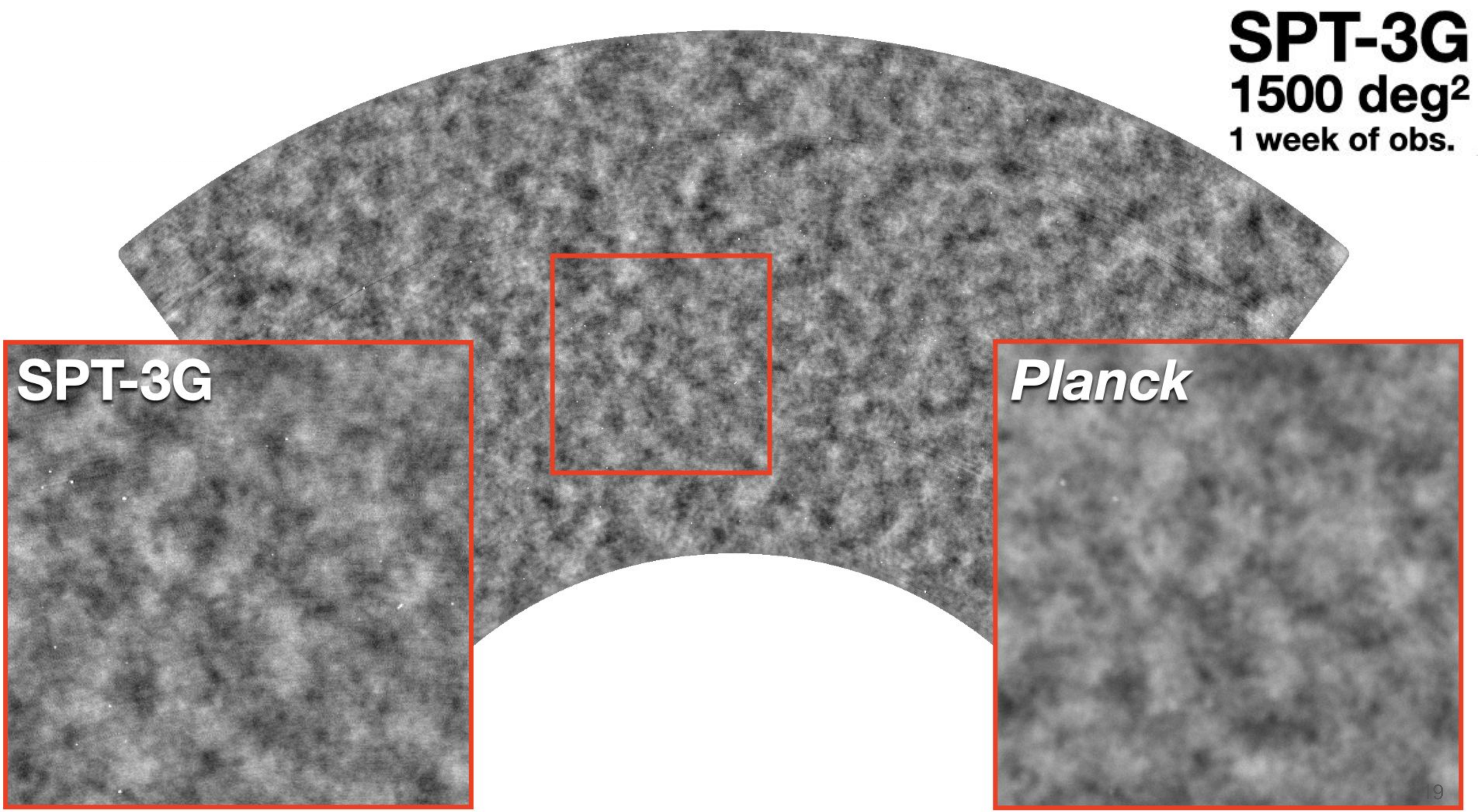
- Combining SPT-3G 2019/20 polarization data with Planck 2018 leads to ~ 2X tighter constraints on Σm_ν than Planck.

Backup Slides

Survey Area



(Prabhu et al 2023)


SPT-3G
1500 deg²
1 week of obs.
SPT-3G
Planck

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

- MUSE implements map-level Bayesian inference, effectively using all N-points statistics to jointly reconstruct CMB lensing potential bandpowers and estimate unlensed CMB bandpowers

$$s_i(\theta, d) = \frac{\partial \mathcal{L}(d|\theta)}{\partial \theta_i}$$

- MUSE expands the map-level score function around MAP (Maximum a Posteriori) estimates of the underlying CMB lensing potential field and the unlensed CMB polarization field.

MUSE

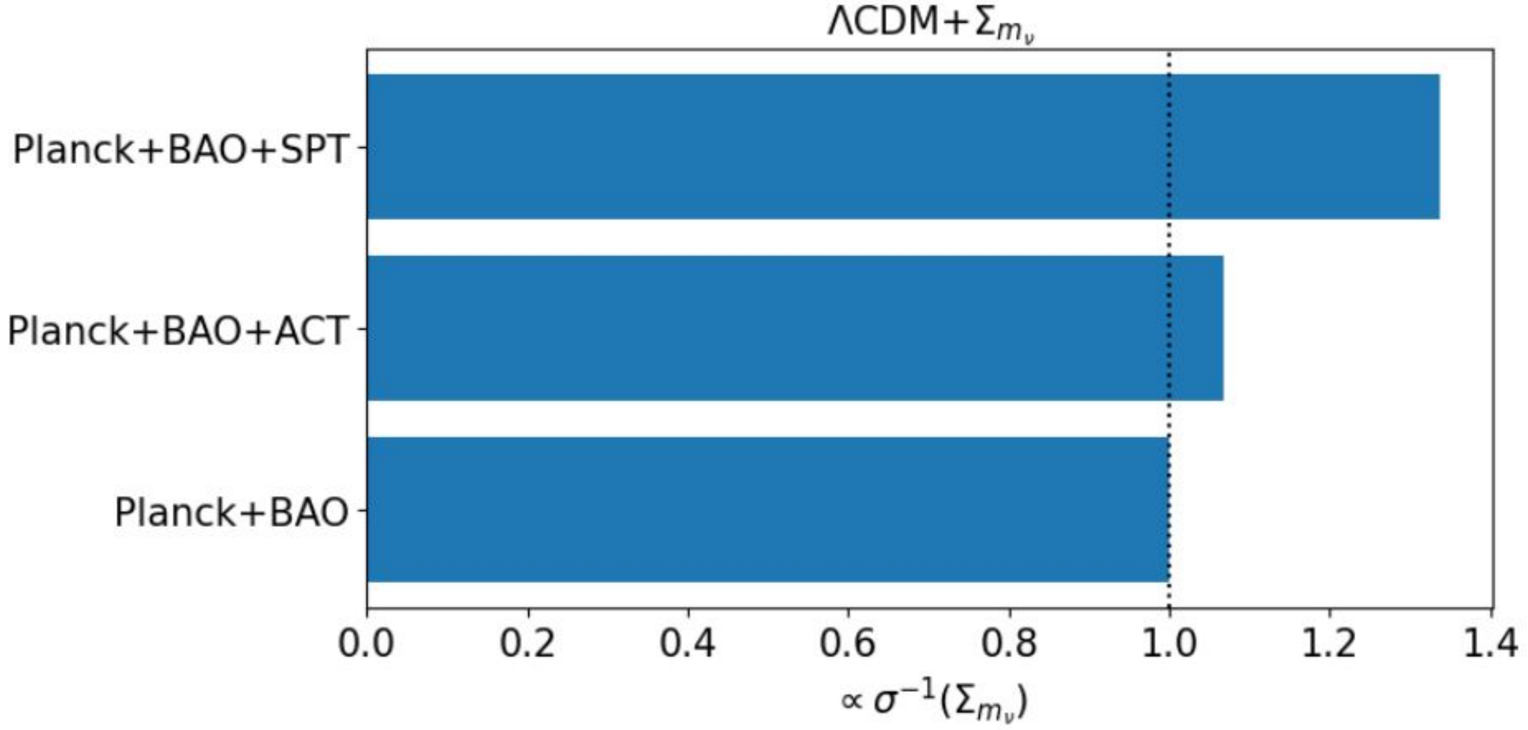
$$s_i^{\mathrm{MAP}}(\hat{\theta}, d) = \left\langle s_i^{\mathrm{MAP}}\left(\hat{\theta}, d'\right)\right\rangle_{d' \sim \mathcal{P}(d'|\hat{\theta})}$$

- Unbiased MUSE estimates rely on accurate and fast simulation of the observed maps.

Observed CMB Maps

Simulated CMB Maps

Cosmological Constraints – LCDM Extensions



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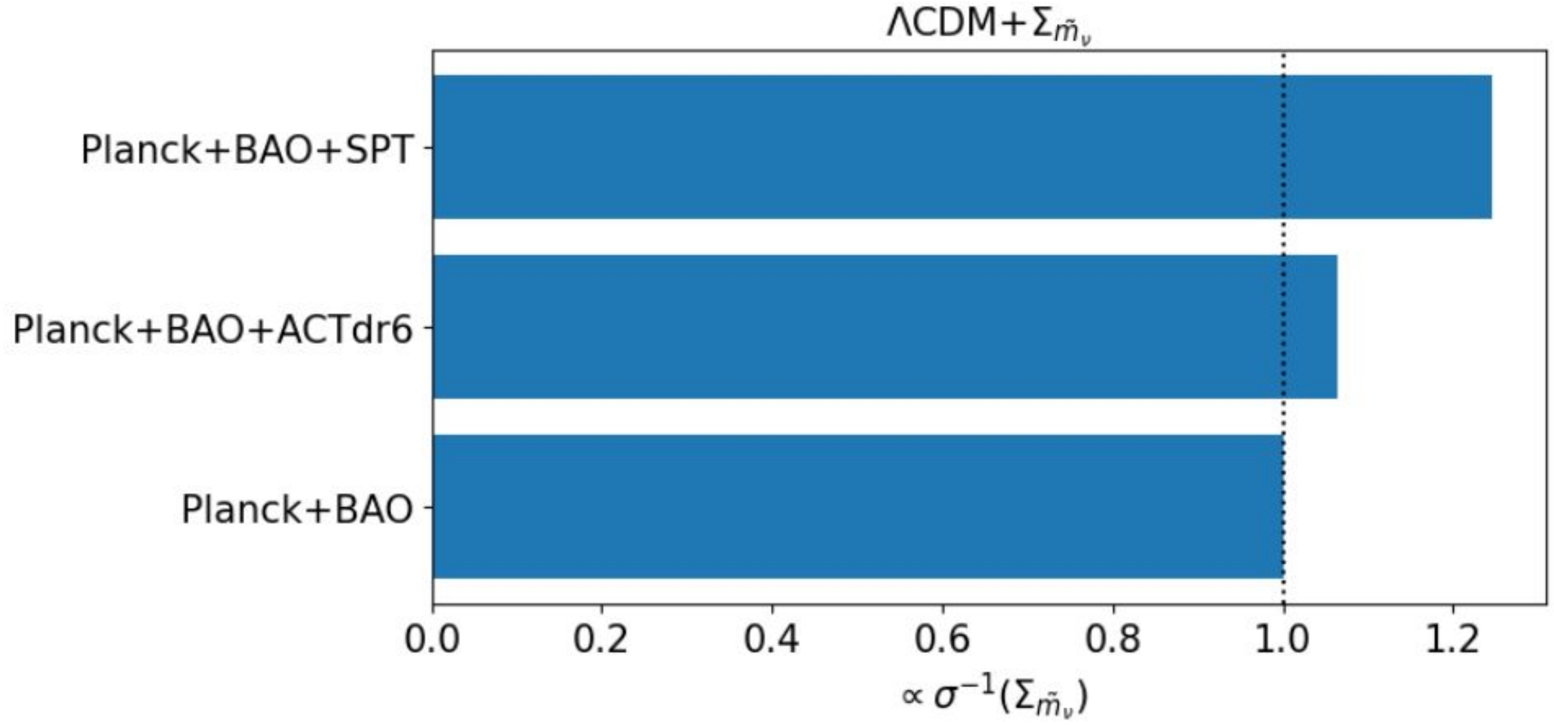
Cosmological Constraints – LCDM Extensions



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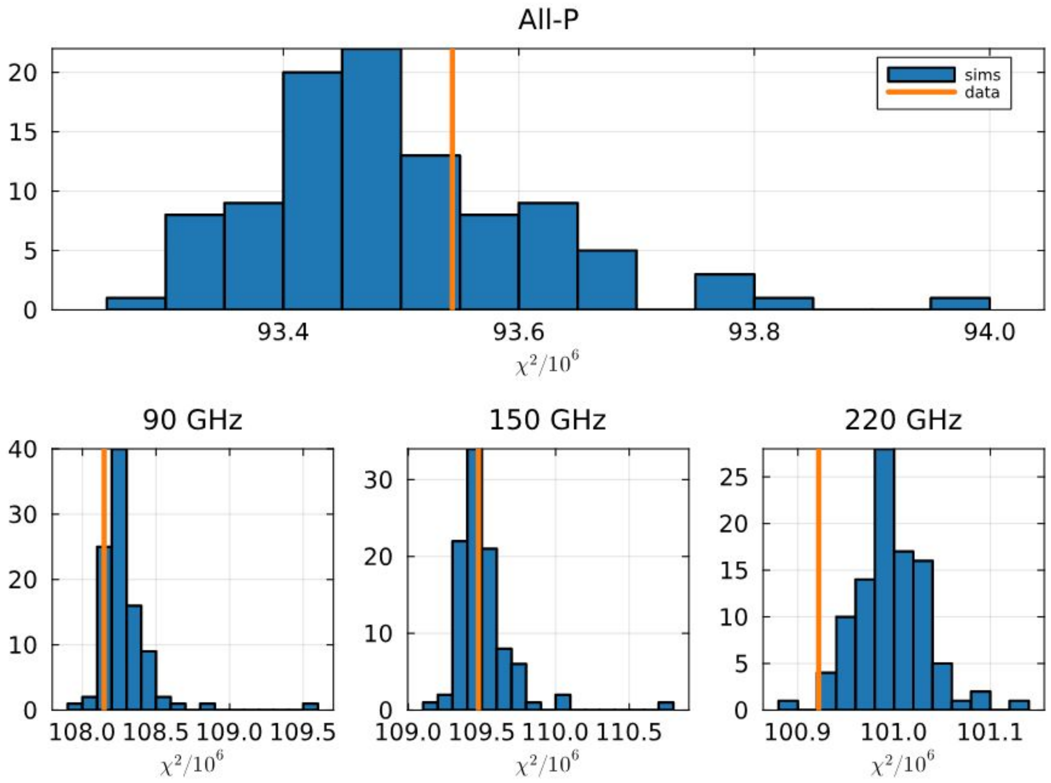
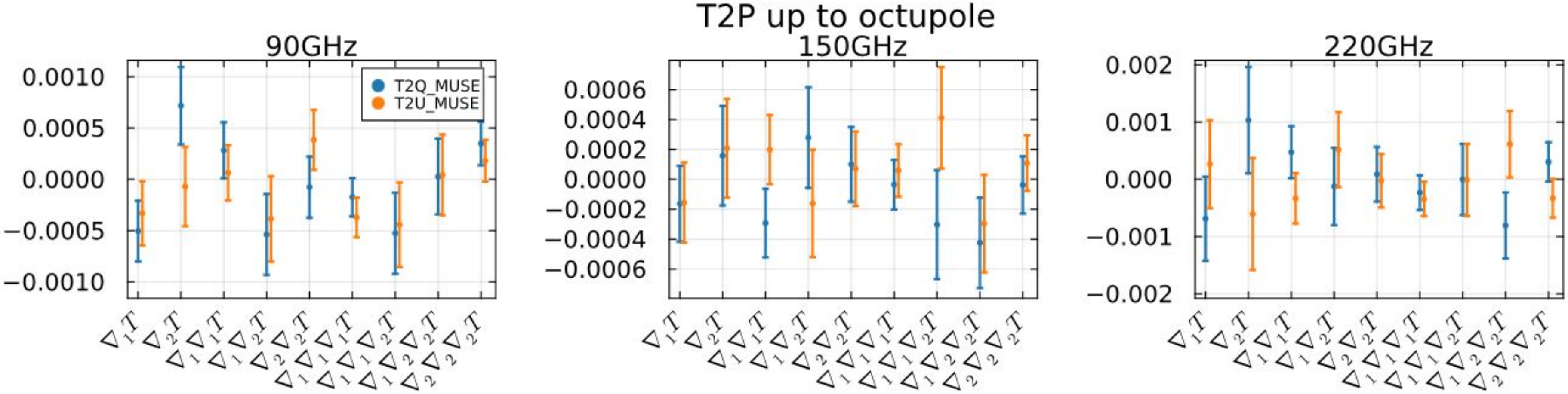
Pipeline test on data – χ^2 distribution



The map-level χ^2 of the all-P and single-freq runs is within 3σ expectation from fits on mocks.

Pipeline test on data – Higher-order T2P leakage



No evidence of higher-order TP leakage beyond monopole when we include these templates and amplitude parameters in the all-P fit (these are then *not* included in the baseline run)