AN ITERATIVE CMB LENSING ESTIMATOR MINIMIZING INSTRUMENTAL NOISE BIAS

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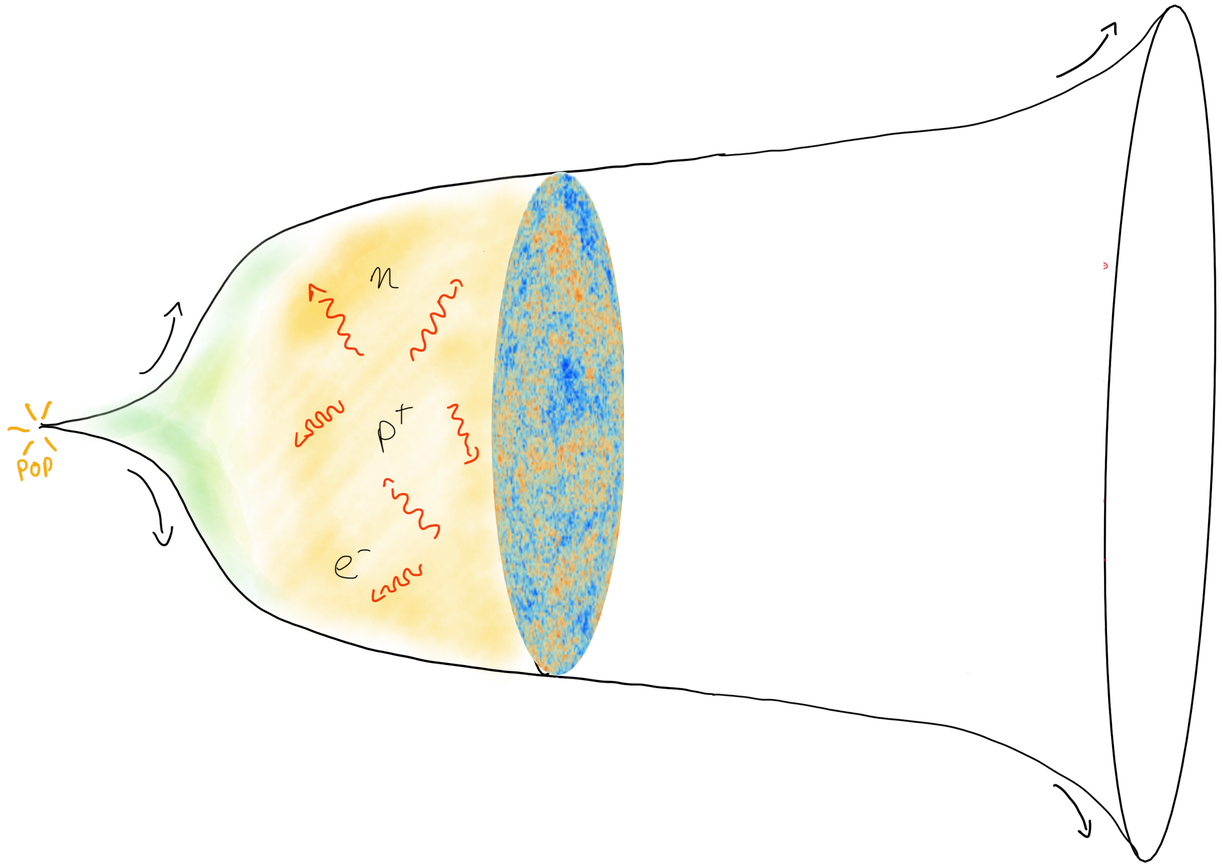
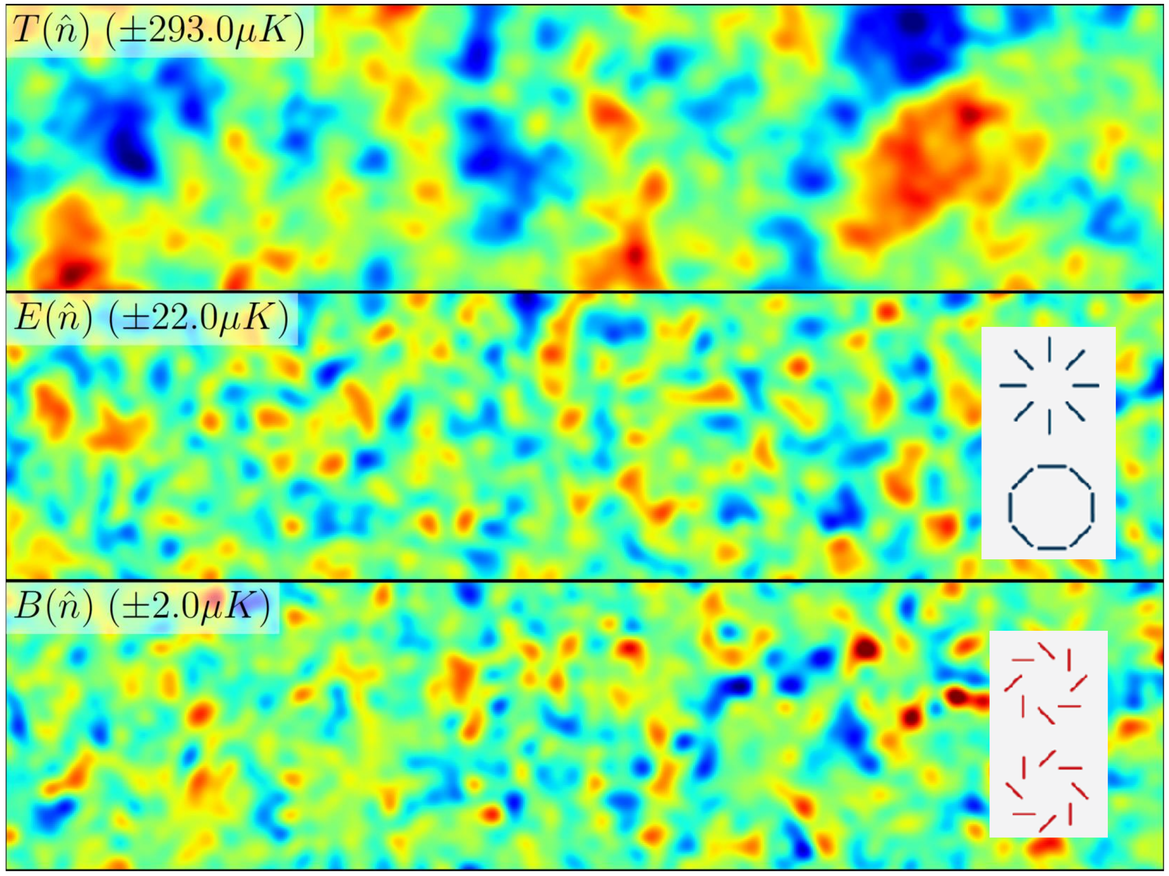
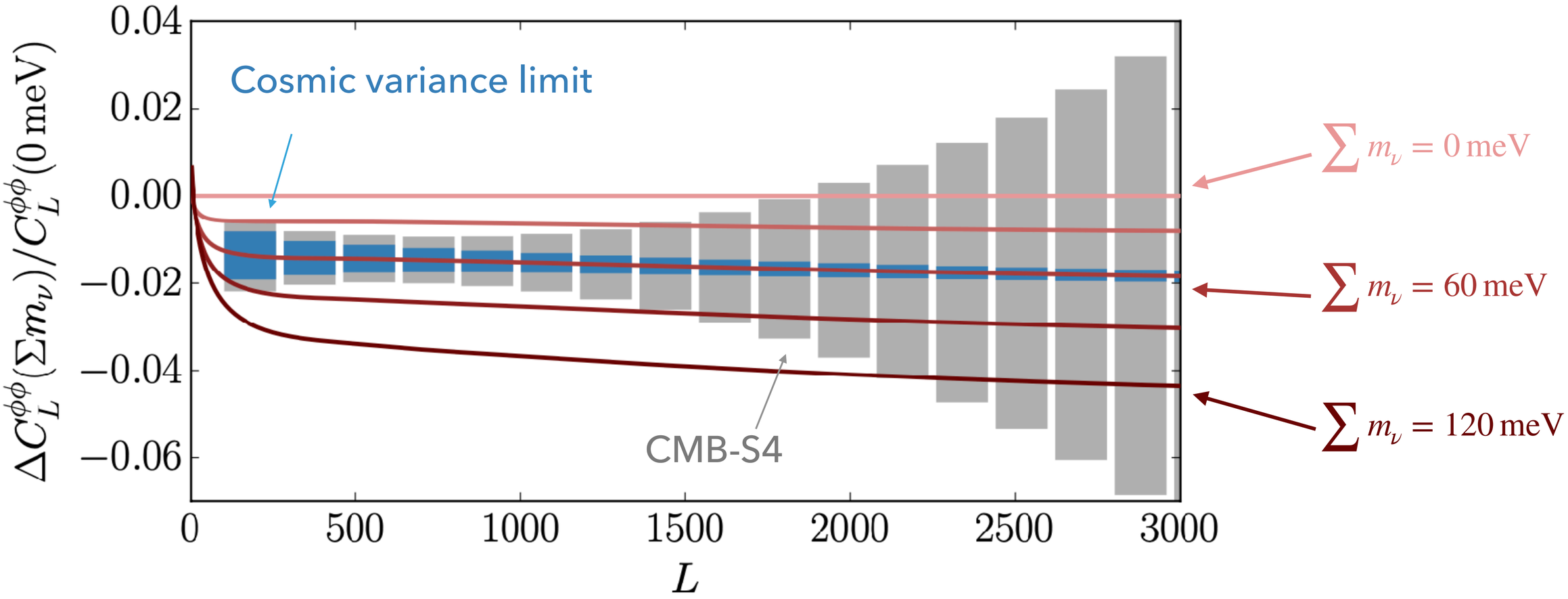
GRAVITATIONAL LENSING OF THE CMB





CMB LENSING AND NEUTRINO MASS



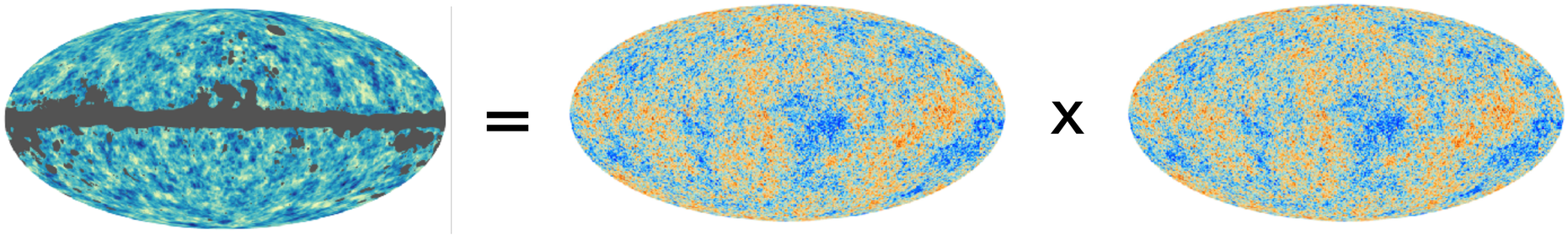
Abazajian et al. 2016

LENSING QUADRATIC ESTIMATOR (QE)

- Lensing creates correlations between different multipole moments

$$\left\langle T^{\rm len}(\boldsymbol{l}) T^{\rm len\,*}(\boldsymbol{l}') \right\rangle_{\substack{\text{fixed lensed} \\ \boldsymbol{l} \neq \boldsymbol{l}',\ \boldsymbol{L} = \boldsymbol{l} + \boldsymbol{l}'}} = f(\boldsymbol{l}, \boldsymbol{l}')\, \phi(\boldsymbol{L})$$

- The ***quadratic estimator*** combines scales of two CMB fields

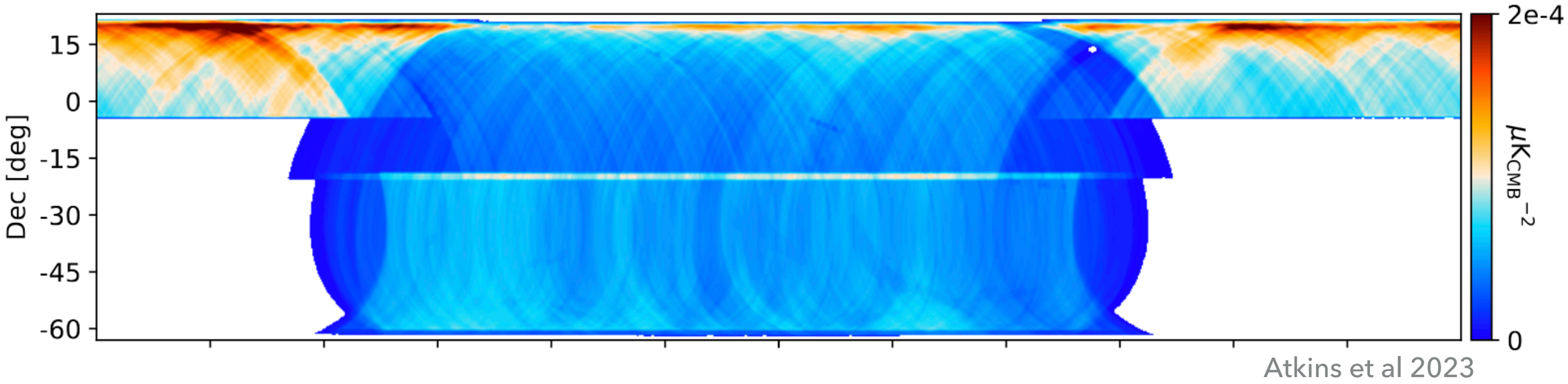


$$\hat{\phi}(\boldsymbol{L}) = \frac{1}{R_L} \int \frac{d^2\boldsymbol{l}}{2\pi}\, f(\boldsymbol{l}, \boldsymbol{L})\, \bar{T}(\boldsymbol{l})\, \bar{T}^*(\boldsymbol{l} - \boldsymbol{L})$$

Inverse variance filtered CMB fields

THE CHALLENGE OF CMB NOISE

Inverse variance ACT noise simulation

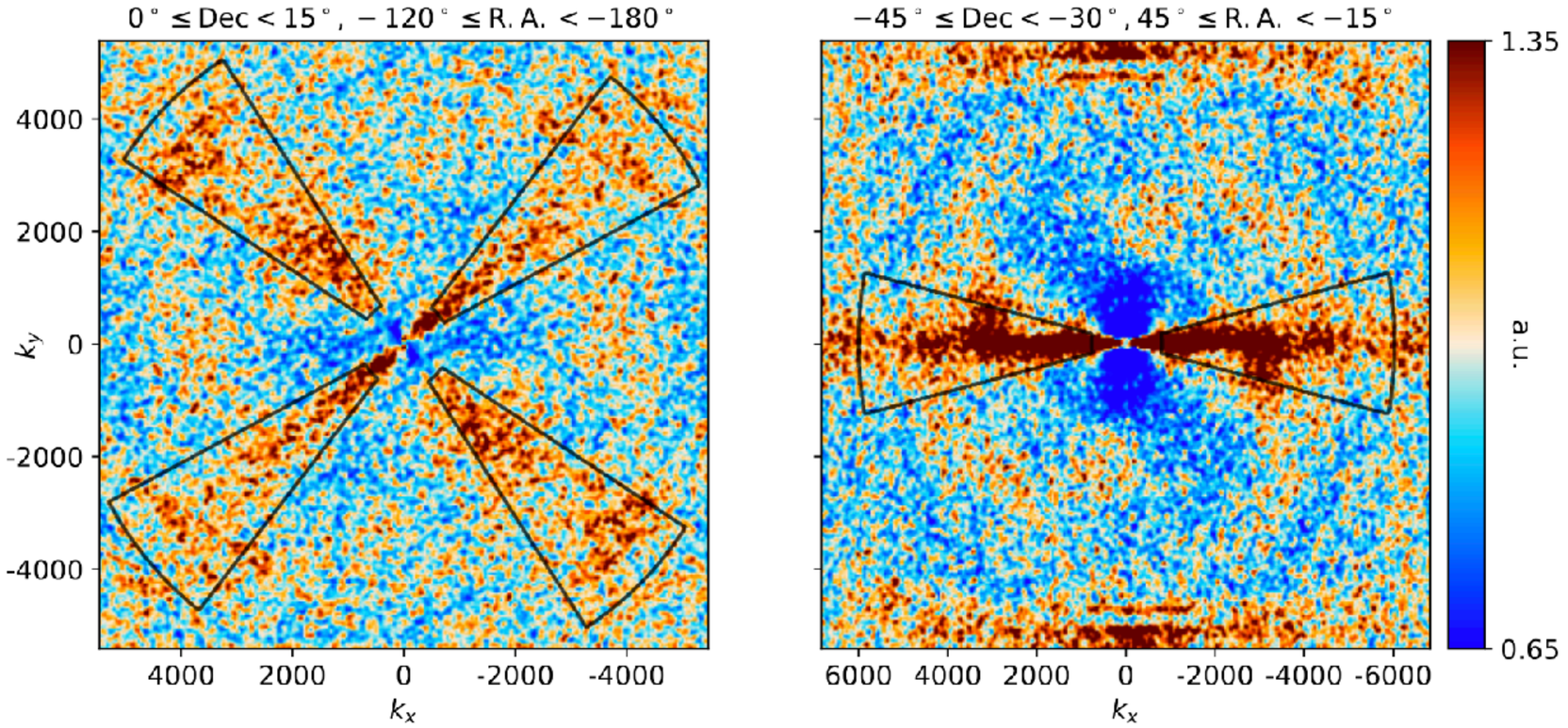


Atkins et al 2023

- Instrumental noise is a source of anisotropy in the CMB maps
  - Scanning strategy
  - Atmospheric conditions
  - Instrumental effects

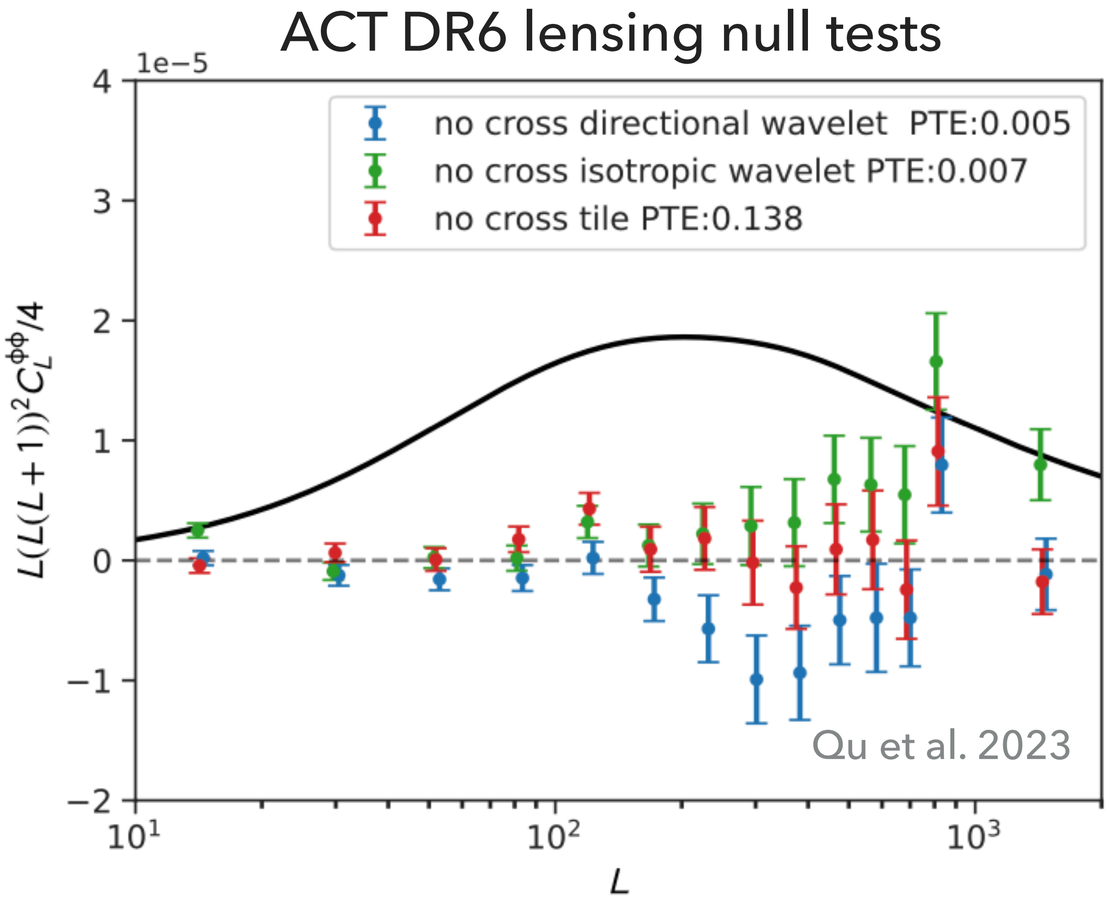
THE CHALLENGE OF CMB NOISE

2D Fourier Power spectra by Region



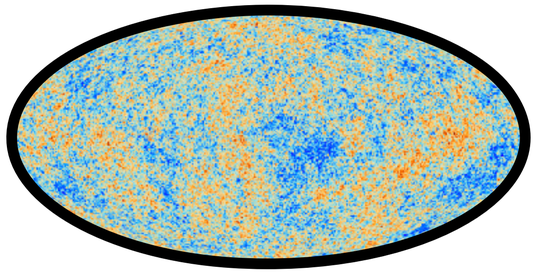
Atkins et al 2023

THE PROBLEM: MIS-MODELING LEADS TO BIAS

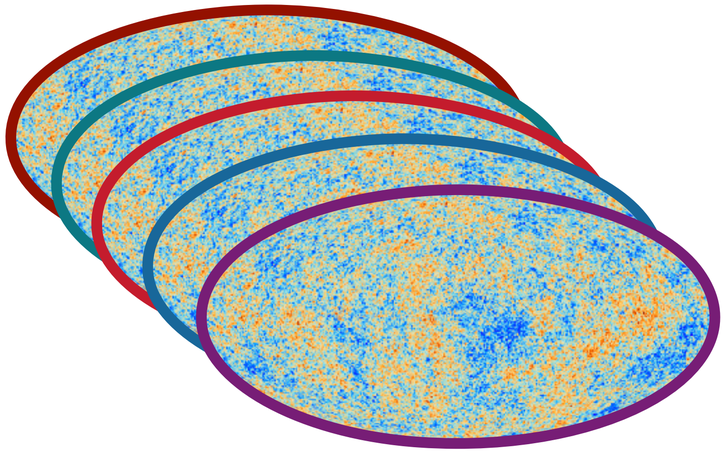


THE POWER OF MAP SPLITS

- Instead of trying to model precisely this very complex noise, we try to cancel the noise by using map splits that possess independent noise realisations



$$T^{\mathrm{obs}} = \frac{1}{n}\sum T_i$$



$$T_i = T^{CMB} + n_i$$

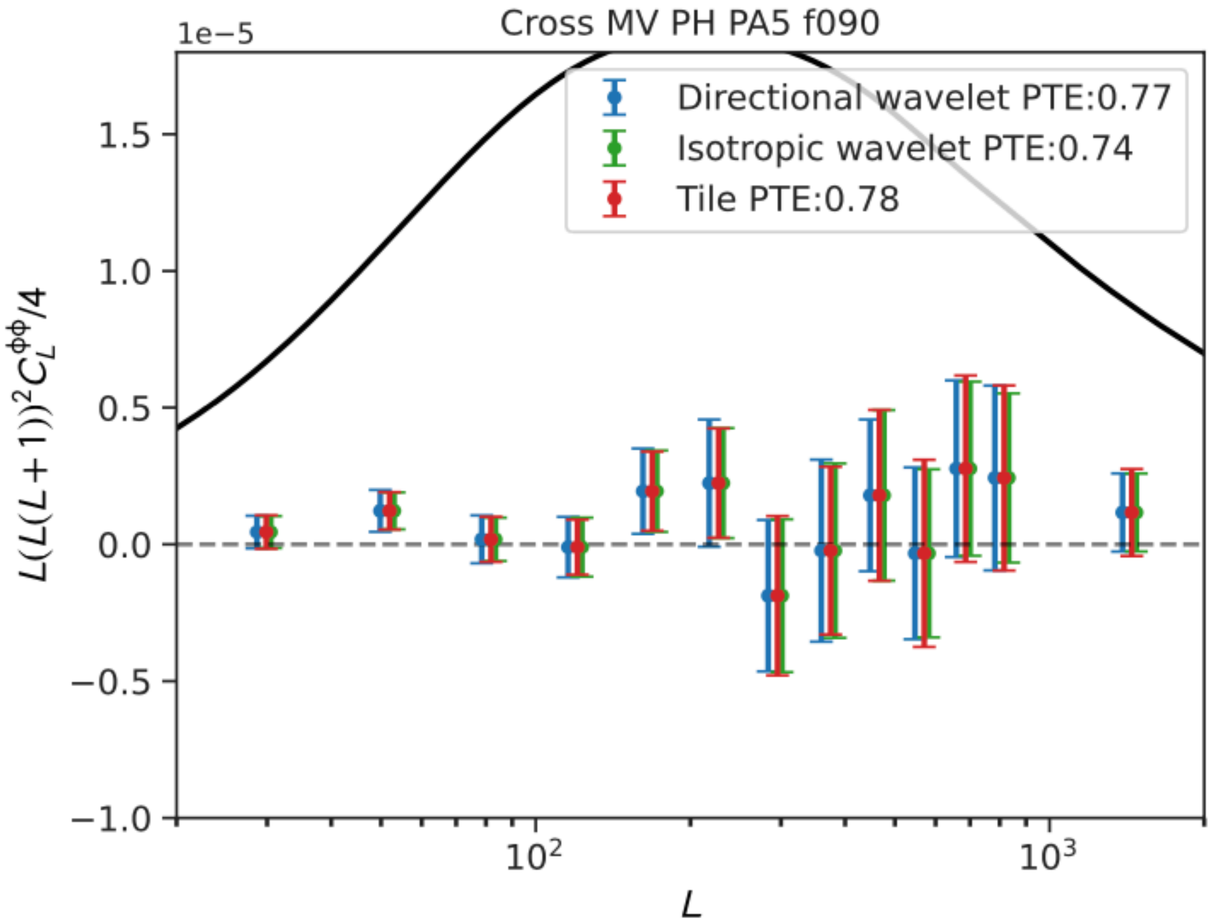
$$T_j = T^{CMB} + n_j$$

$$\left\langle n_i, n_j \right\rangle_{i \neq j} = 0$$

CROSS ONLY ESTIMATOR

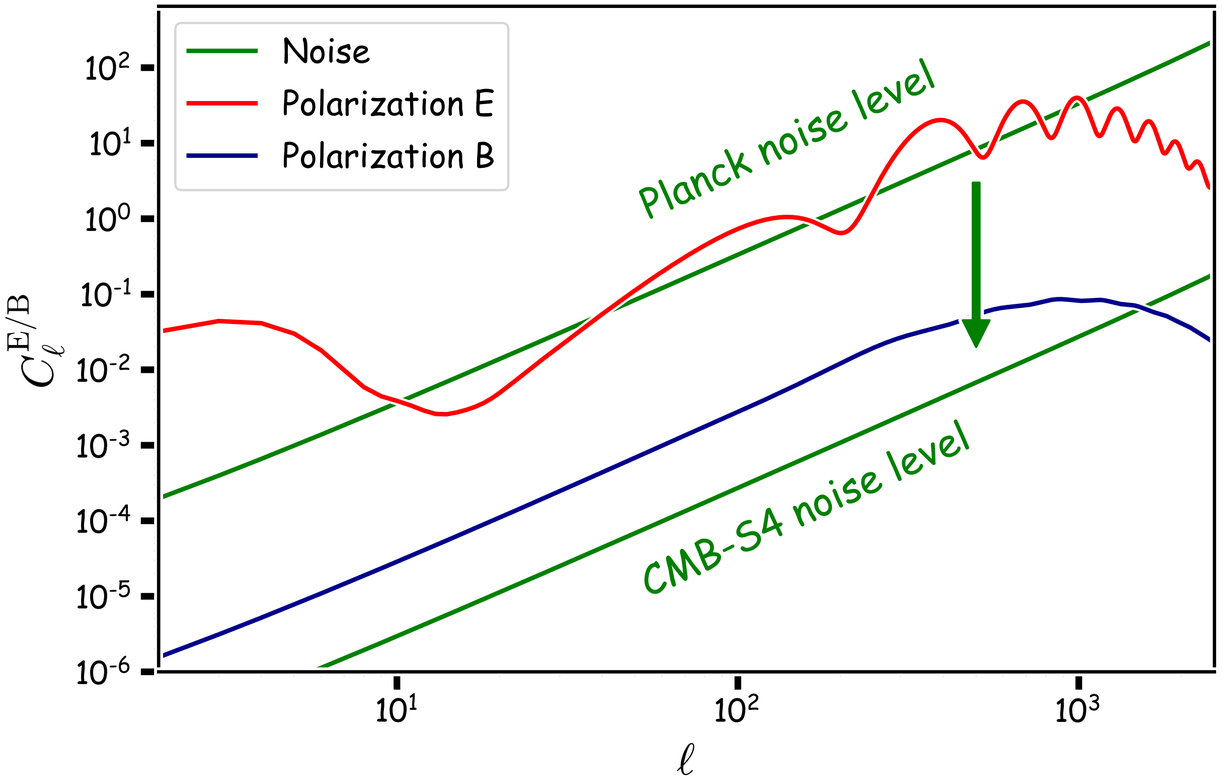
- Build an estimator using only split maps

$$\hat{\phi}^{\times}(\boldsymbol{L}) = \frac{1}{R_L} \int \frac{d^2\boldsymbol{l}}{2\pi} f(\boldsymbol{l}, \boldsymbol{L})\, \bar{T}_i(\boldsymbol{l})\, \bar{T}_j^*(\boldsymbol{l} - \boldsymbol{L})$$



NEXT GENERATION DEEP POLARISATION SURVEYS

- As we move into precise next-generation surveys, eliminating this noise bias becomes more important
- Future CMB surveys will use Bayesian lensing estimators, leveraging the fact that B modes are directly produced by lensing



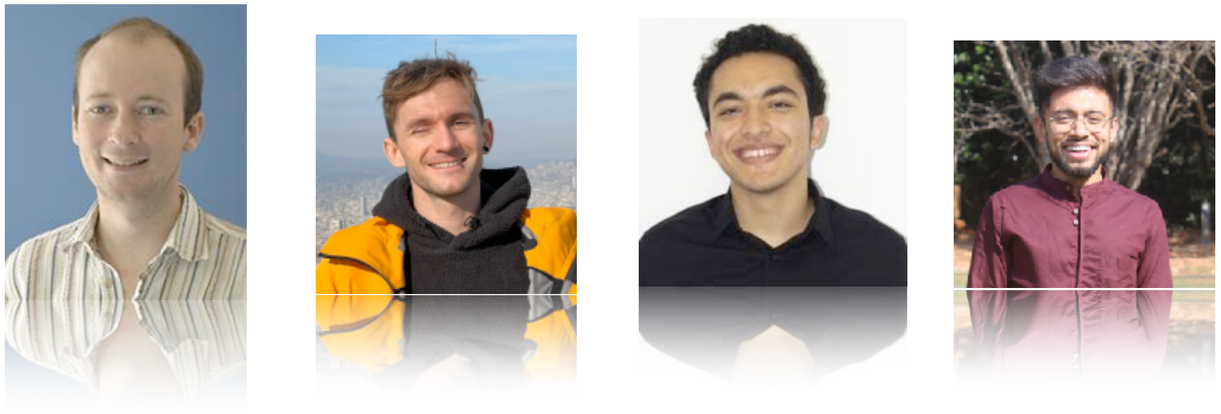
BAYESIAN LENSING ESTIMATOR

- Find lensing potential ϕ (~ 50 millions pixels) maximising the posterior for a given observed CMB
- Hirata & Seljak 2003, Carron & Lewis 2017, Legrand & Carron 2022, 2023, Belkner et al. 2024

$$\ln P(\phi \,|\, X^{\rm dat}) = -\, X^{\rm dat\,\dagger} \mathrm{Cov}_\phi^{-1} X^{\rm dat} - \frac{1}{2} \ln \det \mathrm{Cov}_\phi - \frac{1}{2} \sum_L \frac{\phi_L^2}{C_L^{\phi\phi}}$$

- Newton iterations to find the maximum a posteriori (MAP) lensing field:
  1. Get an estimate of the lensing field (first step is standard quadratic estimator)
  2. Compute the gradient and curvature of the posterior with respect to ϕ
  3. Estimate the next MAP lensing field
  4. Iterate until convergence

D.LENSALOT



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Sir D.Lensalot

https://github.com/NextGenCMB/delensalot

CROSS-ONLY ESTIMATOR

- We extend the ACT approach of the split-only quadratic estimator to the maximum likelihood estimator

Standard likelihood

$$T^{\mathrm{obs}\,\dagger}\mathrm{Cov}_{\phi}^{-1}T^{\mathrm{obs}} = \frac{1}{n^2}\sum_{i,j} T_i^{\dagger}\mathrm{Cov}_{\phi}^{-1}T_j$$

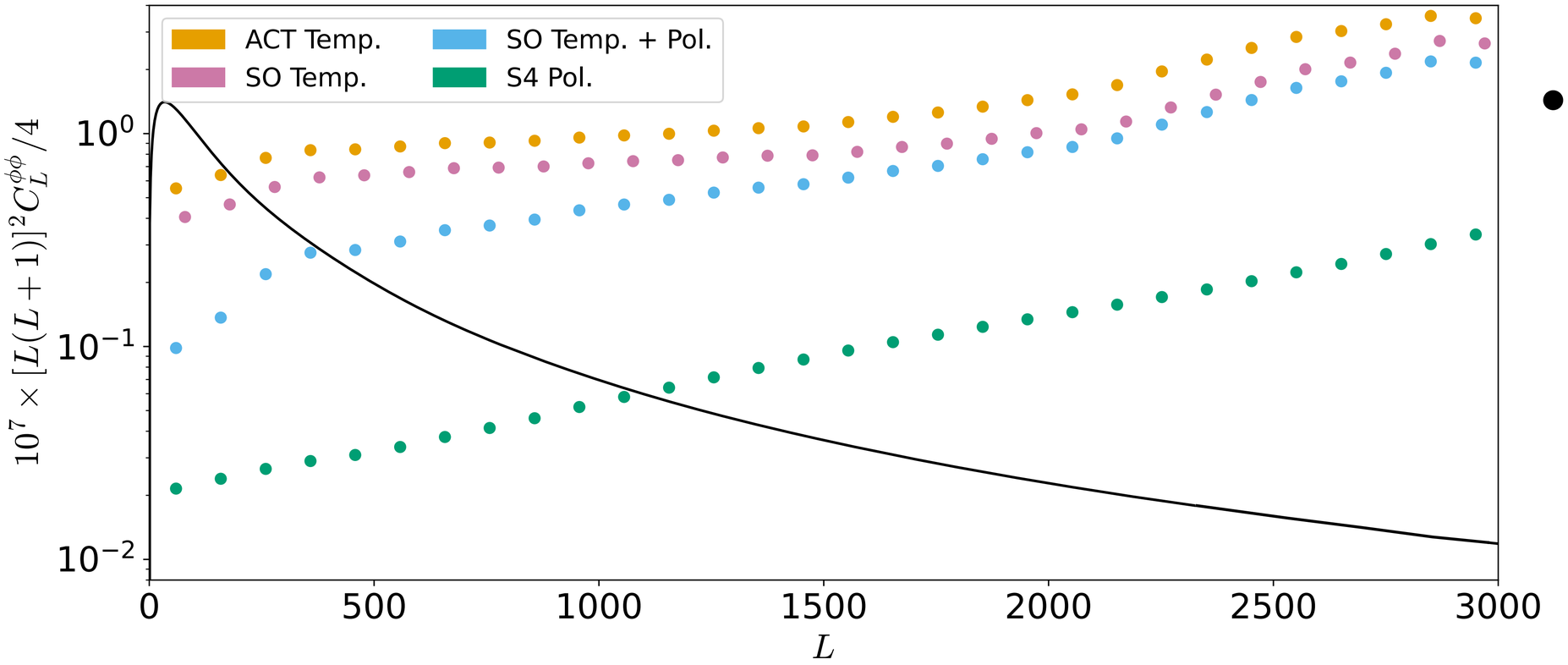
Modified « likelihood »

$$\frac{1}{n(n-1)}\sum_{i\neq j} T_i^{\dagger}\mathrm{Cov}_{\phi}^{-1}T_j$$

- We perform the iterations with the same algorithm, until convergence
- In the regime where of many split-maps, this closely approximates the true likelihood
- But it’s not a likelihood anymore, since it’s not a definite positive quadratic form!
- Julien Carron quote: breakthrough or total crap

VALIDATION WITH SIMULATIONS

- 200 simulations, full sky, isotropic noises, 4 map splits



- Standard estimator

VALIDATION WITH SIMULATIONS

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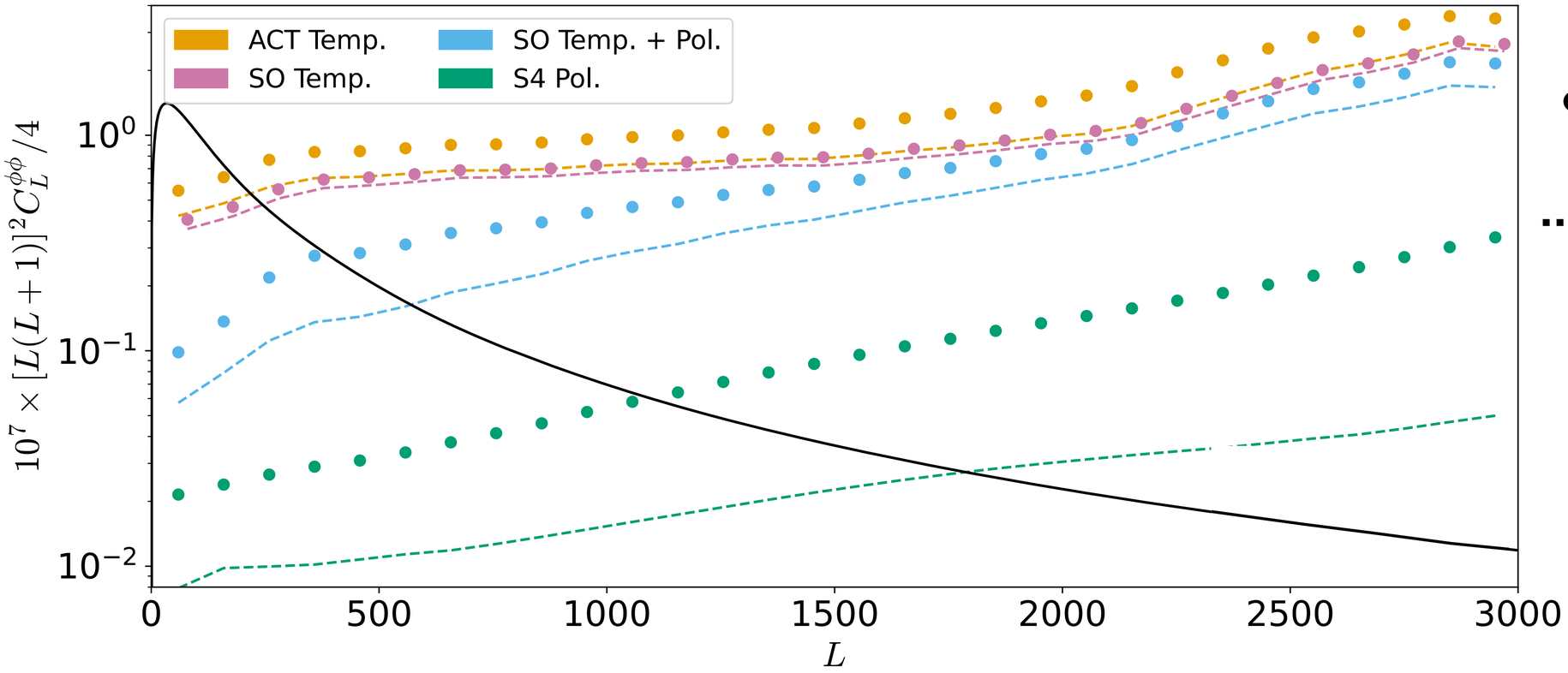

- Standard estimator
- Noiseless sims

VALIDATION WITH SIMULATIONS

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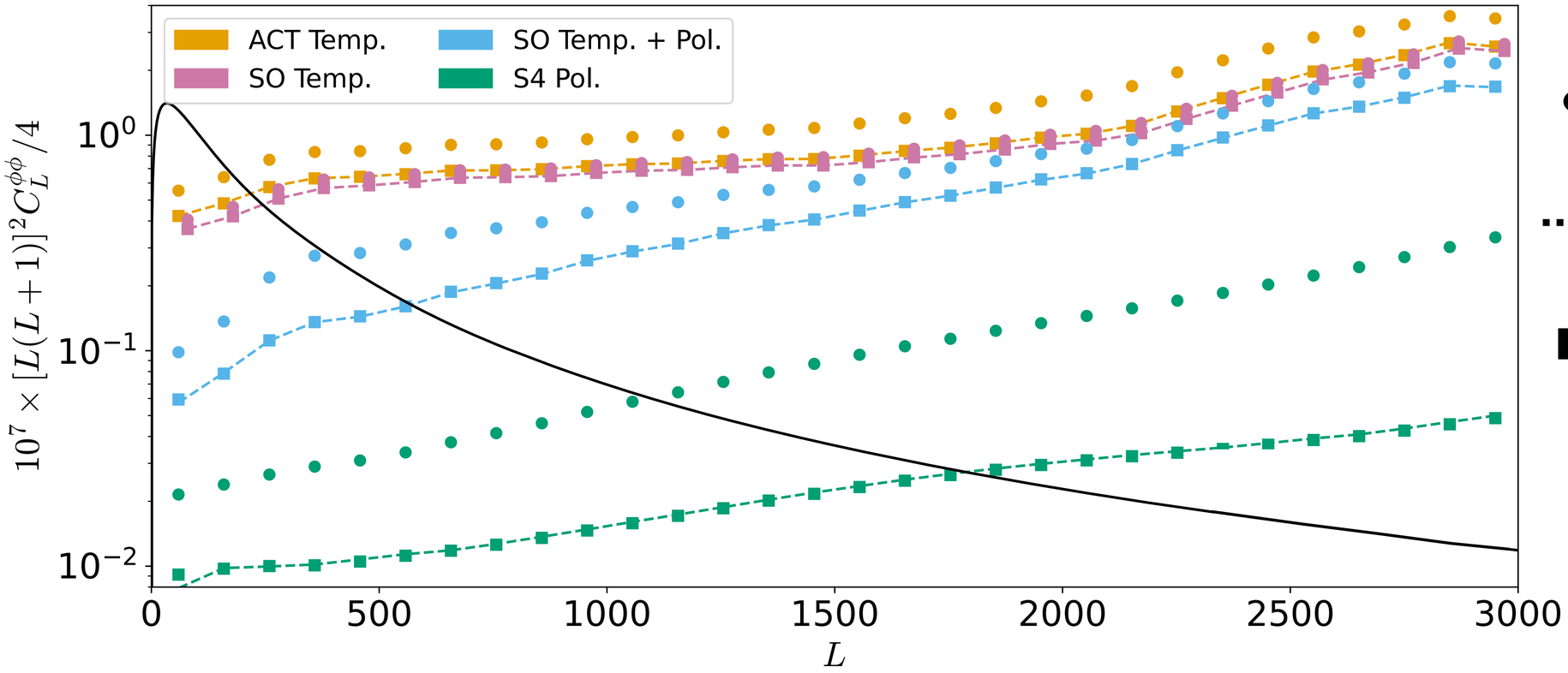
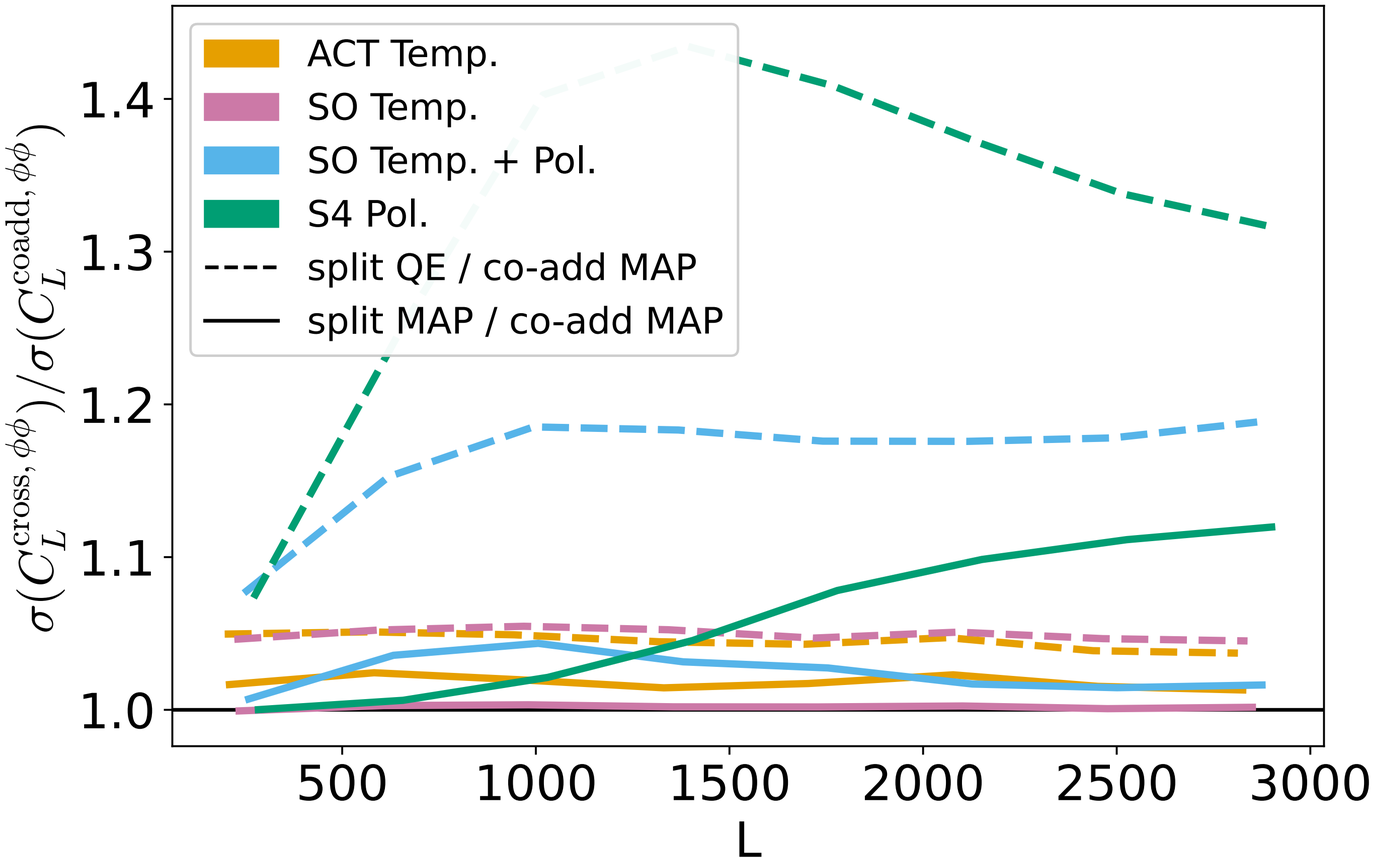


- Standard estimator
- Noiseless sims
- Cross-only estimator

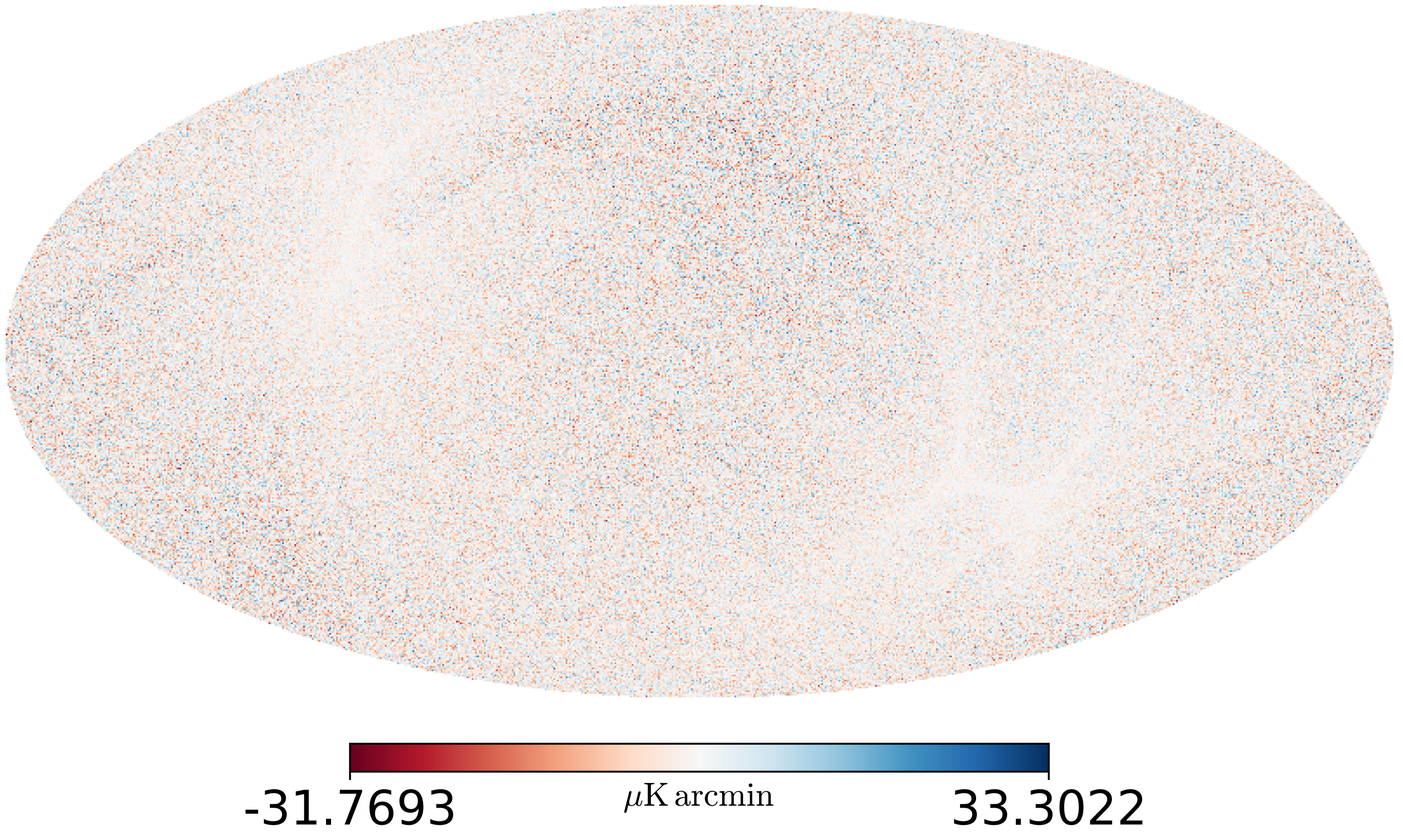
TRADE-OFF: NEGLIGIBLE COST IN VARIANCE



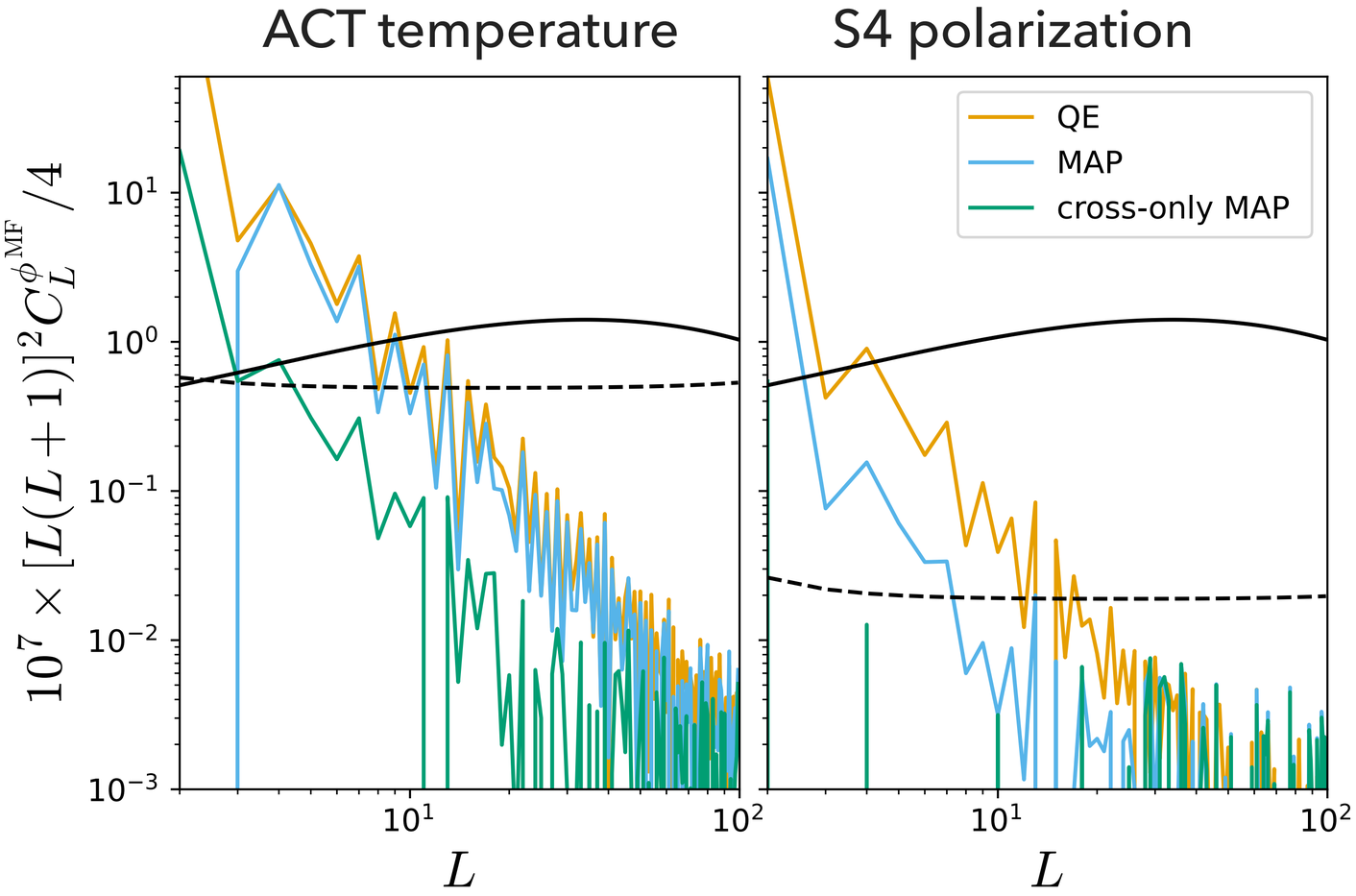
- Band-power variance of the split only estimators over the standard MAP estimator
- Dashed lines are the split quadratic estimator, plain lines are the split MAP estimator
- Limited to about 5 % increase in variance for the split MAP estimator

ANISOTROPIC NOISE BIASES

- Mean field: looks like lensing but is due to any source of anisotropy other than lensing
- 100 simulations with highly anisotropic noise
- Reconstruct the lensing potential assuming isotropic noise



IMMUNITY TO NOISE MIS-MODELING BIAS



CONCLUSION

- We developed an iterative CMB lensing estimator that relies on independent map splits.
- It provides **unbiased and nearly optimal lensing reconstruction**, achieving immunity to complex instrumental noise biases.
- Illustrate that we can easily leverage the already rich diversity of quadratic estimators into the optimal lensing reconstruction framework
- This work is essential for guaranteeing the cosmological reliability of results derived from **next-generation CMB surveys**