The Effects of Instrumental Systematics on CMB Lensing Reconstruction

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Based on arXiv:2011.13910

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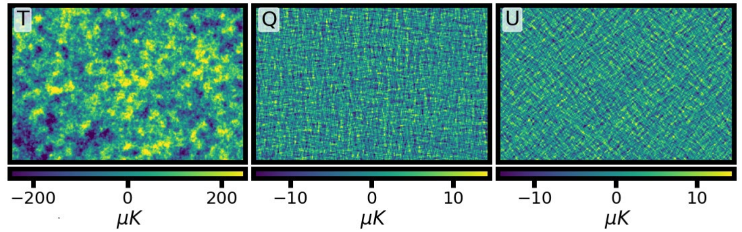
The Effects of Instrumental Systematics on CMB Lensing Reconstruction – summary

- We used TOD simulations to propagate the effects of realistic instrumental systematics to the lensing reconstruction analysis.
- Without correcting for any systematic effects, most systematic-induced biases would be relatively negligible for SO lensing science.
- We should be mindful about differential pointing, boresight pointing and coherent gain drifts.
- This is an ongoing work, and your feedback is much appreciated. For more information about the analysis, please check out our paper: arXiv:2011.13910.



Systematics	T	P	MV
Beam ellipticity	0.06	0.00	0.01
Differential pointing	0.27	0.09	0.28
Boresight pointing	0.52	0.20	0.52
Incoherent gain drift	0.36	0.05	0.04
Coherent gain drift	0.56	0.28	0.64
Calibration mismatch	0.38	0.11	0.09
Crosstalk	0.11	0.06	0.03

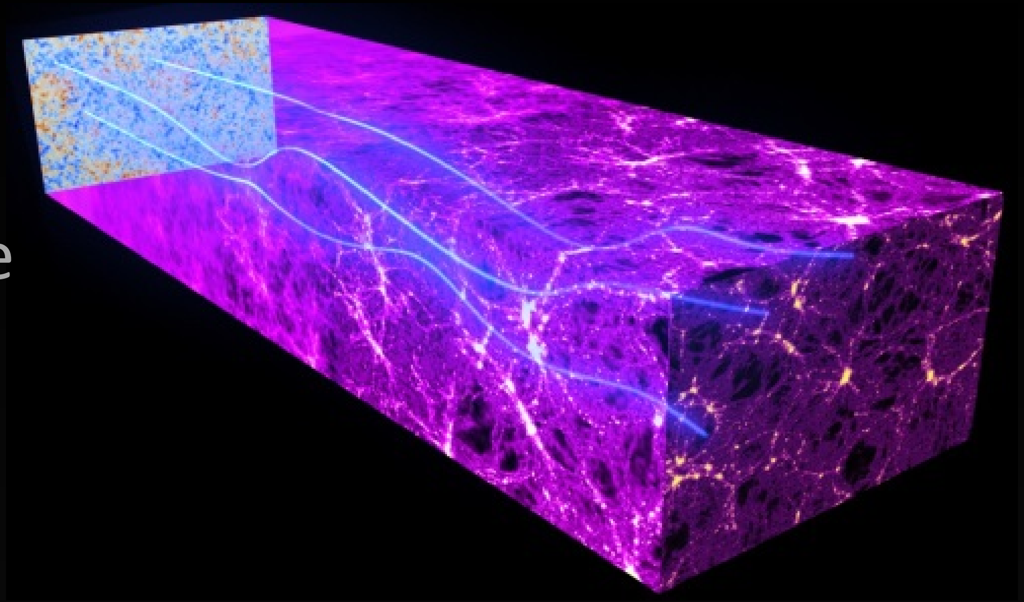
Outline

- Introduction to CMB lensing
- Systematics modeling
- Lensing reconstruction pipeline
- Lensing power spectrum biases
- Bias mitigation
- Conclusions and future work

CMB lensing

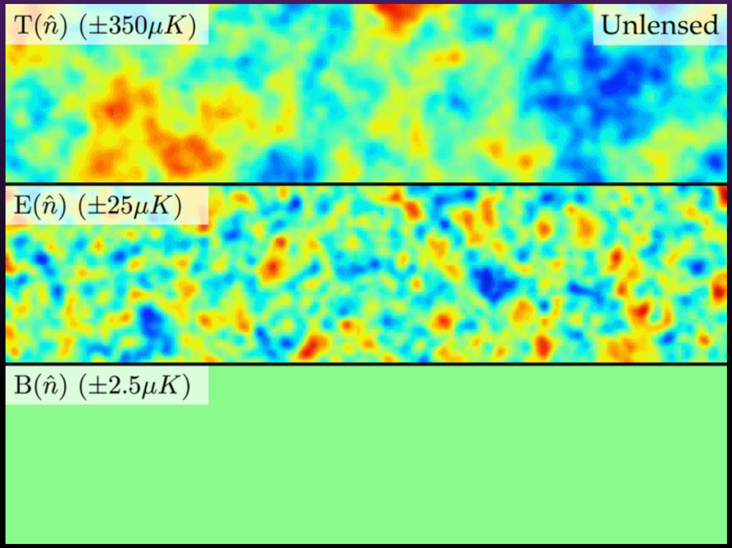
- CMB photons are gravitationally lensed by the large-scale structure in the universe.
- For a projected gravitational potential ϕ, the observed CMB temperature and polarization anisotropies in direction $\boldsymbol{n}$ are

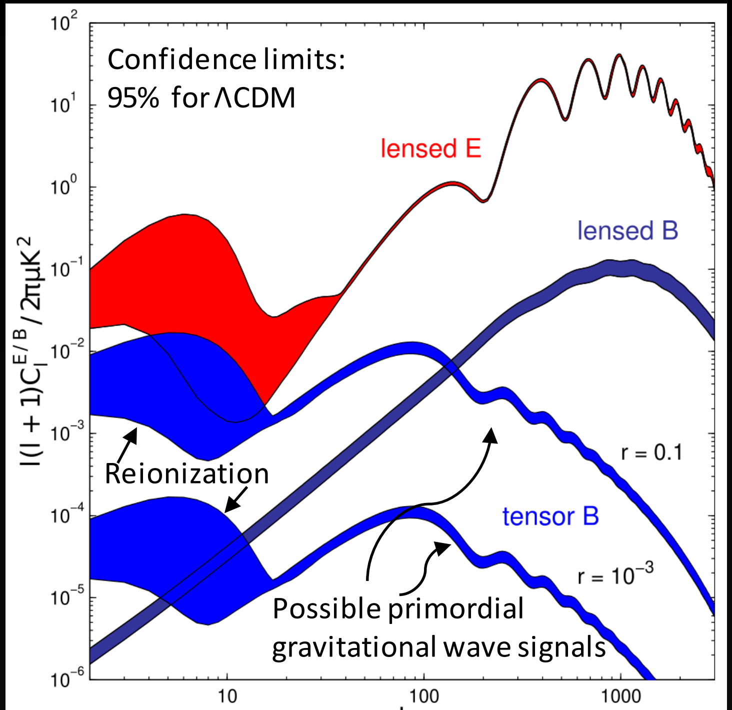
$$T(\boldsymbol{n}) = \tilde{T}(\boldsymbol{n} + \boldsymbol{\nabla}\phi)$$
$$Q(\boldsymbol{n}) = \tilde{Q}(\boldsymbol{n} + \boldsymbol{\nabla}\phi)$$
$$U(\boldsymbol{n}) = U(\boldsymbol{n} + \boldsymbol{\nabla}\phi)$$



CMB lensing

- Lensing induces B-modes
- We can use the measured lensing potential to delens CMB maps
- This is especially important for B-modes to uncover inflationary signals
- For accurate lensing reconstruction, understanding the impact of instrument systematics will be important for lensing reconstruction from upcoming CMB experiments





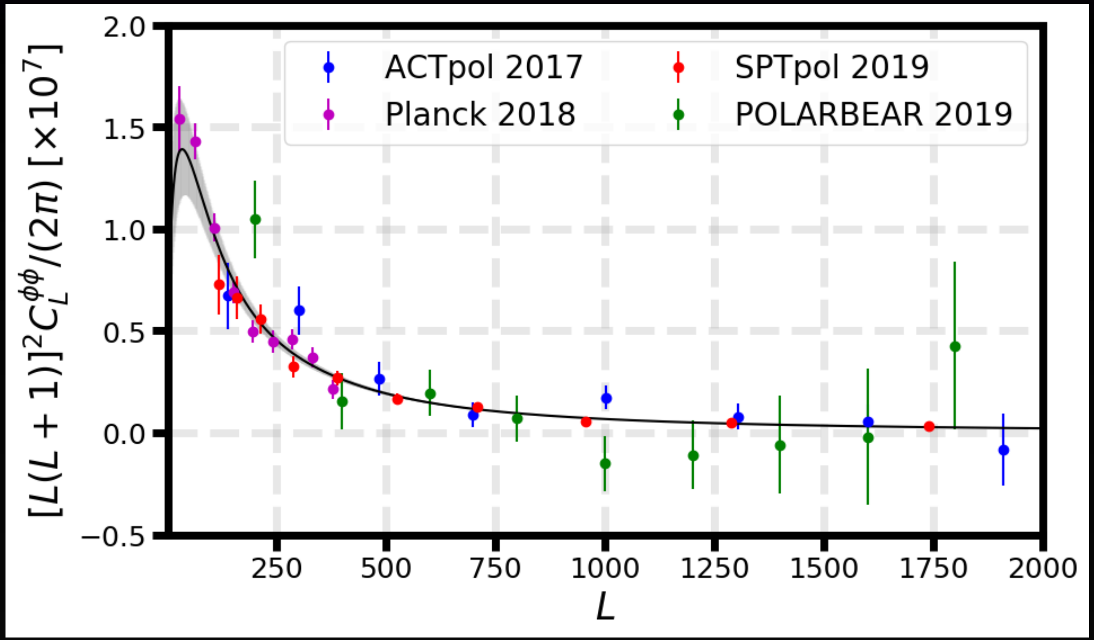
Lewis & Challinor, arXiv:0601594

The lensing potential power spectrum

- Two inverse-variance filtered CMB fields (T, E or B) are required to reconstruct ϕ.
- Quadratic estimator of the lensing potential from $\langle \tilde{X}(\ell)\tilde{Y}(\ell - L)\rangle_{XY}$ expansion:

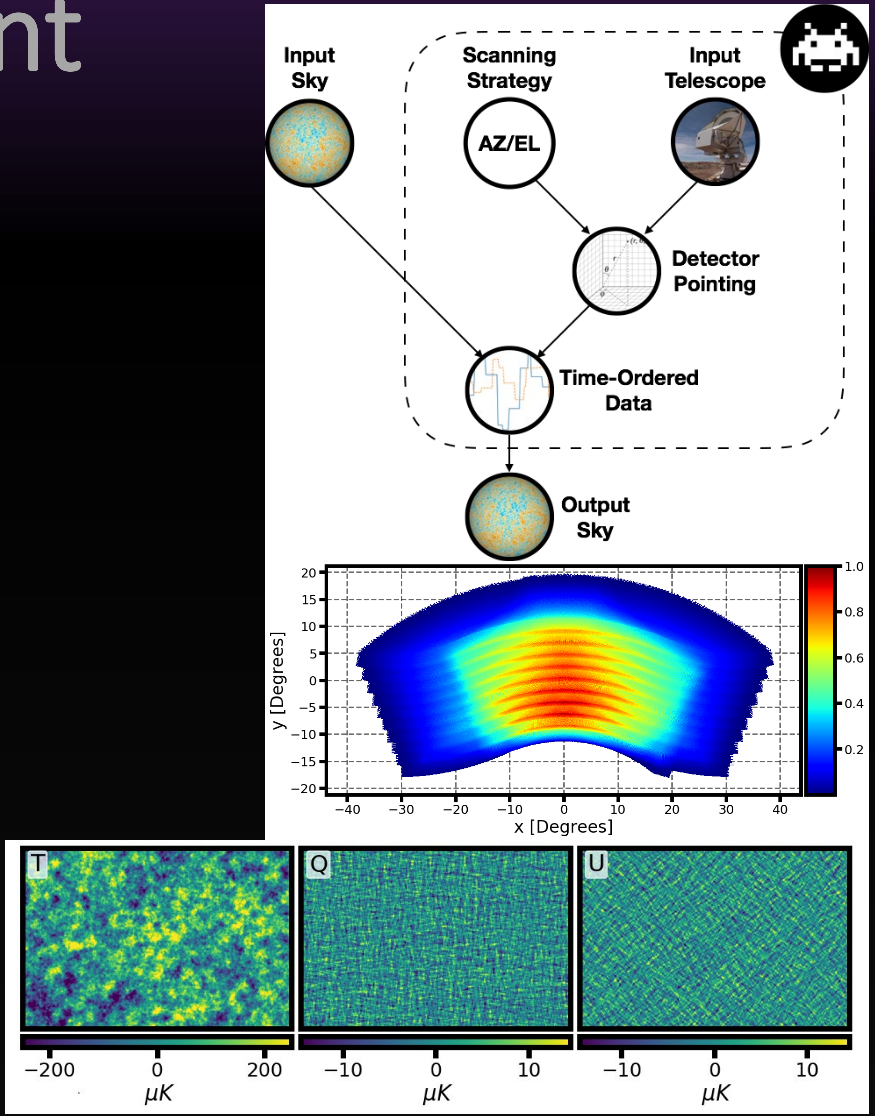
$$\hat{\phi}_{XY}(\boldsymbol{L}) = A_{XY}(\boldsymbol{L}) \int \frac{d^2\ell}{2\pi} g_{\ell L}^{XY} \tilde{X}(\ell)\tilde{Y}(\ell - L)$$

with a weighting function to maximize S/N and a normalization



Simulating an SO-like experiment

- SO LAT baseline noise and beam @ 145 GHz
- Scan composed of 12 constant-elevation scans
- Circularly symmetric beam with 1.4 $arcmin$ width
- Map-level noise: 5.4 $\mu K \cdot arcmin$ for temperature, equivalent to 2.5 years of baseline observations with 20% observation efficiency
- 6,272 detectors on a square focal plane
- No foregrounds, no correlated noise, simple map-making process
- Flat sky simulations, created using [s4cmb]



Beam asymmetry leakages

- Beams are perturbed around a circularly-symmetric (CS) Gaussian beam to get time-stream leakage terms:

$$b(x) \approx \alpha_0 b_{\mathrm{CS}}(x) + \alpha_{1,i} \frac{\partial b_{\mathrm{CS}}(x)}{\partial x^i} + \alpha_{2,ij} \frac{\partial^2 b_{\mathrm{CS}}(x)}{\partial x^i \partial x^j}$$

$$\Downarrow$$

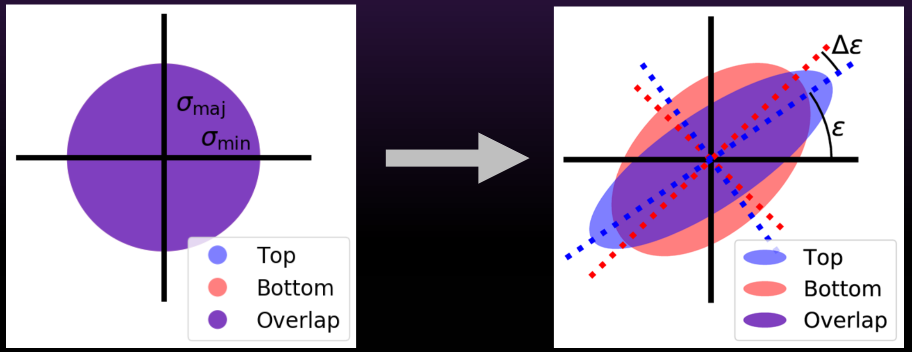
$$\Theta_{\mathrm{obs}}(x) \approx \alpha_0 \Theta_{\mathrm{CS}}(x) + \alpha_{1,i} \frac{\partial \Theta_{\mathrm{CS}}(x)}{\partial x^i} + \alpha_{2,ij} \frac{\partial^2 \Theta_{\mathrm{CS}}(x)}{\partial x^i \partial x^j}$$

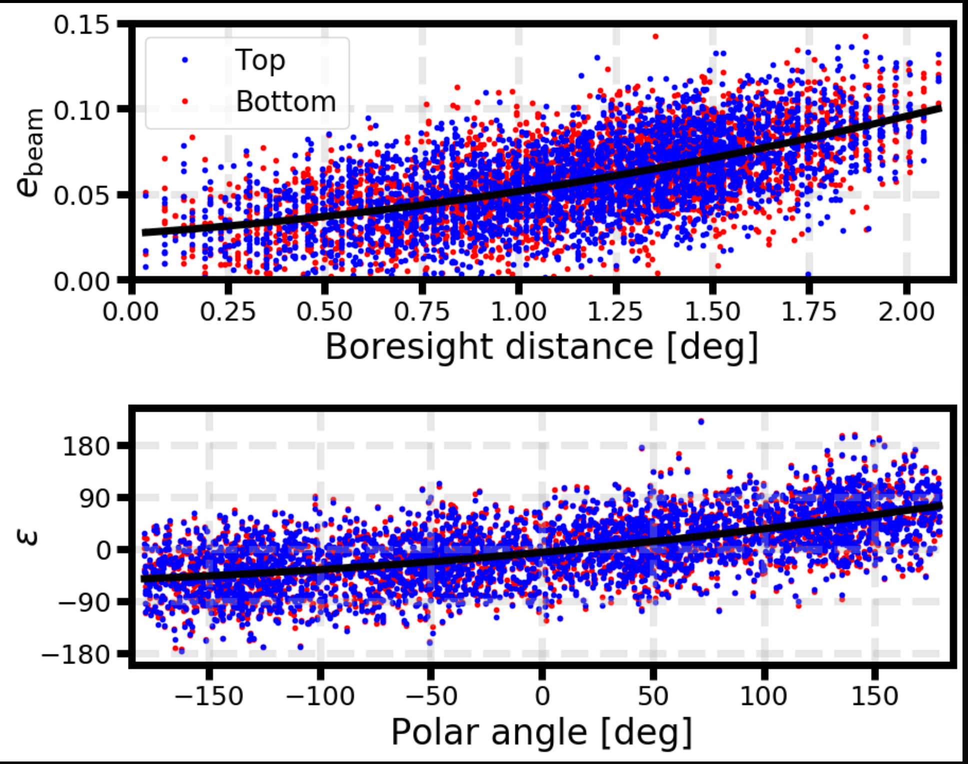
  For beamed data $\Theta_{\mathrm{CS}} \in \{T_{\mathrm{CS}}, Q_{\mathrm{CS}}, U_{\mathrm{CS}}\}$.

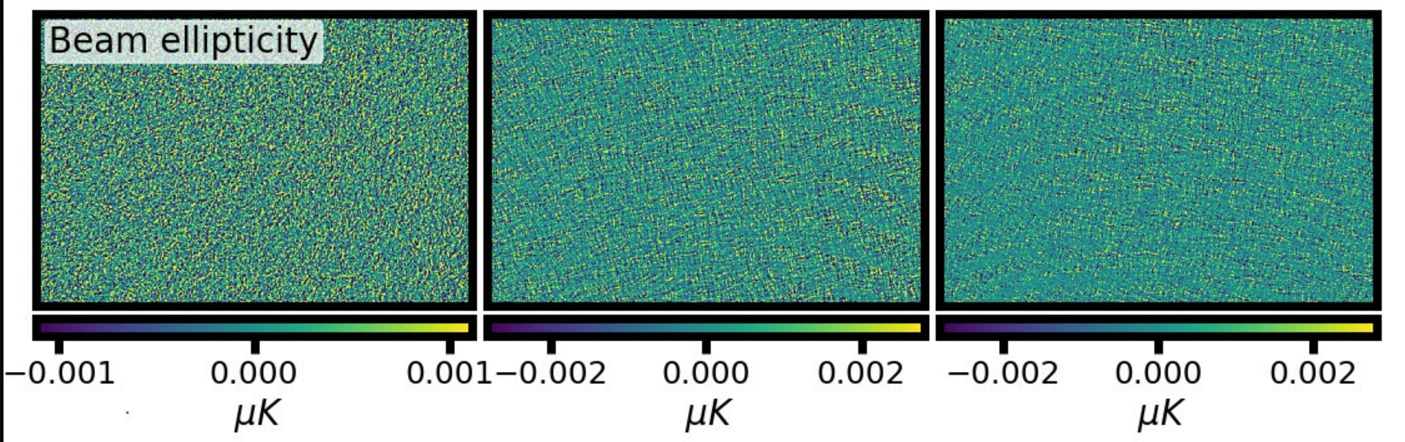
- α coefficients are calculated from the expansion of each beam.

Beam ellipticity

- In-pair (and per-pair) elliptical beams
- Ellipticities and ellipse angles are assumed to be correlated with detector's position in the focal plane

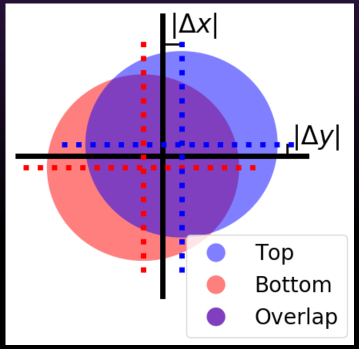






Differential pointing

• In-pair beam-centre offset:
$$(\Delta x, \Delta y)_{\substack{\text{top}\\ \text{bottom}}} = \pm\frac{\rho}{2}(\cos\theta, \sin\theta)$$
where $\rho \in \mathcal{N}(15'', 1.5'')$ and $\theta \in \mathcal{U}(0, 2\pi)$.
• Calculating the α coefficients as with beam ellipticity



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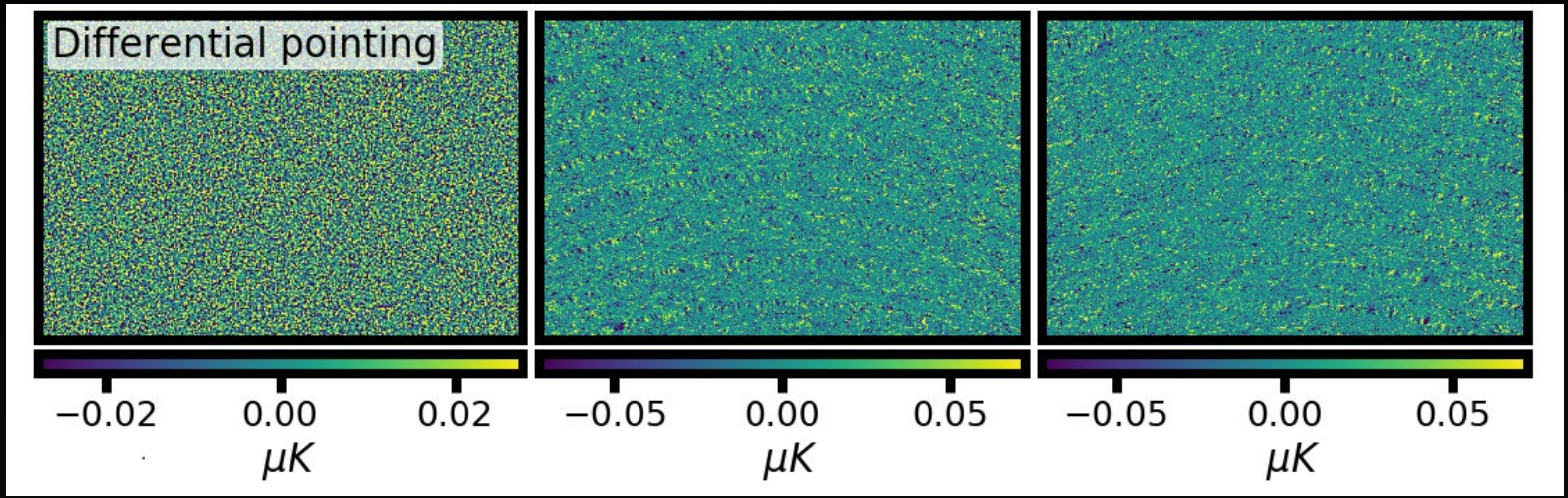
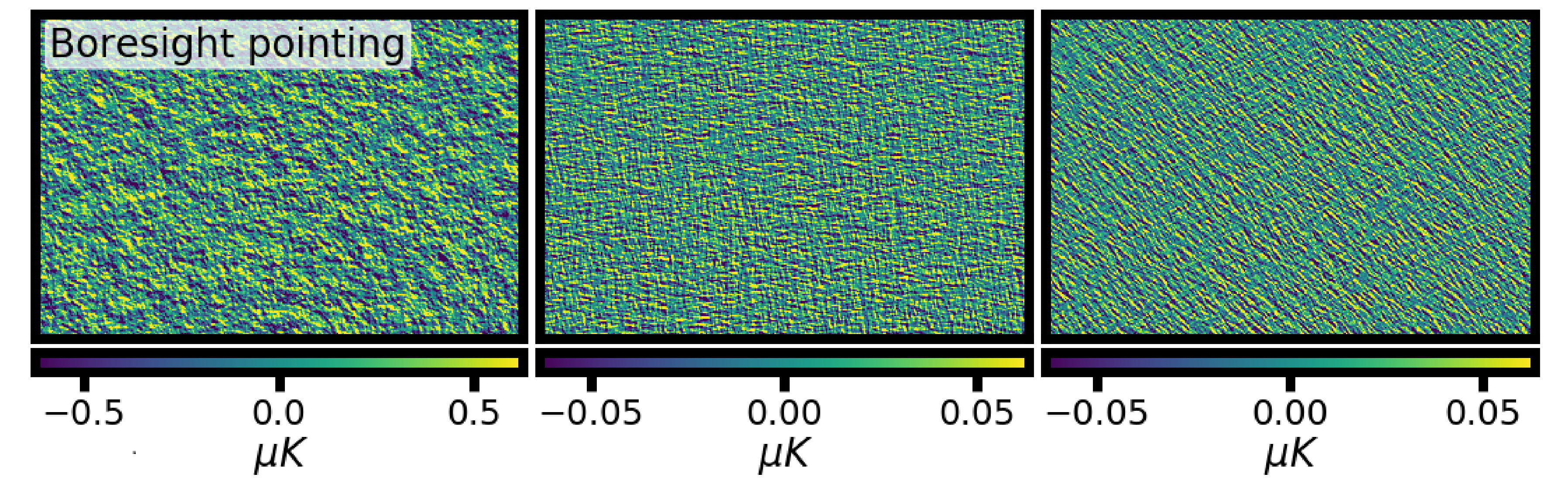


Boresight pointing

- Absolute pointing errors of the focal plane center
- Perturbing azimuth and elevation such that the overall error on the pointing coordinates has a probability distribution $\mathcal{N}(3'',13'')$

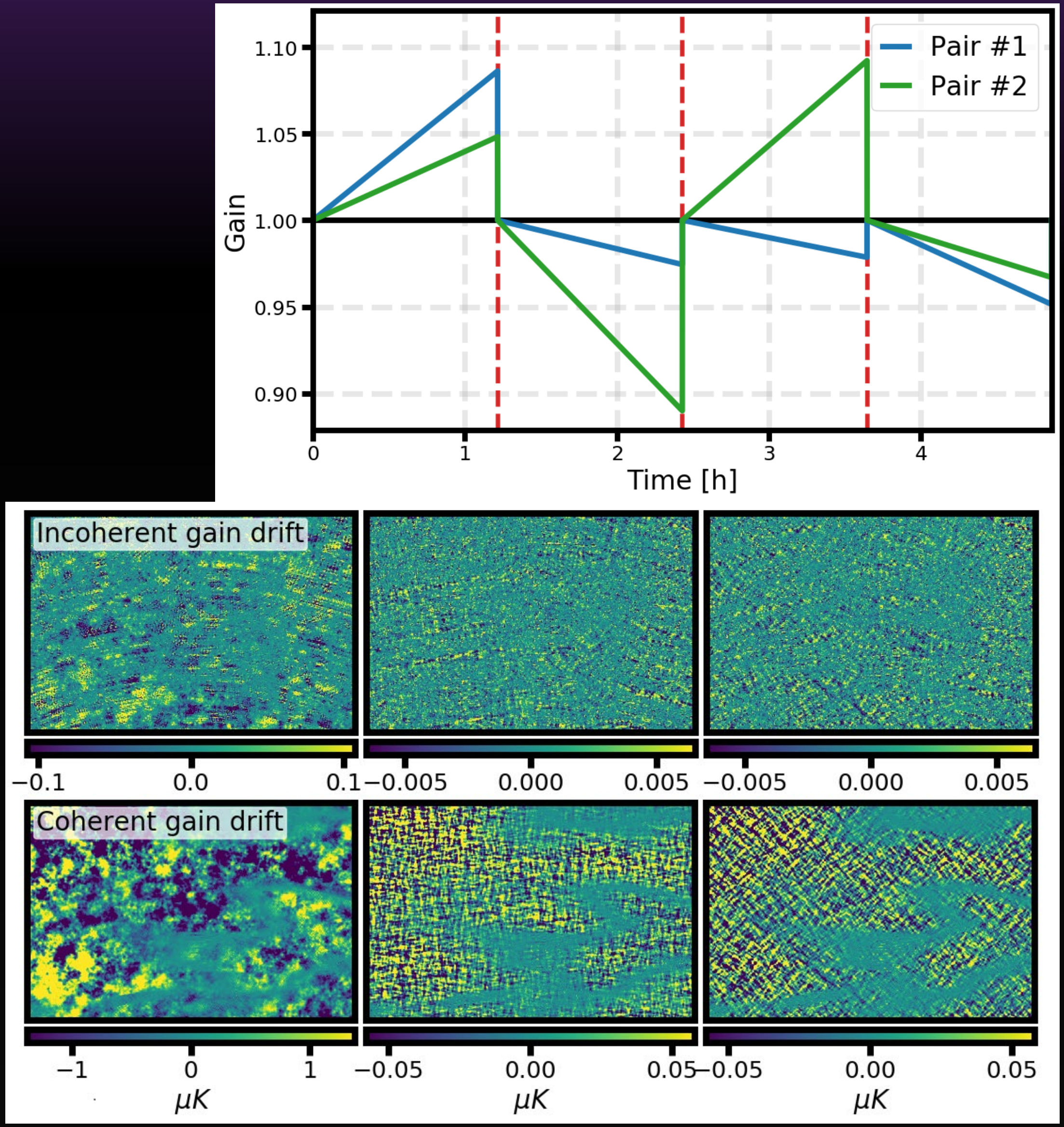


Gain drifts

- Incoherent and coherent drifts across the focal plane
- Time streams:

$$d_{top} = \Delta g[I + Qcos(2\theta) + Usin(2\theta) + n]$$
$$d_{bottom} = \Delta g[I - Qcos(2\theta) - Usin(2\theta) + n]$$

with $\Delta g \in \mathcal{N}(1{,}0.05)$

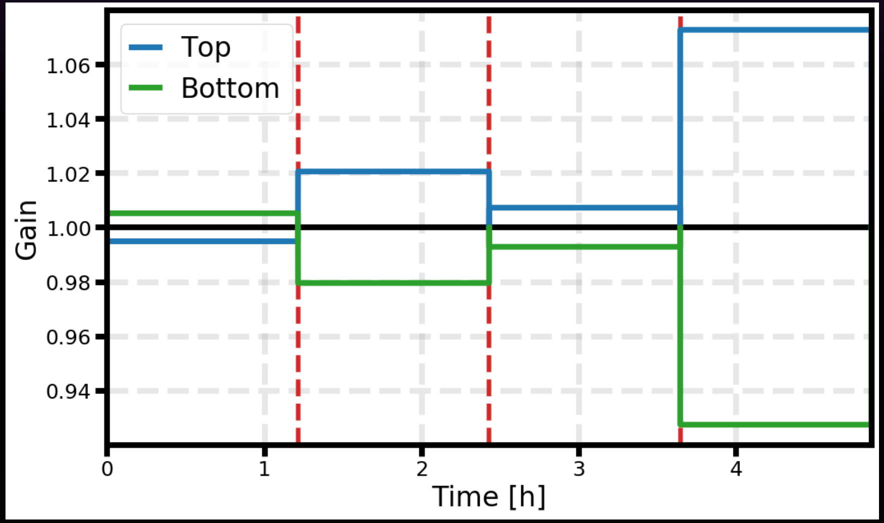


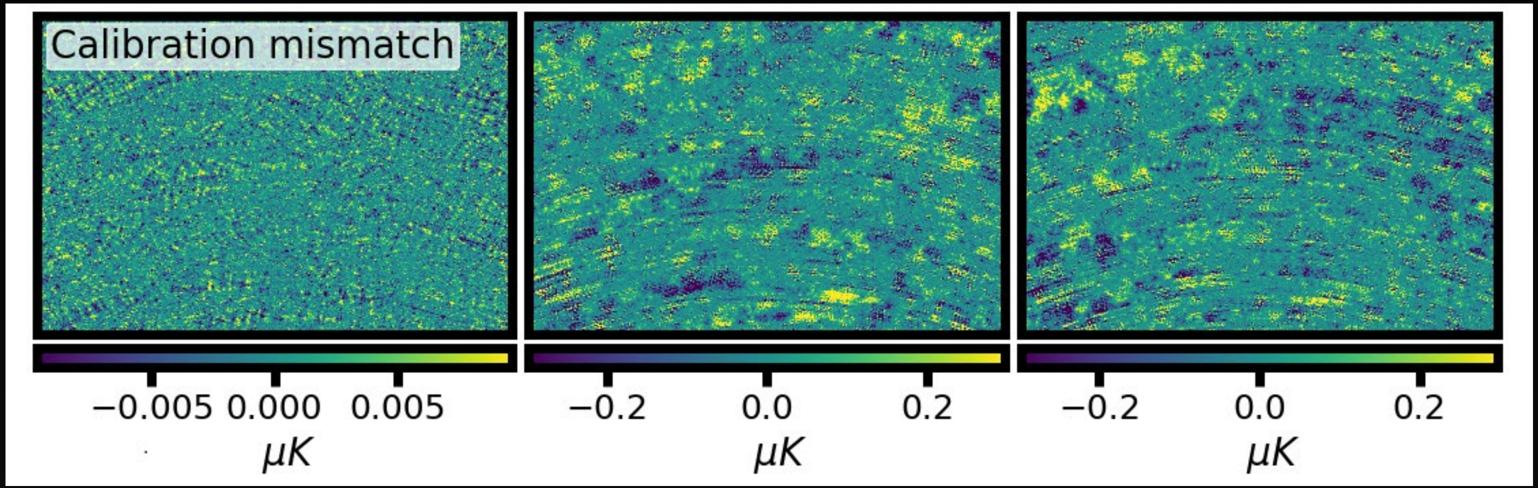
Calibration mismatch

- Gain deviations after calibration
- Time streams:

$$d_{top} = \left(1+\epsilon_g\right)\left[I + Qcos(2\theta) + Usin(2\theta) + n\right]$$
$$d_{bottom} = \left(1-\epsilon_g\right)\left[I - Qcos(2\theta) - Usin(2\theta) + n\right]$$

with $\epsilon_g \in \mathcal{N}(1,0.05)$





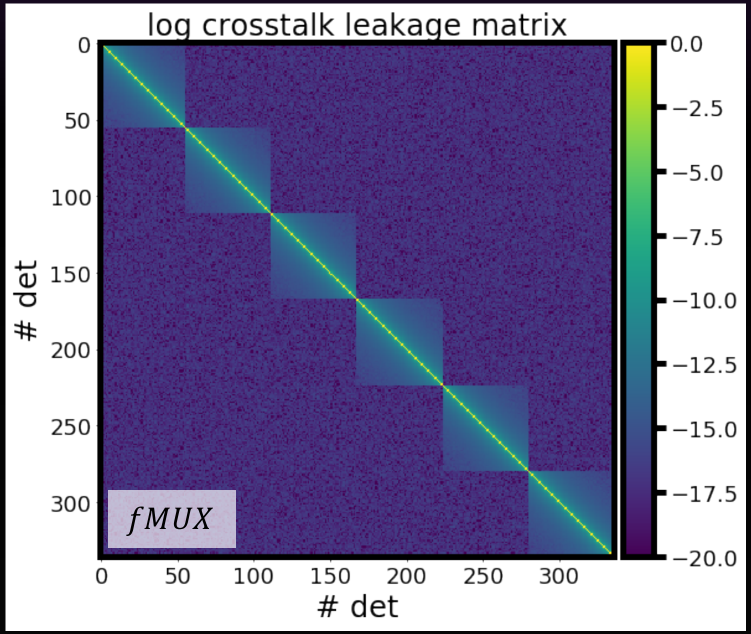
Electric crosstalk

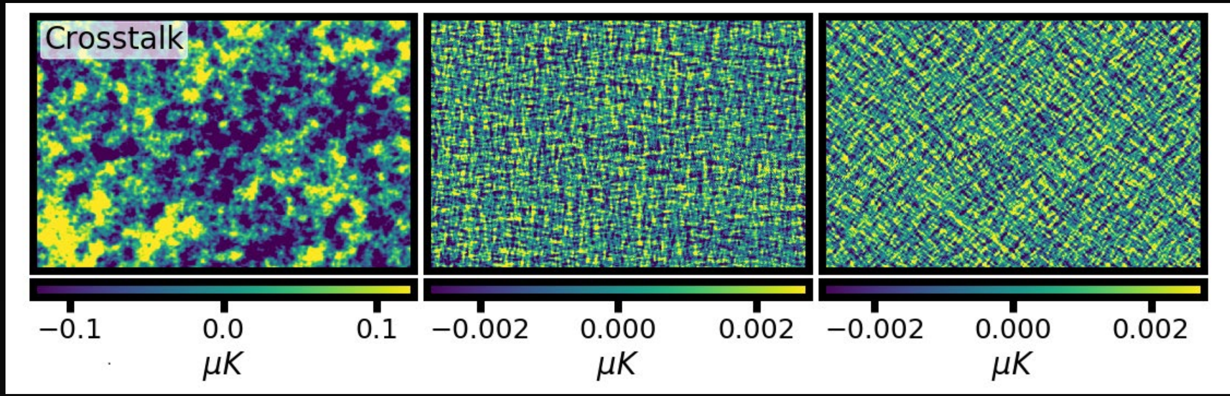
- Current leakage between detectors:

$$d = (\mathbb{1} + L)d^{\text{det}},\ L_{ij} = \frac{k_{ij}}{(\Delta f_{ij})^2}$$

$\Delta f_{ij} = \frac{f_{\text{max}} - f_{\text{min}}}{n_{\text{MUX}}}$, $k \in \mathcal{N}(-0.03\%, 0.01\%)$, and either

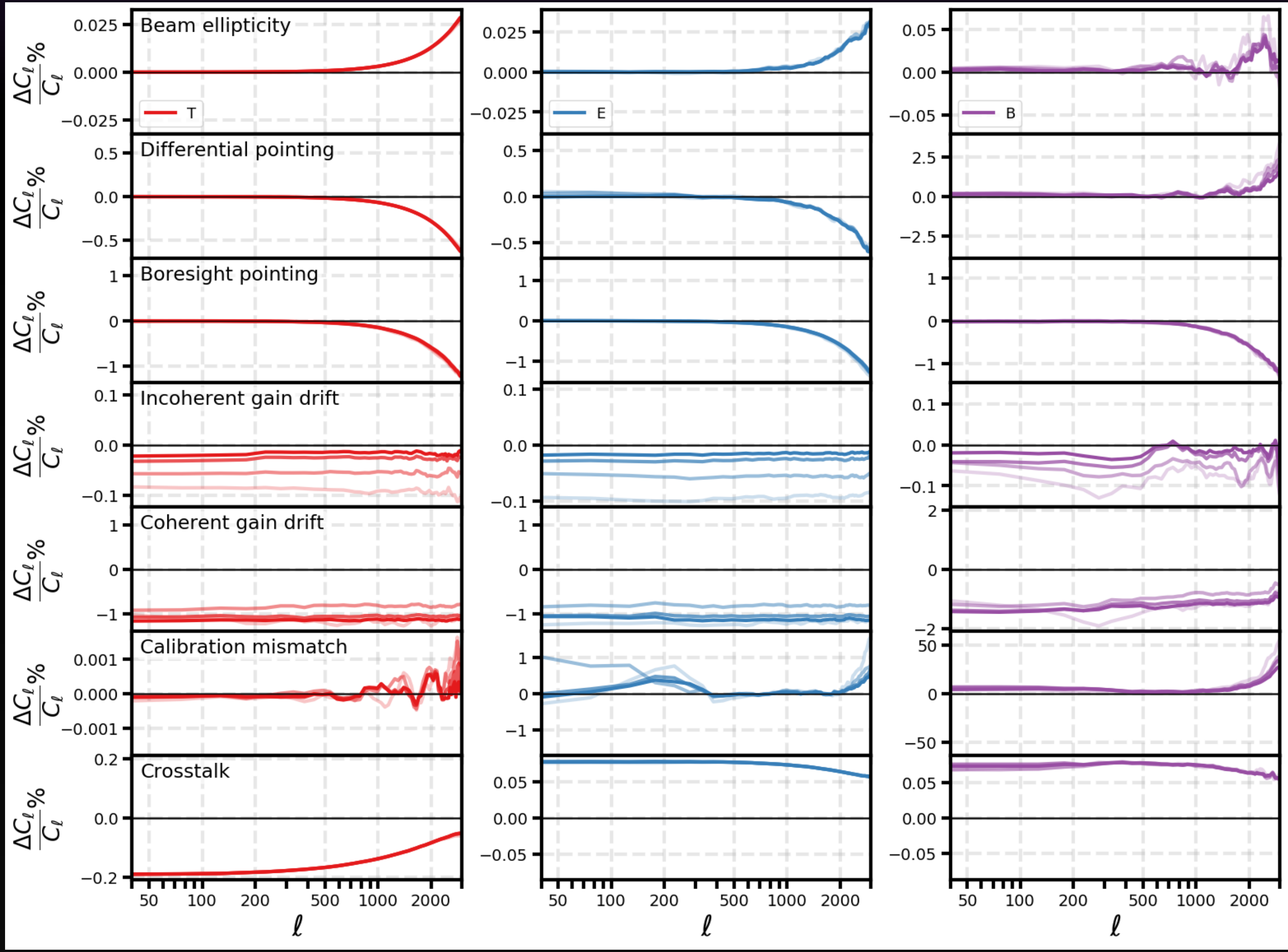
- fMUX: $n_{\text{MUX}} = 56,\ f_{min} = 1\ MHz,\ f_{\text{max}} = 5\ MHz$, or
- μMUX: $n_{\text{MUX}} = 1568,\ f_{min} = 4\ GHz,\ f_{\text{max}} = 8\ GHz$





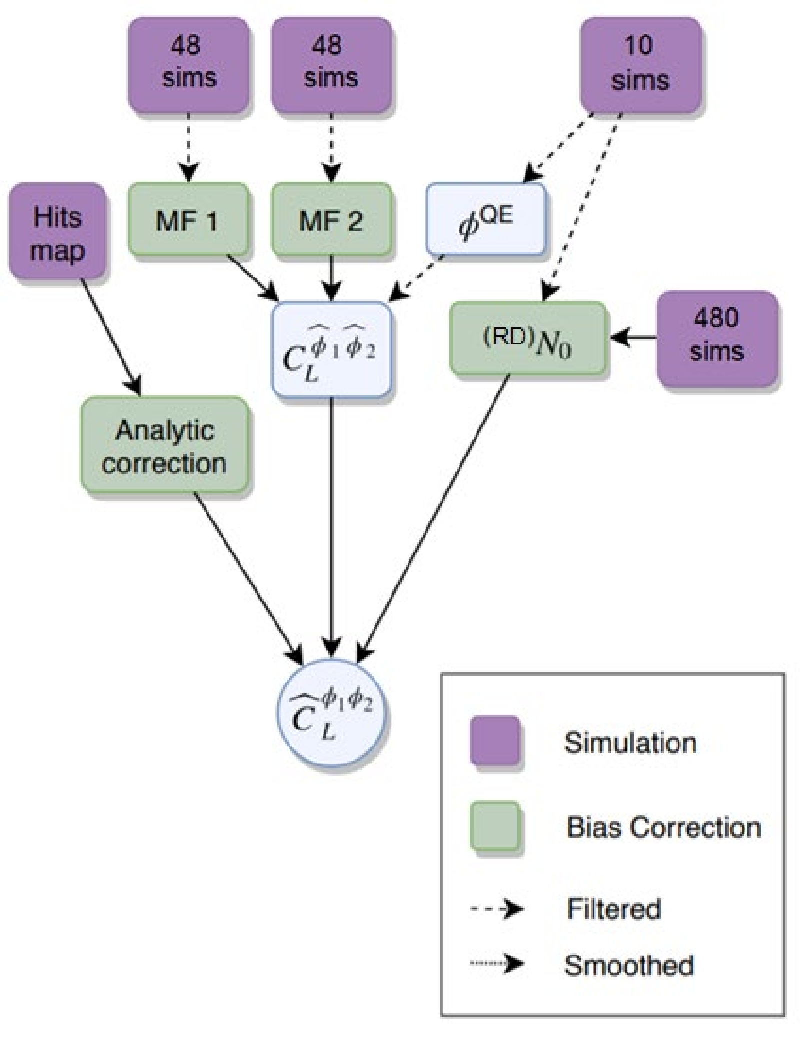
2-point biases (from noise-free simulations)

- Some biases average out with observation time
- Beam-like biases suggest effective beam can be used for bias mitigation
- Coherent gains, boresight pointing and differential pointing induce the most significant biases



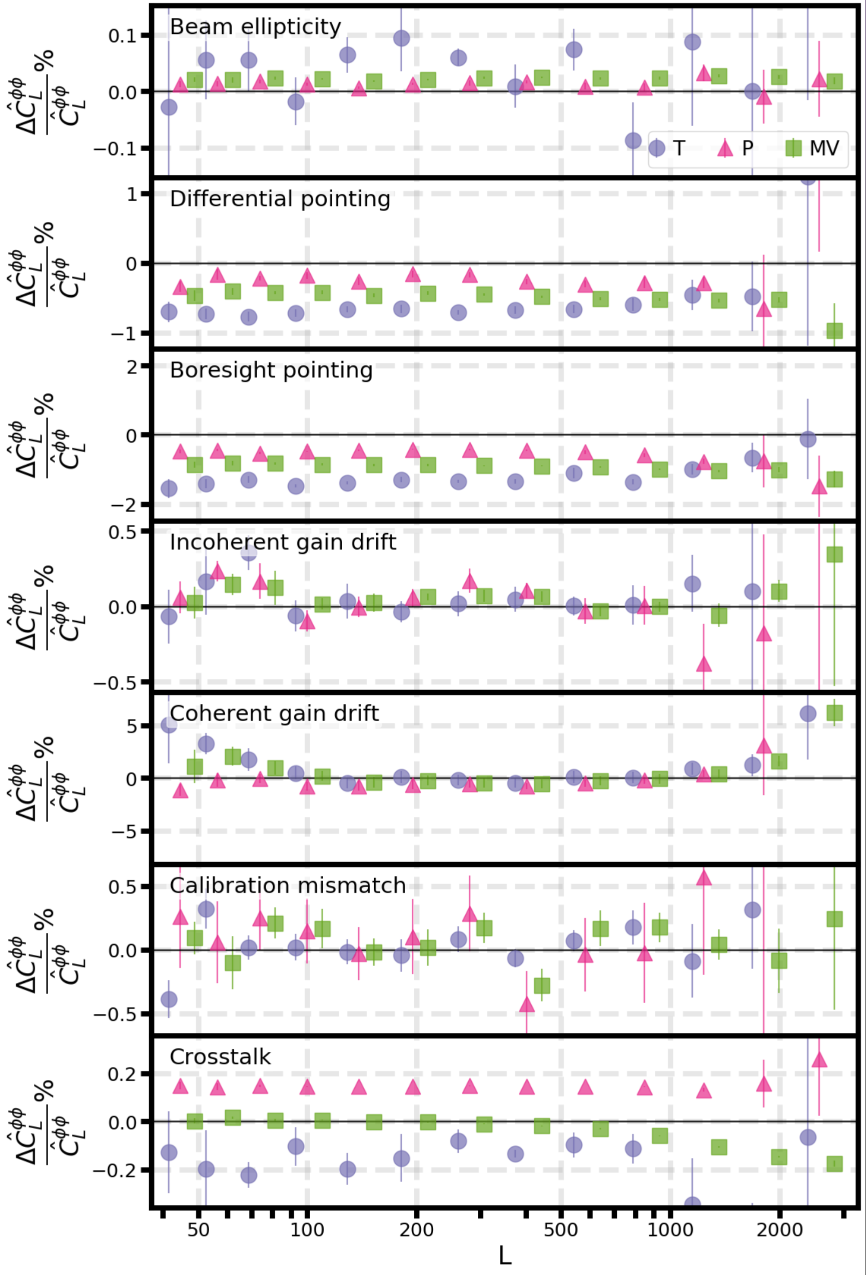
Lensing reconstruction (ArXiv:1909.02653)

- MC simulations are used to calculate mean-field effects and for obtaining the Realisation-Dependent N_0 (RDN_0) from each "data" map
- MC simulations are systematics-free, but are affected by the same white-noise, instrument modelling and scan
- Lensing reconstruction pipeline uses LensIt



Lensing biases

- Most biases are below 0.5%.
- Main biases come from differential pointing, boresight pointing and coherent gain drift.
- Beam ellipticity and differential pointing biases are dominated by T→T and P→P leakages. These can be mitigated by using an effective beam in the lensing reconstruction process.
- Coherent gain drifts could be mitigated by modelling the drift variations or cross-correlating with external CMB maps from e.g. Planck.



Bias detection levels

- Detection likelihood:

$$\mathcal{L} = \sum_{L_{\rm bin}} \frac{A^2 \left(\hat{C}_{L_{\rm bin}}^{\phi\phi,{\rm syst}} - \hat{C}_{L_{\rm bin}}^{\phi\phi}\right)^2}{2\sigma^2_{\hat{C}_{L_{\rm bin}}^{\phi\phi}}}$$

$$\frac{\partial^2 \mathcal{L}}{\partial A^2} = \frac{1}{\sigma_A^2} \quad \Rightarrow \quad \sigma_A = \left[\sum_{L_{\rm bin}} \frac{\left(\hat{C}_{L_{\rm bin}}^{\phi\phi,{\rm syst}} - \hat{C}_{L_{\rm bin}}^{\phi\phi}\right)^2}{\sigma^2_{\hat{C}_{L_{\rm bin}}^{\phi\phi}}}\right]^{-\frac{1}{2}}$$

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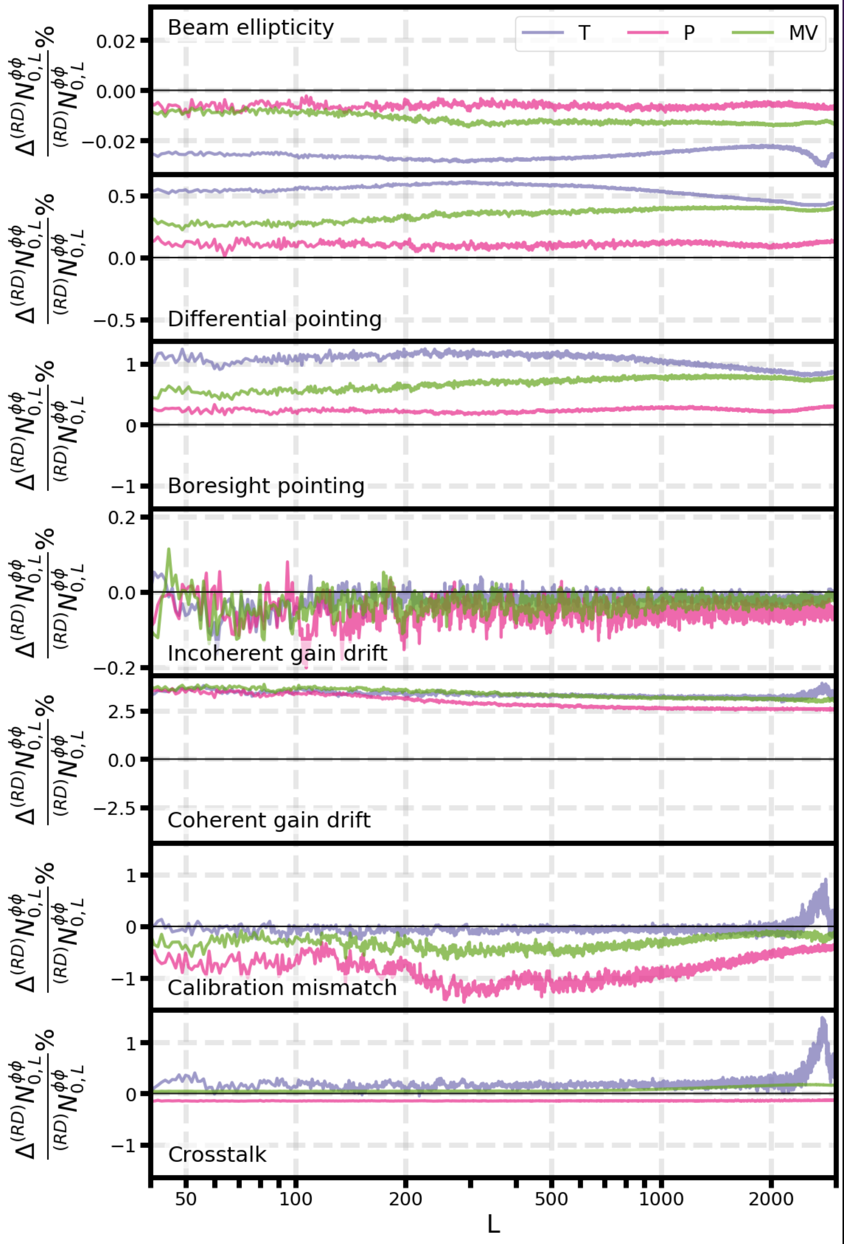
$\mathbf{RDN_0}$ comparisons

- RDN0 is used to unbias the lensing power spectrum:

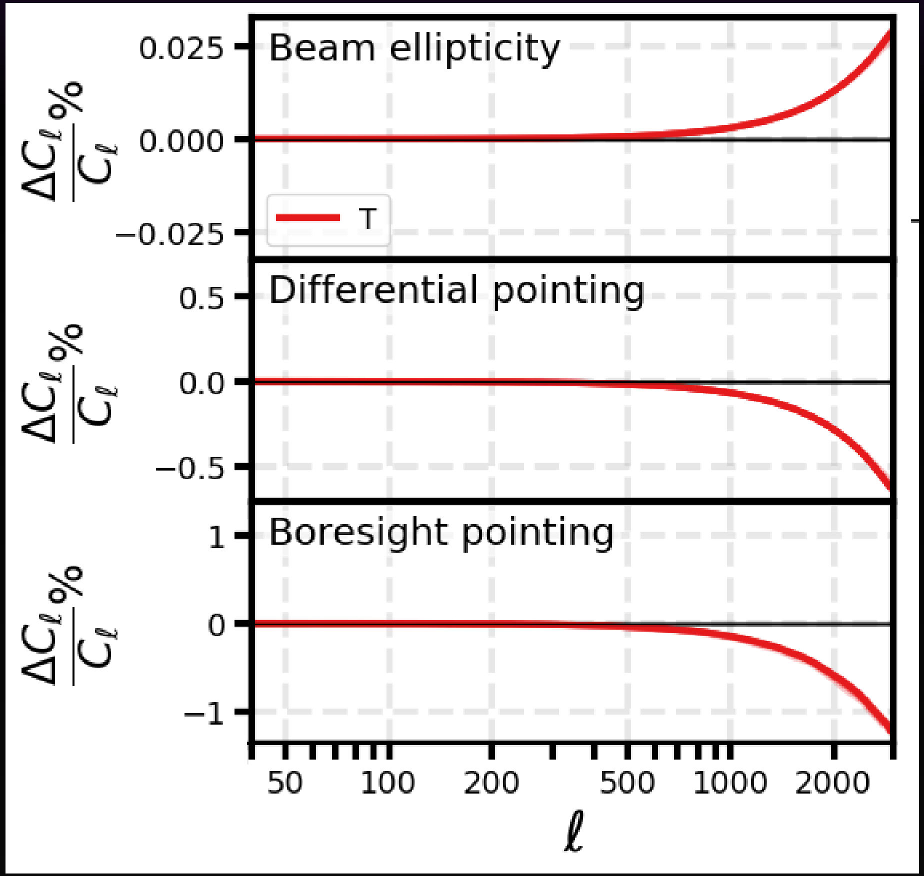
$$\hat{C}_L^{\phi\phi} = C_L^{\widehat{\phi}\widehat{\phi}} - RDN_{0,L}^{\phi\phi}$$

- It corrects most reconstruction noise changes coming from systematics, especially for coherent gain drift, calibration mismatch, boresight pointing and crosstalk.



Mitigation techniques

- Effective beam mitigates main beam ellipticity, differential pointing, and boresight pointing biases.
- Using an effective beam fitted from the power spectrum decreases bias significance considerably.
- It may be more complicated to obtain the effective beam needed for differential pointing from dedicated calibration observations.
- Gain calibrations should account for the main coherent gain drift bias, but reconstruction uncertainty may still be high.



Conclusions and future work (arXiv:2011.13910)

- We demonstrated how several instrumental systematics affect the reconstructed lensing power spectrum given SO-like systematics parameters and instrument.
- Most of the systematics we explored will have a relatively negligible effect on the lensing power spectrum measured by SO-like experiments.
- We will extend this work to include more systematics, such as polarization angle perturbations and time-constant effects, and implement an instrument model and scanning strategy which are more consistent with the current SO design.