The Simons Observatory: A framework for efficient map-based simulations of instrumental systematics for CMB surveys

Challenges at the CMB Frontier

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Magdy Morshed, Alexandre Adler, Adri Duivenvoorden, Giulio Fabbian, Dan Thomas, Martina Gerbino, Luca Pagano

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Context

Simons Observatory Large Aperture Telescope (SO LAT)

- **Instrument:** two 6m mirrors, roughly 60 000 detectors, first light already obtained in 2025!
- **Goal:** Small-scale science including
  - Lensing reconstruction
  - Small scale damping tail exploitation

→ **Unprecedented sensitivity at high resolution, how do we handle systematics?**

Source: SO website

Site photo from drone, Image credits: G. Coppi, R. Dunner, F. Nati, M. Rojas

Motivation

How do we handle instrumental systematics with such large resolution?

Broad aim: Have simulation tools to **assess the impact of systematic effects**, and help **mitigate them**

Goal: Develop an **efficient** method to simulate systematics effect at the map level, **accurate with respect to TOD simulations**

➜ Possibly to obtain thousands of systematics maps at high resolution

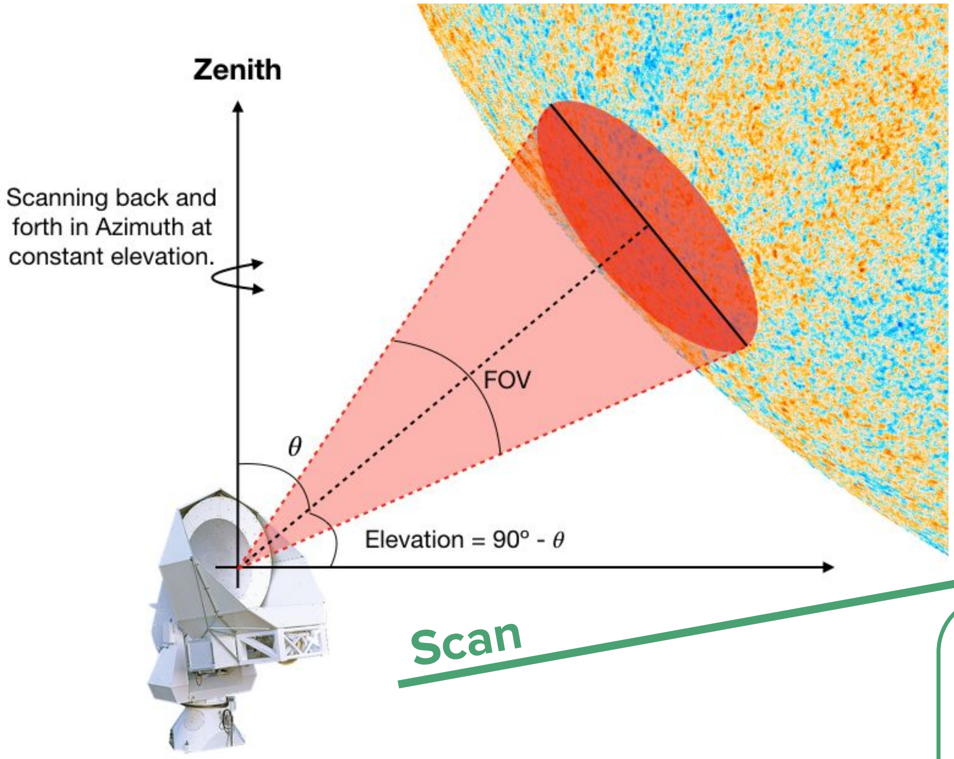
➜ Towards robustness of the power spectrum and lensing analysis

First applications to the LAT and selected main beam systematics

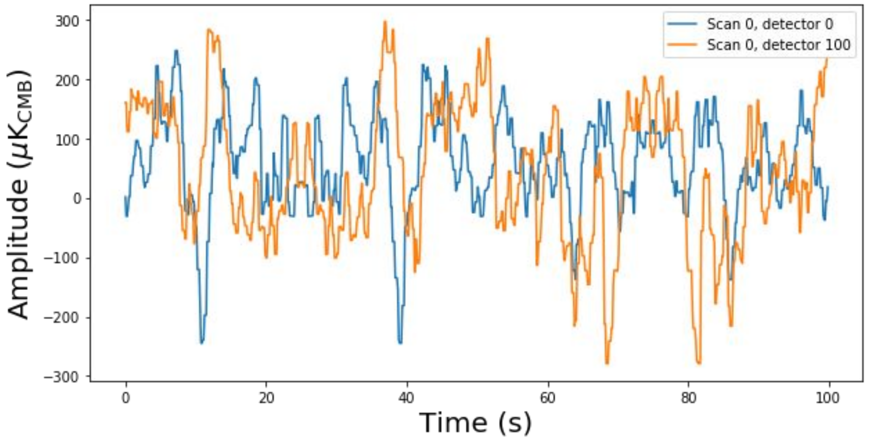
Formalism

How do we efficiently propagate instrumental systematics at the map level?

From a scan to estimated maps



Timestream



Scan

To describe the **scanning in time, per detector**, we introduce the angle of the scan direction with respect to the North, **the parallactic angle** ζ_t

→ **Key to estimate maps!**

Pictures from s4cmb package documentation

Estimating Stokes parameters from a scan

For a single detector, we can express a (noiseless) **timestream** as

$$\underline{d_t} = \underline{I} + \underline{Q} \cos\left(2(\underline{\psi} + \underline{\zeta_t})\right) + \underline{U} \sin\left(2(\underline{\psi} + \underline{\zeta_t})\right)$$

Input sky **Polarization angle (detector)** **Parallactic angle (scan)**

Or equivalently, in terms of **spins quantities**

$$\underline{d_t} = \underline{I} + \frac{1}{2}\left(\underline{Q} + \underline{iU}\right) e^{-2i(\underline{\psi} + \underline{\zeta_t})} + \frac{1}{2}\left(\underline{Q} - \underline{iU}\right) e^{2i(\underline{\psi} + \underline{\zeta_t})}$$

spin 0 **spin +2** **spin -2**

From which we can estimate maps (using binned mapmaking) denoting $\phi_t = \underline{\psi} + \underline{\zeta_t}$

Map estimates

$$\begin{pmatrix} \hat{\mathbf{I}} \\ \hat{\mathbf{Q}} \\ \hat{\mathbf{U}} \end{pmatrix} = \begin{pmatrix} 1 & \langle \cos(2\phi_t) \rangle & \langle \sin(2\phi_t) \rangle \\ \langle \cos(2\phi_t) \rangle & \langle \cos^2(2\phi_t) \rangle & \langle \cos(2\phi_t)\sin(2\phi_j) \rangle \\ \langle \sin(2\phi_t) \rangle & \langle \sin(2\phi_t)\cos(2\phi_t) \rangle & \langle \sin^2(2\phi_t) \rangle \end{pmatrix}^{-1} \begin{pmatrix} \langle d_t \rangle \\ \langle d_t \cos(2\phi_t) \rangle \\ \langle d_t \sin(2\phi_t) \rangle \end{pmatrix}$$

Orientation functions (h-maps)

For **each detector**, a geometrical **orientation function** can be built in TODs **from the crossing angles and scan strategy** as

Pixel domain

$$\tilde{h}_n = \frac{1}{N_{\text{hits}}} \sum_t^{N_{\text{hits}}} \left(\cos(n\phi_t) + i\sin(n\phi_t)\right) = \frac{1}{N_{\text{hits}}} \sum_t^{N_{\text{hits}}} e^{in\phi_t}$$

Timestreams

Similar reasoning to build estimates of spin maps using $\tilde{h}_n$ and **input spin maps** (see McCallum et al. 2021, generalized to HWP in Takase et al. 2024) ➔ **Spin mapmaking**

Spin map estimates

$$\begin{pmatrix} \hat{I} \\ \hat{Q} - i\hat{U} \\ \hat{Q} + i\hat{U} \end{pmatrix} = \begin{pmatrix} \tilde{h}_0 & \frac{1}{2}\tilde{h}_2 & \frac{1}{2}\tilde{h}_{-2} \\ \frac{1}{2}\tilde{h}_2 & \frac{1}{4}\tilde{h}_4 & \frac{1}{4} \\ \frac{1}{2}\tilde{h}_{-2} & \frac{1}{4} & \frac{1}{4}\tilde{h}_{-4} \end{pmatrix}^{-1} \begin{pmatrix} \sum_{k'=-\infty}^{\infty} \tilde{h}_{0-k'} \boxed{S_{k'}} \\ \sum_{k'=-\infty}^{\infty} \tilde{h}_{2-k'} \boxed{S_{k'}} \\ \sum_{k'=-\infty}^{\infty} \tilde{h}_{-2-k'} \boxed{S_{k'}} \end{pmatrix}$$

Input spin map coupled to scanning through $\tilde{h}_n$ maps

⚠️ **Mapmaking equation above valid for 1 detector!**

Generalization to the full focal plane

Redefining the $\tilde{h}_n$ maps for each detector j as:

$$\tilde{h}_n^j = \langle e^{in\zeta_t^j} \rangle = \sum_{t=1}^{N_{\rm hits}} \cos n\zeta_t^j + i \sin n\zeta_t^j$$

with

$$\tilde{h}_n^{tot} = \langle e^{in\phi_t^j} \rangle = \frac{1}{N_{\rm det}} \sum_{j=1}^{N_{\rm det}} e^{in\psi^j} \tilde{h}_n^j$$

Per-detector, only depends on the parallactic angle ζ_t^j

→ **New mapmaking equation**

$$\begin{pmatrix} \hat{\mathbf{I}} \\ \hat{\mathbf{Q}} - \mathbf{i}\hat{\mathbf{U}} \\ \hat{\mathbf{Q}} + \mathbf{i}\hat{\mathbf{U}} \end{pmatrix} = \begin{pmatrix} \tilde{h}_0^{tot} & \frac{1}{2}\tilde{h}_2^{tot} & \frac{1}{2}\tilde{h}_{-2}^{tot} \\ \frac{1}{2}\tilde{h}_2^{tot} & \frac{1}{4}\tilde{h}_4^{tot} & \frac{1}{4} \\ \frac{1}{2}\tilde{h}_{-2}^{tot} & \frac{1}{4} & \frac{1}{4}\tilde{h}_{-4}^{tot} \end{pmatrix}^{-1} \begin{pmatrix} \sum_{j=1}^{N_{\rm det}} \frac{1}{N_{\rm det}} \sum_{k'=-\infty}^{\infty} \tilde{h}_{0-k'}^j \tilde{S}_{k'}^j \\ \sum_{j=1}^{N_{\rm det}} e^{i2\psi_j} \frac{1}{N_{\rm det}} \sum_{k'=-\infty}^{\infty} \tilde{h}_{2-k'}^j \tilde{S}_{k'}^j \\ \sum_{j=1}^{N_{\rm det}} e^{-i2\psi_j} \frac{1}{N_{\rm det}} \sum_{k'=-\infty}^{\infty} \tilde{h}_{-2-k'}^j \tilde{S}_{k'}^j \end{pmatrix}$$

Spin map estimates

Pixel-based mapmaking matrix

Detector-wise input spin map
May be dependent on detector orientation

Implemented in SMARTIES (Spin MAp Reduction Toolkit for systematics Impact EStimation)

Implementation and choice of systematics

Focusing on T-to-P, we can have

$$\mathbf{d}_t^j = \sum_{n=-\infty}^{\infty} \underbrace{\mathbf{Z}_{I,n}^j}_{\text{Perturbation contaminants (T-to-P)}} e^{-in\zeta_t^j} + \mathbf{I} + \frac{1}{2}(\mathbf{Q} \pm i\mathbf{U})e^{\mp i2(\psi^j + \zeta_t^j)}$$

Generalizing to describe T-to-P leakage, we can build physically motivated spin templates of systematic contaminants adding to the intensity signal.

The templates currently implemented in SMARTIES are based on BICEP templates:

- Beam ellipticity
- Beam pointing offset
- Differential beamwidth

→ **Binned mapmaking implementation validated against TOAST, up to numerical precision**

First summary: Strengths of the formalism

- Input spin maps can contain:
  - Input sky: **T**, **Q**, **U**
  - Stationary systematics: systematics without intrinsic time-dependence (perturbations of the main beam, stationary crosstalk, stationary gain)
    ➜ **Time dependence comes from scanning!**
- As demonstrated in McCallum et al. 2021, Takase et al. 2024:
  - Time-deprojection: avoiding TODs operations in mapmaking
  - Ability to quickly **propagate systematics to estimated maps**
  - Ability to **study scan strategy**

Towards application on real data

- How well do systematics propagate under realistic mapmaking? Simplified assumptions with binning mapmaking
- Do we need to store all h-maps for every detector and spin?

Focus in this talk

- How good can be the systematics templates? ➜ **See Camille Demay's talk!**

Applications – Interpolation

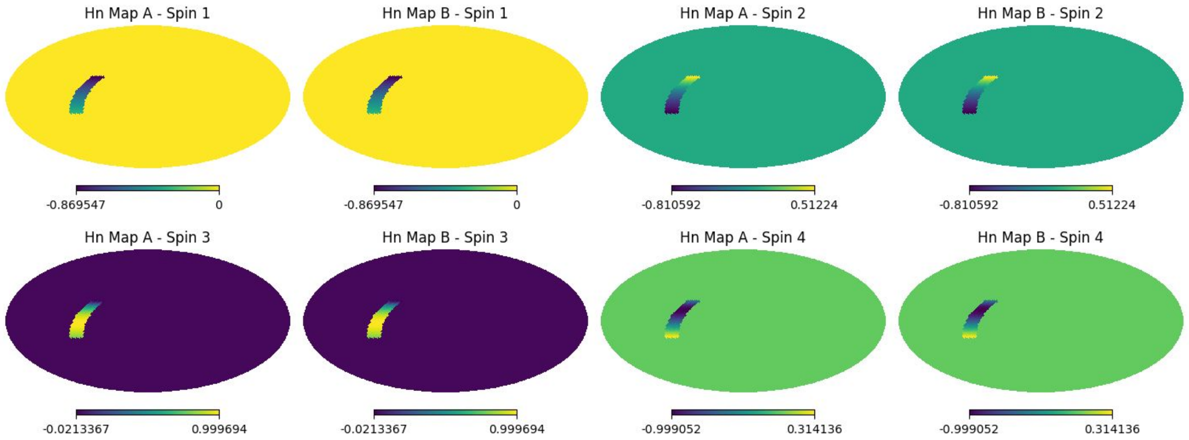
Do we need to store all h-maps for every detector and spin?

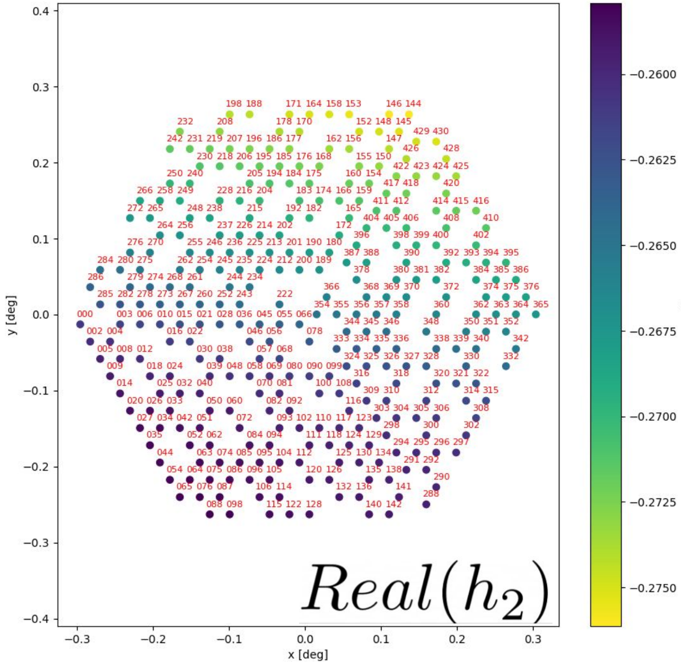
Interpolation of h-maps

To avoid storing h-map for each detector, spin, component (real and imaginary parts), it is possible to use the smoothness of the pointing information to obtain h-maps in two ways:

- Resolution change from **low to high resolution** (**resolution-wise**)
- Interpolation from **few detectors to many** (**detector-wise**)

Example on a simple scan strategy:

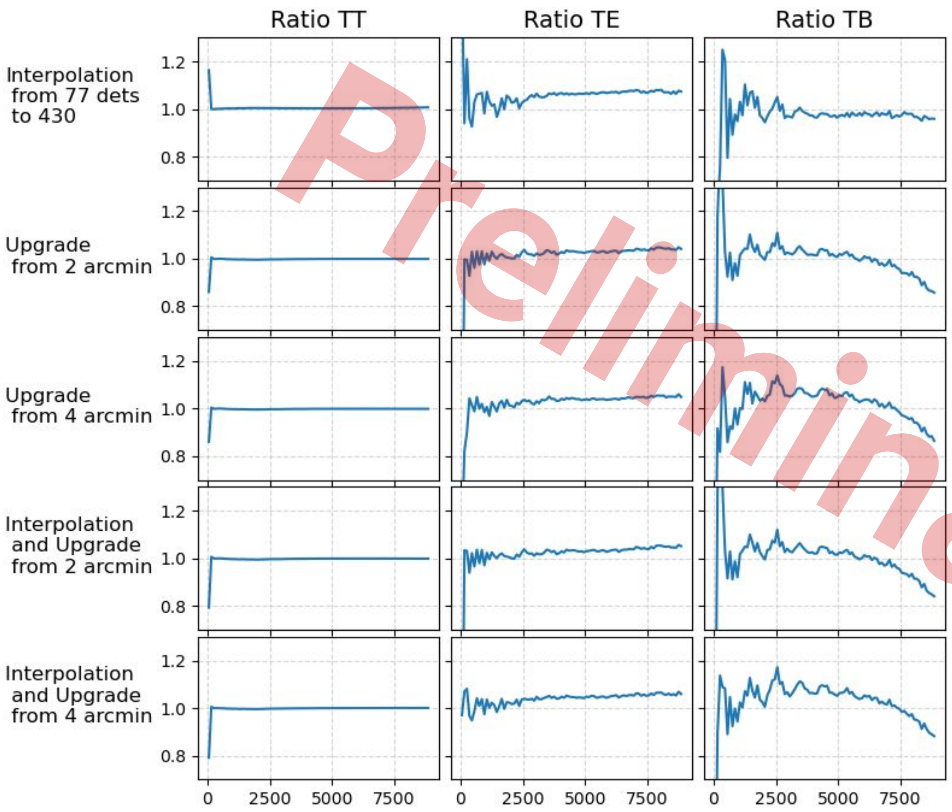




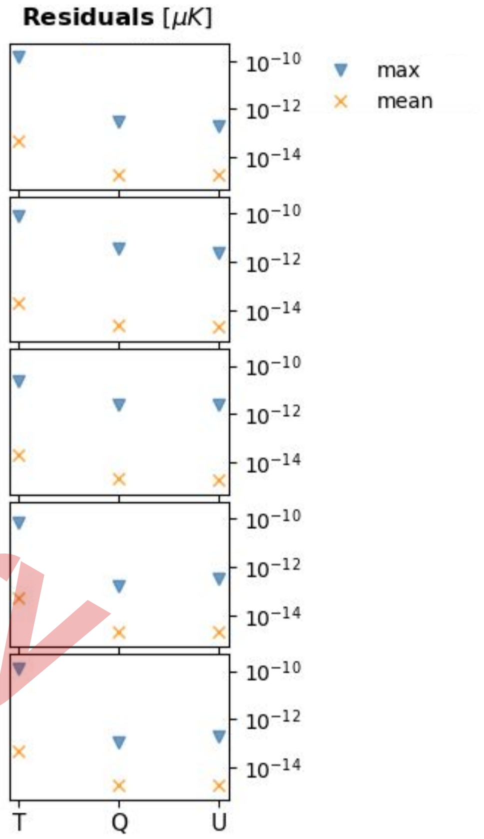
Interpolation of h-maps – Preliminary results

Ratio output over nominal case

First order systematics impact!



Input X Systematics

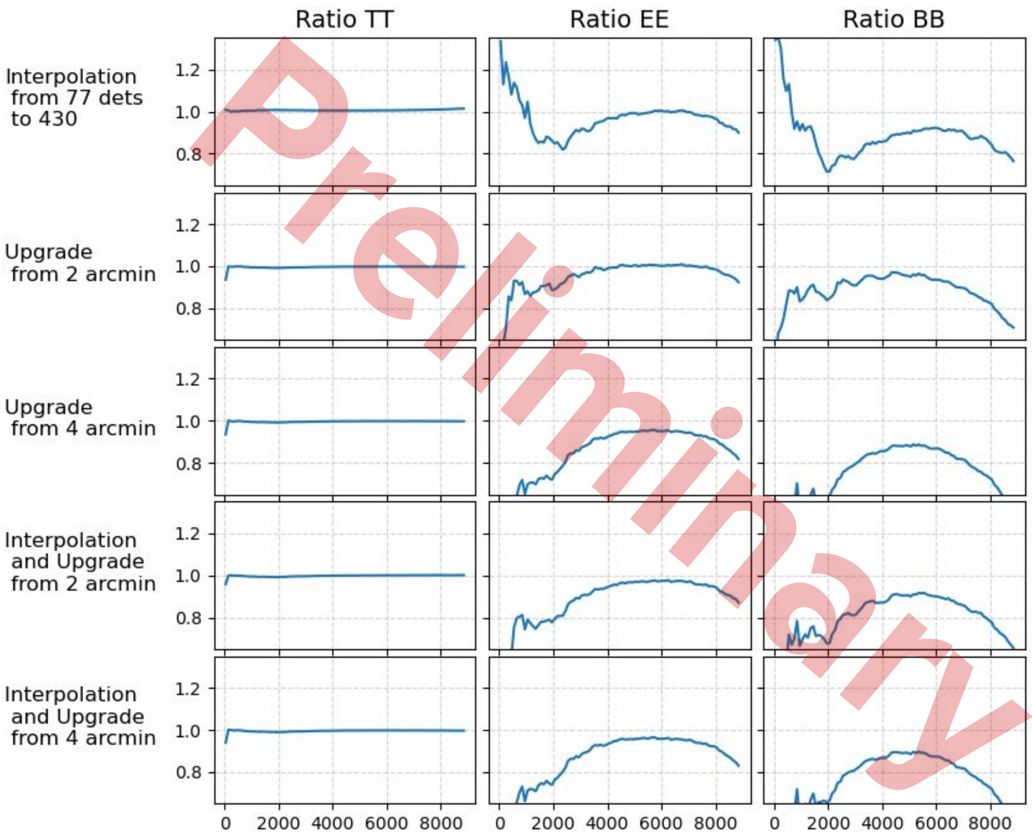


Reconstructed input residuals

All three systematics reconstructed, 14 days mock scan on d56 region, target resolution of 1 arcmin

Interpolation of h-maps – Preliminary results

Ratio output over nominal case



Second order systematics impact!

Systematics X Systematics

All three systematics reconstructed, 14 days mock scan on d56 region, target resolution of 1 arcmin

Applications – Mapmaking

How well do systematics propagate under realistic mapmaking?

Maximum-Likelihood mapmaking

The formalism is built on binned mapmaking ➔ map-based approach

$$\begin{pmatrix} \hat{\mathbf{I}} \\ \hat{\mathbf{Q}} - \mathbf{i}\hat{\mathbf{U}} \\ \hat{\mathbf{Q}} + \mathbf{i}\hat{\mathbf{U}} \end{pmatrix} = \begin{pmatrix} \tilde{h}_0^{tot} & \frac{1}{2}\tilde{h}_2^{tot} & \frac{1}{2}\tilde{h}_{-2}^{tot} \\ \frac{1}{2}\tilde{h}_2^{tot} & \frac{1}{4}\tilde{h}_4^{tot} & \frac{1}{4} \\ \frac{1}{2}\tilde{h}_{-2}^{tot} & \frac{1}{4} & \frac{1}{4}\tilde{h}_{-4}^{tot} \end{pmatrix}^{-1} \begin{pmatrix} \sum_{j=1}^{N_{\rm det}} \frac{1}{N_{\rm det}} \sum_{k'=-\infty}^{\infty} \tilde{h}^j_{0-k'} \tilde{S}^j_{k'} \\ \sum_{j=1}^{N_{\rm det}} e^{i2\psi_j} \frac{1}{N_{\rm det}} \sum_{k'=-\infty}^{\infty} \tilde{h}^j_{2-k'} \tilde{S}^j_{k'} \\ \sum_{j=1}^{N_{\rm det}} e^{-i2\psi_j} \frac{1}{N_{\rm det}} \sum_{k'=-\infty}^{\infty} \tilde{h}^j_{-2-k'} \tilde{S}^j_{k'} \end{pmatrix}$$

Spin map estimates

$$\hat{\mathbf{S}}$$

Pixel-based mapmaking matrix

$$\left(\mathbf{P}^{\mathrm{T}}\mathbf{P}\right)^{-1}$$

Detector-wise input spin map
Dependent on detector orientation

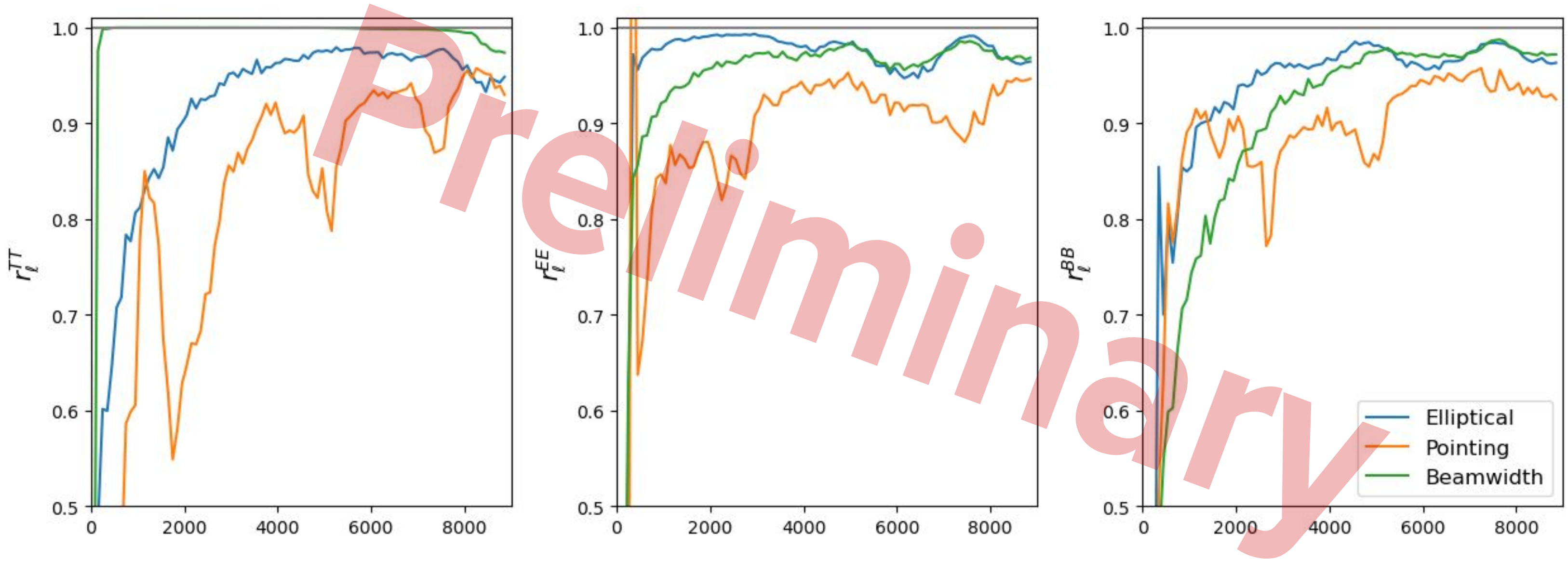
$$\mathbf{P}^{\mathrm{T}}\mathbf{d}$$

➔ Maximum Likelihood (ML) is better suited to downweight the impact of the noise, but possibly leads to different propagation of the systematics

Introducing the **pointing matrix P** (TOD ➔ pixels), we obtain

$$\hat{\mathbf{s}} = \left(\mathbf{P}^{\mathrm{T}}\mathbf{P}\right)^{-1}\mathbf{P}^{\mathrm{T}}\mathbf{d} \quad \rightarrow \quad \hat{\mathbf{s}} = \left(\mathbf{P}^{\mathrm{T}}\mathbf{N}^{-1}\mathbf{P}\right)^{-1}\mathbf{P}^{\mathrm{T}}\mathbf{N}^{-1}\mathbf{d}$$

ML Mapmaker with ACT noise covariance



$$r_\ell^{X_{\mathrm{TOD}}Y_{\mathrm{H-MAPS}}} = \frac{C_\ell^{X_{\mathrm{TOD}}Y_{\mathrm{H-MAPS}}}}{\sqrt{C_\ell^{X_{\mathrm{TOD}}X_{\mathrm{TOD}}}\,C_\ell^{Y_{\mathrm{H-MAPS}}Y_{\mathrm{H-MAPS}}}}}$$

Prospects

Towards mitigation – Examples in power spectrum and lensing analysis

Mitigation at the likelihood level

In the context of the cross-C_ℓ pipeline proposed by the SOLikeT package, the mitigation could be performed through the marginalization of the systematics effect parameters à la **Giardiello et al. 2024**

Giardiello et al. 2024

This work (SMARTIES)

$$\tilde{C}_\ell^{XY,\nu_i\nu_j} = \underbrace{c^{XY,\nu_i\nu_j}}_{\text{Calibration mismatch}} R^{XY}(\underbrace{\alpha_i^{\nu}, \alpha_j^{\nu}}_{\text{Polarization angle}})\left(C_{\ell,\mathrm{CMB}}^{XY} + C_{\ell,\mathrm{FG}}^{XY,\nu_i\nu_j}(\underbrace{\Delta^{\nu_i}, \Delta^{\nu_i}}_{\text{Bandpass mismatch}})\right) + \underbrace{C_{\ell,\mathrm{Templates}}^{XY,\nu_i\nu_j}(\gamma)}_{\text{Beam systematics}}$$

(WIP)

Syslibrary → MFLike ⇒ SOLikeT

SMARTIES templates could be interfaced to the likelihood through **Syslibrary**

→ Many tools already in place, current work to finish the interface and study how the parameters are affected by the new parameters introduced

Lensing: Characterization of map-level systematics

In the context of the lensing analysis, it is crucial to have systematics characterized at the map level

➔ Goal to characterize and mitigate impact of systematics (state of the art: Mirmelstein et al. 2020) with the **mean field** construction

The **mean field** is built from simulations to remove the bias of the quadratic estimator of the lensing potential

$$\underbrace{\hat{\kappa}_{\mathbf{L}}}_{\text{Convergence field}} \equiv \Big(\underbrace{\hat{\phi}_{\mathbf{L}}}_{\text{Lensing estimator (biased)}} - \underbrace{\langle\hat{\phi}_{\mathbf{L}}\rangle_{\mathrm{MC}}}_{\text{Mean field bias (from simulations)}}\Big) \times \frac{2}{L(L+1)}$$

➔ **SMARTIES** can provide many (100s, 1000s) simulations of maps including input sky and systematics with cheaper numerical resources

Lensing estimates could be improved with systematics maps!

Conclusion

Conclusion

Extension of the h-map framework for instrumental systematics simulations

- Multi-detector approach

  ➜ More flexibility on systematics templates, ability to account for instrumental systematics dependent on detector location, independent on polarization angle

- Interpolation and resolution change for h-map
- Tests against maximum-likelihood mapmaking

Implementation in **SMARTIES**, tutorials/documentation to come!

Prospects:

- Developments as mitigation tool
- Possible applications to other scanning experiments! (21cm experiments)

Thank for your attention!