MM is funded by ERC Relics project 101116027

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

*Cosmoglobe 2026 Conference*

*2026, September 9th*

Presenting: **Magdy Morshed**, postdoctoral researcher at INFN Ferrara, Italy
*In the context of The Simons Observatory, including contributions from Alexandre Adler, Adri Duivenvoorden, Giulio Fabbian, Dan Thomas, Martina Gerbino, Luca Pagano*
*Also presenting on behalf of Camille Demay, PhD candidate at the University of Ferrara*

# The Simons Obervatory

Large Aperture Telescope, Source: SO website

Telescopes located in Atacama Desert (altitude 5200m), in Chile

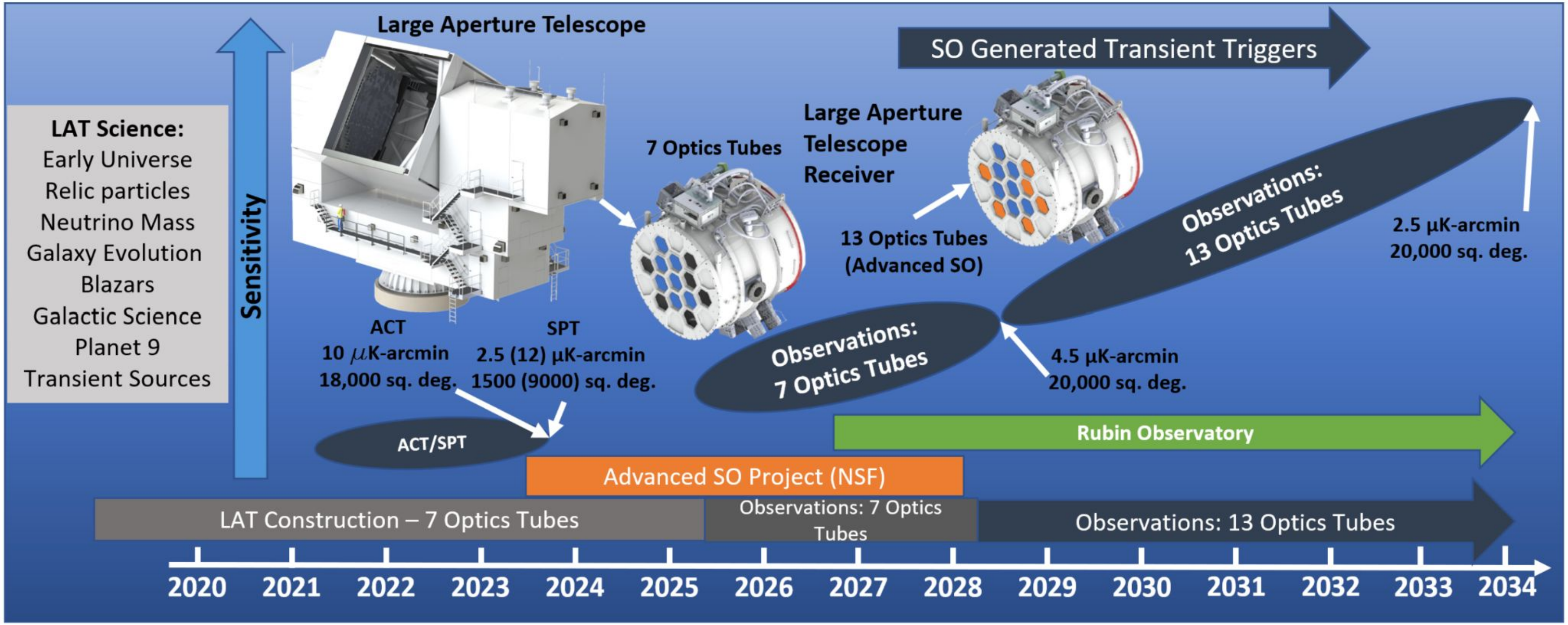
- First lights for SAT (2024) and LAT (2025)!
- Three additional SATs to be installed next year!
- Total of roughly 120,000 detectors across SATs and LAT

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

# The Large Aperture Telescope

Resolution of 1 arcmin, two 6m mirrors, 60,000 detectors over 6 frequencies 27-280 Ghz

→ Each optic tube expected to have sensibility comparable to ACT!




arxiv:2503.00636

# Propagating instrumental systematics

As data is coming, first analyses are being done

**CMB maps → primary CMB and lensing power spectra → Cosmological parameters**

Instrumental systematics such as T-to-P leakage (e.g. with beam) may contaminate CMB maps → Possible bias in cosmological parameters

→ Quantitative assessment and mitigation strategies would need a great number of map simulations **at the LAT large resolution**

**Project led within Simons Observatory**

Development of an **efficient** method to simulate systematics effect at the map level, **accurate with respect to time domain simulations**

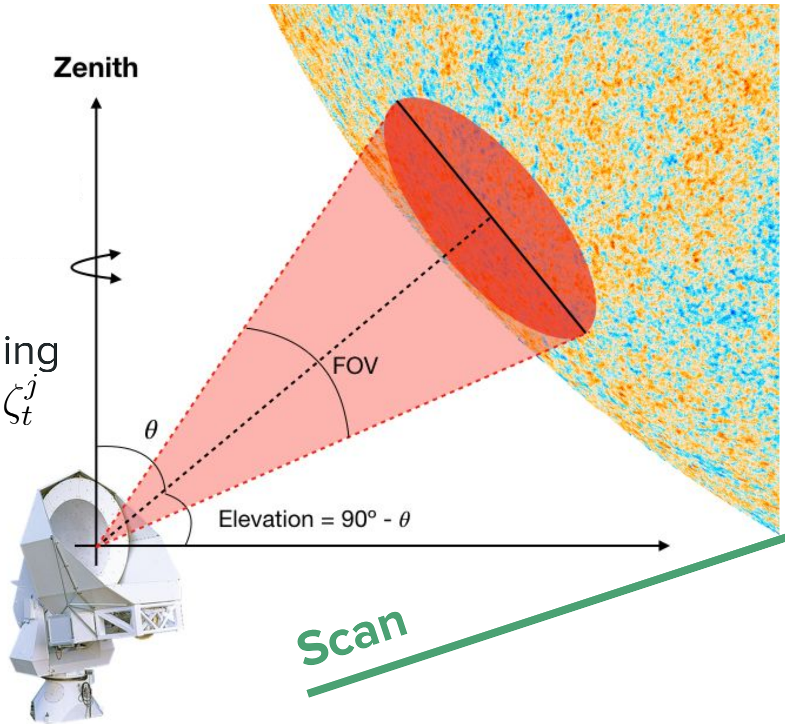
→ Assess the impact of systematic effects, and help mitigate them

→ Possibly to obtain thousands of systematics maps at high resolution

→ Towards robustness of the power spectrum and lensing analyses

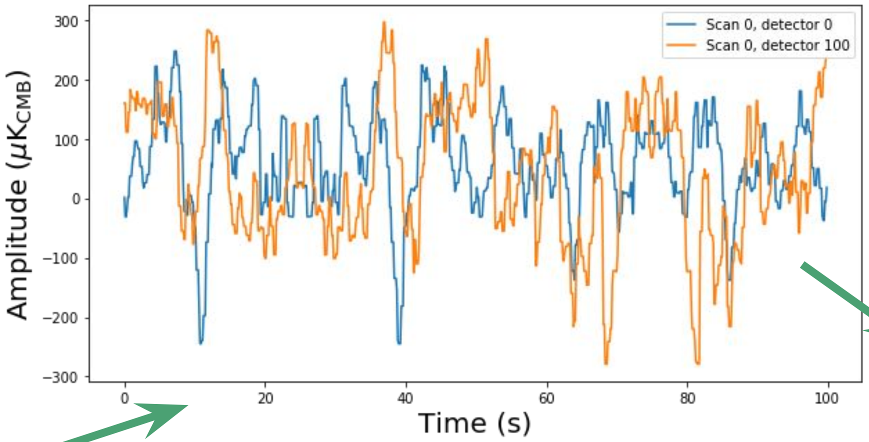
# From a scan to estimated maps

Scanning angle $\zeta_t^j$




Scan

Timestream (or time samples)




Maps

Instrumental systematics naturally propagated with **"end-to-end" time-domaine** simulation softwares
→ **Up to 1e15 time samples!**

Pictures from s4cmb package documentation

→ Alternative approach: **h-maps** to reduce the pointing information $$\tilde{h}_n^j = \langle e^{in\zeta_t^j} \rangle$$

# Formalism – Spin mapmaking

Building on formalism from McCallum et al. 2021 (Takase et al. 2024 with HWP)
→ **Spin mapmaking**

New (noiseless) formalism relying on **h-maps**, detector orientations $\psi^j$

$$\begin{pmatrix}\hat{\mathbf{I}}\\ \hat{\mathbf{Q}}-\mathrm{i}\hat{\mathbf{U}}\\ \hat{\mathbf{Q}}+\mathrm{i}\hat{\mathbf{U}}\end{pmatrix} = \begin{pmatrix} \tilde{\boldsymbol{h}}_0^{tot} & \frac{1}{2}\tilde{\boldsymbol{h}}_2^{tot} & \frac{1}{2}\tilde{\boldsymbol{h}}_{-2}^{tot}\\ \frac{1}{2}\tilde{\boldsymbol{h}}_2^{tot} & \frac{1}{4}\tilde{\boldsymbol{h}}_4^{tot} & \frac{1}{4} \\ \frac{1}{2}\tilde{\boldsymbol{h}}_{-2}^{tot} & \frac{1}{4} & \frac{1}{4}\tilde{\boldsymbol{h}}_{-4}^{tot}\end{pmatrix}^{-1} \begin{pmatrix} \sum_{j=1}^{N_{\mathrm{det}}} \frac{N^j_{\mathrm{hits}}}{N^{\mathrm{tot}}_{\mathrm{hits}}} \sum_{n\in\mathbb{Z}} \tilde{\boldsymbol{h}}^j_{0-n} \mathbf{S}^j_n \\ \frac{1}{2}\sum_{j=1}^{N_{\mathrm{det}}} e^{i2\psi^j} \frac{N^j_{\mathrm{hits}}}{N^{\mathrm{tot}}_{\mathrm{hits}}} \sum_{n\in\mathbb{Z}} \tilde{\boldsymbol{h}}^j_{2-n} \mathbf{S}^j_n \\ \frac{1}{2}\sum_{j=1}^{N_{\mathrm{det}}} e^{-i2\psi^j} \frac{N^j_{\mathrm{hits}}}{N^{\mathrm{tot}}_{\mathrm{hits}}} \sum_{n\in\mathbb{Z}} \tilde{\boldsymbol{h}}^j_{-2-n} \mathbf{S}^j_n \end{pmatrix}$$

**Spin map estimates**

**Pixel-based mapmaking matrix**

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

Main takeaway:

- Mapmaking performed only using maps without further time-domain operation
- Input spin maps encompass both true sky and systematics template

→ **Efficient and accurate mapmaking to propagate systematics!**

# Implementation

Formalism implemented in **SMARTIES**, interfaced with SO and LiteBIRD tools

→ Implementation of **T-to-P leakage** beam related BICEP systematics templates to be injected as input spin maps:

- Beam ellipticity (spin -2/2)
- Beam pointing offset (spin -1/1)
- Differential beamwidth (spin 0)

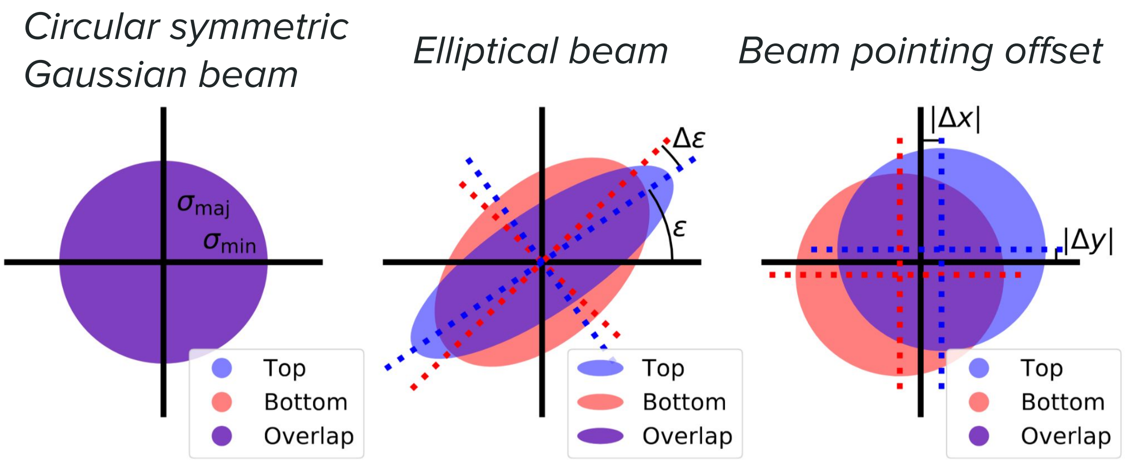



Figure from Mirmelstein et al. 2020

Include features within the mapmaking for **on-the-fly detector-wise interpolation** and **resolution-wise upgrade** of **h-maps** → less files to store (up to 448 TB per split otherwise)

→ Key towards application of the formalism with new generation telescopes

# 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**

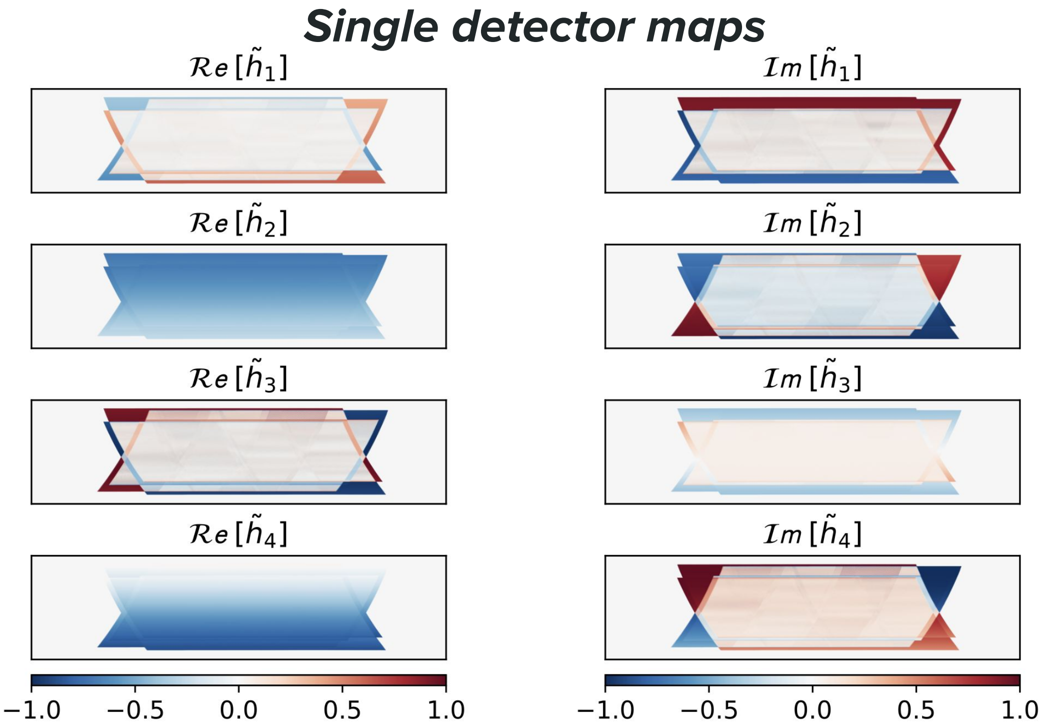
# Towards application on real data

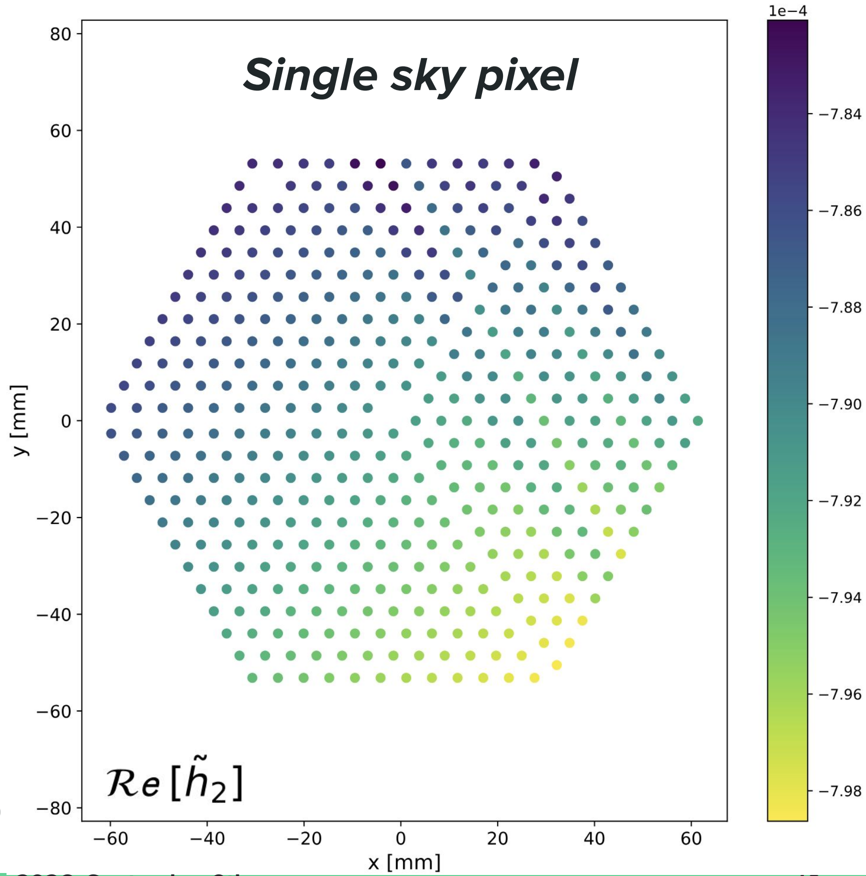
- How do the **h-maps** systematics compare against realistic mapmaking?
  Simplified assumptions with binning mapmaking ➔ **Against ML mapmaking**
- Do we need to store all h-maps for every detector and spin? ➔ **Interpolation**
- How is the formalism able to handle realistic beams? ➔ **Planck**

# Applications – Interpolation

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

# Interpolation of h-maps




Example of 14 days scan on small sky patch (**D56**)

# Interpolation of h-maps – Preliminary results

Scalability: on-the-fly ability to interpolate detector **h-maps** and upgrade their resolution, to avoid storing all of them

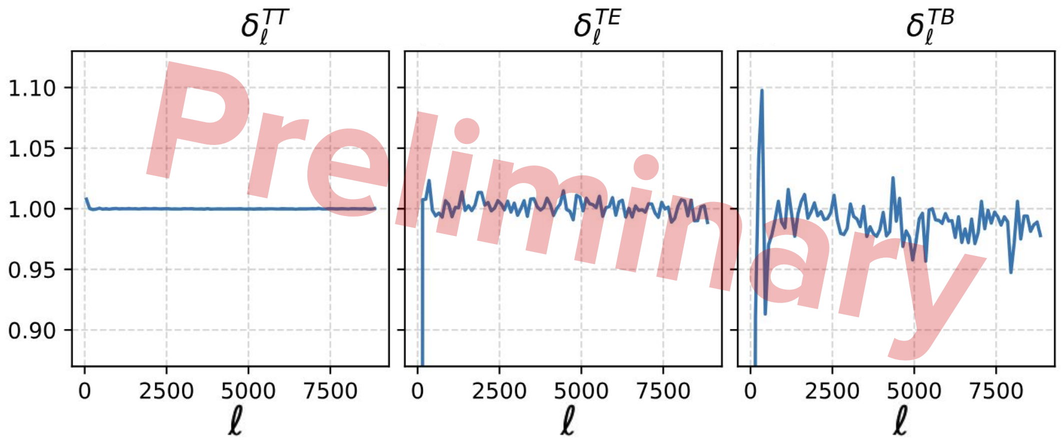
Two cases with all three systematics combined

- 860x4 **h-maps** at 1 arcmin resolution (405 GB)
- 36x4 **h-maps** at 4 arcmin resolution (1 GB), and interpolate+upgrade on-the-fly

**First order systematics impact:**

Ratio of power spectra **Input x Systematics**

**Agreement between the two cases!**




*SO study to be presented in MM et al. (in prep.)*

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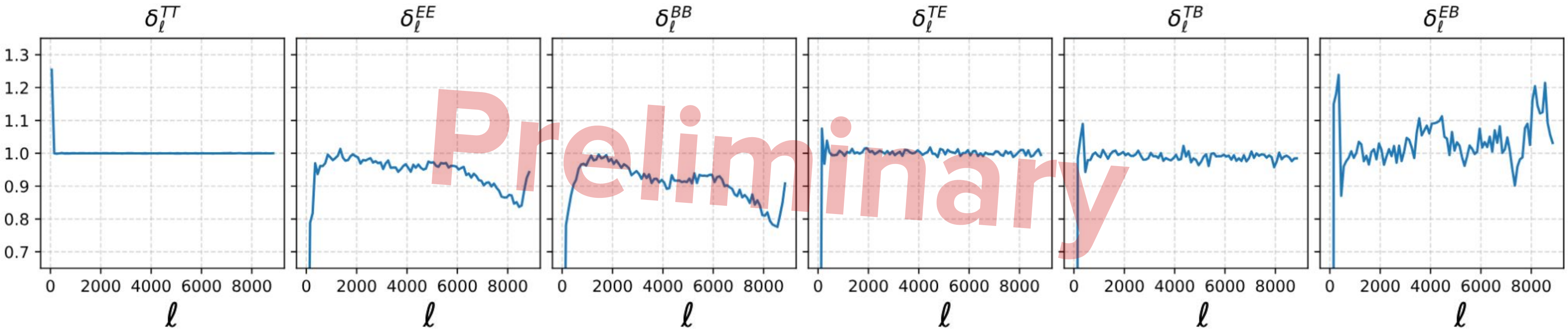



**Second order systematics impact:** Ratio of power spectra **Systematics x Systematics**

→ **Agreement between the two cases!**

*SO study to be presented in MM et al. (in prep.)*

# Applications – Mapmaking

*How well are we able to simulate systematics against realistic mapmaking?*

# Maximum-Likelihood mapmaking

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

$$\begin{pmatrix} \hat{\mathbf{I}} \\ \hat{\mathbf{Q}} - i\hat{\mathbf{U}} \\ \hat{\mathbf{Q}} + i\hat{\mathbf{U}} \end{pmatrix} = \begin{pmatrix} \tilde{\boldsymbol{h}}_0^{tot} & \frac{1}{2}\tilde{\boldsymbol{h}}_2^{tot} & \frac{1}{2}\tilde{\boldsymbol{h}}_{-2}^{tot} \\ \frac{1}{2}\tilde{\boldsymbol{h}}_2^{tot} & \frac{1}{4}\tilde{\boldsymbol{h}}_4^{tot} & \frac{1}{4} \\ \frac{1}{2}\tilde{\boldsymbol{h}}_{-2}^{tot} & \frac{1}{4} & \frac{1}{4}\tilde{\boldsymbol{h}}_{-4}^{tot} \end{pmatrix}^{-1} \begin{pmatrix} \sum_{j=1}^{N_{\rm det}} \frac{N_{\rm hits}^j}{N_{\rm hits}^{\rm tot}} \sum_{n\in\mathbb{Z}} \tilde{\boldsymbol{h}}_{0-n}^j \mathbf{S}_n^j \\ \frac{1}{2}\sum_{j=1}^{N_{\rm det}} e^{i2\psi^j} \frac{N_{\rm hits}^j}{N_{\rm hits}^{\rm tot}} \sum_{n\in\mathbb{Z}} \tilde{\boldsymbol{h}}_{2-n}^j \mathbf{S}_n^j \\ \frac{1}{2}\sum_{j=1}^{N_{\rm det}} e^{-i2\psi^j} \frac{N_{\rm hits}^j}{N_{\rm hits}^{\rm tot}} \sum_{n\in\mathbb{Z}} \tilde{\boldsymbol{h}}_{-2-n}^j \mathbf{S}_n^j \end{pmatrix}$$

**Spin map estimates**

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

**Pixel-based mapmaking matrix**

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

**Detector-wise input spin map**
**Dependent on detector orientation**

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

➔ 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

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

# ML Mapmaker with ACT noise covariance

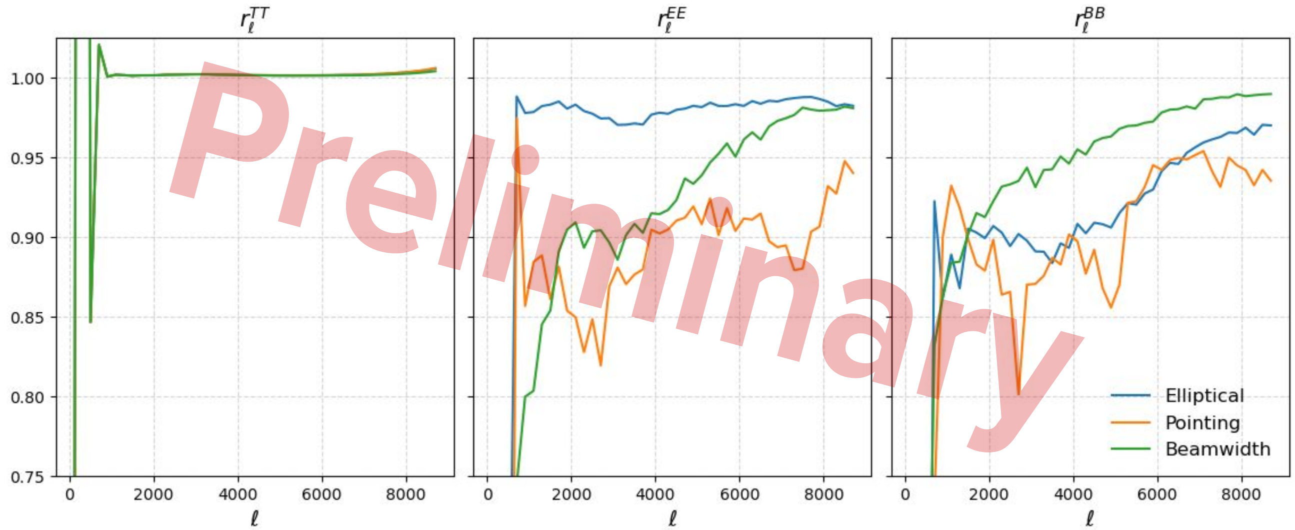
First demonstration of the method against **realistic mapmaking** (Maximum-Likelihood mapmaking)

➜ ACT noise covariance characterized on **atmosphere+white noise** simulation

➜ SO tools (sotodlib/TOAST) used for noise covariance characterization and ML mapmaking

Comparison against ML mapmaker

➜ **Cross-correlation factor show good agreement!**




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

*SO study to be presented in MM et al. (in prep.)*

# Applications – Planck

*Can the formalism handle realistic beams?*

# Applications to Planck beams

**SMARTIES** was extended to ingest harmonic beam decomposition $b_{\ell m}$

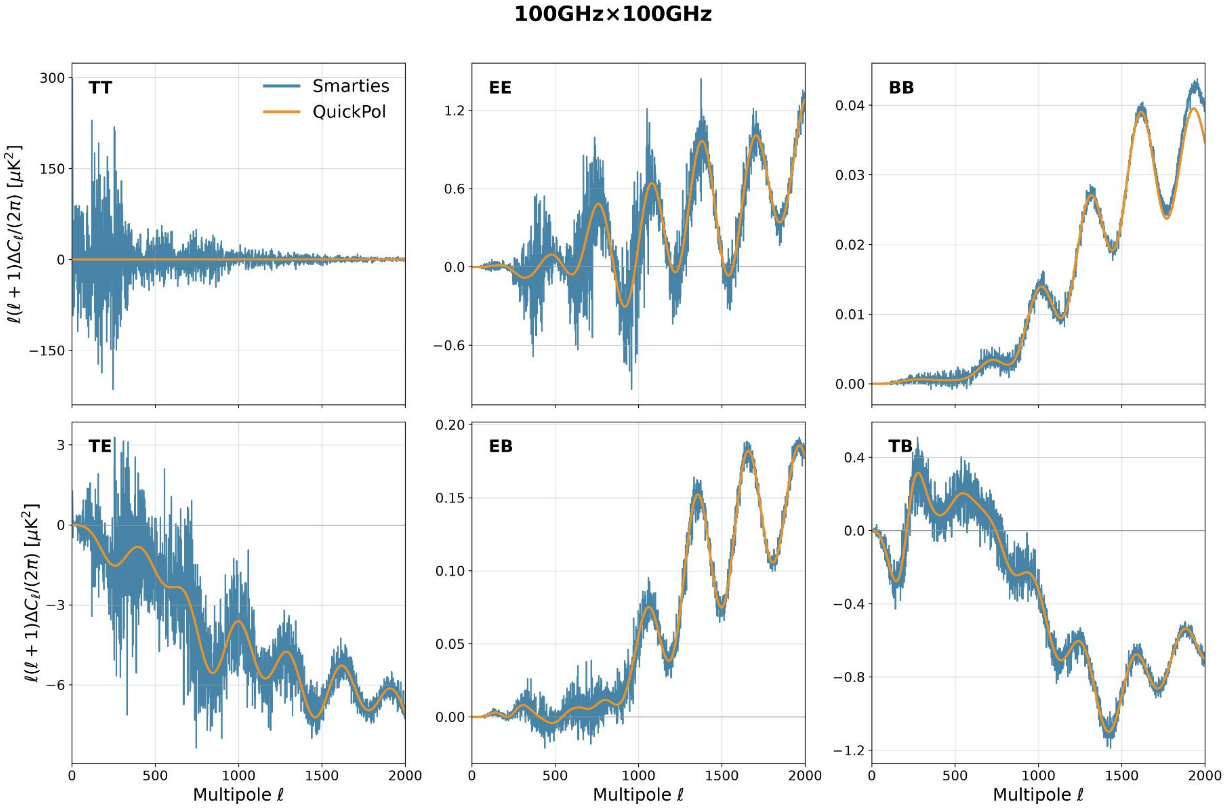
➜ Map-space beam convolution instead of injecting map systematics templates

**First application to detector beams of Planck HFI**

➜ Validated against Quickpol formalism (Hivon et al. 2016), **agreement on the power spectra**!

**PlanckConv** tool derived

➜ Efficient simulation of beam-convolved Planck maps




Credits: Camille Demay (lead of the study)

➜ Extension of the formalism in *Demay, MM, Pagano, Gerbino (in prep.)*

# Mitigation prospects

## Power spectrum pipeline

Marginalization at the likelihood level (Giardiello et al. 2024, **SOLikeT**)

Cross-spectrum

SMARTIES

$$\tilde{C}_\ell^{XY,\nu_i\nu_j} = c^{XY,\nu_i\nu_j} R^{XY}(\alpha_i^\nu, \alpha_j^\nu)\left(C_{\ell,\mathrm{CMB}}^{XY} + C_{\ell,\mathrm{FG}}^{XY,\nu_i\nu_j}(\Delta^{\nu_i}, \Delta^{\nu_i})\right) + C_{\ell,\mathrm{Templates}}^{XY,\nu_i\nu_j}(\gamma)$$

Gain — Polarization angle — Bandpass mismatch — Beam systematics

## Lensing pipeline

Accounting systematics contributions in the mean field bias (Mirmelstein et al. 2021)

$$\hat{\kappa}_{\mathbf{L}} \equiv \left(\hat{\phi}_{\mathbf{L}} - \langle\hat{\phi}_{\mathbf{L}}\rangle_{\mathrm{MC}}\right) \times \frac{2}{L(L+1)}$$

Convergence field

Lensing estimator (biased)

Mean field bias (from simulations)

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

# Conclusion – Take-home message

SO has been taking its first light, currently accumulating its first data

→ More SATs and LAT optic tubes to come!

New generalized formalism to efficiently simulate maps with instrumental systematics

- Implemented in **SMARTIES**, validated against SO tools

  → **Able to propagate systematics for cheap cost and great accuracy wrt TOD**

- Applications:
  - Scalable to SO (on-the-fly procedures)
  - Extensively checked against realistic mapmaking
  - Validated against Planck beams (*Demay, MM et al. in prep.*)

Map-based approach tested in full complexity – *MM et al. in prep.*

→ **Mitigation prospects towards power spectrum and lensing pipelines**

→ **Possibilities towards SAT, or other cosmological surveys** (21cm experiments)

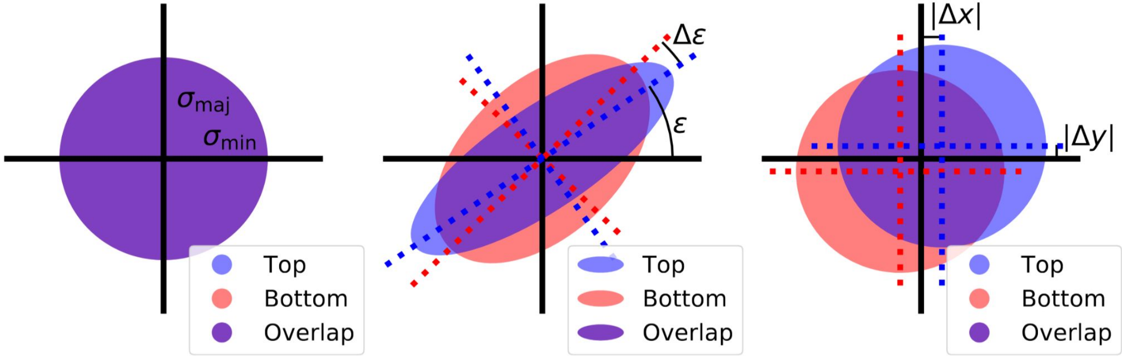
# Thank for your attention!

# Backup

# Backup: Beam leakage à la Mirmelstein et al. 2020

Beam leakage model as Taylor expansion around circularly-symmetric (CS) beam to model T-to-P leakage from differential pointing and ellipticities

$$T_{\rm obs}(\mathbf{x}) \approx \alpha_0 T_{\rm b}(\mathbf{x}) + \alpha_{1,i}\frac{\partial T_{\rm b}(\mathbf{x})}{\partial x^i} + \alpha_{2,ij}\frac{\partial^2 T_{\rm b}(\mathbf{x})}{\partial x^i \partial x^j}$$




(a) CS beams. (b) Differential beam ellipticities. (c) Differential pointing.

Figure from Mirmelstein et al. 2020