THE SIMONS OBSERVATORY: EARLY DATA FROM THE SMALL APERTURE TELESCOPES

Amalia Villarrubia Aguilar

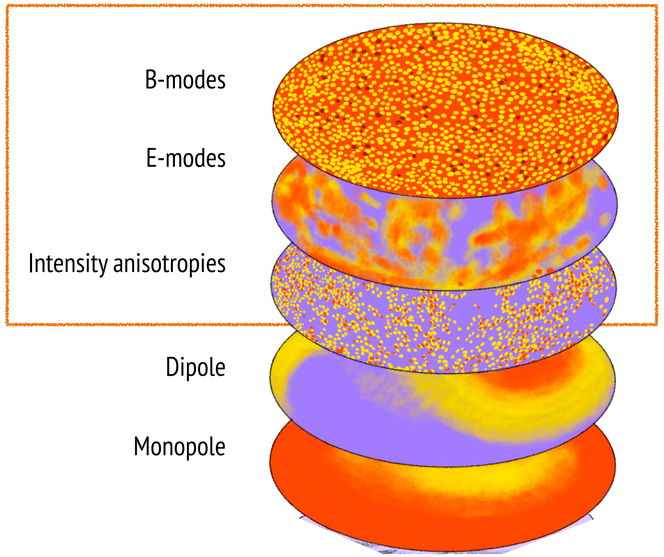
on behalf of the **Simons Observatory Collaboration**

Updated: 2026-03-12

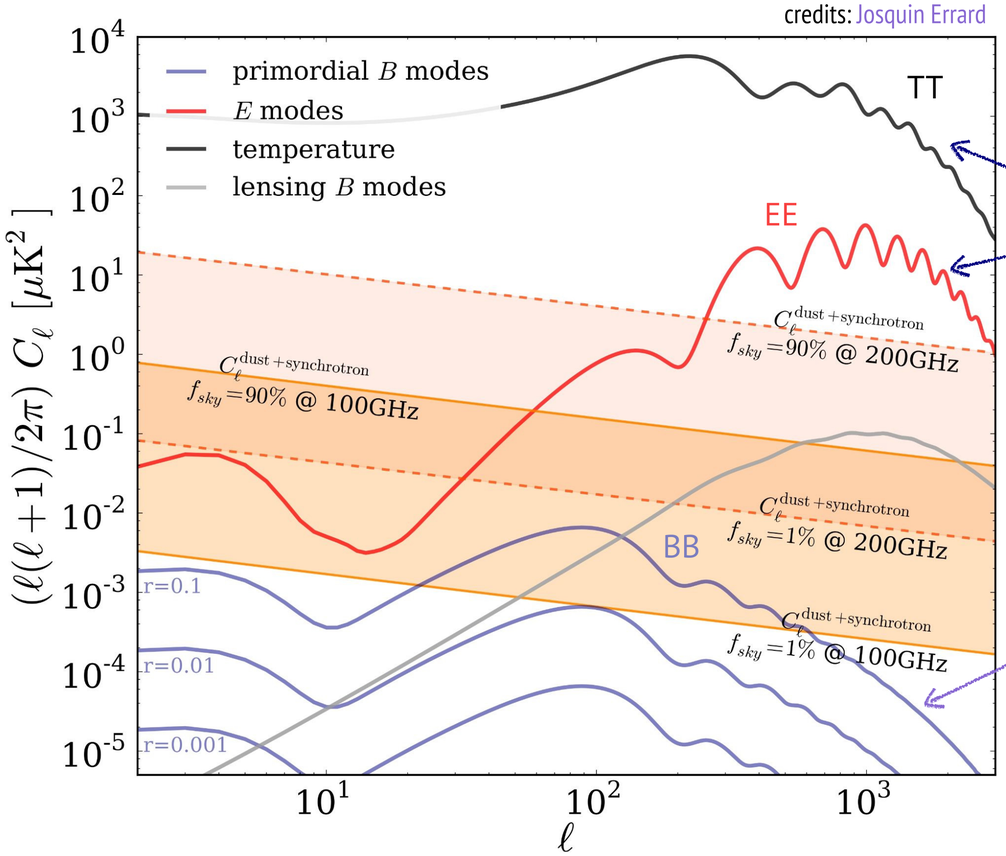
The Simons Observatory: Target Science

These different fluctuations can be described statistically in terms of the angular power spectra:

MULTIPOLE EXPANSION OF THE CMB:



credits: Josquin Errard



SOURCED BY SCALAR PERTURBATIONS

(primordial density fluctuations)

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

SOURCED BY TENSOR PERTURBATIONS

(primordial gravitational waves from inflation)

$$\mathcal{P}_{\mathcal{T}}(k) = A_t \left(\frac{k}{k_0}\right)^{n_t}$$

- The tensor-to-scalar ratio is then defined as: $r = A_t/A_s$ (→ **amplitude of the tensor perturbation power spectrum**);
- If r is non-zero, it would be compelling evidence for **inflationary gravitational waves**.

The Simons Observatory: Target Science

INFLATION
tensor-to-scalar ratio, scalar spectral index, primordial non-gaussianities

EARLY UNIVERSE
sum of neutrino masses, number of relativistic species

REIONIZATION

LARGE SCALE STRUCTURE FORMATION
growth of structure, galaxy cluster catalogs, AGNs, molecular clouds

LATE UNIVERSE
dark energy, dark matter,

TIME-DOMAIN ASTROPHYSICS
gamma ray bursts, interacting supernovae, stellar flares

STELLAR SYSTEM SCIENCE
star formation, exo-Oort clouds, Planet 9

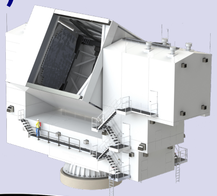
The Simons Observatory: Observatory Site

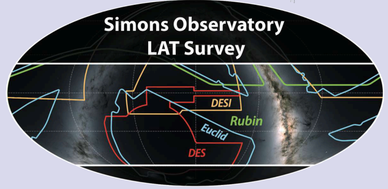
- **CMB observatory** located in the **Atacama desert** (Chile);
- Site offers excellent conditions for CMB observations:
  - Altitude of **5200 m** → average PWV of 1.2 mm,
  - Latitude of **-23°** → possibility to observe up to 80% of the sky.

LARGE APERTURE TELESCOPE (LAT)

Making **wide maps** of the sky with a **high angular resolution**.

- **Cross-Dragone telescope** (6m mirror) with **30 000 TES detectors**;
- Observing in 6 frequency bands **[27, 39, 93, 145, 225, 280] GHz**.

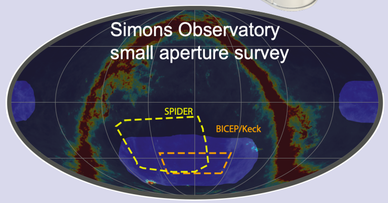


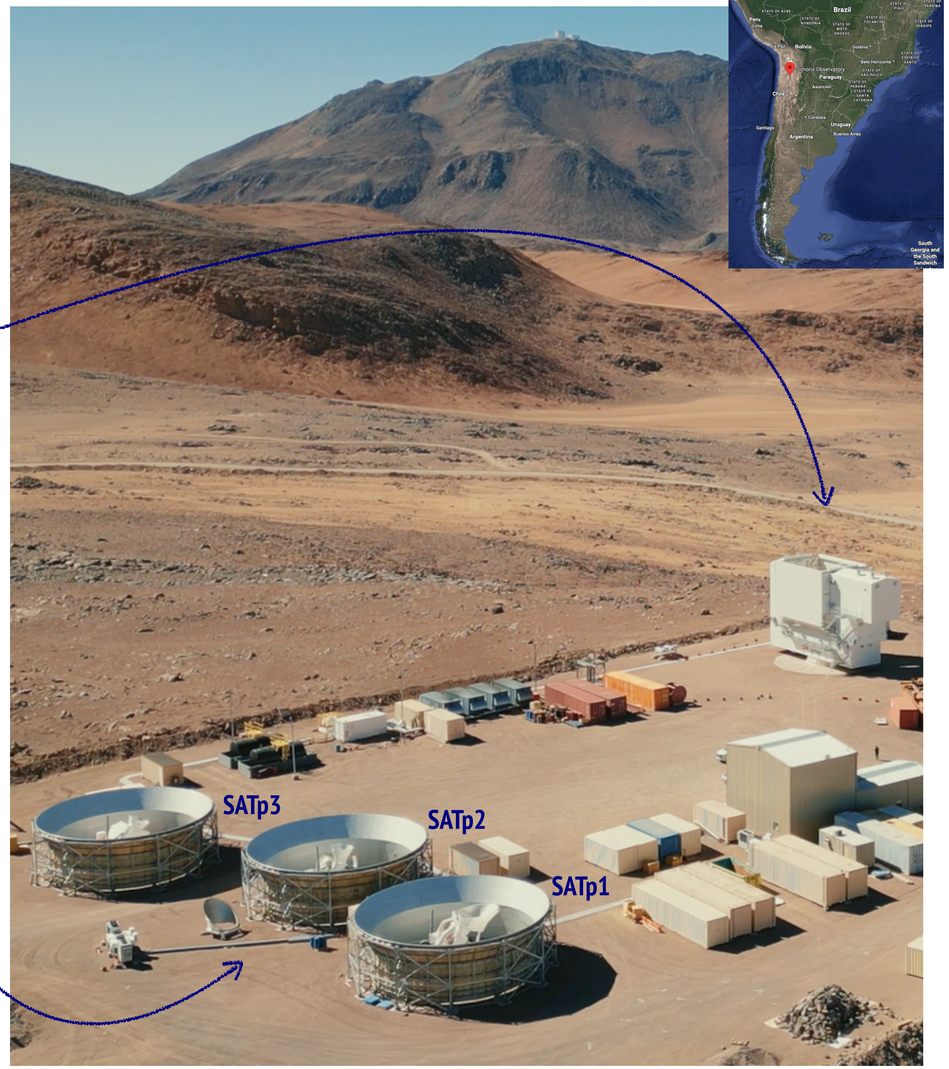


SMALL APERTURE TELESCOPES (SATs)

Making **deep maps** of the sky with a **low angular resolution**.

- **3 "nominal" SATs** + 3 more SATs (SO:UK & SO:JP) deployed in 2026/2027 ("Advanced SO");
- Observing in 6 frequency bands **[27, 39, 93, 145, 225, 280] GHz**;
- **SATp1** & **SATp3** observing at 90/150 GHz are taking **initial science data** since late 2024;
- **SATp2** observing at 220/280 GHz is being **commissioned**.

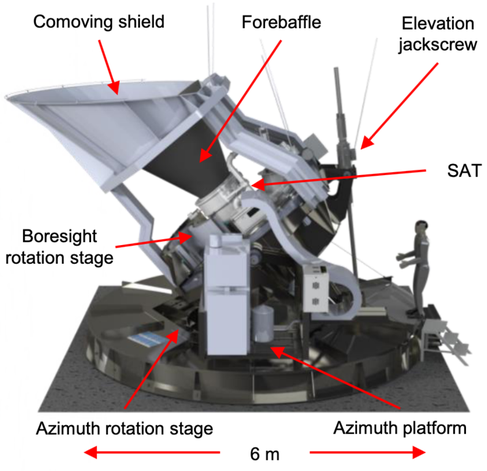




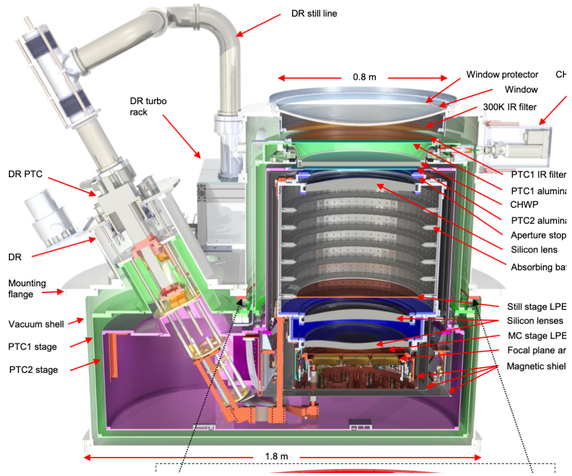
credits: SO Collaboration

The Simons Observatory: SAT Instrument Specifications

Detailed view of the small aperture telescope platform



Cross-section view of a SAT showing the principal components



source: Galitzki et al. 2024

- The SATs have a **0.42 m aperture;**
- They feature a wide **35° field of view;**
- Achieve an angular resolution of **17 arcmin** at 145 GHz;
- The detectors are **transition edge sensor** (TES) **bolometers**;
- Each SAT contains approximately **12 000 TES** detectors;
- Equipped with a continuously rotating **half-wave plate.**

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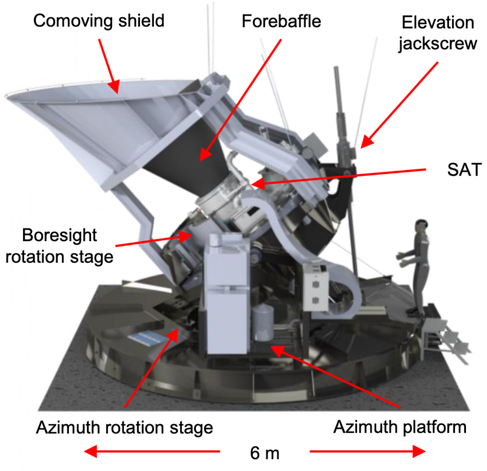

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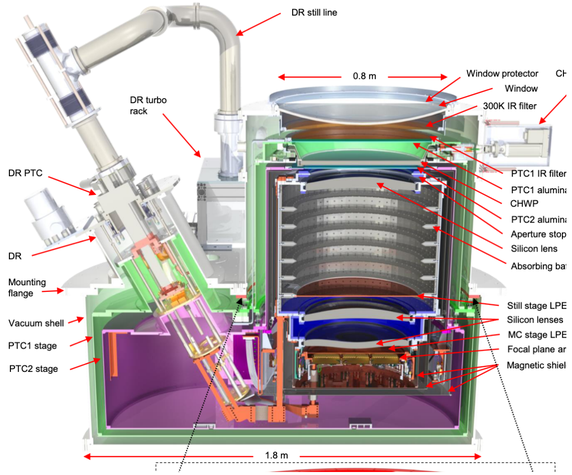

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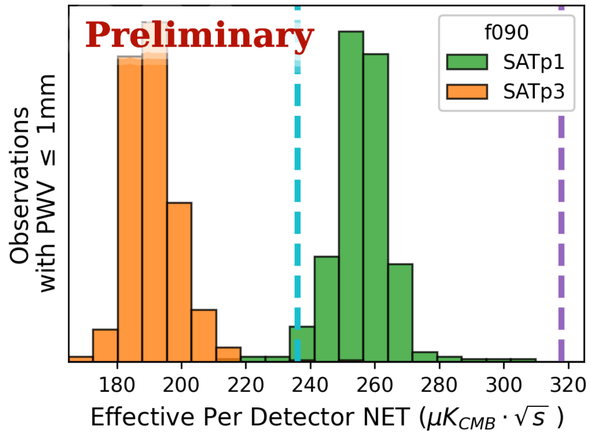
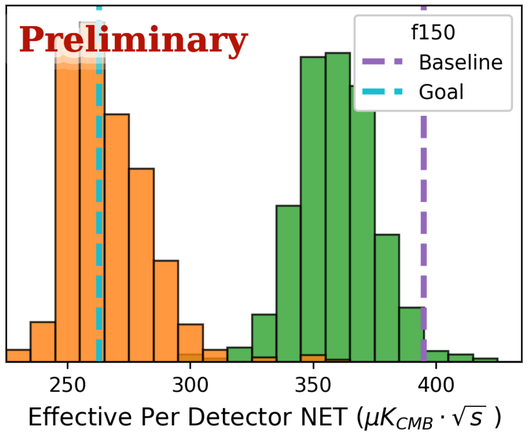
Per-detector performance: SATp1 and SATp3 at **90 GHz**



Per-detector performance: SATp1 and SATp3 at **150 GHz**

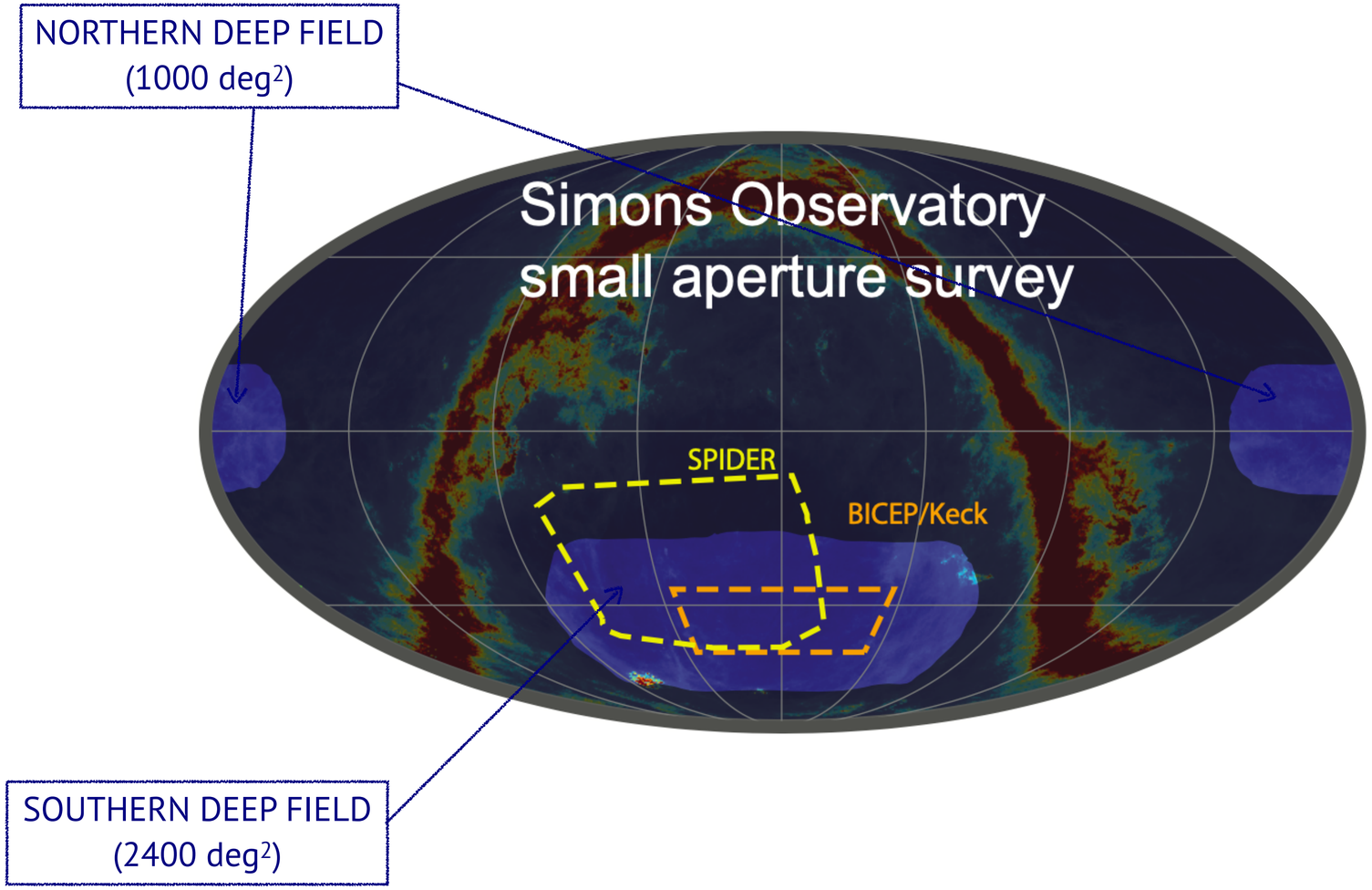


credits: SO Collaboration

- Per-detector sensitivities **exceed forecasted baseline scenario** for both telescopes;
- SATp3 even **surpasses the forecasted goal scenario;**
- These effective NET are consistent with the **required noise at map level**.

The Simons Observatory: SAT Survey Footprint

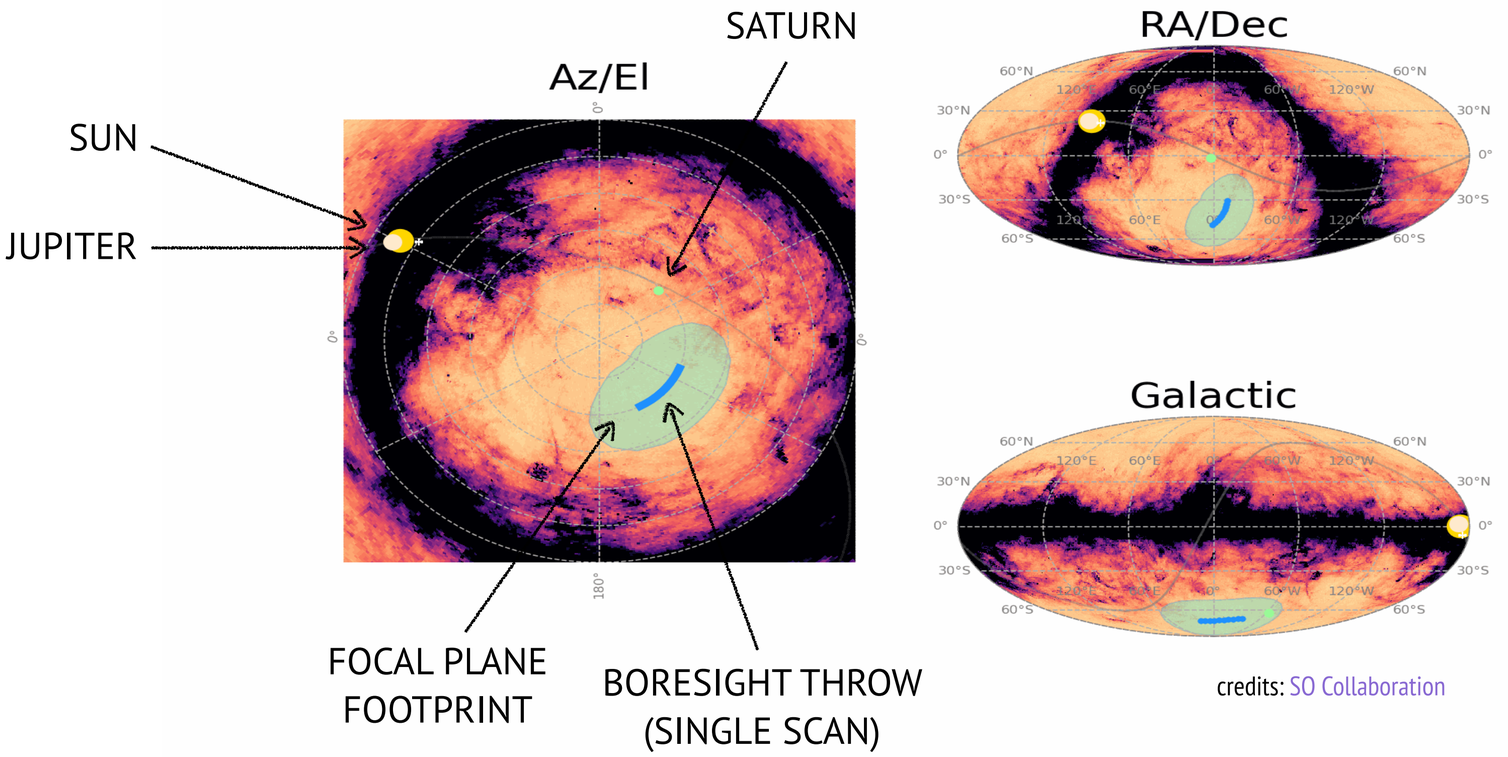
Signal-dominated region:
~10% of the sky



credits: SO Collaboration

The Simons Observatory: SAT Scanning Strategy

Example of SO SAT **scanning strategy** during austral **winter**:



credits: SO Collaboration

USUAL SCAN PARAMETERS:

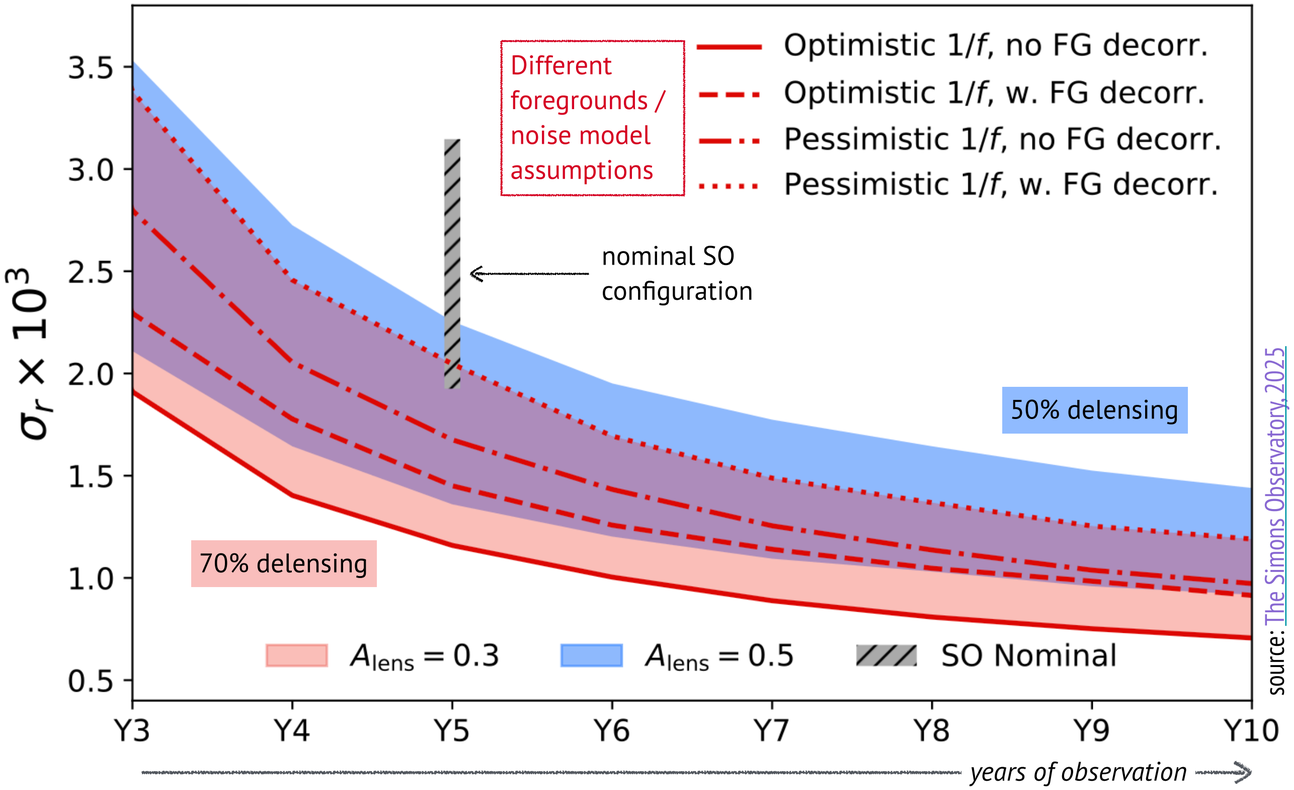
ELEVATION: 60°

BORESIGHT THROW: 40°

SCANNING SPEED: 0.5°/s

The Simons Observatory: Tensor-to-Scalar Ratio Measurement Forecasts

Forecasted 68% contraints on the tensor-to-scalar ratio **r** as a function of time for the **advanced SO** configuration:



SO expects to achieve $\sigma_r \sim 10^{-3}$, pushing current constraints down by an order of magnitude.

SAT Early Observations: Polarization Depth Map

Polarization depth** from **SATp1 + SATp3** at **150 GHz

(Data from **~300 days** taken over 18 months)

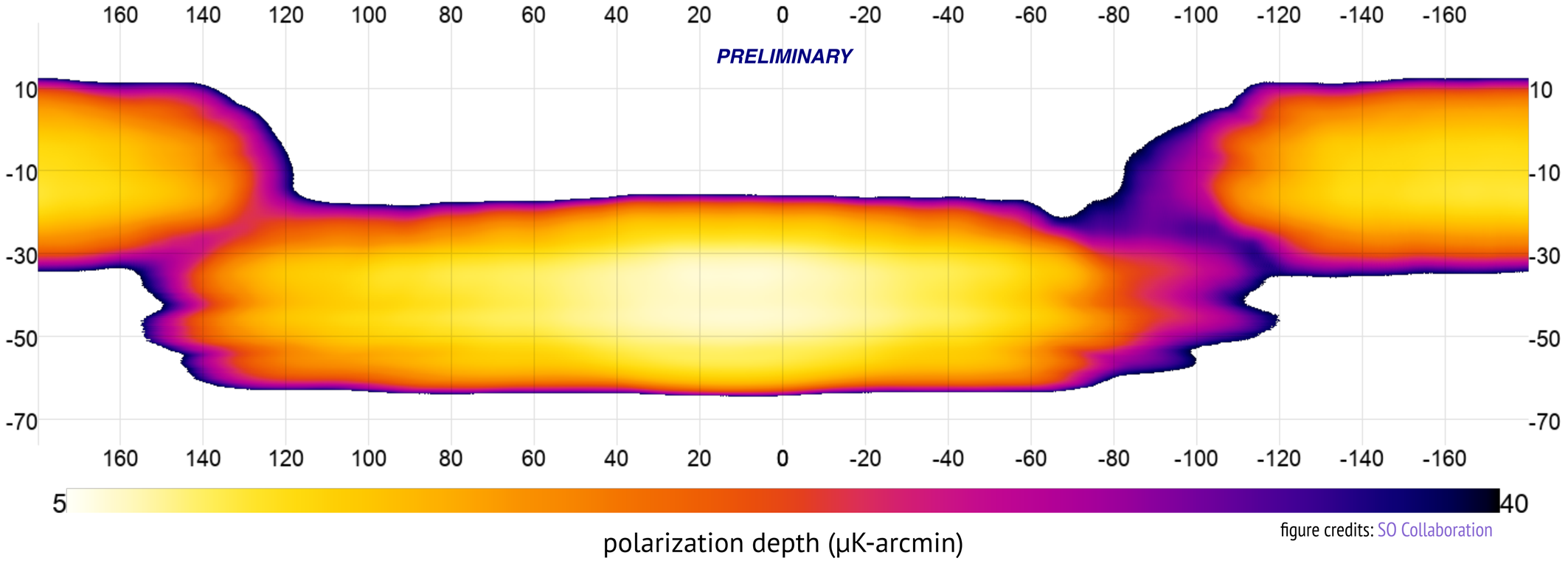
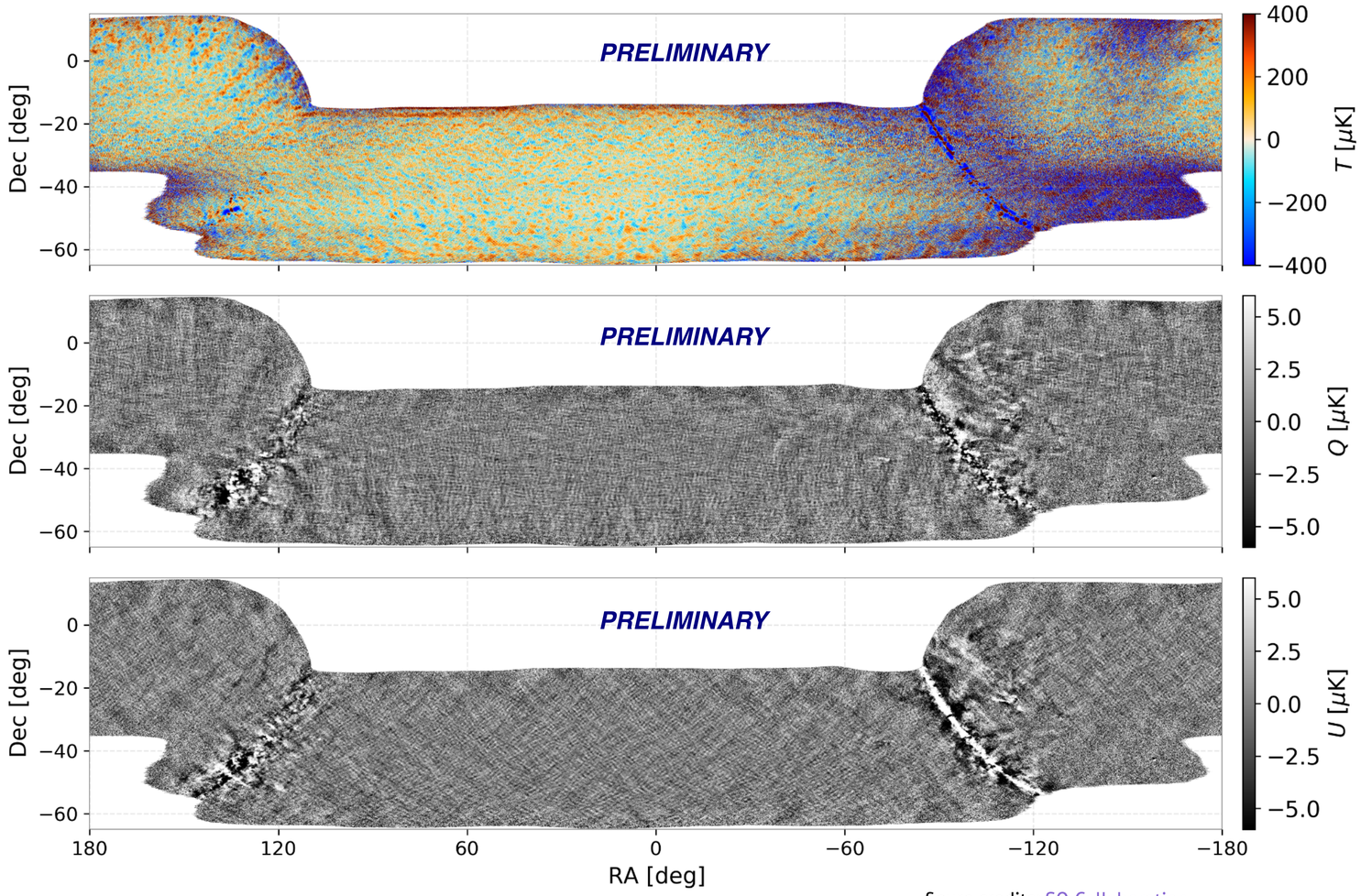


figure credits: SO Collaboration

SAT Early Observations: T/Q/U Maps

Temperature and **polarisation maps** from **SATp1** and **SATp3** at **90** + **150 GHz**

(Data taken over a couple of months)



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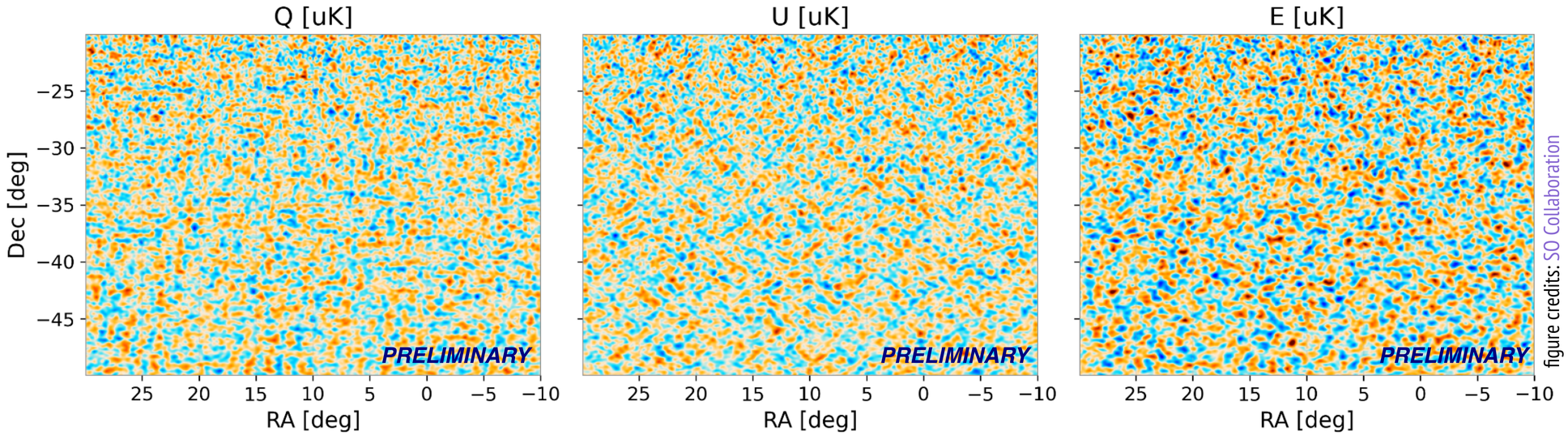
SAT Early Observations: T/Q/U Maps

Temperature and **polarisation maps** from **SATp1** and **SATp3** at **90** + **150 GHz**

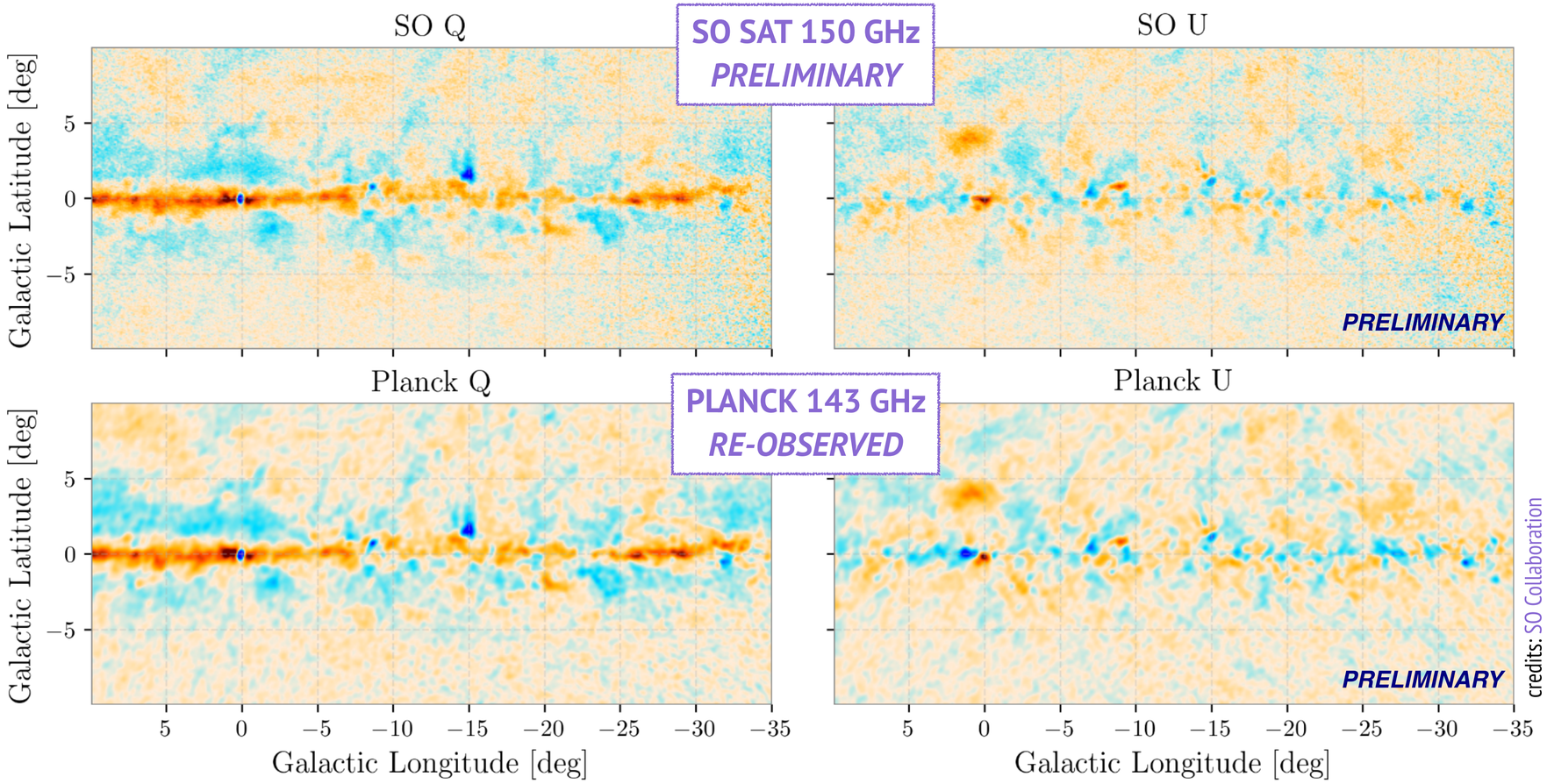
(Data taken over a couple of months; zoom in on the south patch)



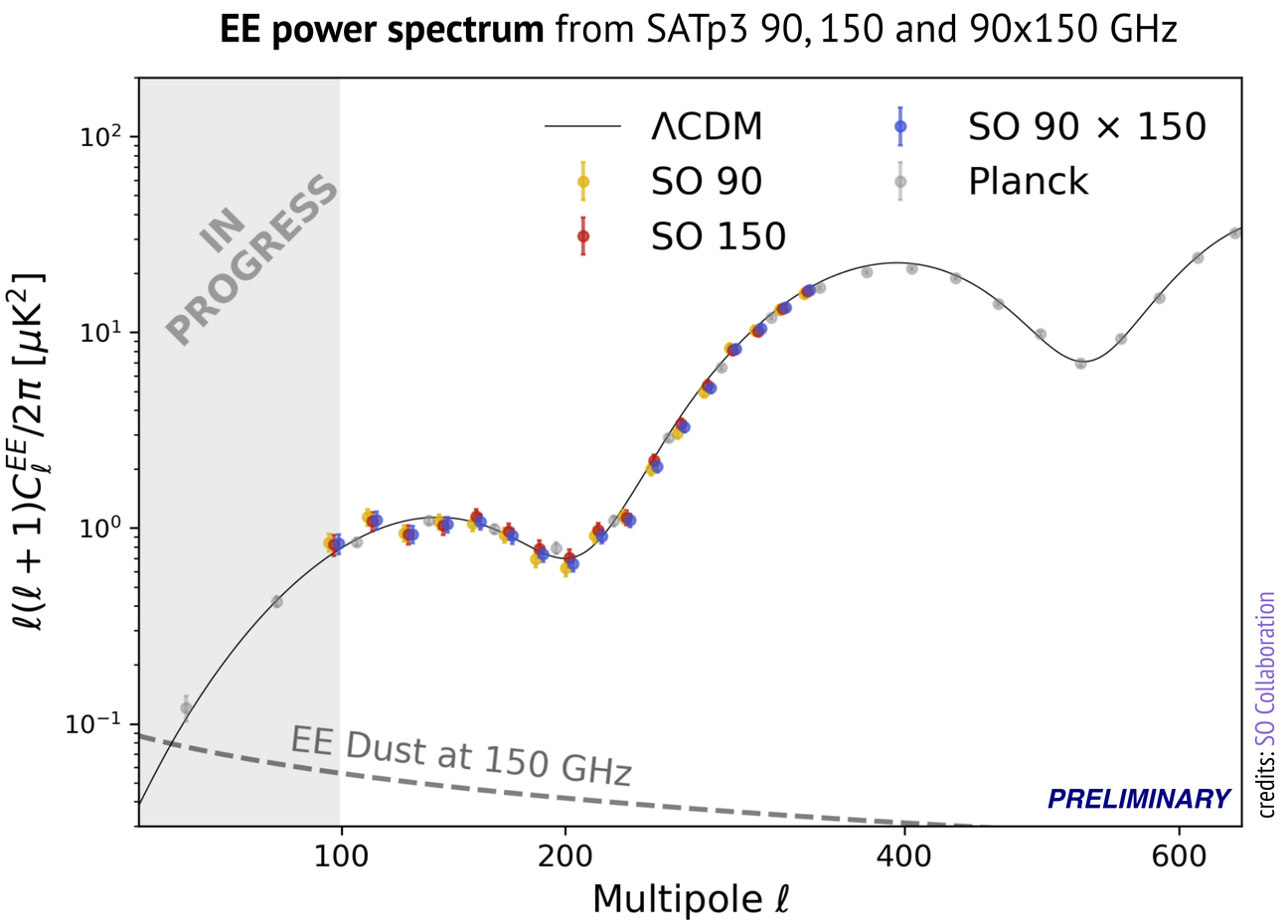
SAT Early Observations: SO vs. Planck Comparison

Polarisation maps from **SATp1** at **150 GHz**

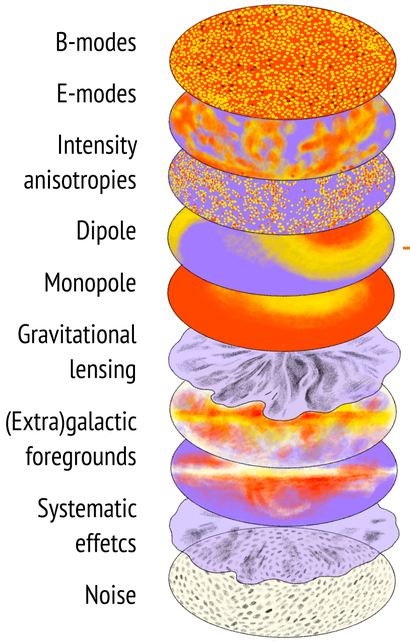
(Data taken over a couple of months)

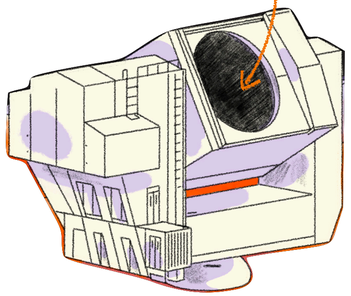


SAT Early Observations: EE Power Spectrum

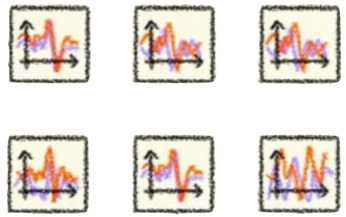


SO SAT Data Analysis: Classic CMB Data Analysis Pipeline





PRE-PROCESSING



Time-ordered data (TODs)

Clean the raw time-ordered data by removing **glitches**, **drifts**, and **atmospheric contamination**.

drawings: Eve Barlier

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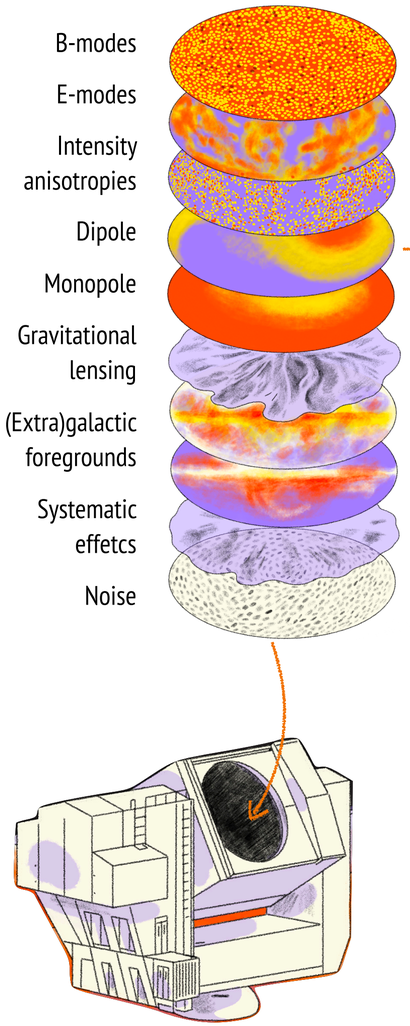

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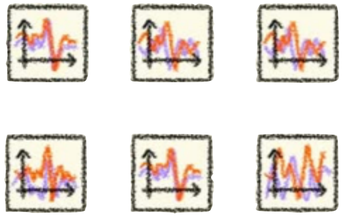

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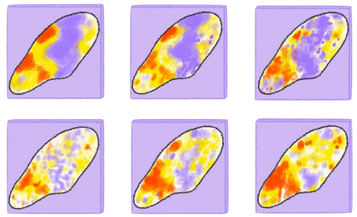
MAP-MAKING



Frequency maps

Re-project TODs to **map domain** to produce **per-frequency sky maps** containing CMB and astrophysical foregrounds.

drawings: Eve Barlier

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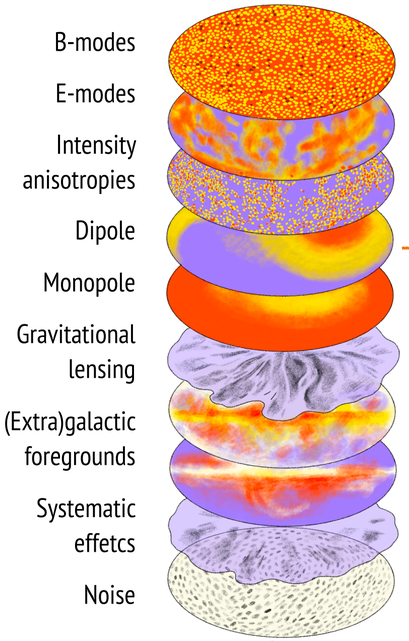

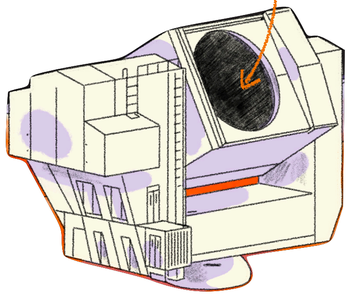

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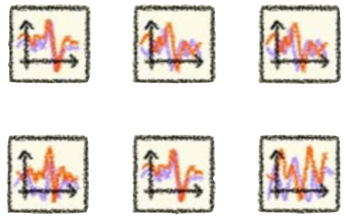

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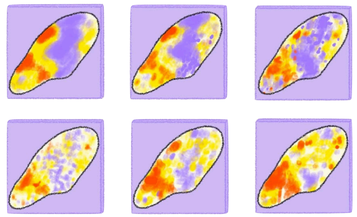

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COMPONENT SEPARATION

Component maps

Separate the CMB signal from astrophysical foregrounds to produce a **clean CMB map**.

drawings: Eve Barlier

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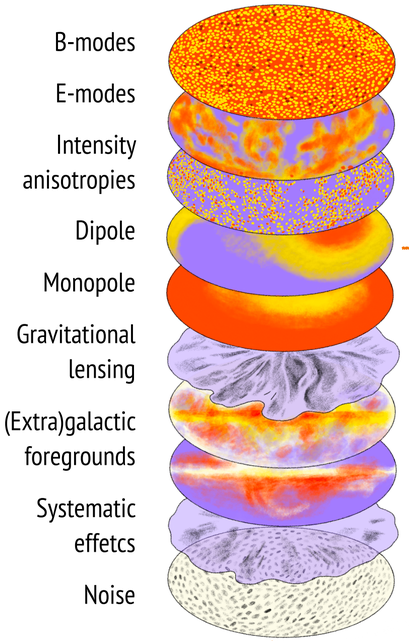

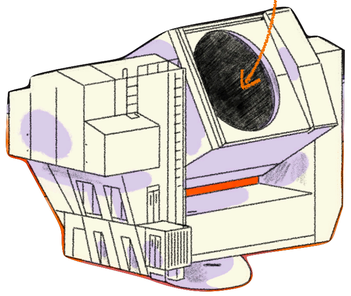

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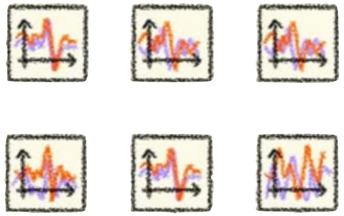

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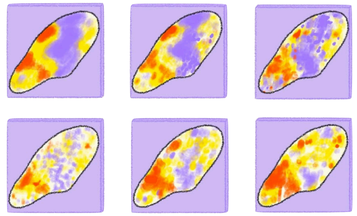

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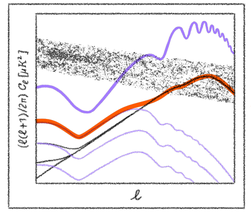
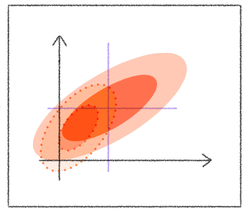


Power spectra

Compute the angular **power spectrum** from the extracted CMB map

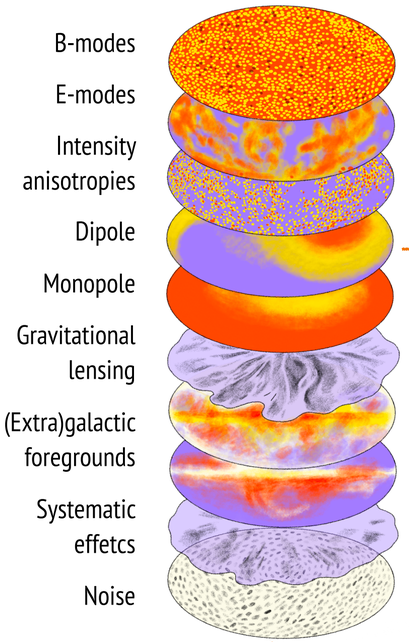


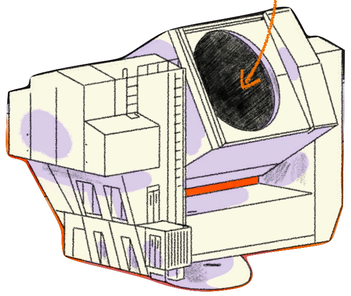
Cosmological parameters

Compare the measured power spectrum to theoretical models through a **likelihood** analysis to **infer cosmological parameters**.

drawings: Eve Barlier

SO SAT Data Analysis: Classic CMB Data Analysis Pipeline





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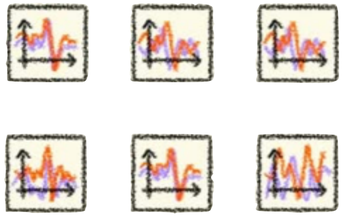

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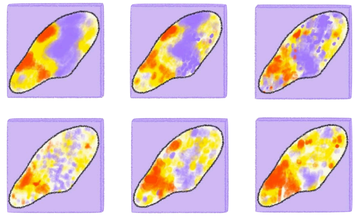

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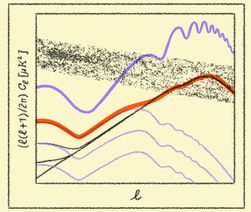

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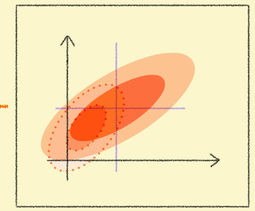

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drawings: Eve Barlier

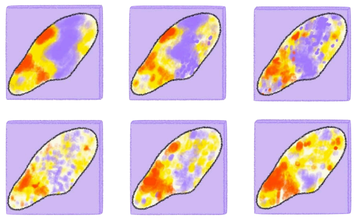
SO SAT Data Analysis: Pipelines Overview (SOOPERCOOL)

- Three main pipelines are developed in SO to perform the analysis from frequency maps to cosmological parameters: **Cross-C_ℓ pipeline** (SOOPERCOOL), **Map-based pipeline** (MEGATOP) and **Needlet-ILC pipeline** (NILC);
- These pipelines rely on **different assumptions and methods**, making them powerful **cross-checks** of one another and increasing our confidence in the final results.

SOOPERCOOL

- **Baseline** pipeline applied to SO SAT initial science data;
- Based on a multi-frequency, **power spectrum based** component separation method.

→ baseline BICEP/Keck [1]



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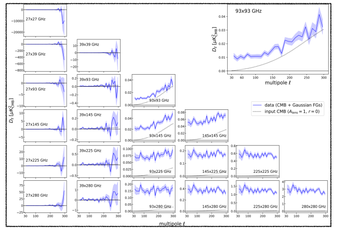
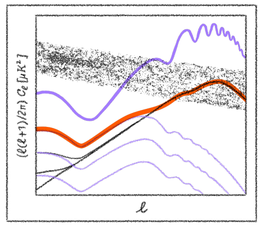
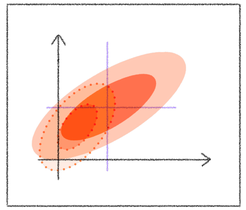


Compute the full set of cross-power spectra between all frequency maps



Propagate the map-level sky model to the power spectrum level.



Compare estimated vs. modeled power spectra through a likelihood to sample cosmological and foreground parameters.

[1] BICEP/Keck Collaboration 2018

drawings: Eve Barlier

— SO SAT Data Analysis: Pipelines Overview (MEGATOP)

- Three main pipelines are developed in SO to perform the analysis from frequency maps to cosmological parameters: **Cross-C$_\ell$ pipeline** (SOOPERCOOL), **Map-based pipeline** (MEGATOP) and **Needlet-ILC pipeline** (NILC);
- These pipelines rely on **different assumptions and methods**, making them powerful **cross-checks** of one another and increasing our confidence in the final results.

MEGATOP

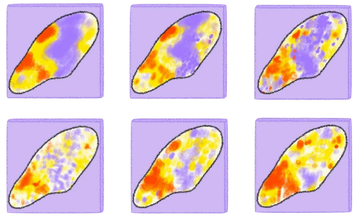
PIPELINE DEVELOPED AT APC (PARIS) WITHIN THE SciPol PROJECT

And more!

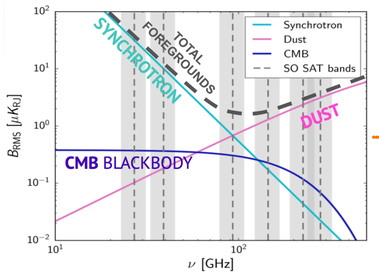
MEGATOP

- Used for **cross checks** of the SOOPERCOOL pipeline;
- Based on a multi-frequency, **map-based** component separation method.

→ similar formalism used in BICEP/Keck 2018 + Planck reanalysis [2]

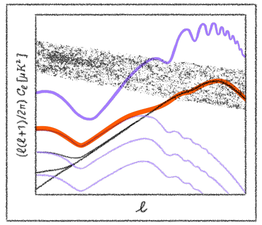


Frequency maps

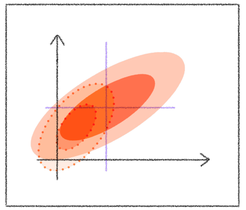


Estimate foreground spectral parameters by minimizing the spectral likelihood

Construct component separated maps (CMB, dust, synchrotron)



Compute the angular power spectrum of each sky component.



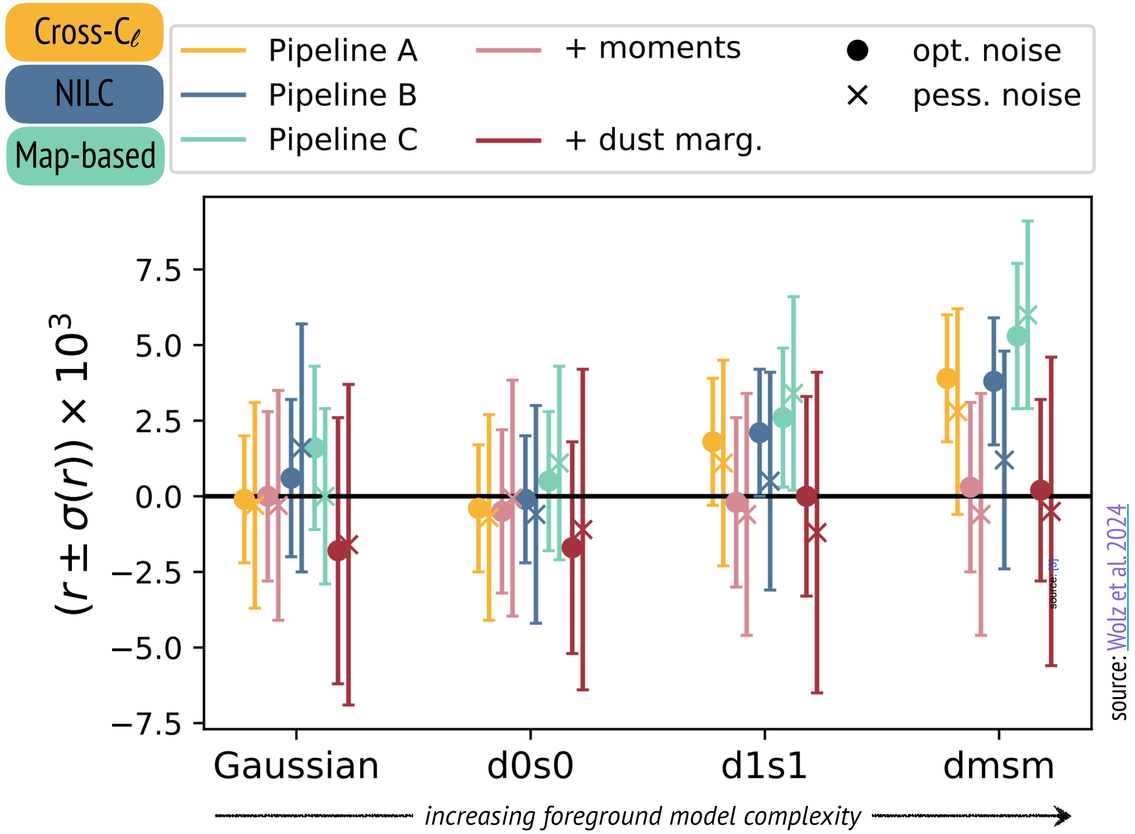
Estimate cosmological parameters by sampling a likelihood.

[2] BICEP/Keck Collaboration 2025

drawings: Eve Barlier

SO SAT Data Analysis Pipelines: Pipelines Overview

These 3 pipelines have been **validated on simulations**; they all achieve unbiased estimates of r across different levels of foreground complexity.



Conclusions

- **SATp1 and SATp3** have accumulated approximately one year of early science data, with per-detector sensitivities meeting or exceeding baseline targets. **SATp2** is currently being commissioned.
- The **data analysis pipeline has been demonstrated** end-to-end and continues to be refined, with first science results potentially expected by the end of this year.
- Three additional SATs are scheduled for **deployment in late 2026/early 2027**, with observations expected to begin in 2027.
- Watch out for **upcoming commissioning and early data papers**!