



Drone-borne calibration of the Simons Observatory Small Aperture Telescopes with POLOCALC

Nadia Dachlythra, 31.03.26

Università degli Studi di Milano-Bicocca

(Some of the) CMB experiments

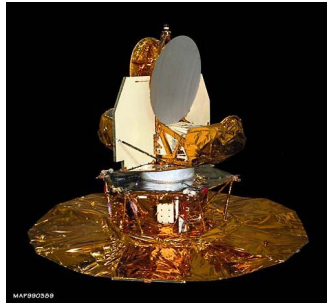
COBE, 1989



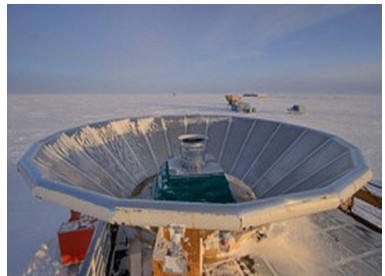
BOOMERanG, 1997



WMAP, 2001



BICEP(1), 2006



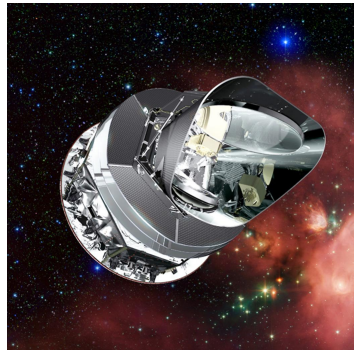
ACT, 2007



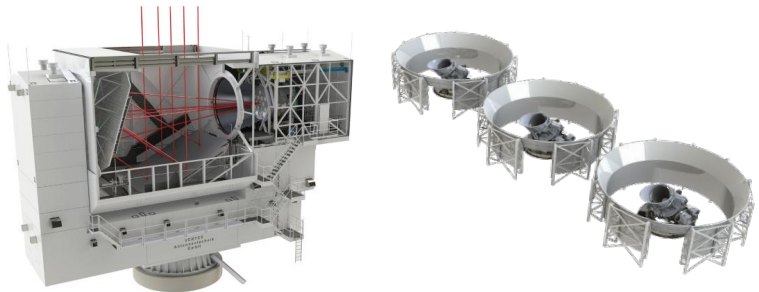
SPIDER, 2015



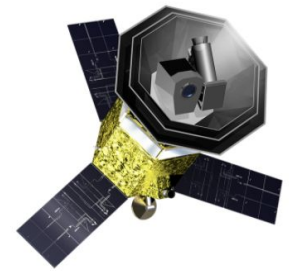
Planck, 2009 (1st)



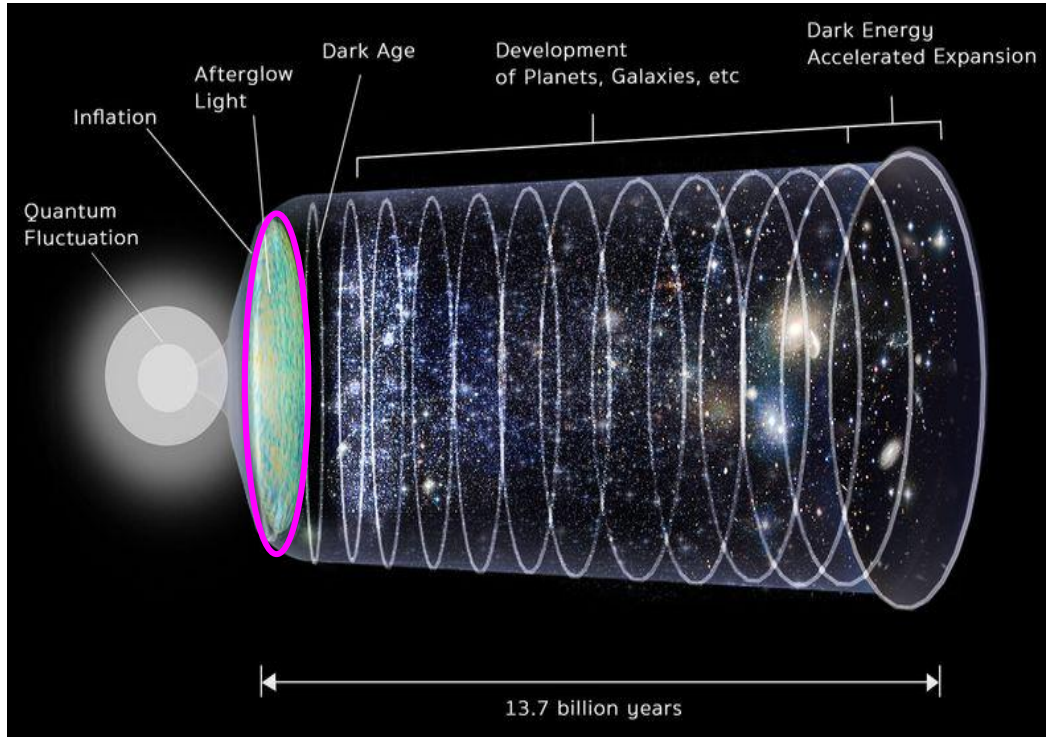
The Simons Observatory, LAT and SATs
(under deployment)



LiteBIRD, \approx 2030



Space story time



**Vacuum fluctuations
during inflation**



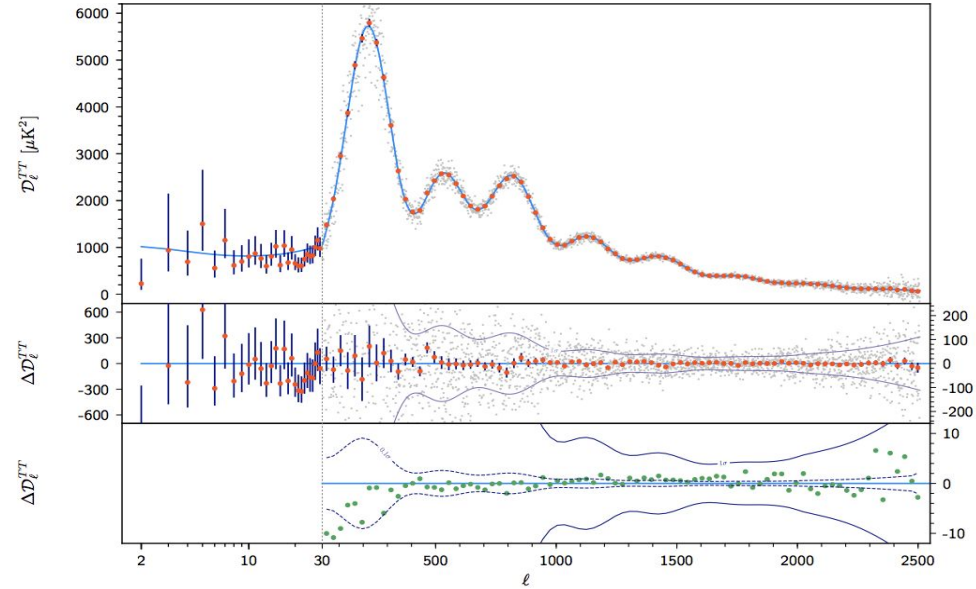
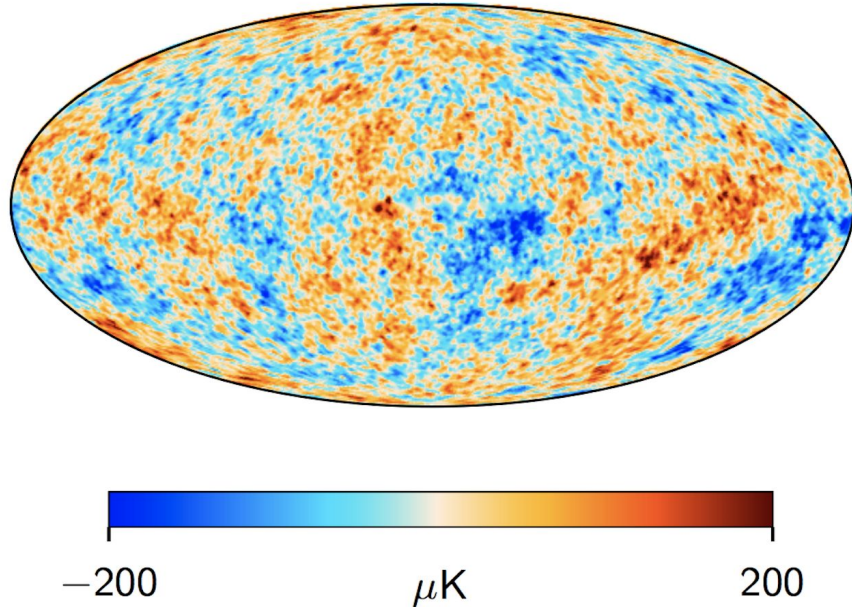
Density perturbations



gravitational collapse

Large-scale structure

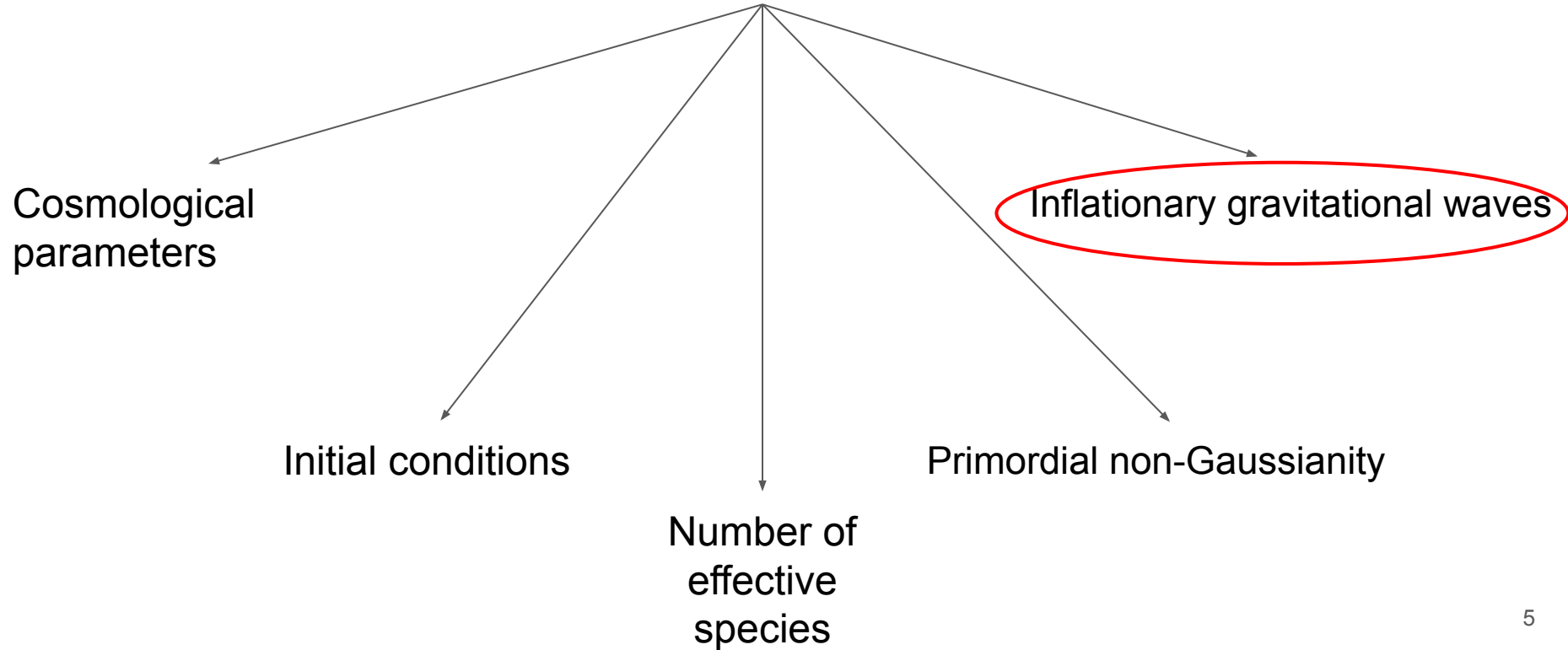
The CMB power spectrum



*Credit: Planck 2018 results. VI. Cosmological parameters
IV. Diffuse component separation*

What information can we draw from the CMB?

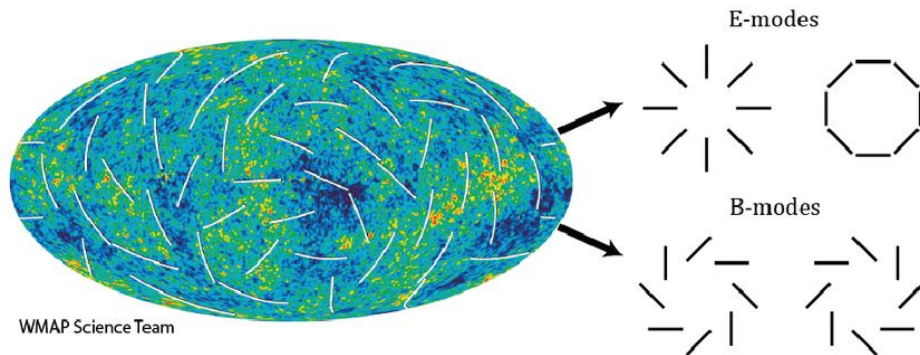
CMB temperature and polarization anisotropies



The CMB polarization

- CMB linear polarization: Thomson scattering of photons by free electrons.
- Circular polarization is not expected.
- E-modes:
 - strong, parity-even, curl-free
 - scalar and tensor perturbations
- B-modes:
 - faint, parity-odd, divergence-free
 - only tensor perturbations

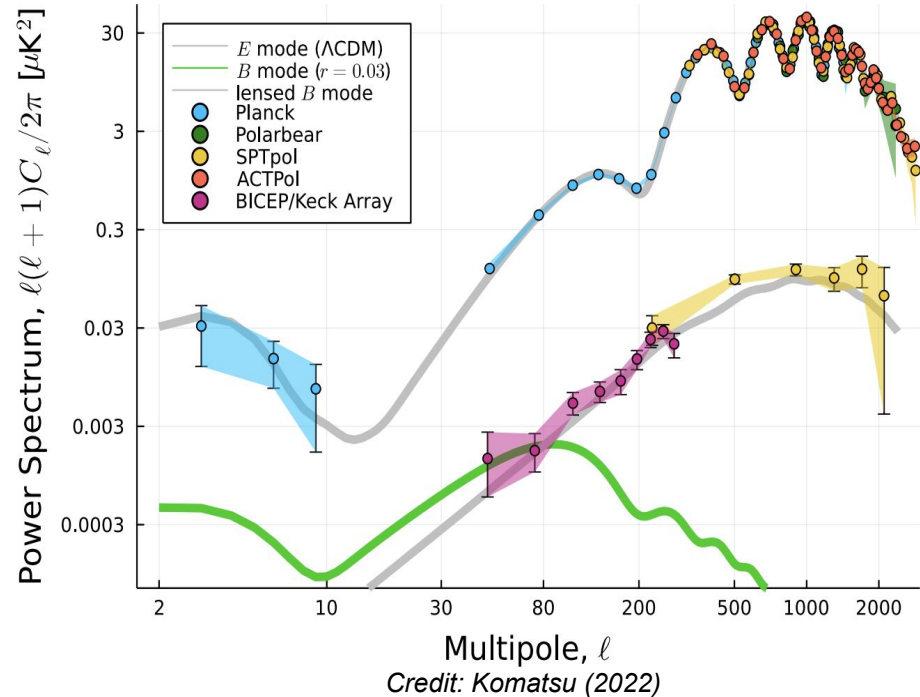
- CMB polarization $\sim 10^{-2}$ · CMB temperature.



Credit: Essinger-Hileman et al. 2020, WMAP collaboration

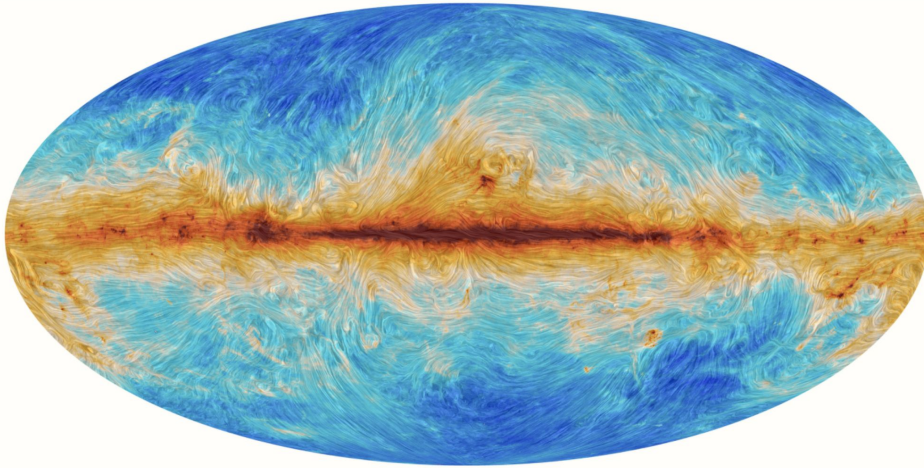
B-modes as imprint of inflationary gravitational waves

- Inflationary gravitational waves \rightarrow metric tensor perturbations.
- Tensor-to-scalar ratio, r : the ratio of the tensor to scalar perturbations amplitude.
- The latest constraints on r come from the BICEP/Keck 2018 and Planck PR4 data: $r < 0.032$ at a 95% confidence level ([Tristram et al. 2022](#)).
- The SO telescopes : $\sigma(r) \leq 0.003$.
- LiteBIRD : $r > 0.003$ detection with a statistical uncertainty $\sigma(r) < 0.001$.

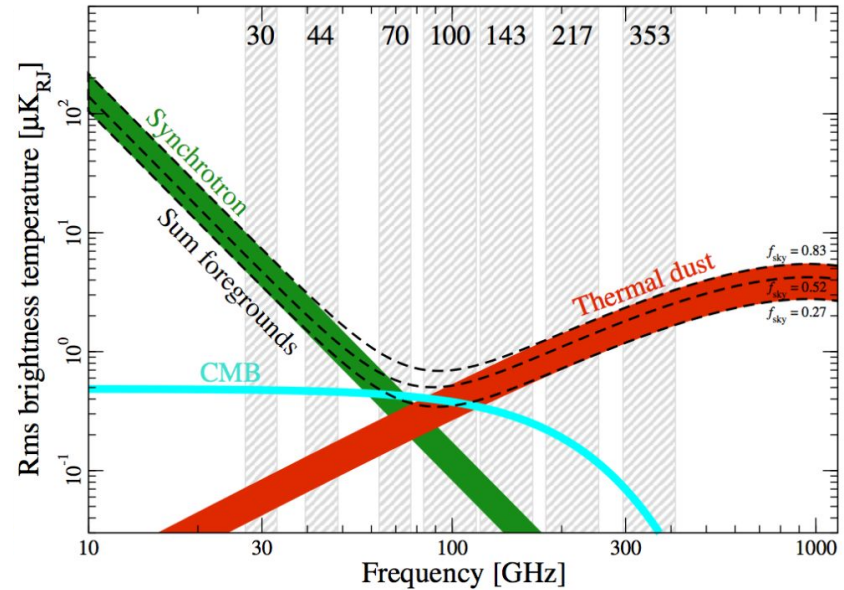


Problems to tackle: I. Foregrounds

- Thermal Dust Emission \rightarrow high frequencies & Synchrotron emission \rightarrow low frequencies.
- Increasing the frequency coverage allows for a better understanding/modeling of the foregrounds.

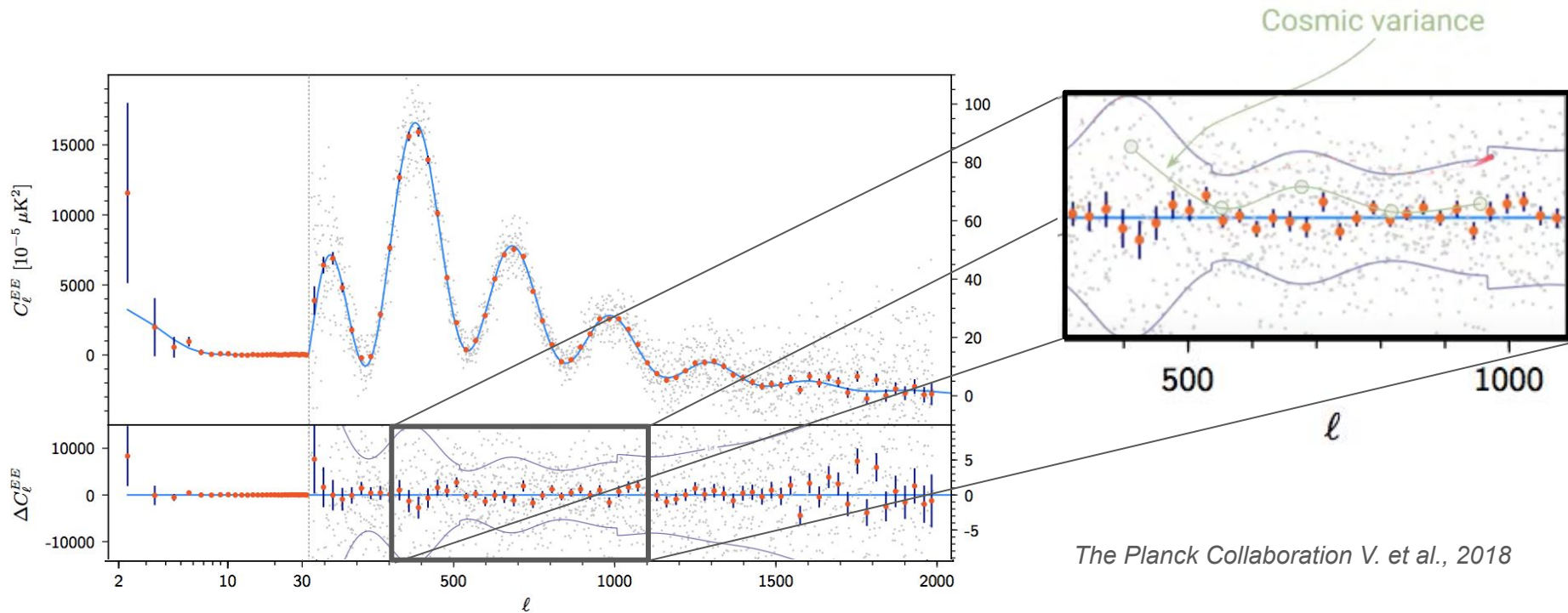


Credit: Planck Collaboration 2015



Credit: Planck Collaboration 2018, XI.

Problems to tackle: II. Noise



The Planck Collaboration V. et al., 2018

Problems to tackle: III. Systematics

- There are various types of systematic:
 - Electric
 - Thermal
 - **Optical**
- If not properly modeled they can mask the faint primordial signal.
- Two main categories of optical systematics are the *beam and polarization angle systematics*.

How do these impact the cosmological analysis?

How does pol. angle miscalibration manifest in cosmological analysis?

- The orientation that specifies how the instrument's polarization-sensitive detectors measure the linear polarization direction of the incoming microwave radiation.
- A polarization angle error would manifest as a uniform rotation across all multipoles, mixing the E and B components.
- This would be indistinguishable from a signal attributable to isotropic cosmic birefringence ([Komatsu, 2022](#)): parity-violating process in which a pseudoscalar field is coupled to CMB photons via the Chern-Simons term.

Beams (Point-Spread-Functions)

- Telescope's response to a point source \rightarrow depends on the instrument design.
- CMB telescopes often have circular apertures \rightarrow E/M gets diffracted \rightarrow Airy pattern.
- Ideal beam: no sidelobes + no cross-polarization.

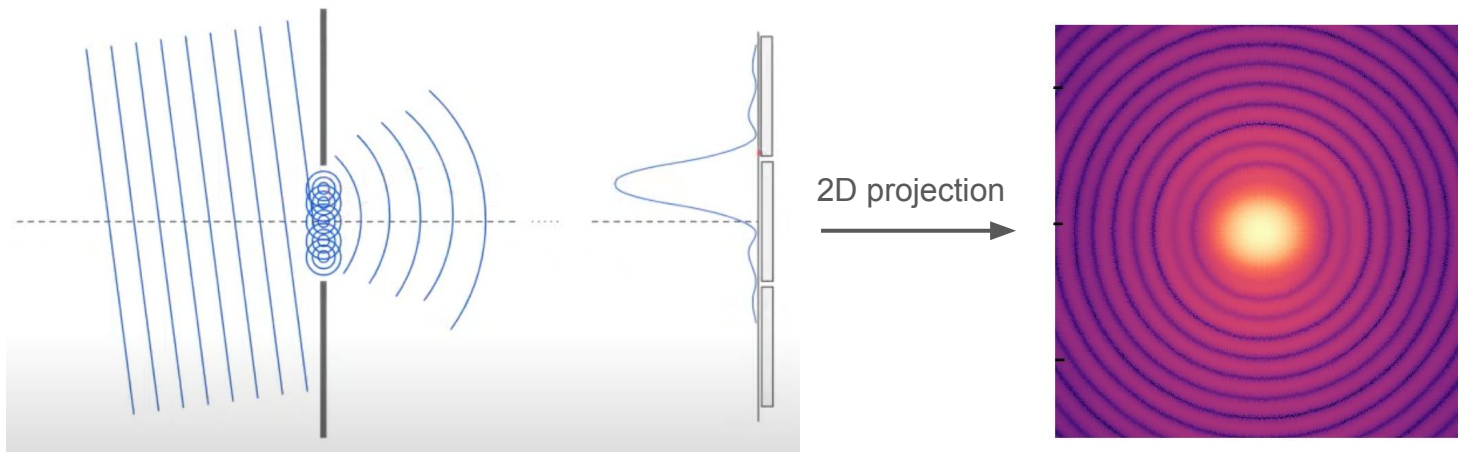


Figure credit: Jon E. Gudmundsson

Beam modeling

- Beam map $\xrightarrow{\text{Radial binning}}$ Beam profile, $B(\theta)$ [dB] $\xrightarrow{\text{Legendre transform}}$ Beam transfer function, B_ℓ .

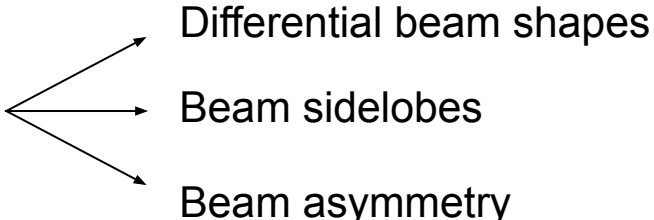
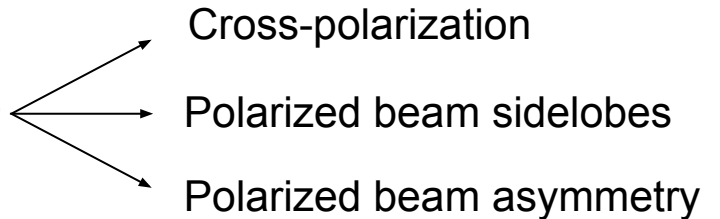
- The measured spectra, \tilde{C}_ℓ , are connected to the true spectra, C_ℓ , as:

$$\langle \tilde{C}_\ell \rangle = \sum_{\ell'} M_{\ell\ell'} F_{\ell'} B_{\ell'}^2 \langle C_{\ell'} \rangle + \langle \tilde{N}_{\ell'} \rangle$$

F_ℓ : filter function, N_ℓ : Fourier transform of the noise covariance matrix, $M_{\ell\ell'}$: mode-mixing kernel.

- The beam deconvolution commonly happens by dividing the measured spectra by the beam transfer function.

How do beam systematics manifest in cosmological analysis?

- $T \rightarrow P$ (Temperature-to-Polarization) leakage 
 - Differential beam shapes
 - Beam sidelobes
 - Beam asymmetry
- $E \rightarrow B$ (mixing of polarized components) leakage 
 - Cross-polarization
 - Polarized beam sidelobes
 - Polarized beam asymmetry

Astrophysical sources

- Planets are common candidates for beam calibration ([Weiland et al. 2011](#), [The Planck Collaboration VII et al. 2013](#), [Hasselfield et al. 2013](#), [Lungu et al. 2022](#), [Dachlythra et al. 2023](#)).
- The Moon is also a promising candidate for calibrating beam sidelobes but can saturate the telescope's detectors ([Xu et al. 2020](#)).
- Planets are not always available for observations using ground experiments.
- Not all planets are bright enough to calibrate the beam response of every CMB telescope.
- Tau A (Crab Nebula), with a measured angle of uncertainty 0.33° is the only natural polarized source that can be used for angle calibration ([Kusaka et al. 2018](#), [Aumont et al., 2018](#), [Masi et al., 2021](#)). However modern experiments require 0.2° ([Abitbol et al., 2021](#)). Alternative methods use a sparse wire grid ([Nakata et al. 2025](#)) or EB nulling ([Krachmalnicoff et al., 2021](#)).



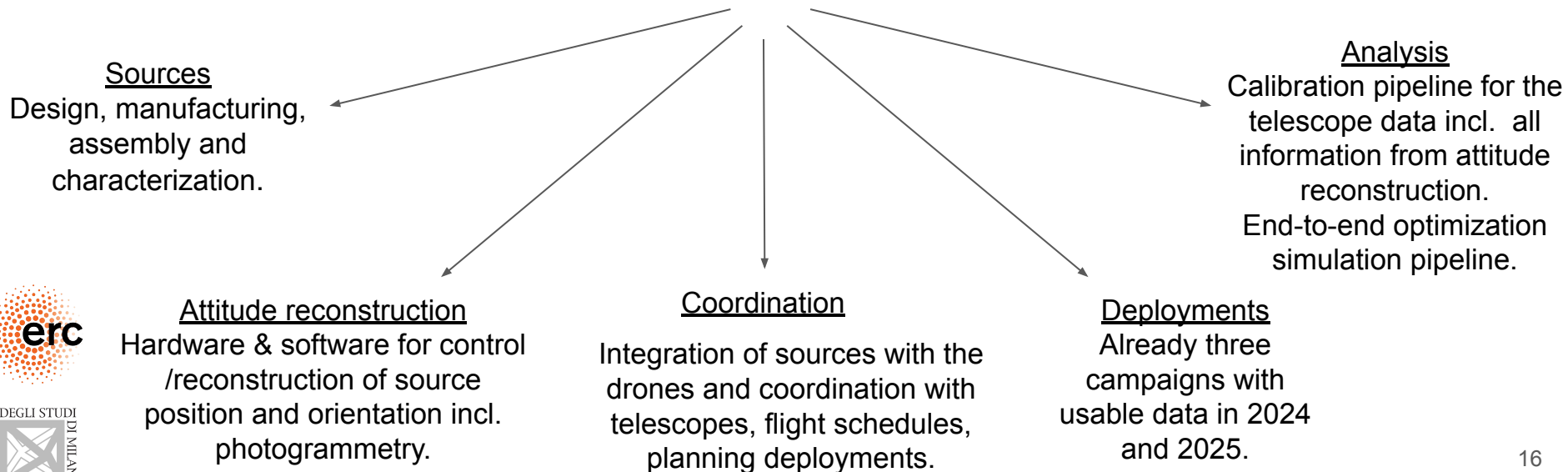
P L C L C

F. Nati, ERC Advanced Grant #101096035

[Nati et al., 2017](#), [Coppi et al., 2022](#), [Coppi et al., 2025](#)

F. Nati, M. Zannoni, G. Coppi, N. Dachlythra, A. Novelli, T. Souverin, F. Cacciotti, L. Bizzarri, F. Astori, G. R. Cattaneo, N. Mezzananza (MIB), R. Dunner, M. Rojas, M. Donoso, C.H. Hervias, (Catolica) E. C. Shaw, JB Lloyd, N. Galitzki +++

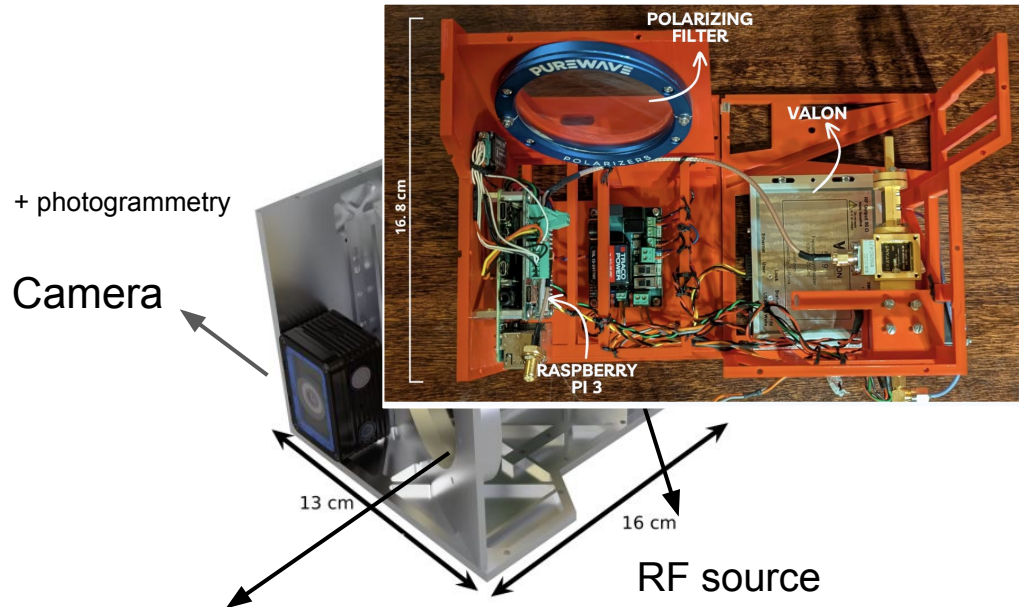
Absolute polarization angle calibration accuracy baseline 0.1° and goal 0.01° & beam calibration



Advantages and challenges inherent to this method

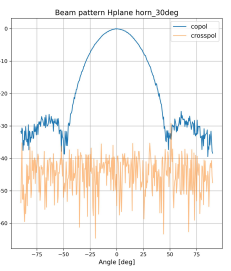
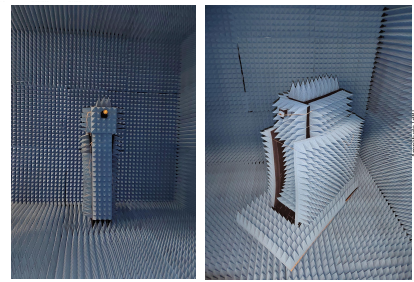
- A fully-controlled calibration source that is in principle always available for observations.
- The emitted signal is modulated at specific frequency → not mixed with other contaminants → very high SNR
- The source can account for the parts of the focal plane for which planet observations were challenging.
- Narrow-band signal allowing to study the frequency scaling of the beam ([Dachlythra et al., 2025](#)), polarization angle, HWP properties inside the wide observing bands.
- Limited flight time due to the life of the lithium batteries → need to optimize drone/ telescope parameters for maximum coverage.
- The thermal emission of the drone can saturate the detectors for the higher frequency bands → need to send the drone further out → not very safe.
- Limitations to the distance at which we can fly the drone making it impossible to do far-field calibration for telescopes with large aperture (e.g. SO LAT).
- Dangerous to fly with wind speed > 15 km/h.

Drone and source system



Wire-grid

Align source polarization with the camera



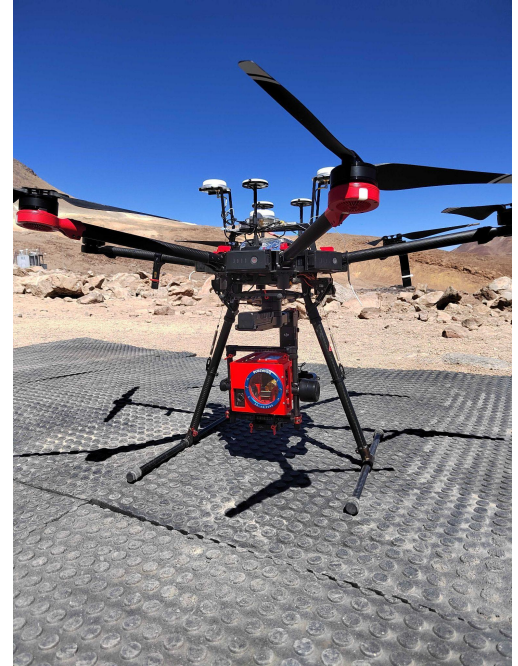
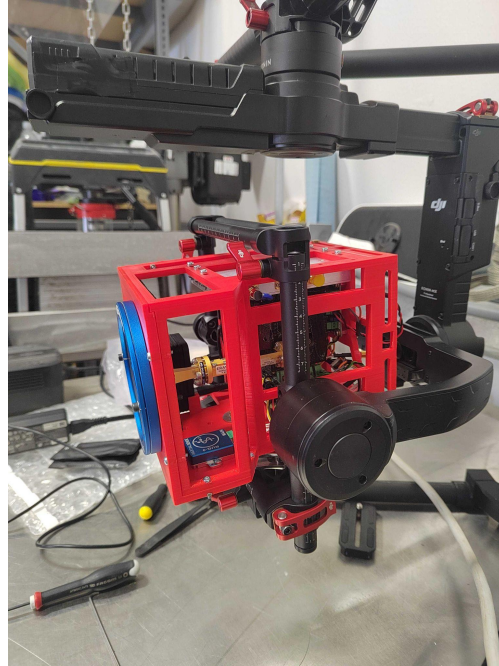
Credit: L. Bizzari

Gimbal

Stability within sub-degree

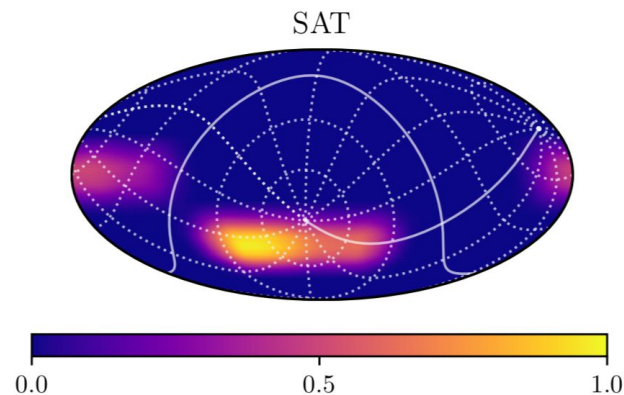
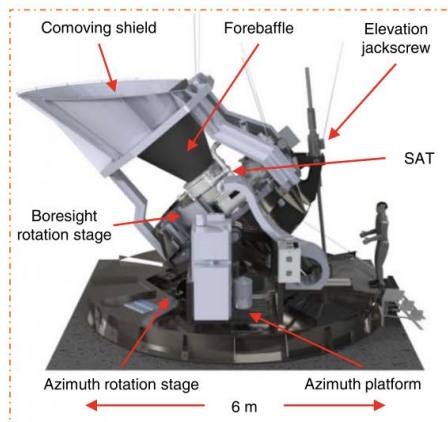
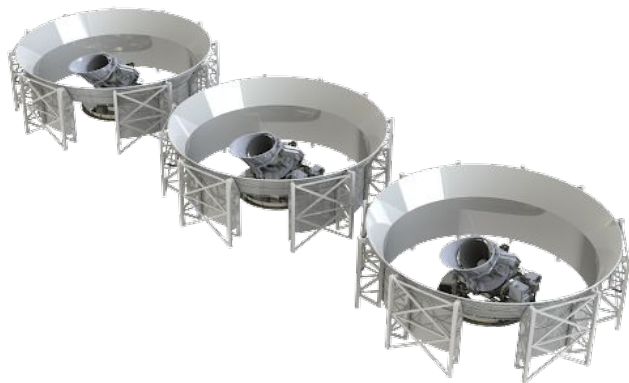


Drone and source system



The Simons Observatory Small Aperture Telescopes (SO SATs)

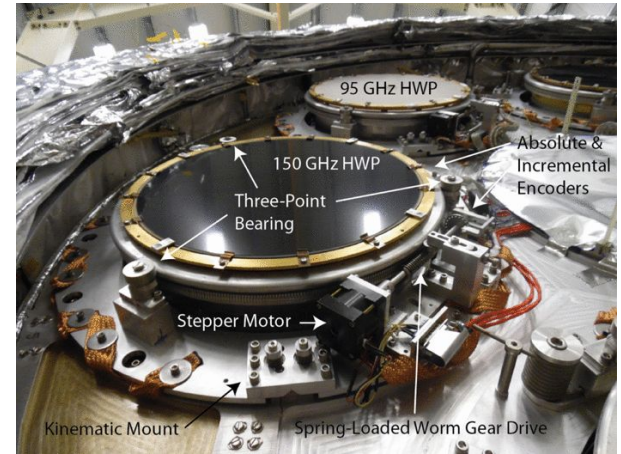
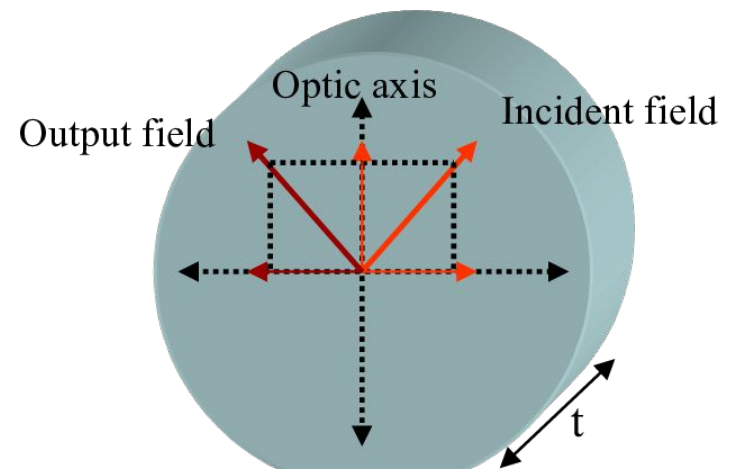
- Scientific goal: constrain the tensor-to-scalar ratio, r , at a target level of $\sigma(r) = 0.003$.
- Six frequency bands centered on 27, 39, 93, 145, 225 and 280 GHz (roughly 25% bandwidth).
- Each SAT will cover approx. 10% of the full sky, observing from the Atacama Desert in Chile.
- Optics-wise: 3-lens refracting telescope equipped with a Half-Wave-Plate (HWP)**.



*Credit: The Simons Observatory
Collaboration and Hensley et. al, 2021*

Half-Wave Plates (HWPs)

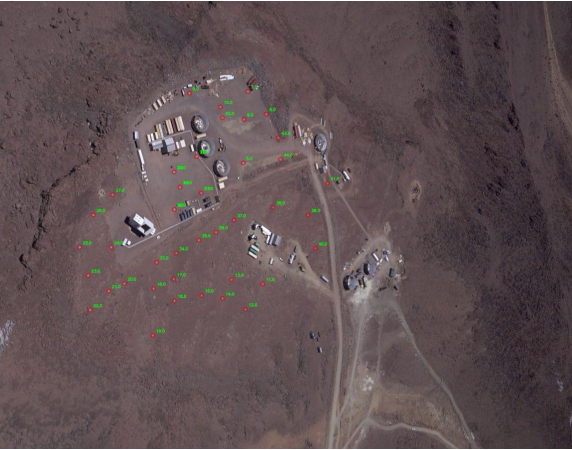
- HWPs are polarization modulators commonly used in CMB experiments : POLARBEAR, SPIDER, SO Small Aperture Telescope (SAT), LiteBird.
- They are composed of birefringent materials that shift the polarization angle of the linearly polarized light (for example sapphire).
- By definition a HWP will modulate the polarized signal at $4 \cdot f_{\text{HWP}}$. Non-ideal HWPs can carry other contributions: $1f_{\text{HWP}}$, $2f_{\text{HWP}}$



Credit: [Bryan et al., 2018](#)

A typical calibration campaign

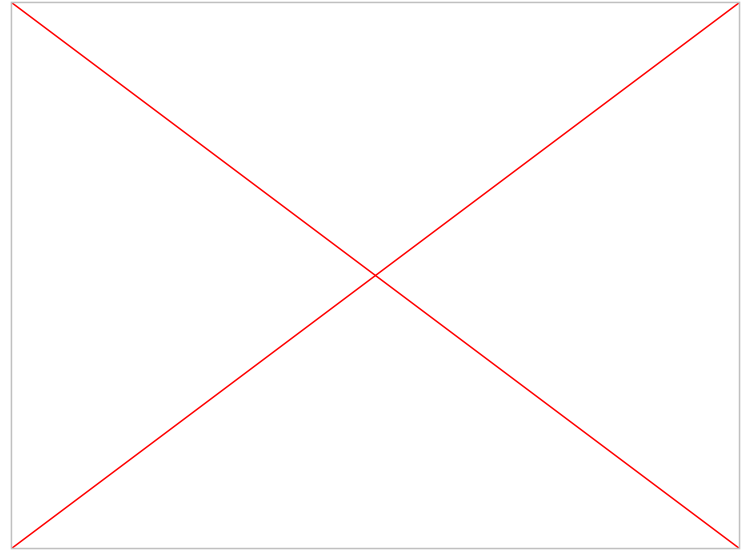
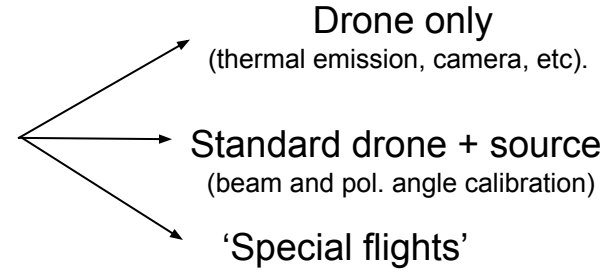
Setting the targets for the camera



Measure targets with the GPS



Start flights



A non-typical calibration campaign



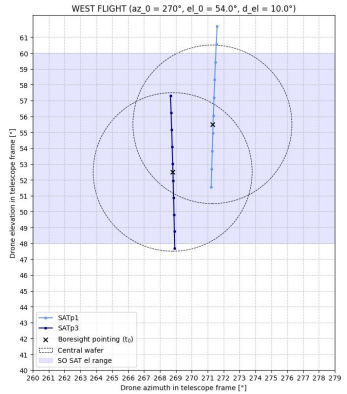
Scan strategy - improvements in the last year

Expectation

Reality

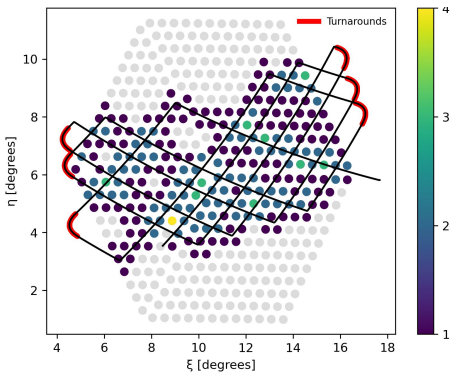
December 2024

Goal: Full center wafers
Just estimating positions



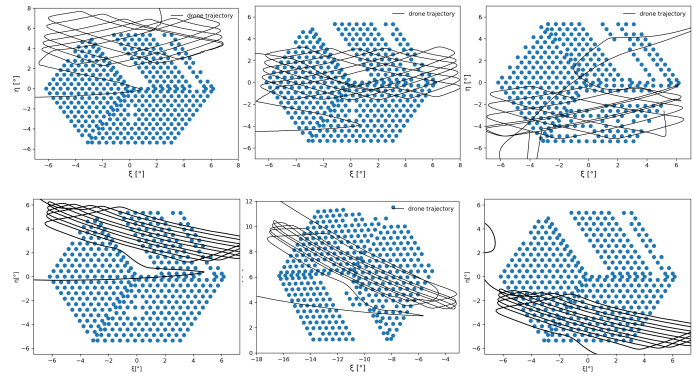
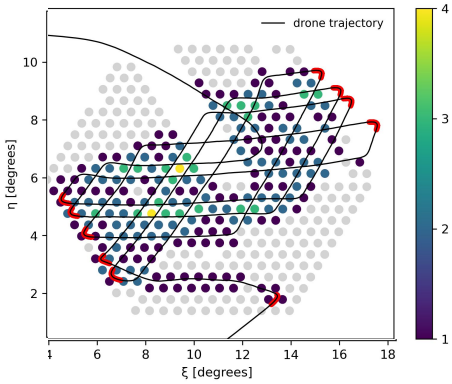
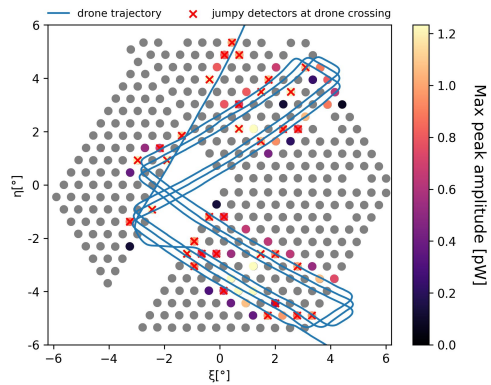
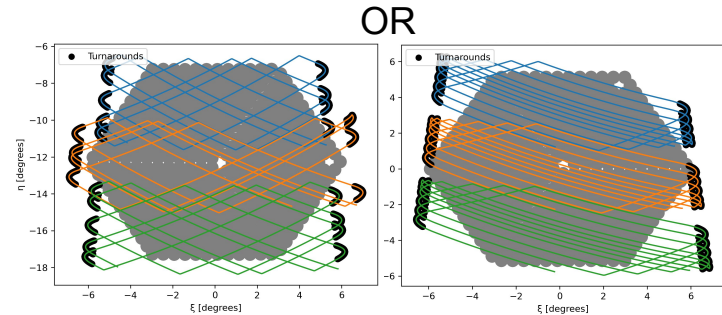
April 2025

Goal: Middle part of >1 wafer
Full simulation pipeline



December 2025

Goal: Different parts of >1 wafer
Full simulation pipeline



December 2025 campaign by the numbers

- Total of 102 flights during the full campaign,
- Total of 21 standard flights for satp1, ws0.
- Total of 36 standard flights for satp3, ws0.
- Total of standard flights for satp3, ws3.
- Flights with different source frequency, power and modulation frequency.
- Tests with new sources emitting at 150, 225 and 280 GHz bands.

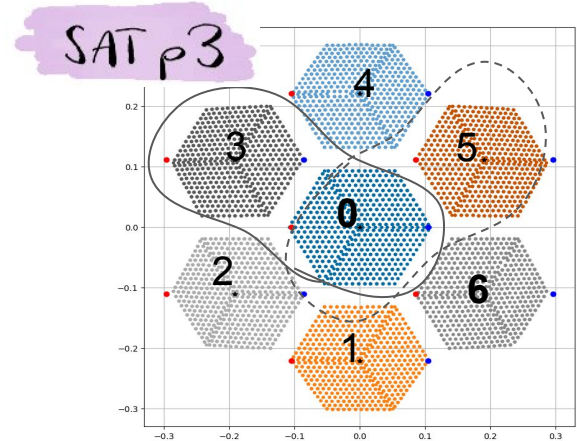
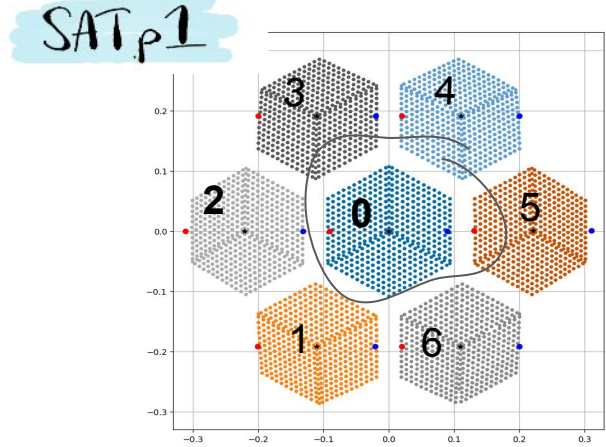
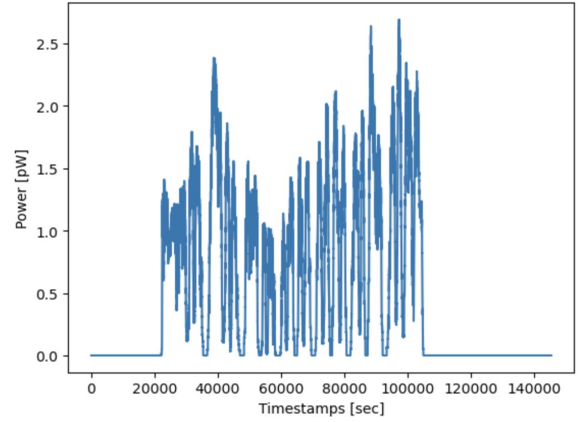


Figure credit: E. Shaw

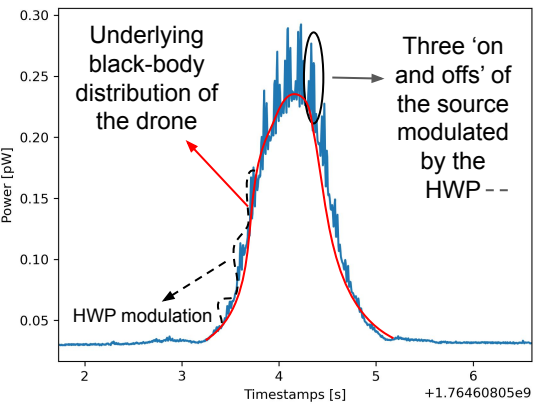
Data from a typical flight

*Plots refer to an example flight of satp1, center wafer at 93 GHz, the source signal is chopped at $f_{\text{chop}} = 37$ Hz.

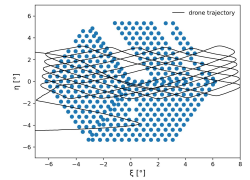
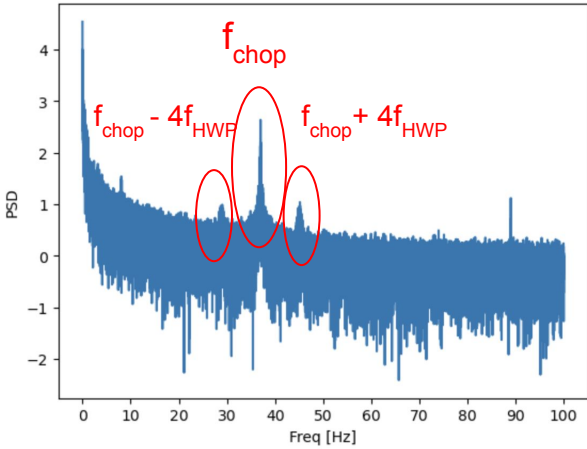
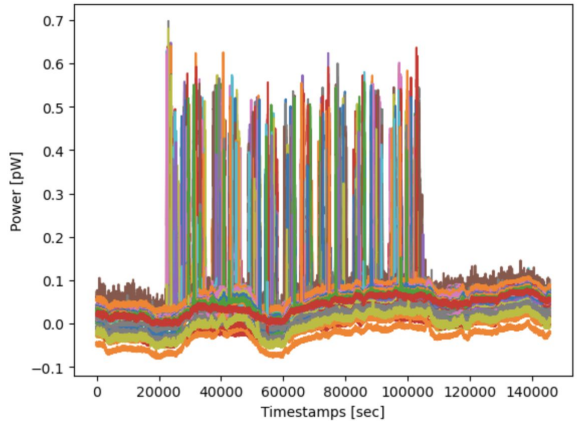
Masked and stacked signal



A typical crossing

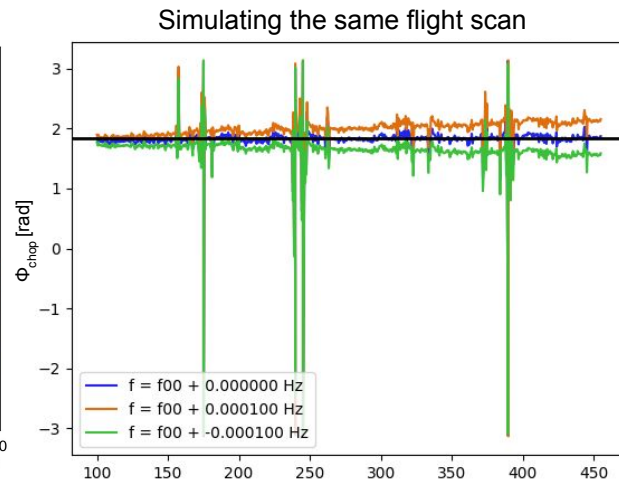
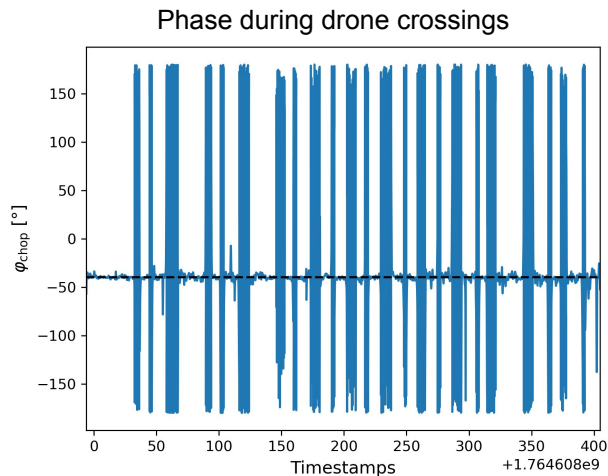
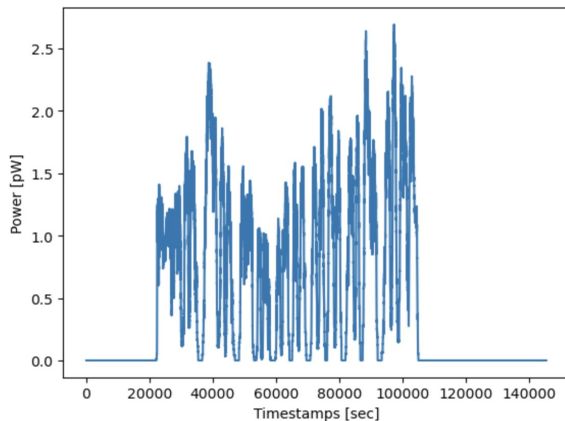


A typical flight



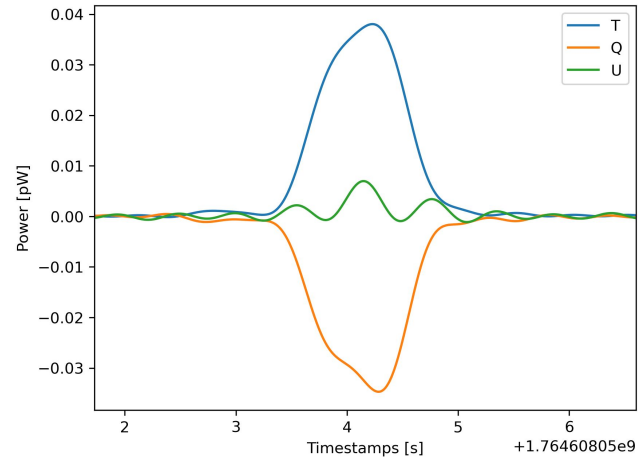
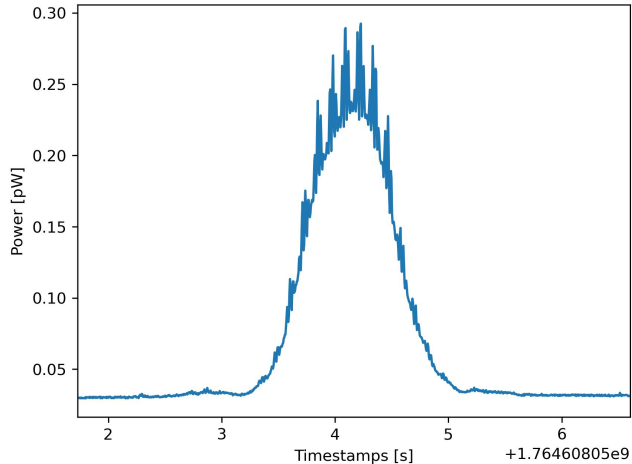
Analysis summary (II) - Fitting chopping frequency and phase

- To determine φ_{chop} and Δf_{chop} :
 - If d_{mod} is our reference, stacked signal, we first apply $d_{\text{demod}} = d_{\text{mod}} * \exp(2j * \pi * f_{\text{chop}} * (t-t_0))$.
 - We then low-pass (lp) the signal from 0 to 2 Hz = f_{HWP} to avoid any of the HWP systematics.
 - The phase is finally estimated as $\varphi_{\text{chop}} = \arctan2(\text{lp}(\text{Im}(d_{\text{demod}})), \text{lp}(\text{Re}(d_{\text{demod}})))$.
 - Deviations from the assumed f_{chop} will show up as a slope of the phase across time (also compared to the source data).



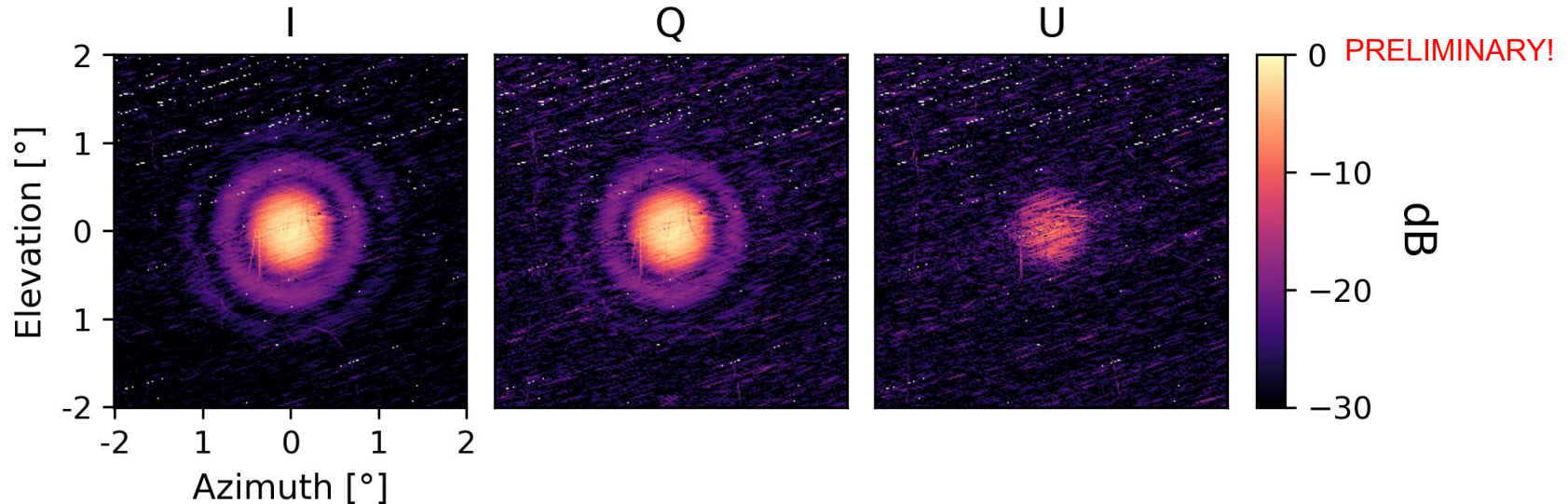
Modulated vs double-demodulated (chopper and HWP)

- To demodulate the chopper signal we apply to the initial TOD data (not the stacked version):
$$d_{\text{demod_c}} = d_{\text{mod}} * \exp(2j * \pi * f_{\text{chop}} * (t - t_0) + \varphi_{\text{chop}}).$$
- To demodulate the HWP:
 - We bandpass (bp) $d_{\text{demod_c}}$ between $[3f_{\text{hwp}}, 5f_{\text{hwp}}]$ and apply $\text{bp}(d_{\text{demod_c}})^* = \exp(4 * j * \theta_{\text{HWP}})$, where θ_{HWP} is read directly from the encoder.
 - We assign the real and imaginary parts of the double-demodulated signal to Q and U.
- We low-pass (independently) T, Q, U using a cut-off of $0.95 * f_{\text{hwp}}$.



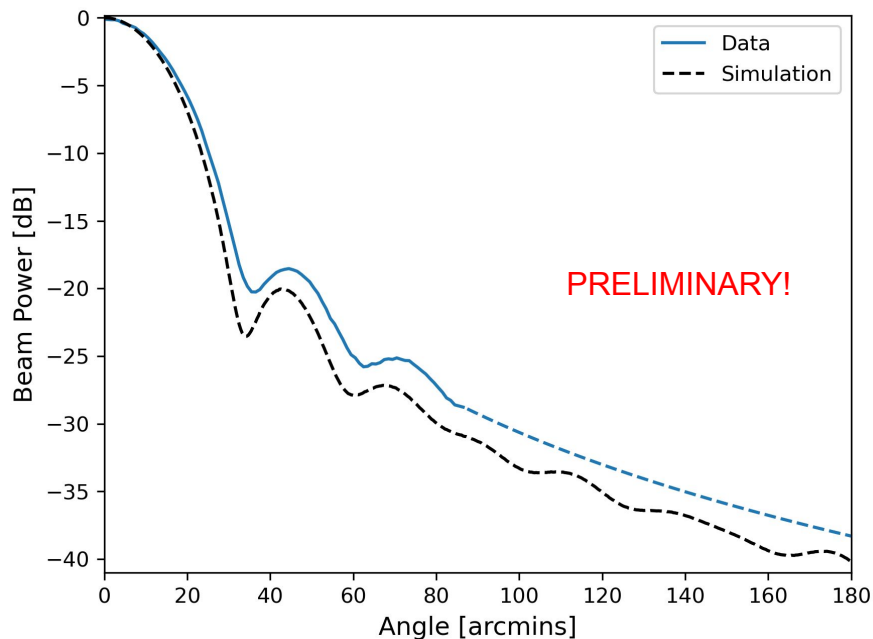
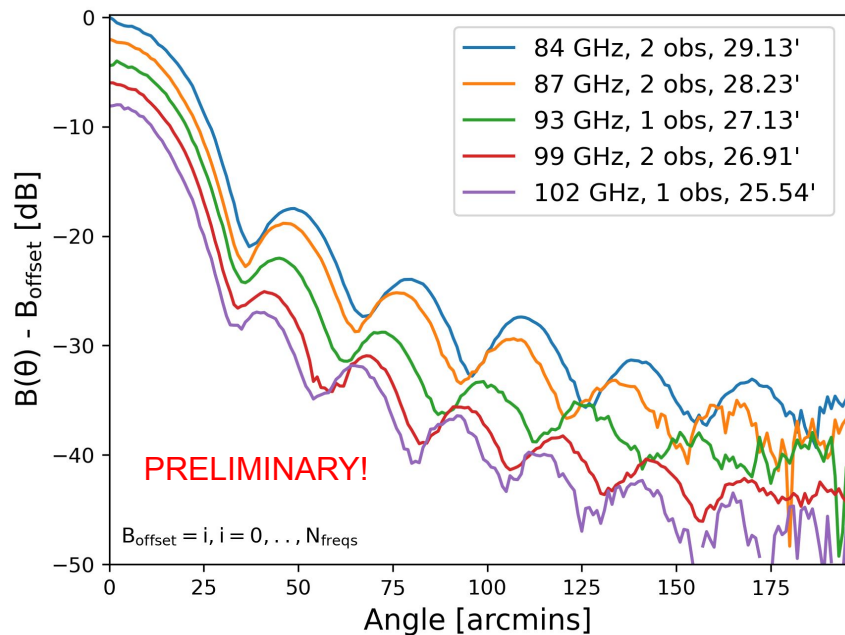
Absolute polarization angle calibration

- Pol. angle calibration $\theta = \frac{1}{2} \arctan(U, Q)$
- Relative polarization angle is estimated per crossing and averaged per detector.
- Absolute polarization angle is derived from the maps.
- In this case we find $\theta_{\text{data}} = 89.93^\circ$ while photogrammetry results suggest $\theta_{\text{ph}} = 91.58^\circ$.



Frequency-resolved beam calibration

- Typically done with planets (Jupiter and Saturn for SATs) → gray-bodies.
- With drone calibration, we measure the beam ‘from the inside out’ → novelty for CMB experiments → we can check for beam chromaticity ([see Dachlythra et al, 2025](#)).
- The simulation is done only for the boresight pixel, the beam ellipticity increases at larger radii.
- Increasing SNR will improve the agreement between data and simulation.

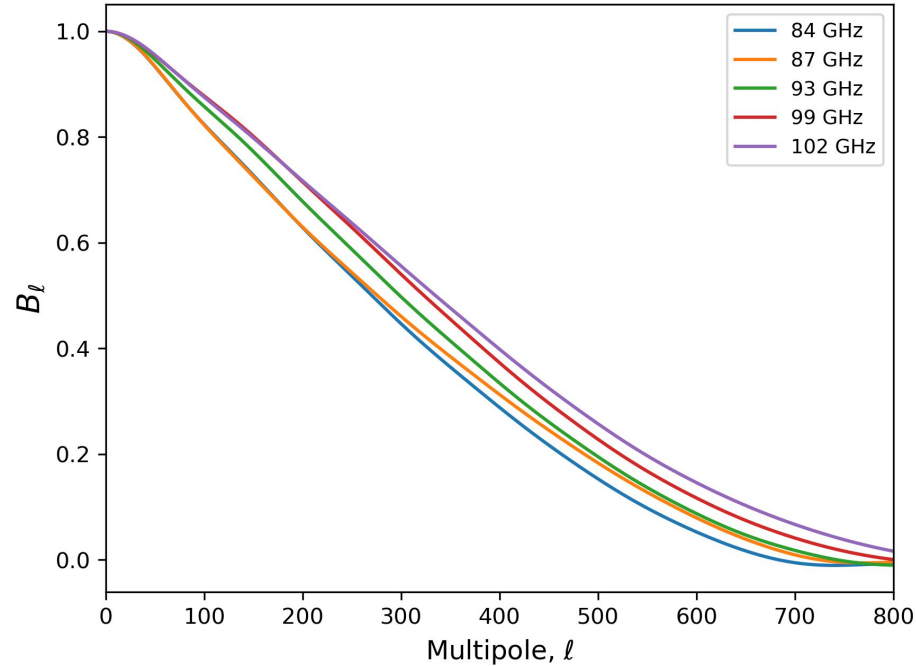


Chromaticity modeling

- We use the harmonic transform of measurements of different frequencies to construct a frequency-dependent beam transfer function model.
- We fit the data to the formalism employed in [Giardello et al., 2024](#), using $\ell > 150$ which is mostly informed by the higher SNR region of the beam profile:

$$b_{\ell, \nu} = \exp \left(-\frac{1}{2} \ell(\ell + 1) \left(\frac{\text{FWHM}(\nu)}{2\sqrt{2 \ln 2}} \right)^2 \right)$$

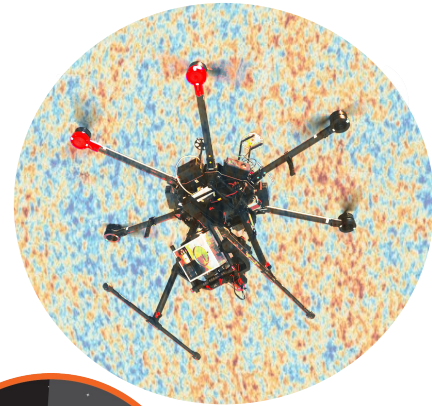
$$\text{FWHM}(\nu) = \text{FWHM}(\nu_0) \left(\frac{\nu}{\nu_0} \right)^{-\alpha/2}$$



...and find $\alpha = 1.59 \pm 0.02$

Future outlook

- Calibration of high-frequency bands → important for galactic foreground characterization.
- Dichroic sources, switching frequencies during the flight.
- Drones that can support longer flight times → more coverage.
- Improving the attitude reconstruction system.
- Polarization angles for all SAT platforms and arrays.



Thank you!