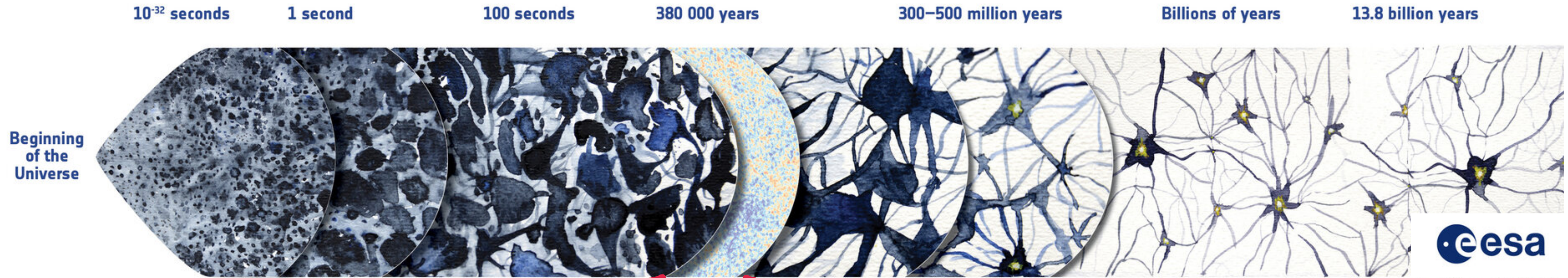


Calibration challenges for next generation CMB experiments

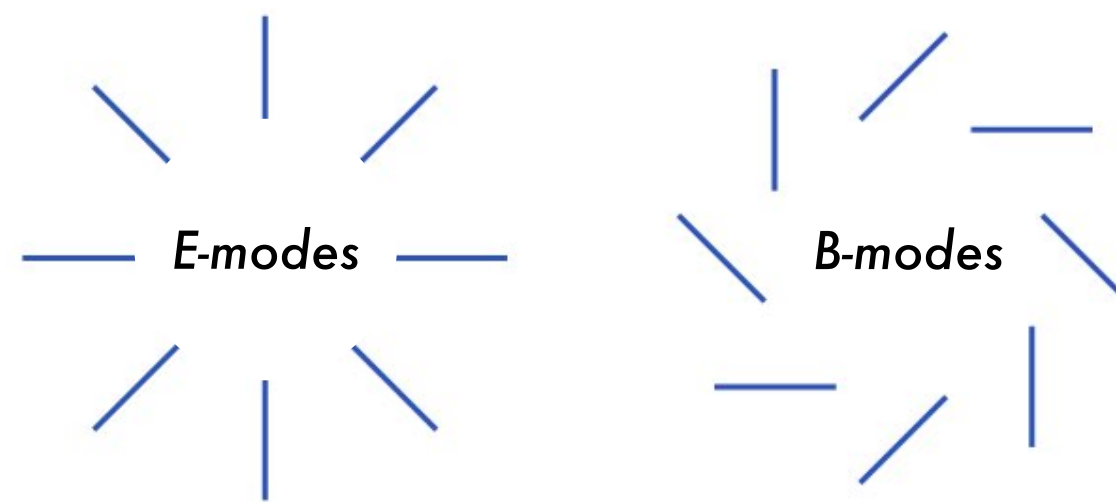
The Cosmic Microwave Background



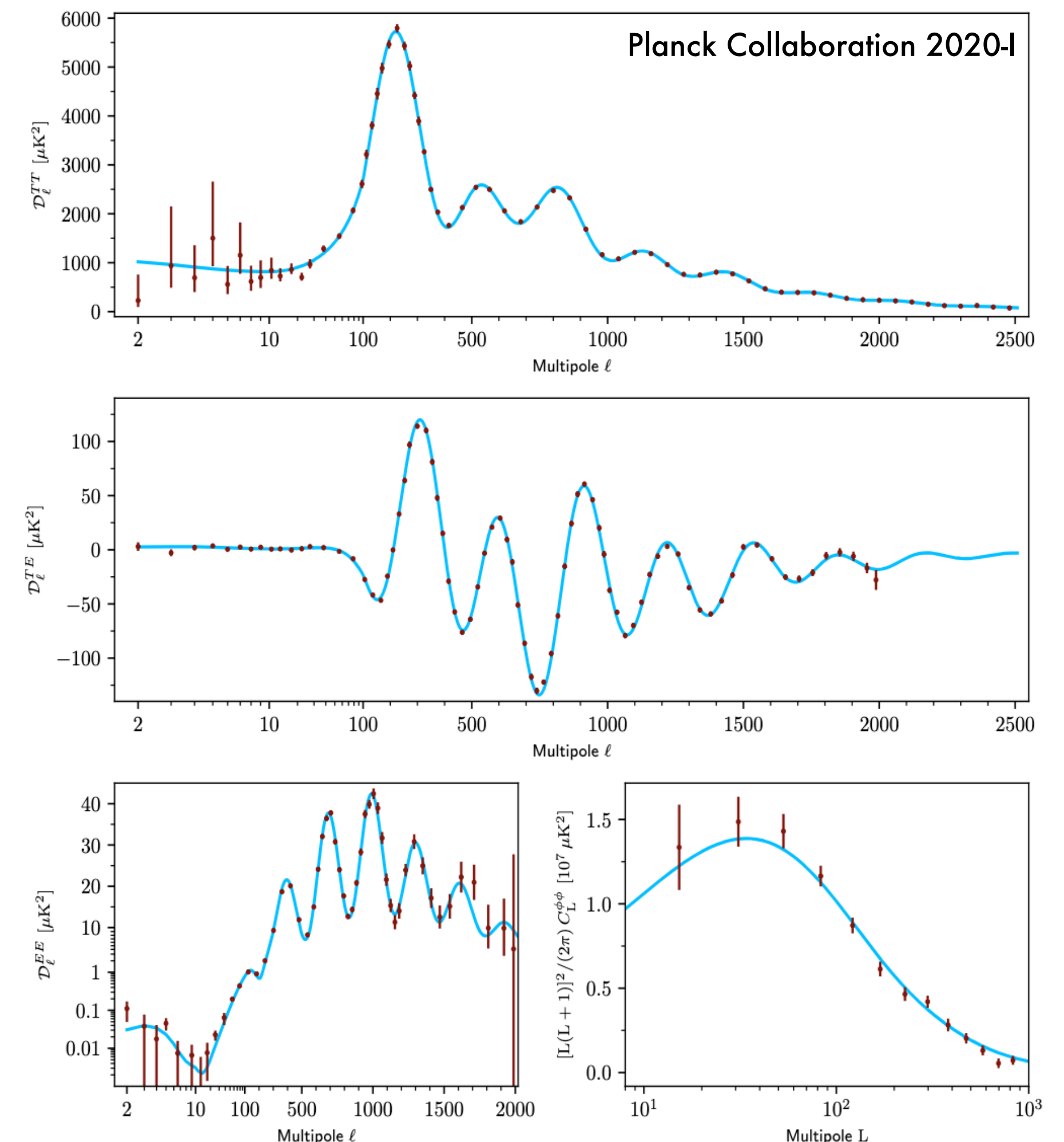
- The CMB photons released at recombination are observed today as a blackbody(-ish)
- Inflation stretched primordial fluctuations to astrophysical scales
- Their signature is imprinted in the CMB as temperature and polarization anisotropies

CMB temperature and polarization

- CMB radiation is linearly polarized
- We distinguish two patterns of different parity:

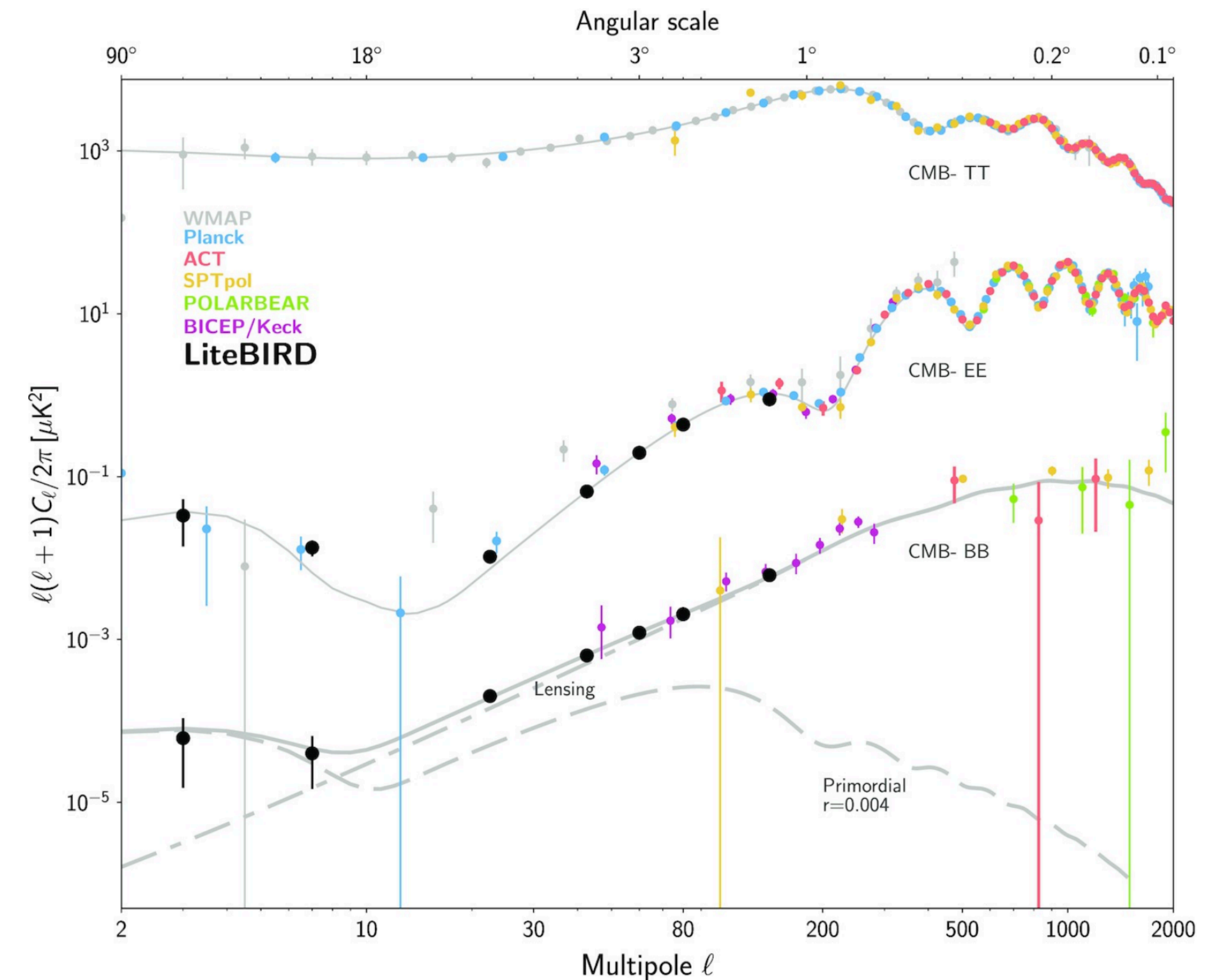


- Temperature anisotropies, E-mode polarization and lensing B-modes observations allowed for selecting the Λ CDM cosmological model as the standard one



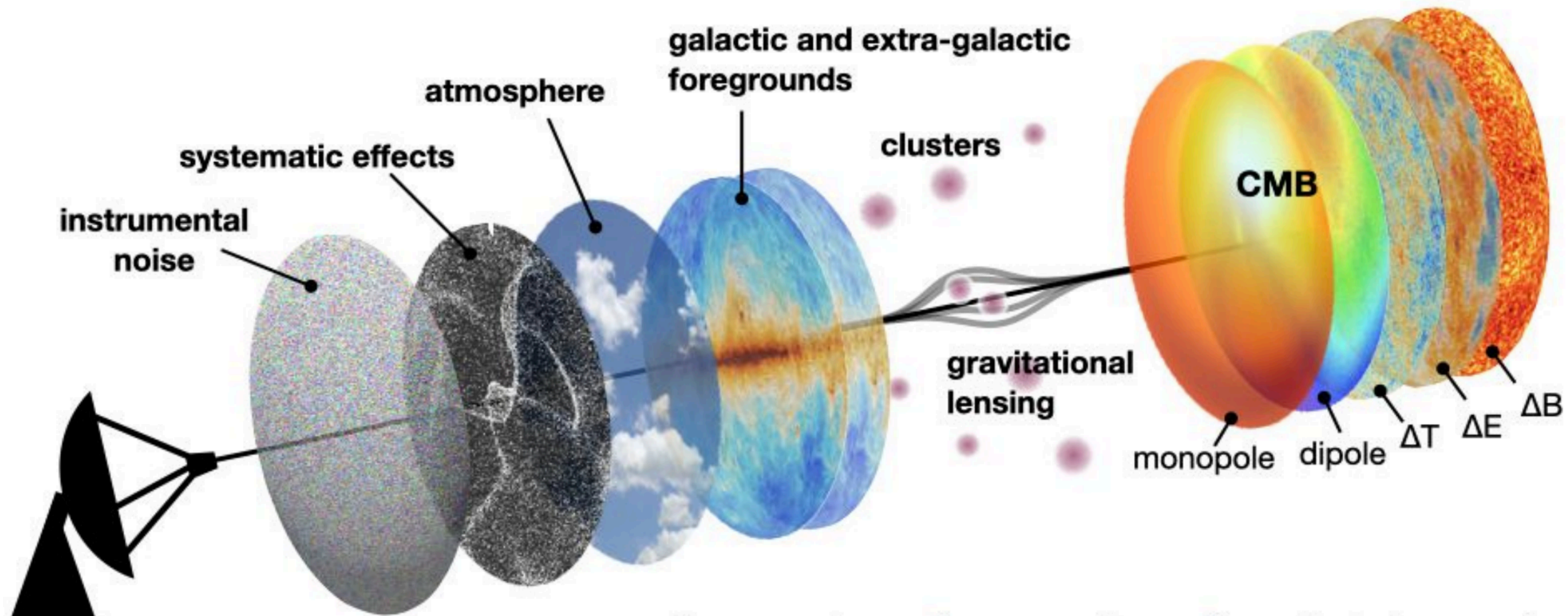
The quest for CMB B-modes

- **B-modes** from gravitational lensing and primordial gravitational waves leave a distinctive shape in the angular power spectrum: $C_\ell^{BB} = rC_\ell^{GW} + C_\ell^{lens}$
- **Tensor-to-scalar ratio**
 $r = A_t/A_s$
upper limit 0.032 at 95% CL (Tristram+2022)
- **Primordial B-modes** detection could provide:
 - › *Ultimate evidence for inflation*
 - › *Constraints on reionization history*
 - › *Hints of new physics*



LiteBIRD collaboration 2023

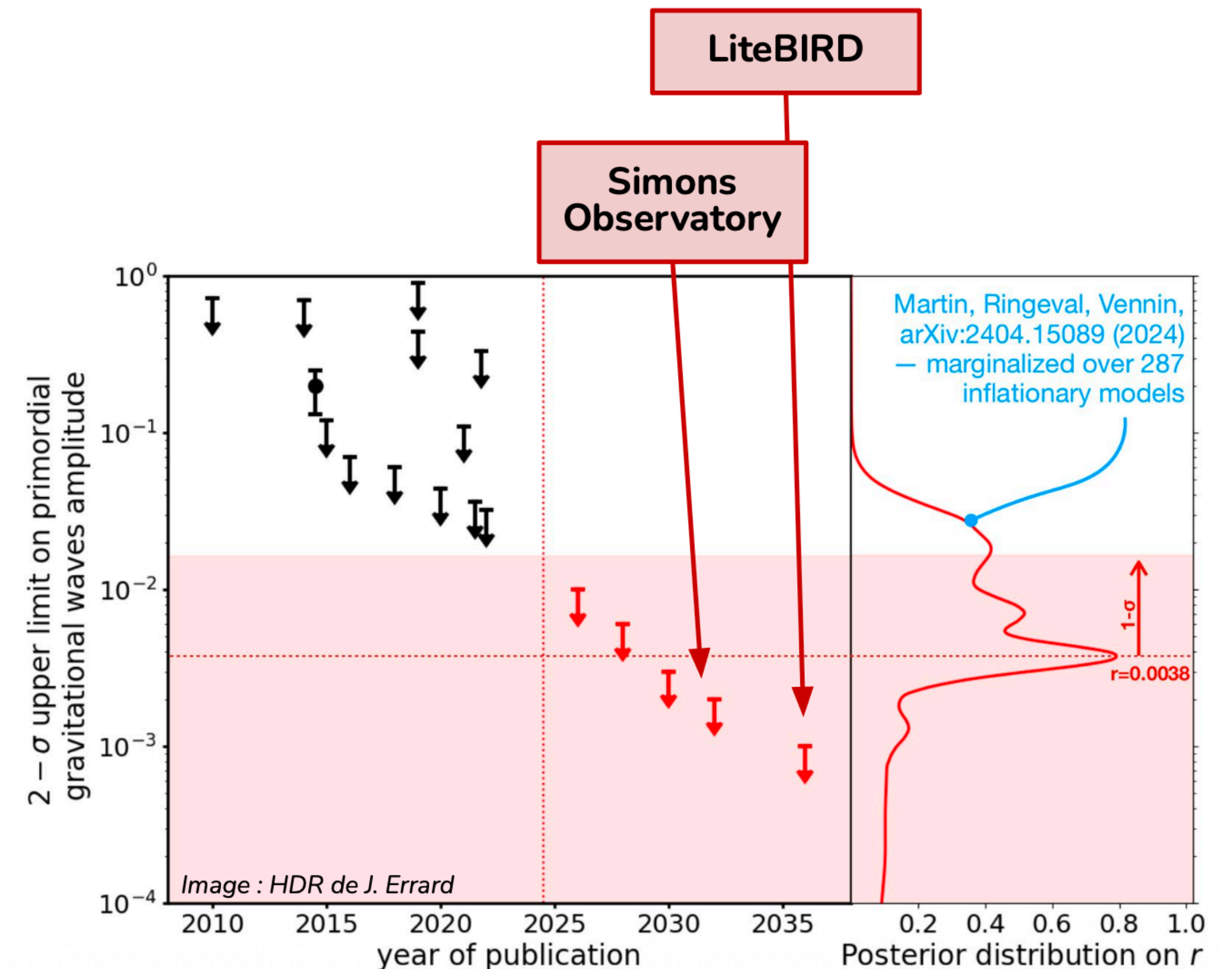
What can limit current experiments?



Credit: J. Errard

What can limit current experiments?

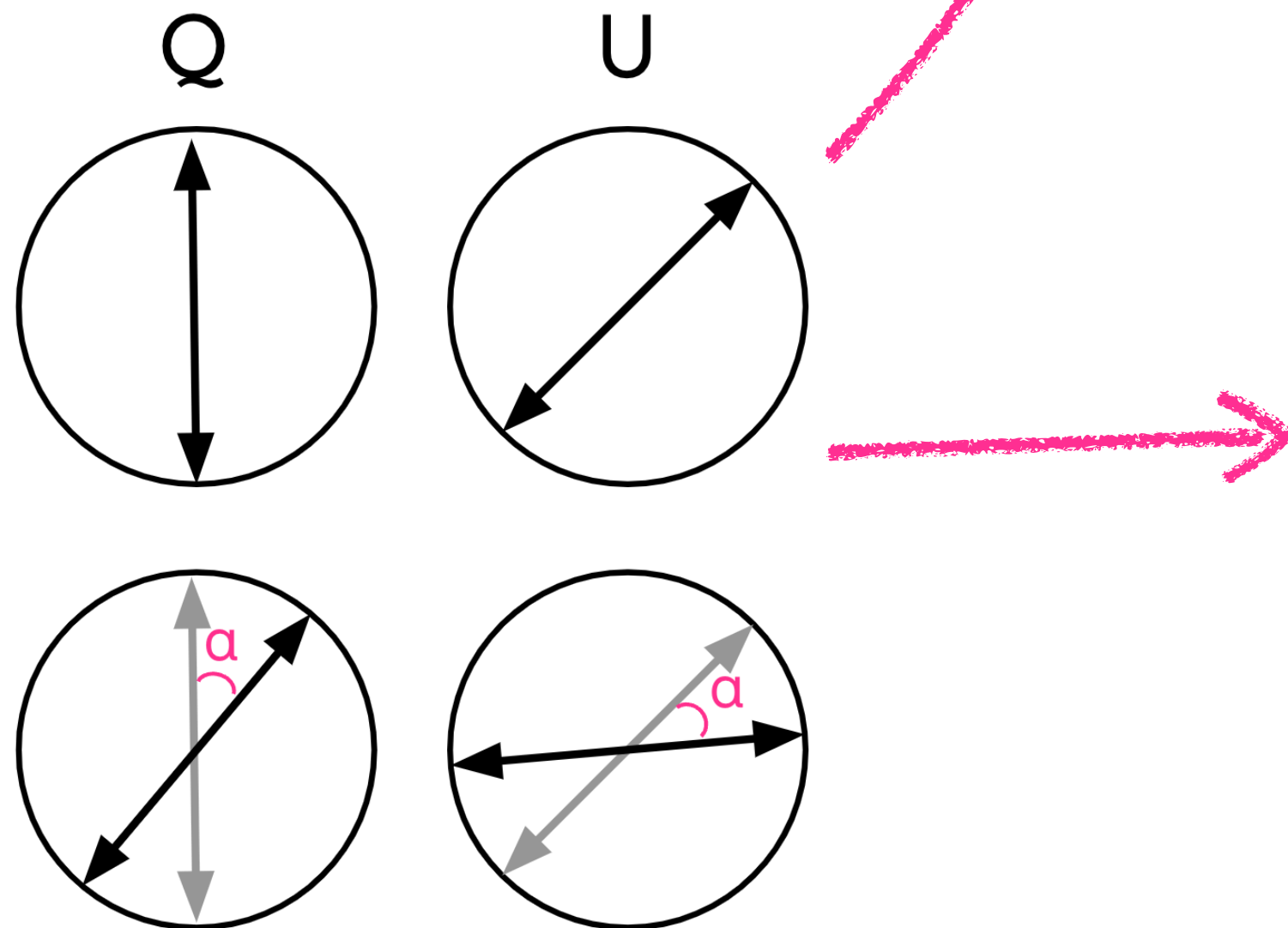
- As **sensitivity** improves, systematic effects increasingly dominate over statistical noise
- Several contaminants are present in the sky (atmosphere, galactic foregrounds, gravitational lensing...)
- Contamination also comes from instrumental noise and hardware imperfections: **calibration and control of systematic effects becomes critical**



Different rotations can occur

$$\mathbf{S}_\nu = \mathbf{R}(\alpha_\nu) \mathbf{B}(\theta_\nu) [\mathbf{R}(\beta) \mathbf{A}_{CMB}, \mathbf{A}_{dust}^\nu, \mathbf{A}_{sync}^\nu] \begin{bmatrix} \mathbf{S}_{CMB} \\ \mathbf{S}_{dust} \\ \mathbf{S}_{synch} \end{bmatrix} + \mathbf{n}_\nu$$

Detector's polarization
angle miscalibration

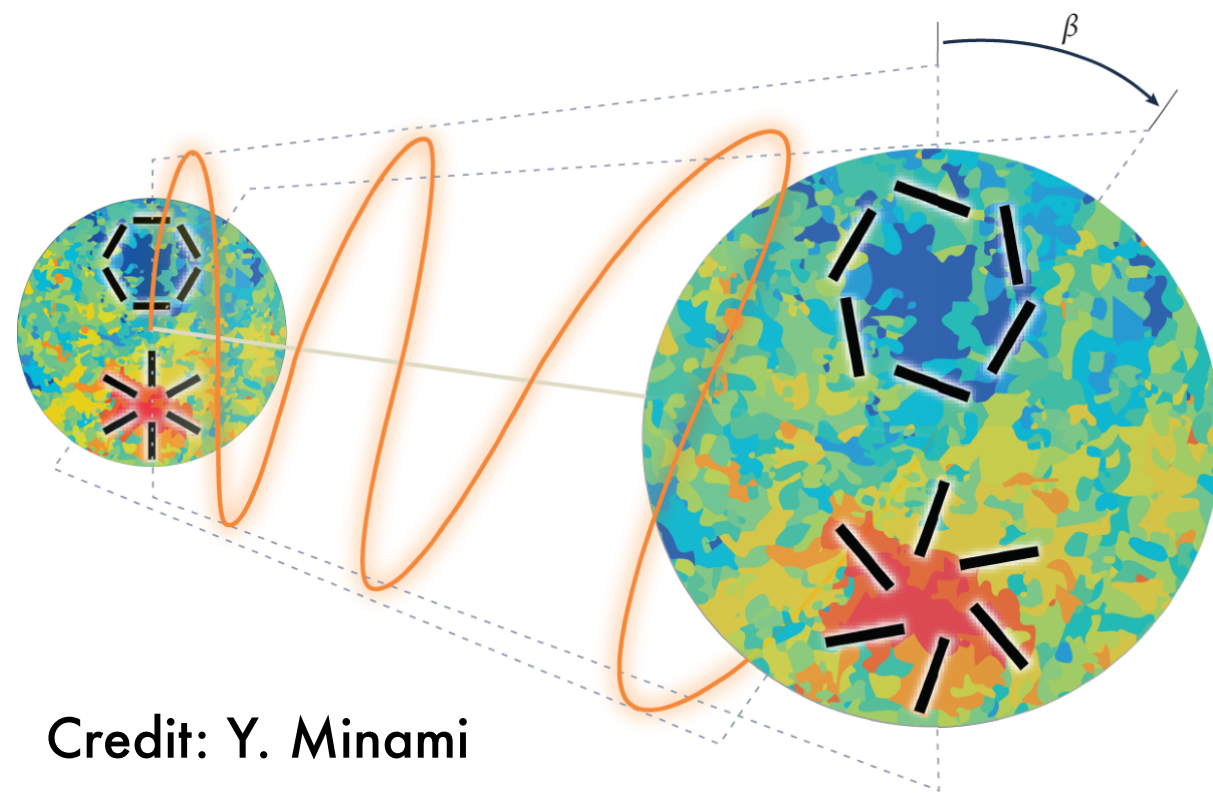


$$C_\ell^{BB,obs} = \sin^2(2\alpha) C_\ell^{EE} + \cos^2(2\alpha) C_\ell^{BB}$$

$$C_\ell^{EB,obs} = \frac{1}{2} (C_\ell^{EE} - C_\ell^{BB}) \sin(4\alpha)$$

Different rotations can occur

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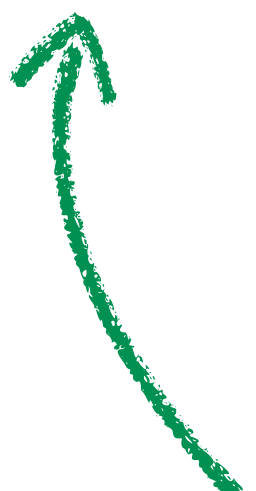
Credit: Y. Minami

Cosmic
Birefringence

- Coupling between CMB photons and a pseudo-scalar field (e.g. axions)
- CMB linear polarization rotates as photons propagate through the universe
- $E \rightarrow B$ conversion, non-zero EB correlation

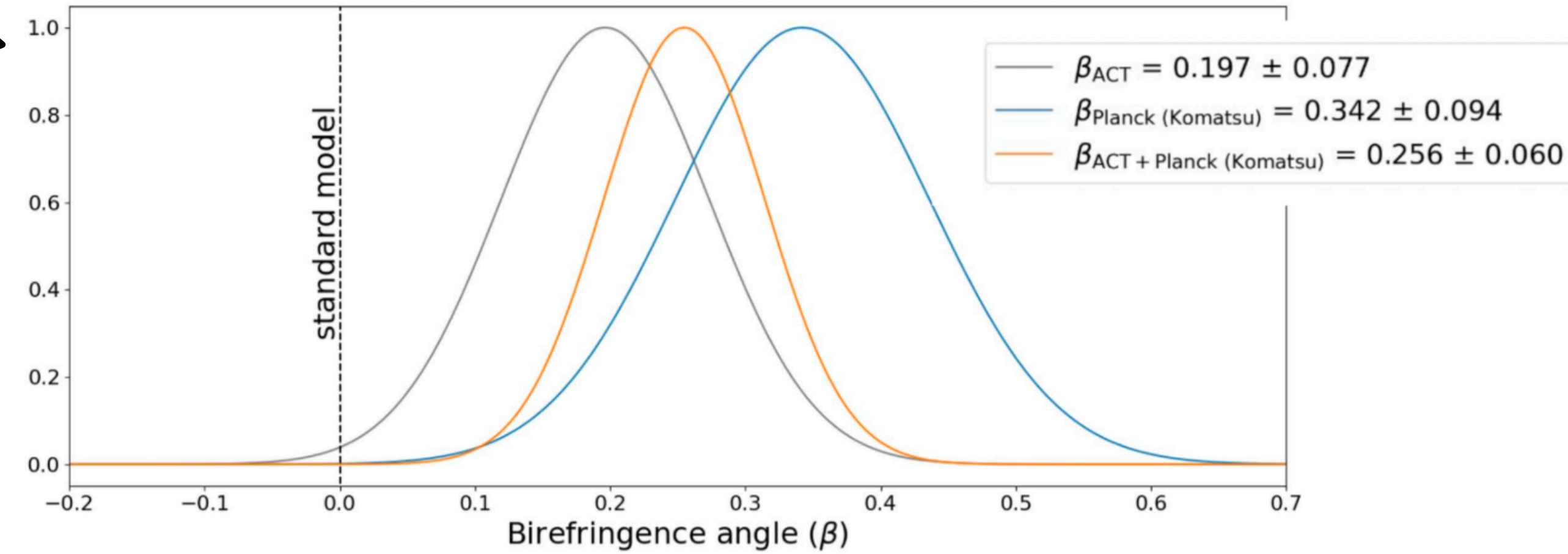
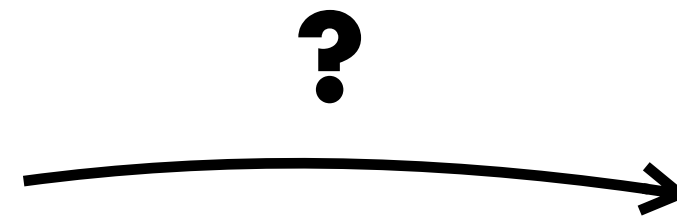
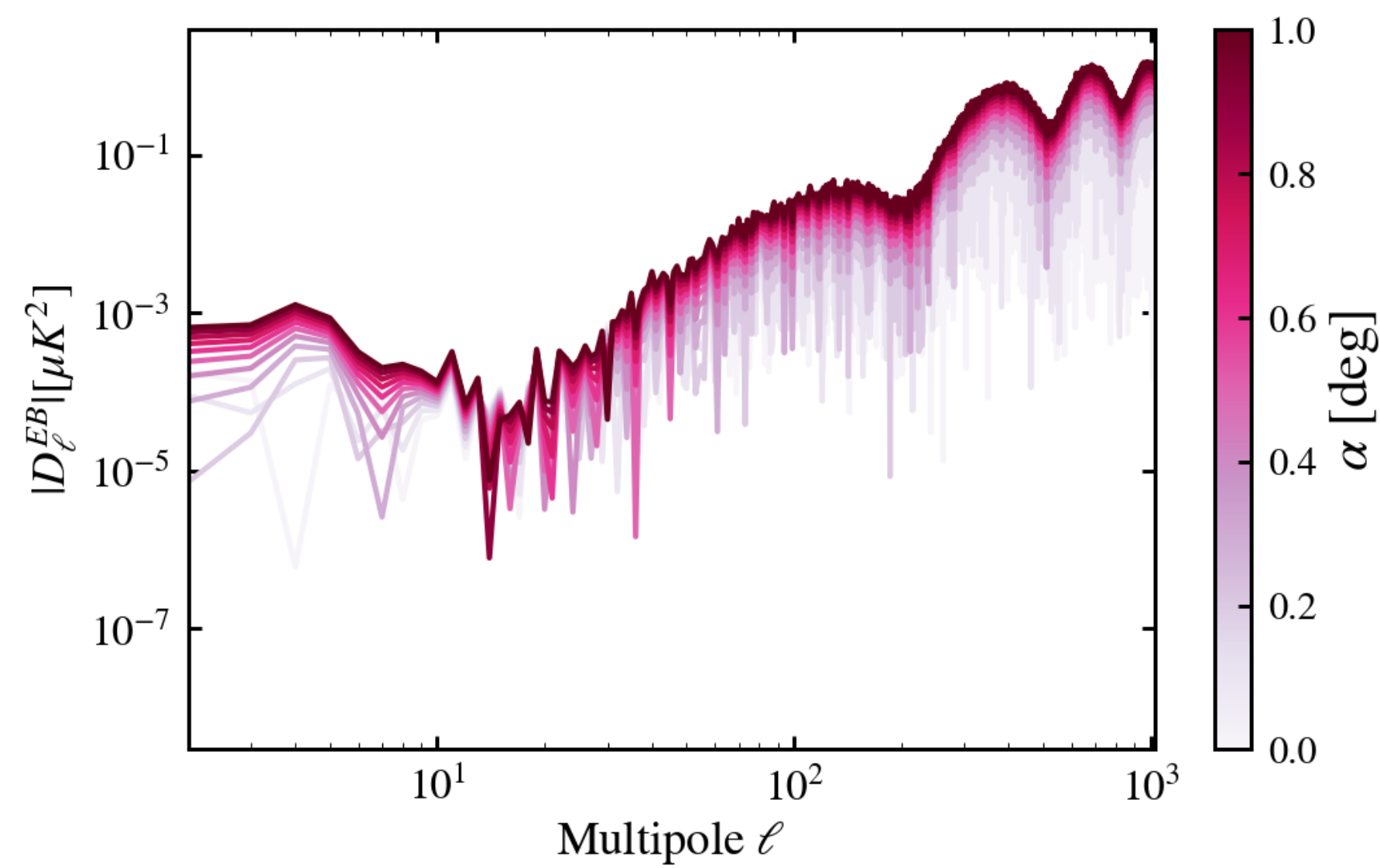
Different rotations can occur

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Galactic parity-violating
signals

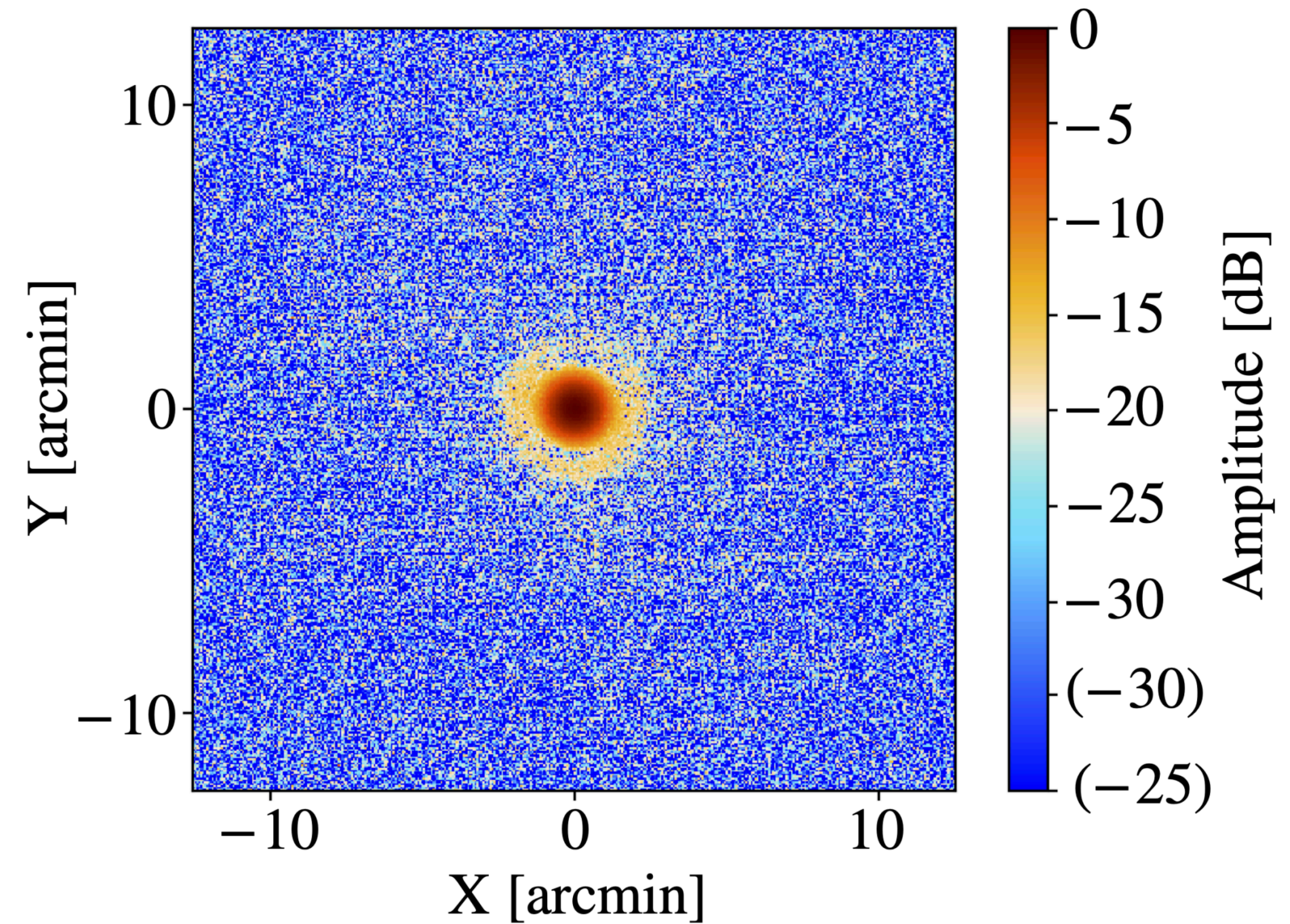
Polarization angle calibration



Adapted by F. Boulanger from
Diego-Palazuelos et al. 2022, 2025

(Polarization) beam calibration

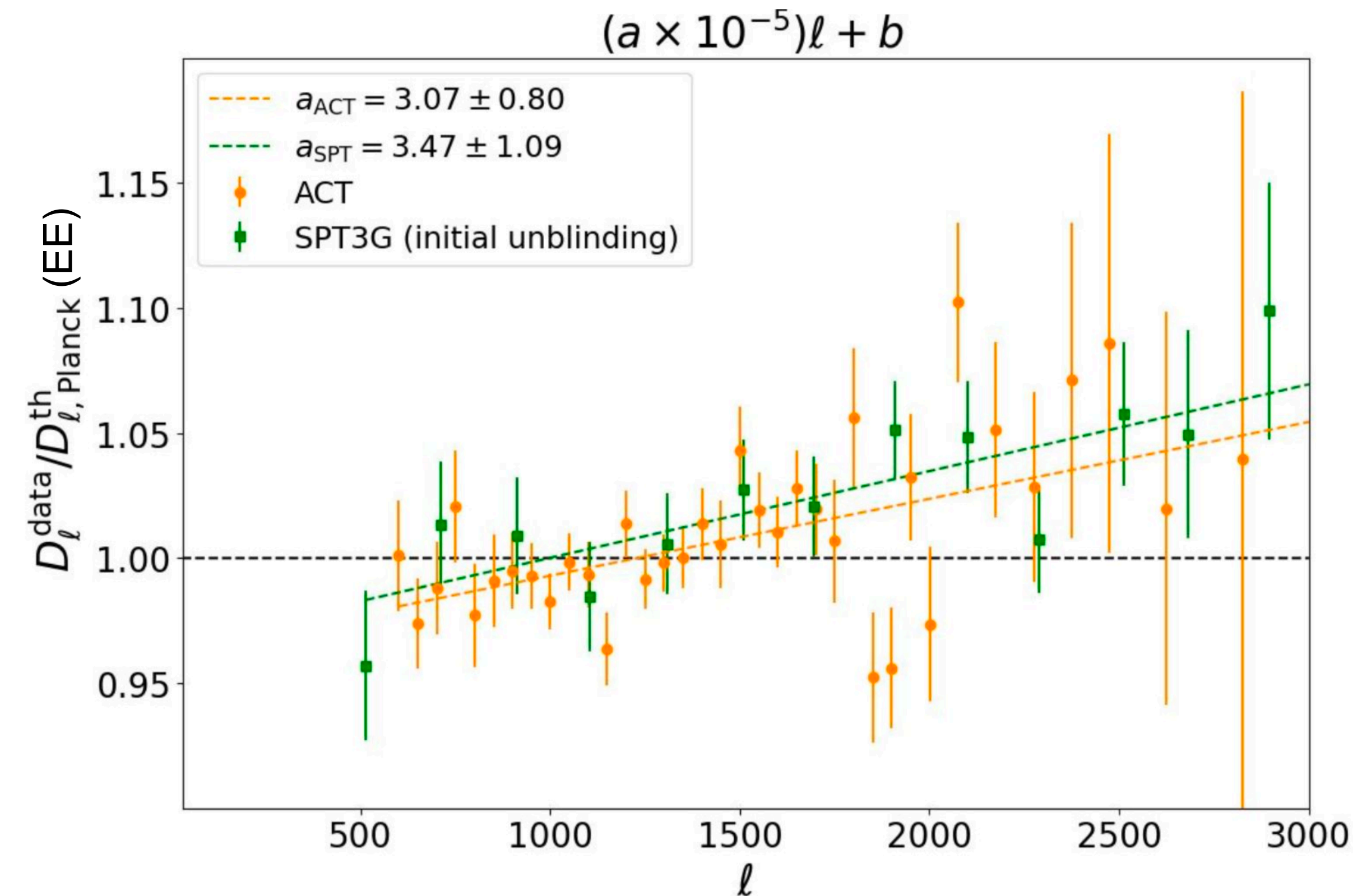
- Planets are used to calibrate the beam in total intensity



Uranus observed by ACT @ 150 GHz (Lungu+2022)

(Polarization) beam calibration

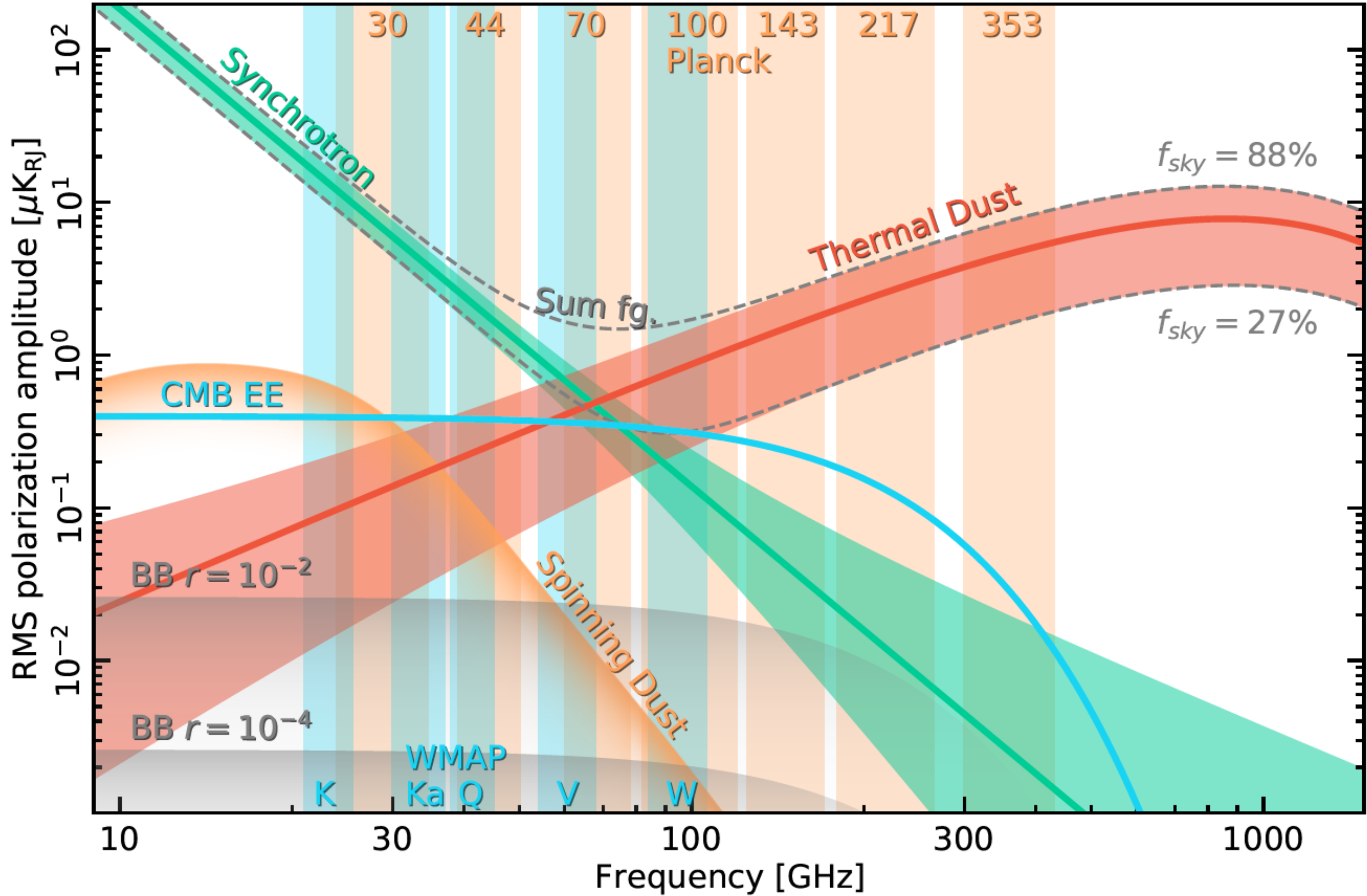
- Planets are used to calibrate the beam in total intensity
- In polarization, there is no astrophysical source accurate enough
- Recent results from SPT and ACT show the same deviation from Planck:
systematics or new physics?



Adapted by T. Louis from SPT and ACT Collaborations, 2025

Characterization of astrophysical foregrounds

Credit: BeyondPLANCK Collaboration

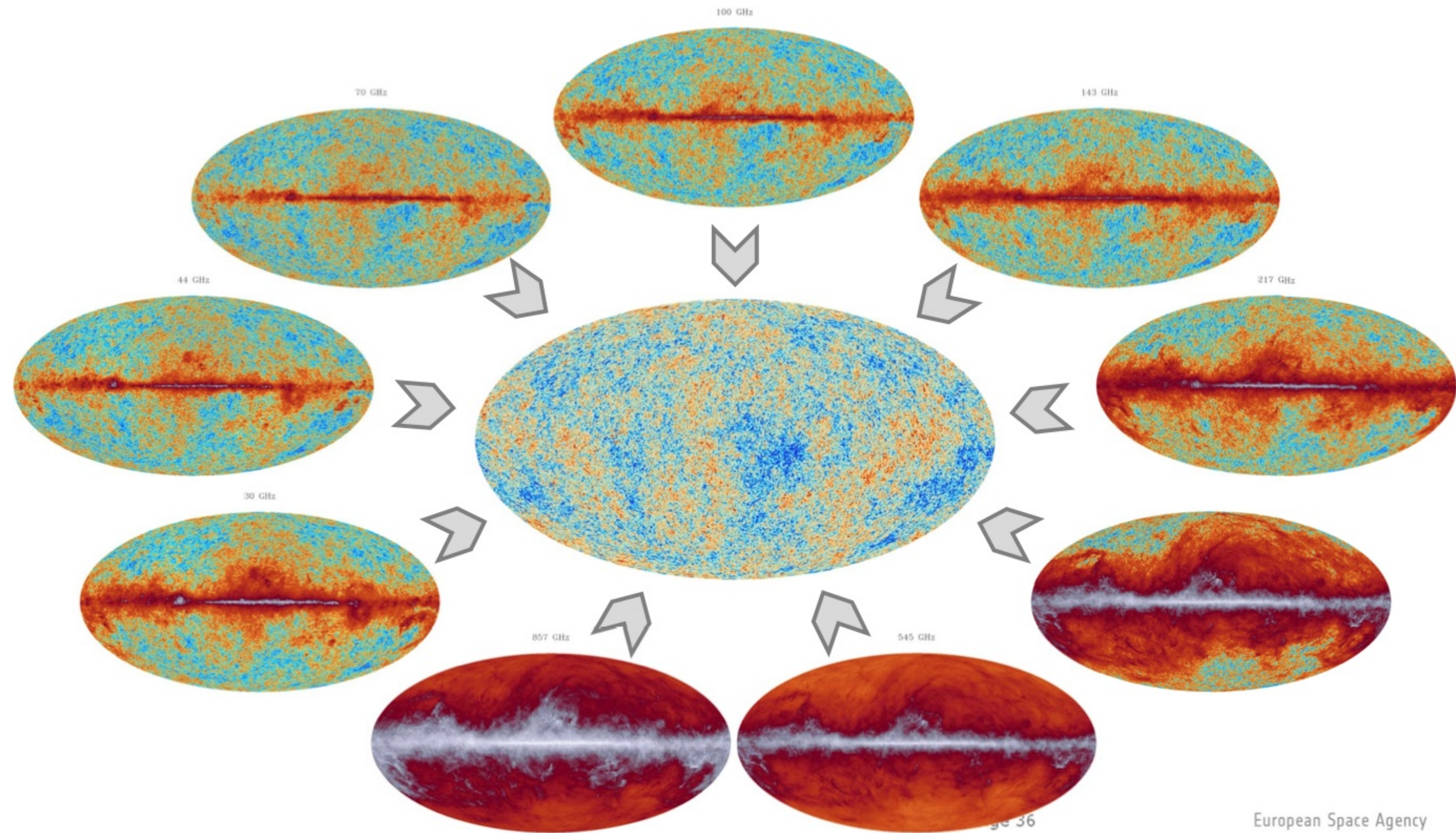


$$S_{dust}(\nu, \hat{n}) = A_d^S(\hat{n}) \left(\frac{\nu}{\nu_0} \right)^{\beta_d(\hat{n})} \frac{B_\nu(T_d(\hat{n}))}{B_{\nu_0}(T_d(\hat{n}))}$$

$$S_{synch}(\nu, \hat{n}) = A_s^S(\hat{n}) \left(\frac{\nu}{\nu_0} \right)^{\beta_s(\hat{n})}$$

Characterization of astrophysical foregrounds

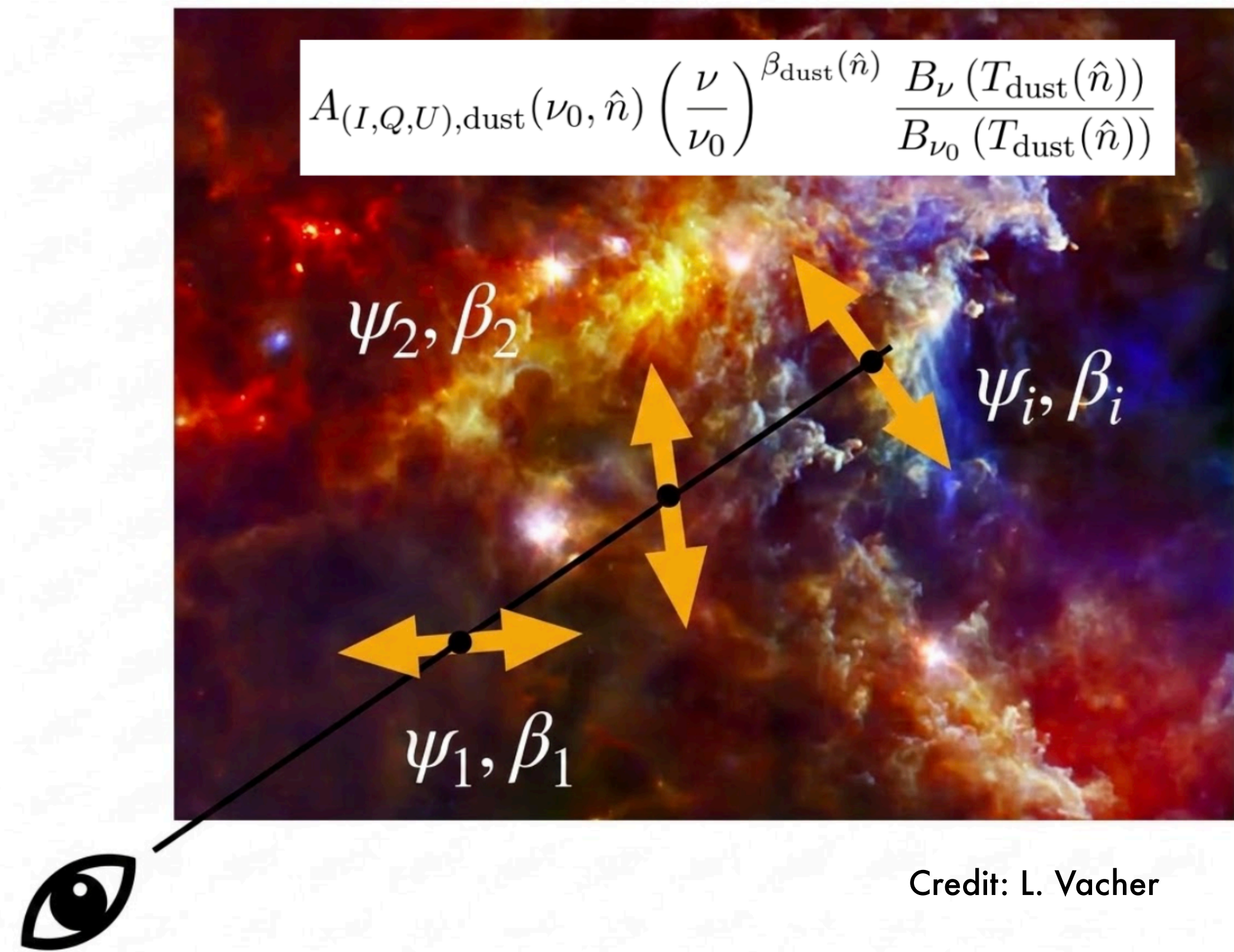
We can perform component separation!



Characterization of astrophysical foregrounds

- Galactic dust can produce *EB* signal from magnetic misalignment (Hervías-Caimapo 2024)
- Spectral parameters of SEDs and galactic magnetic field vary across the sky and with frequency (Ritacco et al. 2023, Vacher et al. 2023, Guillet et al. 2025)
- Bias on cosmic birefringence analyses? (Diego-Palazuelos et al. 2023)

Absolute calibration of the polarization angle will also allow us to better characterize the complexity of foregrounds emission



Characterization of astrophysical foregrounds

What is the impact of having this kind of complexity in the dust emission on cosmological analyses?

Are we able to correct for the miscalibration if the sky is so complex?

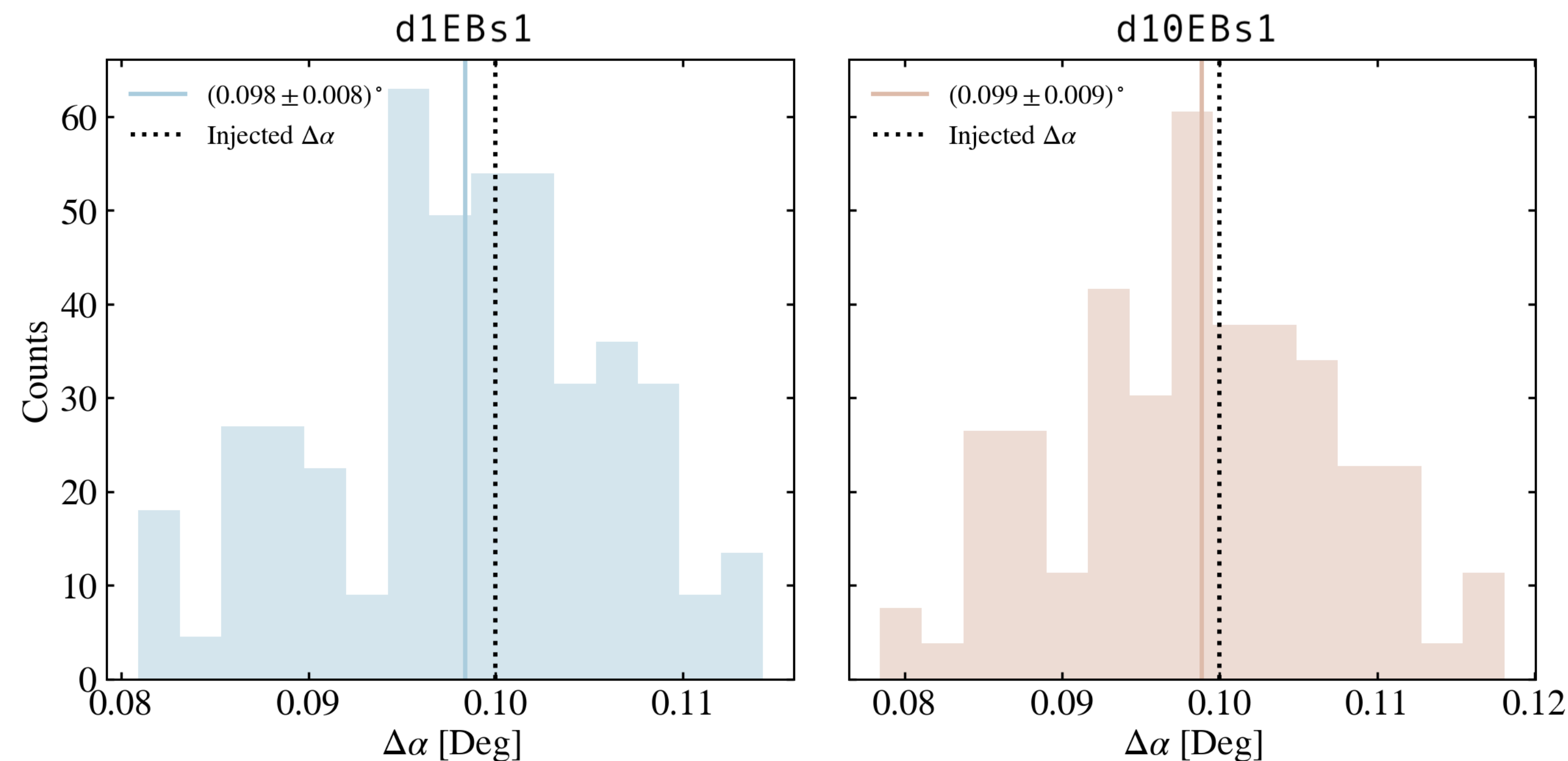
Are we completely dominated by dust residuals?

Characterization of astrophysical foregrounds

What is the impact of having this kind of complexity in the dust emission on cosmological analyses?

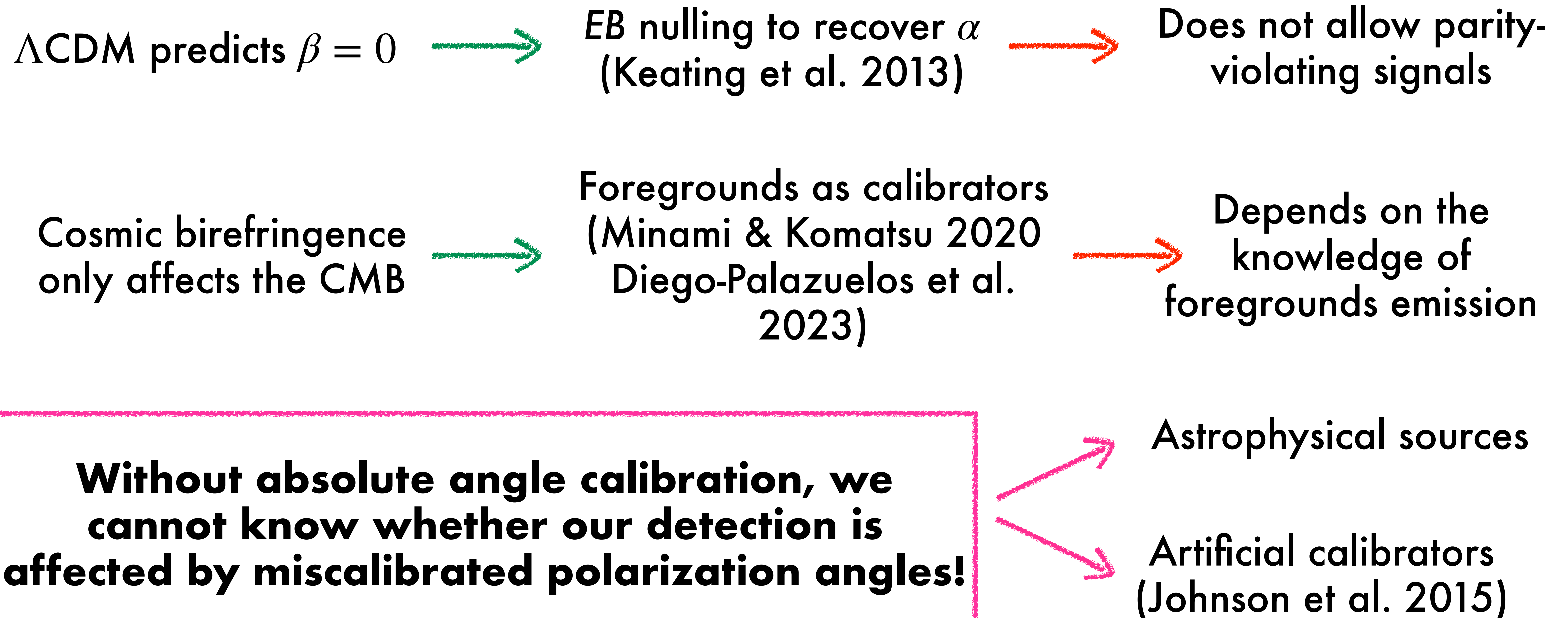
Are we able to correct for the miscalibration if the sky is so complex?

Are we completely dominated by dust residuals?



Micheli et al. 2026

How to perform calibration



How to perform *absolute* calibration

- An artificial calibrator must operate in the far-field limit:

$$d_f = \frac{2D_{ant}^2}{\lambda}$$

- Small aperture telescopes can use artificial calibration sources on drones (Nati et al. 2017, Coppi et al. 2022)
- Large aperture telescopes need a source in space



POLOCALC drone used for calibration of SO-SATs & CLASS in the Atacama desert



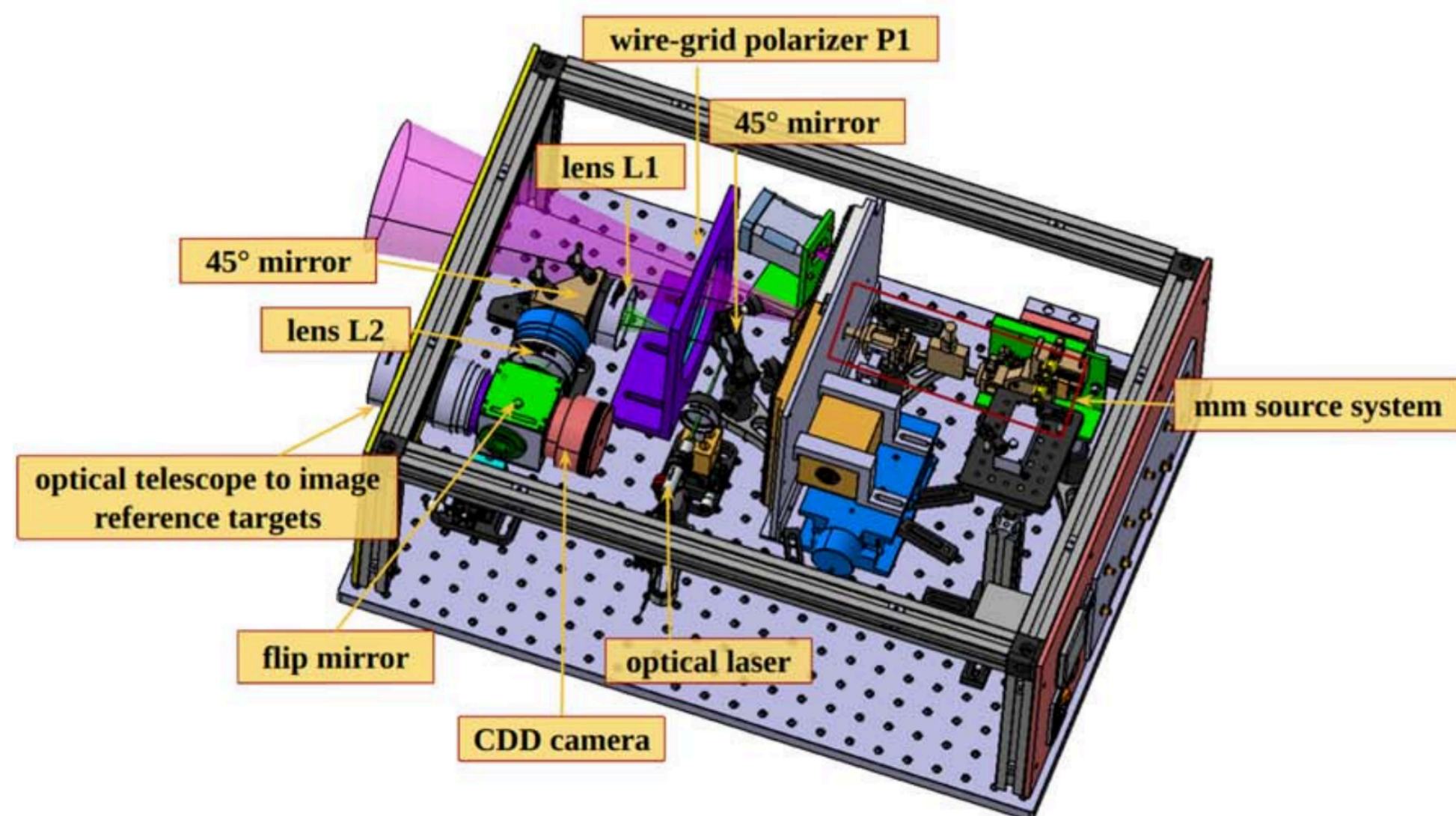
The COSMOCaI project

PI: A. Ritacco

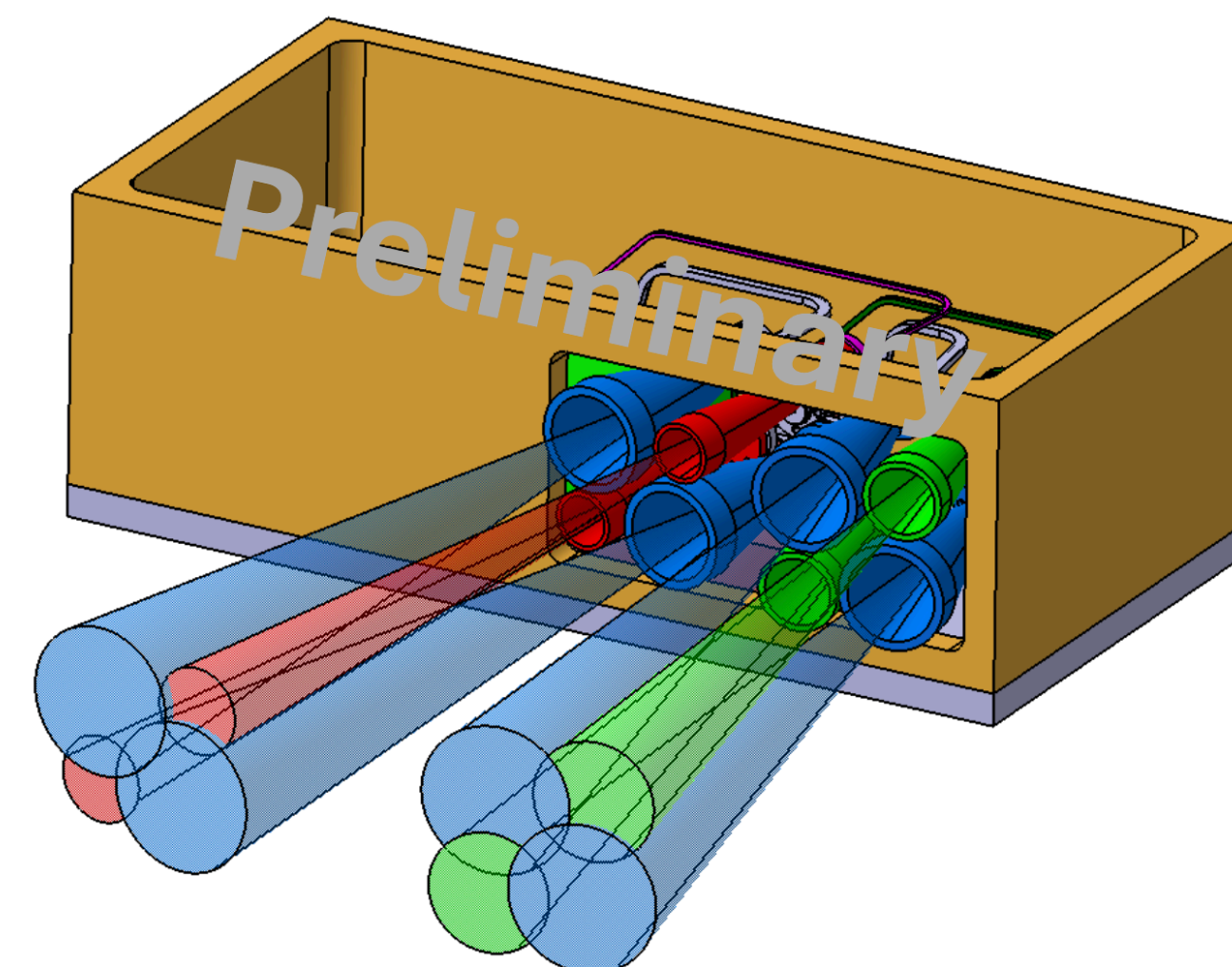
- Calibration source in space for CMB telescopes
- High power microwave source at 90 (SRT, SO-LAT), 150 (SO-LAT) and 270 GHz (IRAM), fully linearly polarized
- Visible from Chile and Europe
- Guest payload on a commercial platform operated by the private company Eutelsat (launch in 2031)
- Project started in 2022 (Ritacco et al. 2024)
- Currently in the development phase, monitored by CNES (expected Phase A review in early 2027)



The COSMOCaI project



First prototype assembled at LPENS (Paris) and tested at LPSC (Ritacco et al. 2024) and used in the IRAM 30-m telescope campaign (oct.2024)



Simplification of the design for space
Credit: P. Morfin

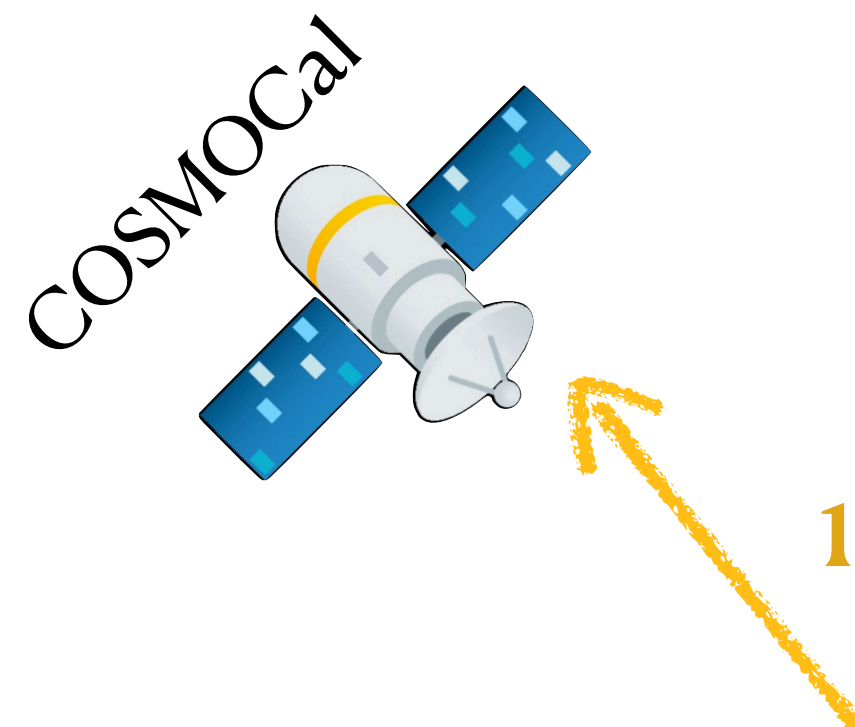
Optimization of the design is ongoing!



The COSMOCaI project

1. Direct observation

- beam calibration
- absolute calibration of the polarization angle measurement with **0.1° accuracy**

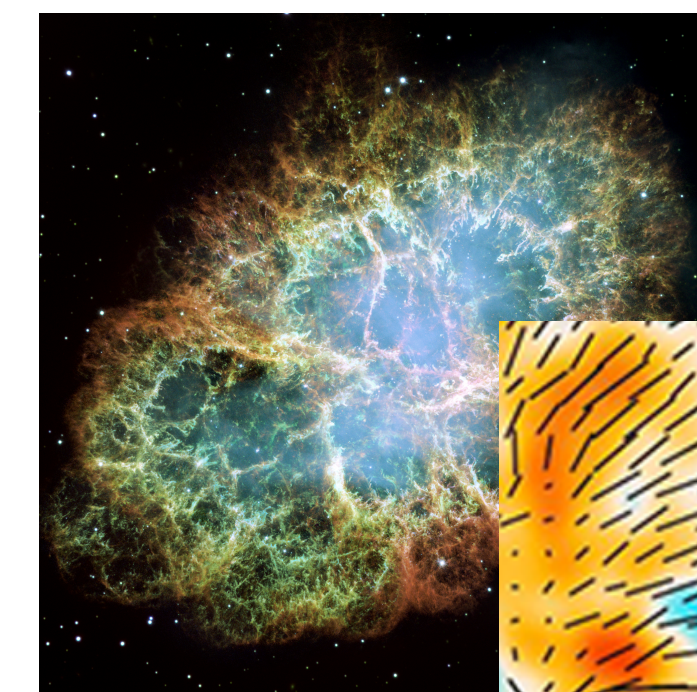
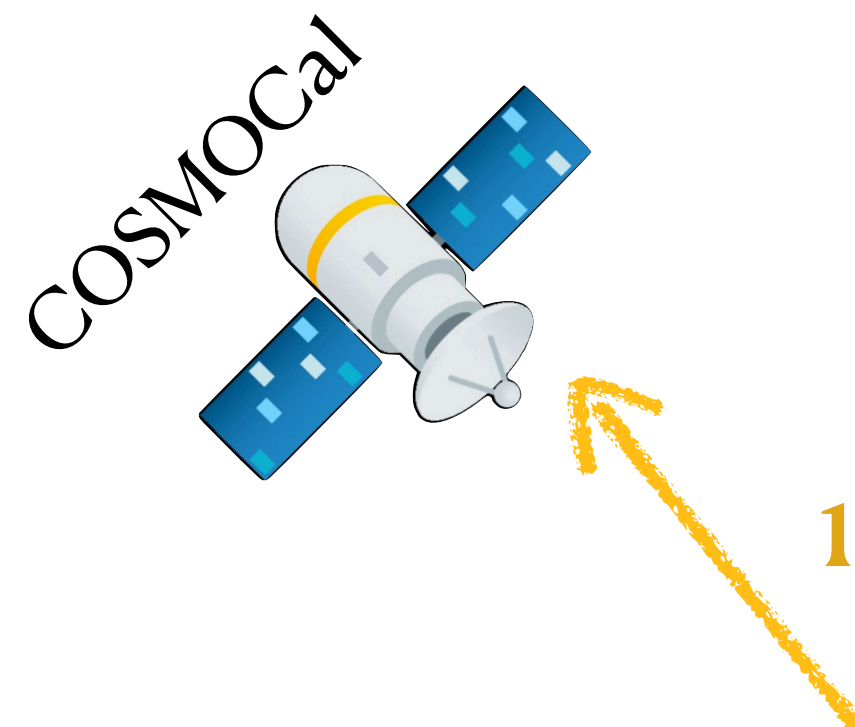




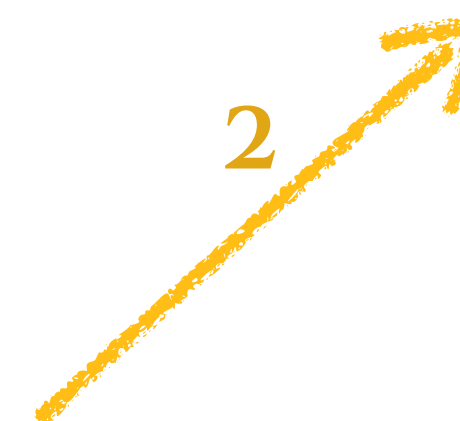
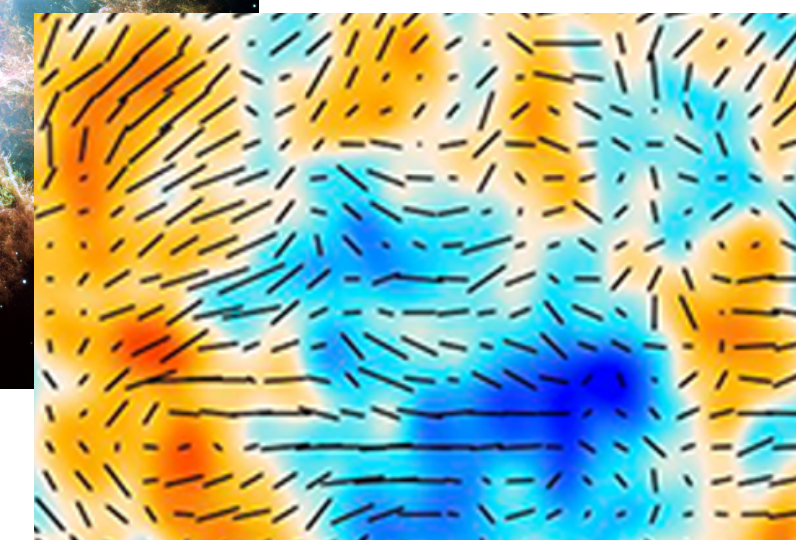
The COSMOCaI project

1. Direct observation

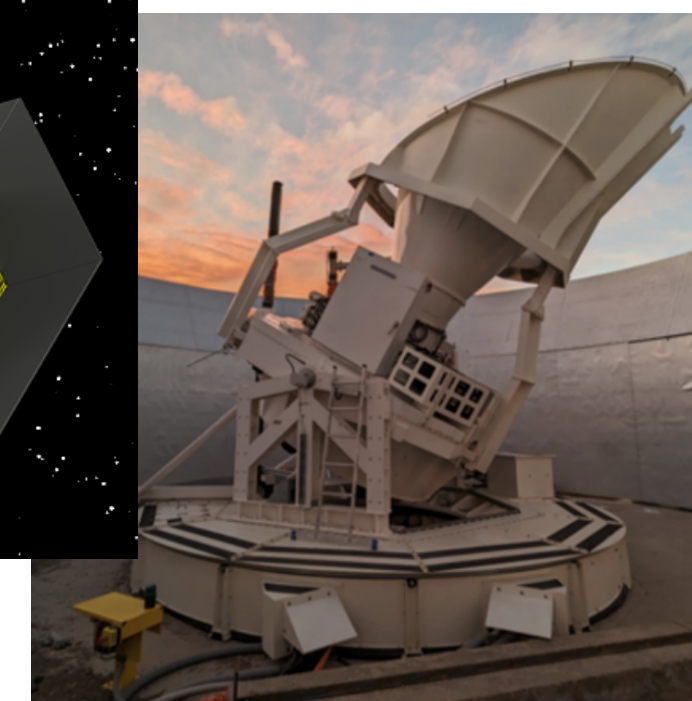
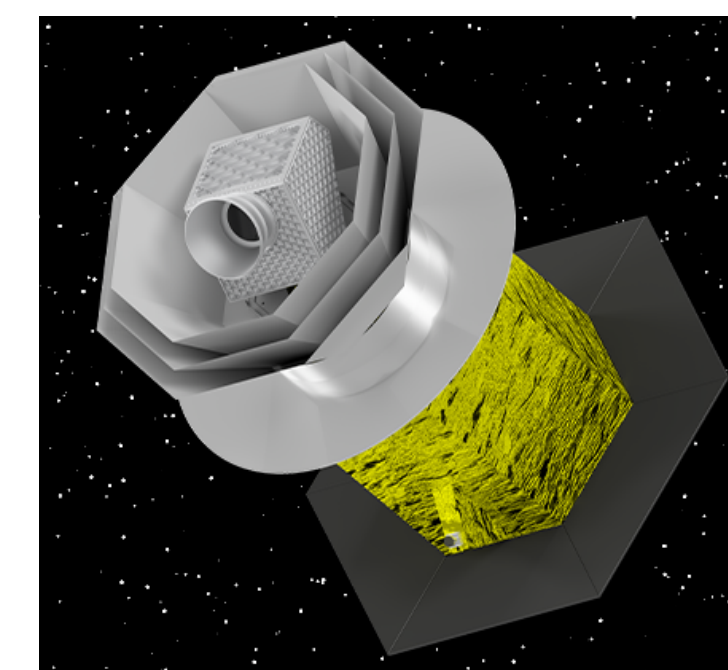
- beam calibration
- absolute calibration of the polarization angle measurement with 0.1° accuracy



Standard maps



Other CMB telescopes



- ## 2. Standard reference maps
- CMB polarization from SO-LAT
 - astrophysical polarized sources (e.g. Crab nebula)

Conclusions

- Absolute polarization calibration is essential for CMB science, as instrumental and foreground systematics can bias the reconstruction of the CMB signal
- Characterizing Galactic foregrounds is key to understanding and mitigating their impact, representing a fundamental synergy between astrophysics and precision cosmology
- Future experiments will benefit from cross-calibration and complementary observations to control systematic biases and fully exploit their sensitivity
- At LPSC, we are contributing to this effort with the COSMOCaI project!