Challenges for **unbiased** observations of the cosmic microwave background **polarization**

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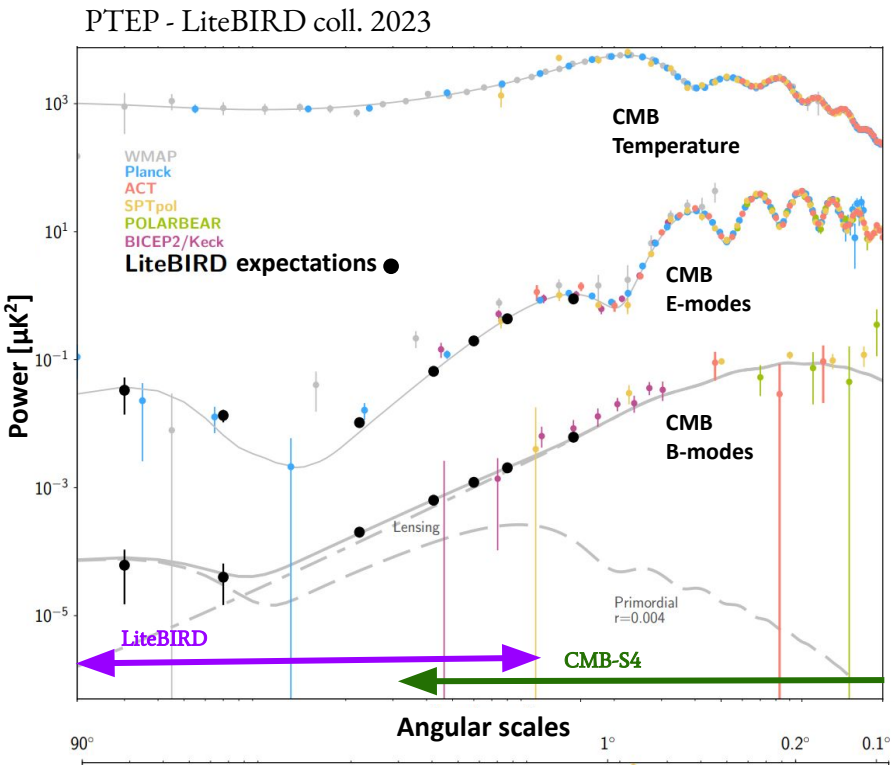
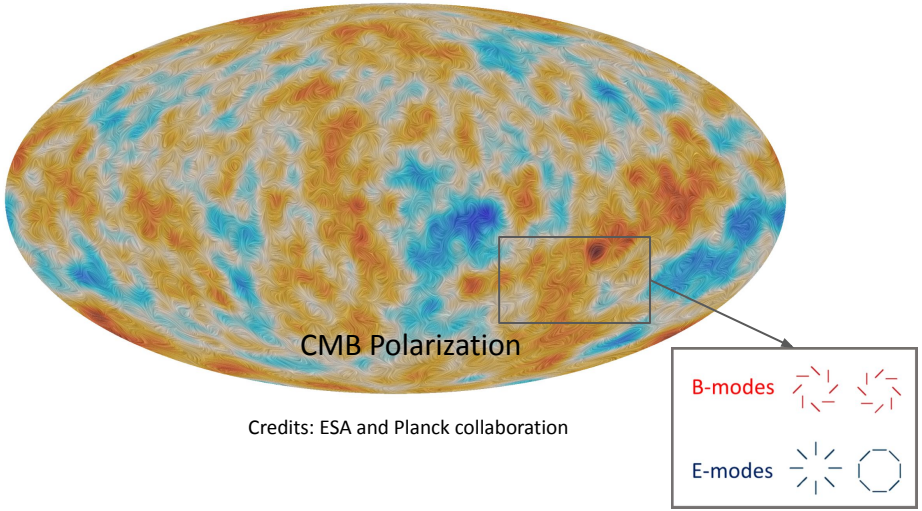
Outline

- **Context**
- **Challenges for CMB experiments**
  - **Calibration of the polarization angle**
  - **Dust foreground subtraction**
- **COSMOCal project: CO**smic **S**urvey of **M**illimeter wavelengths **O**bjects for CMB experiments **Cal**ibration

Cosmic **M**icrowave **B**ackground

as probe of the early Universe





Credits: ESA and Planck collaboration

Unbiased detection of the CMB *B-modes*

- Instrument sensitivity
- Instrumental systematic effects
- Absolute calibration of the polarization angle
- Foreground emission subtraction

Scientific advances:

- Inflationary Gravitational Waves
- Primordial magnetic fields
- Cosmic Birefringence

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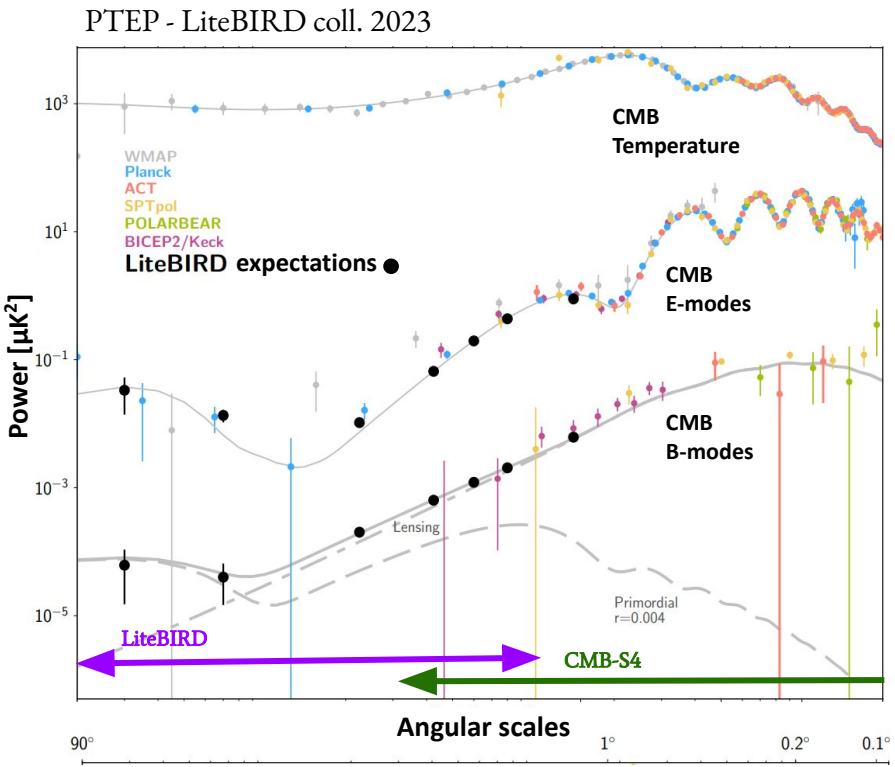

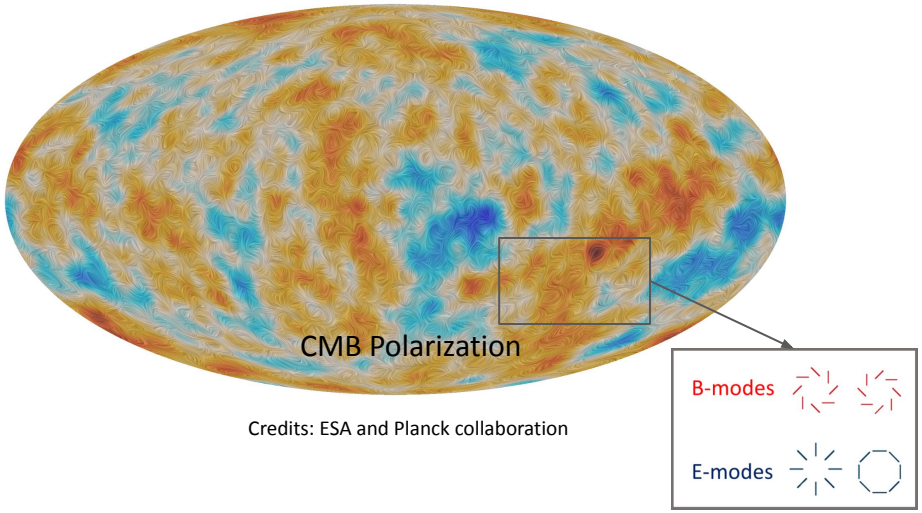

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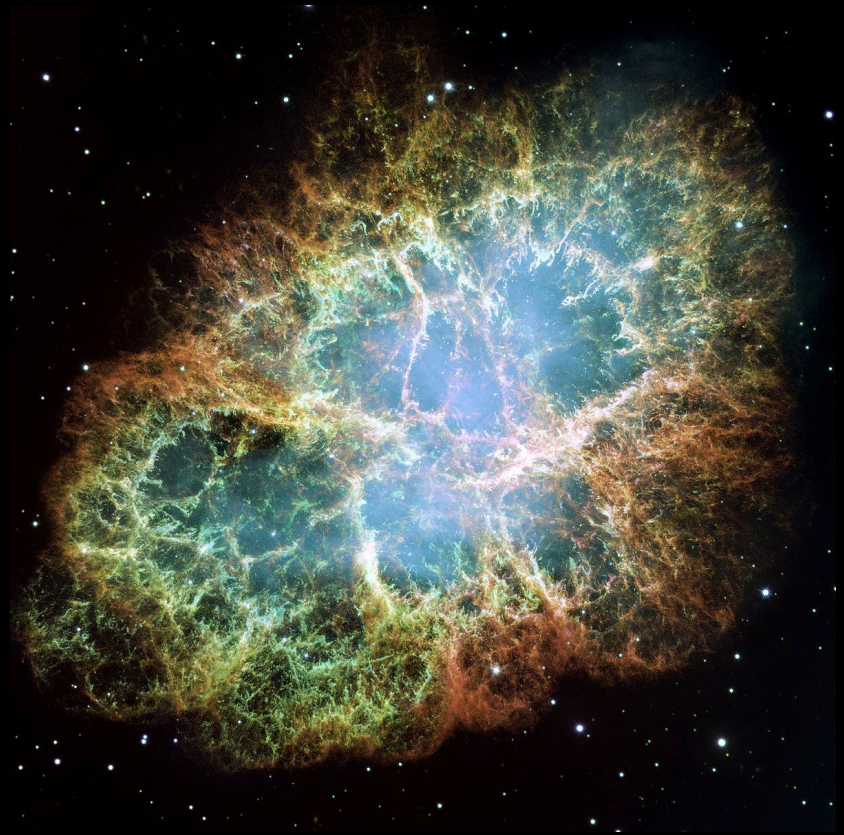
Polarization angle calibration accuracy

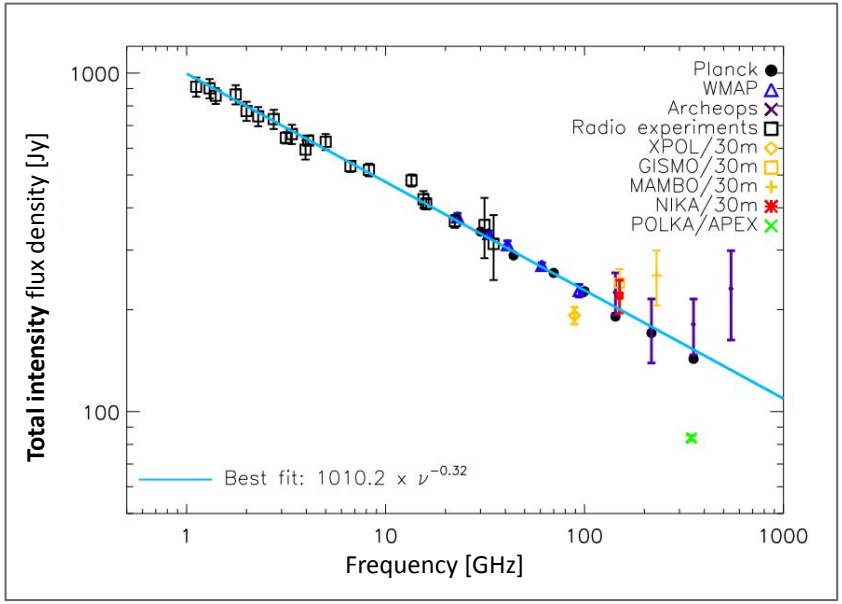
The Crab nebula as a sky calibrator

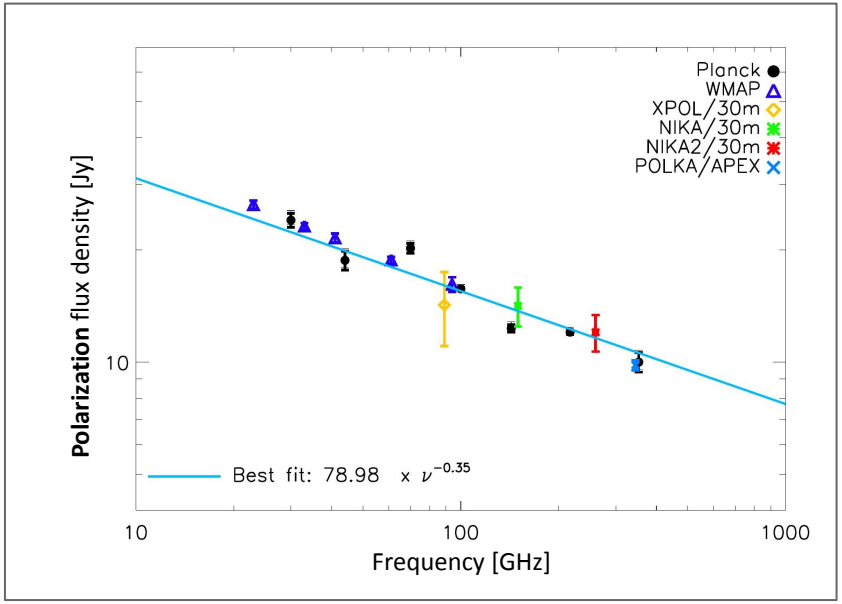


- ★ The **Crab Nebula** (Tau A) is a plerion-type supernova remnant, observed from radio to X-rays
- ★ The microwave emission has an extension of about 5′ × 7′
- ★ Highly polarized synchrotron emission with a polarization fraction of ~ 20%
- ★ It is relatively isolated in the microwave sky within 1 degree scale

CRAB nebula as standard calibrator

Ritacco et al. A&A 616, A35 (**2018**)





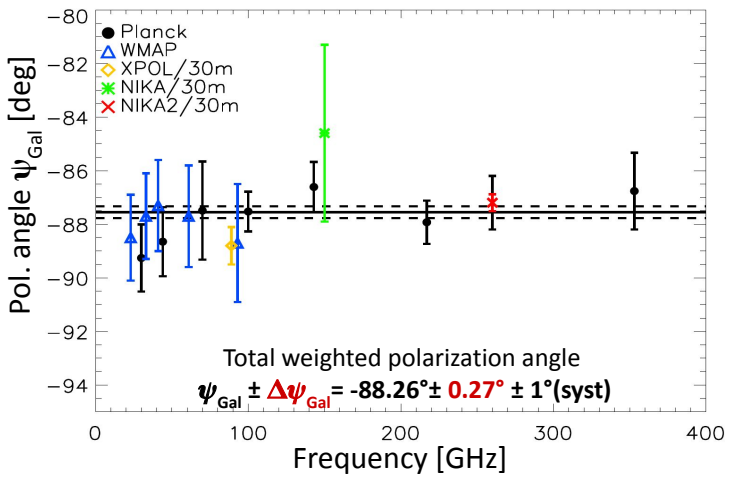
In a *Planck-like* beam the polarization is powered by one single population of electrons as in total intensity

More complicate for a LiteBIRD wide-beam (*Masi et al. ApJ 2021*)

CRAB nebula as standard calibrator

1) Aumont, Macías-Pérez, **Ritacco** et al. A&A 634, A100 (**2020**)
2) **Ritacco**+EPJ Web of Conferences (**2022**)

Using the **Crab nebula** as sky calibrator in the frequency range 20-353 GHz.



A miscalibration of the polarization angle ψ creates a spurious CMB B-modes signal mixing ***E*** and ***B-modes***

$$\Delta C_\ell^{BB} \simeq (2\Delta\psi_{\rm Gal})^2 C_\ell^{EE}$$

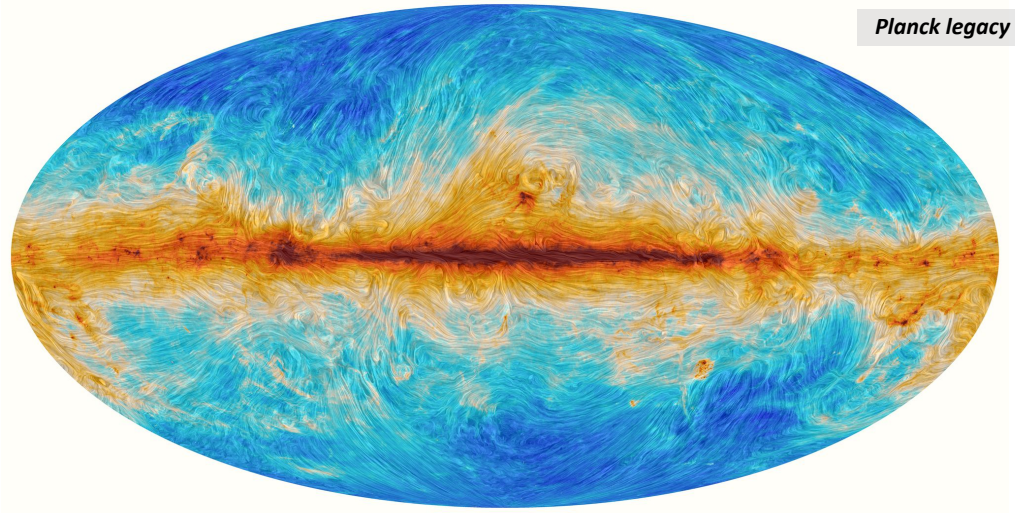
Current measurement allows to probe $r \simeq 10^{-2}$

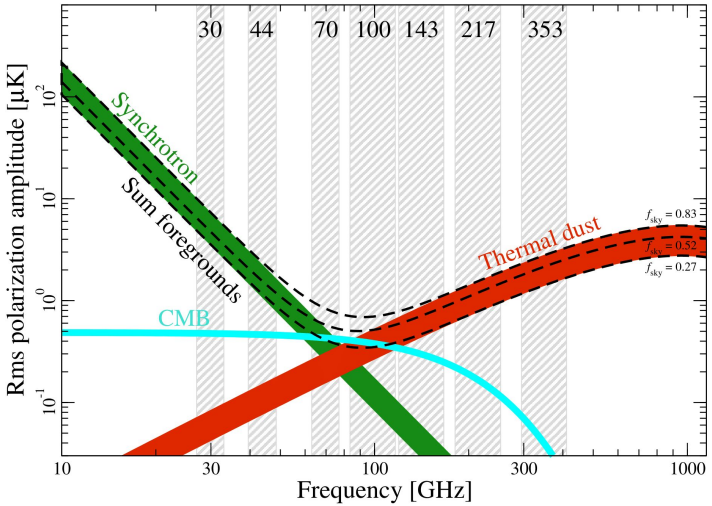
Limited by the systematic error of each instrument

★ **Target accuracy to probe *B*-modes $\Delta\psi < 0.1°$**

Polarized dust emission as CMB foreground

Polarized **dust** emission

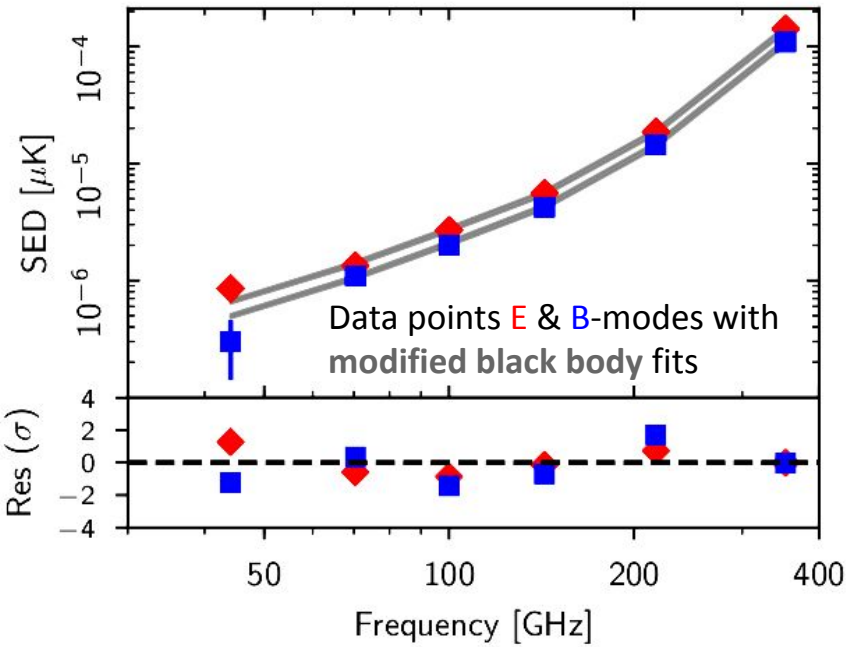




To subtract the sky dust **polarization** we need to have a full-sky modelling
→ So we need to understand how dust polarization behaves

Dust Spectral Energy Distribution

Planck 2018 results XI



The dust SED in polarization from Planck 2018 fits a **single temperature modified black-body emission law** from 353 GHz to 44 GHz.

Significant advance in constraining dust models in astrophysics & for CMB foreground dust component separation methods.

⇒ Characterizing spatial variations of polarization SEDs, (i.e. the local frequency dependence of polarized intensity and angles)

Spatial SED variation of dust polarization from Planck HFI data

Ritacco A., Boulanger F., Guillet V. et al **A&A 670, A163 (2023)**

Spatial SED variation of the dust polarization

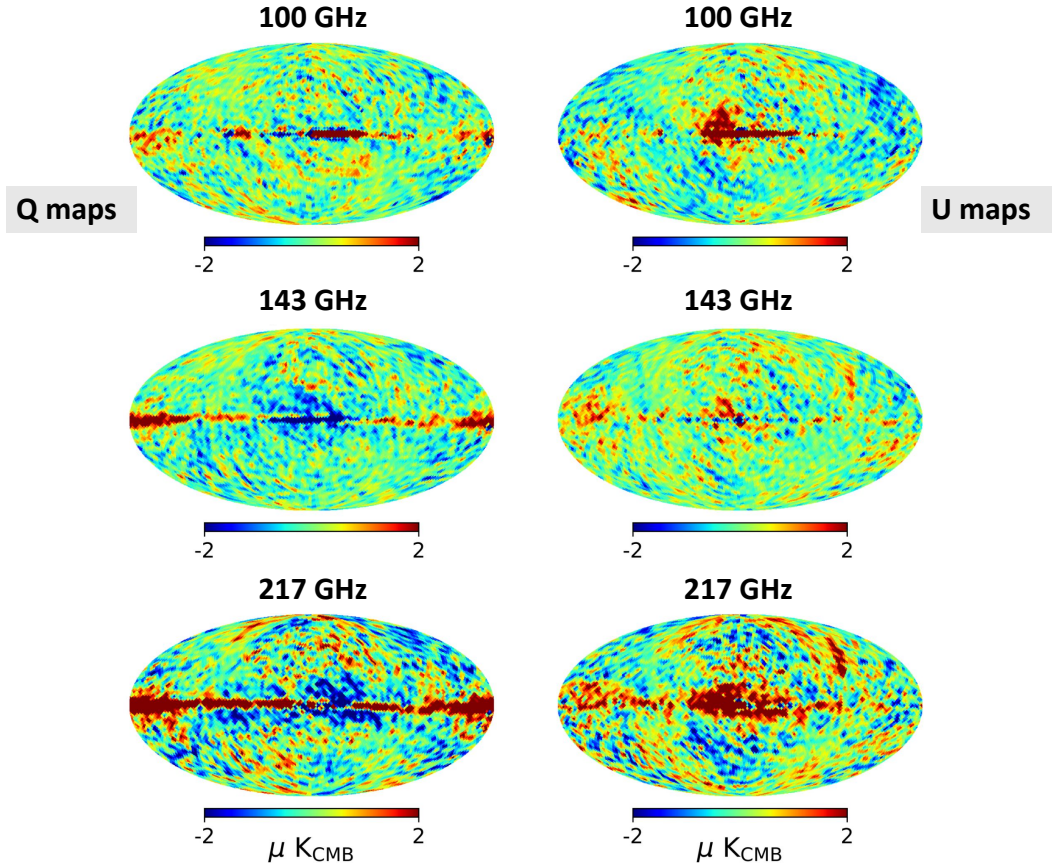
Residual maps

$$R_Q(\nu) = Q'_P(\nu) - \gamma_P(\nu) \cdot Q_P(\nu_0)$$
$$R_U(\nu) = U'_P(\nu) - \gamma_P(\nu) \cdot U_P(\nu_0)$$

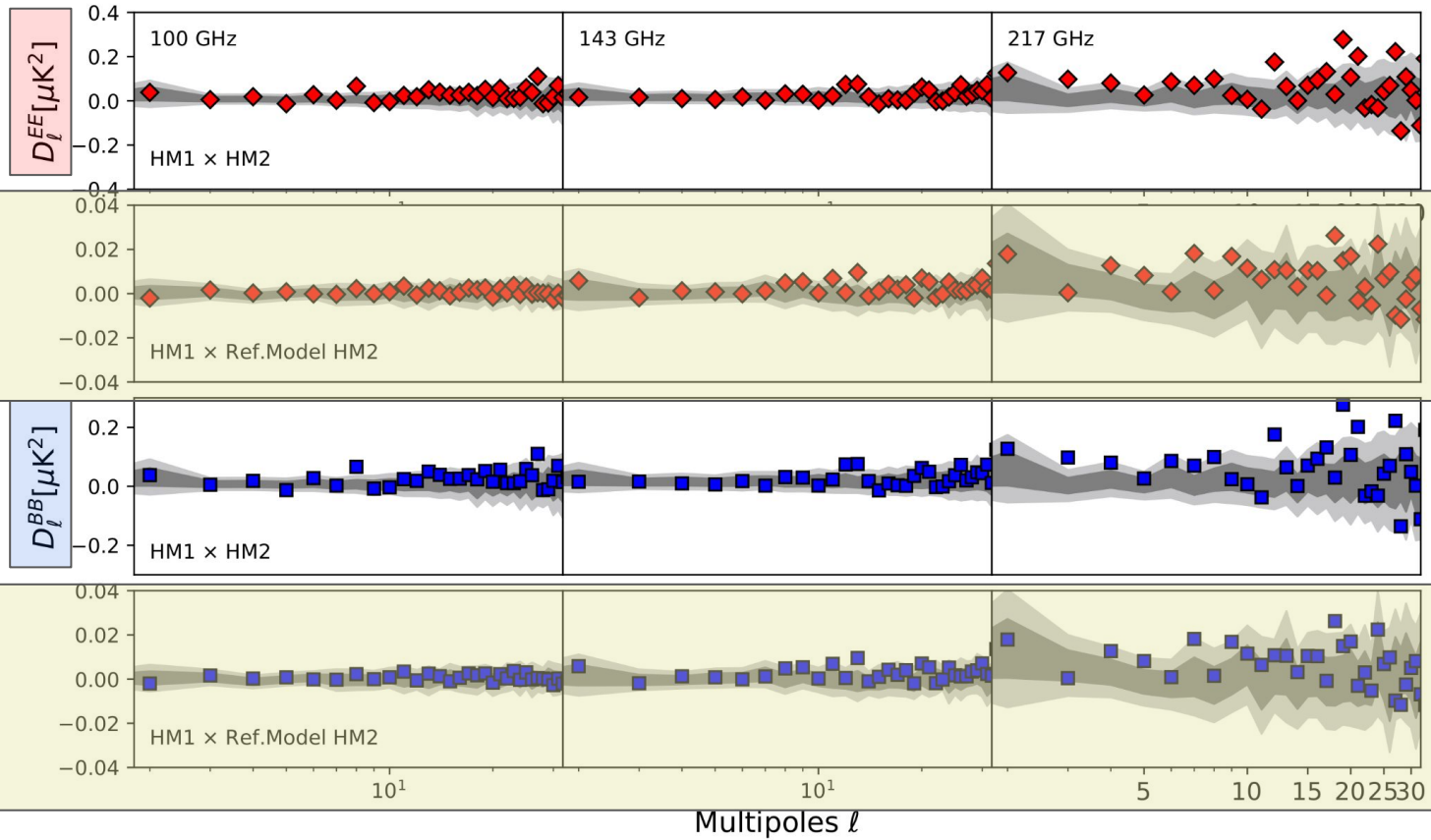
Planck maps

Dust Mean SED

$\gamma_P(\nu)$ - estimated on *Planck Sroll2* release maps
ν = 100, 143, 217 GHz
ν_0 = 353 GHz



Cross power spectra analysis of residual maps



HM1 x HM2

DATA HM x Model

HM1 x HM2

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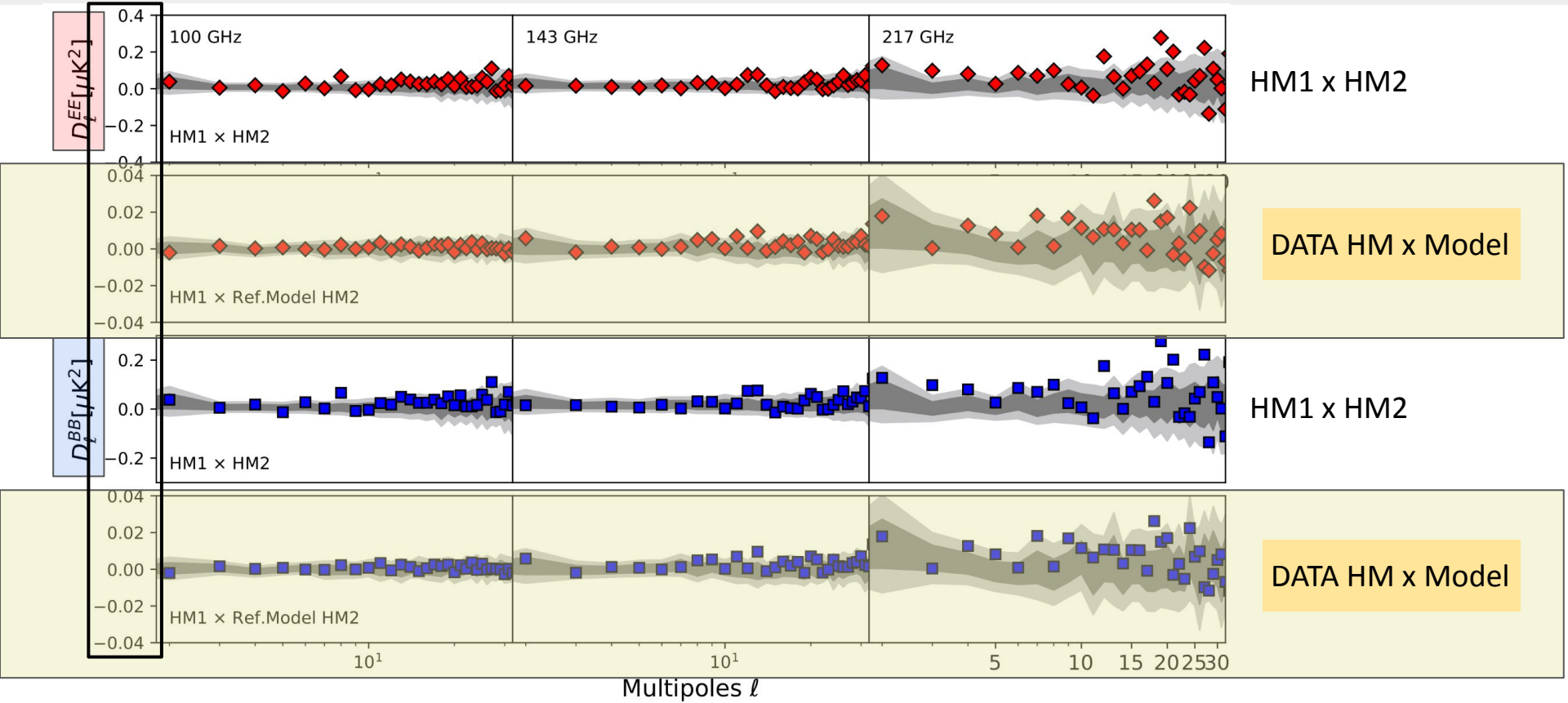
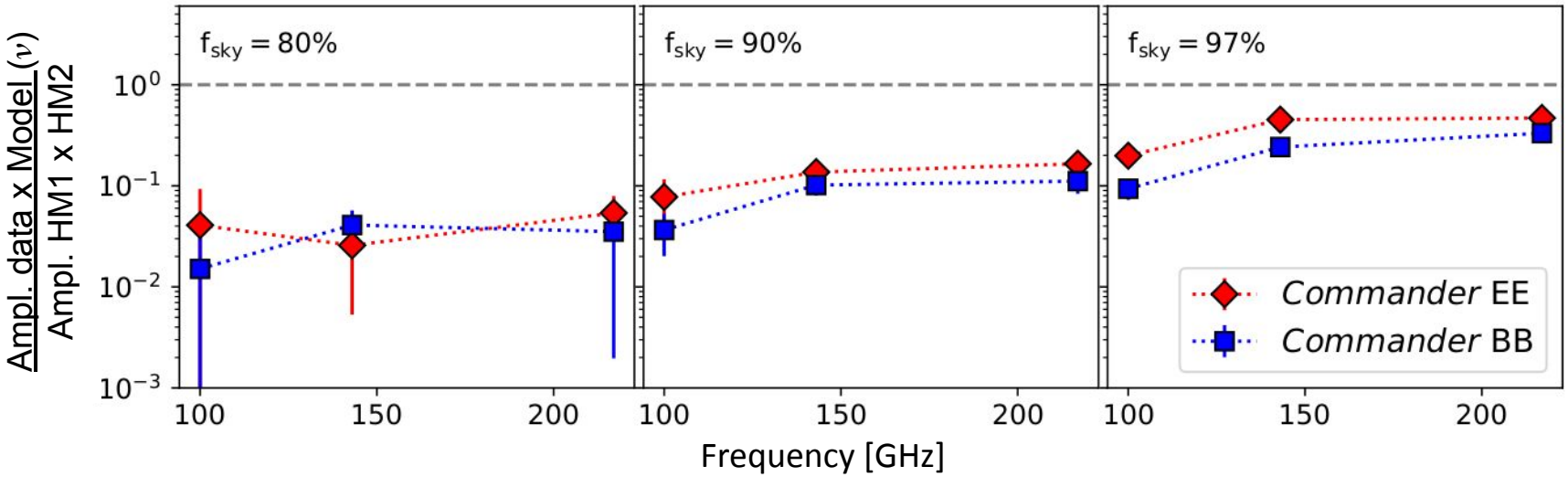
Cross power spectra analysis of residual maps



Frequency dependance of residuals amplitudes in ℓ=4-32

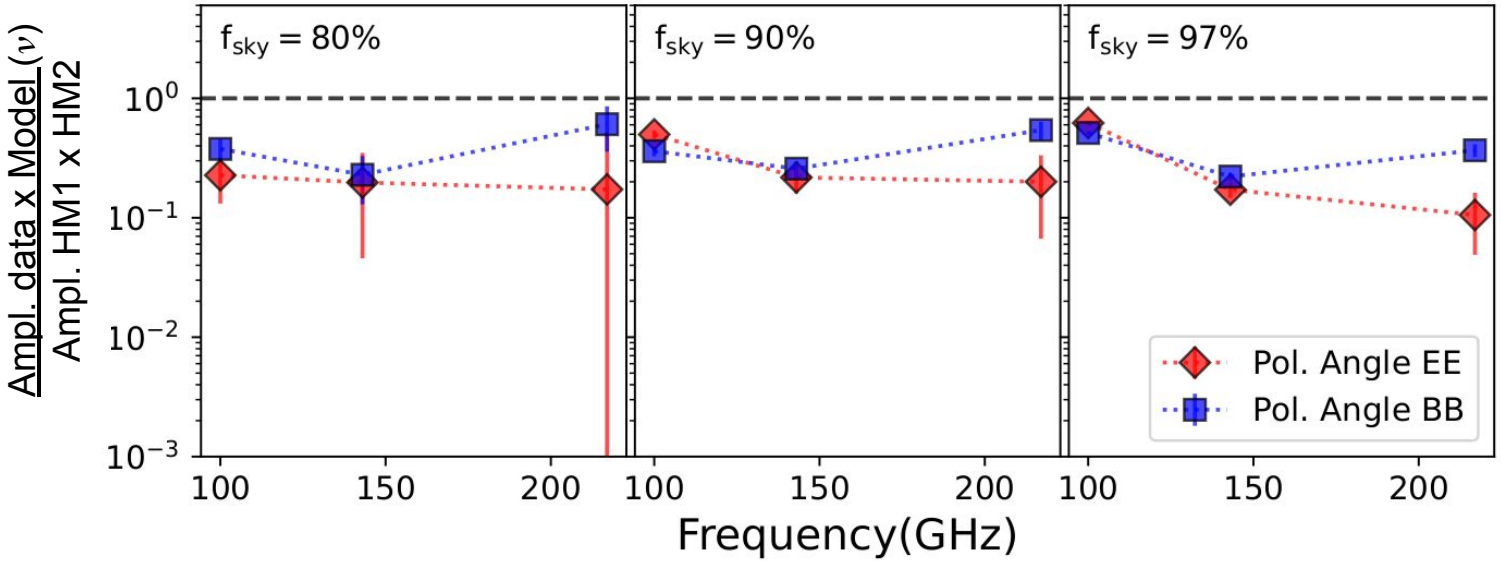


At high latitudes→less f_{sky} correlation with total intensity models based is low

Current models are not sufficient to reproduce the spatial SED variations detected in polarization data

Frequency dependance of residuals amplitudes in ℓ=4-32

derived from polarization angle maps only



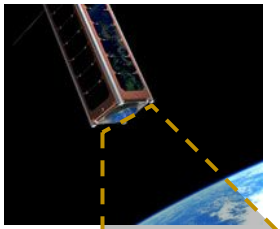
Polarization angle significantly contribute to the total spatial variation SED detected

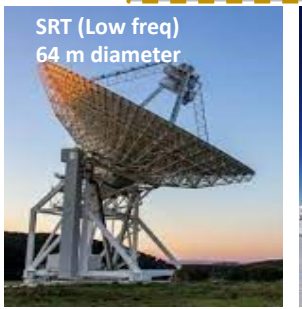
EE and BB seems to behave differently (need to be accounted in next dust models)

Ritacco A. et al. A&A 670, A163 (**2023**)

Wherever we do look, polarisation angle is messing up ...

COSMOCal project



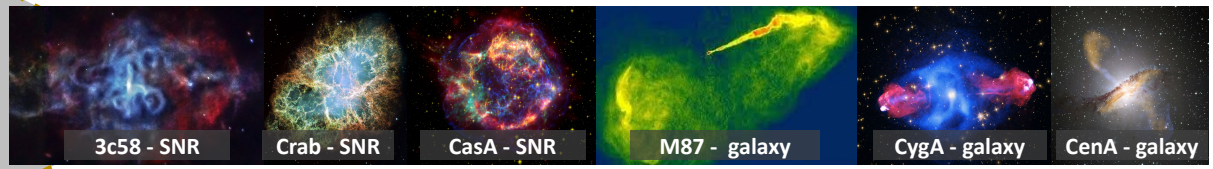


PROJECT IDEA:

- **Artificial source on a nanosatellite** to calibrate ground-based telescopes
- Observations in the range **20-400 GHz** on primary and secondary calibrators

Scientific goal: **Unbiased** detection of the CMB polarization

Challenge: **Polarization angle accuracy $\Delta\psi < 0.1°$**



Improvements on observations:

- statistics on the polarization angle **calibration**
- knowledge of instrumental **systematic effects**
- **foreground emissions** understanding

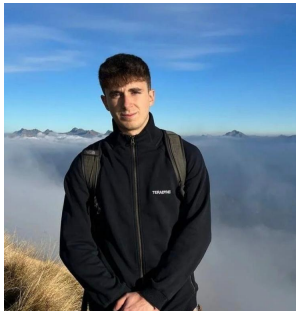
COSMOCal legacy:

a public release available to the community
to calibrate **any CMB Telescope** from **Earth** and **space**

We are developing the prototype

Intermediate goal:

Testing the prototype with the **NIKA2 camera** ($\nu \simeq 260$ GHz) from the IRAM 30m telescope in Spain.



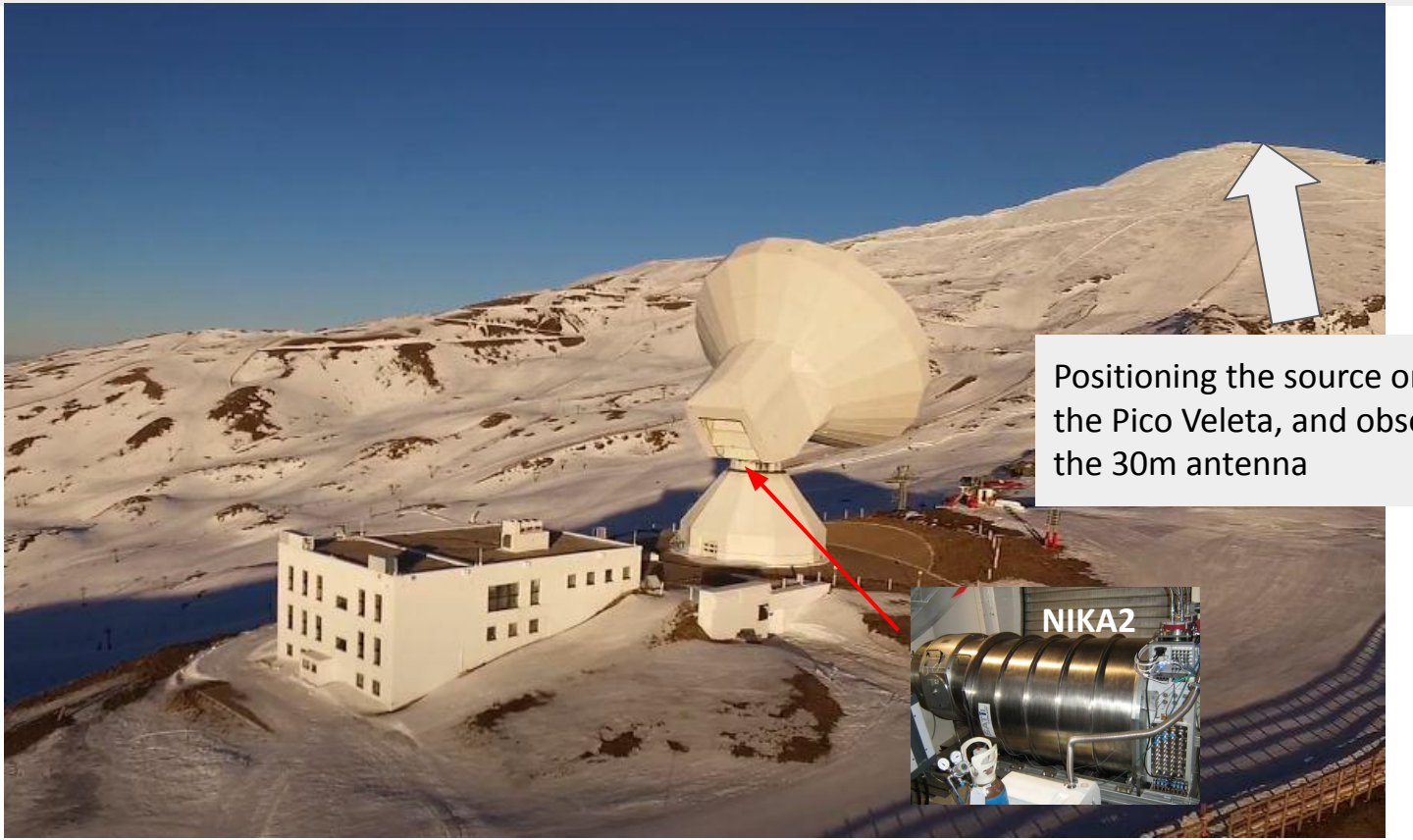
Ludovico Bizzarri

Timeline

2022-2023: Feasibility study funded by **CENSUS (CE**ntre for **N**anosatellites in **S**ciences of the **U**niver**S**e**)**

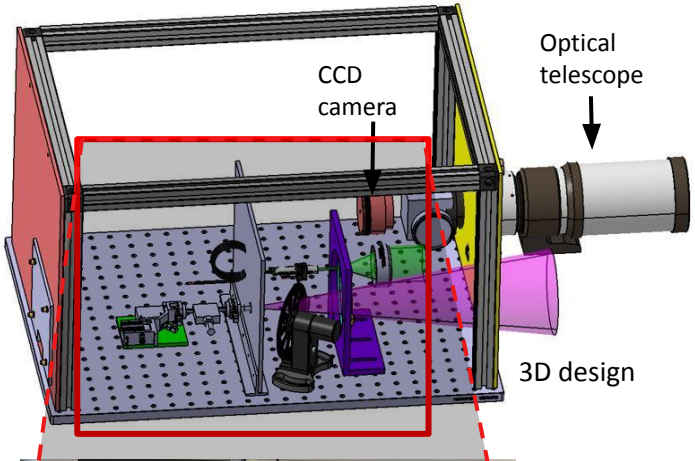
2023: Building the proof of concept for IRAM telescope. CNES likes the project idea. (Let's see …)

Idea for the measurements at IRAM site (Spain)

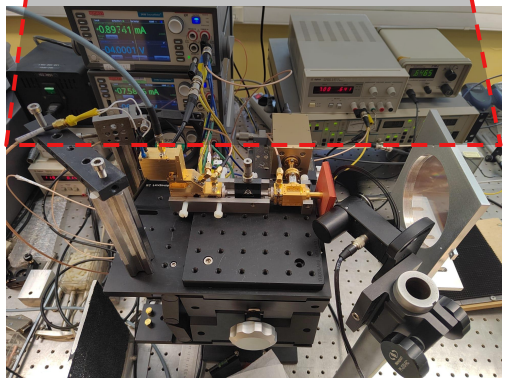


Positioning the source on the top of the Pico Veleta, and observe it with the 30m antenna

Status of the project

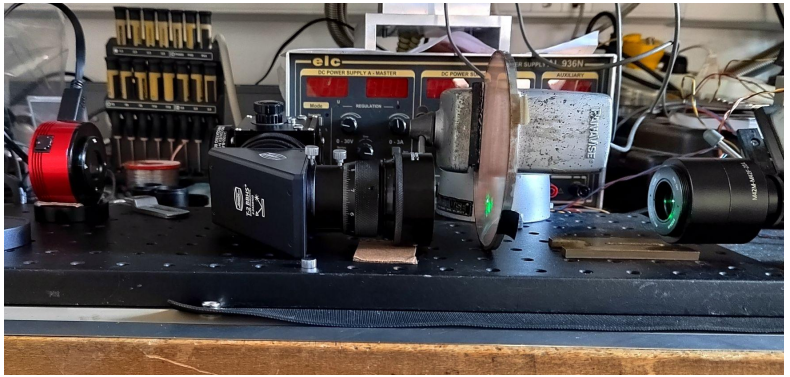


3D design

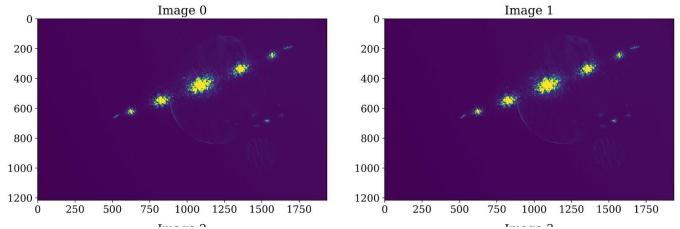


Almost totally assembled

Being tested at LERMA institute (Paris)



The reconstruction of the diffraction pattern will give us the orientation of the polarization at any moment



Conclusions

Polarization angle absolute calibration: **one** of the most important technical **challenges** to address for **future CMB experiments**.

COSMOCal project: **model and instrument independent method** to ensure a calibration strategy for polarization telescopes at millimeter wavelengths, allowing us to:

- **cross check the calibration** of ground telescopes at any time;
- study astrophysical sources in detail to select the best **calibrators** in a wide range of frequencies;
- **release a sky references** catalog for satellites;
- making **different data sets** (small and large angular scales) **compatible** in polarization.

Backup slides

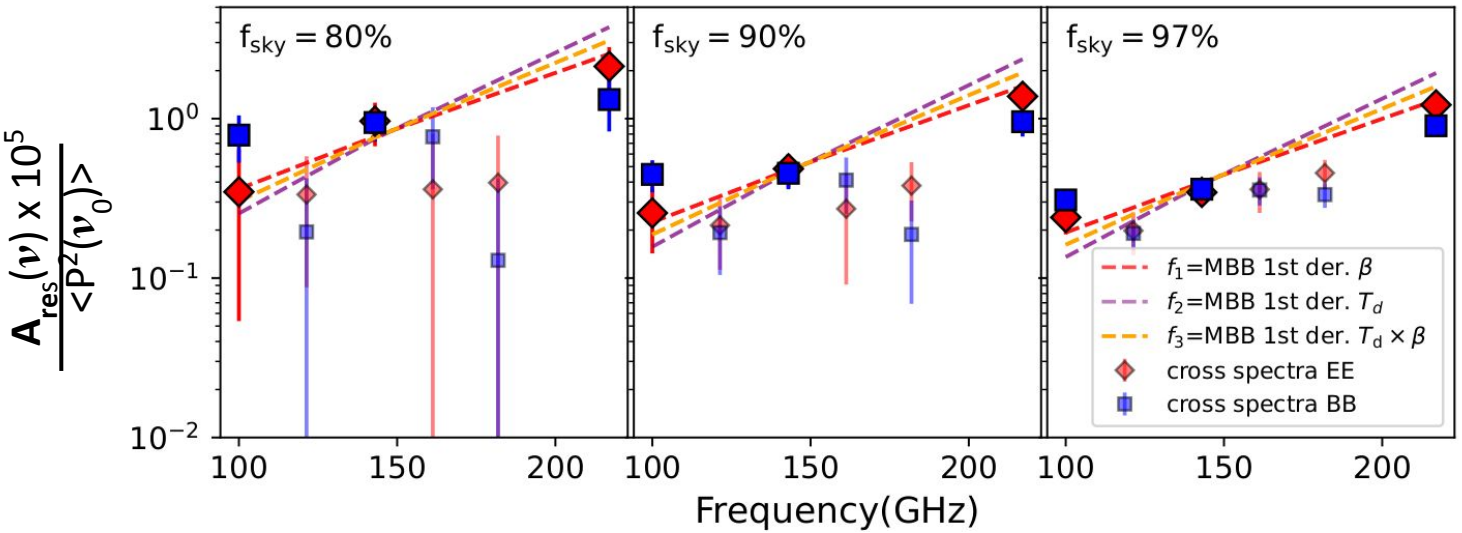
Frequency dependance

Taylor expansion of the MBB emission law

MBB 1st order deriv. β

MBB 1st order deriv. T

MBB T-β cross term



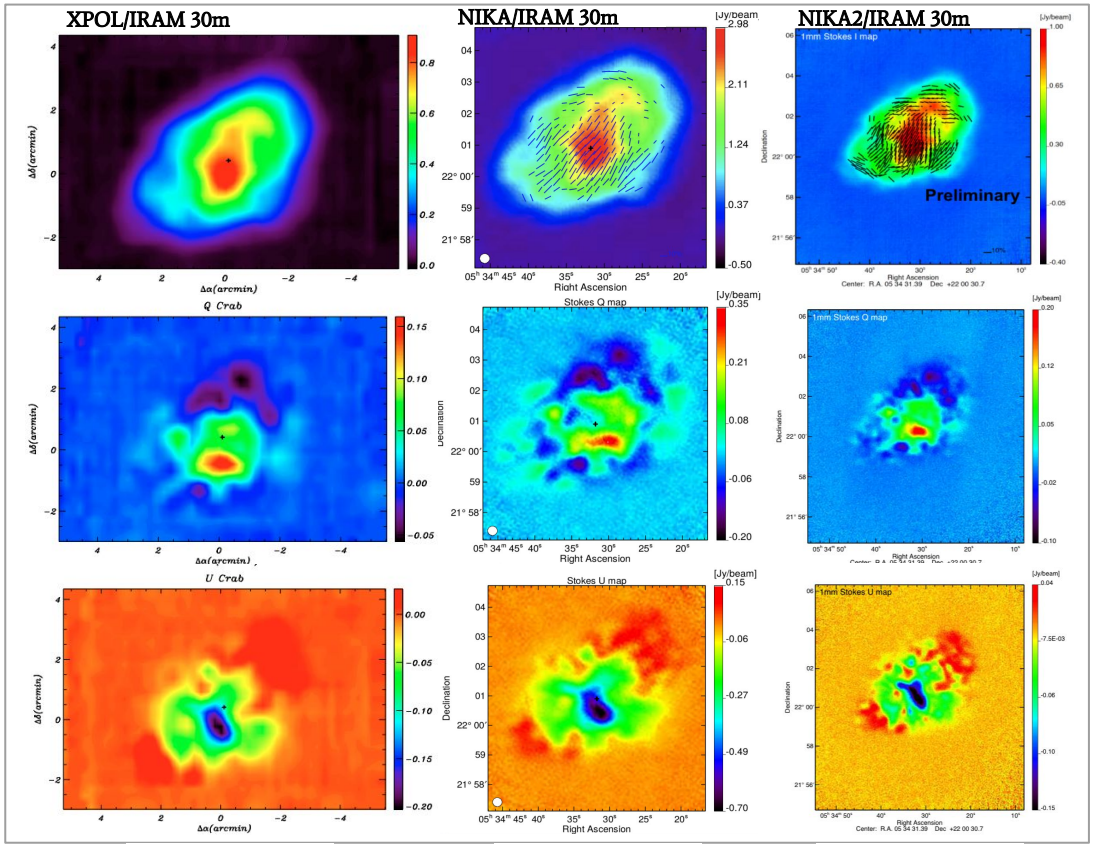
- Dust polarization ***EE*** SED variation well described by MBB deriv. in β
- ***BB*** SED tends to flat towards high angular latitudes
- Residual maps between the three frequencies are not fully correlated

High angular resolution observations at mm-wavelengths

XPOL/IRAM 30m
Freq. **89 GHz** ; FWHM 27″

NIKA/IRAM 30m
Freq. **150 GHz** ; FWHM 18″

NIKA2/IRAM 30m
Freq. **260 GHz** ; FWHM 12″



Aumont+2010 Ritacco+2018 Ritacco+2022

Scientific implications in cosmology

Absolute polarisation angle accuracy of $\Delta\psi \leq 0.1°$

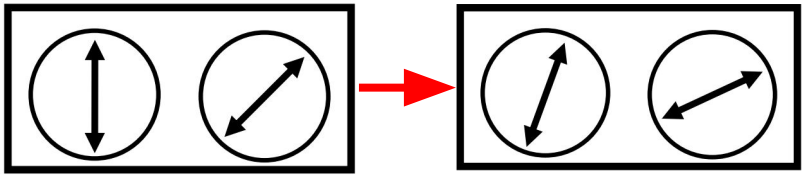
➔ **Ensuring an unbiased determination of CMB *B*-modes**

➔ **Potential discovery of the cosmic birefringence**

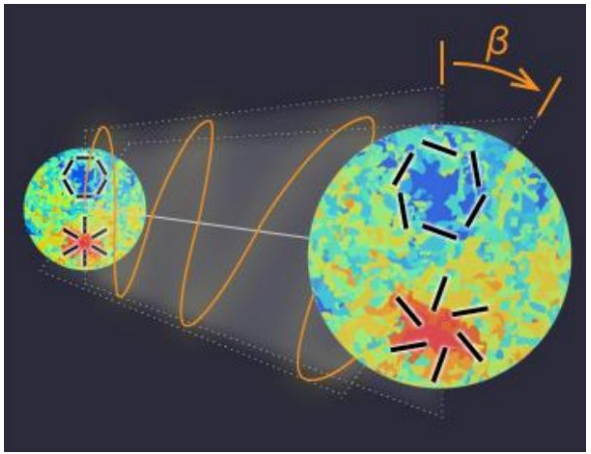
Cosmic birefringence naturally convert *E*<->*B*

$$\begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix}^{obs} = \begin{pmatrix} \cos(2\beta) & -\sin(2\beta) \\ \sin(2\beta) & \cos(2\beta) \end{pmatrix} \begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix}$$

But **miscalibration** introduces a rotation as well

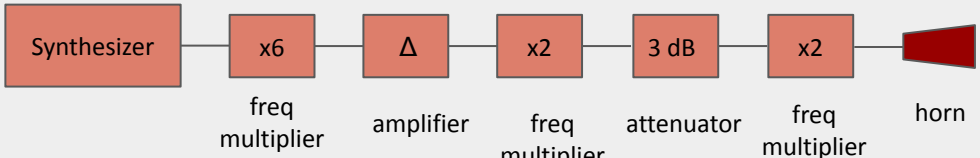


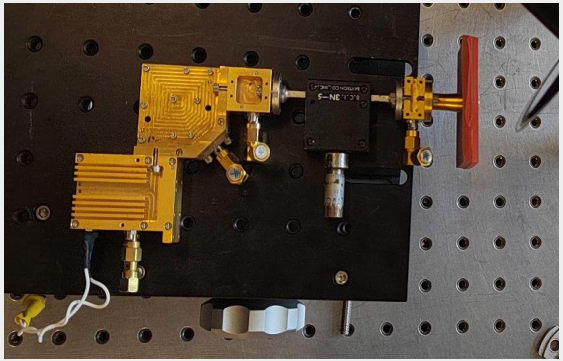
Krachmalnicoff et al. 2022



Minami, Yuto et al. 2018

Sketch of the calibration system





Millimeter source: assembled at LERMA institute **freq: (260-320)GHz**