Absolute calibration of the polarization angle through Crab nebula (Tau A) observations

Alessia Ritacco (IAS, ENS Paris-France)
on behalf of the Crab calibration team: J. Aumont, J.F. Macías-Pérez, N. Ponthieu, R. Génova-Santos ...

@ESO credits

Outline

Scientific motivations

Ground-based high angular resolution observations

Spectral energy distributions, polarization degree and angle stability

Impact on measurements of the *r* parameter for CMB B-modes detection

Plan for reducing the total uncertainty on the polarization angle calibration.

Scientific motivations: CMB-B modes detection constraints

TT spectrum: cosmological parameters from density perturbations

EE spectrum: model coherence, break degeneracies

BB lensing spectrum: gravitational lensing of EE-modes, large-scale structures

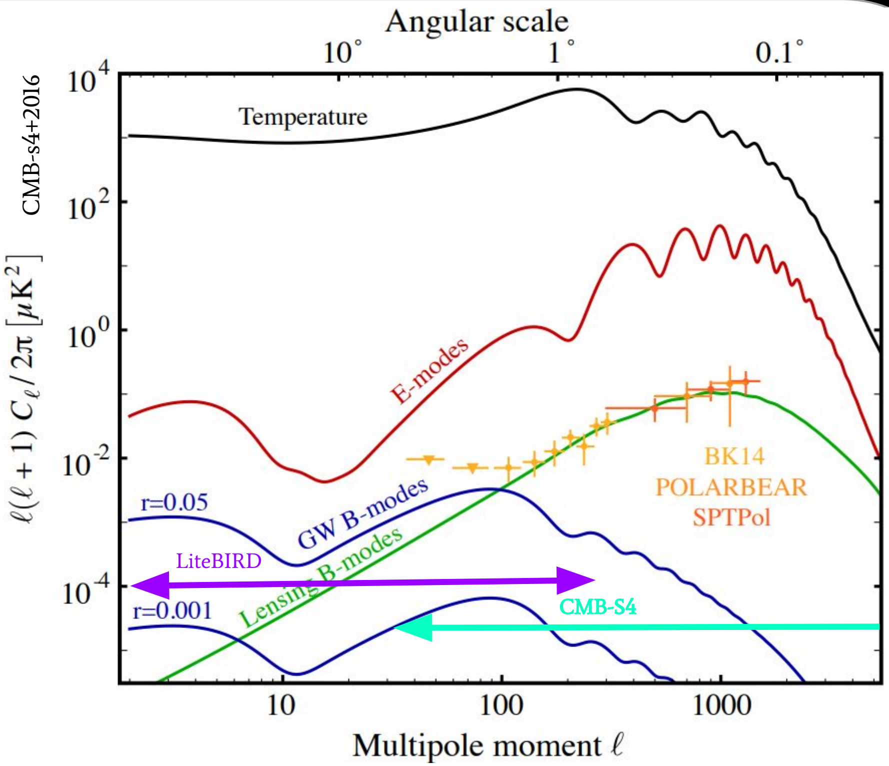
BB primordial spectrum: tensor perturbations from primordial GW background, scaled by tensor to scalar ratio r

Best upper limit is r < 0.056 [PLANCK+ *BICEP2/ Keck Array- A&A 641, A10 (2020)*]

Experiments under development are designed to target σ(r) <0.001

LiteBIRD $2 \leq \ell \leq 300$

CMB-S4 $30 \leq \ell \leq 5000$



Scientific motivations: CMB-B modes detection constraints

How does impact a mis-calibration of the polarization angle on the detection of the parameter r?

★ Timestream of data for a single polarization sensitive detector:

$$d_i(t) = g_i \left[T(\mathbf{n}) + \frac{1-\varepsilon_i}{1+\varepsilon_i} \left(Q(\mathbf{n}) \cos 2\psi_i + U(\mathbf{n}) \sin 2\psi_i \right) \right]$$

With:

$$\psi_i = \psi_i^{\text{design}} + \Delta\psi$$

- ψ_i: Detector's polarization angle projected onto the sky
- ψ_i^{design}: Intended orientation of the detector onto the sky
- $\Delta\psi$: Miscalibration (or birefringence)

Credits: Aumont +20
talk @mm-Universe-NIKA2

Scientific motivations: CMB-B modes detection constraints

A miscalibration of the absolute polarization angle by $\Delta\psi_{Gal}$ will lead to a mixing of E and B modes. In the CMB and because $C_\ell^{EE} >> C_\ell^{BB}$, this is often referred to as an "E to B leakage" and reads

$$\tilde{C}_\ell^{BB} = C_\ell^{BB} \cos^2 2\Delta\psi_{Gal} + C_\ell^{EE} \sin^2 2\Delta\psi_{Gal}$$

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

Spurious bias component

Accuracy in the calibration of the polarization angle:

- Ground calibration: very good but need to be validated during operations
- External calibration source: good accuracy but never done before, instrumental limits ?!
- Self-calibration: we expect no scientific signal from TB and EB → only instrumental
  → Losing constraints on fundamental phenomena
- Sky calibration: frequency dependence, time variability → **Best option: CRAB NEBULA**

Crab nebula

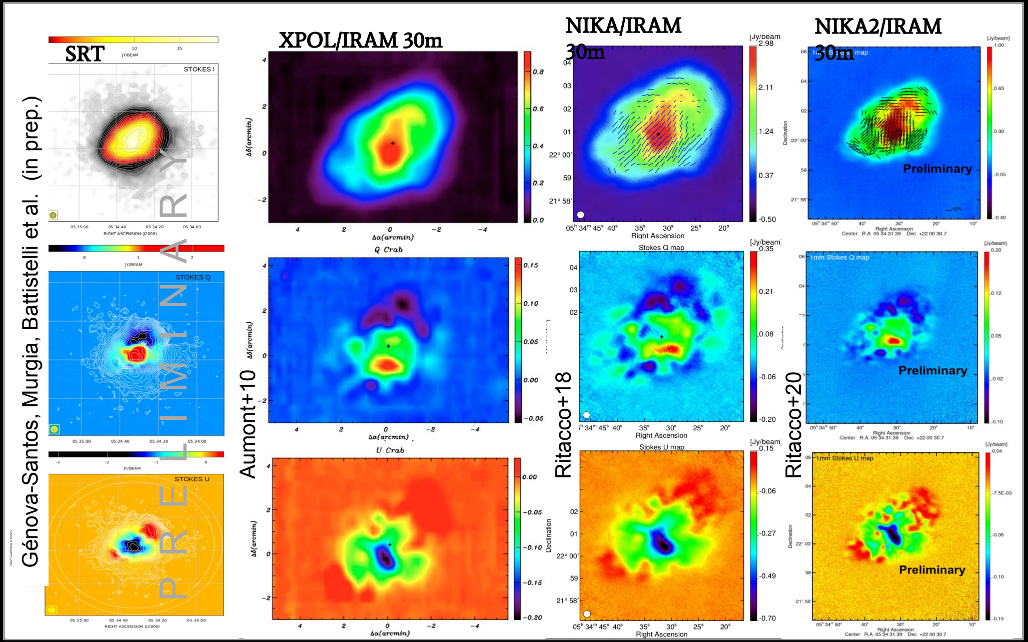
The **Crab Nebula** (Tau A) is a plerion-type supernova remnant, observed from radio to X-rays

The microwave emission has an extension of about 5′ × 7′

Most intense polarized source in the microwave sky, at angular scales of few arcminutes

Highly polarized synchrotron emission with a polarization fraction of ~ 20%

It is relatively isolated in the microwave sky within 1 degree scale



Ground based high angular resolution observations

SRT - K band
Freq. 23 GHz ; FWHM 0.8′

XPOL/IRAM 30m
Freq. 89 GHz ; FWHM 27″

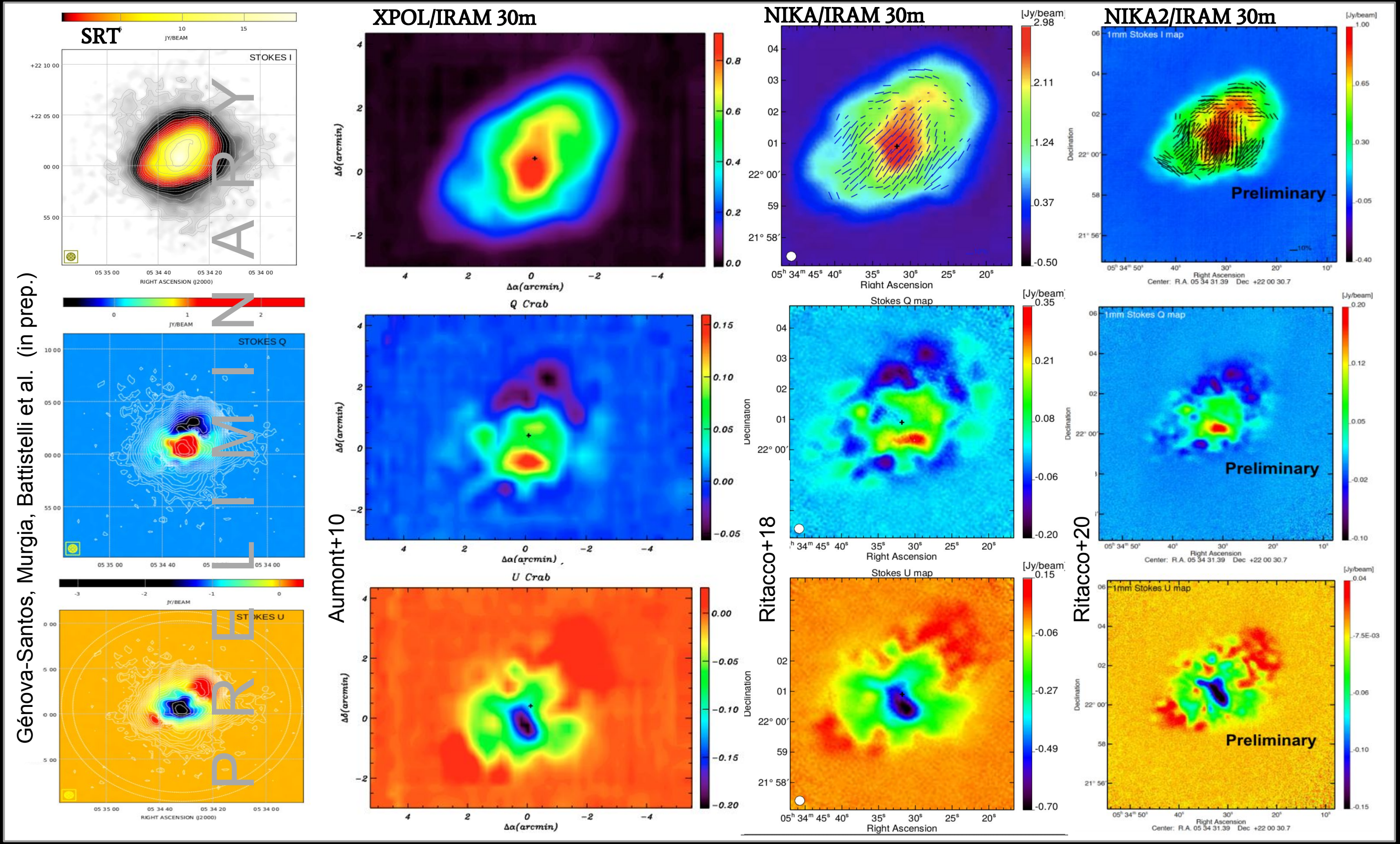
NIKA/IRAM 30m
Freq. 150 GHz ; FWHM 18″

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

NIKA2 results to be confirmed, last successful campaign (10-17 Nov. 2020)

★ excellent weather conditions: opacity $\tau \sim 0.1$

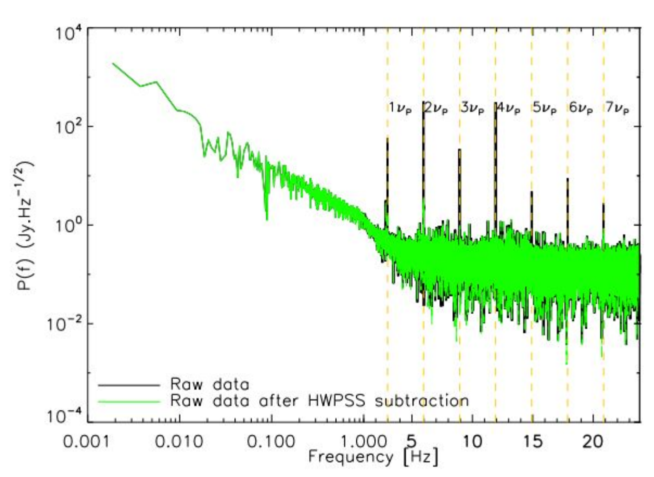
★ stable measurements from one day to another



Ground-based instruments accuracy

Ritacco et al. A&A 599, A34 (2017)

* Absolute flux calibration instabilities due to atmospheric fluctuations
* Absolute angle calibration
* High level of instrumental polarization → I to P leakage ⇨ Telescope not built for polarization only
* Side lobes …
* Polarization efficiency



NIKA-example: continuous rotating multi-layers HWP produced a modulation also of the background signal

This HWP synchronous signal (HWPSS) is peaked at harmonics of the HWP rotation frequency ν
Ritacco et al. 2017 modeled the HWPSS (and subtracted it per TOI)

A template subtraction per sub-scans has been considered crucial to avoid background residuals

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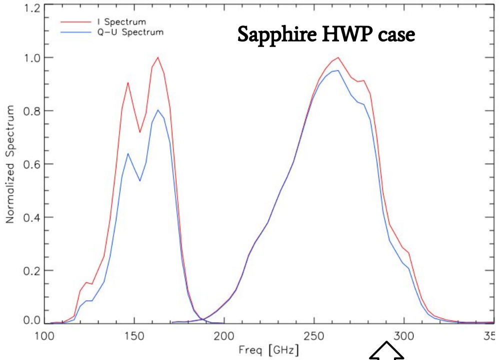
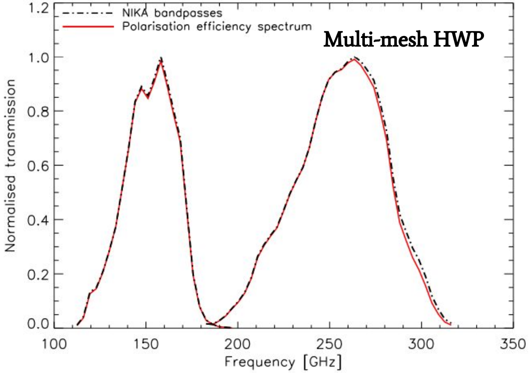


NIKA spectral transmission
Polarisation transmission of the across the NIKA's bandwidth

A. Ritacco 2016 PhD thesis

Pisano+2020arXiv200612081P

NIKA bandpasses
Polarisation efficiency across the NIKA bandwidth



Multi-mesh HWP

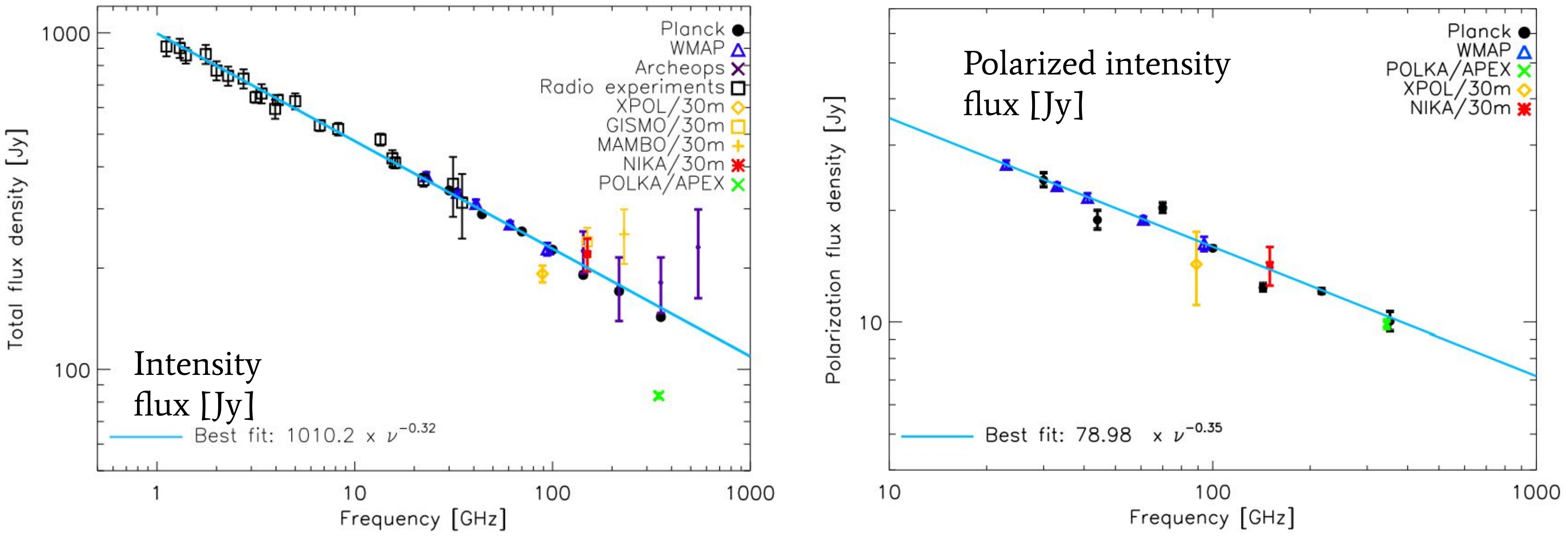
Polarization efficiency in-band:
260 GHz (1.15 mm)
ρ_{POL}= 0.9956 ± 0.0002

150 GHz (2.05 mm)
ρ_{POL}=0.9941 ± 0.0002

High-accuracy of the polar system
No loss of signal in polarization

Spectral energy distribution (SED)

The polarization spectral index is consistent with the total power index confirming that the synchrotron radiation from a single population of relativistic electrons is responsible for the emission of the nebula.
$\beta = -0.323 \pm 0.001$; $\beta_{POL} = -0.347 \pm 0.026$.



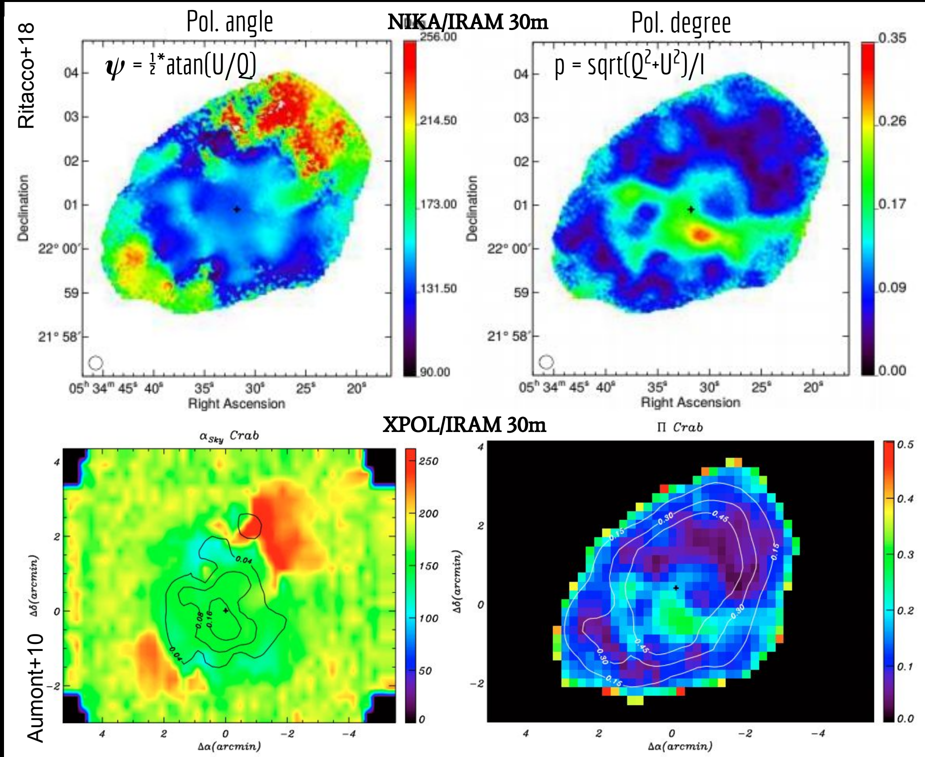
⋆Planck HFI fluxes have been recomputed here by using aperture photometry techniques

Ritacco et al. 2018, A&A, 616, A35

Ground based high angular resolution observations

A variation from small to large angular scales is observed on both the polarization angle and degree

The polarization direction appears stable with the frequency and constant within a radius of 2 arcmin from the Nebula center



Ground based high angular resolution observations

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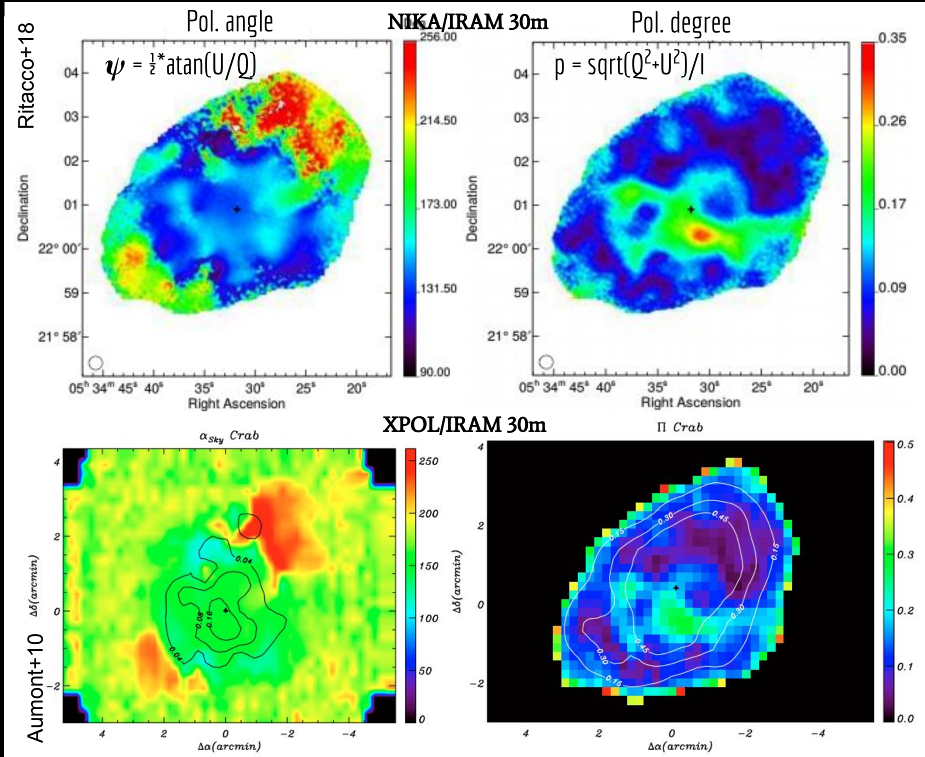
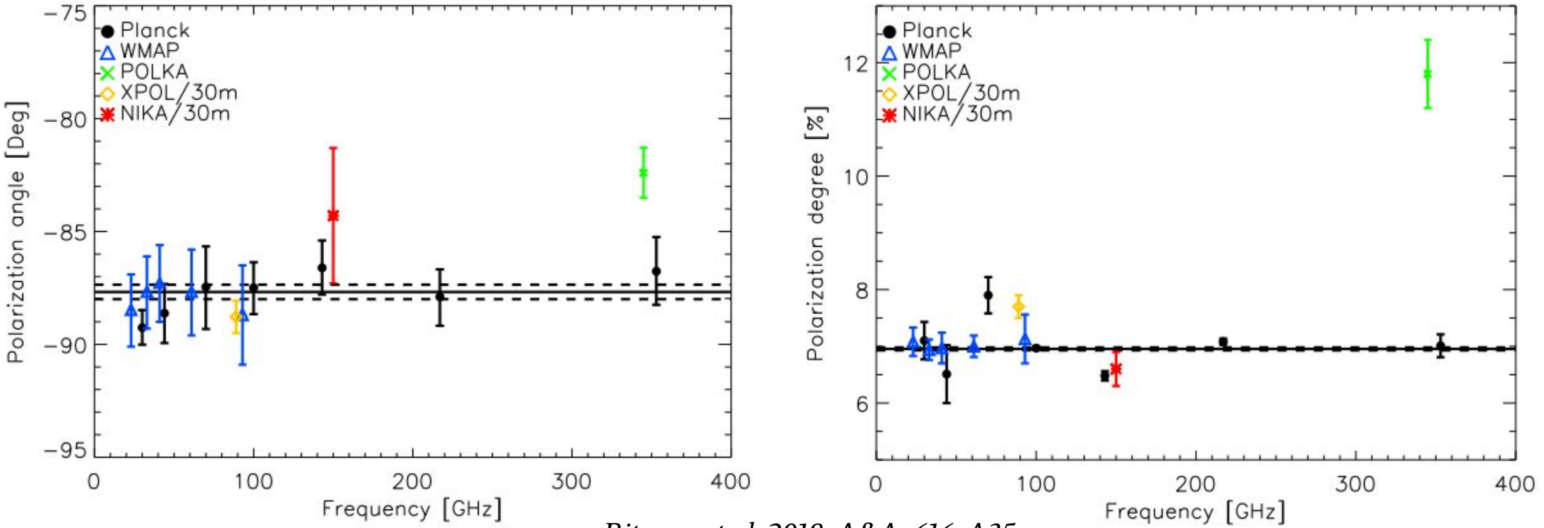
In order to compare with CMB experiments results let's now compute integrated flux across the source



Alessia Ritacco

Compendium of most of existing polarization data

*Planck HFI and NIKA data have been computed by using aperture photometry



Ritacco et al. 2018, A&A, 616, A35

* Polarization angle constant at arcmin scales with a value ψ = -87.7 +- 0.3 deg
* Strong case for a constant polarization degree below 217 GHz. Averaged value: p = 6.95 +- 0.03 %
* POLKA results (green ones) are outliers.

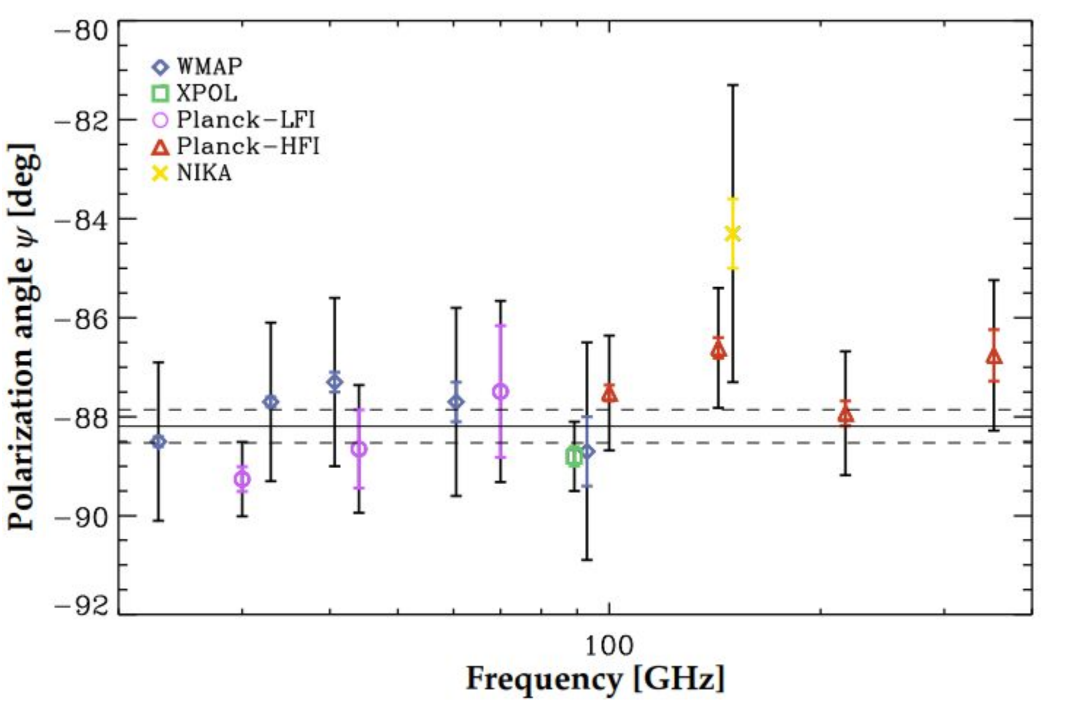
Constraints of the absolute calibration

Excluding Polka data outliers

* Compilation of:
WMAP [Weiland+11]
Planck-LFI [Planck 2015 XXVI],
Planck-HFI, re-analyzed in [Ritacco+18])
XPOL\IRAM-30m [Aumont+10]
and NIKA\IRAM-30m [Ritacco+18]

Total weighted polarization angle average:

ψ = -88.26°± 0.27°



J. Aumont , J.F. Macías-Pérez, A. Ritacco, N. Ponthieu, A. Mangilli A&A 634, A100 (2020)

Combining current (and future) measurements

Name	Assumption	Statistical error	Systematic error	Planck Systematics	New experiment	Crab pol. angle uncertainty $\Delta\psi$ (1σ)
max	Maximum difference between the mean value and one measurement	✗	✗	✗	✗	3.96°
stddev	Standard deviation of the measurements	✗	✗	✗	✗	1.24°
cst-PlanckGround	Constant angle	✓	✓	Ground	✗	0.27°
cst-PlanckEB	Constant angle	✓	✓	*EB*	✗	0.22°
cst-PlanckTB	Constant angle	✓	✓	*TB*	✗	0.17°
cst-PlanckTB+future	Constant angle	✓	✓	*TB*	✓	0.11°

2 bands with 0.2° total error

Credits: Aumont +20
talk @mm-Universe-NIKA2

Combining current (and future) measurements

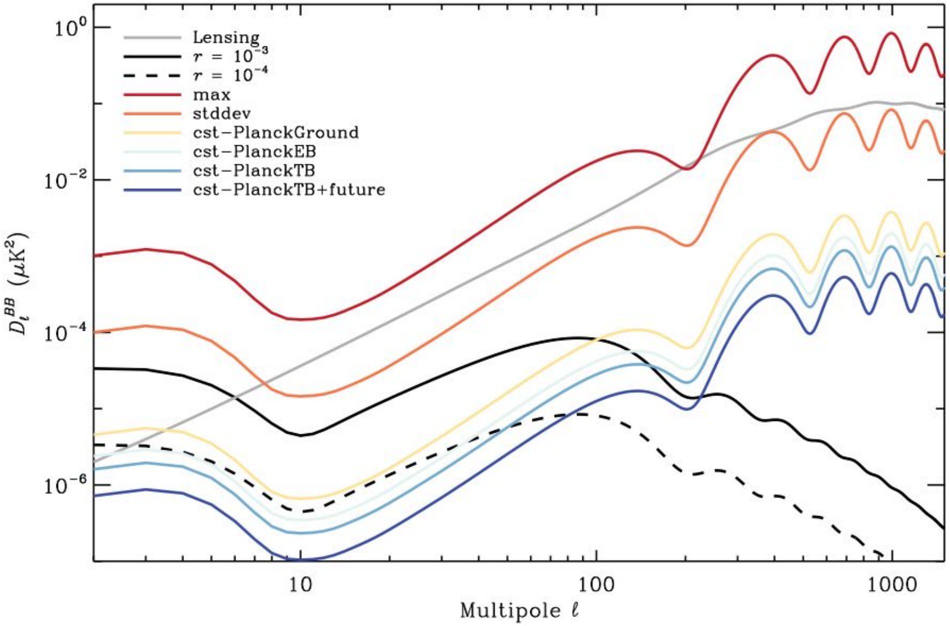
Power spectrum bias from E–B mixing due to the miscalibration of the absolute polarisation angle

Aumont+2020

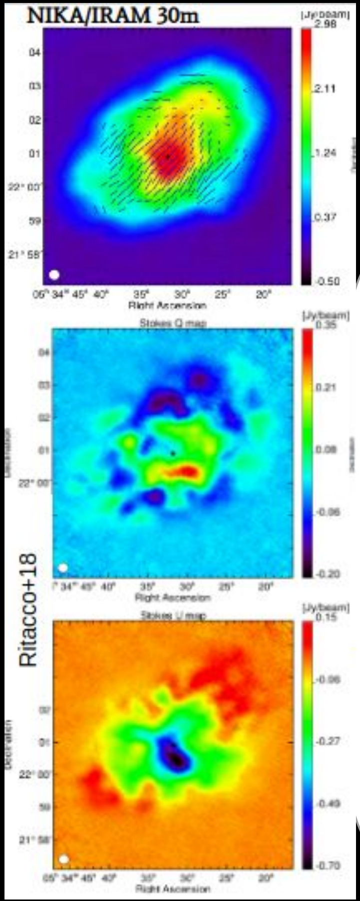
* Assumption of constant polarization angle is necessary to lower the $\mathbf{D_\ell^{BB}}$ **bias**

* Current measurements could allow to probe $\boldsymbol{r = 10^{-2}}$

* Future accurate measurements of the Crab are needed to meet the requirements of future CMB experiments to measure $\boldsymbol{r = 10^{-3}}$



SUMMARY



A miscalibration of the absolute polarisation angle by $\Delta\psi_{Gal}$ leads to a mixing of E and B modes producing a spurious bias component $\Delta C_\ell^{BB} \simeq (2\Delta\psi_{Gal})^2 C_\ell^{EE}$

HIGH ACCURACY IS REQUIRED FOR A CLEAR DETECTION OF THE PRIMORDIAL B-MODES SIGNAL

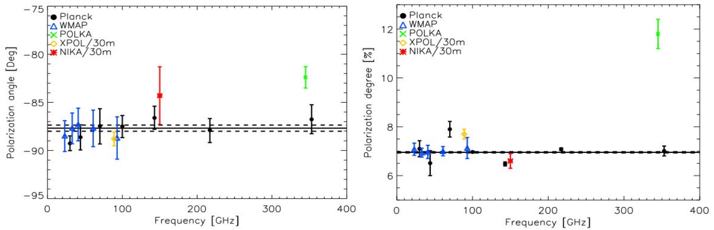
SKY calibrator: CRAB NEBULA
Weighted average total polar fraction (30-217 GHz): $p = 6.95$ +- 0.03%
and angle $\boldsymbol{\psi}$ **= -88.26°± 0.27°**

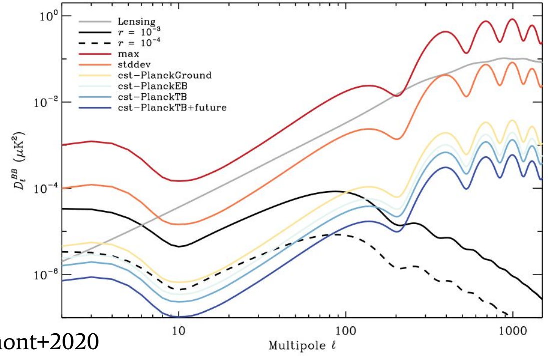
⇨ Current measurements could allow to probe $\boldsymbol{r = 10^{-2}}$

Additional measurements with total uncertainties of 0.2° could help to decrease the bias on r from miscalibration **probing $\boldsymbol{r = 10^{-3}}$**

👉Proposal: joint session of observations, at different angular resolutions covering a large frequency range, telescopes: SRT+JMCT+IRAM30m

Ritacco+2018





Aumont+2020

Conclusions & Perspectives

→ An order of magnitude lower **($\sigma(r) < 10^{-3}$)** is required for any unambiguous detection of the primordial B-modes.

A step forward to **improve** the current modelling of the Crab and its **angle uncertainty $\Delta\psi$** could be achieved by performing a joint session of observations, at different angular resolutions, and more importantly covering a large frequency range

Proposal

* 1deg^2 size map to study the background dust emission by using state-of-art ground instruments:

NIKA2/IRAM-30m (12″) 260 GHz
SRT (0.8′) 23 GHz
SCUBA2-POL-2/JMCT (13″) 350 GHz