Highly precise polarization observations from ground and space

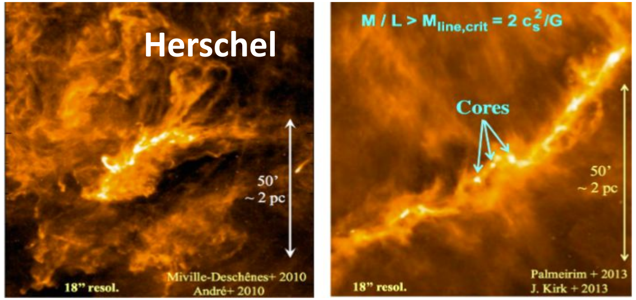
Alessia Ritacco

Laboratoire de Physique de l'École normale supérieure (LPENS) - Paris
Institut d'Astrophysique Spatiale (IAS) Orsay

Current challenges

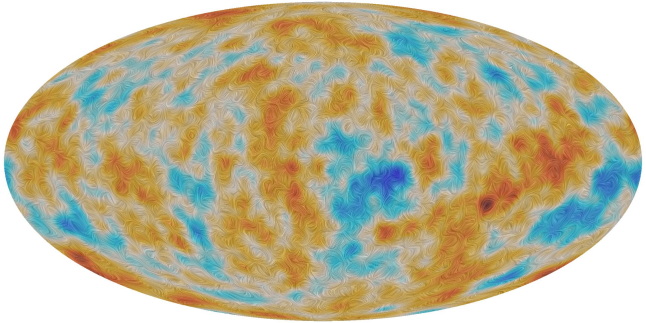
Scientific Challenges

Star formation process



- Magnetic fields at small angular scales (0.01-0.05 pc)

Primordial gravitational waves



- Cosmic Microwave Background **polarization**

Technical Challenges

- Sensitivity of the instruments
- Calibration accuracy
- Systematic effects control

HIGHLY PRECISE POLARIZATION OBSERVATIONS

Outline

- NIKA2 polarimeter to unveil the galactic magnetic fields
  - ★ Half wave plates to modulate the polarization
  - ★ Control of systematic effects: the lessons learnt on NIKA(1)

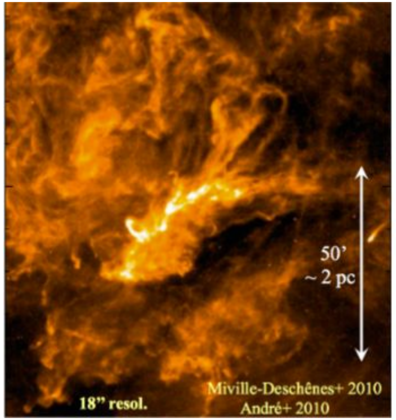
- Cosmic Microwave Background B-modes detection
  - ★ Absolute Calibration
  - ★ Foreground challenge

Magnetic field structures in galactic regions

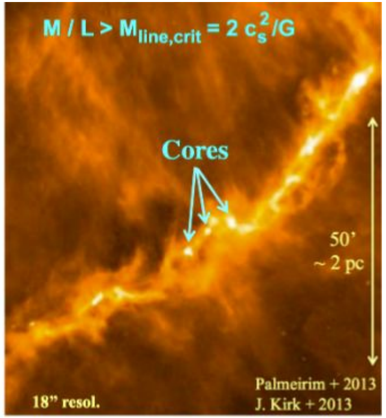
Herschel satellite results suggest a filamentary paradigm of star formation

Large scale MHD turbulent flows generate filaments

Gravity fragments the densest filaments into prestellar cores



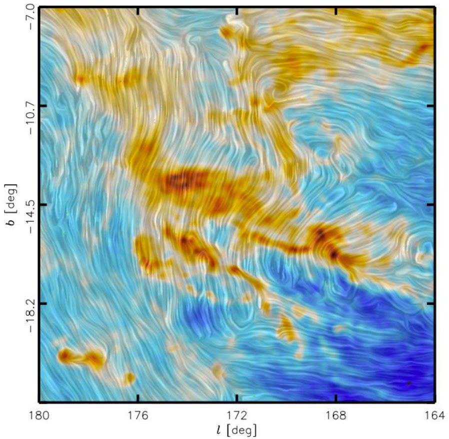
Polaris - Herschel/Spire 250 μm
Ref: Protostars and Planets VI review



Taurus B211/3 - Herschel
André, Di Francesco, Ward-Thompson+2014

Planck polarization results reveal a well organized magnetic field at large angular scales

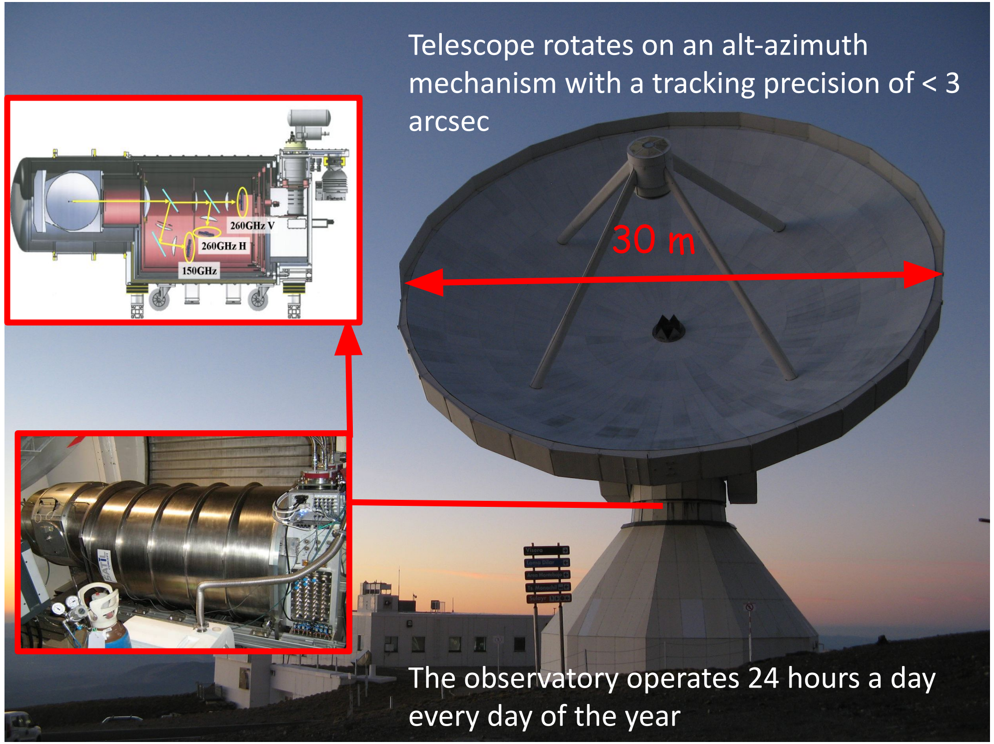
Taurus: columns density + B lines



Planck int. results XXXV

Need of high angular resolution observations to resolve the width of filaments ~ 0.01-0.05 pc

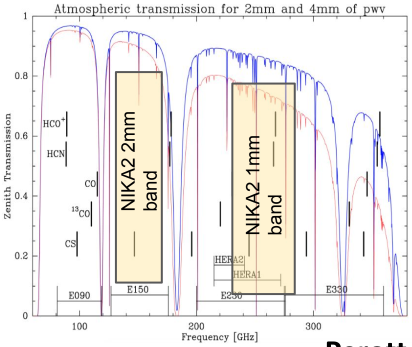
NIKA2 at IRAM 30m telescope



NIKA2 continuum camera: **6.5 arcmin of FoV**

2mm band: 125-170 GHz **FWHM 17 arcsec**

1mm band: 240-280 GHz **FWHM 11 arcsec**



Perotto et al. 2020

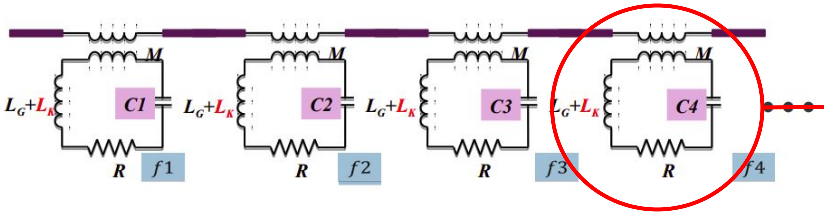
Science:
- **Star formation;**
- **Galactic and extragalactic physics;**
- **Cosmology through the SZ effect in galaxy clusters;**
- **Solar system.**

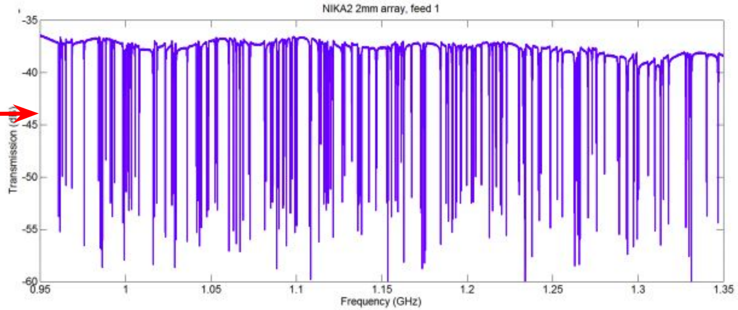
Current challenges

- Big arrays of high sensitive detectors to increase SNR
- Instrumental systematic effects control
- Absolute calibration of the polarization angle
- Accurate component separation of foreground emissions

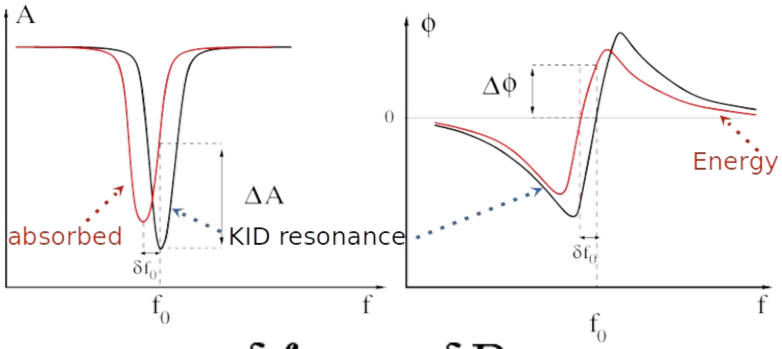
Kinetic Inductance Detectors

KIDs are RLC superconducting resonators

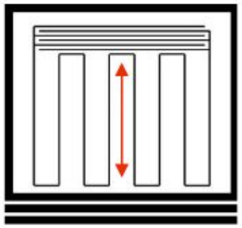




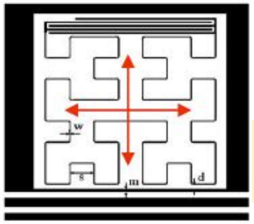
KIDs are intrinsically suited for Frequency Domain Multiplexing



$$\delta f_0 \propto -\delta P_{opt}$$



Sensitive to one polarization



Sensitive to both linear polarizations

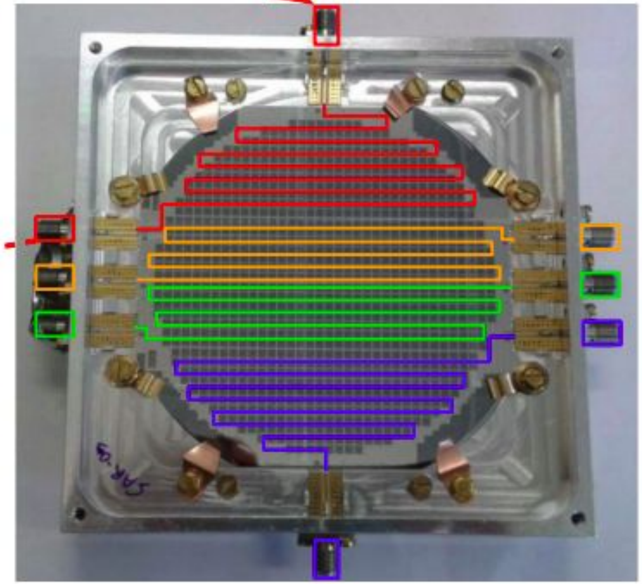
Hilbert geometry

NIKA/NIKA2 detectors

NIKA2 Kinetic Inductance Detectors array

- 2 mm array: 616 pixels → 4 feedlines
- 1.15 mm arrays: 1140 pixels → 8 feedlines

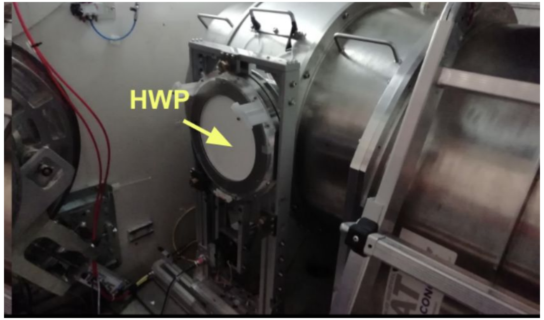
O. Bourrion et al., 2012 JINST 7 P07014

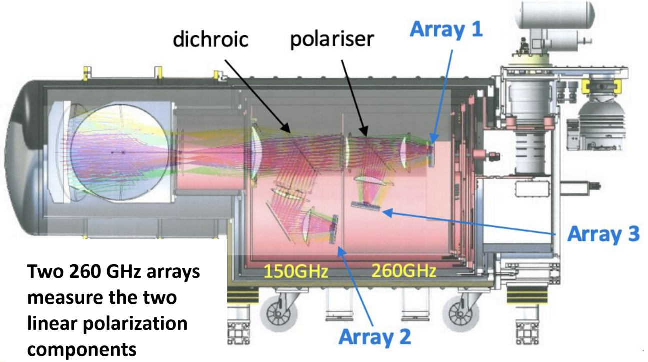


NIKA and NIKA2 polarimeter

Half wave plate modulator

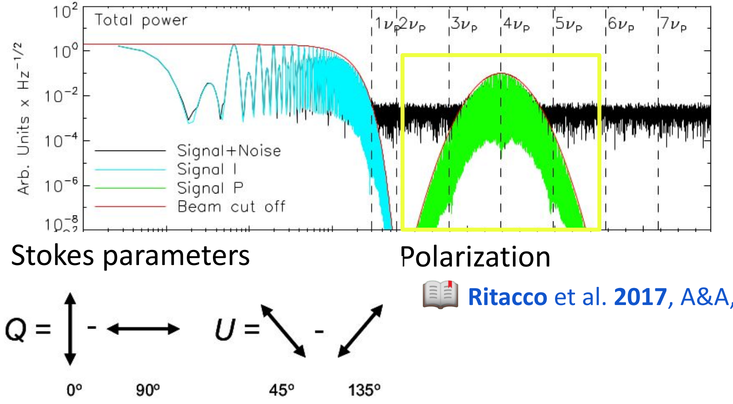
IRAM 30m receiver cabin





Two 260 GHz arrays measure the two linear polarization components

Simulation



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

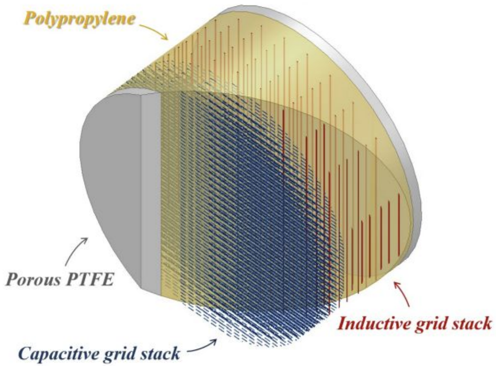
$$\hat{S} = I + Q\cos(4\nu_P+\psi) + U\sin(4\nu_P+\psi)$$

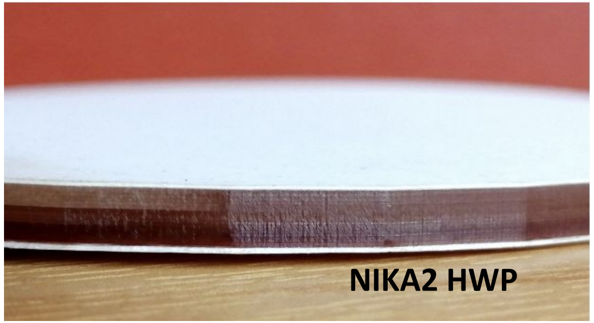
S = Ŝ + **HWP Synchronous Signal** + **Detector Noise** + **Glitches terms** + **Electronic Noise** + **Cryogenic Noise** + **Instrumental polarization**

Systematic effects control for an accurate observation

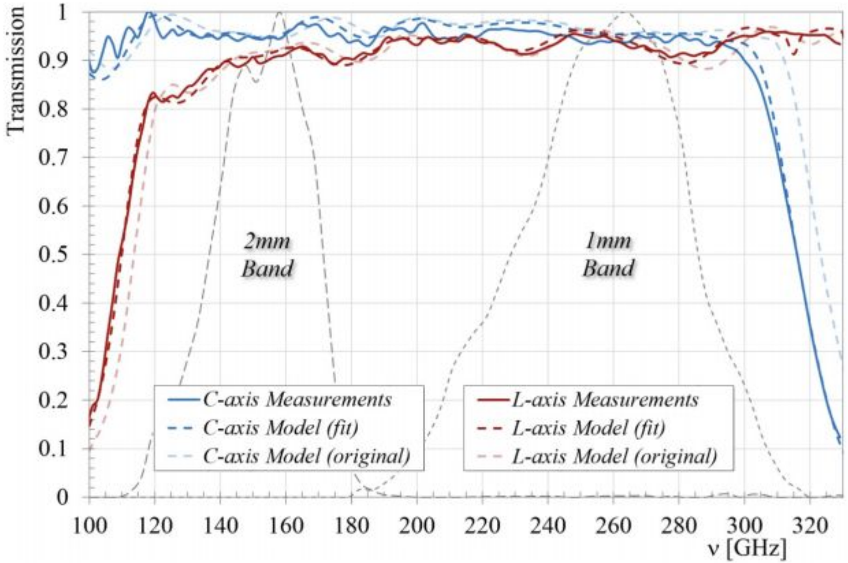
NIKA-NIKA2 Half-wave-plate

Metal mesh layers used to optimize the transmission in a large freq. range



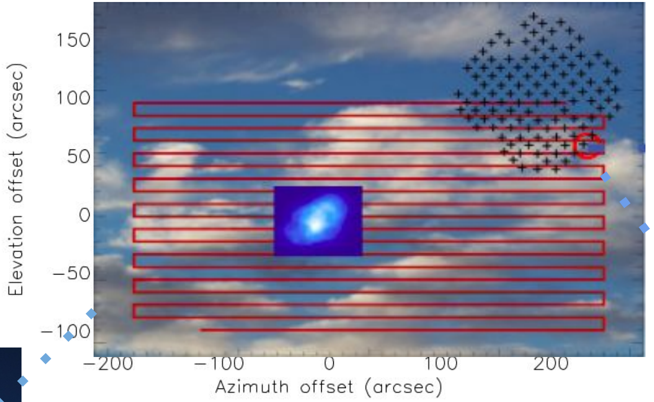


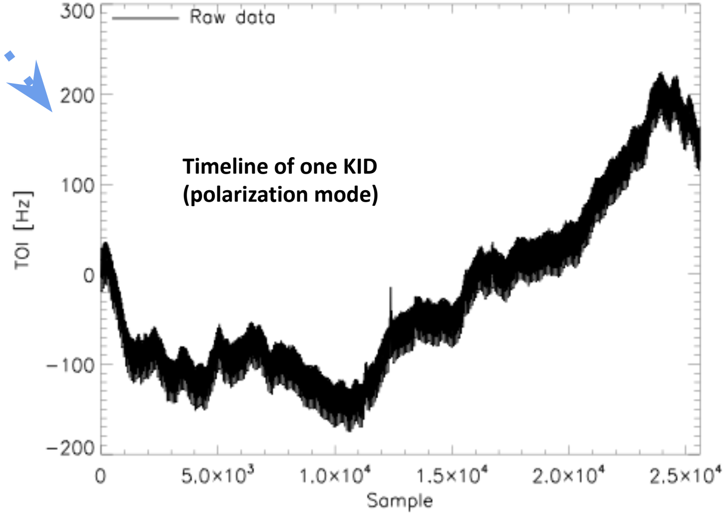
Pisano, **Ritacco**+2021 A&A (*in press*)



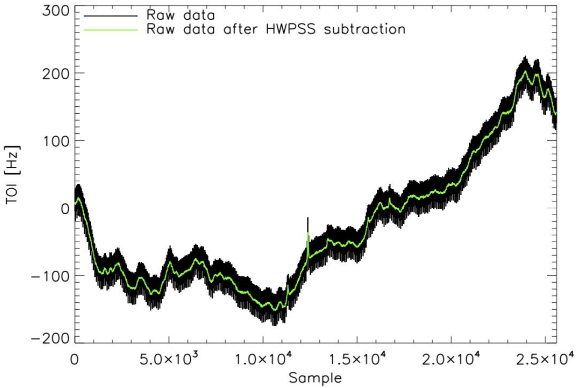
99.6% of the polarization is transmitted

NIKA2 polarimeter on the sky

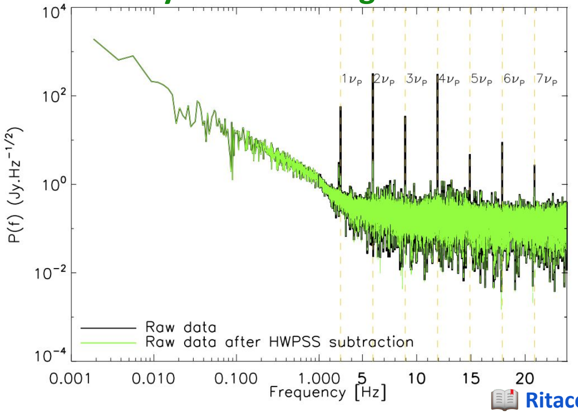


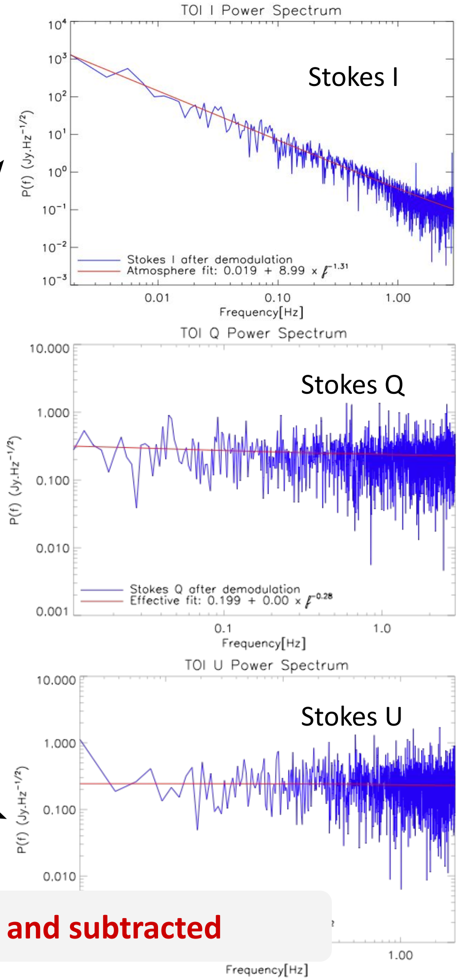


NIKA instrument: a test bench for HWP systematic effects



HWP synchronous signal subtraction



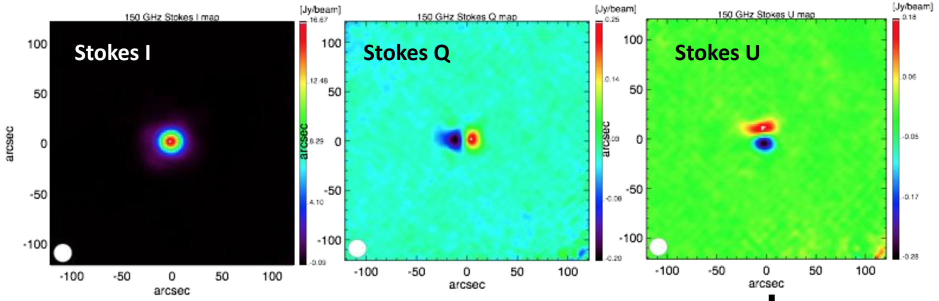


Ritacco et al. **2017**, A&A, 599, A34

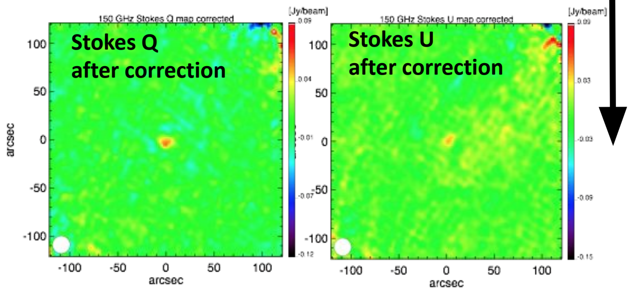
HWP systematic effects well characterized and subtracted

NIKA instrument: prototype of NIKA2 polarimeter

Instrumental polarization: Intensity to polarization leakage

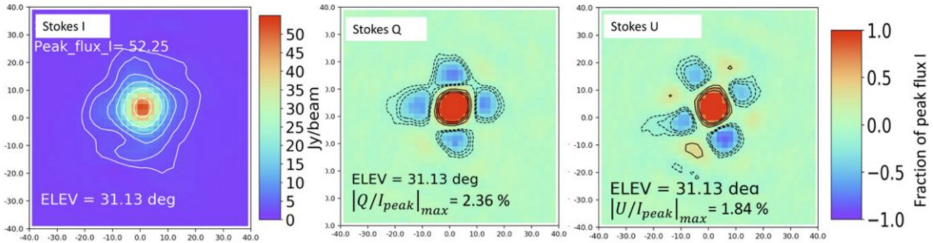


IP reduced from 3% of I to 0.6 %



Ritacco et al. **2017**, A&A, 599, A34

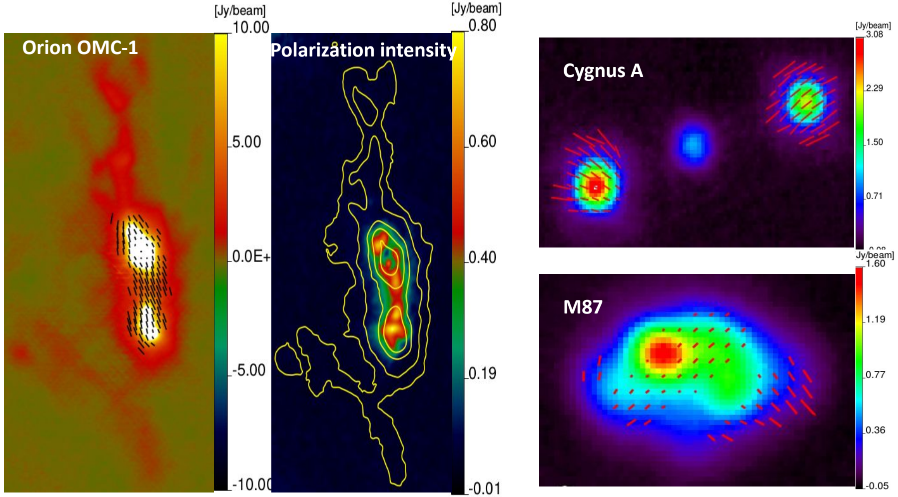
NIKA2 instrumental polarization ~ 2% of I   Ajeddig+2020



In NIKA2 we are improving the characterization thanks also to the optics modelling

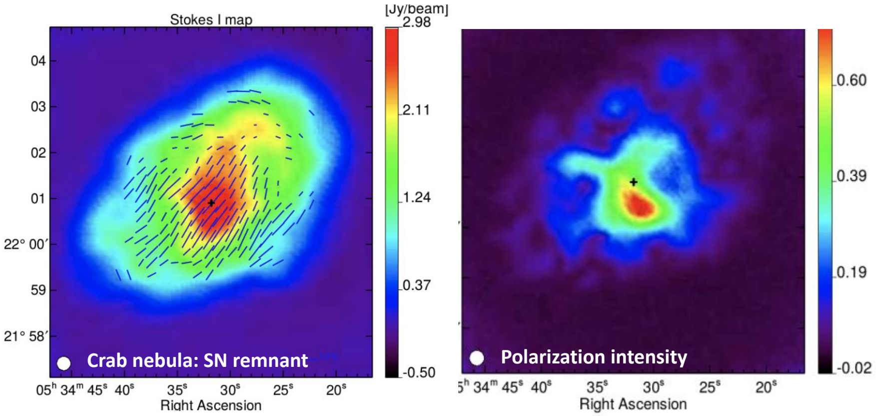
NIKA instrument scientific results

Calibration and performances shown on different astrophysical sources



📖 Ritacco et al. **2017**, A&A, 599, A34

First high-resolution observation of the Crab nebula at 150 GHz that brought to significative advances in calibration studies for CMB experiments



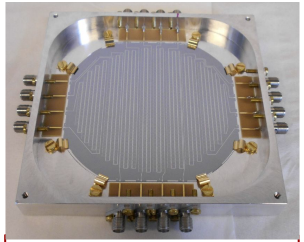
📖 Ritacco et al. **2018** A&A, 616, A35

NIKA2: better sensitivity, larger Field of View

Exciting science yet to come

NIKA2 instrument

IRAM 30m telescope

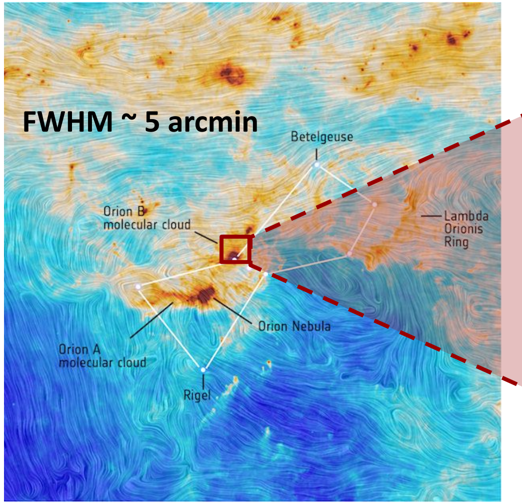


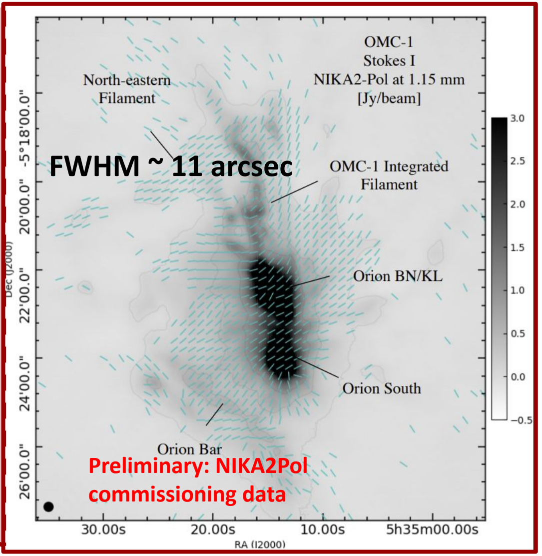
NIKA2 KID ARRAY
~ thousands of pixels

FWHM: 17.5 - 11 arcsec
Frequencies: 150, 260 GHz
Wavelengths: millimetre
FoV:6.5 arcmin

📖 NIKA2 coll. A&A 609, A115 (2018)

Polarization @260 GHz goal
Unveiling galactic magnetic fields where star formation takes place





Next year

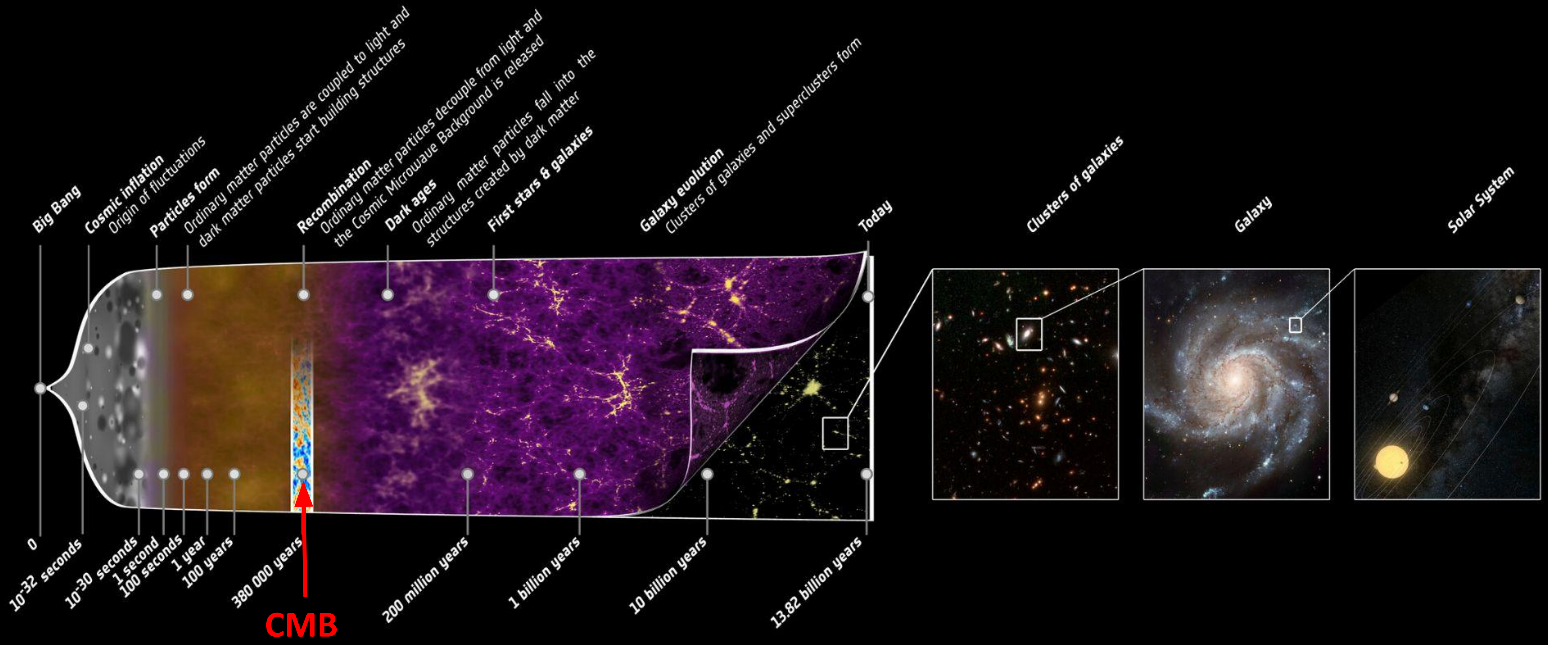
Polarization available to the community

Outline

- NIKA2 polarimeter to unveil the galactic magnetic fields
  - ★ Half wave plates to modulate the polarization
  - ★ Control of systematic effects: the lessons learnt on NIKA(1)

- Cosmic Microwave Background B-modes detection
  - ★ Absolute Calibration
  - ★ Foreground challenge

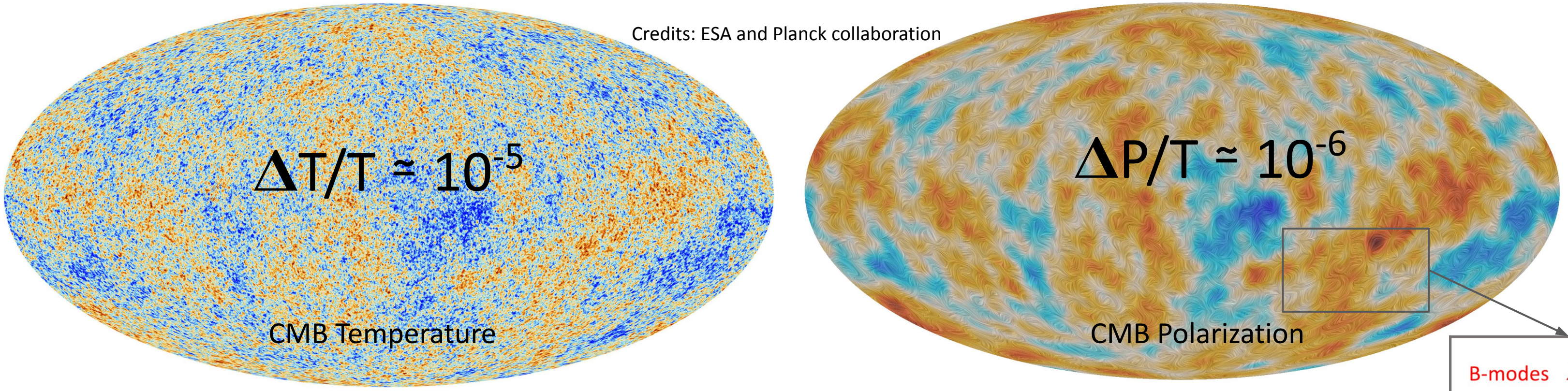
History of the Universe

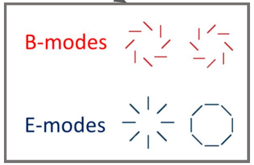


LPENS
LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

Probing the primordial Universe

Planck satellite provided the best full-sky maps of Cosmic Microwave Background (CMB) in both temperature and polarization.





CMB polarization patterns can be expressed:
E-modes, of even parity, and the **B-modes**.

B-modes can only be produced by primordial gravitational waves in the early universe.

If detected, will probe the existence of the inflation and give us access to a physics beyond the current Standard Model.

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

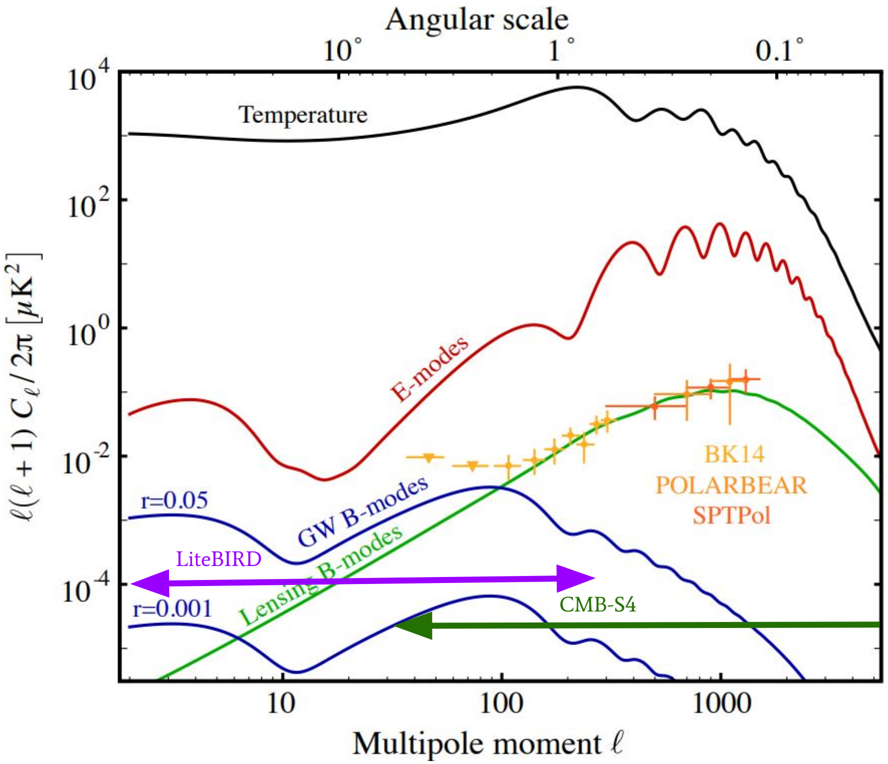
BB primordial spectrum: tensor perturbations from primordial GW background, scaled by tensor to scalar ratio r

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 $2 \leq \ell \leq 300$

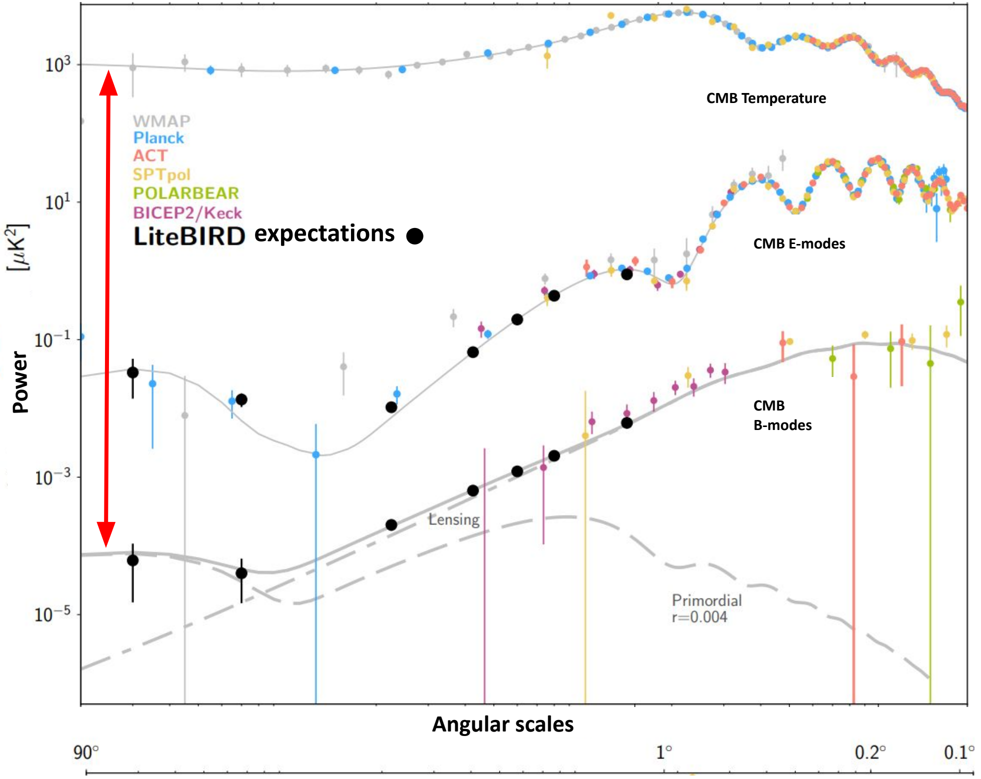
CMB-S4 $30 \leq \ell \leq 5000$



Constraints on the CMB B-modes detection

Sensitivity gain 10^7

B-modes
r parameter ~ 10^{-3}



LiteBIRD

Hazumi+2020

JAXA Space mission

Expected launch: 2029

Polarization system as NIKA2:
Rotating HWP

Frequency range:
40-402 GHz

Angular resolution: 70-18 arcmin

Current challenges

- Big arrays of high sensitive detectors to increase SNR
- Instrumental systematic effects control
- Absolute calibration of the polarization angle
- Accurate component separation of foreground emissions

Absolute polarization angle challenge

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

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

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

Spurious bias component

Ground calibration: very good but **need to be validated during operations**

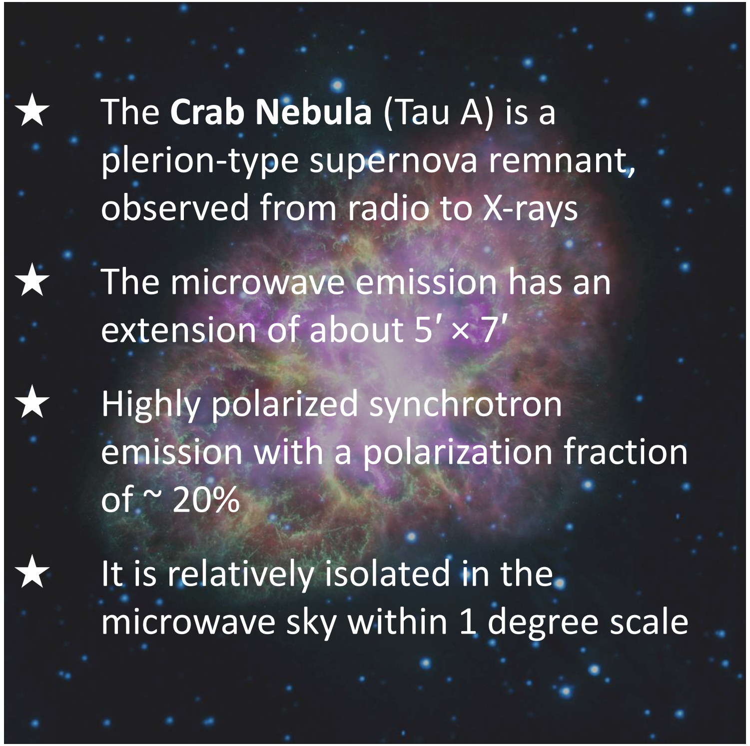
External calibration source: good accuracy (POLOCALC [Nati et al. 2017]) but **never done before, instrumental limits ?!**

Self-calibration: no scientific signal from TB and EB → only instrumental
Losing constraints on fundamental phenomena

Sky calibration: **frequency dependence, time variability** →
Best option: **CRAB NEBULA**

Accuracy of the polarization detection

A sky calibrator: the 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′
- ★ Highly polarized synchrotron emission with a polarization fraction of ~ 20%
- ★ It is relatively isolated in the microwave sky within 1 degree scale

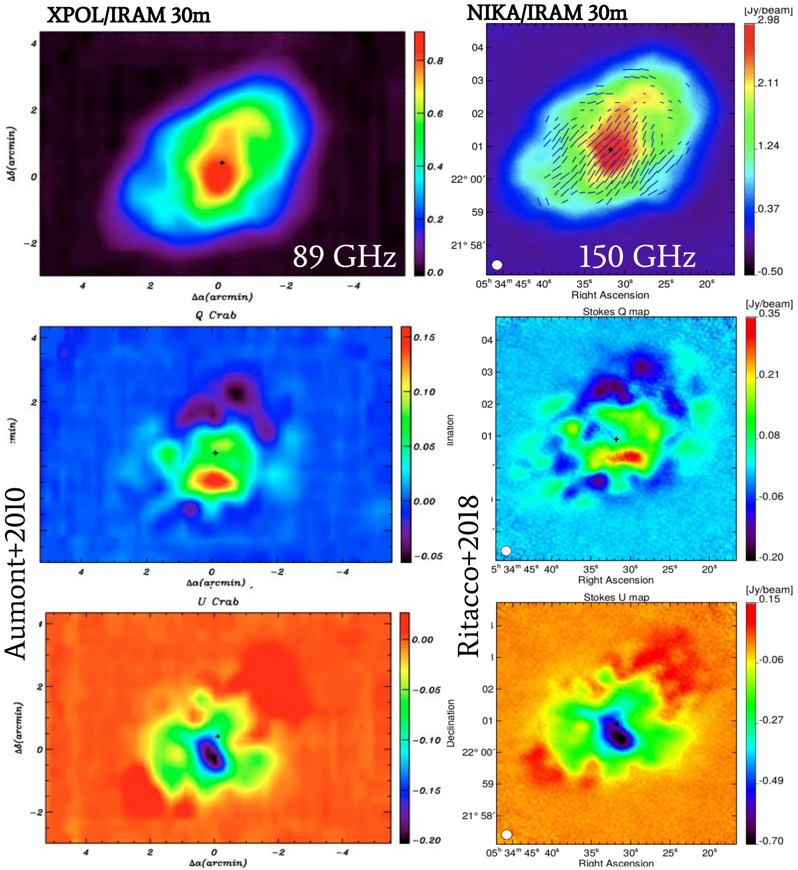
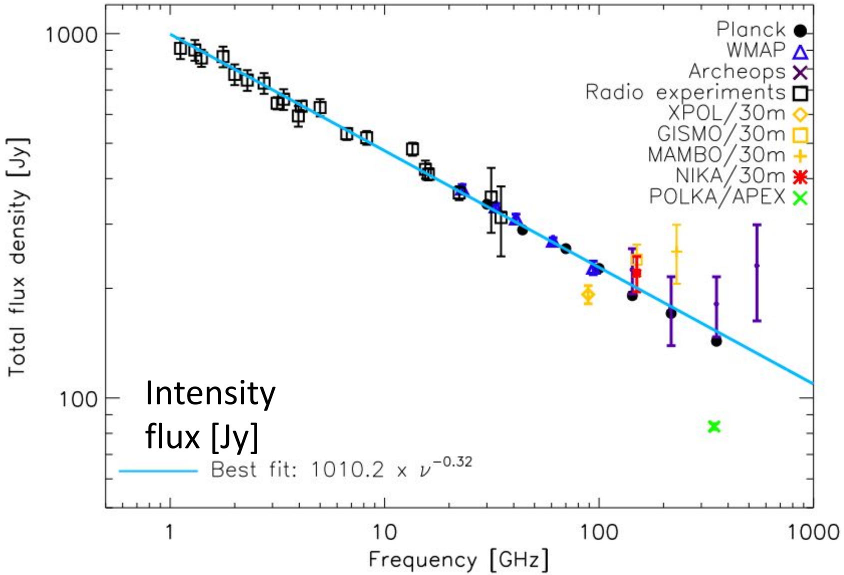
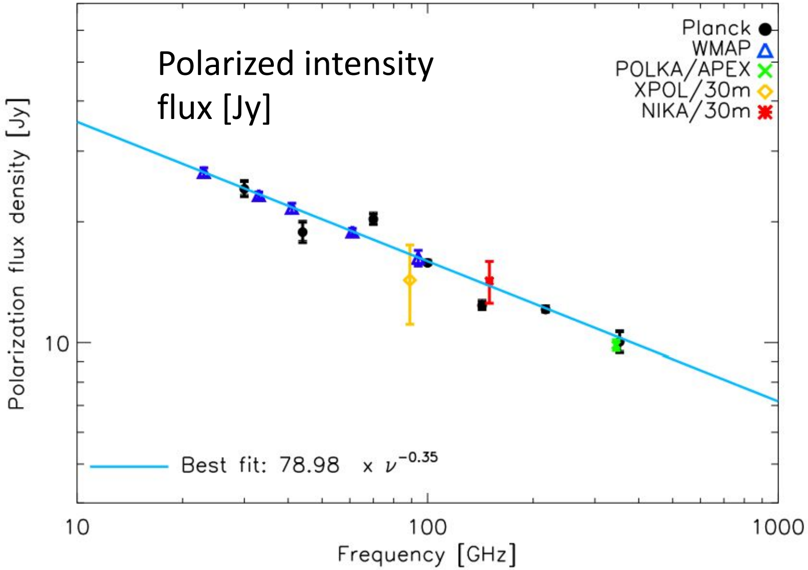


Image Credit: NASA, ESA, NRAO/AUI/NSF and G. Dubner (University of Buenos Aires)

Spectral energy distribution (SED)

Polarization spectral index consistent with the total power one confirming synchrotron as driver emission $\beta = -0.323 \pm 0.001$; $\beta_{POL} = -0.347 \pm 0.026$.





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

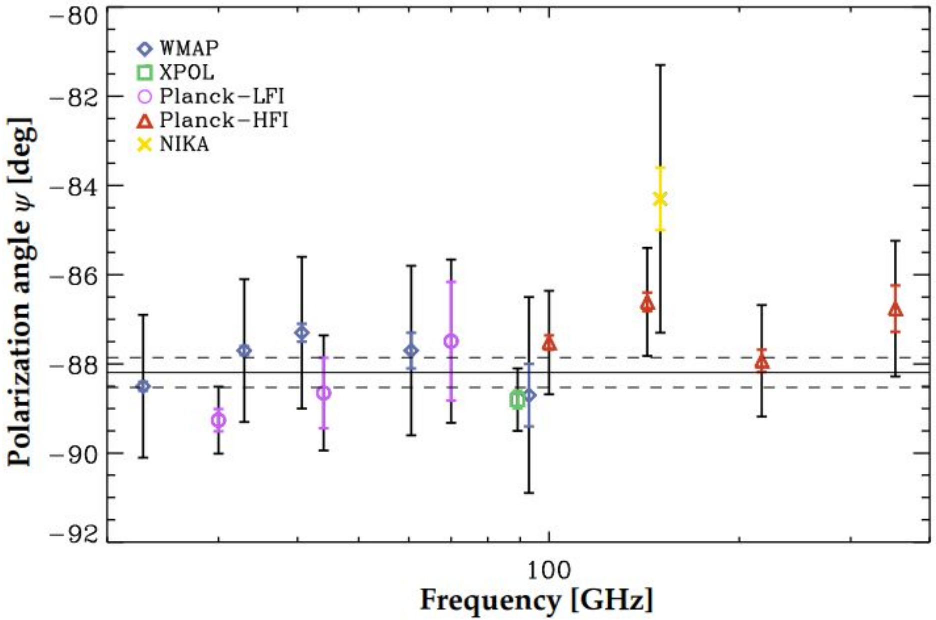
Ritacco et al. 2018 A&A, 616, A35

Crab nebula polarization angle stability

* 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:

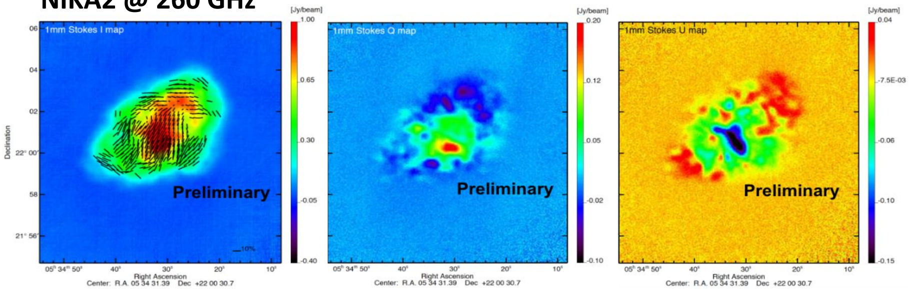
ψ = -88.26°±0.27°



J. Aumont , J.F. Macías-Pérez, **A. Ritacco** et al. A&A 634, A100 (2020)

NIKA2 Crab nebula observations @260 GHz

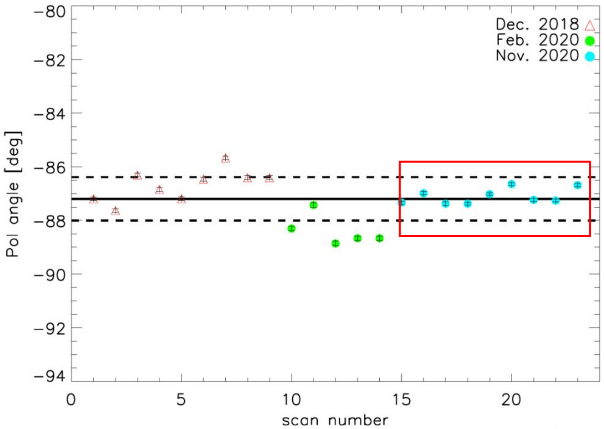
NIKA2 @ 260 GHz



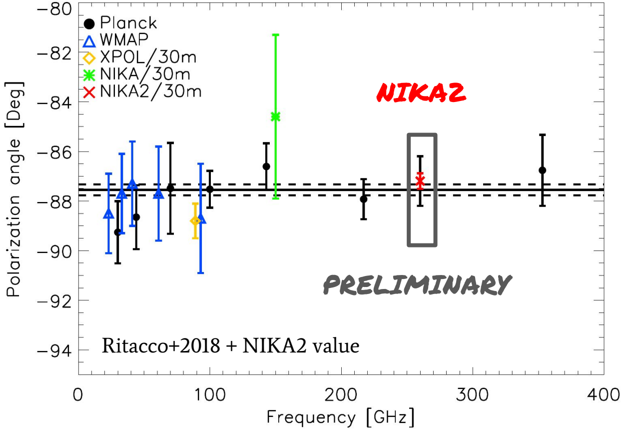
Total weighted polarization angle

ψ = -87.55 ± 0.22 deg

NIKA2 polarization angle removes the uncertainty on the polarization angle reconstruction at higher frequencies.



NIKA2 Nov. 2020 campaign data more stable with mean value of **-87.23 ± 0.29 deg**



The stability of the polarization angle with frequency is the key to use the Crab nebula as a sky calibrator.

Combining current (and future) measurements

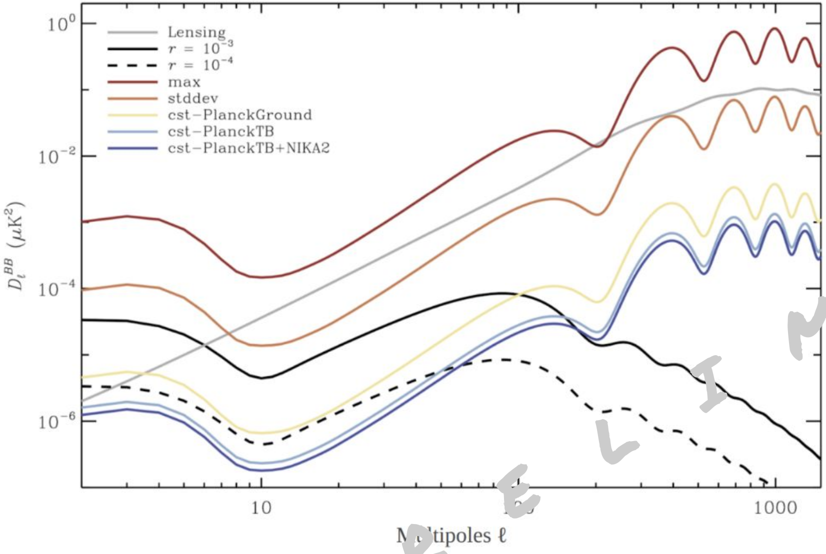
Name	Assumption	Statistical error	Systematic error	Planck Systematics	New experiment	Crab pol. angle uncertainty $\Delta\psi$ (1σ)
max	Maximum difference between the mean value and one measurement	✗	✗	✗	✗	3.96°
stddev	Standard deviation of the measurements	✗	✗	✗	✗	1.24°
cst-PlanckGround	Constant angle	✓	✓	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

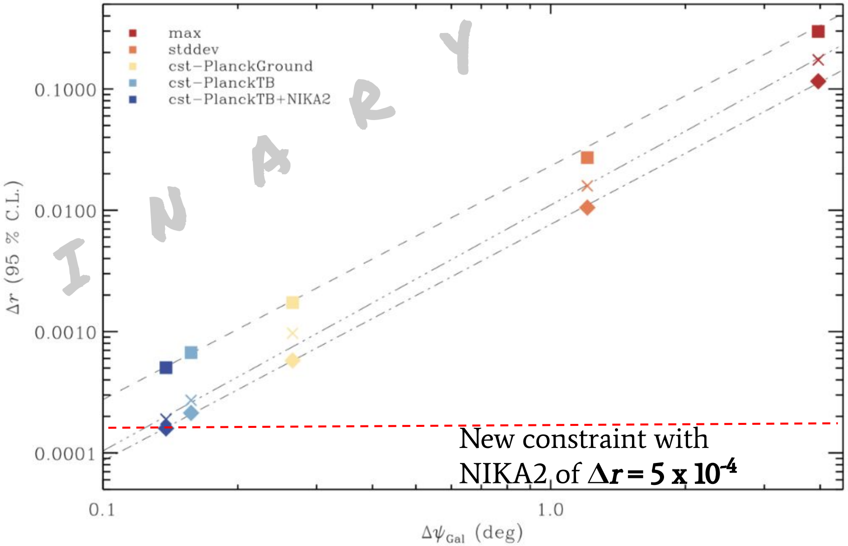
J. Aumont , J.F. Macías-Pérez, **A. Ritacco** et al. A&A 634, A100 (2020)

Constraints on CMB B-modes detection

Power spectrum bias from E−B mixing due to miscalibration



Computing limit of ***r*** parameter detection



A. Ritacco et al. 2021 (submitted)

Accounting for NIKA2 polarization angle

NIKA2 polarization angle stability improves the uncertainty Δr by 30% w.r.t previous studies (Aumont+2020)

PROMISING FOR CMB SCIENCE

Reference catalog for CMB experiments calibration

Joint study on Crab with new observations

353 GHz @SCUBA2Pol (just observed)

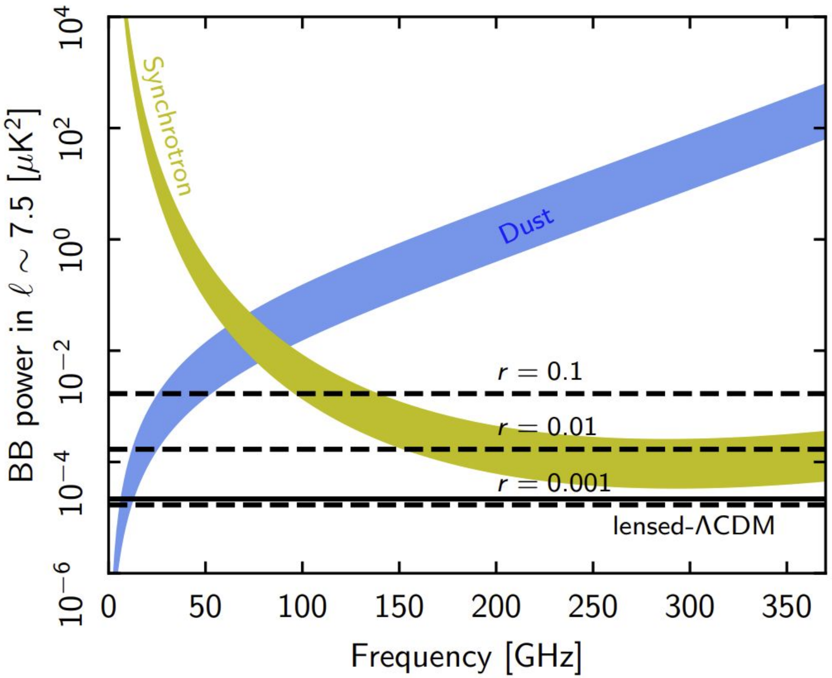
260 GHz @NIKA2 *(Ritacco+2021, in prep)*

23 GHz @Sardinia telescope (to be published)

Start study on secondary calibrators

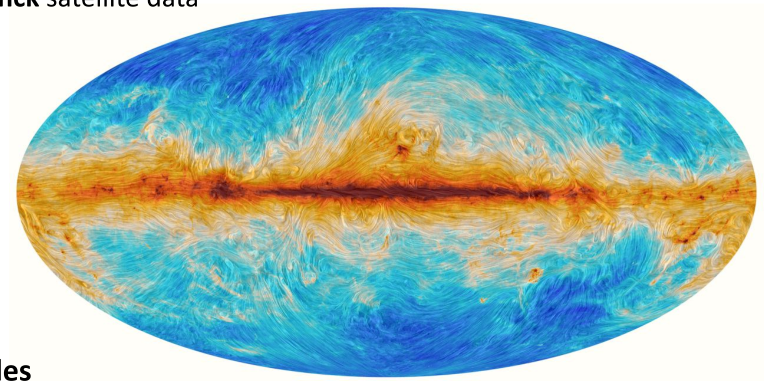
- ★ Cassiopeia A and 3c58 (SNR);
- ★ M87, Cygnus A (radio-galaxies);
- ★ Cen A (galaxy);
- ★ 3c286 (for ground experiments).

Foreground challenge: the dust emission



} **CMB B-modes level expected**

Planck satellite data

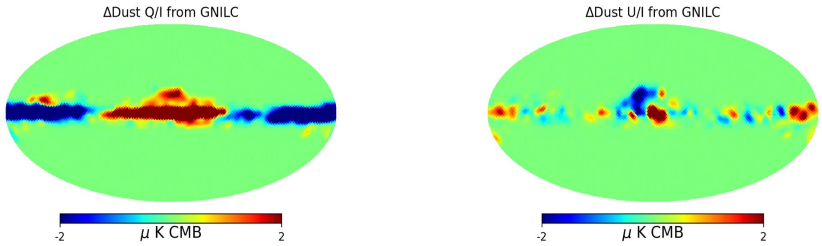


Polarization and total intensity SED difference suggests **spatial variation SEDs**. (Planck 2018 XI)

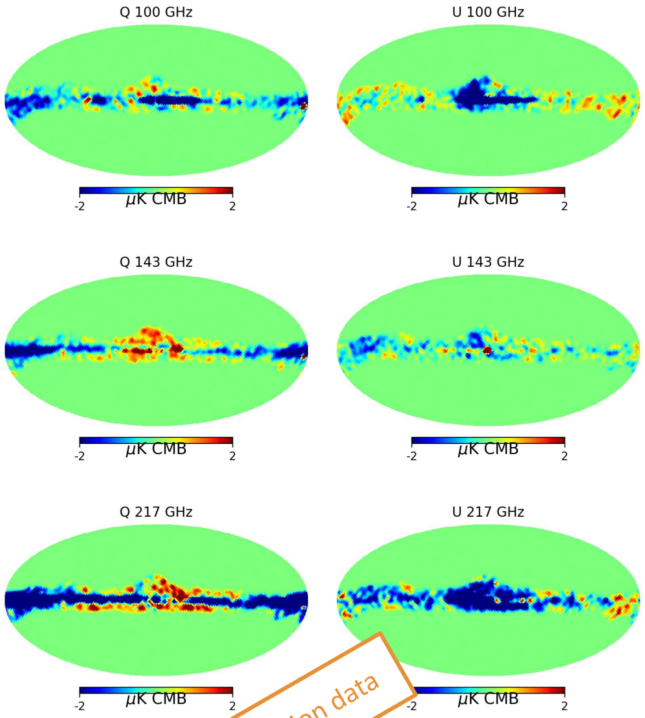
Dust SED variation crucial for CMB B-modes detection

Accuracy in foreground dust emission subtraction

From temperature dust model we extract **expected** polarization **dust SED variation maps**



Frequency-dependent variation detected on polarization Planck data along the galactic plane



Correlation detected on the galactic plane and part of the diffuse emission.

The spatial variation of the spectral parameters should account for the polarization angle variation along the line of sight (Tassis & Pavlidou 2015).

Work in progress

📖 **Ritacco**, Delouis, Boulanger, Puget 2021, (*in prep*)

Summary

- ★ **High control of the systematics** induced by optical elements;
- ★ Modelling optical effects is the only way to choose the best configuration of polarization modulators;
- ★ **Sky absolute calibration** in a large frequency range is crucial for CMB
  - current measurements could allow to probe **$r = 10^{-2}$**;
  - future accurate measurements of the Crab (e.g. NIKA2, SCUBA-2) are required to calibrate future CMB experiments to measure **$r \lesssim 10^{-3}$** (e.g. LiteBIRD, CMB-S4).
- ★ **Dust foreground analysis:** spatial variation of the spectral parameters accounting for the effect of polarization angle variation seems to be crucial for CMB foreground dust emission treatment.

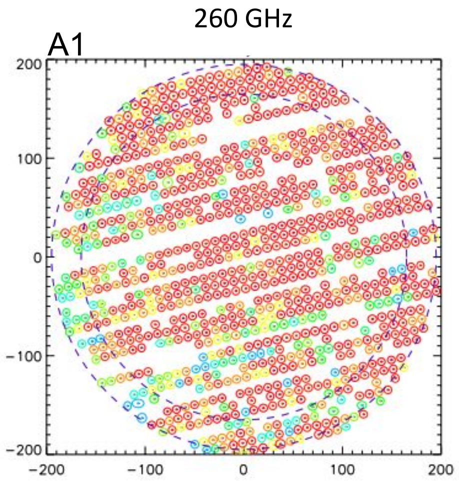
BACKUP SLIDES

Focal plane characterization

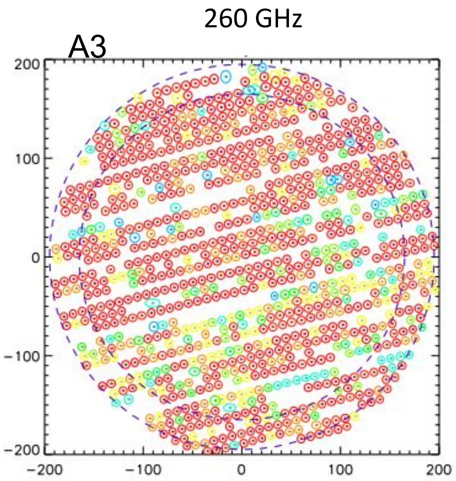
Many detectors on the same feedline

We need to determine the resonances, i.e. spatial pixel table (F.P. geometry)

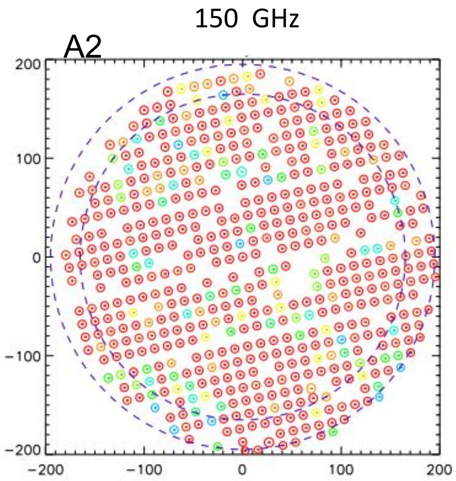
Repeated beam maps on strong, point like sources, e.g. planets.



952
(1140)



961
(1140)



553
(616)

Perotto et al. 2019, A&A

fraction of “valid” (=stables in at least 2 scans) KIDs: 84% at 260 GHz and 90% at 150GHz

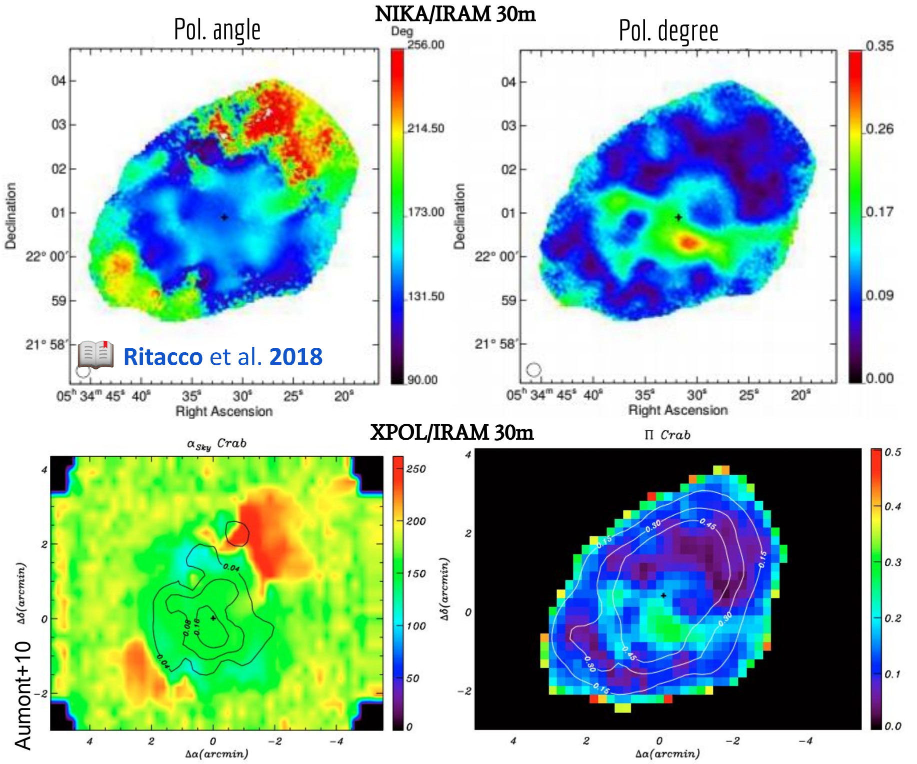
Ground based high angular resolution observations

Polarization angle

$$\psi = \frac{1}{2} * \mathrm{atan}(U/Q)$$

Polarization degree

$$p = \mathrm{sqrt}(Q^2+U^2)/I$$



High resolution highlights features from small to large angular scales

For CMB experiments we are interested to the emission of whole nebula