The QUIJOTE CMB Experiment
(+ other low-frequency experiments)

R. Belén Barreiro

Instituto de Física de Cantabria (CSIC-UC)

The QUIJOTE Collaboration

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC

IFCA Instituto de Física de Cantabria

DICOM

UNIVERSITY OF CAMBRIDGE

MANCHESTER 1824 The University of Manchester

idom

Q-U-I JOint TEnerife CMB Experiment

The QUIJOTE Experiment

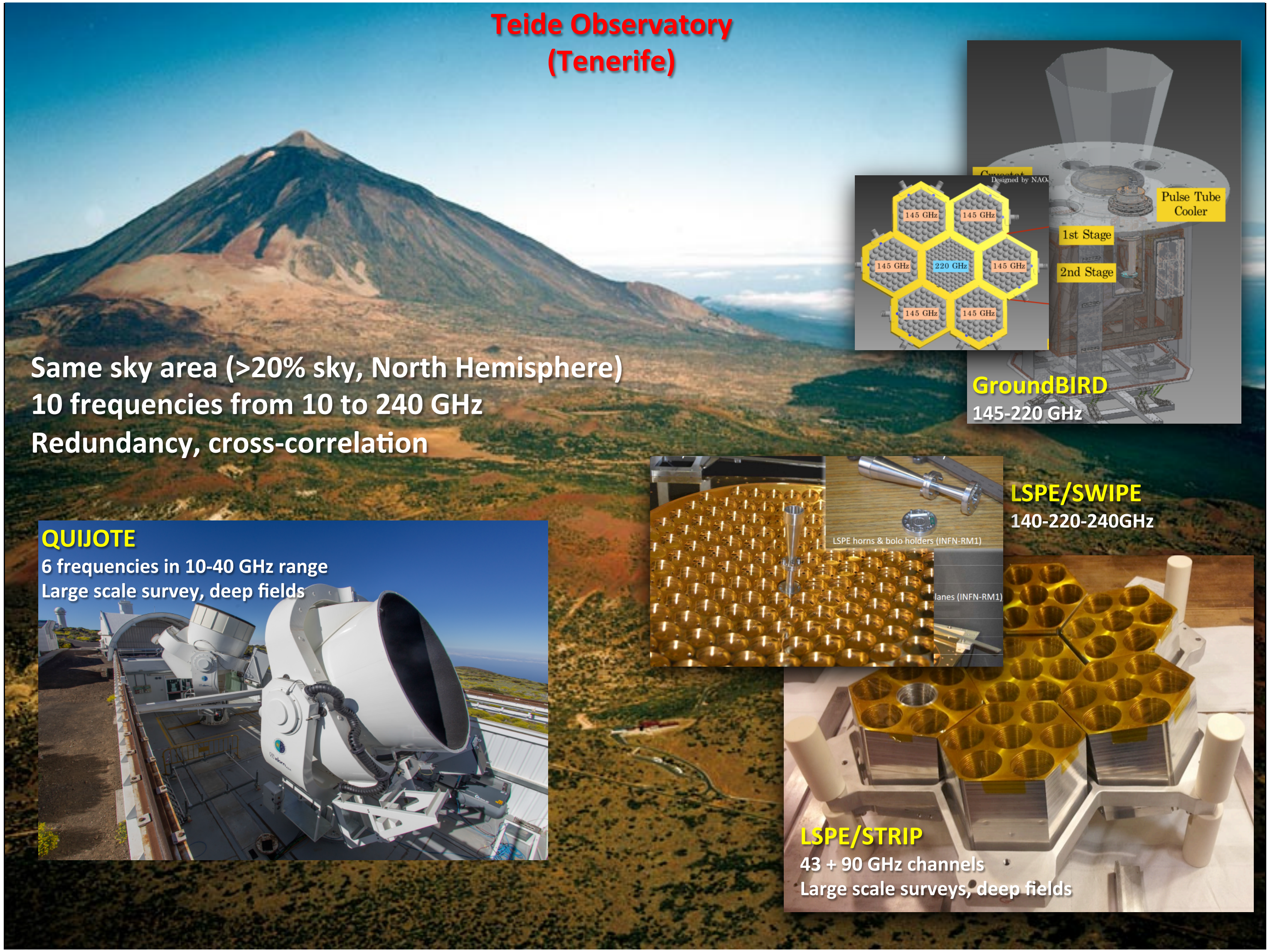
- **Site**: Teide Observatory (altitude 2400 m, 28.3º N, 16.5 W)
- **Frequencies**: 11, 13, 17, 19, 30 and 40 GHz.
- **Angular resolution**: 0.92º to 0.26º
- **Sky coverage**: -32º < Dec. < 88º (fsky=0.65).

- **2 telescopes and 3 instruments:**
  - Two telescopes installed (2012 and 2014)
  - Multi-Frequency Instrument (MFI) with 4 polarimeters at 10-20 GHz. In operation since Nov 2012
  - Second Instrument (TGI) with 31 polarimeters @ 30 GHz
  - Third instrument (FGI) at 42 GHz (31 polarimeters).
  - TGI and FGI in joint comissioning phase (14 + 15)

- **Observing strategy**: Deep observations in selected areas plus wide survey

The Teide Observatory

The Teide Observatory



Scientific goals

- To provide polarization maps at 6 frequencies in the range 10 - 40 GHz with sufficient sensitivity to correct foreground emission (synchrotron and AME) and to constrain the imprint of B-modes down to r=0.05

- Observational strategy
  - Wide survery

    Covering 20,000 deg^2

    ≈ 30 μK/(beam 1^o) with the MFI @ 11, 13, 17 and 19 GHz in Q and U

  - Deep cosmological survey

    It will cover around 3,000 deg^2 in three separated fields. The scientific goal is to reach r=0.05 after 3 years of operations of the TGI+FGI

    10 μK/(beam 1^o) after 1 year with the MFI @ 11, 13, 17 and 19 GHz

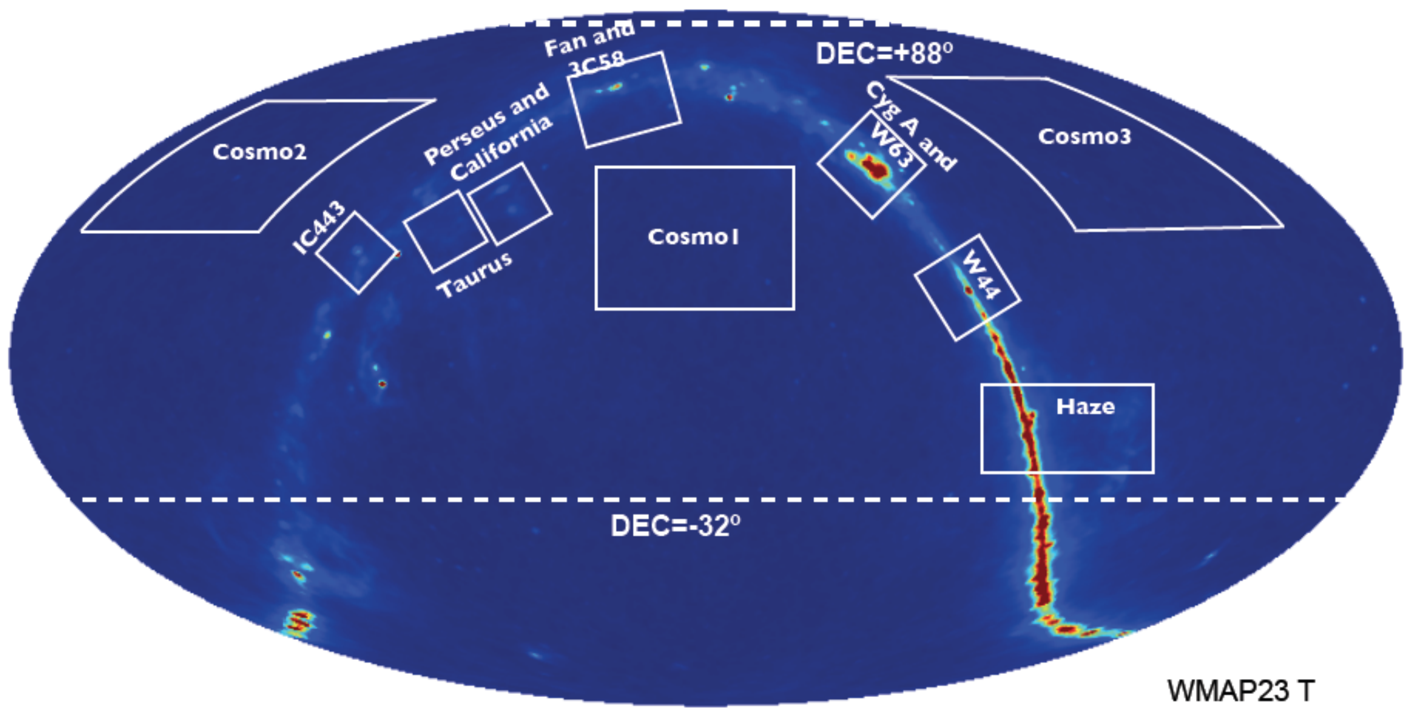
    ≈ 1 μK/(beam 1^o) after 1 year with the TGI and FGI @ 30 and 40 GHz

  - Other Galactic regions

    Covering few hundred deg^2 . To understand radio foregrounds

    ≈ 30-40 μK/(beam 1^o) with the MFI @ 11, 13, 17 and 19 GHz

QUIJOTE cosmological and Galactic fields

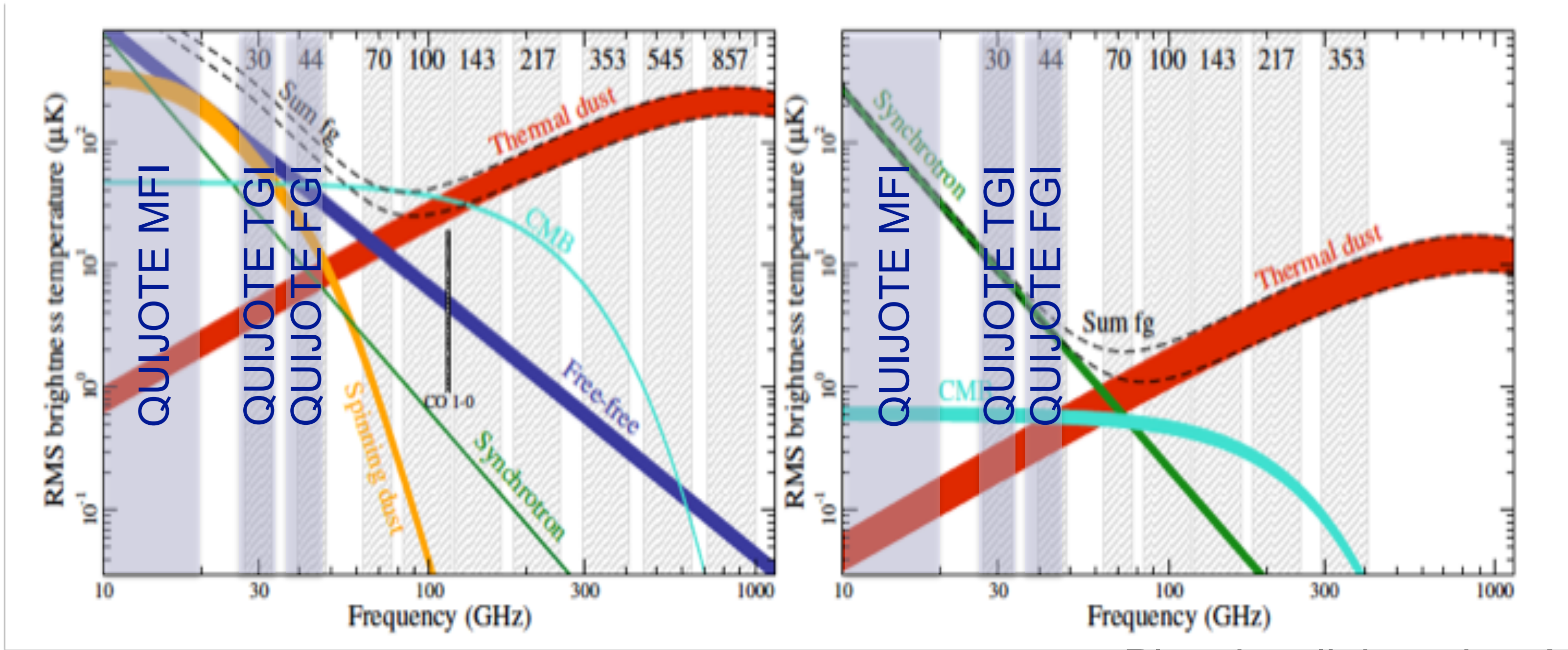


Observation time ~25.500 hours of MFI data
~2.9 years of effective time (with ~50% efficiency)

- Wide survey: 10.800 hrs on a region of 20,000 deg^2 in the northern sky.
- Goal: ~30 μK/deg in Q,U. Current sensitivities around 40-55 μK/deg

Science with MFI

- The MFI maps provides a unique frequency range (10-20 GHz) to characterise the polarization properties of radio foregrounds:
  - Synchrotron emission: should dominate the emission at the MFI frequencies. WMAP 23 GHz shows it to be polarised at ~5-15%, depending on the Galactic latitude
  - Anomalous microwave emission: little known about its polarisation. Polarization fraction could be at the level of a few per cent

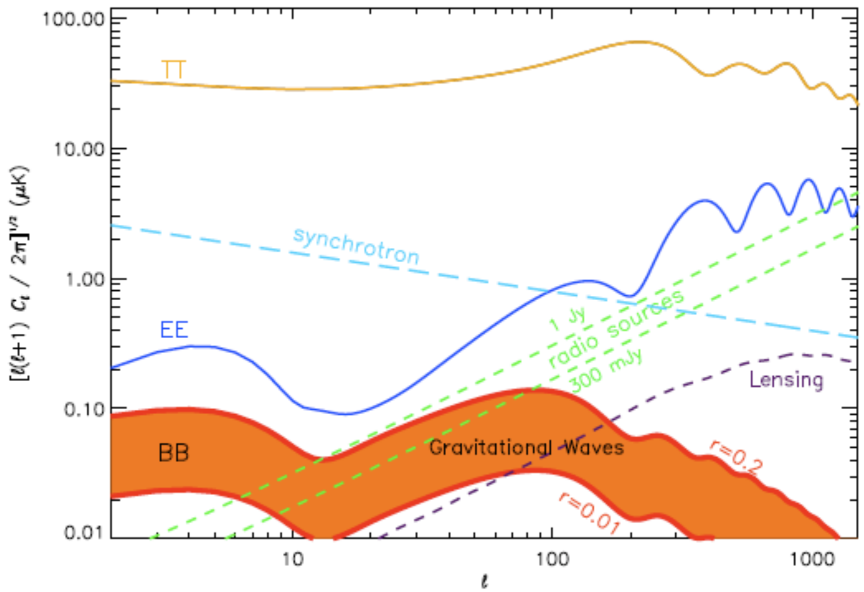


Planck collaboration X (2015)

Science with MFI

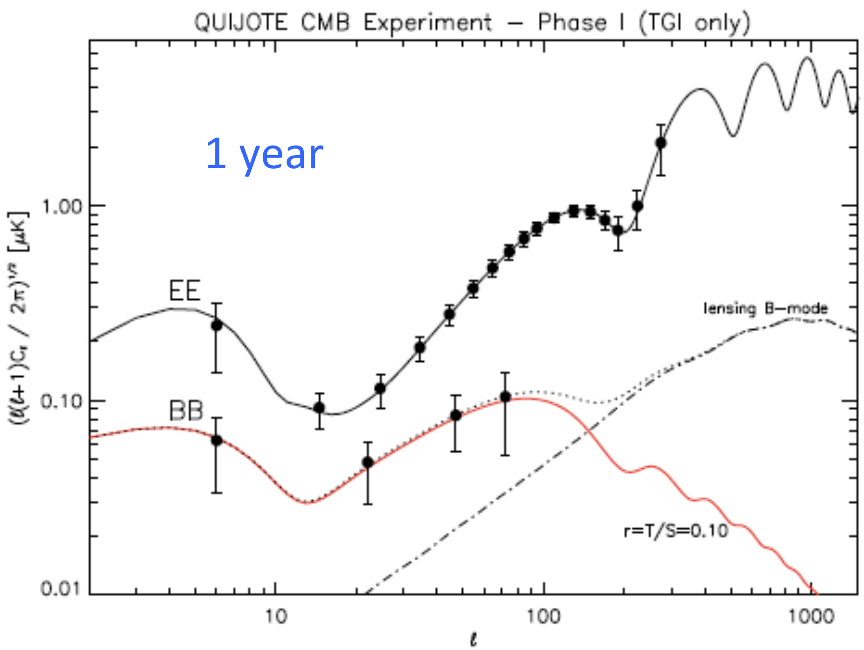
- MFI maps will be used to clean the 30 GHz and 40 GHz maps obtained with the 2nd (TGI) and 3rd (FGI) QUIJOTE instruments.

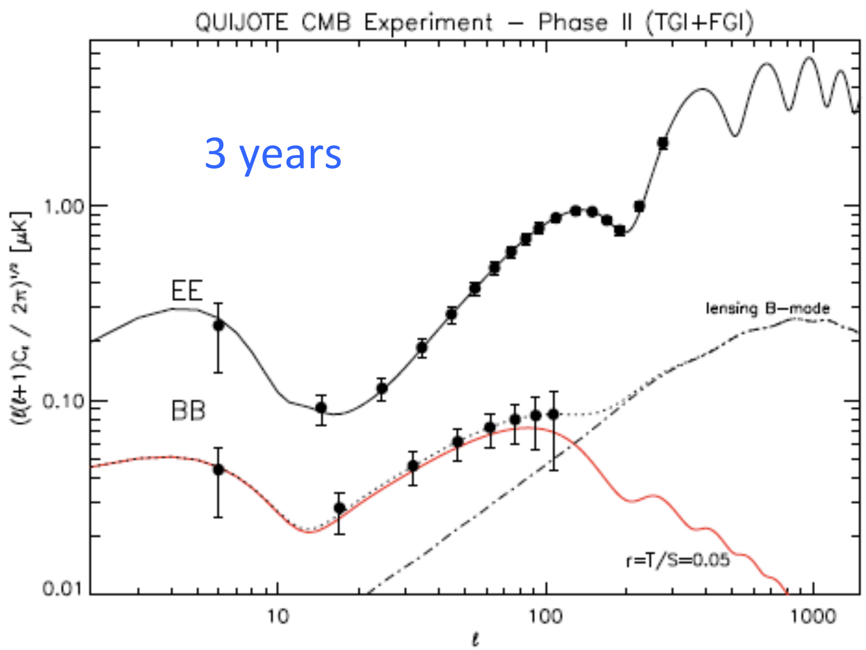
- Radio-sources: low contribution at degree scales, but potentially relevant for B-modes science ⇨ follow-up observations with VLA to correct for polarised sources selected from PLANCK maps. Observations in different epochs are being performed to study variability



30 GHz

Science with QUIJOTE second (TGI) and third (FGI) instruments





Left: Example of the QUIJOTE scientific goal after 1 year (effective) observing time, and a sky coverage of 3,000 deg^2. The red line corresponds to r = 0.1.
Right: 3 years of effective operations with the TGI plus 2 years of effective operation of FGI. The red line now corresponds to r = 0.05.

Wide survey with the QUIJOTE MFI (10-20 GHz)

PRELIMINARY MAPS

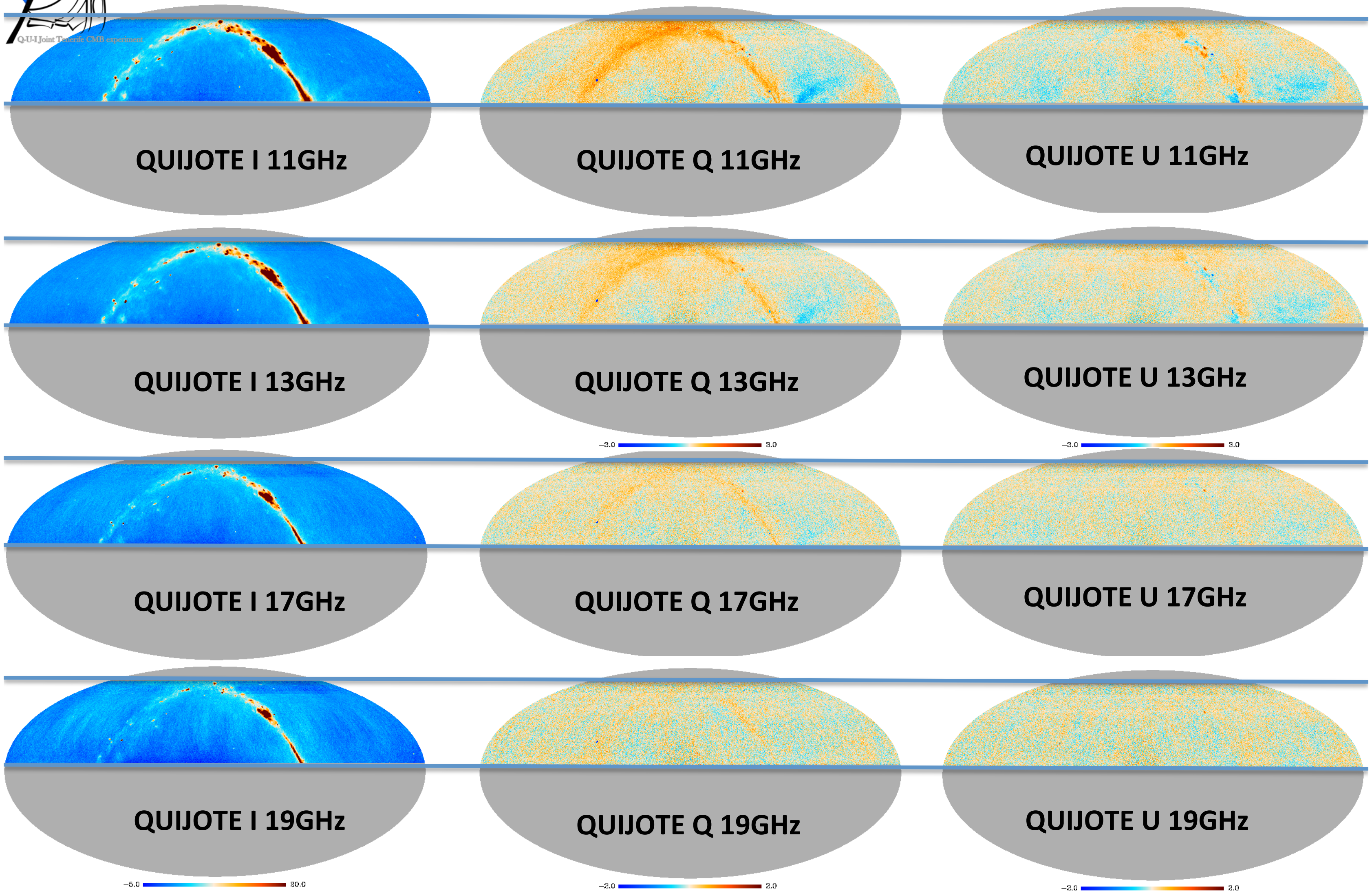
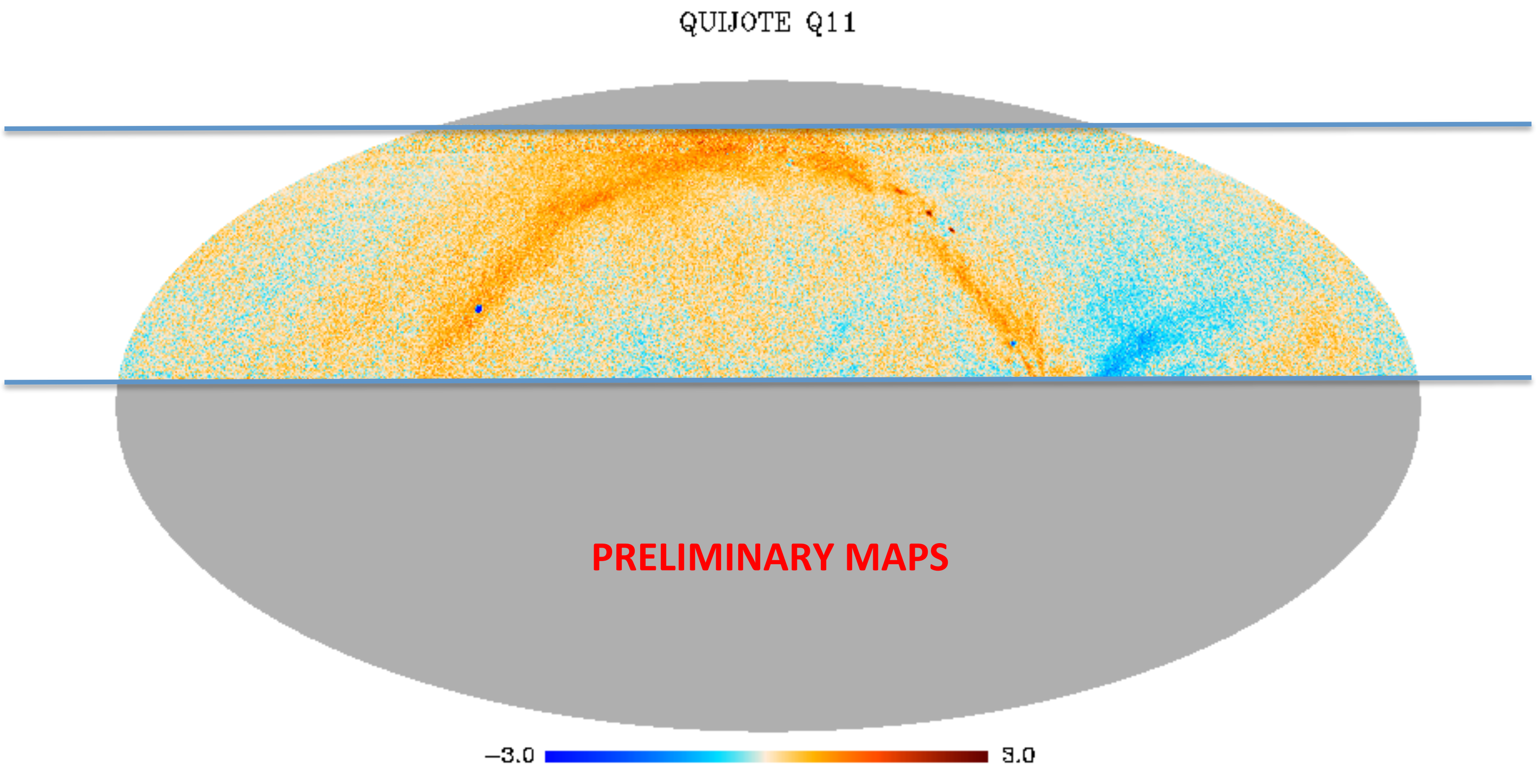


Figure from J.A. Rubiño-Martín

Wide survey with the QUIJOTE MFI (10-20GHz)

- Example of polarization maps at 11GHz from one horn (using Equatorial projection).

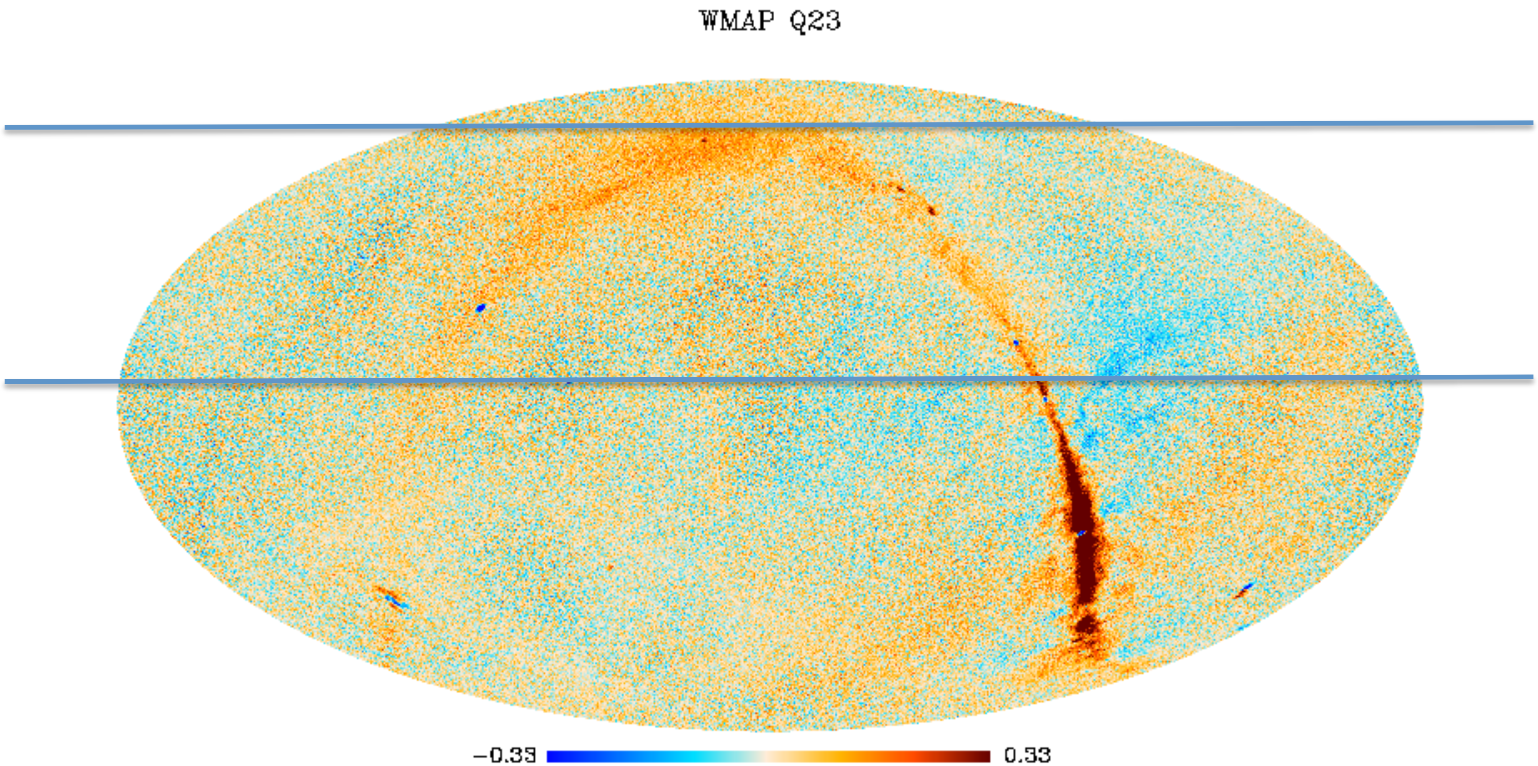


(scaled to preserve the same color for a signal with β=-3)

Figure from J.A. Rubiño-Martín

Wide survey with the QUIJOTE MFI (10-20GHz)

○ Example of polarization maps at 11GHz from one horn (using Equatorial projection).

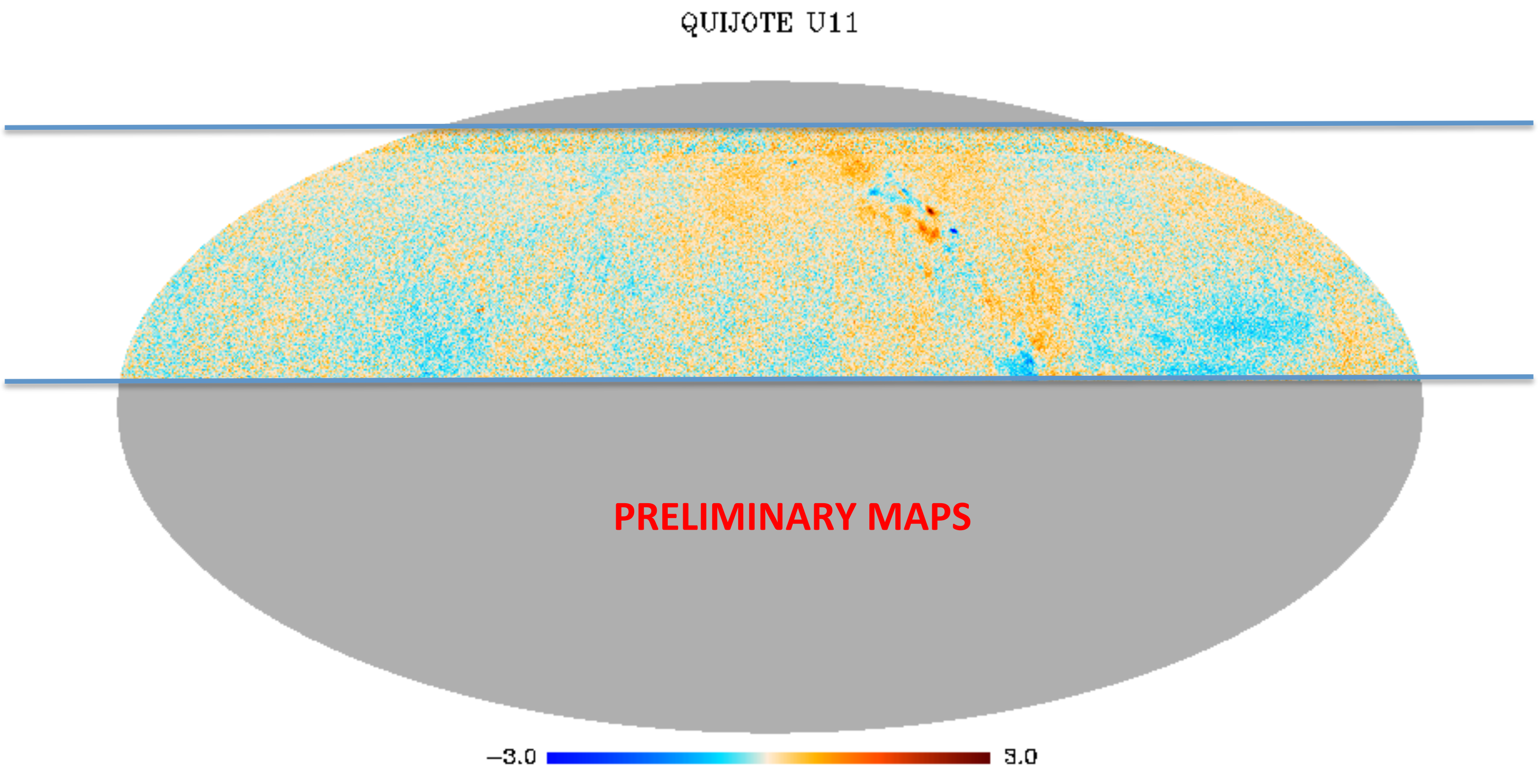


(scaled to preserve the same color
for a signal with β=-3)

Figure from J.A. Rubiño-Martín

Wide survey with the QUIJOTE MFI (10-20GHz)

○ Example of polarization maps at 11GHz from one horn (using Equatorial projection).

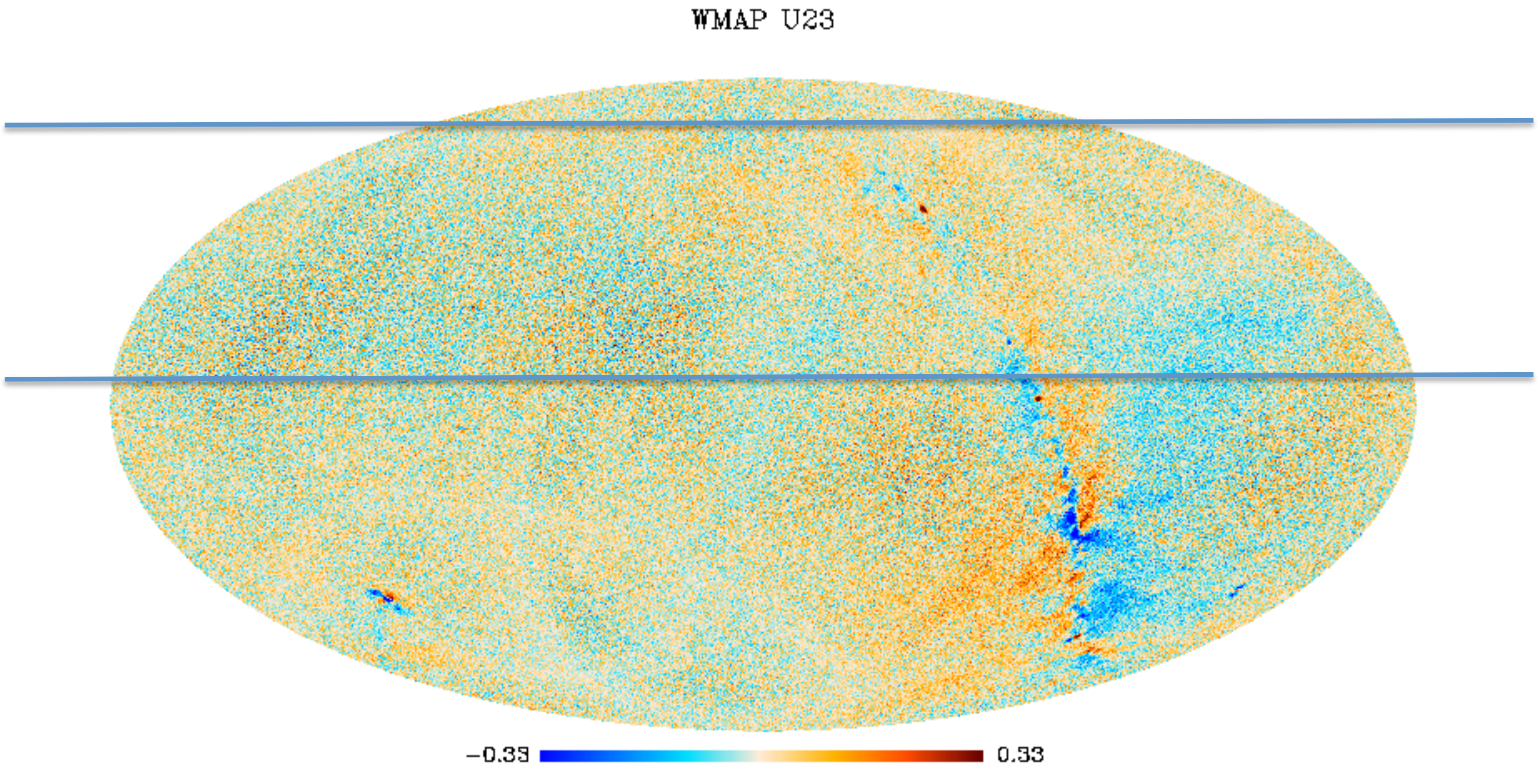


(scaled to preserve the same color
for a signal with β=-3)

Figure from J.A. Rubiño-Martín

Wide survey with the QUIJOTE MFI (10-20GHz)

○ Example of polarization maps at 11GHz from one horn (using Equatorial projection).



(scaled to preserve the same color
for a signal with β=-3)

Figure from J.A. Rubiño-Martín

Anomalous microwave emission

- Dust correlated emission, first detected in COBE data (Kogut et al. 1996)
- Proposed models of the emission:
  - Electric dipole emission (spinning dust) (Draine & Lazarian 1998)
    - Polarization typically predicted to be very low (<1 %), with a polarization fraction that decreases with frequency
  - Magnetic dipole emission (Draine & Lazarian 1999)
    - Magnetic dust polarization expected to be higher (<5% at 10-20 GHz, Draine & Hensley 2013)
  - Difficult to make predictions about these models due to many free parameteres

Which is the impact of AME polarization on detecting B-modes?

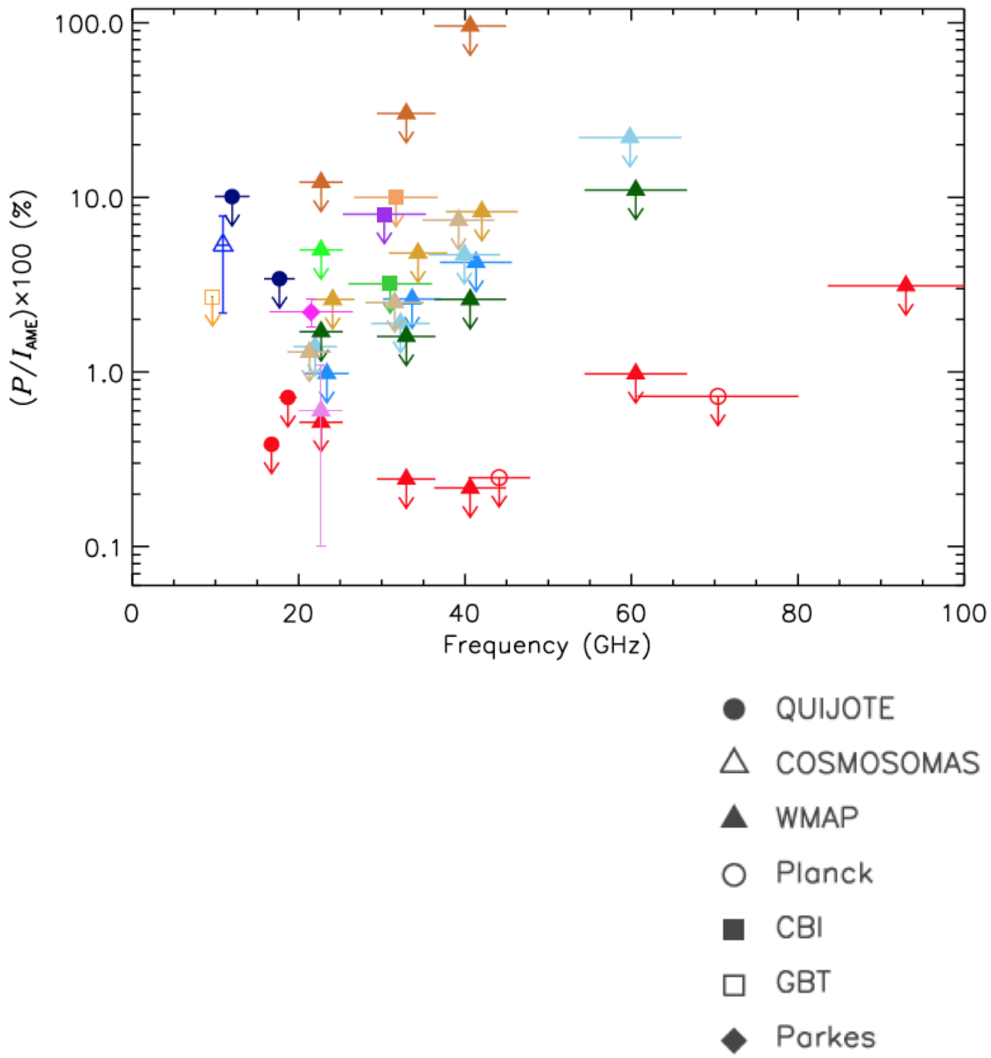
- Spinning dust polarization expected to be very low
- However, it may not be negligible if AME arising from other physical mechanisms
- Most stringent constraints have been obtained in individual regions, but what about diffuse AME?
- Ignoring an AME component with Π=1% may lead to biases on r ~10^{-3}(Remazailles et al. 2016)
- More ancillary observations are needed to make sure that we do not need to worry

Anomalous microwave emission: polarization constraints

- Diffuse emission
  - Π < 5% at 22.8 GHz with WMAP (Macellari et al. 2011)
  - Π = 0.6 +/- 0.5 % (Planck 2015 results, XXV)
- Individual regions (from QUIJOTE data)
- Perseus molecular complex

  Π < 6.3% at 12GHz and < 2.8% at 18 GHz (95% C.L.) (Génova-Santos et al. 2015)
- W43 molecular complex

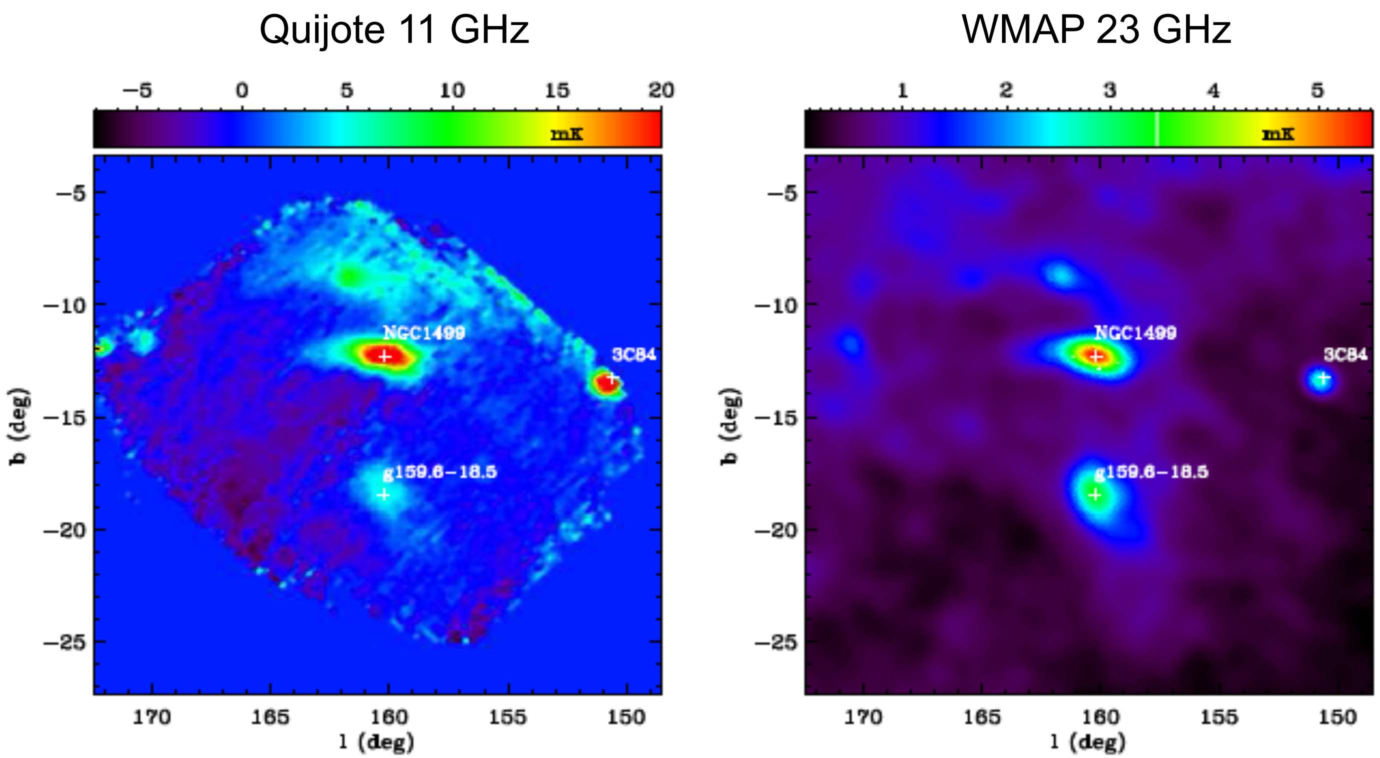
  Π < 0.39% at 18.7 GHz and < 0.22% at 40.6 GHz (95% C.L.) (Génova-Santos et al. 2017)



See Dickinson et al. (2018) for a review

Perseus molecular complex

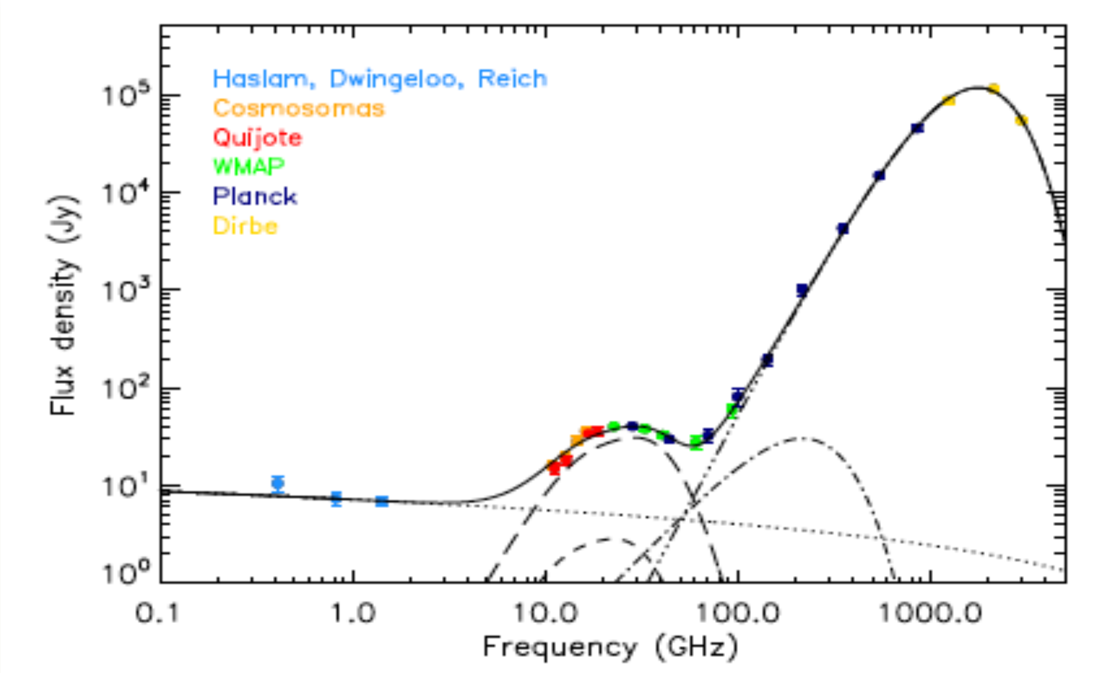
- Large observation program (~200 hours, 12/2012 to 04/2013), on an area covering ~250 deg^2 around the Perseus molecular complex.
- One of the brightest AME regions on the sky
- Final map sensitivity of ≈30 μK/beam



Génova-Santos et al. (2015), MNRAS, 452, 4169

Perseus molecular complex

SED modelling on G159.6-18.5 in intensity



Well fitted by a combination of free-free, CMB, spinning dust and thermal dust, and two spinning dust components associated to a high-density molecular phase and to a low-density atomic phase.

- AME (spinning dust) shows up at intermediate frequencies
- Most precise spinning dust spectrum to date (13 independent data points in the relevant range)
- No polarisation detection.
- Π < 6.3% at 12GHz and < 2.8% at 18GHz (95% C.L.)
- AME is being studied in more than 40 regions

Impact of synchrotron on detecting B-modes

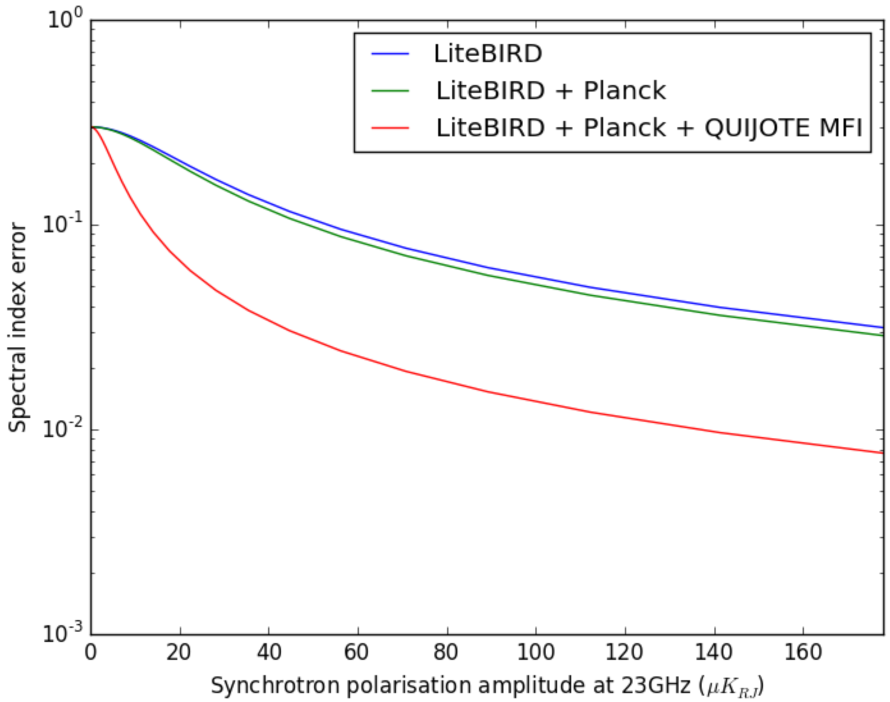
- Even in the cleanest ~1% region of the sky, synchrotron emission could be as large as r_{SYN}=0.005 @ 110 GHz [Krachmalnicoff et al. 2016], so it can not be ignored

- Error $\Delta\beta_s$~ 0.02 $\Rightarrow$error Δr ~ 10^{-3} when extrapolated from 23 to 145 GHz [see talk by M. Remazeilles]

- Low-frequency experiments (as e.g. QUIJOTE) are essential to monitor the synchrotron especially for spatially varying spectral indices [Errard et al. 2015]

Impact of synchrotron on detecting B-modes

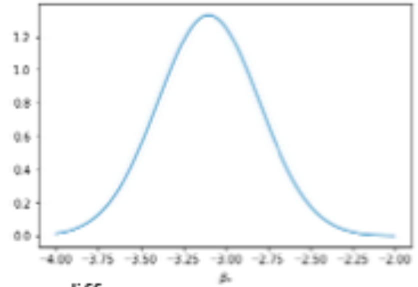
The unique frequency range explored by QUIJOTE MFI (10-20 GHz) provides very useful and complementary information to the future sensitive experiments searching for cosmological B-modes (such as LiteBIRD)



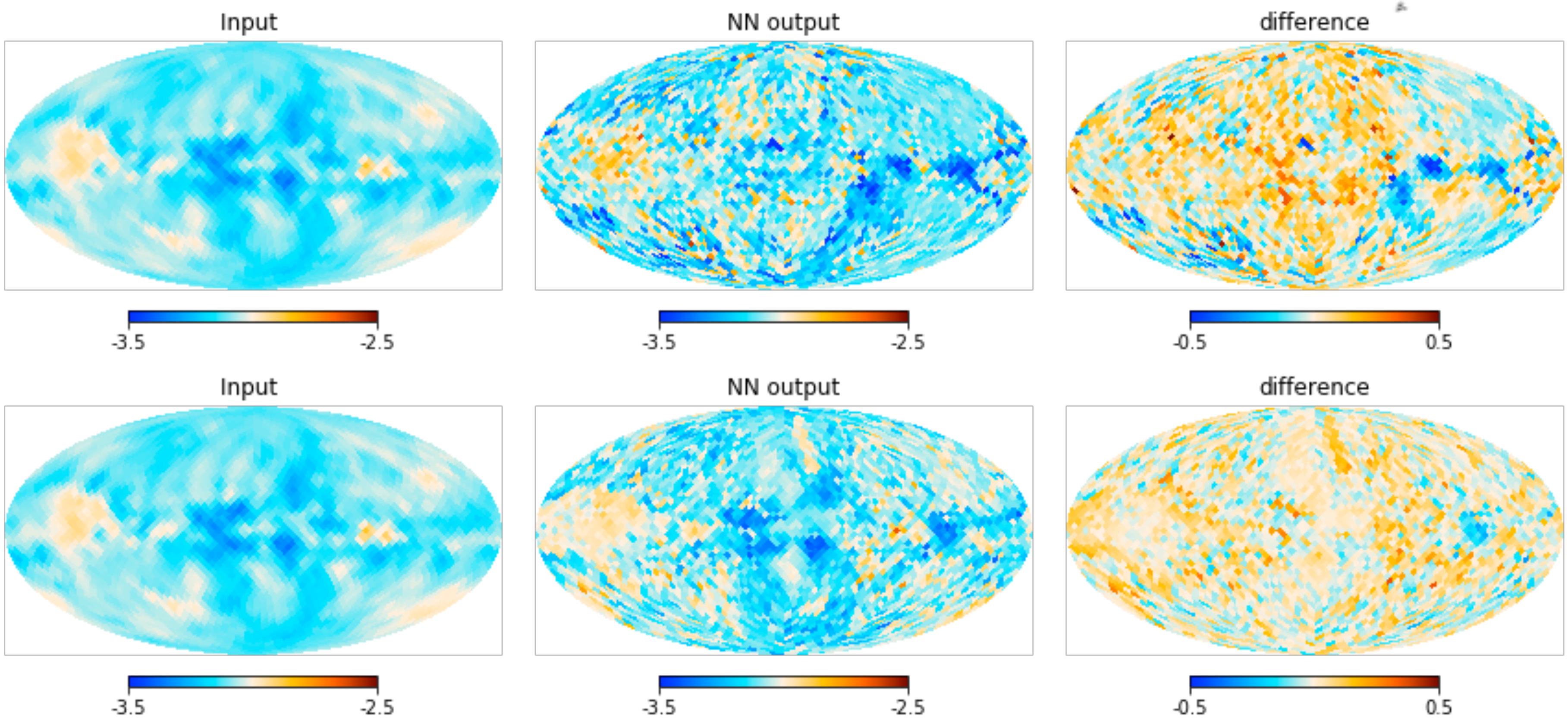
Forecast on the error on the estimation of β_s (figure from B. Casaponsa)

- When adding QUIJOTE MFI [10-20 GHz], errors in the estimation of β_s significantly reduced with respect to using only LiteBIRD [40-400 GHz]
- These frequencies will be even more important if considering more complicated models for synchrotron
- Impact on reducing the level of residuals and the bias on r

Recovery of the synchrotron spectral index with NN



Only Planck frequencies

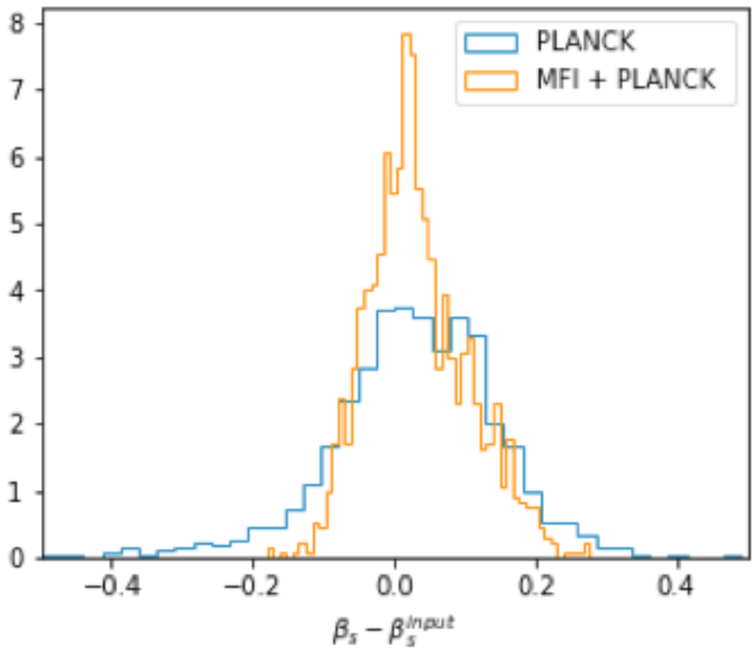


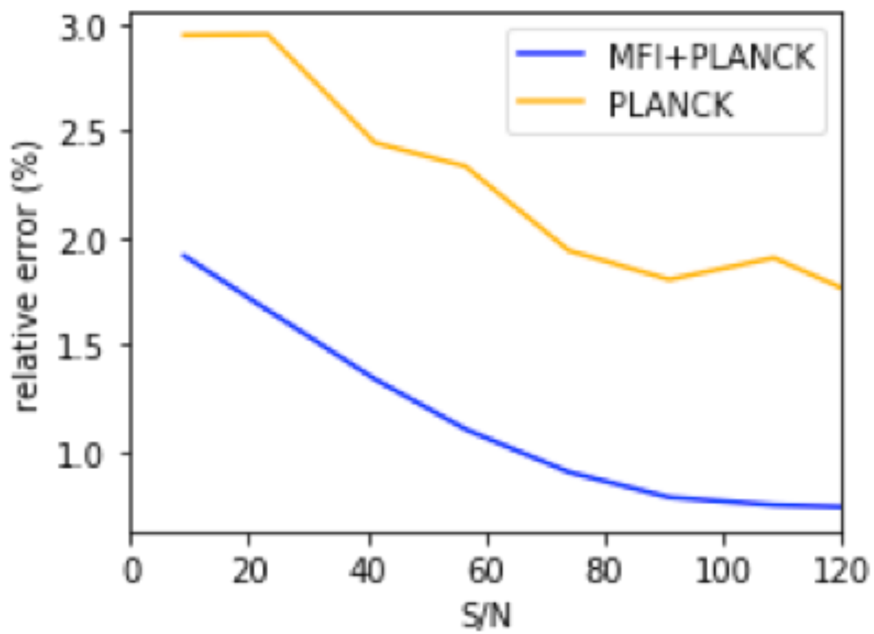
Planck frequencies + MFI

Figures from B. Casaponsa

Component separation from Planck + QUIJOTE: simulations

Recovery of the synchrotron spectral index

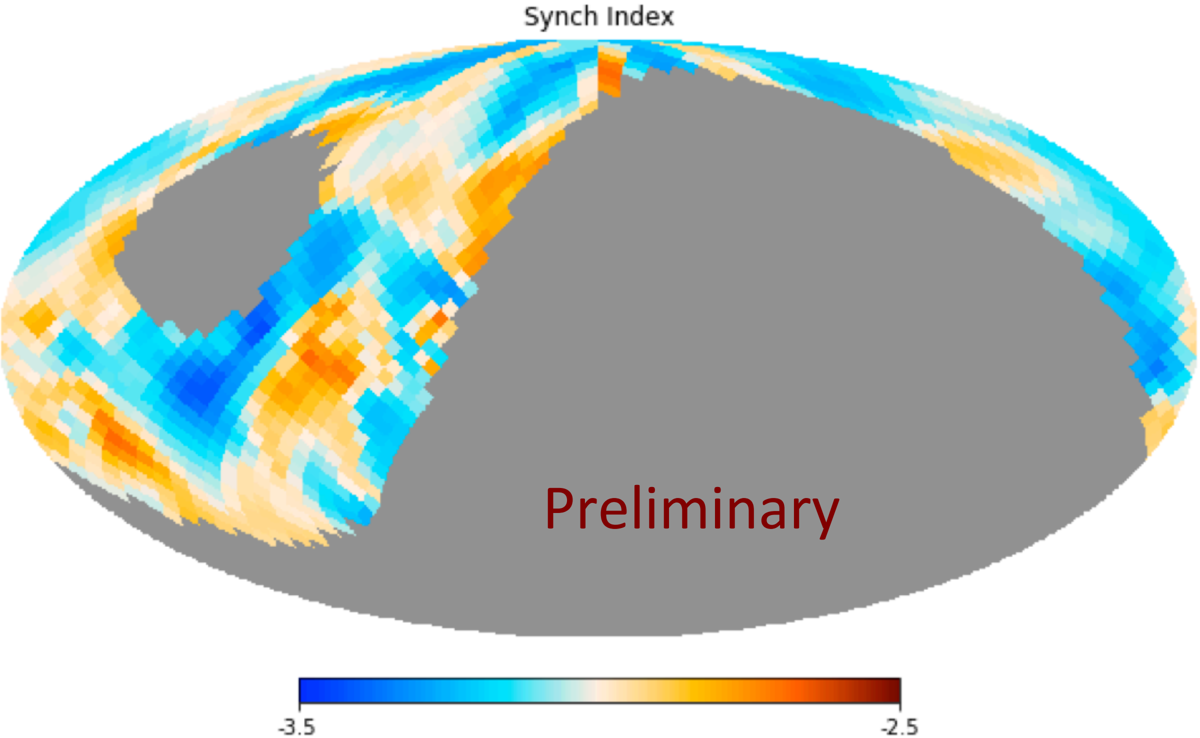




Figures from B. Casaponsa

Component separation from Planck + QUIJOTE: data

Recovery of the synchrotron spectral index



Full sky: β_s=-3.05+/-0.14

Figure from B. Casaponsa

QUIJOTE: plans

- Upgrade of MFI
  - Increasing sensitivity by a factor ~ 1.7
  - Ready in ~1 year (already funded)
- Extending QUIJOTE to the South Hemisphere
  - Use QT-1 telescope and MFI instrument
- Construct a *super-QUIJOTE* instrument
  - Covering the QUIJOTE frequencies with significant better sensitivity
  - Adding the 10-20 GHz from a super-QUIJOTE instrument to LiteBIRD improves the constraints on r by a factor of 1.7, for simulations with a spatially varying spectral index for the synchrotron [Fernández-Cobos et al., in preparation]

RADIOFOREGROUNDS Project

http://www.radioforegrounds.eu

H2020-COMPET-2015. Grant agreement **687312:**
Ultimate modelling of Radio Foregrounds (RADIOFOREGROUNDS).
3-year grant 2016-18 (IAC; UC; Cambridge; Manchester; SISSA; Grenoble; TREELOGIC).

By combining MFI QUIJOTE, Planck and other ancillary data, the project will provide:

- state-of-the-art legacy maps of the synchrotron and the anomalous microwave emission (AME) in the Northern sky
- a detailed characterization of the synchrotron spectral parameters
- a model of the large-scale properties of the Galactic magnetic field
- a detailed characterization of the AME, including its contribution in polarization
- To characterise the population of radio sources measured by Planck by adding unique information at 10-20 GHz
- specific (open source) software tools for data processing, data visualization and public information.

RADIOFOREGROUNDS Project

- Visualization tool for CMB data
- Prediction of foreground maps at a given frequency
- Point source catalogues
- Basic operations with maps
- Work with data base or upload user's maps

Summary of QUIJOTE

- QUIJOTE is a polarization experiment designed with the aim of reaching the level of r=0.05 in the B-mode angular power spectrum and of characterising the foregrounds at low frequencies
- QUIJOTE is able to measure synchrotron and AME polarization in a frequency range not covered by other experiments so far [10-20] GHz. Excellent complement for future satellite experiments such as LiteBIRD, CORE, PICO and also for other sub-orbital experiments
- First results with MFI providing the best constraints on AME polarization at different regions of the sky already published
- TGI (30 GHz) and FGI (40 GHz) in joint commissioning phase
- Legacy polarization maps (10-40 GHz) and derived products will be publicly available.
- Plans to improve QUIJOTE: upgrade for MFI, extension to the South
- Technological development for the new generation of low-frequency instruments with larger number of detectors are on-going

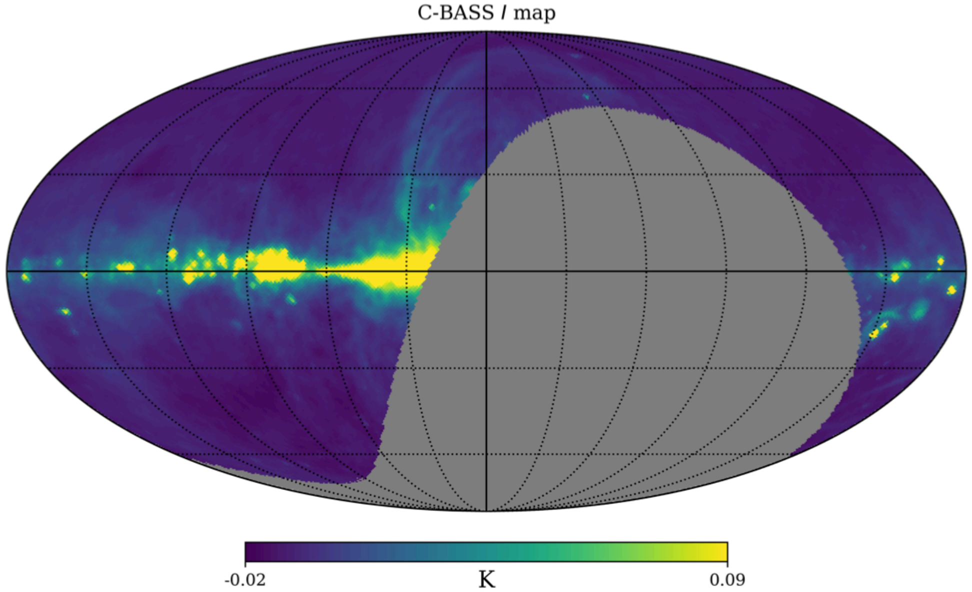
C-BASS: The C-Band All-Sky Survey

- All-sky Survey @ 5 GHz
  - Northen Site: OVRO, California
  - Southern Site: MeerKAT/SKA site, Karoo, South Africa
- Angular resolution: 0.75° (45')
- Sensitivity: 6000μK/arcmin1@15GHz

  → 0.75 μK/arcmin1@100 GHz
  (assuming β_s=-3)
- C-BASS North completed (first results imminent)
- C-BASS South continuing to observe (at least for 12-18 months)

C-BASS North

N_{side}=64
1° resolution



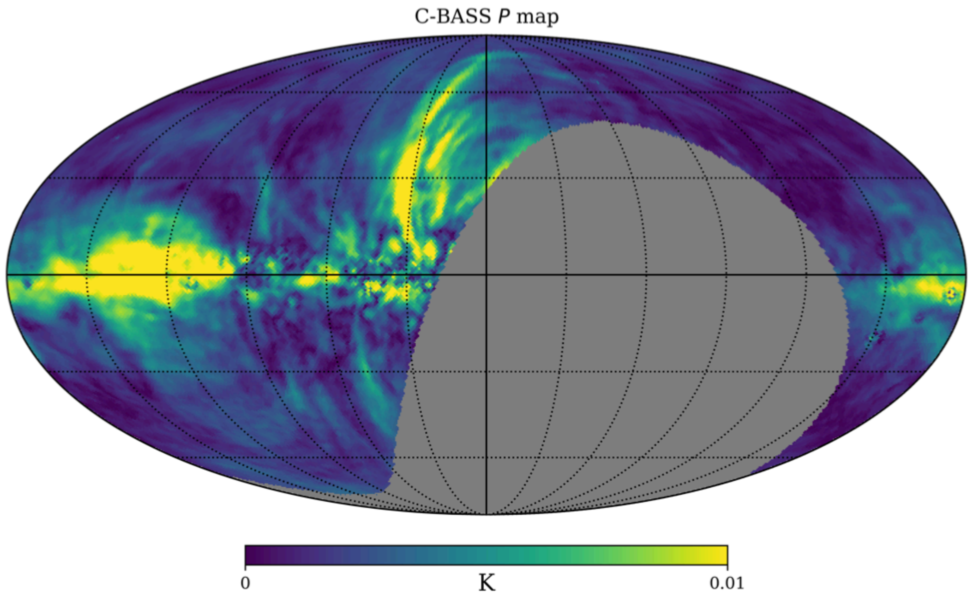


Figure from L. Jew

Polarized spectral index

C-BASS/*Planck* 30 GHz, β

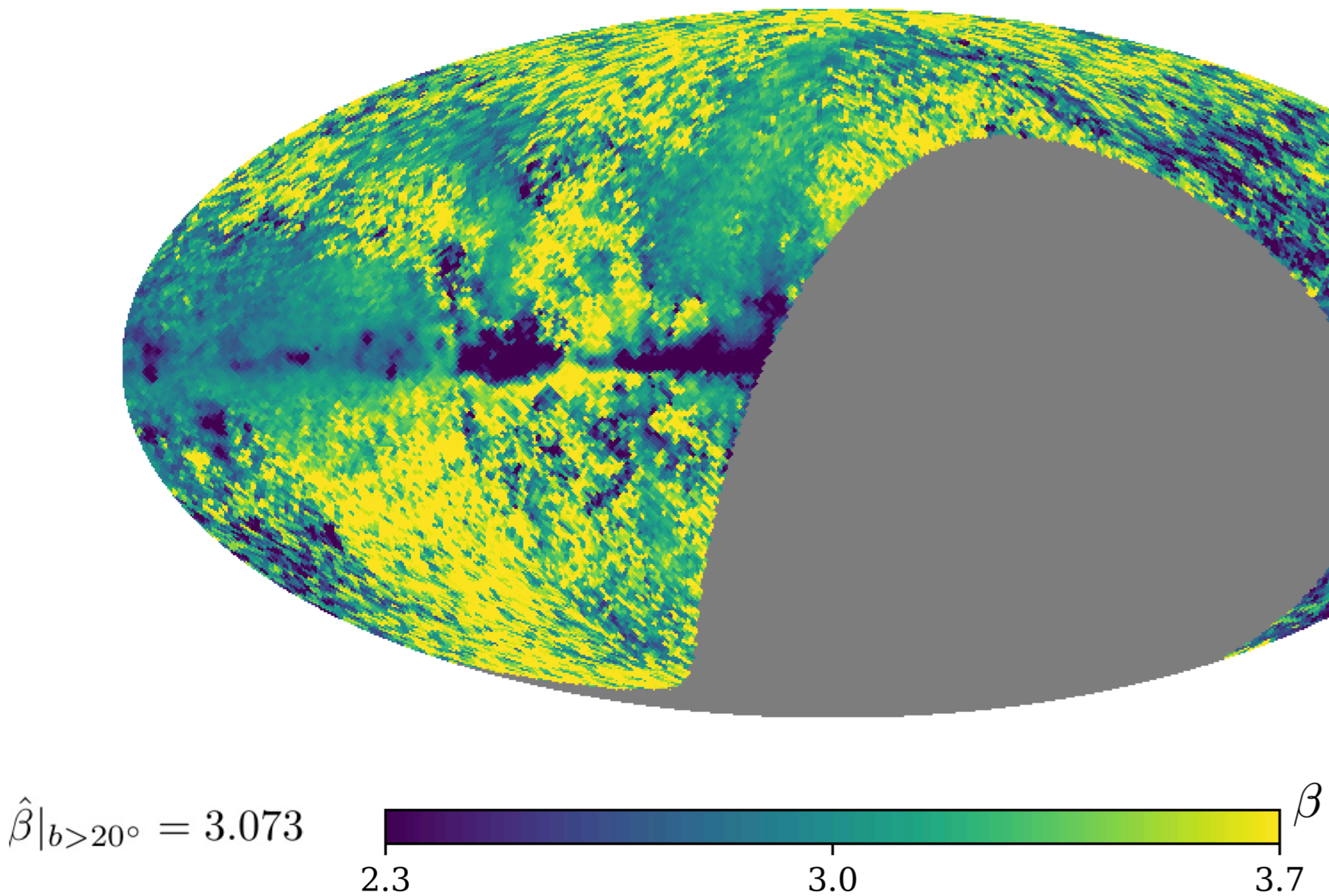


Figure from L. Jew

S-PASS: S-band Polarization All Sky Survey

- Polarization survey @ 2.3 GHz
- Angular resolution ~ 9 arcmin
- Sky coverage ~ 50% (South hemisphere)
- Parkes Radio Telescope (64m), Australia
- 2000 h (175 nights in 2.5 yrs)
- Started Oct 2007, completed in January 2010

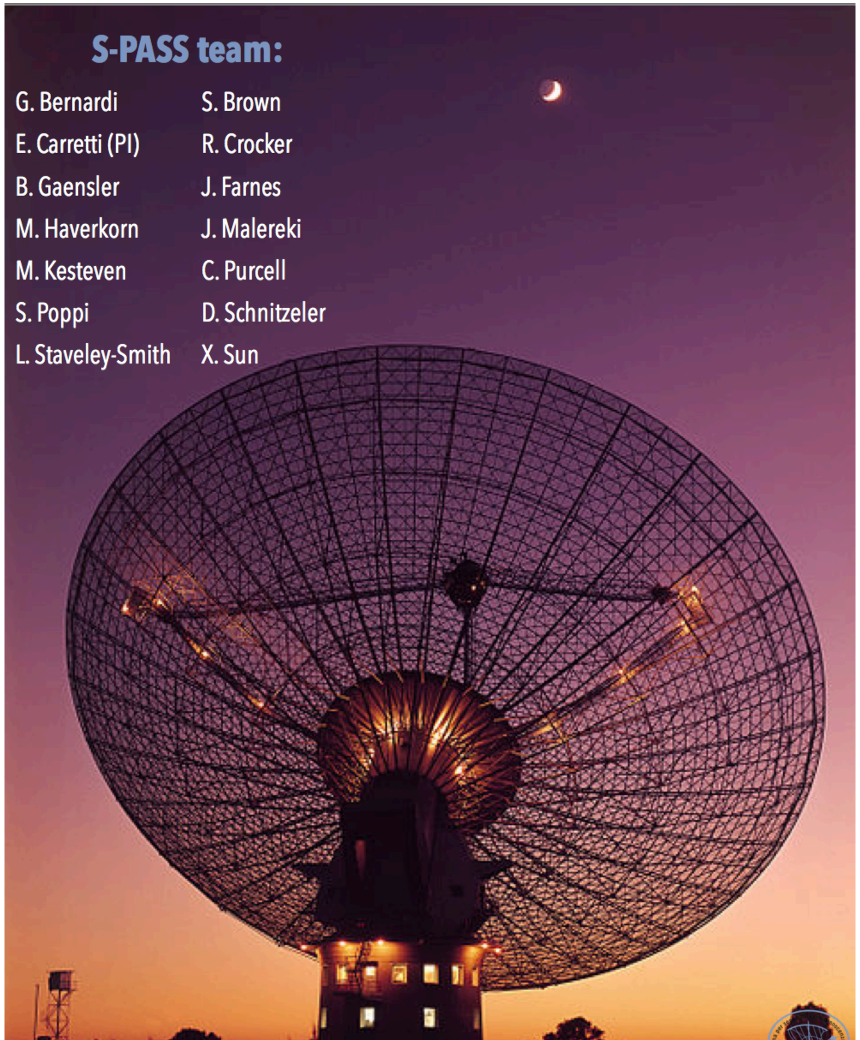


Figure from N. Krachmalnicoff

S-PASS polarized intensity map **@2.3 GHz**

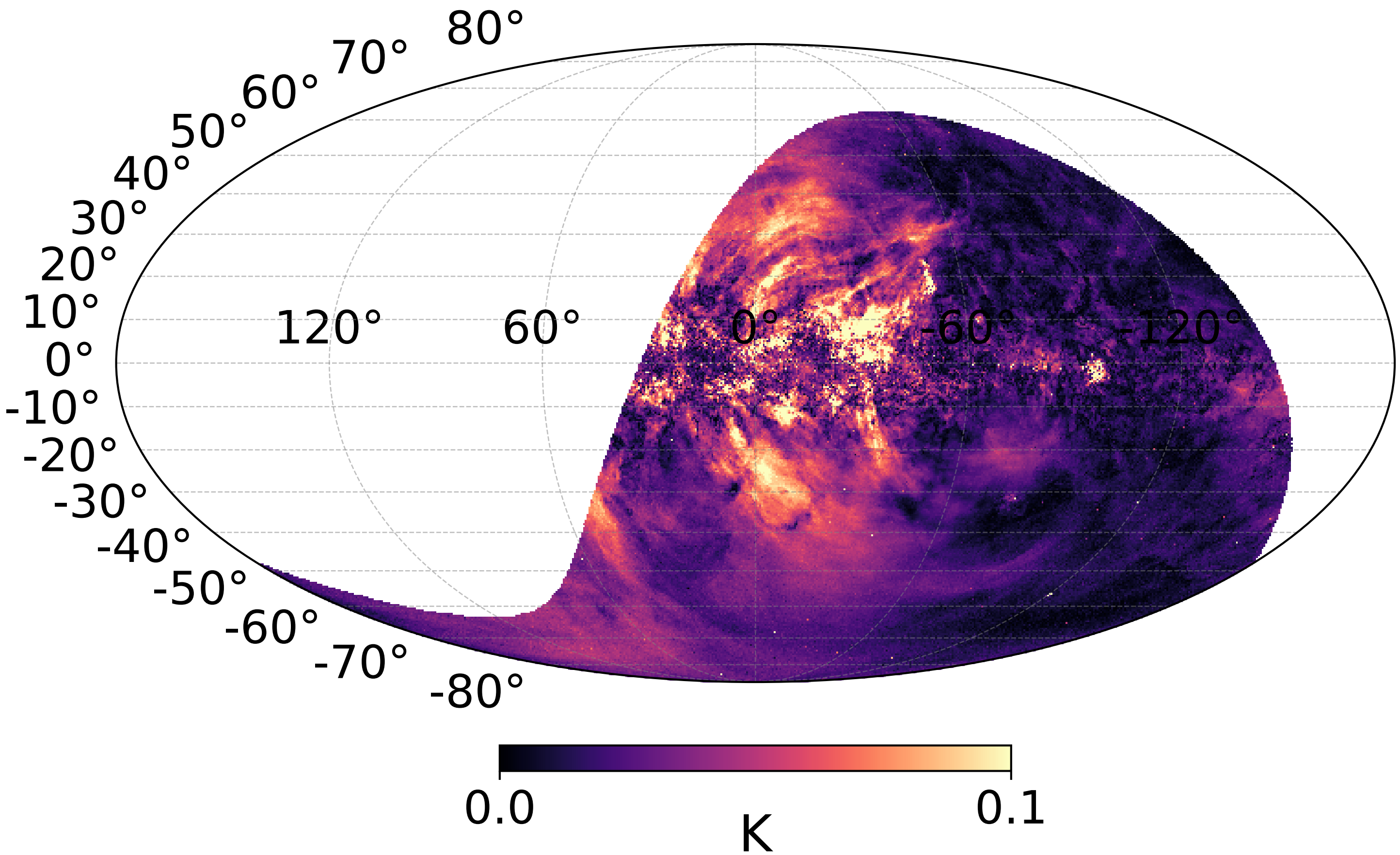


Figure from N. Krachmalnicoff

WMAP-K polarized intensity map **@23 GHz**

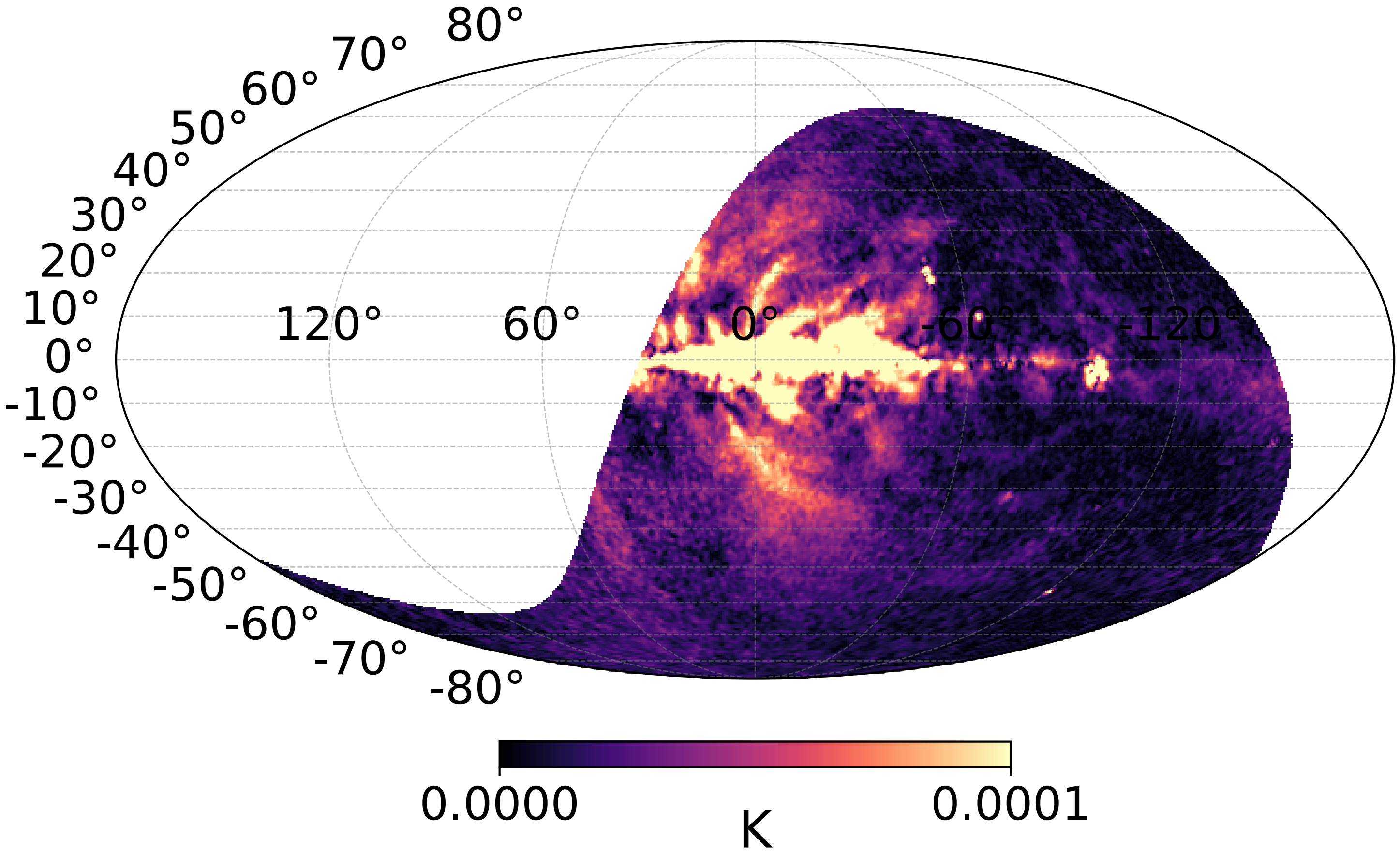
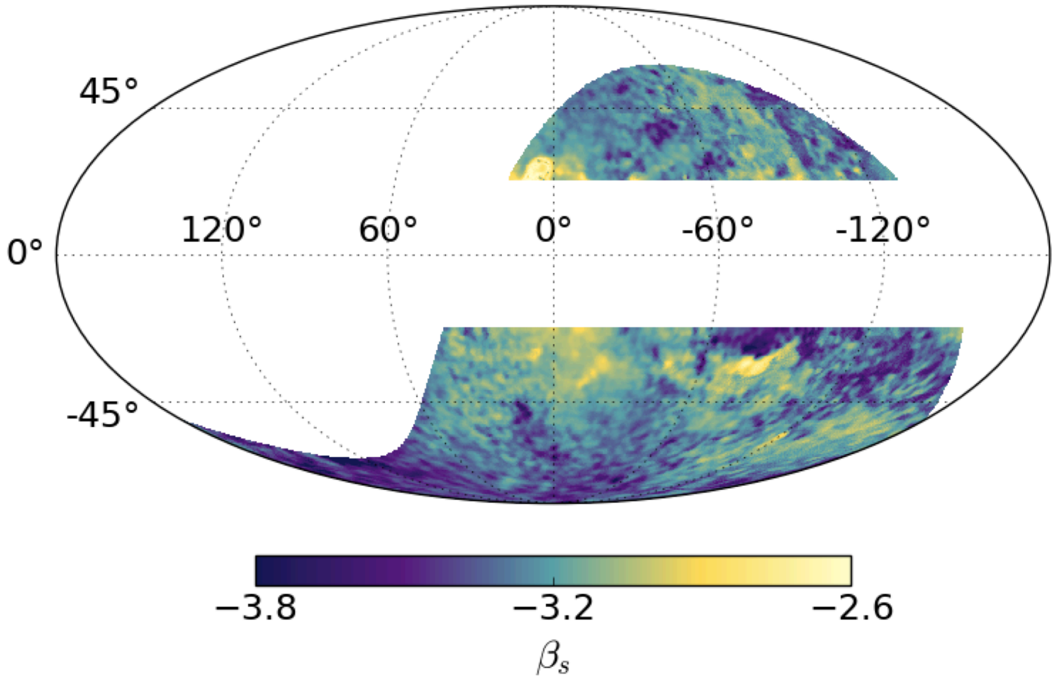


Figure from N. Krachmalnicoff

S-PASS

- Synchrotron spectral index map from S-PASS (2.3 GHz), WMAP (23 and 33 GHz) and Planck (30 GHz)

$\langle\beta_s\rangle=-3.20$
$\sigma(\beta_s)=0.15$



- Power law fit in range 2.3 -33 GHz
- Fit in each pixel in total polarization
- Sky coverage ~30°
- Angular resolution of 2°

- First constraints on synchrotron curvature
  - → Compatible with zero
- Also found that EE spectra show more power than BB spectra: A_{BB}/A_{EE} ~0.5

(Krachmalnicoff et al. 2018)