The QUIJOTE experiment and other CMB projects at the Teide Observatory

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Cosmic Orbital and Suborbital Microwave ObservationS

4th ASI/COSMOS workshop
4-5 March 2019

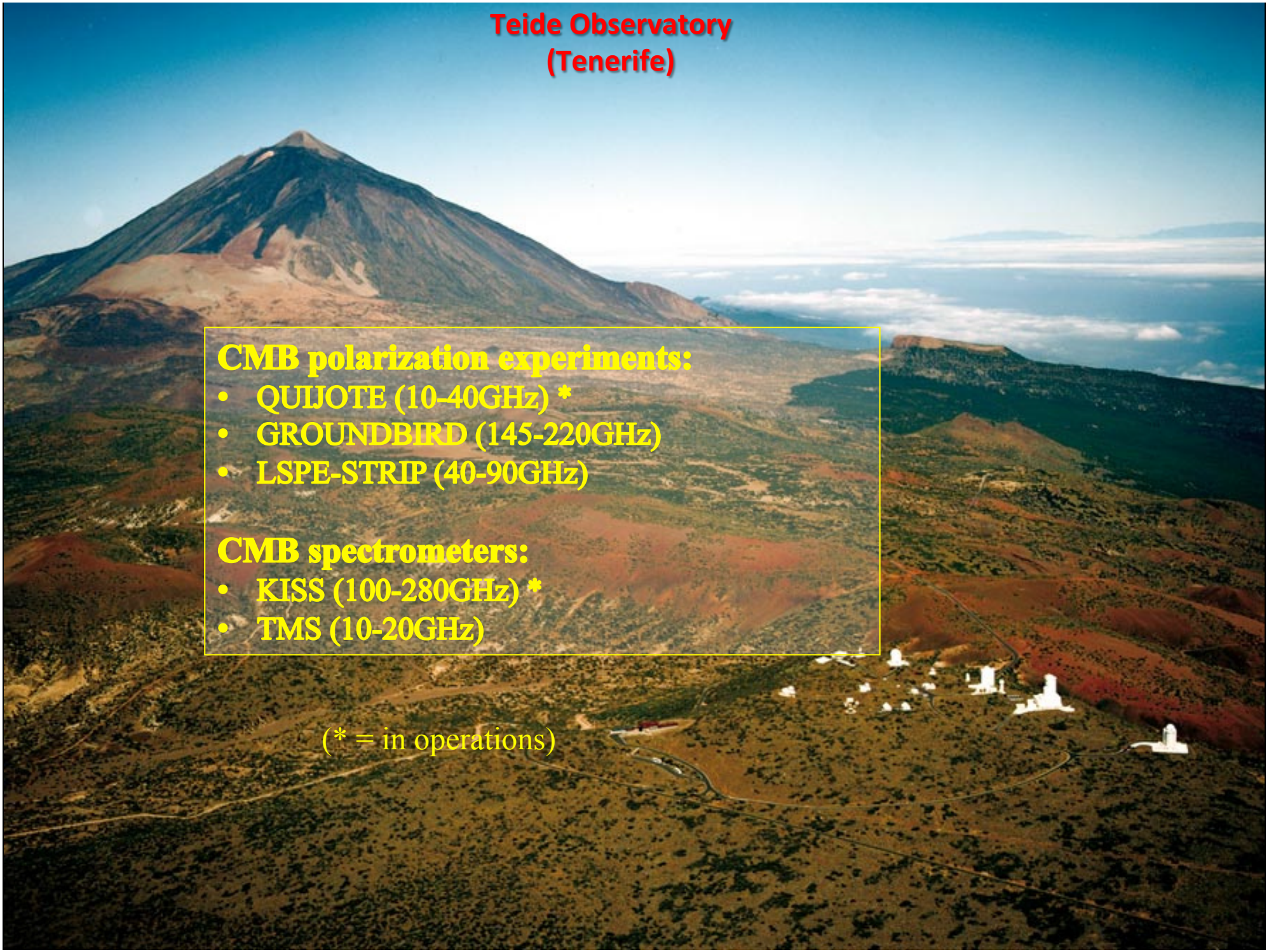
Teide Observatory (Tenerife)

- Altitude: 2.400 m
- Longitude: 16º 30' W
- Latitude: 28º 17' N
- Typical PWV: 3 mm, and below 2mm during 20% of time.
- High stability of the atmosphere.
- Good weather: 90%
- Long history of CMB experiments since mid 80s.

Tenerife experiment
10, 15, 33 GHz

COSMOSOMAS
11, 13, 15, 17 GHz

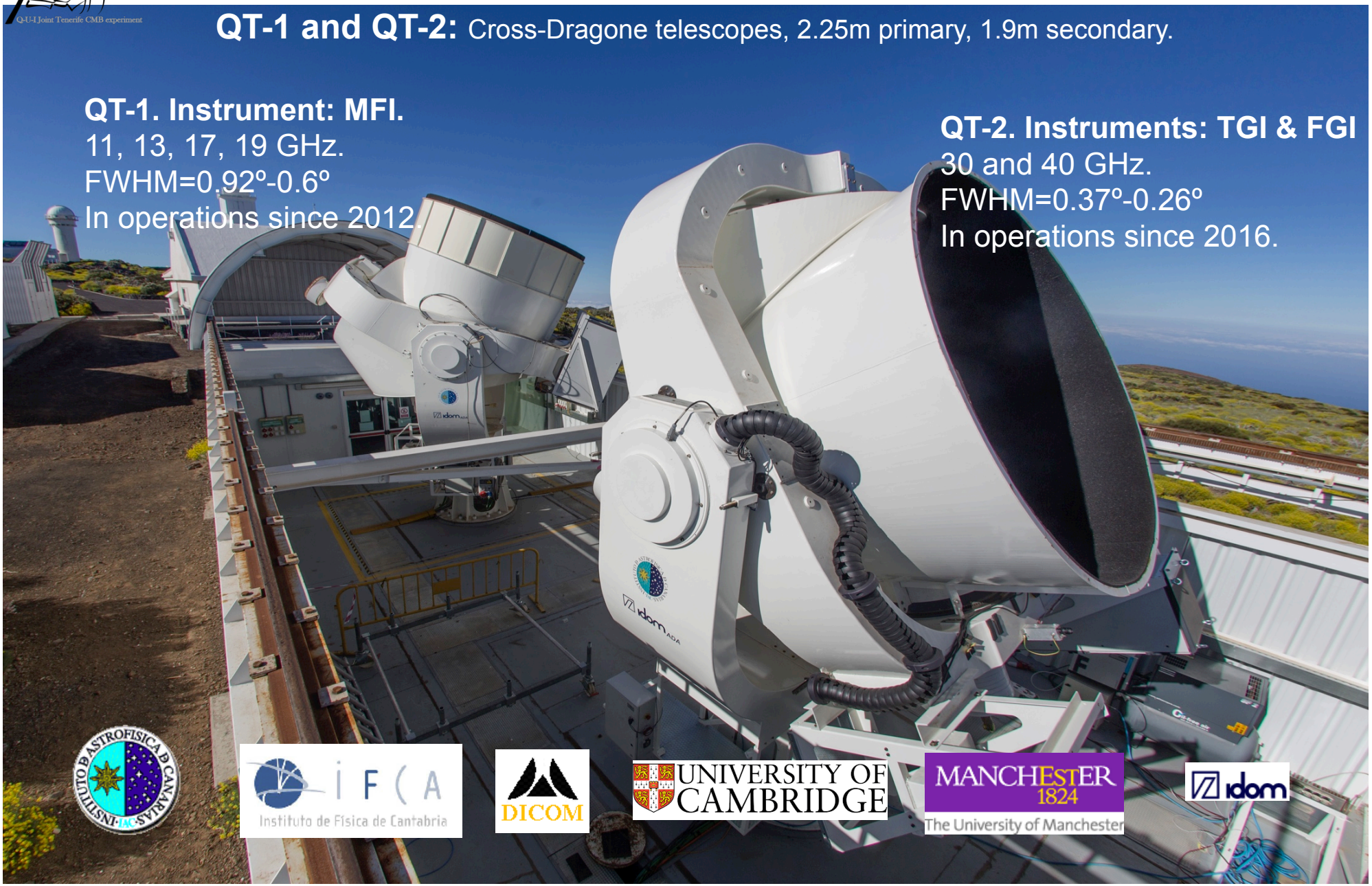
The Very Small Array
30GHz


Teide Observatory
(Tenerife)
CMB polarization experiments:
• QUIJOTE (10-40GHz) *
• GROUNDBIRD (145-220GHz)
• LSPE-STRIP (40-90GHz)
CMB spectrometers:
• KISS (100-280GHz) *
• TMS (10-20GHz)
(* = in operations)

The QUIJOTE experiment

Q-U-I Joint Tenerife CMB experiment

QT-1 and QT-2: Cross-Dragone telescopes, 2.25m primary, 1.9m secondary.



QT-1. Instrument: MFI.
11, 13, 17, 19 GHz.
FWHM=0.92º-0.6º
In operations since 2012.

QT-2. Instruments: TGI & FGI
30 and 40 GHz.
FWHM=0.37º-0.26º
In operations since 2016.

Instituto de Física de Cantabria

DICOM

UNIVERSITY OF CAMBRIDGE

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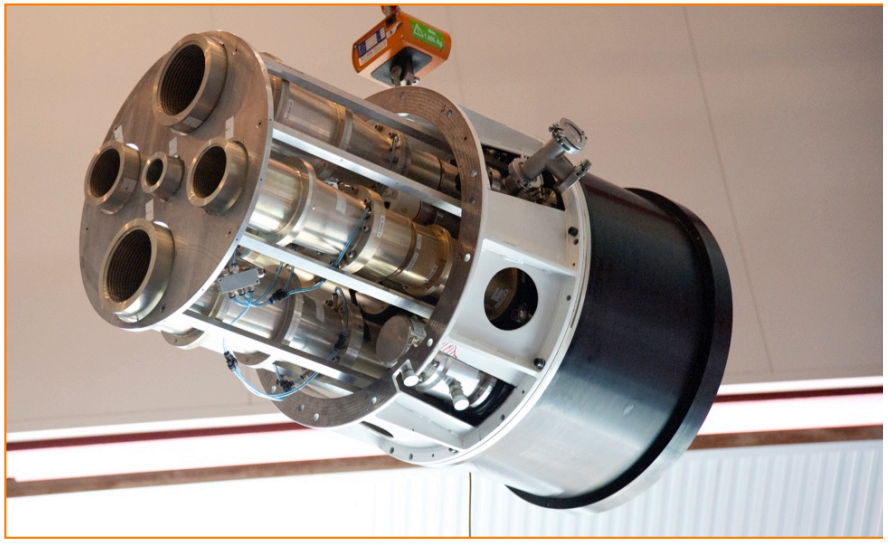
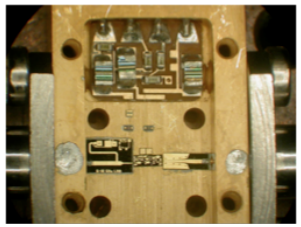
The University of Manchester

idom

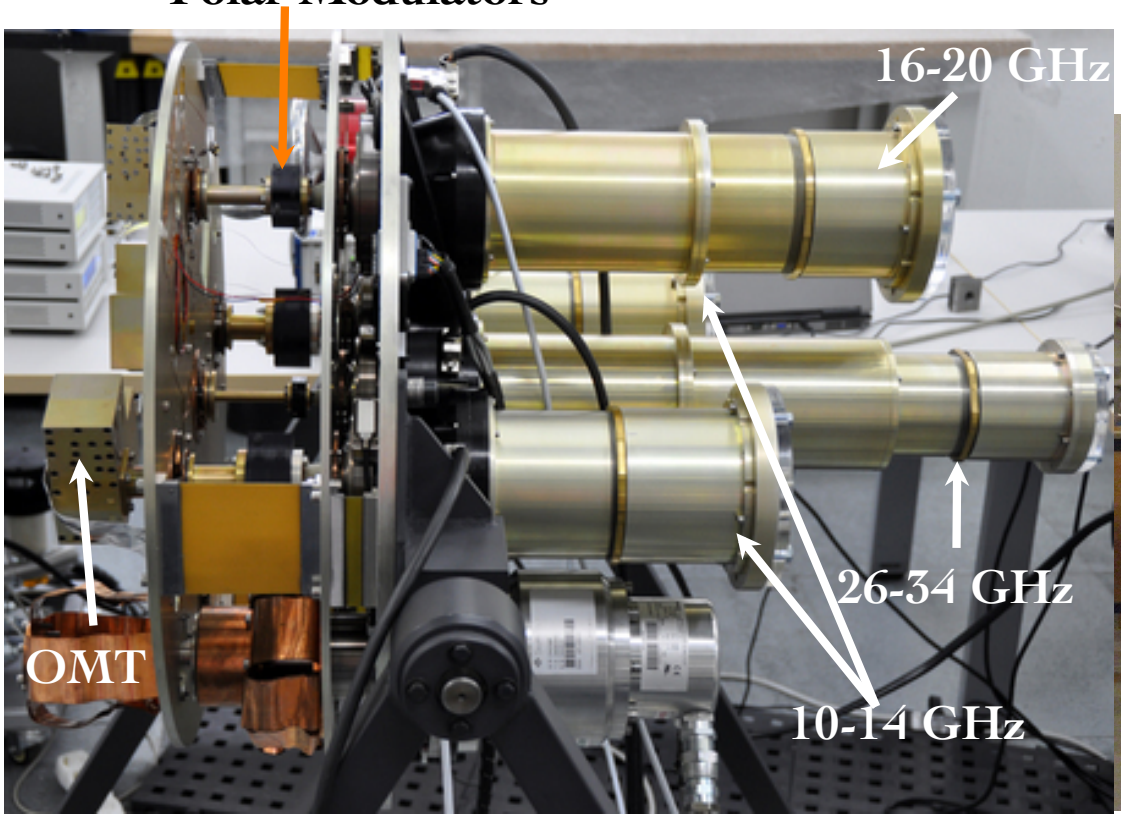
MFI Instrument (10-20 GHz)

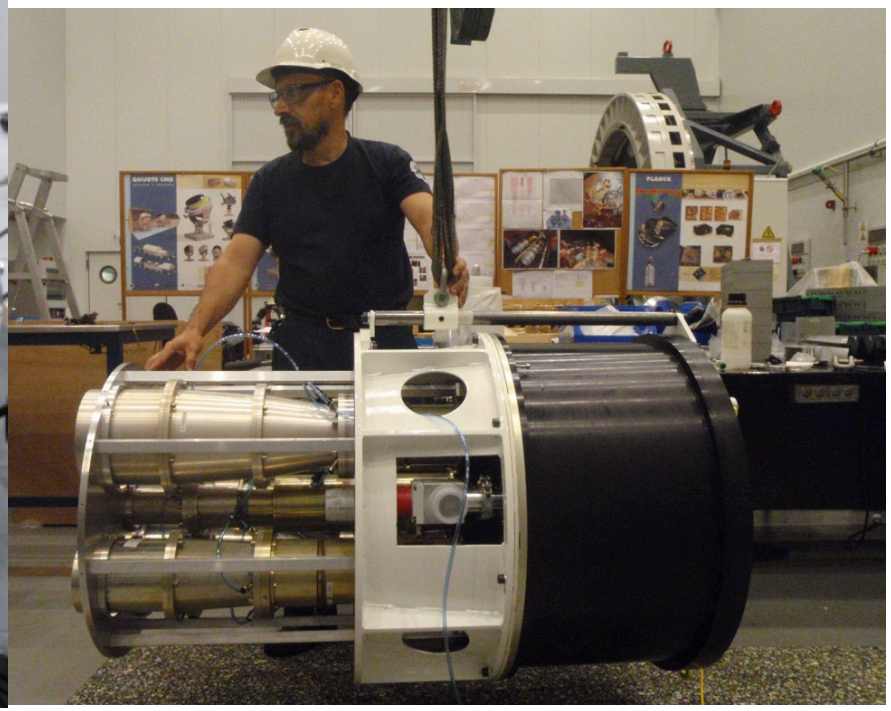
- In operations since Nov. 2012.
- 4 horns, 32 channels. Covering 4 frequency bands: 11, 13, 17 and 19 GHz.
- Sensitivities: ~400-600 μK $s^{1/2}$ per channel.
- **MFI upgrade (MFI2)**. Funds secured. Aim: to increase the integration speed by a factor of 3.





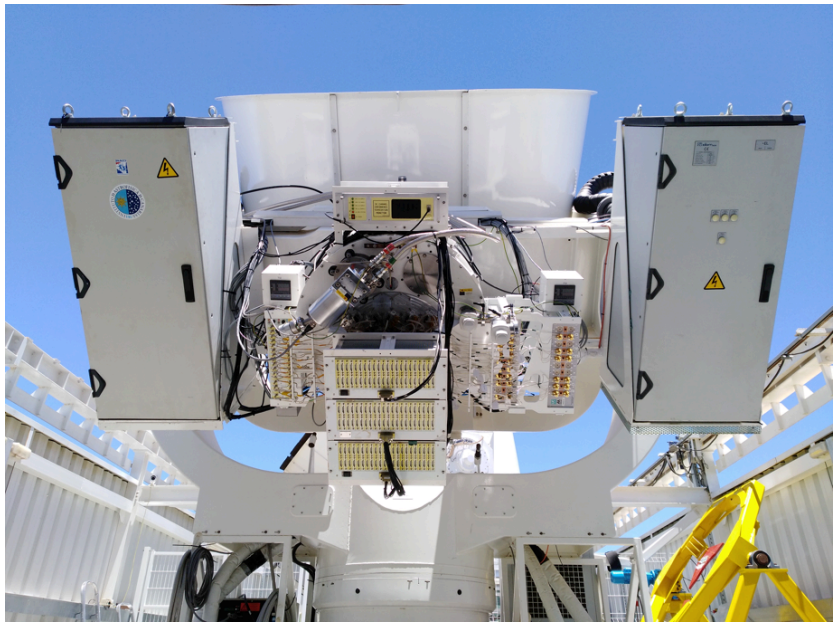
LNA

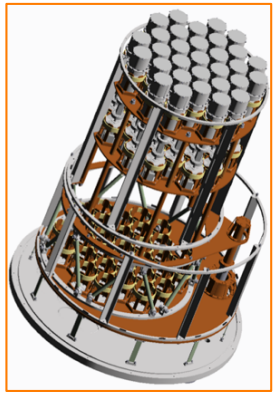


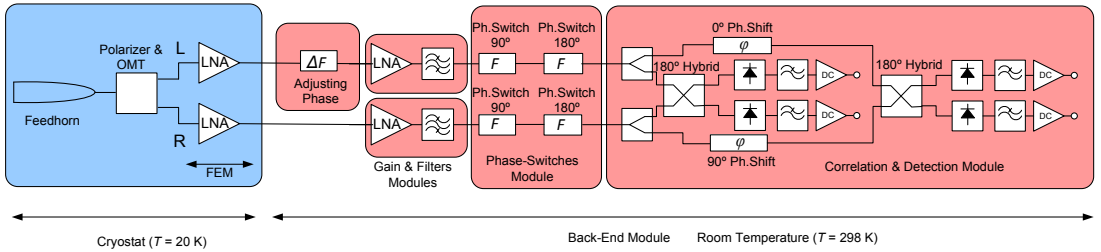


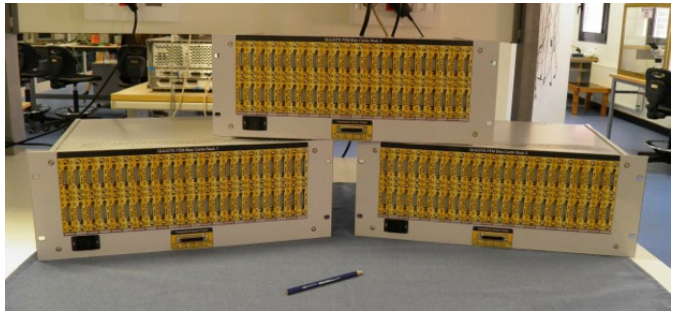
TGI (30 GHz) and FGI (40GHz) instruments

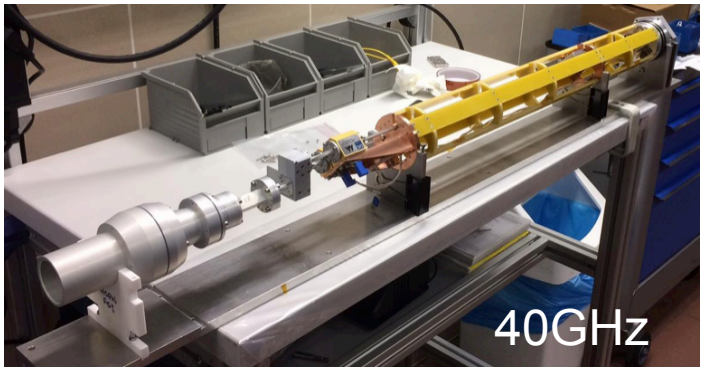
- **TGI**: 31 pixels at 30GHz. Measured sensitivity: 50 μK $s^{1/2}$ for the full array. First light May 12th 2016.
- **FGI**: 31 pixels at 40GHz. Expected sensitivity: 60 μK $s^{1/2}$ for the full array. In commisioning phase.
- Joint comissioning started in 2018.

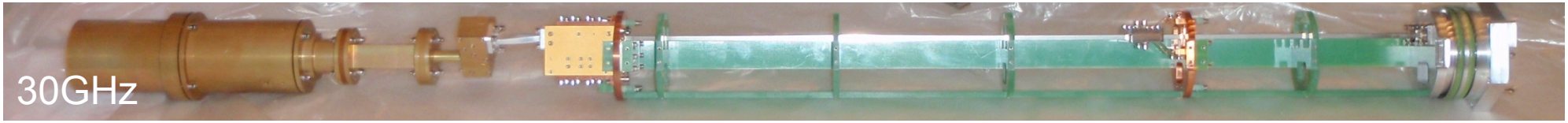












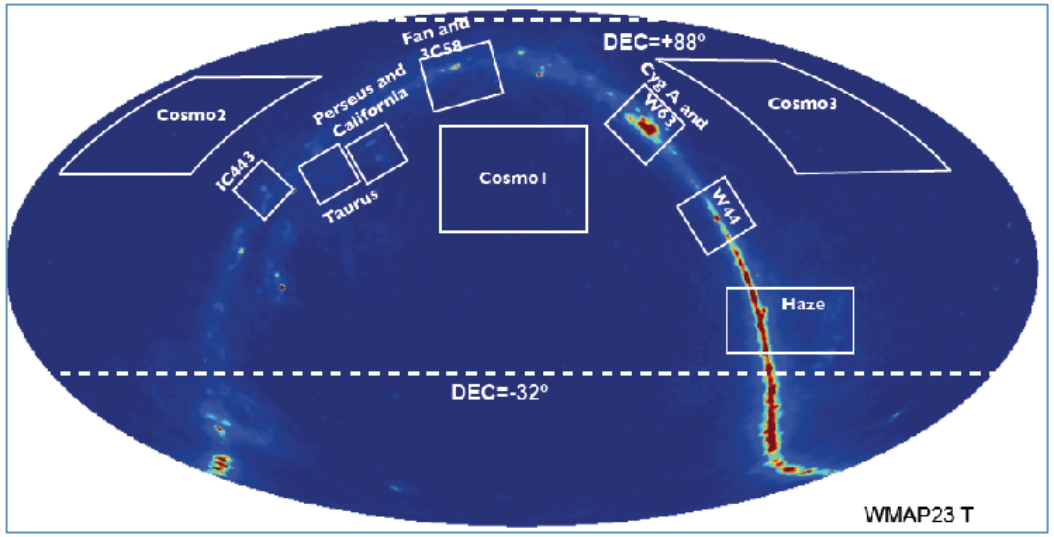
Science with QUIJOTE first instrument (MFI)

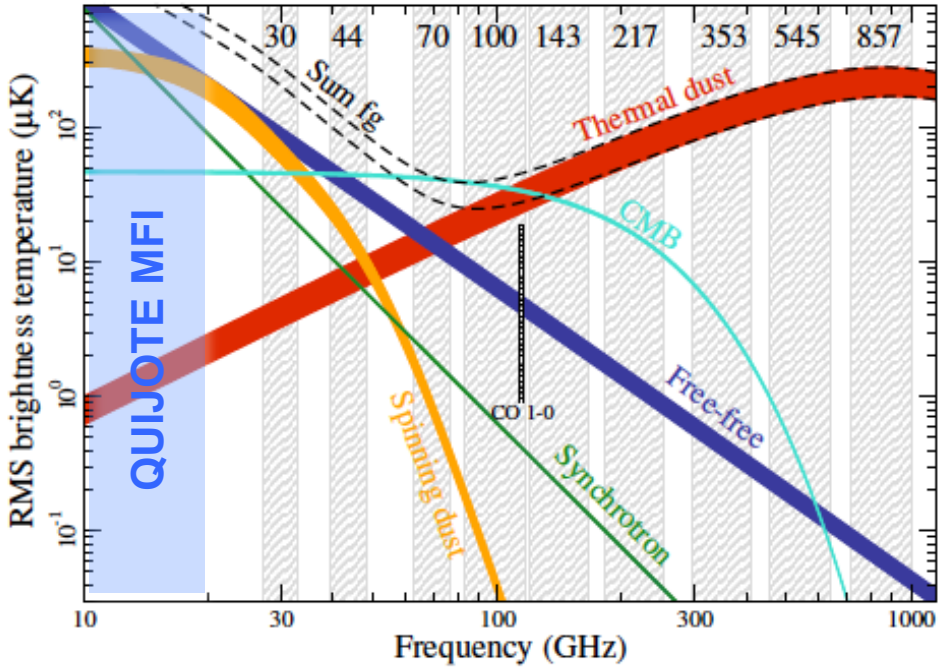
Excellent complement to PLANCK at low frequencies. Legacy for future experiments.

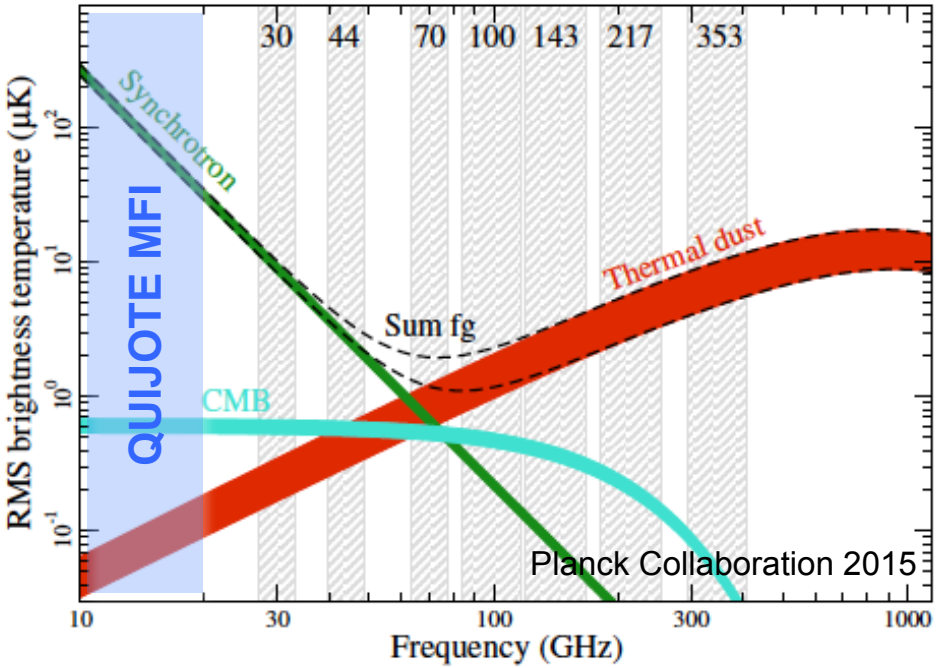
MFI Science phase

- Wide survey (10,800h)
- Cosmological fields (6,500h)
- Daily calibrators (Crab, Cass A, Jupiter, sky dips)
- Galactic centre and Haze (930h)
- Perseus molecular cloud (600h)
- Fan region and 3C58 (460h)
- Taurus region (450h)
- SNRs (W44, W47, IC443, W63) (900h)

Total: ~**25,500 h** of MFI data (2.9 effective years), with ~50% efficiency.







RADIOFOREGROUNDS project

http://www.radioforegrounds.eu

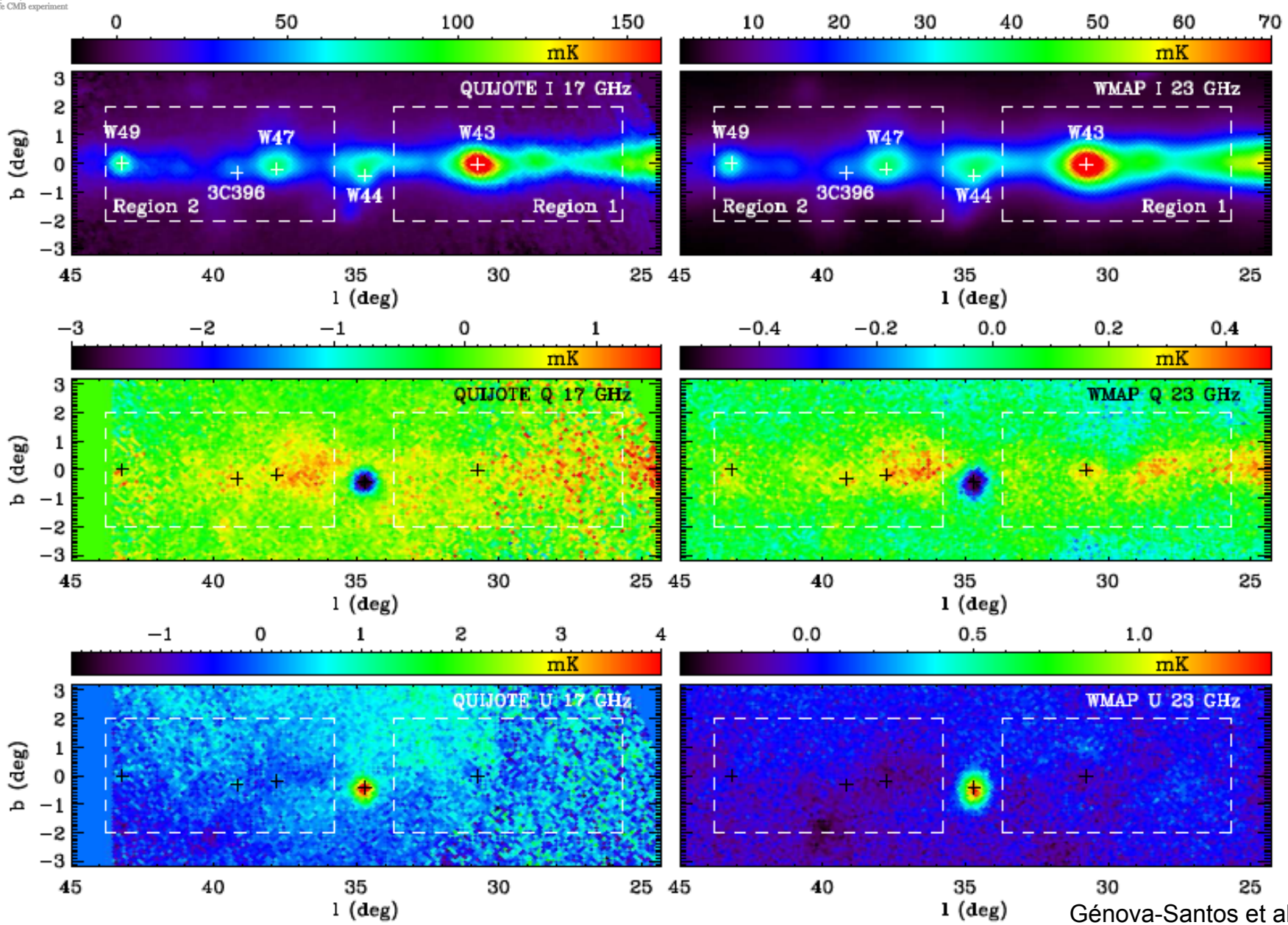
H2020-COMPET-2015. Grant agreement **687312:** "Ultimate modelling of Radio Foregrounds" (RADIOFOREGROUNDS).
3-year grant 2016-18 (IAC; IFCA; Cambridge; Manchester; SISSA; Grenoble; TREELOGIC).

Combining QUIJOTE data with PLANCK and WMAP, this project will provide specific products:

a) state-of-the-art legacy maps of the synchrotron and the anomalous microwave emission (AME) in the Northern sky;
b) a detailed characterization of the synchrotron spectral index, and the implications for cosmic-rays electron physics;
c) a model of the large-scale properties of the Galactic magnetic field;
d) a detailed characterization of the AME, including its contribution in polarization; and
e) a complete and statistically significant multi-frequency catalogue of radio sources in both temperature and polarization.
f) specific (open source) software tools for data processing, data visualization and public information.

W43, W44 and W47 (25º<l<45º)

(W44 is a bright SNR. Both W43 and W47 are molecular complexes)

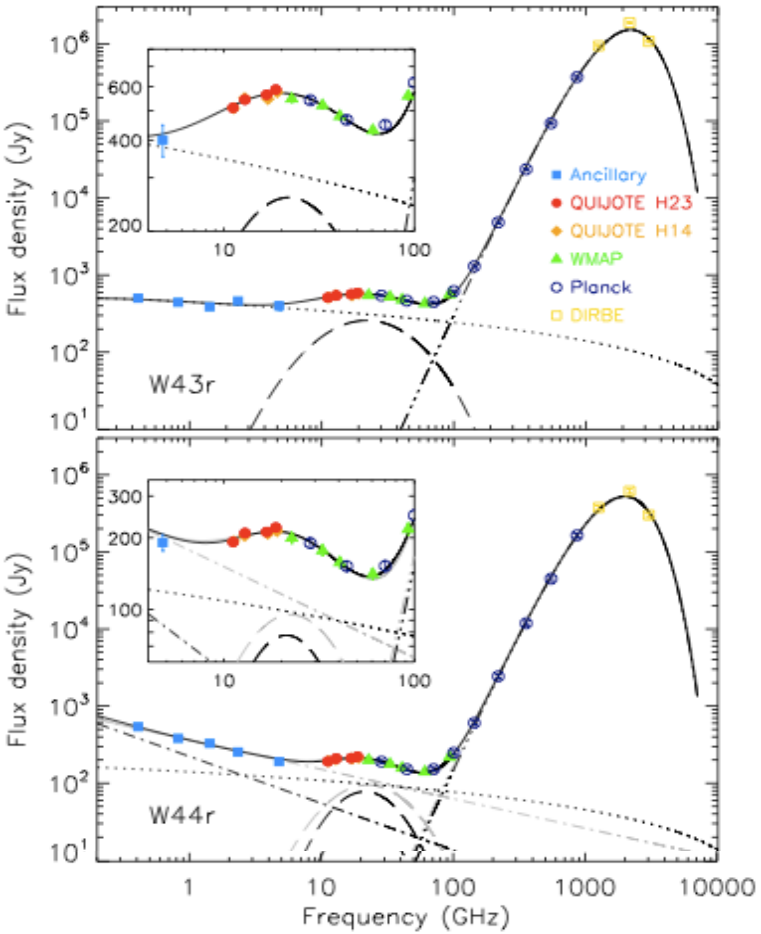


Génova-Santos et al. (2017)

W43, W44 and W47 (25º<l<45º)

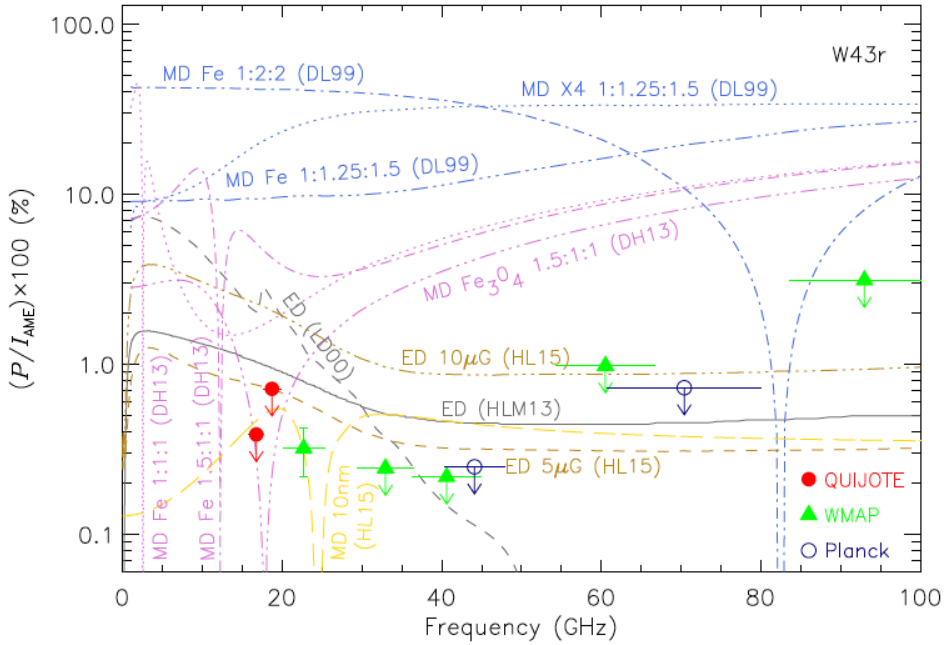
INTENSITY

- QUIJOTE provides a clean separation of the AME and free-free components. The later is consistent with RRL measurements.
- Commander Planck alone overestimates the free-free and underestimate the AME.



POLARIZATION

Constraints on AME polarization fraction and comparison with ED models. **Best upper limits to date** (< 0.4% at 17GHz from QUIJOTE, and < 0.22% at 23GHz from WMAP).



Génova-Santos et al. (2017)

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

- 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.

- **Observing strategy**: "nominal mode", consisting in continuous 360º AZ scans at constant elevation.
  - EL = 30º, 35º, 40º, 50º, 60º, 65º and 70º.
  - Data accumulated during 5 years, in different periods.

- **Data processing**:
  - Basic processing similar to other QUIJOTE data (Genova-Santos et al. 2015, 2017)
  - Primary flux calibration: CASS. Polarization calibrator: CRAB.
  - Gain model. Based on a (thermally stabilised) noise diode. Signal injected during 1s every 30s.
  - RFI correction. Mainly due to geostationary satellites. Objects are flagged, and the far sidelobe contamination (only detectable at 11 and 13GHz in intensity) is removed using signal templates based on data stacks in AZ.
  - Post-processing: removal of large scale residual by substraction of a dipole component to the final maps.

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

PRELIMINARY MAPS

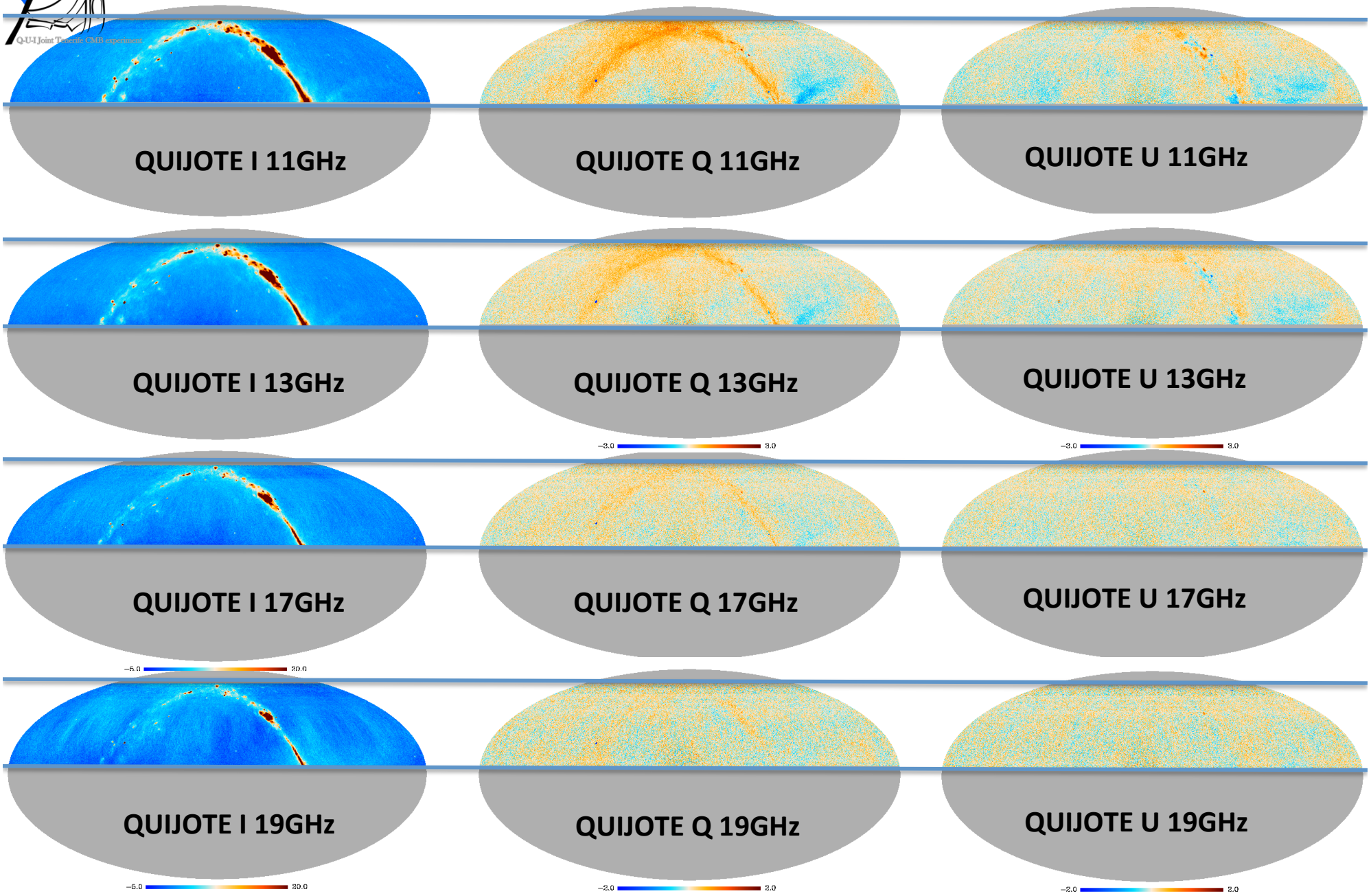
HORN	Freq. [GHz]	Beam [deg]	σ_Q [μK/deg]	σ_U [μK/deg]	NET [mK $s^{1/2}$]
2	16.8	0.63	70.6	70.7	1.71
2	18.7	0.63	90.8	91.3	2.17
3	11.2	0.84	54.3	54.3	1.21
3	12.9	0.85	48.6	48.3	1.05
4	17.0	0.65	40.9	41.0	0.98
4	19.0	0.65	42.6	42.6	0.95

- Noise estimates based on null-tests, splitting the data in two epochs.
- Last column shows the instrument instantaneous (equivalent) sensitivity in polarisation, taking into account the integration time per pixel.
- Preliminary maps have
  - ~50 μK/deg at 11, 13GHz
  - ~40 μK/deg at 17, 19GHz.

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

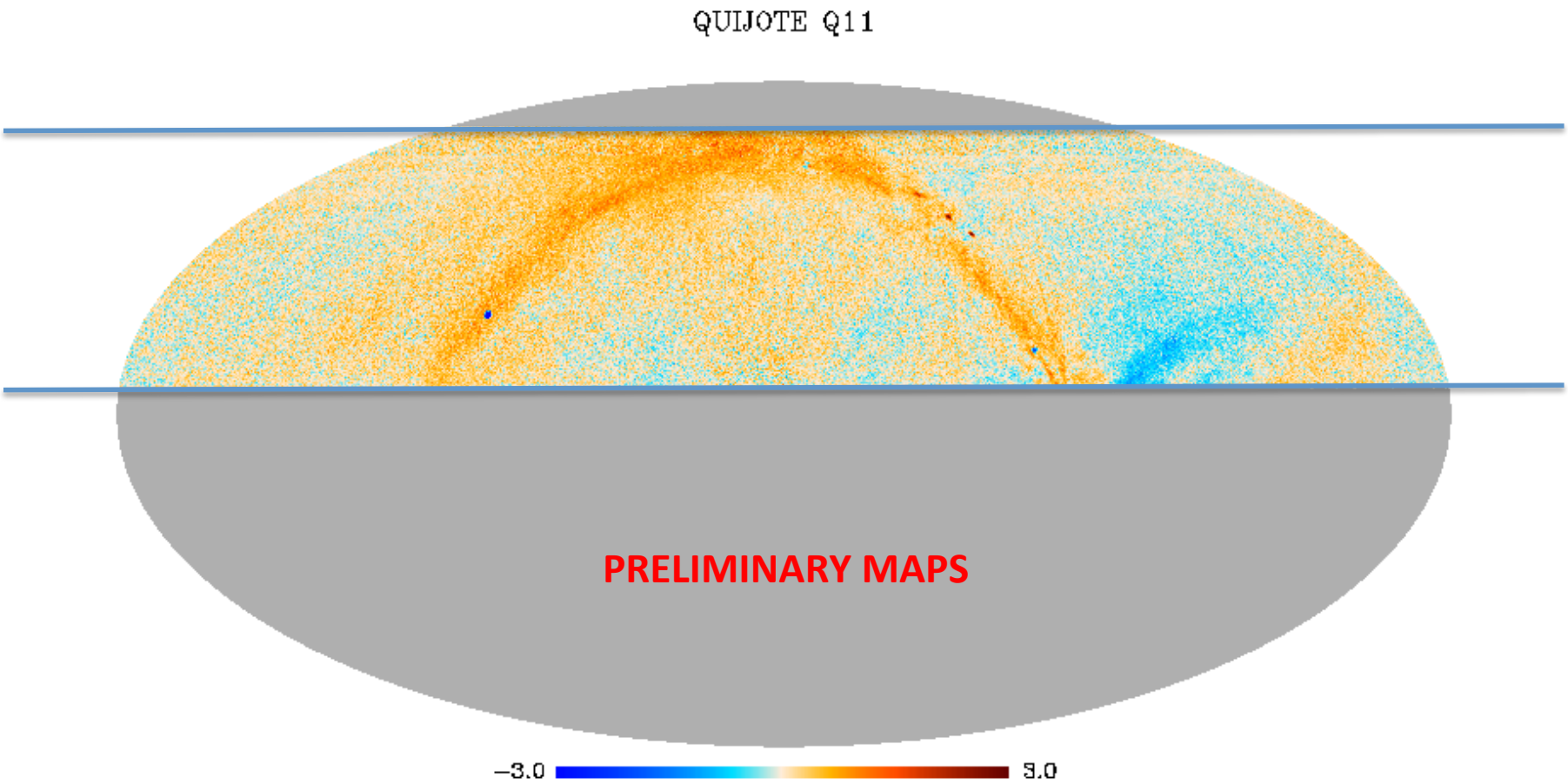
PRELIMINARY MAPS

(Note: Q, U defined in Galactic coords.)



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

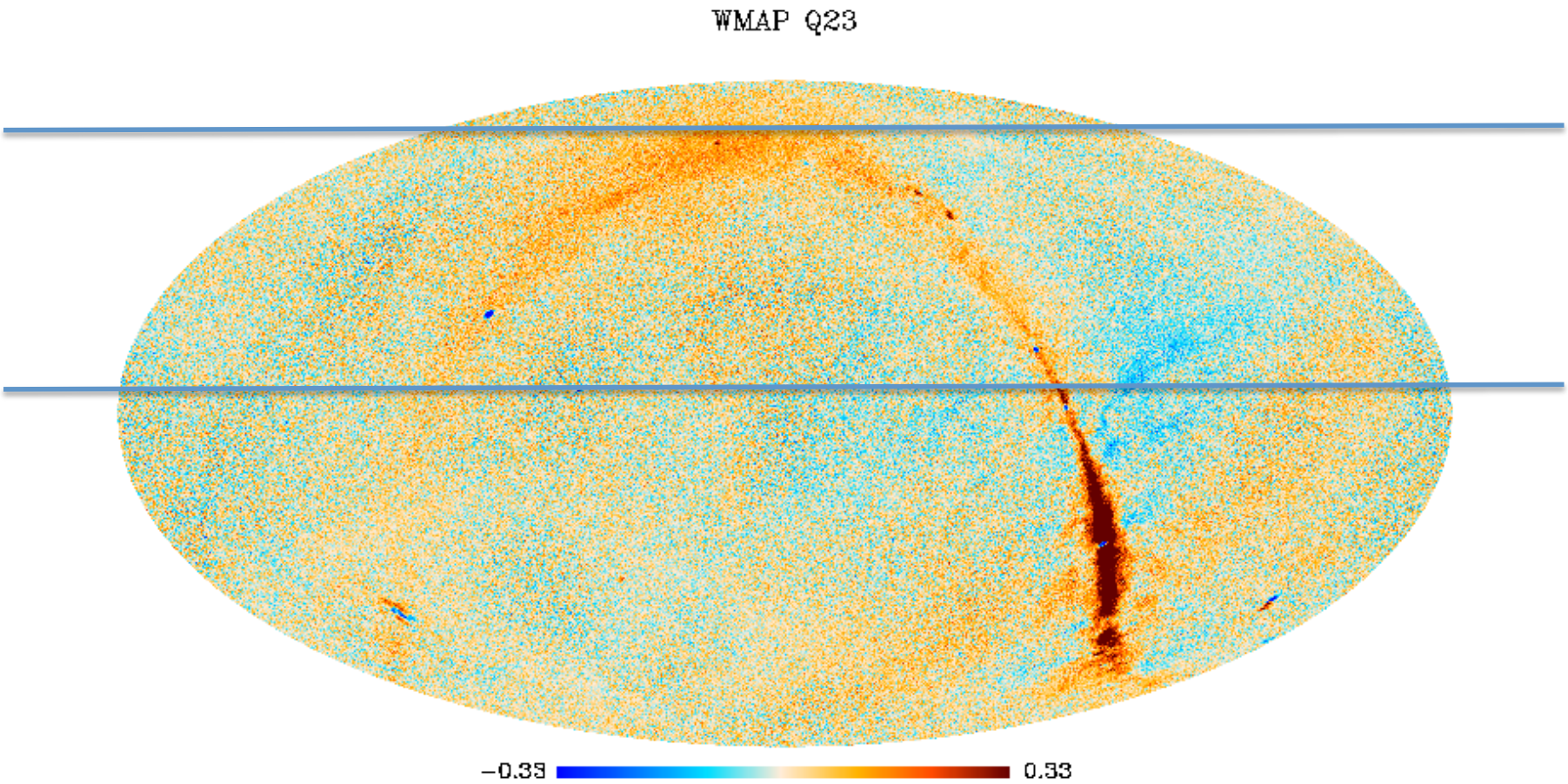
- Example of polarization maps at 11GHz from one horn (using Equatorial projection).



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

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

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



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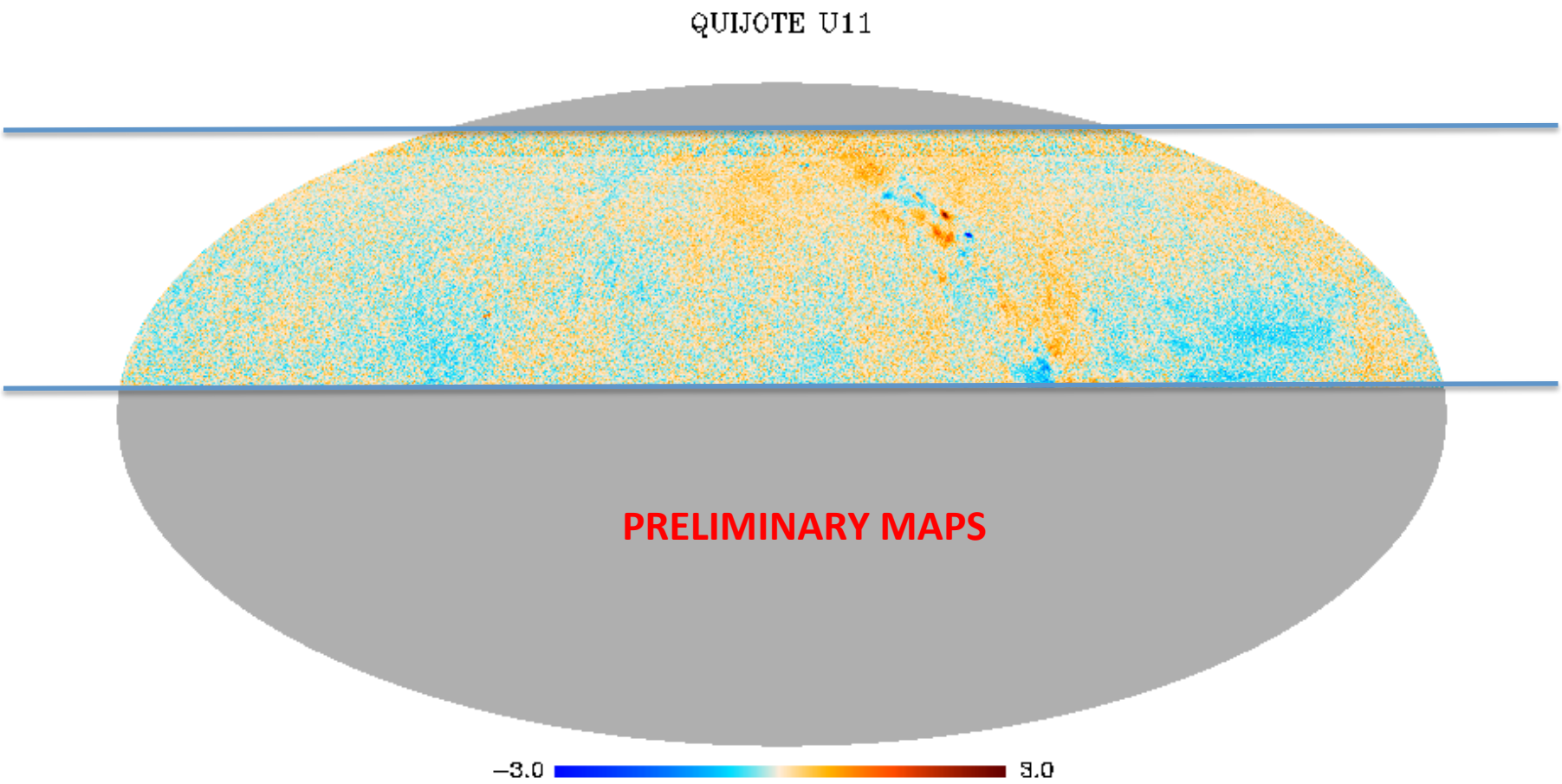

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Wide survey with the QUIJOTE MFI (10-20GHz)

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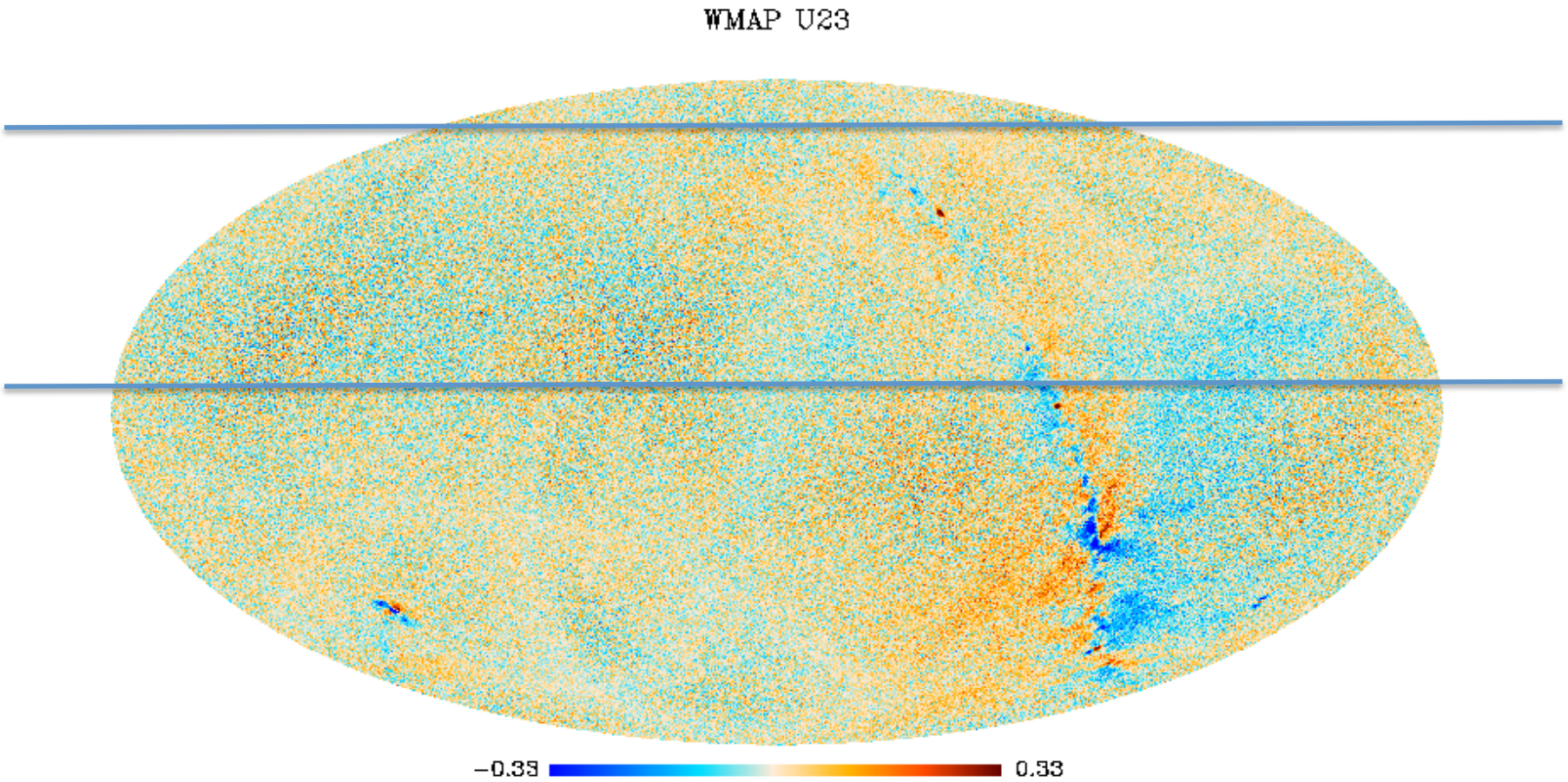


(scaled to preserve the same color
for a signal with β=-3)

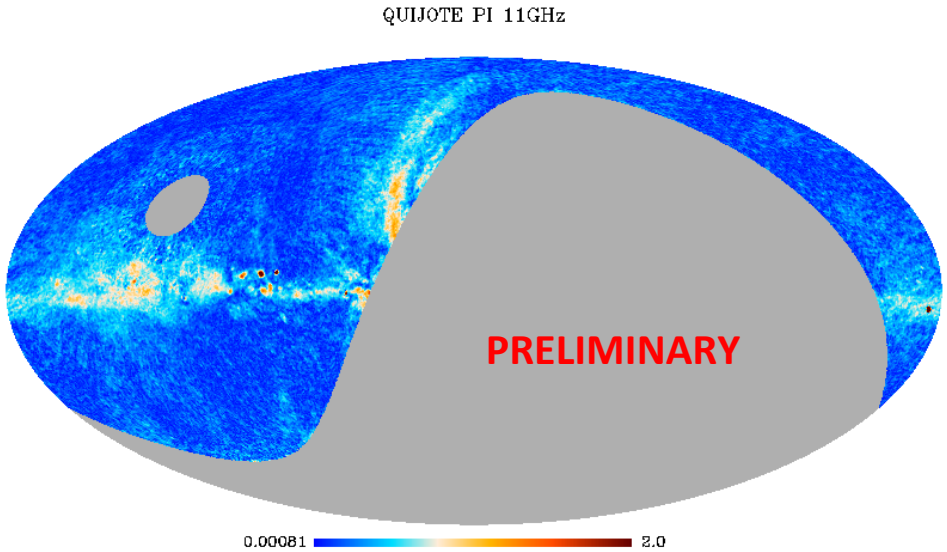
Wide survey with the QUIJOTE MFI (10-20GHz)

Papers: QUIJOTE wide-survey (in preparation, to be submitted soon):

I. A northern sky survey at 10-20GHz with the Multi-Frequency Instrument.
II. Galactic AME sources in the MFI wide survey.
III. Analysis of the polarised synchrotron emission at the power spectrum level in the MFI wide survey.
IV. The FAN region as seen by QUIJOTE-MFI
V. The North Galactic Spur as seen by QUIJOTE-MFI.
VI. Component separation in intensity with the QUIJOTE-MFI wide survey
VII. Component separation in polarization with the QUIJOTE-MFI wide survey.
VIII. Radiosources in the QUIJOTE-MFI wide survey.
IX. W49, W51 and IC443 SNRs as seen by QUIJOTE.

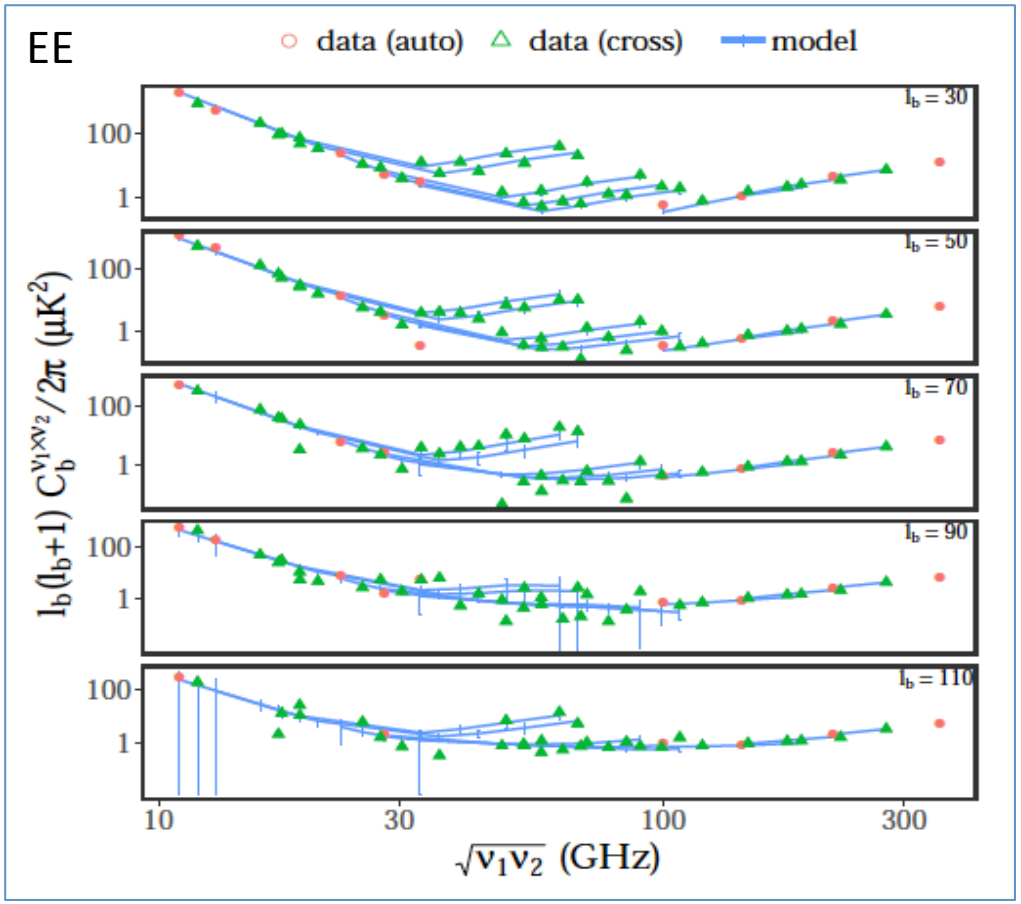
Maps will be publicly available once the first paper is accepted for publication.

(Preliminary results presented in the CMBforegrounds18 conference, Tenerife, October 15-18, 2018).
http://www.iac.es/congreso/cmbforegrounds18/

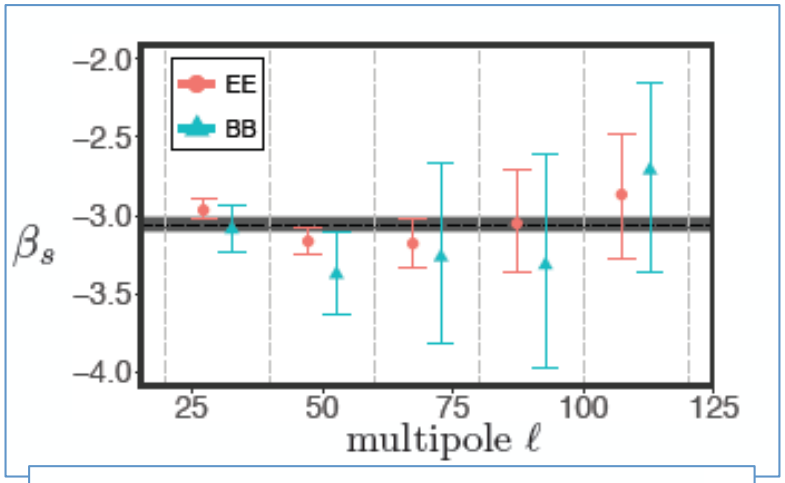


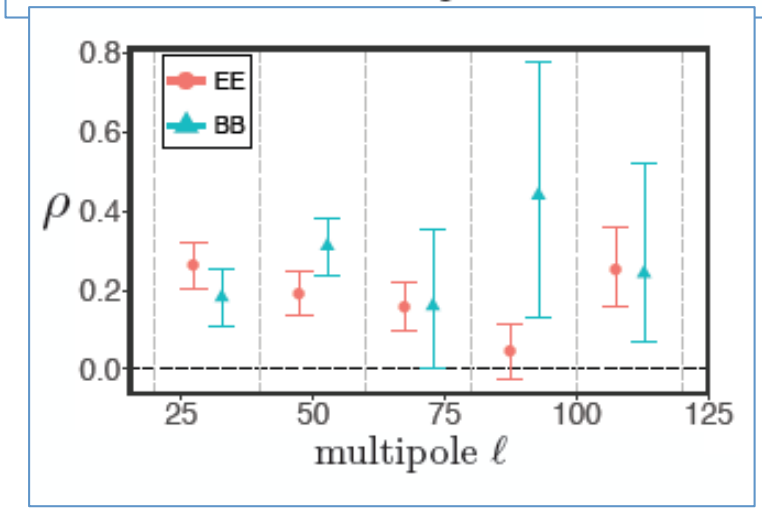
QUIJOTE-MFI wide survey results: synchrotron polarization

- Auto- and cross-spectra of QUIJOTE, WMAP, PLANCK maps in northern sky (|b|>10º).
- Pol. Synchrotron spectral index: -3.00±0.05. [**Planck**: -3.13±0.13**, S-PASS**: -3.22±0.08].
- Dust-synchrotron correlation: ~ 0.20±0.06.
- Variability on sky (compared to other results: Planck Col. XI 2018, Krachmalnikoff et al. 2018).



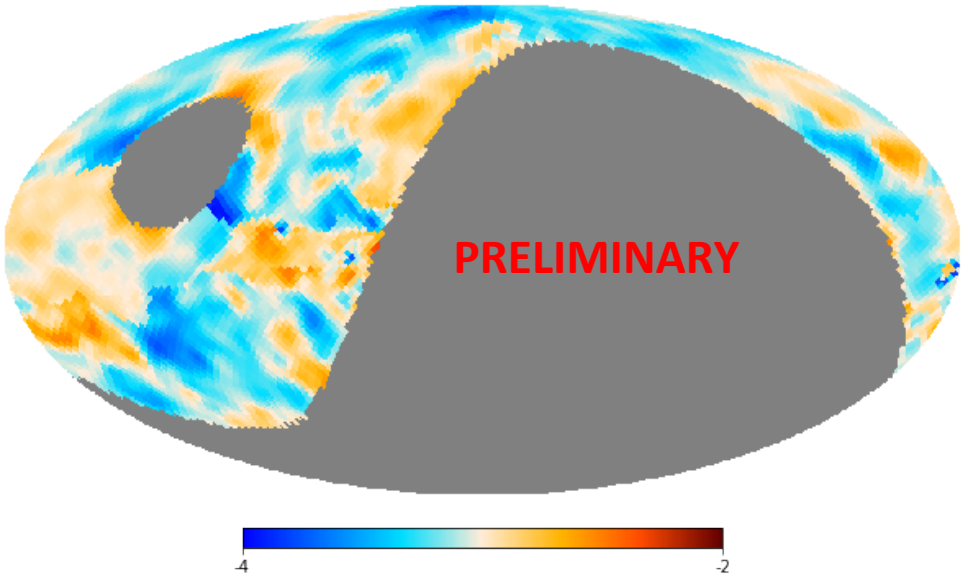
(Vansyngel et al. in prep)



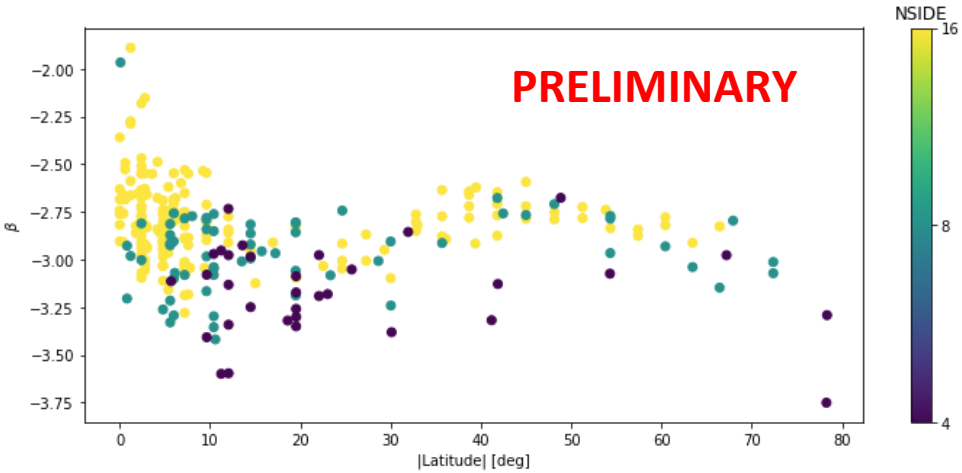


QUIJOTE-MFI wide survey results: component separation

- **Parametric component separation methods** have been tested.
- QUIJOTE-MFI data provide additional information to constrain the synchrotron polarization spectral index from the combination with PLANCK(+WMAP).
- Possibility to explore curvature of the spectral index.
- Preliminary results in polarization.
  - Neural networks (Casaponsa, IFCA). Synchrotron spectral index: -3.08±0.22. → variability on sky
  - Adaptative parametric method FGBuster (Poletti, SISSA). → variability on sky.



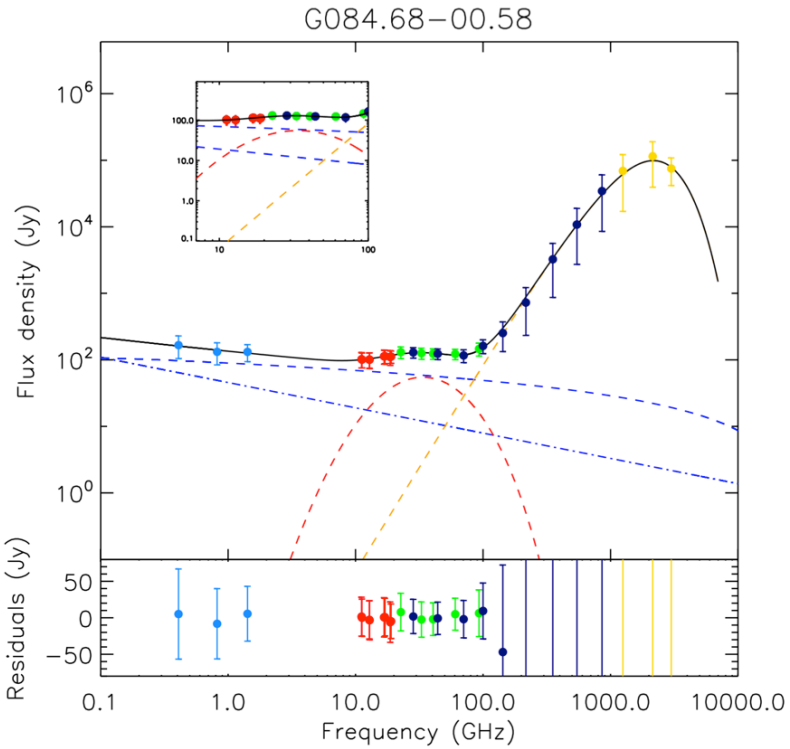
Synchrotron spectral index in polarization, using Quijote 11+13 + Planck (Casaponsa et al.)

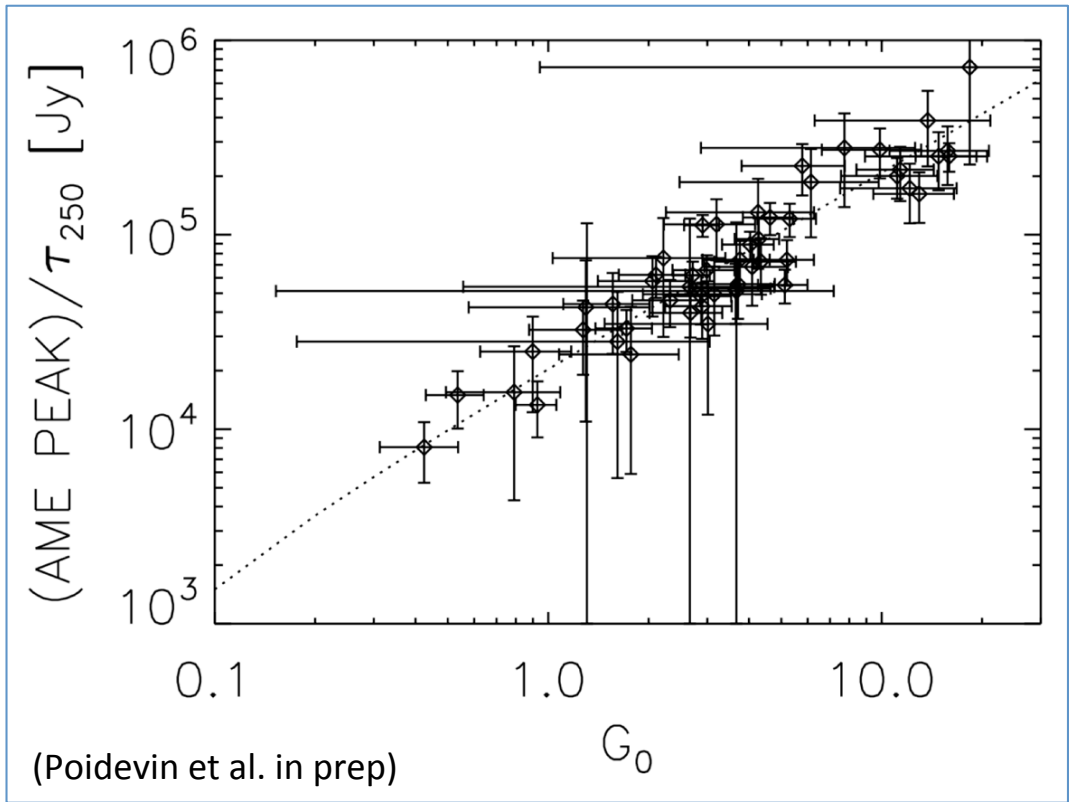


Synchrotron spectral index in polarization as function of galactic Latitude (Poletti et al.)

QUIJOTE-MFI wide survey results: modelling the AME

- Systematic study of 63 AME sources. Includes 51 targets from PIR XV (2014).
- **Intensity**.
  - QUIJOTE-MFI provides a clean separation of the AME, free-free and synchrotron components. Generally, higher AME and lower free-free.
  - New (unexpected) result: clear correlation of AME/tau$_{dust}$ with radiation field G0.
- **Polarization**. Synchrotron component, and upper bounds on AME emission.



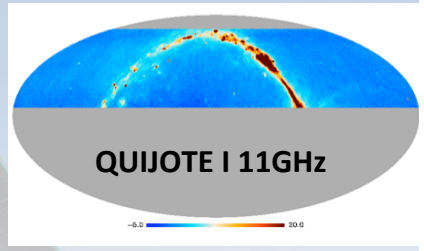


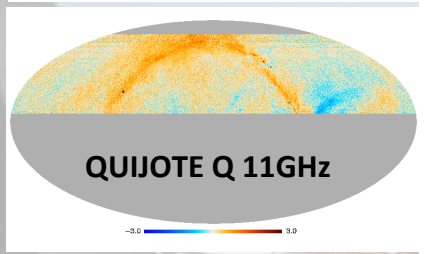
(Poidevin et al. in prep)

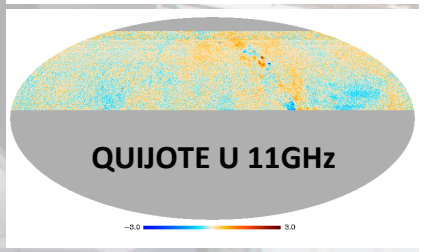
QUIJOTE project: status and plans

MFI (10-20 GHz). In operations since Nov 2012.

- 4 horns, 32 chan, 4 bands: 11, 13, 17, 19 GHz, 400-600 μK $s^{1/2}$ per channel.
- Observations (> 24,000 hrs completed): COSMO fields (> 5,200 h), Wide survey (>10,000 h), galactic fields (Taurus, W49, IC443, W63, FAN, galactic center). Results published in Perseus and W43 (Genova-Santos et al. 2015; 2017). Best upper limit to date on AME pol fraction (0.2%).
- **MFI upgrade (MFI2)**. Funds secured. Cryostat in fabrication. Aim: to increase the speed by at least a factor of 3.
- Extension of QUIJOTE-MFI to Southern hemisphere is being studied.
- **E-CMB.** Plans for full-sky low frequency survey ("super QUIJOTE").

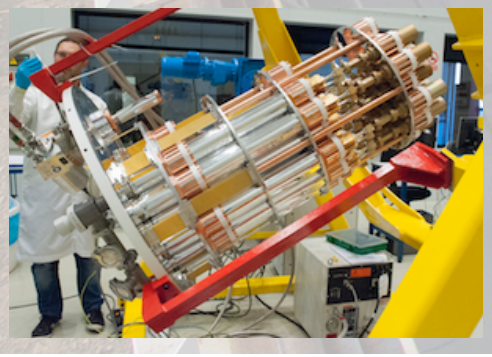


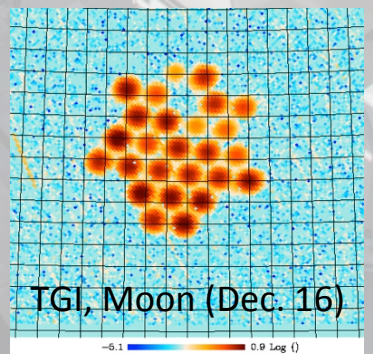


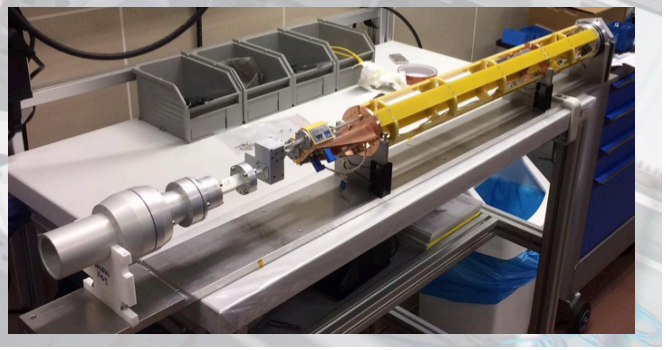


TGI (30 GHz) and FGI (40 GHz)

- All 30 TGI receivers integrated during 2016.
- Commissioning of 27 TGI pixels started early 2017.
- All 30 FGI receivers integrated during 2017.
- 2018**: Joint TGI/FGI operation** in the same cryostat (14/15)
- Observing plan for TGI/FGI science phase: cosmo survey in 3 effective years.

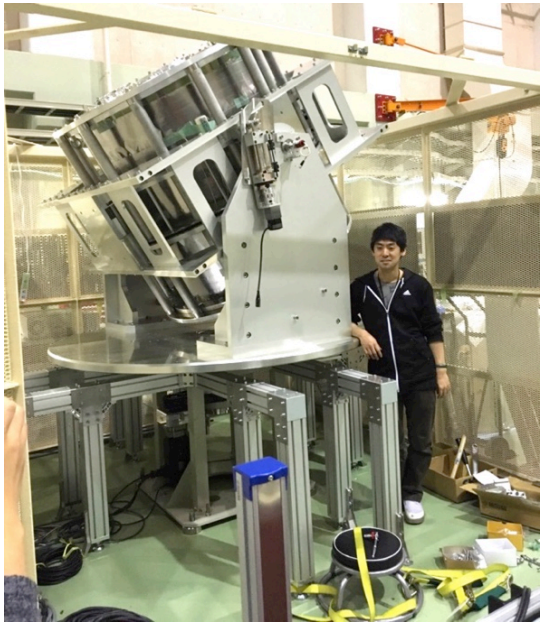


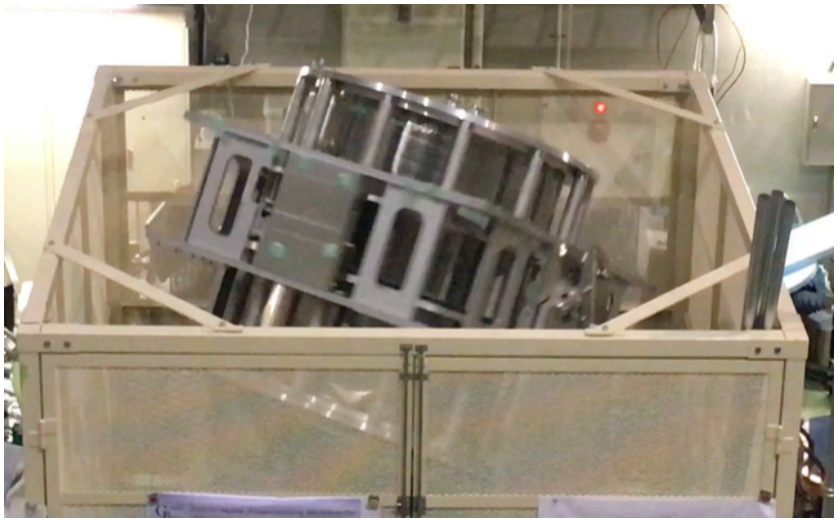

TGI, Moon (Dec. 16)



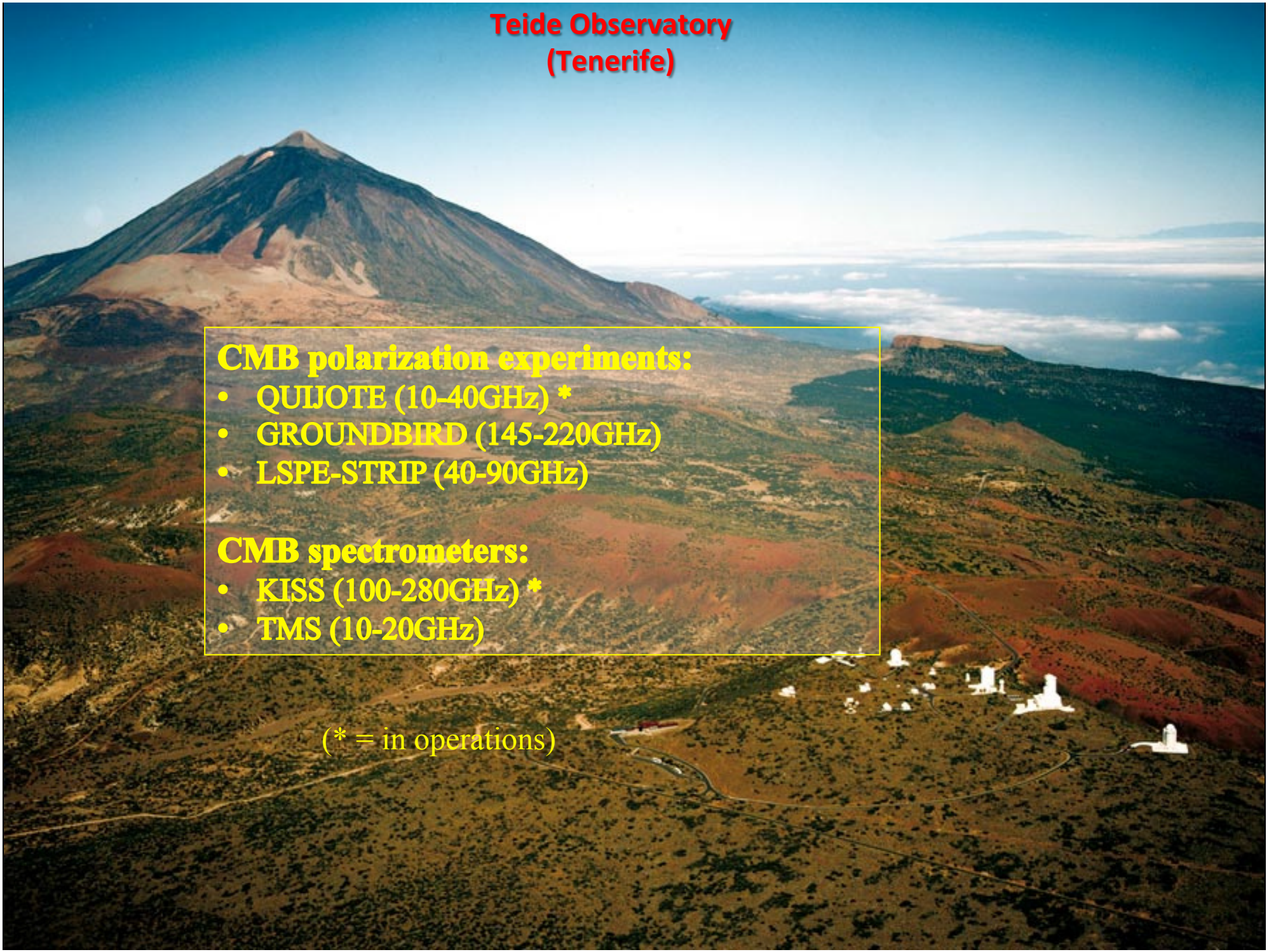
GroundBIRD

- Teide observatory. Former VSA enclosure (next to STRIP). Dome already installed.
- 3-year northern-sky survey, starting this summer (telescope being shipped now – arriving to Tenerife this Friday, 8/Mar/19).
- Large angular scales (fsky=0.5) and coarse angular resolution (FWHM = of 0.6 deg @ 145 GHz), with a 20 deg FOV
- High-speed AZ scans (20 rpm) to reduce the atmospheric noise
- AZ-scans plus Earth rotation provide very large angular scales
- 145 GHz (660 KIDs) and 220 GHz (224 KIDs)
- Expected sensitivity: 300 muK*sqrt(s)/ detector (including the atmosphere).





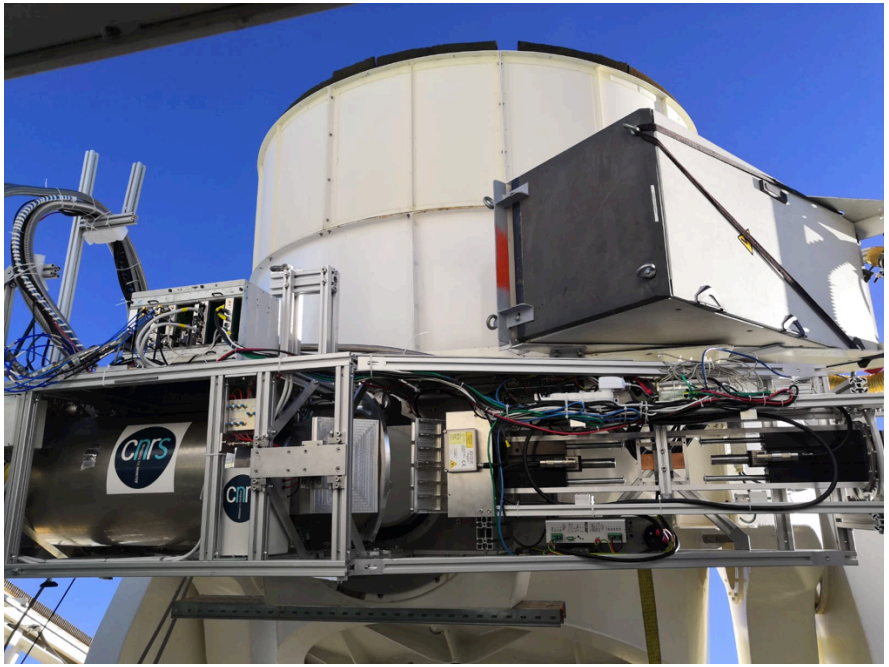
KEK-JAPAN RIKEN KYOTO UNIVERSITY FOUNDED 1897 KYOTO JAPAN NAOJ Saitama University 埼玉大学 東京大学 TOHOKU UNIVERSITY INSTITUTO DE ASTROFISICA DE CANARIAS IAC KOREA UNIVERSITY 1905 TUDelft ibs Institute for Basic Science


Teide Observatory
(Tenerife)
CMB polarization experiments:
• QUIJOTE (10-40GHz) *
• GROUNDBIRD (145-220GHz)
• LSPE-STRIP (40-90GHz)
CMB spectrometers:
• KISS (100-280GHz) *
• TMS (10-20GHz)
(* = in operations)

KISS KID Imager-Spectrometer Survey

Grenoble (Institut Néel, LPSC & IPAG), Tenerife (IAC) & Roma (La Sapienza)

KISS : Low-resolution ($\Delta\nu$ = 1-3 GHz) Martin-Puplett interferometer (MPI) coupled to a KID based camera (80-280 GHz). Visitor instrument mounted at QT-1 telescope (Teide Observatory, Tenerife).



Design

- NIKA camera adapted for KISS optical design.
- Large frequency band (100-300GHz) 600 KID arrays.

Scientific motivation and concept

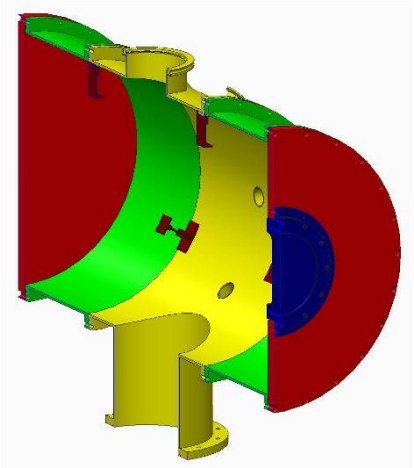
- Low resolution spectroscopy to separate the different components in the millimeter emission of low-z clusters.
- Extract physical properties of the clusters from the SZ signal: total pressure (tSZ), temperature (RtSZ), LOS velocity (kSZ).

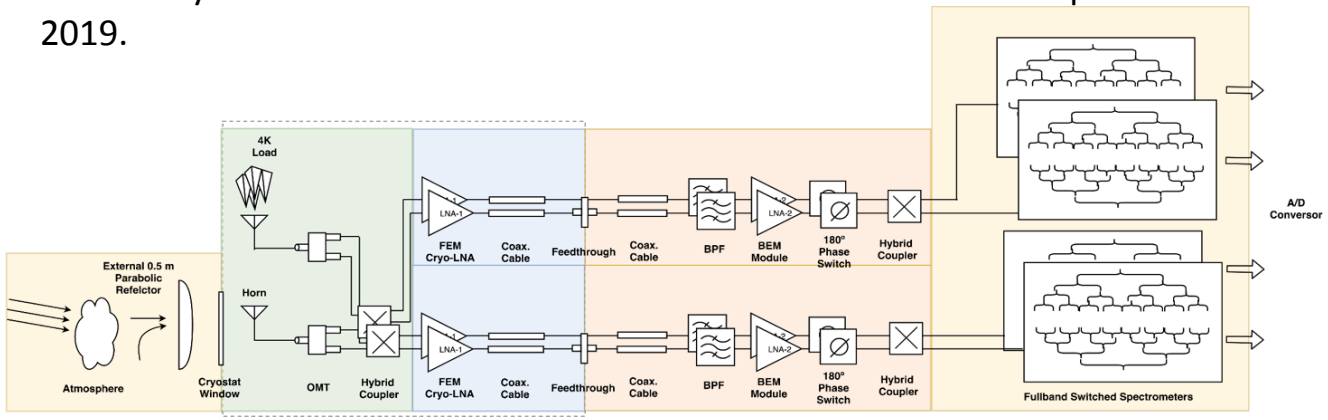
Status

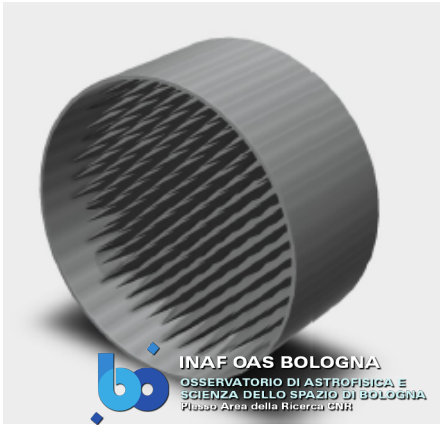
- Installation completed (December-January).
- Now in commissioning phase.

Tenerife Microwave Spectrometer (TMS), 10-20GHz

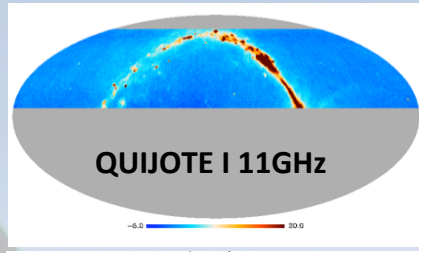
- IAC project. Already funded.
- **Science driver**: Ground-based low resolution spectroscopy observations in the 10-20GHz range to characterize foregrounds (monopole signals; spectral dependence of monopole signals; ARCADE results) and CMB spectral distortions. Provides frequency intercalibration-calibration for QUIJOTE.
- **Proposed instrument**:
  - FEM cooled to 4-10K (HEMTs).
  - Reference load to 4K in collaboration with INAF OAS, Bologna.
  - Novel FTS spectrometer providing √N increase in sensitivity with wideband simultaneous adquisition.
  - ~2deg beam, 0.25 GHz spectral resolution (40 bands).
- **Location**: Teide Observatory (former VSA enclosure). Independent pedestal (copy of a QUIJOTE telescope). Full sky dome.
- **Status**: cryostat and cold structure will be received at the IAC in April 2019.

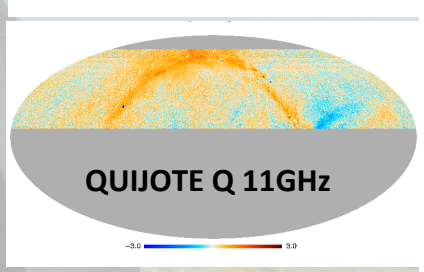


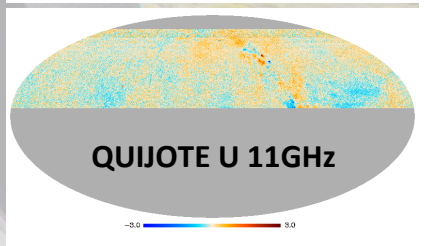




Conclusions







- **QUIJOTE-MFI** maps (11, 13, 17, 19 GHz) provide valuable and complementary information to PLANCK data, allowing to characterize the low frequency foregrounds (RADIOFOREGROUNDS).
- **QUIJOTE-MFI** helps to properly separate **the AME component** in intensity. This opens the possibility to explore the physical properties of the emission (e.g. peak frequencies, specific intensity), and also to study the polarization emission of the AME signal. In particular, we provide the best upper limit to date on the pol fraction (<0.2%).
- **QUIJOTE-MFI** also helps in the separation and characterization of the **synchrotron polarised emission**. The average spectral index is found to be ~-3.00, but it shows significant spatial variations. Same for the dust-synchrotron correlation.
- **CMB polarization experiments from the Teide Observatory**: QUIJOTE, LSPE-STRIP and Groundbird. Same sky area (>20% sky, unique in Northern sky!). Ten frequencies from 10 to 240 GHz. Redundancy, cross-correlation.
- **CMB spectroscopy**. KISS, TMS. An important niche to be further explored.
- **Lessons learned for future European CMB collaborations:**
  - Very positive experience of RADIOFOREGROUNDS.
  - Build on current and successful collaborations at Teide Observatory for future plans →European Low Frequency Survey.