QUIJOTE: status and future plans

José Alberto Rubiño-Martín (IAC), on behalf of the QUIJOTE Collaboration

B-modes from Space
MPA, 16-19 December 2019

The QUIJOTE Collaboration

(http://research.iac.es/project/cmb/quijote)

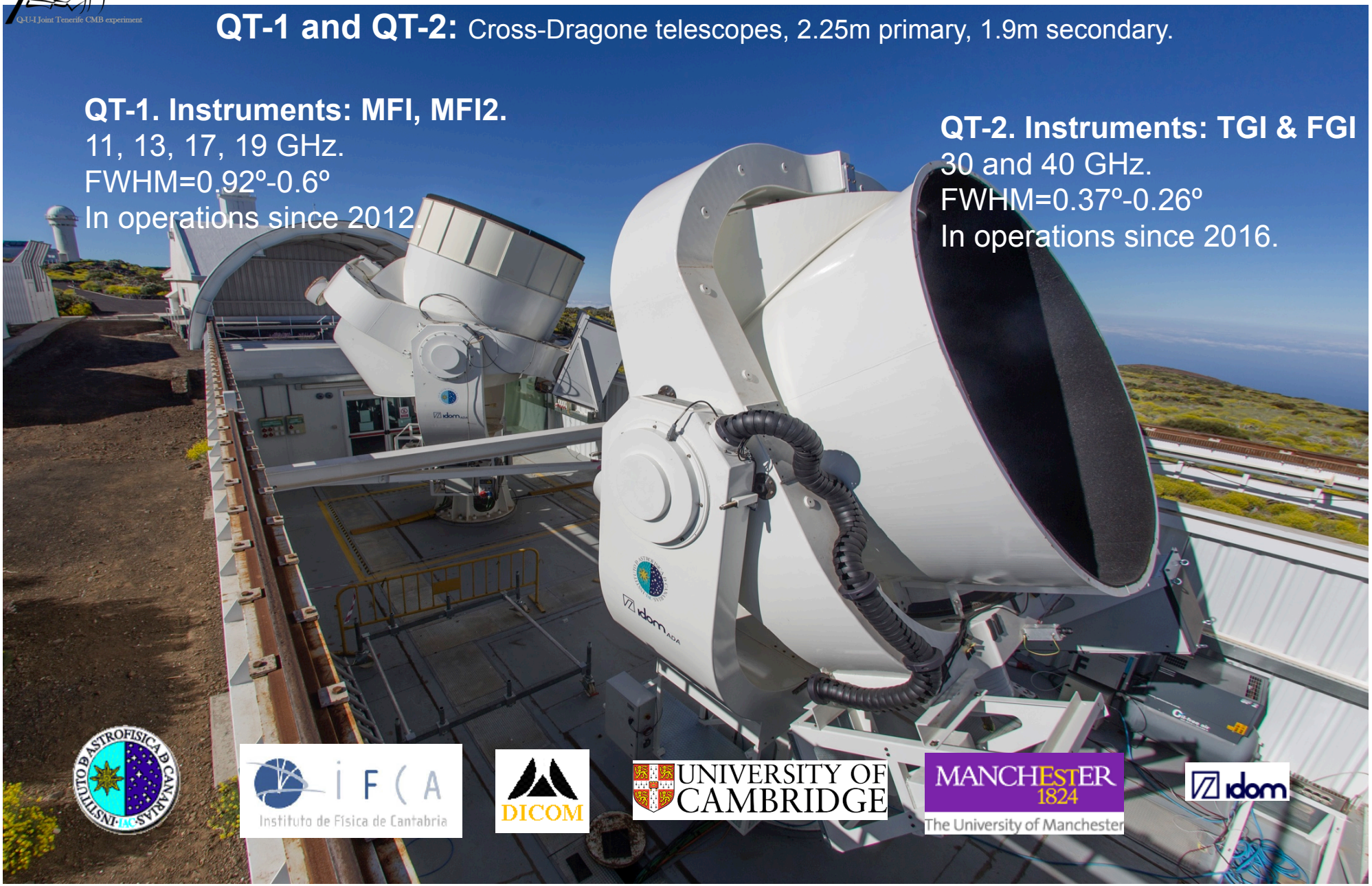
The QUIJOTE experiment

Q-U-I Joint Tenerife CMB experiment

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

QT-1. Instruments: MFI, MFI2.
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 ASTROFISICA DE CANARIAS · IAC

IFCA Instituto de Física de Cantabria

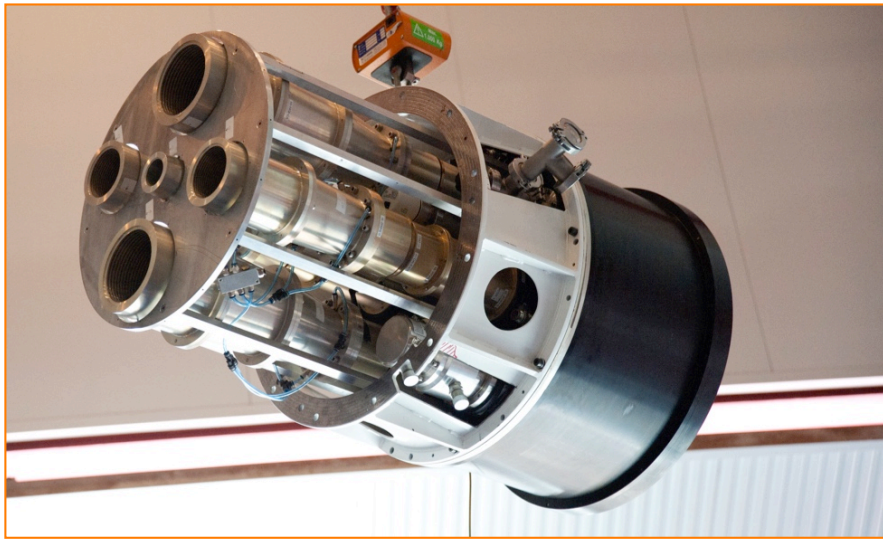
DICOM

UNIVERSITY OF CAMBRIDGE

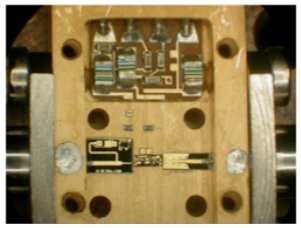
MANCHESTER 1824 The University of Manchester

idom

MFI Instrument (10-20 GHz)

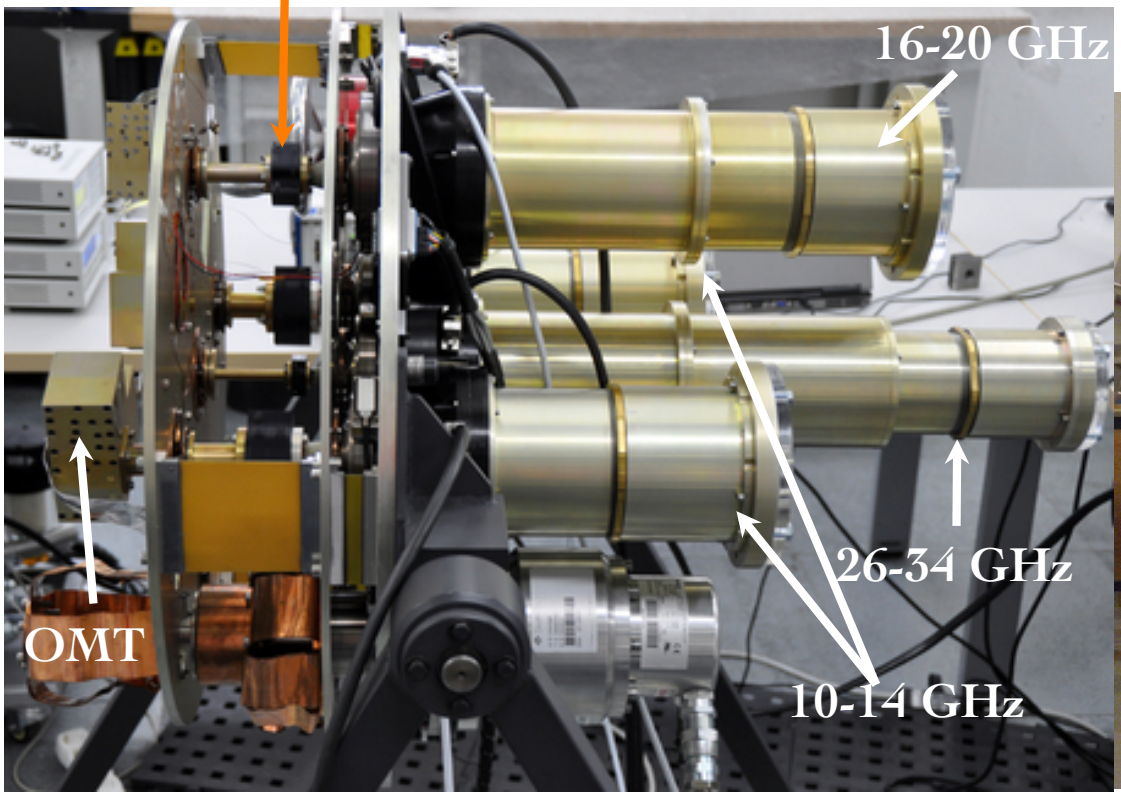


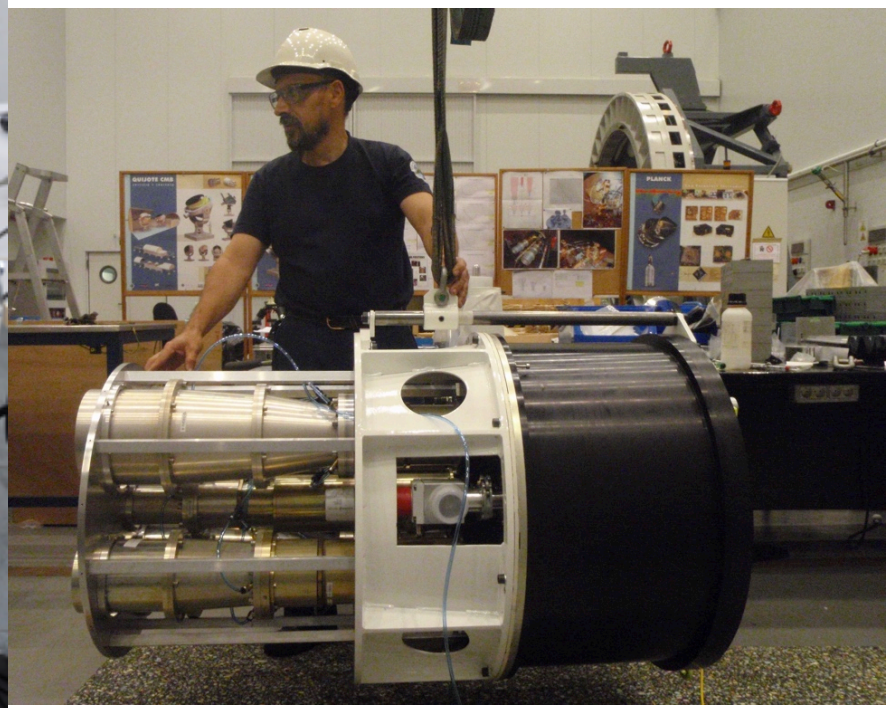
- **Operations**: Nov. 2012 – Dec. 2018.
- 4 horns, 32 channels. Covering 4 frequency bands: 11, 13, 17 and 19 GHz.
- **Sensitivities**: ~400-600 μK $s^{1/2}$ per channel.



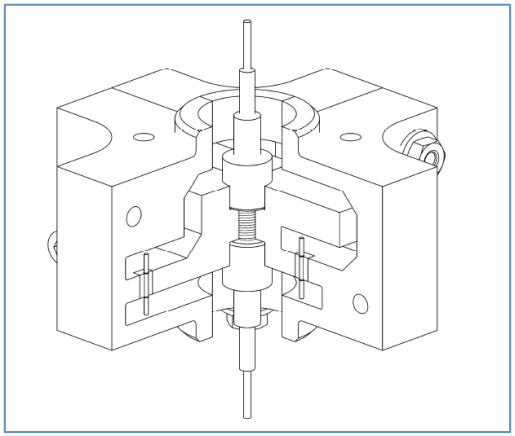
LNA

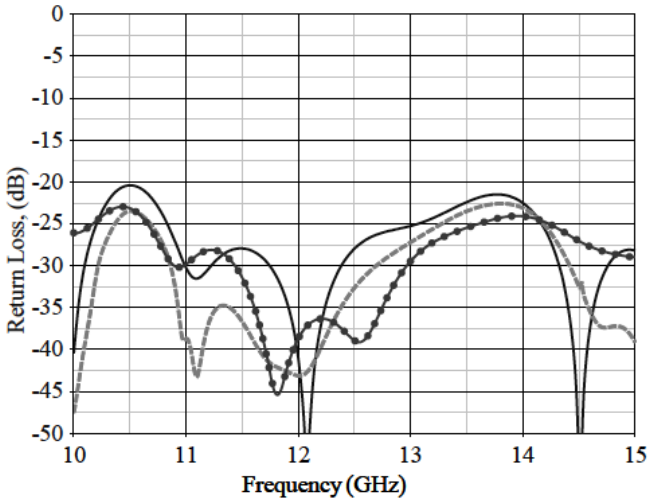
Polar Modulators

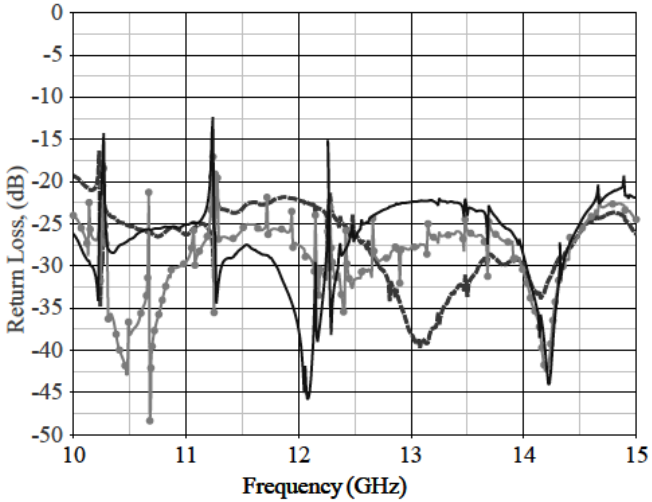


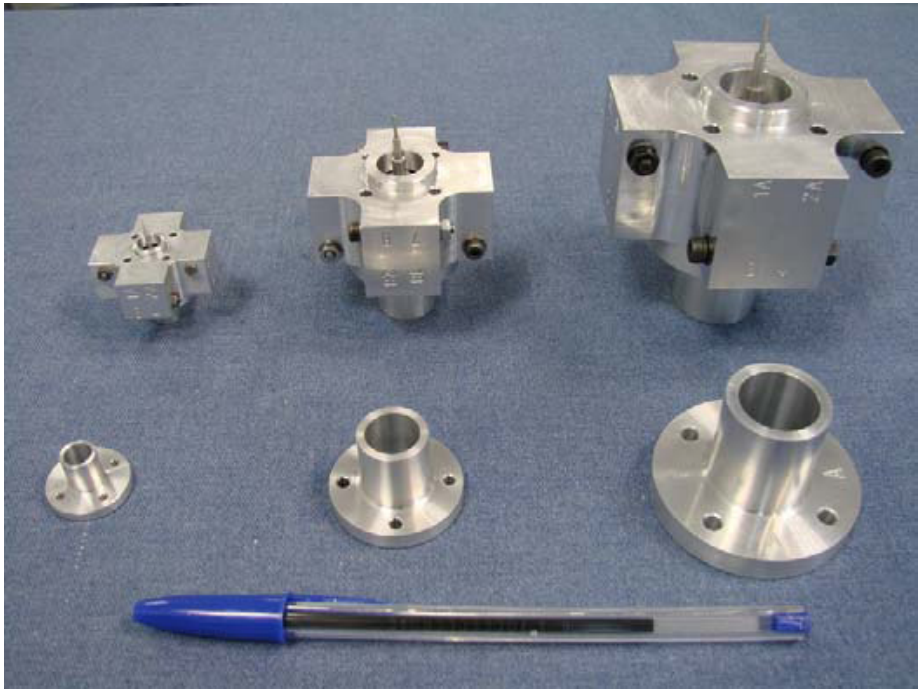


MFI Instrument (10-20 GHz). Polar modulator.

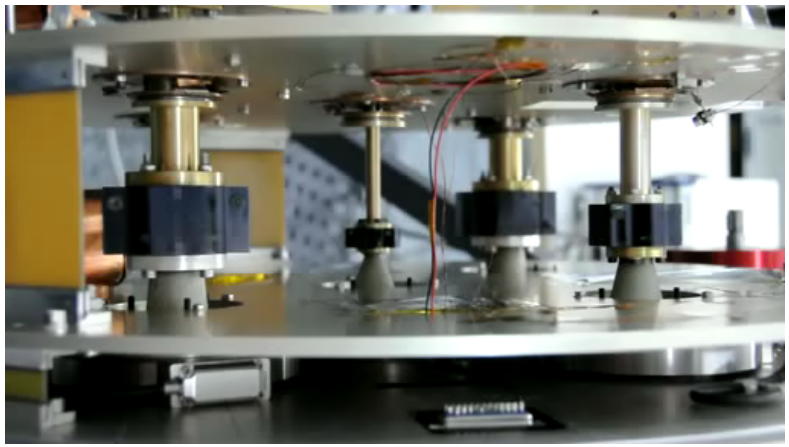








"HWP": a polar modulator based on a turnstile junction, in waveguide. Advantages: broad band, cooled down in the criostat, and high performance (Return Losses < -20dB, insertion losses < -0.15dB, isolation < -40 dB) .



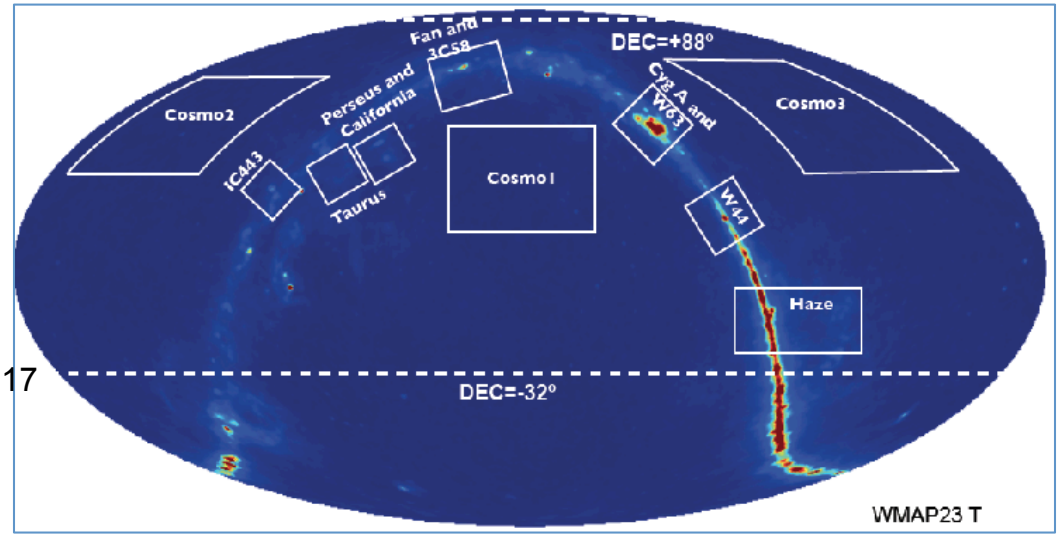
Science with QUIJOTE first instrument (MFI)

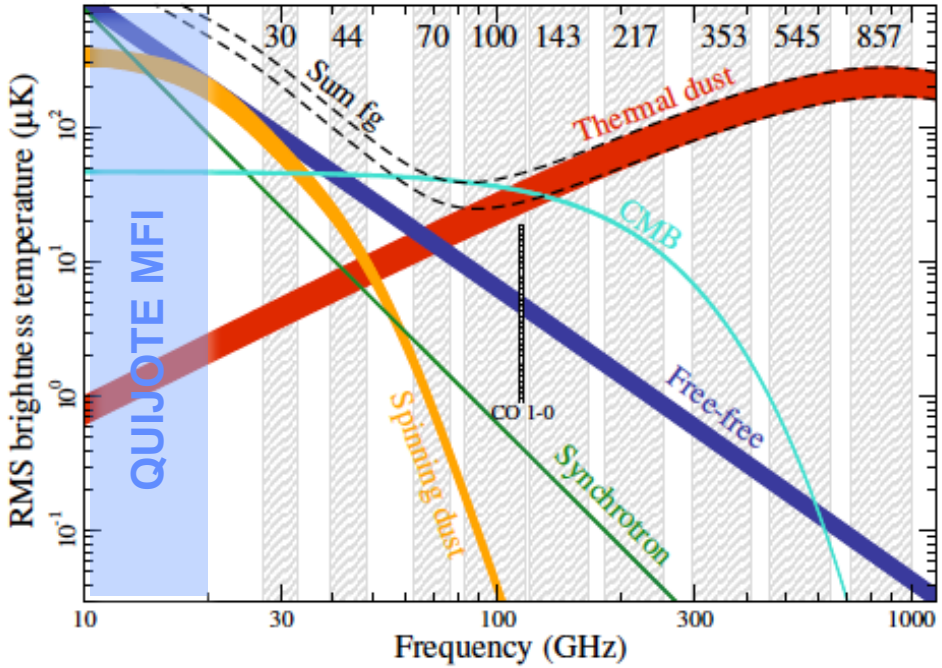
Excellent complement to PLANCK at low frequencies. Legacy for future experiments (→Litebird)

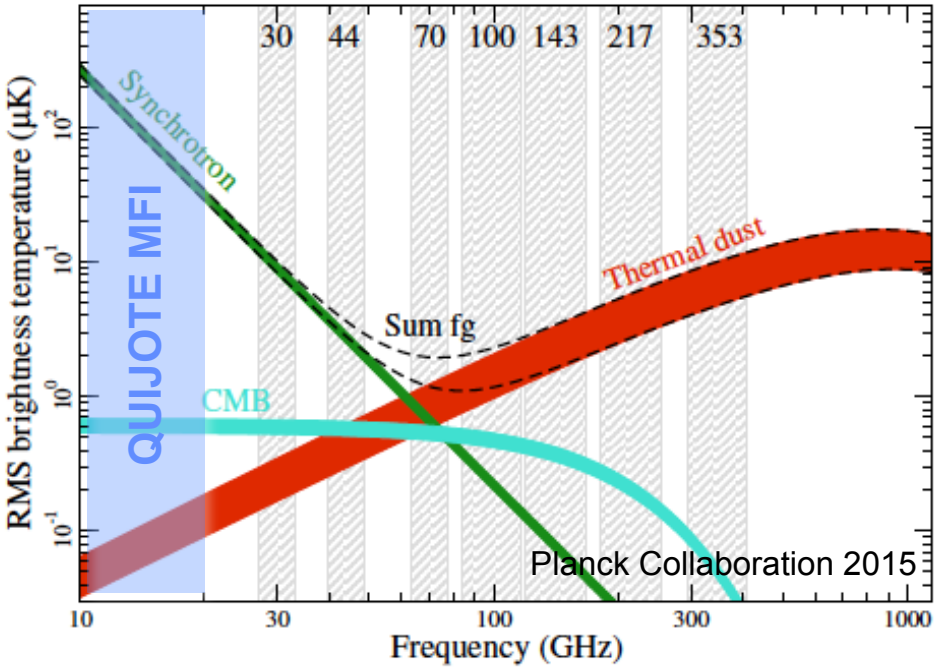
MFI Science phase

- 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) → Genova-Santos+15
- Fan region and 3C58 (460h)
- Taurus region (450h) → Poidevin+19
- SNRs (W44, W47, IC443, W63) (900h) →Genova-Santos+17

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



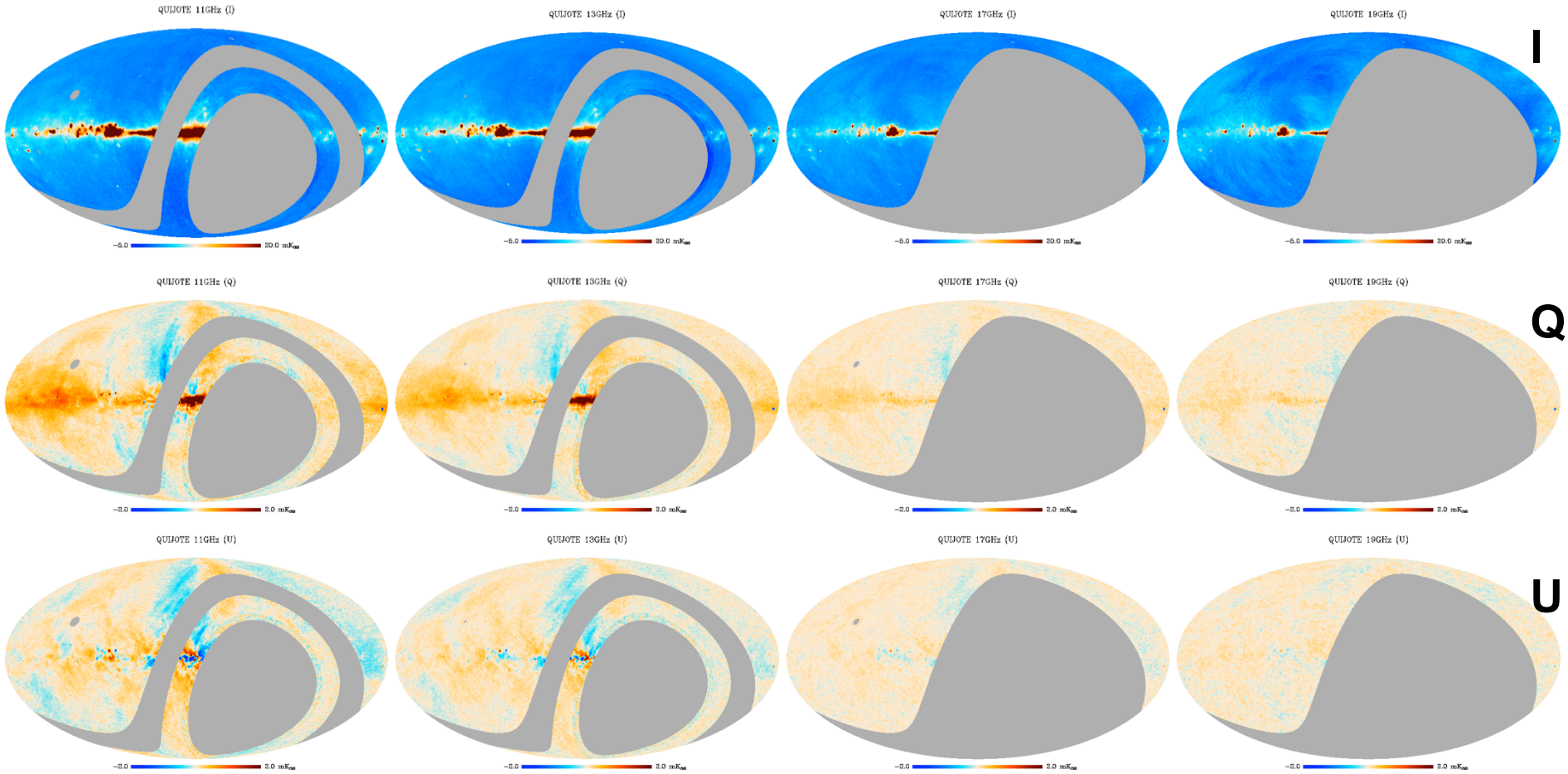




Wide survey with the QUIJOTE MFI (10-20 GHz)

Preliminary maps

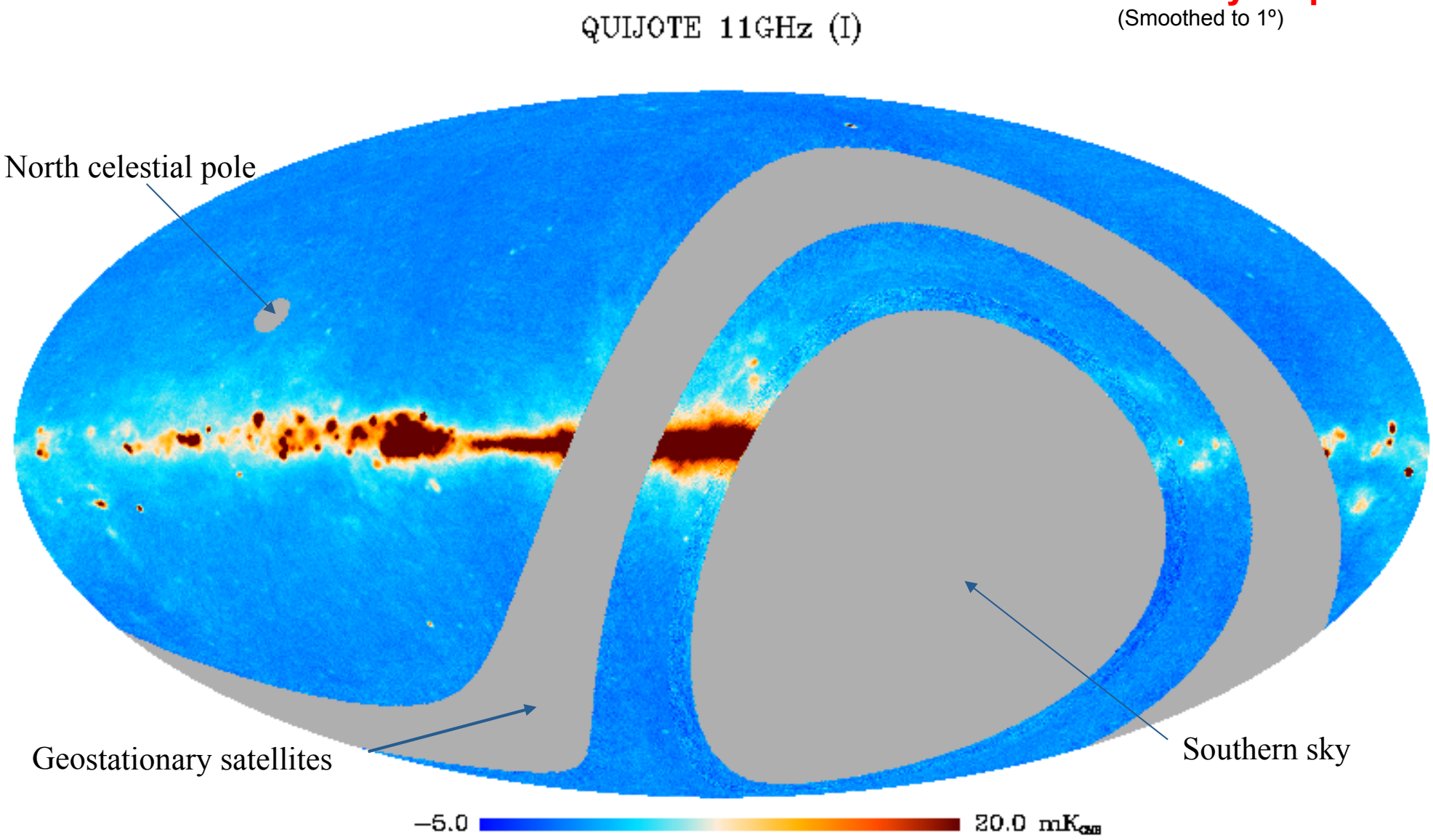
(Smoothed to 1º)



Scans at constant elevation (12deg/s). Sensitivities in polarization (Q,U): ~40 μK/deg.

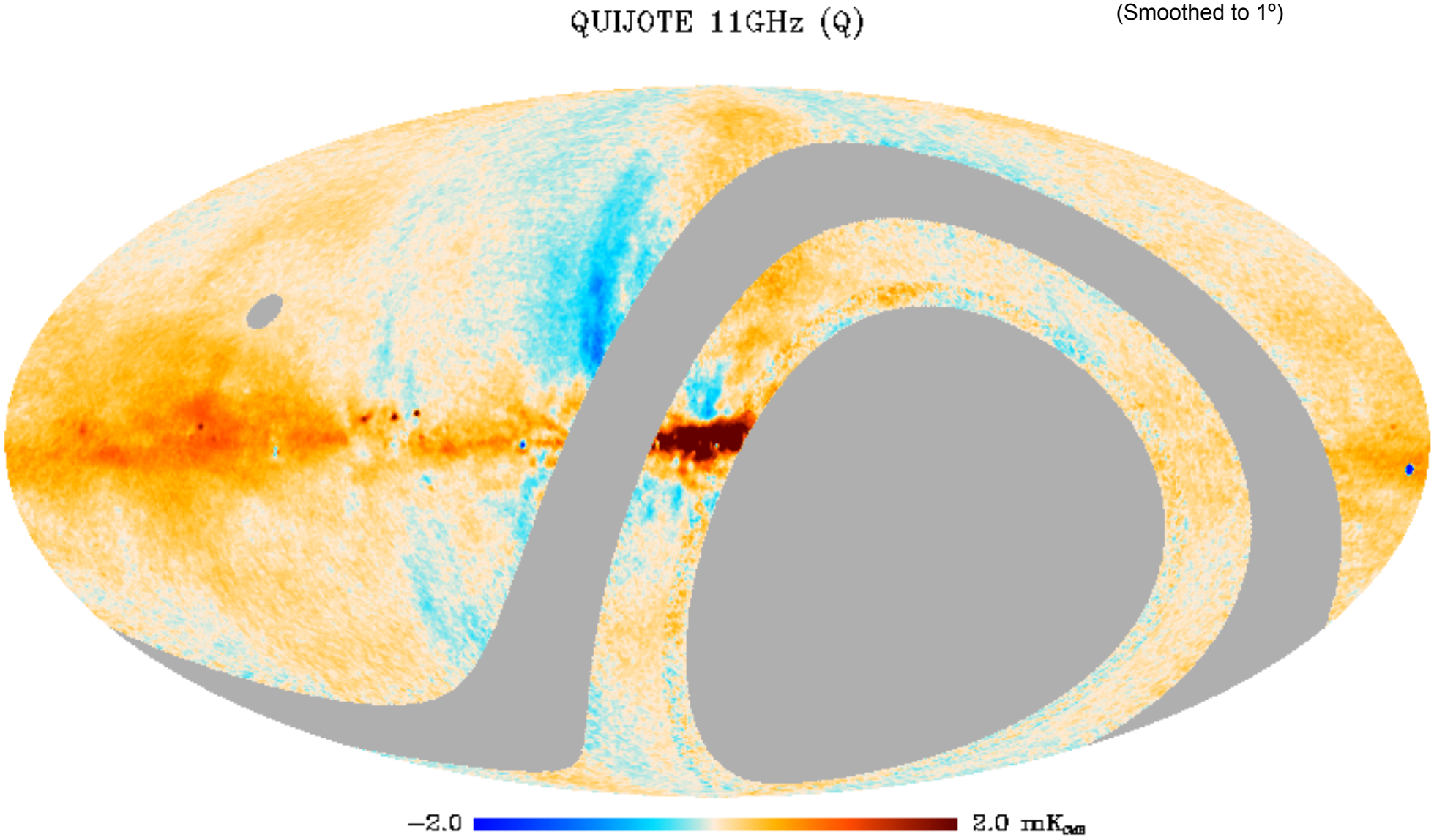
Wide survey with the QUIJOTE MFI (10-20 GHz)

Preliminary maps
(Smoothed to 1º)

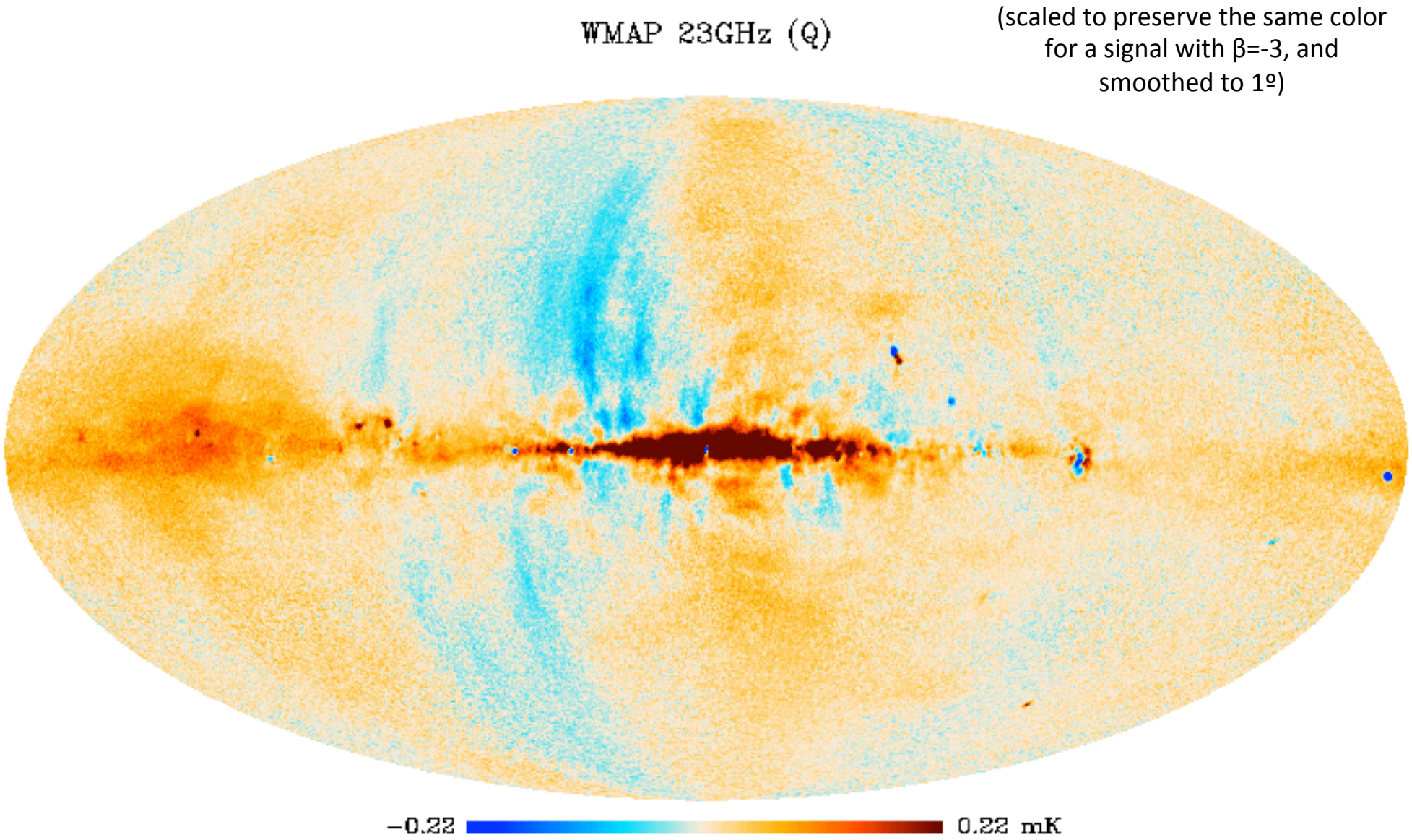


Wide survey with the QUIJOTE MFI (10-20 GHz)

Preliminary maps
(Smoothed to 1º)



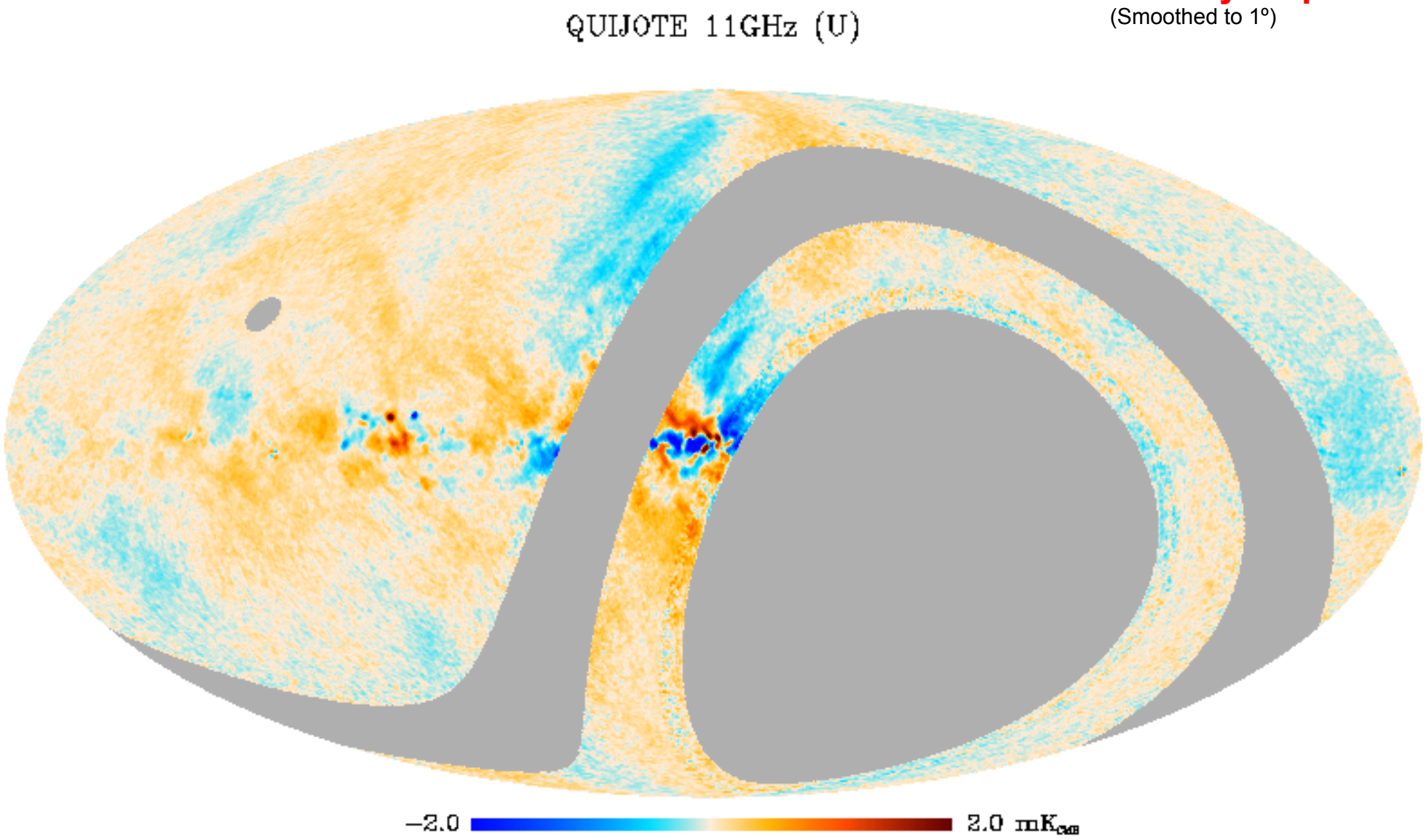
Wide survey with the QUIJOTE MFI (10-20 GHz)



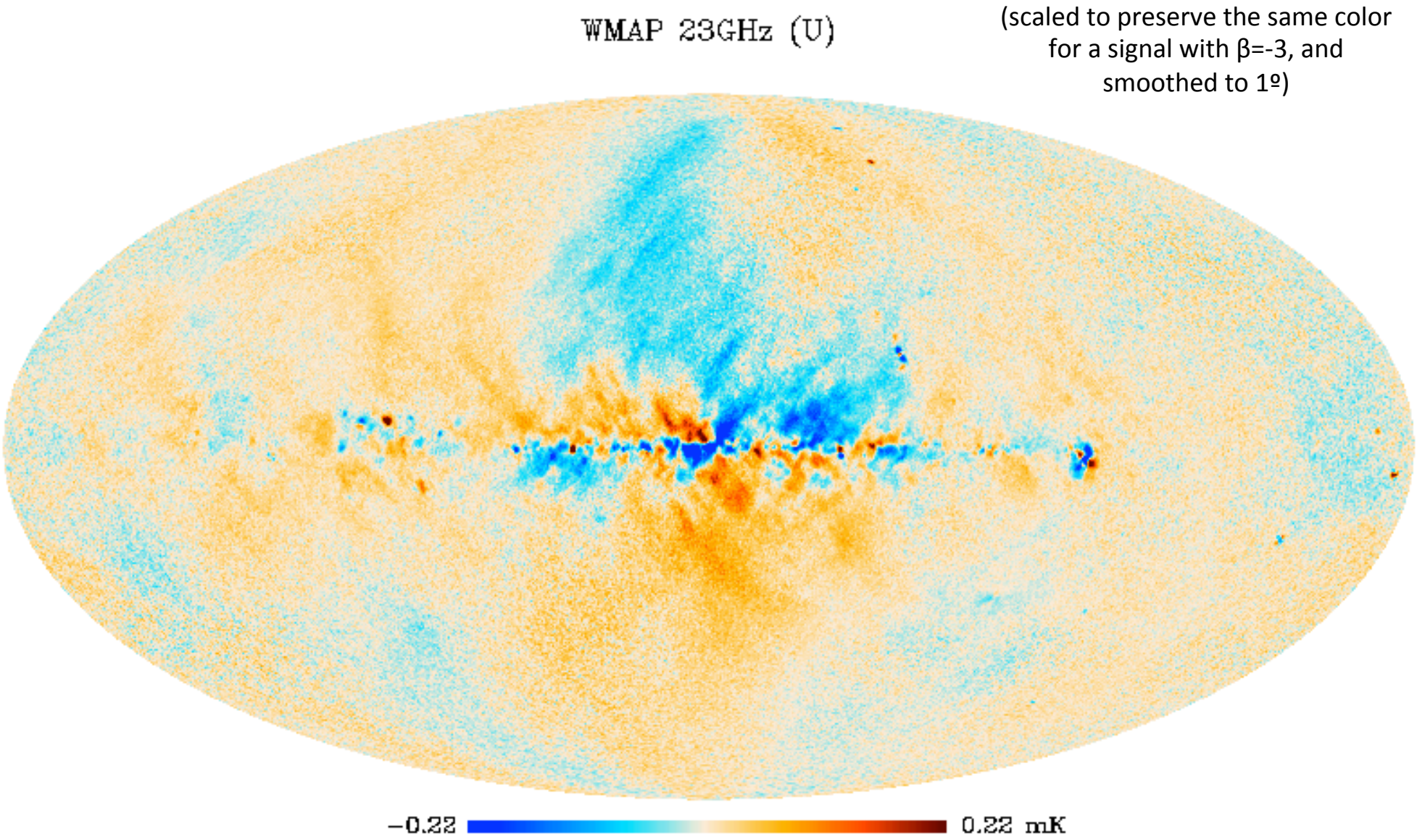
(scaled to preserve the same color for a signal with β=-3, and smoothed to 1º)

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

Preliminary maps
(Smoothed to 1º)



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



(scaled to preserve the same color for a signal with β=-3, and smoothed to 1º)

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

Recent progress:

- **Beam and window function.**
  - Improved description of the full beam, based on simulations. Verified on maps (radial profile of point sources).

- **Transfer function at low multipoles**
  - Characterising the recovery of the sky signal at l<20 using simulations. Main effect: mode at constant declination due to scanning strategy.

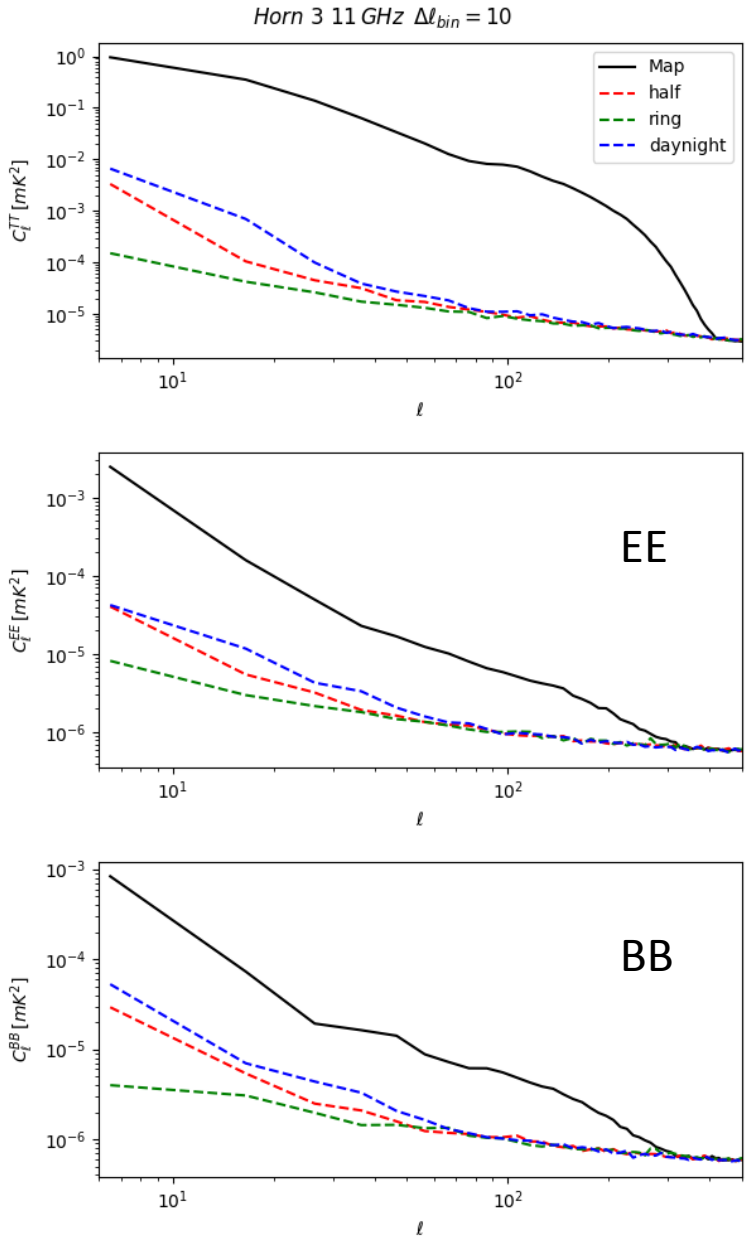
- **Null tests** (periods, horns, half data, …).

- **Calibration** (amplitude).
  - **Overall calibration scale set from point sources** on the final maps (Cass-A, Crab, Cygnus-A, based on models from Weiland et al. 2011). Also using TT-plot analysis of free-free dominated regions (Cygnus area). Error: 3%.
  - **Test 1: CMB signal (l in [30,200]).** CMB detected via cross-correlation QUIJOTE x Planck (SMICA). **11GHz**: 1.03±0.09, **13GHz**: 1.06±0.07.
  - **Test 2: CMB dipole.** Dipole signal detected via direct measurement and also with cross-correlations. Error: 10%. **11GHz**: 0.91±0.10, **13GHz**: 0.95±0.12.

- **Calibration (polarization angle). Error: 0.3º.** Faraday rotation only seen in bright regions in the plane. Excluding those, the stdv diff between 11GHz and LFI30 is ~1º.

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

Recent progress:



Examples of null-tests at 11GHz

- Half data
- Ring (odd-even)
- Daynight (correlated with pwv content)

EE @ 11GHz is signal dominated (ΔI=10) for:

- l<300 on full sky.
- l<150 for |b|> 10º

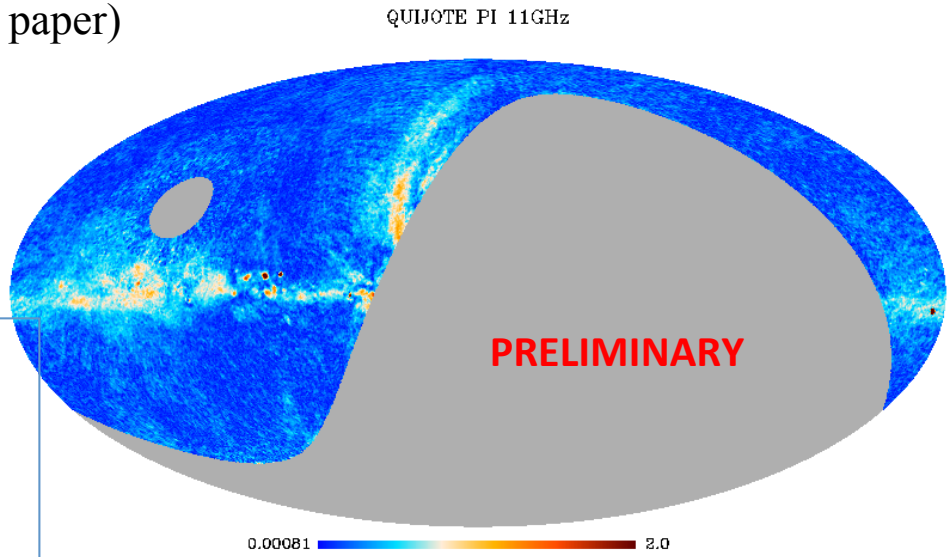
Wide survey with the QUIJOTE MFI (10-20GHz)

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

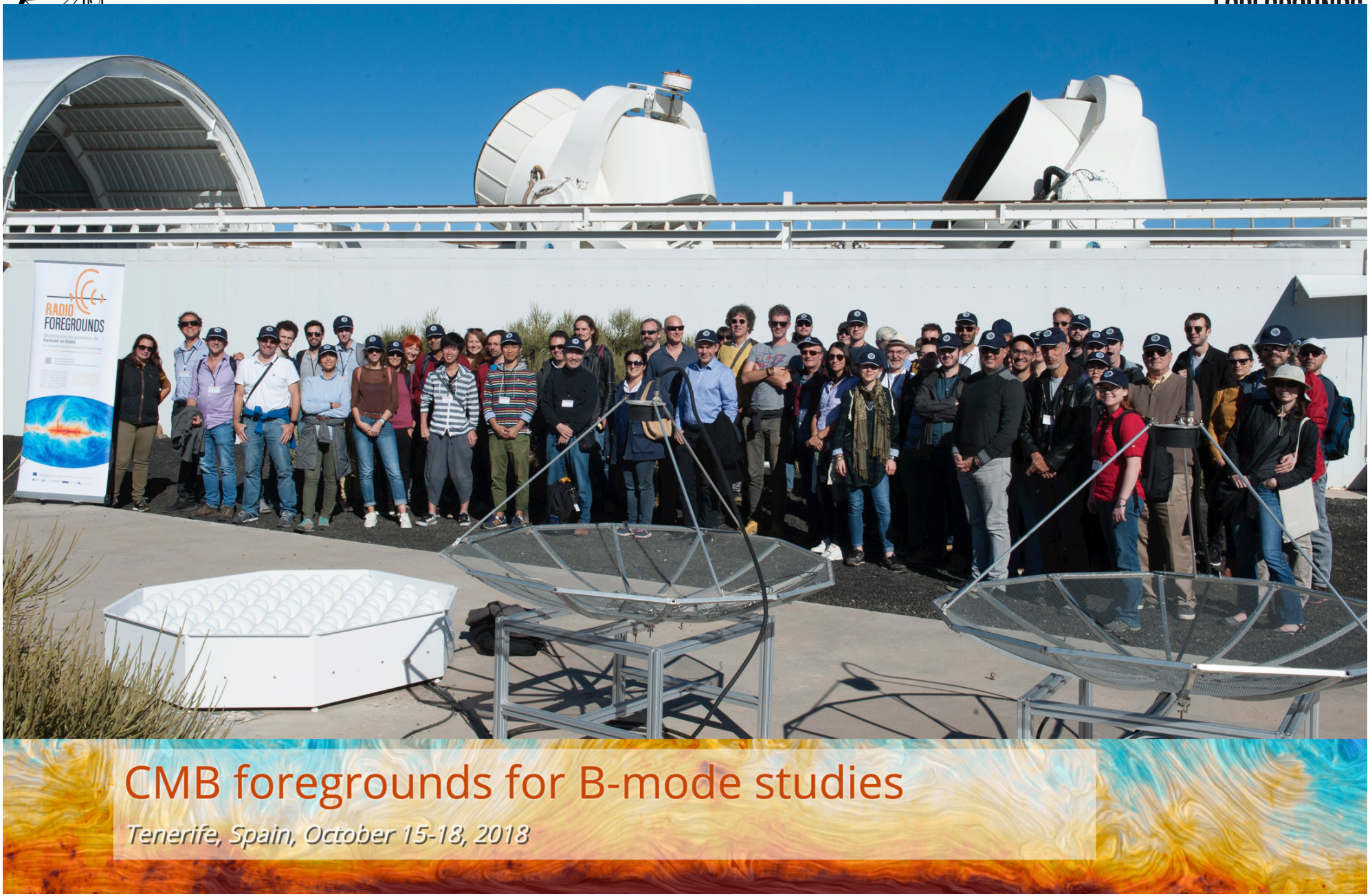
I. A northern sky survey at 10-20GHz with the Multi-Frequency Instrument.
II. Galactic AME sources in the MFI wide survey.
III. Analysis of the polarised synchrotron emission at the power spectrum level in the MFI wide survey.
IV. The FAN region as seen by QUIJOTE-MFI
V. The North Galactic Spur as seen 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.
X. AME Lambda Orionis (Joint QUIJOTE-CBASS paper)
XI. The Haze region as seen by QUIJOTE-MFI.

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://research.iac.es/congreso/cmbforegrounds18/

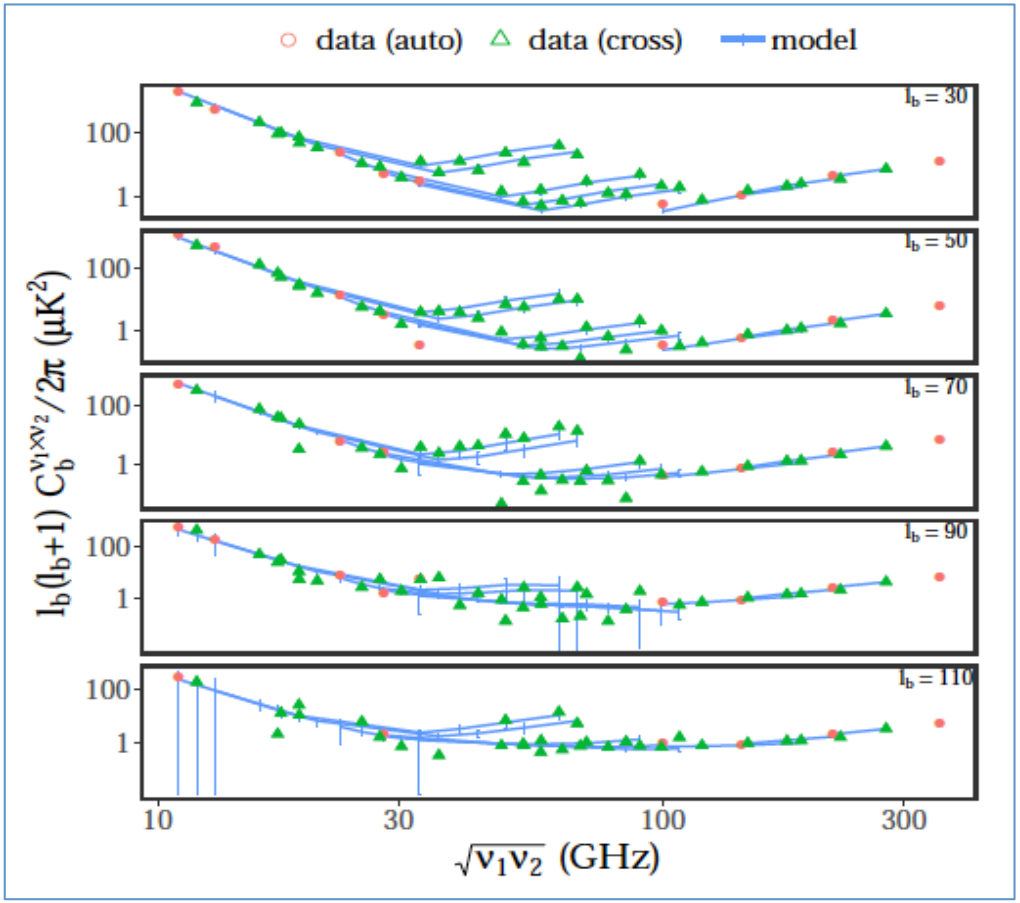


Wide survey with the QUIJOTE MFI (10-20GHz)



QUIJOTE-MFI wide survey results: synchrotron polarization

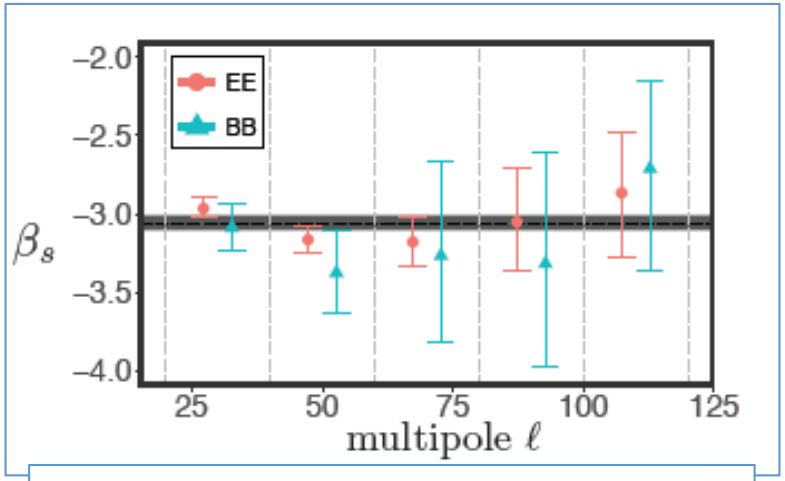
- Auto- and cross-spectra of QUIJOTE, WMAP, PLANCK maps in northern sky (|b|>10º).
- Pol. Synchrotron spectral index: -3.00±0.05. [**Planck**: -3.13±0.13**, S-PASS**: -3.22±0.08].
- Dust-synchrotron correlation: ~ 0.20±0.06.
- Variability on sky (compared to other results: Planck Col. XI 2018, Krachmalnikoff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

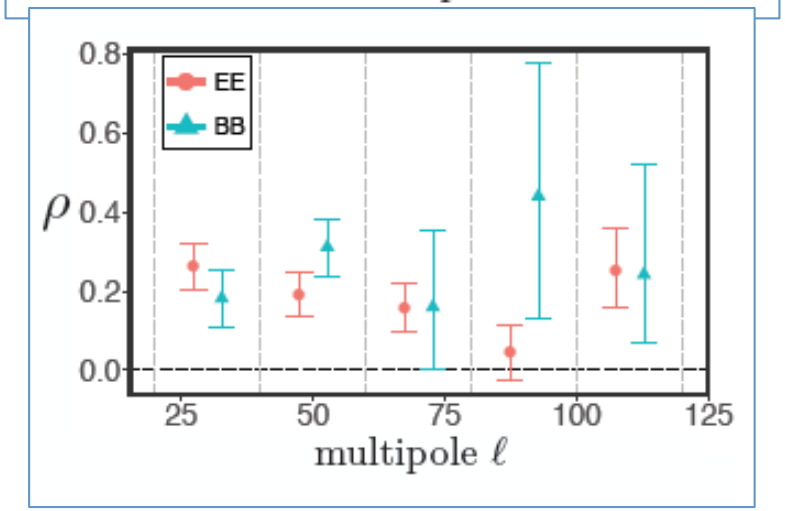


(Vansyngel et al. in prep)

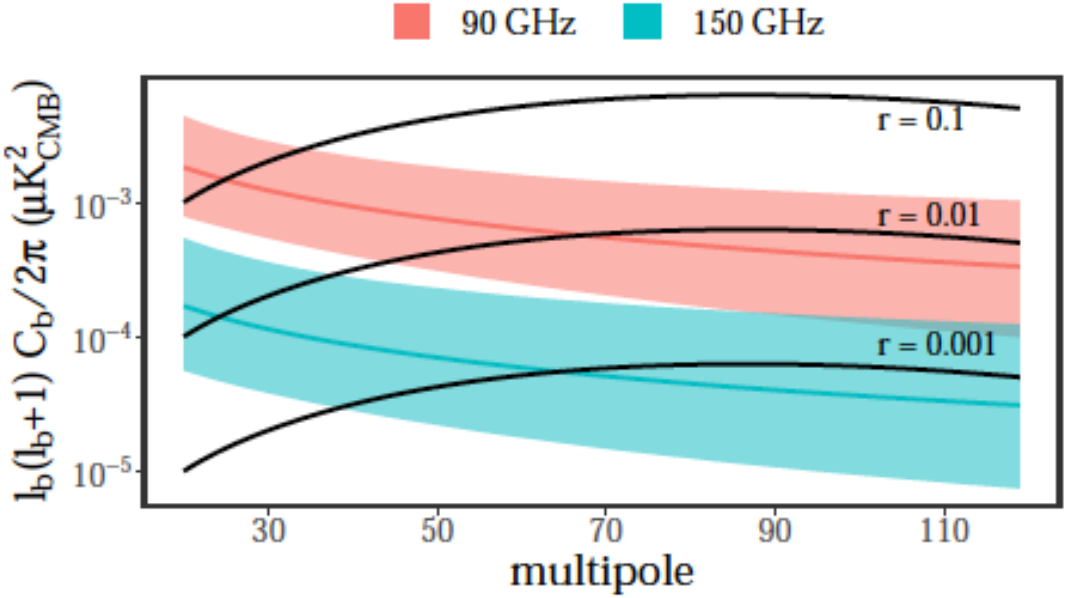
QUIJOTE-MFI wide survey results: synchrotron polarization

- 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).





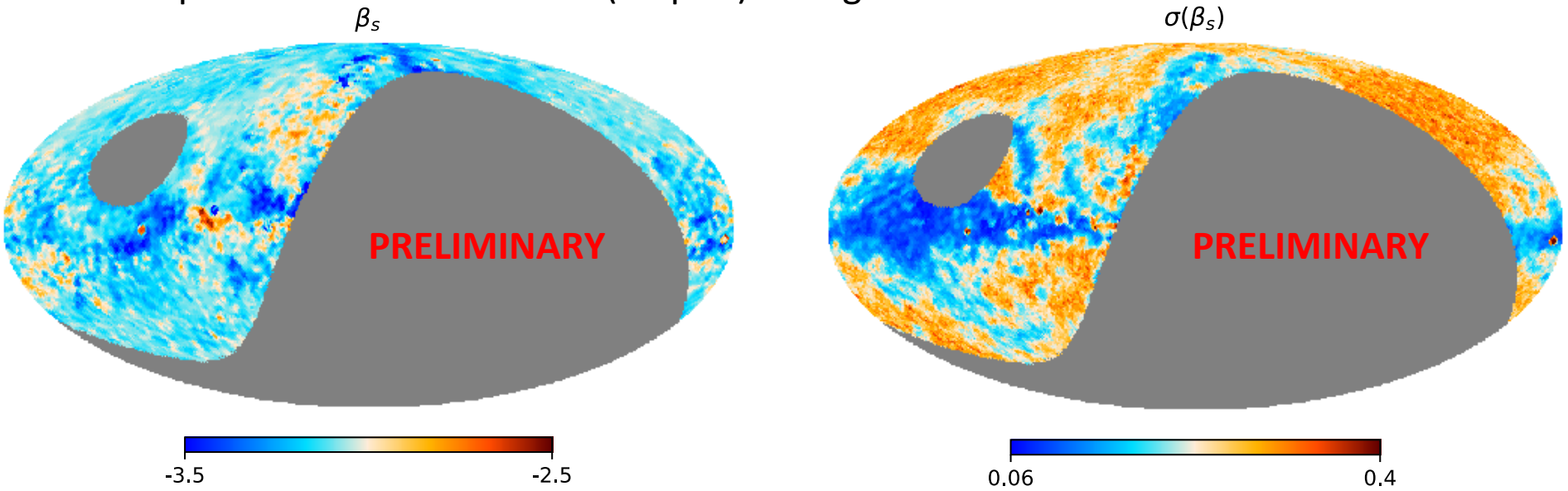
Contamination of the CMB at 90 and 150GHz by the synchrotron B-modes. Regions at 95% C.L. :



(Vansyngel et al. in prep)

QUIJOTE-MFI wide survey results: component separation

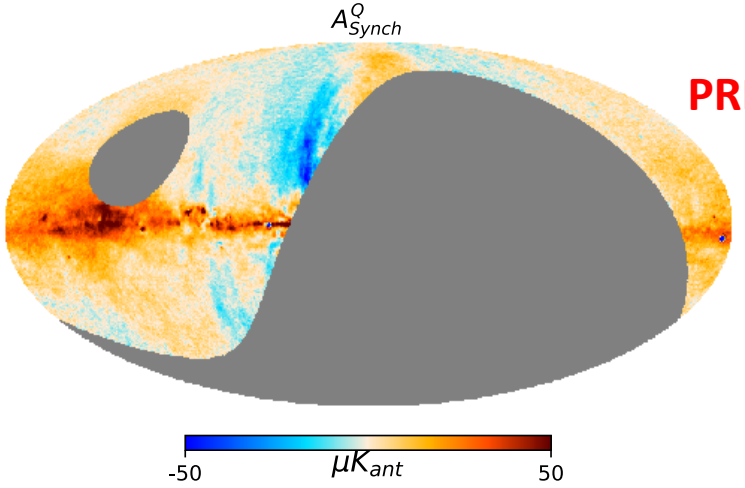
- **Parametric component separation methods** tested and used.
- QUIJOTE-MFI data provide additional information to constrain the synchrotron polarization spectral index from the combination with PLANCK(+WMAP).
- **Possibility to explore curvature of the spectral index.**
- **Results in polarization** (preliminary).
  - Neural networks (Casaponsa, IFCA). Synchrotron spectral index: -3.14±0.10 (full sky) → variability on sky
  - Adaptative parametric method FGBuster (Poletti, SISSA). → variability on sky.
  - Comparison with correlations (TT-plot) in large areas.



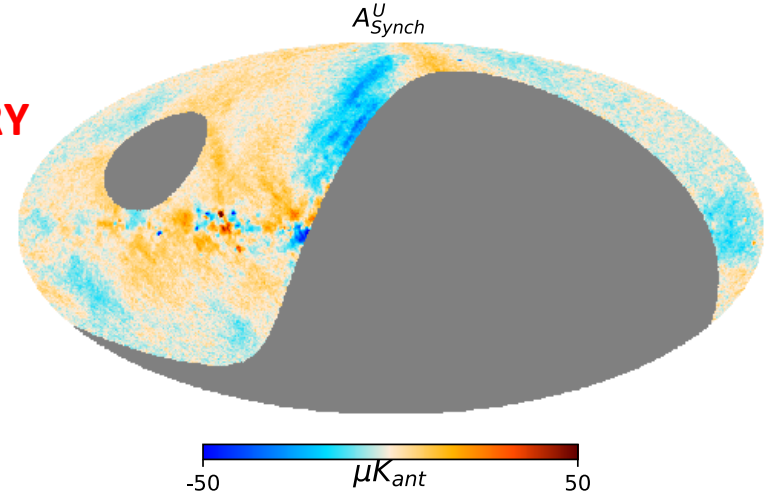
Synchrotron spectral index in polarization, using Quijote 11+13 + Planck (Casaponsa et al.)

QUIJOTE-MFI wide survey results: component separation (II)

- **Neural networks**. Recovered synchrotron amplitude at 30GHz



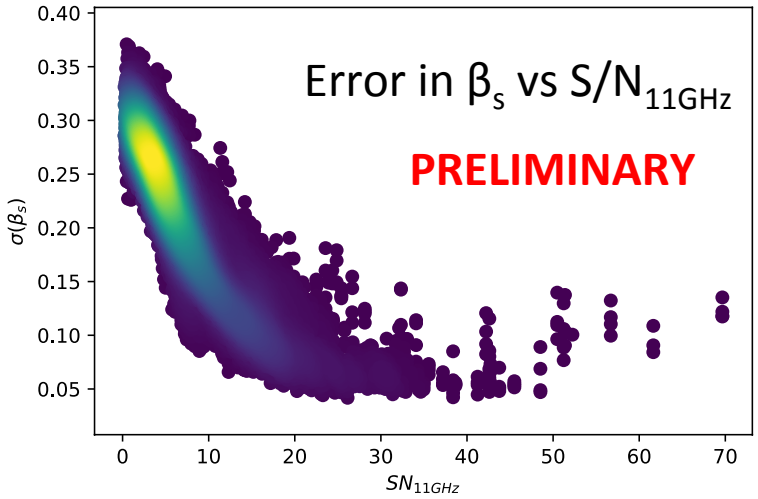
PRELIMINARY



(Casaponsa et al. in prep)

Correlation between input and output from simulations:

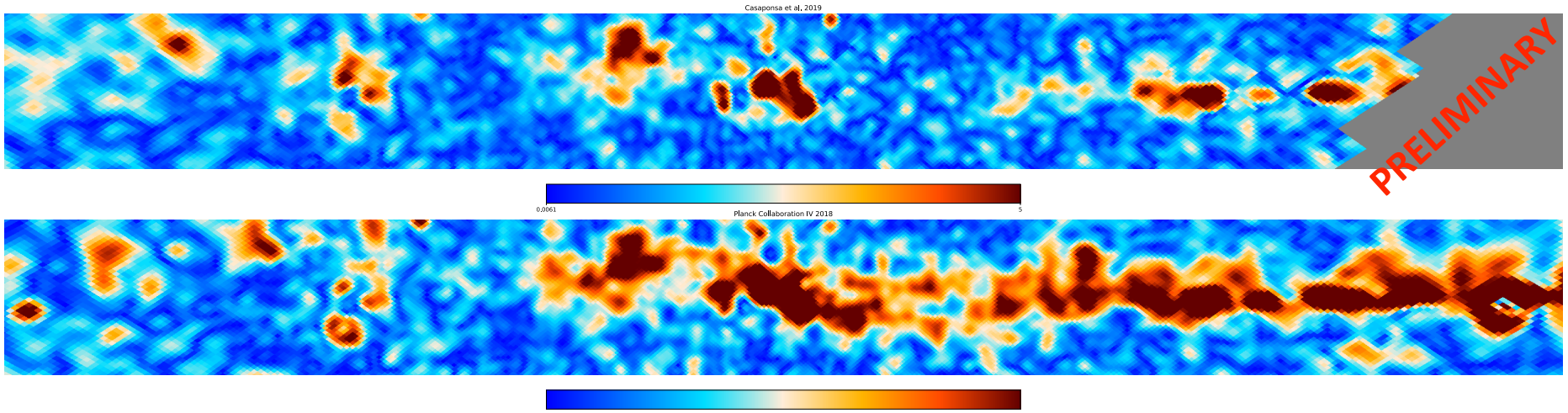
Component	Planck	Planck + QUIJOTE
CMB Amplitude	0.96	0.96
Synch Amplitude	0.95	0.98
β_s	0.25	0.72
Dust Amplitude	>0.999	>0.999



QUIJOTE-MFI wide survey results: component separation (III)

- **Neural networks**. CMB reconstruction in the galactic plane:

QUIJOTE 11+13 + Planck varying spectral index

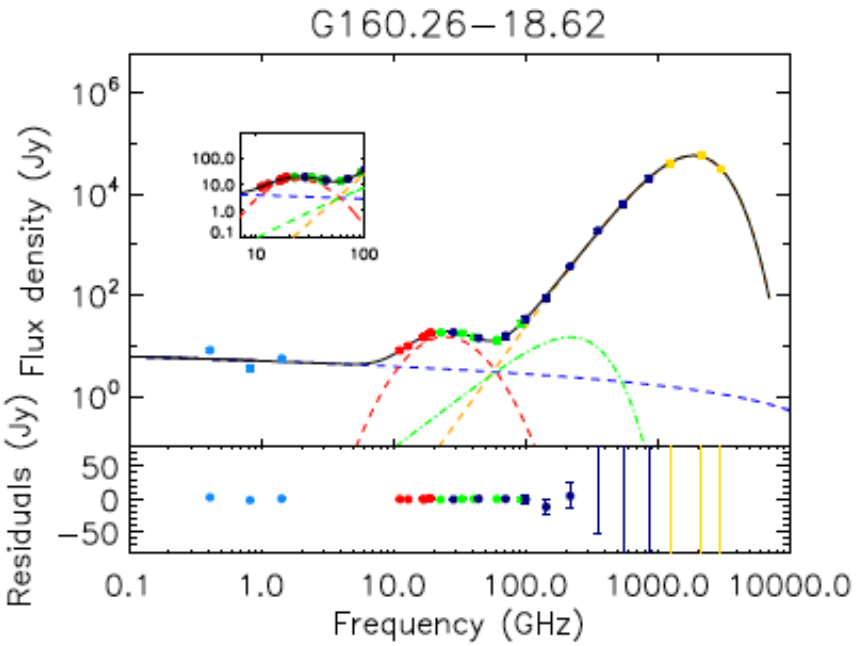


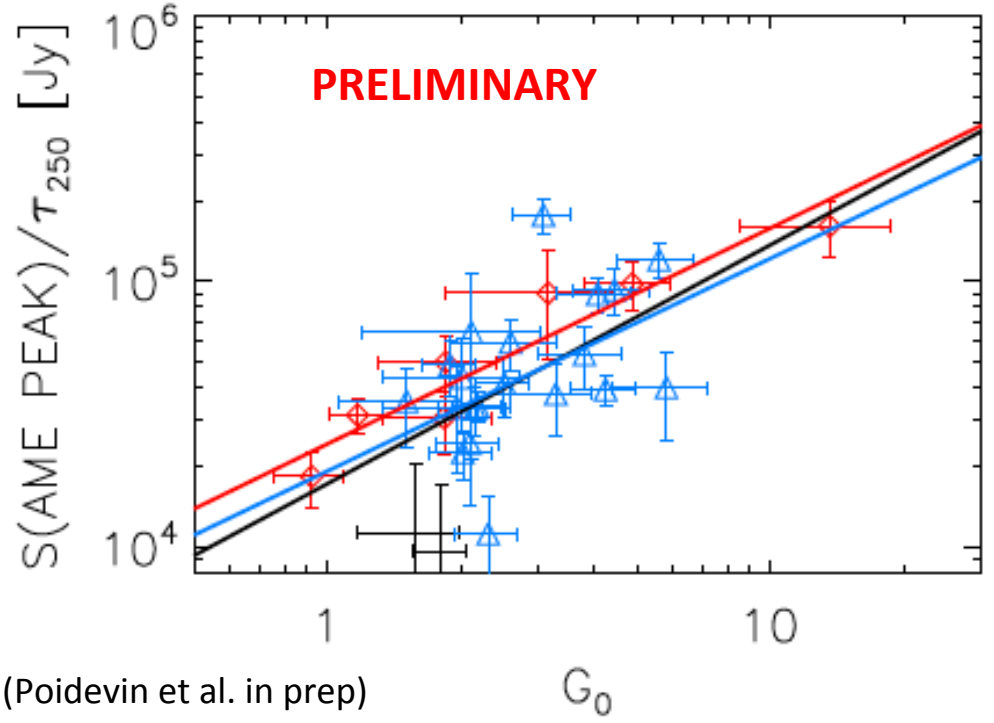
Planck alone fixed spectral index (*Planck Collaboration IV 2018*)

(Casaponsa et al. in prep)

QUIJOTE-MFI wide survey results: modelling the AME

- **Génova-Santos et al. (2017):** Best upper limits to date, from W44 region (< 0.4% at 17GHz from QUIJOTE, and < 0.22% at 23GHz from WMAP).
- **Paper in prep**: 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.
  - Clear correlation of AME/tau_{dust} with radiation field G0. Seen in Tibbs et al. (2011, 2012), and PIR XV (2014).
- **Polarization**. Synchrotron component, and upper bounds on AME emission.

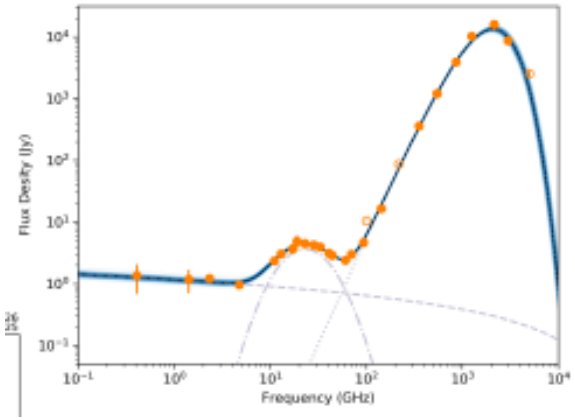




(Poidevin et al. in prep)

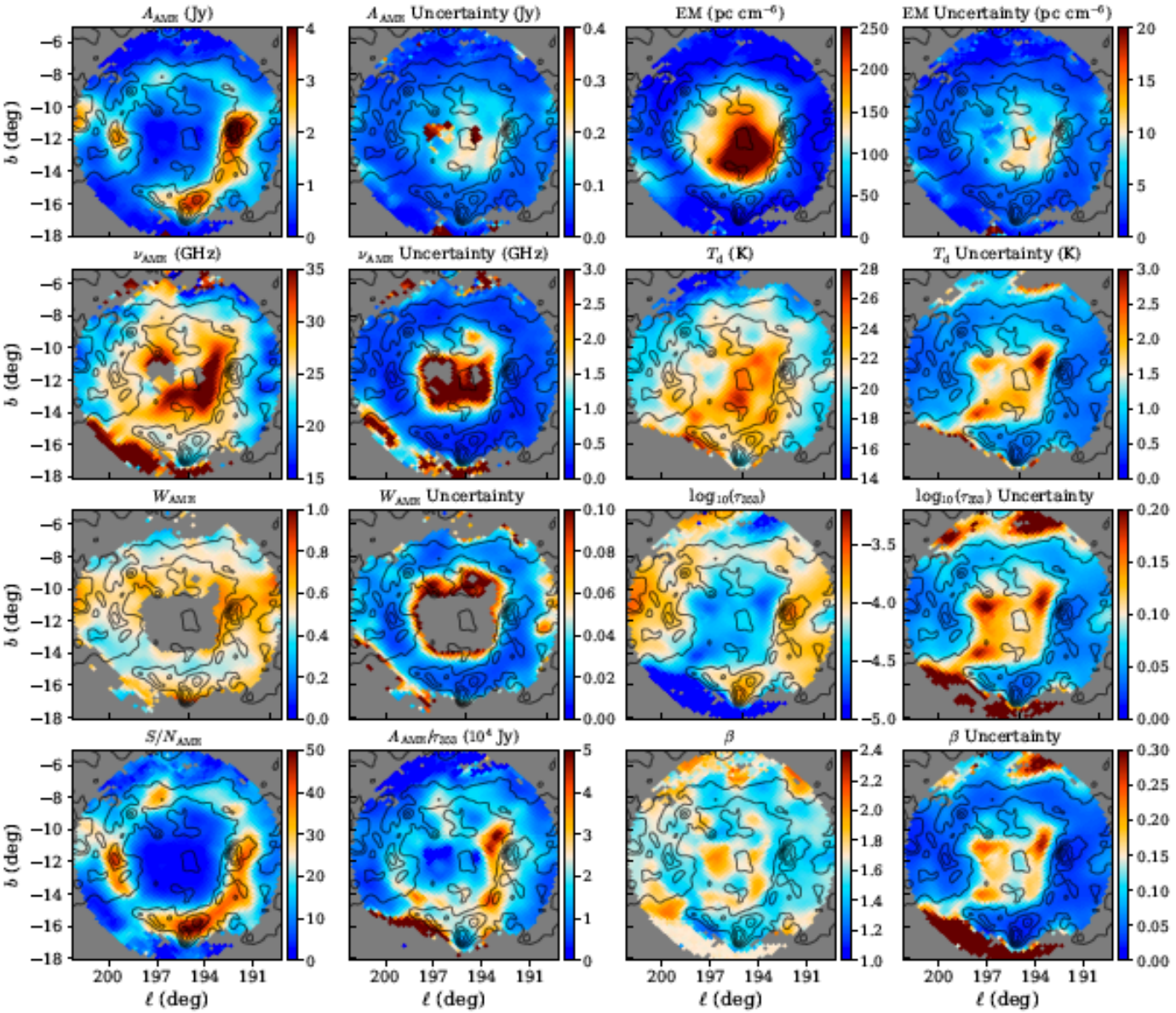
QUIJOTE-MFI wide survey results: modelling the AME (II)

- Detection of spectral variations of AME properties in the Lamda Orionis region,~10ºx10º (Cepeda-Arroita et al. 2019, in prep).
- **Joint QUIJOTE & C-BASS paper,** in prep.
- Spatial variability of AME properties.

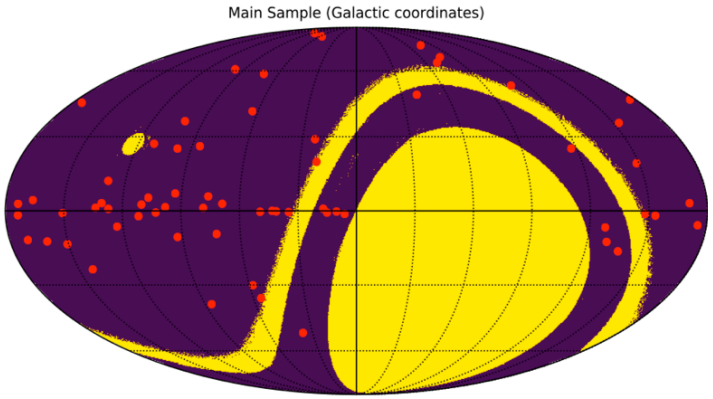


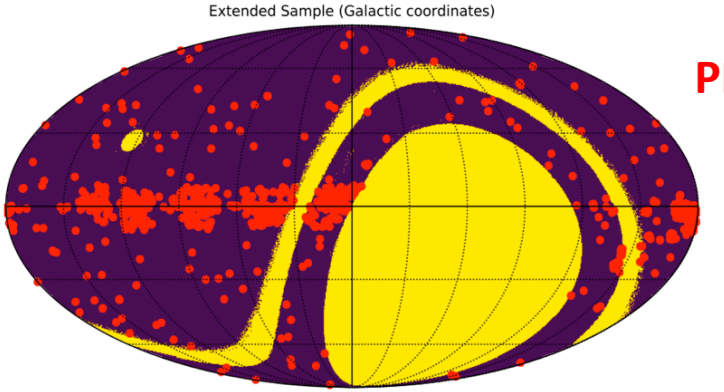
(Cepeda-Arroita et al. in prep)

PRELIMINARY



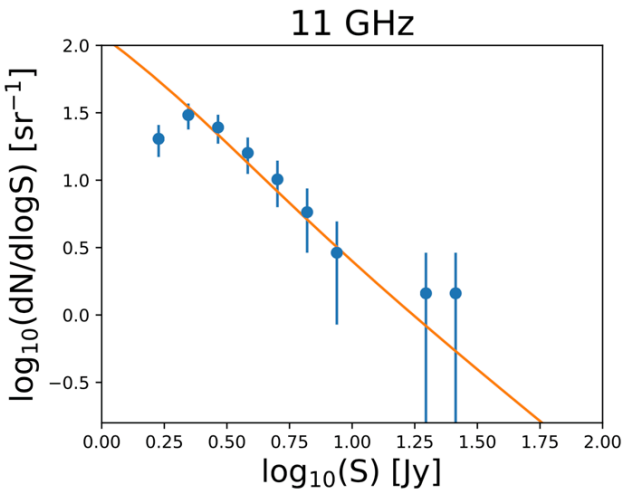
QUIJOTE-MFI wide survey results: radiosources





PRELIMINARY

Positions of the 64/1008 sources in main (left) and extended (right) *Planck-selected* sample.



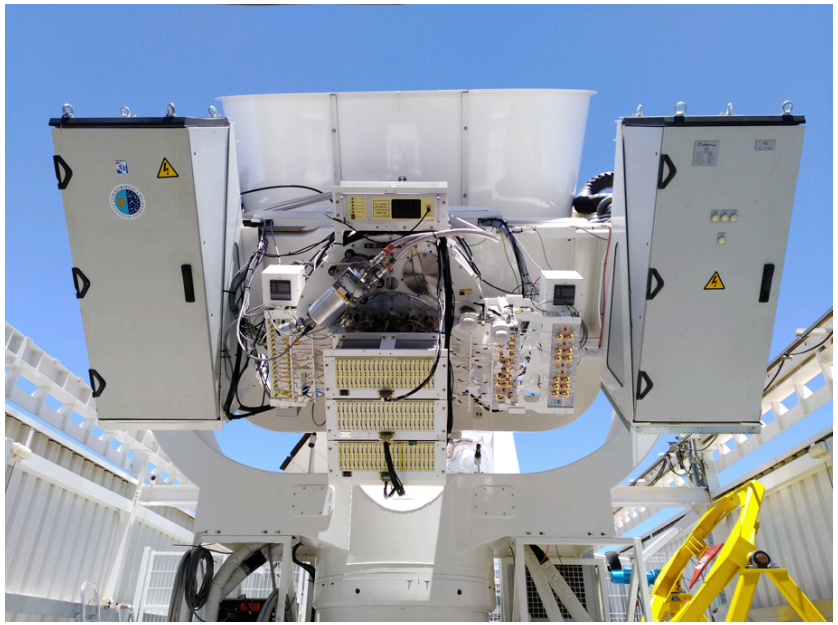
Differential source number counts for the MHW2 **blind sample** at 11 GHz compared to predicted radio source number counts from de Zotti et al. (2005).

Threshold	11 GHz	13 GHz	17 GHz	19 GHz
99.99	47 (1)	39 (2)	79 (8)	73 (2)
99.9	48 (2)	39 (2)	82 (8)	74 (2)
99.0	63 (4)	49 (4)	106 (9)	96 (7)
95.0	109 (12)	88 (5)	186 (13)	176 (13)
90.0	154 (14)	130 (9)	249 (22)	248 (17)
0.0	935 (106)	932 (106)	987 (117)	999 (119)

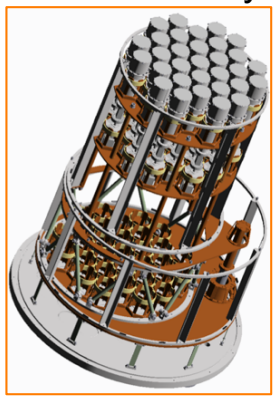
Number of objects in the extended sample with P significance level [%] >= a given threshold. Sources outside Planck GAL070 mask are shown in ().

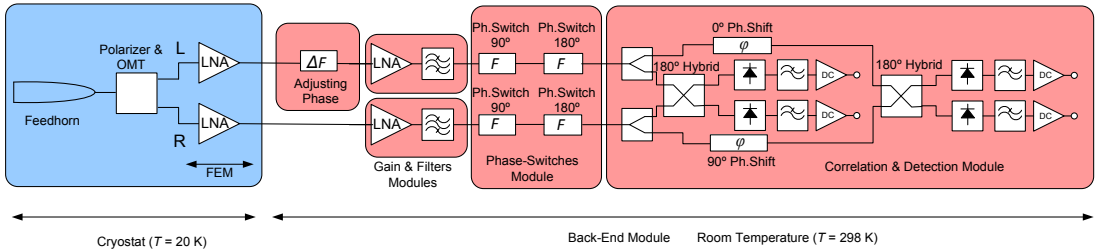
(Herranz et al. in prep)

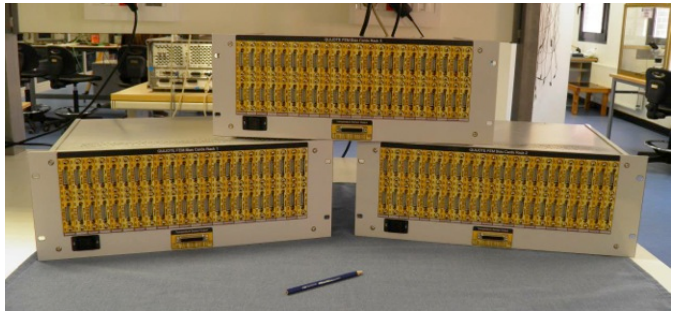
TGI (30 GHz) and FGI (40GHz) instruments

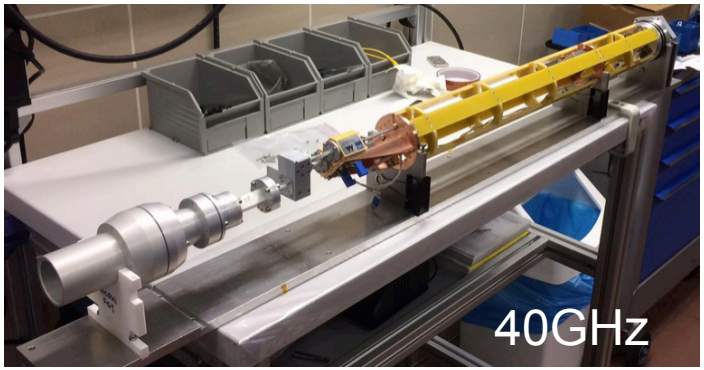


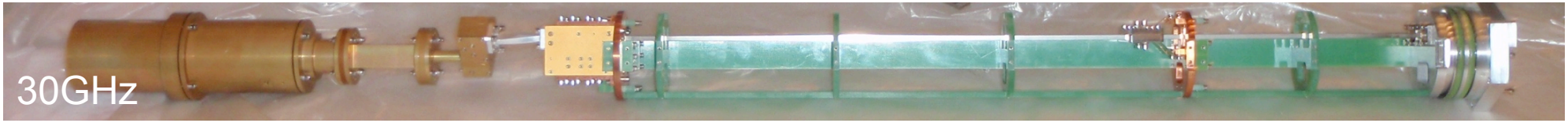
- **TGI**: 31 pixels at 30GHz. Measured sensitivity: 50 μK $s^{1/2}$ for the full array. First light May 12th 2016.
- **FGI**: 31 pixels at 40GHz. Sensitivity: 60 μK $s^{1/2}$ for the full array. First obsrvations in 2018-19 (with 14 pixels).
- **Joint TGI/FGI observations started in 2018**. Now changing configuration and fixing problem with the cryostat. → 2020.





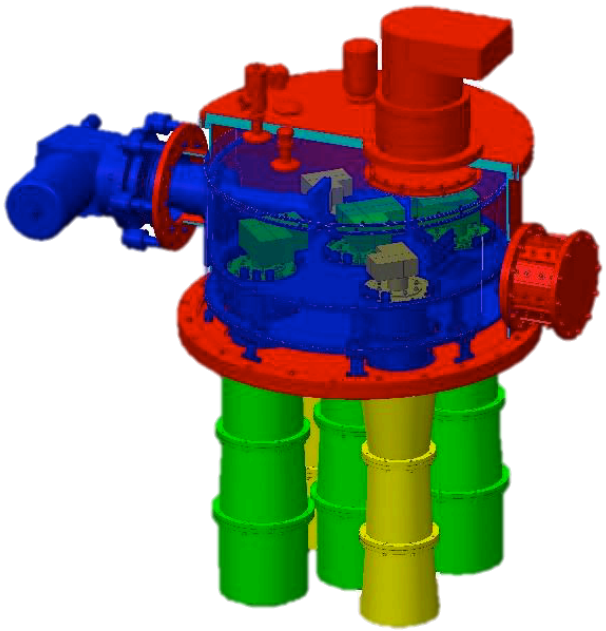


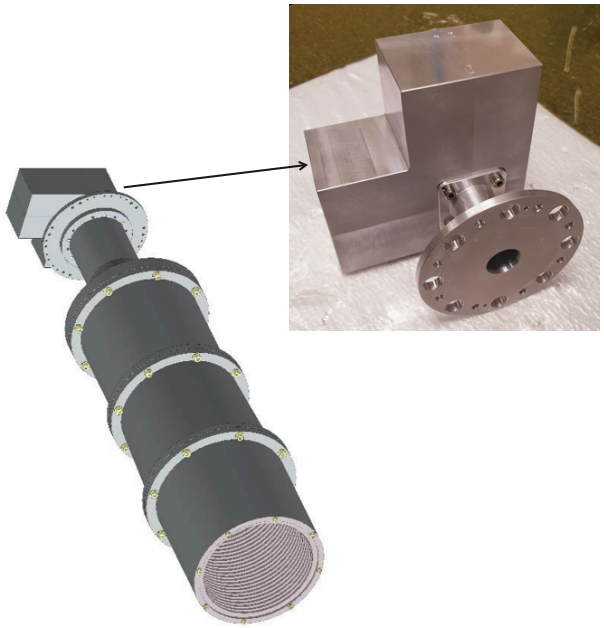


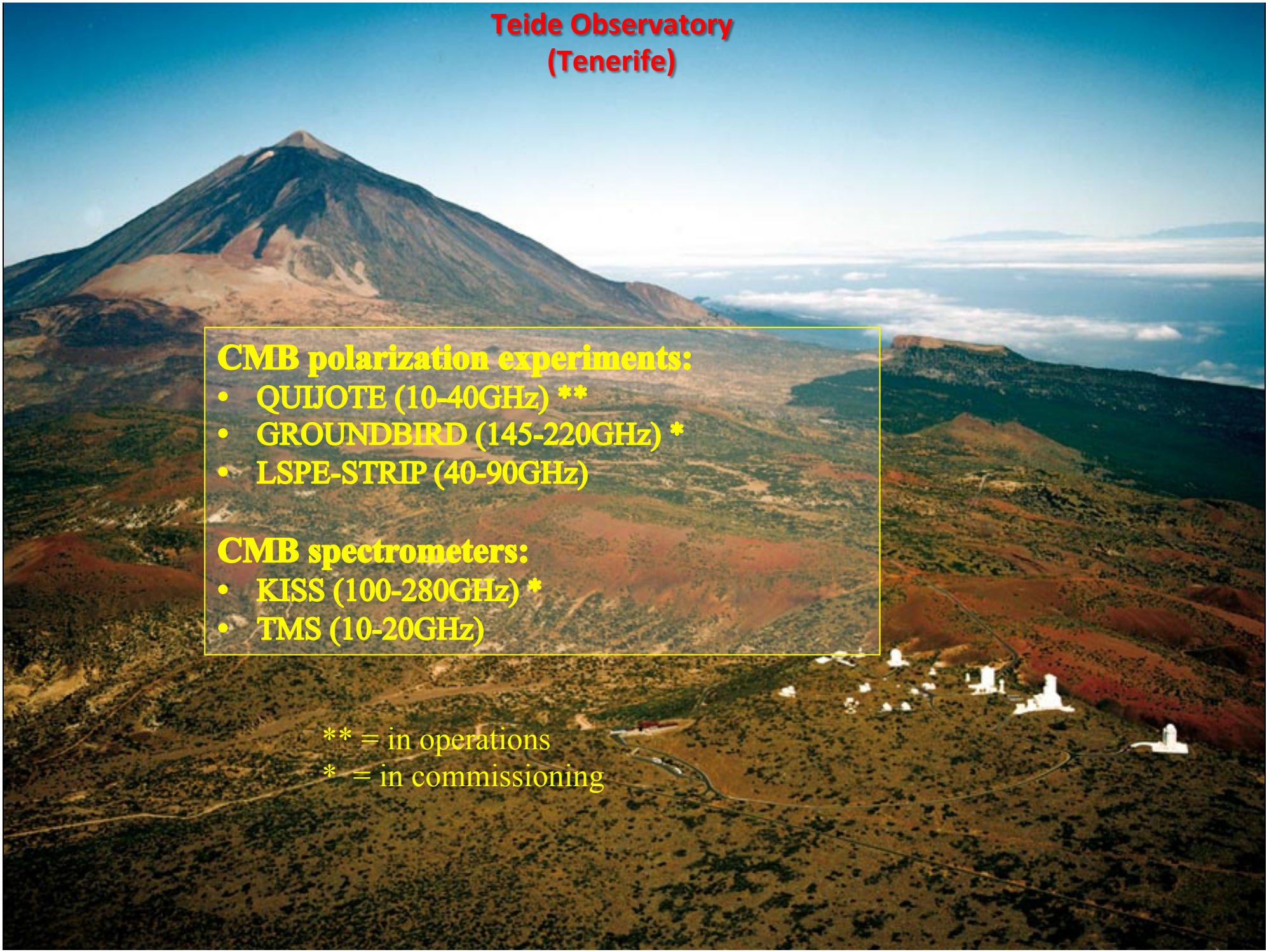


MFI2 Instrument (10-20 GHz)

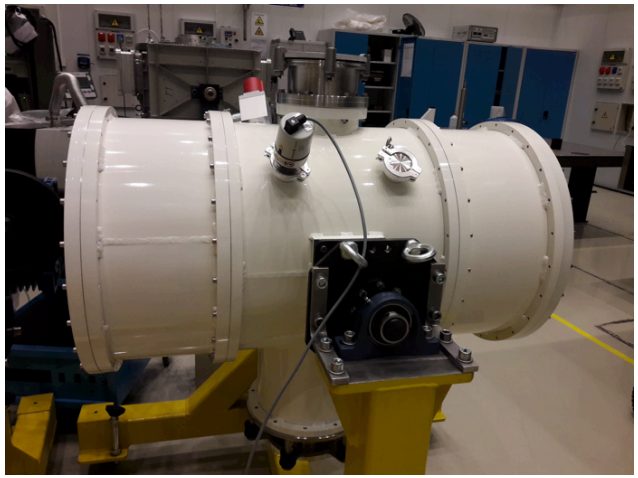
- **MFI upgrade (MFI2)**. Fully funded. Aim: to increase the integration speed of the MFI by a factor 3 (mainly coming from the new LNAs) → Sensitivity of < 1μK.arcmin @ 100GHz (β=-3) in widey survey. Now 2.4μK.arcmin @100GHz.
- **5 horns**. Two covering the 10-14GHz band, and three coverning 16-20GHz.
- Full digital back-end (FPGAs) → RFI removal.
- **Status**: Cryostat fabricated. Opto-mechanical components being fabricated. Assembly in the coming months.
- **Operations**: 3 effective years, starting summer 2020.



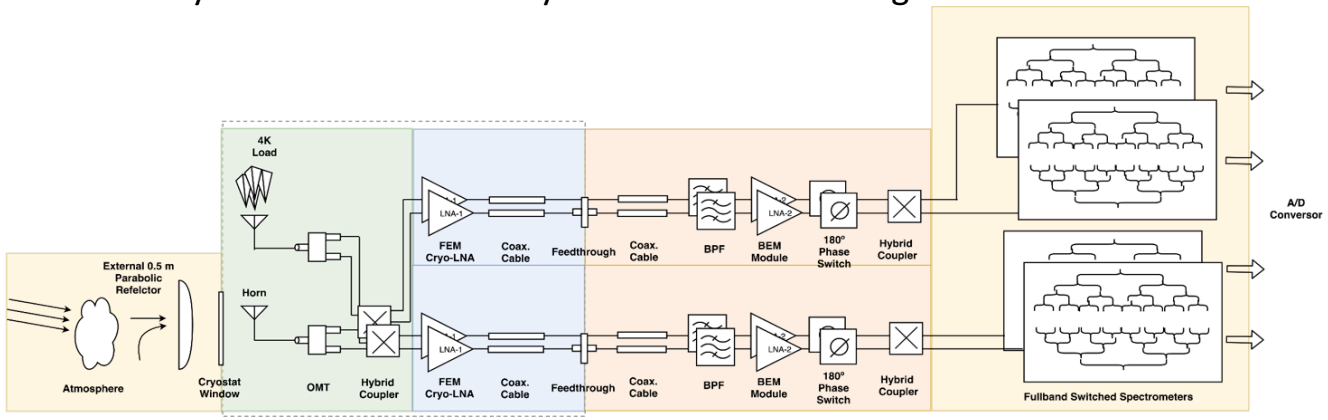


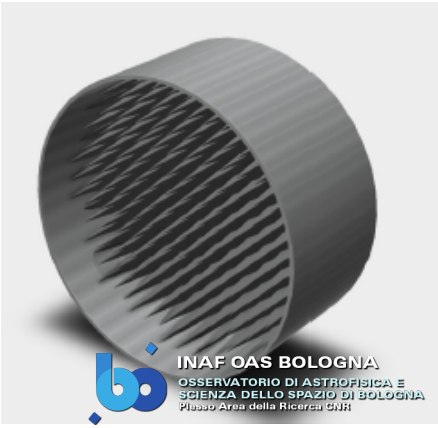

Teide Observatory
(Tenerife)
CMB polarization experiments:
• QUIJOTE (10-40GHz) **
• GROUNDBIRD (145-220GHz) *
• LSPE-STRIP (40-90GHz)
CMB spectrometers:
• KISS (100-280GHz) *
• TMS (10-20GHz)
** = in operations
* = in commissioning

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 at the IAC in July 2019. Commissioning in 2021.

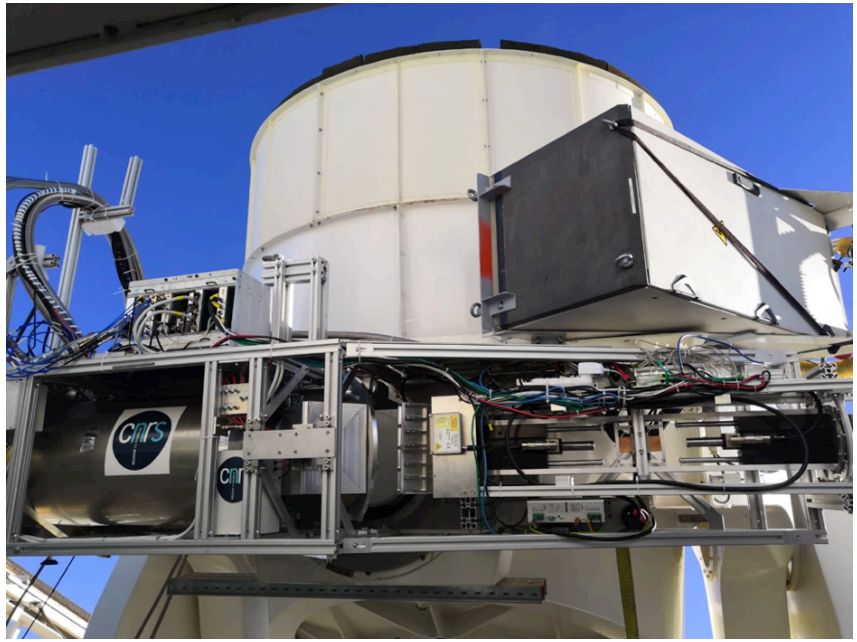




KID Imager-Spectrometer Survey

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 (100-280 GHz). Visitor instrument mounted at QT-1 telescope (Teide Observatory, Tenerife).



Design

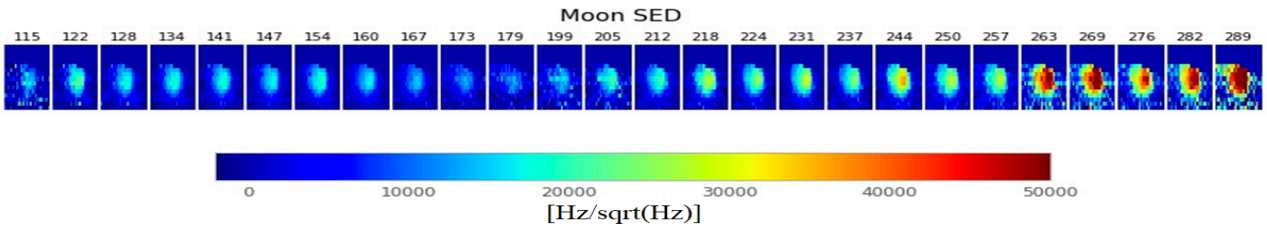
- NIKA camera adapted for KISS optical design.
- Large frequency band (100-300GHz) 600 KID arrays.

Scientific motivation and concept

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

Status

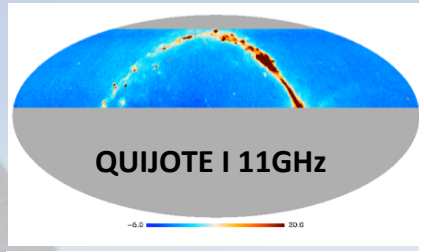
- Installation completed (January 2019) → commisioning.
- Sensitivities as expected (~0.7mK/Hz$^{1/2}$).
- Observations: Moon, Jupiter, Crab. New obs. run now.

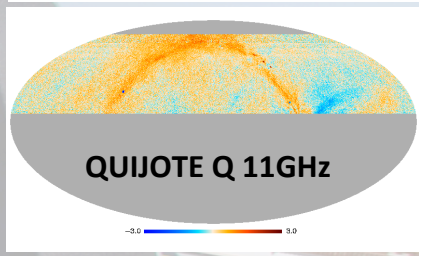


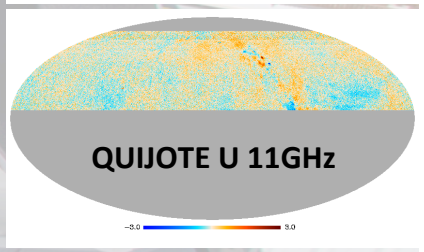
QUIJOTE: status and future plans

QT1 + MFI (10-20 GHz). 2012-2018.

- Observations completed. COSMO fields (> 6,500h), Wide survey (>10,000h), galactic fields (Taurus, W49, IC443, W63, FAN, galactic center). Results published. Best upper limit to date on AME pol fraction (0.2%). Wide survey data release will happen soon. Legacy value (e.g. Litebird).







-------- Funded --------

QT2 + TGI (30 GHz) and FGI (40 GHz). 2018-2024.

- 2018-: **Joint TGI/FGI operation** in the same cryostat (14/15).
- Observing plan for TGI/FGI science phase: cosmo survey in 3 effective years.

QT1 + MFI2 (10-20 GHz). 2020-2024.

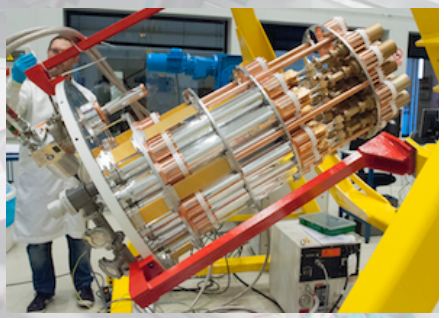
- Funds secured. Cryostat in fabrication. Aim: to increase the sensitivity by a factor of 3.

TMS (10-20GHz). 2021-2024.

- **Spectroscopy.** Absolute scale for QUIJOTE. Synchrotron monopole.

Combination with other experiments at Teide Obs. 2021-2024.

- **Groundbird, LSPE-STRIP** (→ measurements at >90GHz).



-------- Not funded yet --------

Extension to Southern Hemisphere. 2023-2027?

- Extension QUIJOTE-MFI/MFI2 to south is being studied (ZA? Atacama?)
- **ELFS-S** @5m → Synergy grant submitted. Uses MFI2 for 10-20GHz.

ELFS north from Teide Observatory. 2024-2027?

- **Full sky ELFS** @ 6m. Re-using QUIJOTE instrumentation (MFI2)?.