The QUIJOTE MFI wide survey: A northern sky survey in intensity and polarization at 10–20GHz

J.A. Rubiño-Martín on behalf of the QUIJOTE Collaboration

Quijote
Q-U-I Joint Tenerife CMB experiment

RADIO FOREGROUNDS

GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA E INNOVACIÓN
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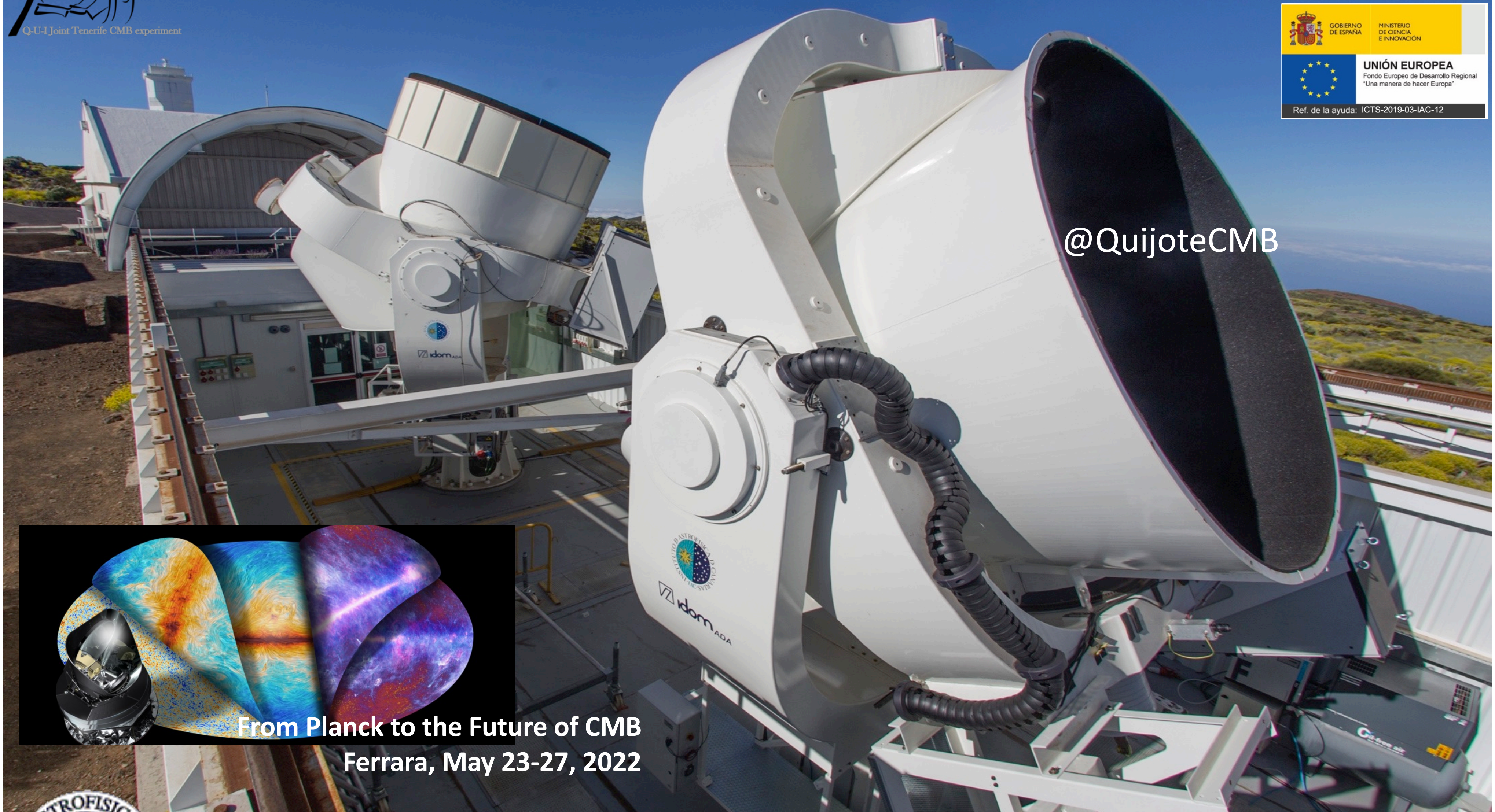
"Una manera de hacer Europa"
Ref. de la ayuda: ICTS-2019-03-IAC-12



From Planck to the Future of CMB
Ferrara, May 23-27, 2022

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IFCA Instituto de Física de Cantabria
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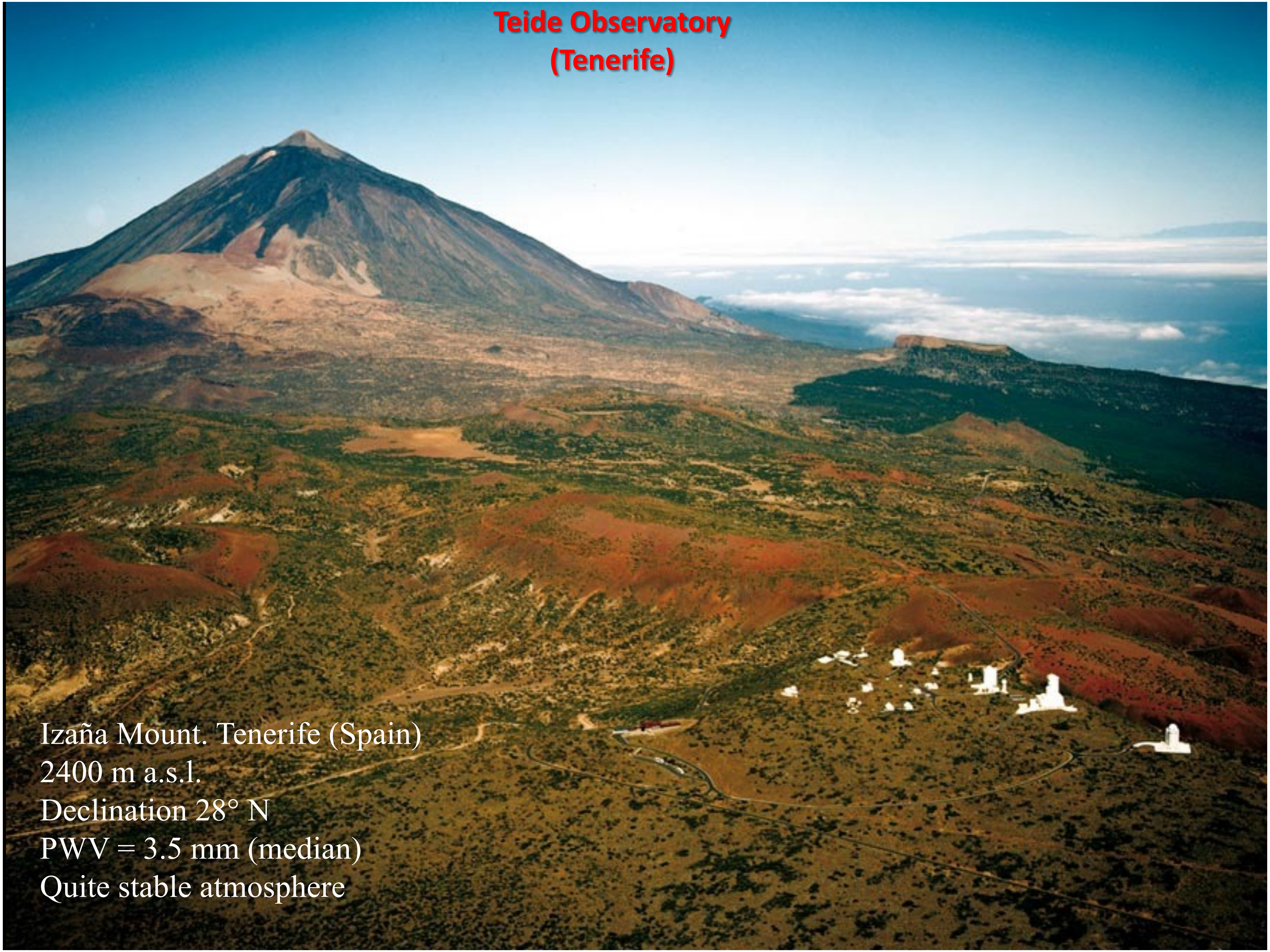
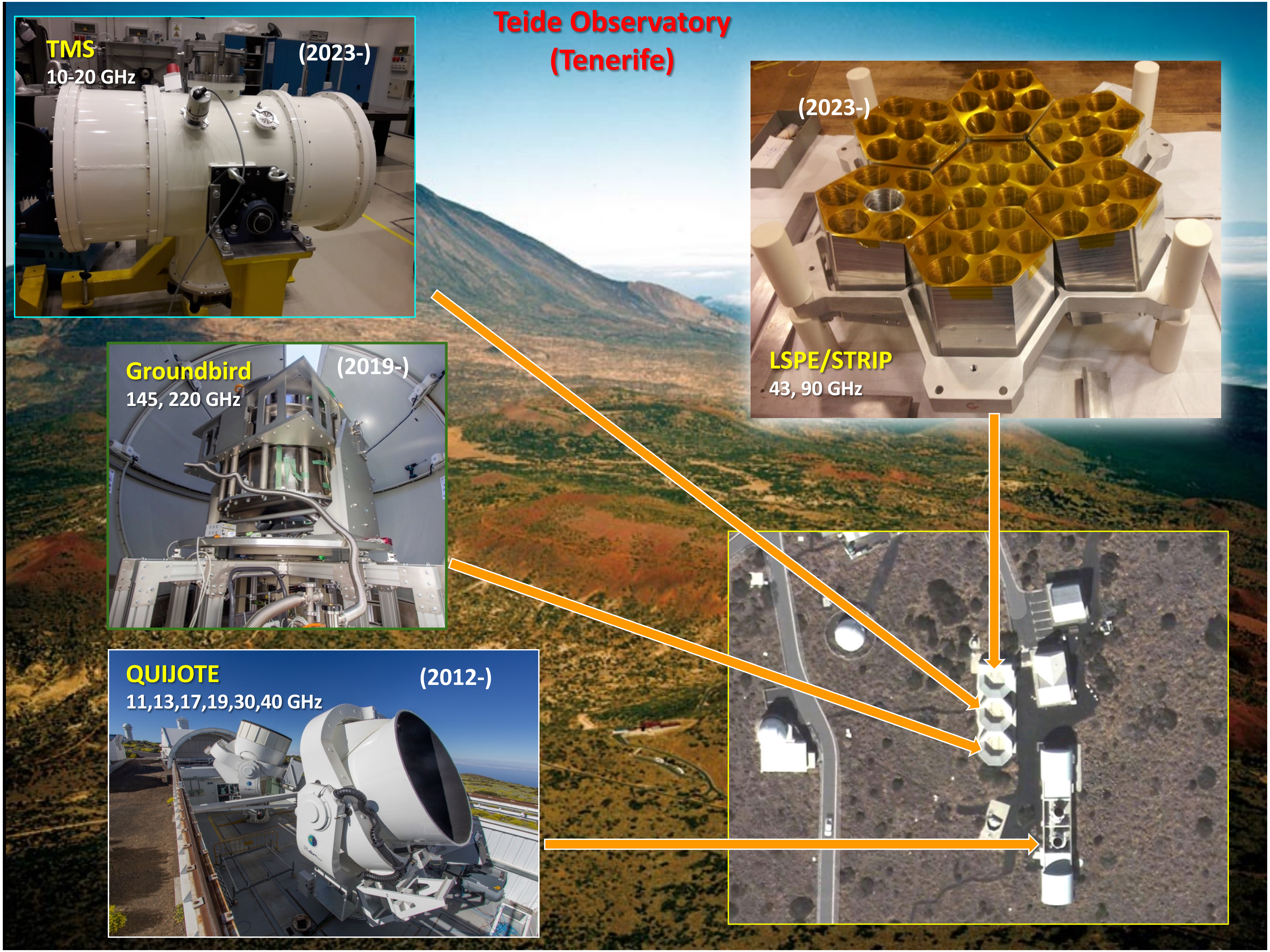
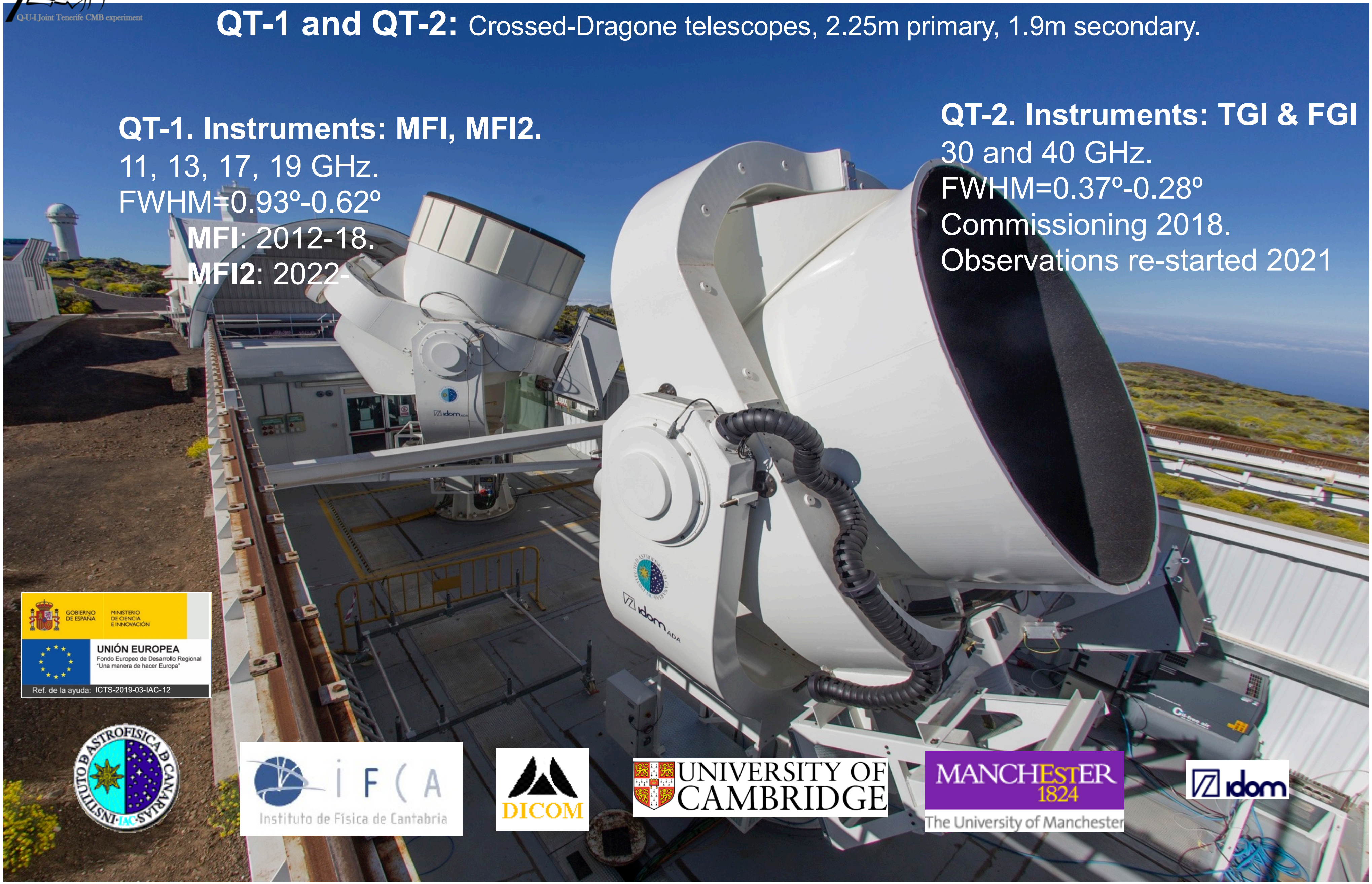

Teide Observatory
(Tenerife)
Izaña Mount. Tenerife (Spain)
2400 m a.s.l.
Declination 28° N
PWV = 3.5 mm (median)
Quite stable atmosphere


Teide Observatory
(Tenerife)
TMS
10-20 GHz
(2023-)
(2023-)
LSPE/STRIP
43, 90 GHz
Groundbird
145, 220 GHz
(2019-)
QUIJOTE
11,13,17,19,30,40 GHz
(2012-)

The QUIJOTE Collaboration

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

The QUIJOTE experiment



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

QT-1. Instruments: MFI, MFI2.
11, 13, 17, 19 GHz.
FWHM=0.93º-0.62º
MFI: 2012-18.
MFI2: 2022-

QT-2. Instruments: TGI & FGI
30 and 40 GHz.
FWHM=0.37º-0.28º
Commissioning 2018.
Observations re-started 2021

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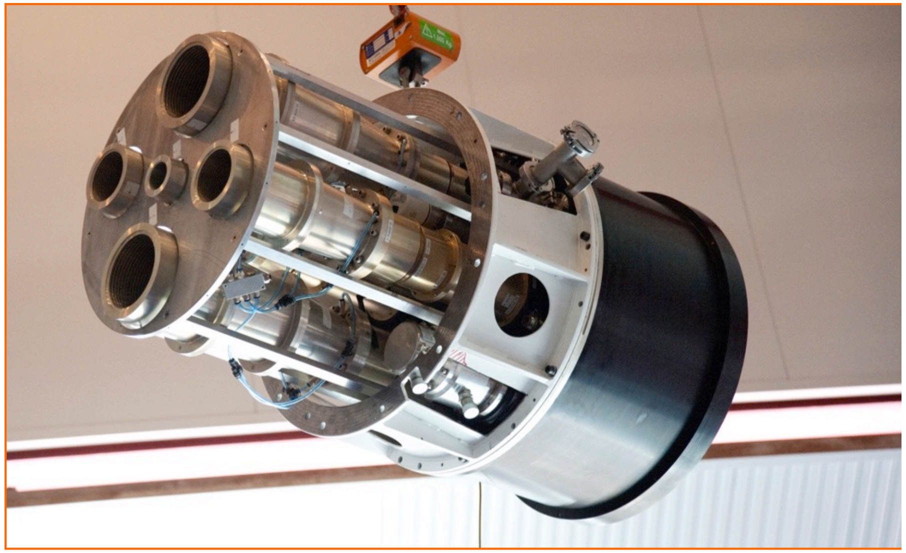
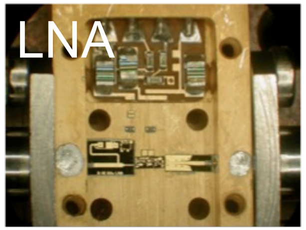
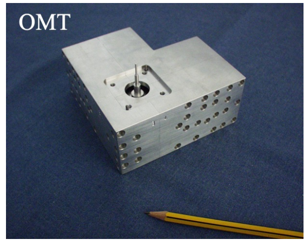
Quijote
Q-U-I Joint Tenerife CMB experiment

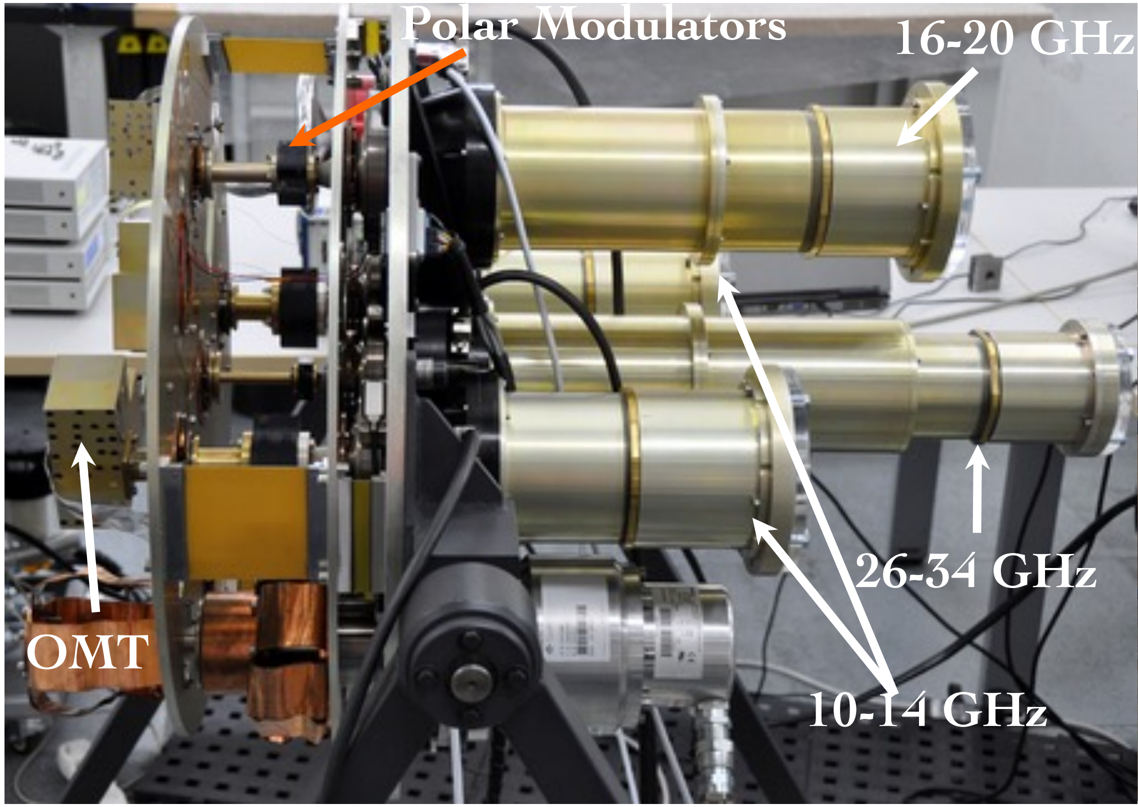
MFI Instrument (10-20 GHz)

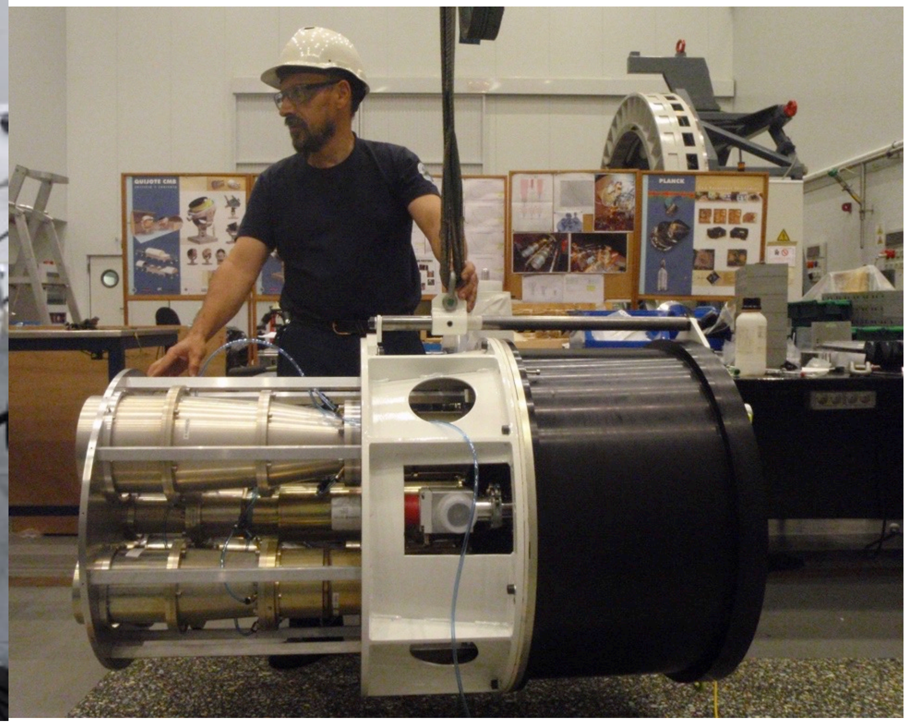
- **Operations**: Nov. 2012 – Dec. 2018.
- 4 horns, 32 channels. Covering 4 frequency bands: 11, 13, 17 and 19 GHz.
- **Sensitivities**: ~400-600 μK $s^{1/2}$ per channel.
- Near sidelobes ~ 35 dB, far-sidelobes < 80 dB
- f_{knee} ~ **250 mHz** (pol), **~50 Hz** (int)
- "**HWP**": steeping polar modulator (RL<-20dB, IL< -0.15dB, I<-40 dB)









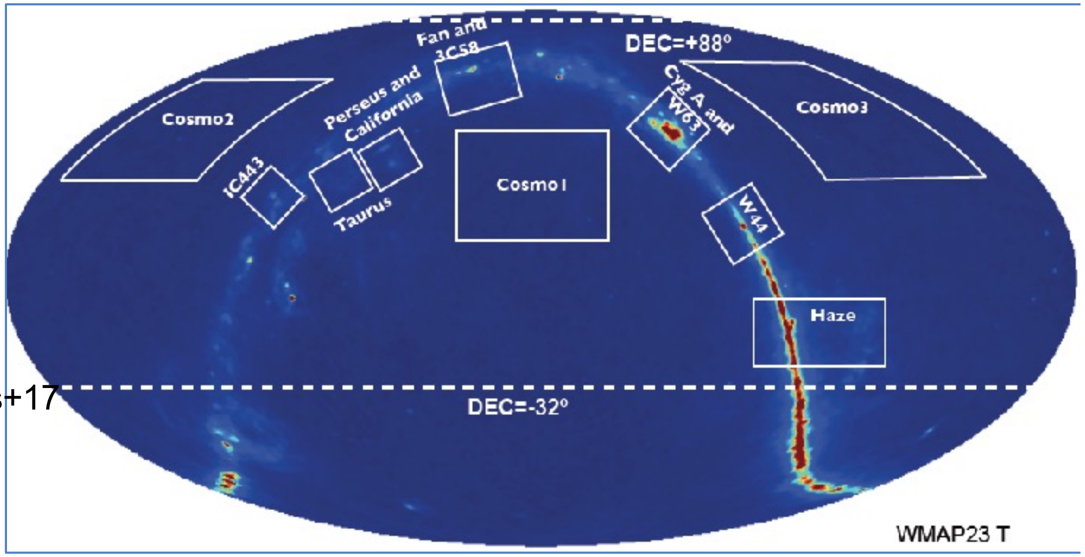


Science with QUIJOTE first instrument (MFI)

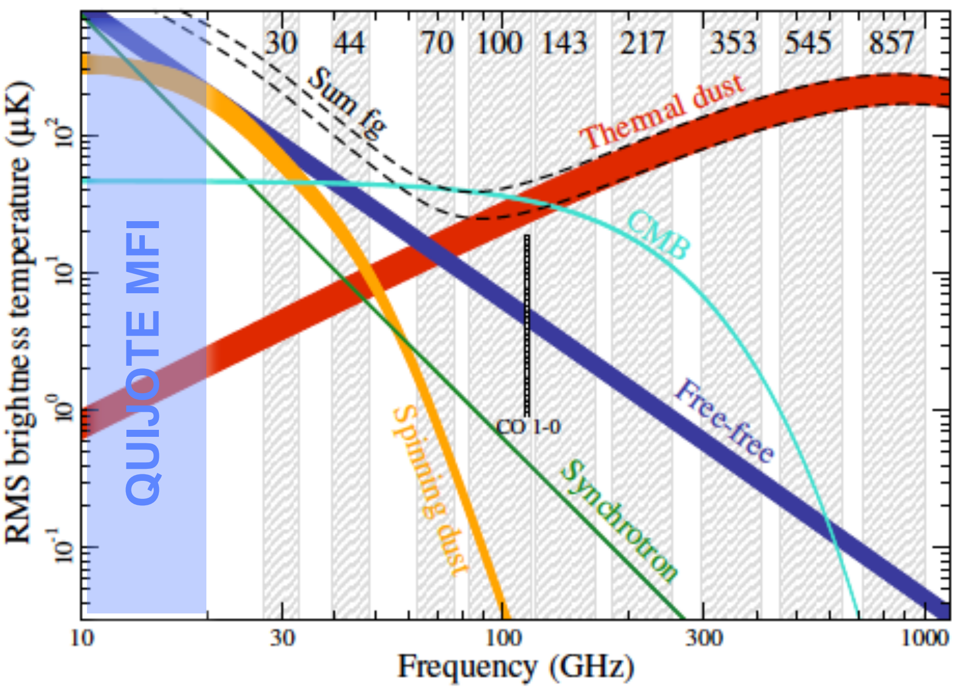
Excellent complement to PLANCK at low frequencies. Legacy for future experiments (→LiteBIRD)

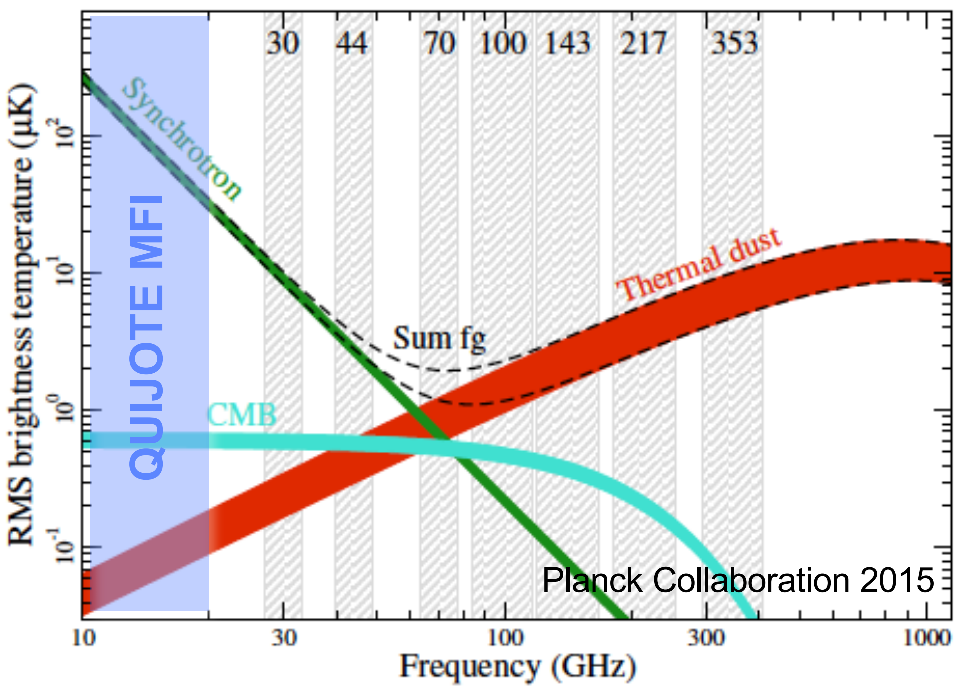
MFI Science phase (Nov 2012- Dec 2018)

- Wide survey (10,800h) → RAW 10TB, binned TOD 340 GB.
- Cosmological fields (~3,000 deg^2) (6,500h)
- Daily calibrators (Crab, Cass A, Jupiter, sky dips,..) (1,700h)
- Galactic centre and Haze (1,400h)
- Perseus molecular cloud (750h) → Genova-Santos+15
- Fan region and 3C58 (500h)
- Taurus region (450h) → Poidevin+19
- SNRs (W44, W47, IC443, W63) (1,150h) → Genova-Santos+17
- M31 (540h)



Total: ~**26,000 h** of MFI data (3 effective years).
→ ~50% efficiency during science phase.





QUIJOTE MFI science papers

MFI early results (3 papers, published):

I. Intensity and polarization of the AME in the Perseus molecular complex (Génova-Santos et al. 2015)
II. Polarization measurements in the Galactic MCs W43 and W47 and SNR W43 (Génova-Santos et al. 2017)
III. Microwave spectrum of intensity and polarization in the Taurus MC complex and L1527 (Poidevin et al. 2019)

MFI wide survey (13 papers, associated to MFI wide survey data release):

IV. A northern sky survey at 10-20 GHz with the Multi-Frequency Instrument (Rubino-Martín et al. in prep)
V. W49, W51 and IC443 SNRs as seen by QUIJOTE-MFI (Tramonte et al. in prep)
VI. The Haze region and the Galactic Centre as seen by QUIJOTE-MFI (Guidi et al. in prep)
VII. Galactic AME sources in the MFI wide survey (Poidevin et al. in prep)
VIII. Component separation in polarization with the QUIJOTE-MFI wide survey. (de la Hoz et al. in prep)
IX. Radio-sources in the QUIJOTE-MFI wide survey (Herranz et al. in prep)

To be submited in June

X. Polarised synchrotron loops and spurs. (Peel et al. in prep)
XI. Spatial variability of AME parameters in the Galactic Plane (Fernández-Torreiro et al. in prep)
XII. Analysis of the polarised synchrotron emission at the power spectrum level (Vansyngel et al. in prep)
XIII. Intensity and polarization study of Supernova Remnants (López-Caraballo et al. in prep)
XIV. The FAN region as seen by QUIJOTE-MFI (Ruiz-Granados et al. in prep)
XV. The North Galactic Spur as seen by QUIJOTE-MFI (Watson et al. in prep)
XVI. Component separation in intensity with the QUIJOTE-MFI wide survey (de la Hoz et al. in prep)

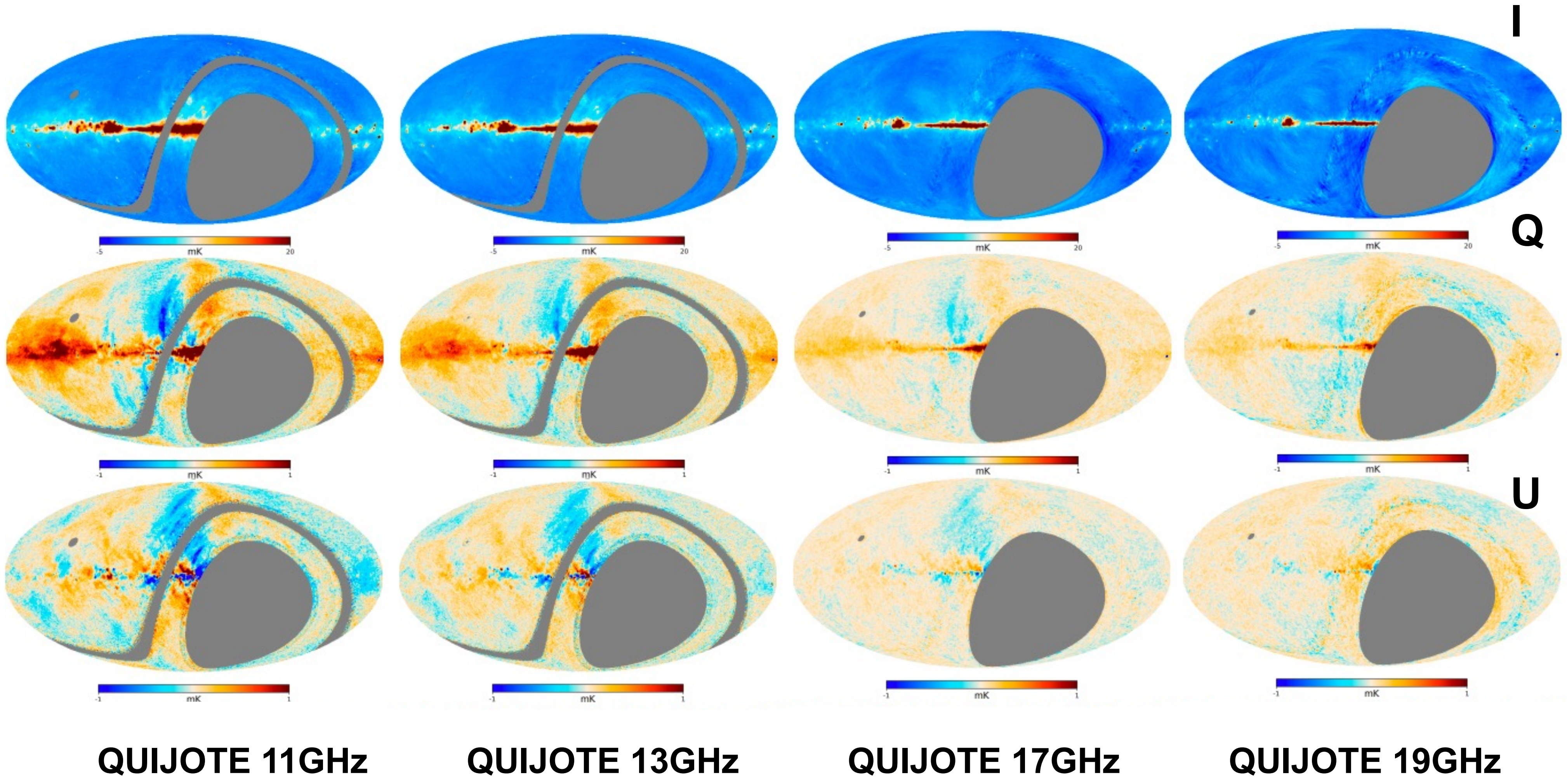
Other MFI papers:

- Detection of spectral variations of AME with QUIJOTE and C-BASS (Cepeda-Arroita al. 2021)
- The PICASSO map-making code: application to a simulation of the QUIJOTE MFI survey (Guidi et al. 2021)
- MFI data processing pipeline (Genova-Santos et al. in prep).

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

Smoothed 1 deg maps

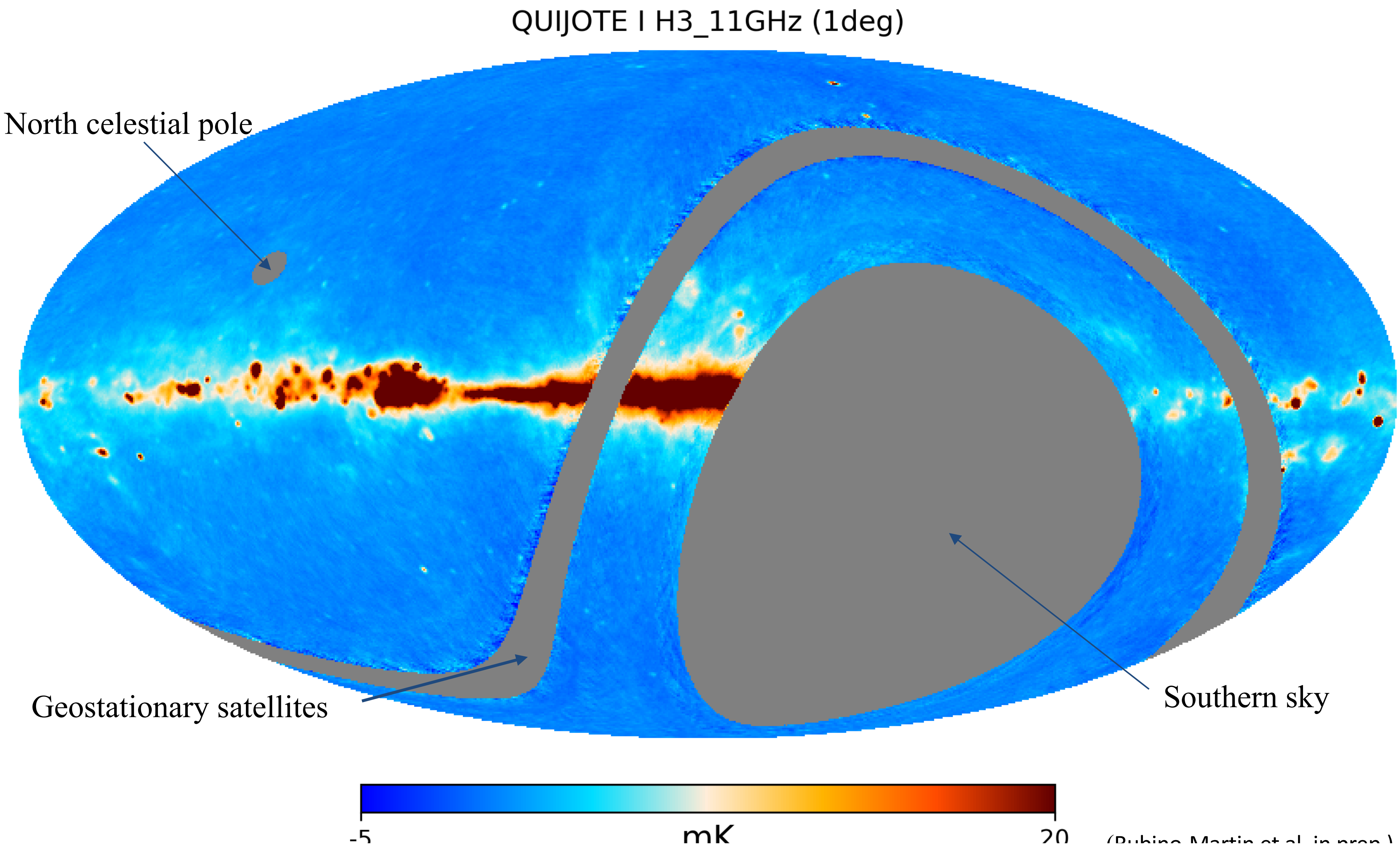
(Rubino-Martin et al. in prep.)



Approx. 29,000 deg^2. Scans at constant elevation (12deg/s). Sensitivities in polarization (Q,U): ~35-40 μK/deg → equivalent to 2.4 μK.arcmin @ 100GHz with β=-3.

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

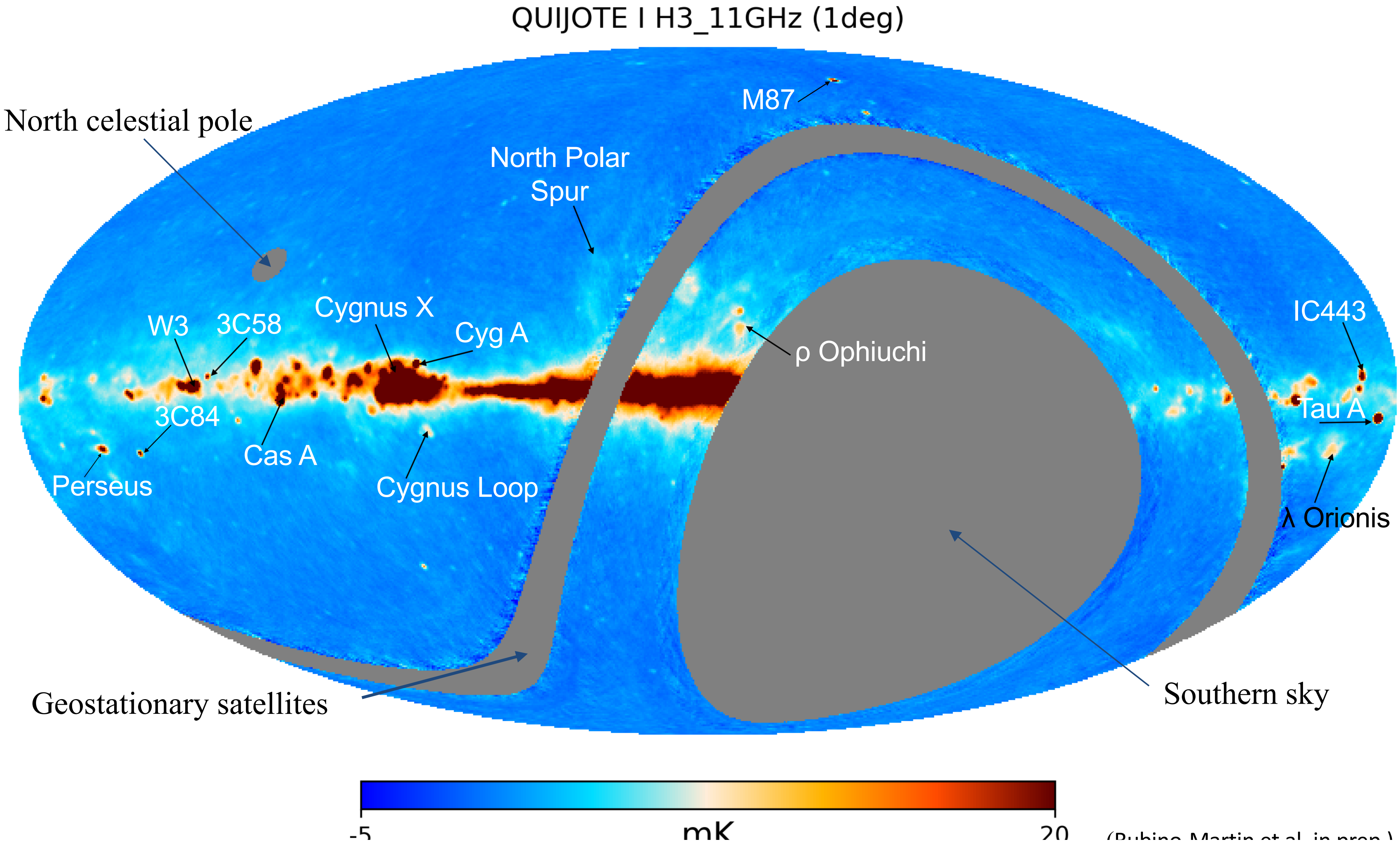
Final maps
(Smoothed to 1º)



(Rubino-Martin et al. in prep.)

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

Final maps
(Smoothed to 1º)

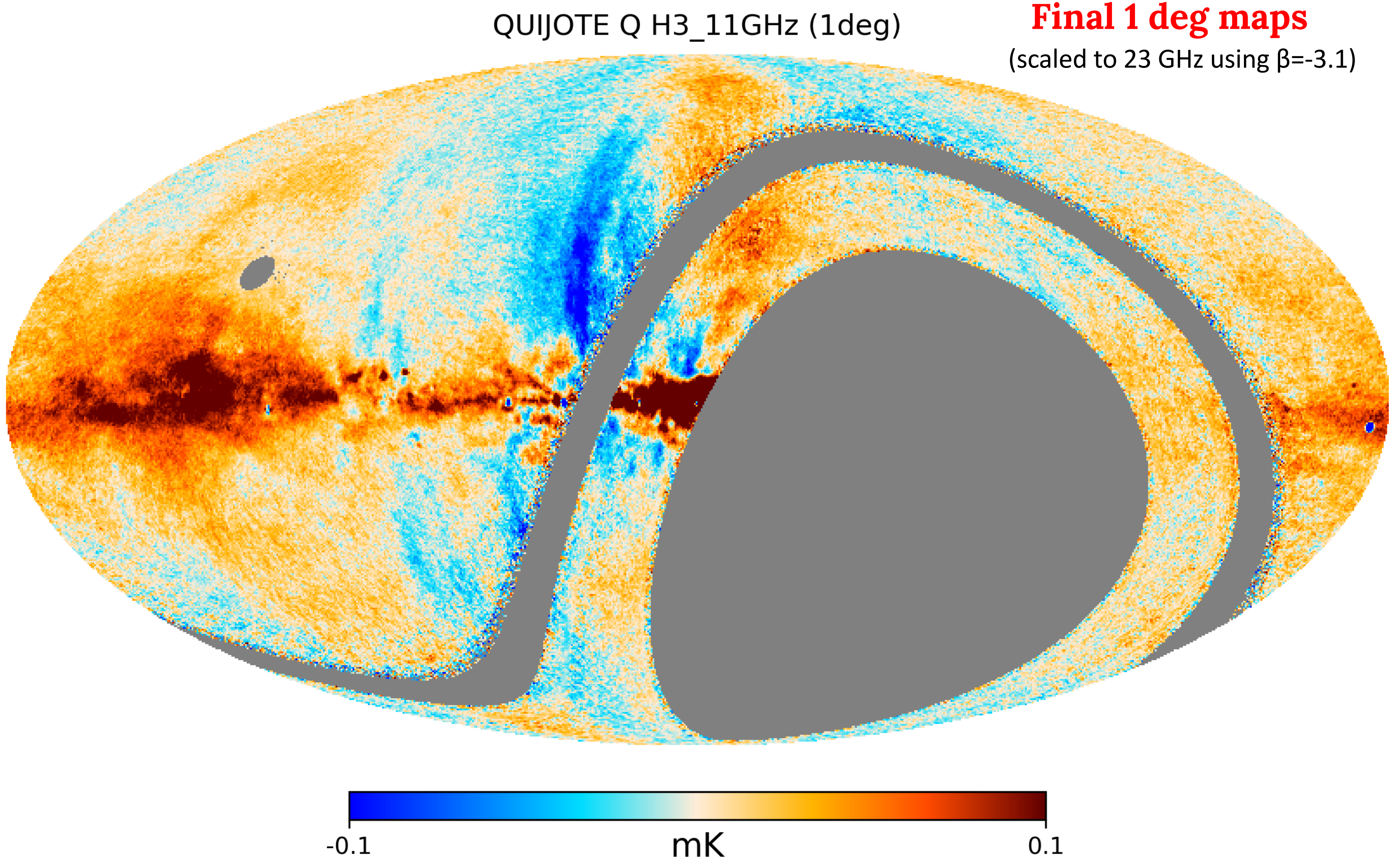


(Rubino-Martin et al. in prep.)

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

Final 1 deg maps

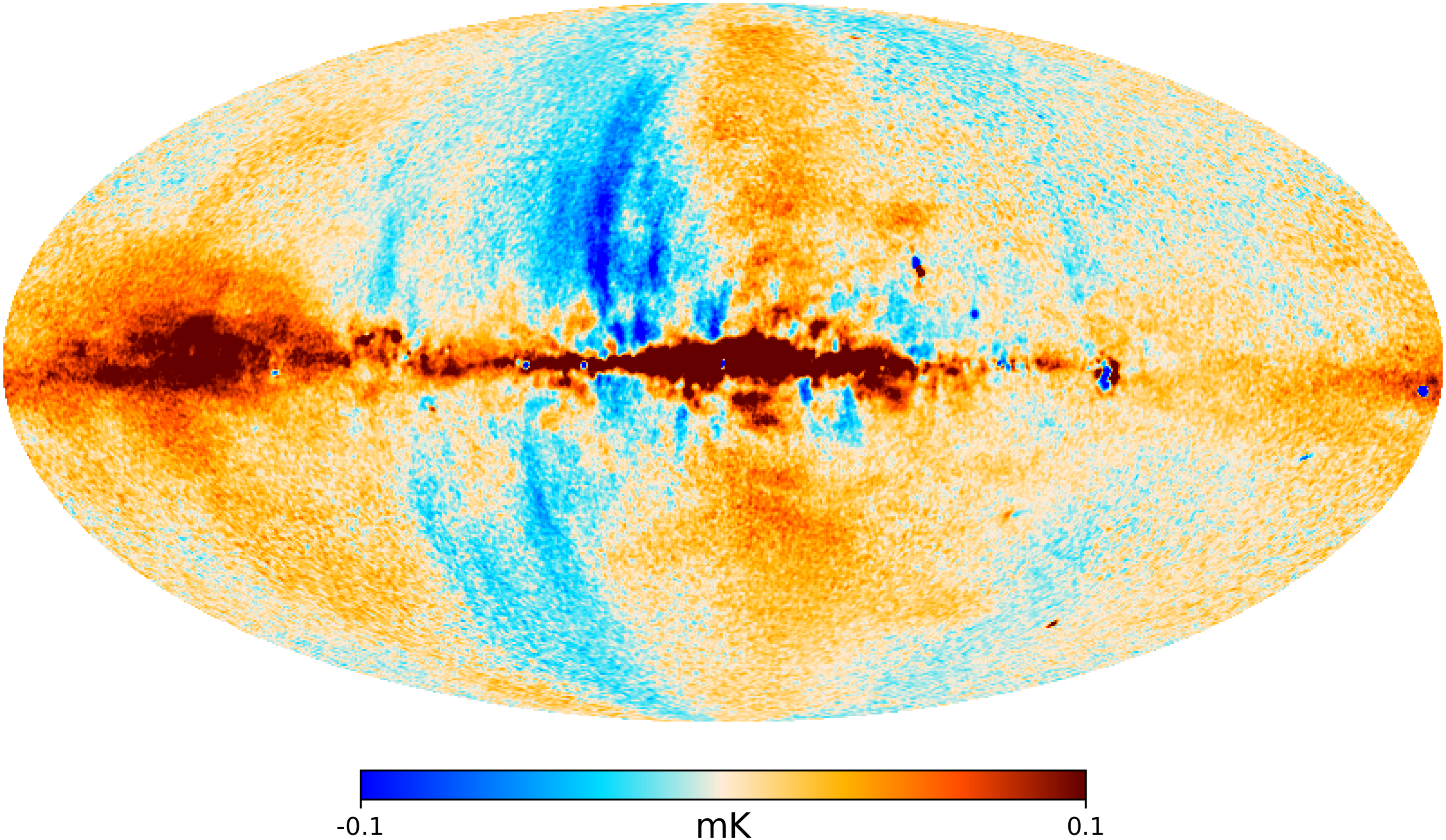
(scaled to 23 GHz using β=-3.1)



(Rubino-Martin et al. in prep.)

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

WMAP 23GHz Q (1deg)

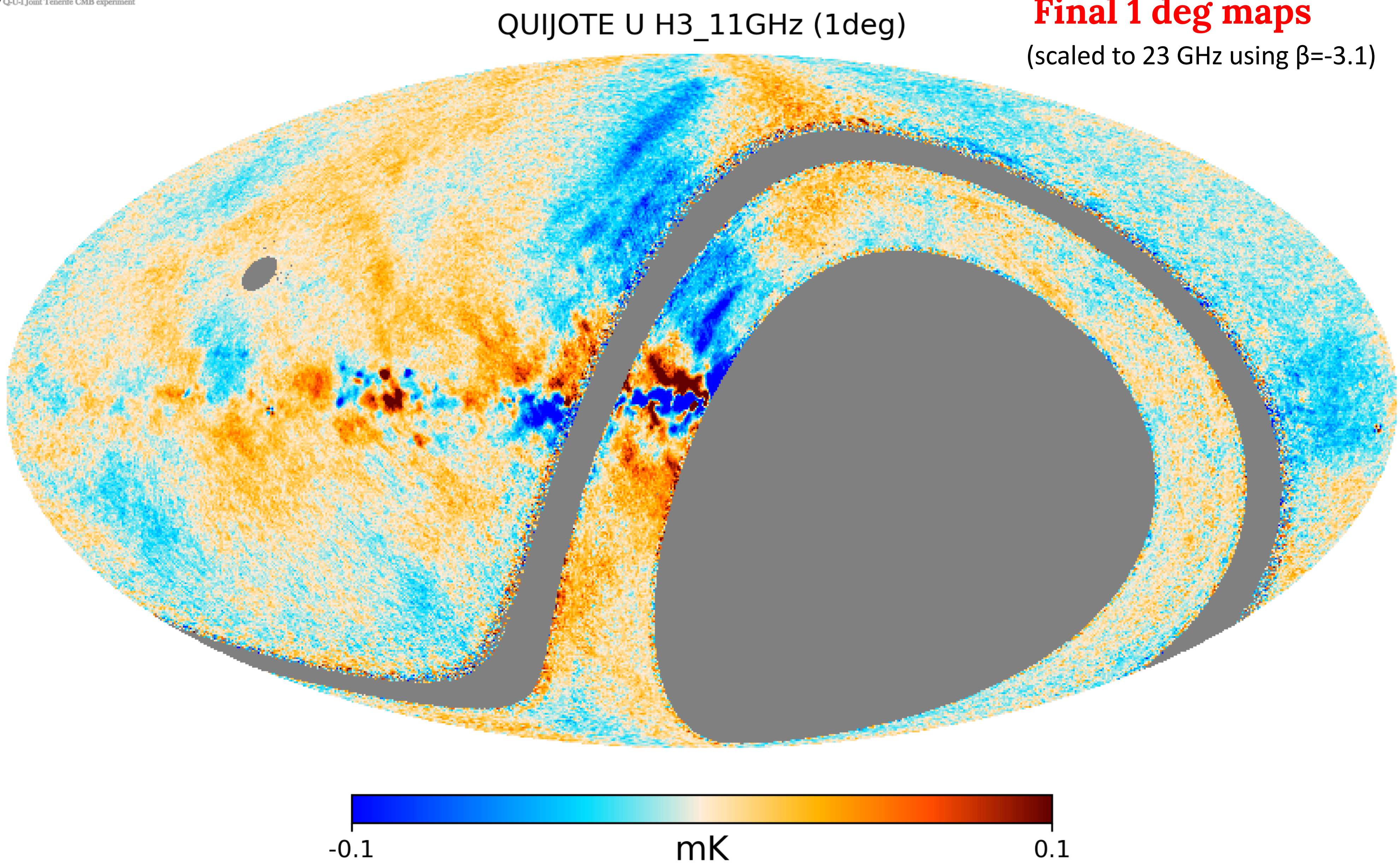


(Rubino-Martin et al. in prep.)

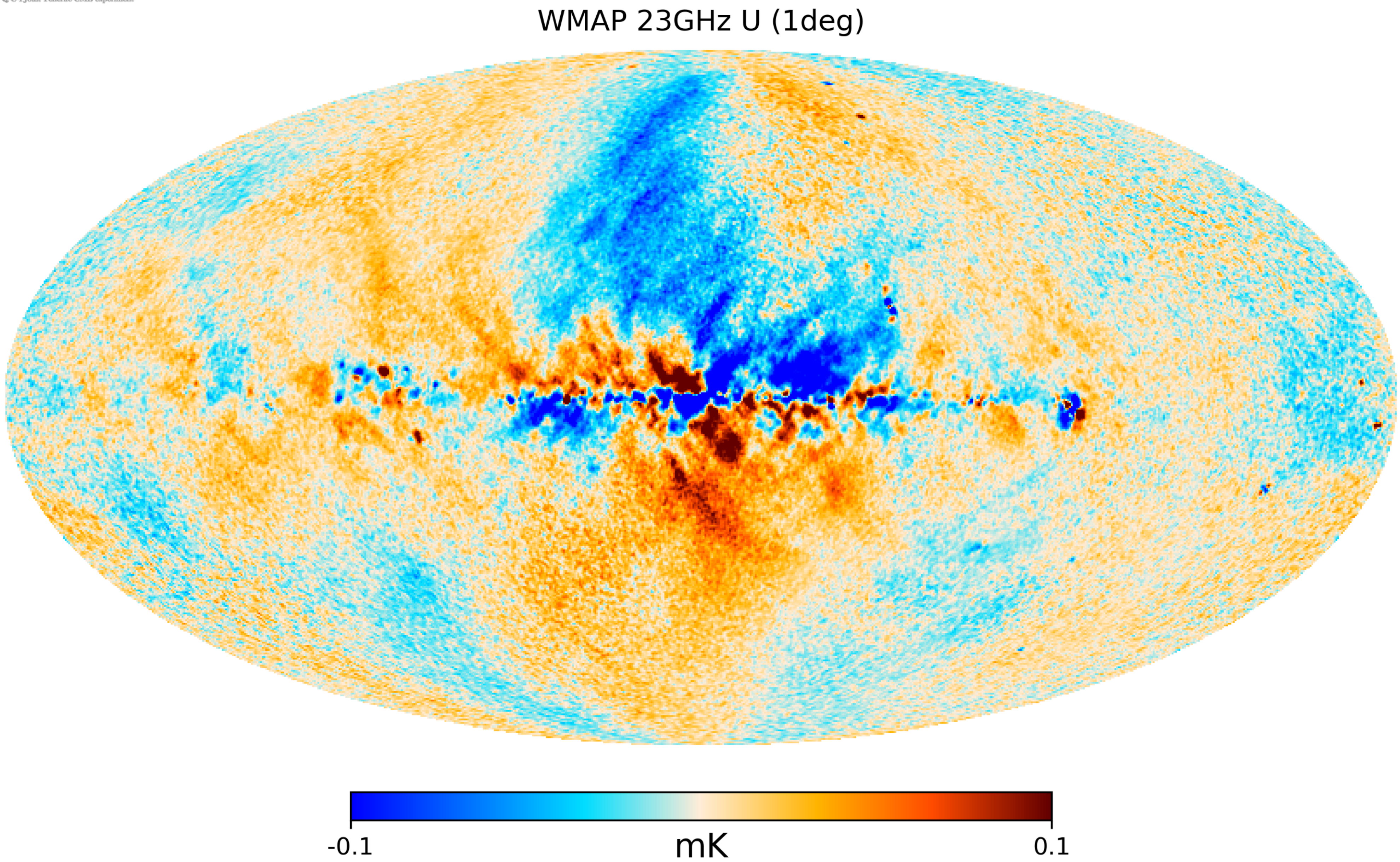
Wide survey with the QUIJOTE MFI (10-20 GHz)

Final 1 deg maps

(scaled to 23 GHz using β=-3.1)

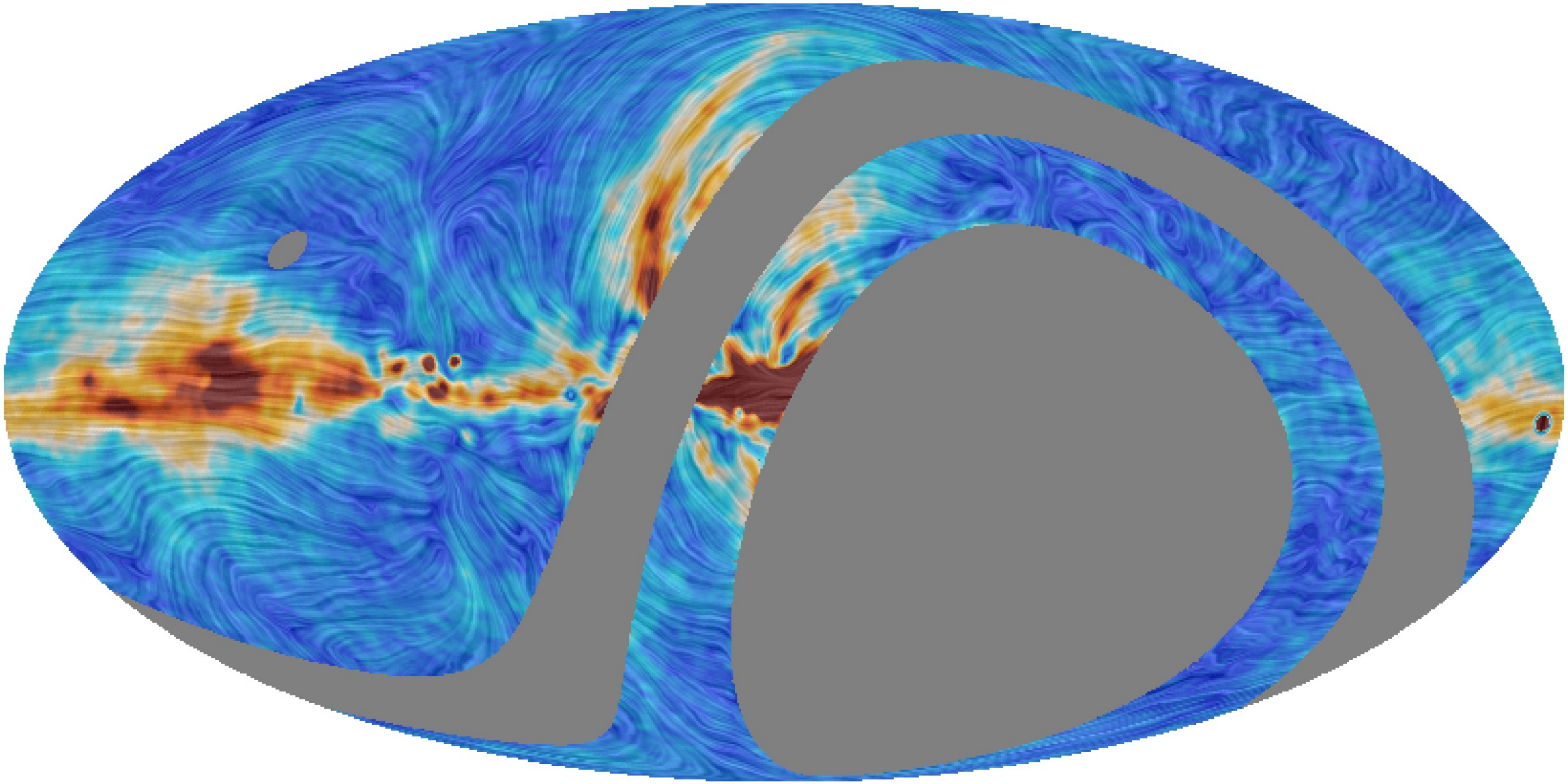


Wide survey with the QUIJOTE MFI (10-20 GHz)



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

MFI 11GHz - LIC



Angles: Comparison to WMAP and PLANCK in high SNR regions, excluding calibrators (CRAB) and high FR regions (galactic center). E.g. the median difference MFI11GHz - LFI30: -0.5º (error=0.6º).

Magnetic fields lines
(Rubino-Martin et al. in prep.)

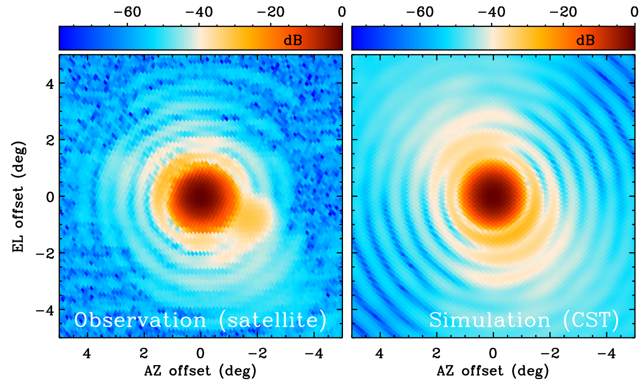
Wide survey with the QUIJOTE MFI (10-20GHz)

Calibration and systematic effects

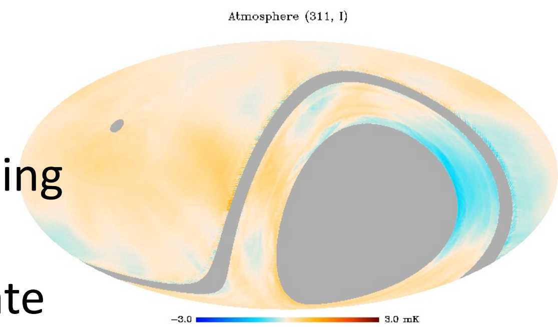
(Rubino-Martin et al. in prep; Genova-Santos et al. in prep)

(see details in https://indico.ipmu.jp/event/380/contributions/5429/)

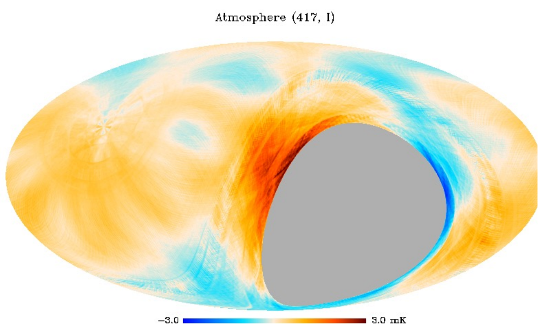
- **Calibration/ Gain modelling.** Overall uncertainty: 5%. Internal consistency: <1% (null tests).
  - Primary. Point sources (Tau A, Cas A).
  - Secondary. Calibration diode.
- **Beam model.** Based on FEM computations with CST.
  - Verified on maps (e.g. Tau A). Geostationary sat (~45dB).



- **Bandpass, polarization efficiency.** Dedicated measurements.
- **Polarization angle**. Tau A. Accuracy of 0.6º at 11GHz (consistency with LFI30 and WMAP23).
- **RFI and atmosphere:**
  - **FDEC**: removing mode at constant declination to correct for RFI. Affecting low multipoles (l<15).
  - **Atmosphere** (Intensity only):template every ~2h, based on common large-scale modes between horns (PCA).



Atmosphere 11GHz



Atmosphere 17GHz

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

Validation of wide survey maps

(Rubino-Martin et al. in prep)

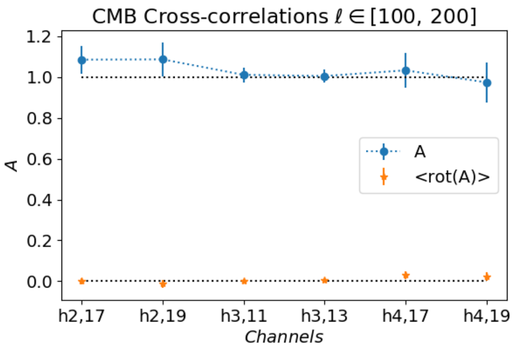
(see details in https://indico.ipmu.jp/event/380/contributions/5429/)

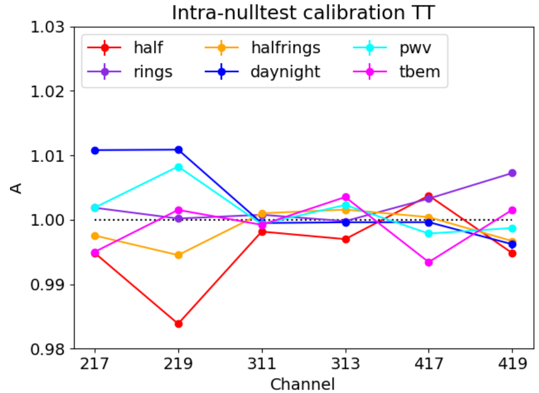
- **Null tests (half, daynight, pwv, rings, halfrings, T_{BEM})→** Global uncertainty of 5-6% in polarization. Internal consistency in intensity ~1%.

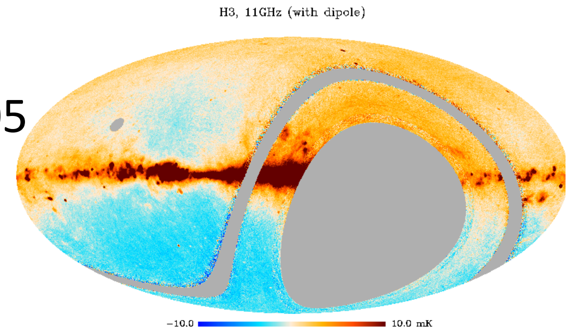
- **CMB signal.** CMB detected via cross-correlation QUIJOTE x Planck (SMICA). **11GHz**: 1.01±0.04 in l=100-200 (0.98±0.05 in l=30-200). **Combined**: 1.02±0.03.

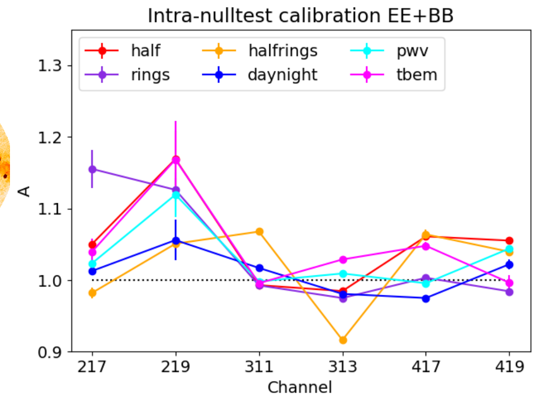
- **CMB dipole.** Dipole signal detected via direct measurement and also with cross-correlations: D=0.92±0.09. (10-sigma).

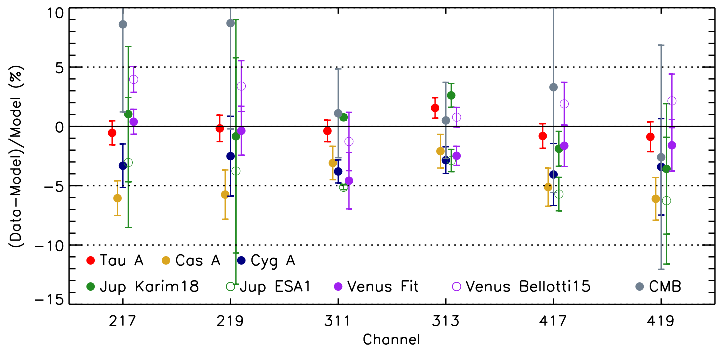
- **Radiosources and planets.** Consistency with TauA, CasA, CygA, Jupiter and Venus.





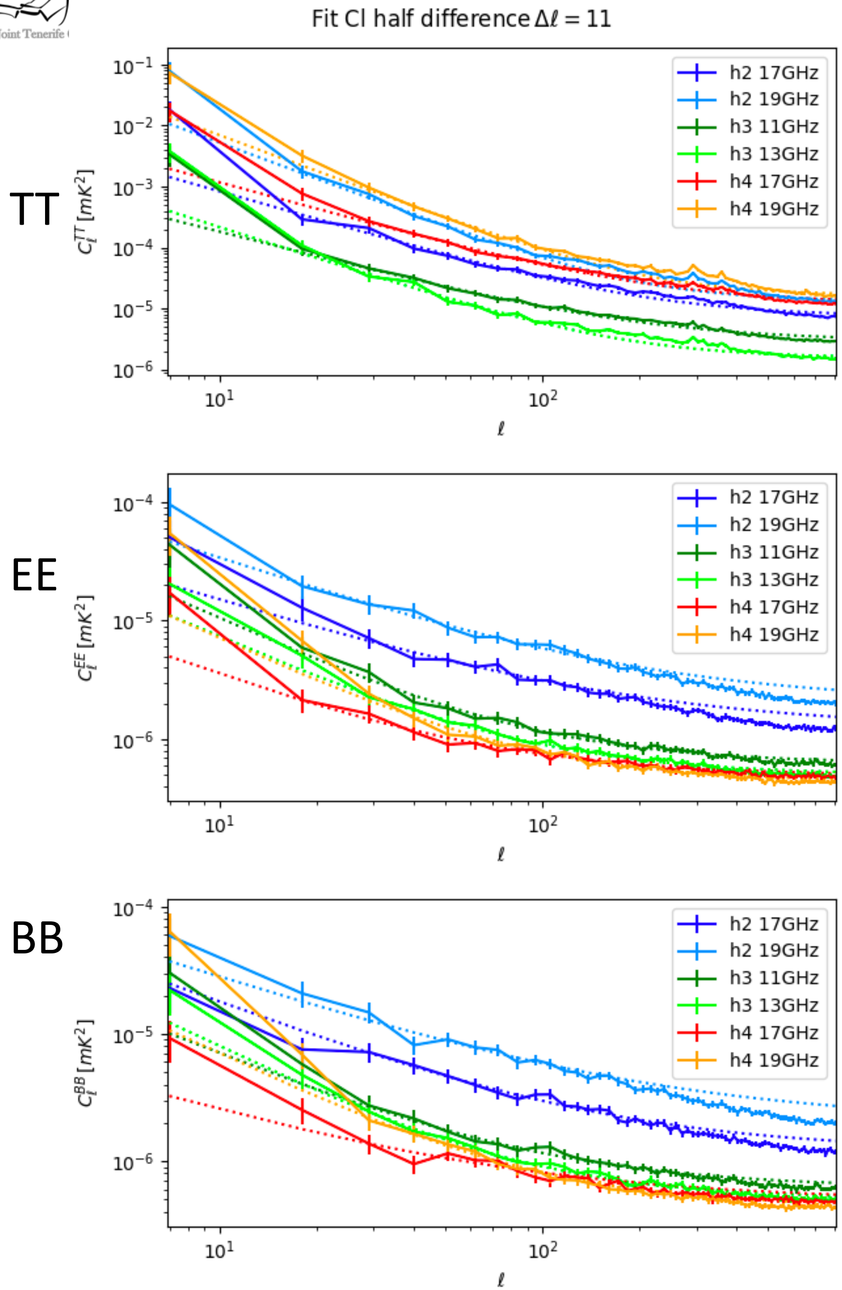






Wide survey with the QUIJOTE MFI (10-20GHz)

Noise properties of the maps



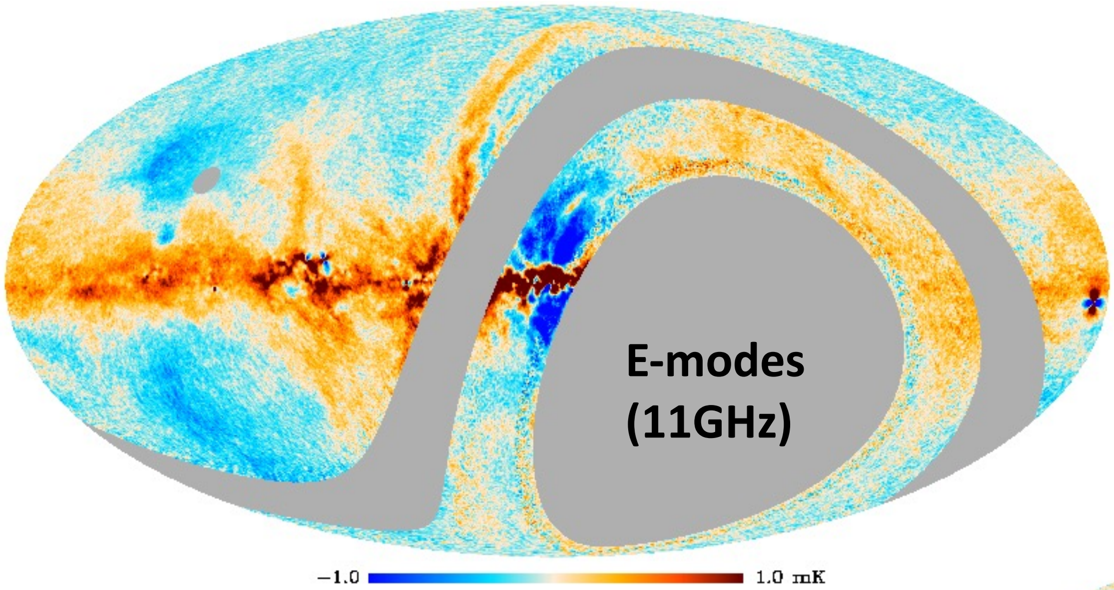
Channel [HFF]	C_w [mK^2 sr]	$\sigma_{1\text{-deg}}$ [μK]	α	ℓ_k
Intensity (TT)				
217	5.82×10^{-6}	130.0	0.94	239.8
219	9.94×10^{-6}	169.0	1.19	254.9
311	2.43×10^{-6}	84.1	0.83	219.4
313	1.24×10^{-6}	60.0	1.02	209.5
417	1.03×10^{-5}	172.7	0.92	281.0
419	1.33×10^{-5}	196.6	1.16	289.2
Polarization (EE)				
217	1.18×10^{-6}	58.5	1.07	115.0
219	1.81×10^{-6}	72.5	1.16	147.7
311	5.95×10^{-7}	41.6	0.91	57.3
313	4.83×10^{-7}	37.5	1.10	53.4
417	4.31×10^{-7}	35.4	0.66	18.5
419	4.88×10^{-7}	37.6	0.76	33.9

- Noise correlations between frequencies of the same horn (H). E.g. ~80% between 11 and 13GHz in intensity, and ~33% in polarization.

(Rubino-Martin et al. in prep.)

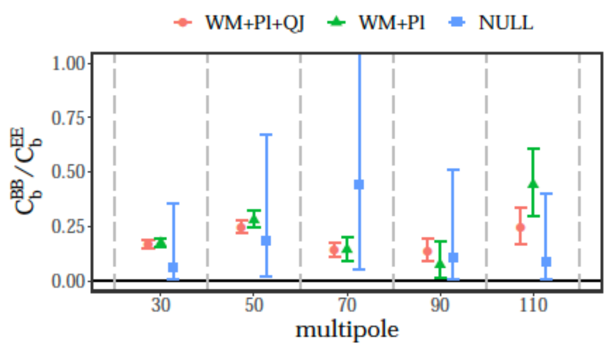
Wide survey with the QUIJOTE MFI (10-20GHz)

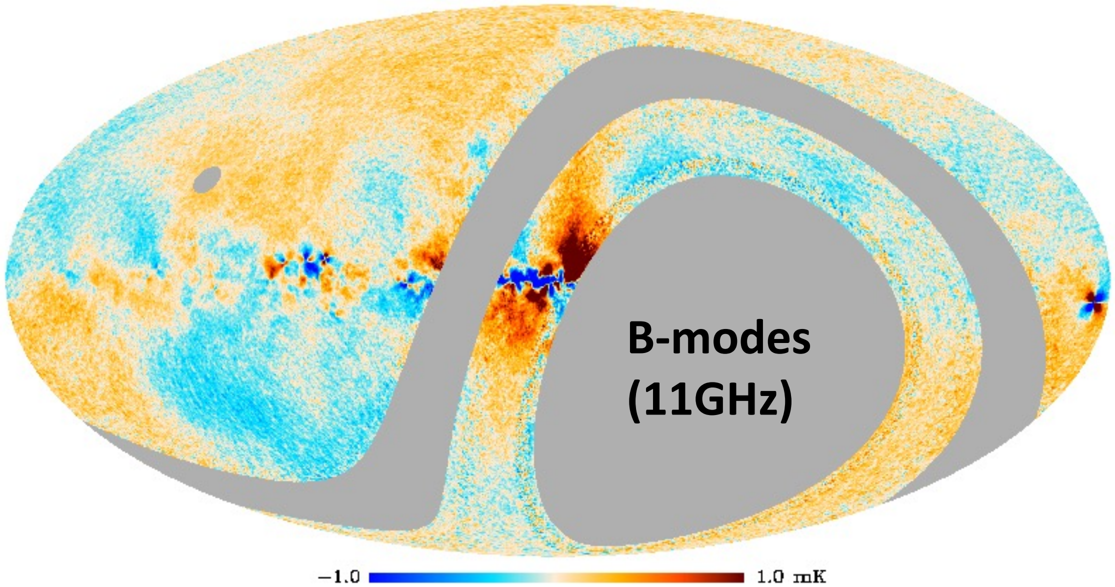
Synchrotron E-B modes and E/B ratio



- Most prominent polarized structures (Fan, NPS, loops) appear in the E-map.
- **EE/BB ratio is approx. 4 at large scales** (Rubino-Martin et al. in prep.). Consistent with Martire et al. 2022 (WMAP+Planck).
- For thermal dust, the ratio was closer to 2 (BB/EE~0.5, Planck Collaboration XI 2018).
- We measure **EB and TB consistent with zero**. Positive TE at large angular scales.

Analysis at the power spectrum level confirms this result (Vansyngel et al. in prep.)





(Rubino-Martin et al. in prep.)

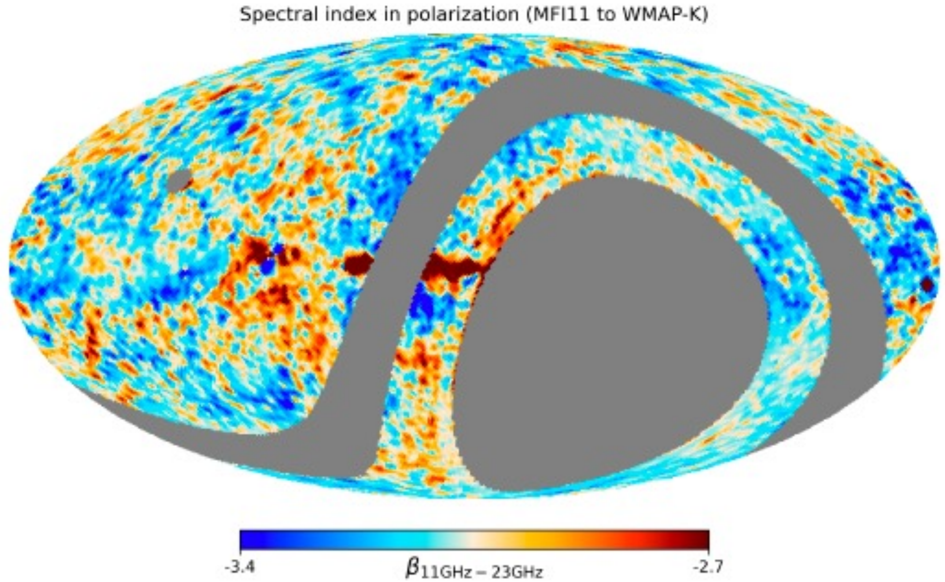
QUIJOTE-MFI wide survey results: synchrotron polarization

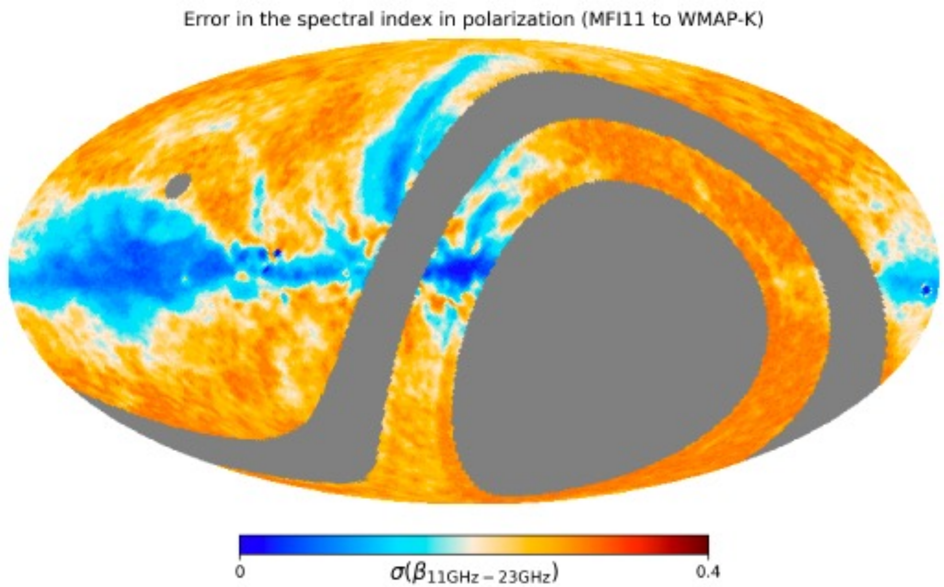
Spectral index of the polarized signal (**between QUIJOTE MFI 11GHz and WMAP 23GHz).** Maps at 2 deg and nside=64, and prior N(-3.1,0.3):

$$\beta(11\text{-}23\text{GHz}) = -3.09 \pm 0.14$$

Significantly broader than existing models. E.g. PySM synch model 1 (Thorne et al.2017), which corresponds to "Model 4" of Miville-Deschênes et al. (2008) gives -2.99 ± 0.06.

Component separation using parametric methods (B-Secret) with QUIJOTE, WMAP and Planck data gives same results → **see talk by Elena de la Hoz.**



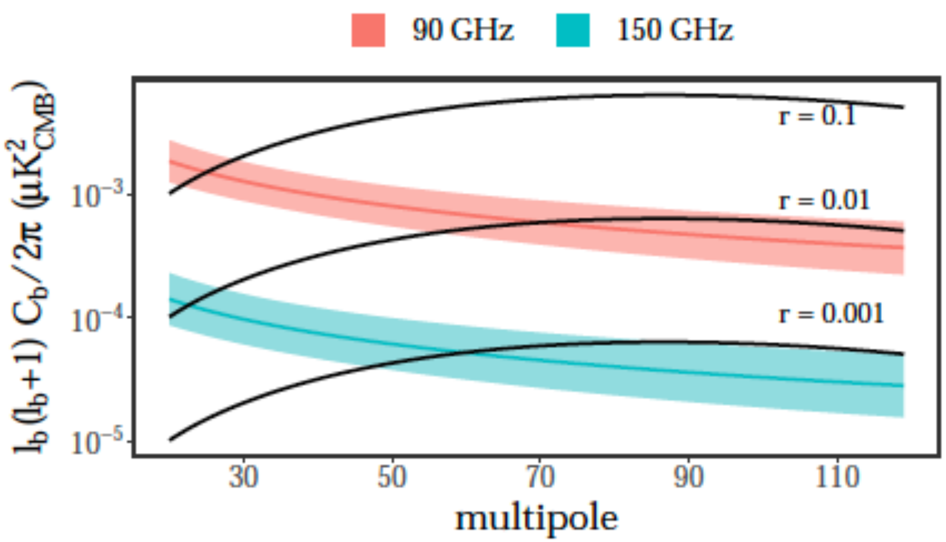


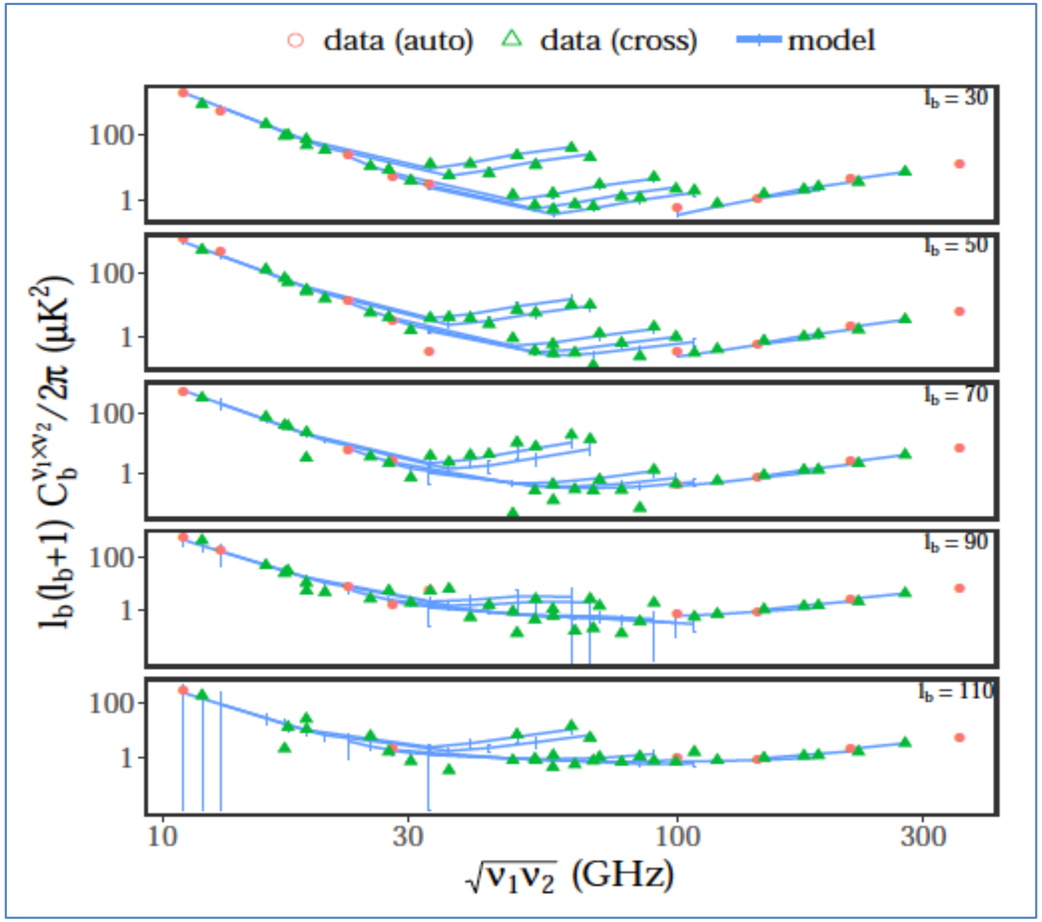
(Rubino-Martin et al. in prep.)

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: -3.20±0.05. [**Planck**: -3.13±0.13**, S-PASS**: -3.22±0.08].
- Dust-synchrotron correlation: ~ 0.18±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. :

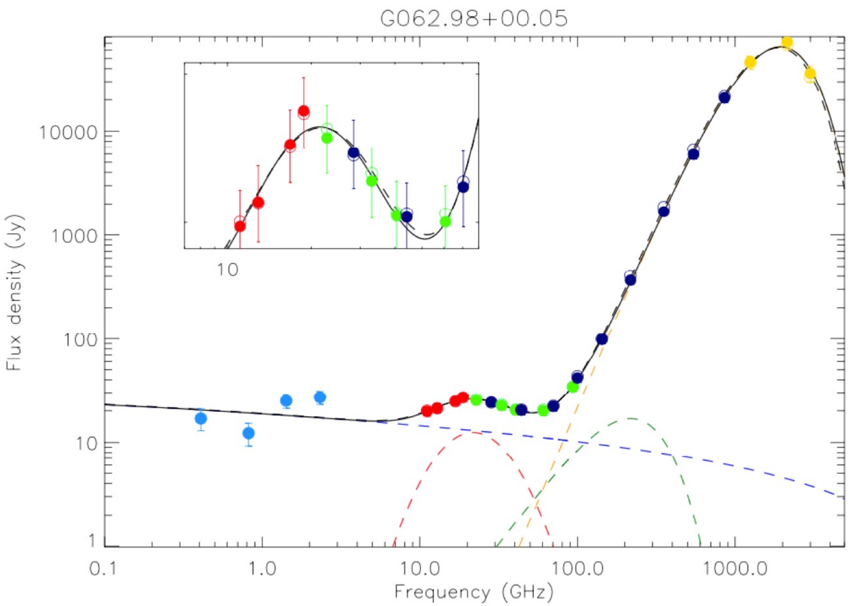


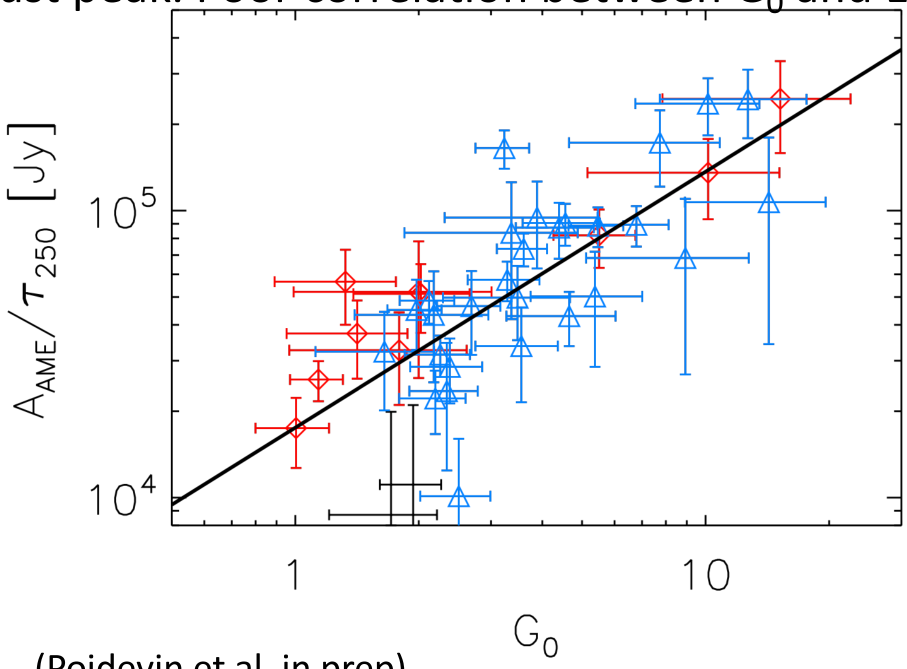


(Vansyngel et al. in prep)

QUIJOTE-MFI wide survey results: 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 41GHz from WMAP).
- **See poster by Raul Gonzalez** (re-analysis of W43+W44+W47 and ρ Ophiuchi).
- **Poidevin et al. (in prep)**: Study of 56 AME sources (includes targets from PIR XV 2014).
- **Intensity:**
  - QUIJOTE-MFI provides a cleaner separation of the AME, free-free and synchrotron components. Generally, higher AME and lower free-free.
  - Clear correlation (90%) of AME/tau_{dust} with radiation field G_0. Seen in Tibbs et al. (2011, 2012), and PIR XV (2014).
  - Clear correlation between AME and dust peak. Poor correlation between G_0 and EM.

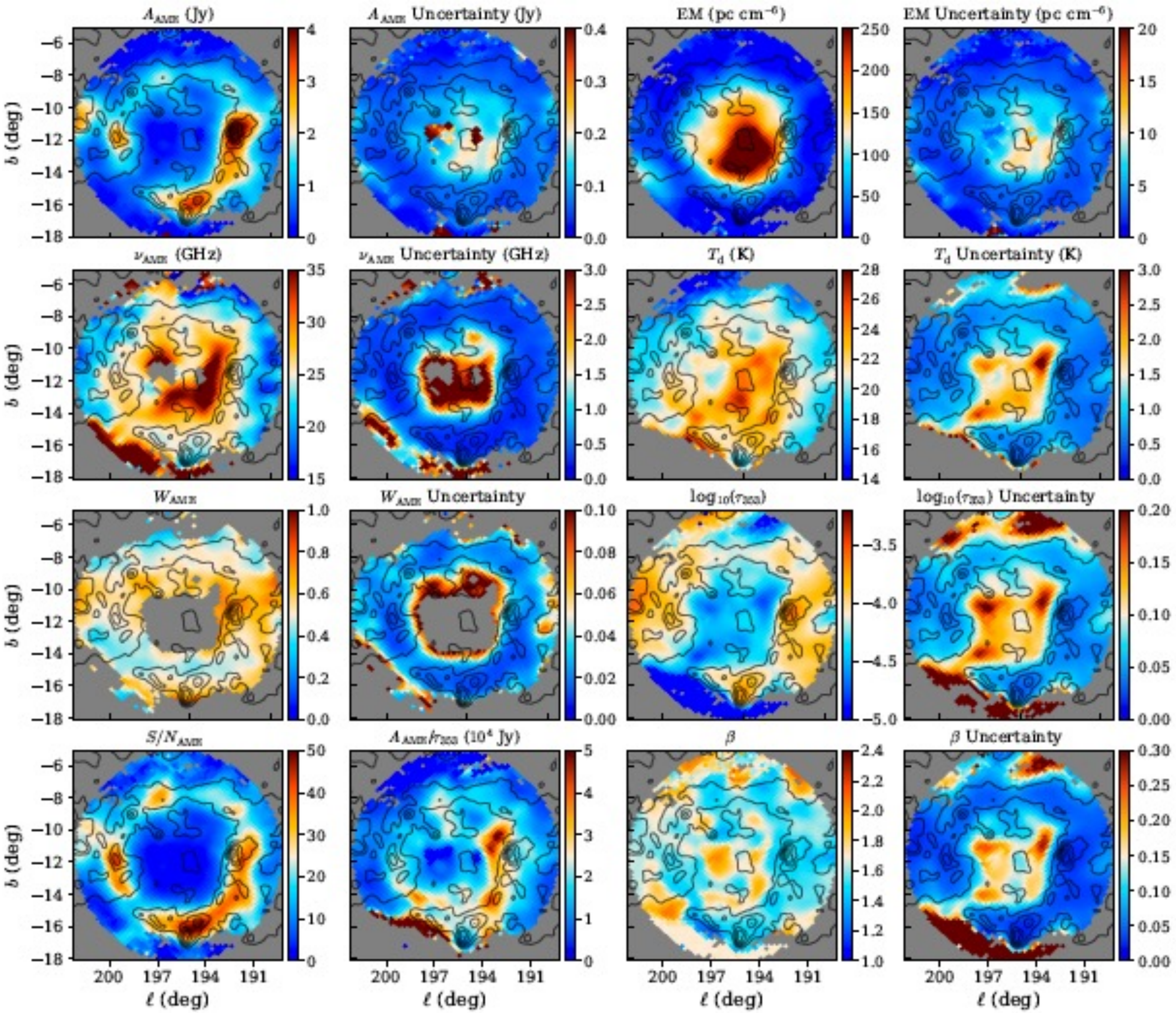


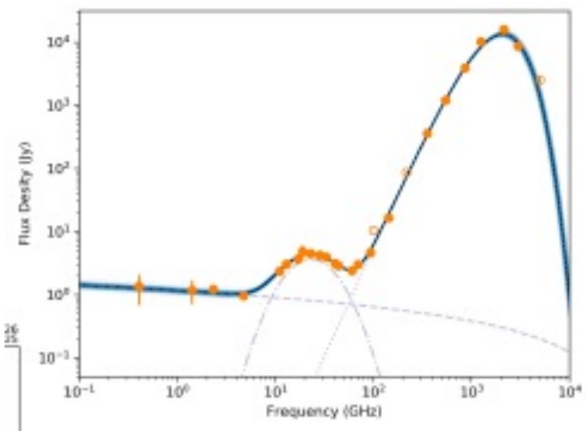


(Poidevin et al. in prep)

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. 2021).
- **Joint QUIJOTE & C-BASS paper**.
- Spatial variability of AME properties.



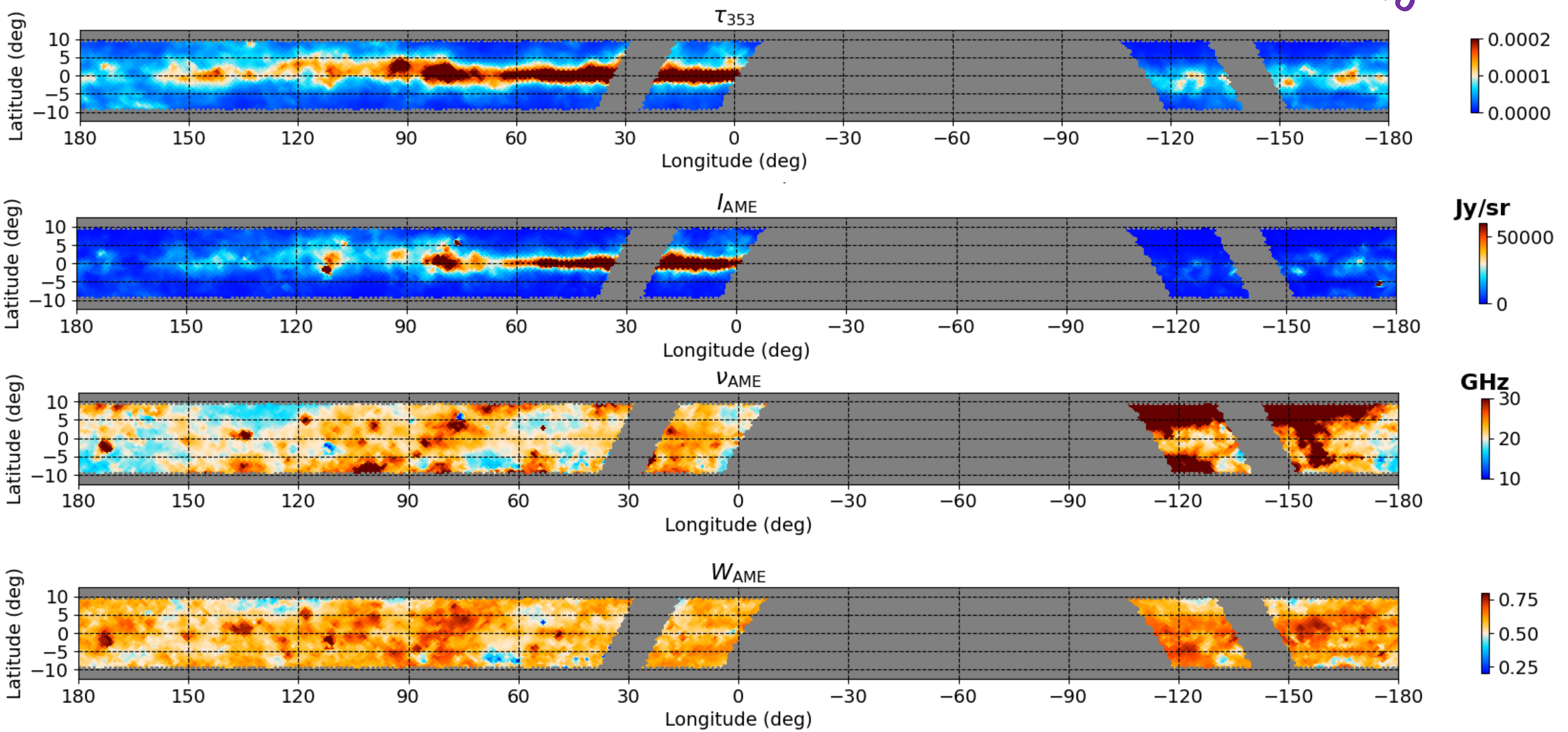


(Cepeda-Arroita et al. 2021)

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

See poster by Mateo Fernandez-Torreiro

Variability of AME parameters in the galactic plane



- Extending the previous work to the Galactic plane (|b|<10º) seen by QUIJOTE MFI.
- AME parameterization: parabola in log S – log ν plane, three params (A, ν_{AME}, width).
- Spatial variability of AME properties seen in other regions. Correlations.

(Fernandez-Torreiro et al. in prep).

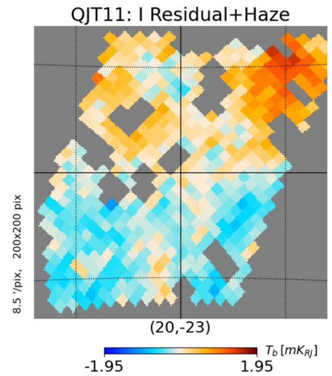
QUIJOTE-MFI wide survey results: Haze emission

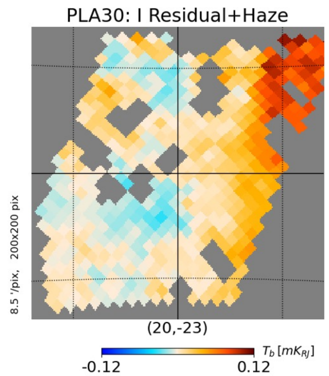
See poster by Federica Guidi

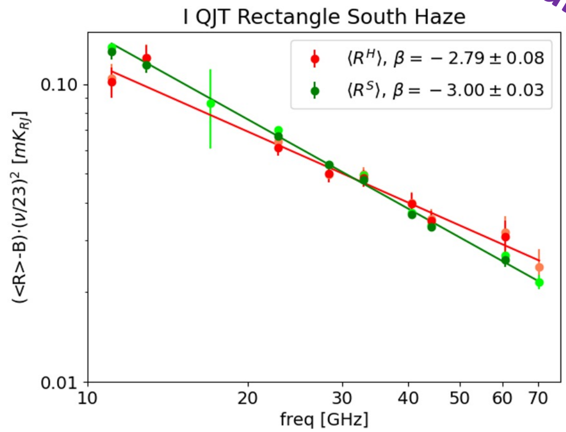
Data: wide-survey + raster scans

Intensity

- Haze component is detected at 9σ, at 11 GHz.
- Spectrum steeper than previous measurements (β=−2.56±0.05, Planck IX, 2013).

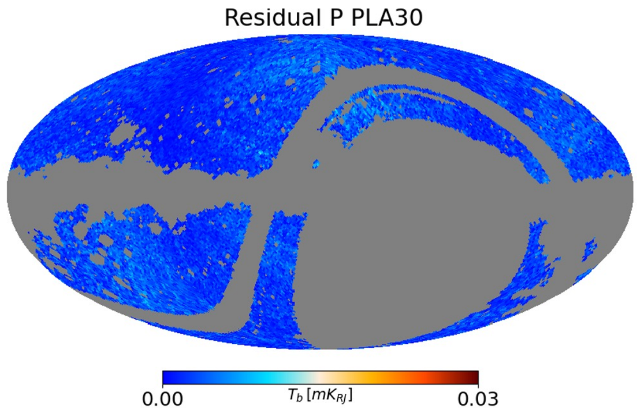


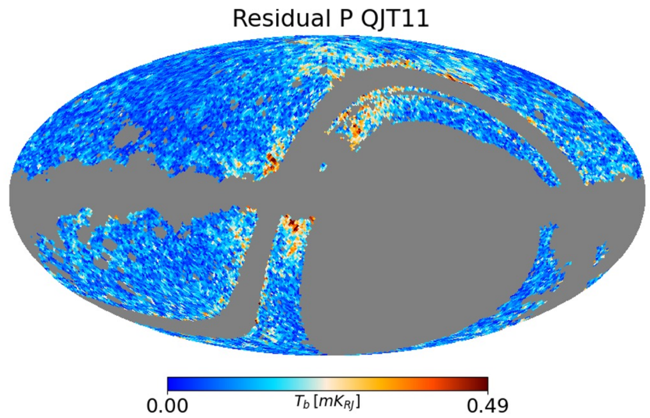


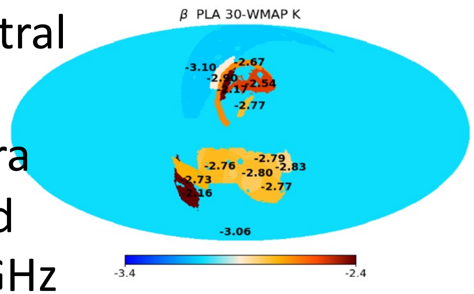


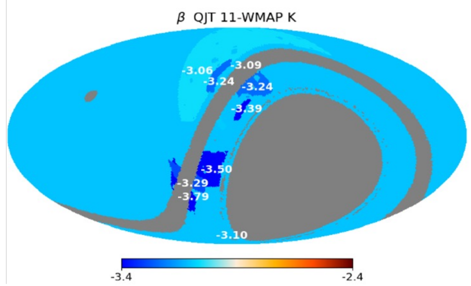
Polarization

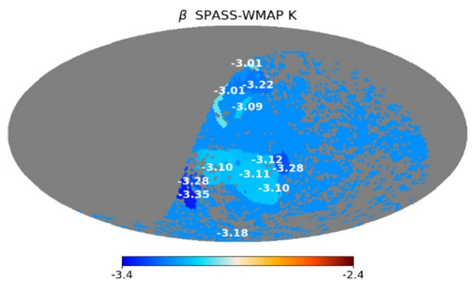
- Sky signal residuals observed in polarization after subtracting other foregrounds. Possibly due to curvature of the spectral index.
- TT-plots show flat spectra indices at 23-30 GHz and steep spectra at 11-23 GHz and 2.3-23 GHz.









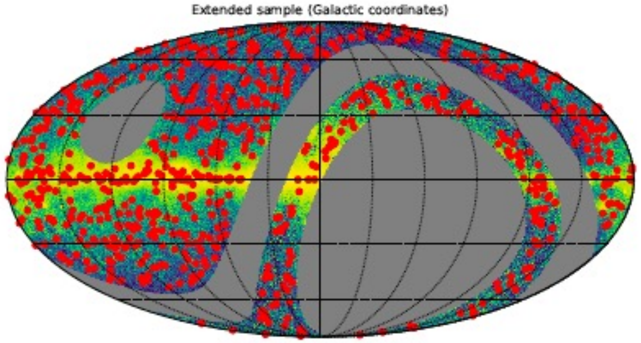


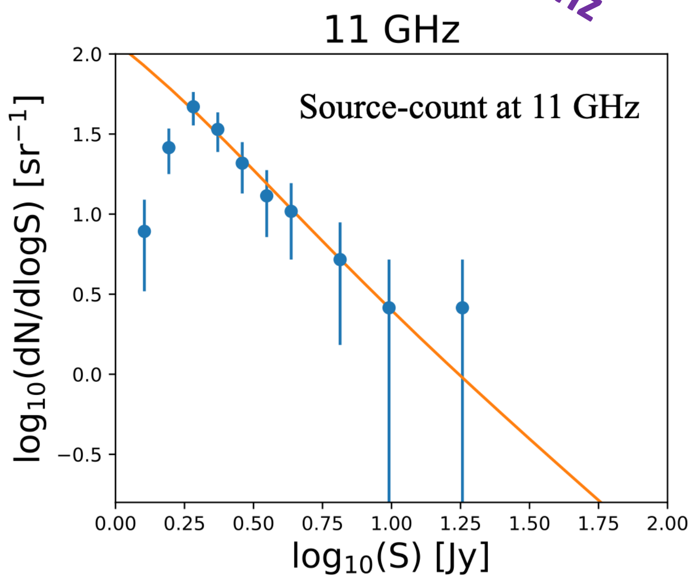
(Guidi et al. in prep)

QUIJOTE-MFI wide survey results: radiosources

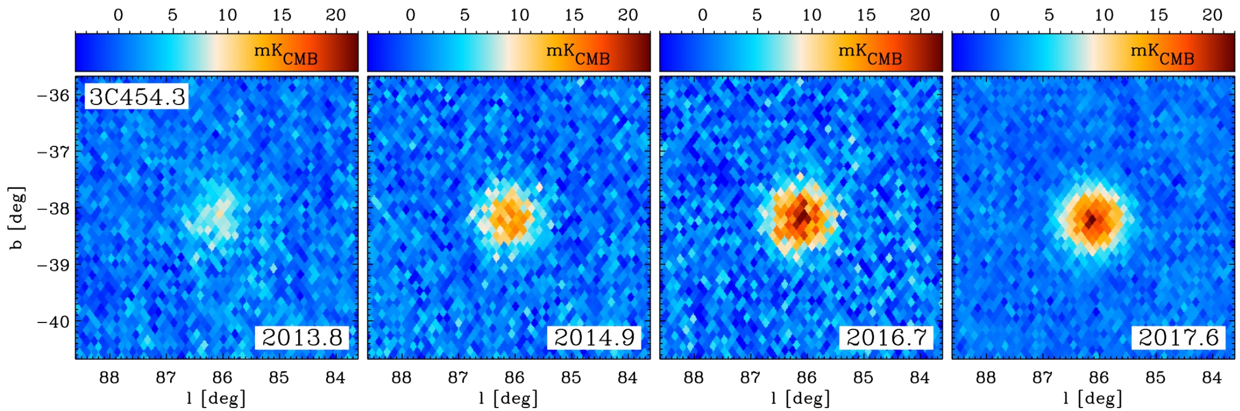
See poster by Diego Herranz

- Systematic study of a catalogue of **782 sources** in the QUIJOTE wide-survey maps
- Completeness limit at 11 GHz **~1.8 Jy**
- Study of polarisation properties of ~35 sources **<Π> = [2.8,4.7] %**

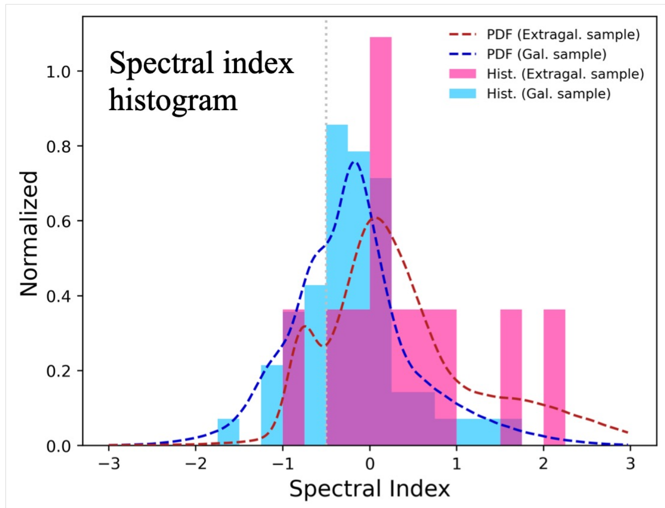




- Blind variability search → 7 variable sources, with 3 being strongly variable:



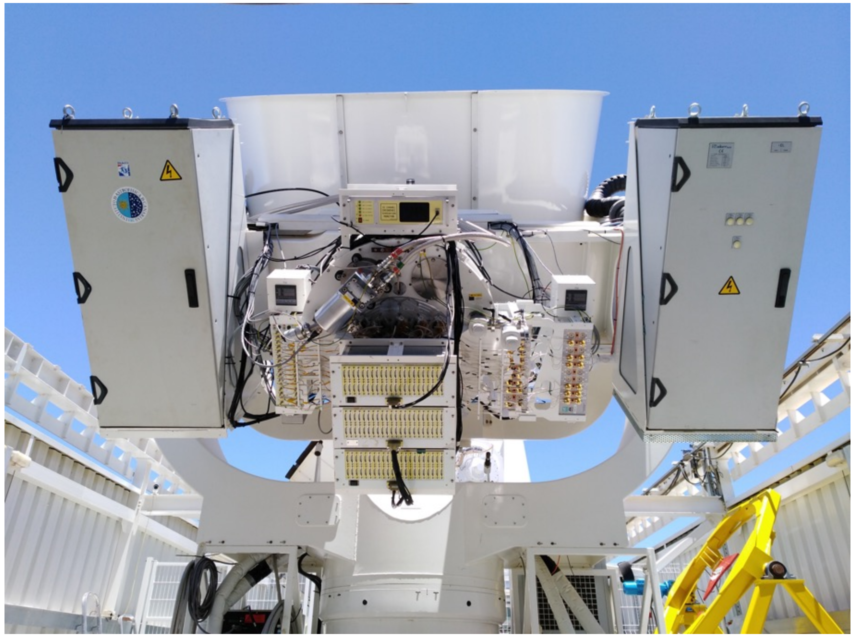
Variability of 3C454.3 in the four-period maps

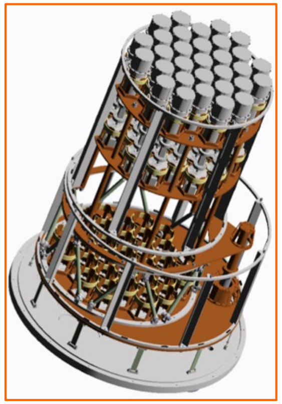


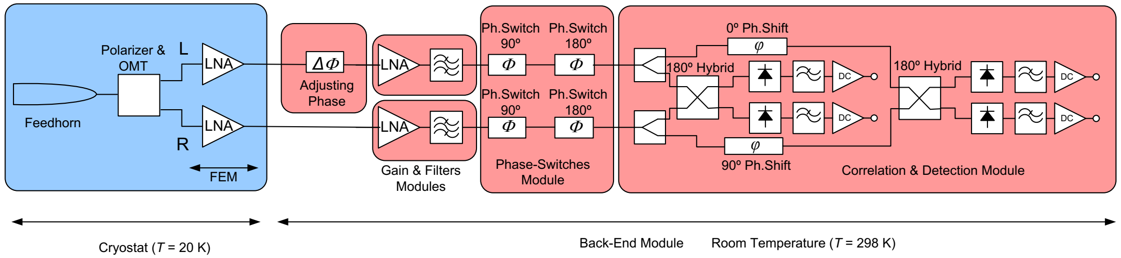
(Herranz et al. in prep)

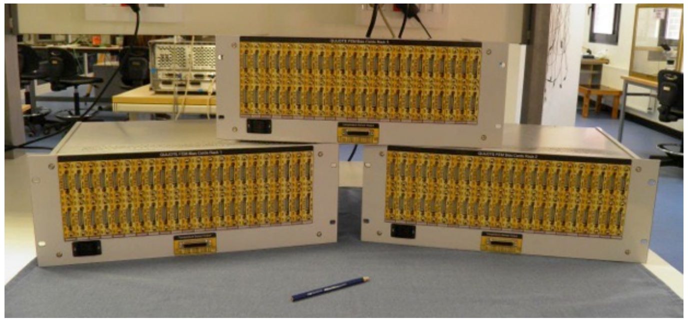
TGI (30 GHz) and FGI (40GHz) instruments @ QT2

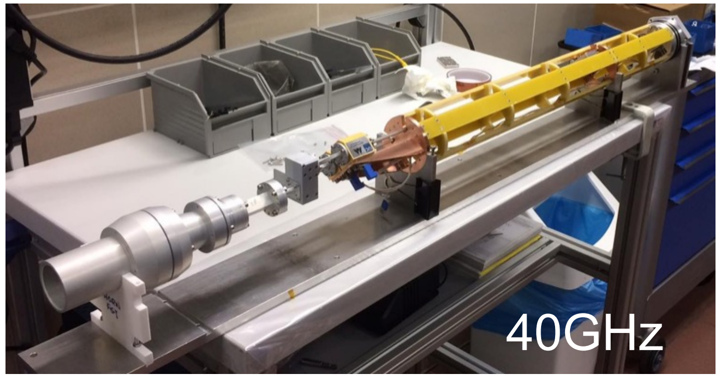
- **TGI**: 31 pixels at 30GHz. Measured sensitivity: 50 μK $s^{1/2}$ for the full array. First light May 12th 2016.
- **FGI**: 31 pixels at 40GHz. Sensitivity: 60 μK $s^{1/2}$ for the full array. First observations in 2018-19 (with 14 pixels).
- **Joint TGI/FGI observations started in 2018**. Stopped during 2020. Problem with the cryostat fixed → re-started Nov 2021 with 7 pixels.

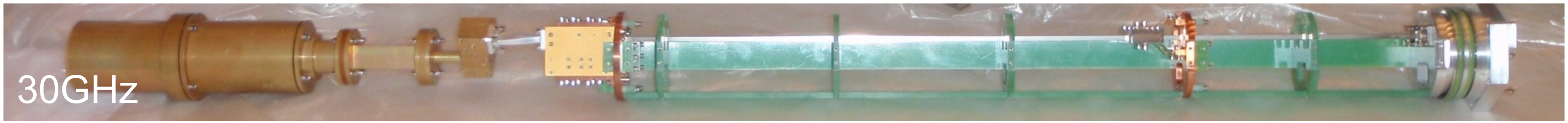






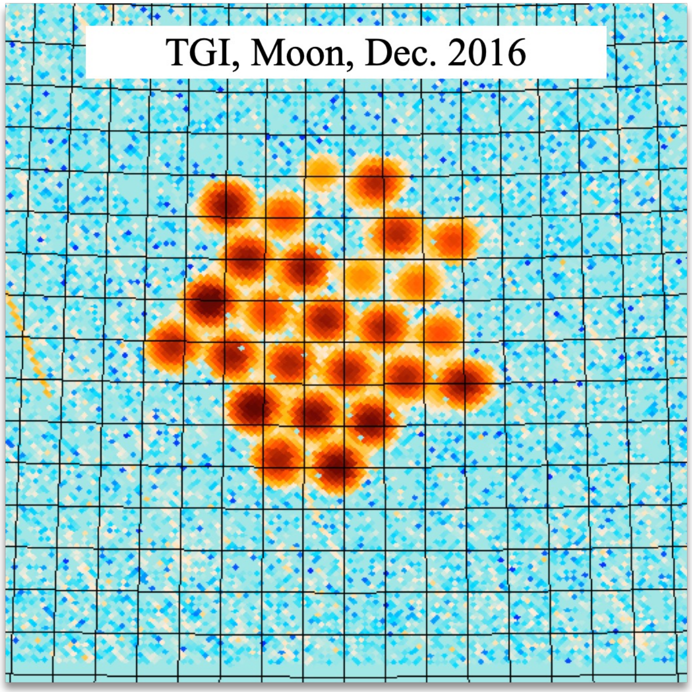




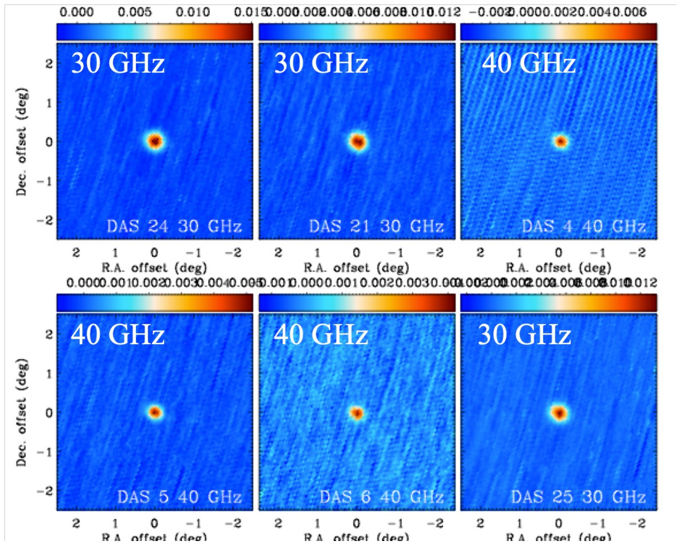


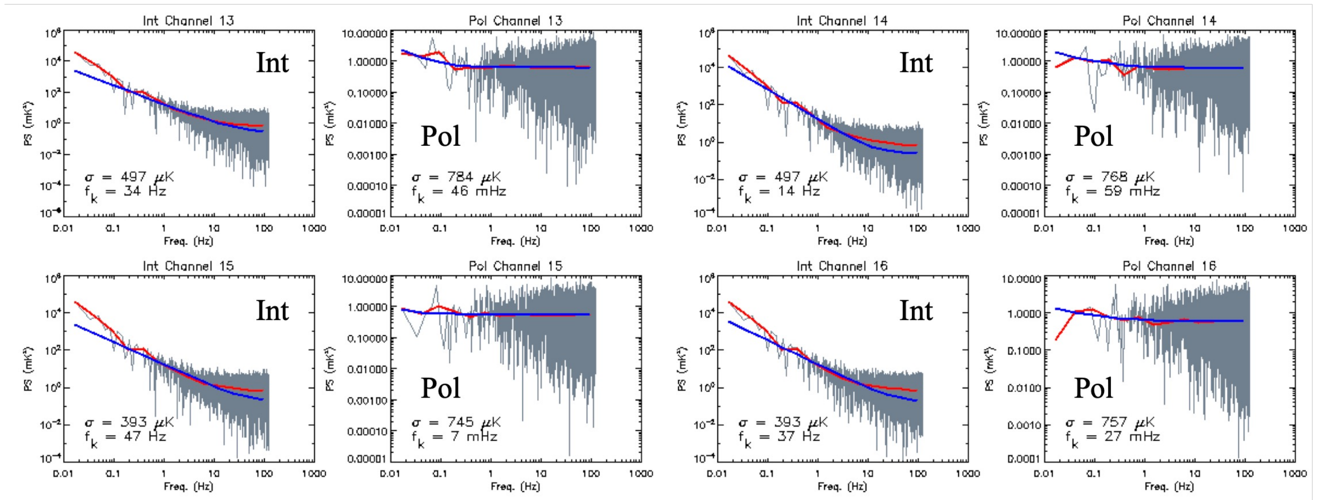
TGI (30 GHz) and FGI (40GHz) instruments @ QT2

- **TFGI**: December 2021 – new commissioning observations
- Preliminary characterisation of the instrument performance
- Noise properties
  - White noise level ~ 400-900 μK·$s^{1/2}$ per channel
  - f_k ~ 20 - 50 Hz in intensity
  - f_k < 100 mHz in polarisation.
- Beam characterisation
  - FWHM (30 GHz) ~ 22 arcmin.
  - FWHM (40 GHz) ~ 17.5 arcmin.



Tau A (December 2021)

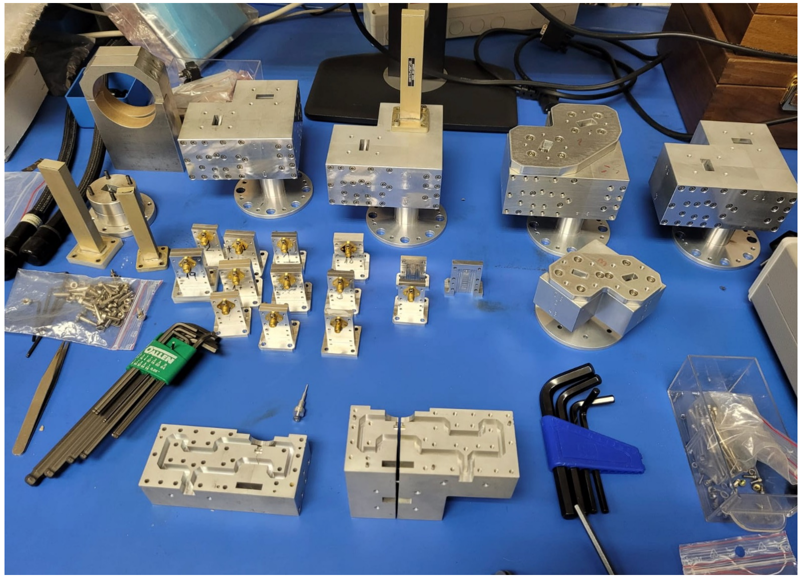


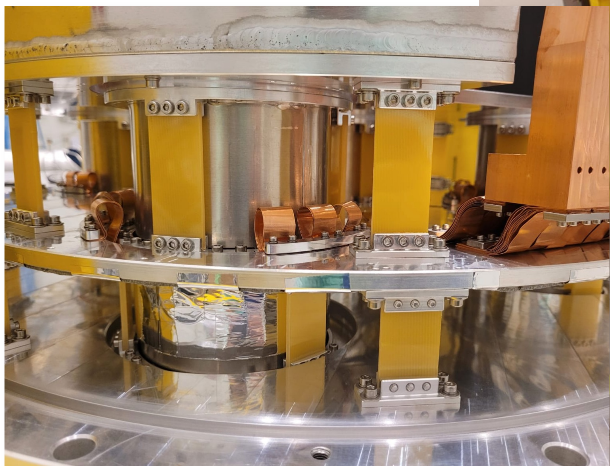


Sky dips (January 2022)

MFI2 Instrument (10-20 GHz)

- **MFI upgrade (MFI2 @ QT-1)**. 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**. Three covering the 10-14GHz band, and two covering 16-20GHz.
- Full digital back-end (FPGAs) → RFI removal.
- **Status**: Cryostat fabricated and tested. Opto-mechanical components fabricated. Now in assembly phase.
- **Operations**: 3 effective years, starting late 2022.

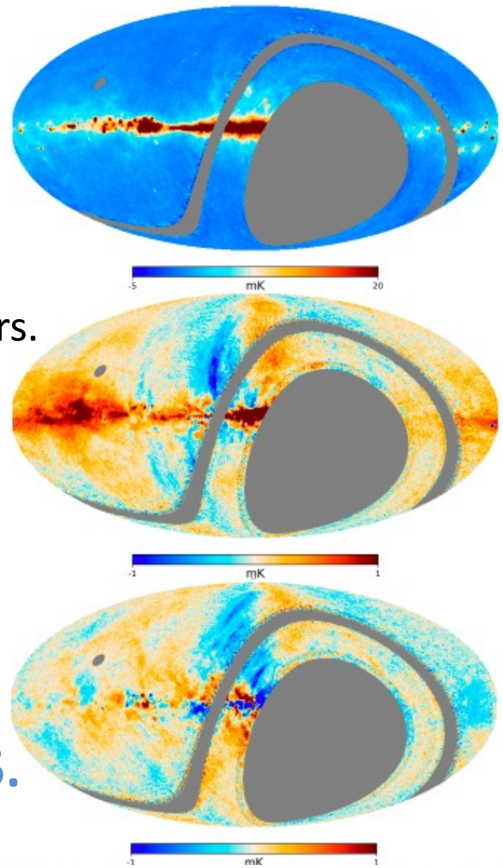




Summary and conclusions

QT1 + QUIJOTE MFI 10-20 GHz: 2012-2018.

- **Wide survey** (>10,000h) completed. Four maps at 11, 13, 17, 19GHz, with sensitivities ~35-40 μK/beam in polarization. 13 papers in preparation. Data release will happen after acceptance of first 6 papers. Legacy value for LiteBIRD.
- **4 posters in this conference!**
- **Implications for foreground studies of QUIJOTE MFI data**
  - Synchrotron. Spatial variability of synchrotron spectral index. Curvature. Dust-synchrotron correlation (~20%).
  - AME modelling (AME pol. fraction < 0.22%)



QT2 + TGI (30 GHz) and FGI (40 GHz): 2018-2025.

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

QT1 + MFI2 (10-20 GHz): 2023-2025.

- Final integration phase. Higher sensitivity by a factor 3 x MFI. Less RFI.

TMS (10-20GHz): 2023-2025.

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

Combination with other experiments at Teide Obs.: 2023-2025.

- **Groundbird** (150, 220GHz), **LSPE-STRIP** (43, 90GHz). Northern sky.