Modelling RADIOFOREGROUNDS: Combining Planck and QUIJOTE data

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future work with planck data

ESAC, 3-4 December 2018

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.

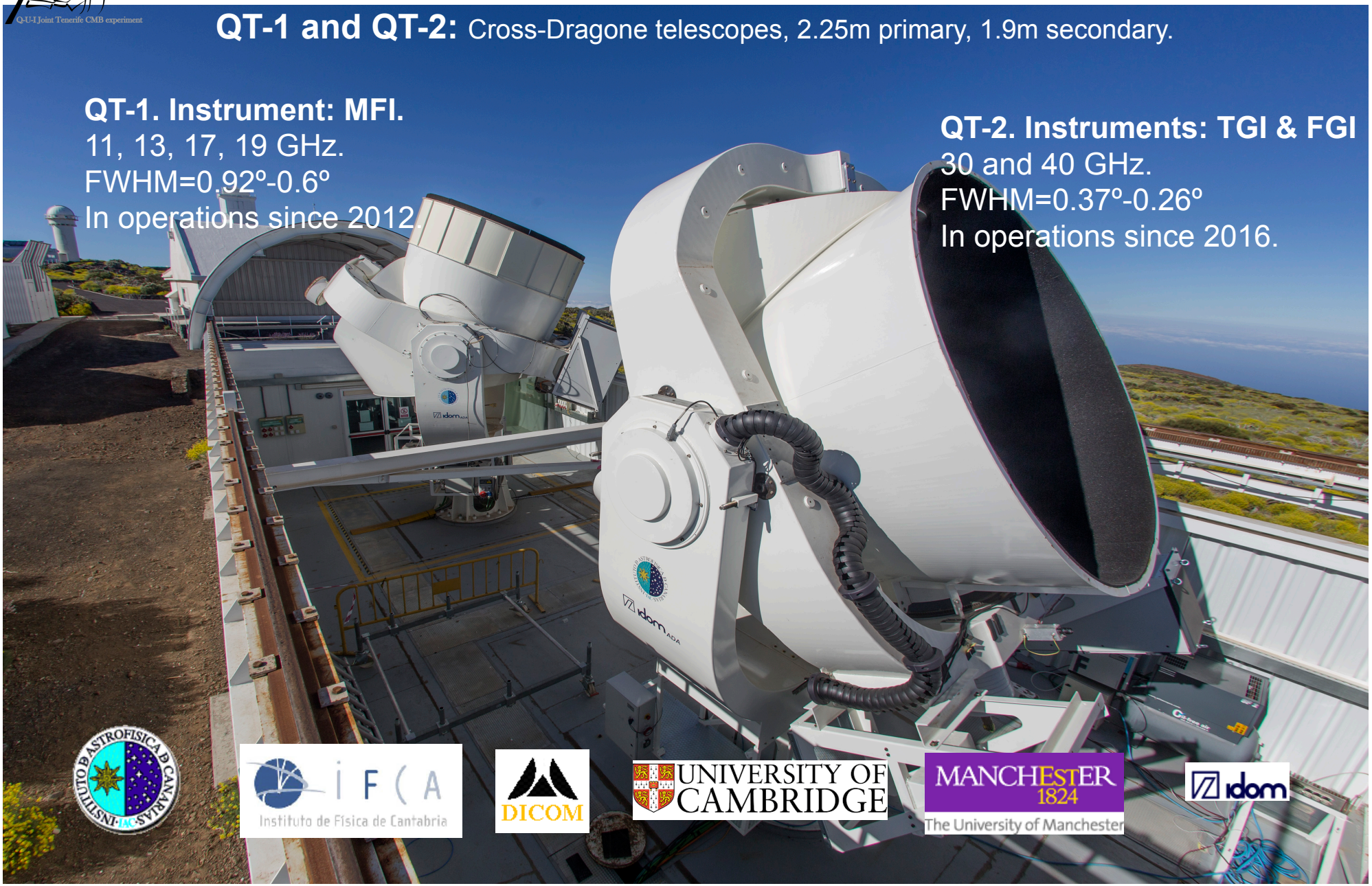
The QUIJOTE experiment

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.



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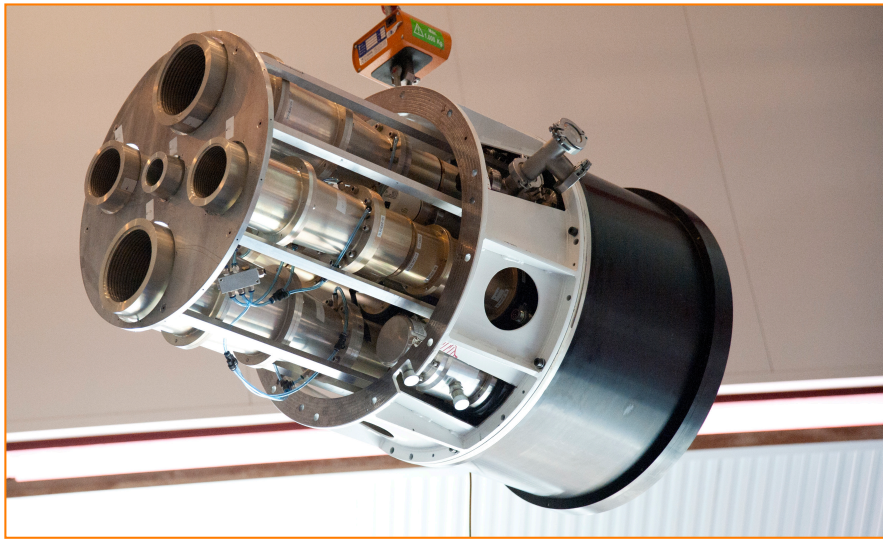
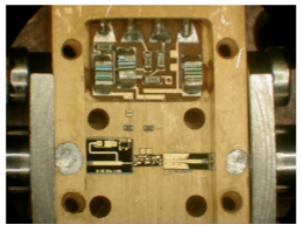
MANCHESTER 1824 The University of Manchester

idom

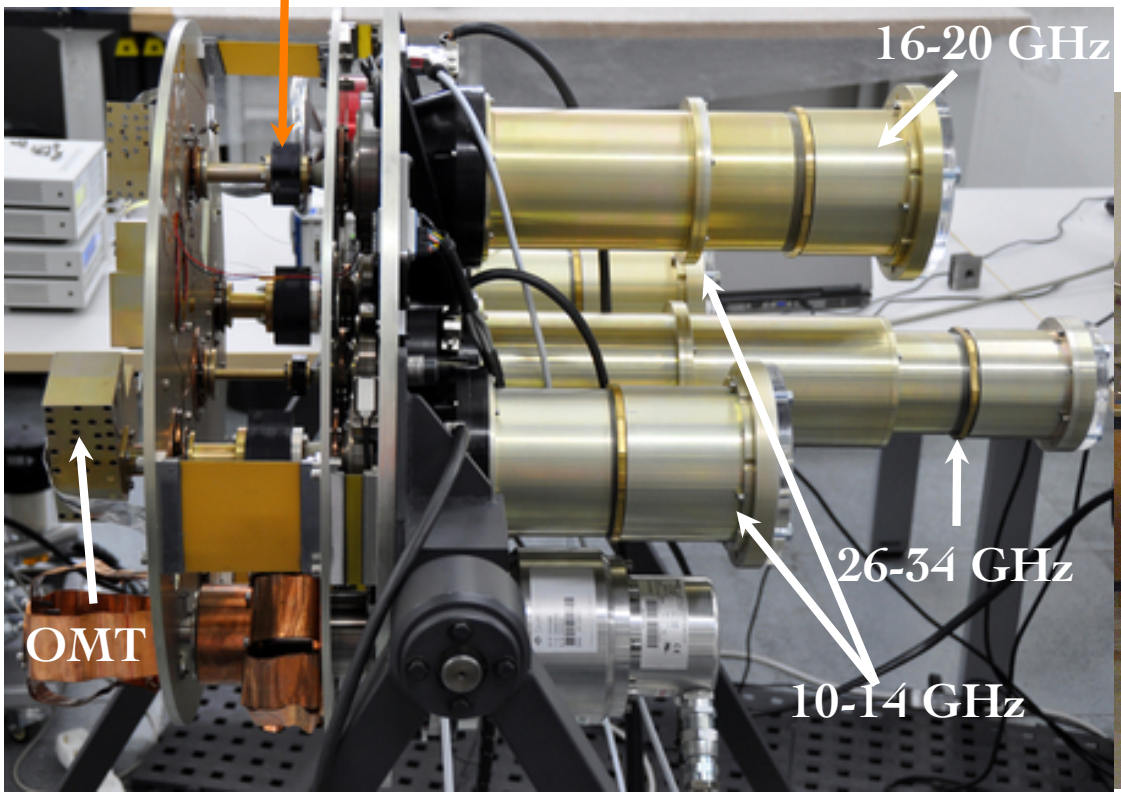
MFI Instrument (10-20 GHz)

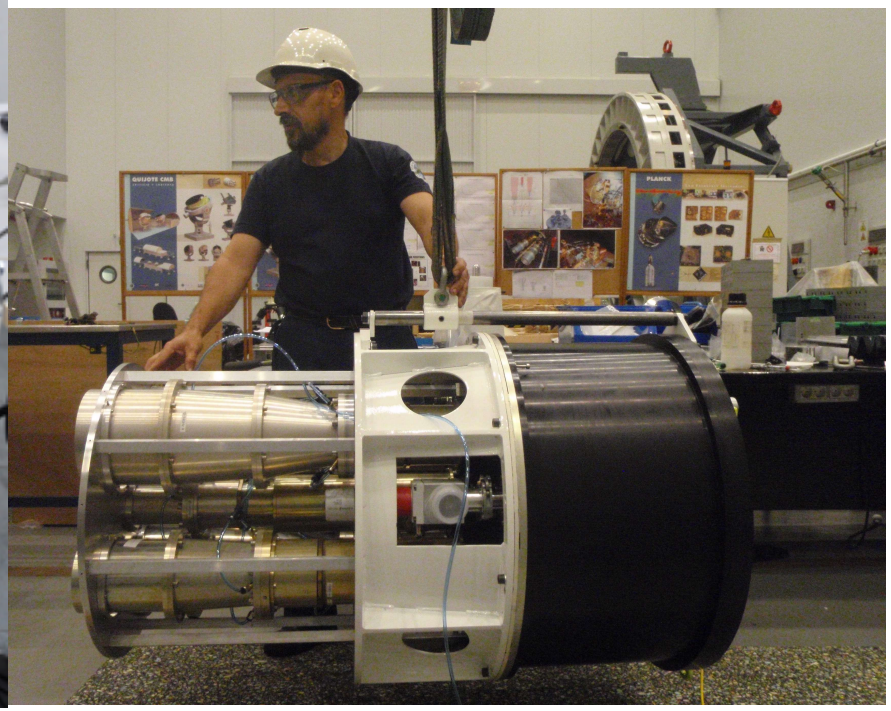
- In operations since Nov. 2012.
- 4 horns, 32 channels. Covering 4 frequency bands: 11, 13, 17 and 19 GHz.
- Sensitivities: ~400-600 μK $s^{1/2}$ per channel.
- **MFI upgrade (MFI2)**. Funds secured. Aim: to increase the integration speed by a factor of 3.





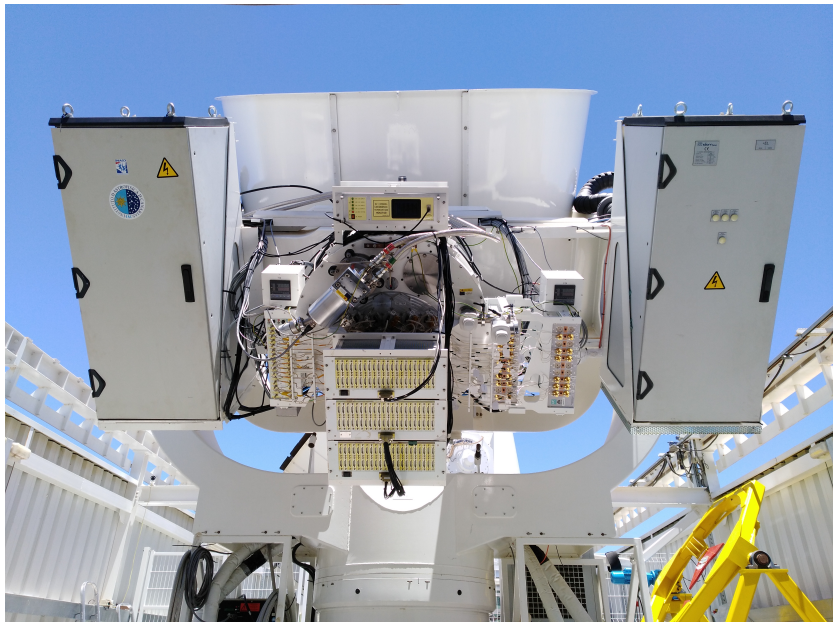
LNA

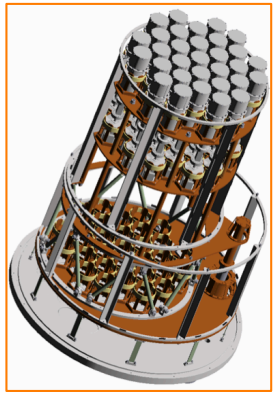


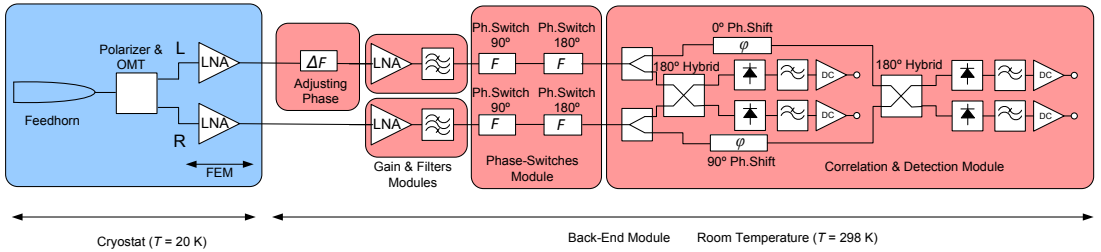


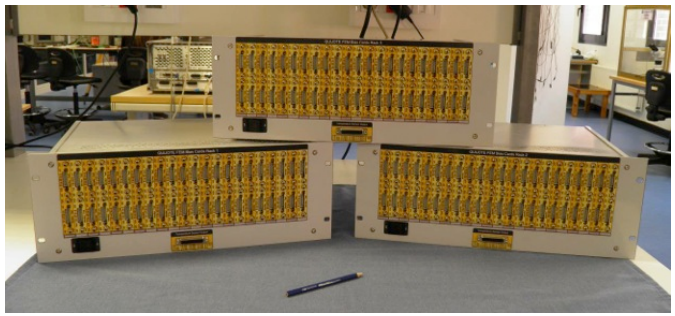
TGI (30 GHz) and FGI (40GHz) instruments

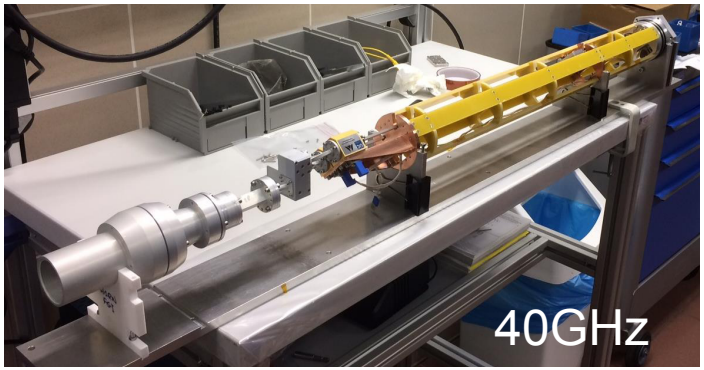
- **TGI**: 31 pixels at 30GHz. Measured sensitivity: 50 μK $s^{1/2}$ for the full array. First light May 12th 2016.
- **FGI**: 31 pixels at 40GHz. Expected sensitivity: 60 μK $s^{1/2}$ for the full array. In commisioning phase.
- Joint comissioning started in 2018.

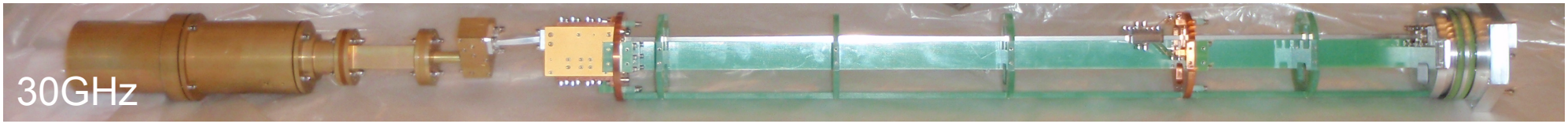












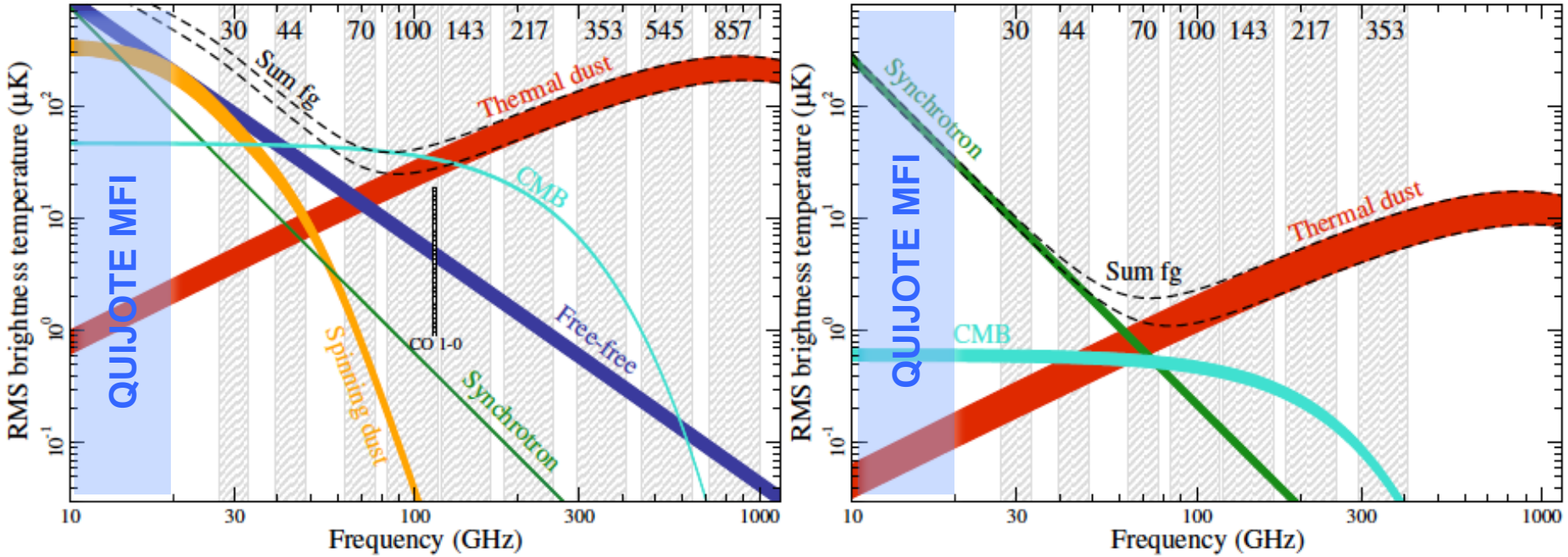
Science with QUIJOTE first instrument (MFI)

- **Shallow Galactic survey**. Covering 20,000 deg^2 (almost 10000 hrs completed)
  - ≈ **30 μK/(beam 1º)** with the MFI @ 11, 13, 17 and 19 GHz, in both Q and U.
- **Deep cosmological survey**. It will cover around 3,000 deg^2 in three separated fields.
  - ≈ **10 μK/(beam 1º)** after 1 year with the MFI @ 11, 13, 17 and 19 GHz.

- These maps will provide valuable information about the **polarization** properties of:
  - Synchrotron: main emission mechanism at our frequencies.
  - Anomalous microwave emission (spinning dust?). Current best upper limits of polarization fraction are 0.2% (Génova-Santos et al. 2017) .
- Excellent complement to PLANCK at low frequencies. Legacy for future experiments.

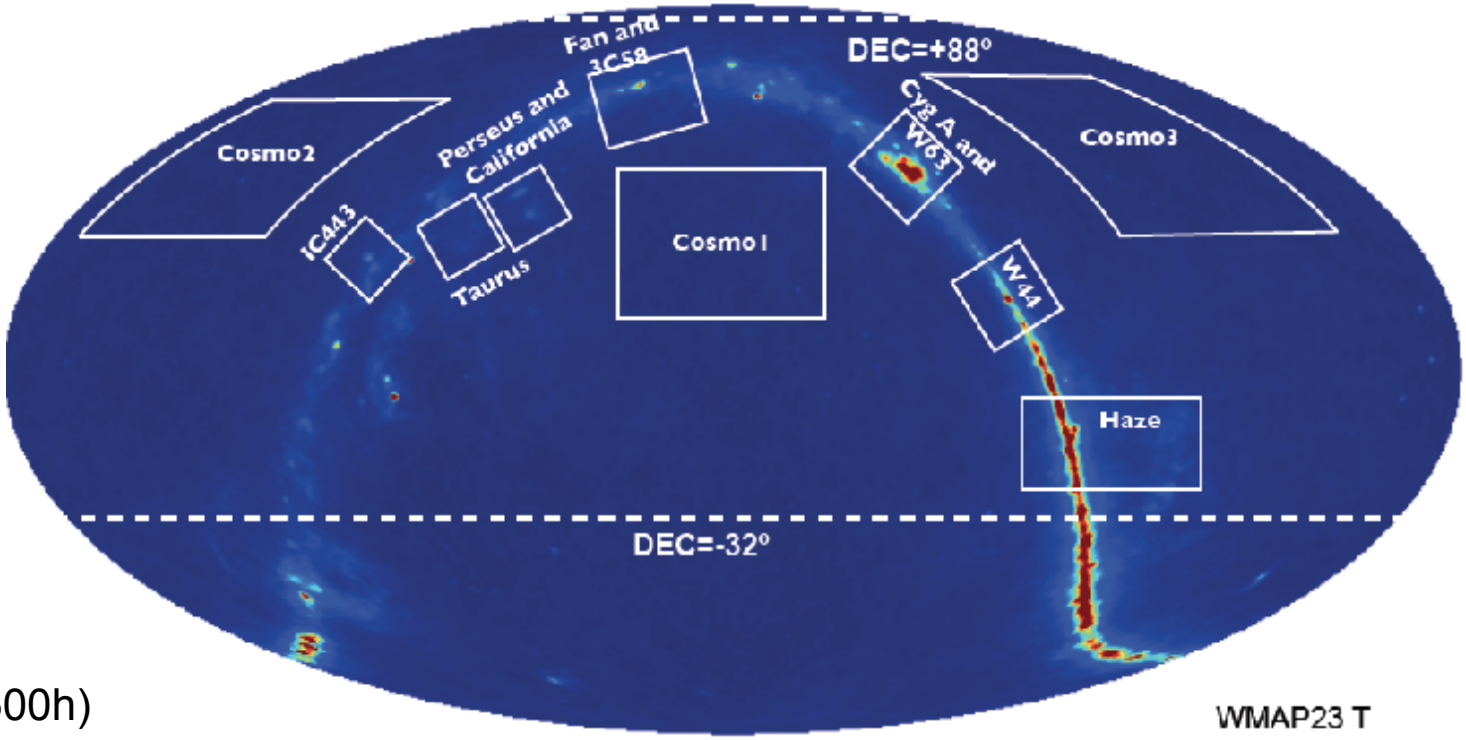
RADIO FOREGROUNDS

Planck Collaboration 2015



QUIJOTE cosmological and galactic fields

Observing strategy: Deep observations in selected areas using raster scans, plus wide survey.



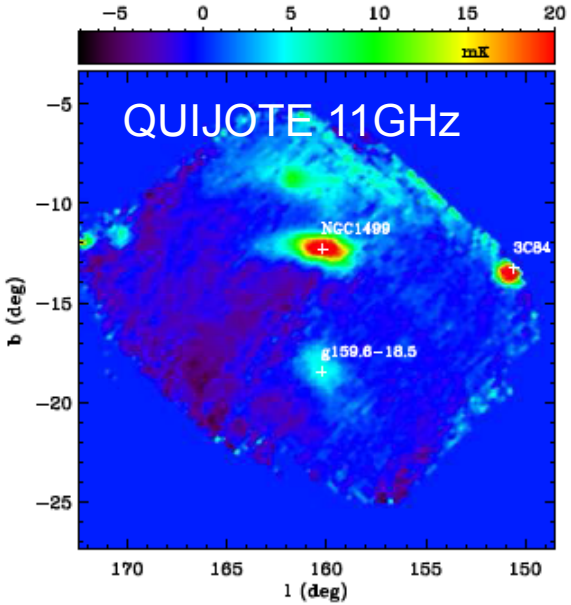
MFI Science phase
(April 2013 - now)

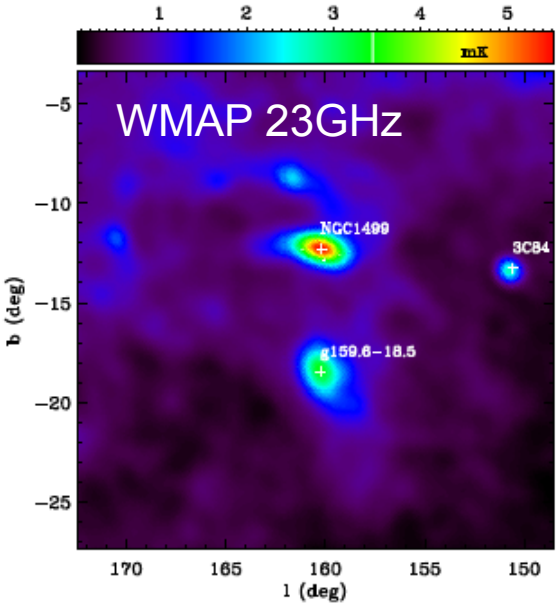
- Wide survey (10,800h)
- Cosmological fields (6,500h)
- Daily calibrators (Crab, Cass A, Jupiter, sky dips)
- Galactic centre and Haze (930h)
- Perseus molecular cloud (600h)
- Fan region and 3C58 (460h)
- Taurus region (450h)
- SNRs (W44, W47, IC443, W63) (900h)

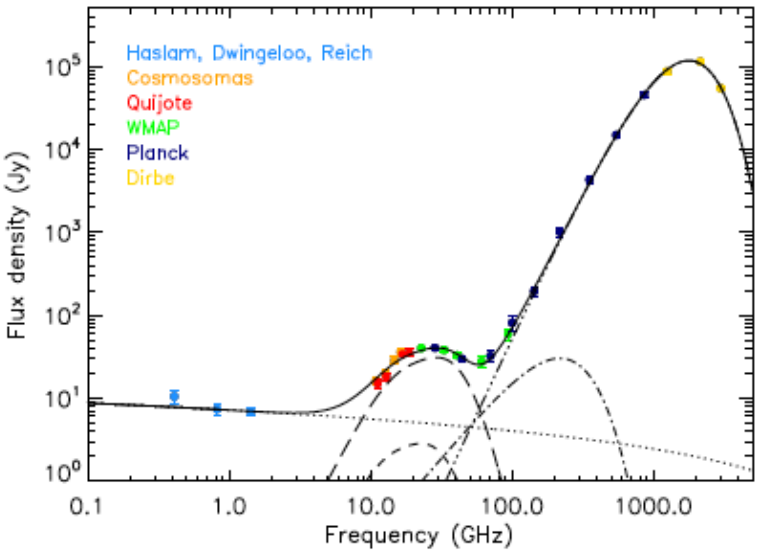
Total: ~**25,500 h** of MFI data (2.9 effective years), with ~50% efficiency.

Perseus Molecular Complex

- Large observing programme (**200h**, taken during Dec-2012 to Apr-2013), on an area covering 200 deg^2 around the **Perseus molecular complex**. One of the brightest AME regions on sky (Watson et al. 2005; Planck Collaboration 2011).
- Also covering California nebula or NGC1499 (HII region, a null polarization control region).
- Final integration time of ~3000s/beam, yielding ~30mJy/beam in Q, U maps.





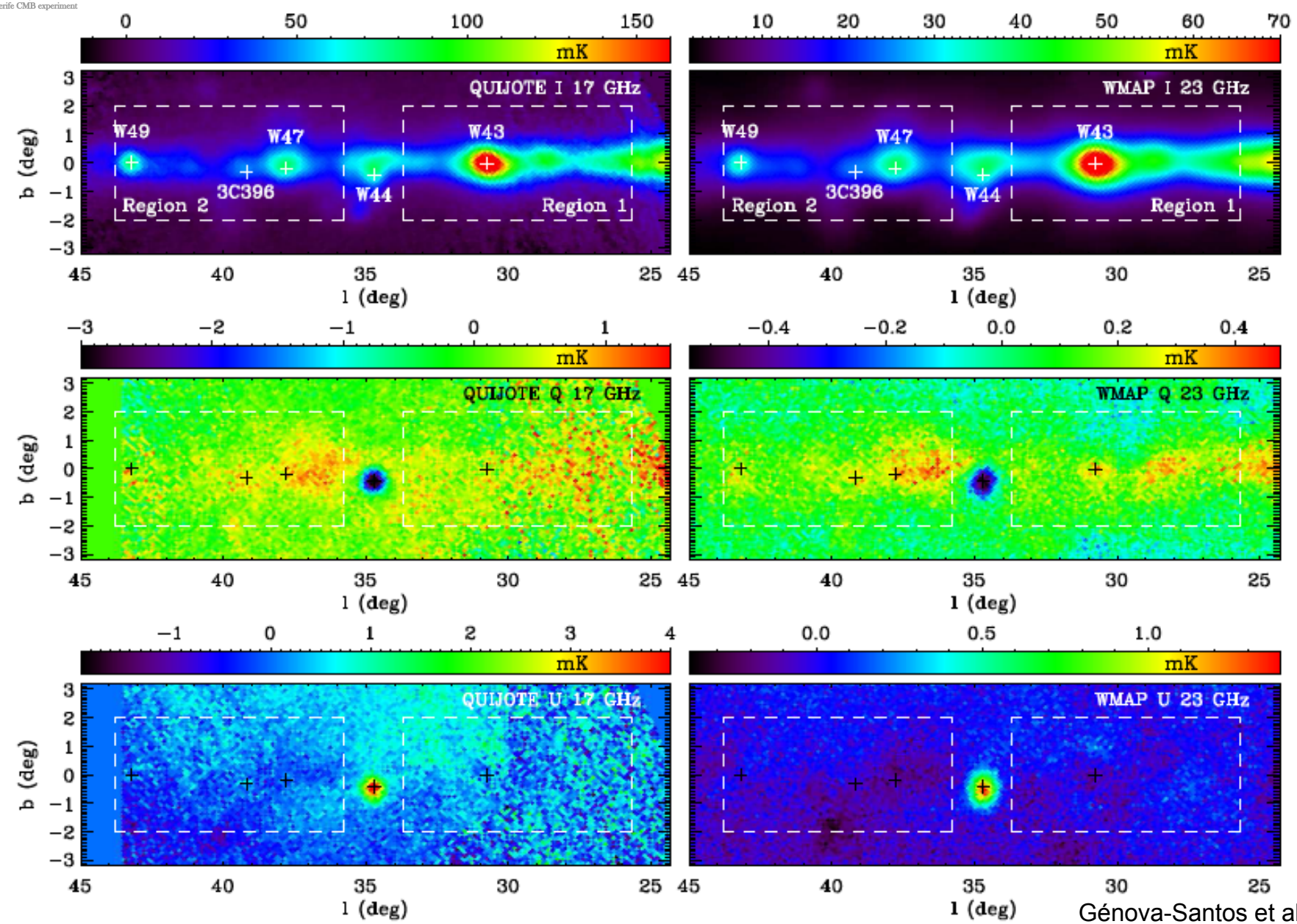


- AME component clearly detected (QUIJOTE+WMAP+PLANCK).
- **No polarization detection**. Π < 6.3% at 12GHz and < 2.8% at 18GHz (95% C.L.).

(Genova-Santos et al. 2015)

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)

★ Fits to intensity SEDs

★ Fit AME with the a 3-parameter parabola:

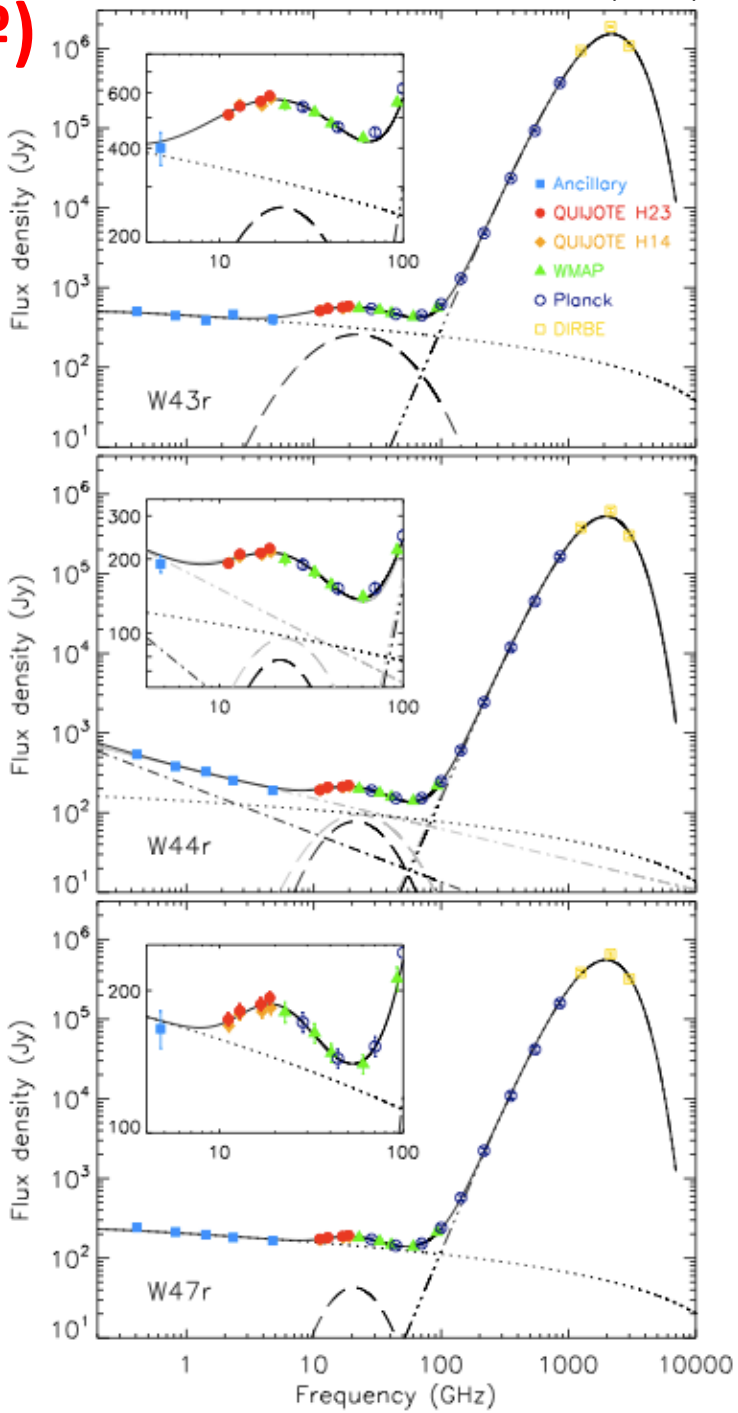
Region	S_{AME} (Jy)	*EM* (cm^{-6} pc)	χ^2/dof
W43	258 ± 7	3911 ± 68	5.4
W44	78 ± 6	1264 ± 22	1.0
W47	43 ± 2	1849 ± 20	1.0

★ *EM* estimates from Commander or from RRL (Alves et al. 2015):

Region	Commander	RRL
W43	5888	4020 - 6190
W44	1667	990 - 1340
W47	1806	1360 - 1840

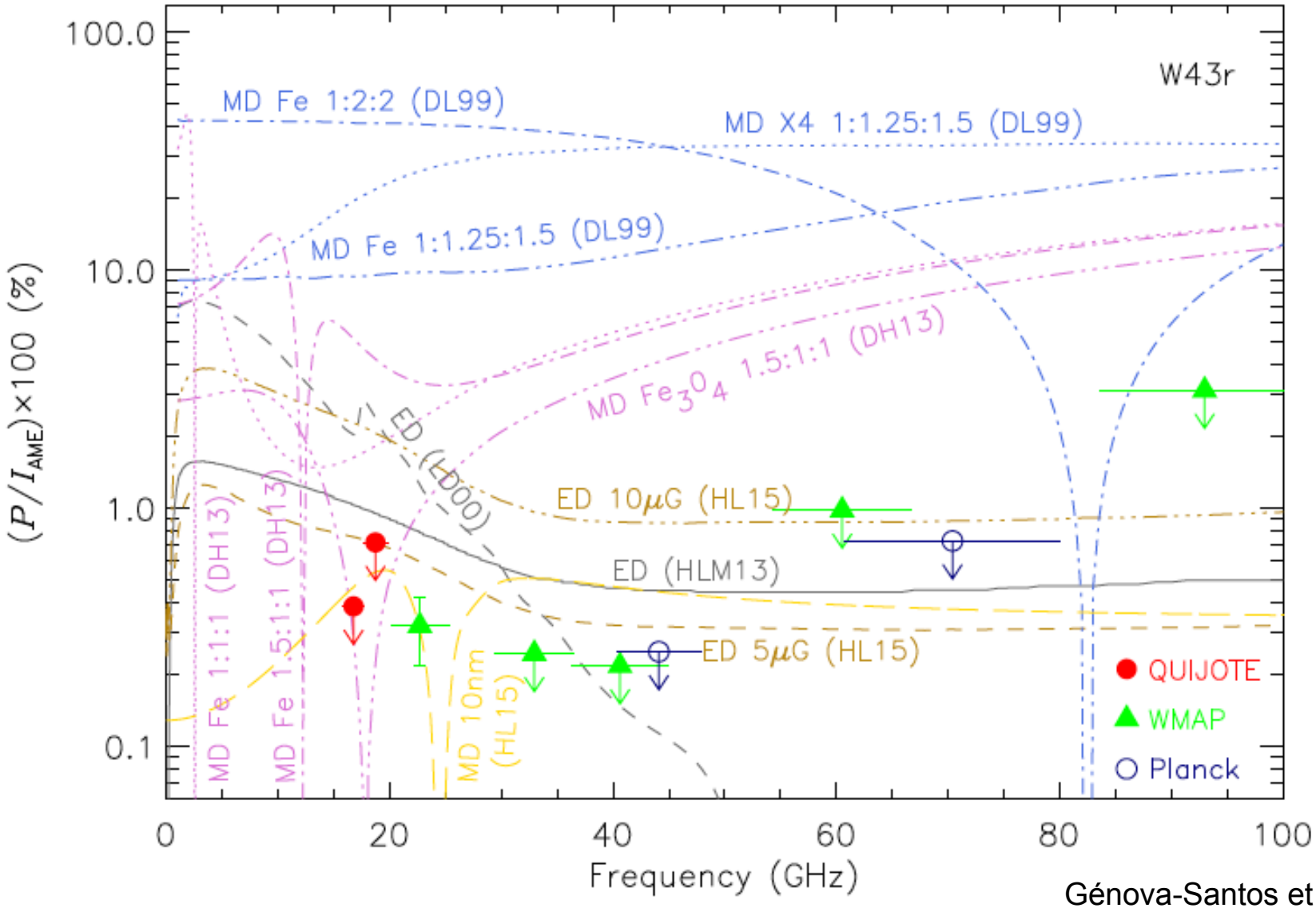
Commander seems to overestimate the free-free and underestimate the AME

Génova-Santos et al. (2017)



W43 molecular complex

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: CRAB. Also the polarization calibrator.
  - 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

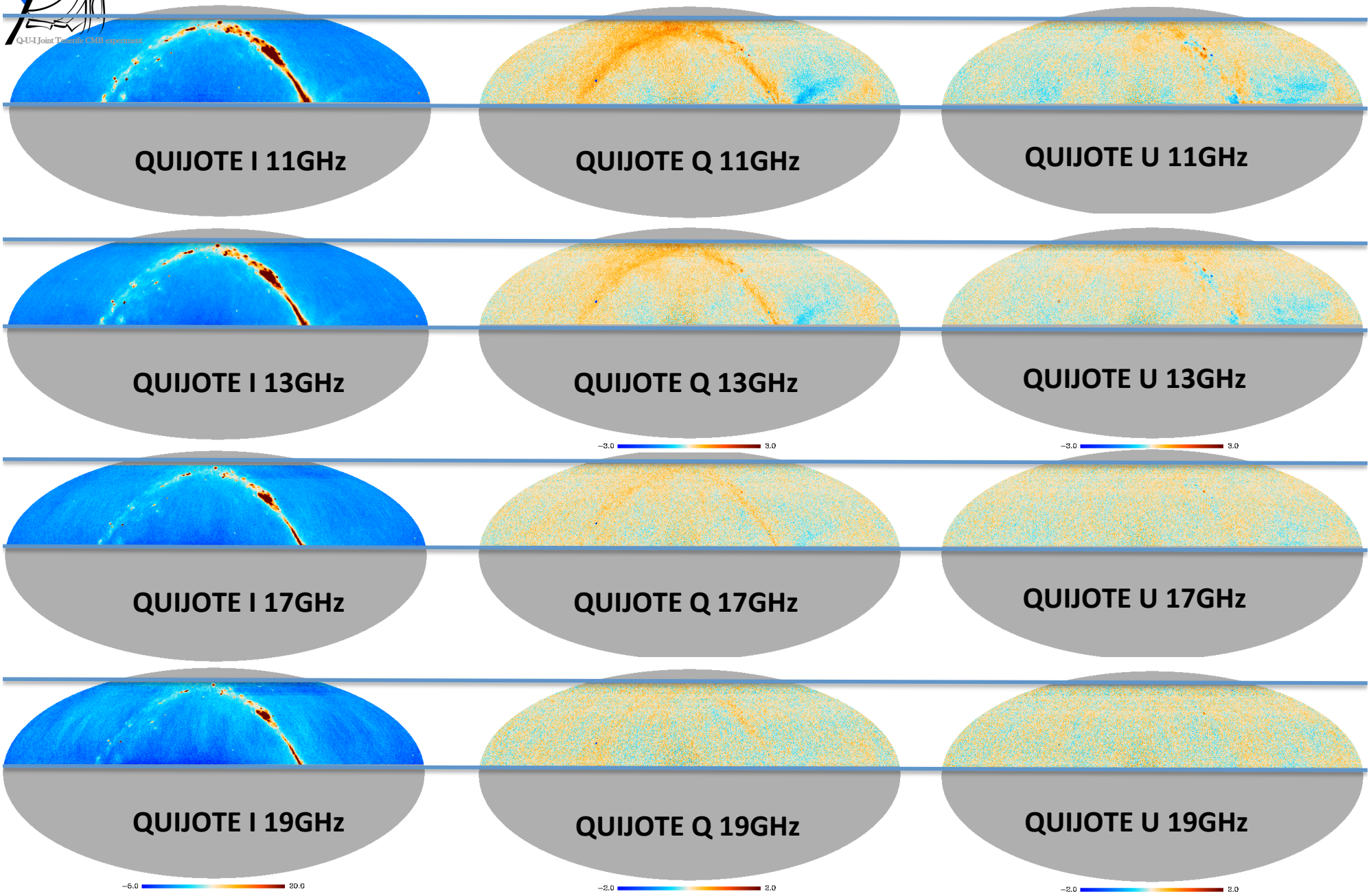
HORN	Freq. [GHz]	Beam [deg]	σ_Q [μK/deg]	σ_U [μK/deg]	NET [mK $s^{1/2}$]
2	16.8	0.63	70.6	70.7	1.71
2	18.7	0.63	90.8	91.3	2.17
3	11.2	0.84	54.3	54.3	1.21
3	12.9	0.85	48.6	48.3	1.05
4	17.0	0.65	40.9	41.0	0.98
4	19.0	0.65	42.6	42.6	0.95

- 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)

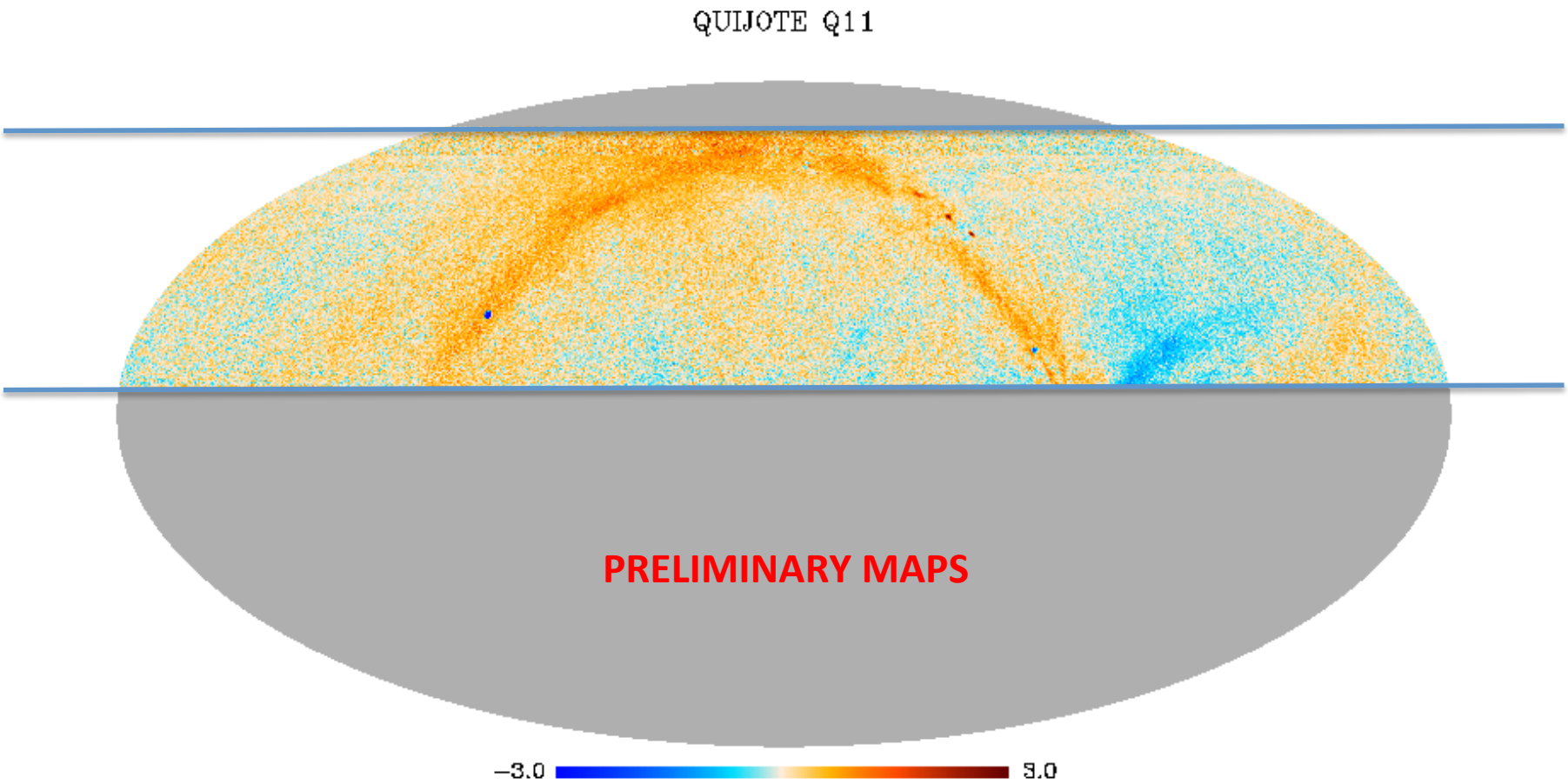
PRELIMINARY MAPS

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



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

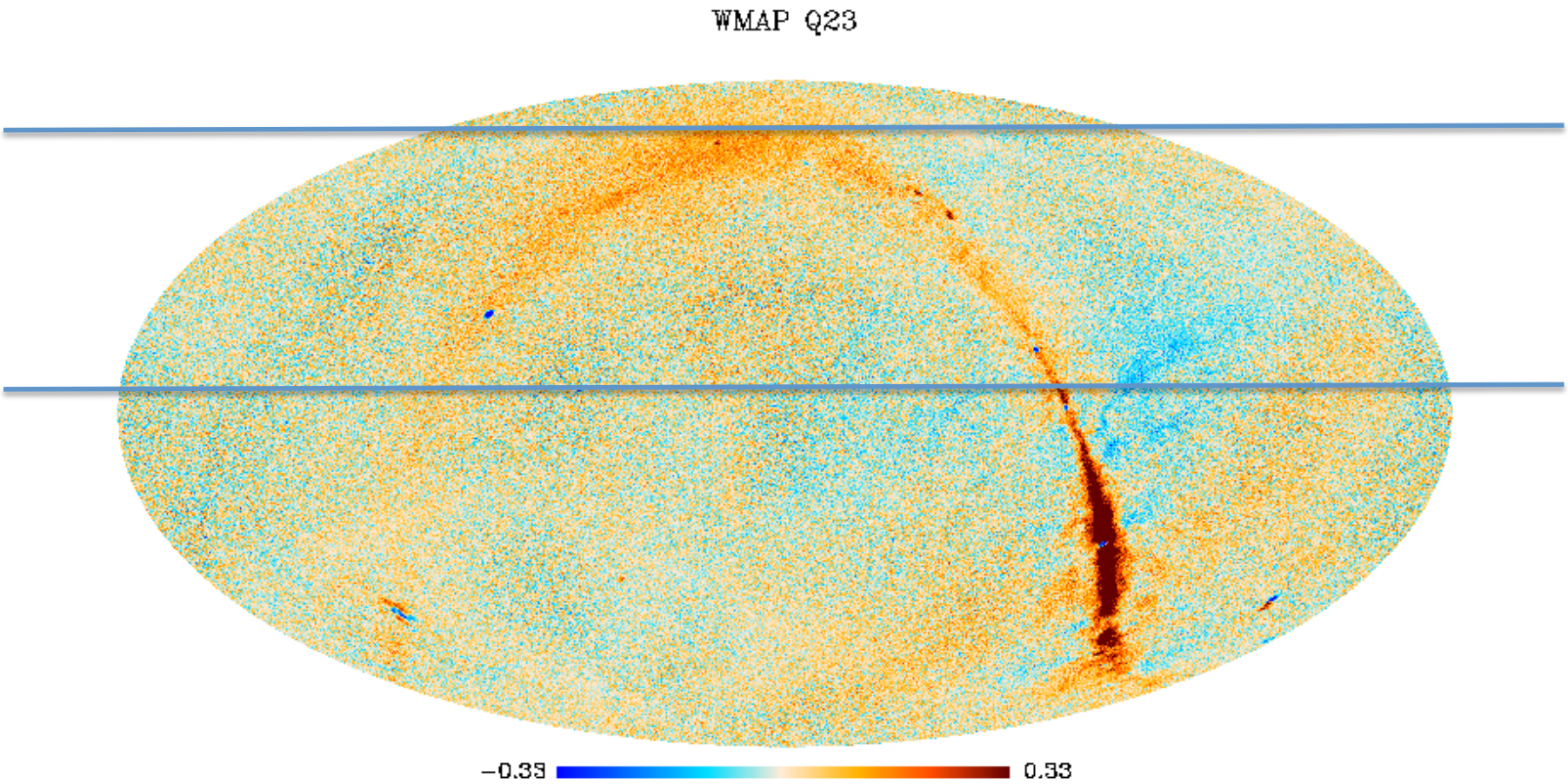
- Example of polarization maps at 11GHz from one horn (using Equatorial projection).



(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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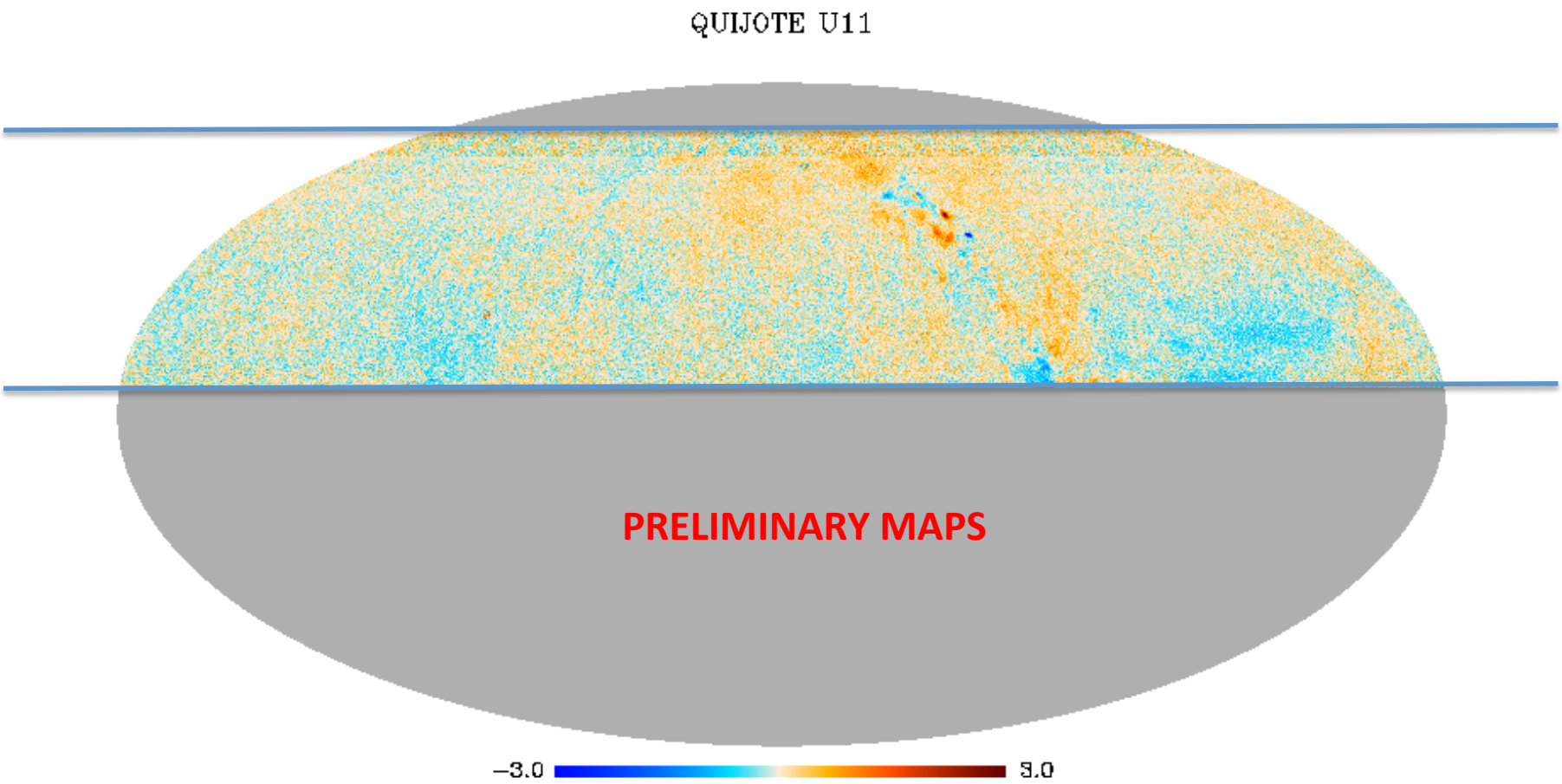

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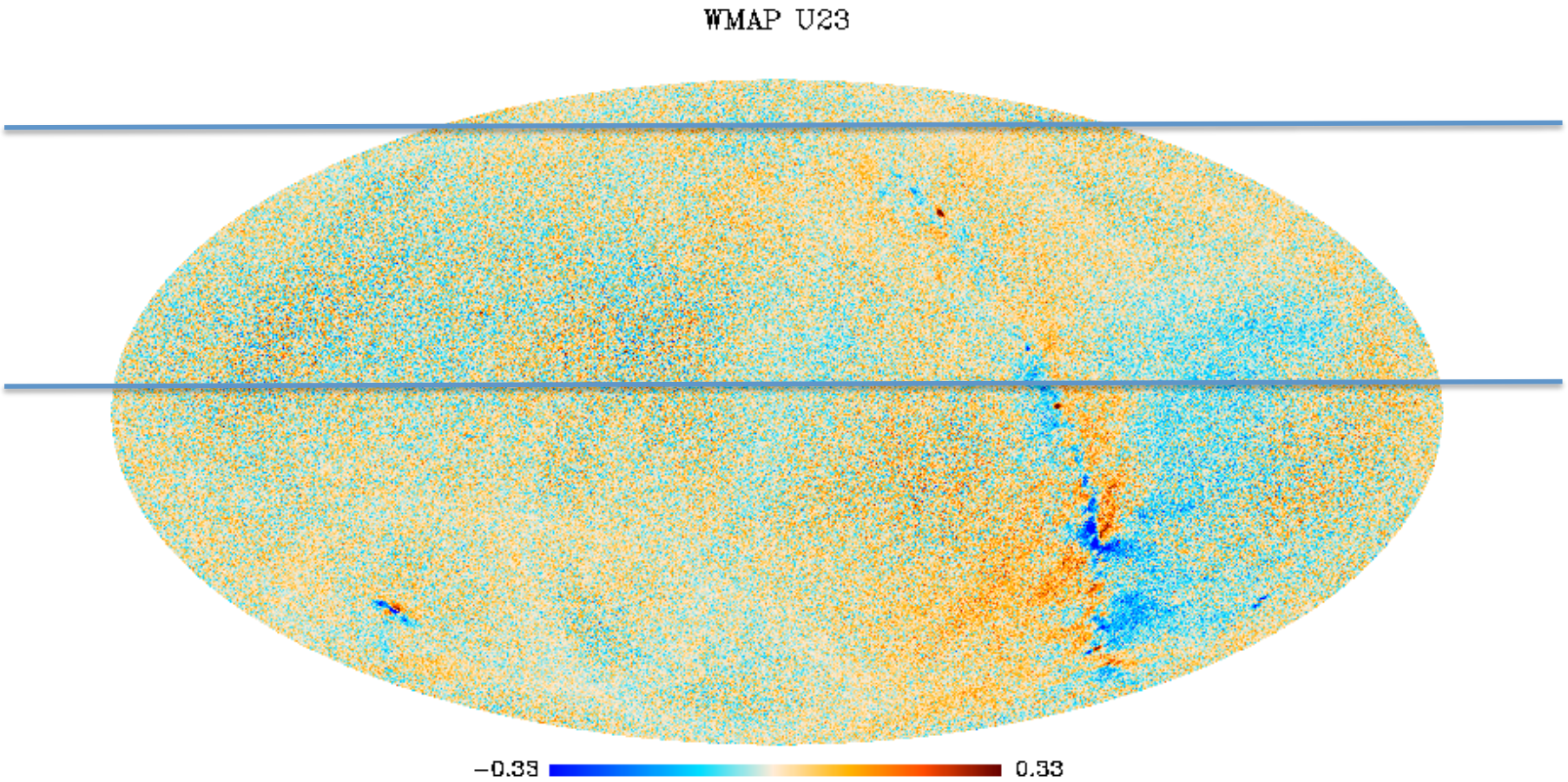


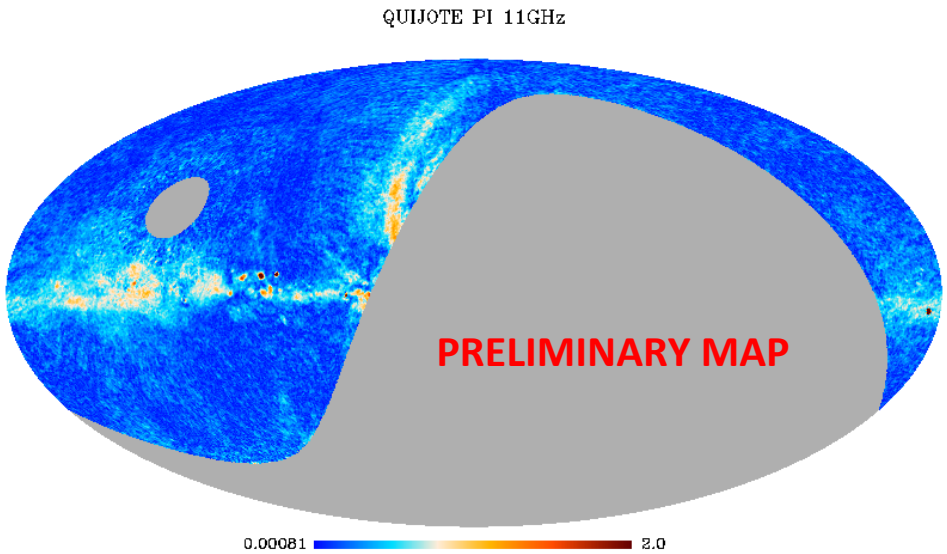
(scaled to preserve the same color
for a signal with β=-3)

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

Expected set of results for the first release:

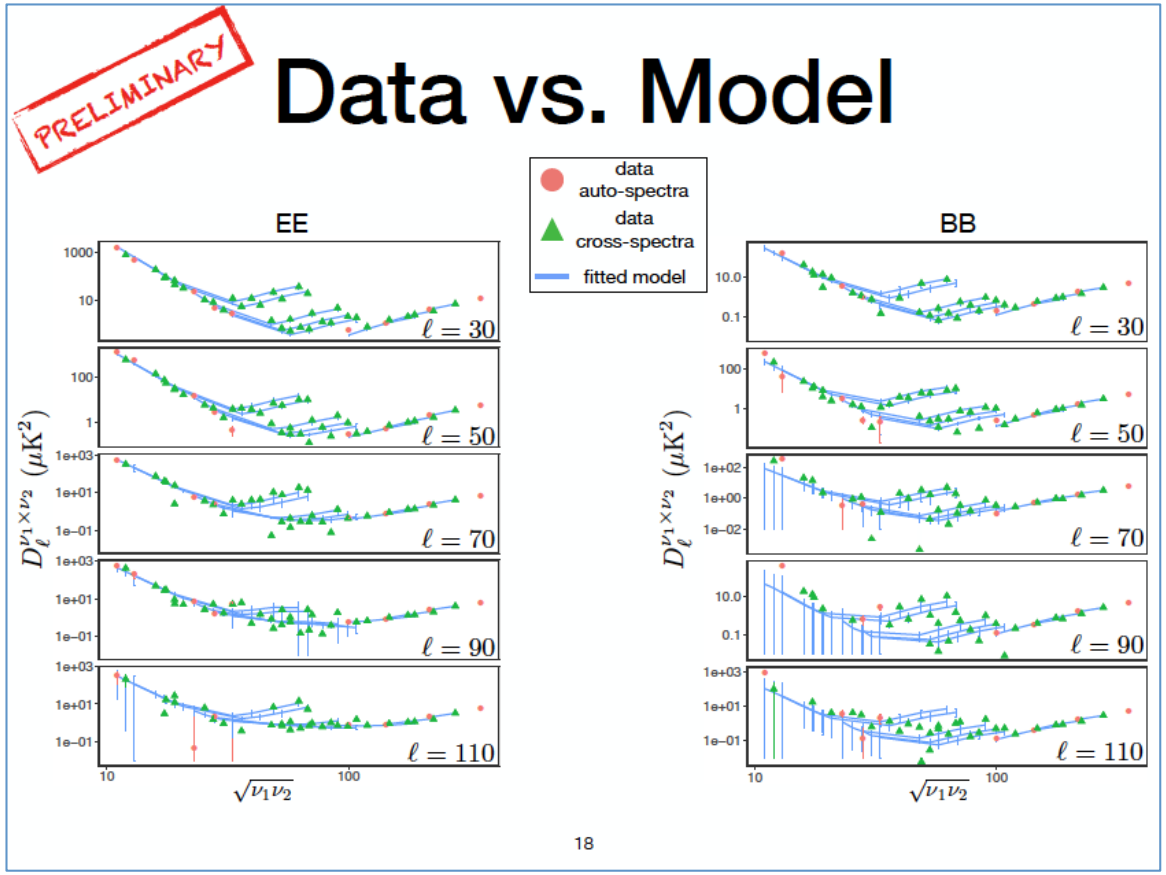
- Four QUIJOTE-MFI maps (11, 13, 17, 19GHz). (Rubino-Martin et al.)
- Synchrotron spectral index, curvature and correlation with dust.(Vansyngel et al.)
- Component separation of the polarised synchrotron, combining PLANCK+WMAP+QUIJOTE (Casaponsa et al.) → see talk
- AME in more than 40 regions (Poidevin et al.) → see talk.
- Radiosources in the QUIJOTE maps (Herranz et al.)
- Synchrotron in the North Polar Spur (Watson et al.)
- Synchrotron emission in the FAN region (Ruiz-Granados et al.)
- Tools for visualization of maps and models.

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

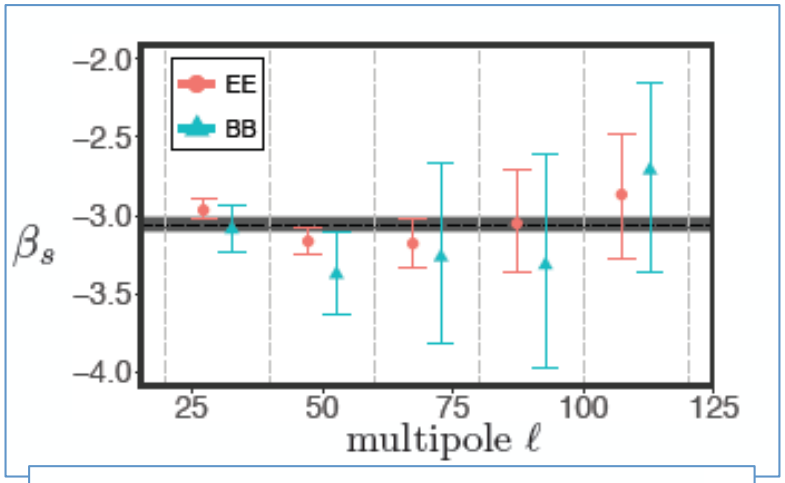


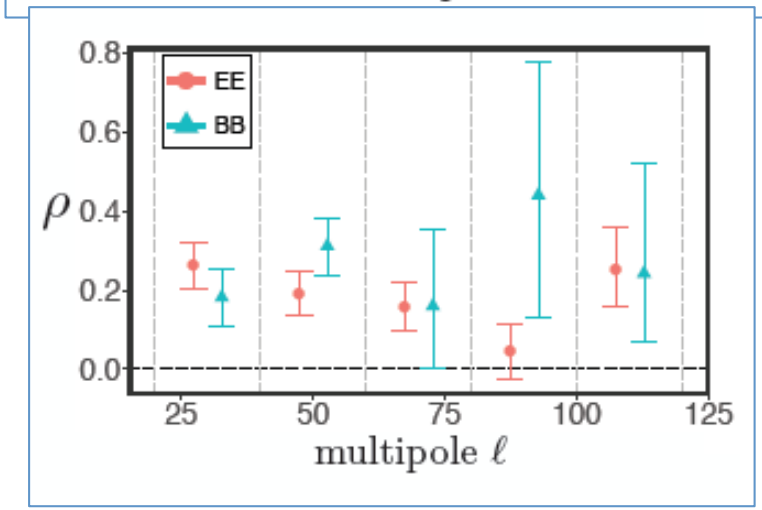
QUIJOTE-MFI wide survey: synchrotron polarization

- Auto- and cross-spectra of QUIJOTE, WMAP, PLANCK maps in northern sky (|b|>10º).
- Pol. Synchrotron spectral index: -3.06±0.04. [**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).



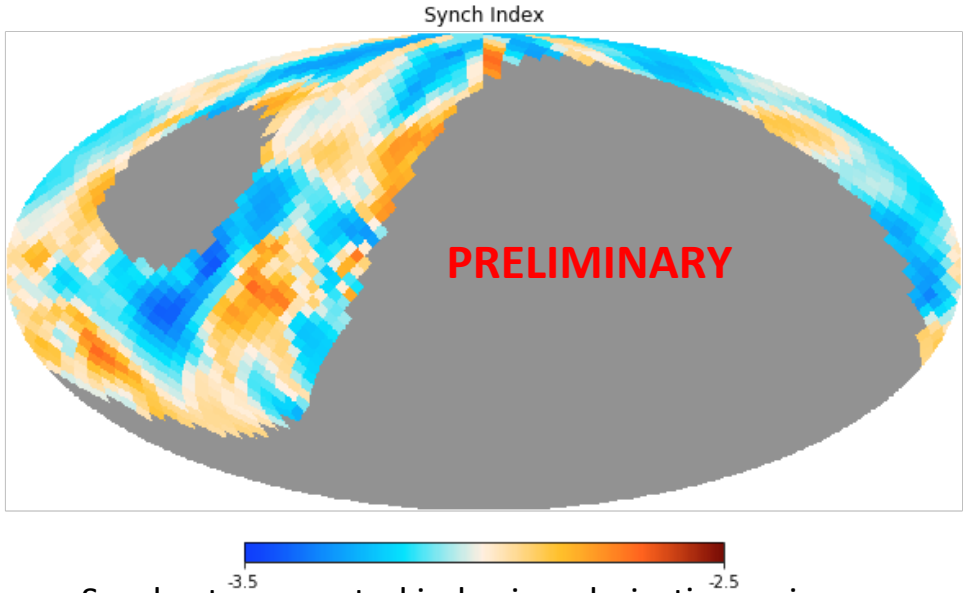
(Vansyngel et al. in prep)



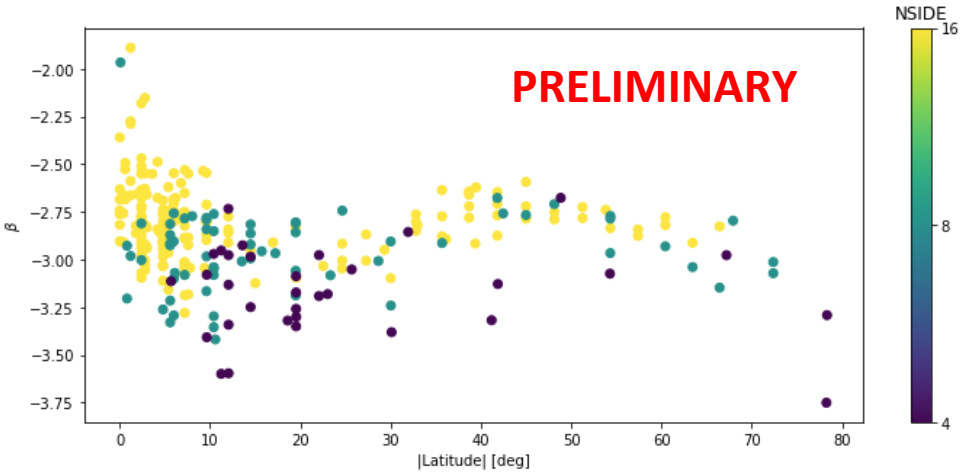


QUIJOTE-MFI wide survey: component separation

- **Parametric component separation methods** have been tested (→ see talk Casaponsa, NN).
- 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: -3.05±0.14. → variability on sky
  - Adaptative parametric method (Poletti, SISSA). → variability on sky.



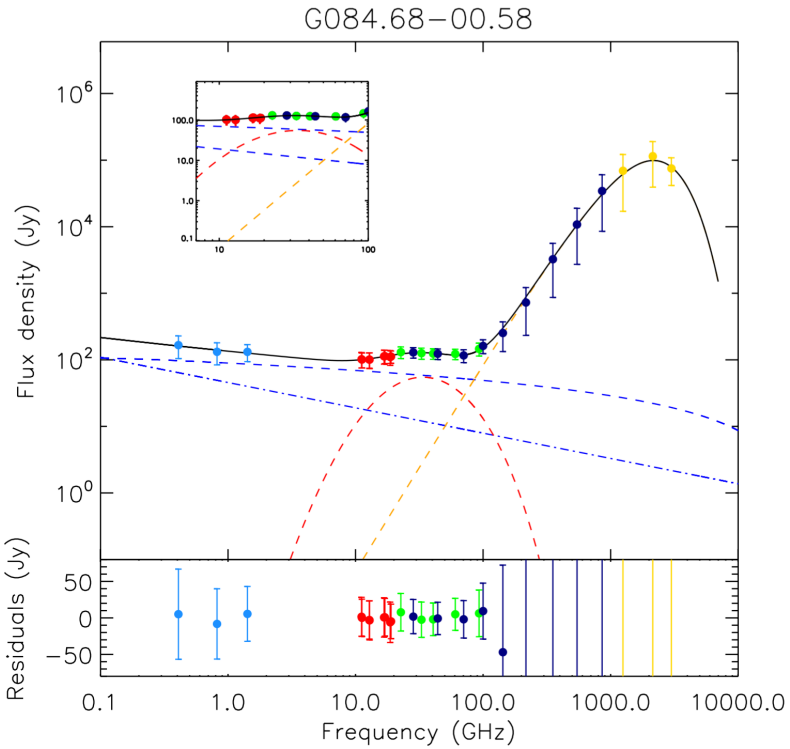
Synchrotron spectral index in polarization, using Q11 + LFI30 (Casaponsa et al.)

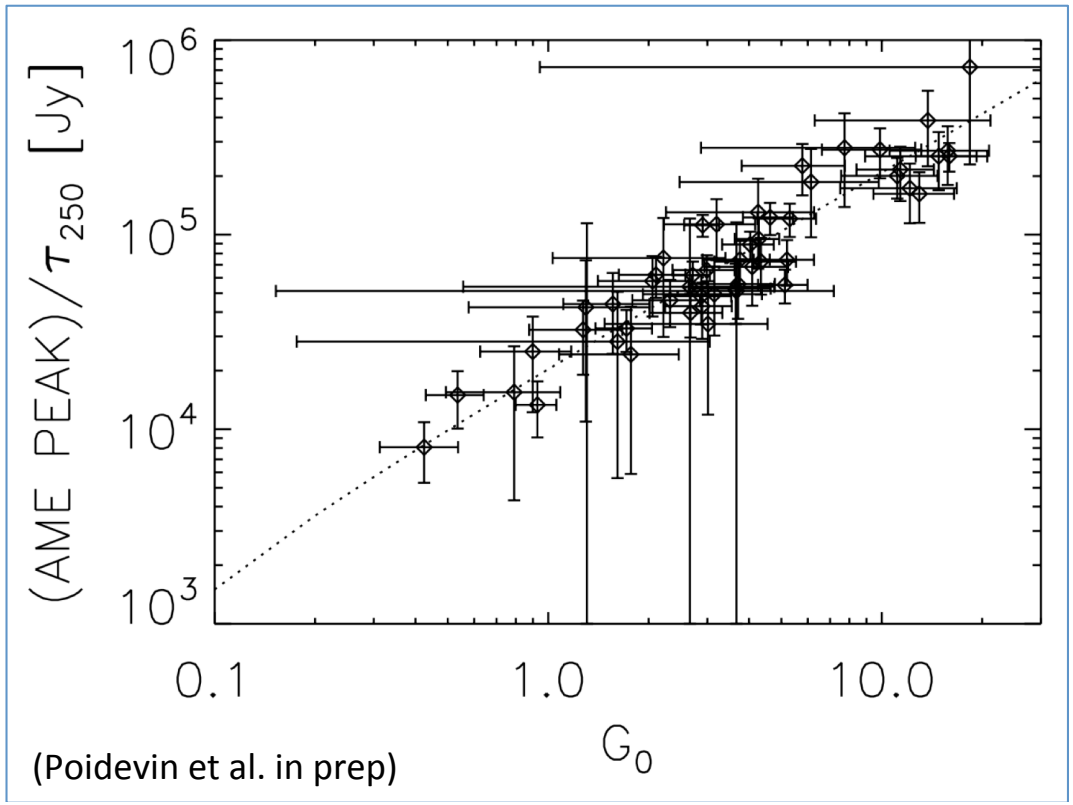


Synchrotron spectral index in polarization as function of galactic Latitude (Poletti et al.)

QUIJOTE-MFI wide survey: modelling the AME

- Systematic study of 63 AME sources. Includes 51 targets from PIR XV (2014). → see Poidevin's talk.
- **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.

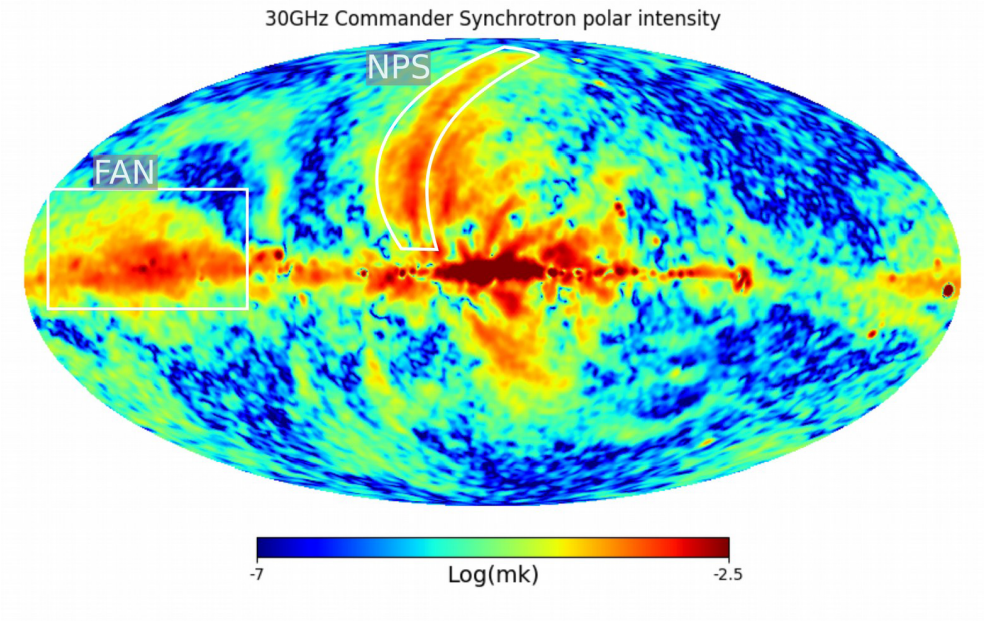




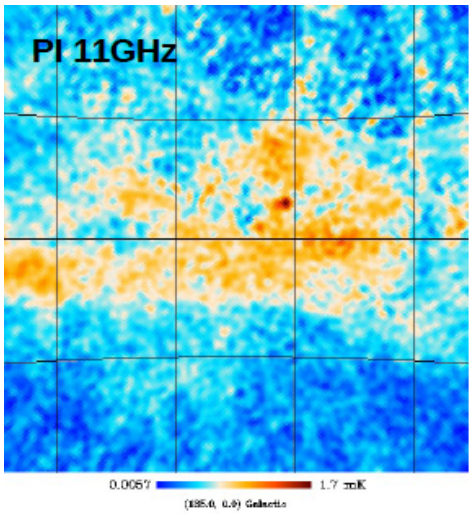
(Poidevin et al. in prep)

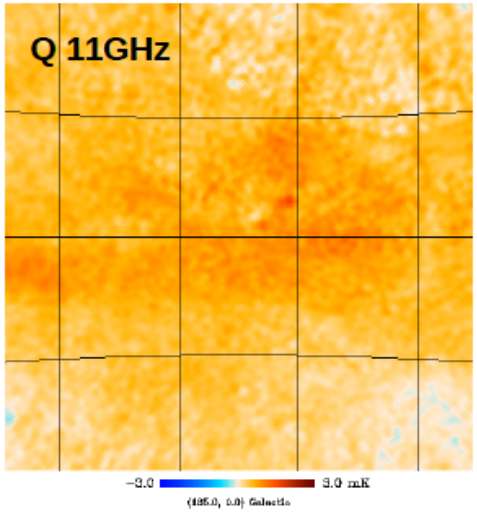
QUIJOTE-MFI wide survey: NPS and Fan region

- **North Polar Spur (NPS)**. Measured spectral index (I&P) between QUIJOTE-MFI and Planck 30GHz. No curvature seen (no departure from the weighted mean β=-3.15±0.02).
- Modelling NPS: consistent with an evolved (400kyr) SNR inside a super-shell (>1.5Myr).
- **FAN region**.
  - Flattening of the synchrotron spectral index (**11-22GHz**: -2.89 ; **22-30GHz**:-2.65). Two populations of CRs?
  - AME detected in W3, W4, W5 (molecular complexes). SED in polarization of 3C85.



(Watson et al. in prep)





(Ruiz-Granados et al. in prep)

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).

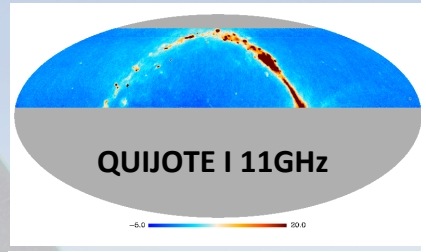
- **QUIJOTE-MFI** helps to properly separate **the AME component** in intensity. This opens the possibility to explore the physical properties of the emission (e.g. peak frequencies, specfic intensity), and also to study the polarization emission of the AME signal. In particular, we provide the best upper limit to date on the pol fraction (<0.2%).

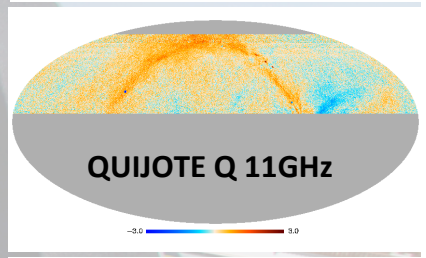
- **QUIJOTE-MFI** also helps in the separation and characterization of the **synchrotron polarised emission**. The average spectral index is found to be ~-3.00, but it shows significant spatial variations. Same for the dust-synchrotron correlation.

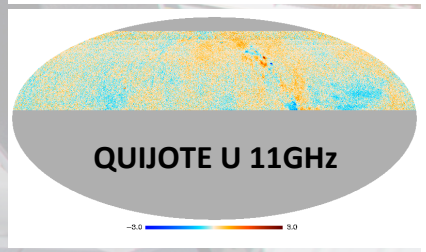
- **QUIJOTE-MFI** provides also flux densities (I&P) for tens of **radio sources**.

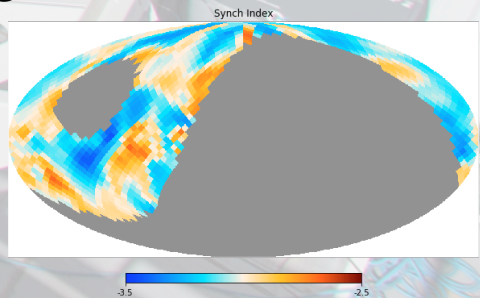
- SED modelling of several Galactic regions (FAN, North Polar Spur).

- **RADIOFOREGROUNDS** (public results by end of project; maps available once the papers are accepted).





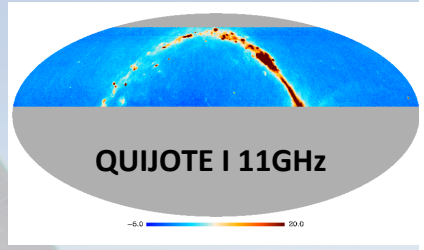


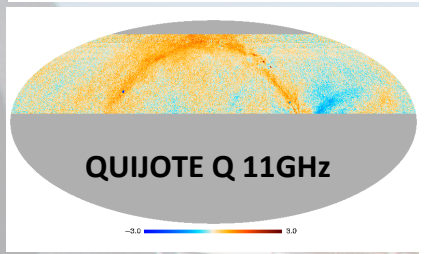


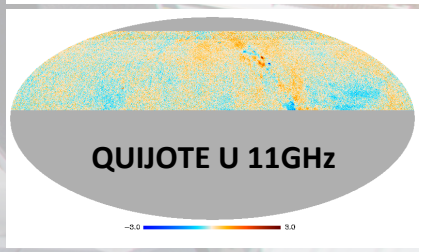
QUIJOTE project: current status

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. Aim: to increase the speed by at least a factor of 3.
- Extension of QUIJOTE to Southern hemisphere is being studied.
- **E-CMB.** Plans for full-sky low frequency survey ("super QUIJOTE").

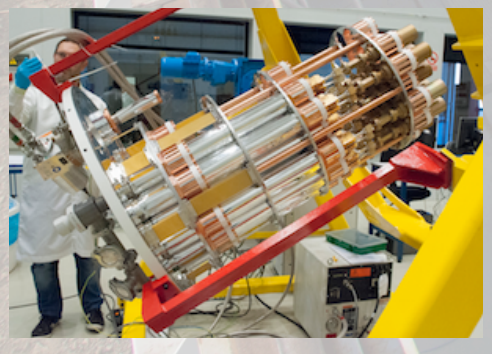


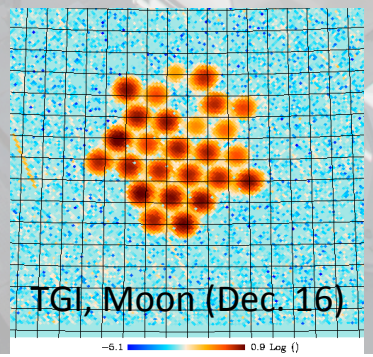


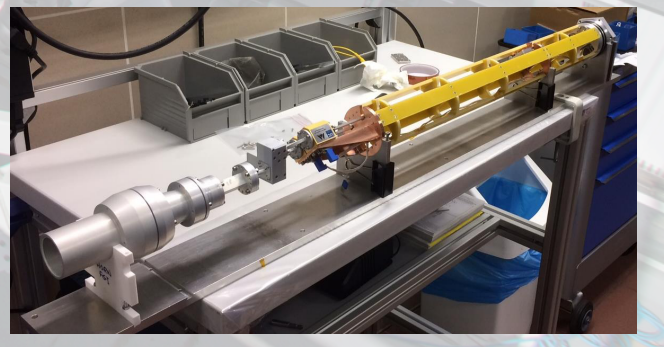


TGI (30 GHz) and FGI (40 GHz)

- 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.








Quijote
Q-U-I Joint Tenerife CMB experiment
Thank you!
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