The QUIJOTE experiment: status and first results

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

Madrid 2016 Cosmology with 21 cm Surveys,
Cosmic Microwave Background and Large Scale Structure

The QUIJOTE Collaboration

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

Quijote

Q-U-I Joint Tenerife CMB experiment

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC

IFCA Instituto de Física de Cantabria

DICOM

UNIVERSITY OF CAMBRIDGE

MANCHESTER 1824 The University of Manchester

idom

The QUIJOTE experiment

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

Q-U-I Joint Tenerife CMB experiment

Instituto de Física de Cantabria

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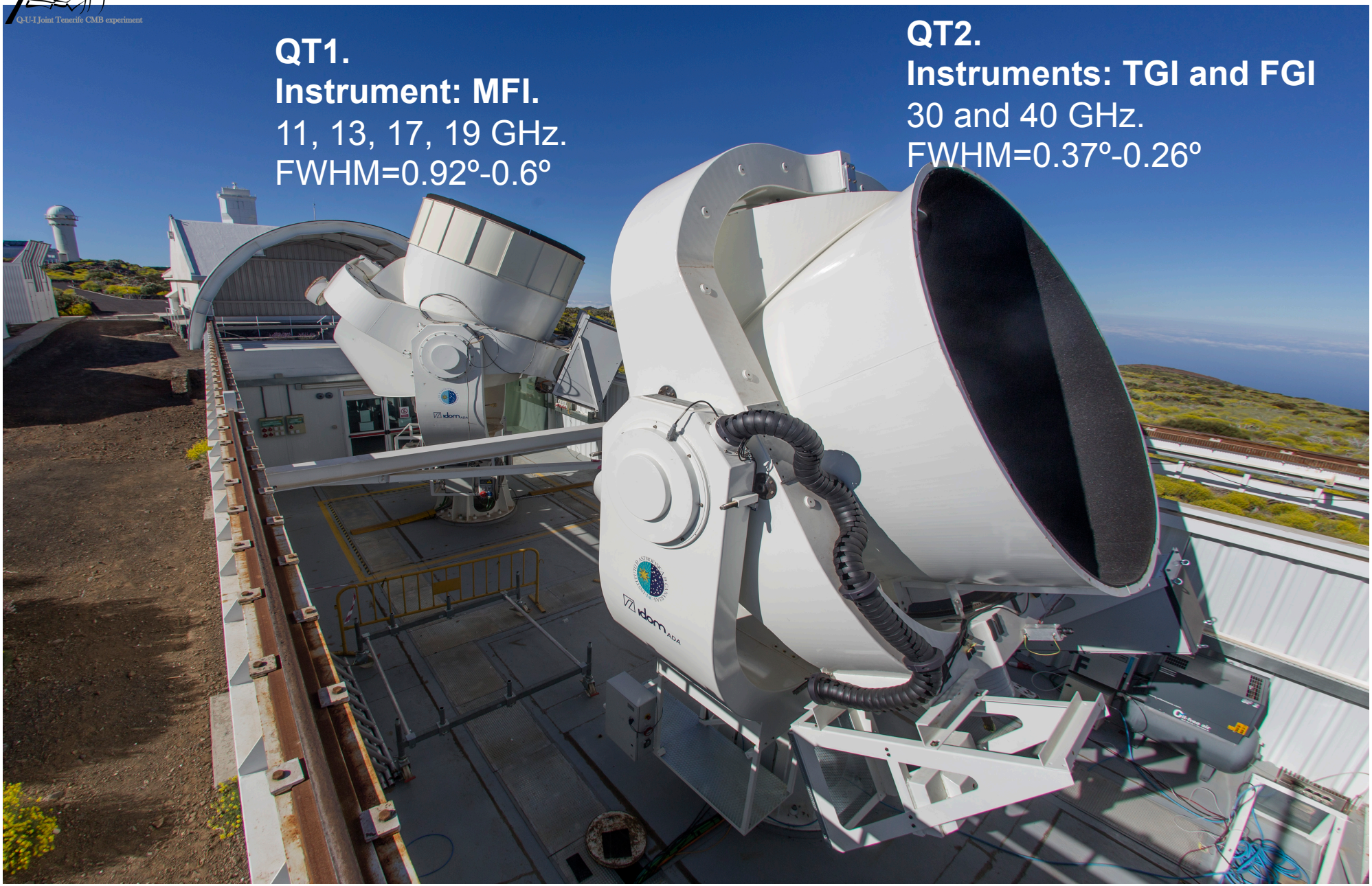
Tenerife experiment
10, 15, 33 GHz

COSMOSOMAS
11, 13, 15, 17 GHz

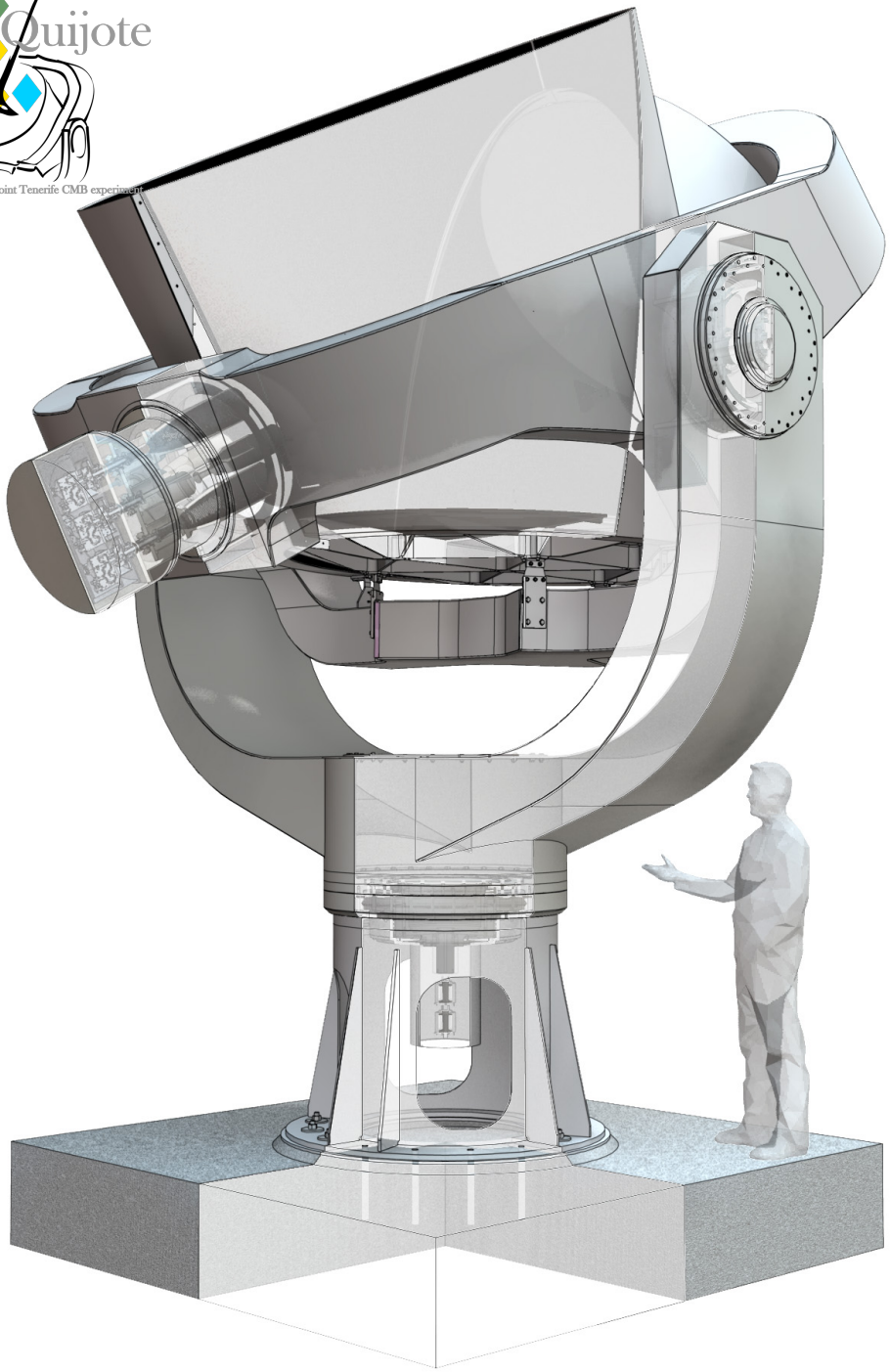
The Very Small Array
30GHz

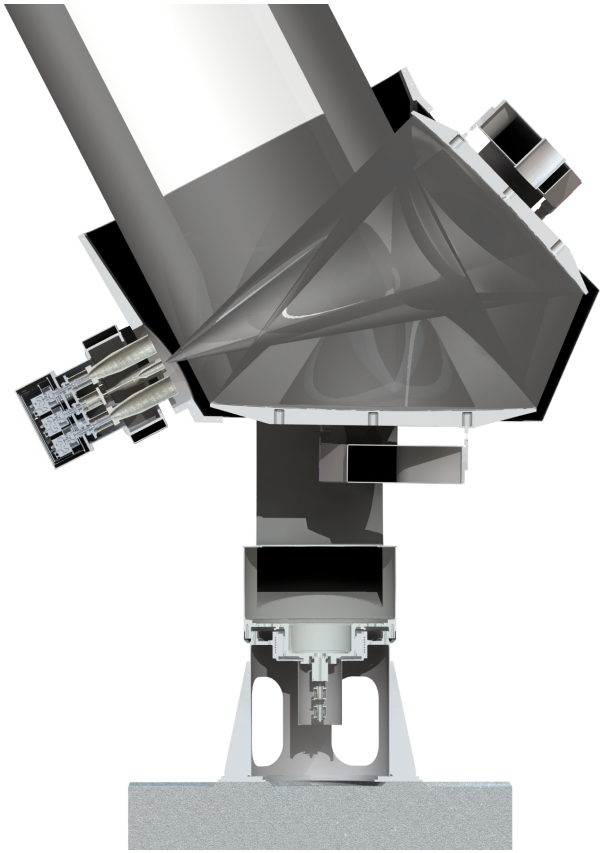
Teide Observatory (altitude 2400 m; 28.3° N, 16.5 W)

The QUIJOTE experiment

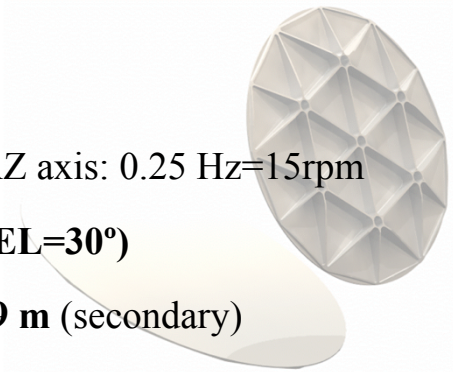


QUIJOTE telescopes

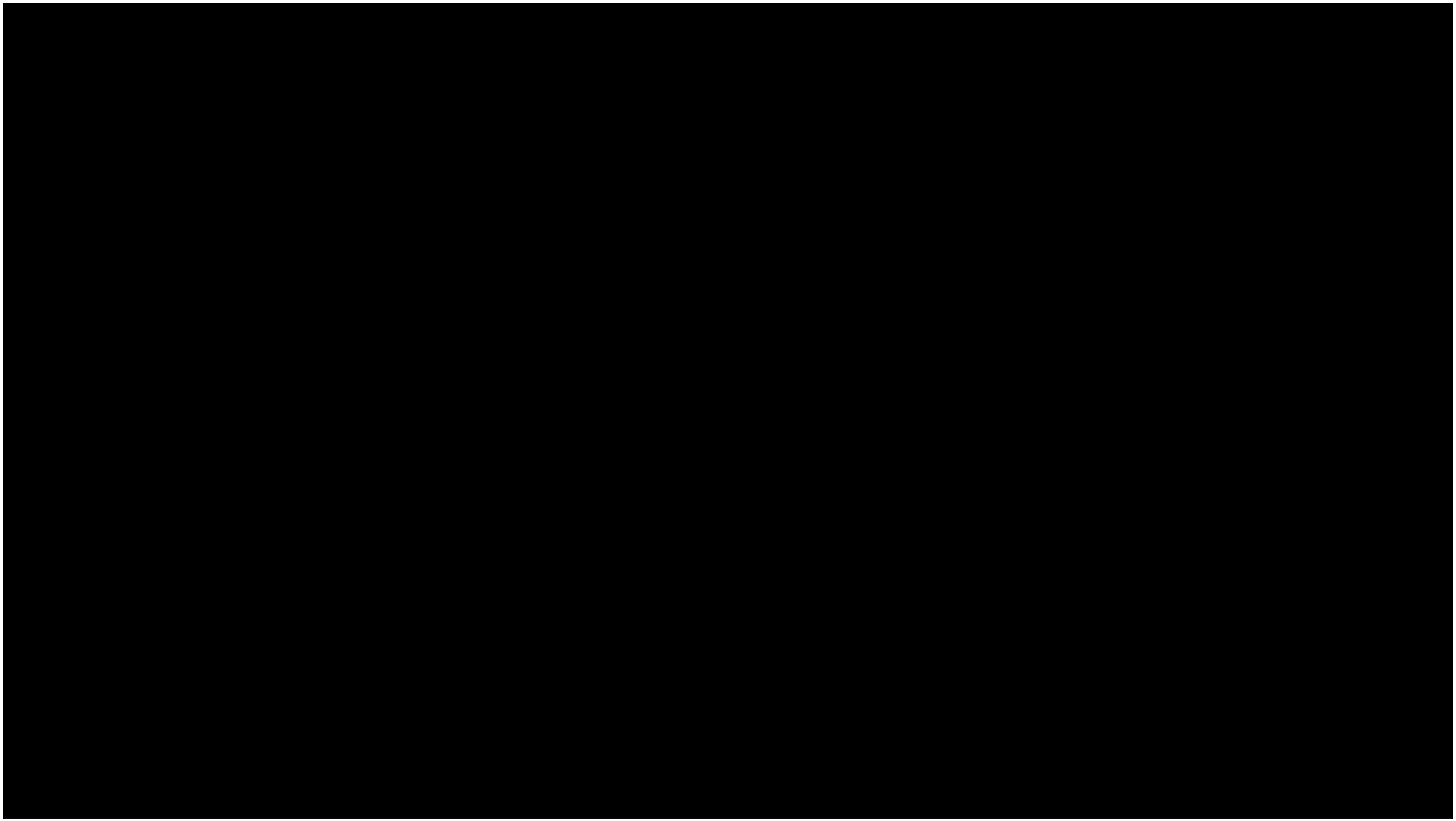




- **Cross-Dragonian design.**
- **Alto-azimutal mount**
- Maximum rotation speed around AZ axis: 0.25 Hz=15rpm
- Maximum zenith angle**: 60º (min EL=30º)**
- Aperture: **2.25 m** (primary) and **1.9 m** (secondary)

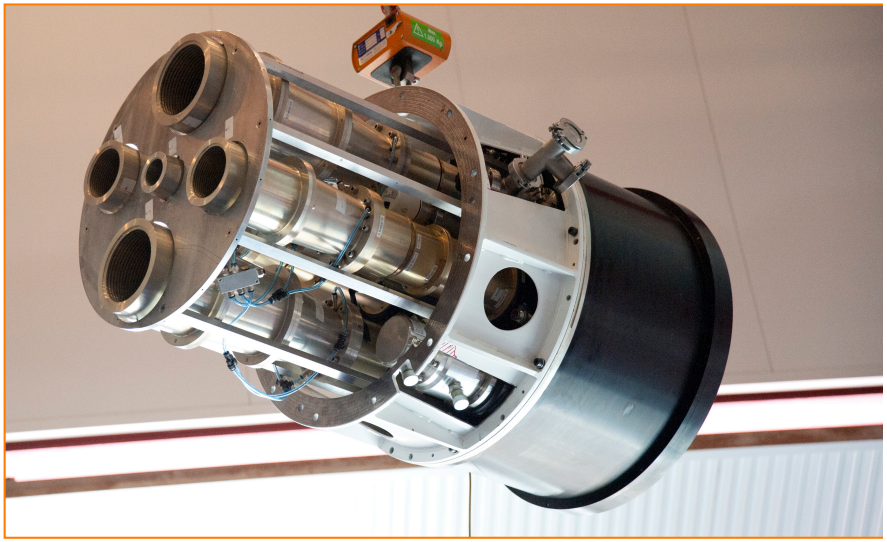


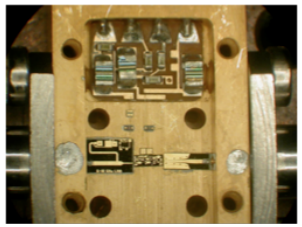
The QUIJOTE experiment



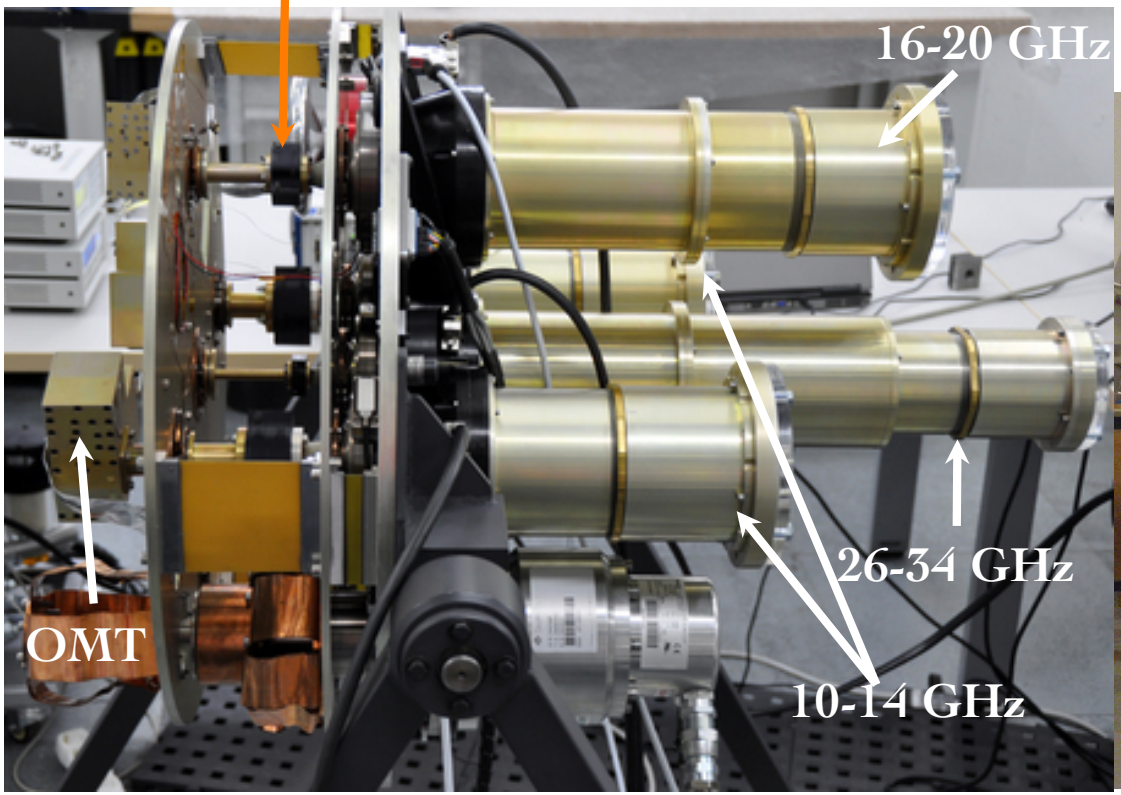
MFI Instrument (10-20 GHz)

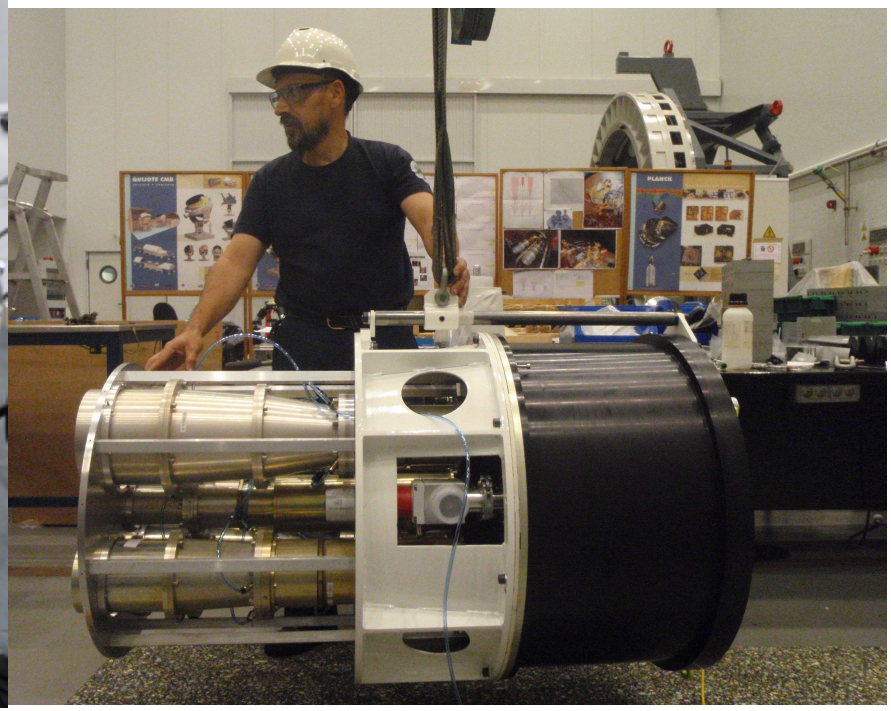
- In operations since Nov. 2012.
- 4 horns, 32 channels. Covering 4 frequency bands: 11, 13, 17 and 19 GHz.
- Sensitivities: ~400-600 μK $s^{1/2}$ per channel.



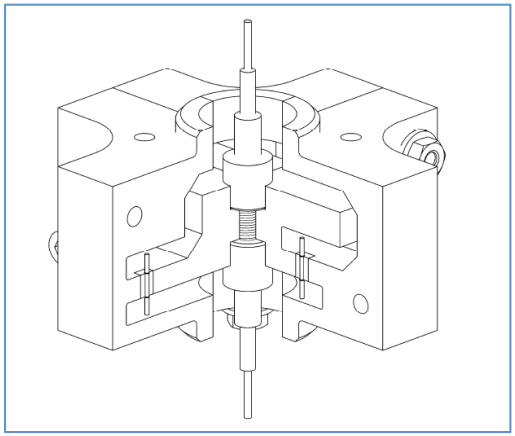


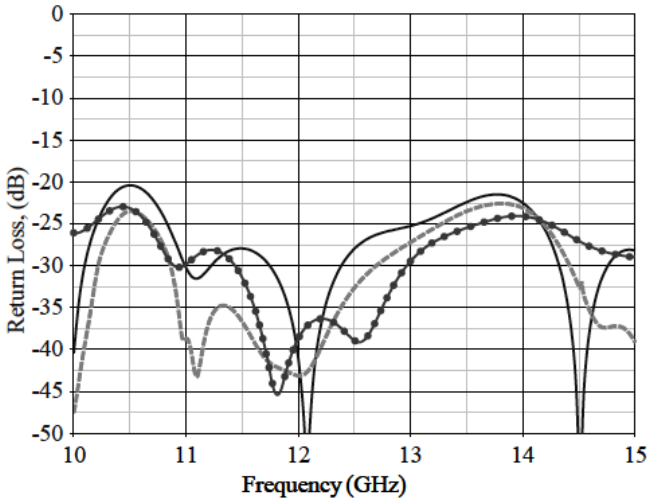
LNA

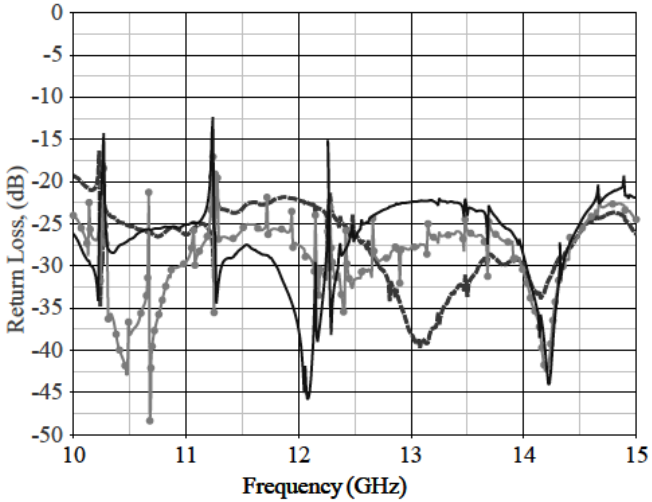


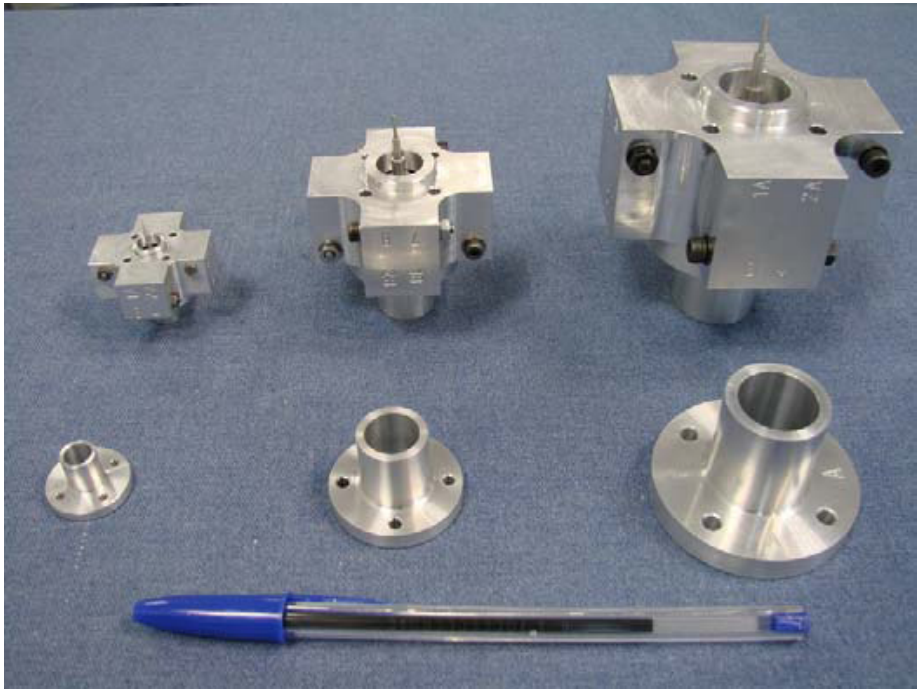


MFI Instrument (10-20 GHz). Polar modulator.

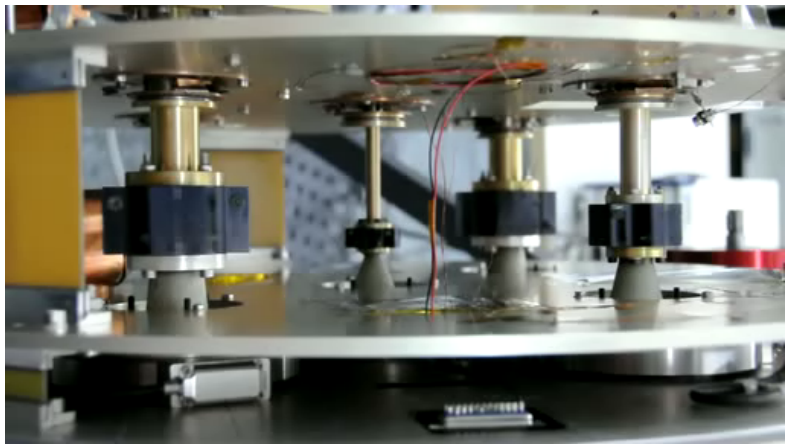






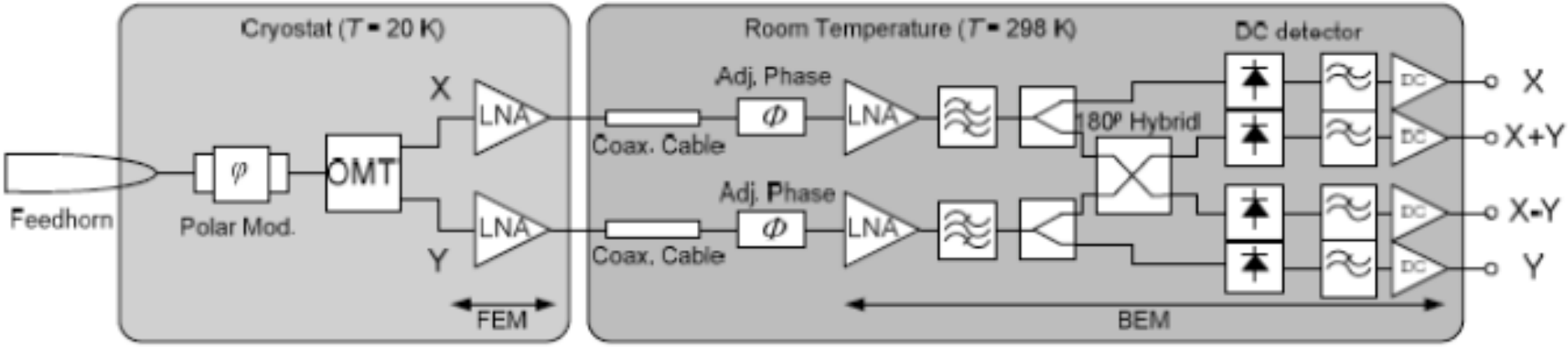


"HWP": a polar modulator based on a turnstile junction, in waveguide. Advantages: broad band, cooled down in the criostat, and high performance (Return Losses < 20dB, insertion losses < -0.15dB, isolation < -40 dB) .



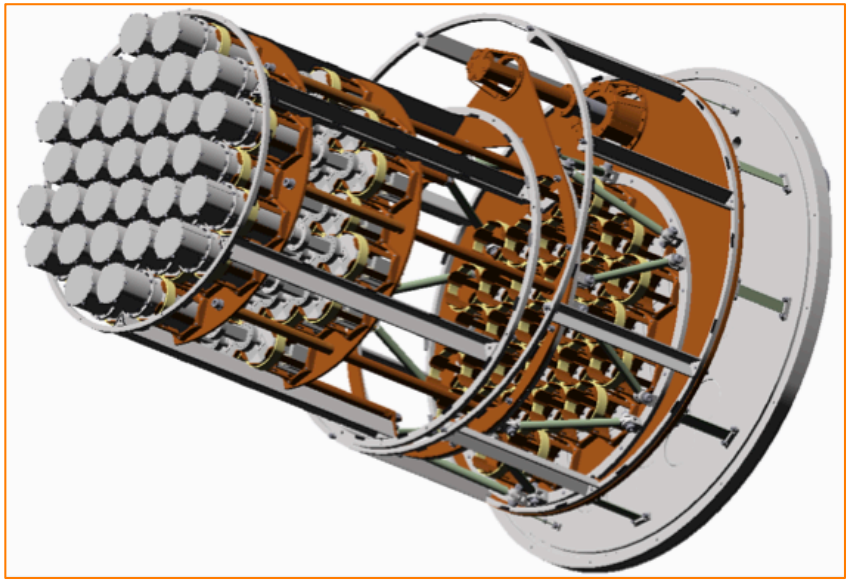
MFI Instrument (10-20 GHz). Instrument response

- FEM: partially-cooled feed-horn, polar modulator, OMT and LNAs
- BEM: phase adjuster, further amplification, band pass filter and correlation.
- Output: two channels (x) and (y) measuring Q (un-correlated), two channels (x+y) and (x-y) measuring U (correlated)

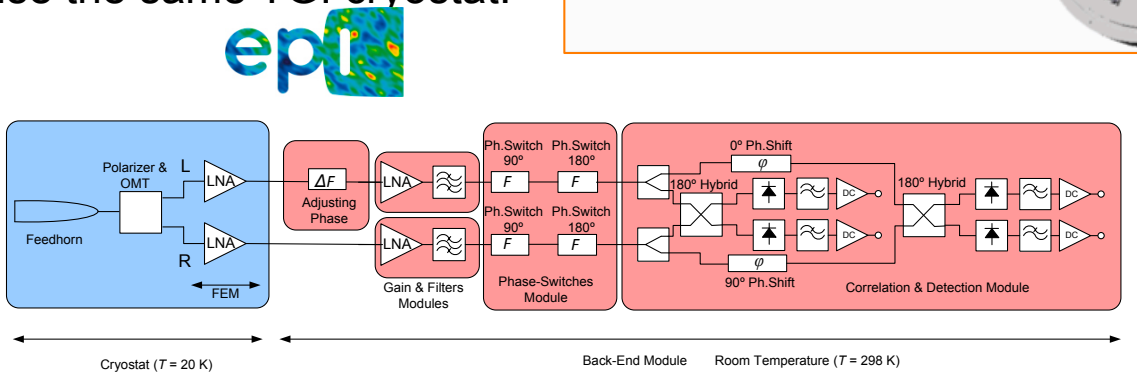


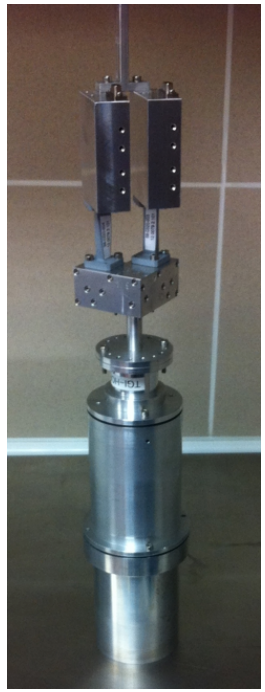
- Continuous spinning of the polar modulators provides independent measurement of I, Q and U for each channel, while switching out the 1/f noise. But we operate in 4 discrete positions (0º,22.5º,45º,67.5º)
- Each of the four outputs are divided into a lower frequency and an upper frequency band.

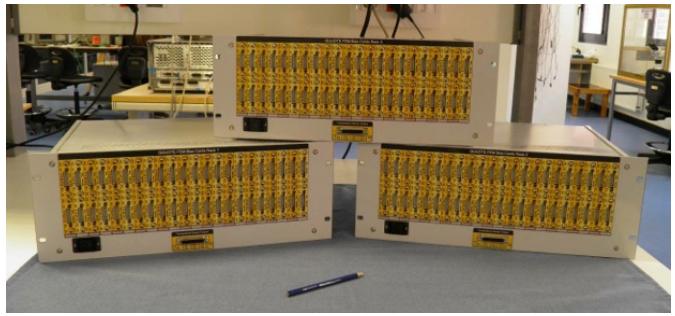
TGI (30 GHz) and FGI (40GHz) instruments

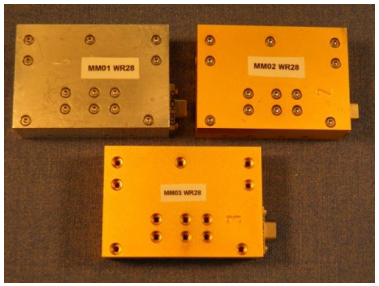


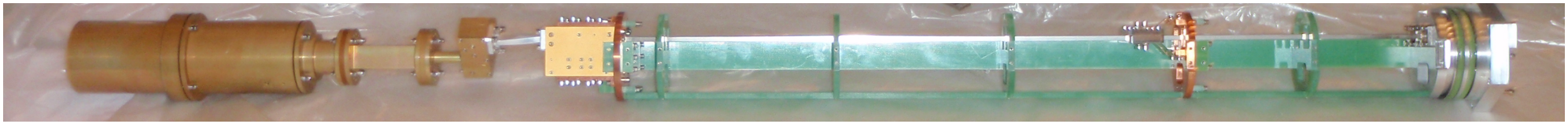
- **TGI**: 31 pixels at 30GHz. Expected sensitivity: 50 μK $s^{1/2}$ for the full array. First light May 12th 2016. In commissioning phase.
- **FGI**: 31 pixels at 40GHz. Expected sensitivity: 60 μK $s^{1/2}$ for the full array. Will use the same TGI cryostat.









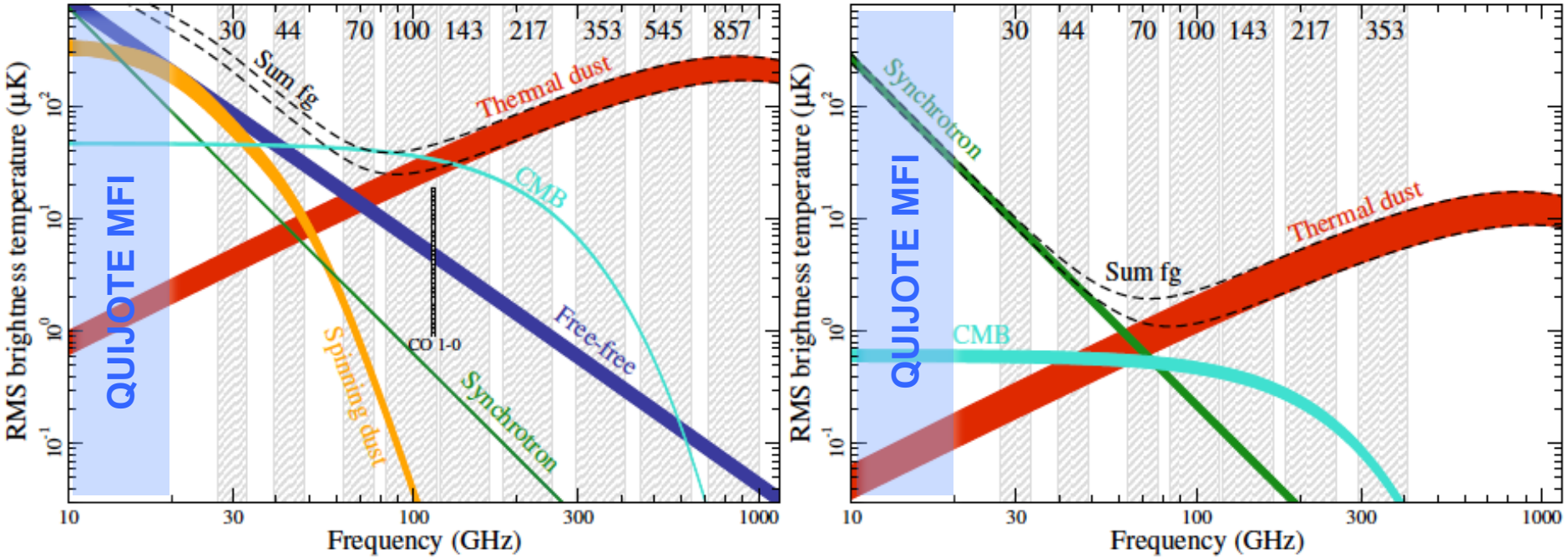


Science with QUIJOTE first instrument (MFI)

- **Shallow Galactic survey**. Covering 20,000 deg^2 (almost 5000 hrs completed)
  - ≈ **15 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 ~1% (López-Caraballo et al. 2011, Dickinson et al. 2011).
- Excellent complement to PLANCK at low frequencies. Legacy for future experiments.

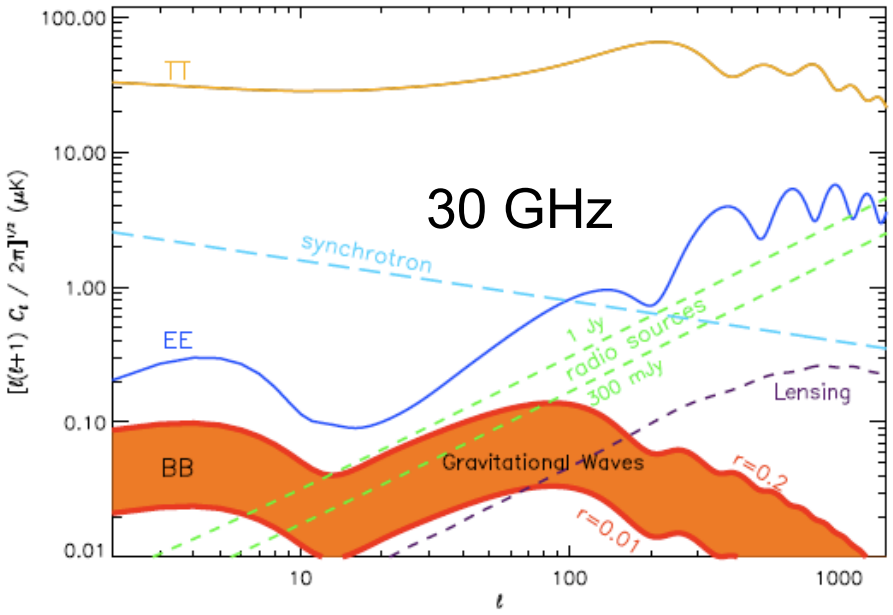
Planck Collaboration 2015

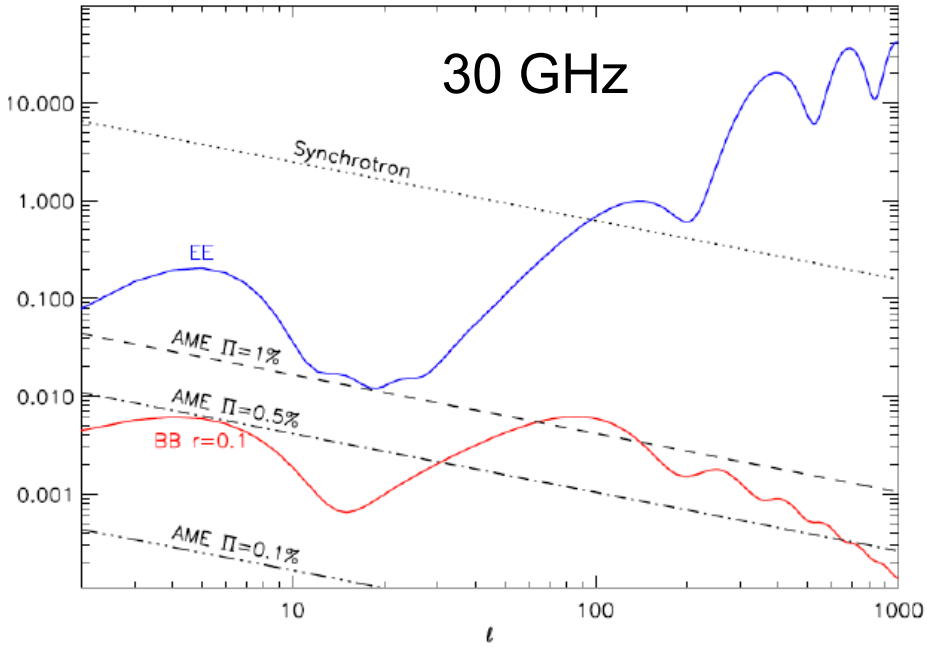


Science with QUIJOTE second (TGI) and third (FGI) instruments

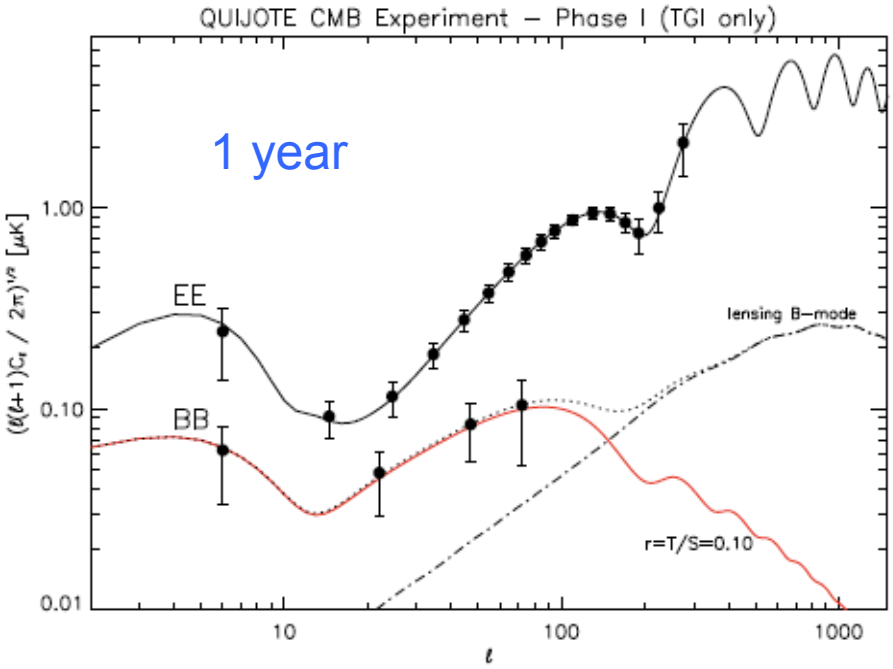
- **Shallow Galactic survey**. Covering 20,000 deg^2. Estimated duration: 5 months.
  ≈ 2 μK/(beam 1º) with the TGI @ 30 GHz and with the FGI @ 40 GHz, afer 5 months.
- **Deep cosmological survey**. It will cover around 3,000 deg^2. 1 year
  ≤ 1 μK/(beam 1º) with the TGI @ 30 GHz and with the FGI @ 40 GHz.

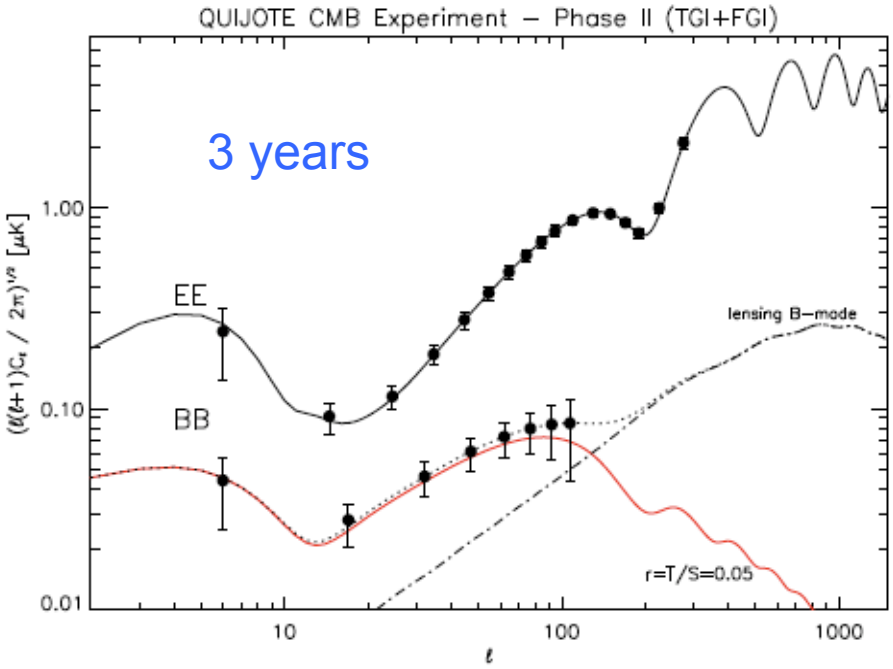
- MFI maps will be used to clean the 30 GHz and 40 GHz maps of the 2nd (TGI) and 3rd (FGI) QUIJOTE instruments.
- Radio-sources: low contribution at degree scales, but potentially relevant for B-modes science → specific VLA program to correct for polarised sources selected from PLANCK maps. Observations of 1st epoch of sources are being reduced.





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





Left: Example of the QUIJOTE scientific goal after the Phase I: 1 year (effective) observing time, and a sky coverage of 3,000 deg^2. The red line corresponds to r = 0.1.

Right: QUIJOTE Phase II. Here we consider 3 years of effective operations with the TGI, and that during the last 2 years, the FGI will be also operative. The red line now corresponds to r = 0.05.

MFI Commissioning phase
(November 2012 – March 2013)

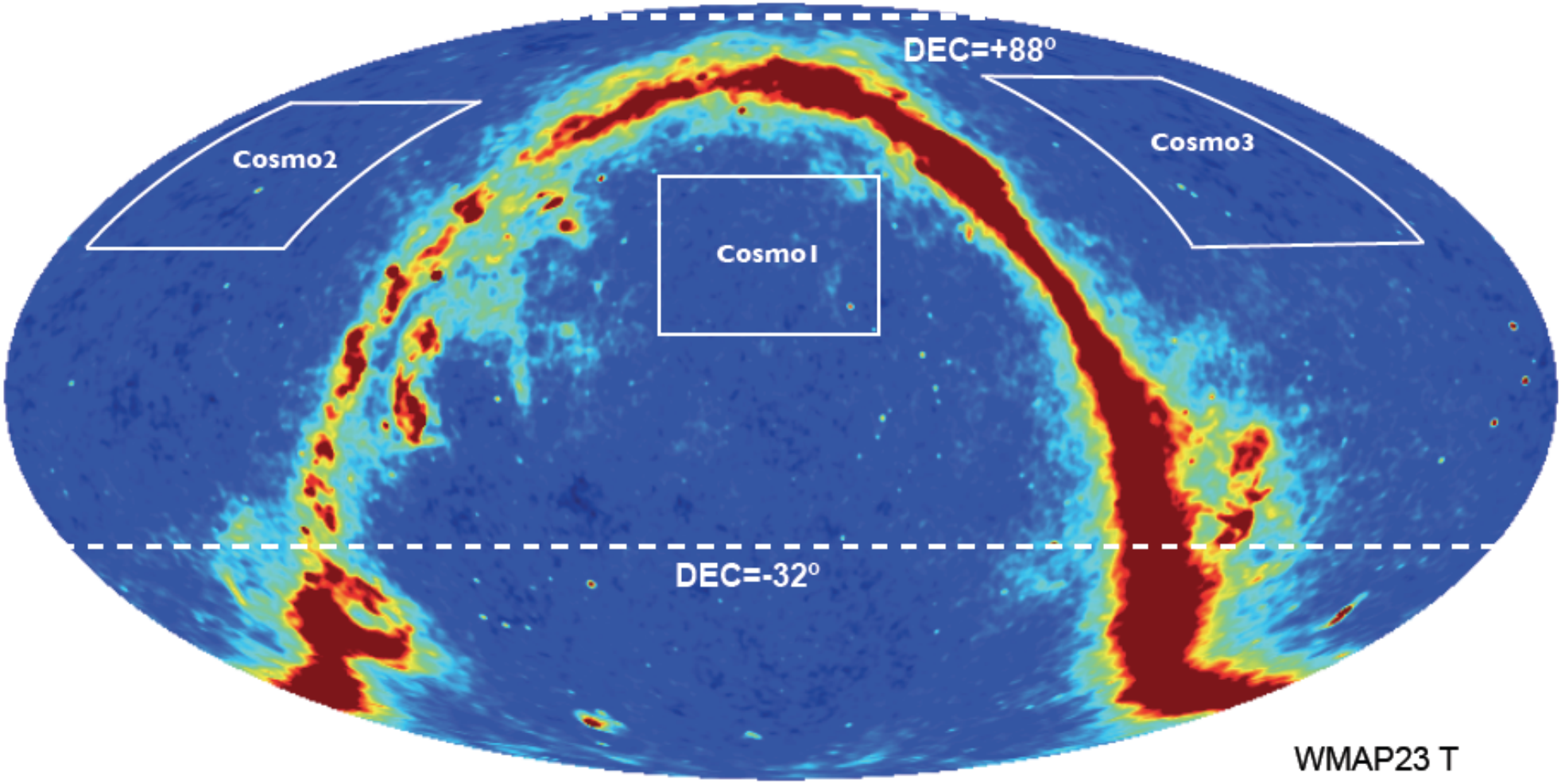
- Calibrators (>100 hrs observing CRAB, CASS-A, Moon, Jupiter).
- Polarization tests.
- Local interference map (~10 hrs)
- Tsys calibration (~10hrs).
- Science demonstration cases: Cygnus region, Fan region, Perseus molecular cloud.

MFI Science phase
(April 2013 - now)

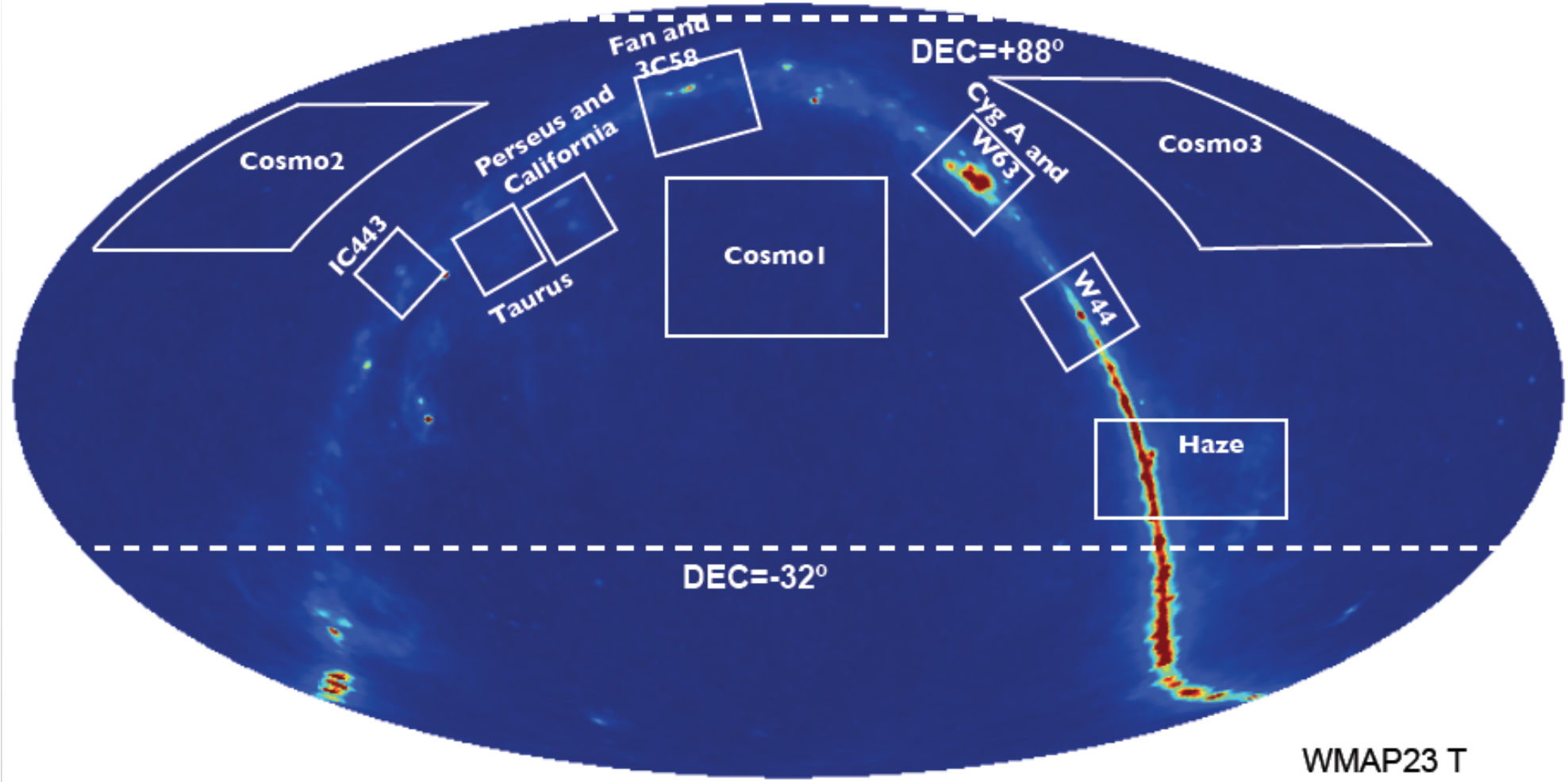
- Wide survey (5000h)
- Cosmological fields (2000h)
- Daily calibrators (Crab, Cass A, Jupiter, sky dips)
- Galactic centre (550h)
- Perseus molecular cloud (300h)
- Fan region and 3C58 (170h)
- Taurus region (400h)
- SNRs (W44, W47, IC443, W63) (700h)

Total: **10700 h** (447 effective days), with 50% efficiency.

QUIJOTE cosmological fields

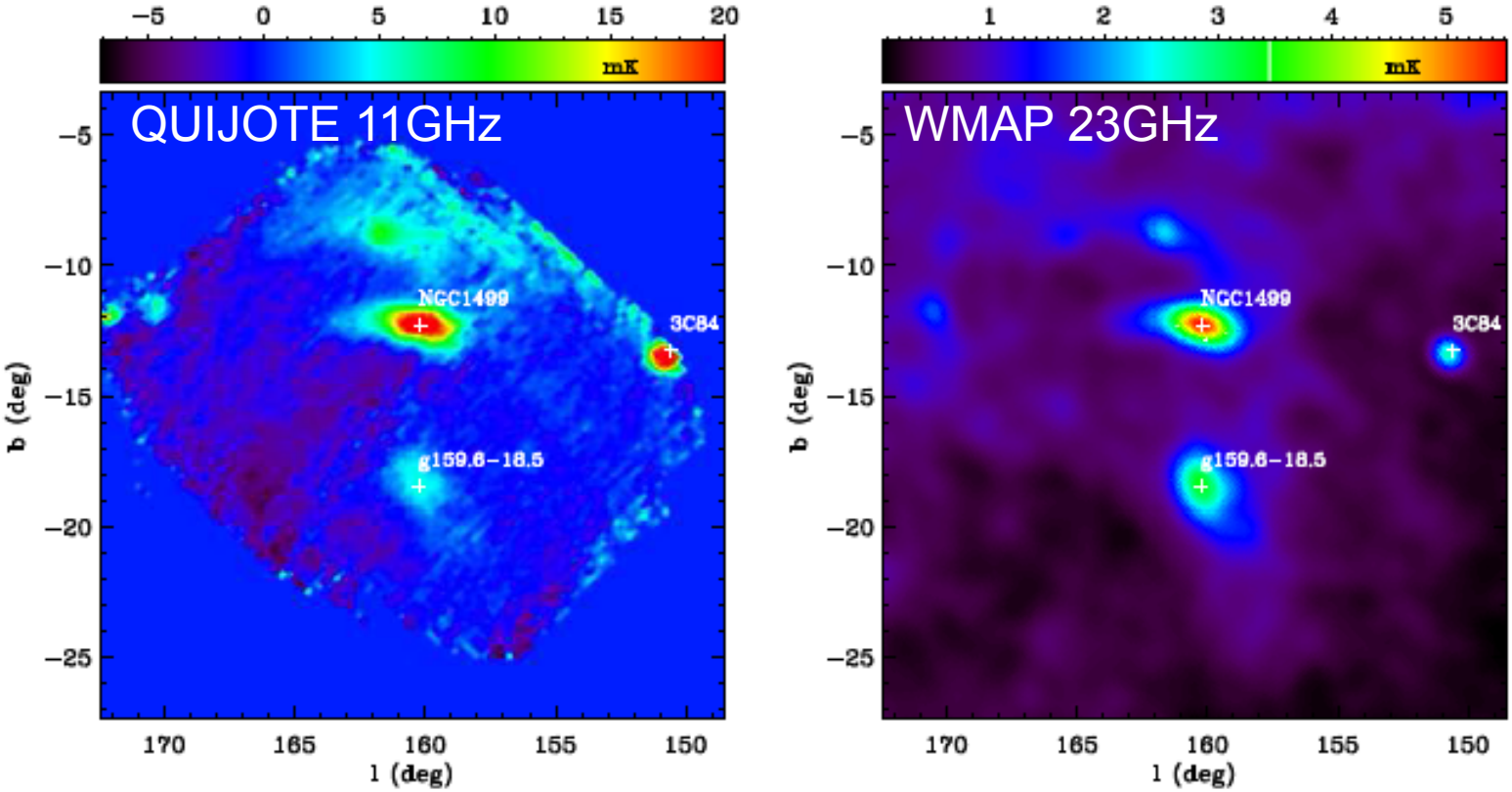


QUIJOTE cosmological and galactic fields



Perseus Molecular Complex

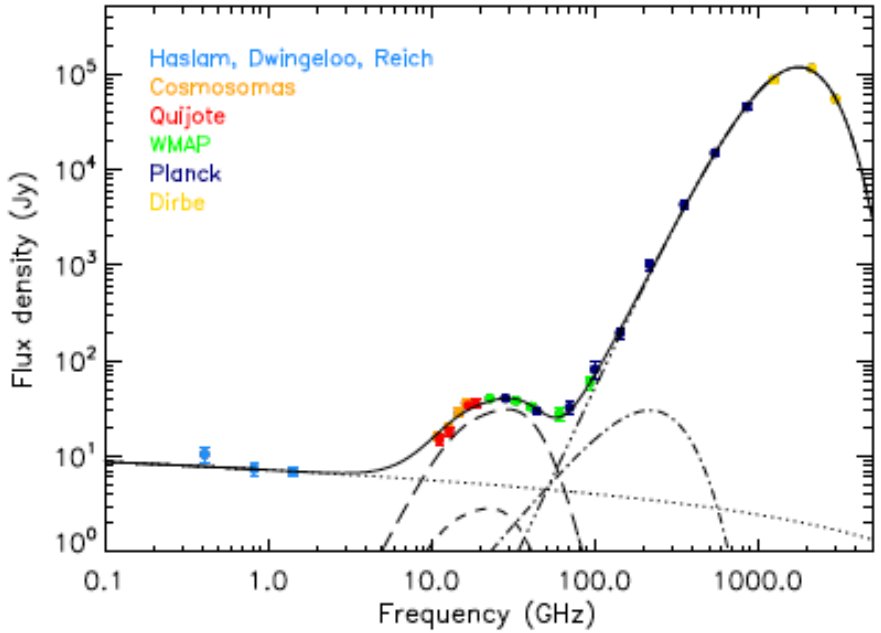
- Large observing programme (**200h**, taken during Dec-2012 to Apr-2013), on an area covering 200 deg^2 around the **Perseus molecular complex**. One of the brightest AME regions on sky (Watson et al. 2005; Planck Collaboration 2011).
- Also covering the California nebula or NGC1499 (HII region, a null polarization control region).
- Final integration time of 3300s/beam, yielding ~30mJy/beam in Q, U maps.



(Genova-Santos et al. 2015, MNRAS, arXiv:150104491G)

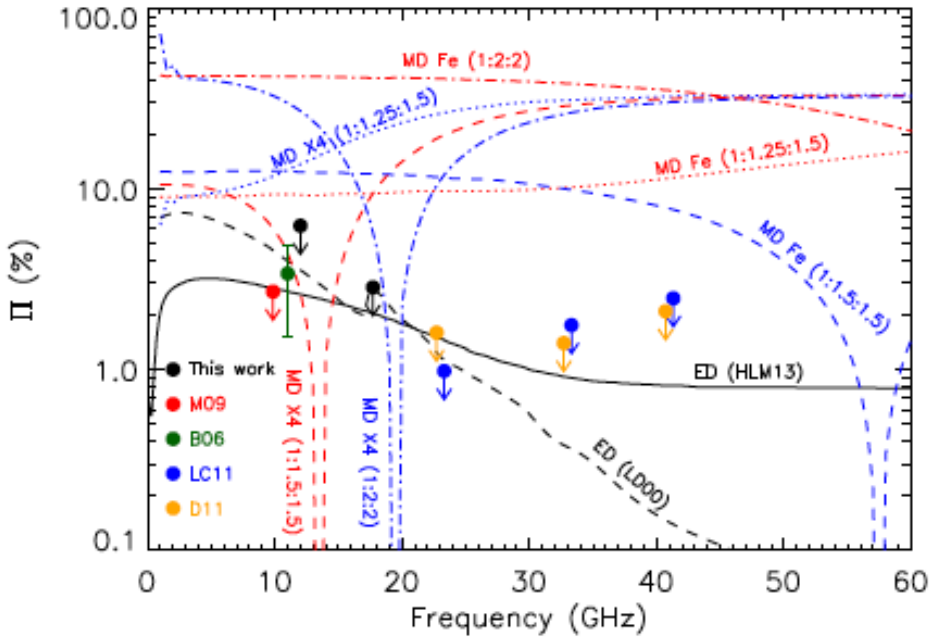
Perseus Molecular Complex

SED modeling for G159.6-18.5



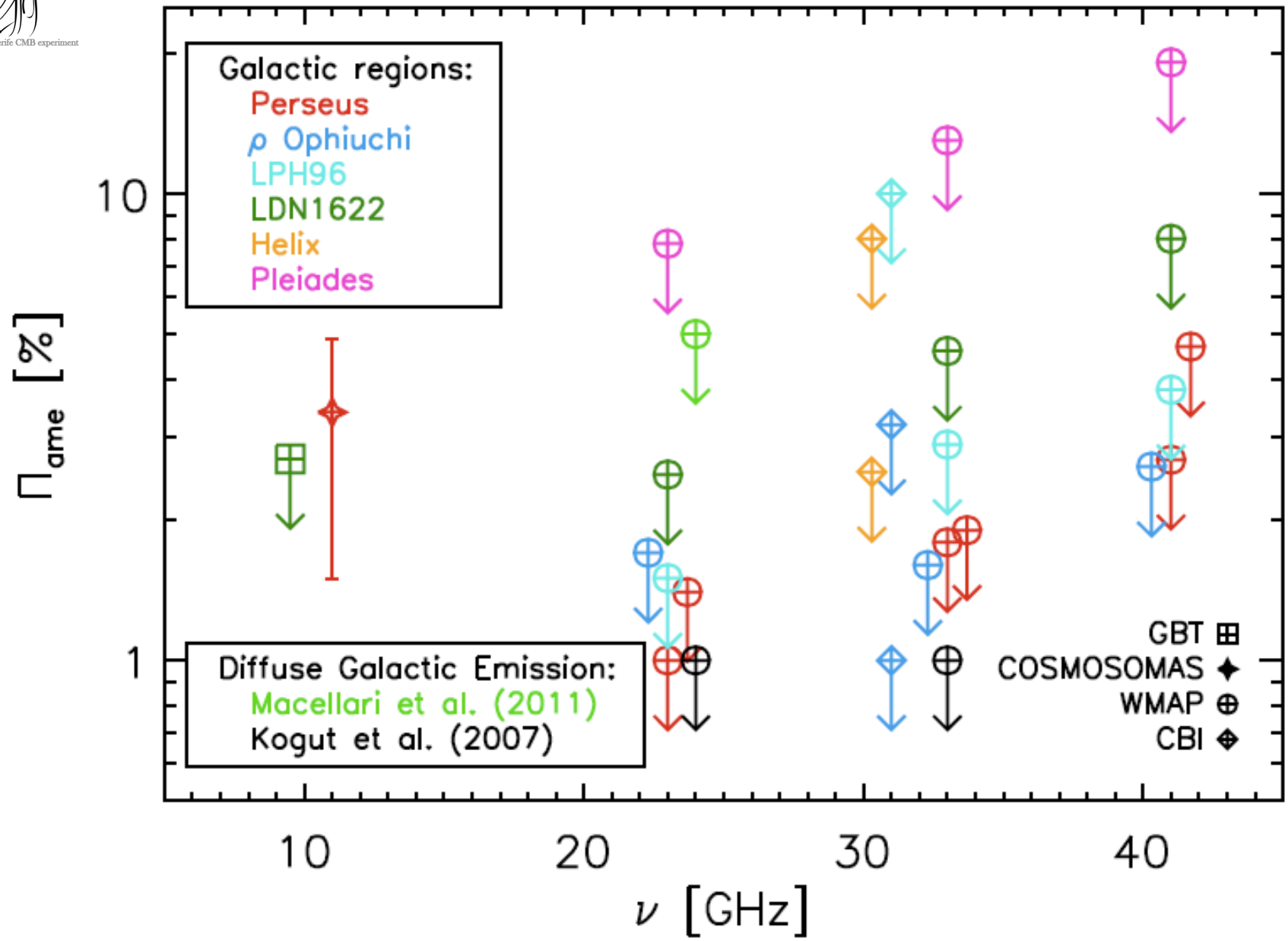
- AME (spinning dust) shows up at intermediate frequencies.
- Simultaneous fit of all components gives χ^2/dof = 1.08.
- Most precise spinning dust spectrum to date (13 independent data points in the relevant range).

Limits on AME polarization



- **No polarization detection**.
- Π < 6.3% at 12GHz and < 2.8% at 18GHz (95% C.L.)
- Models predict up to 2-3% in this range.
- Stringent upper limits can be derived from WMAP at 23GHz (López-Caraballo et al. 2011) where the signal is expected to be lower.

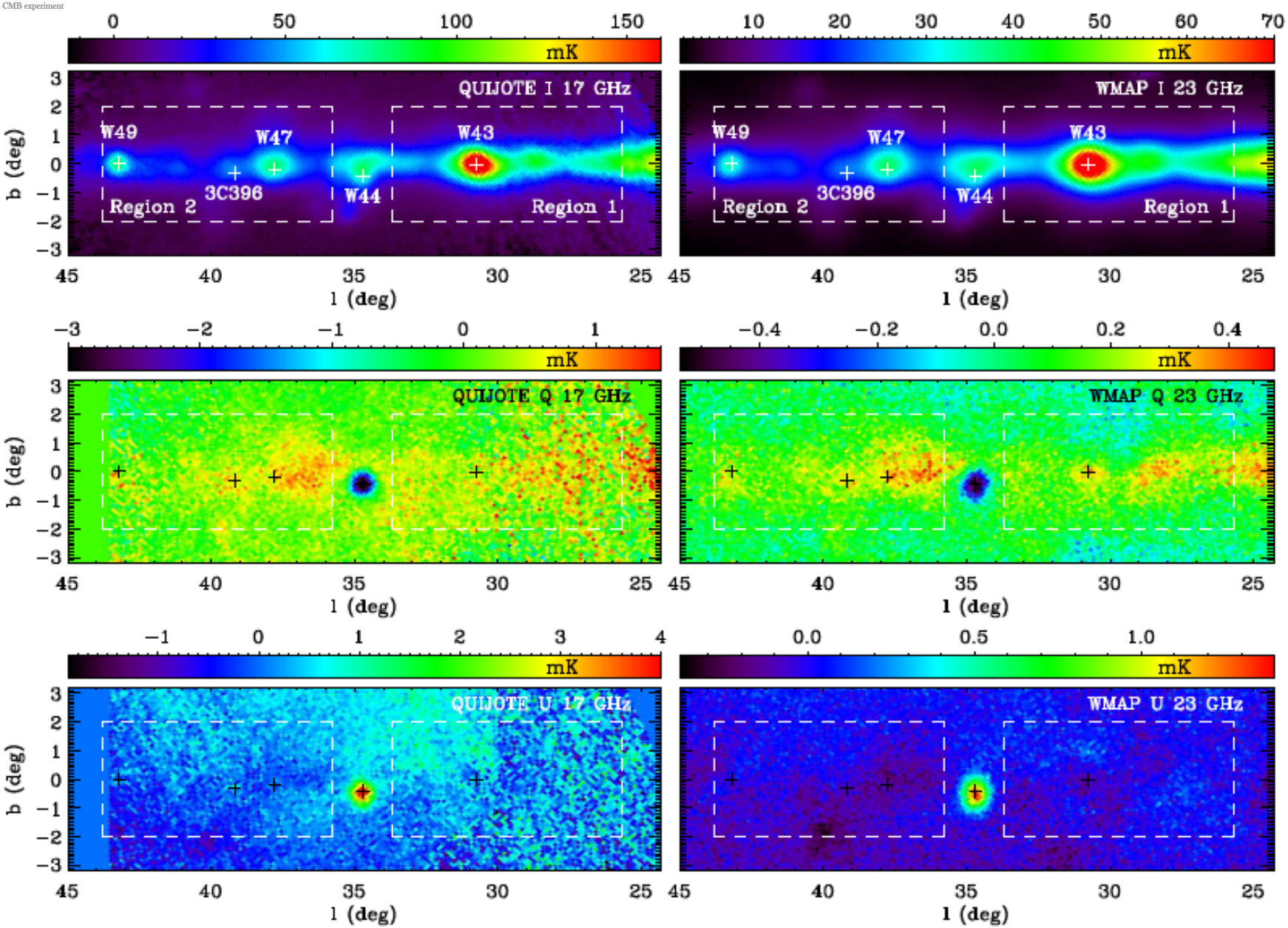
Previous status of AME polarization measurements



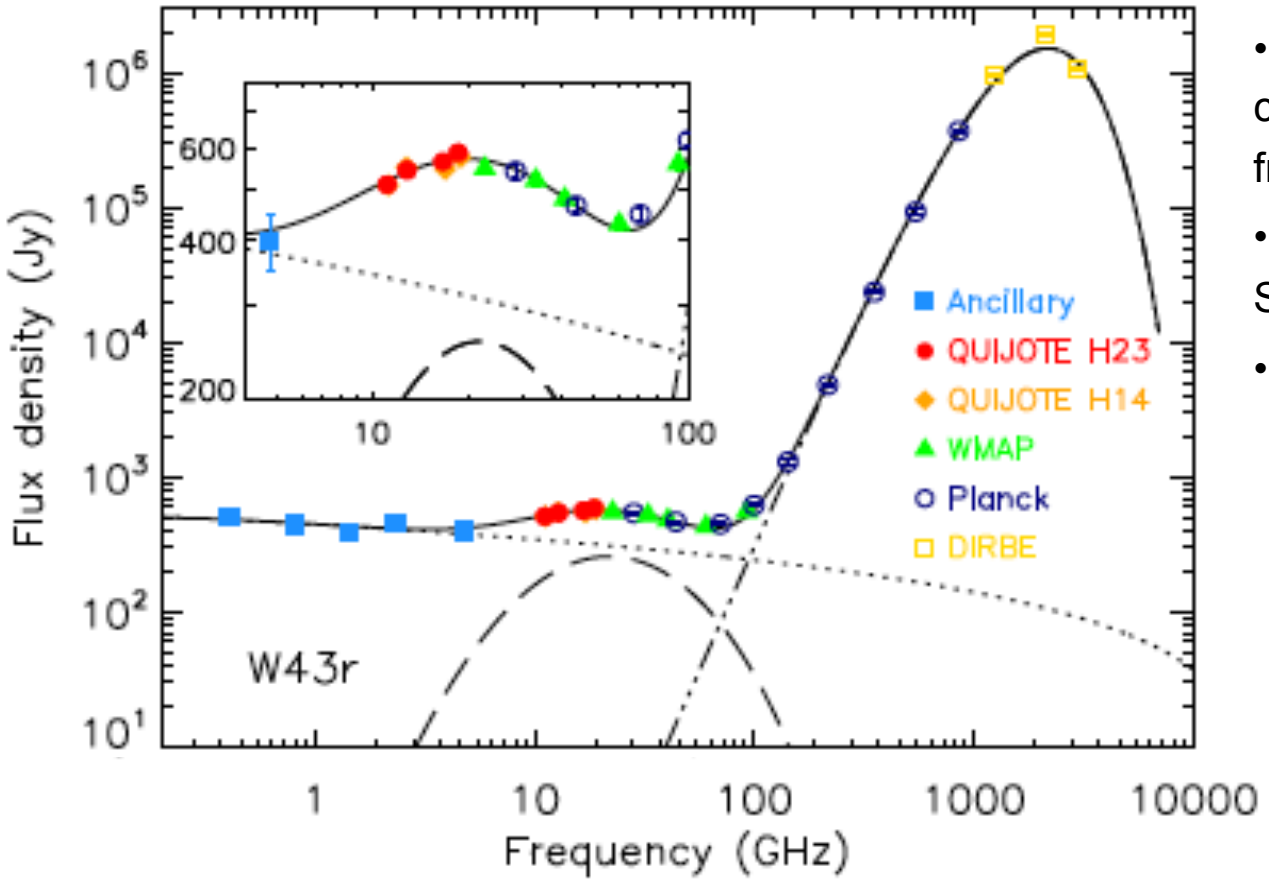
Rubiño-Martín et al. (2012)

W43, W44 and W47 (25º<l<45º)

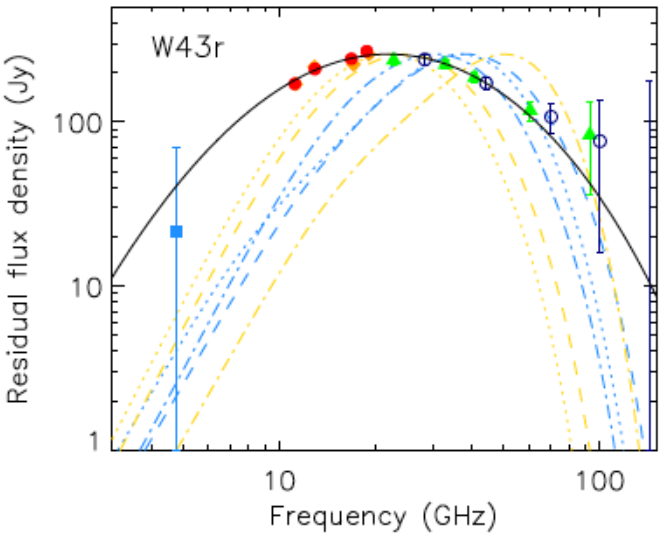
(W44 is a bright SNR. Both W43 and W47 are molecular complexes)



W43 molecular complex



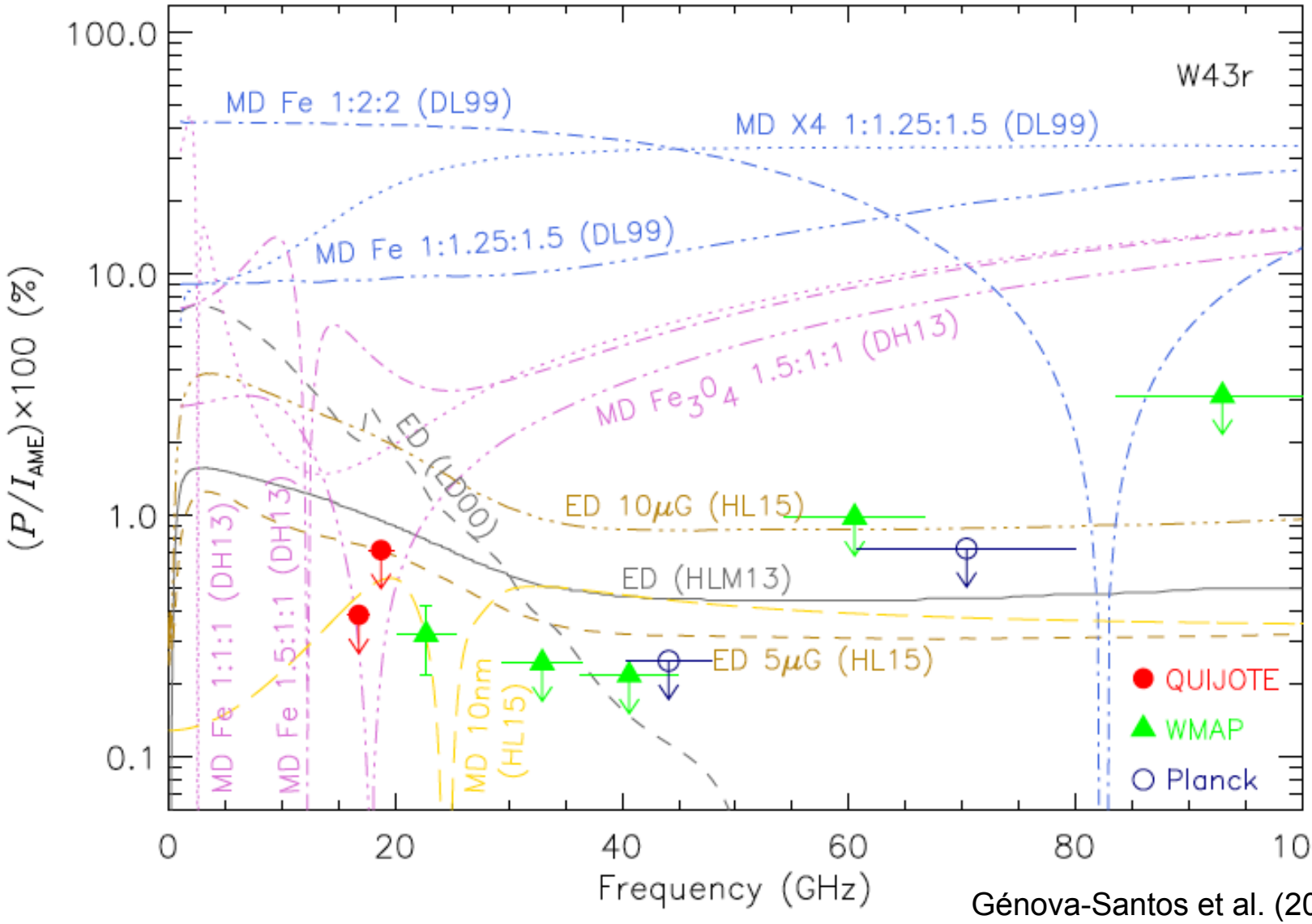
- The four QUIJOTE data points confirm the downturn at low-frequencies due to spinning dust.
- Free-free dominated intensity SED.
- AME peak brighter than Perseus.



Génova-Santos et al. (2016), MNRAS submitted, arXiv:1605.04741.

W43 molecular complex

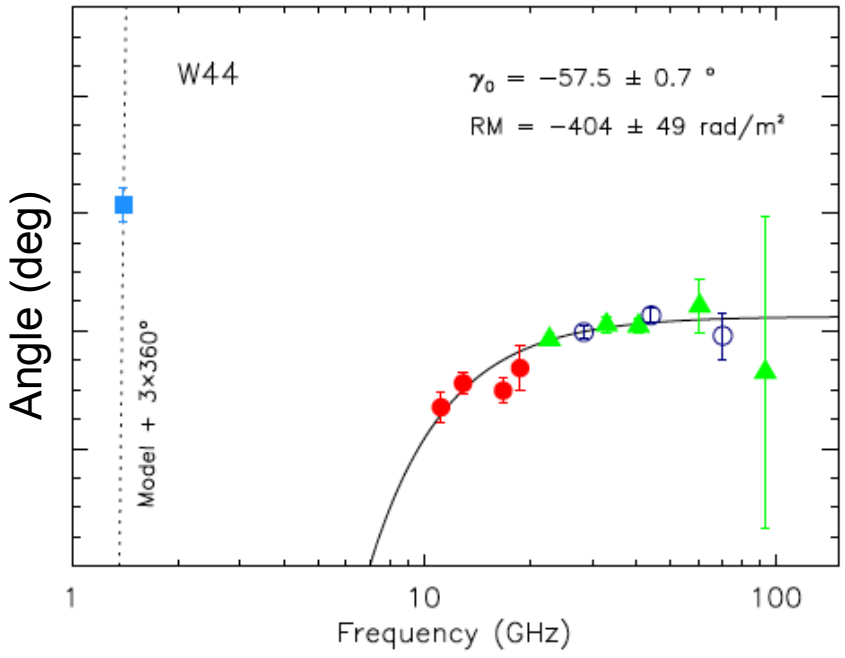
Constraints on AME polarization fraction and comparison with ED models. Best upper limits to date (< 0.4% at 17GHz from QUIJOTE, and < 0.22% at 23GHz from WMAP).

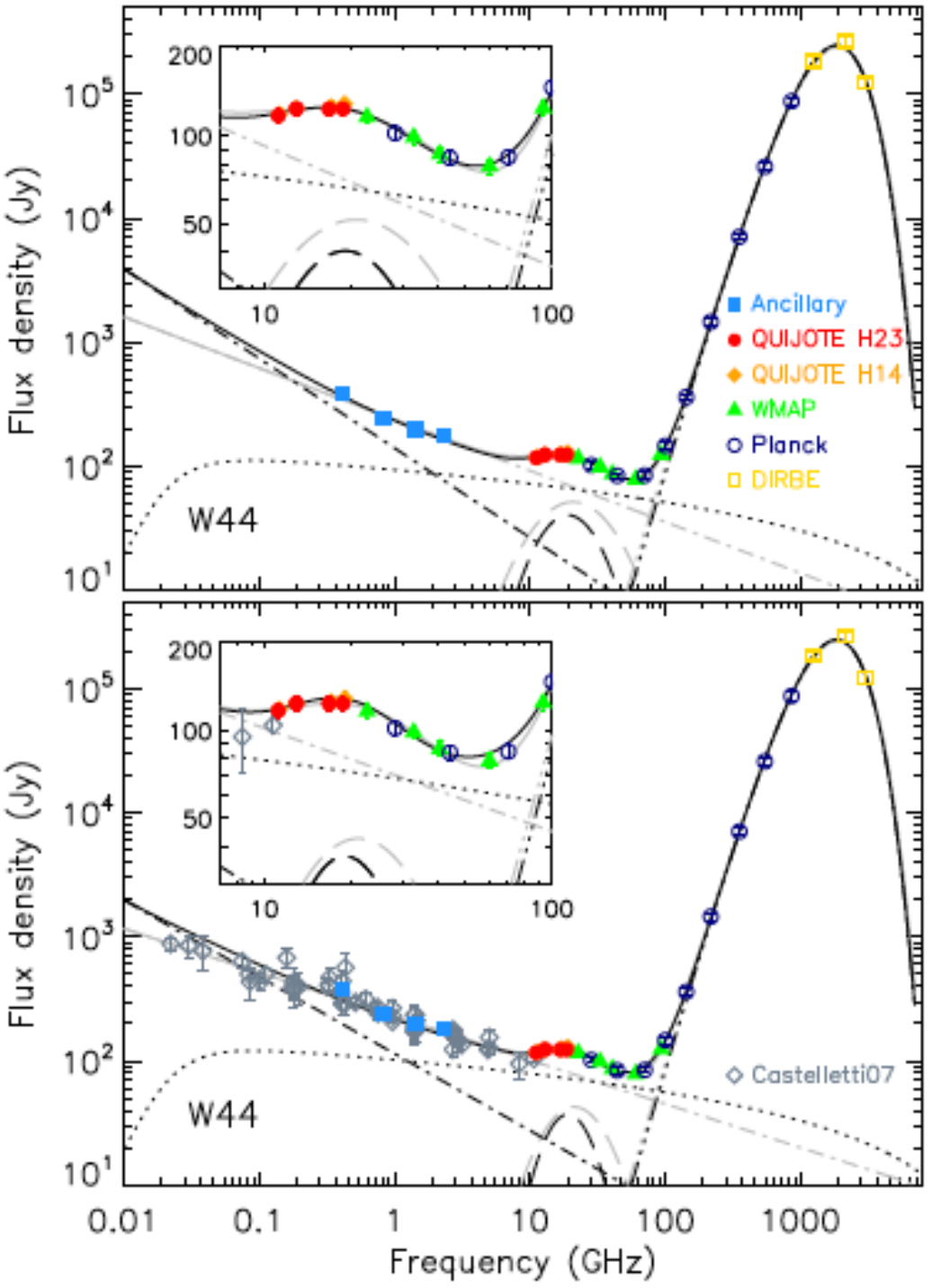


Génova-Santos et al. (2016, submitted)

SNR W44

- High significance detection of AME in a SNR.
- Possibility to determine the spectral index of the synchrotron emission: β_{sync} =-0.62 ± 0.03. Important to constrain the nature of CRs (pion-decay feature detected in W44 with Fermi LAT, Ackermann et al.2013).
- Downturn in the polarisation angle at <20GHz associated with Faraday rotation in the direction of W44 with rotation measure −404 ± 49 rad/m^2.

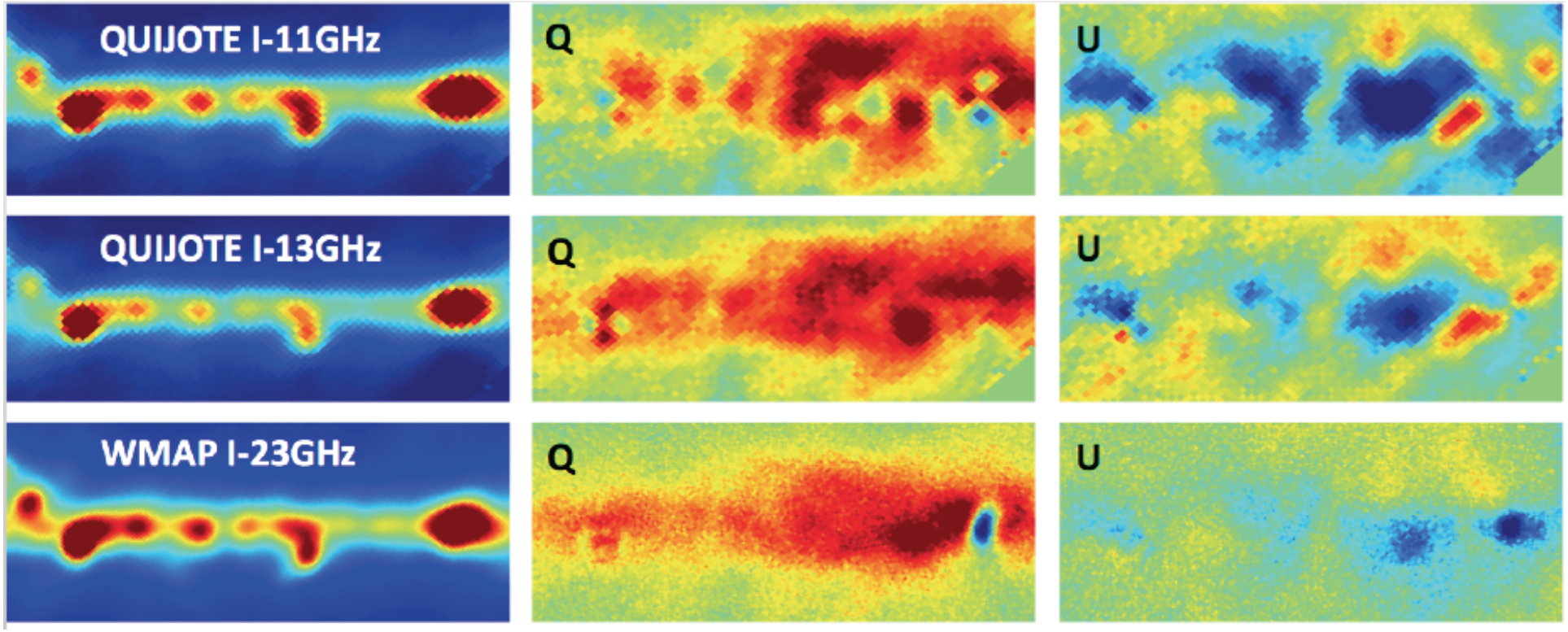




Génova-Santos et al. (2016, submitted)

Galactic centre (0º<l<20º)

- Large observation program still ongoing (~300hrs), on an area covering ~1000 deg^2 around the Galactic centre.
- The goal is to study the polarized emission in the region, with particular interest on the characterization of the Haze emission.
- Preliminary 11 and 13 GHz maps (20x6 deg^2) of the Galactic plane around the Galactic centre, in comparison with WMAP 23 GHz.



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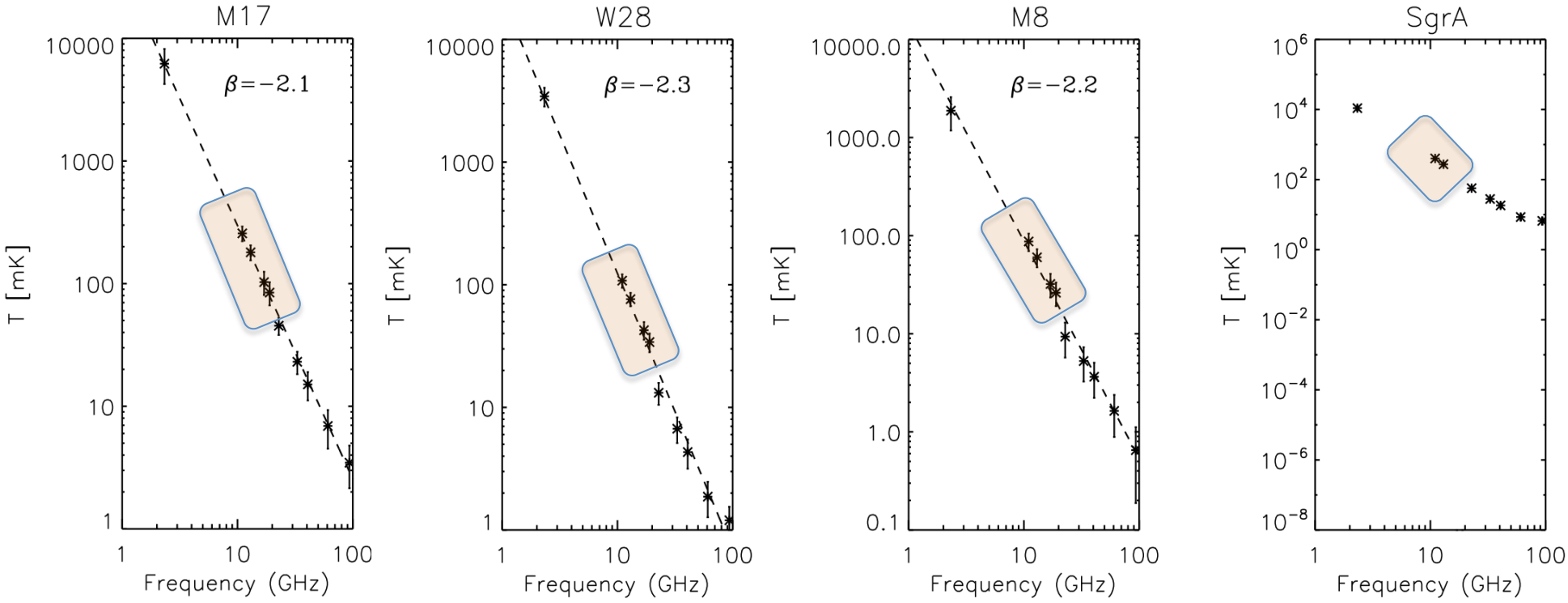
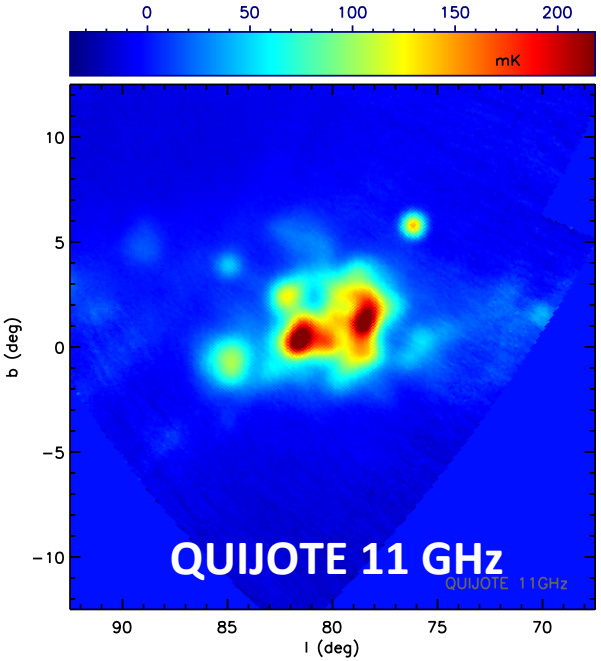
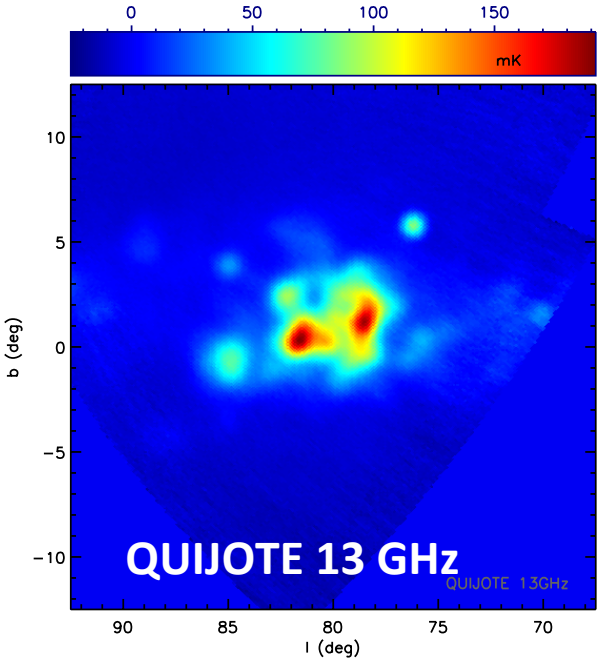
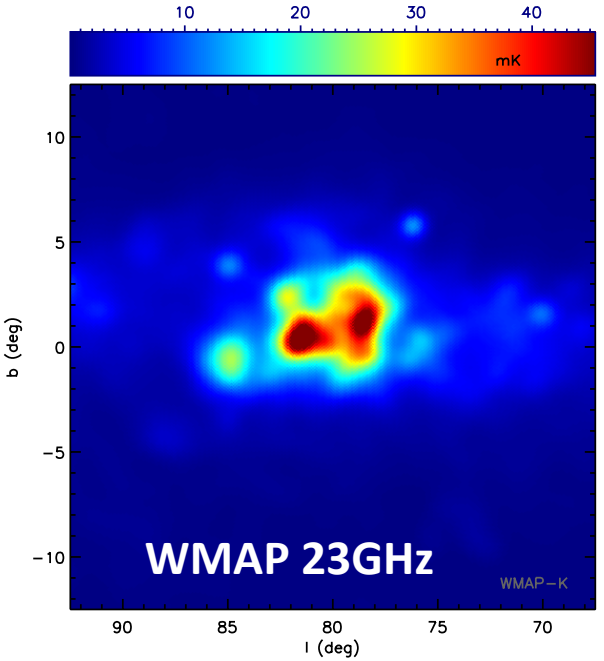


Cygnus region (70º<l<90º)

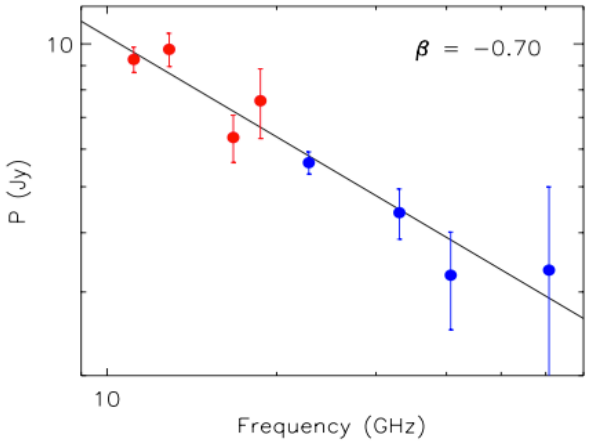
- Data in raster mode (W63 region) for ~200hrs.
- Destripping map-making solution, with 2.5s baseline.

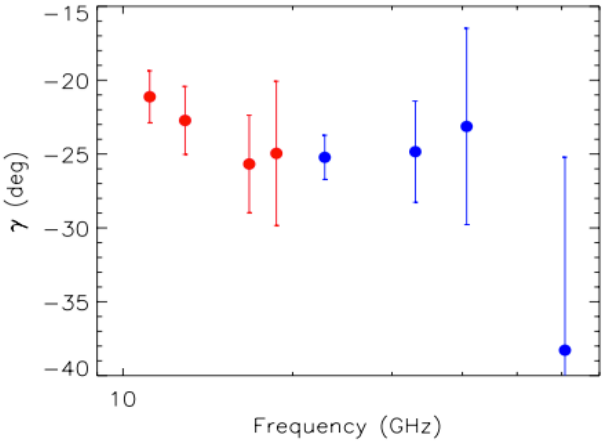






Polarization SED on W63:

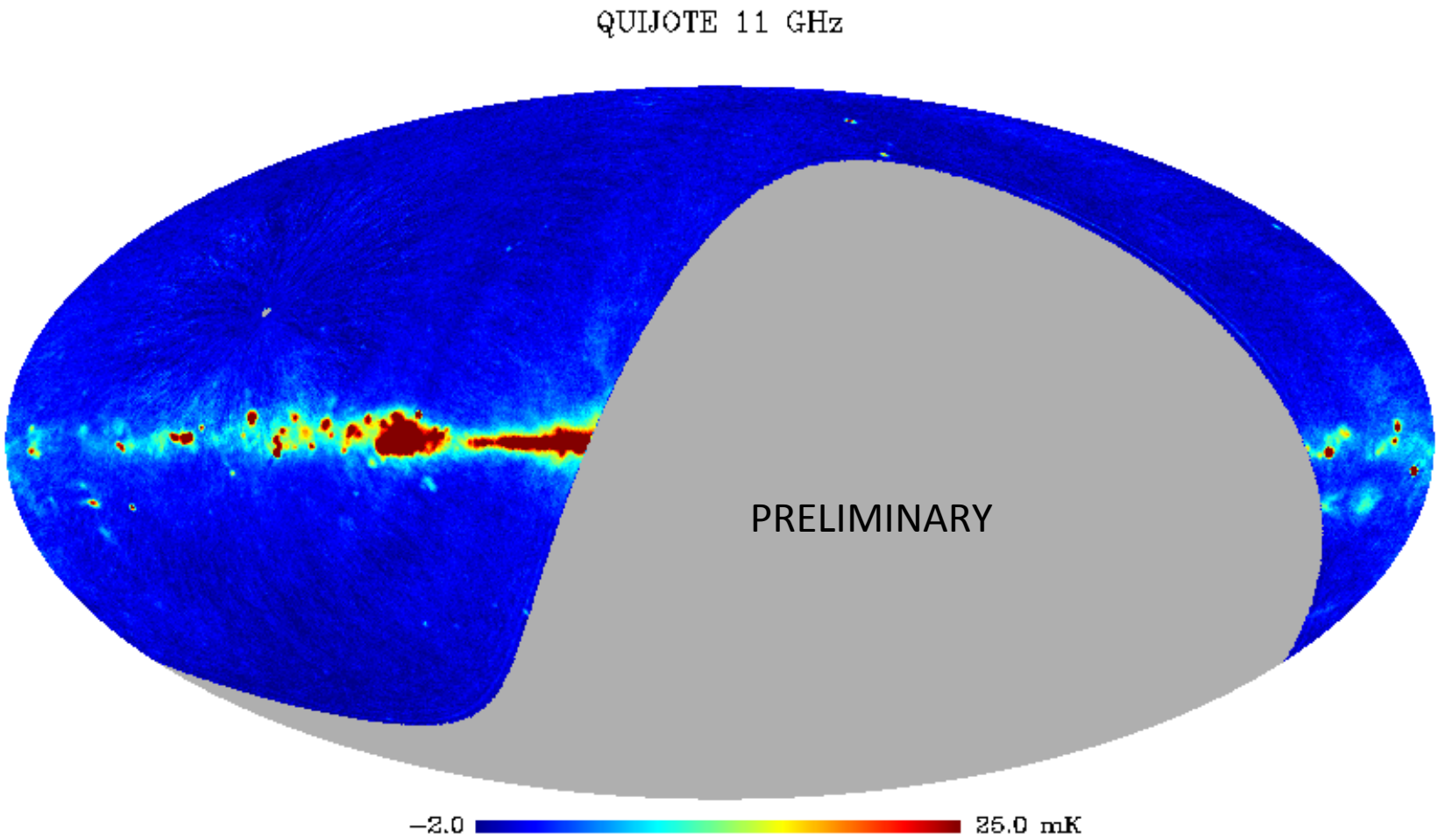




Wide survey

- 5000 hrs on a region of 20,000 deg^2 in the northern sky.
- Still on-going (will reach ~5500 hrs).
- Goal: ~15 μK/beam in Q,U and, ~50 μK/beam in I.

Example of QUIJOTE maps from 700 h observations. Case of 11GHz (with EL>60º):



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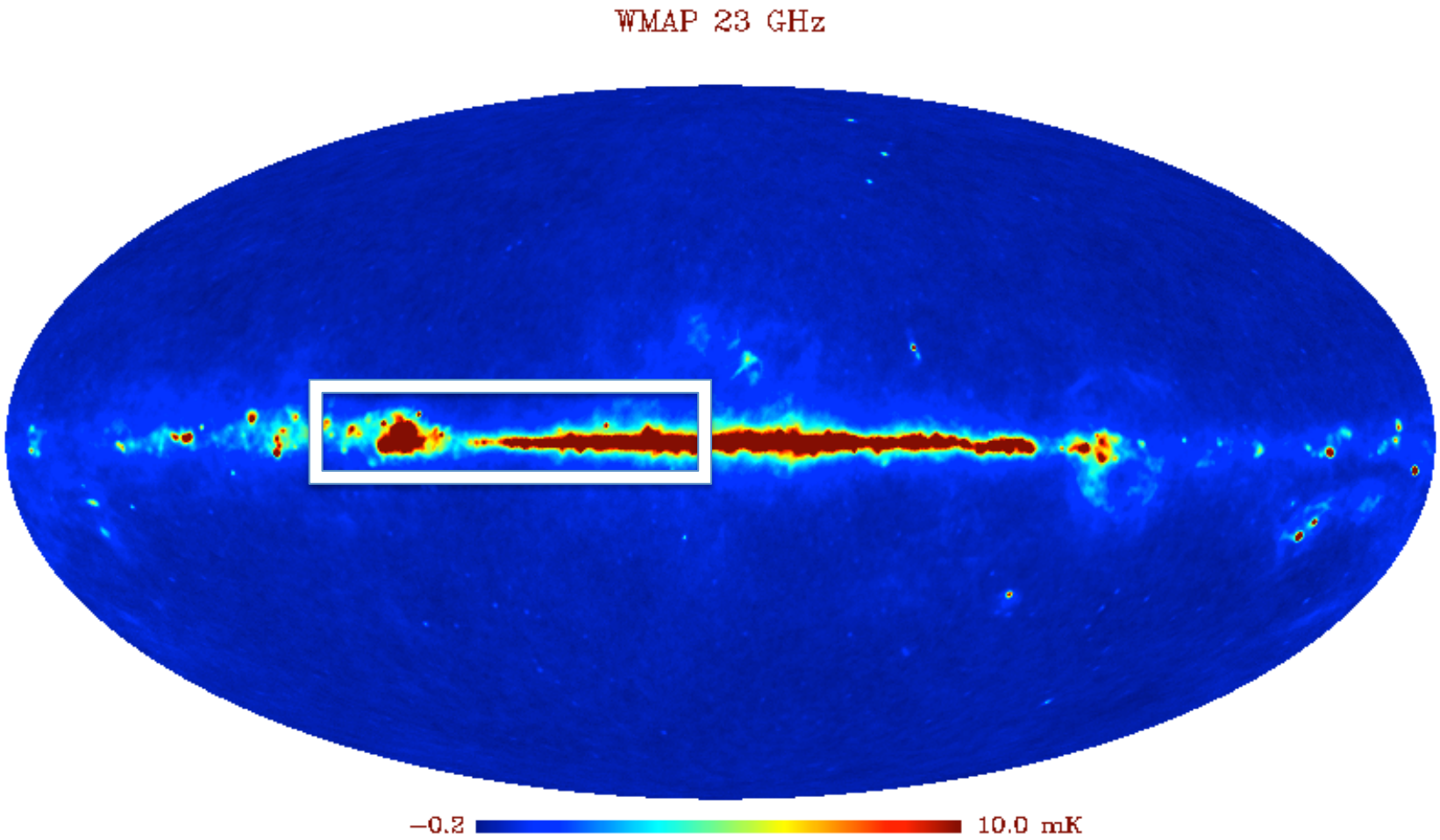


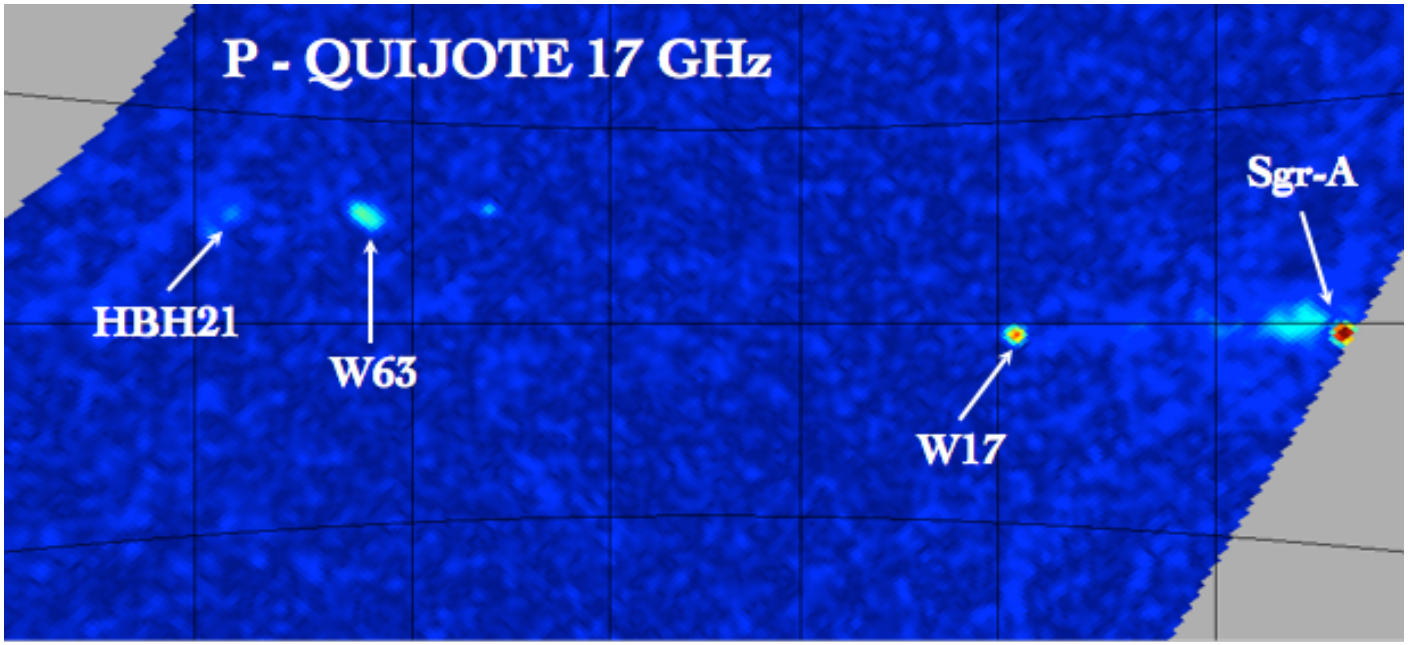
Wide survey

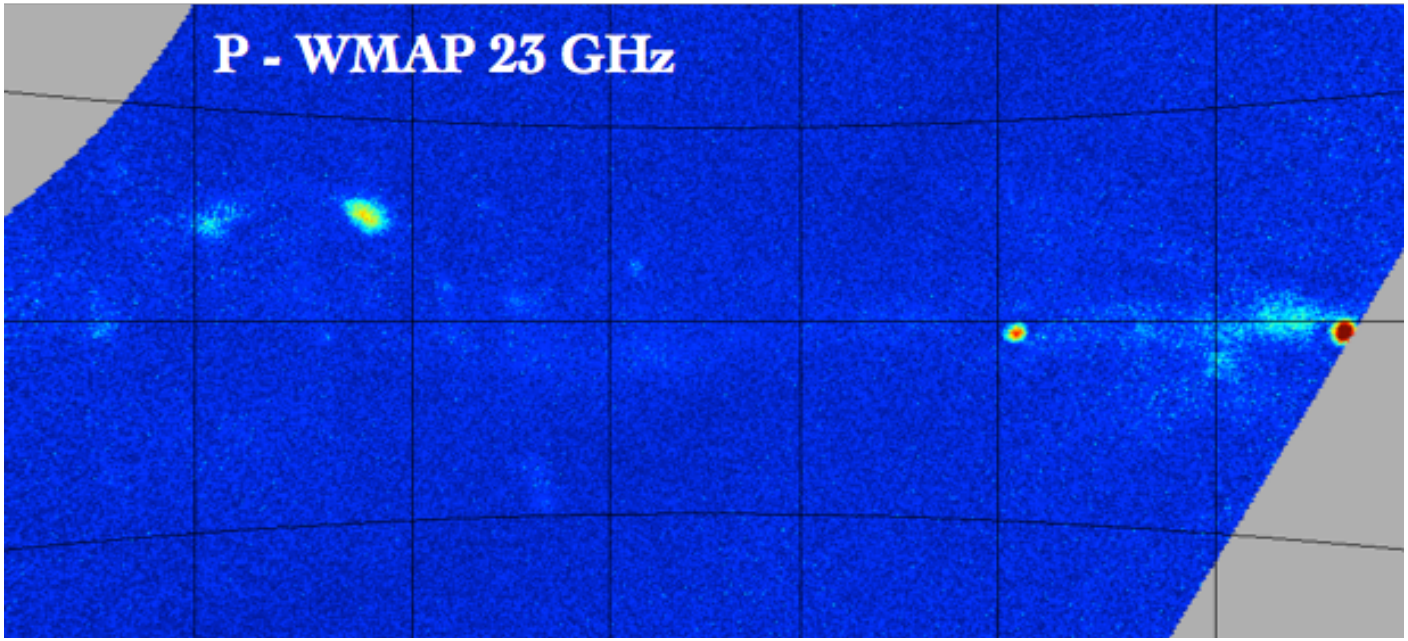
PRELIMINARY

- Polarized intensity at 17GHz, compared to WMAP 23 GHz.

- Even with a preliminary map-making, compact objects and diffuse emission is starting to be seen.

- **Legacy value**. Combination of these maps with future experiments (e.g. CORE, LiteBird) will improve the ability to correct for synchrotron and AME (see e.g. Errard et al. 2015).





TGI installation. April 20th, 2016.

Quijote
Q-U-I Joint Tenerife CMB experiment

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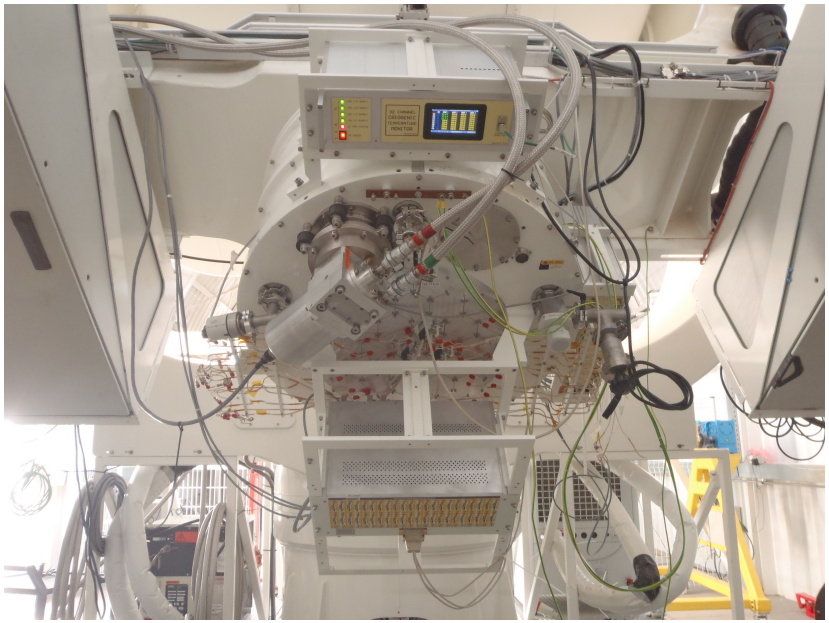
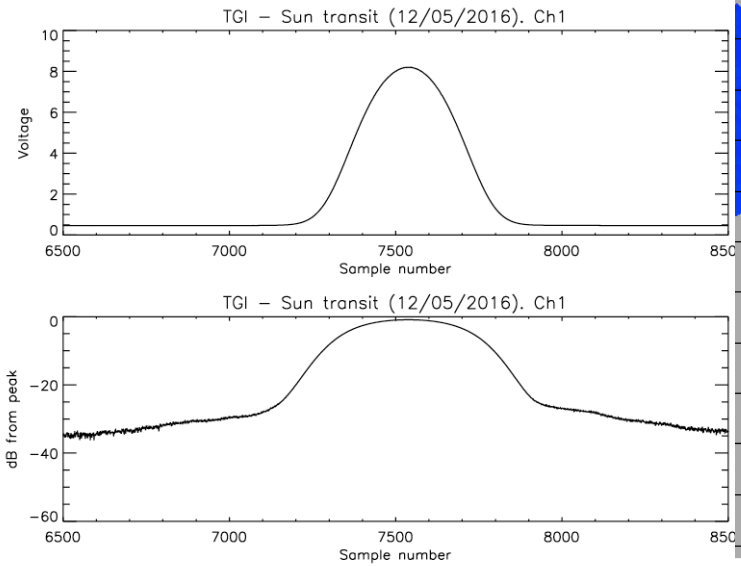
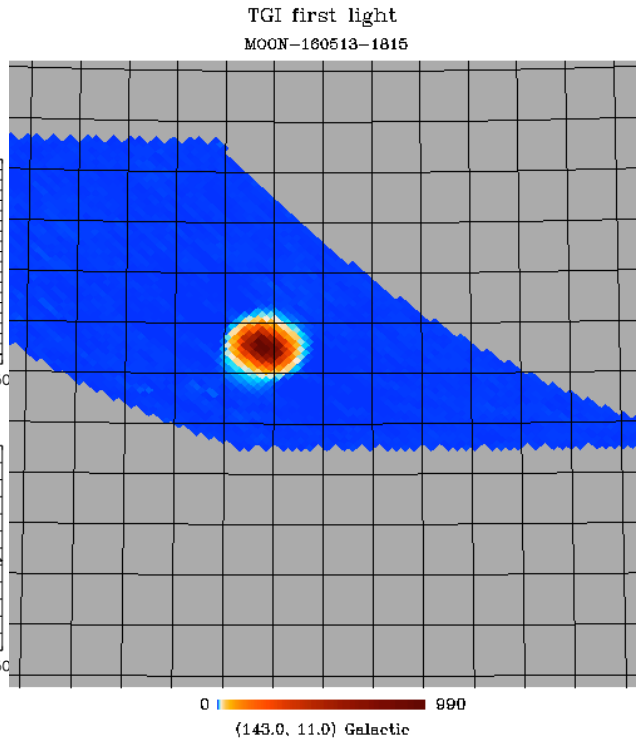
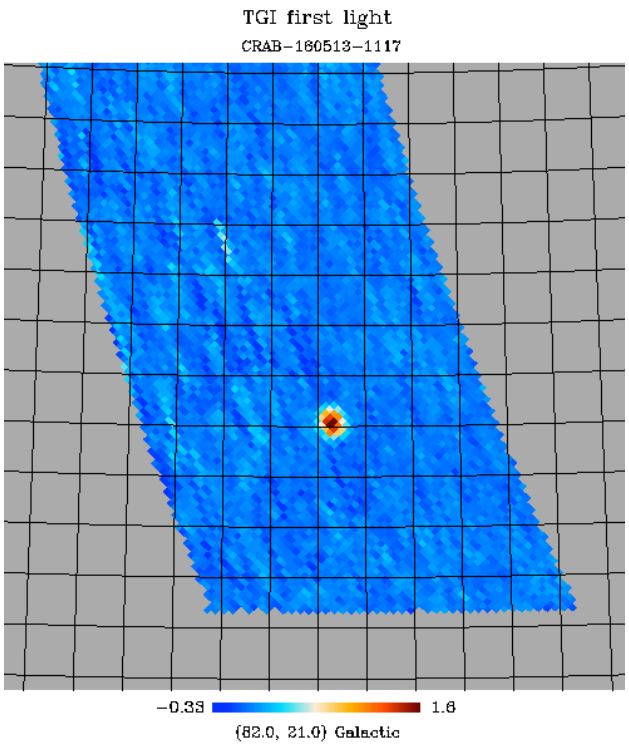
TGI. Commissioning phase.



- Instrument calibrated on lab during Feb-Apr 2016.
- Installed at QT2 focal plane on April 20th.
- First light on May 12th , 2016.
- In commissioning phase.
- Routine operations with all 30 pixels will start in summer.







RADIOFOREGROUNDS project

http://www.radioforegrounds.eu

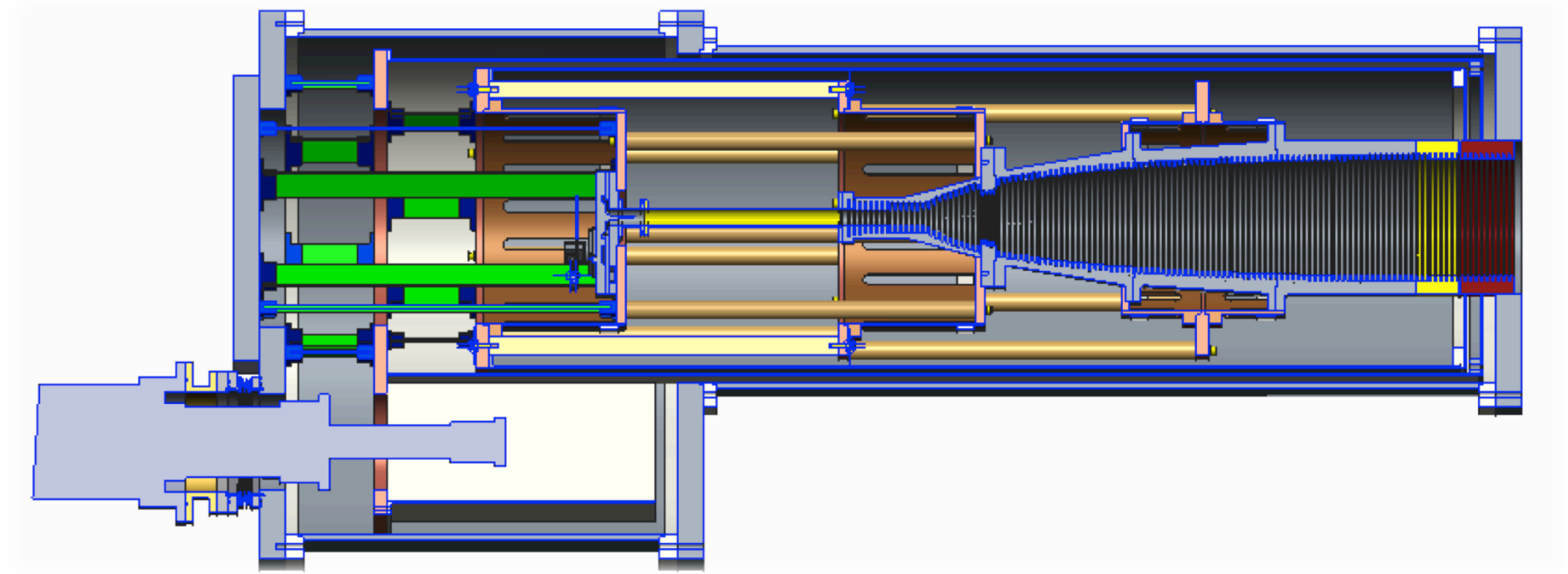
H2020-COMPET-2015. Grant agreement **687312:** "Ultimate modelling of Radio Foregrounds" (RADIOFOREGROUNDS).
3-year grant (IAC; IFCA; Cambridge; Manchester; SISSA; Grenoble; TREELOGIC).

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.

QUIJOTE: Plans for full sky coverage

- We are exploring the possibility of building a replica of QUIJOTE in the southern hemisphere (South Africa).
- In collaboration with Wits University (ZA) , a prototype of a MFI pixel is already funded.
- MFI-S will be fabricated during 2016, and will be tested at the 7.6m telescope at HartRAO.
- A complete MFI instrument and a full replica of a QUIJOTE telescope will come later, if observations with the prototype instrument are successful (funds not approved yet).



Conclusions

- **QUIJOTE** is a polarization experiment designed with the aim of reaching the level of r=0.05 in the B-mode angular power spectrum.

- QUIJOTE is able to measure the synchrotron and AME polarization in a frequency range not covered by other experiments so far. **Excellent complement to PLANCK at low frequencies. Legacy value for CORE, LiteBird and other sub-orbital experiments.**

- **MFI (10-20 GHz)** on **QT1** had first light on Nov. 2012. Since then, we are doing routine observations on selected Galactic regions and Cosmological fields. **MFI and QT1 are performing well**, producing intensity and polarization maps at 4 frequencies.

- **First MFI papers are being finalised**. We have preliminary constraints on the AME polarization from the Perseus molecular cloud and W43 molecular cloud (best upper limits to date). Diffuse Galactic polarization detected along the Galactic plane. Several SNRs, etc.

- **QT2 is installed. TGI (30 GHz)** had first light on May 12th 2016. Now in commissioning phase. FGI (40 GHz) will come soon. One year of observations with TGI should allow to reach a sensitivity r=0.1. Combined FGI/TGI data should reach r=0.05 (3 years of operation).

- **Legacy polarization maps** (10-40GHz) **and derived products will be publicly available**.


Quijote
Q-U-I Joint Tenerife CMB experiment
Thank you
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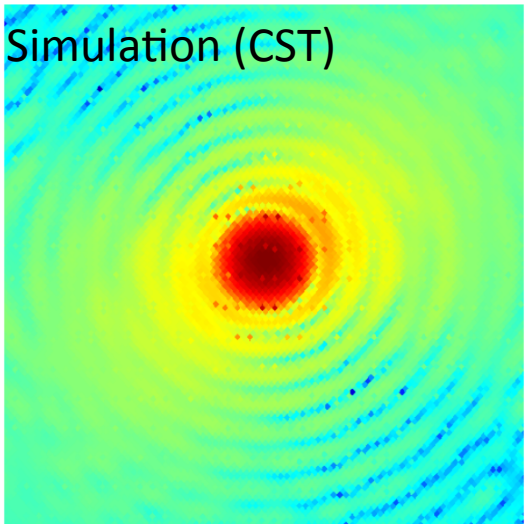
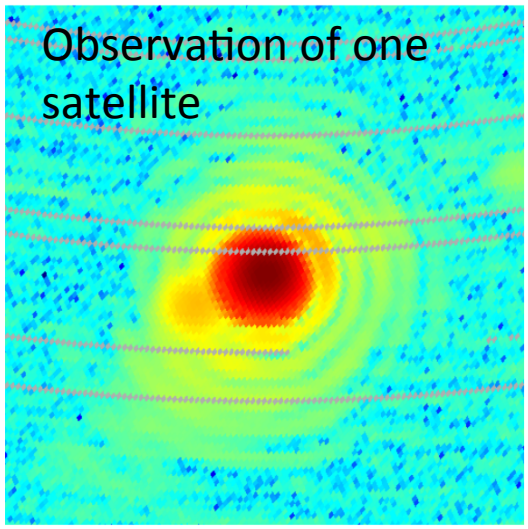
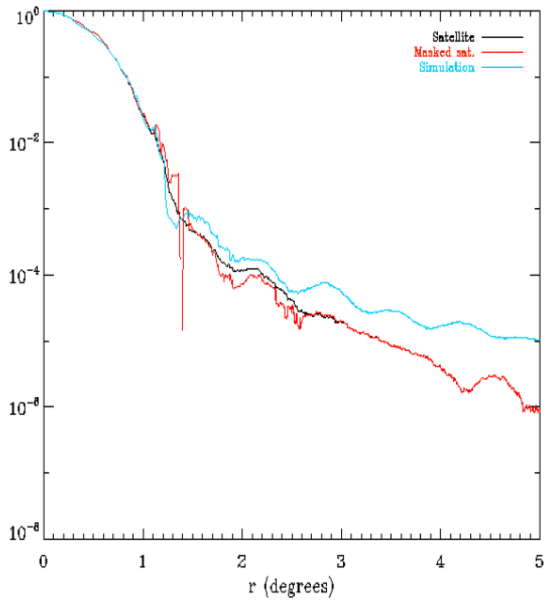
MFI beams and window functions

- Observations of point sources (CRAB, CASS A).
- At low freqs (10-12GHz) geo-stationary satellites can be used. A single 10 min observation allows to reach -50 dB. First side lobes below -30dB.

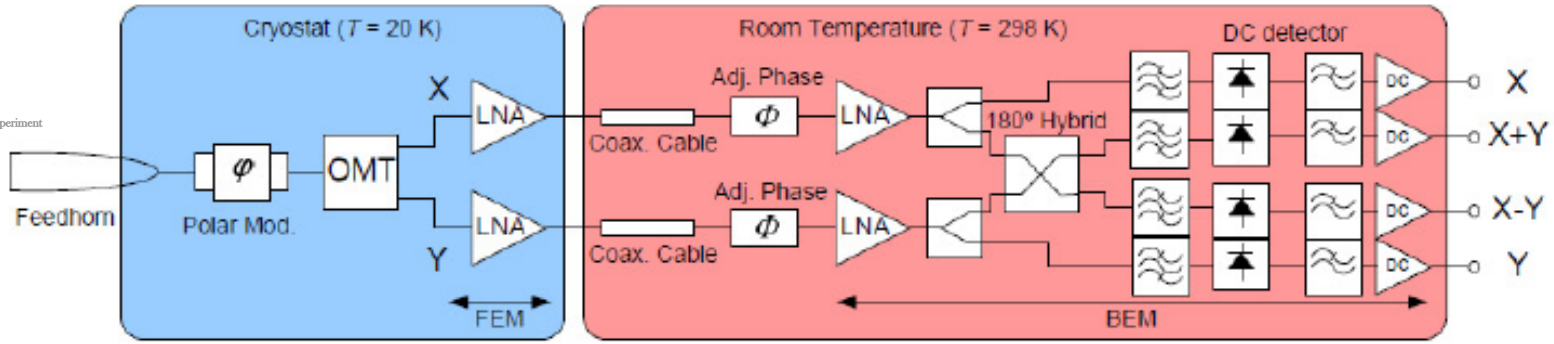
	FWHM (º)	FWHM (º) (nominal)	e	Ω (msr)	Γ(μK/Jy)
Horn1	0.89±0.01	0.91	0.99	0.273	949.8
Horn2	0.65±0.01	0.75	0.87	0.145	496.8
Horn3	0.85±0.01	0.82	0.92	0.245	775.0
Horn4	0.64±0.06	0.66	0.99	0.141	602.1







MFI channel response



$$V_x = s_x g_1^2 \frac{1}{2}(I + Q\cos(4\theta) - U\sin(4\theta))$$

$$V_y = s_y g_2^2 \frac{1}{2}(I - Q\cos(4\theta) + U\sin(4\theta))$$

$$V_{x+y} = s_{x+y}\frac{1}{2}\left(\frac{g_1^2+g_2^2}{2}I + \frac{g_1^2-g_2^2}{2}(Q\cos(4\theta) - U\sin(4\theta)) + g_1 g_2(Q\sin(4\theta) + U\cos(4\theta))\right)$$

$$V_{x-y} = s_{x-y}\frac{1}{2}\left(\frac{g_1^2+g_2^2}{2}I + \frac{g_1^2-g_2^2}{2}(Q\cos(4\theta) - U\sin(4\theta)) - g_1 g_2(Q\sin(4\theta) + U\cos(4\theta))\right)$$

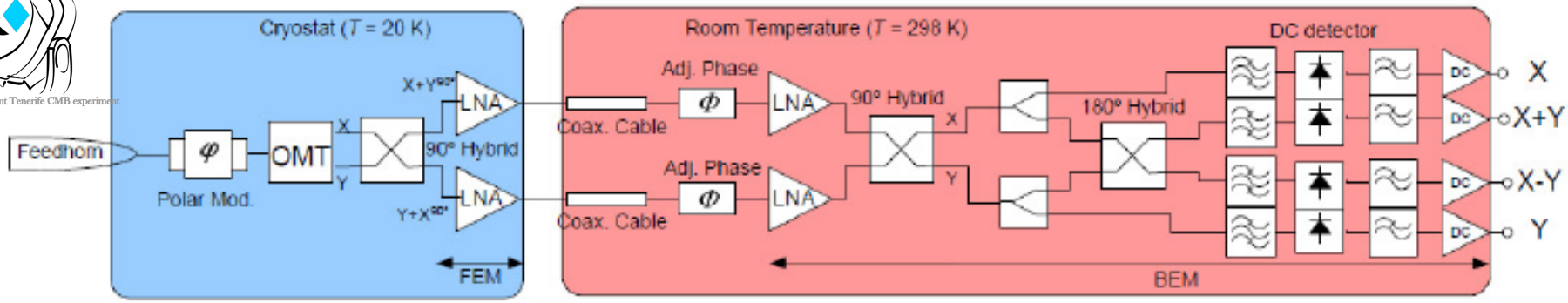
$$V_x + r_u V_y = s_x g_1^2 I$$

$$V_x - r_u V_y = s_x g_1^2 (Q\cos(4\theta) - U\sin(4\theta))$$

$$V_{x+y} + rV_{x-y} = s_{x+y}\left(\frac{g_1^2+g_2^2}{2}I + \frac{g_1^2-g_2^2}{2}(Q\cos(4\theta) - U\sin(4\theta))\right)$$

$$V_{x+y} - rV_{x-y} = s_{x+y} g_1 g_2 (Q\sin(4\theta) + U\cos(4\theta))$$

MFI channel response. New configuration (with two 90º-hybrids)



$$V_x = \frac{s_x}{2}\left[\frac{g_1^2+g_2^2}{2}I - g_1 g_2 (Q\cos(4\theta) - U\sin(4\theta))\right]$$

$$V_y = \frac{s_y}{2}\left[\frac{g_1^2+g_2^2}{2}I + g_1 g_2 (Q\cos(4\theta) - U\sin(4\theta))\right]$$

$$V_{x+y} = s_{x+y}\frac{1}{2}\left(\frac{g_1^2+g_2^2}{2}I + g_1 g_2 (Q\sin(4\theta) + U\cos(4\theta))\right)$$

$$V_{x-y} = s_{x-y}\frac{1}{2}\left(\frac{g_1^2+g_2^2}{2}I - g_1 g_2 (Q\sin(4\theta) + U\cos(4\theta))\right)$$

$$V_x + r_u V_y = s_x \frac{g_1^2+g_2^2}{2} I$$

$$V_x - r_u V_y = s_x g_1 g_2 (-Q\cos(4\theta) + U\sin(4\theta))$$

$$V_{x+y} + r V_{x-y} = s_{x+y}\frac{g_1^2+g_2^2}{2} I$$

$$V_{x+y} - r V_{x-y} = s_{x+y} g_1 g_2 \left[Q\sin(4\theta) + U\cos(4\theta)\right]$$