The QUIJOTE-CMB CMB Experiment

(Studying the polarization of the Galactic and Cosmological microwave emissions)

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Polarized foreground for Cosmic Microwave Background
MPA, Garching, 26-28 November 2012

Outline

- Project overview
    - Scientific objectives
    - Time baseline
- Technical aspects
    - Telescopes (QT1 and QT2)
    - Instruments (MFI, FGI, TGI)
- Science
    - Core science (Foregrounds and B-modes)
    - Non-core science
- First observations, scientific commissioning (very preliminary!)

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❖ **Goal:** to perform high sensitivity observations of the polarization of the CMB and Galactic foregrounds at low frequencies (10-40 GHz) and large angular resolution (1°)

❖ **Main science driver:**

- To constrain (or to detect) primordial B-modes down to r=0.05
- Complement Planck at low frequencies. In combination with Planck data, push the r upper limit to lower values
- To measure and characterize foregrounds (synchrotron and anomalous emissions) with high sensitivity at 10-20 GHz, allowing correction in future space missions aiming at r~0.001

❖ **Project baseline:**

- **Site:** Teide Observatory (altitude: 2400 m, latitude: 28º), Spain
- **Angular resolution:** 1 degree
- **Sky coverage:** 10,000 deg^2
- **Telescope and instruments:**
  - Phase I: First Telescope (QT1), equipped with the Multifrequency Instrument (MFI) with 4 polarimeters @ 10-20 GHz (undergoing commissioning). Second Instrument (TGI) with 31 polarimeters @ 30 GHz (funded, starts operations in 2013). Polarized Source Subtractor (close to start commissioning)
  - Phase II: Second Telescope (QT2), and FGI with 40 polarimeters @ 40 GHz (funded)
  - Phase III: instrument with 100 polarimeters @ 90 GHz (not funded)

❖ **Polarization detection:** modulation (similar to half-wave plate)

❖ **Observing strategy:** deep observations in selected areas using raster scans, plus a large-scale map using "nominal mode" (azimuth scans at constant elevation)

❖ **Time baseline:**

- Main science goal (r=0.1) by 2014, and r=0.05 by 2016
- Possible extension of the observations for additional 4 years

	MFI				TGI	FGI
Frequency (GHz)	11	13	17	19	30	40
Bandwidth (GHz)	2	2	2	2	8	10
Number of horns	2		2		31	40
Channels per horn	4	4	4	4	4	4
Beam FWHM (deg)	0.92	0.92	0.60	0.60	0.37	0.28
T_{sys} (K)	25	25	25	25	35	45
NEP ($\mu K\ s^{1/2}$)	280	280	280	280	50	50
Sensitivity per beam ($Jy\ s^{1/2}$)	0.30	0.42	0.31	0.38	0.06	0.06

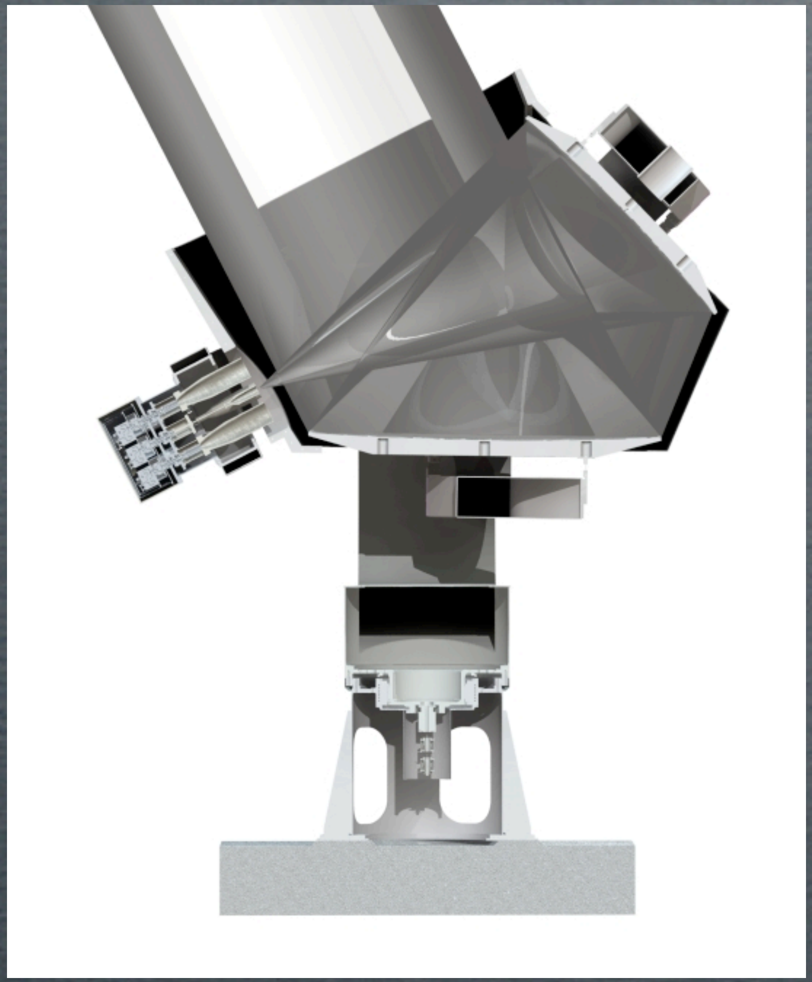
- Sensitivity per beam given by: $\Delta Q = \Delta U = \sqrt{2}\frac{T_{\rm sys}}{\sqrt{\Delta\nu\ t_{\rm int}\ N_{\rm chan}}}$

- Definition of Q: $Q = T_x - T_y$

QUIJOTE platform

QUIJOTE telescope 1 (QT1)

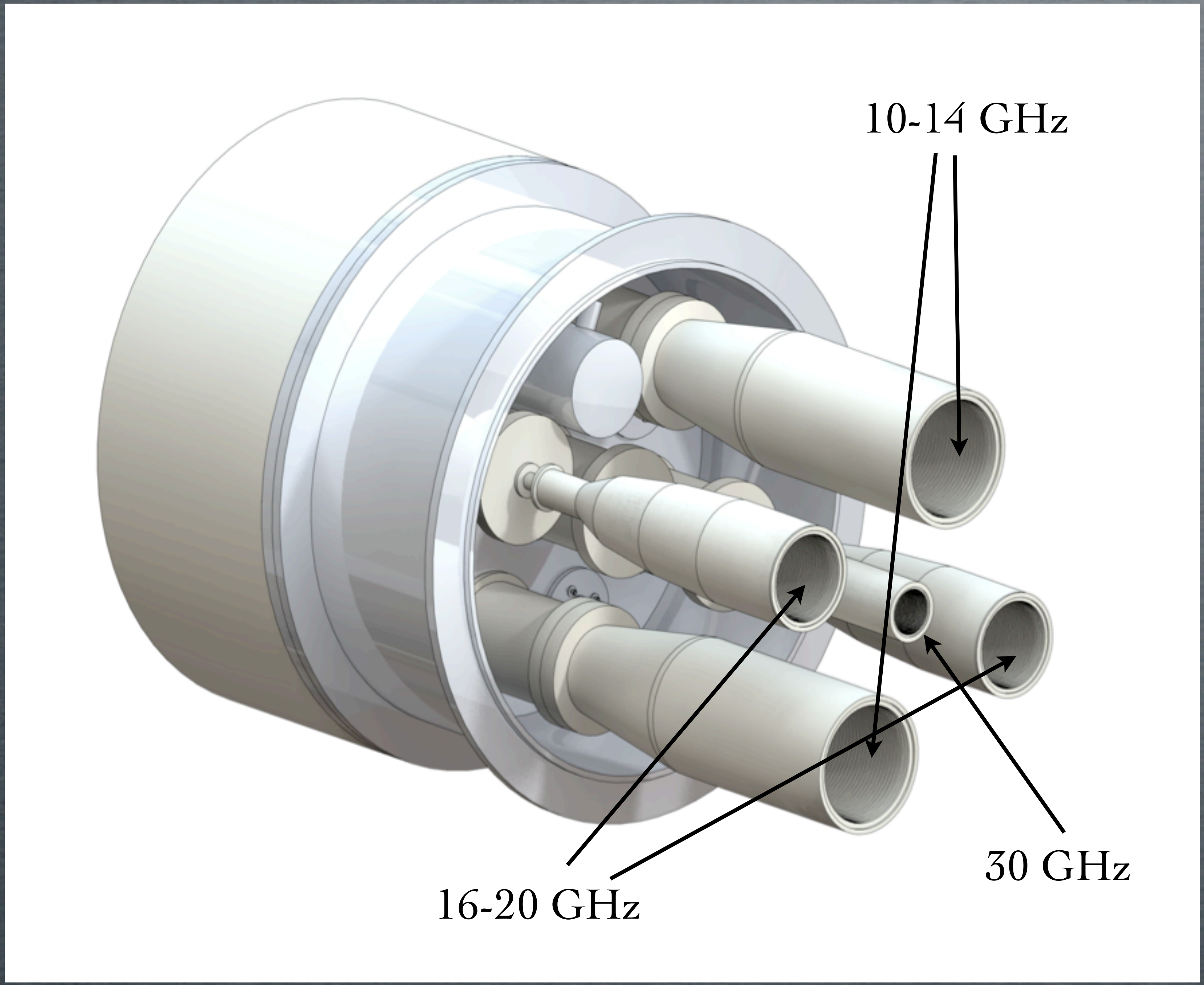
- Alto-azimutal mount
- Maximum rotation speed around AZ axis: 0.25 Hz
- Maximum zenith angle: 60°
- Cross-Dragonian design
- Aperture: 3 m (primary) and 2.6 m (secondary)
- Maximum frequency: 90 GHz (rms ≤20 μm and max deviation =100 μm)

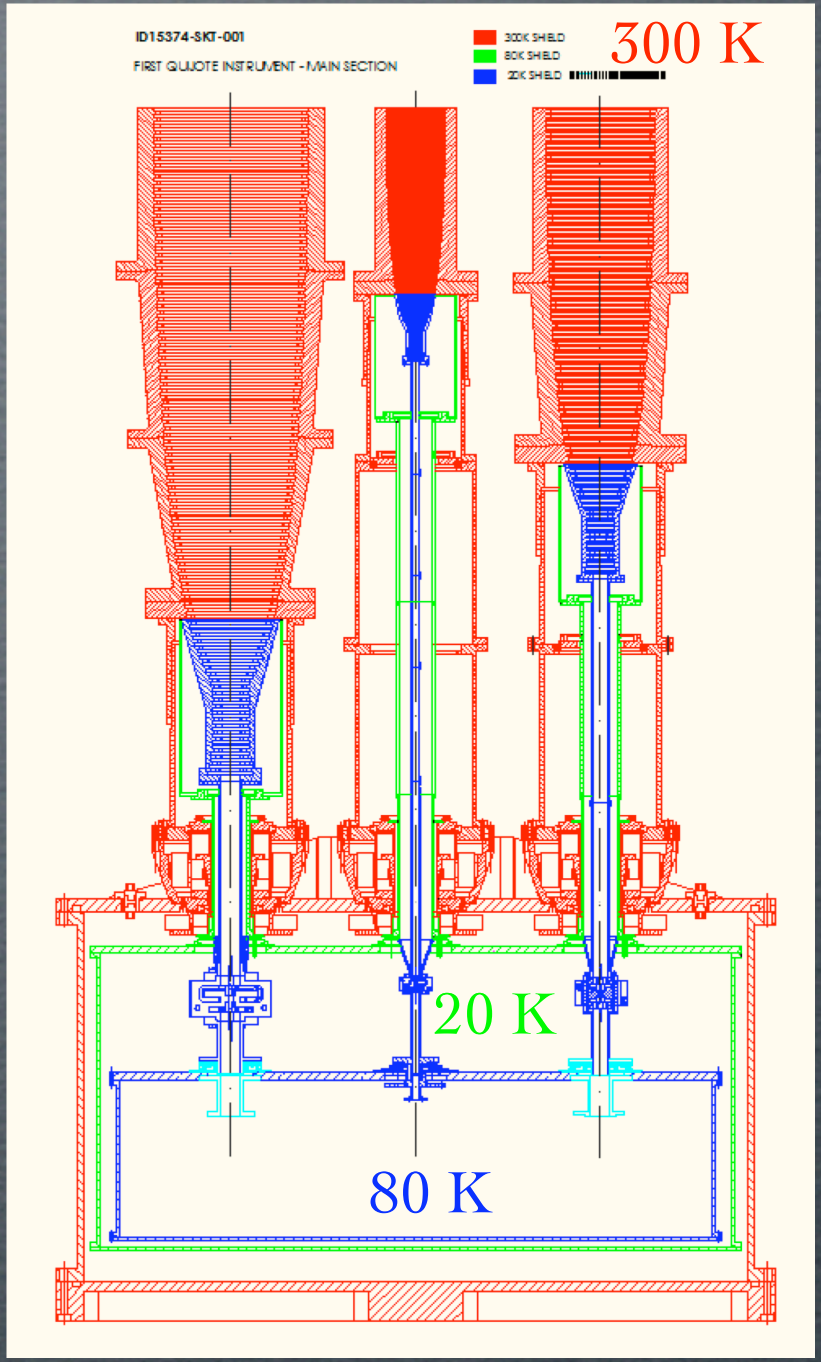


QT1 installed at the Teide observatory in May 3rd, 2012

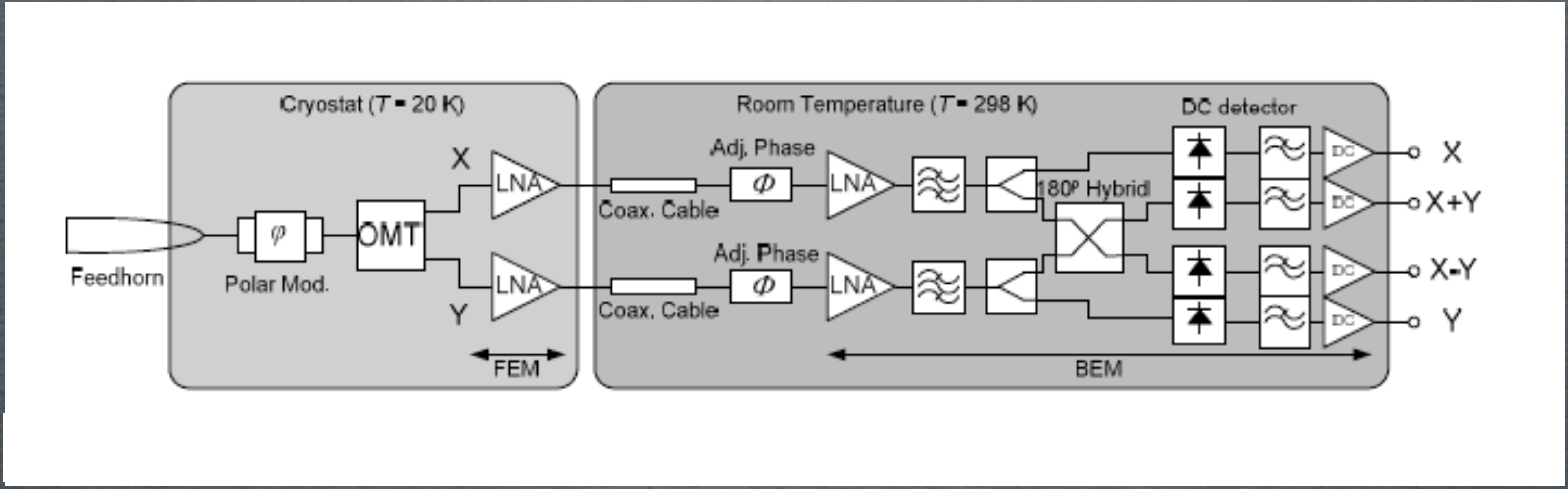
Multi-frequency instrument (MFI)

- 5 conical corrugated feedhorns
- 2 horns providing channels at 11 and 13 GHz
- 2 horns providing channels at 17 and 19 GHz
- 1 horn providing one channel at 30 GHz (removed)





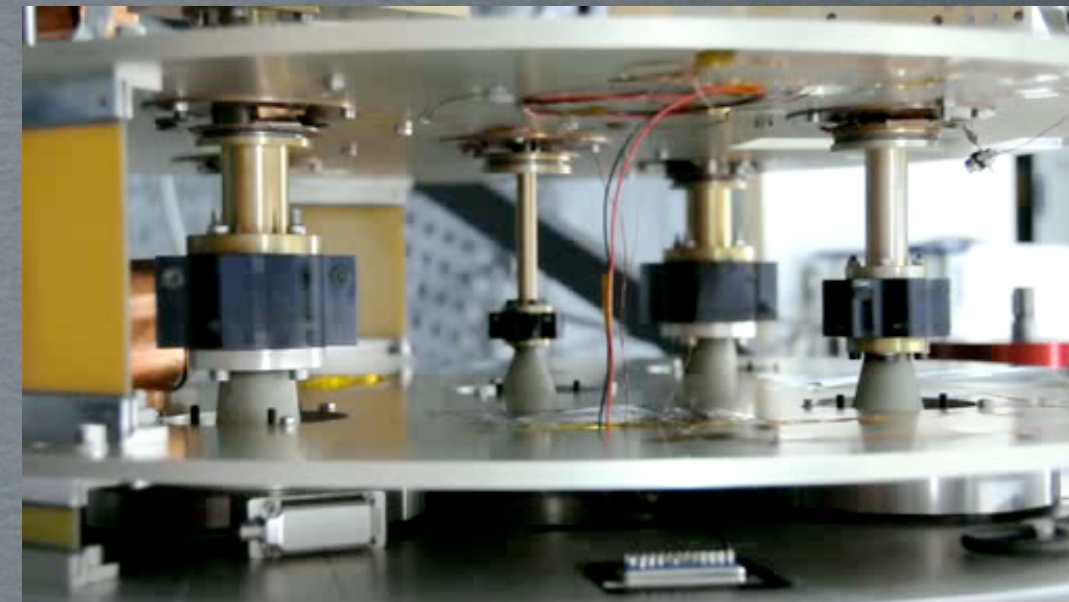
- MFI polarimeter configuration
- FEM: partially-cooled feed-horn, polar modulator, OMT and LNAs
- BEM: phase adjuster, further amplification, band pass filter and correlation
- Output: two channels (x) and (y) measuring Q (un-correlated), two channels (x+y) and (x-y) measuring U (correlated)



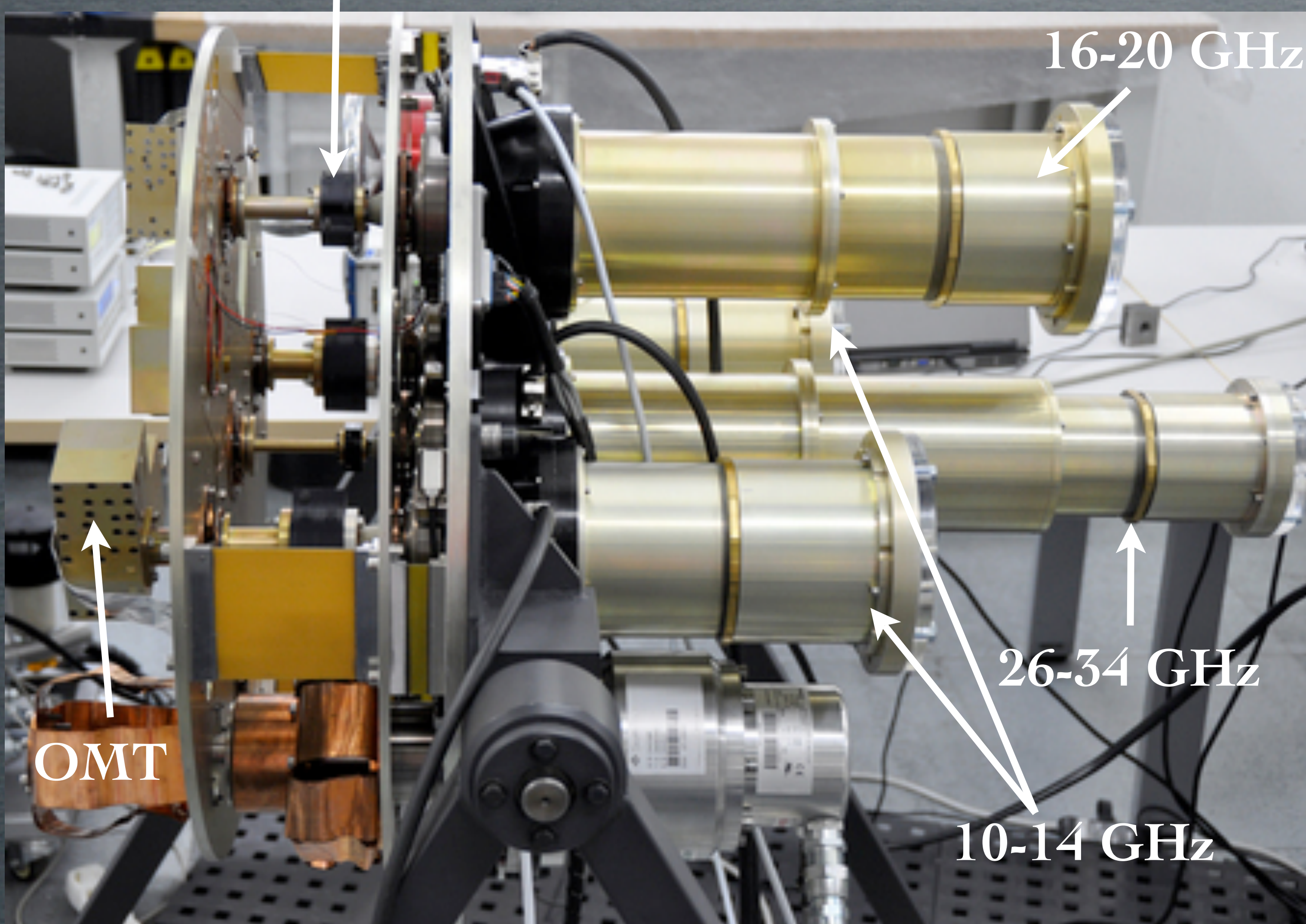
- Continuous spinning of the polar modulators allows independent measurement of I, Q and U for each channel, while switching out the 1/f noise
- Each of the four outputs are divided into a lower frequency and an upper frequency band

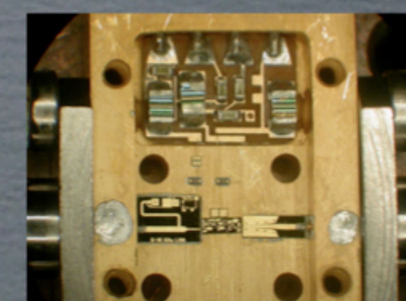
- 5 conical corrugated feedhorns
- Polar modulator spinning at speeds up to 40 Hz (polar modulation 160 Hz)
- Wide-band cryogenic Ortho-Mode-Transducer (OMT)
- MMIC 6-20 GHz Low Noise Amplifiers. Gain: 30dB
- Noise temperature: ~7-10 K (10-14 GHz), ~10-20 K (16-20 GHz)

Spinning polar modulators



Polar Modulators

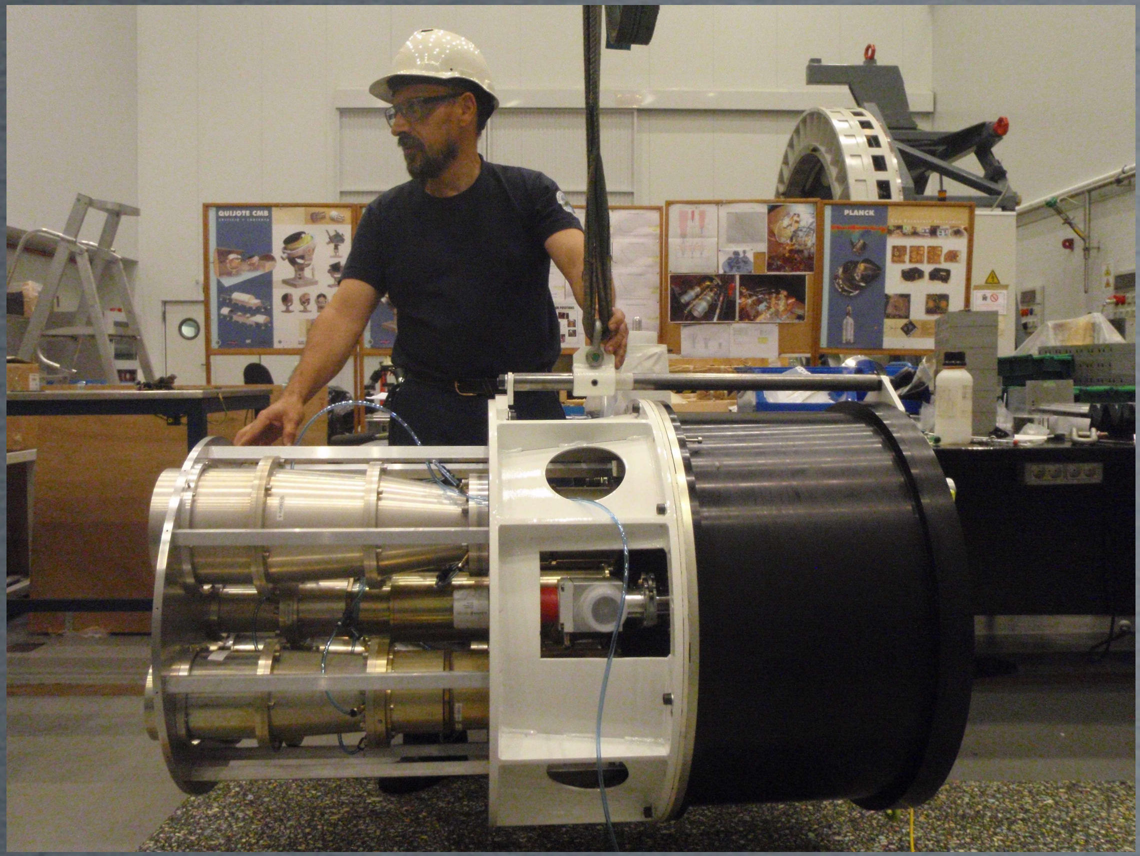


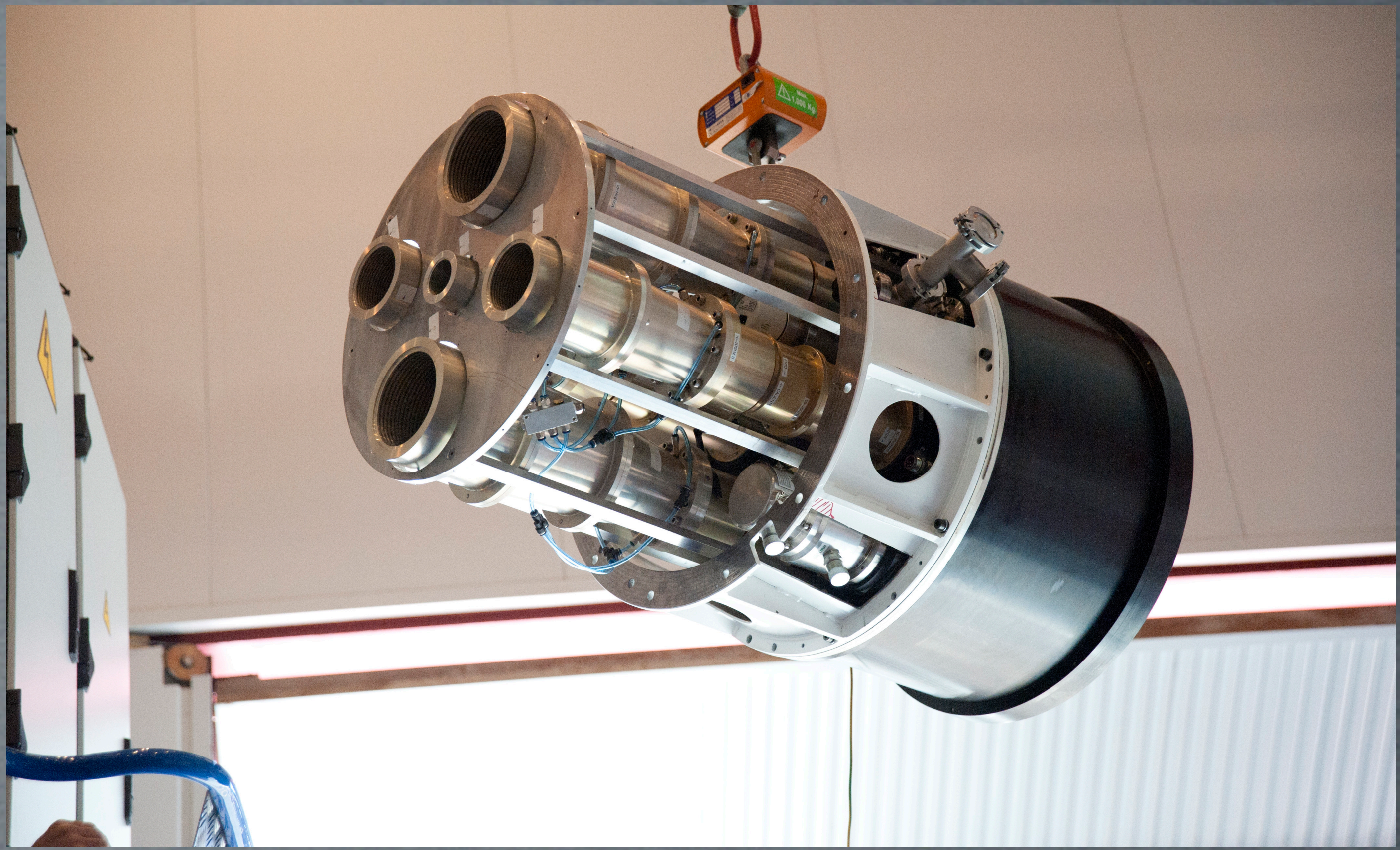


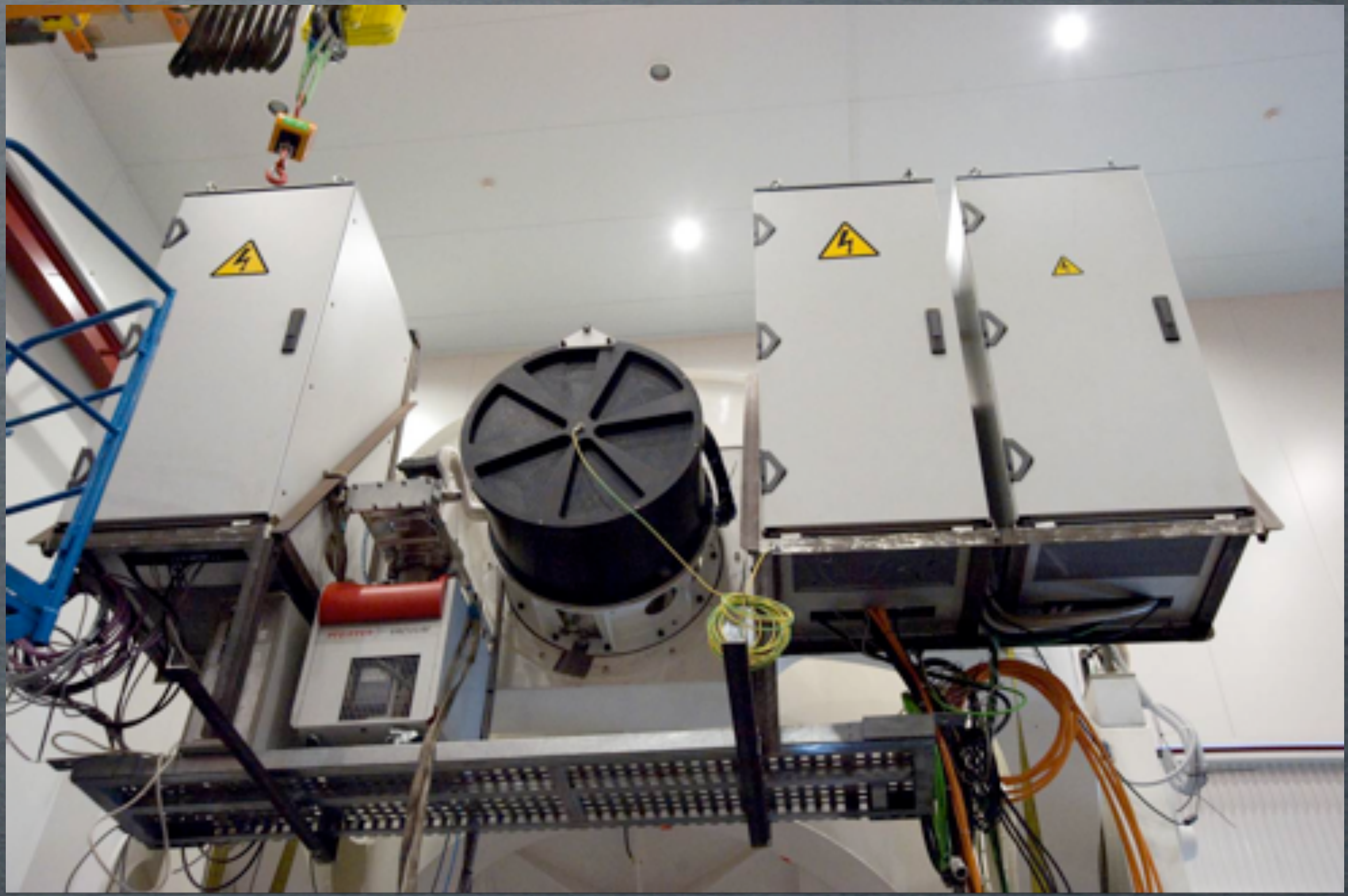
LNA

Polar modulator

Feedhorns







- MFI integration tests on the QT1 at the AIV room. March 2012
- Currently undergoing scientific commissioning

Polarized source subtractor

- Dedicated instrument at 33 GHz. VSA Source Subtractor converted to a polarimeter
- Installed a dielectrically embedded mesh-HWP

- Twofold subtraction strategy:

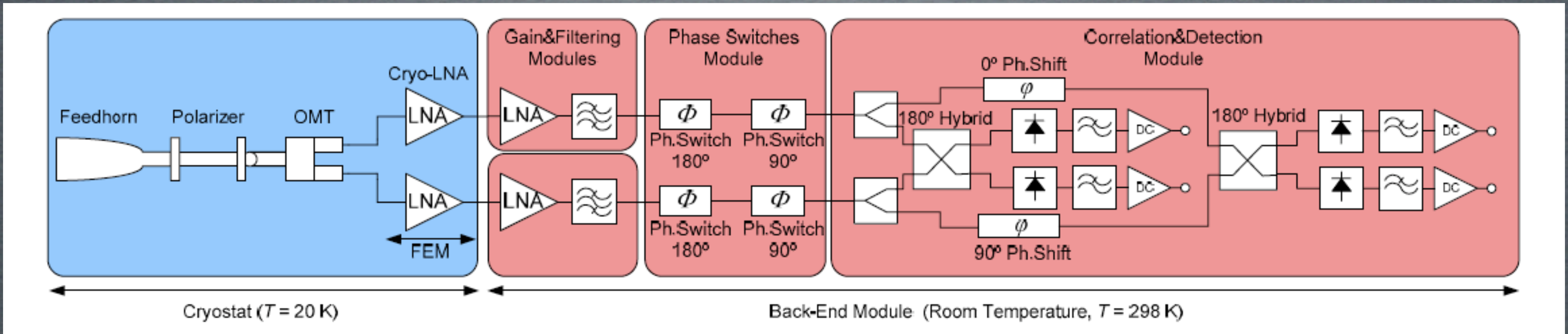
  - NVSS-GB6 extrapolation. ~300 sources with Stokes-I flux > 300 mJy at 30 GHz. Flux sensitivity per source ~2-3 mJy in ~100 days
  - Identify sources in the low-frequency channels by MH wavelet filters (López-Caniego et al. 2009)

- Interferometer of two 3.7m antennae with a 9m baseline
- Primary beam: 9’
- Synthesized beam: 4’
- Dec. range: $-5^{\circ} < \delta < +60^{\circ}$

- Close to start commissioning in intensity

Thirty Gigahertz instrument (TGI)

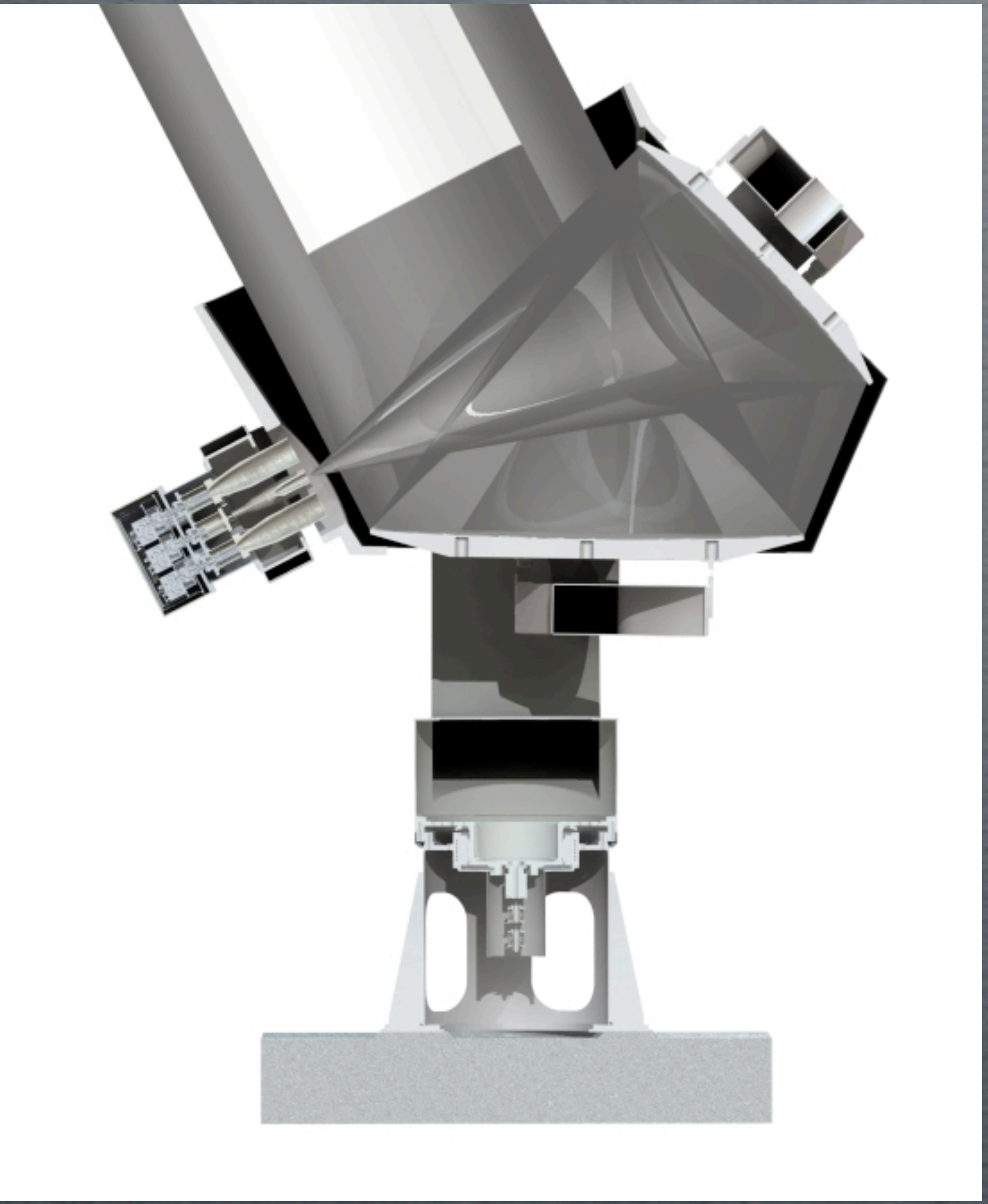
- 31 polarimeters at 30 GHz (4 channels each)
- Nominal sensitivity: 50 μK $s^{1/2}$



- MFI design (rotating polar modulator) not appropriate for the long-term operations required for the TGI
- Alternative design based on a fixed polarizer
- Fixed polarizer combined with two 90º and 180º phase switches to generate the four polarization states in each branch, to minimize the 1/f noise and other systematics
- To be commissioned early 2014
- The TGI (40 polarimeters at 40 GHz) will have the same design

QUIJOTE telescope 2 (QT2)

- Replica of QT1. Optical specifications to work up to 100 GHz
- Manufacturing time: 9 months
- Ready for operations by April 2014
- To be commissioned together with the TGI



❖ Main objectives of QUIJOTE-CMB:

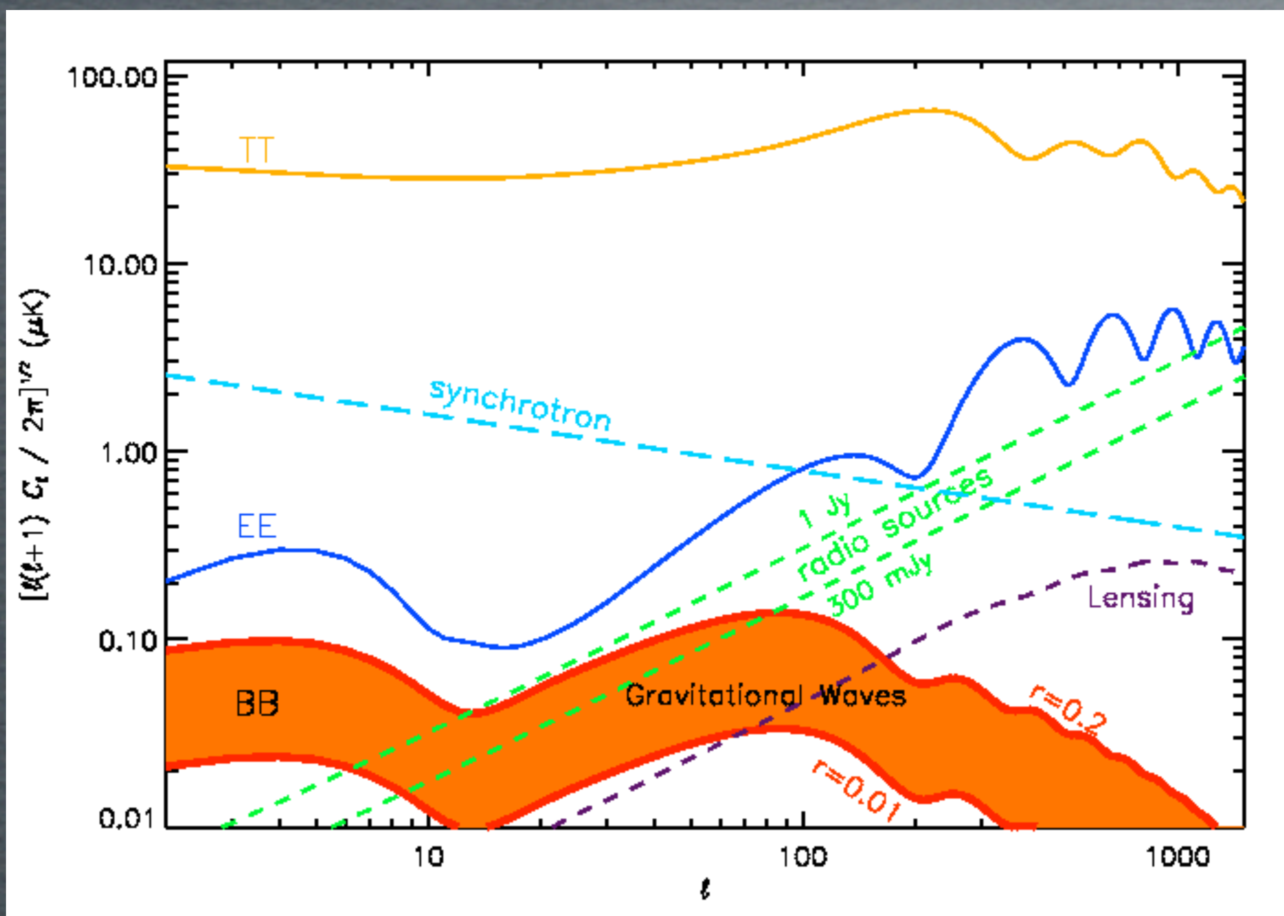
- To detect the imprint of the gravitational B-modes if $r \geq 0.05$
- To provide essential information of the polarization of the synchrotron and of the AME from our galaxy at low frequencies (10-40 GHz)

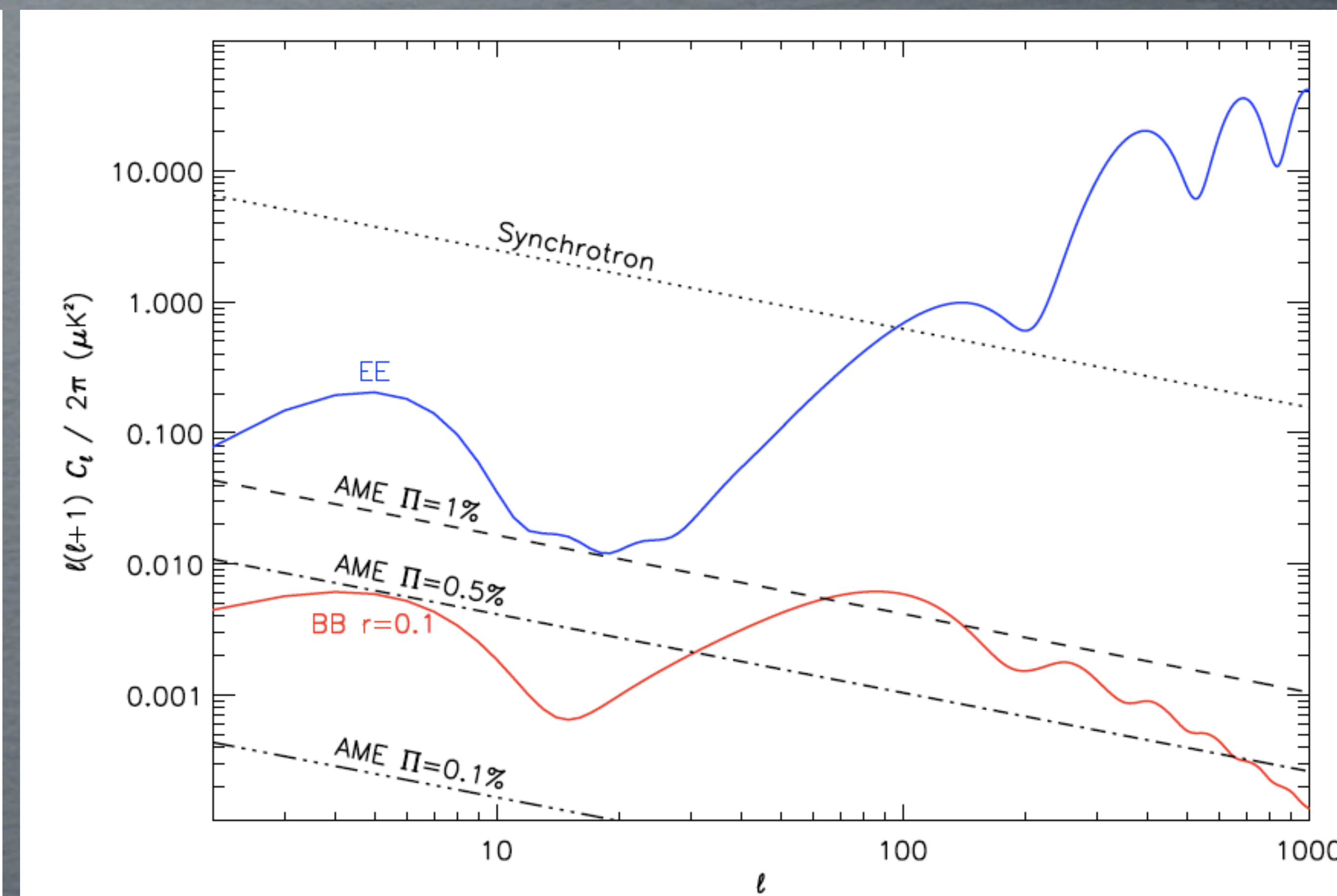
❖ Two large surveys in polarization

- Shallow Galactic survey. It will cover 10,000 deg^2, and will be finished after 3 months of observations with each instrument. Expected sensitivities:
    - ≈ 10 μK/(beam 1º) with the MFI @ 11, 13, 17 and 19 GHz, in both Q and U
    - ≤ 2 μK/(beam 1º) with the TGI @ 30 GHz and with the FGI @ 40 GHz
- Deep cosmological survey. It will cover around 3,000 deg^2. Expected sensitivities after 1 year:
    - ≈ 5 μK/(beam 1º) with the MFI @ 11, 13, 17 and 19 GHz
    - ≤ 1 μK/(beam 1º) with the TGI @ 30 GHz and with the FGI @ 40 GHz

Science with the MFI

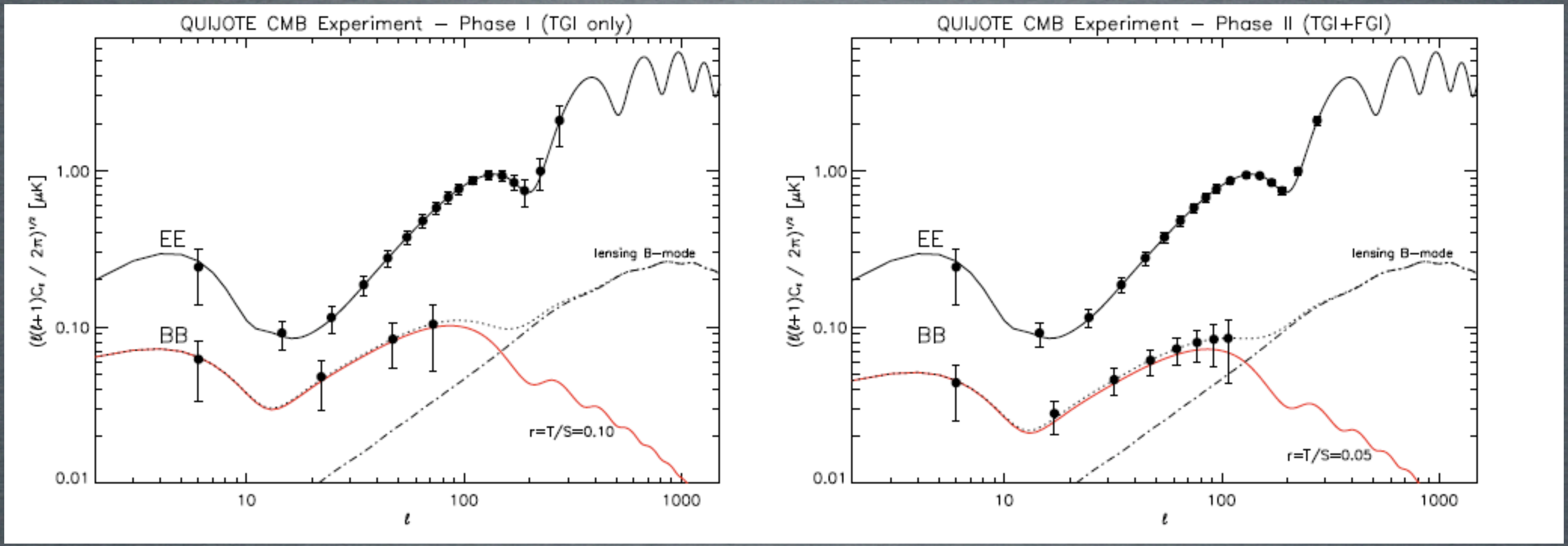
- Contamination introduced by synchrotron and AME at 30 GHz:





- Maps of the MFI deep survey at will be used to determine the synchrotron spectrum at 10-20 GHz
- Extrapolation to higher frequencies. Pixel-by-pixel correction of the TGI and FGI maps
- The residual synchrotron will have a contribution to the total noise less than one order of magnitude with respect to the thermal noise of the TGI maps after 1 year

Science with the TGI and FGI



1 year effective time with the TGI over 3,000 deg^2

3 years effective time with the TGI and 2 years with the FGI over 3,000 deg^2

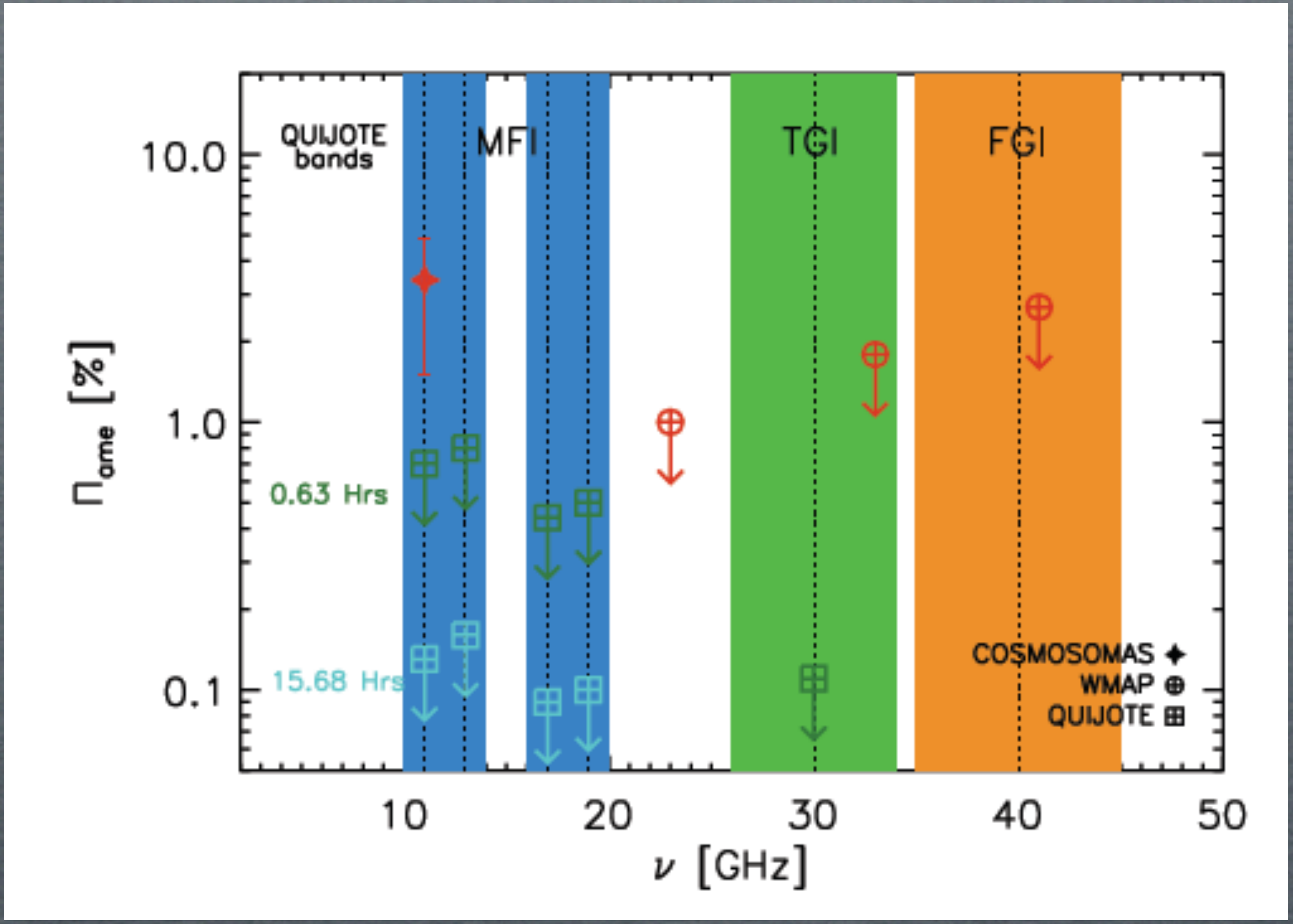
- Sensitivity to r=0.1 (number of sigmas):

1 year case	T_{inst}=20K	T_{inst}=30K	T_{inst}=40K
N_{horns}=19	2.24	1.77	1.49
N_{horns}=25	2.53	2.29	1.84

3 years case	T_{sys}=20K	T_{sys}=30K	T_{sys}=40K
N_{horns}=19	3.75	2.85	2.33
N_{horns}=25	4.28	3.25	2.64

AME polarization

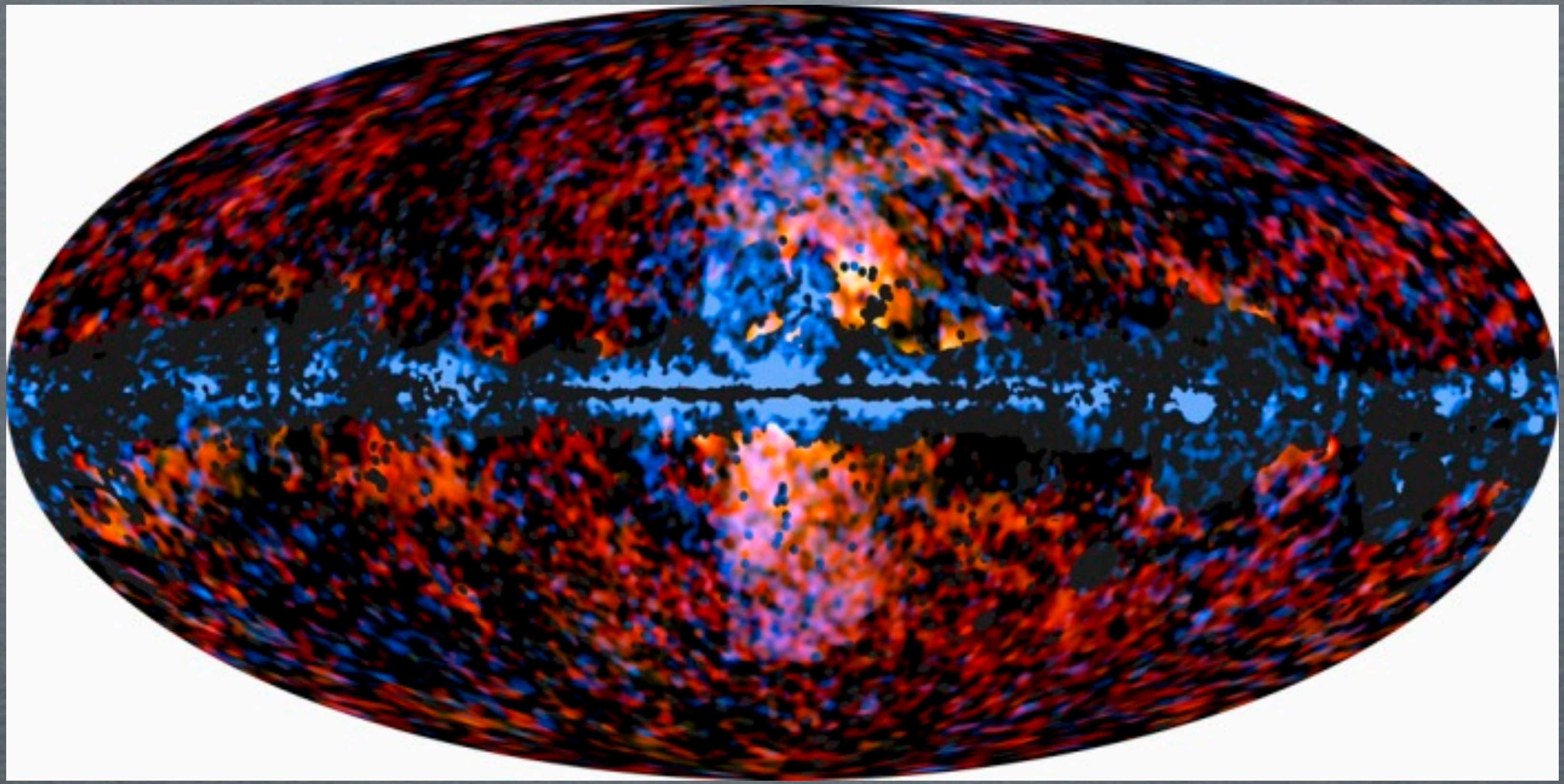
- Studying the polarization of the AME in compact clouds (Perseus, ρ-Ophiuchi,...)
- Current upper limits are at the level of ~1% (95% CL) from WMAP (López-Caraballo et al. 2011, Dickinson et al. 2011)
- Prospects for QUIJOTE-CMB in the Perseus molecular complex:



- MFI data will allow to reach ~0.1% in relatively short integrations
- This will allow to test the models predicting the level of polarization of the electric dipole (Lazarian & Draine 2000) and of the magnetic dipole (Draine & Hensley 2012) emissions

Haze polarization

- Bright signature in the GC with hard-synchrotron spectrum found in WMAP7 (Finkbeiner 2004) data, with a gamma-ray counterpart (Dobler et al. 2010)

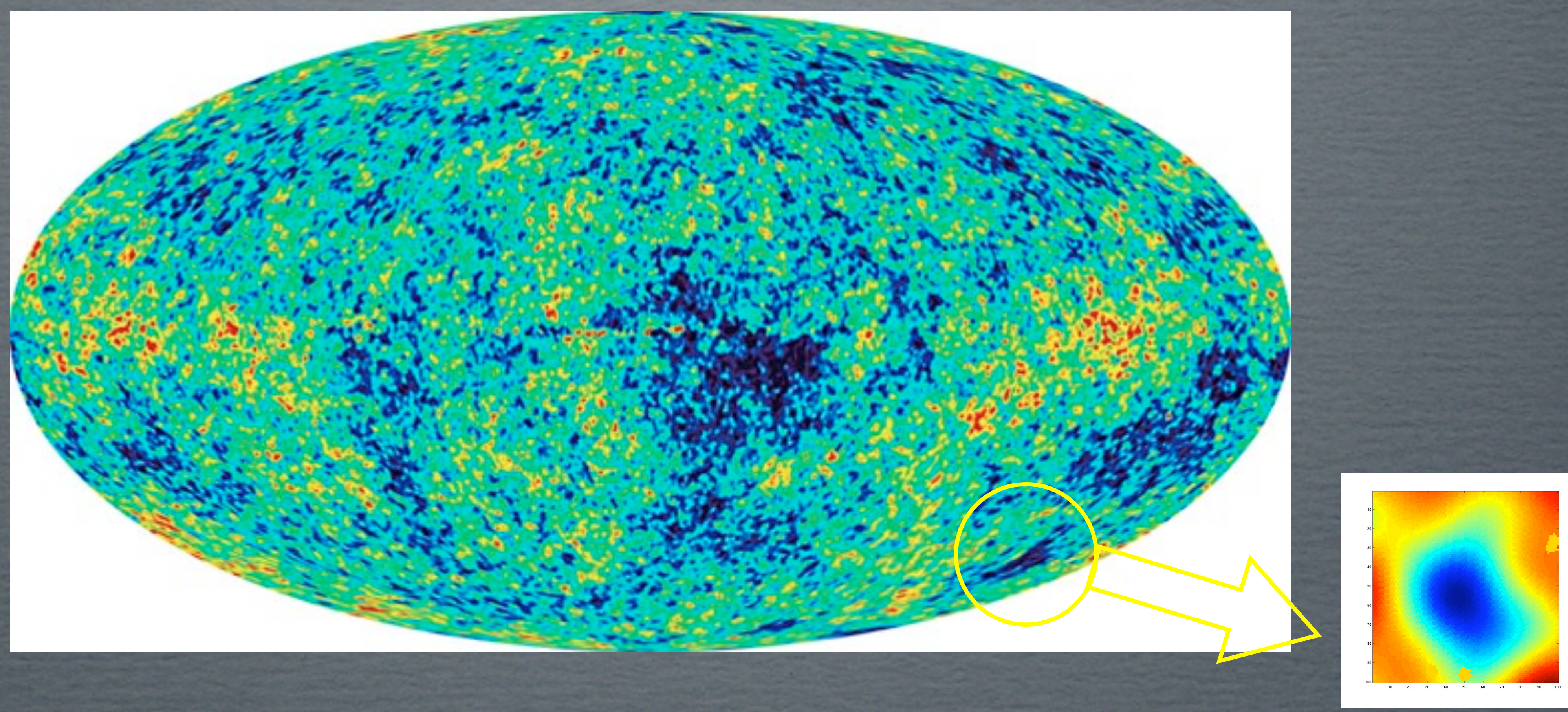


(Planck collaboration et al. 2012)

- Measuring the level of polarization is essential to disentangle between different proposed physical mechanisms (dark matter annihilations, cosmic-ray ions coming from star formation in the GC)

Cold spot

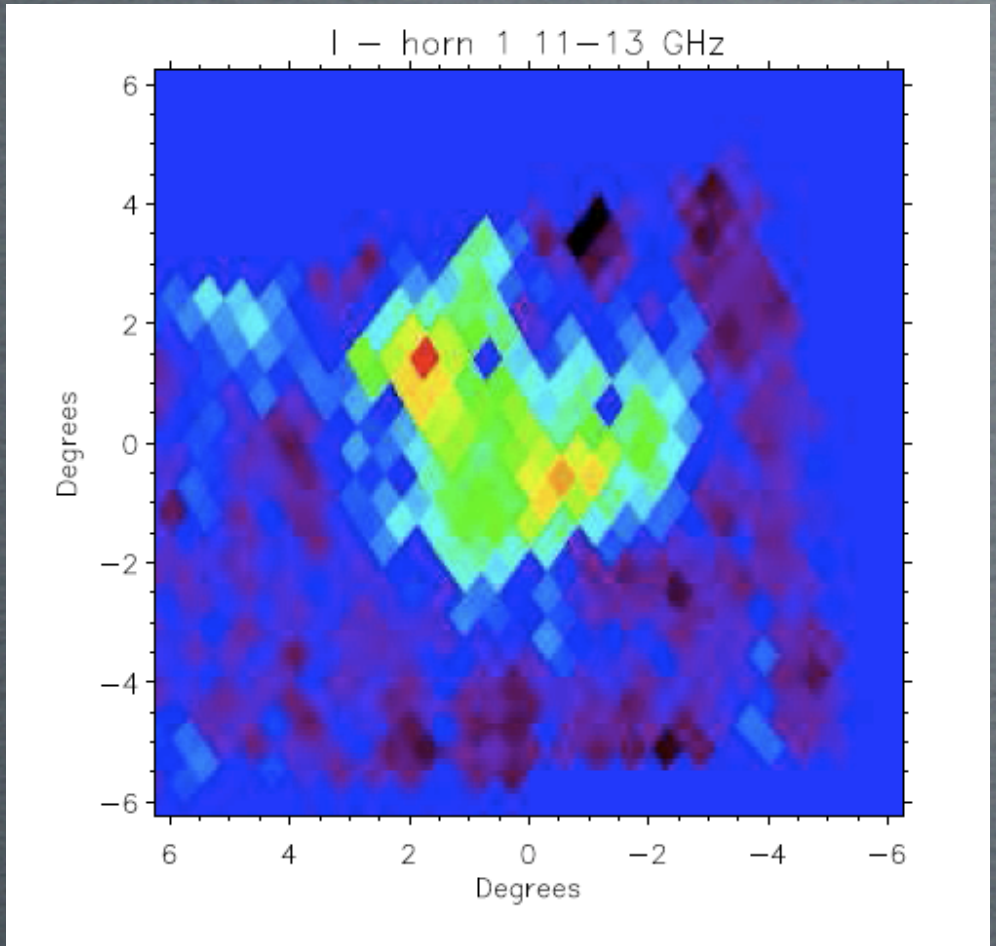
- Non-Gaussian feature found in WMAP data (Vielva et al. 2004)
- One possible explanation is a cosmic texture in the primordial universe (Cruz et al. 2007)



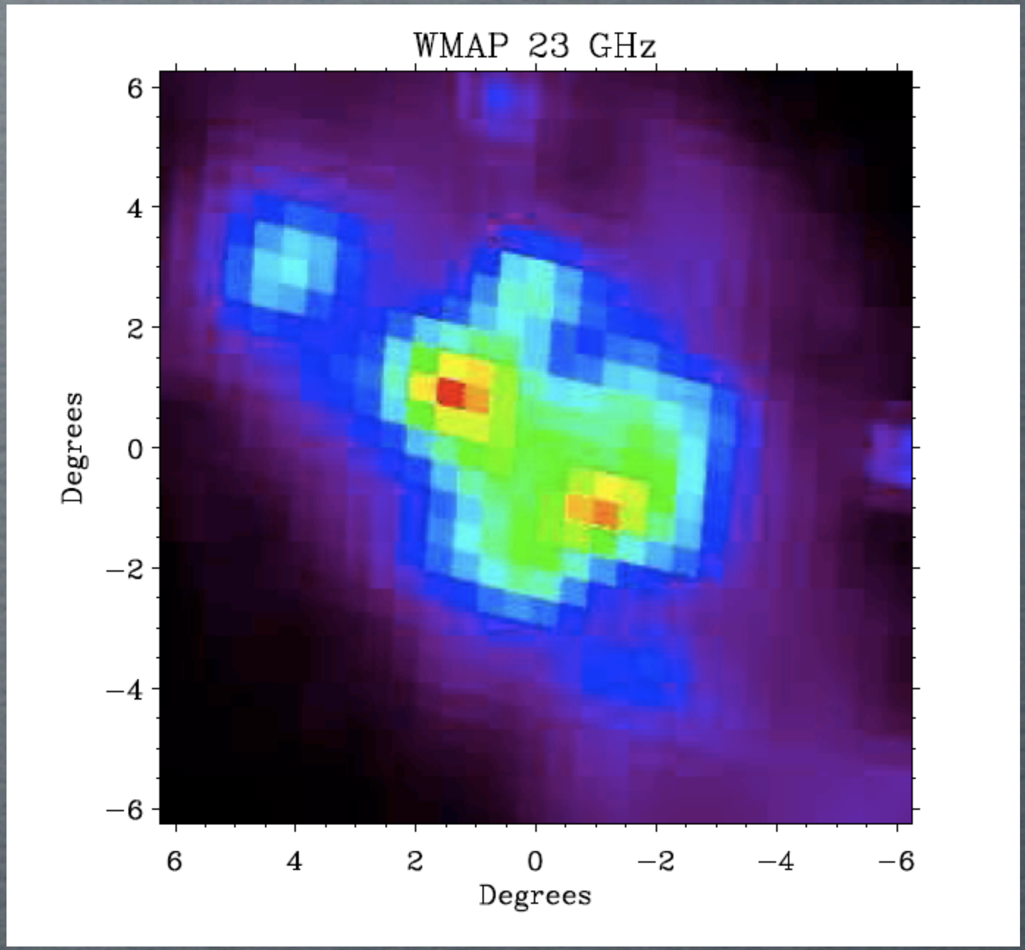
- If this hypothesis were correct, a lack of polarization would be expected in this position
- QUIJOTE-CMB data would be able to reject the Gaussian hypothesis (in favour of the texture one) with a significance better than 1% (Vielva et al. 2010)

- First light: 13/11/2012

- Cygnus-loop observations:

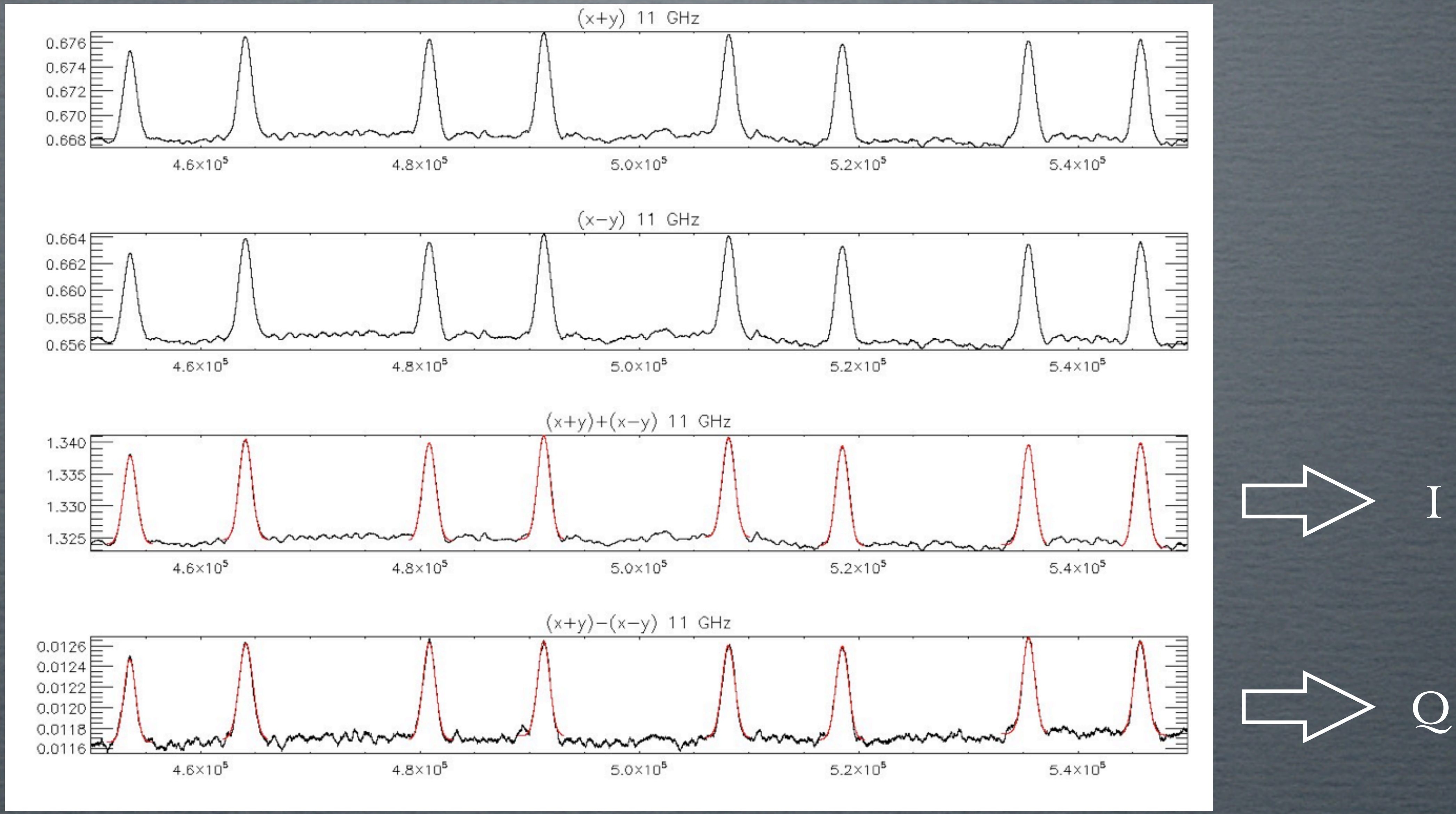


QUIJOTE 11-13 GHz



WMAP 23 GHz

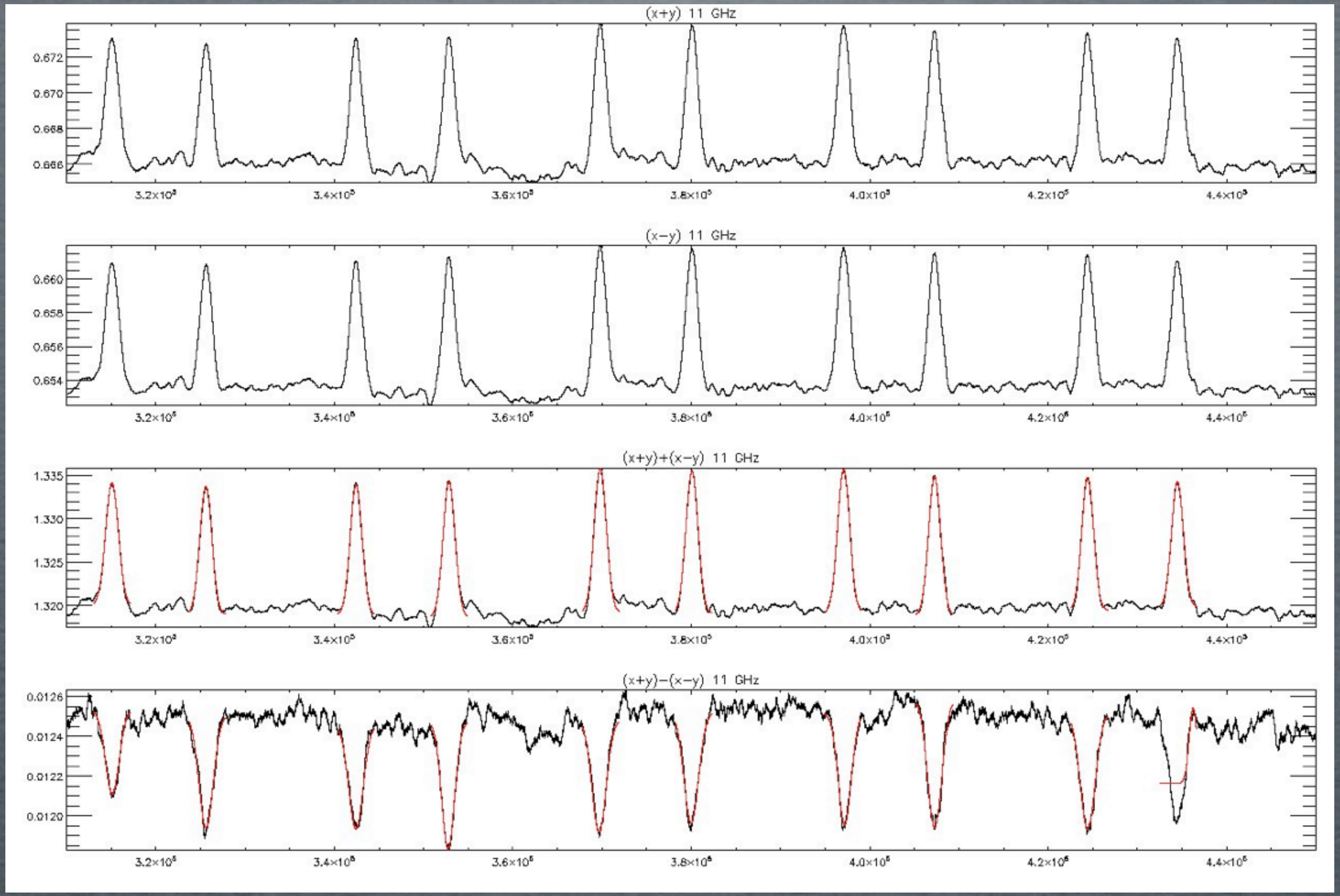
- Crab observations on 15/11/2012: Modulators fixed at 0°



$\langle Q/I \rangle = 0.0579 \pm 0.002$

- Crab observations on 15/11/2012:

Modulators fixed at 22.5°



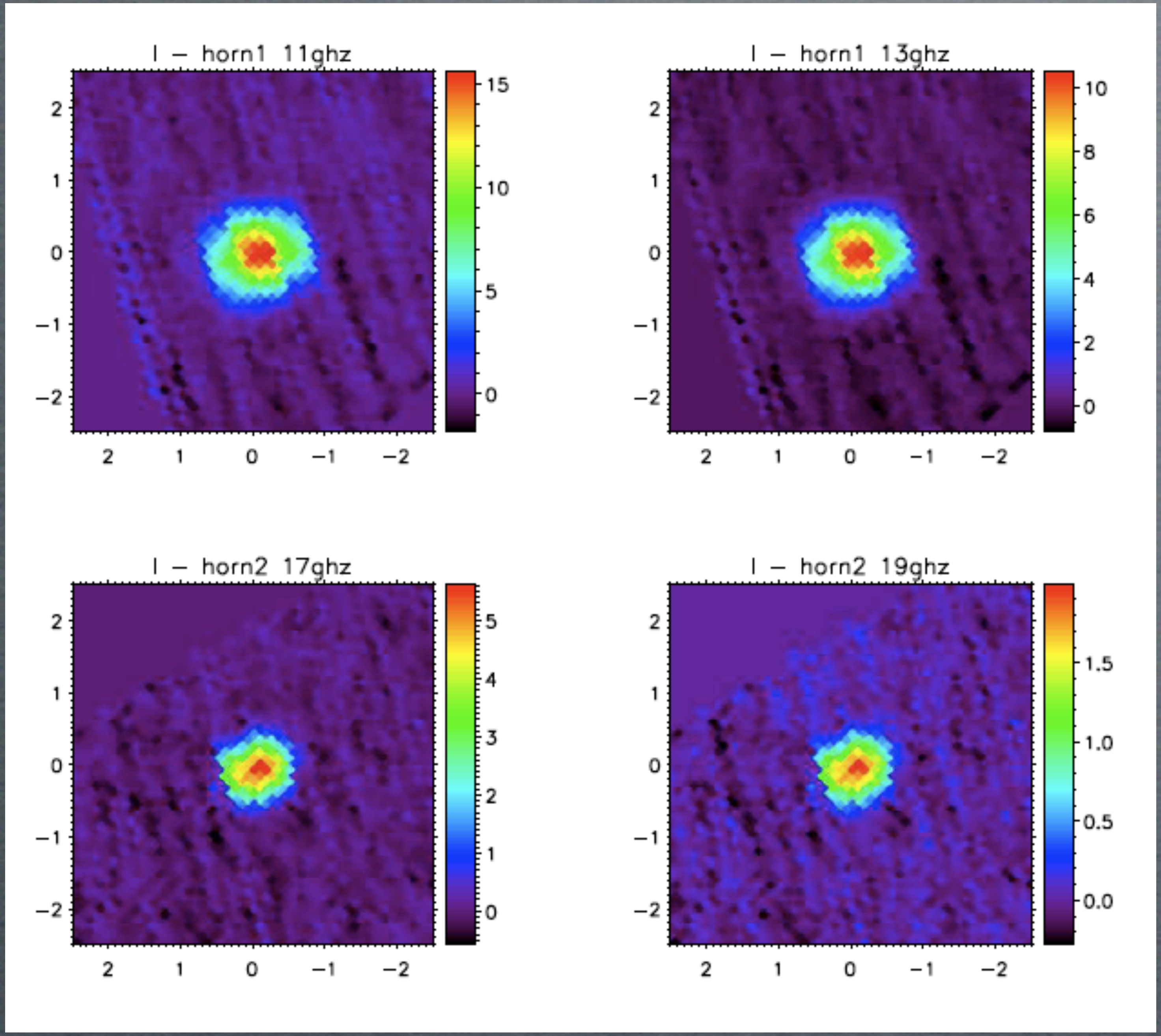
I

U

<U/I> = -0.0360±0.004

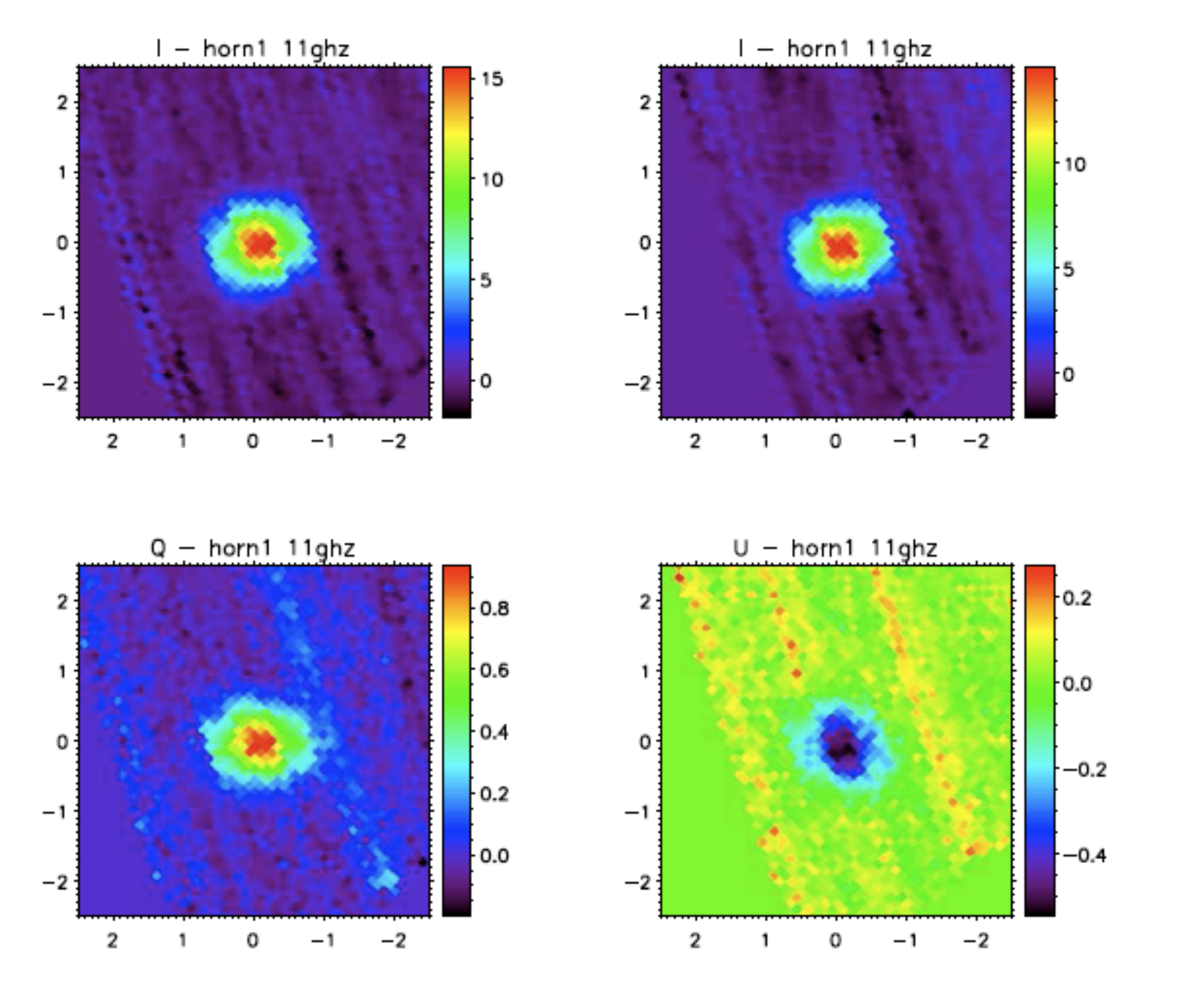
<P/I> = 6.8±0.8 % at 11 GHz (Consistent with WMAP 23 GHz, 7.08±0.25%)

- Crab maps (intensity):



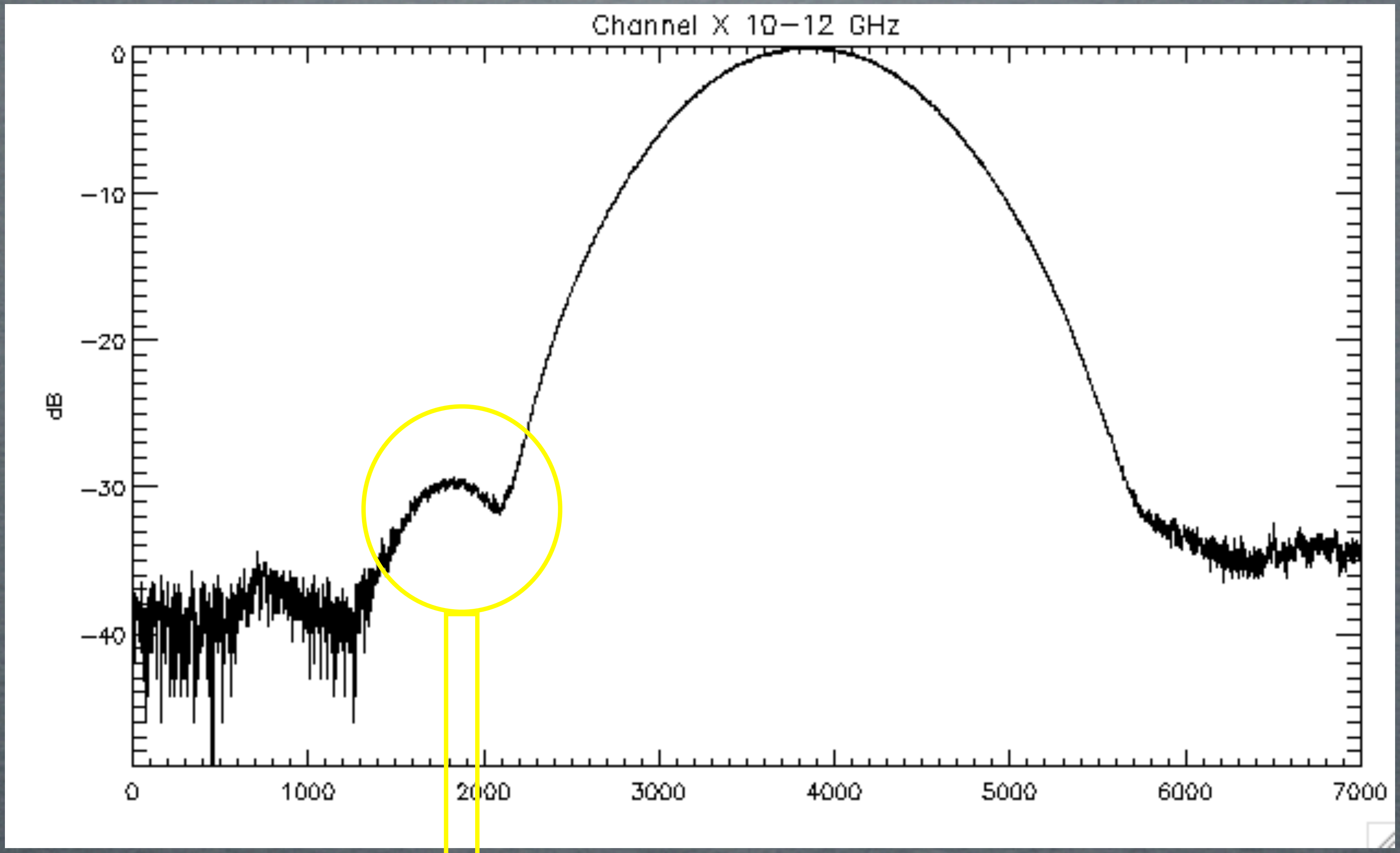
Freq	$FWHM_x$	$FWHM_y$
11	0.977	0.879
13	0.977	0.880
17	0.722	0.657
19	0.723	0.682

- Crab maps (IQU):



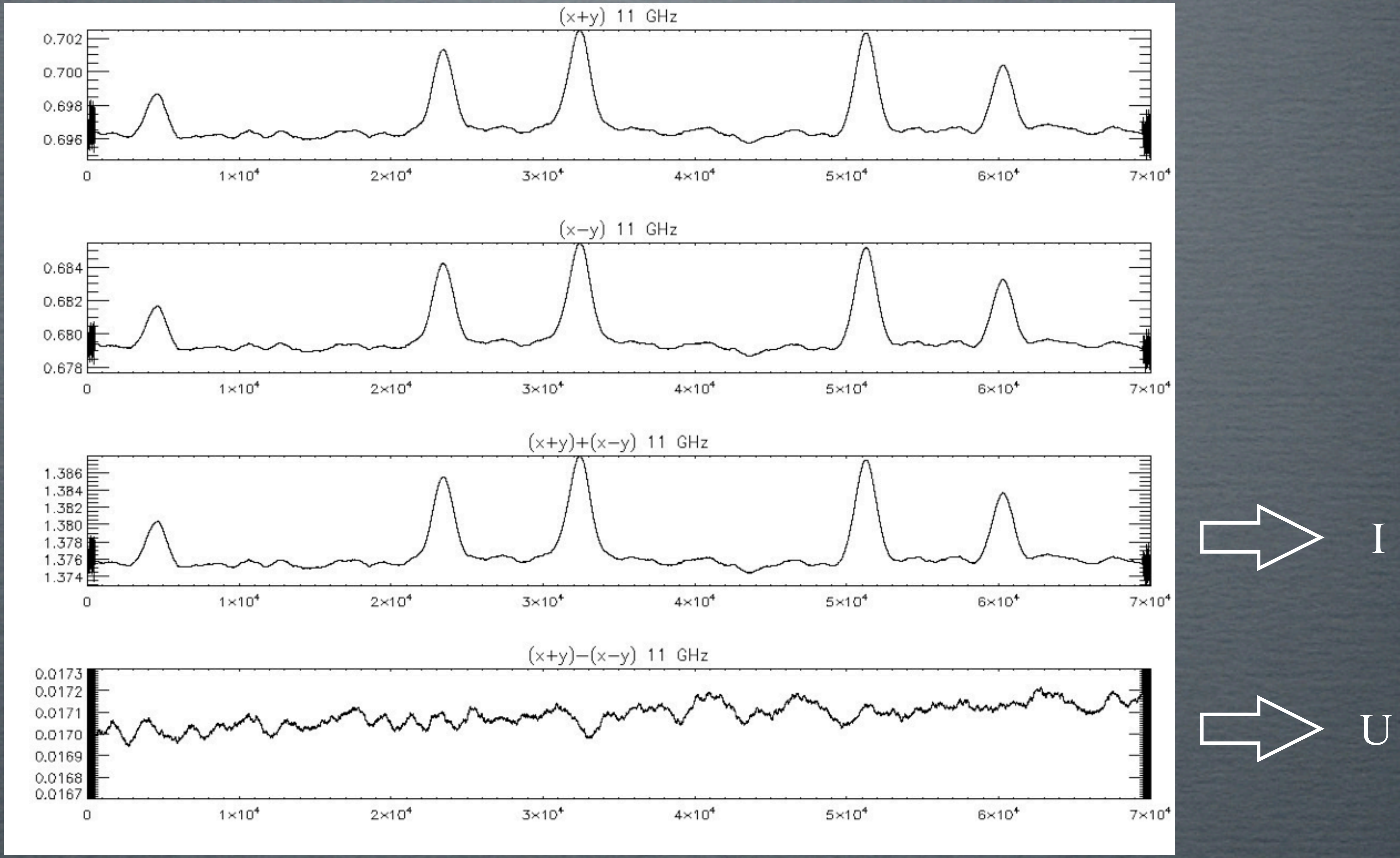
<P/I> = 7.4 %

- Satellite:



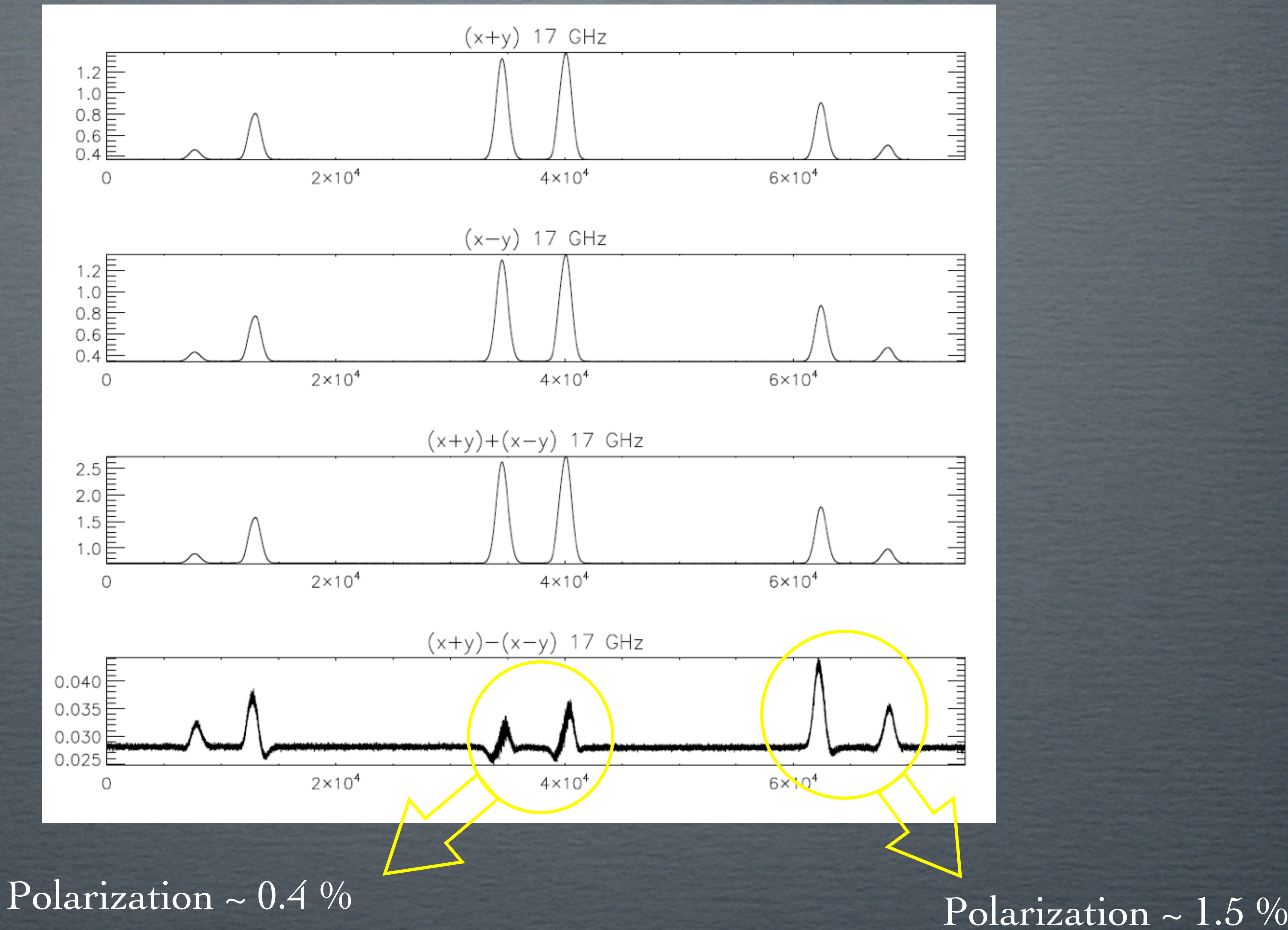
First sidelobe at -30 dB

- Cas-A observations on 20/11/2012:

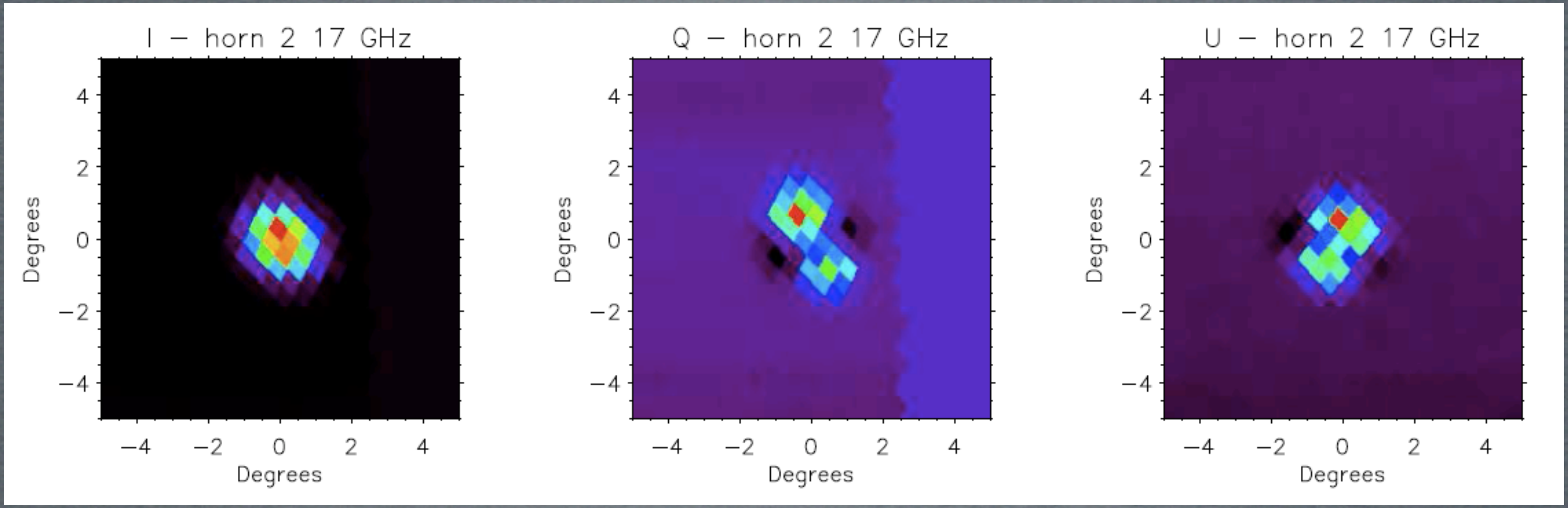


- Polarization compatible with zero (P/I=0.35% at 23 GHz)
- Noise estimate: 730 μK $s^{1/2}$ (consistent with nominal values)

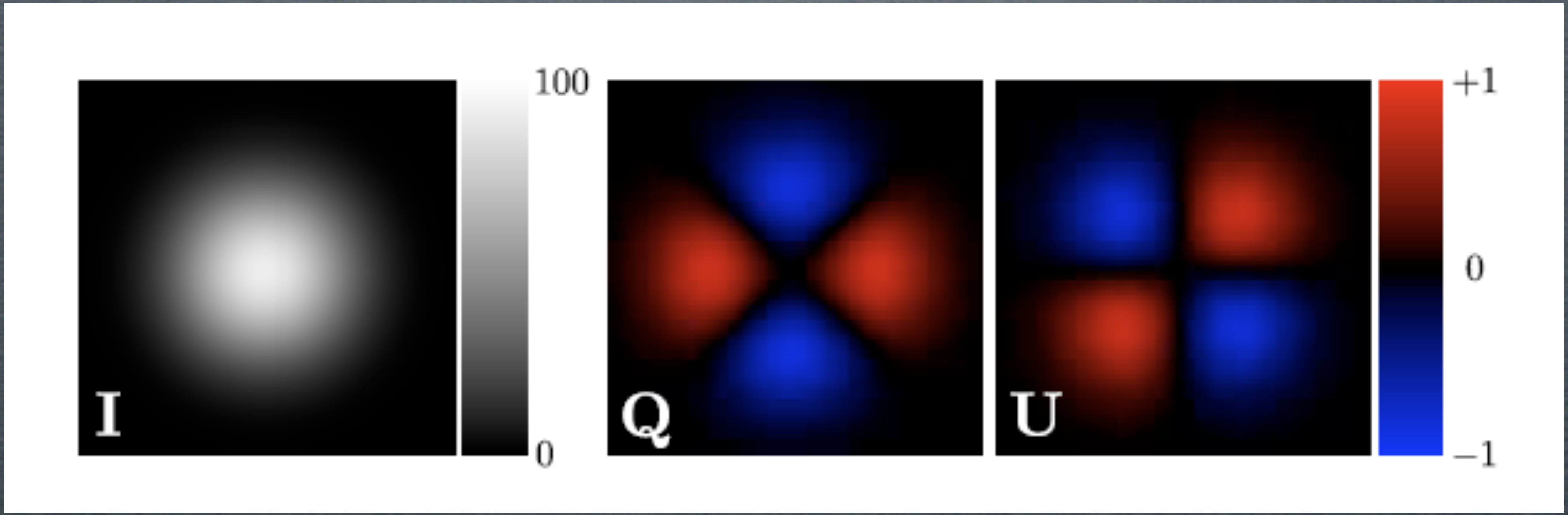
- Moon observations on 20/11/2012:



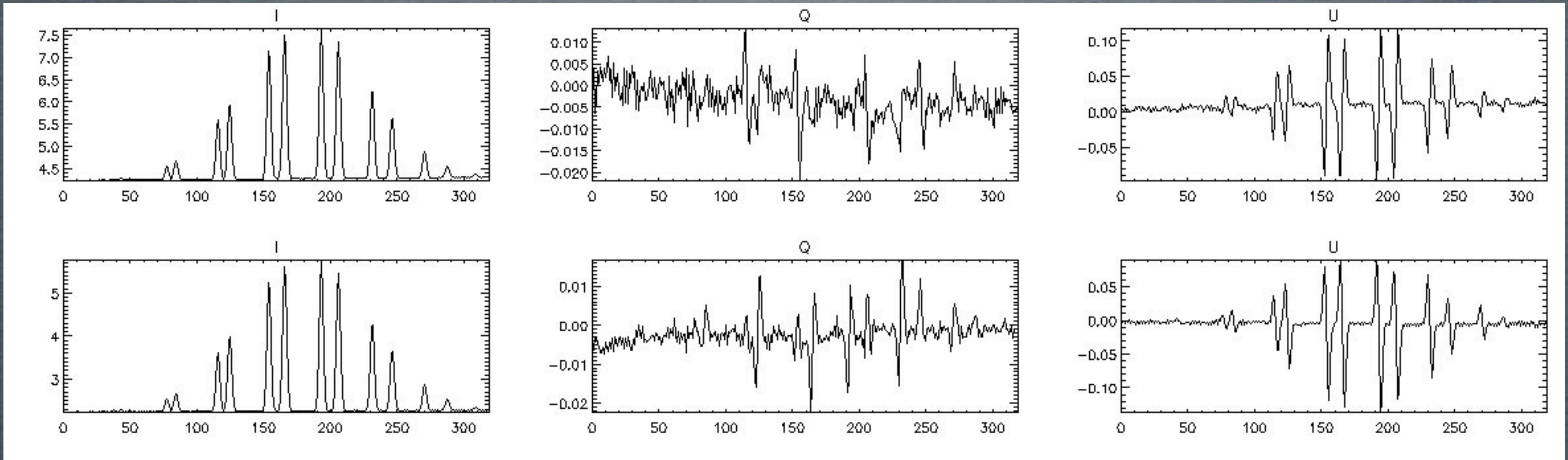
- Moon observations on 20/11/2012:



- Model (Bischoff 2010):



- Moon observations on 22/11/2012 (continuous movement of the modulators):



- Quijote-CMB is a new CMB polarimeter operating at 10-40 GHz, with 1-degree angular resolution and f_{sky} = 0.25

- MFI data at 10-20 GHz (10 μK/beam sensitivity after 3 months over 10,000 deg^2) will help to improve current WMAP measurements of the polarized synchrotron amplitude and spectral indices

- These will bridge the gap between lower frequency surveys (5 GHz, C-BASS) and higher frequencies (>23 GHz, WMAP), and will be a essential complement of Planck data (>100 GHz) providing the characterization of the thermal dust polarization

- Later TGI data at 30 GHz and FGI data at 40 GHz (sensitivity ≤ 2 μK/beam after 3 months) will help to improve these measurements, to fit for a possible curvature of the synchrotron spectrum, and to constrain the polarization properties of the AME

- A deep survey with the TGI over 3,000 deg^2 will allow a detection of r=0.1 at the level of 2-sigmas after 1 year of observations, and at the level of 3-sigmas after 3 years of observations

- Combination with subsequent FGI data at 40 GHz will allow to reach r=0.05

- MFI is currently undertaking scientific commissioning. Preliminary data looks promising. Sensitivity according to nominal values. Preliminary polarization fractions at 11 GHz on a couple of sources compatible with expectations

- TGI instrument and QT2 will start commissioning in a about a year from now