QUIJOTE: a CMB polarization experiment

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Fundamental Physics, CMB and LSS in the light of Planck and DES
IFT, Madrid, 7-31 October 2013

Outline

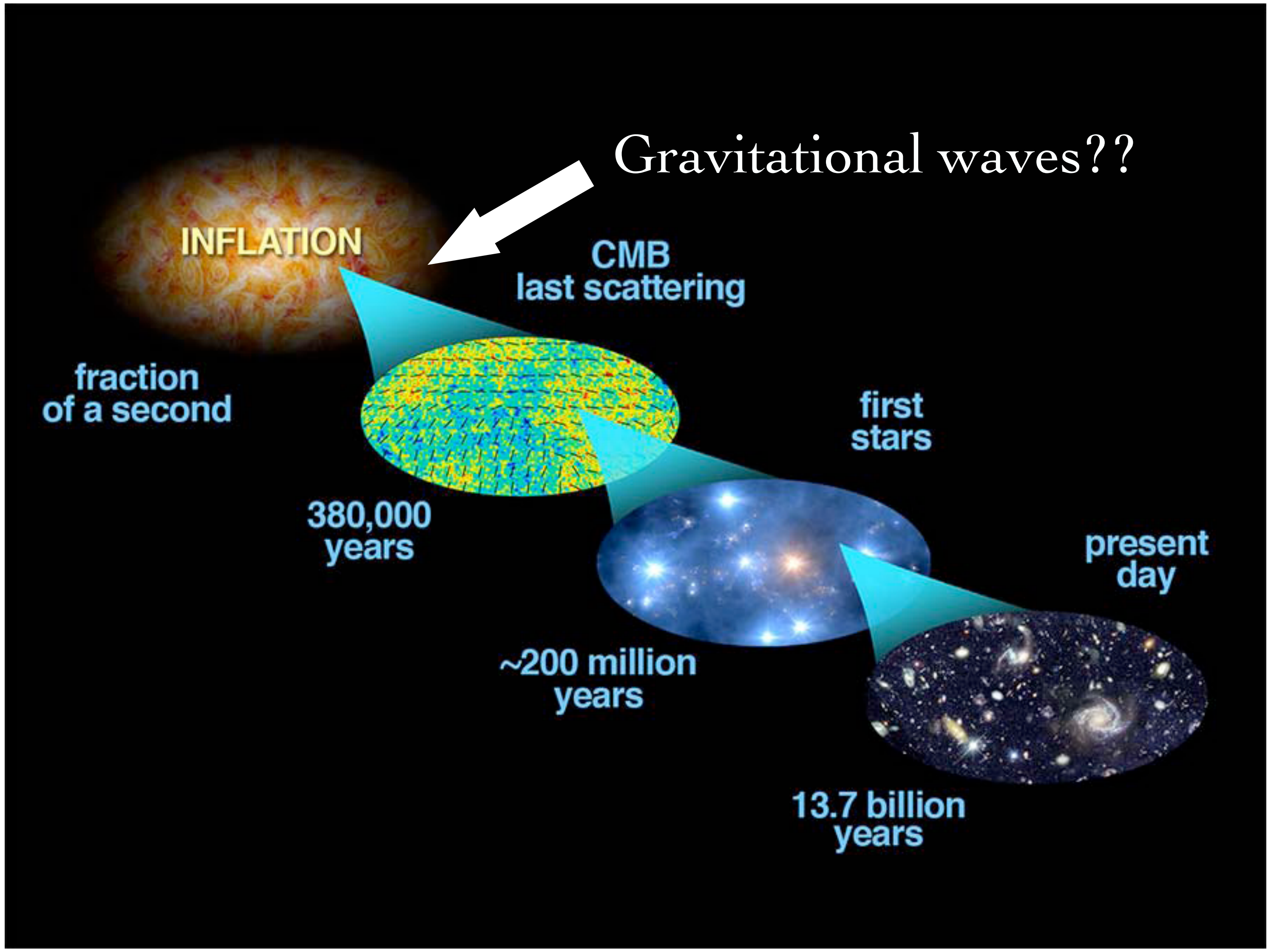
★ CMB polarization

- Inflation and B-modes
- B-modes observability. Foregrounds
- Current status of the observations. E-modes and lensing B-modes detection. Primordial B-modes upper limits

★ The Quijote-CMB experiment

- Project baseline and science goals
- Site. MFI, TGI and FGI technical description
- Science goals for the MFI (Galactic foregrounds) and for the TGI/FGI (B-modes)
- MFI calibration
- Preliminary maps and results from the MFI

The inflationary paradigm



- Inflation (Guth 1981, Linde 1982), an early epoch of accelerated with nearly constant energy density, reflects our present best understanding for the physics of the very early Universe and the generation of primordial density perturbations

- Physical processes underlying inflation reach the scale of GUT of 10^{15} GeV

- Inflation resolves the homogeneity, isotropy and flatness problems

- Inflation is predicted to have created a Gravitational Wave Background (GWB), that should be observable as a B-mode anisotropy in the polarization pattern of the CMB

- Measuring this B-mode anisotropy would provide essential information about the energy scale of inflation and would in turn allow to discriminate between different inflationary models

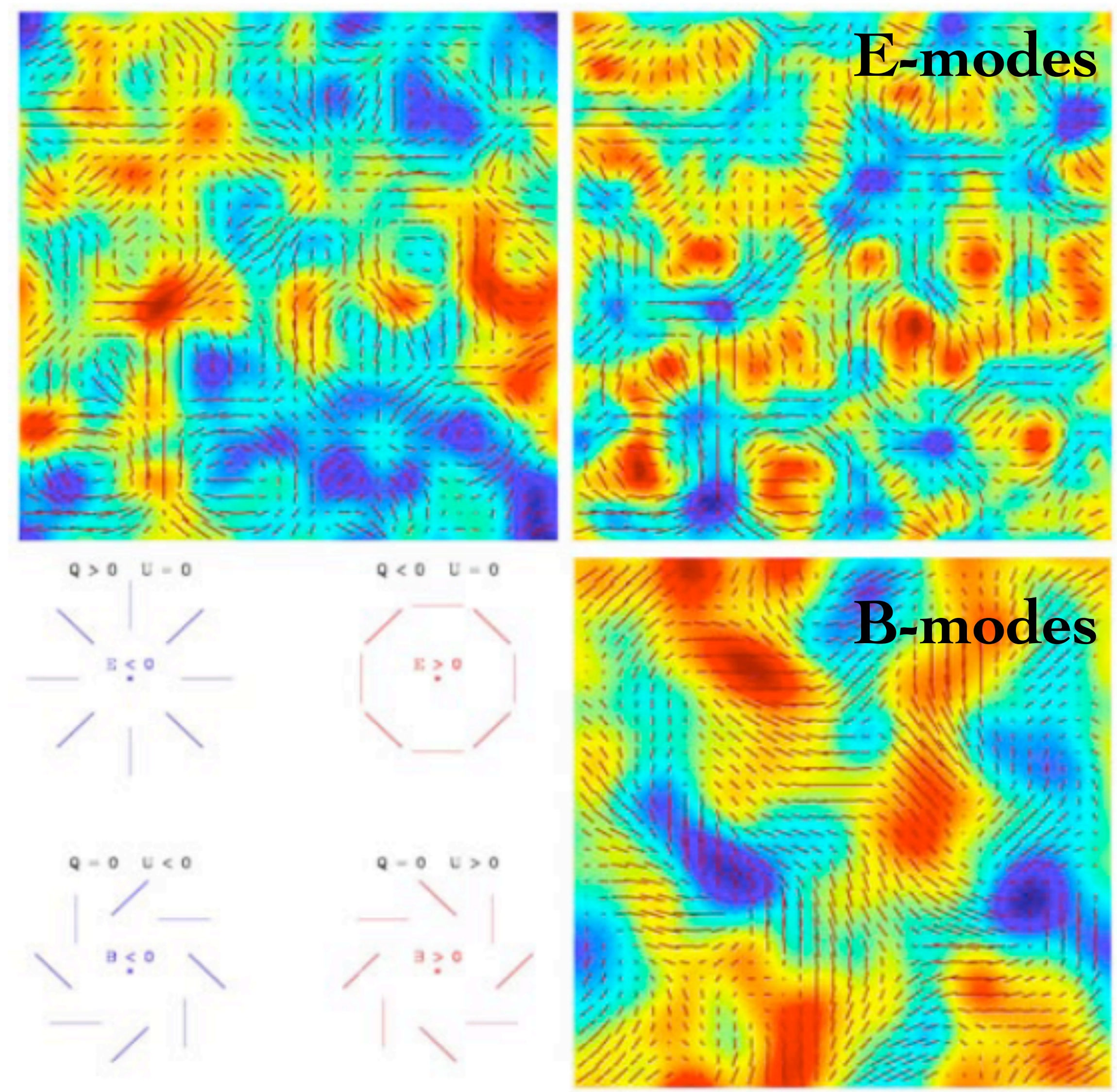
What are the B-modes?

• Polarization maps can usually be decomposed into two different patterns, usually called E-modes (analog to gradient component) and B-modes (analog to curl component) - (Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997)

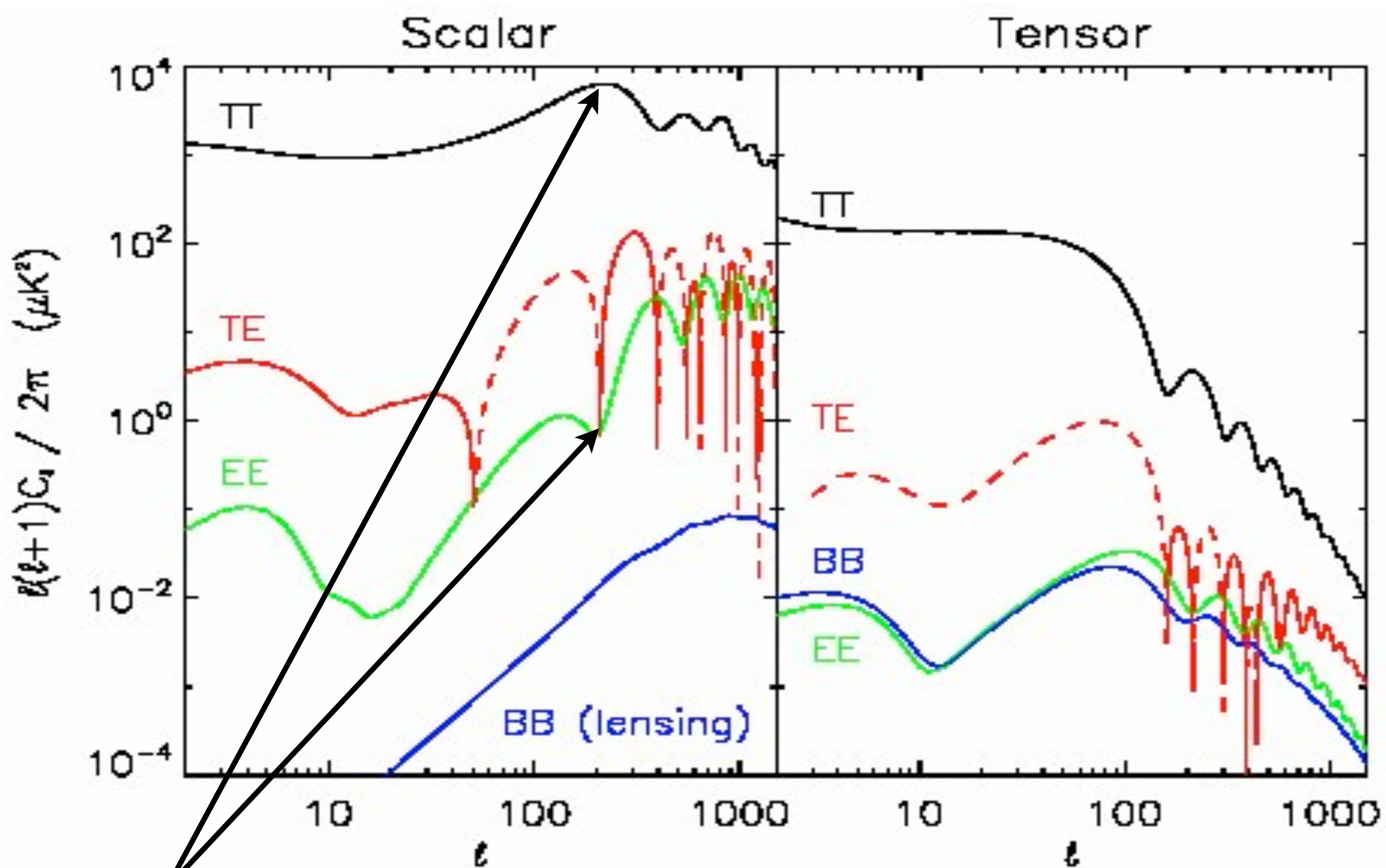
• These two components are independent on the coordinate system and are related to the Q and U Stokes parameters by a non-local tranformation

• Physics of polarization generation. Different sources of anisotropies in the primordial Universe generate different types of modes

	E-modes	B-modes
Scalar (density perturbations)	Yes	No
Tensor (gravitational waves)	Yes	Yes



CMB polarization theory



The polarization signal arises from the gradient of the peculiar velocity of the photon fluid⇒ TT and EE peaks are out of phase

Effects only on large scales because gravity waves damp inside horizon

What would a detection of GW tell us?

- It would provide strong evidence that inflation happened!

- The amplitude of the power spectrum is a (model-independent) measurement of the energy scale of inflation

$$P_{tensor} = \frac{8}{m_{Pl}^2}\left(\frac{H}{2\pi}\right)^2 \propto E_{\inf}^4$$

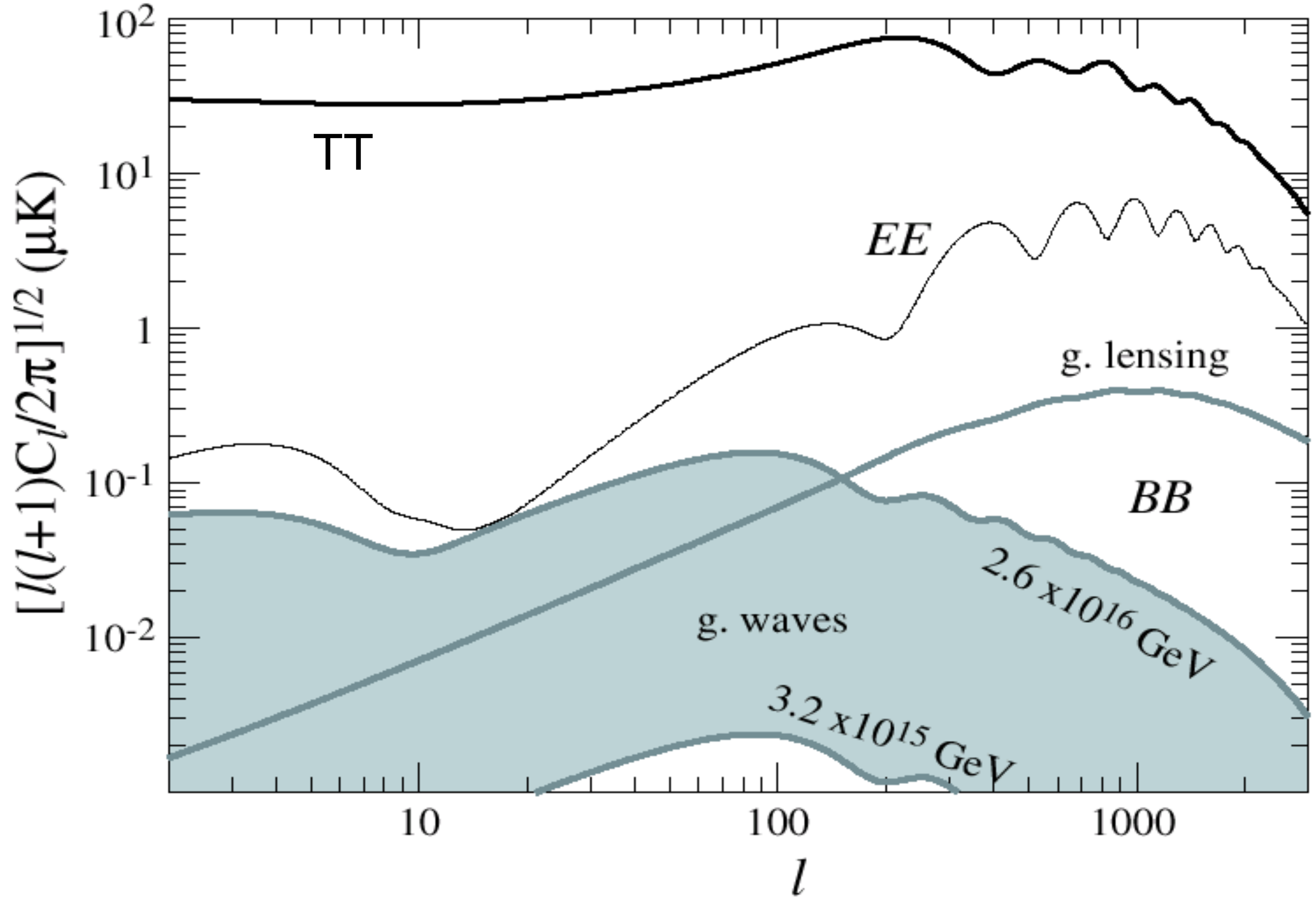
- By defining the **tensor to scalar ratio r** at a given scale k_0 (e.g. at 0.001 Mpc^{-1}), we have

$$r \equiv \frac{P_{tensor}(k_0)}{P_{scalar}(k_0)} = 0.008\left(\frac{E_{\inf}}{10^{16}GeV}\right)^4$$

  - Values of the tensor to scalar ratio of the order or larger than r=0.01 would imply that inflation occurred at the GUT scale
  - These scales are 12 orders of magnitude larger than those reachable at LHC!

- Amplitude of the B-mode power spectrum:

(From http://cosmology.berkeley.edu/~yuki/CMBpol/CMBpol.htm)

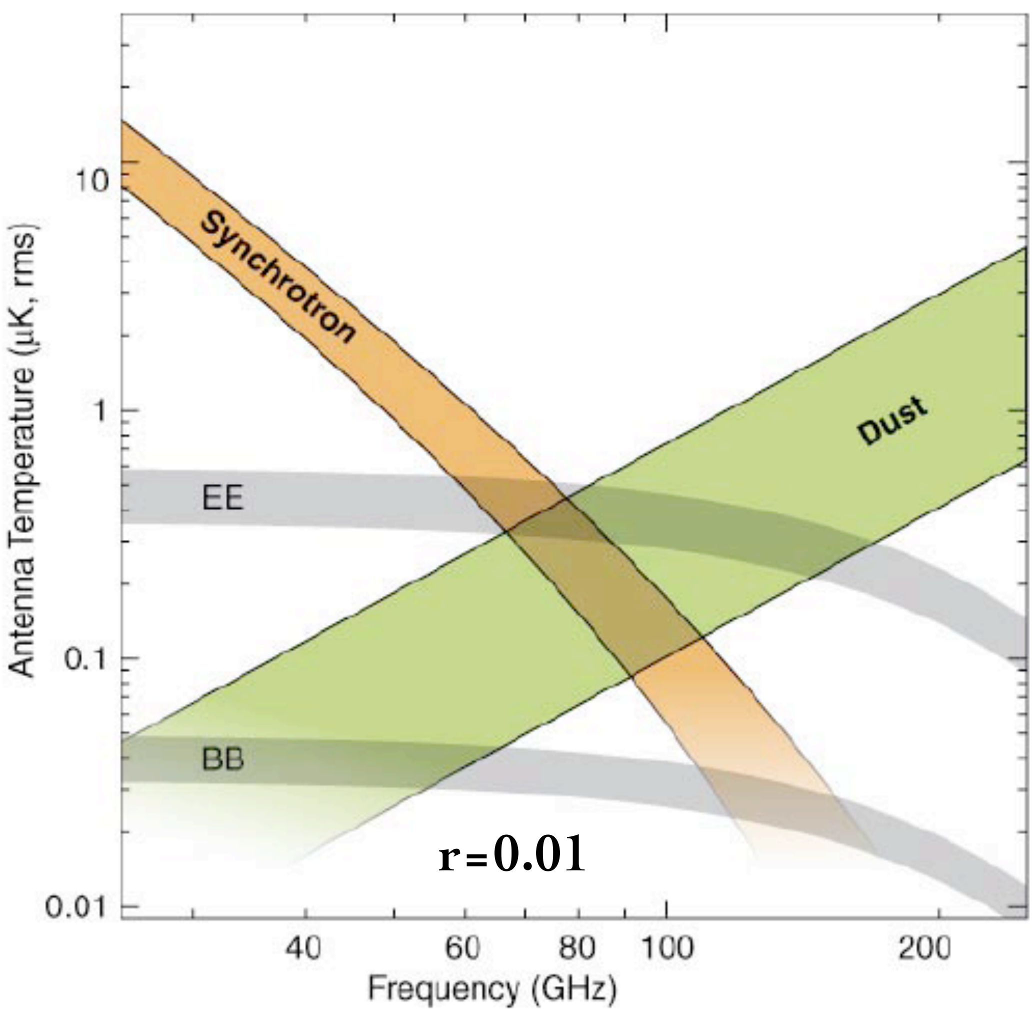


- $E_{inf}=2.6\times10^{16}$ GeV corresponds to $r=0.37$, and $E_{inf}=3.2\times10^{15}$ GeV to $r=8.4\times10^{-5}$
- $r=0.1$ corresponds to $E_{inf}=2\times10^{16}$ GeV

Observability of B-modes

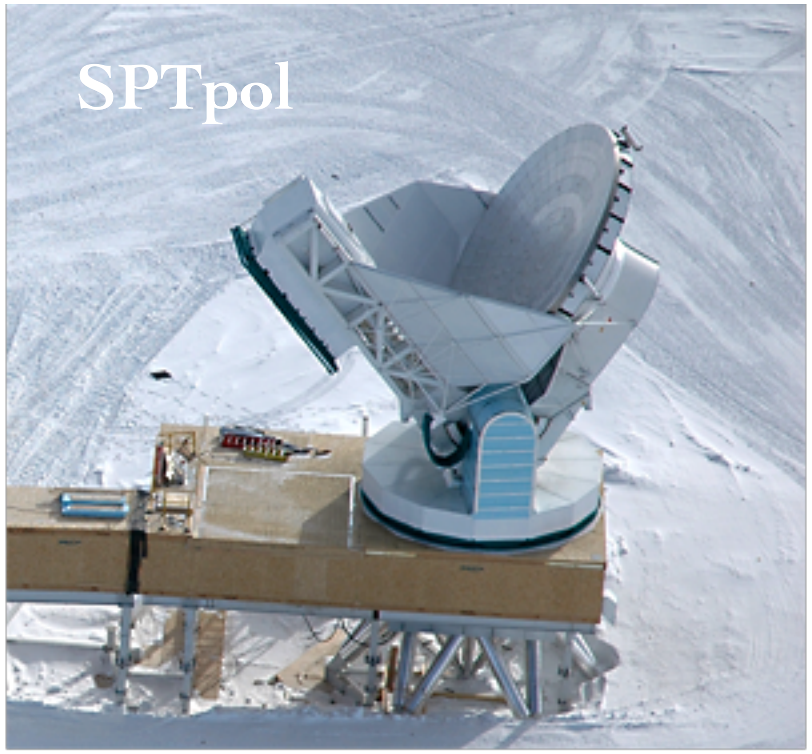
- Signals are extremely small ⇒ large number of receivers with large bandwidths are required
- Accurate control of systematics (cross-pol, spillover,...) is mandatory
- **Foregrounds**. B-mode signal is subdominant over Galactic foregrounds
  - Free-free, low-freq, not polarized
  - Synchrotron, low-freq, pol ~10%
  - Thermal dust, high-freq, pol ~10%
  - Anomalous emission, 20-60 GHz, pol ~3%?
  - Point sources, low-freq, pol ~5%

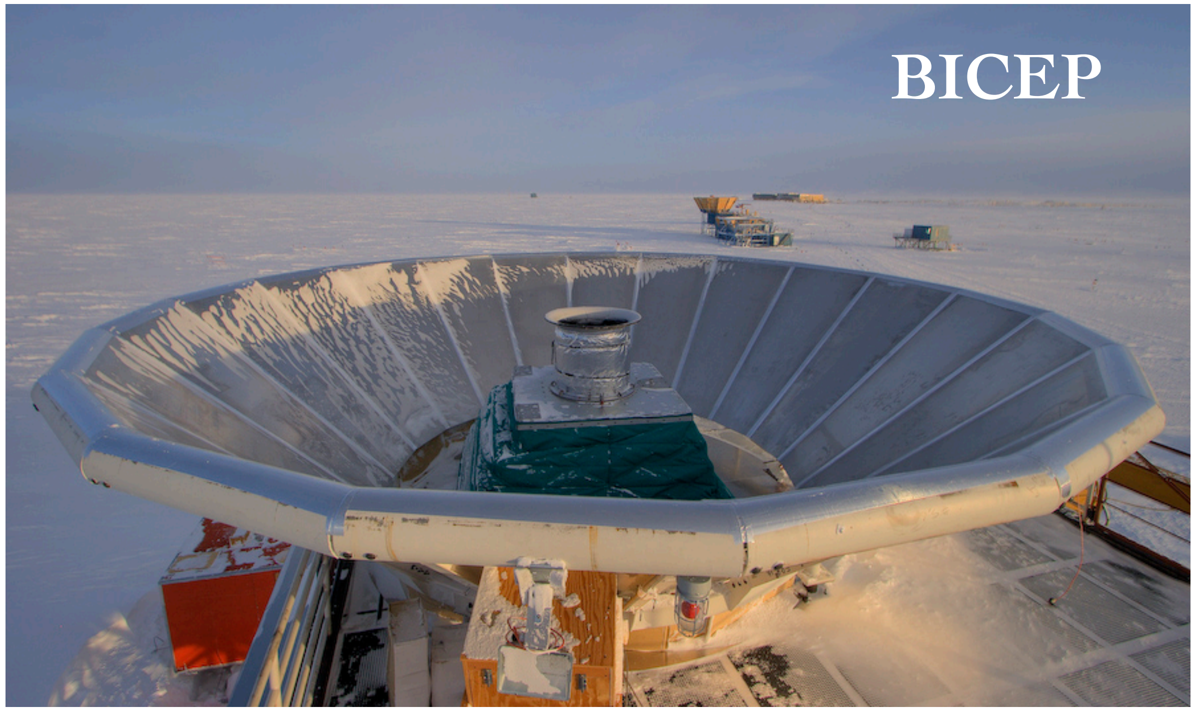
(WMAP7)



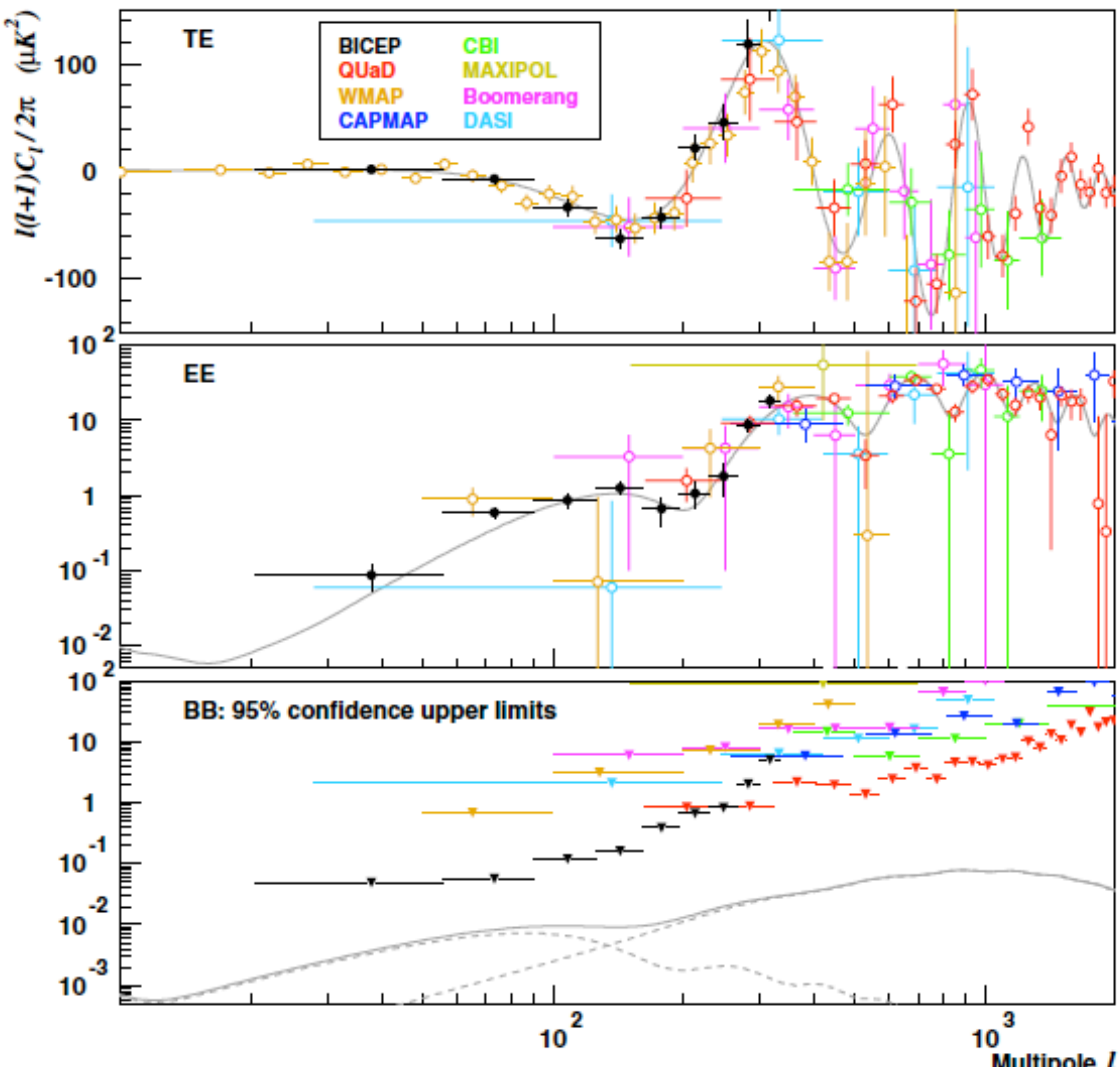
- Systematic program to study polarized astrophysical foreground signals is needed (see NASA-NSF report "Task Force on CMB research" and ESA-ESO report on "Fundamental cosmology")

Observations status





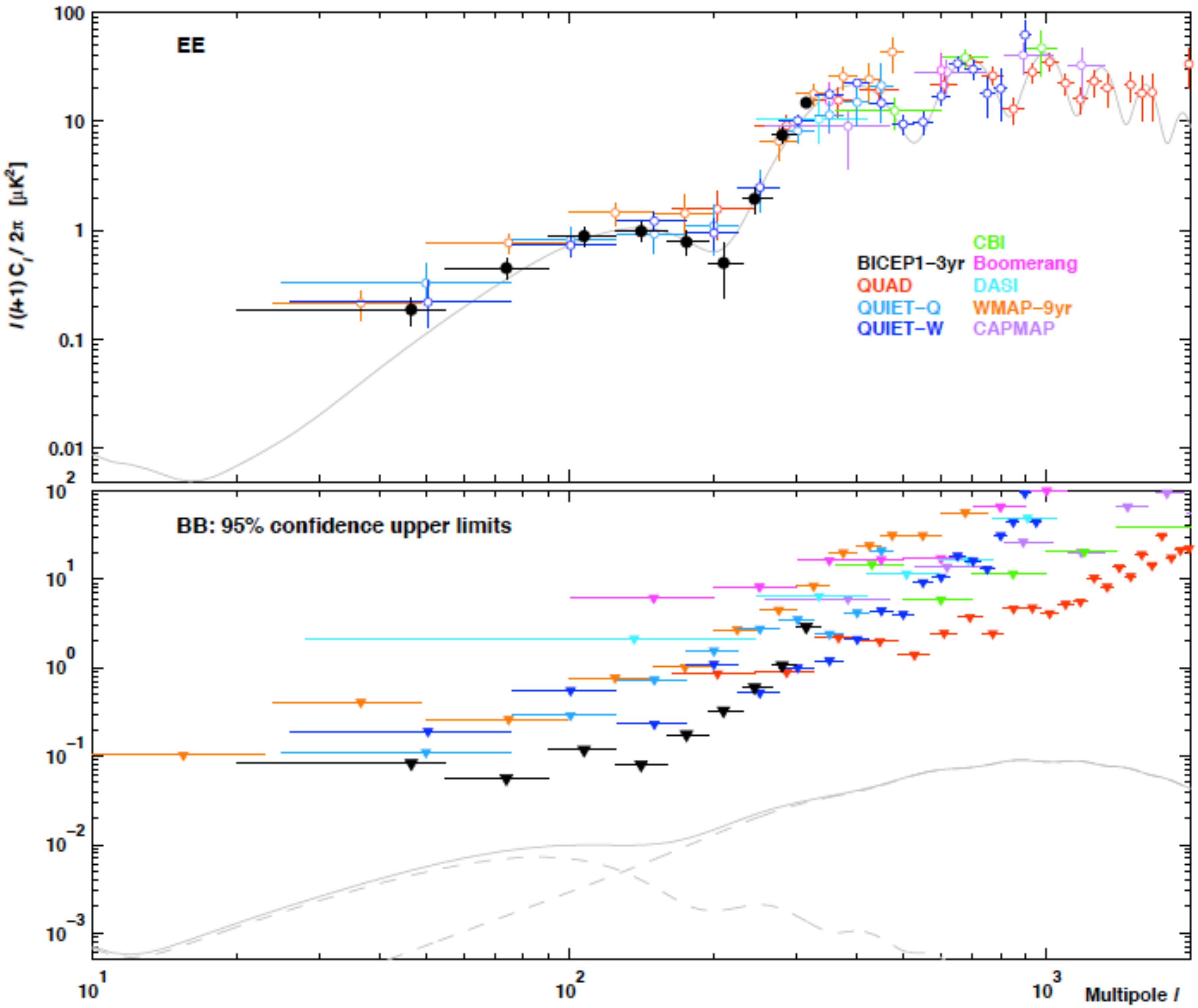
Observations status



(Chiang et al. 2010)

- First E-mode detection by DASI experiment (Kovac et al. 2002)
- Characterization of the EE and TE power spectra provided by many other experiments: CAPMAP, QUaD, Boomerang, WMAP, BICEP, QUIET,...

Observations status



BICEP results

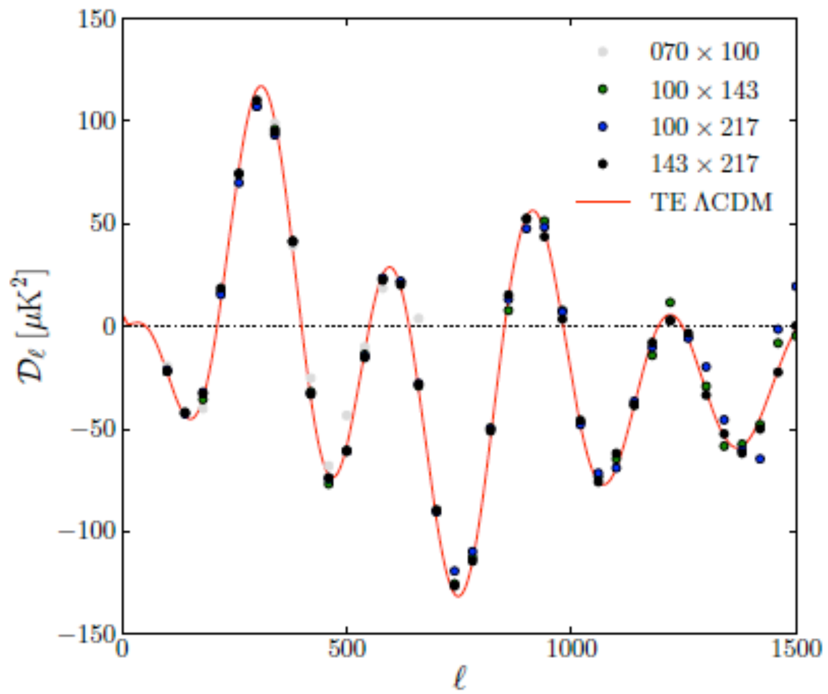
(Barkats et al. 2013)

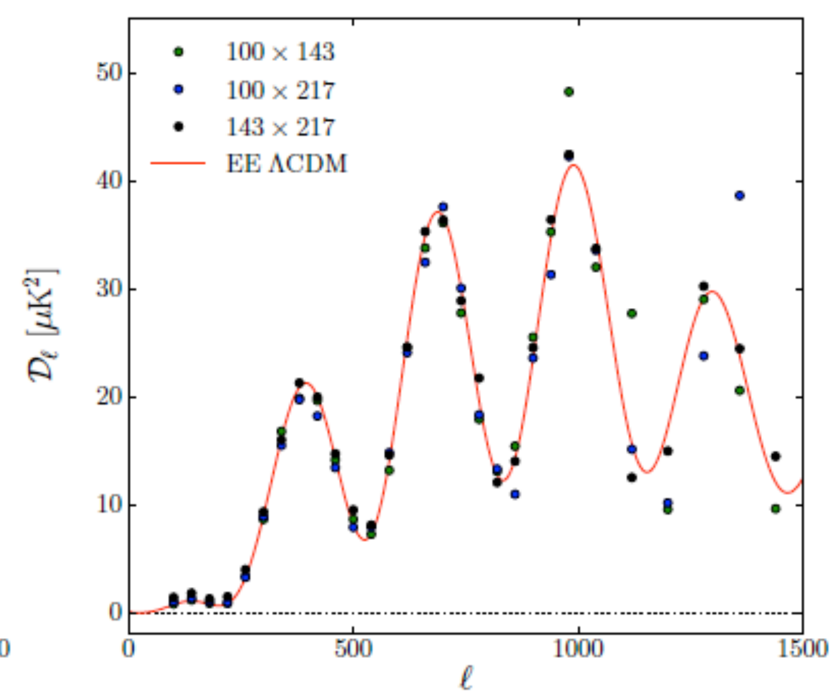
- Best BB constraints coming from BICEP: r<0.72 (Chiang et al. 2010), **r<0.70** (Barkats et al. 2013) at 95% CL
- QUIET results: r<2.7 (QUIET collaboration 2012)
- WMAP7 gives r<0.93 at 95% CL using TE/EE/BB, and r<2.1 with BB alone
- WMAP7+BAO+SN gives r<0.2 (Komatsu et al. 2010)

Planck preliminary results

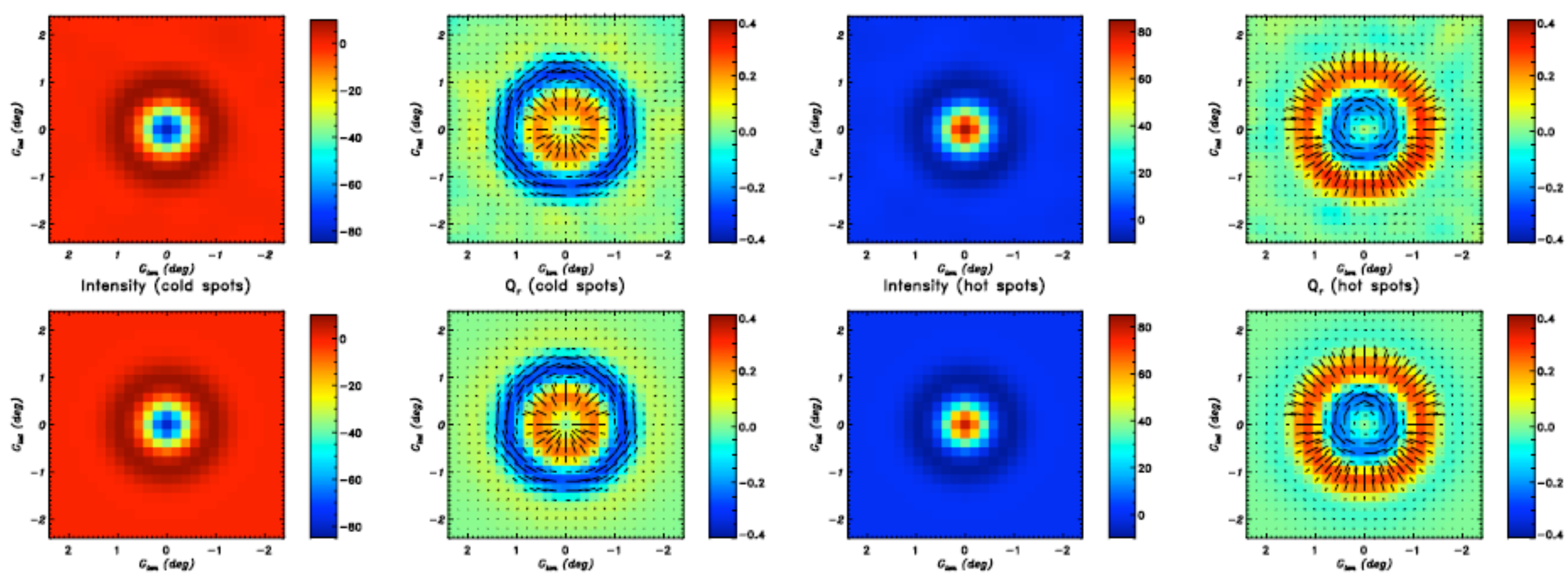
EE and TE power spectra

(CPP15, arXiv:1303.5075)





Stacked I and Q maps around hot and cold spots. Detection of the signal from adiabatic scalar fluctuations from inflation (CPP1, arXiv:1303.5062):

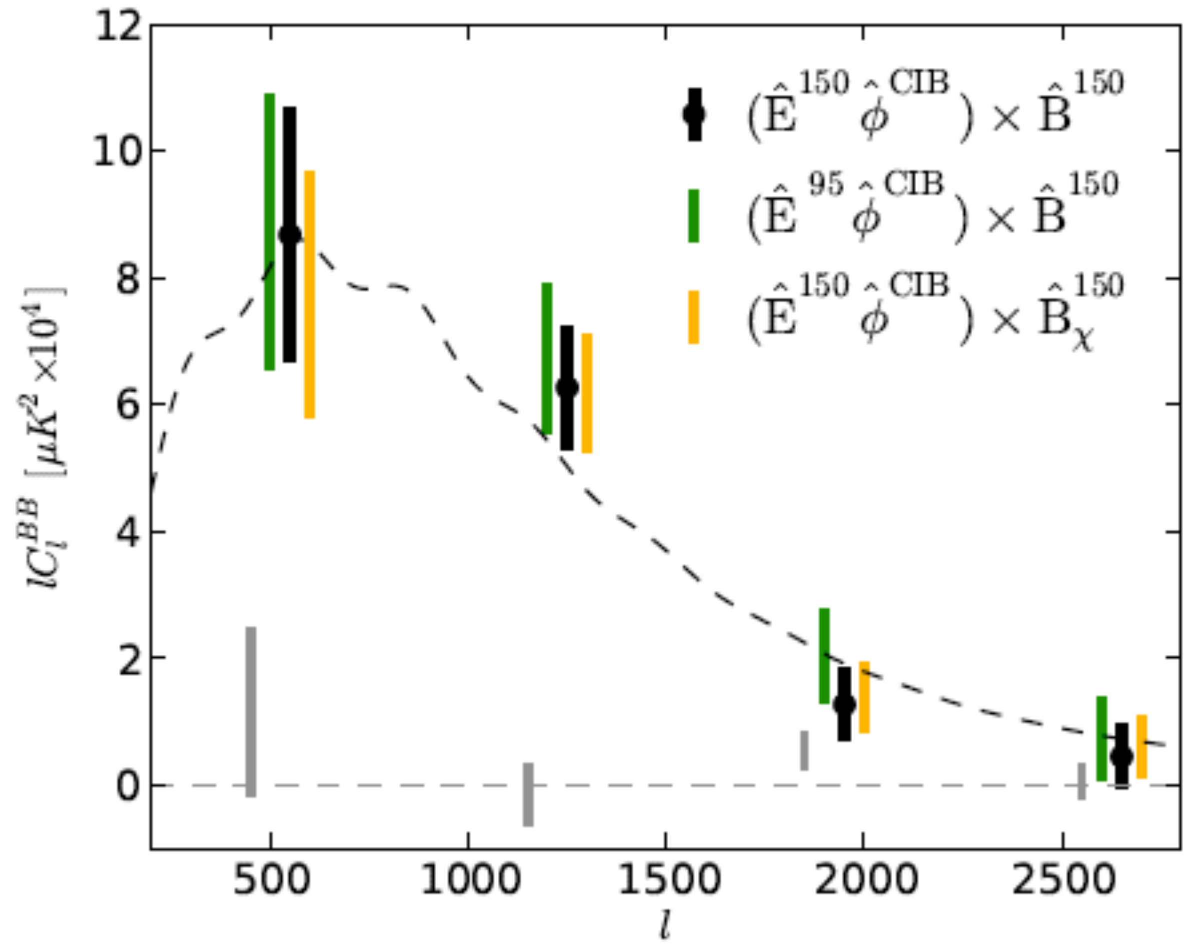


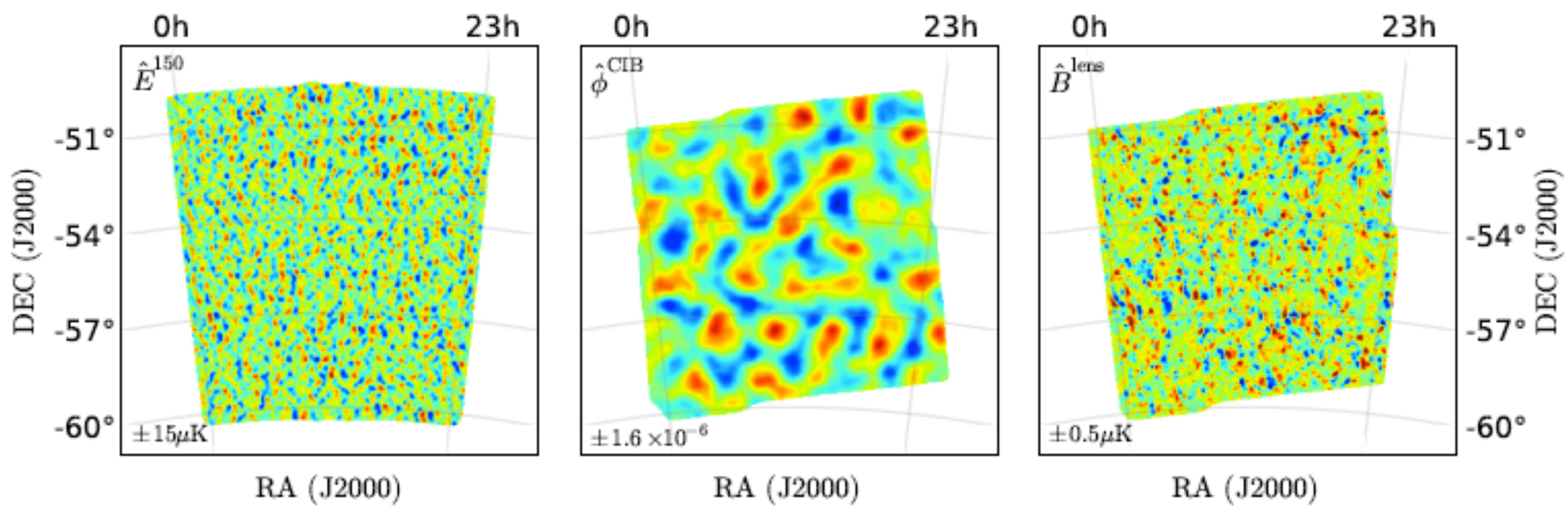
SPTpol results

- First detection of BB signal from lensing!
(Hanson et al. 2013, arXiv: 1307.5830)

- Indirect detection by cross-correlating SPTpol maps of the B-mode signal with templates tracing the lensing potential built from the E-mode signal measured by SPT pol and maps of the CIB from Herschel

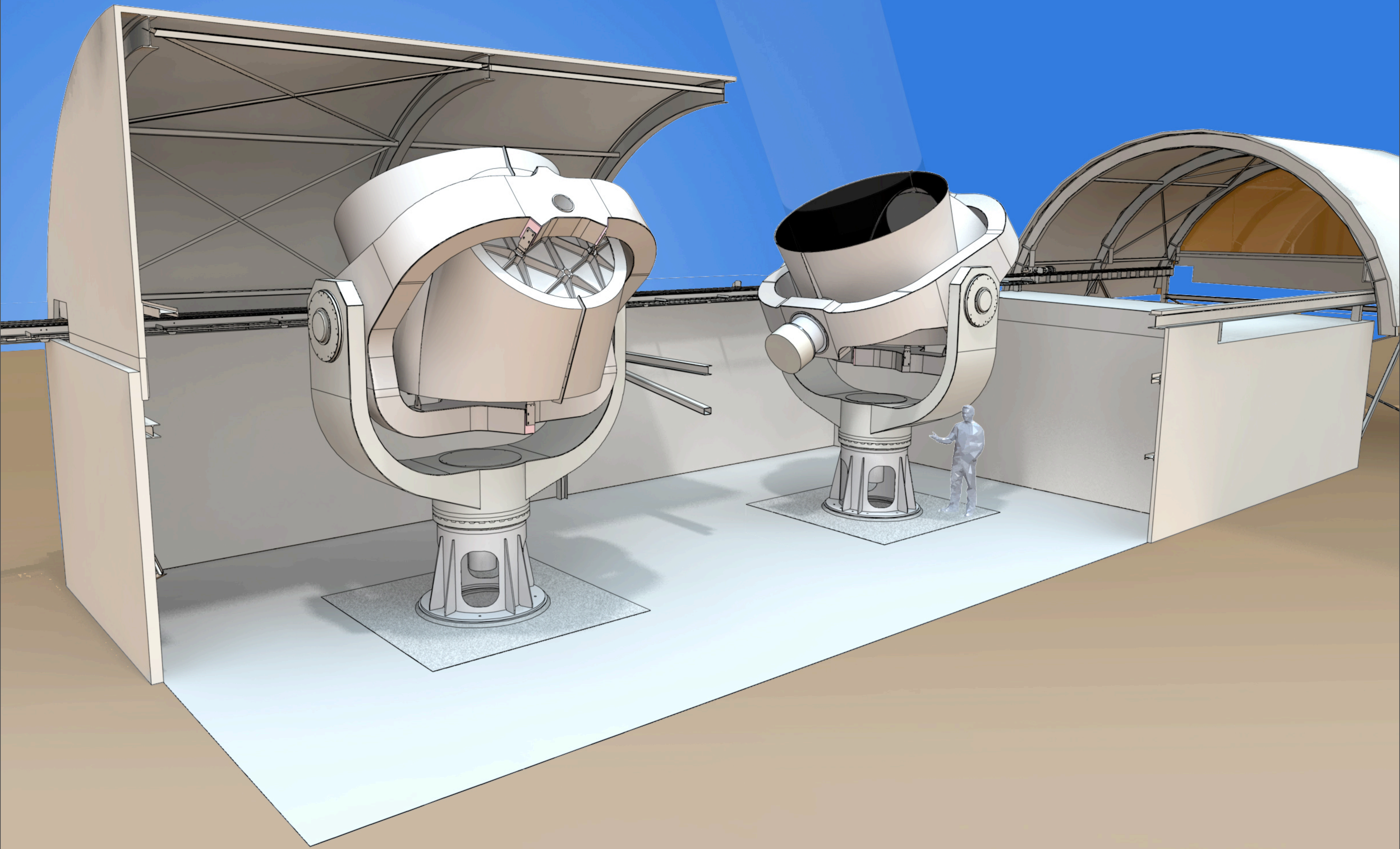
- This gives a *7.7σ* correlation





(Hanson et al. 2013)

The QUIJOTE-CMB experiment



(Q-U-I JOint TEnerife Cosmic Microwave Background experiment)

The QUIJOTE collaboration

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Scientific goals

★ Main science driver: to constrain (or to detect) gravitational B-modes down to a sensitivity of r=0.05

★ To measure low-frequency polarized foregrounds (synchrotron and, if polarized, the anomalous microwave emission) with high sensitivity to correct them in future space missions aiming to reach r=0.001

★ To complement Planck at low frequencies. In combination with Planck data, push the upper limits on r below 0.05

★ **Goals:**

• To obtain six polarization maps in the frequency range **10-40 GHz** with sufficient sensitivity to correct **foreground emission** (synchrotron and AME) and constrain the imprint of **B-modes down to r=0.05**

★ **Site:** Teide Observatory (altitude: 2400 m, latitude: 28º), Spain

★ **Observability:** -32º<Dec.<88º (f_{sky} ~0.65)

★ **Frequencies:** **11,13, 17, 19, 30** and **40 GHz**

★ **Angular resolution:** 1 degree (52 arcmin @ 11 GHz)

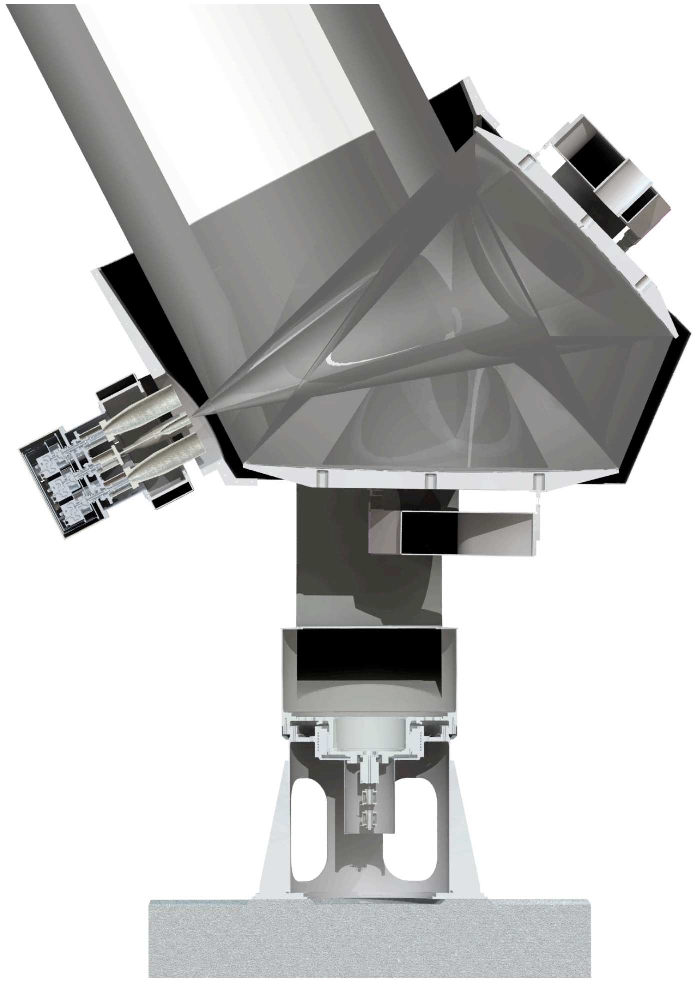
★ **Telescope and instruments:**

- **Phase I**:
  - First Telescope (**QT1**)
  - Equipped with a Multifrequency Instrument (**MFI**) with 4 polarimeters @ **10-20 GHz**. Started operations Nov. 2012
  - Second Instrument (**TGI**) with 31 polarimeters @ **30 GHz**. Funded; to start operations at the beginning of 2014
  - Polarized Source Subtractor (undergoing commissioning)
- **Phase II**:
  - Second Telescope (**QT2**). Under construction (beginning of 2014)
  - **FGI** with 40 polarimeters @ **40 GHz**. Funded (mid 2014)

★ **Scientific operation plan:** 2012-2018

QUIJOTE platform

QUIJOTE telescope I



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

QUIJOTE telescope I

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

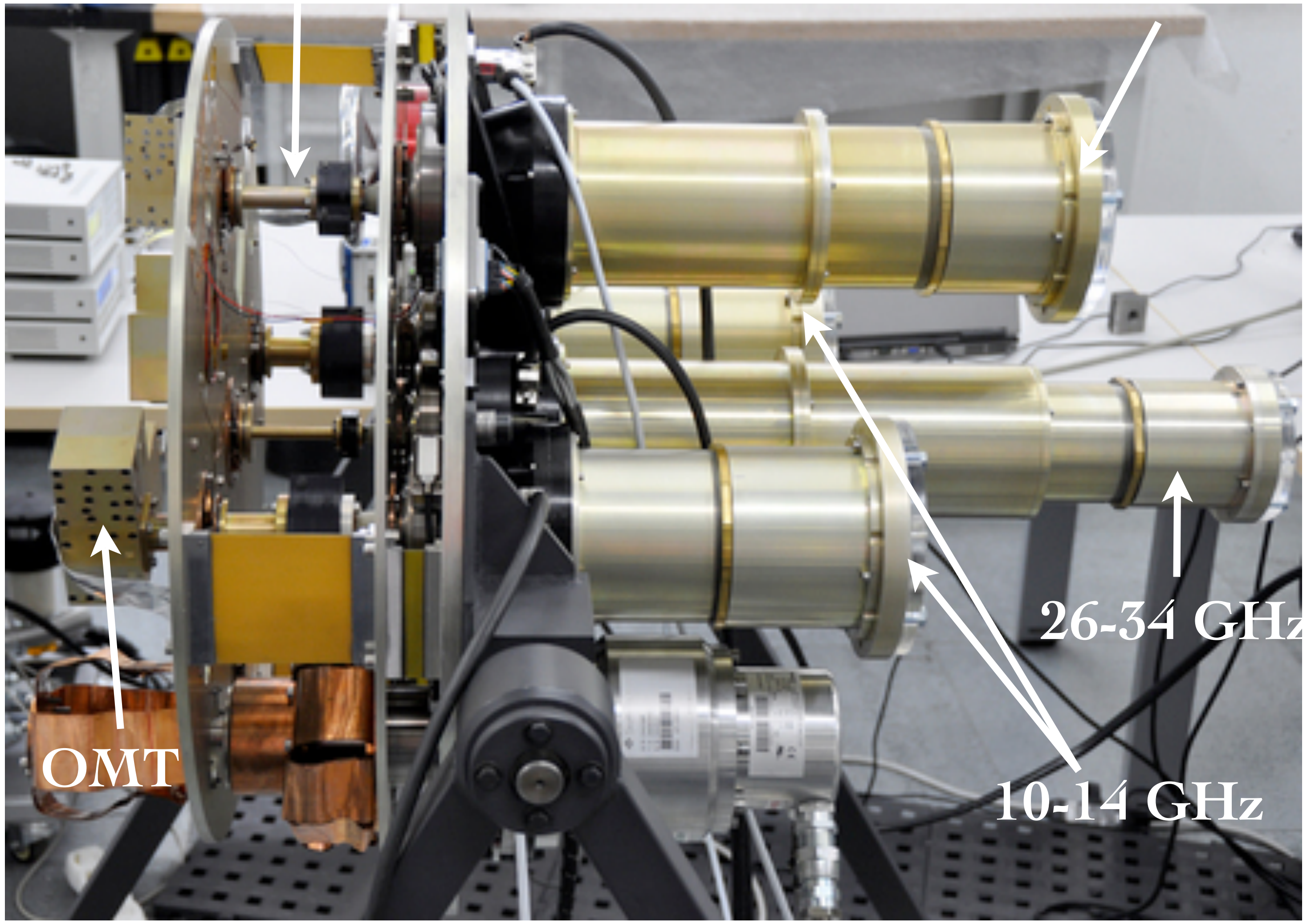
- QT2 is a replica of QT1. Under construction

MultiFrequency Instrument (MFI)

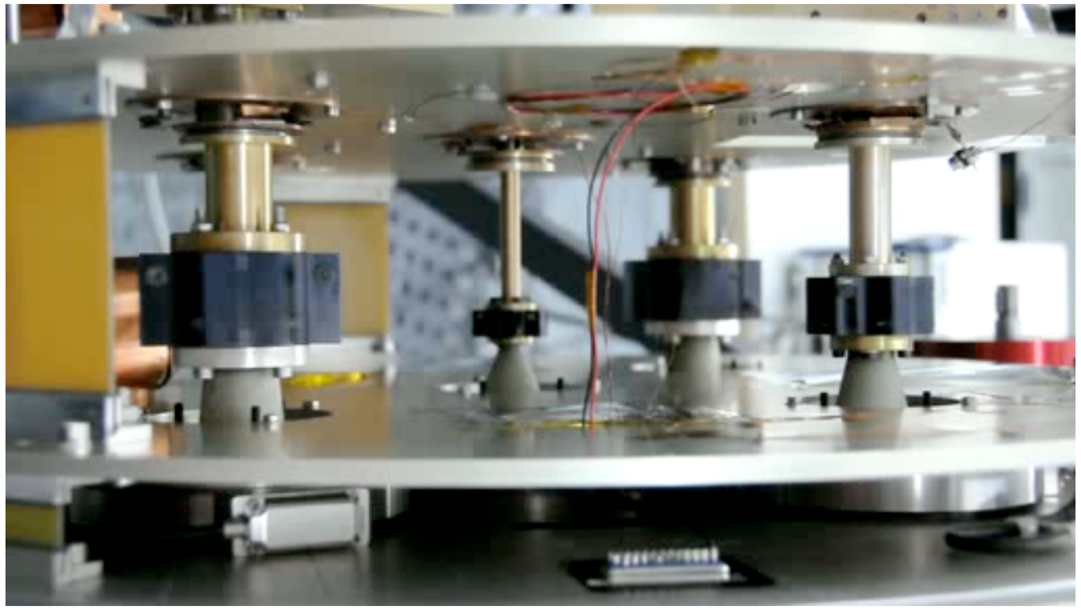
- 4 conical corrugated horns (2 at 10-14 GHz and 2 at 16-20 GHz)
- Polar modulator spinning at speeds up to 40 Hz
- Wide-band cryogenic Ortho-Mode-Transducer (OMT)
- MMIC 6-20 GHz Low Noise Amplifiers. Gain: 30dB
- Noise temperature: ~7-10 K (10-14 GHz), ~10-20 K (16-20 GHz)

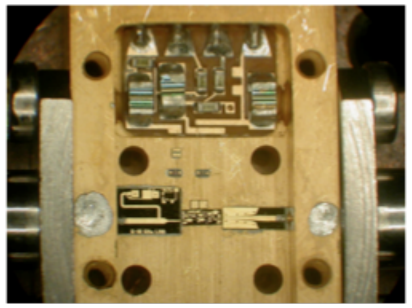
Polar Modulators

16-20 GHz



Spinning polar modulators

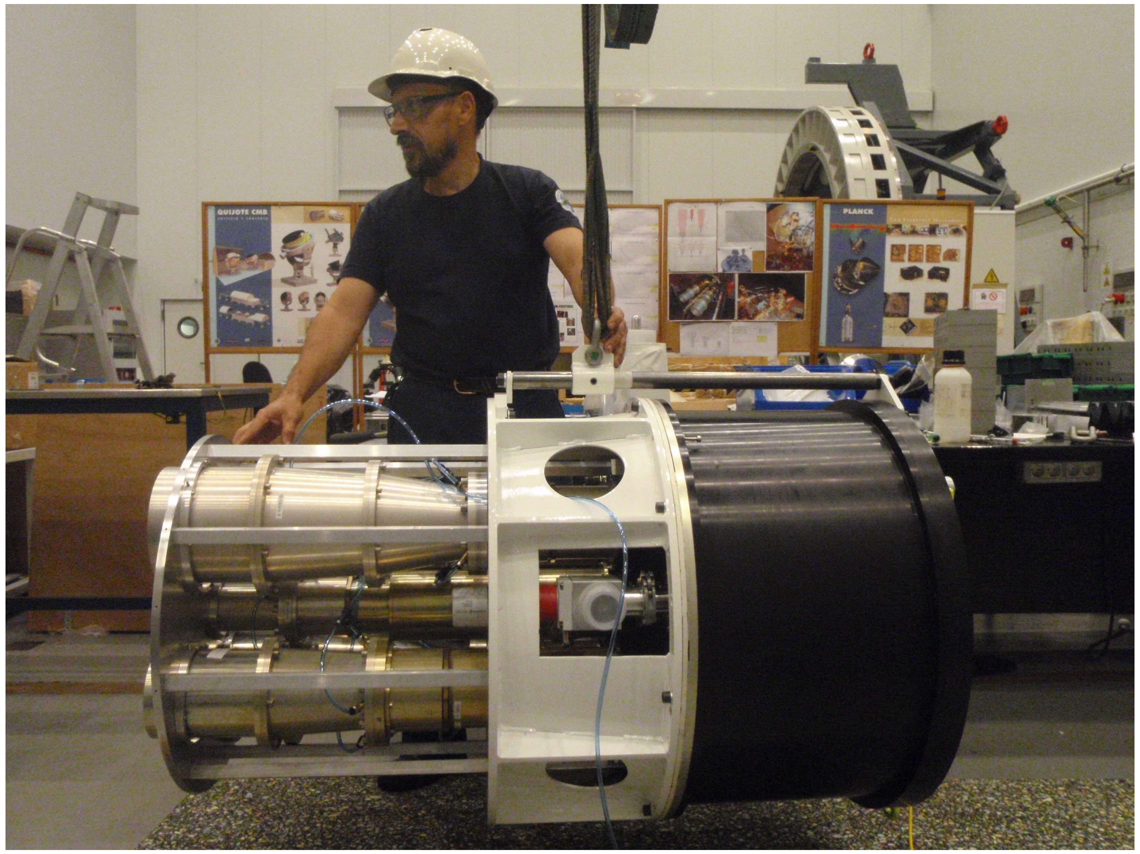


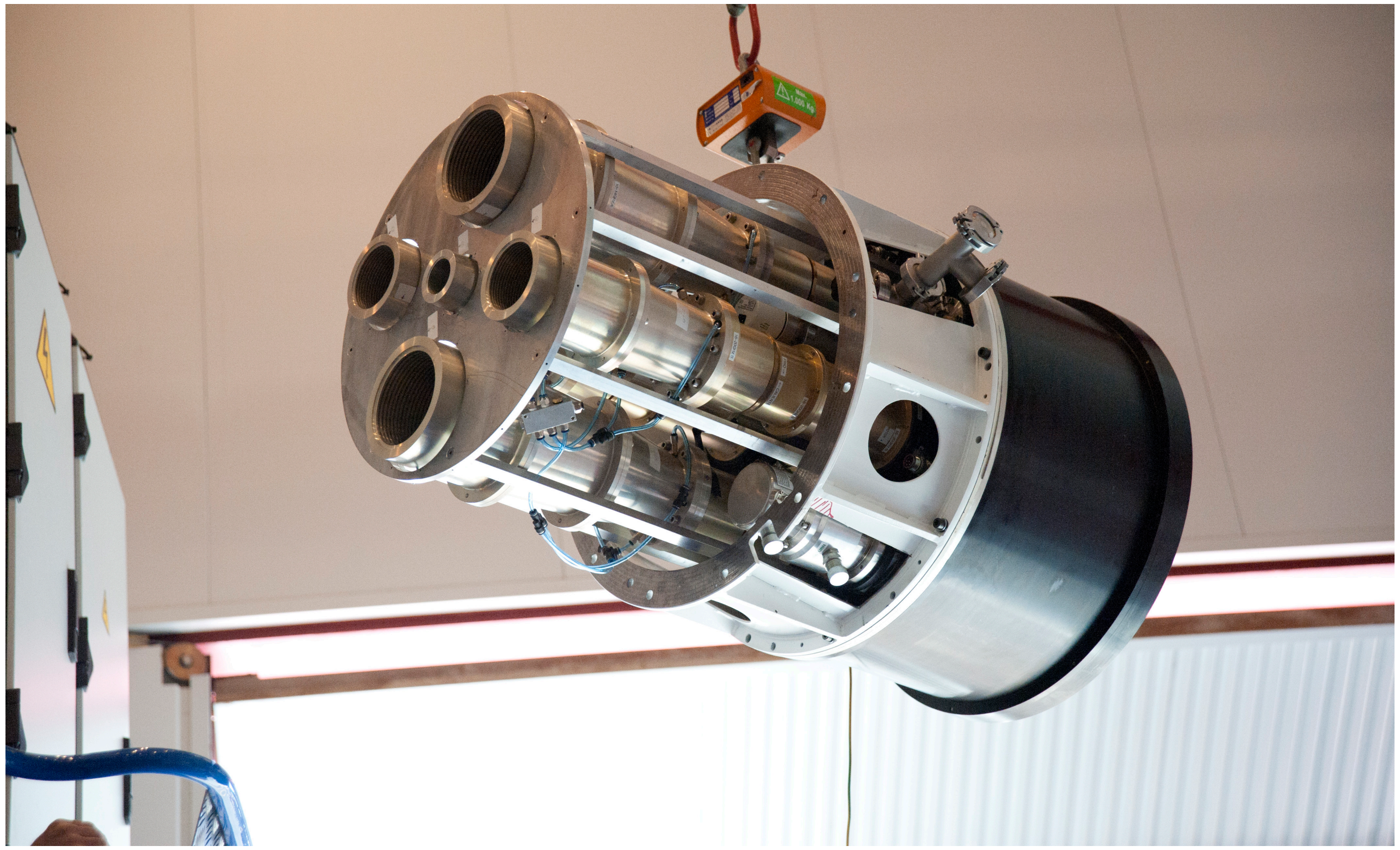


LNA

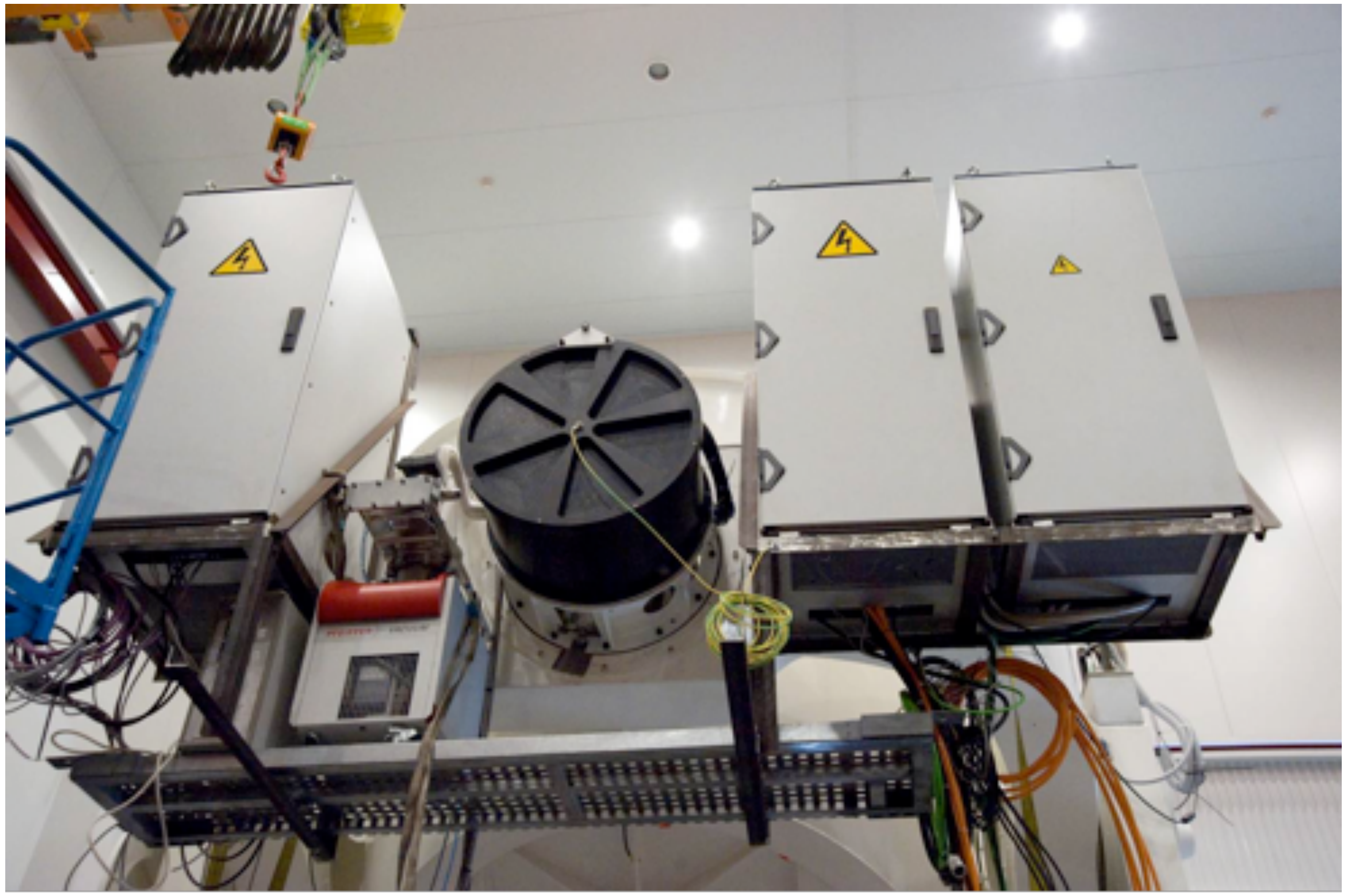
OMT and motor

Horns

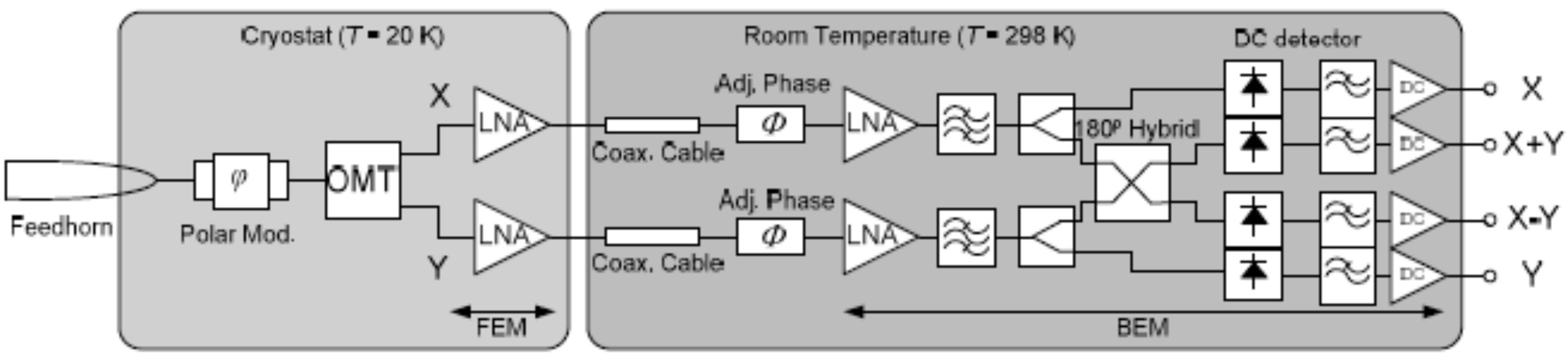




- MFI integration tests on the QT1 at the AIV room. March 2012
- Currently on scientific operation (since Nov. 2013)



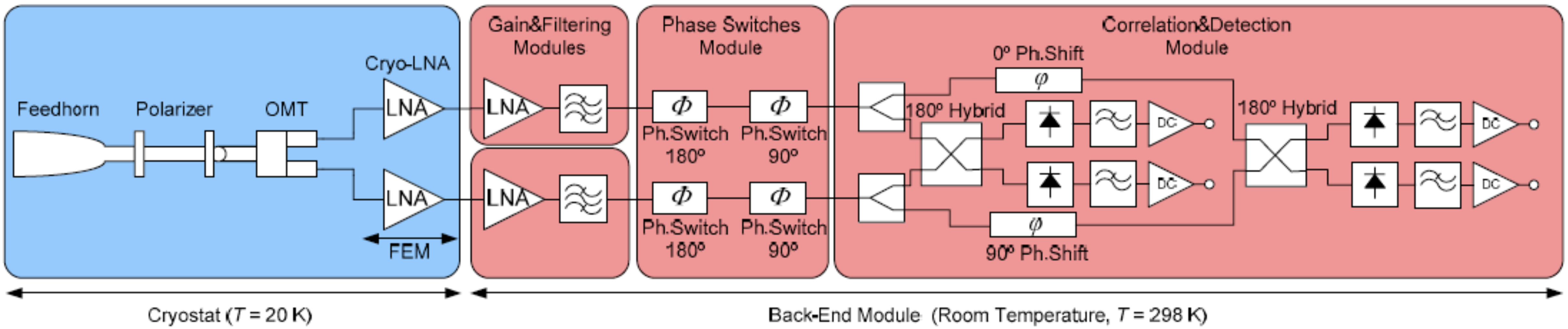
- MFI polarimeter configuration
- FEM: partially-cooled feed-horn, polar modulator, OMT and LNAs
- BEM: phase adjuster, further amplification, band pass filter and correlation
- Output: two channels (x) and (y) measuring Q (un-correlated), two channels (x+y) and (x-y) measuring U (correlated)



- 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

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 four polarization states in each branch, to minimize the 1/f noise and other systematics
- To be commissioned in 2014
- The **TGI** (**40 polarimeters at 40 GHz**) will be based on the same design

★ Sensitivities:

	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	2	2	2	2	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 (μK $s^{1/2}$)	396	396	396	396	50	50
Sensitivity (Jy $s^{1/2}$)	0.42	0.59	0.44	0.54	0.06	0.06

★ Temperature sensitivity per beam given by:

$$\Delta Q = \Delta U = \sqrt{2}\frac{T_{sys}}{\sqrt{\Delta\nu \times t_{\rm int} \times N_{chan}}}$$

Polarized Source Subtractor

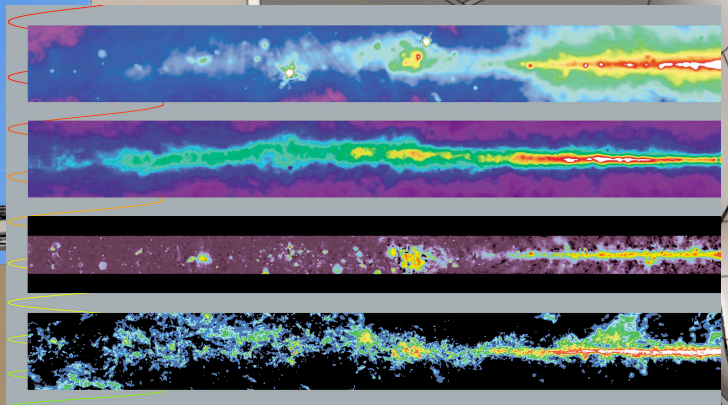
- Dedicated instrument at **30 GHz**. VSA Source Subtractor converted to a polarimeter
- Installed a dielectrically embedded mesh-HWP designed and produced at the University of Manchester

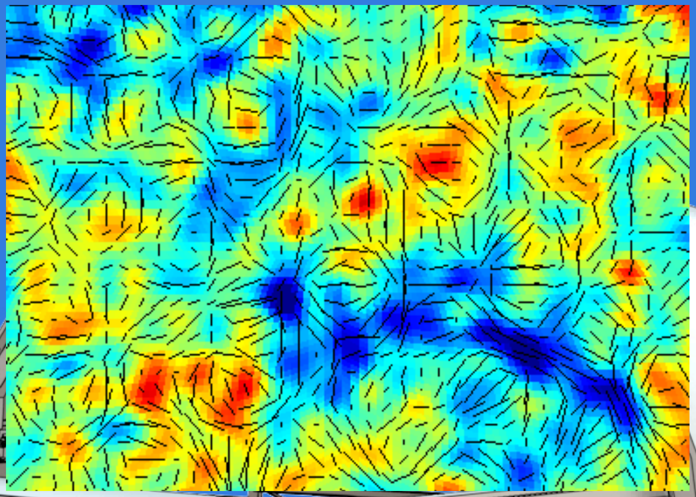
- Twofold subtraction strategy:

  - 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: $-5° < \delta < +60°$

Scientific goals of QUIJOTE



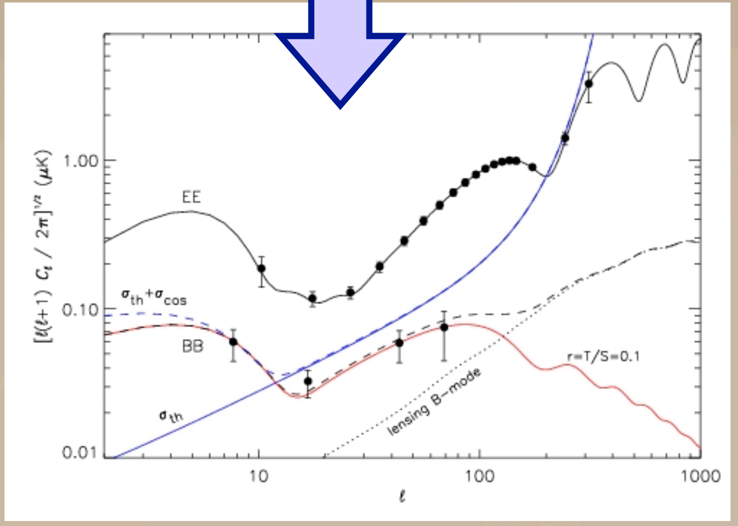


Phase II

- Second QUIJOTE telescope
- Forty Gigahertz Instrument: 40 GHz

Phase I

- Enclosure and First QUIJOTE telescope
- Multi Frequency Instrument: 10-20 GHz
- Thirty Gigahertz Instrument: 30 GHz
- Polarized SS baseline @ 30 GHz



★ Main goals of QUIJOTE-CMB:

- To detect the imprint of the gravitational B-modes if **r ≥ 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)

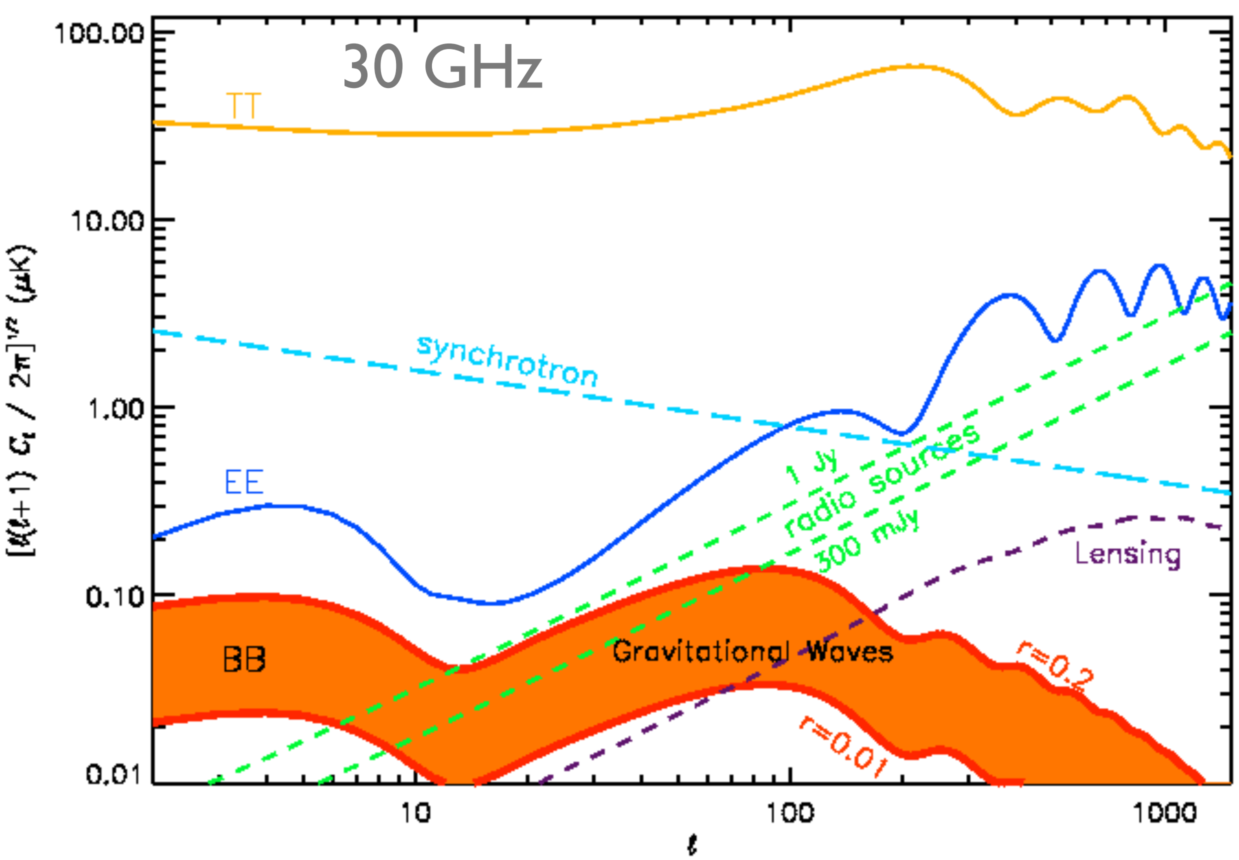
★ Two large surveys in polarization

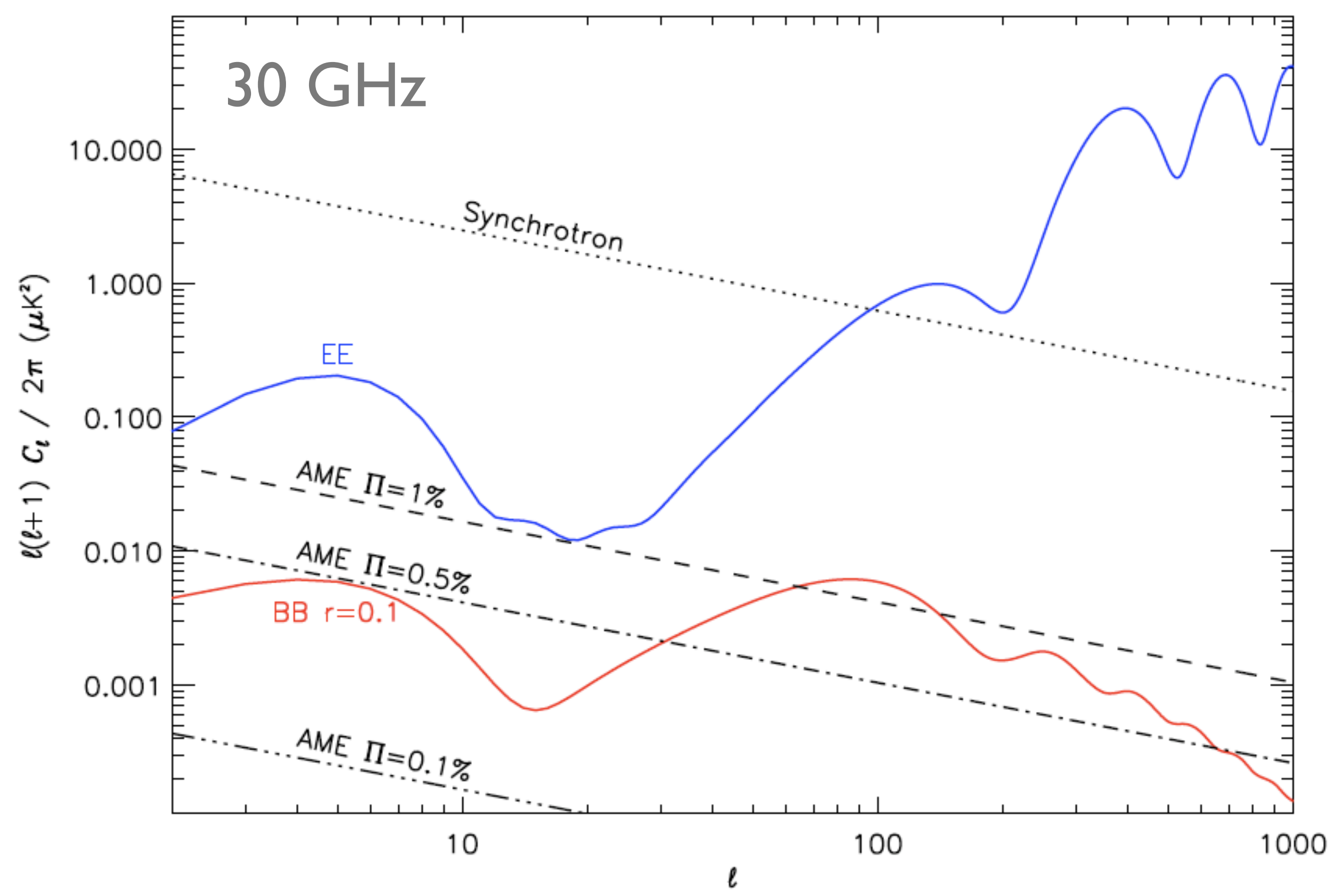
- **Wide Galactic survey**. It will cover 20,000 deg^2, and will be finished after 4 months of observations with each instrument (half-way through with the MFI). Expected sensitivities:
  - ≈ 12 μK/(beam 1°) with the MFI @ 11, 13, 17 and 19 GHz, in both Q and U
  - ≤ 3 μK/(beam 1°) with the TGI @ 30 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 1°) with the MFI @ 11, 13, 17 and 19 GHz
  - ≤ 1 μK/(beam 1°) with the TGI @ 30 GHz and with the FGI @ 40 GHz

Science with the MFI

★ These maps will provide valuable information about the polarization properties of:

- Synchrotron emission: should dominate the emission at the MFI frequencies. WMAP 23 GHz shows it to be polarized at ~5-15%, depending on the Galactic latitude
- Anomalous microwave emission: little known about its polarization. Best upper limits on the polarization fraction: <1% (López-Caraballo et al. 2011, Dickinson et al. 2011)





★ MFI maps will be used to clean the 30 GHz and 40 GHz maps of the second (TGI) and third (FGI) QUIJOTE instruments

★ Excellent complement of Planck at low frequencies. Planck will provide information about the polarization of the thermal dust emission at high frequencies (April 2014)

AME polarization

★ Probing the electric (spinning dust) and magnetic dipole emission models:

- Electric and dipole emissions present different polarization spectra

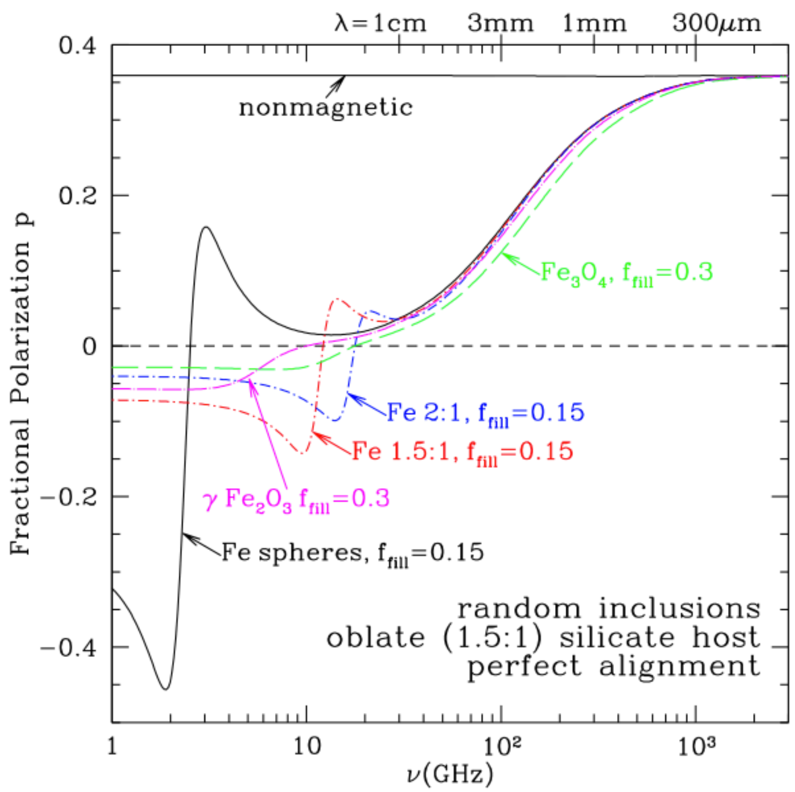
★ Different theoretical models predicting the polarization level of the ED (Lazarian & Draine 2000, Hoang et al. 2013) and of the MD (Draine & Hensley 2012) emissions

★ Current upper limits on the fractional polarization at ~ 1%

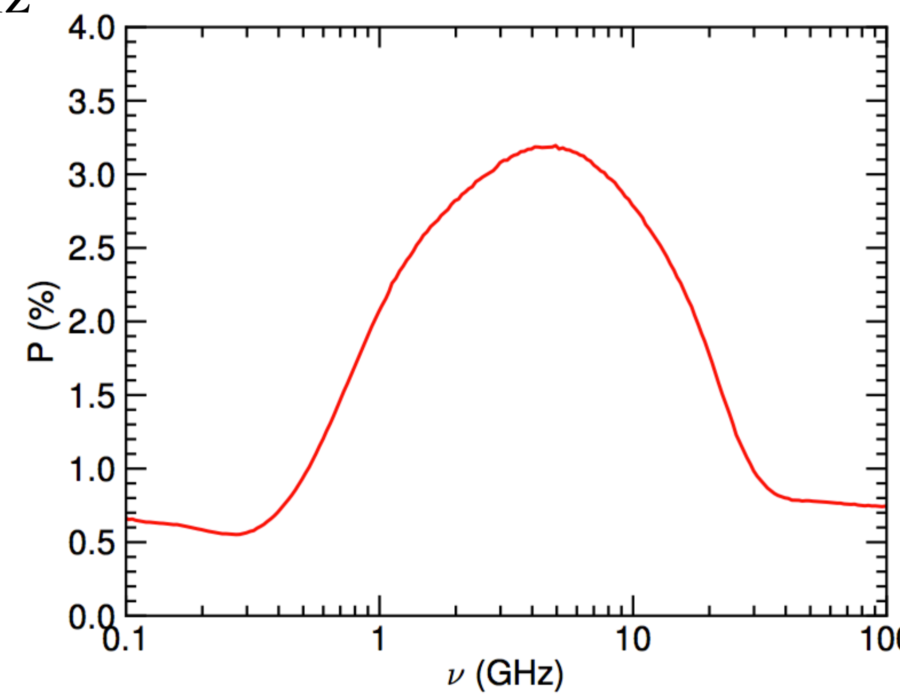
★ Observational status:

- Cosmosomas experiment on Perseus G160.26-18.62: **Π = 3.4 +1.5 -1.9 %** (2σ) at 11 GHz (Battistelli et al. 2006)
- CBI on ρ Ophiuchus G353.05+16.90: **Π<1.0%** (3σ) at 31 GHz (Casassus et al. 2008)
- GBT on LDN1622: **Π<2.7 %** (2σ) at 9.65 GHz (Mason et al. 2009)
- WMAP7 on Perseus G160.26-18.62: **Π < 1.0%, 1.8% and 2.7%** (2σ) respectively at 23, 33 and 41 GHz (López-Caraballo et al. 2011). Also, Dickinson et al. (2011)
- Limits on diffuse Galactic AME from WMAP: **Π < 1.0%** (Kogut et al. 2003), **Π < 5.0%** (Macellari et al. 2011)

MD - Draine & Hensley 2012



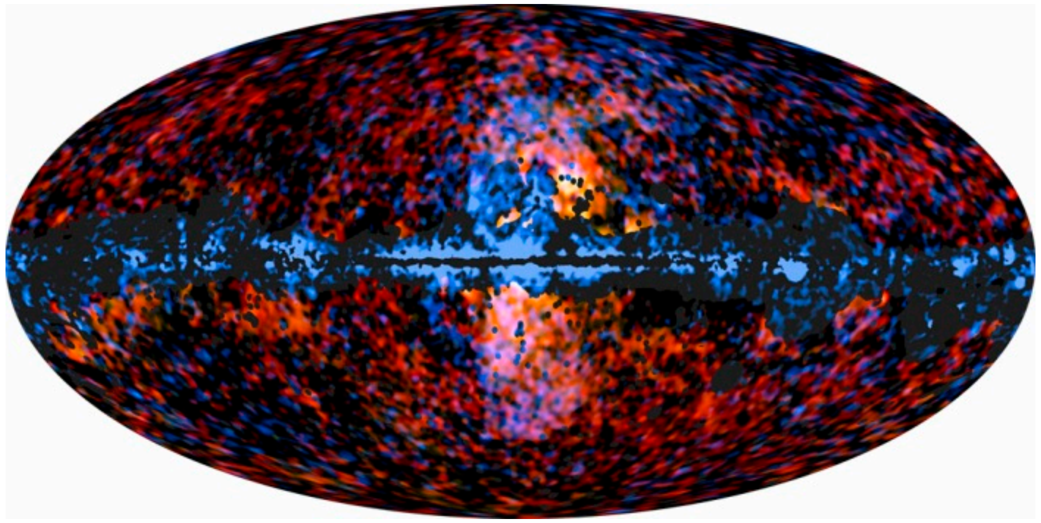
ED - Hoang et al. (2013)



Non-core science with the MFI

★ Study of the polarization of the Galactic Haze / Fermi bubbles

- Bright GC signature found in WMAP7 data (Finkbeiner et al. 2004), with a γ-ray counterpart in Fermi data(Dobler et al. 2010)
- Hyptoheses:
  - ➡ Hard synchrotron radiation from relativistic electrons and positrons produced by dark matter particle annihilation (Hooper et al. 2007)
  - ➡ Cosmic-ray ions coming from star formation in the galactic centre (Carretti et al. 2013)

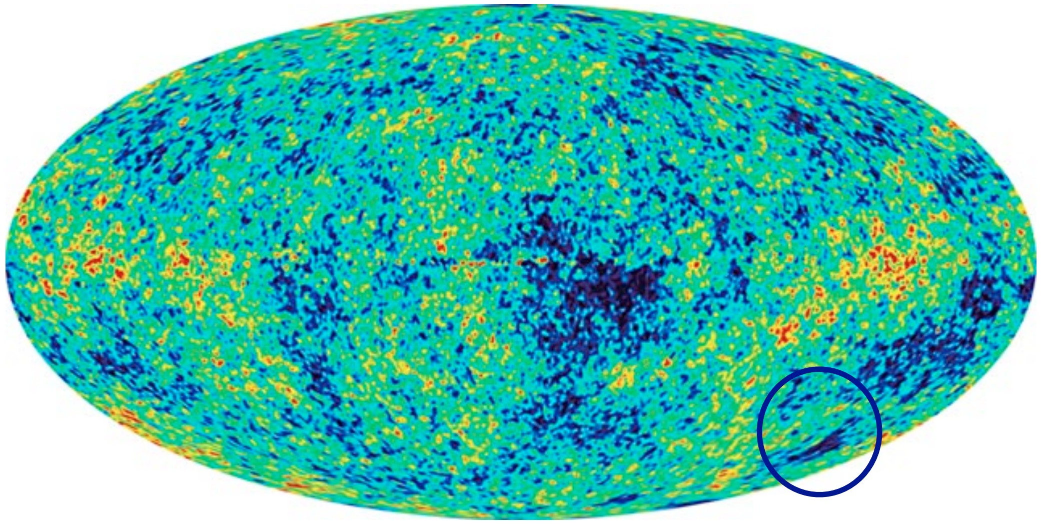


(Planck collaboration et al. 2012)

- Polarization data is key to disentangle between these different hypotheses

★ Study of the polarization of the Cold Spot

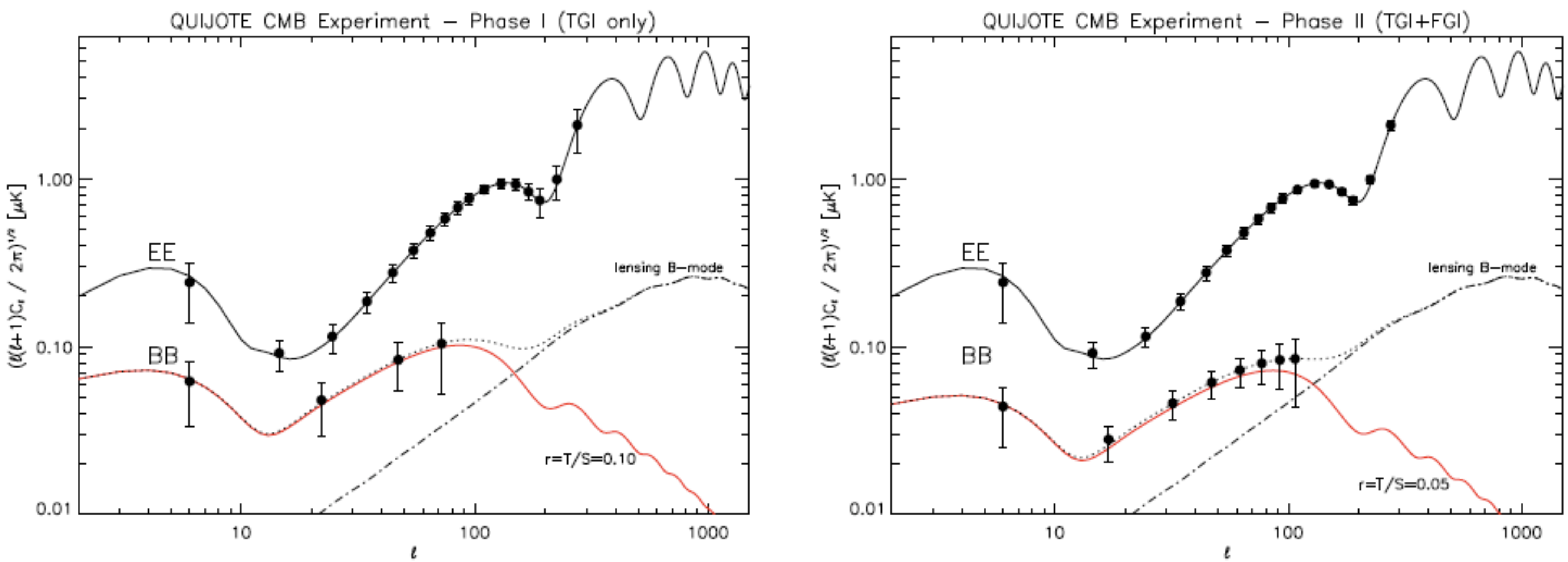
- Highly non-Gaussian feature found in WMAP data (Vielva et al. 2004)
- Possible explanation: cosmic texture in the primordial universe (Cruz et al. 2007)



★ Study of the polarization of the North Polar Spur, and of other filaments emerging from the Galactic plane

★ Catalogue of polarized point sources

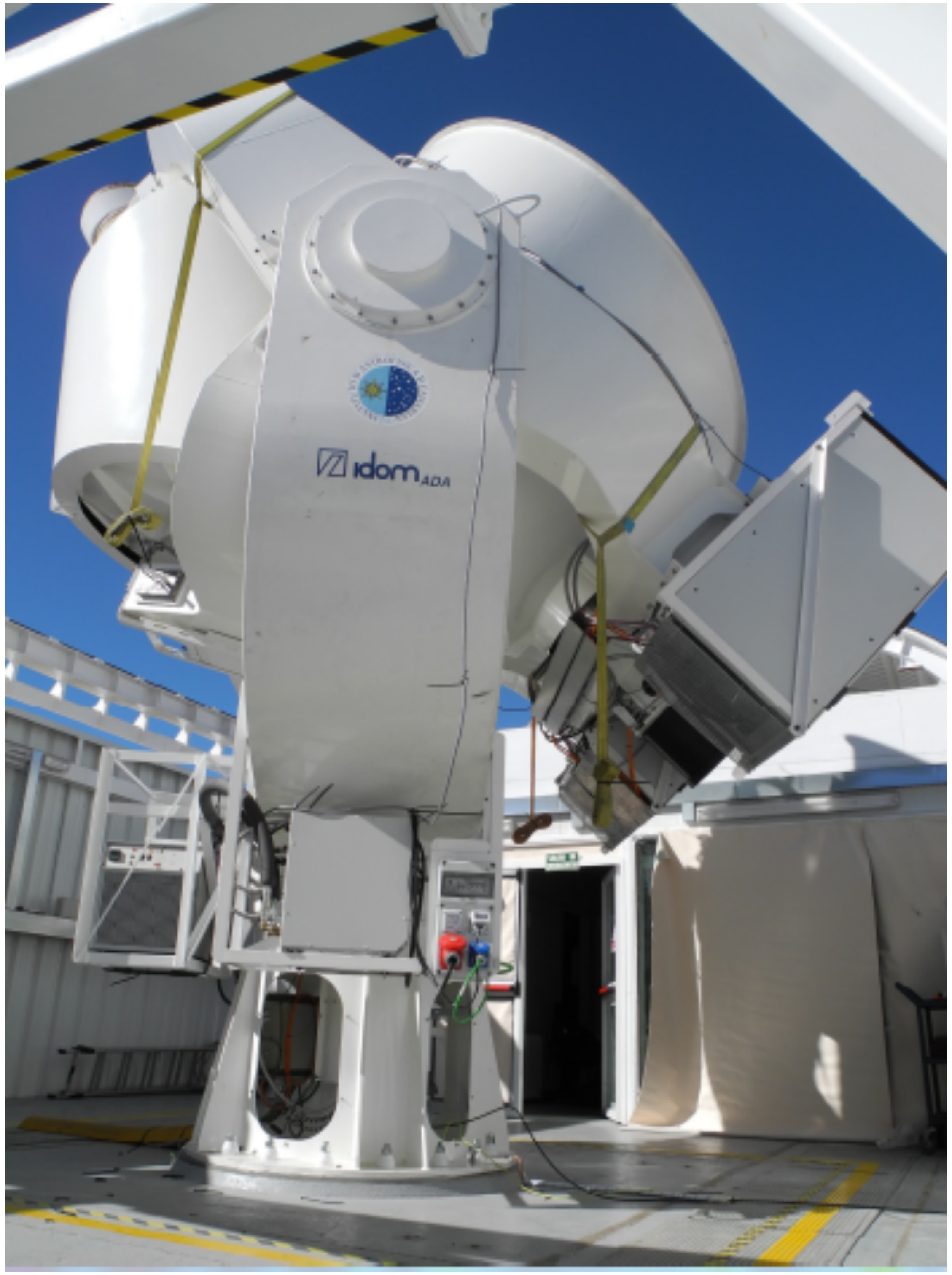
Science with the TGI and FGI



★ **Left**: example of the QUIJOTE-CMB scientific goal after the Phase I. It is shown the case for 1 year (effective) observing time with the TGI, and a sky coverage of 3,000 deg^2. The red line corresponds to the primordial B-mode contribution in the case of **r = 0.1**

★ **Right**: QUIJOTE-CMB 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 observations status



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 loop (~1hr)
    - Fan region (> 135 hrs)
    - Perseus molecular cloud (>125hrs)

Science phase
(April 2013 - now)

- Wide survey (1500h; will repeat this)
- Cosmological fields (1400h)
- Daily calibrators (Crab, Cas A, Jupiter, sky dips)
- 3C58 in the Fan region (25h)
- Galactic Haze (200h)
- Perseus molecular cloud
- Some faint point sources (3C273, NGC7027,..)

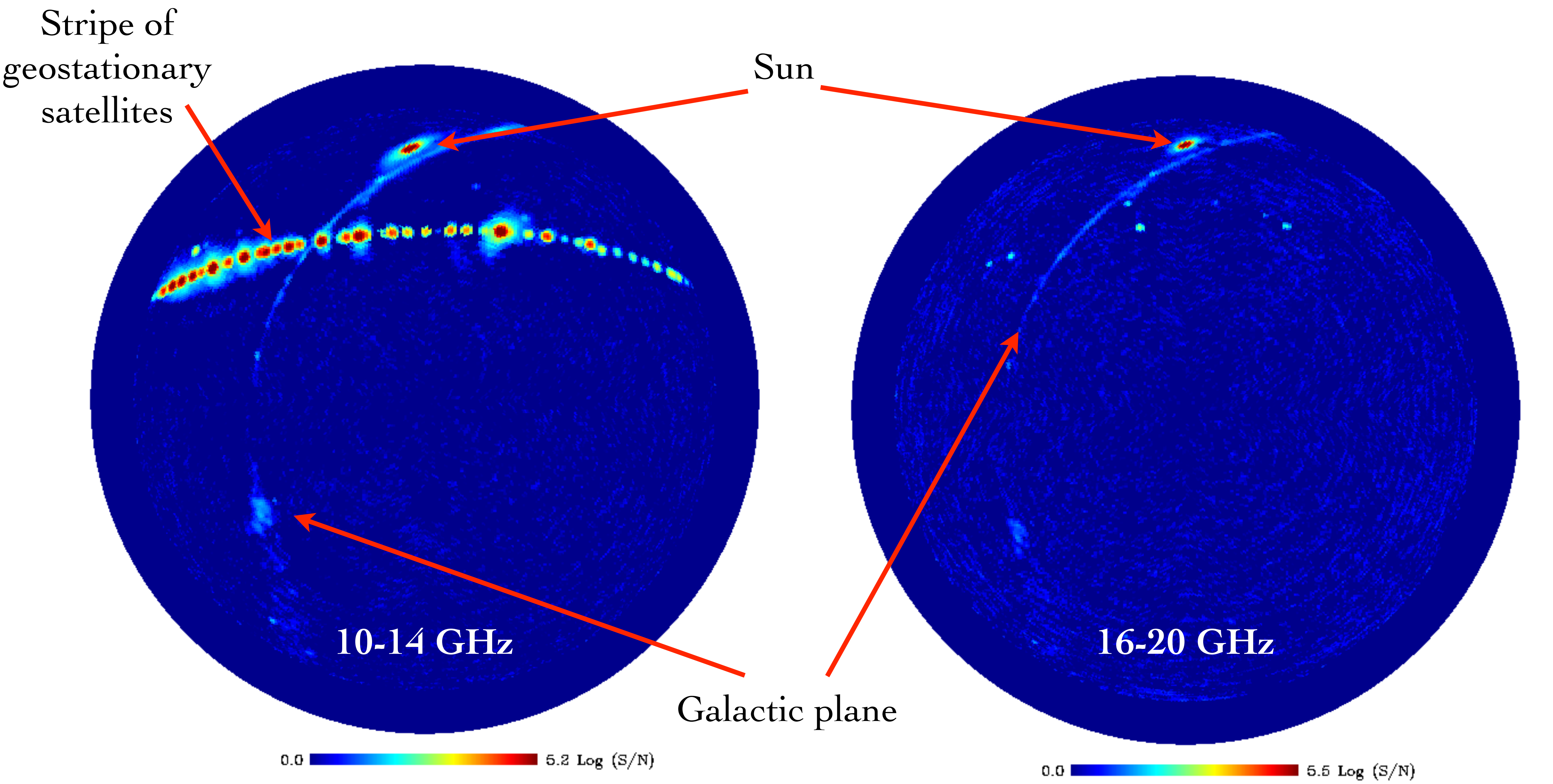
Observing efficiency **~ 85%** (including bad weather & technical problems).

Local interference maps

★ Study the local radio contamination around the telescope

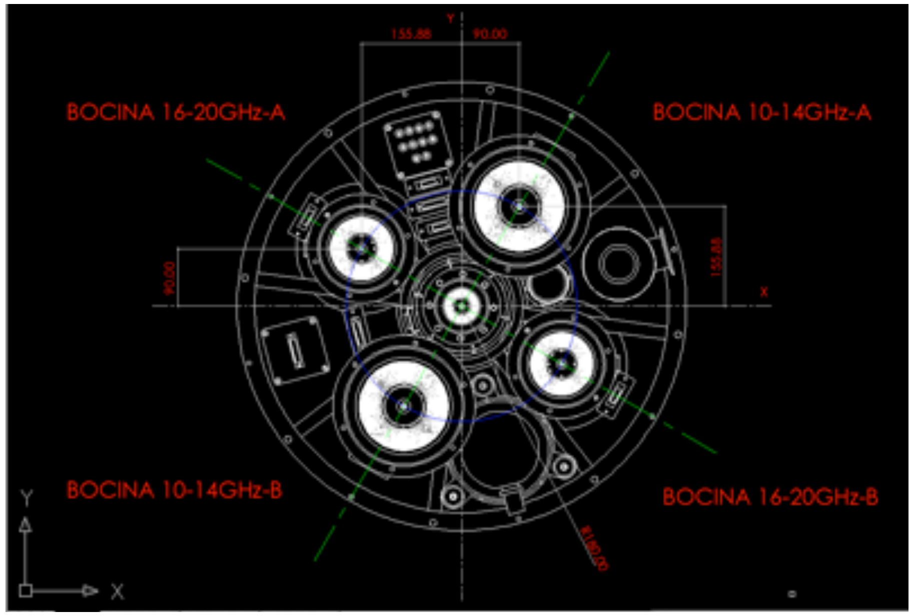
★ Uses nominal mode, and it represents local coordinates centred in the zenith (N is bottom, E is left). A full map is produced in 3h, covering elevations from 30 to 90º, with steps of 0.2º, and telescope velocity of 4º/s

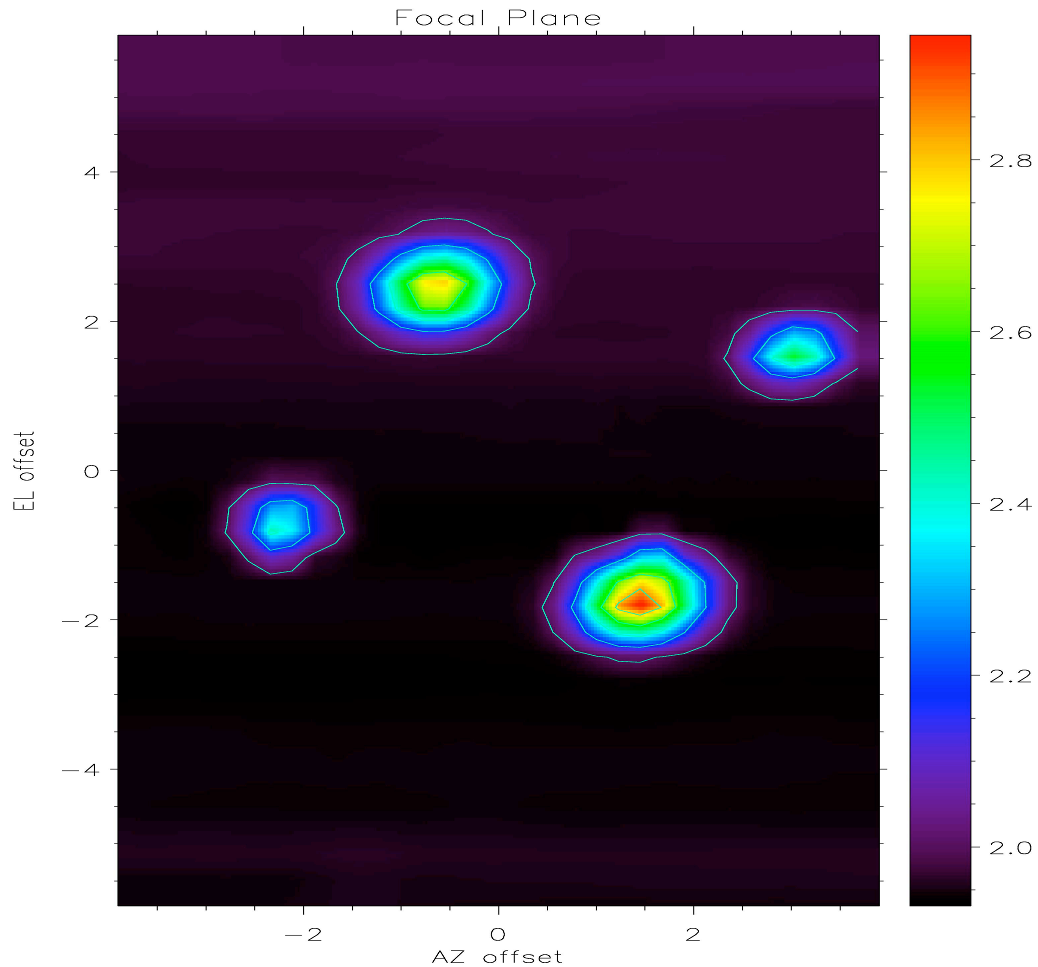
★ The following maps were produced on Dec 27th, 2012



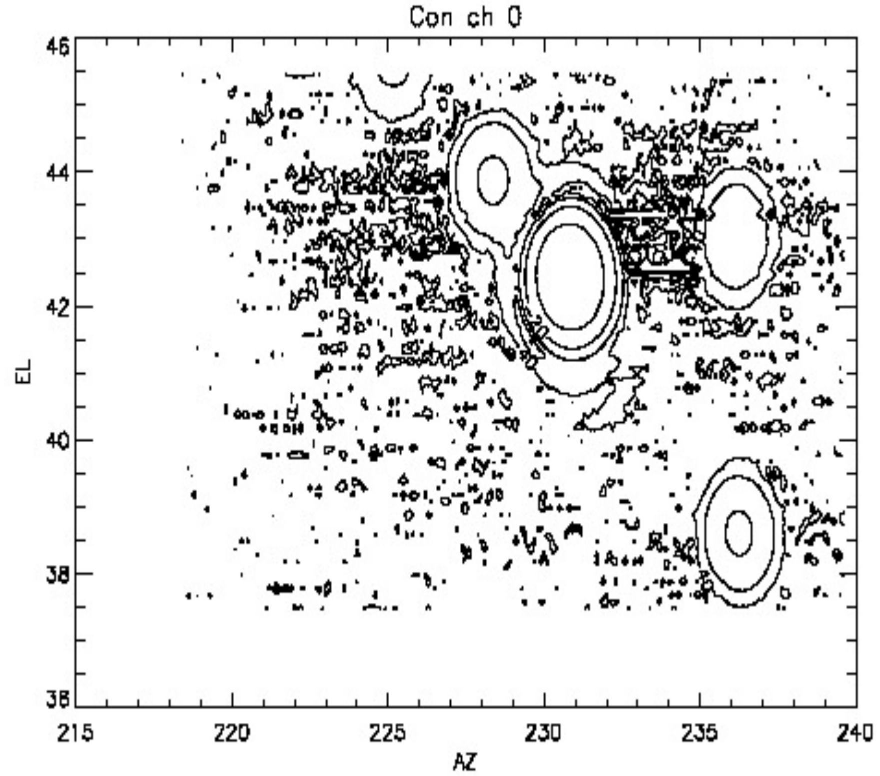
Focal plane and beams

★ MFI focal plane from Moon observations





★ Geostationary satellites at δ~0° ⇒ first sidelobes below -30 dB



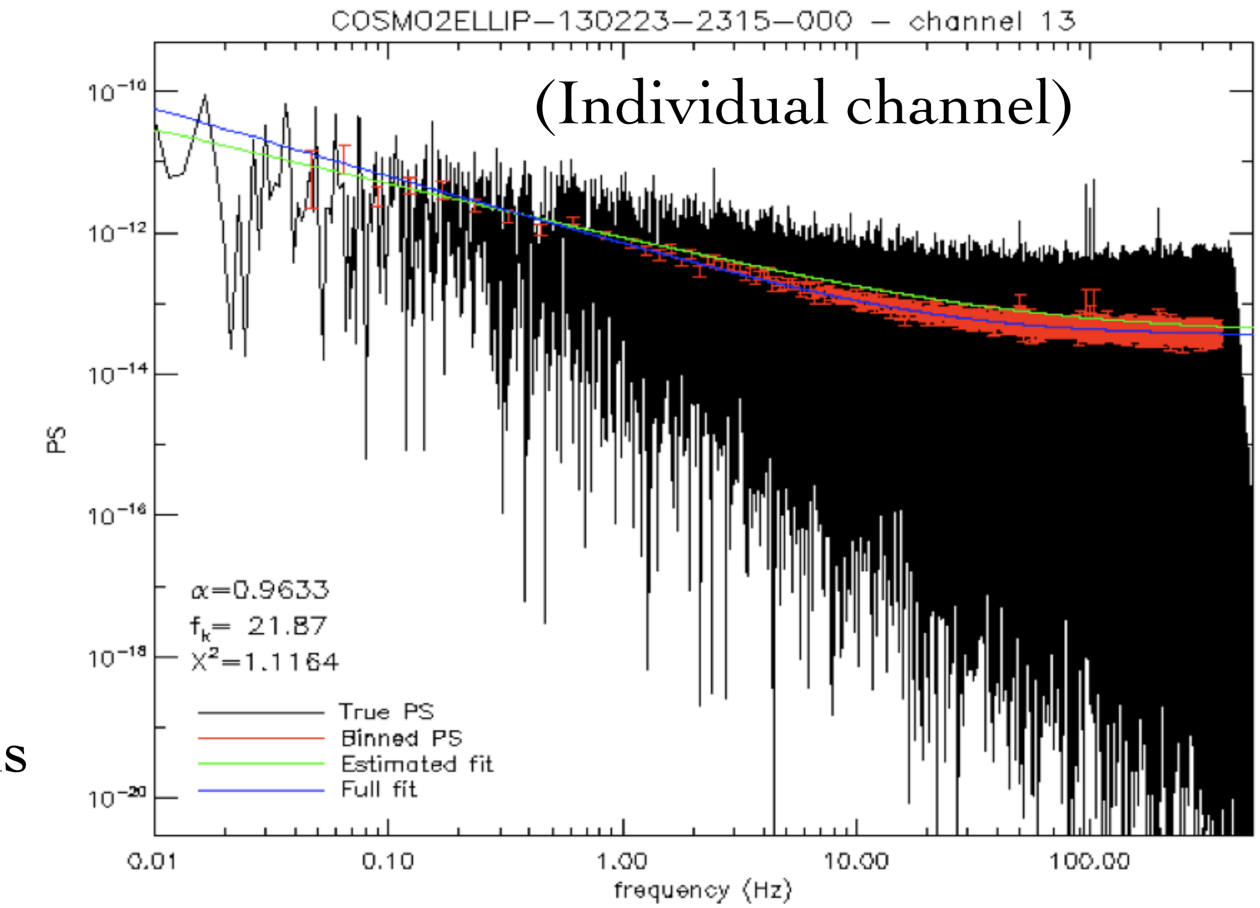
★ Beam main-lobe FWHMs:

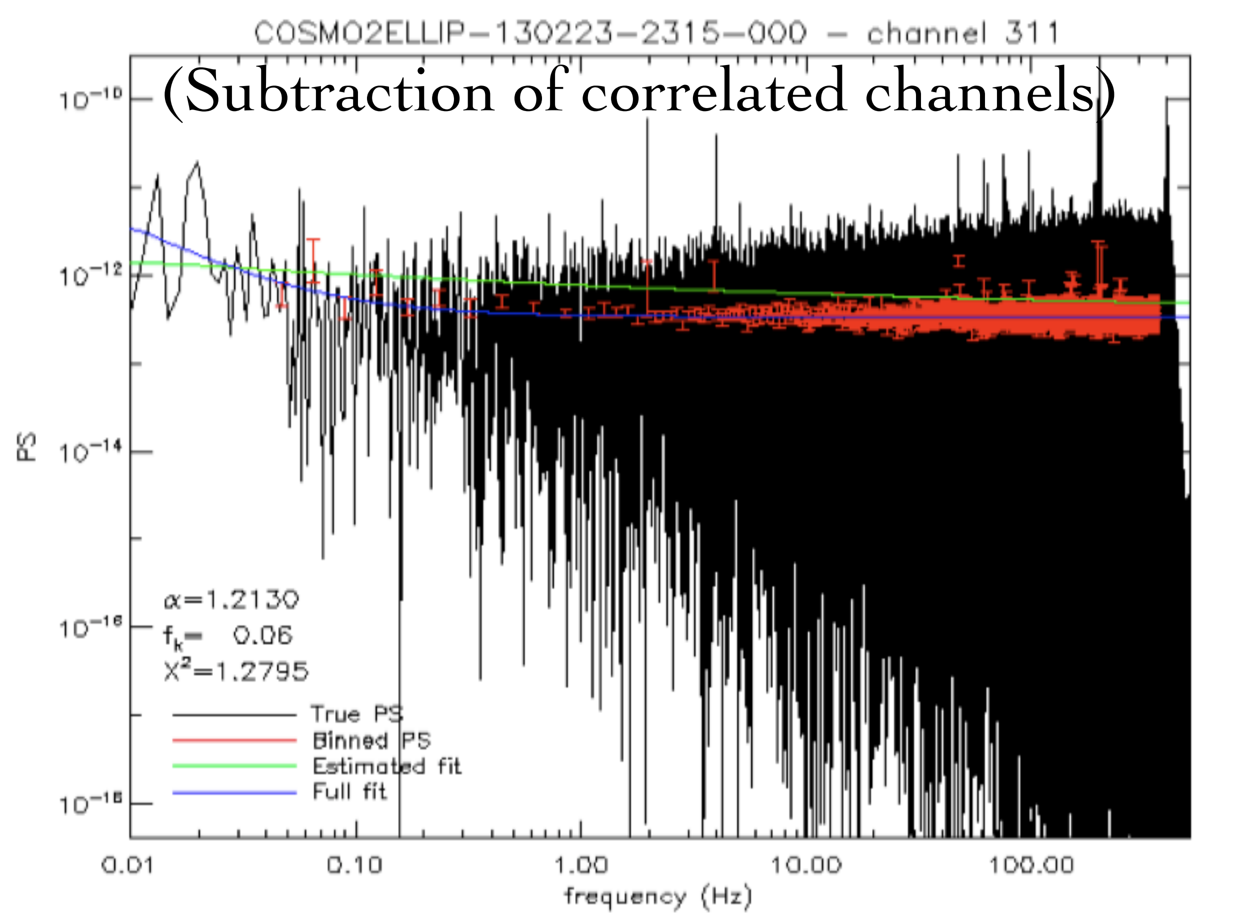
Horn	FWHM AZ (deg)	FWHM EL (deg)
1 - 11 GHz	0.89	0.88
1 - 13 GHz	0.89	0.89
2 - 19 GHz	0.66	0.67
3 - 11 GHz	0.81	0.85
3 - 13 GHz	0.82	0.88
4 - 19 GHz	0.63	0.66

Noise properties

★ MFI noise characterization:

- Noise power spectrum is measured using long observations on blank fields
- 2 Hz signal + harmonics that could be caused by the coolying system frequency. It is also present a 50 Hz signal
- The anti-aliasing filter cuts off at > 400 Hz
- The 1/f noise knee-frequency (in intensity) is typically ~10-20 Hz
- When subtracting correlated channels the knee-frequency is consistently reduced down to around 100 mHz

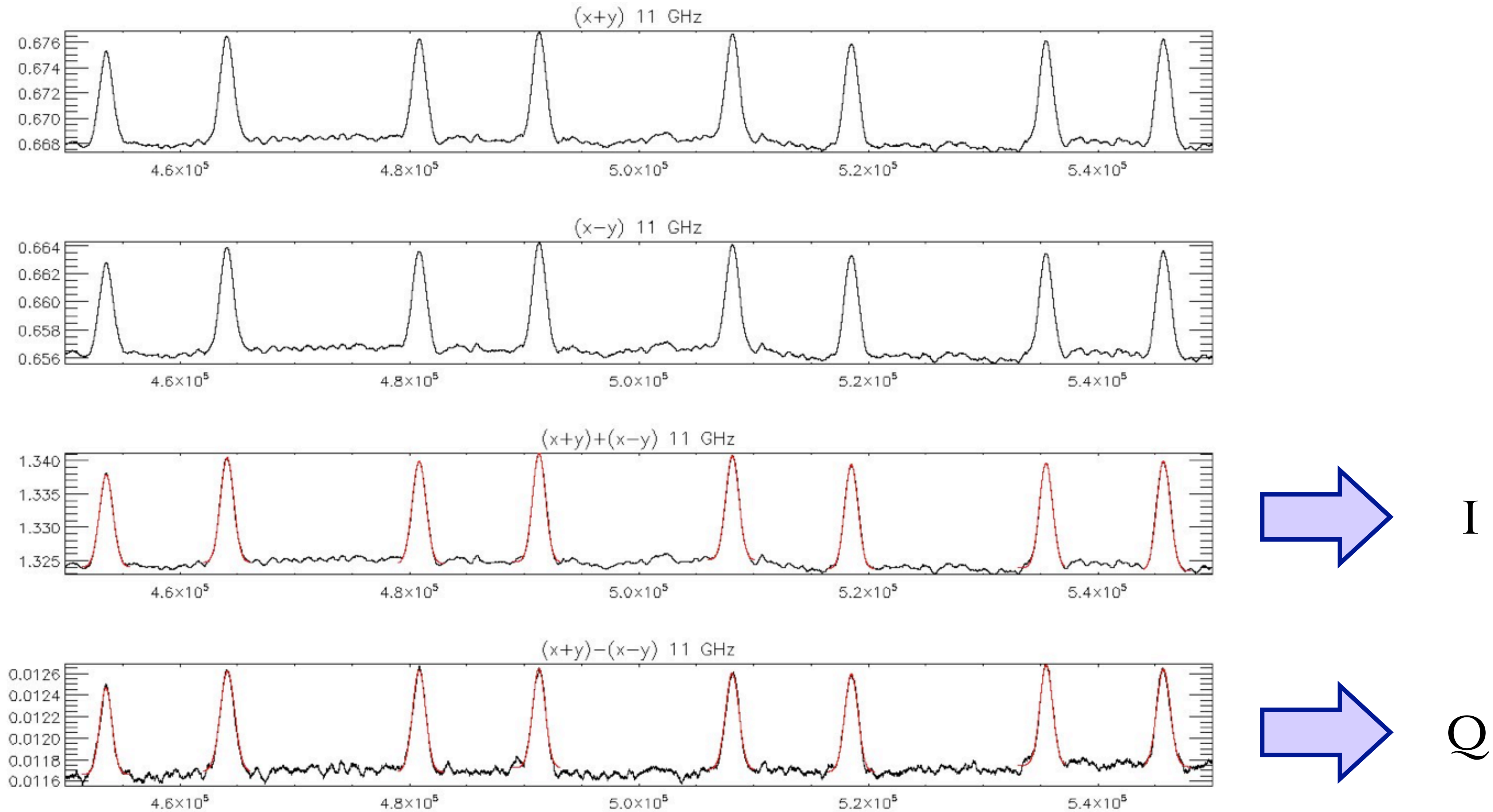




Calibrators

★ Crab observation:

- AZ scans at 1 deg/s (1 second on source)
- Modulators fixed at 22.5º

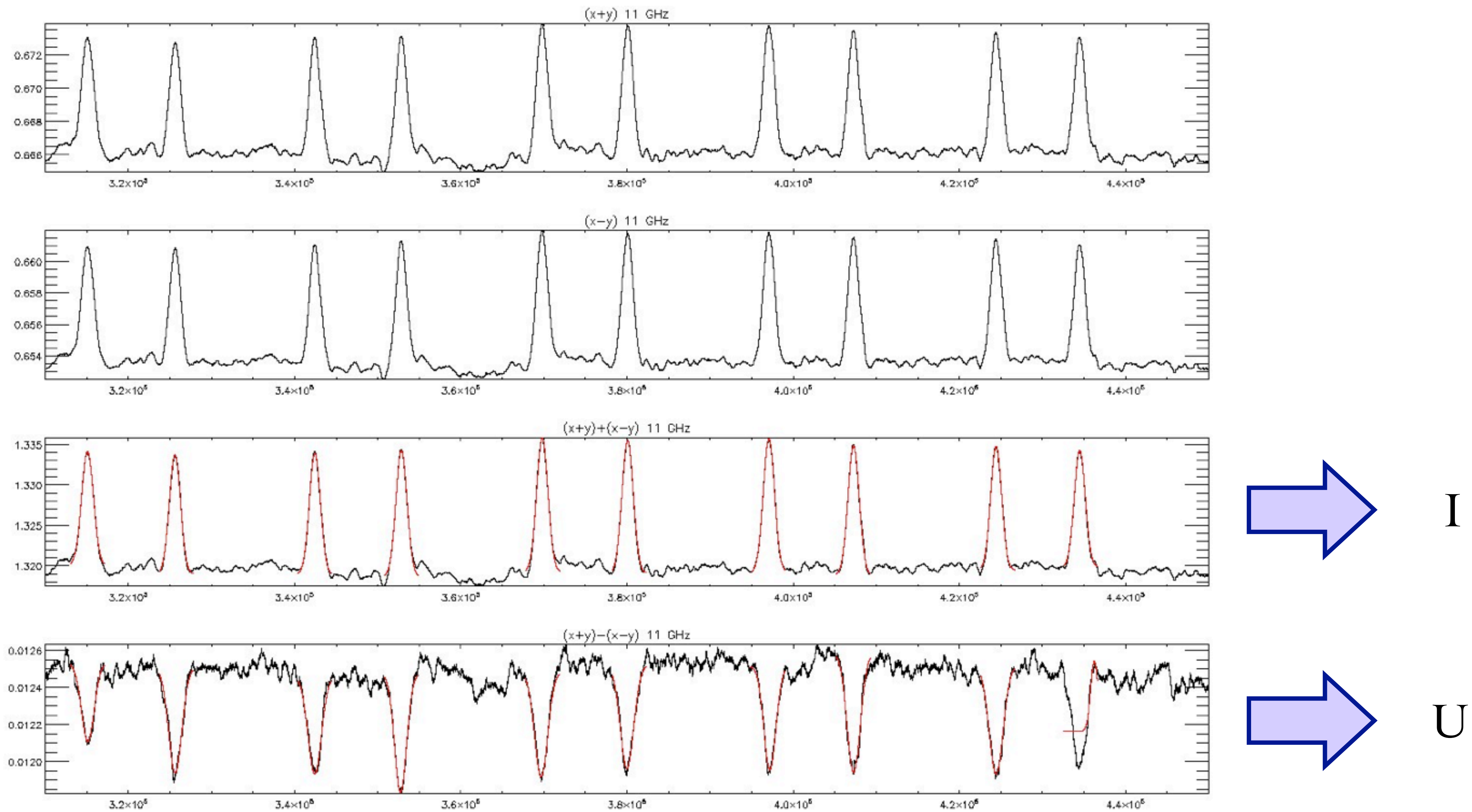


<Q/I> = 5.79±0.2 %

Calibrators

★ Crab observation:

- AZ scans at 1 deg/s (1 second on source)
- Modulators fixed at 0º

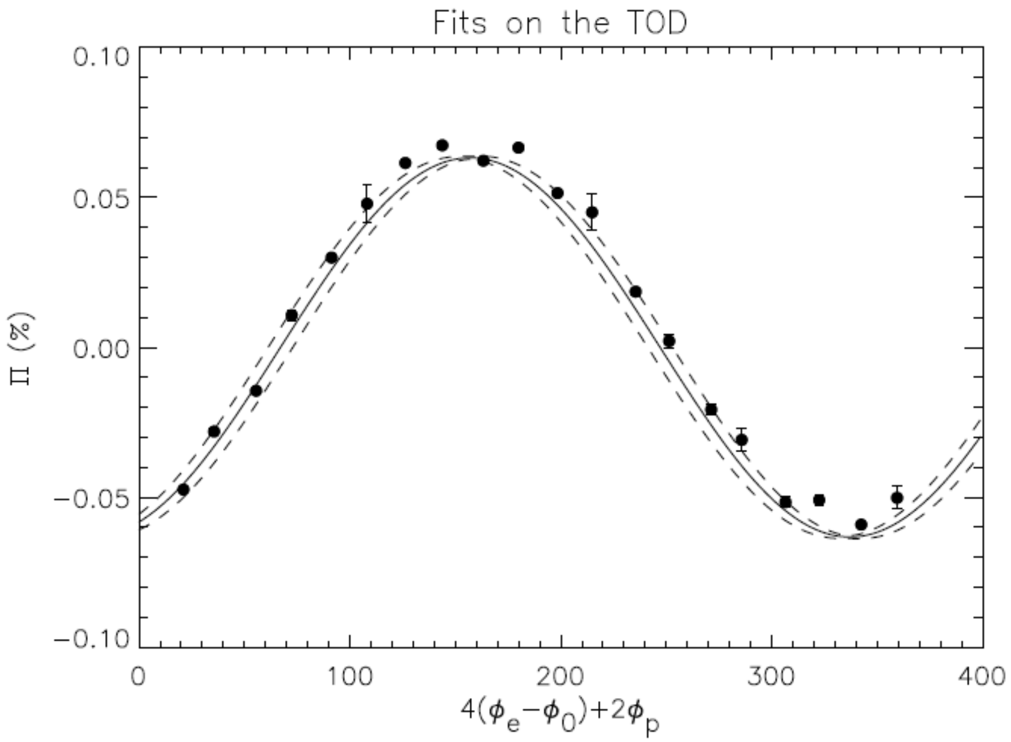


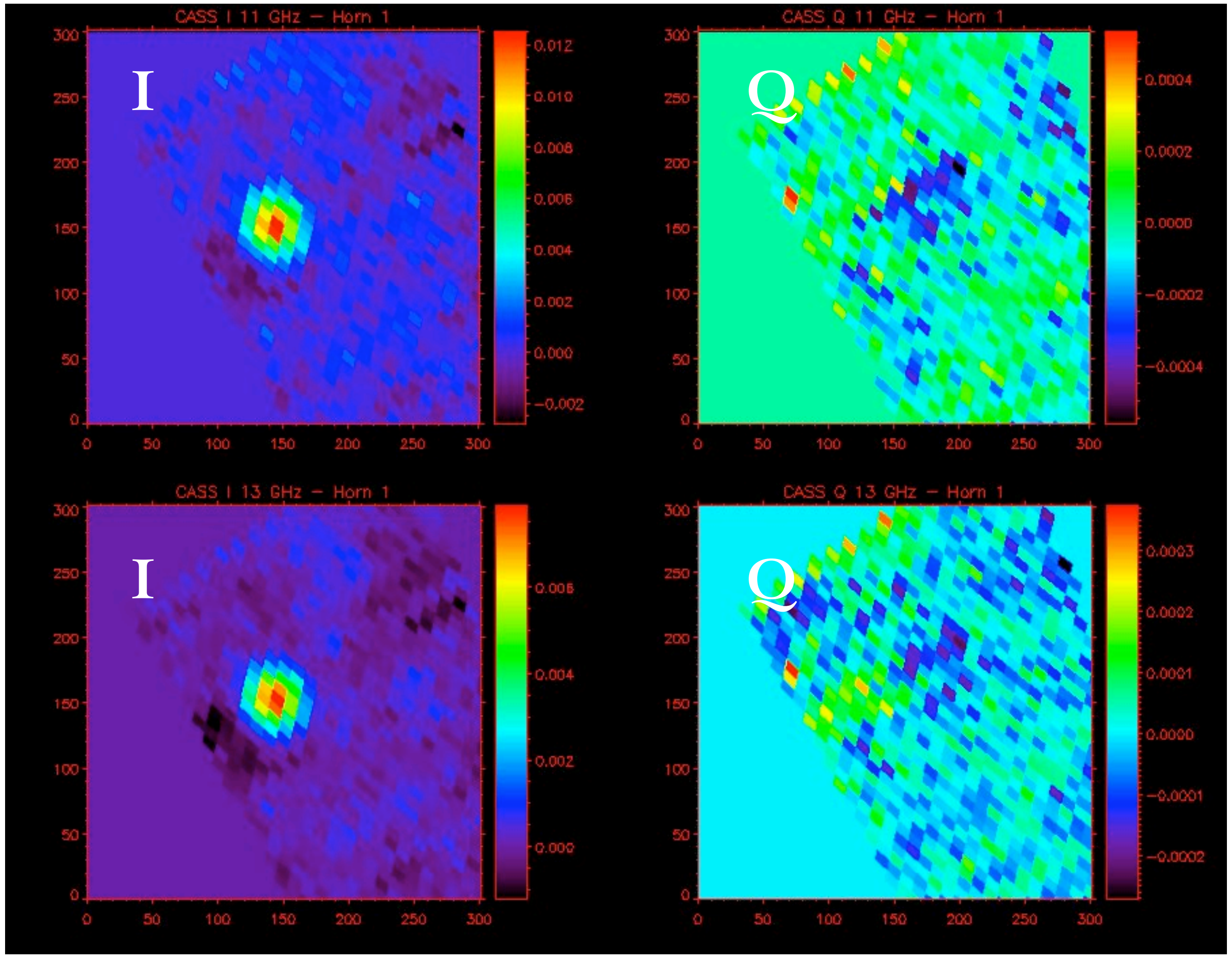
<U/I> = -3.60±0.4 %

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

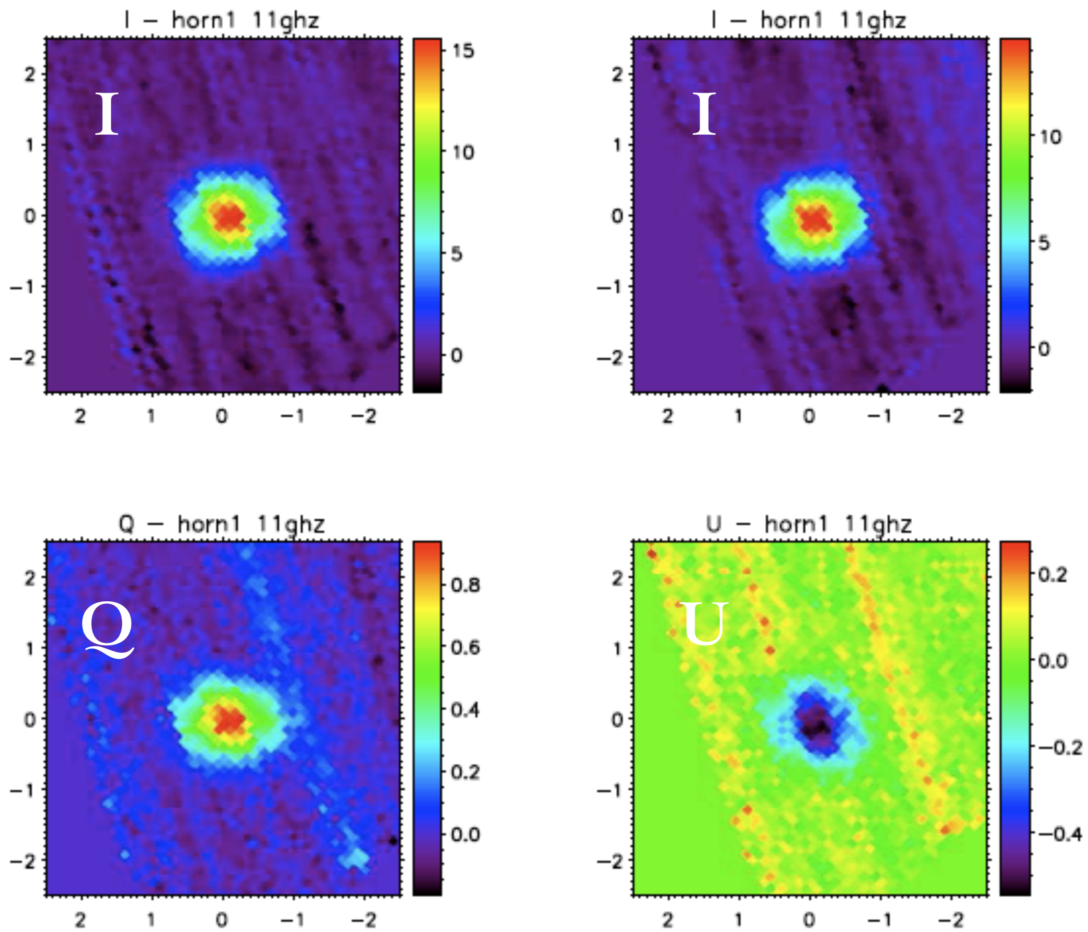
Calibrators

- Crab (Π=7%) - polarization angle calibrator
- Cas-A (Π=0.7%) - null polarization calibrator to adjust the gain mismatch between pairs of channels





Cas A observation (30 s on source)

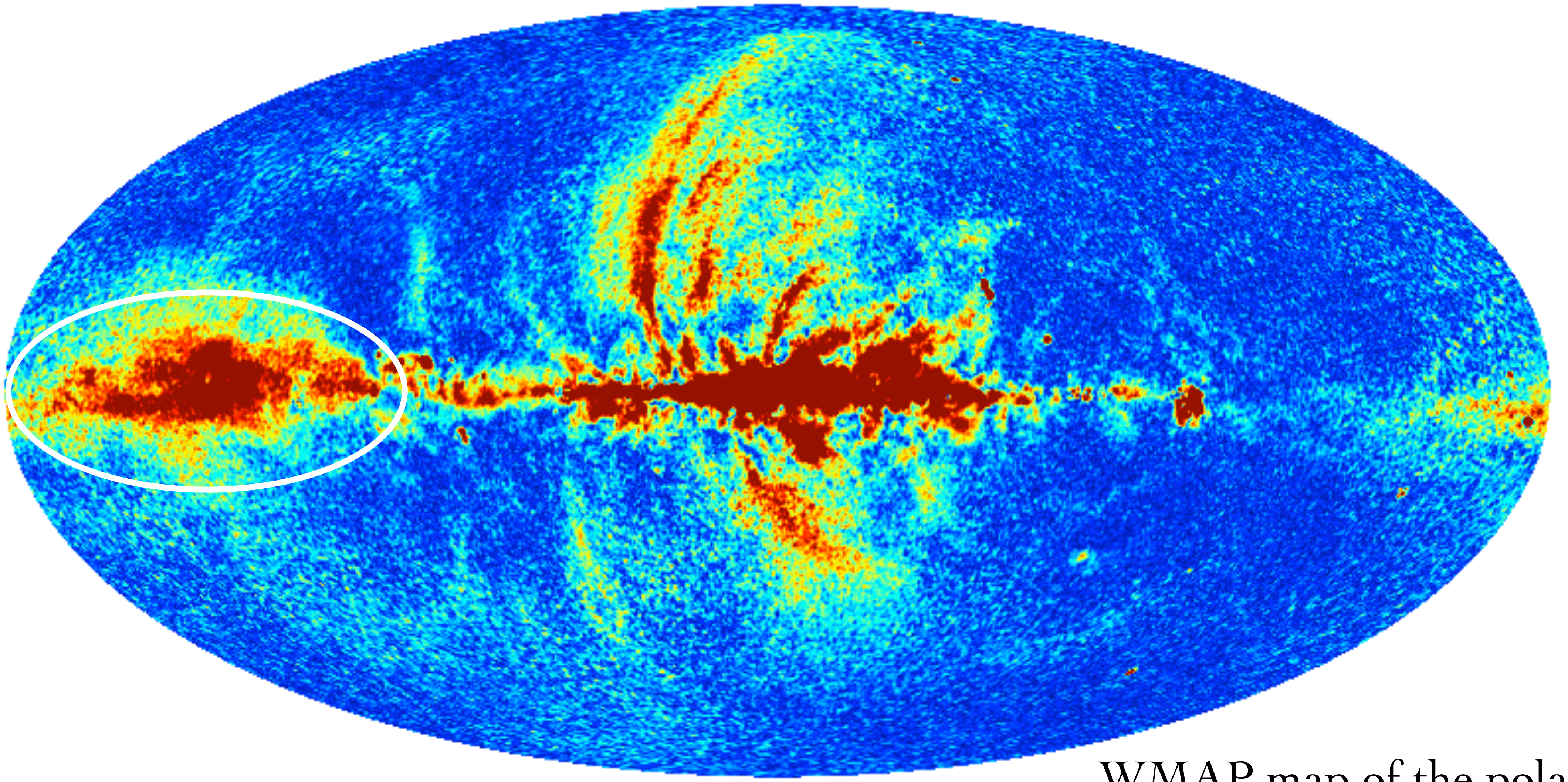


Crab observation (30 s on source)

Fan

★ Large observation program (~130 hours), on an area covering ~300 deg^2 located on the Fan region.

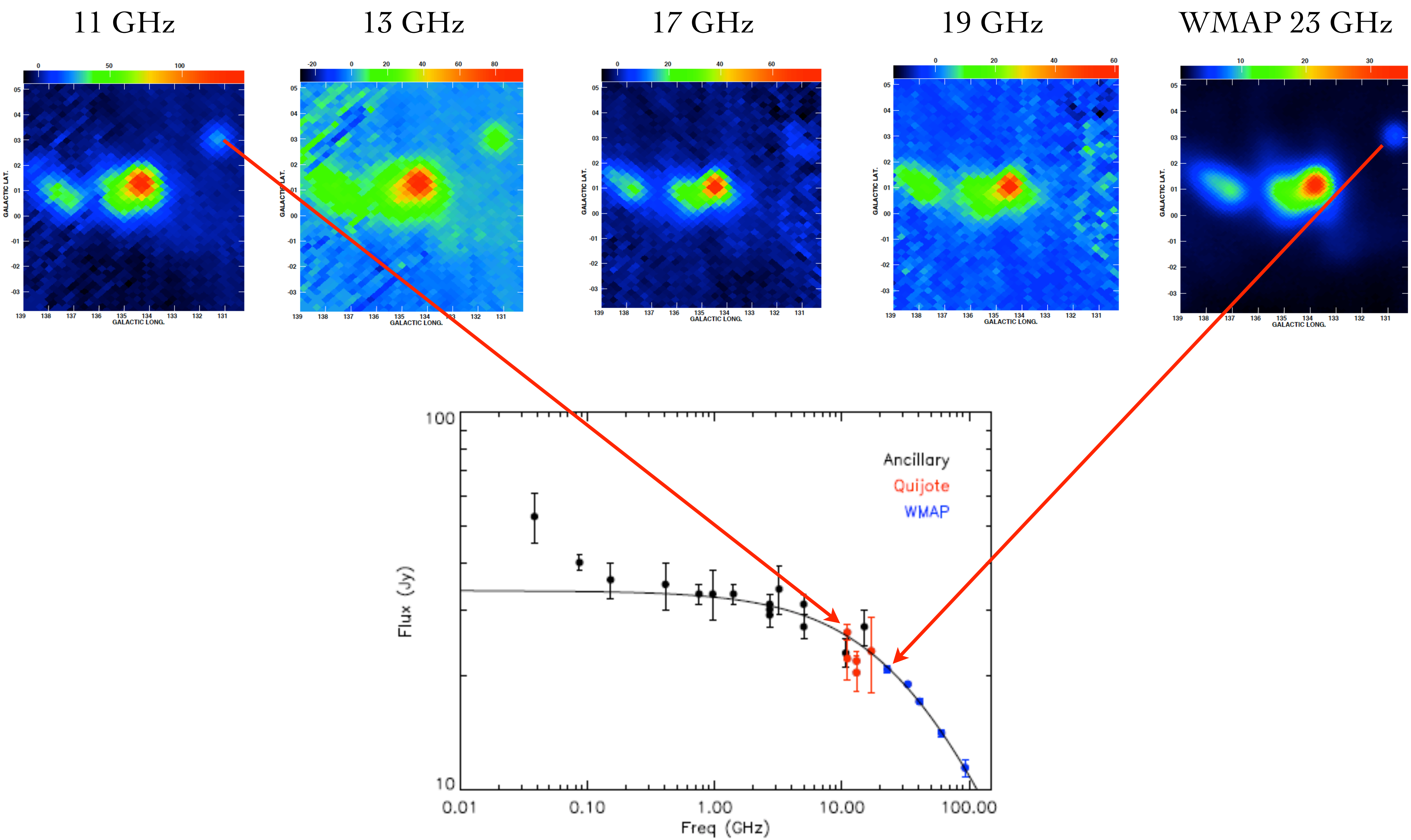
★ One of the regions in the Galactic plane with bright diffuse polarized emission



WMAP map of the polarized intensity at 23 GHz

Fan

★ QUIJOTE observations of 3C58, a bright SNR with a curved synchrotron spectrum



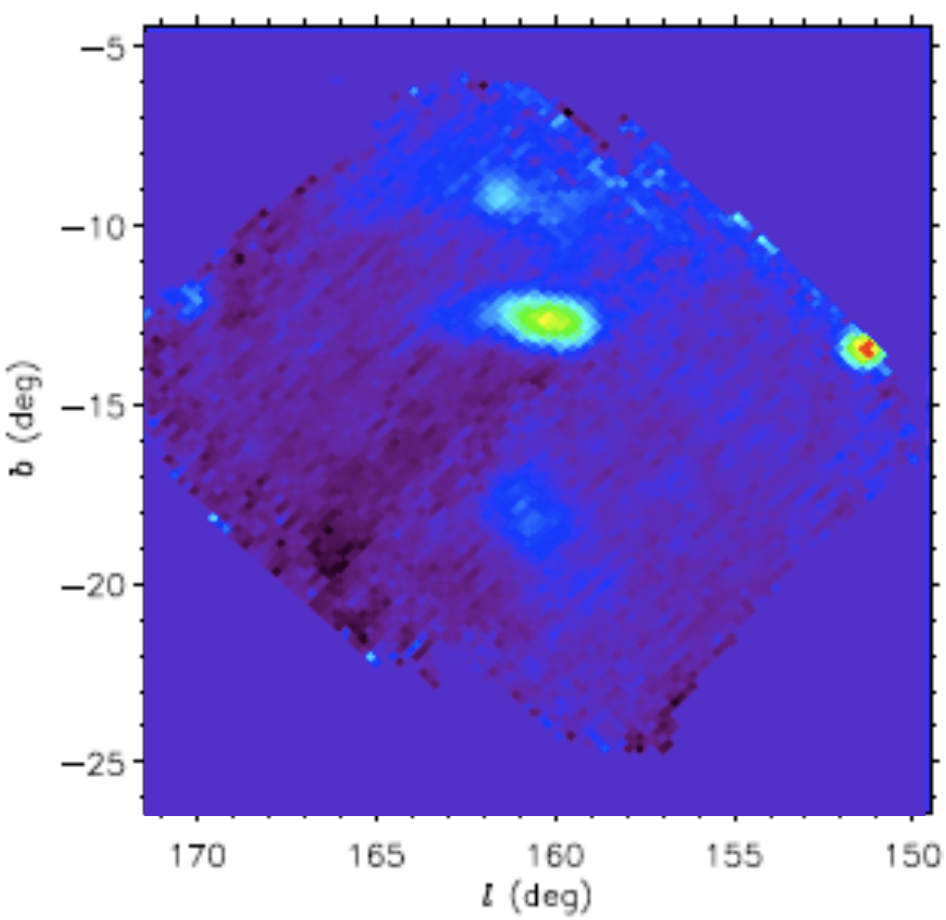
Perseus molecular complex

★ Large observation program (~132 hours, 12/2012 to 04/2013), on an area covering ~200 deg^2 around the Perseus molecular complex. One of the brightest AME regions on the sky (Watson et al. 2005, Planck collaboration 2011)

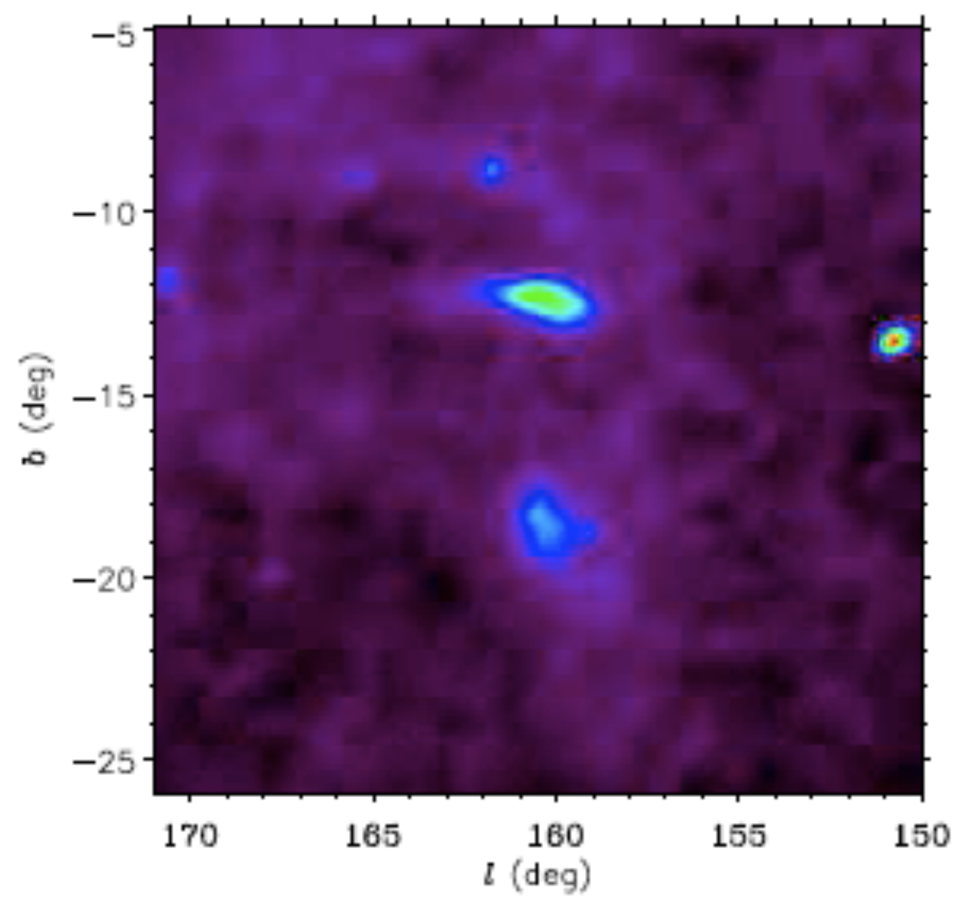
★ Also covering the California nebula (HII region - null polarization control region)

★ Final integration time of ~ 3300 s/beam, yielding a sensitivity of ~ 30 mJy/beam in Q and U

Quijote 11 GHz



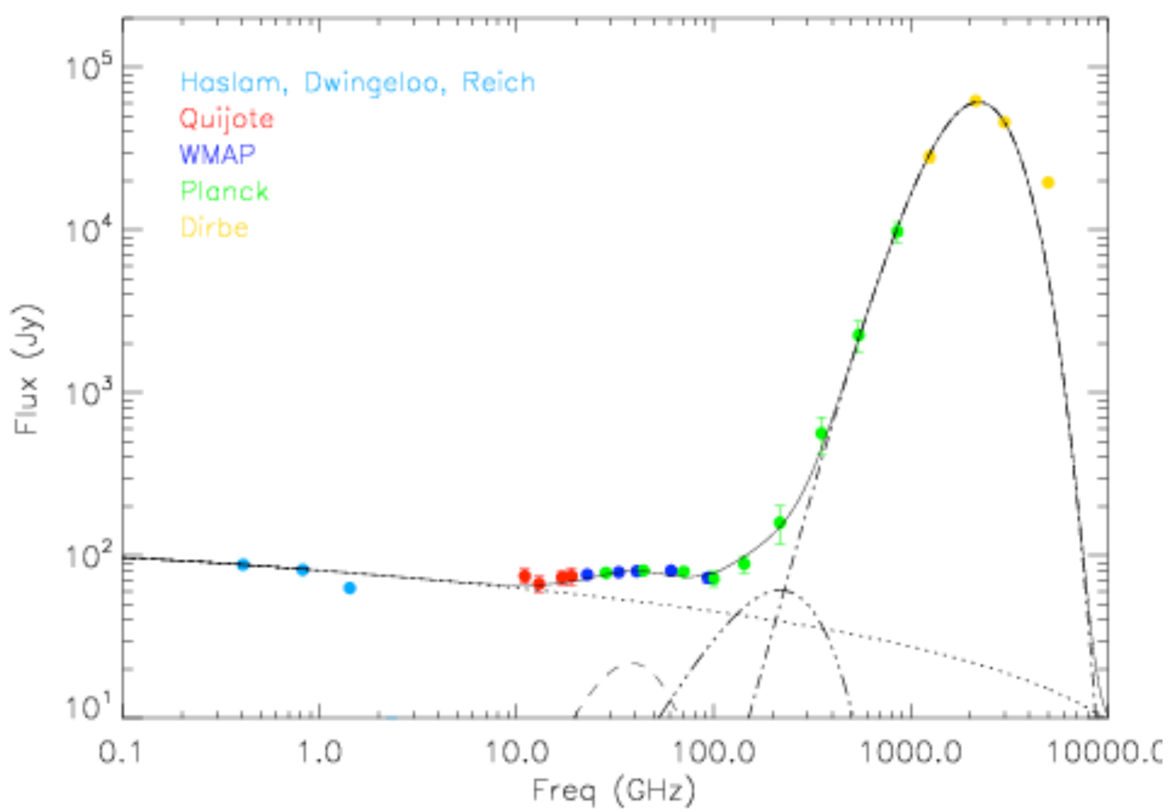
Planck 30 GHz

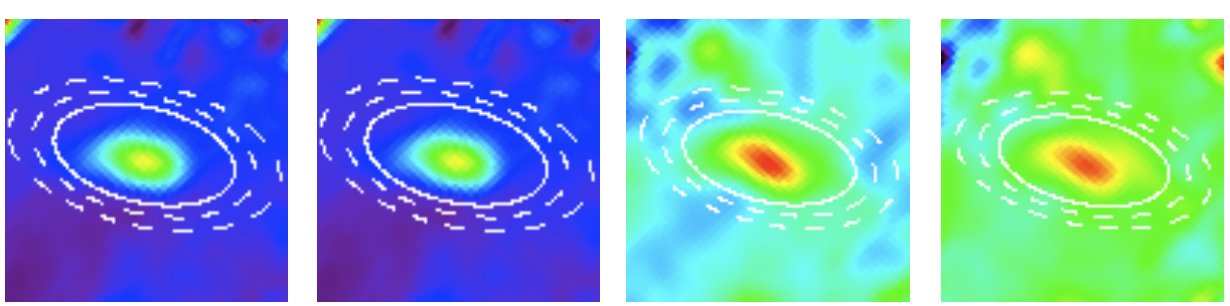


Perseus molecular complex

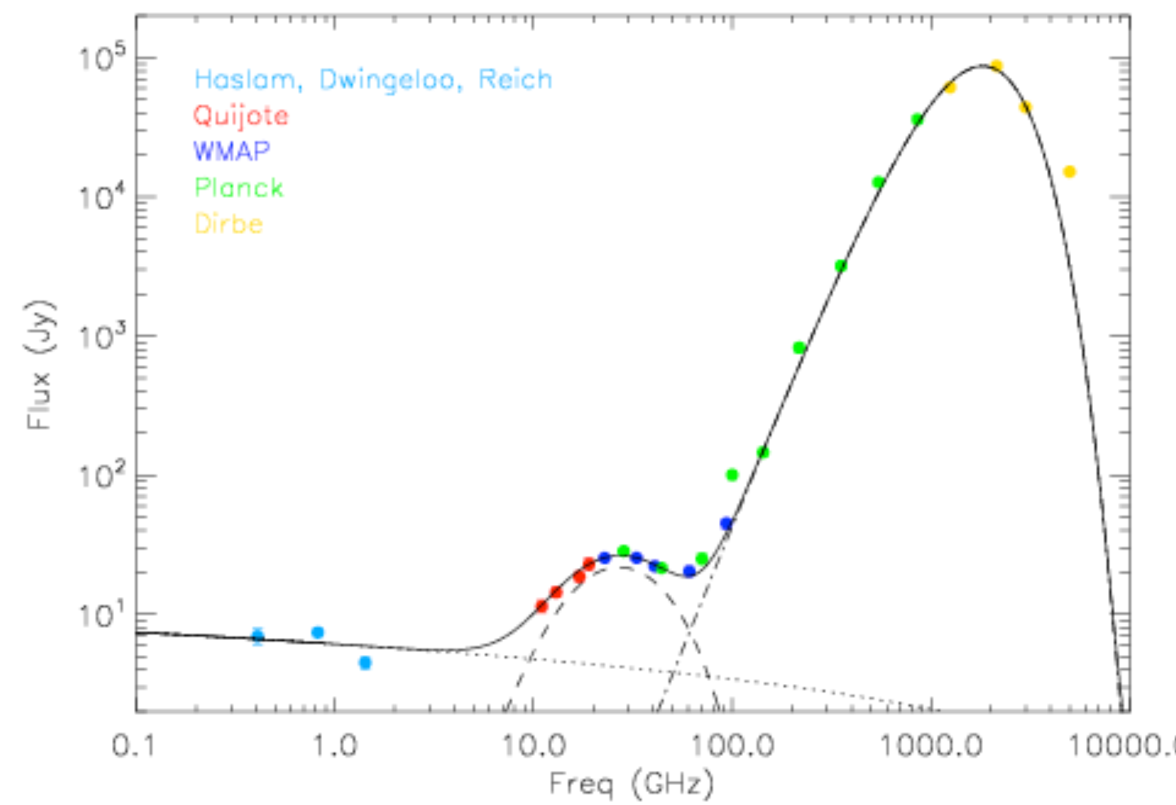
★ Spectral energy distributions (SEDs) of the Perseus molecular complex and of the nearby California (NGC1499) HII region:

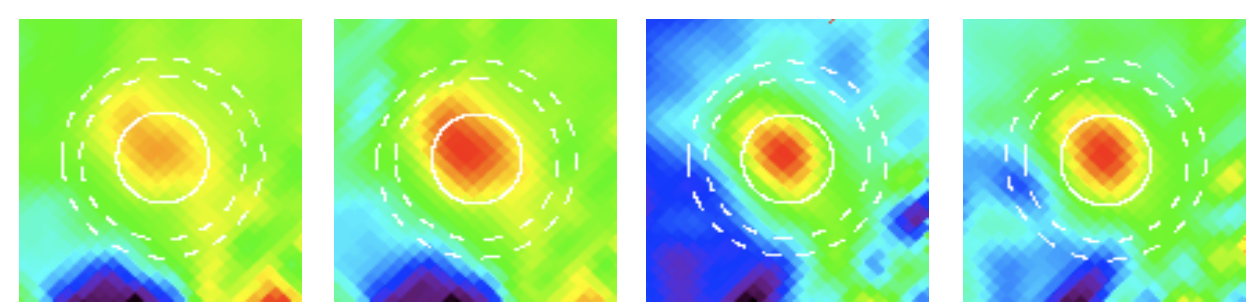
California HII region





Perseus G160.26-18.62

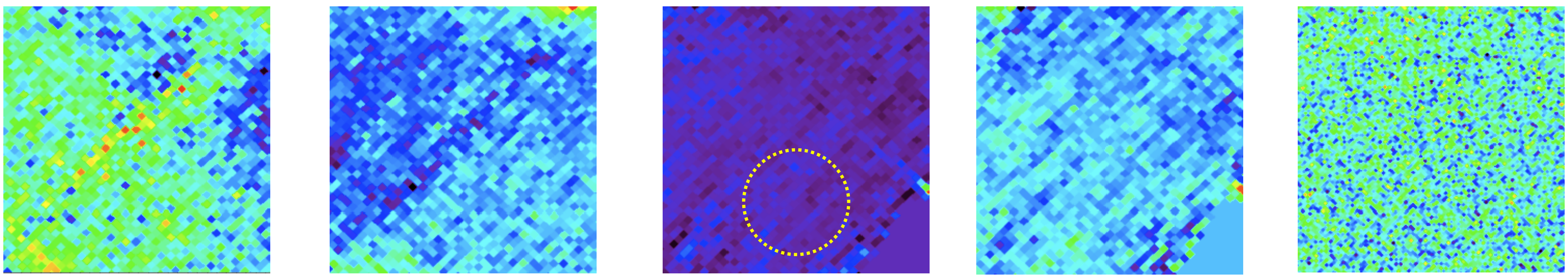




Perseus polarization maps

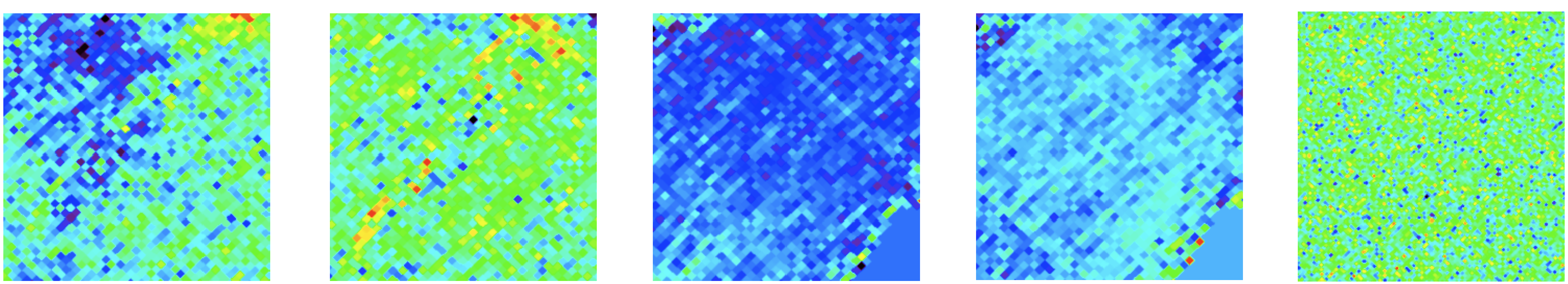
Q maps

11 GHz | 13 GHz | 17 GHz | 19 GHz | WMAP 23 GHz



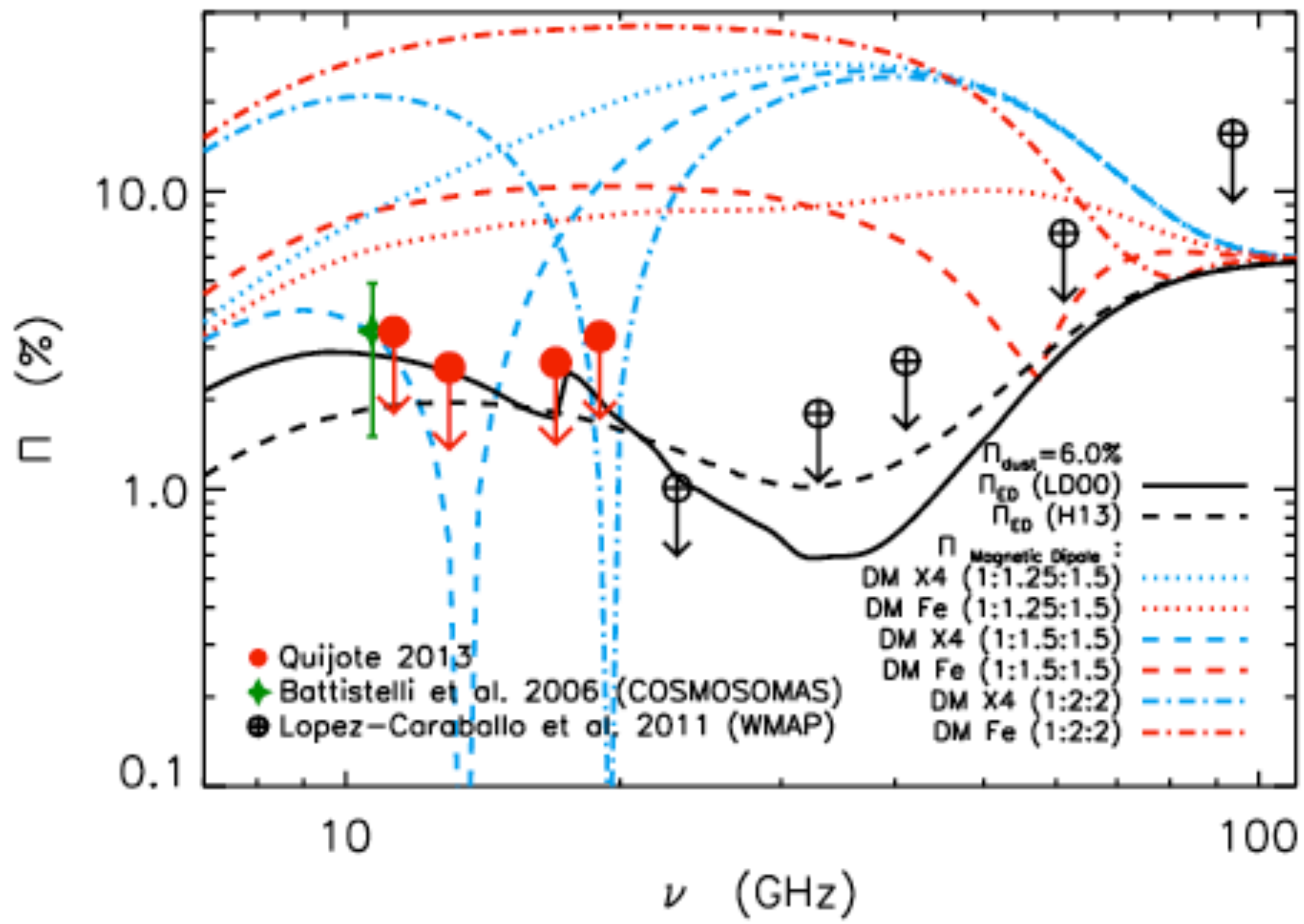
U maps

11 GHz | 13 GHz | 17 GHz | 19 GHz | WMAP 23 GHz



Perseus polarization upper limits

ν (GHz)	I (Jy)	Q (Jy)	U (Jy)	P (Jy)	$P_{\rm db}$ (Jy)	Π (%)	$\Pi_{\rm db}$ (%)
11	11.4 ± 1.1	0.12 ± 0.23	-0.075 ± 0.27	0.14 ± 0.24	< 0.27	1.26 ± 2.11	< 2.35
13	14.4 ± 1.1	-0.05 ± 0.22	-0.19 ± 0.27	0.19 ± 0.27	< 0.29	1.34 ± 1.87	< 1.98
17	18.7 ± 1.6	-0.10 ± 0.42	-0.19 ± 0.46	0.21 ± 0.45	< 0.47	1.14 ± 2.43	< 2.49
19	22.9 ± 2.4	0.41 ± 0.72	-0.06 ± 0.54	0.42 ± 0.71	< 0.70	1.83 ± 3.11	< 3.05

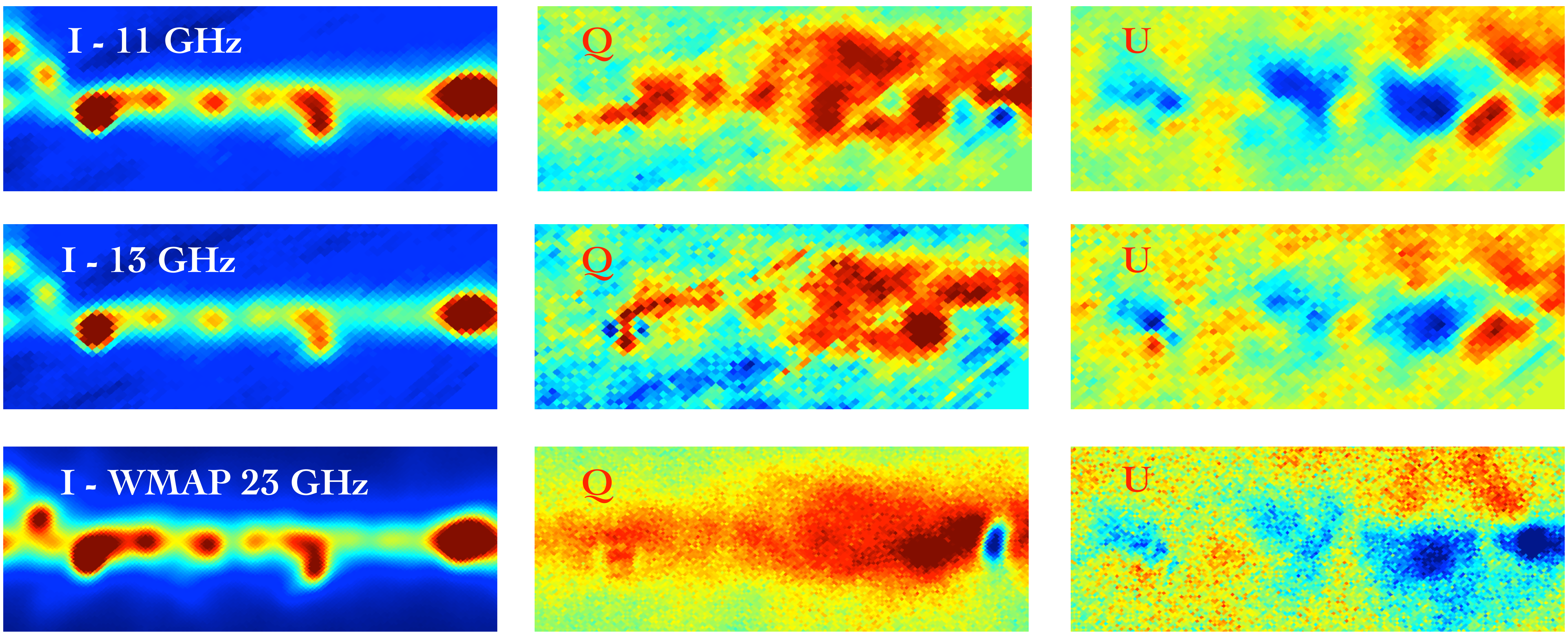


Galactic Haze

★ Large observation program still ongoing (~200 hours, from June until now), on an area covering ~1000 deg^2 around the Galactic centre

★ The goal is to study the polarization of the Galactic Haze emission

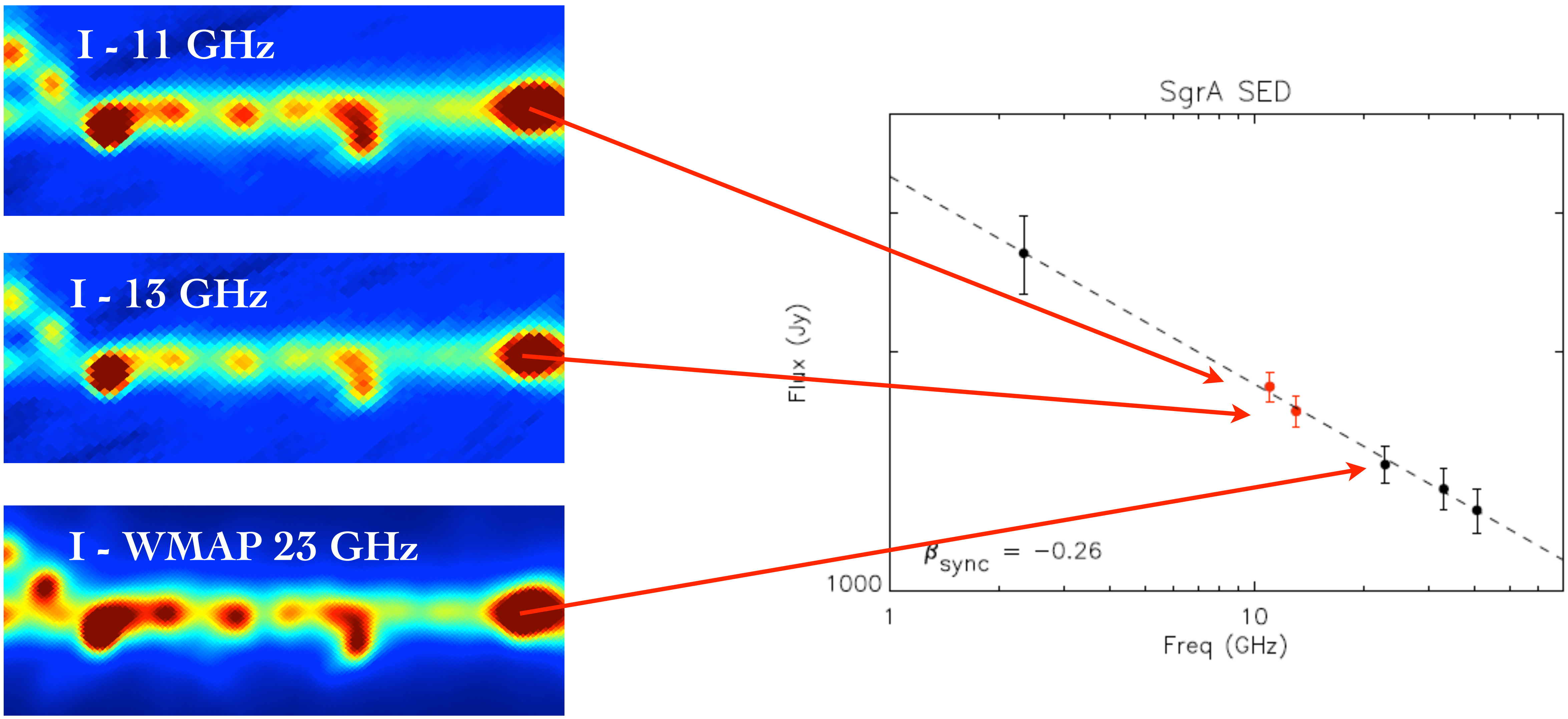
★ Preliminary 11 and 13 GHz maps (20×6 deg^2) of the Galactic plane around the Galactic centre, in comparison with WMAP 23 GHz



★ Quijote maps trace the large-scale polarized emission, but fails to detect polarized emission from Sgr-A (possible Faraday depolarization?)

Galactic Haze

★ Sgr-A intensity spectral energy distribution:



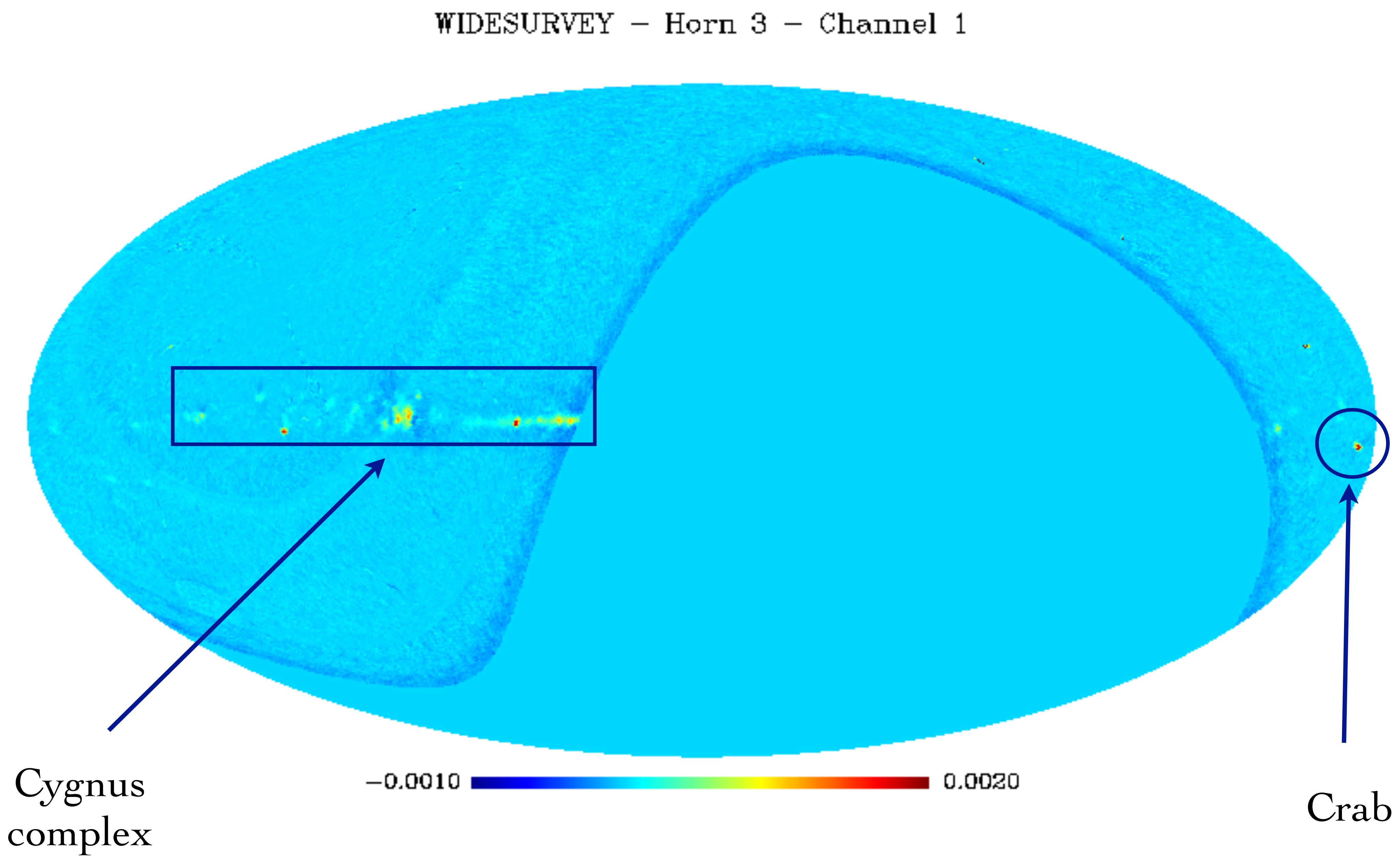
★ Well-defined synchrotron spectrum with spectral index β=-0.26

Wide survey

★ 1500h of a large region of ~20,000 deg^2 of the north sky to study diffuse foreground emission

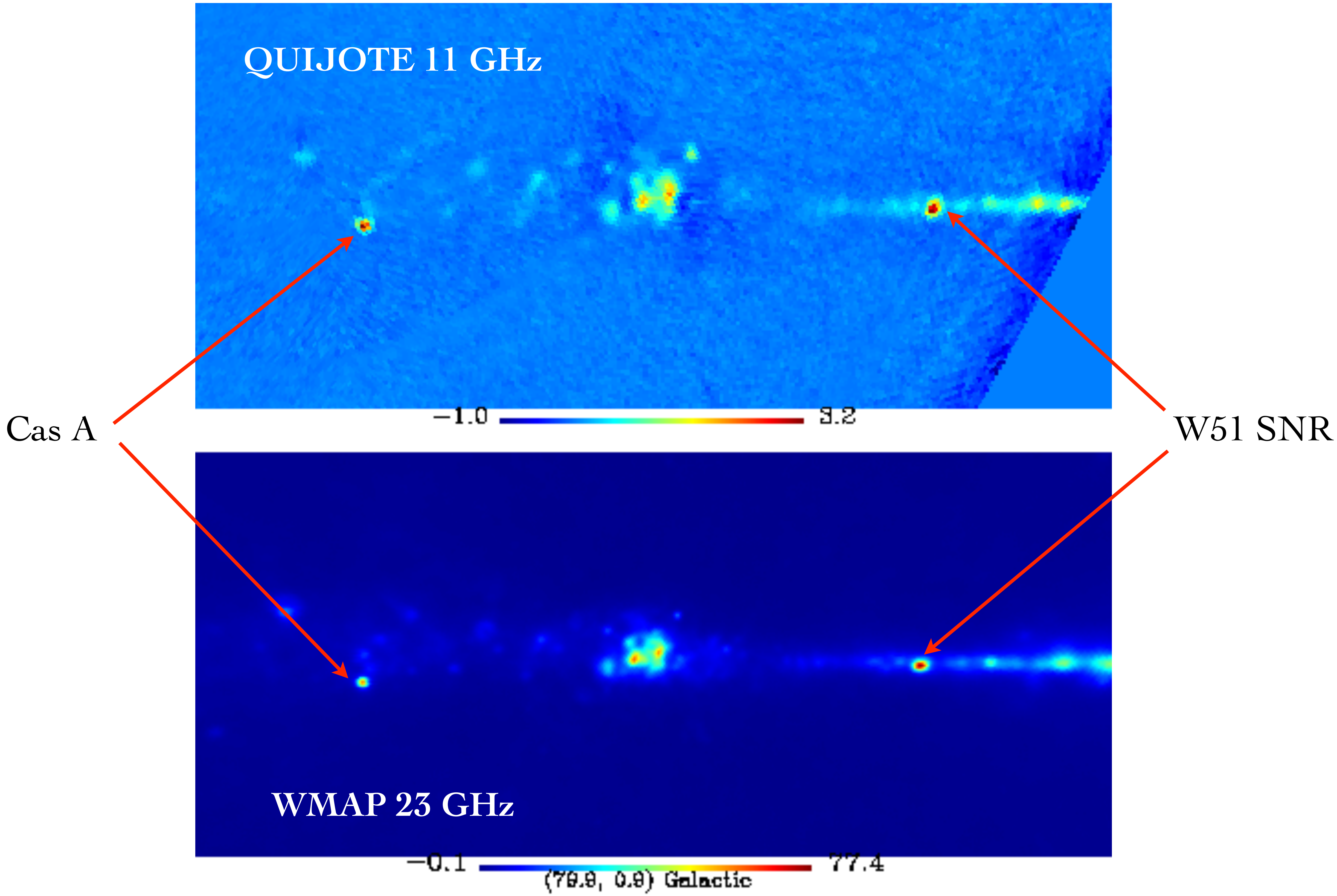
★ Conducted between April and June (65 days of continuous observations). Will repeat the same survey, starting next month

★ Resulting map after stacking ~10 “good" days:



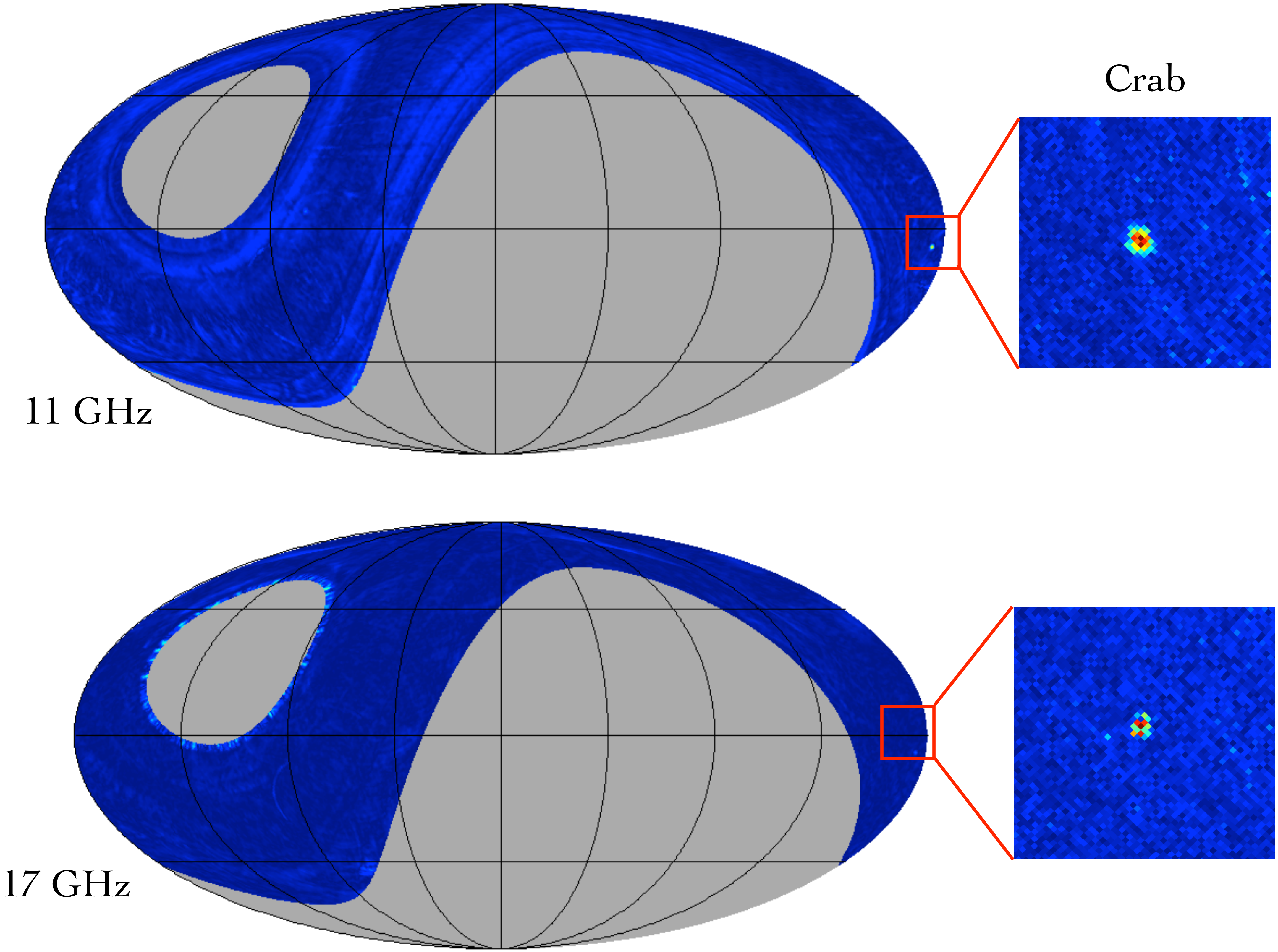
Wide survey

Map of the Galactic plane centre at l=80°



Wide survey

★ First polarization (P) maps from the wide survey (preliminary), obtained combining 8 days of "good" data:



Summary

Dalí 1945

★ QUIJOTE-CMB is a new CMB polarization experiment aimed at characterizing the Galactic emission and B-modes at 10-40 GHz

★ MFI (10-20 GHz) on QT1 had first light on Nov. 2012. Ever since we are doing routine observations on selected Galactic and Cosmological fields

★ MFI and QT1 are performing well, producing intensity and polarization maps at 4 frequencies

★ Preliminary constraints on the AME polarization from the Perseus molecular cloud

★ TGI (30 GHz) to be commissioned in 2014, and FGI (40 GHz) after it

★ Combined FGI/TGI data should allow to reach r=0.05 after 3 years of operation