The QUIJOTE-CMB Project
13th Rencontres du Vietnam

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On Behalf of the QUIJOTE team
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Marie Skłodowska-Curie Actions under Horizon2020

MARIE CURIE ACTIONS

Outline

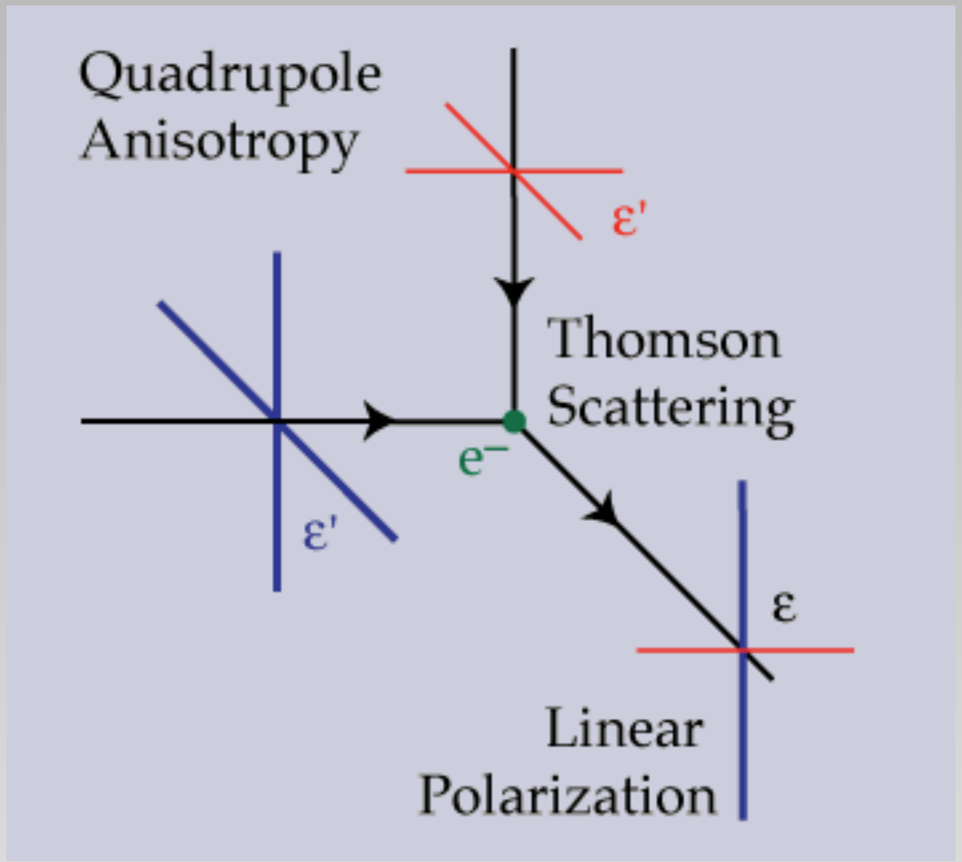
- ★ Introduction
- ★ The QUIJOTE-CMB Experiment
- ★ The Multi-Frequency Instrument : MFI
- ★The Thirty and the Forty GHz Instruments: TGI & FGI
- ★ Science with the MFI: Galactic Results and Foreground Characterisation
- ★ Conclusion

CMB polarisation - Thomson scattering

✤ The CMB anisotropies are intrinsically polarized due to Thomson scattering

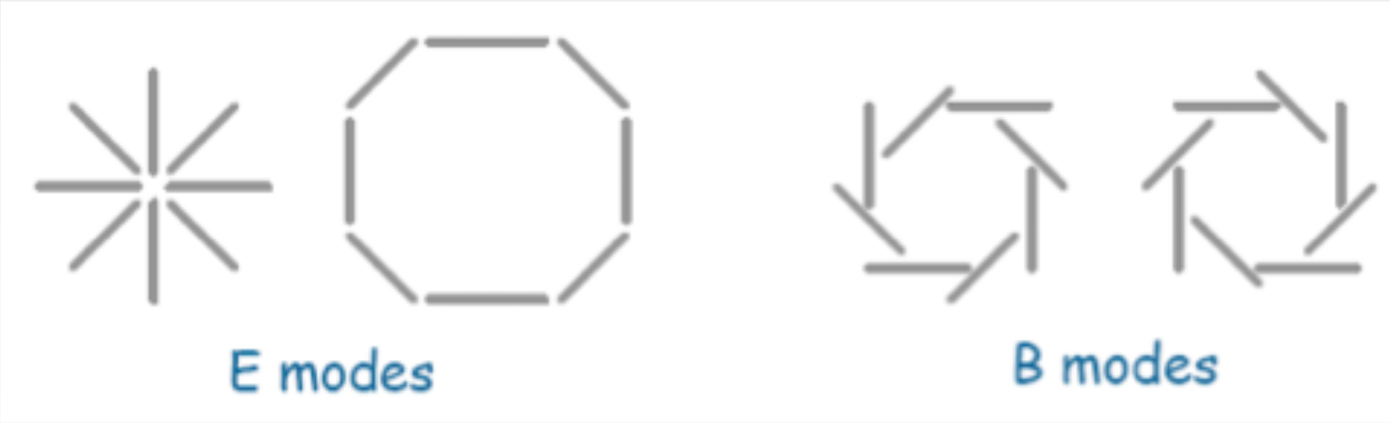
✤ A net polarization is generated during recombination in the presence of a quadrupole in the incident radiation field

✤ The resulting polarization is linear, i.e. the CMB will have non-zero Stokes parameters Q and U, but V=0



✤ Polarization maps can usually be decomposed into:

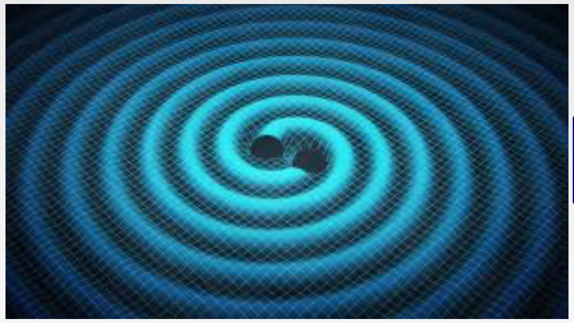
- **E-modes** (analog to gradient component)
- **B-modes (analog to curl component)**

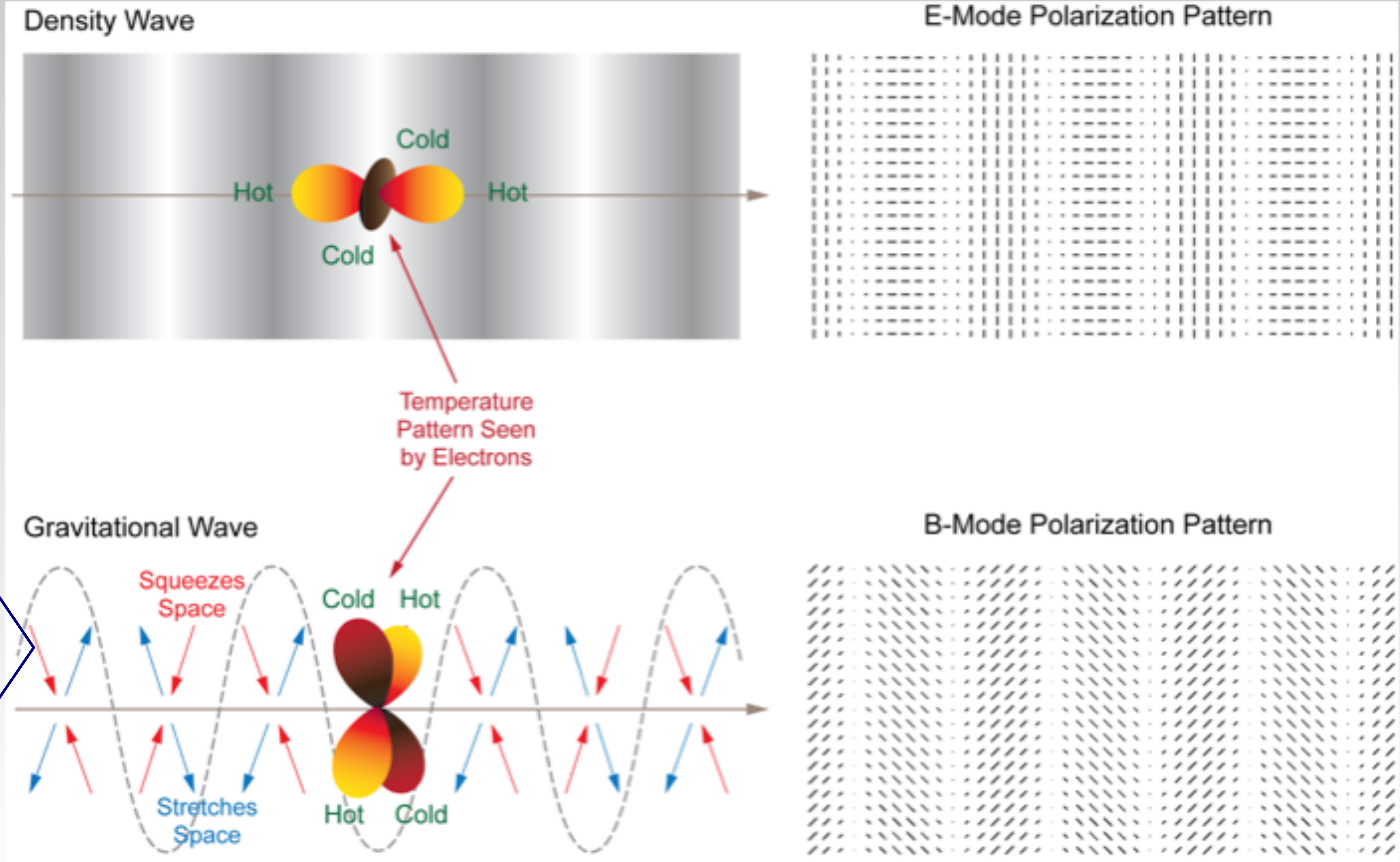


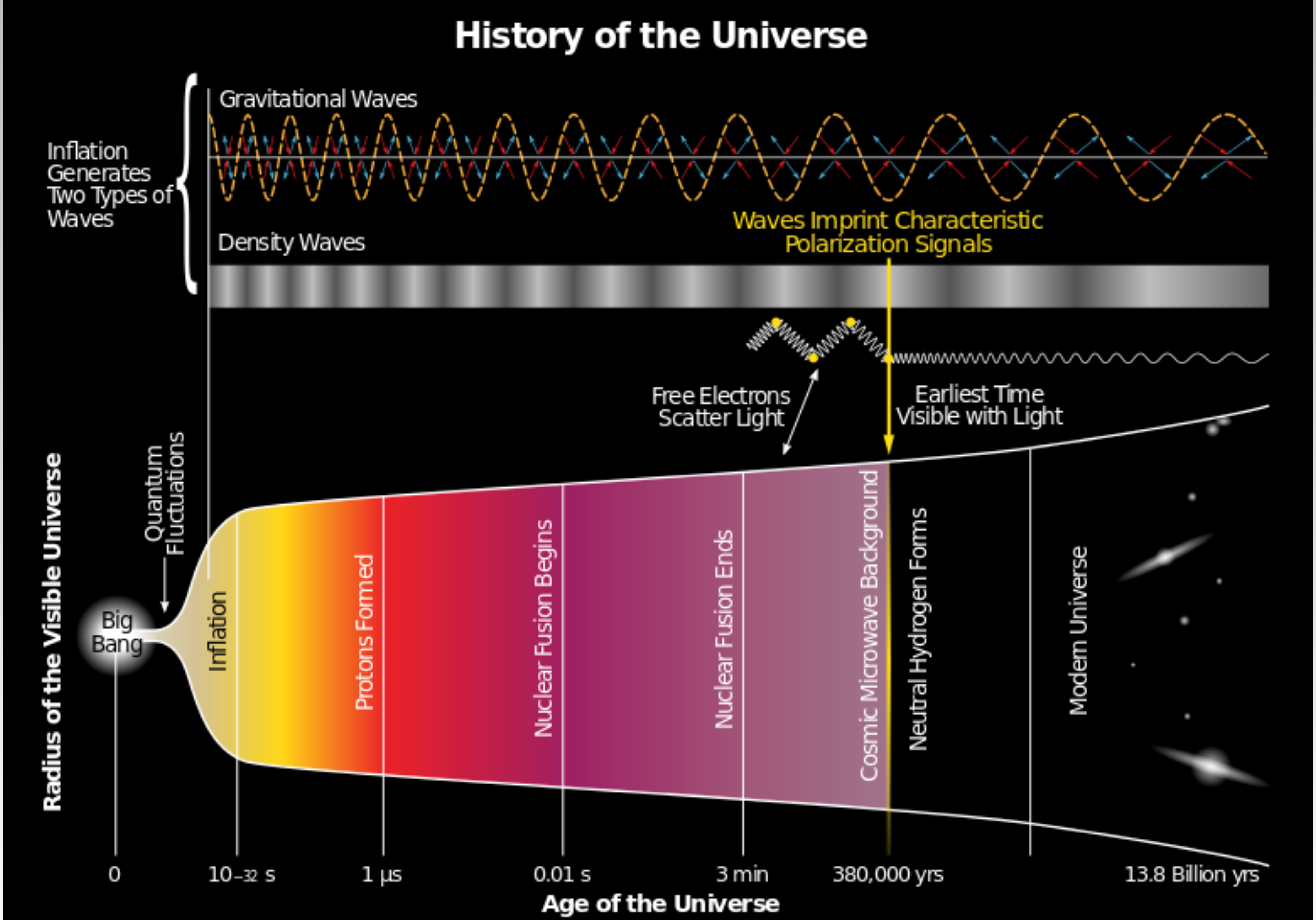
Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997

✤ **Different types of anisotropies in the primordial universe create different types of modes**

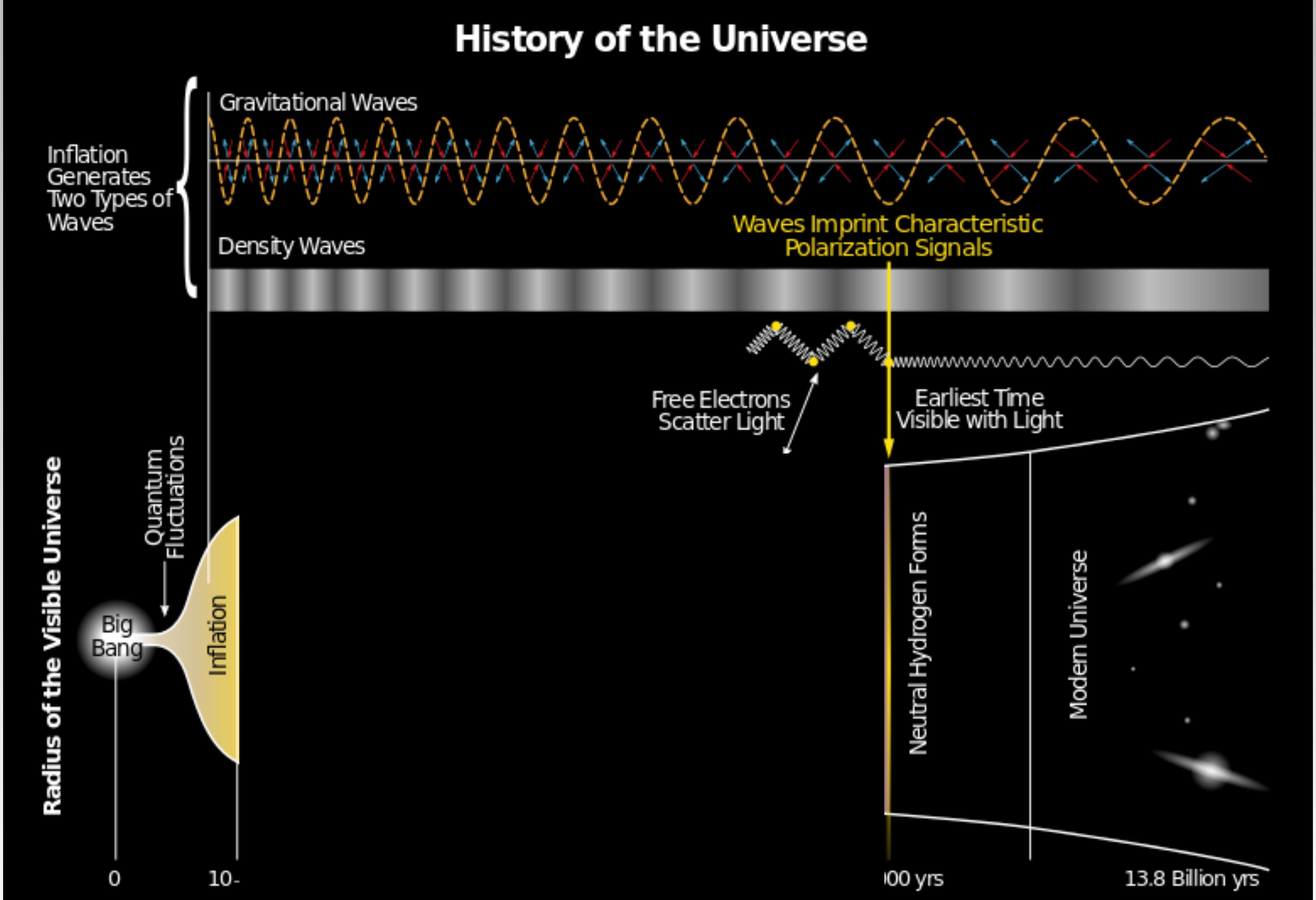
	E-modes	B-modes
Scalar (density perturbations)	✓	X
Tensor (gravitational waves)	✓	✓



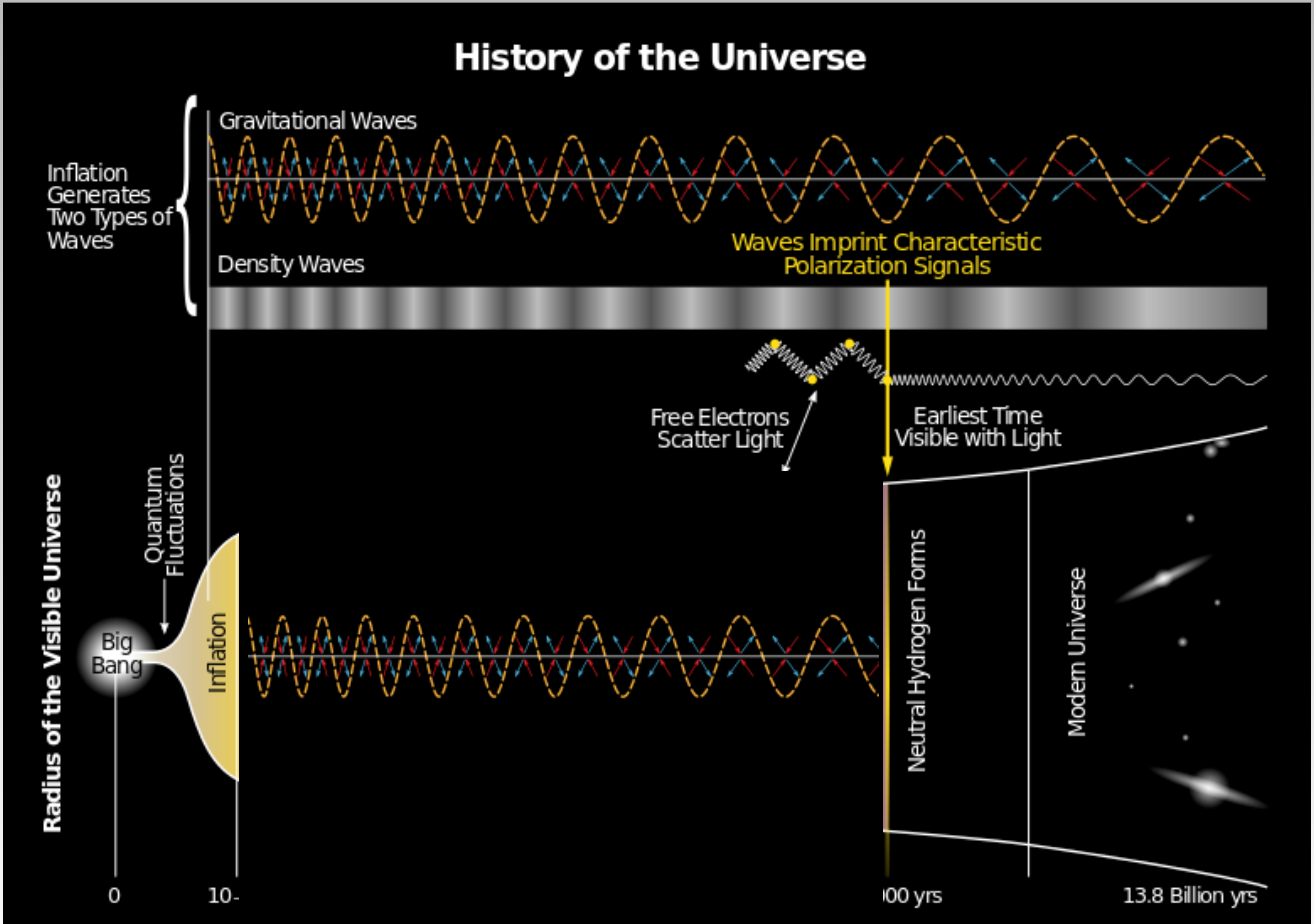




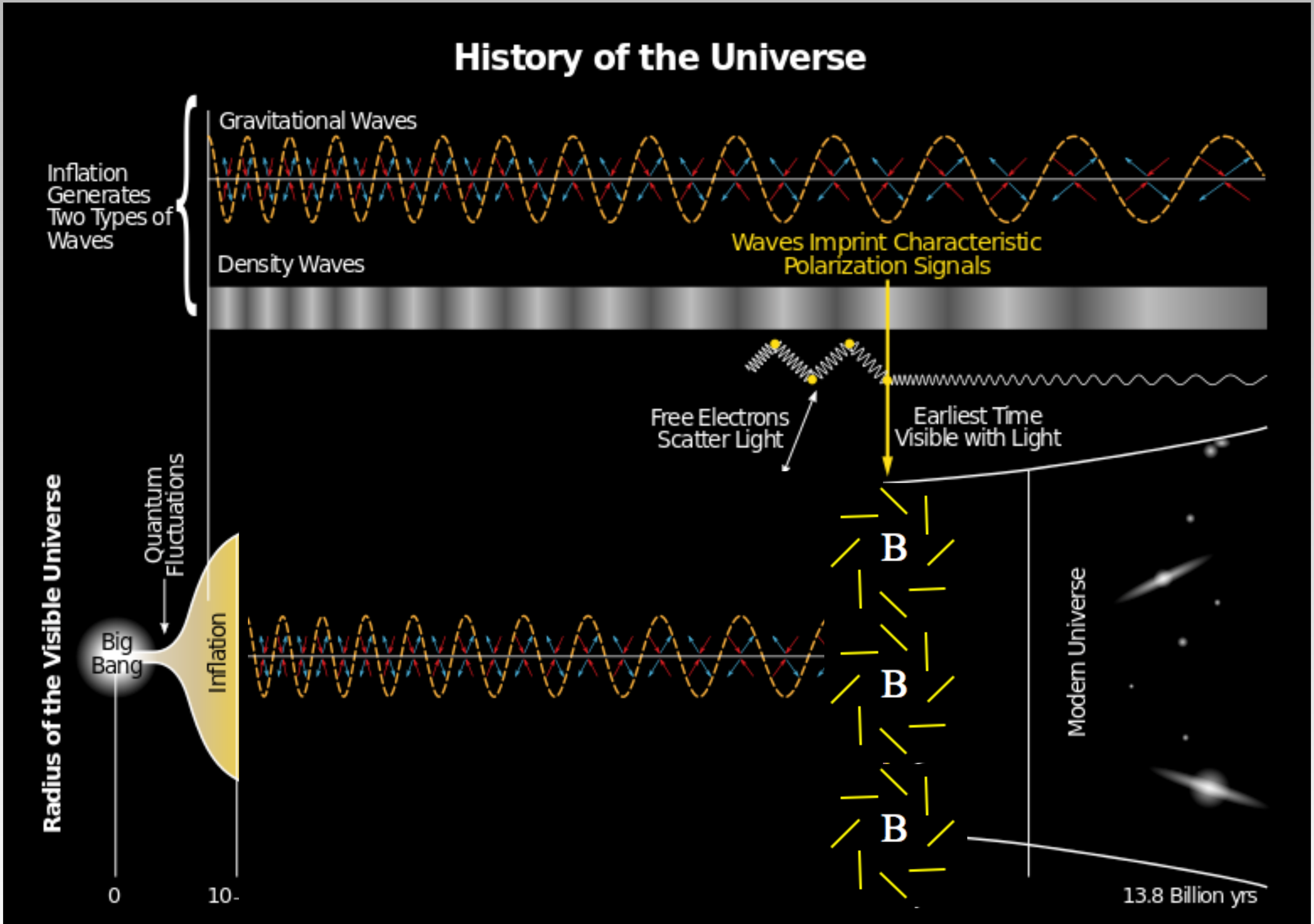
BICEP2 results release



BICEP2 results release

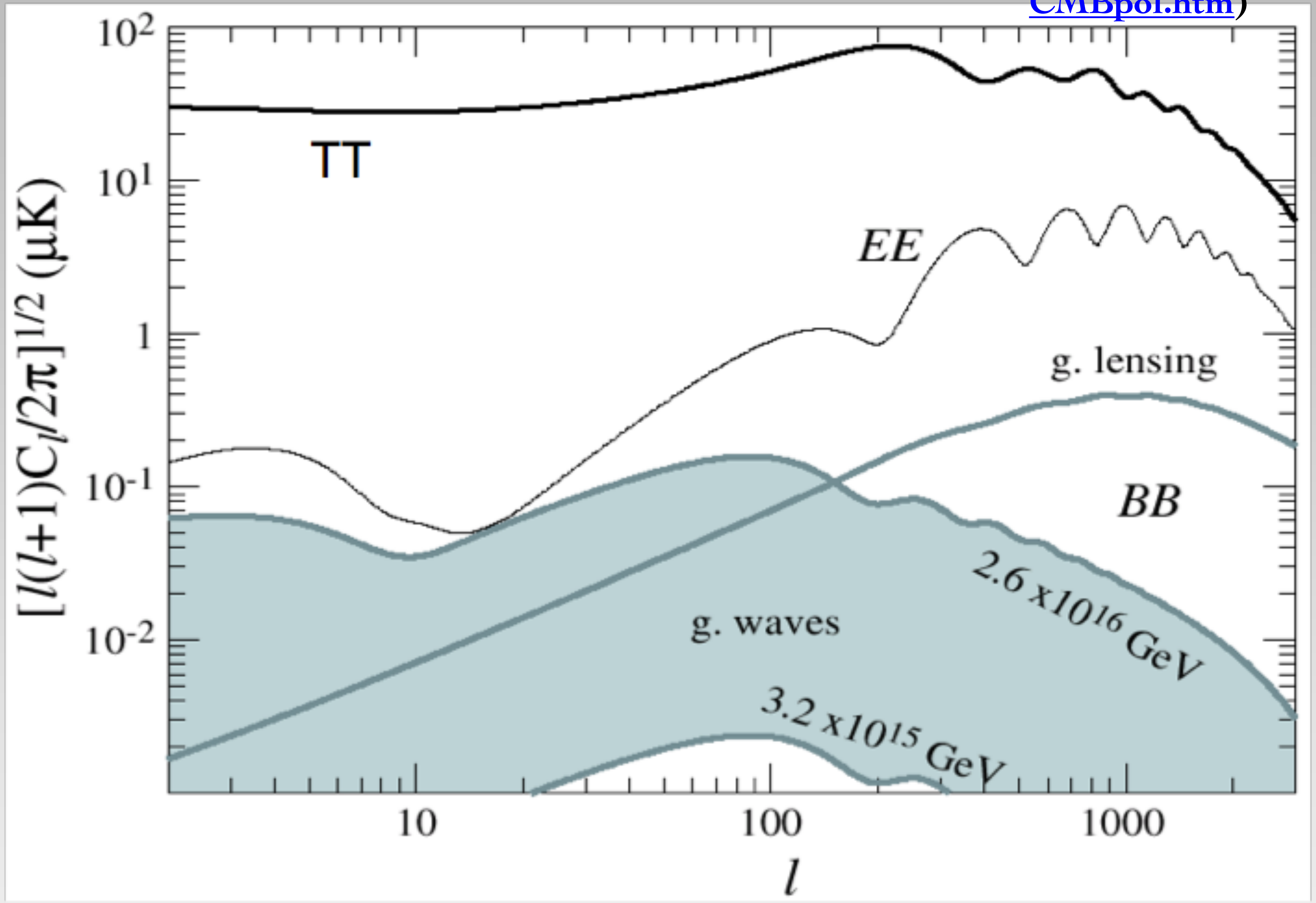


BICEP2 results release



BICEP2 results release

✤ Amplitude of the B-mode power spectrum: (From http://cosmology.berkeley.edu/~yuki/CMBpol/CMBpol.htm)



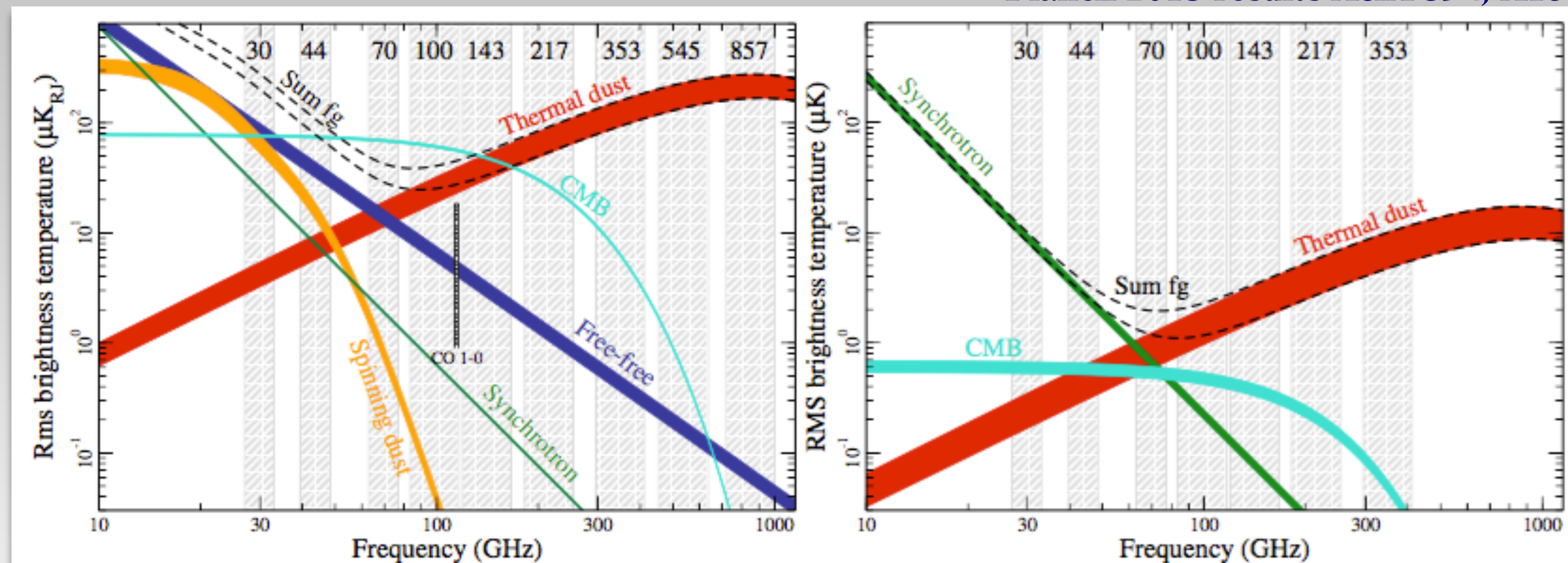
$$r = \frac{P_{tensor}(k_0)}{P_{scalar}(k_0)} = 0.008\left(\frac{E_{inf}}{10^{16}GeV}\right)^4$$

- $E_{inf}=2.6\times10^{16}$ GeV corresponds to r=0.37, and $E_{inf}=3.2\times10^{15}$ GeV to $r=8.4\times10^{-5}$
- r=0.01 corresponds to the GUT scale (~10^{16} GeV)

Observability of B-modes

➡ Foregrounds. B-mode signal is subdominant over Galactic foregrounds

Planck 2015 results A&A 594, A13



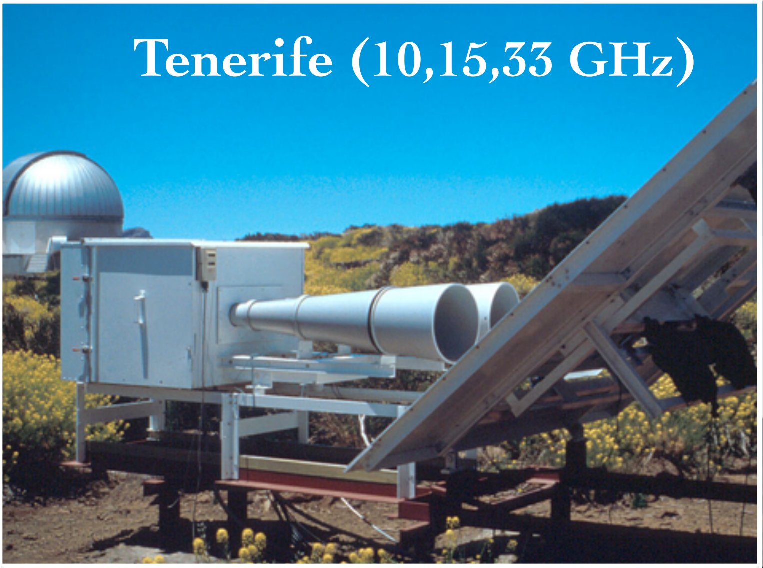
➡ Systematic program to study polarized astrophysical foreground signals is needed (see NASA-NSF report "Task Force on CMB research" and ESA-ESO report on "Fundamental cosmology", 2006)

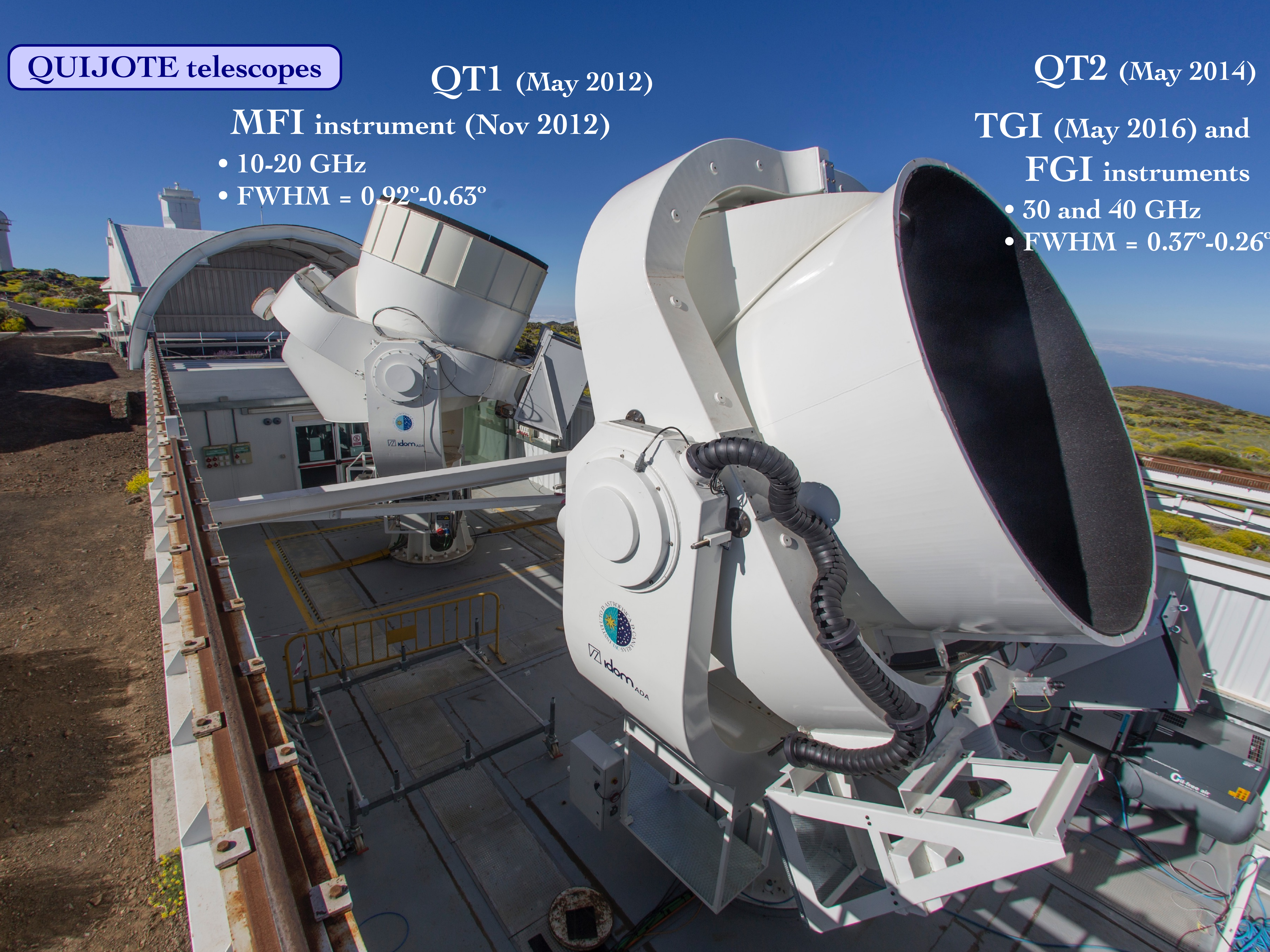
QUIJOTE collaboration

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

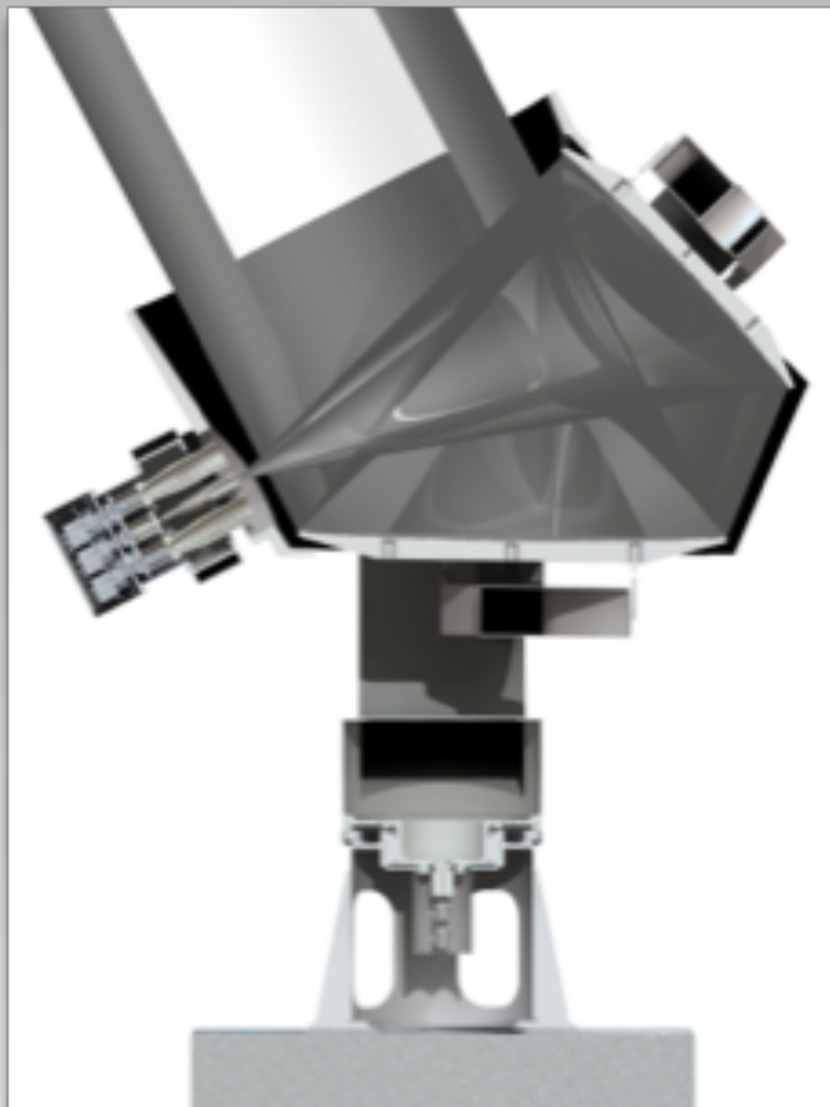
QUIJOTE site

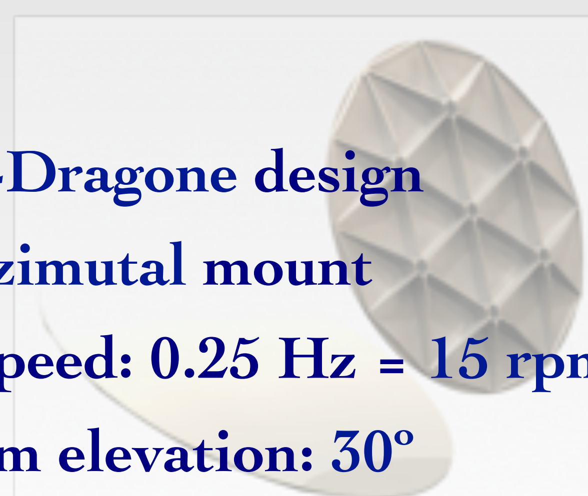
Quijote
Q-U-I Joint Tenerife CMB experiment



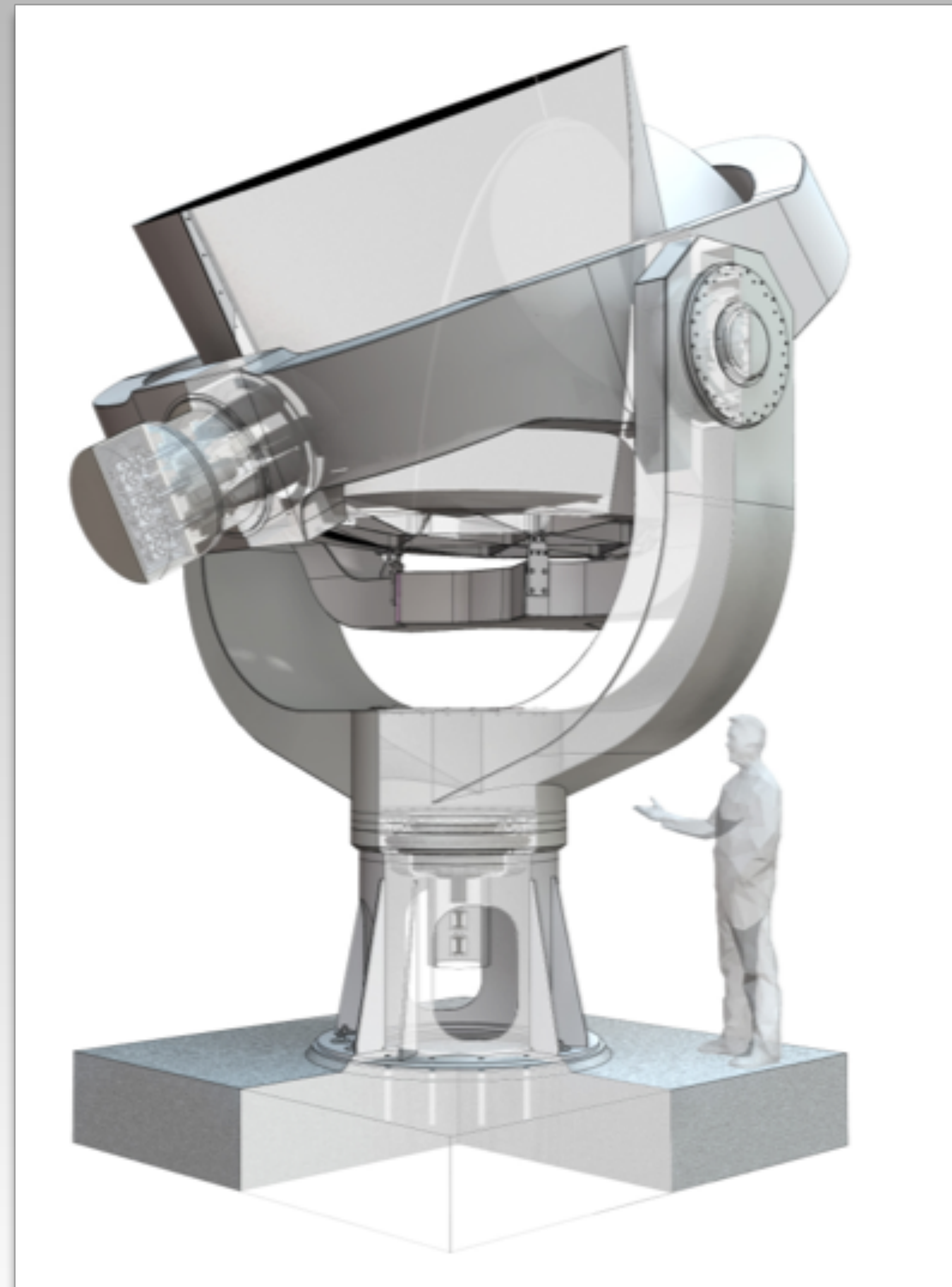

QUIJOTE telescopes
QT1 (May 2012)
MFI instrument (Nov 2012)
• 10-20 GHz
• FWHM = 0.92°-0.63°
QT2 (May 2014)
TGI (May 2016) and
FGI instruments
• 30 and 40 GHz
• FWHM = 0.37°-0.26°

QUIJOTE telescopes



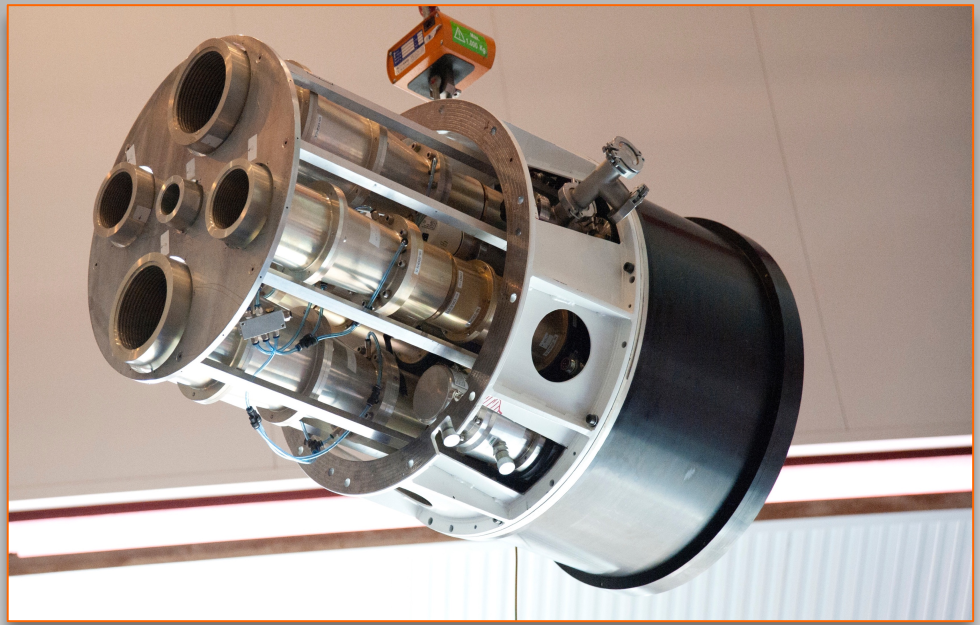


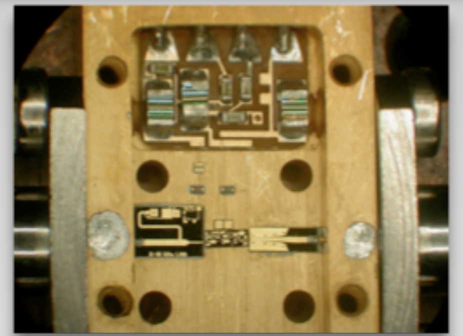
- Crossed-Dragone design
- Alto-azimutal mount
- Maximum AZ speed: 0.25 Hz = 15 rpm
- Minimum elevation: 30º
- Aperture: 2.25 m (primary) and 1.9 m (secondary)



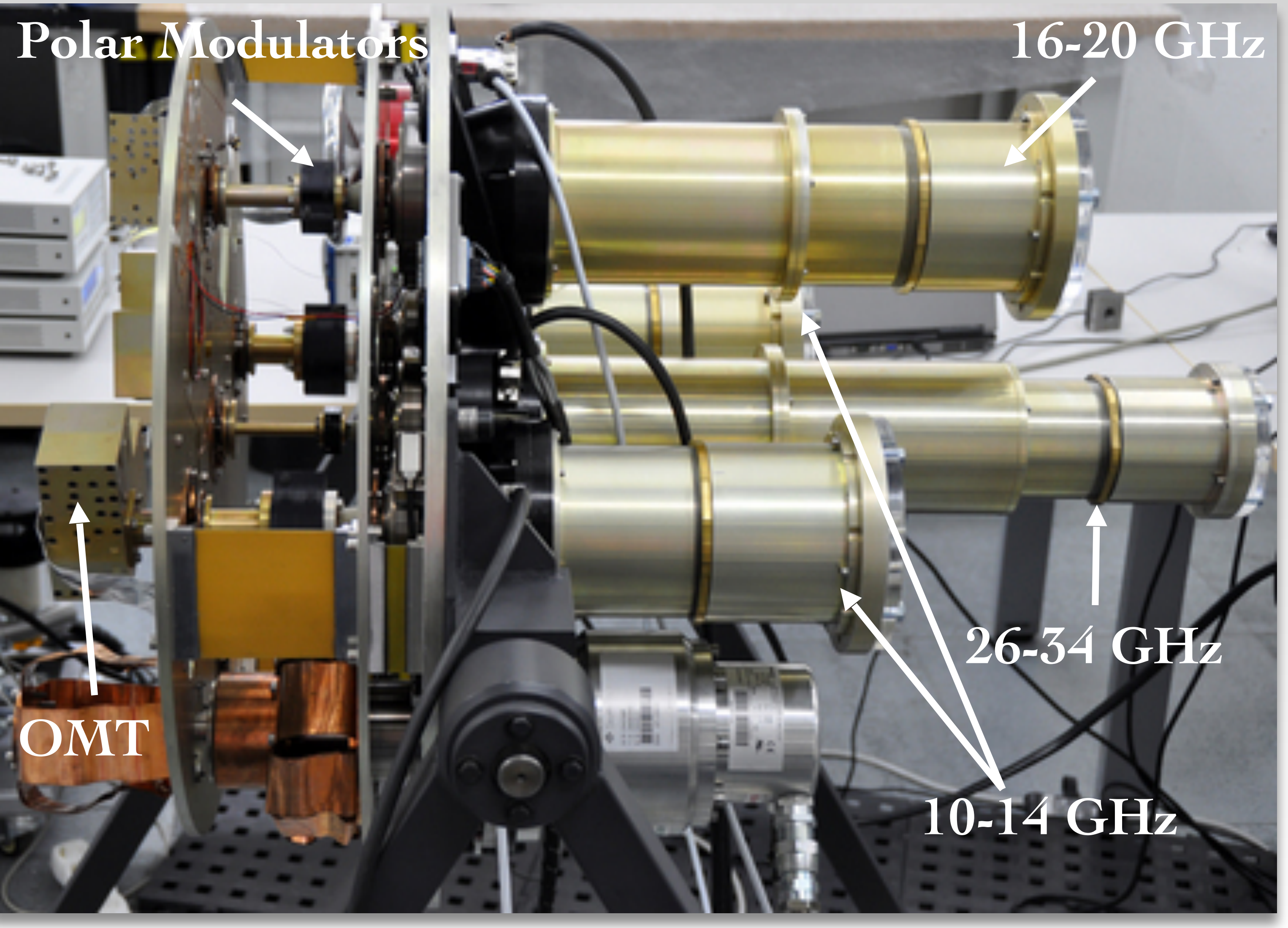
Multi-Frequency Instrument (MFI)

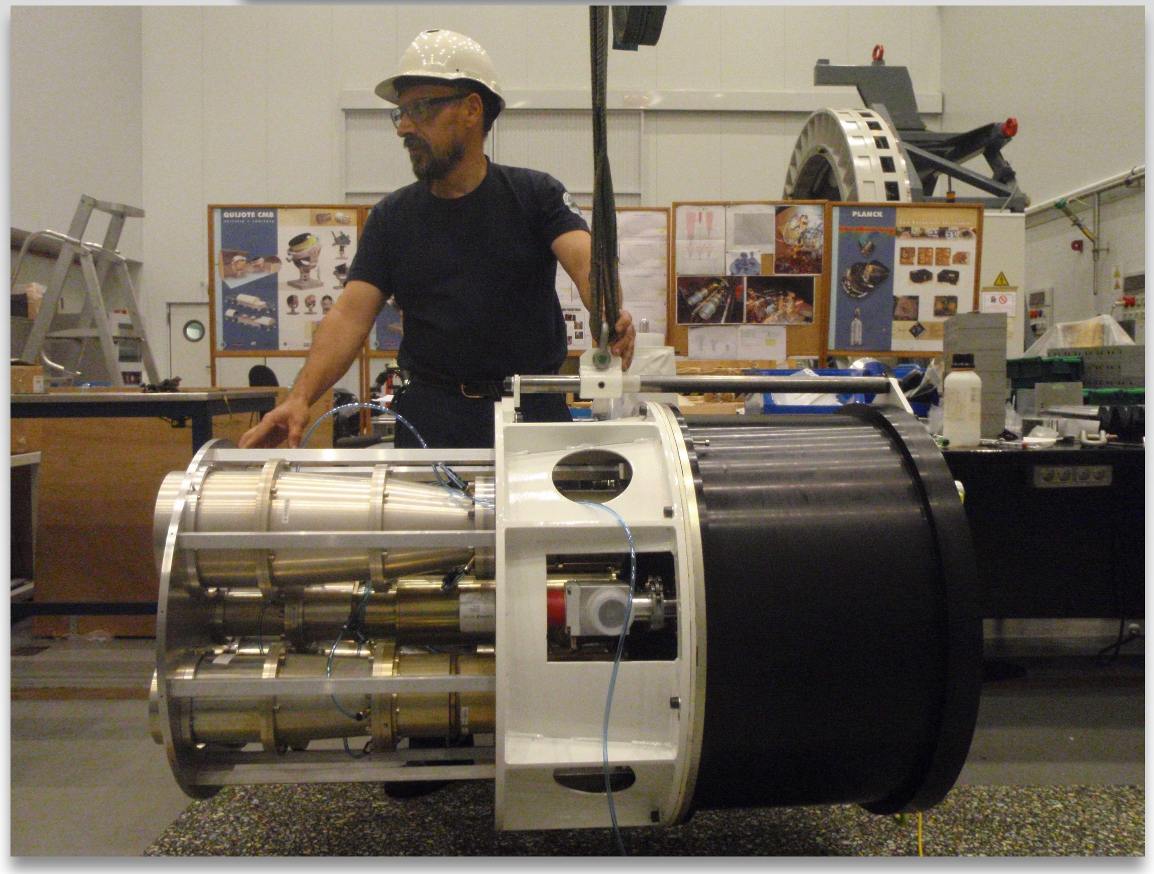
- Observing since November 2012
- HEMT technology
- Stepping polar modulator (HWP) to modulate the incoming polarised signal
- 4 horns, 32 channels, covering 4 frequency bands: 11, 13, 17 and 19 GHz
- Sensitivities: ~400-600 μK·s$^{1/2}$ per channel



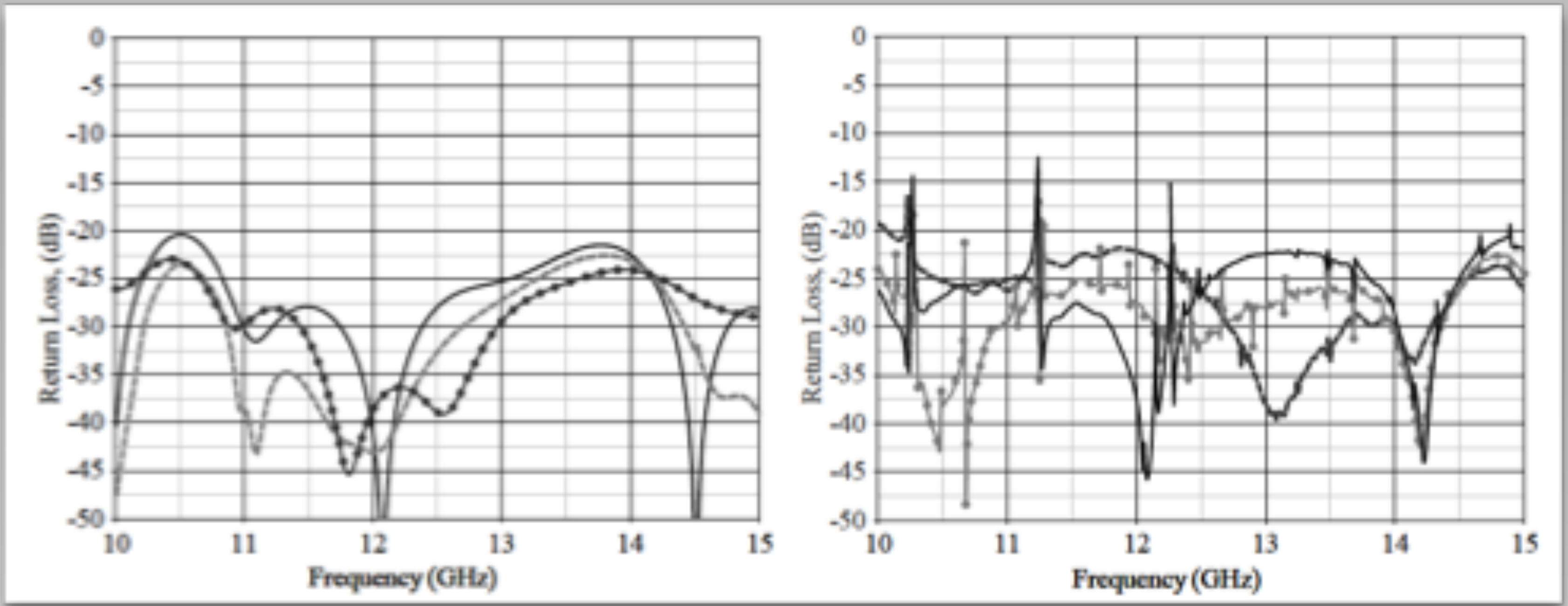


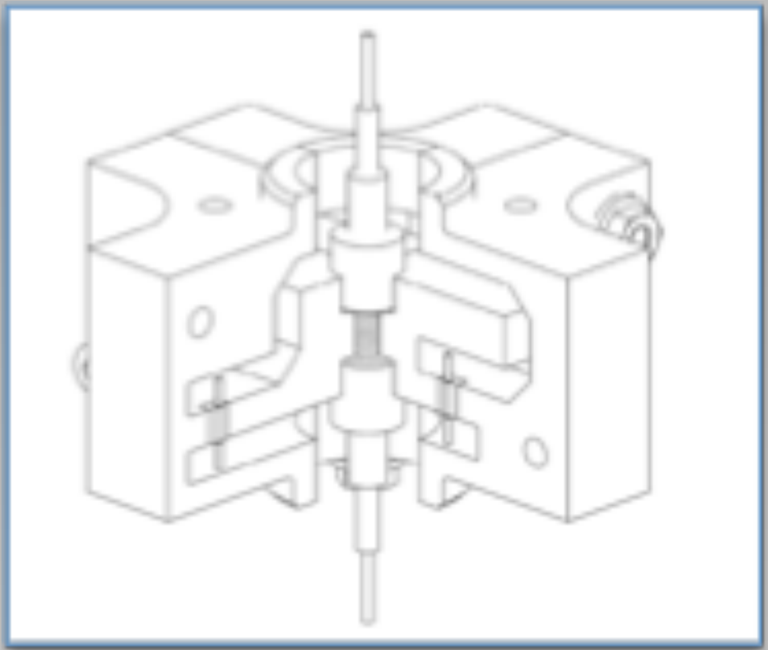
LNA



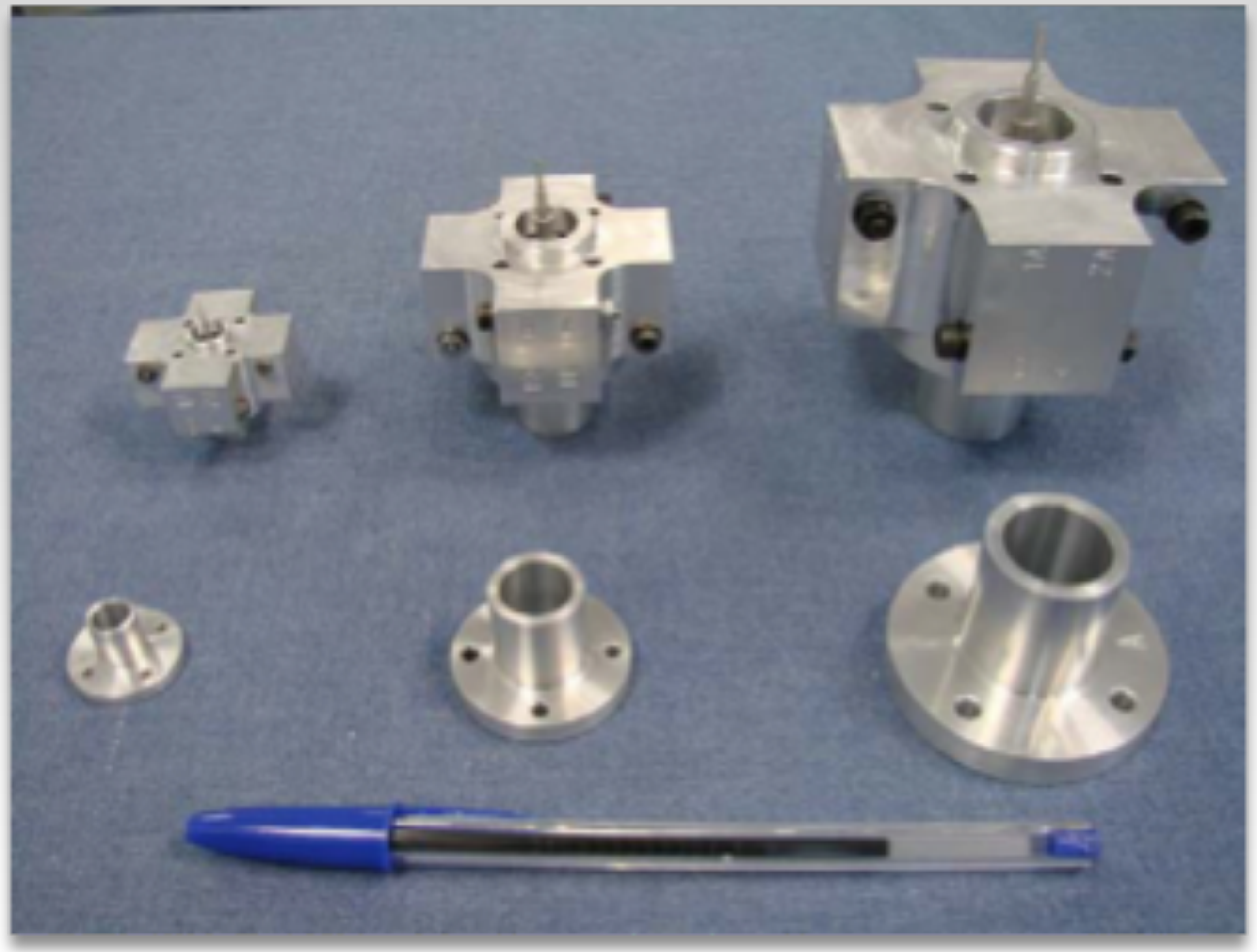


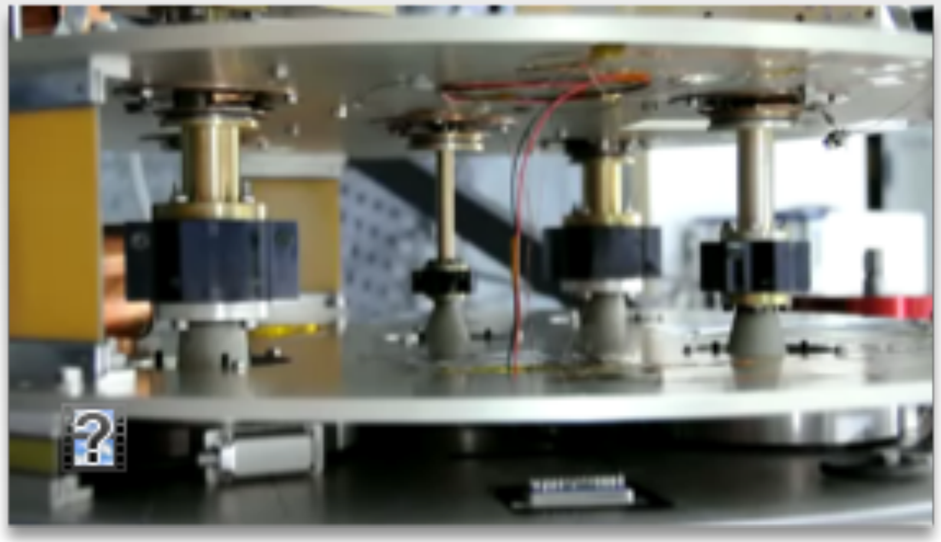
Multi-Frequency Instrument (MFI)





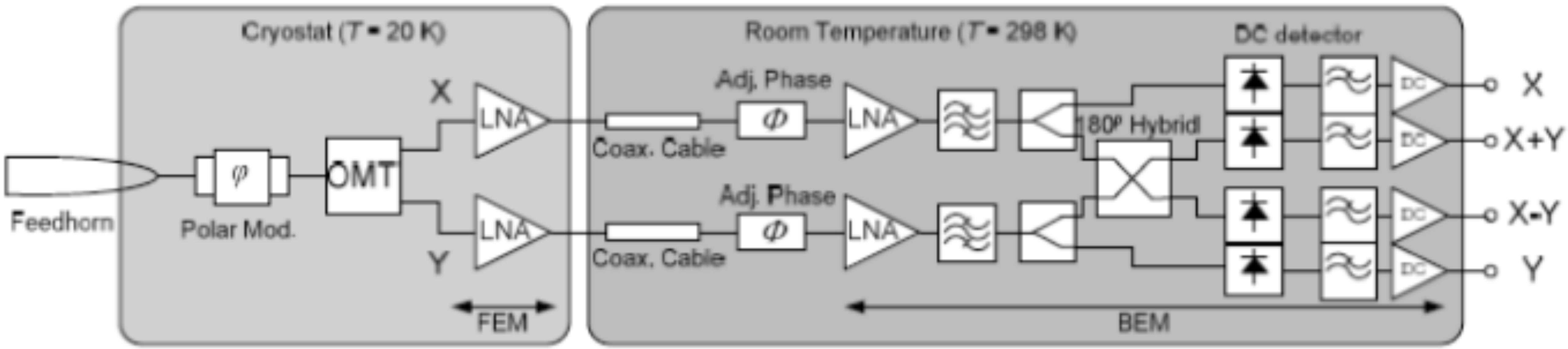
- Polar modulator (HWP): based on a turnstile junction, in waveguide
- Broad-band, cooled down in cryostat, and high performances:
  - Return losses < -20 dB
  - Insertion losses < -0.15 dB
  - Isolation < -40 dB





Multi-Frequency Instrument (MFI)

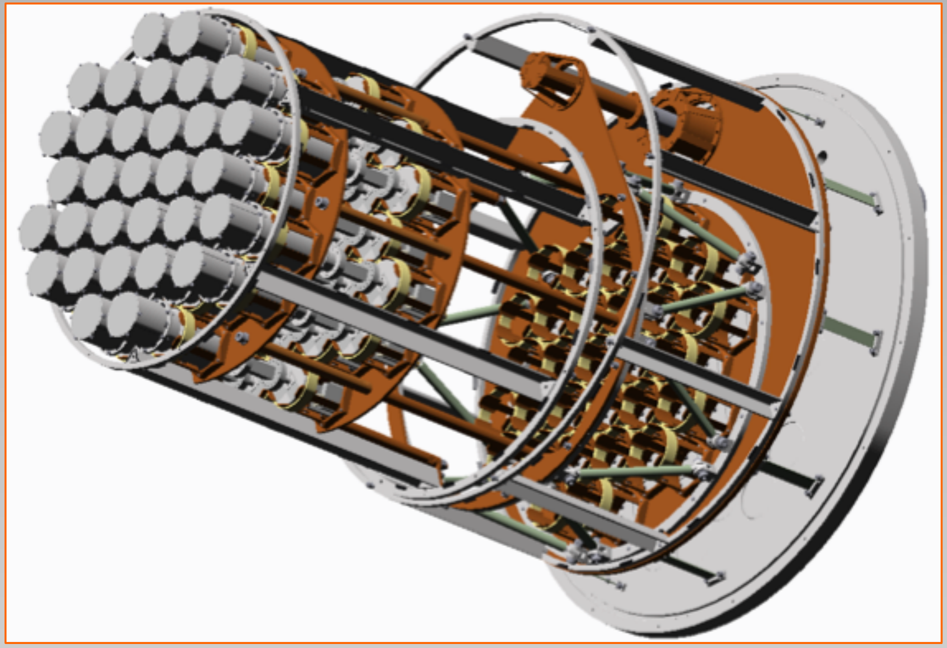
- **FEM: partially-cooled feed-horn, polar modulator, OMT and LNAs**
- **BEM: phase adjuster, further amplification, band pass filter and correlation.**
- **Output: two channels (x) and (y) measuring Q (un-correlated), two channels (x+y) and (x-y) measuring U (correlated)**

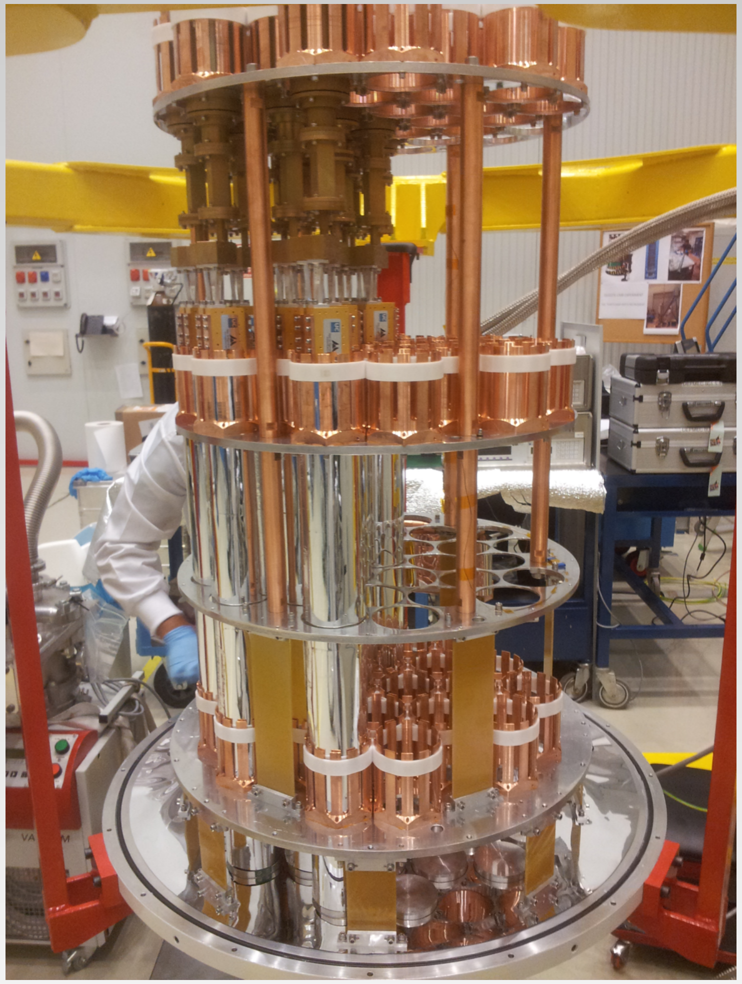


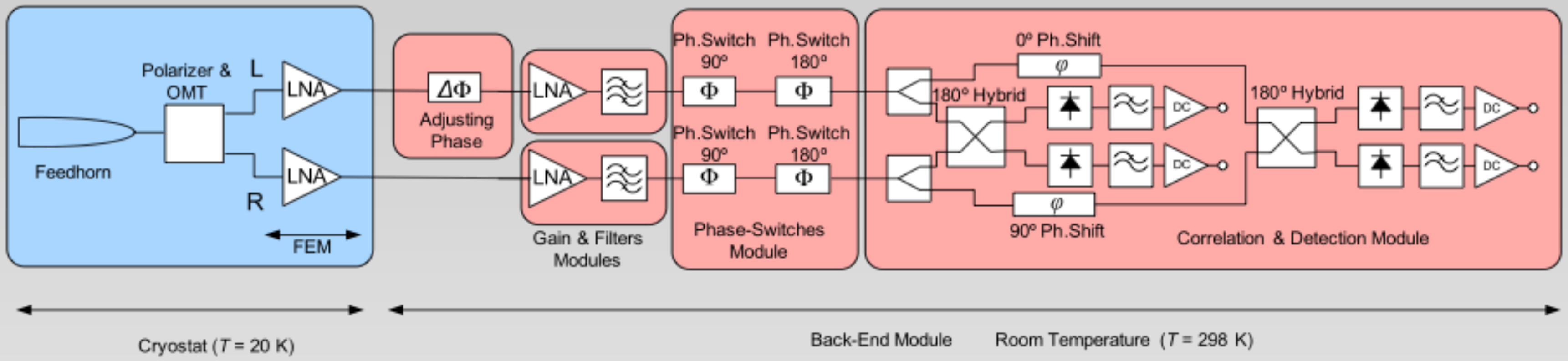
- **Continuous spinning of the polar modulators provides independent measurement of I, Q and U for each channel, while switching out the 1/f noise. But we operate in 4 discrete positions (0º,22.5º,45º,67.5º)**
- **Each of the four outputs are divided into a lower frequency and an upper frequency band.**

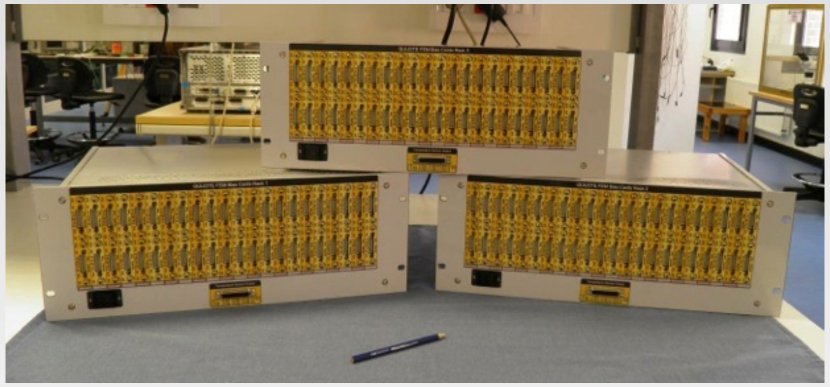
Thirty and Forty-GHz Instruments

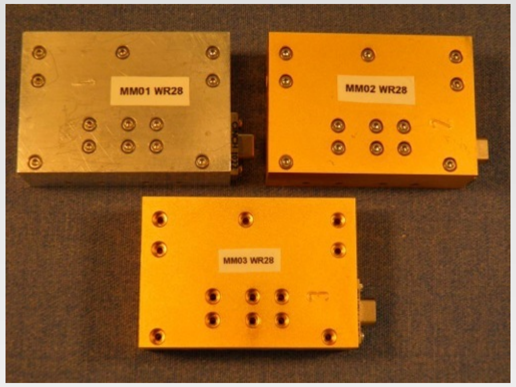
- The TGI First light: May 2016
- 30 pixels at 31 GHz
- Expected sensitivity of the full array: ~50 μK·s$^{1/2}$
- The FGI will consist of 31 pixels at 42 GHz, with sensitivity ~60 μK·s$^{1/2}$

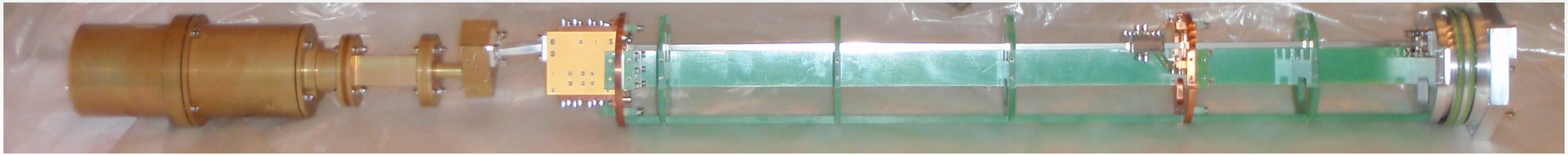




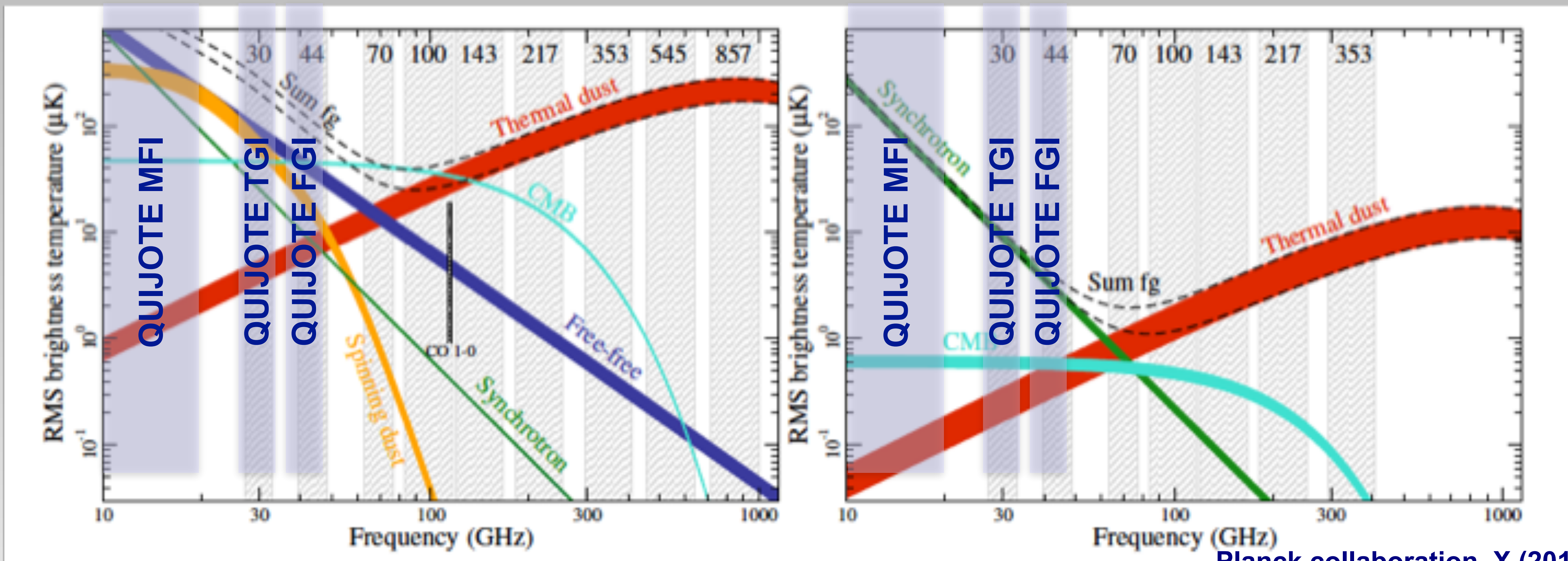








Science with the MFI



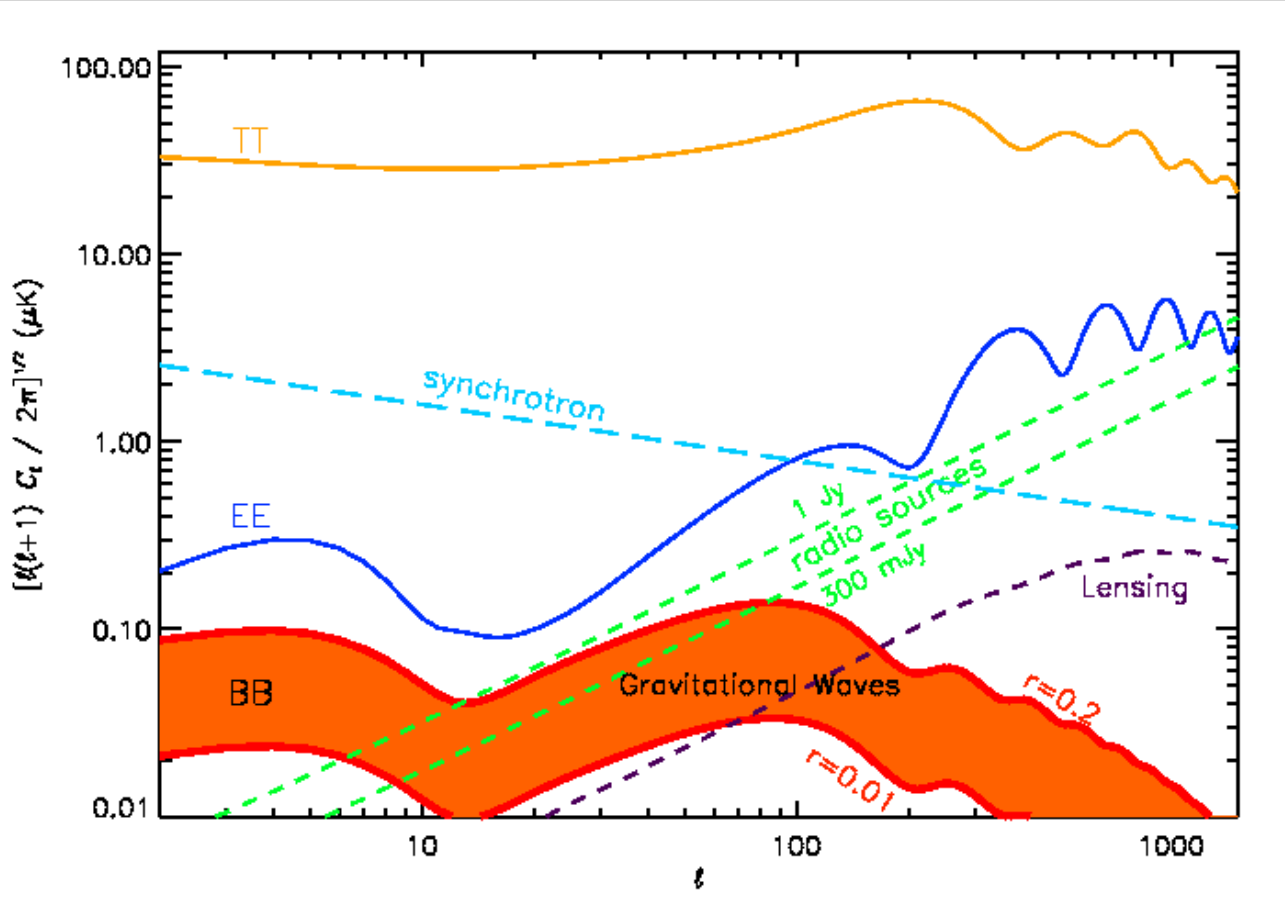
Planck collaboration X (2015)

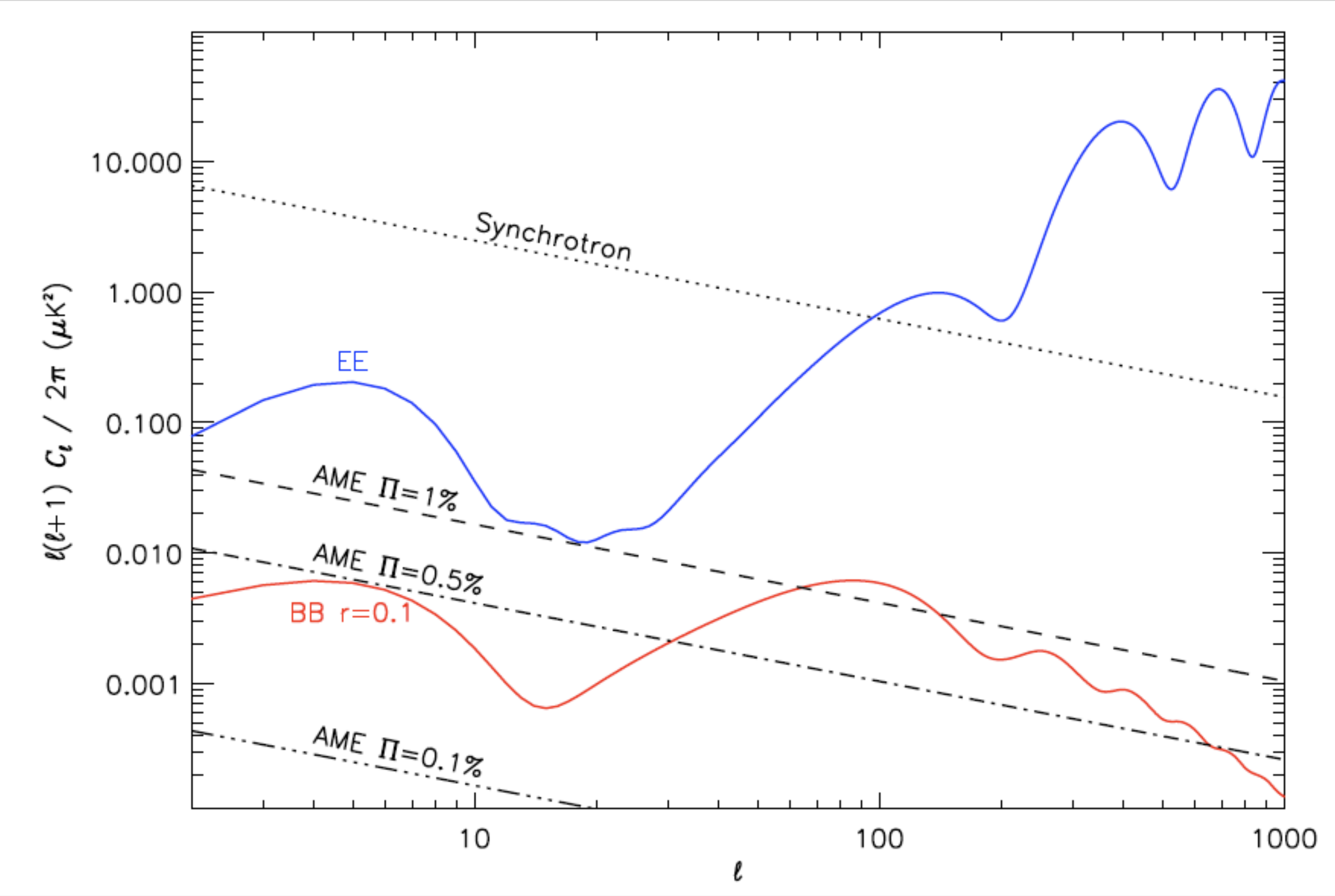
★ The MFI maps provide valuable information about the polarisation properties of:

- Synchrotron emission: should dominate the emission at the MFI frequencies. WMAP 23 GHz shows it to be polarised at ~5-15%, depending on the Galactic latitude
- Anomalous microwave emission: little known about its polarisation. Best upper limits on the polarisation fraction: <0.2% (Génova-Santos et al. 2016), previously <1% (LC11, D11)

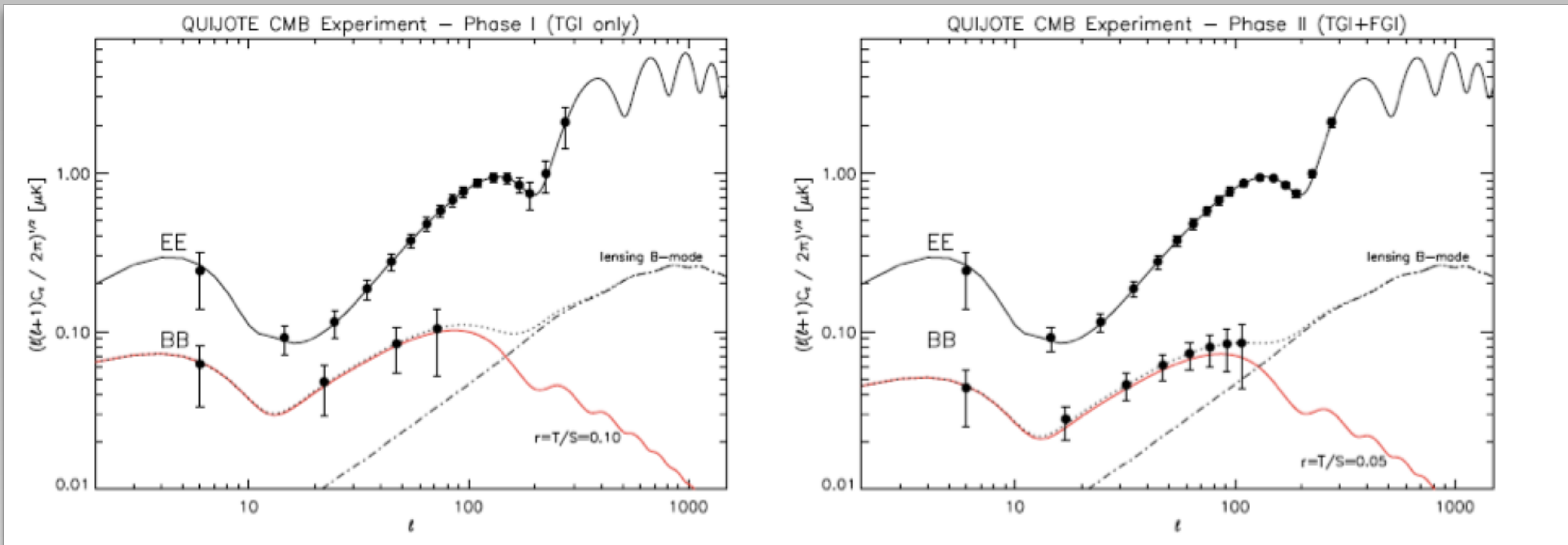
Science with the MFI

- Wide Galactic survey. Covering 20,000 deg^2 (finished - 8000 hours)
  - ≈ 15 μK/(beam 1°) 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 (3 fields). After 1 year
  - ≈ 10 μK/(beam 1°) with the MFI @ 11, 13, 17 and 19 GHz





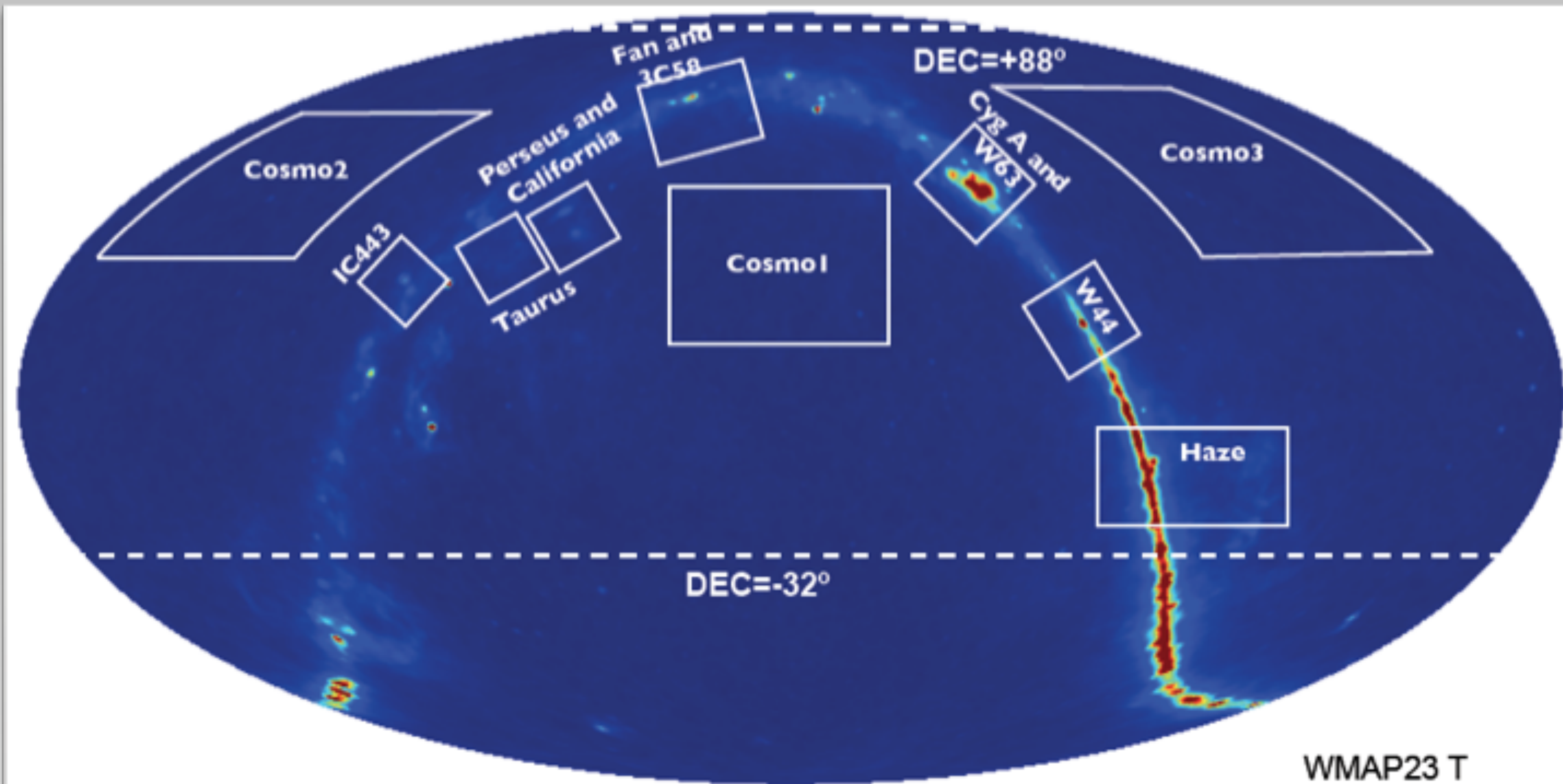
Science with the TGI and FGI



★ **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**

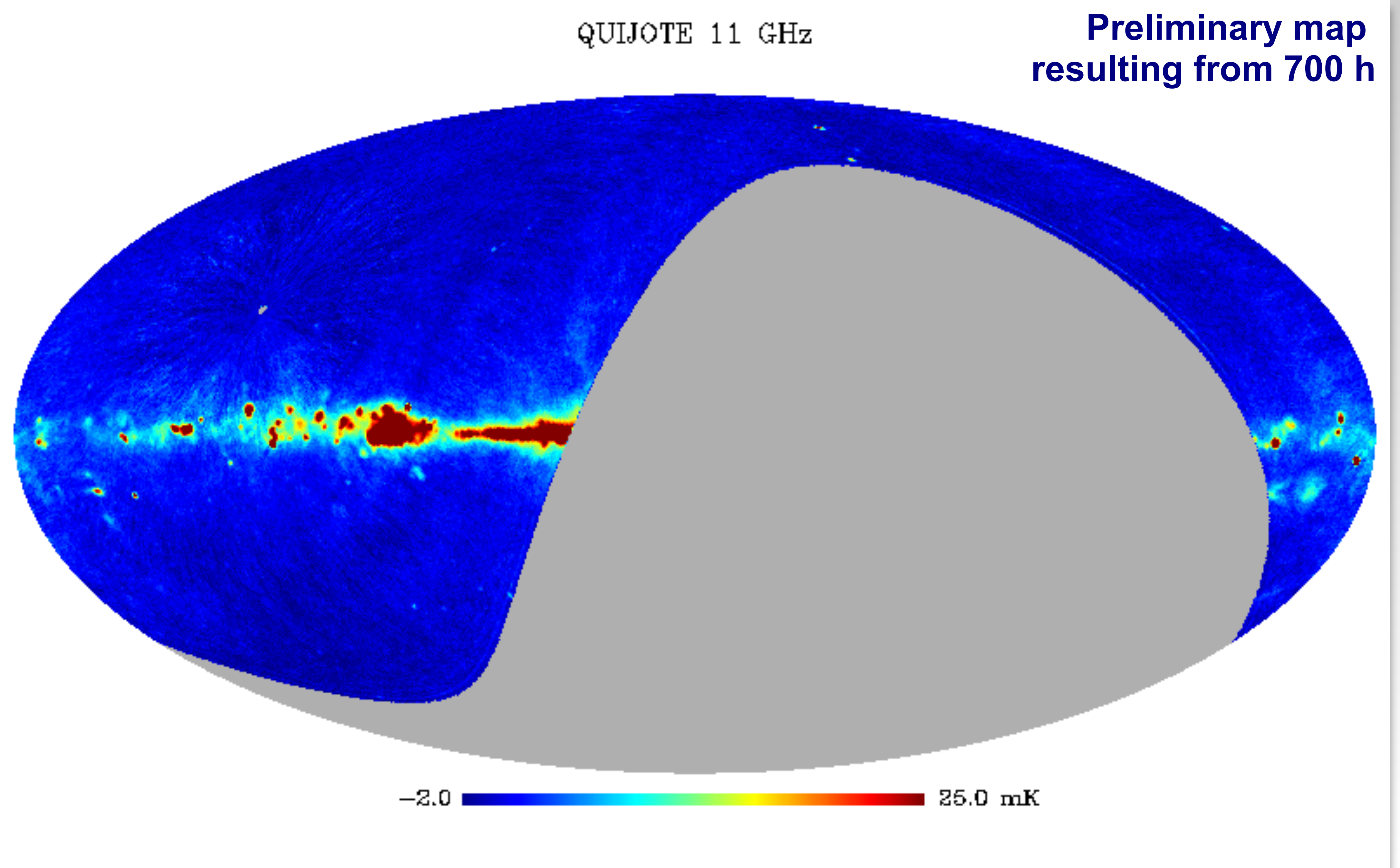
★ **Right**: QUIJOTE-CMB Phase II. Here we consider 3 years of effective operations with the TGI, and that during the last 2 years, the FGI will be also operative. The red line now corresponds to **r = 0.05**

QUIJOTE fields



Wide survey

- ★ Full coverage of the northern sky in nominal mode (telescope rotates in AZ at 12 deg/s at various fixed elevations)
- ★ Total of 8000h over 20,000 deg^2
- ★ Expected sensitivities: ~15 μK/beam in Q,U and, ~50 μK/beam in I



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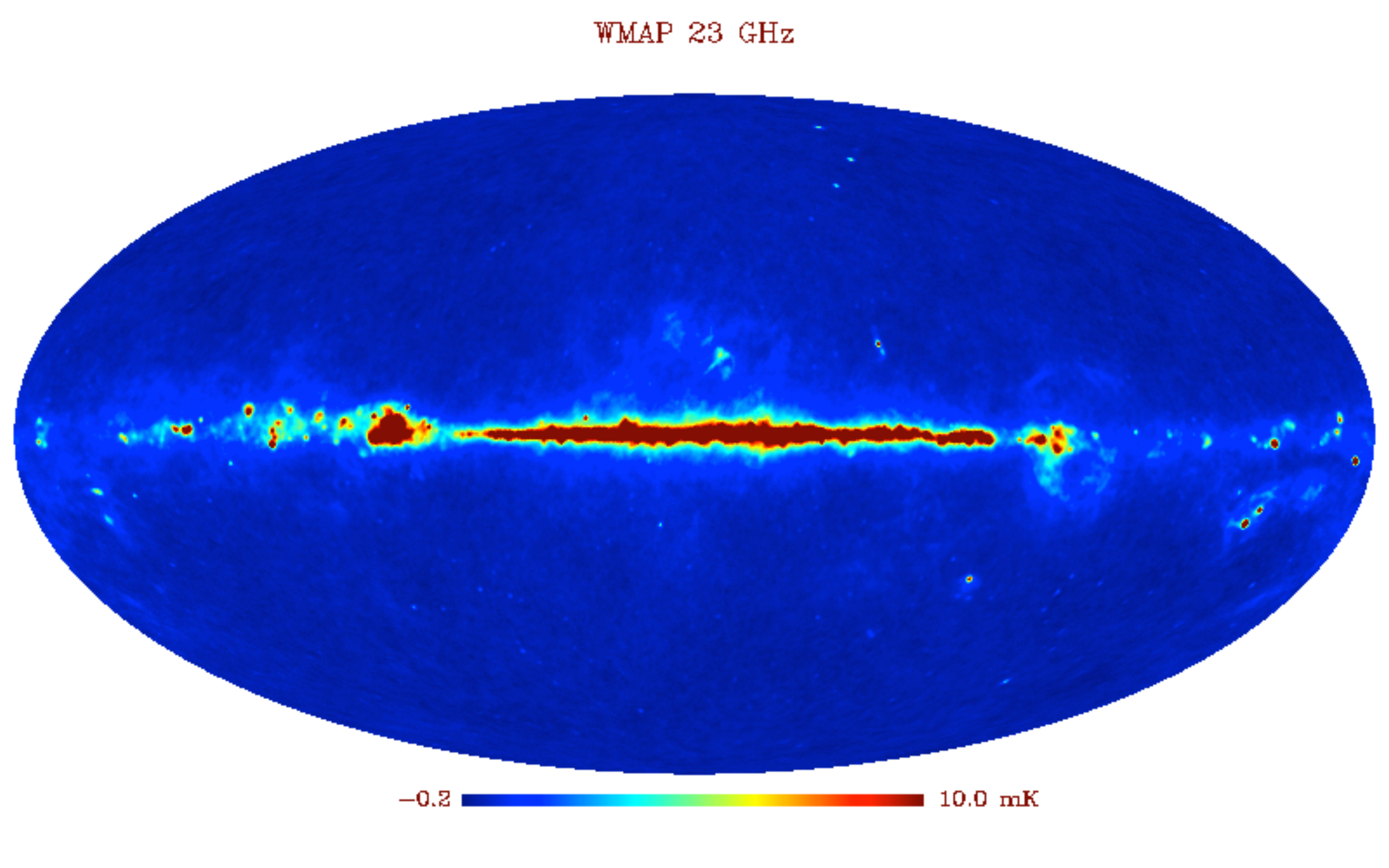
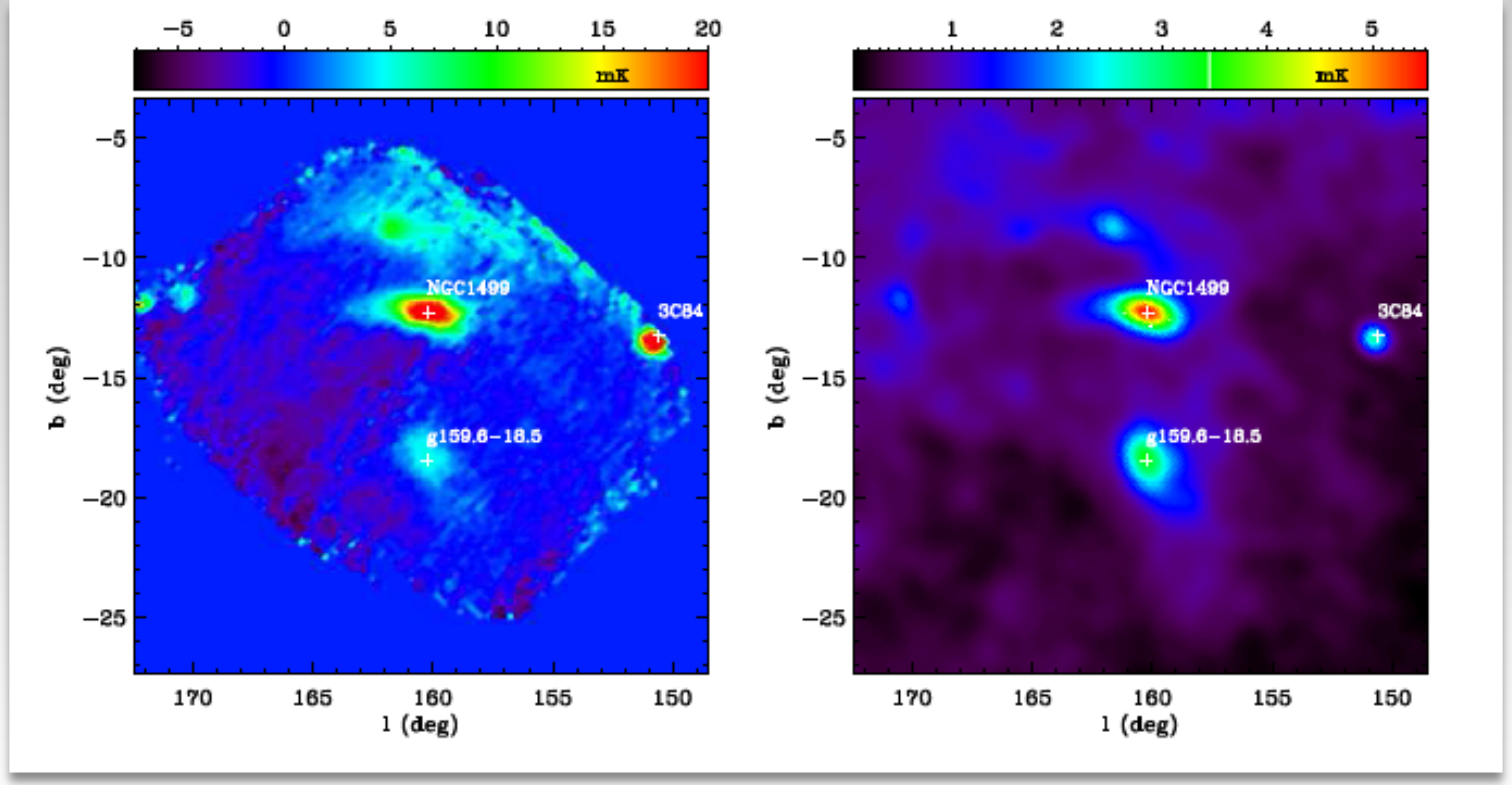


QUIJOTE

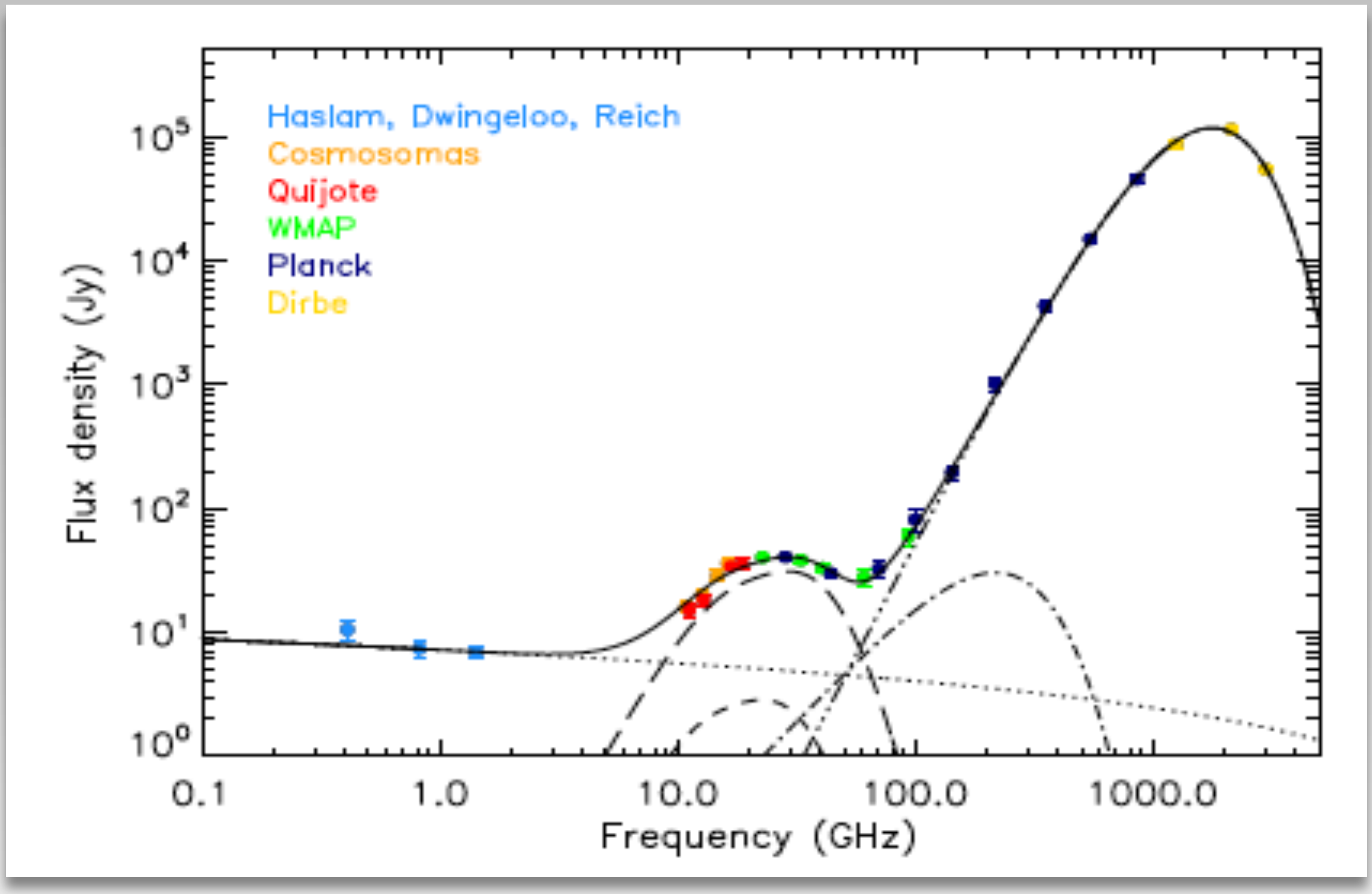
Perseus molecular complex

- ~200 hours, 12/2012 to 04/2013, on an area covering ~250 deg^2 around the Perseus molecular complex.
- One of the brightest AME regions on the sky (Watson et al. 2005, Planck collaboration 2011)
- Final integration time ~3000 s/beam, yielding a final map sensitivity of ≈30 μK/beam



- First QUIJOTE paper: Génova-Santos et al. (2015), MNRAS, 452, 4169

Perseus molecular complex



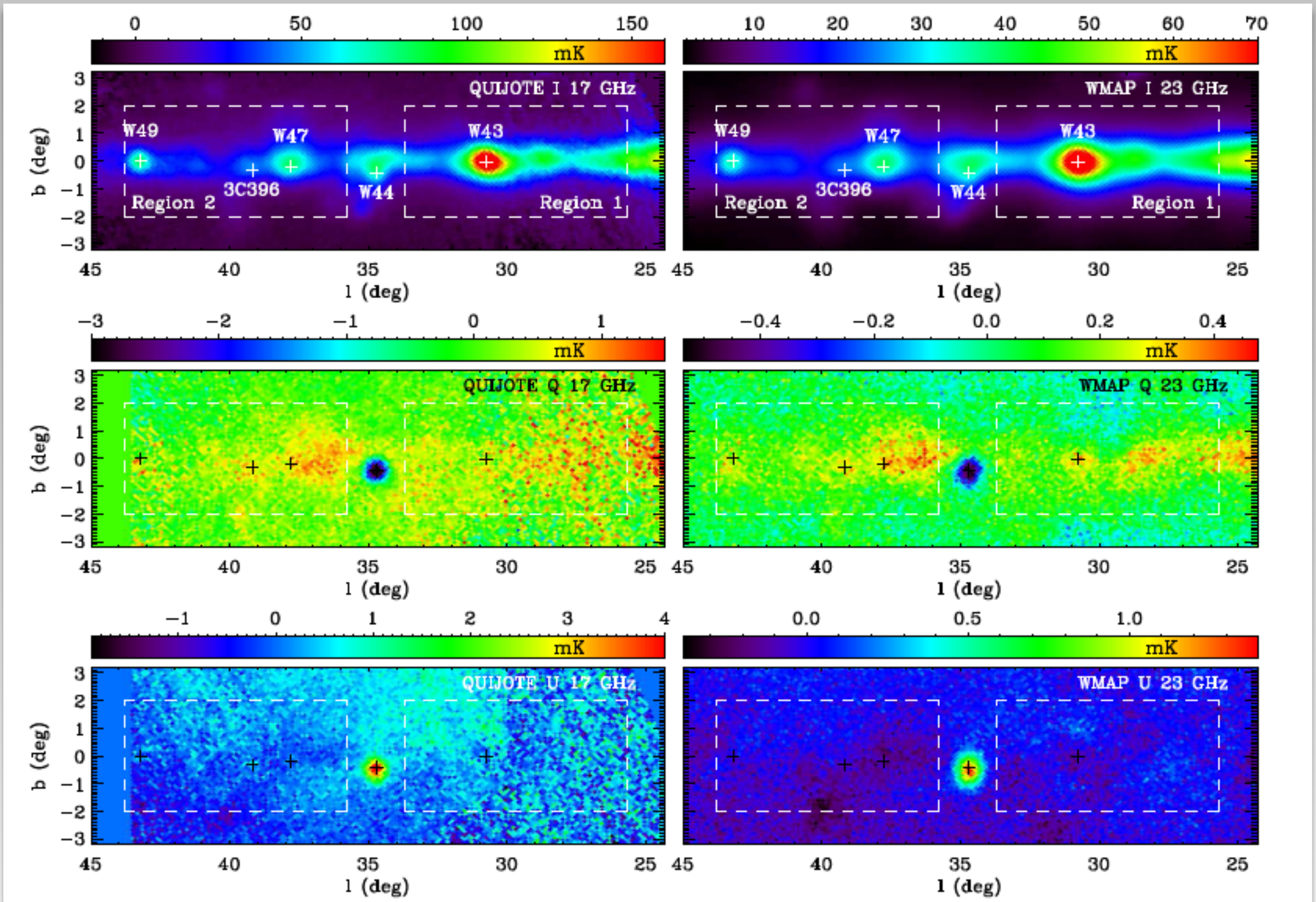
- AME (spinning dust) shows up at intermediate frequencies
- Most precise spinning dust spectrum to date (13 independent data points in the relevant range)

- No polarisation detection.
- Π < 6.3% at 12GHz and < 2.8% at 18GHz (95% C.L.)

W43, W44 and W47

Second QUIJOTE paper Génova-Santos et al. 2017, MNRAS, 464, 4107

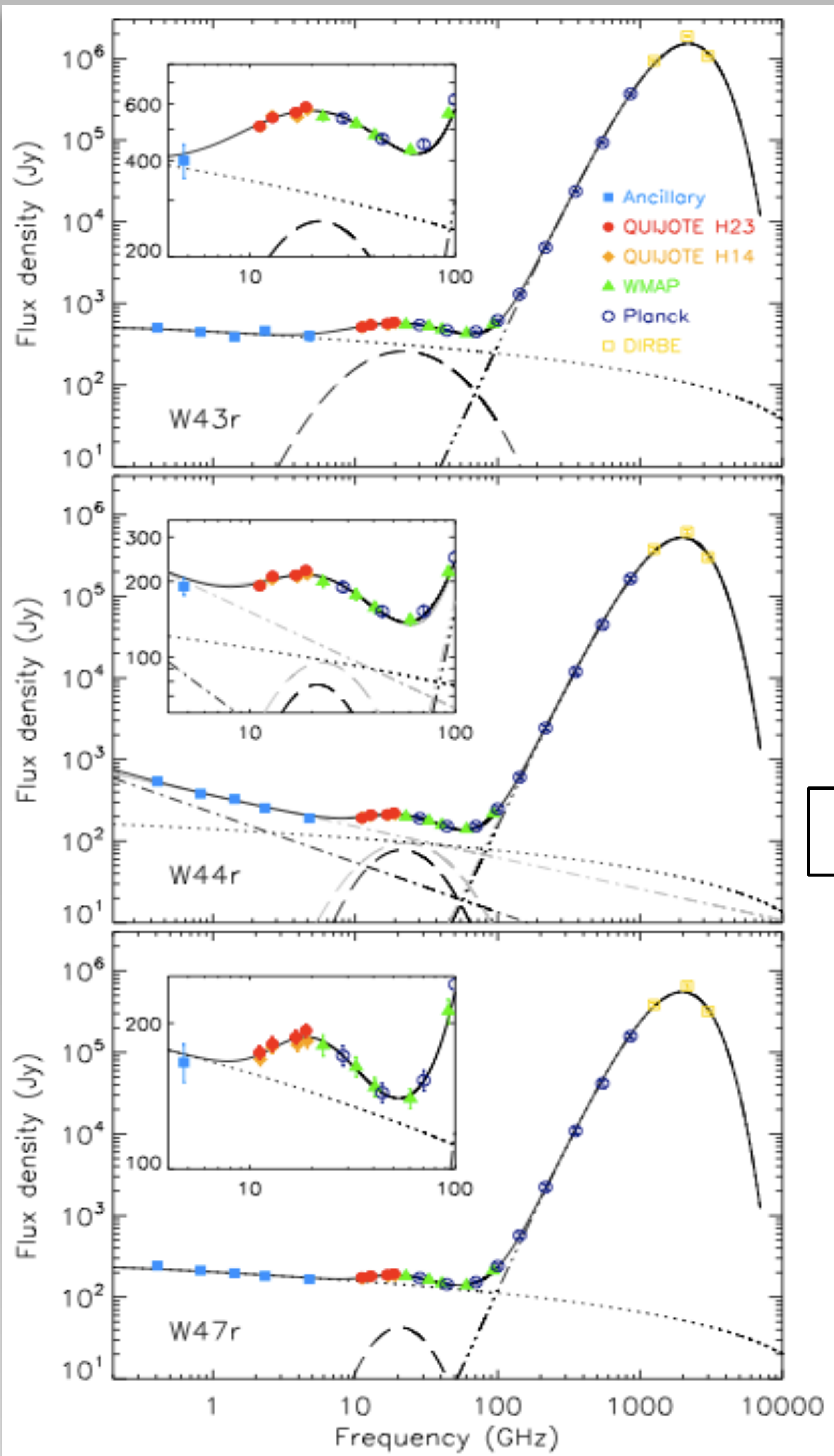
- Galactic plane survey 25º < l < 45º
- W43 and W47 are molecular complexes, and W44 is a SNR

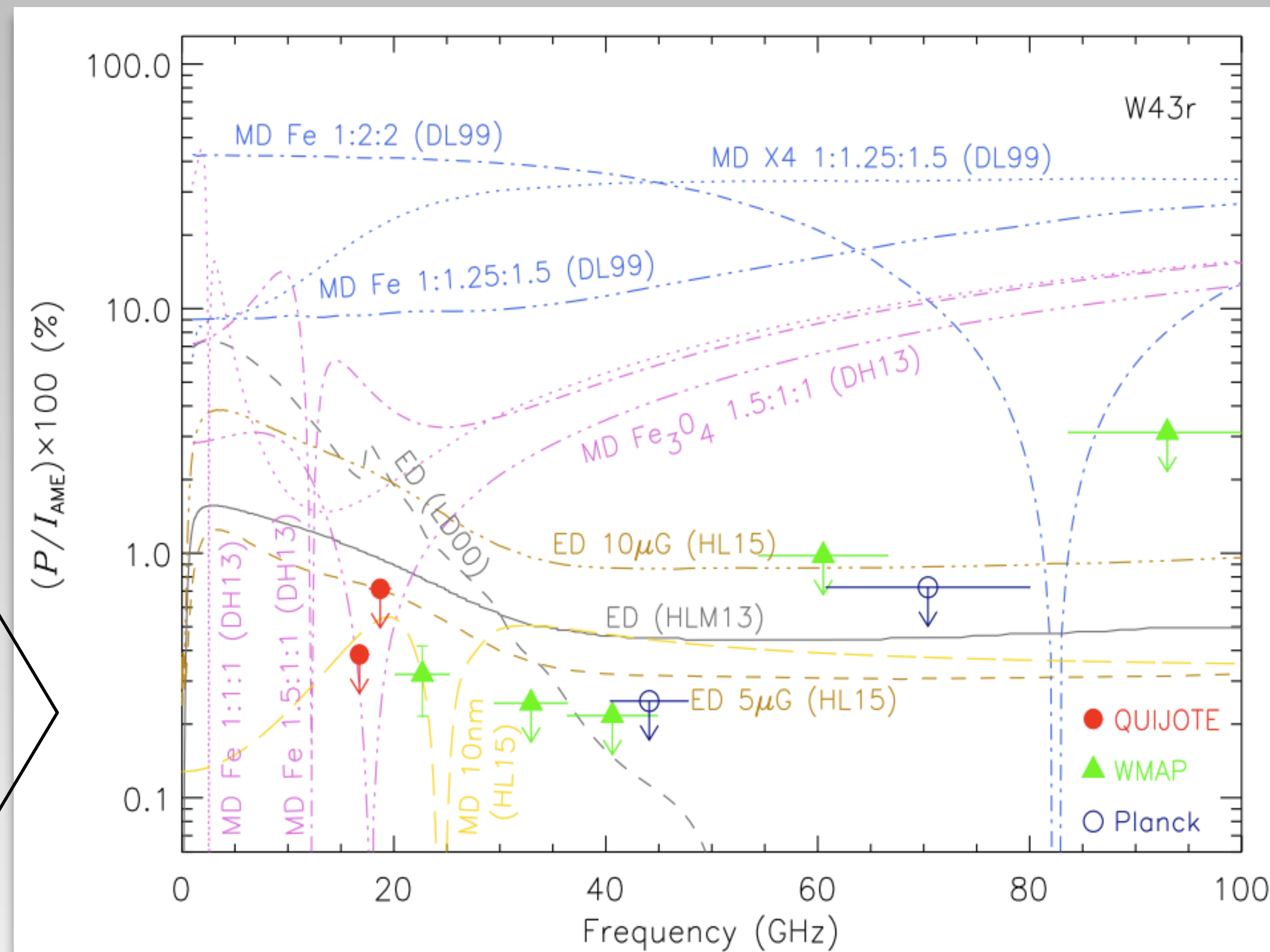


QUIJOTE

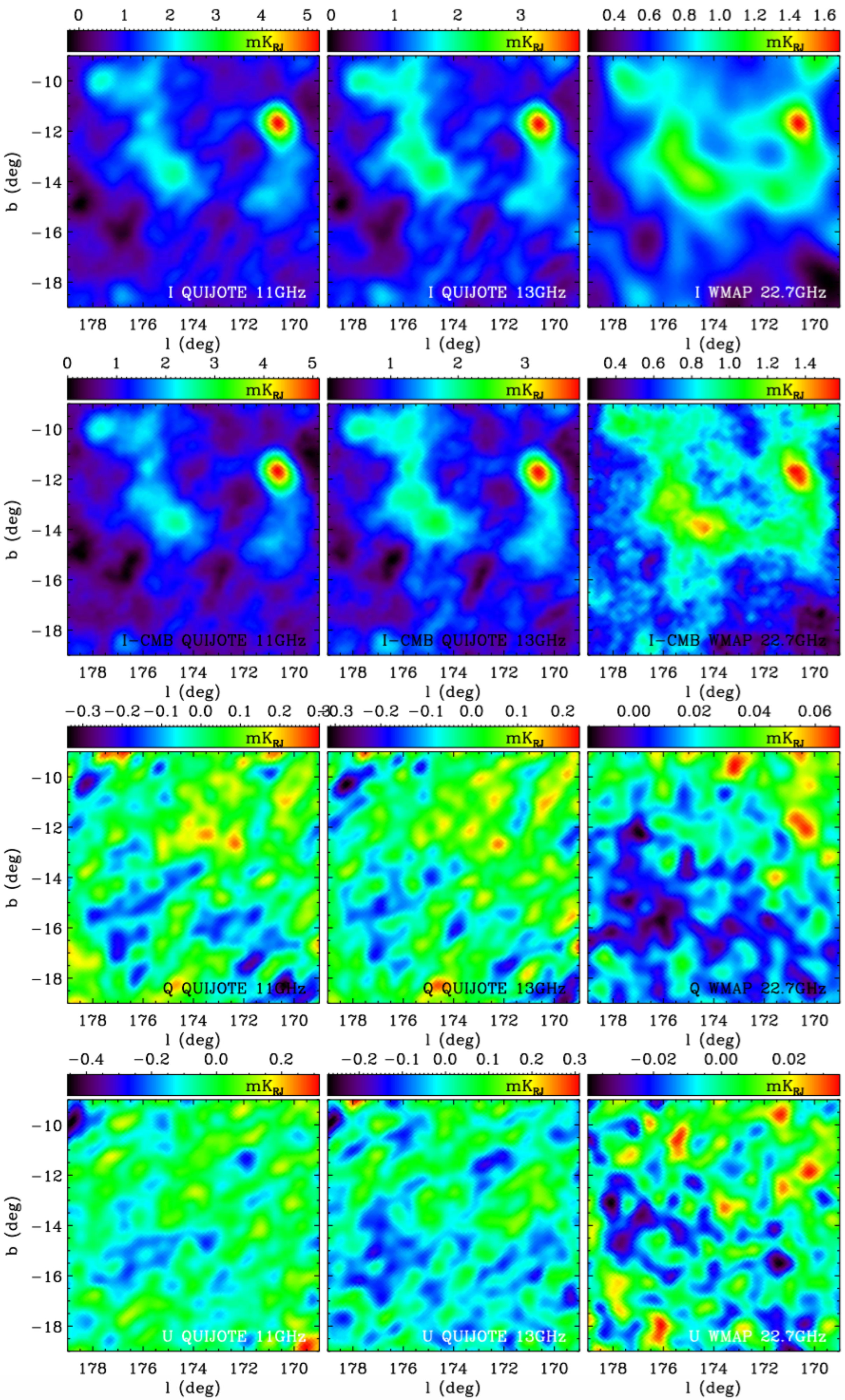
W43, W44 and W47

Génova-Santos et al. (2017)





Constraints on the AME polarisation fraction, inconsistent with optimised conditions of many models!



The Taurus Molecular Cloud Complex

Poidevin al. (in prep.)

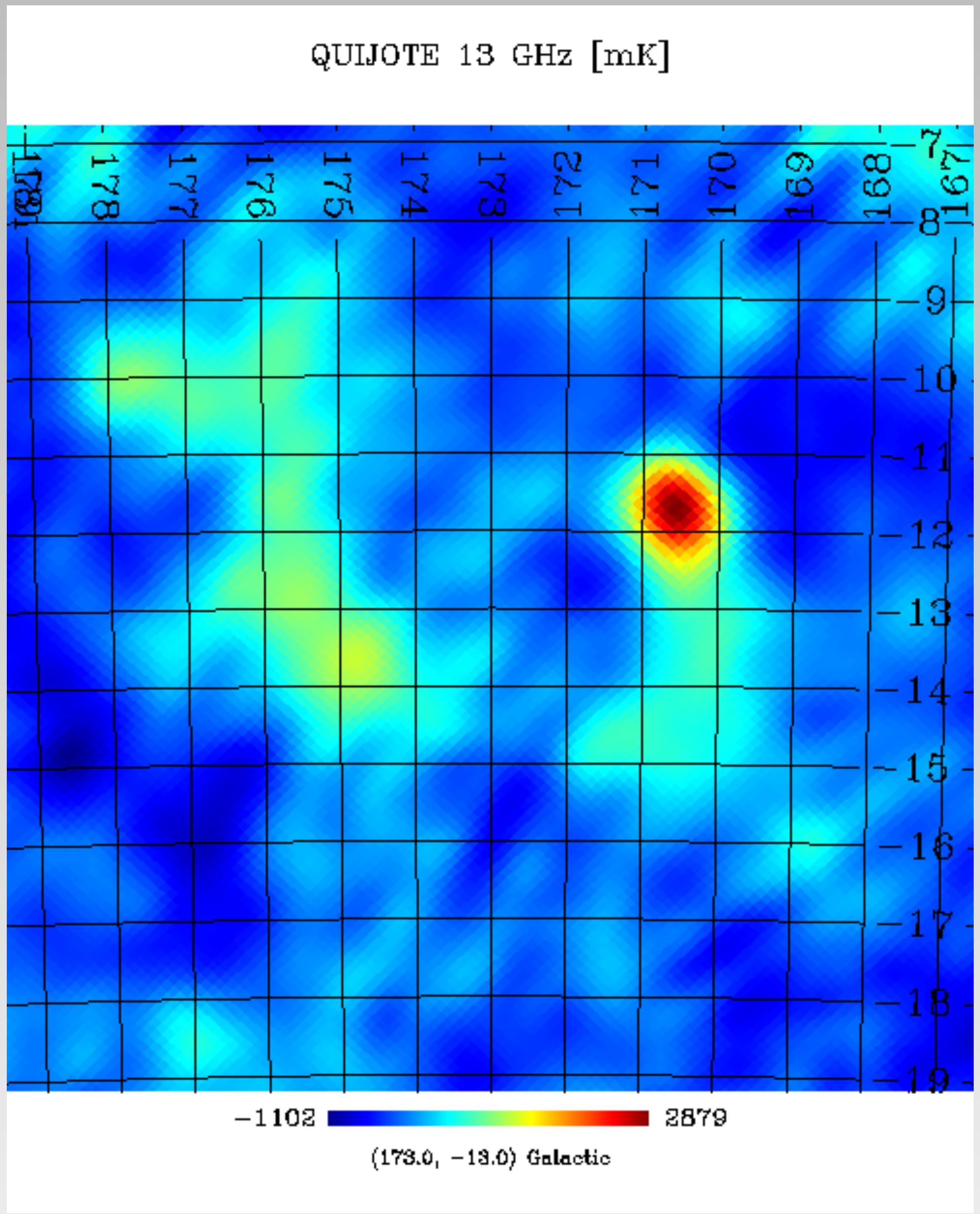
- **Map obtained from of about 423 hours of observations**
- **RFI filtered**
- **I,Q,U Stokes parameters maps**
- **Taurus is a faint region at the MFI frequencies -> CMB subtracted at the map level**

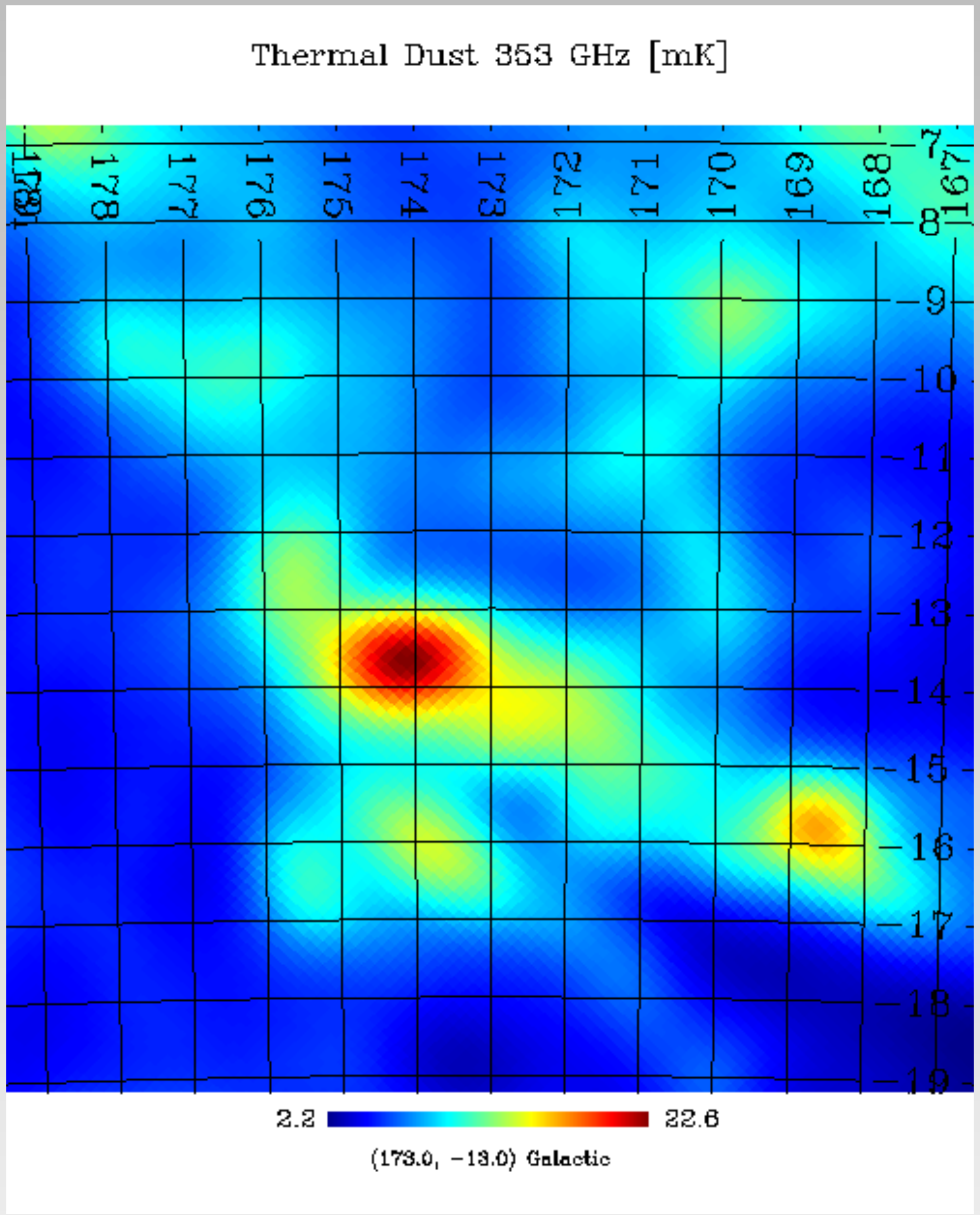
Horn	Freq. (GHz)	σ_I (μK/beam) Map	σ_I (μK/beam) JK	σ_Q (μK/beam) Map	σ_Q (μK/beam) JK	σ_U (μK/beam) Map	σ_U (μK/beam) JK	$\sigma_{Q,U}$ (mK s$^{1/2}$) JK
1	11	77.3	57.1	21.1	16.3	24.4	18.9	1.0
1	13	54.7	41.5	17.0	12.2	15.8	12.4	0.7
2	17	132.5	89.4	30.6	20.9	21.4	21.6	1.1
2	19	193.8	138.2	34.3	32.4	34.0	40.2	1.8
3	11	87.8	66.8	26.4	17.9	26.9	18.5	1.0
3	13	65.6	50.2	27.2	19.5	27.5	20.7	1.1
4	17	147.7	103.8	23.3	17.5	23.4	19.6	0.9
4	19	201.9	140.6	34.5	22.6	30.1	29.8	1.3

Maps sensitivities

Taurus Complex

Poidevin al. (In Prep.)





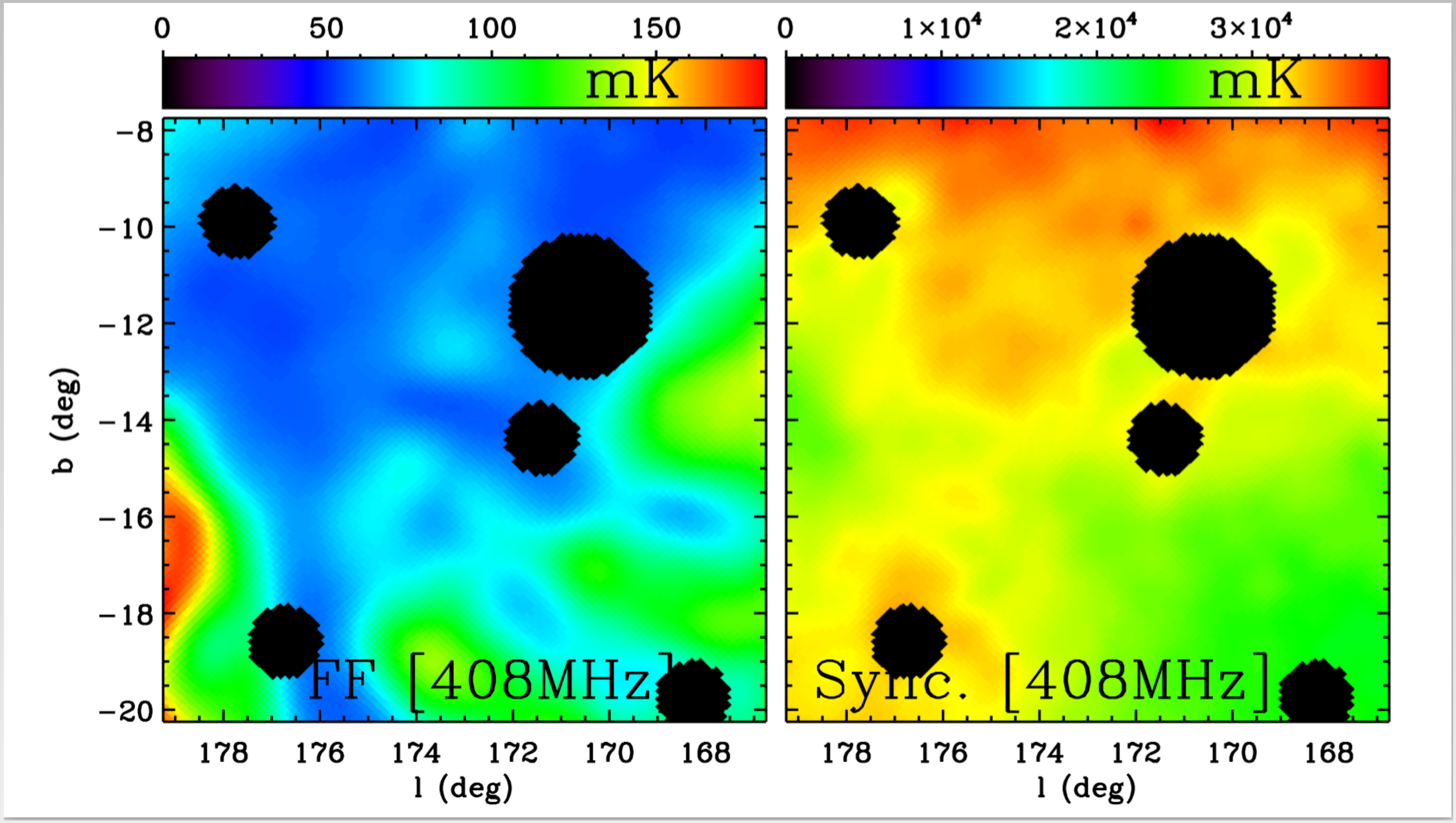
Left: QUIJOTE map at 13 GHz - Right: Planck map at 353 GHz

The QUIJOTE map mainly probe AME while the Planck map probe Thermal Dust.

QUIJOTE

Taurus Complex

Poidevin al. (In Prep.)



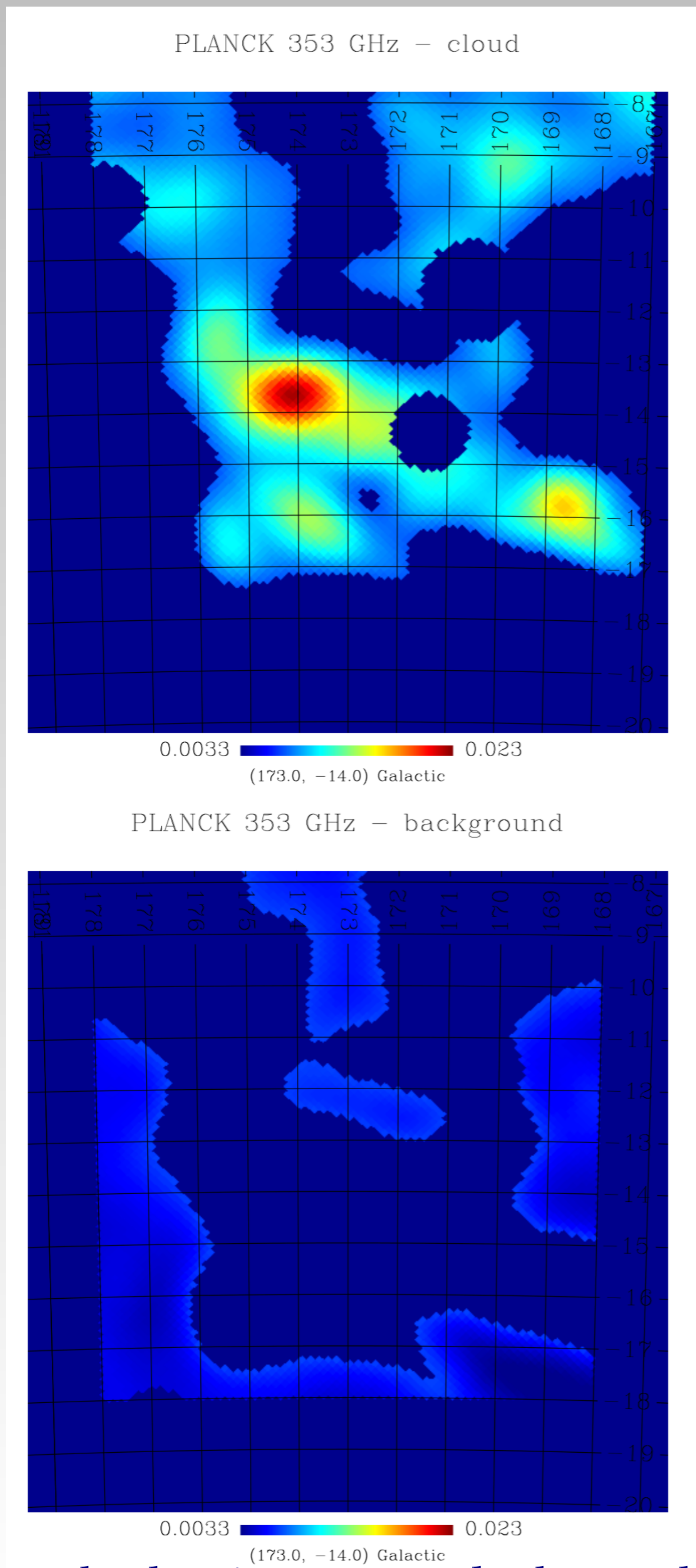
Left: Free-Free map as calculated from the H(alpha) map (Dickinson etal. 2003).

Right: Synchrotron map once the Free-Free has been subtracted.

-> The Free-Free contribution in the Taurus region is of order a fraction of a percent in the temperature maps at 0.408 GHz and 1.420 GHz.

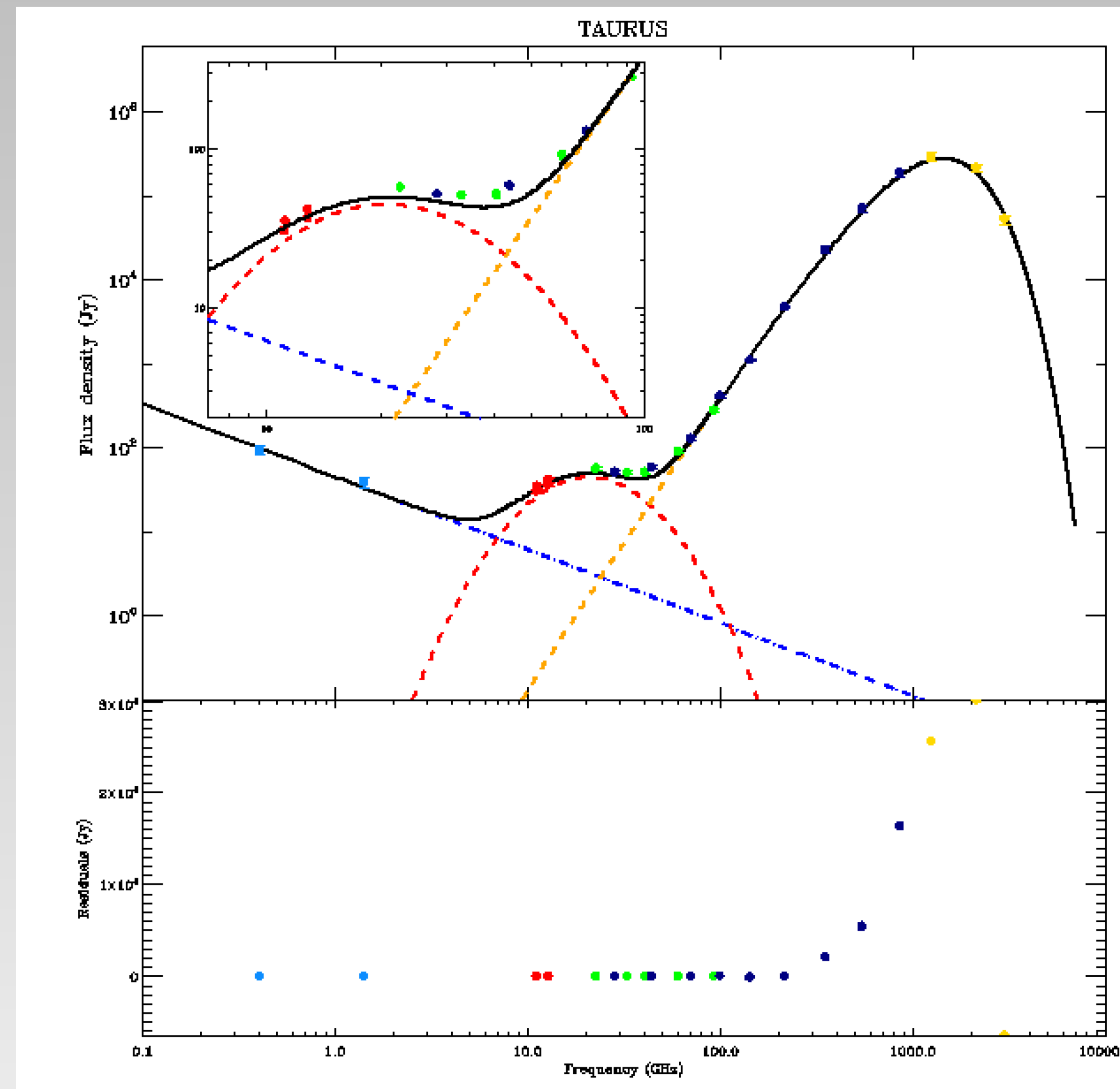
The Taurus Molecular Cloud Complex

Poidevin al. (in prep.)



Top: cloud region. Bottom: background

Characterisation of the AME with the QUIJOTE 11 GHz and 13 GHz maps.



SED Component Separation Parameter	Value
EM (cm^6/pc)	0.3 +/- 79.8
Amplitude of the free-free at 1 GHz (Jy)	0.0 +/- 8.8
Amplitude of the synchrotron at 1 GHz (Jy)	45.6 +/- 6.9
Beta of the synchrotron at 1 GHz	-0.87 +/- 0.12
Frequency of the peak of the spinning dust emission (GHz)	21.0 +/- 0.0
Maximum spinning dust emission (Jy)	44.1 +/- 0.0
Tdust (K)	15.5 +/- 0.6
beta dust (K)	1.52 +/- 0.07
tau250 (K)	0 .0043 +/- 0.0008

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.

CMB polarization experiments

Name	Platform	Area [°]	FWHM	Freq [GHz]	Detectors	r_{lim}	Starts
BICEP	Ground	800	$\sim 1°$	100,150	PSB bol.	0.1	2010
QUIET-II	Ground	1600	4'-30'	40,90	MMIC HEMT	0.01	2010
QUIJOTE	Ground	5000	$\sim 1°$	10-40	MMIC HEMT	0.05	2012
PolarBear	Ground	1200	3'-7'	90,150,220	TES Bol.	0.01	2012
QUBIC	Ground	800	$\sim 1°$	90,150,220	Bol. Interf.	0.01	2014
ACTPol	Ground	4000	$\sim$ 1'	150,218,277	Bolometer	0.03?	2013
SPTPol	Ground	500	1'-1.6'	100,150,220	TES Bol.	0.03	2013
EBEX	Balloon	350	8'	150,250,350,450	TES Bol.	0.03	2012
SPIDER	Balloon	24000	17'-50'	90,145,280	TES Bol.	0.03	2013
LSPE	Balloon	9500	30'	40-250	Bol.+HEMTs	0.03	2015
Planck	Satellite	Full sky	5'-33'	30-353	MMIC/Bol.	0.05	2009
LiteBIRD	Satellite	Full sky	30'	50-270	TES Bol.	0.001	2020
PIXIE	Satellite	Full sky	1.6°	30-6000	Bolometers	0.0005	2018?
EPIC/CMBPol	Satellite	Full sky	~10'	30-300	Bolometers	0.001	2025?

Conclusions

- Studies of the CMB temperature anisotropies, reflecting scalar (density) perturbations in the LSS 380,000 years after the Big Bang, have consolidated the ΛCDM model
- The study of the polarization of the CMB opens a new window to study tensor (gravitational waves) perturbations from the inflationary epoch only 10^{-36}s after the Big Bang
- Detection of the B-mode signal requires i) high sensitivity in large angular scales, ii) accurate characterisation and subtraction of foregrounds (thermal dust, but also maybe synchrotron)
- Therefore we need: i) high number of detectors with good sensitivity, ii) large sky coverage, iii) accurate control of systematics, iv) different frequency channels with wide frequency coverage (⇒ combination of different technologies)
- QUIJOTE covers 10-40 GHz (synchrotron, spinning dust). One year of observations with the TGI could allow to reach a sensitivity r=0.1. Three years TGI+FGI would allow r=0.05
- Joint QUIJOTE+GroundBIRD (same angular resolution, different frequencies) analysis could potentially allow for even more stringent r constraints, and simultaneous correction for synchrotron+dust for possible future experiments operating at intermediate frequencies (~90 GHz)