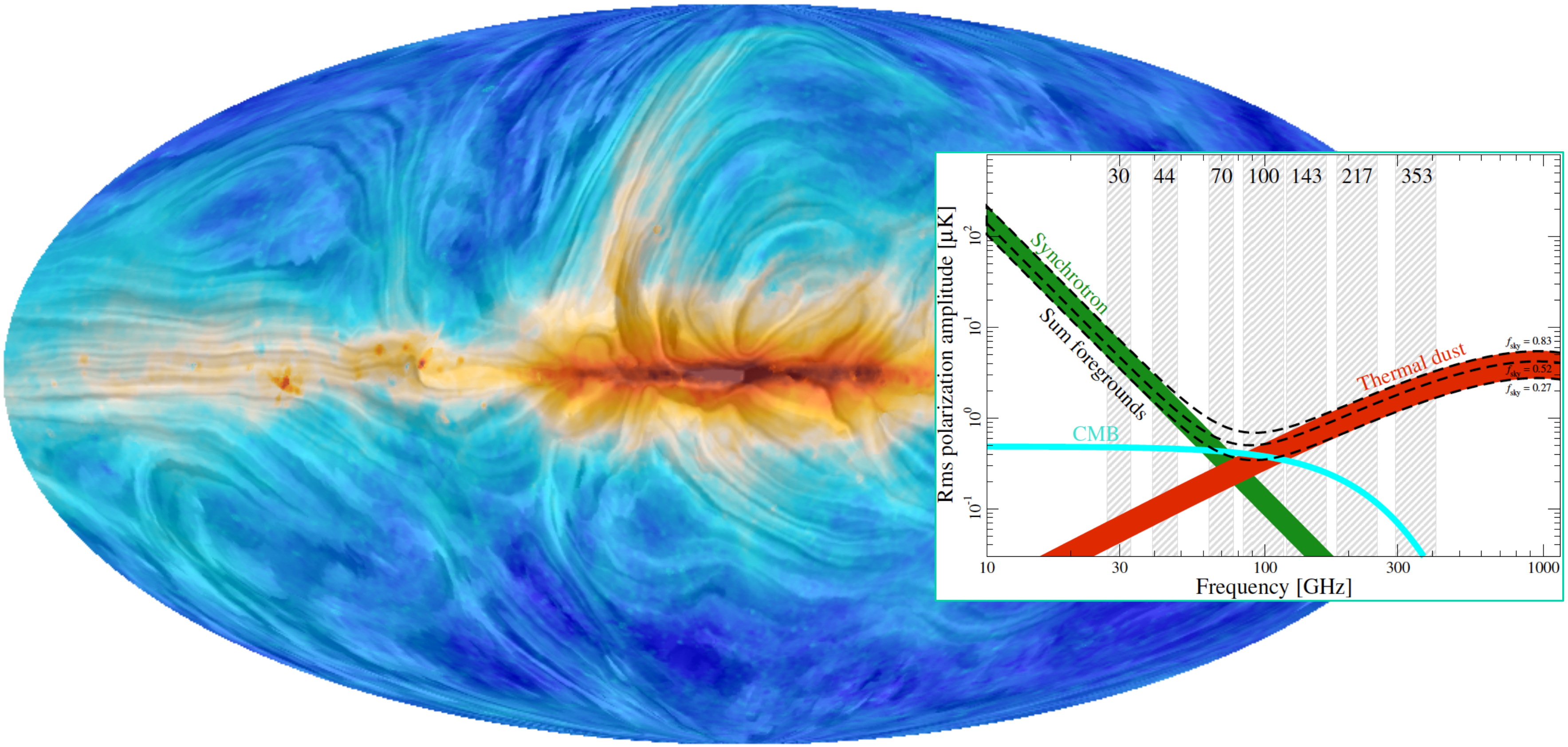
A full-sky synchrotron survey



J.A. Rubiño-Martín (IAC)

With contributions from: M. Bersanelli, C. Baccigalupi, P. Casas, R. Genova-Santos, M. Jones, E. Martinez-Gonzalez, A. Taylor

Florence, September 20-21, 2018

A full-sky synchrotron survey

- **Experimental landscape in Europe at low frequencies.**
  - Past experience at low frequencies (pre-Planck, PLANCK).
  - Observing sites.
  - Current Small aperture telescopes at low-frequencies (<100GHz): C-BASS, QUIJOTE, STRIP, KISS, others.

- **Modelling low frequency foregrounds for B-mode studies.**
  - Current view from existing experiments at low frequencies.
  - Synchrotron modeling.
  - AME polarization?

- **On-going mid-term activities.**
  - Towards a full-sky synchrotron survey.
- **Long-term plan.**
  - Full-sky synchrotron survey → next talk by A. Taylor.

A full-sky synchrotron survey

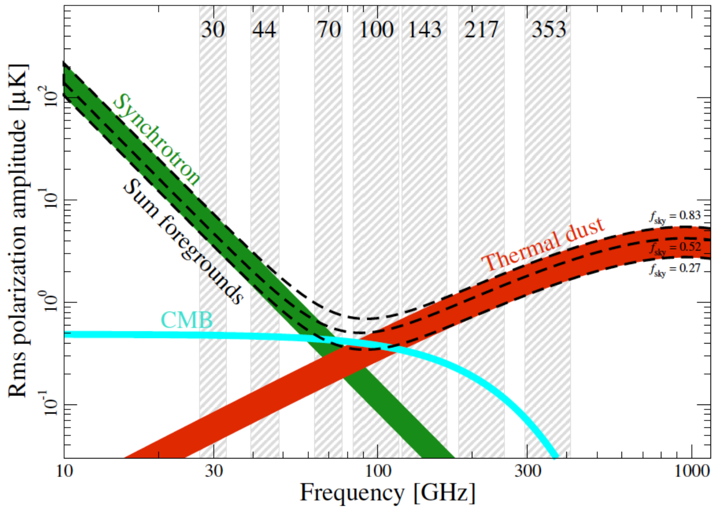
- **Experimental landscape in Europe at low frequencies.**
  - Past experience at low frequencies (pre-Planck, PLANCK).
  - Observing sites.
  - Current Small aperture telescopes at low-frequencies (<100GHz): C-BASS, QUIJOTE, STRIP, KISS, others.

- **Modelling low frequency foregrounds for B-mode studies.**
  - Current view from existing experiments at low frequencies.
  - Synchrotron modeling.
  - AME polarization?

- **On-going mid-term activities.**
  - Towards a full-sky synchrotron survey.
- **Long-term plan.**
  - Full-sky synchrotron survey → next talk by A. Taylor.

Experimental landscape at low frequencies

- **Low frequencies**: those around a below the foreground minimum (< 100GHz).
- **HEMT-based** instruments have shown to have good performances (stability, 1/f noise, low noise, …) for CMB observations up to 70GHz. In Europe: Tenerife, Planck-LFI, C-BASS, QUIJOTE. They have also been used for **interferometry**: e.g. VSA, AMI. Potential use for **spectroscopy**.
- **KIDs** detectors have excellent performances above 80GHz. E.g. OLIMPO, NIKA, NIKA2, KISS, Groundbird.



Planck Collaboration: *Planck* 2013 results. I.

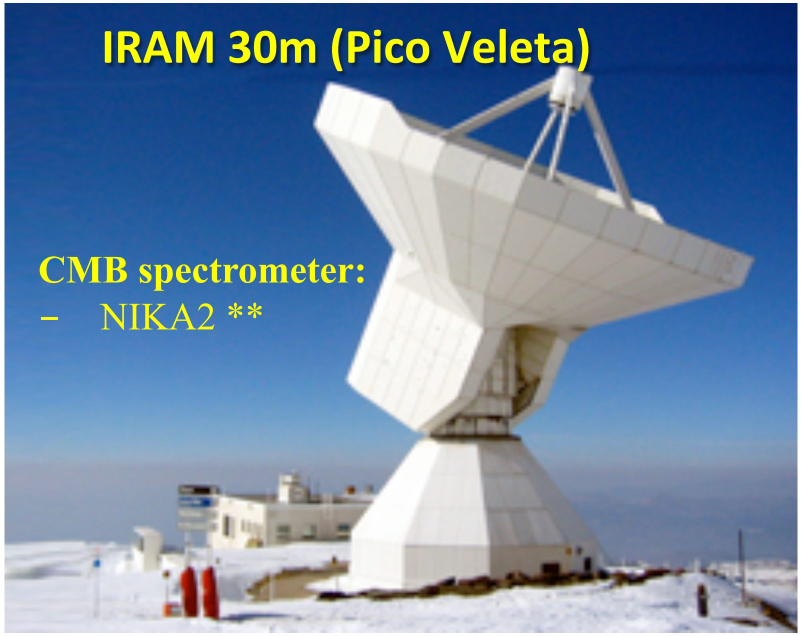
Table 2. *Planck* performance parameters determined from flight data.

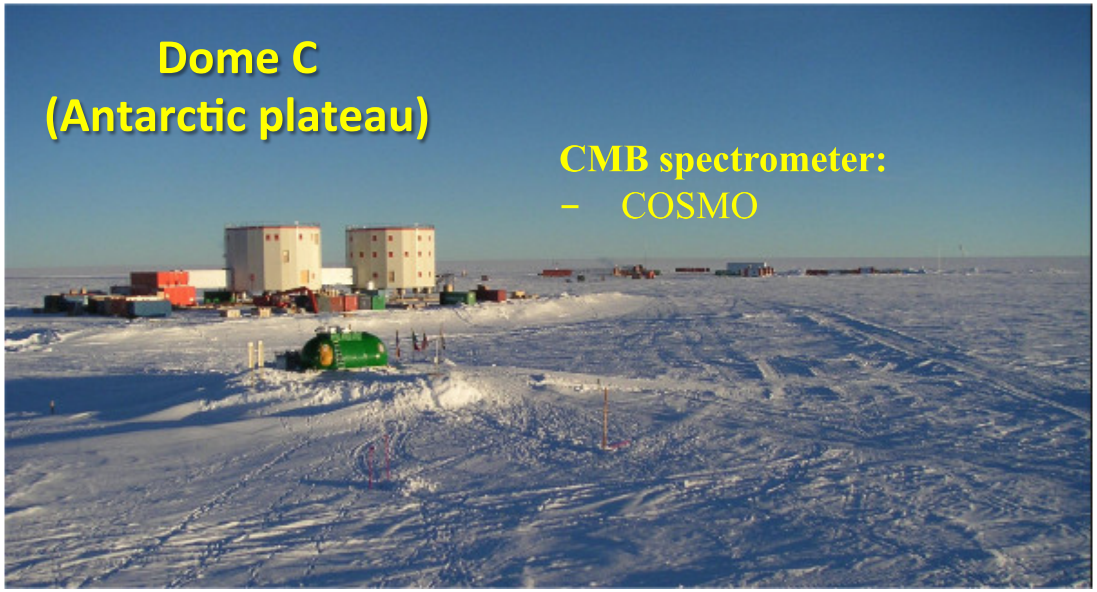
Channel	$N_{detectors}$[a]	ν_{centre}[b] [GHz]	Scanning beam[c] *FWHM* [arcm]	Scanning beam[c] Ellipticity	Noise[d] sensitivity [μK_{RJ} $s^{1/2}$]	Noise[d] sensitivity [μK_{CMB} $s^{1/2}$]
30 GHz	4	28.4	33.16	1.37	145.4	148.5
44 GHz	6	44.1	28.09	1.25	164.8	173.2
70 GHz	12	70.4	13.08	1.27	133.9	151.9
100 GHz	8	100	9.59	1.21	31.52	41.3
143 GHz	11	143	7.18	1.04	10.38	17.4
217 GHz	12	217	4.87	1.22	7.45	23.8
353 GHz	12	353	4.7	1.2	5.52	78.8
545 GHz	3	545	4.73	1.18	2.66	0.026[d]
857 GHz	4	857	4.51	1.38	1.33	0.028[d]

Notes. [(a)] At 30, 44, and 70 GHz, each *detector* is a linearly polarized radiometer, and there are two orthogonally polarized radiometers behind each horn. Each radiometer has two diodes, both switched at high frequency between the sky and a blackbody load at ~4.5 K (Mennella et al. 2011). At 100 GHz and above, each *detector* is a bolometer (Planck HFI Core Team 2011a). Most of the bolometers are sensitive to polarization, in which case there are two orthogonally polarized detectors behind each horn. Some of the detectors are spider-web bolometers (one per horn) sensitive to the total incident power. Two of the bolometers, one each at 143 and 545 GHz, are heavily affected by random telegraphic signals (RTS; Planck HFI

planck

European CMB experiments & sites





(** = in operation)

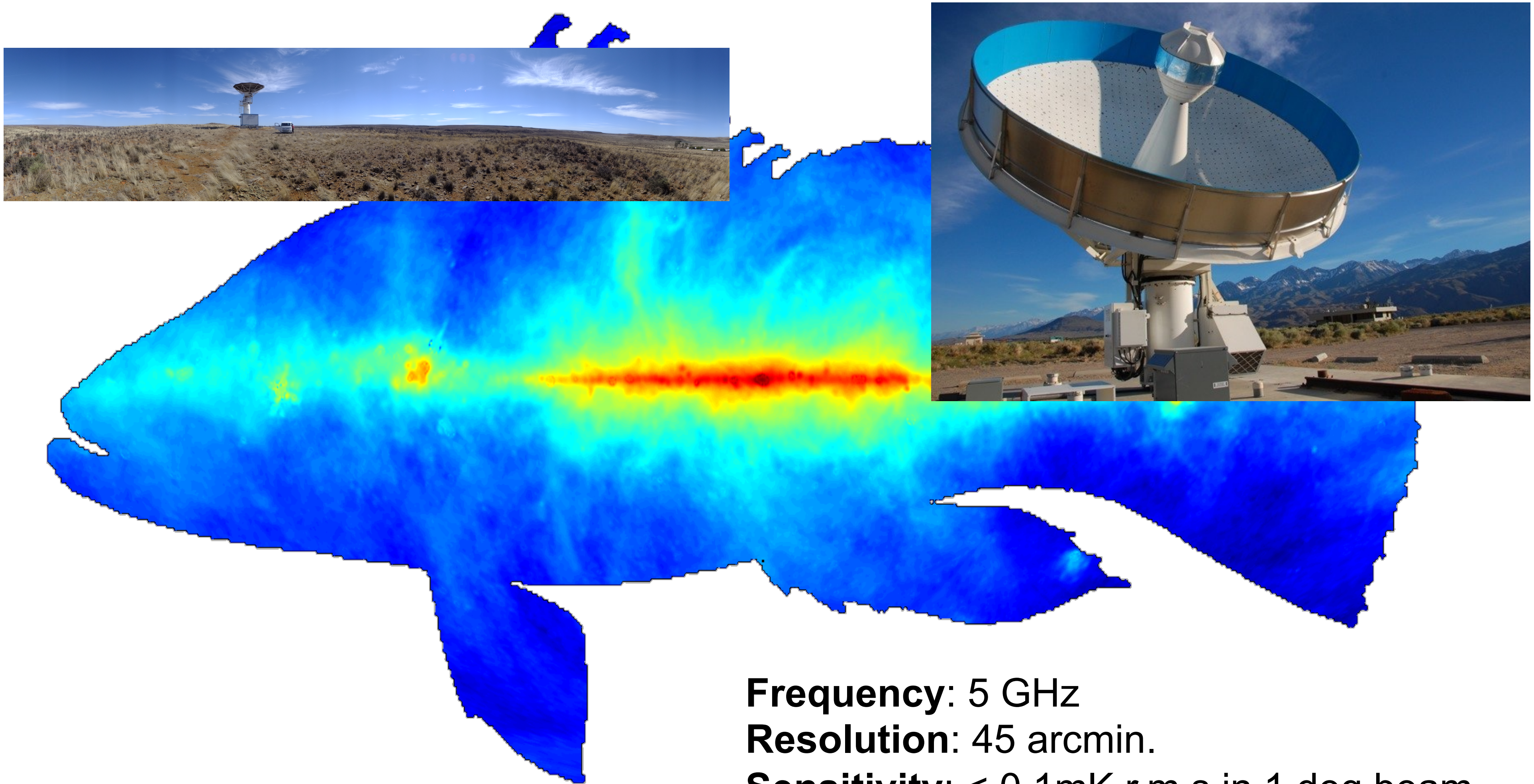
(J.A. Rubiño. Florence 2017, https://indico.in2p3.fr/event/14661/timetable)

Other sites & other wavelenghts

- **S-PASS** (S-band Polarization All Sky Survey) a polarization survey at 2.4 GHz (Carretti et al 2010, Krachmalnicoff et al 2018). South hemisphere with Parkes radiotelescope. Plans for doing north hemisphere with Sardinia Radio telescope.

- **C-BASS** (C-Band All Sky Survey) at 5 GHz. Two sites (OVRO in north, Karoo in the south). Observations at the northern site completed.

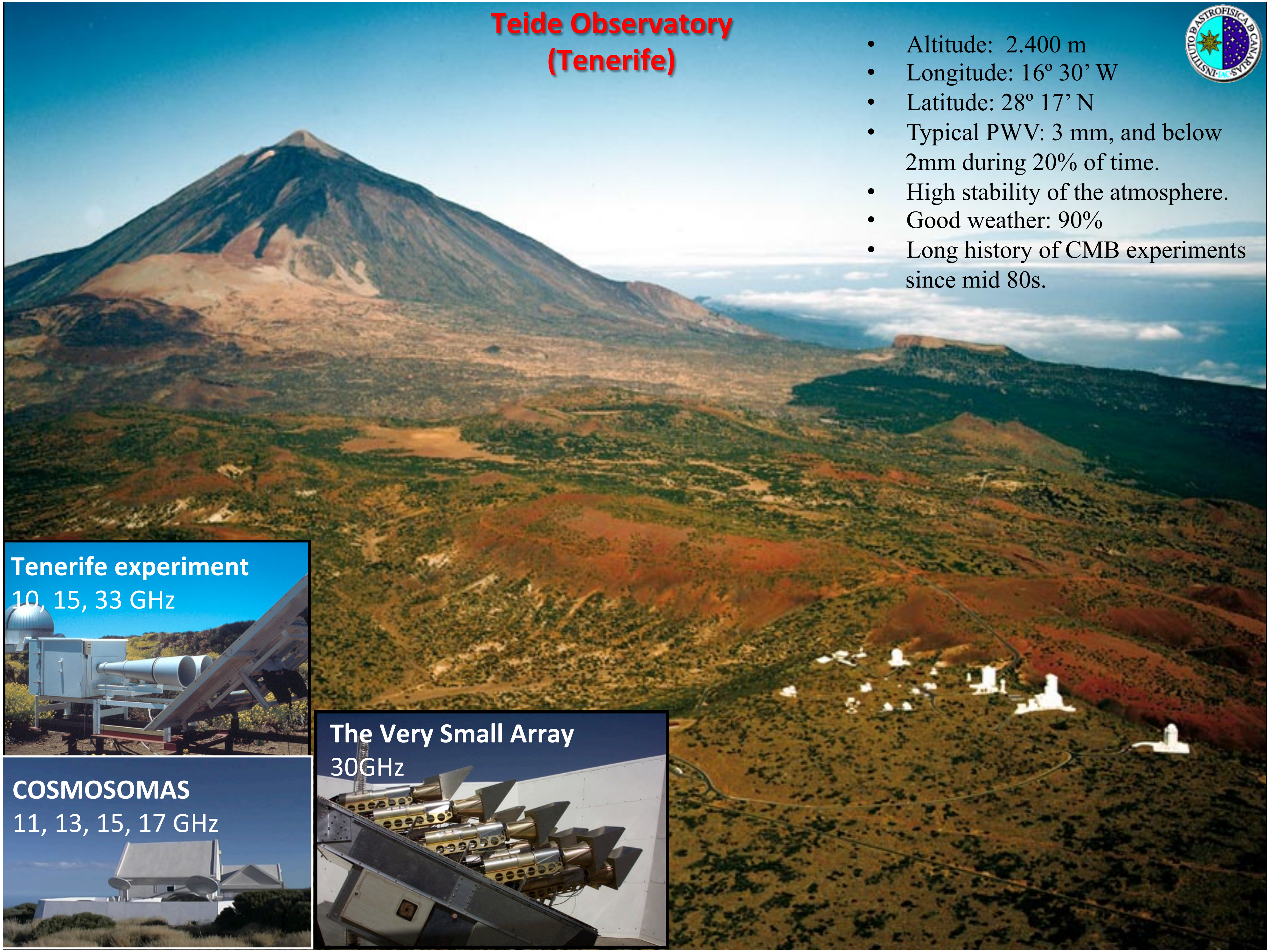
C-Band All-Sky Survey (C-BASS)

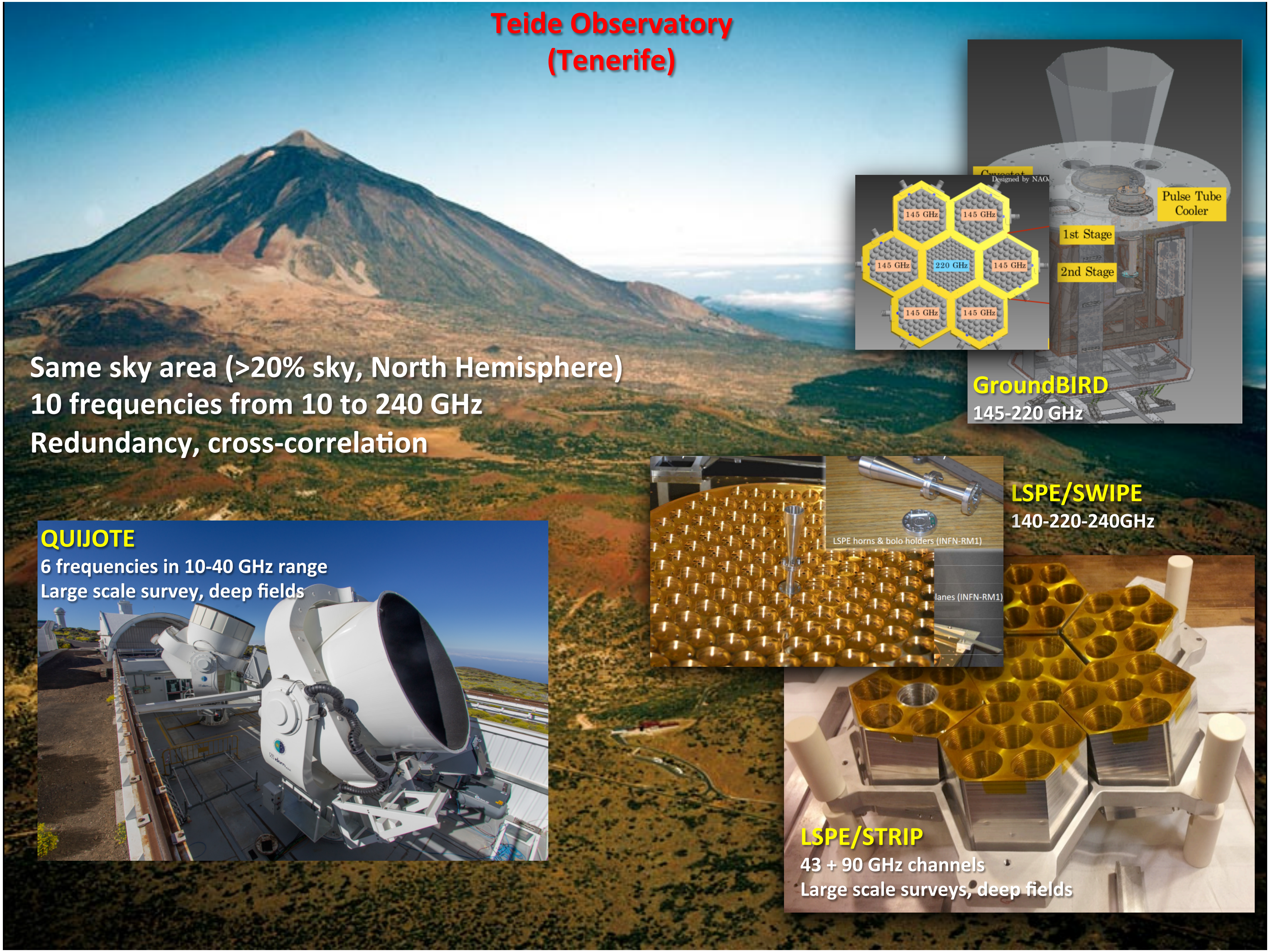


Frequency: 5 GHz
Resolution: 45 arcmin.
Sensitivity: < 0.1mK r.m.s in 1 deg beam

Teide Observatory (Tenerife)

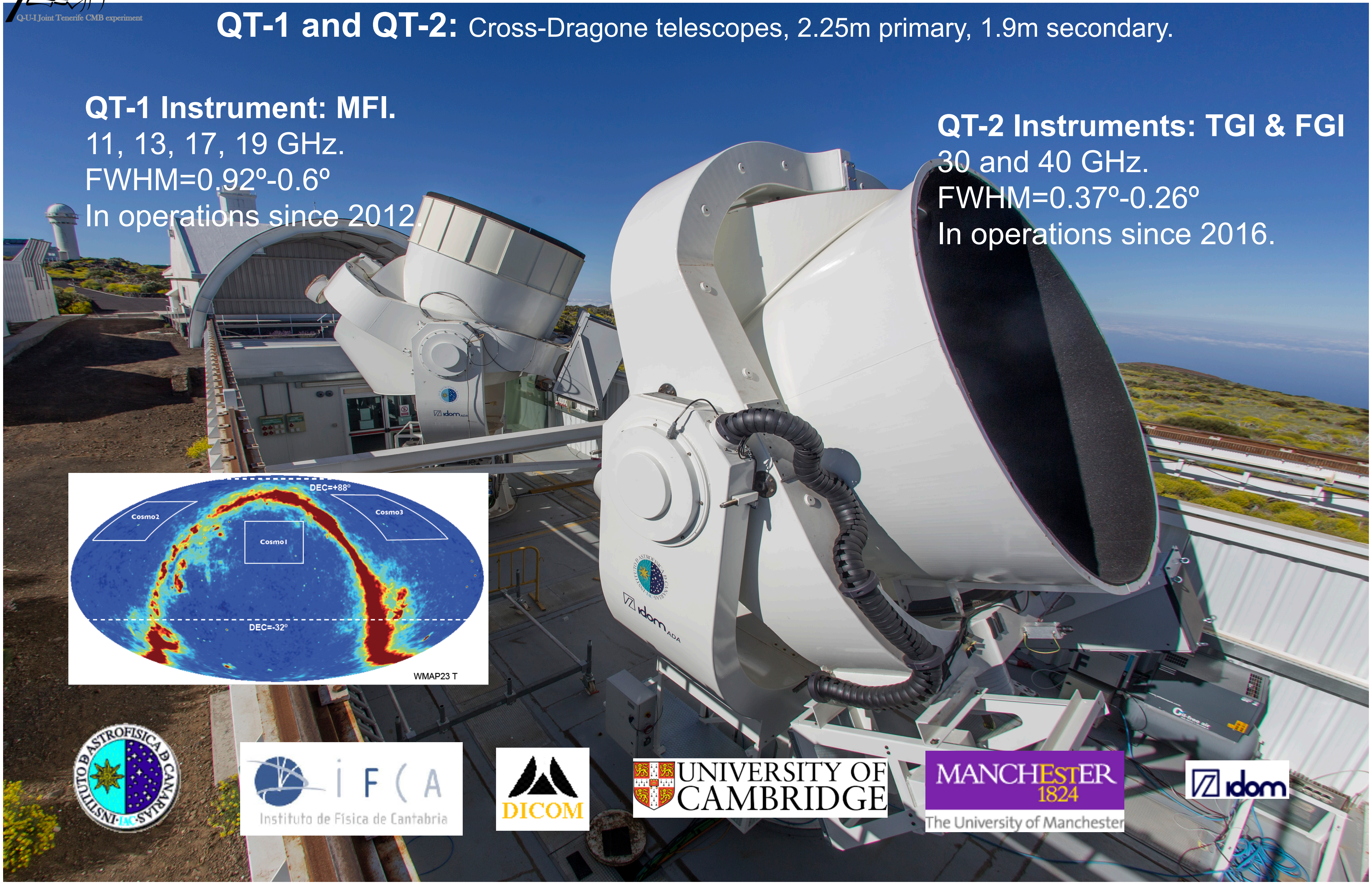
- Altitude: 2.400 m
- Longitude: 16º 30’ W
- Latitude: 28º 17’ N
- Typical PWV: 3 mm, and below 2mm during 20% of time.
- High stability of the atmosphere.
- Good weather: 90%
- Long history of CMB experiments since mid 80s.




Teide Observatory
(Tenerife)
Same sky area (>20% sky, North Hemisphere)
10 frequencies from 10 to 240 GHz
Redundancy, cross-correlation
145 GHz
145 GHz
145 GHz
220 GHz
145 GHz
145 GHz
145 GHz
Pulse Tube
Cooler
1st Stage
2nd Stage
GroundBIRD
145-220 GHz
LSPE horns & bolo holders (INFN-RM1)
LSPE/SWIPE
140-220-240GHz
QUIJOTE
6 frequencies in 10-40 GHz range
Large scale survey, deep fields
LSPE/STRIP
43 + 90 GHz channels
Large scale surveys, deep fields

The QUIJOTE experiment

QT-1 and QT-2: Cross-Dragone telescopes, 2.25m primary, 1.9m secondary.

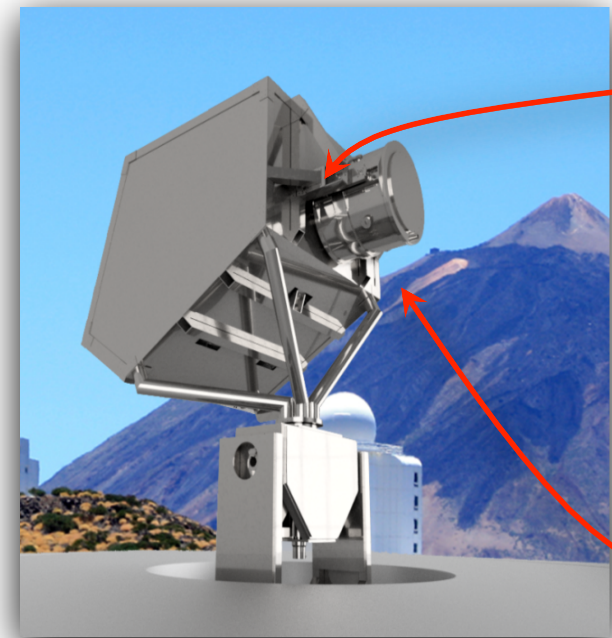


QT-1 Instrument: MFI.
11, 13, 17, 19 GHz.
FWHM=0.92º-0.6º
In operations since 2012.

QT-2 Instruments: TGI & FGI
30 and 40 GHz.
FWHM=0.37º-0.26º
In operations since 2016.

LSPE/STRIP

Deployment at Teide Observatory (Tenerife): Fall 2019

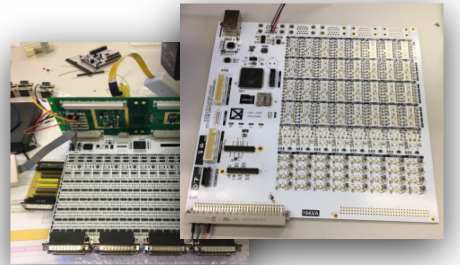


1.5m cross-Dragone telescope

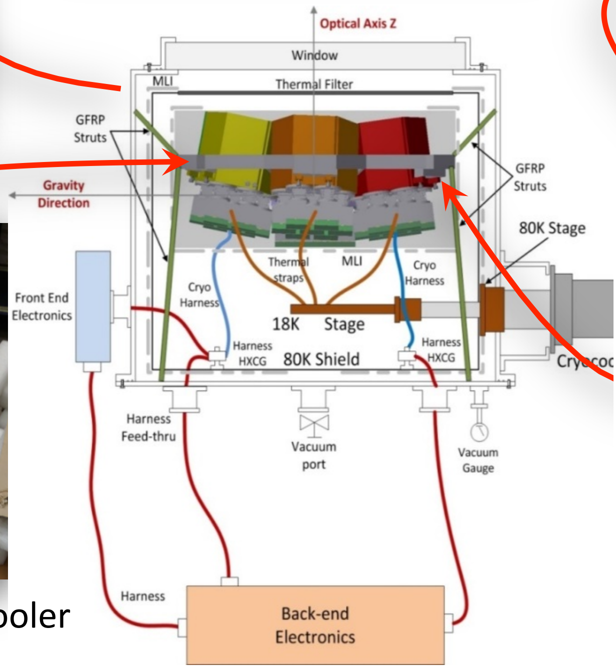
Direct measurement of Q & U, low systematics

Q band: 49-element array, resolution 20’, sensitivity 1.5μK/deg

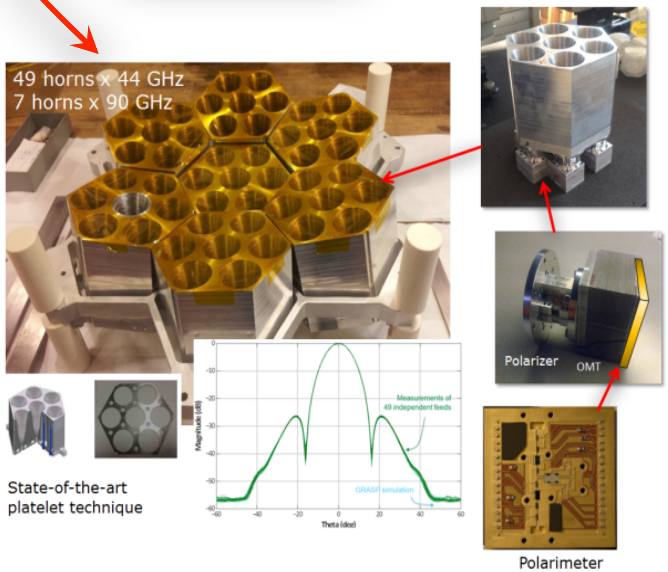
W-band: 6 elements, atmospheric monitor, calibration channel



- STRIP Electronics



- High efficiency 2-stage 18-20K cooler
- Intermediate 80-100K shield



- STRIP focal plane

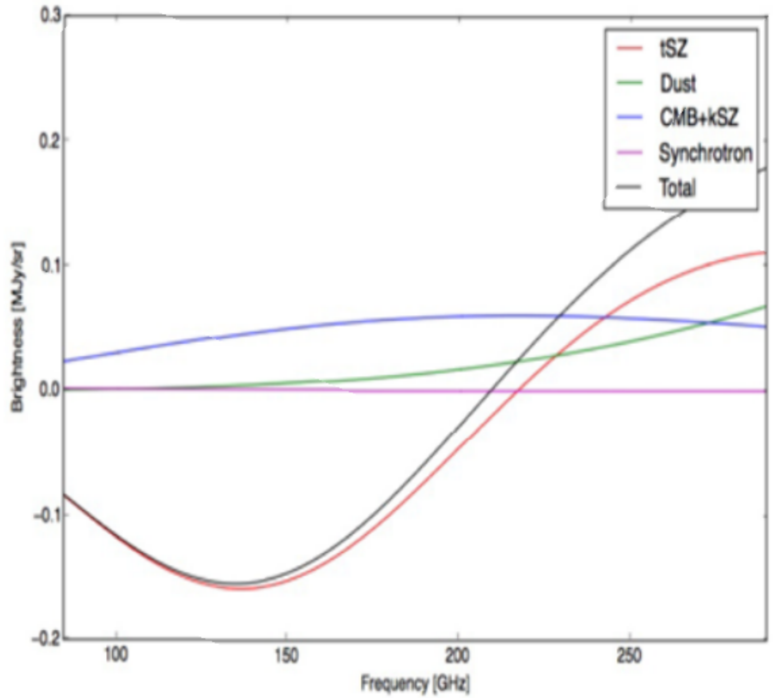
KID Imager-Spectrometer Survey

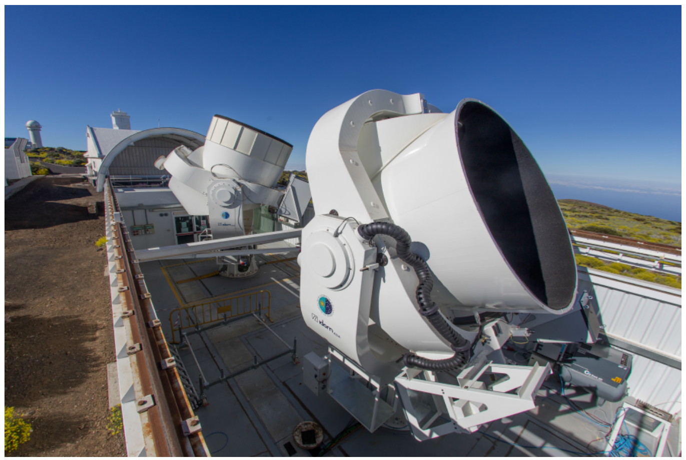
Grenoble (Institut Néel, LPSC & IPAG), Tenerife (IAC) & Roma (La Sapienza)

(see talk from A. Catalano)

Scientific motivation and concept

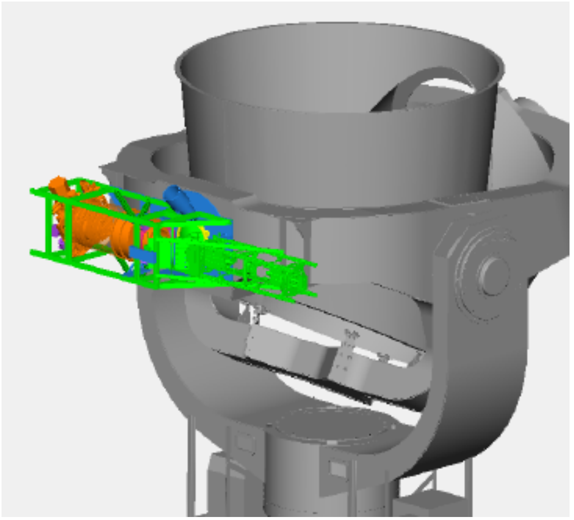
- Use low resolution spectroscopy to separate different components in the millimeter emission of clusters.
- Map low redshift clusters physical properties from their SZ spectral distorsions: pressure (tSZ), temperature (RtSZ), LOS velocity (kSZ)





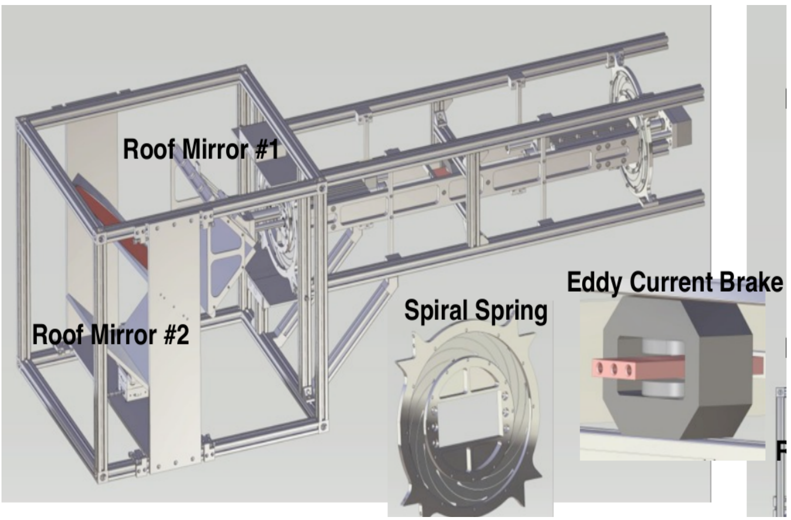
KISS : Low-resolution (Δν = 1-3 GHz) Martin-Puplett interferometer (MPI) coupled to a KID based camera (80-280 GHz). Visitor instrument mounted at QT-1 telescope (Teide Observatory, Tenerife).

Instrument design and status

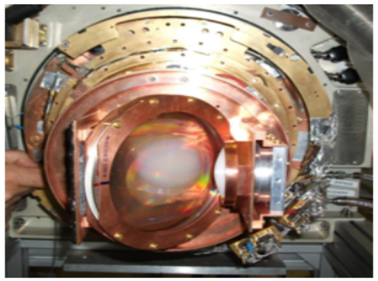


- MPI has been built, currently under test at Grenoble labs.
- NIKA camera has been adapted for KISS optical design
- Large frequency band (80-300 GHz) 500 KID arrays has been constructed
- Readout electronic ready for use

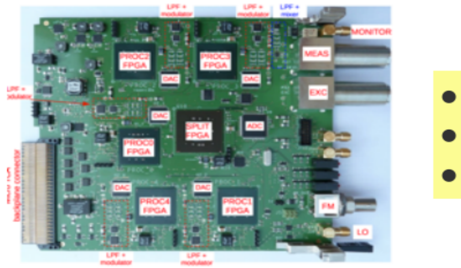
(see talk from A. Catalano)

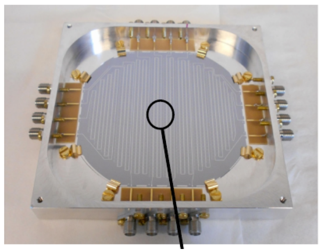


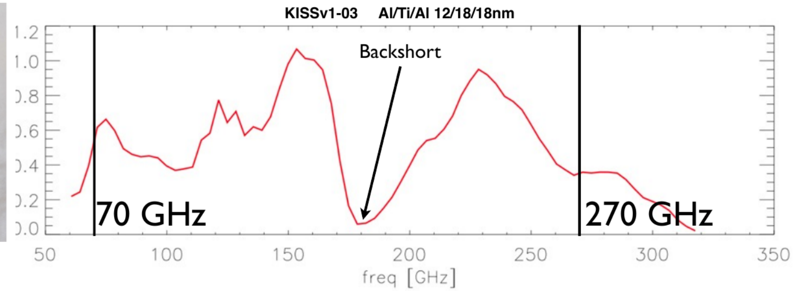
Dilution Cryostat 3He-4He (100 mK)



Frequency Multiplexing Read-Out Electronics : NIKEL







Tenerife Microwave Spectrometer (TMS), 10-20GHz

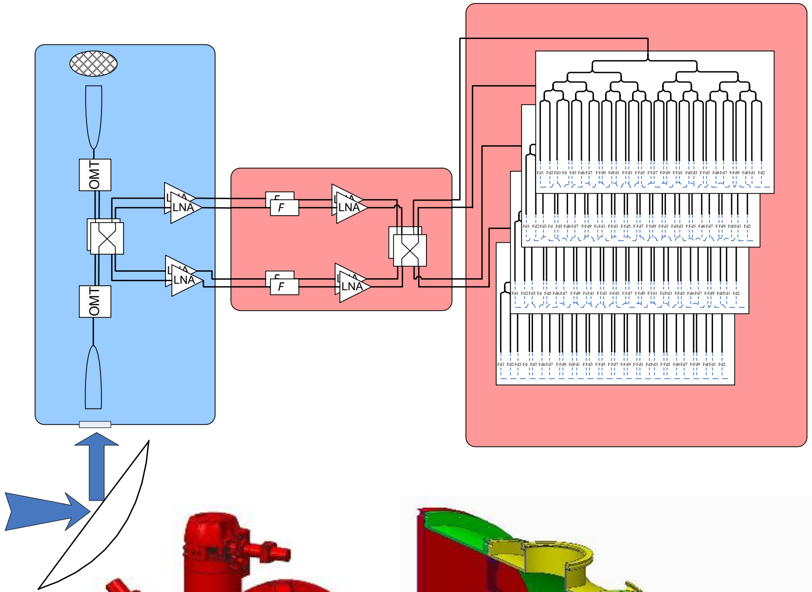
- IAC project. Already funded.

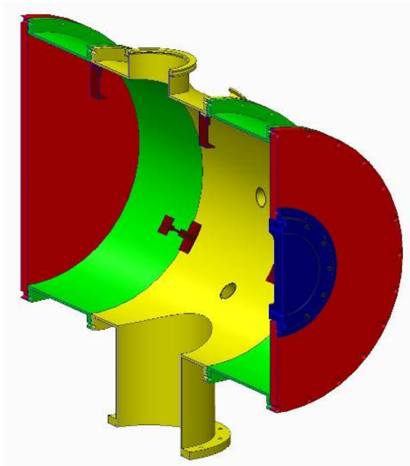
- **Science driver**: Ground-based low resolution spectroscopy observations in the 10-20GHz range to characterize foregrounds (monopole signals; spectral dependence of monopole signals; ARCADE results) and CMB spectral distortions. Provides frequency cross-calibration for QUIJOTE.

- **Proposed instrument**:
  - FEM cooled to 4-10K (HEMTs), reference load to 4K.
  - Novel FTS spectrometer providing √N increase in sensitivity with wideband simultaneous adquisition.
  - ~2deg beam, 0.25 GHz spectral resolution (40 bands).

- **Location**: Teide Observatory (former VSA enclosure).

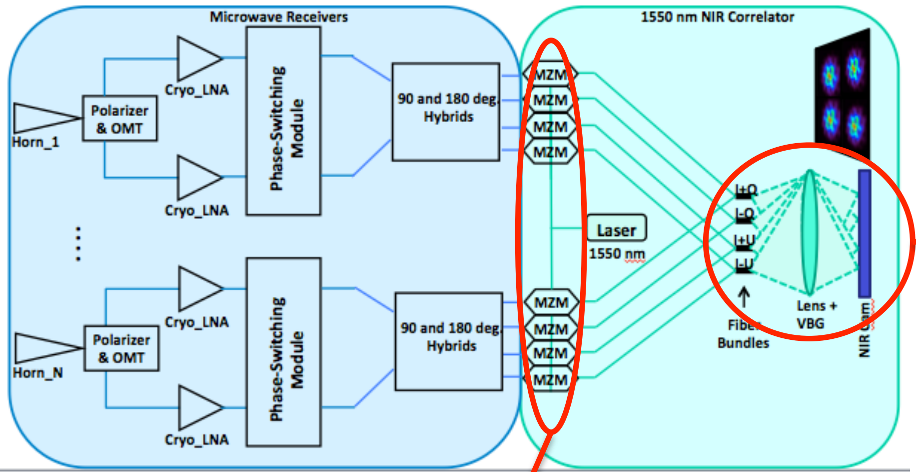
- **Status**: cryostat and cold structure will be received at the IAC in Dec 2018.



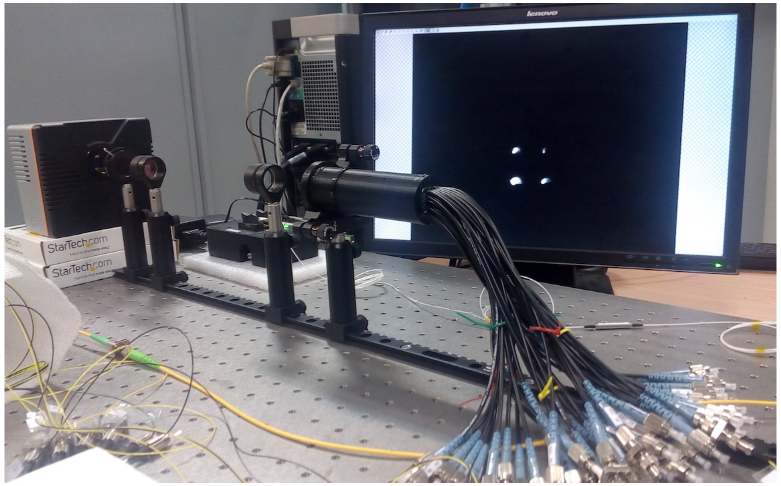


Ongoing Progress Towards a Large Format Interferometer with Optical Correlator.

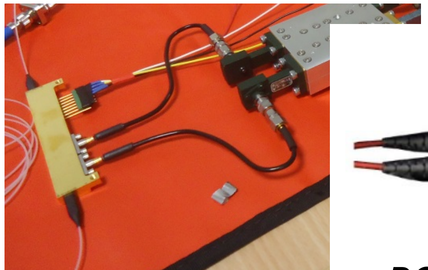
Up-conversion of MW Signals to the NIR



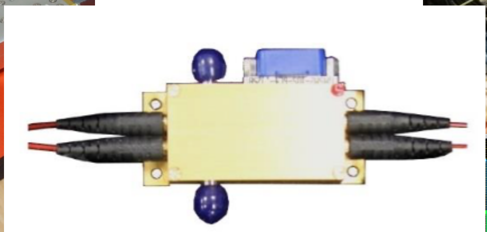
Optical Correlation and Detection



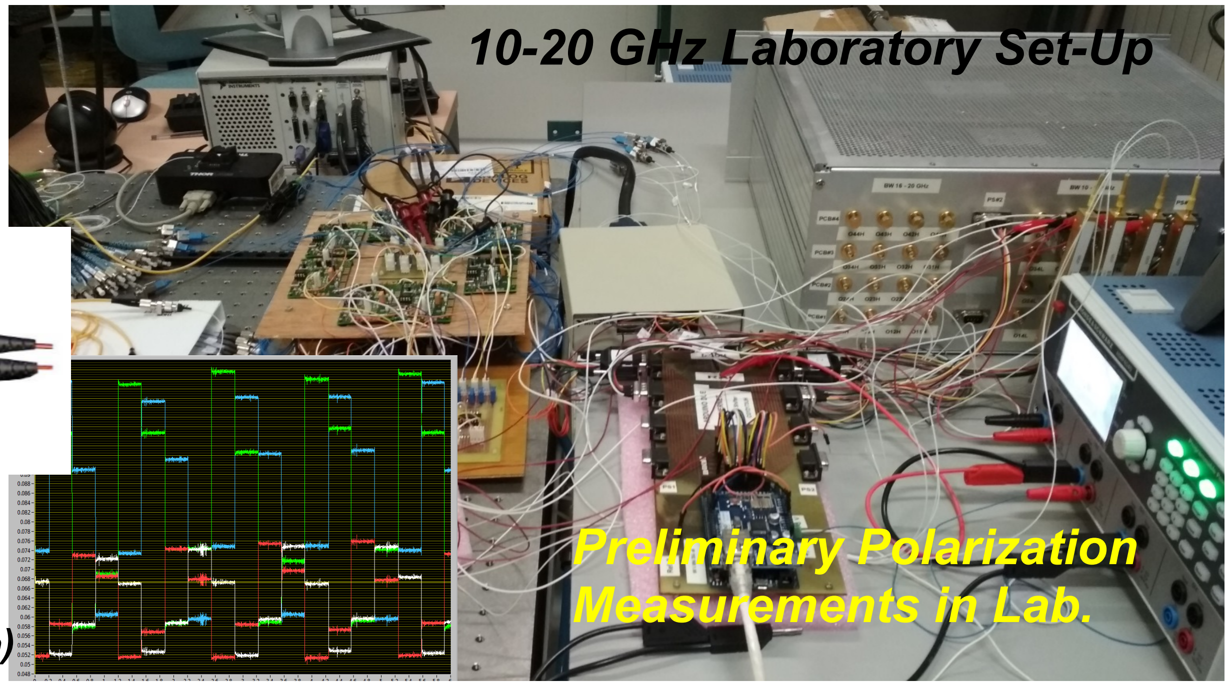
Viability Study: Large-Bandwidth and Integrated Solution for frequency up-conversion of MW Signals



DC-20 GHz Commercial MZM. Non-Integrated $LiNbO_3$ technology from Thorlabs



DC-50 GHz MZM module with 2 units. Integrated InP technology from Fraunhofer HHI (Berlin)

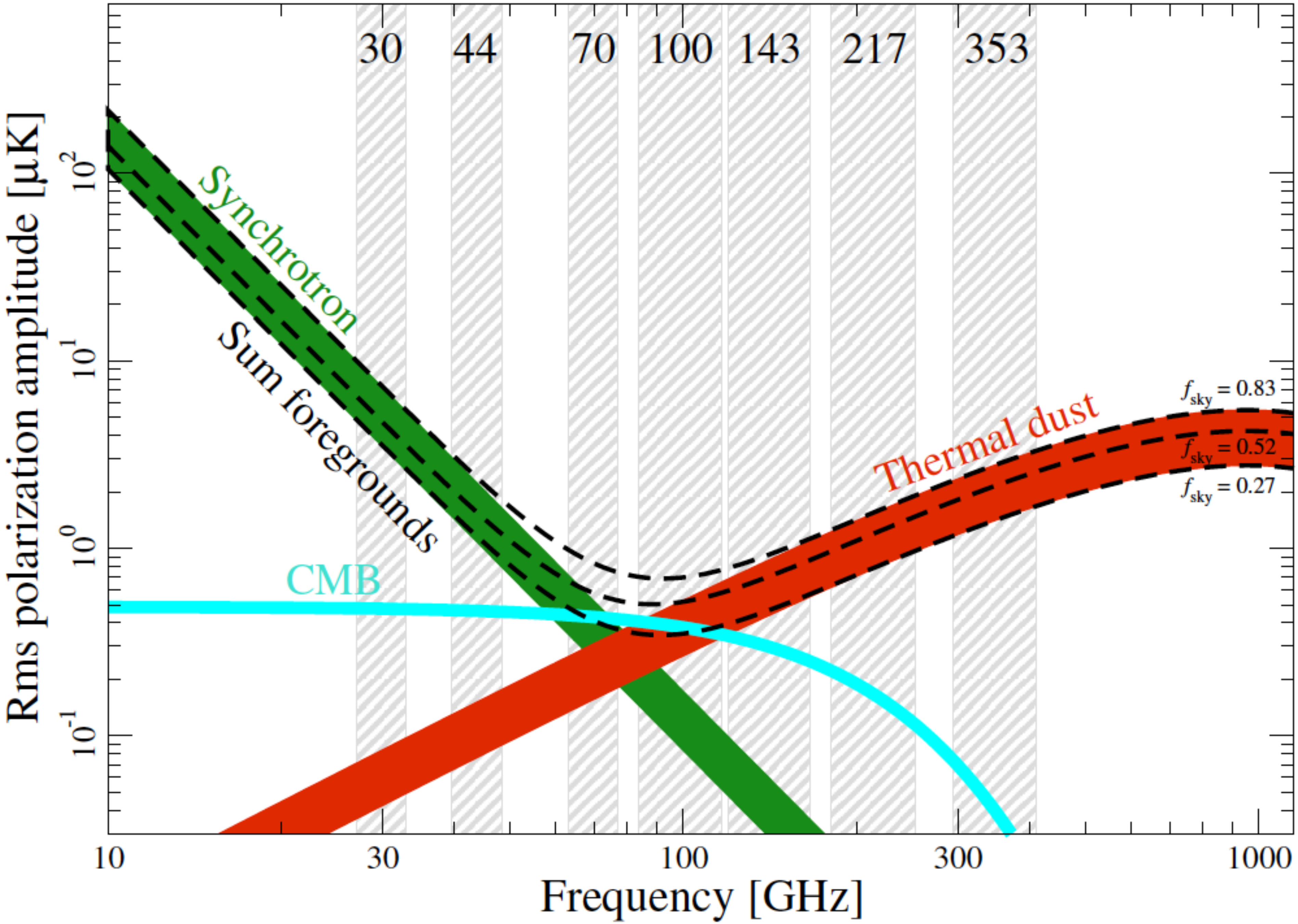


A full-sky synchrotron survey

- **Experimental landscape in Europe at low frequencies.**
  - Past experience at low frequencies (pre-Planck, PLANCK).
  - Observing sites.
  - Current Small aperture telescopes at low-frequencies (<100GHz): C-BASS, QUIJOTE, STRIP, KISS, others.

- **Modelling low frequency foregrounds for B-mode studies.**
  - Current view from existing experiments at low frequencies.
  - Synchrotron modeling.
  - AME polarization?

- **On-going mid-term activities.**
  - Towards a full-sky synchrotron survey.
- **Long-term plan.**
  - Full-sky synchrotron survey → next talk by A. Taylor.



(Planck Collaboration I 2018)

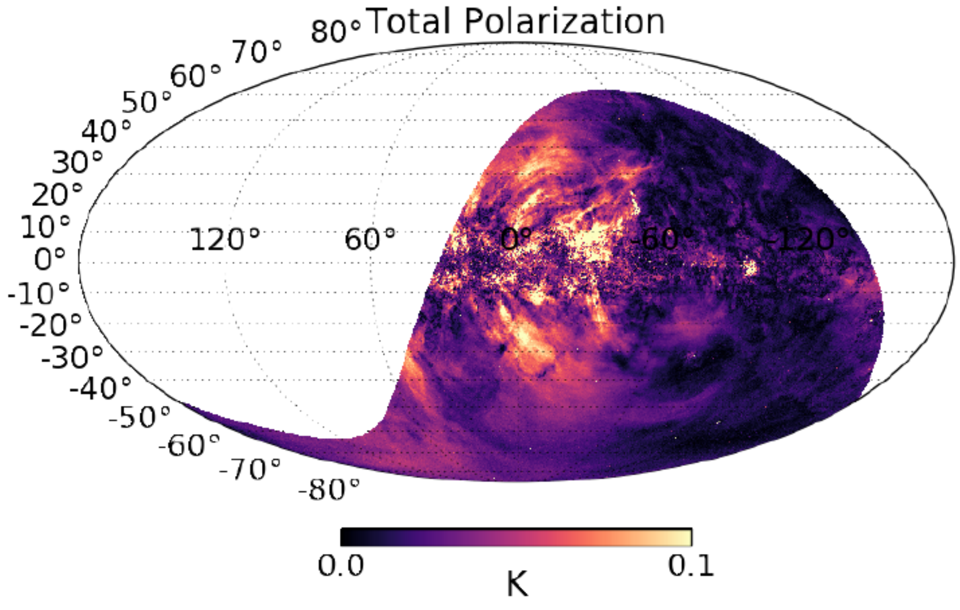
S-PASS

Linear polarization at **2.3 GHz** as observed by the S-band Polarization All Sky Survey (S-PASS).

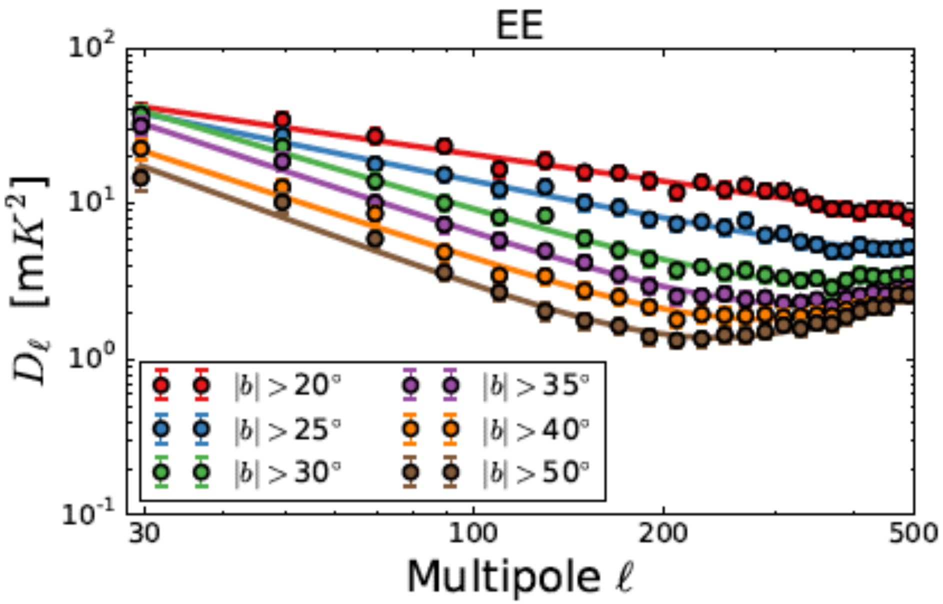
Power spectra show a decay of the amplitude as a function of multipole for l<200, typical of the diffuse emission.

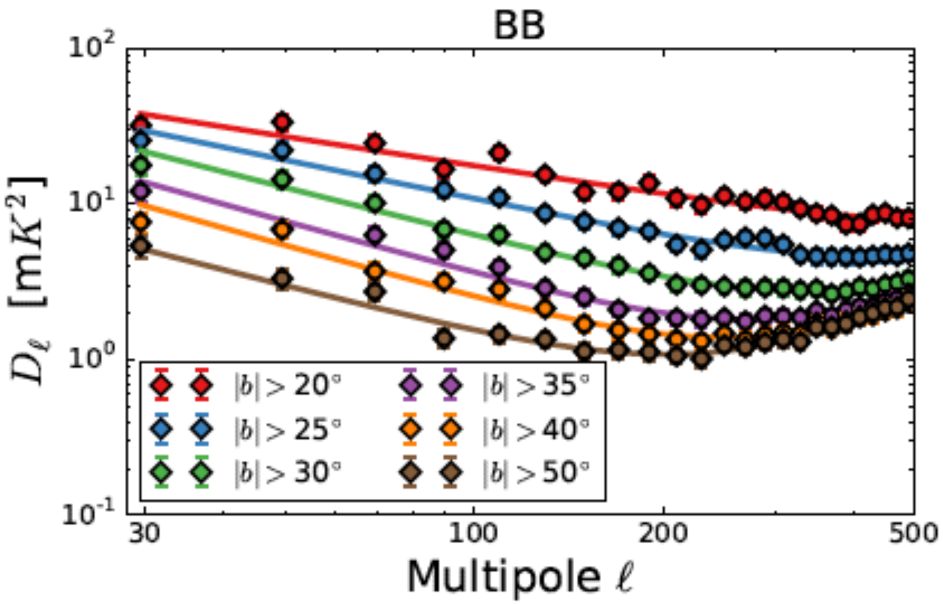
The recovered SED, in the frequency range 2.3-33 GHz, is compatible with a power law with index **-3.22 ± 0.08. It shows complexity (spatial variations of spectral index).**

Dividing the sky in small patches (with fsky=1%), the minimal contamination at 90GHz, in the cleanest regions of the sky, is at the level of equivalent tensor-to-scalar ratio $\mathbf{r_{synch}=10^{-3}}$.



(see previous talk by C. Baccigalupi)

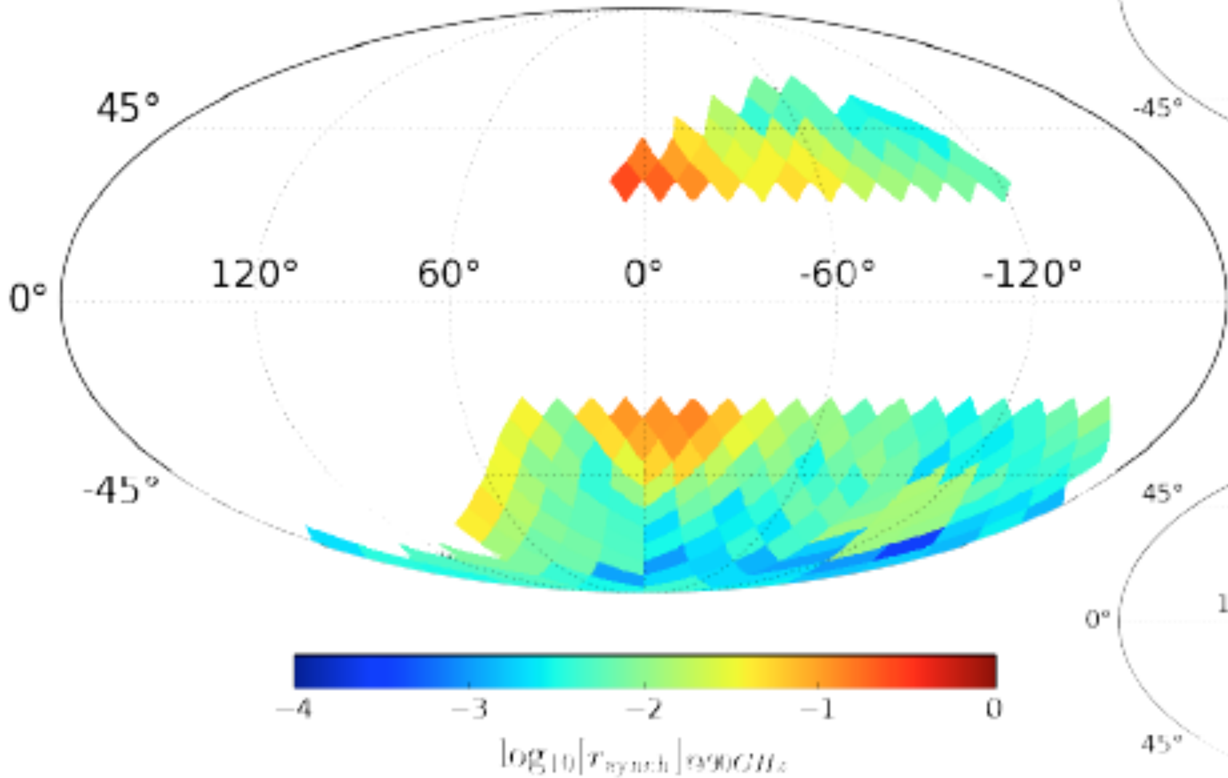




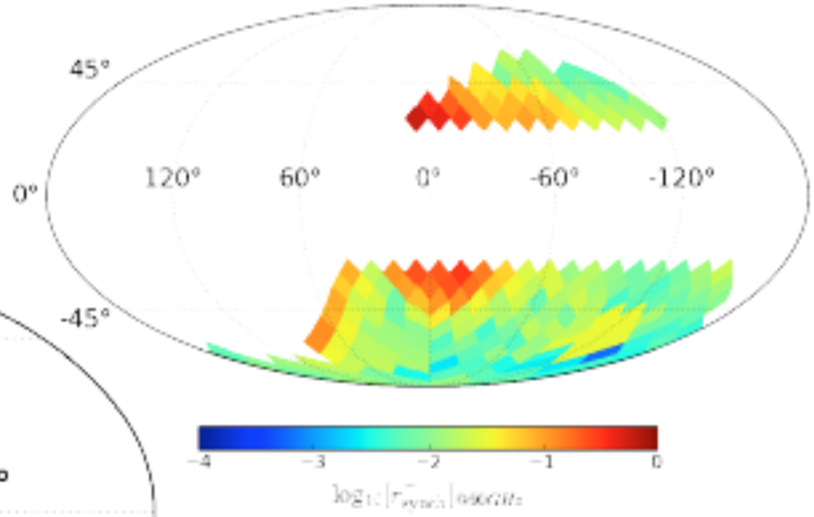
Krachmalnicoff et al. (2018), arXiv: 1802.01145.

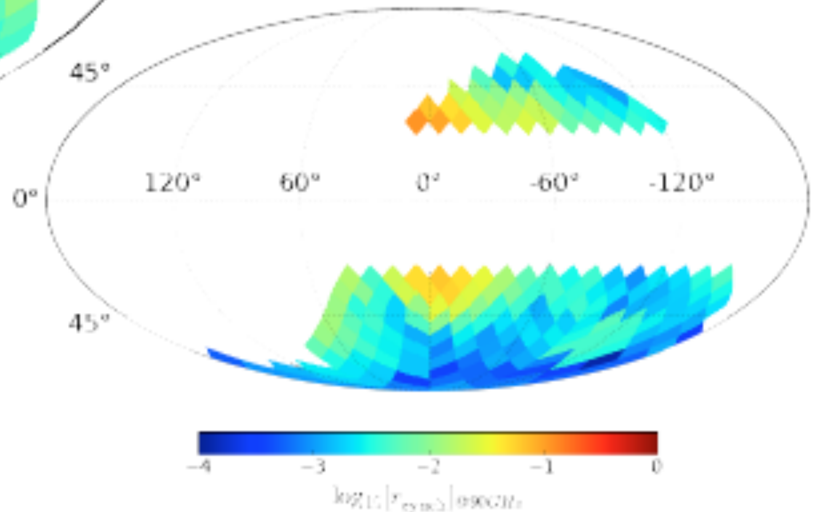
S-PASS

Minimal contamination at 90GHz, in the cleanest regions of the sky, is at the level of equivalent tensor-to-scalar ratio $\mathbf{r_{synch}=10^{-3}}$.



$\mathbf{Log_{10}(|r_{synch}|)}$ @ 90GHz



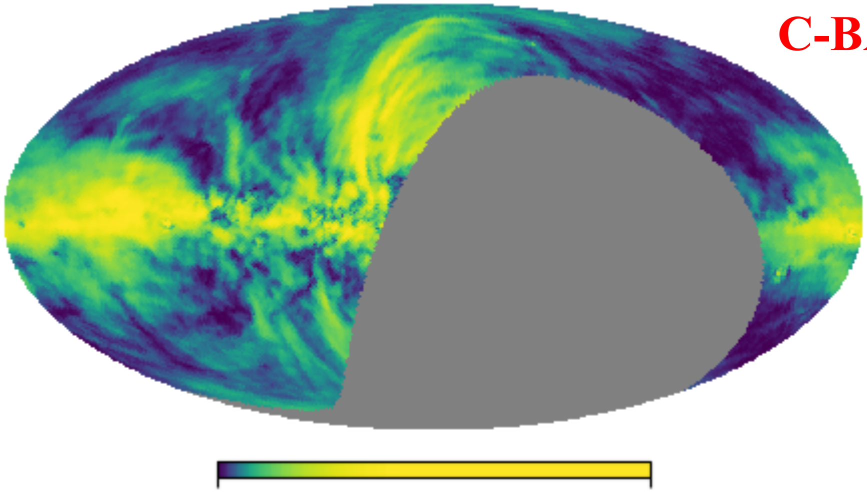


(see previous talk by C. Baccigalupi)

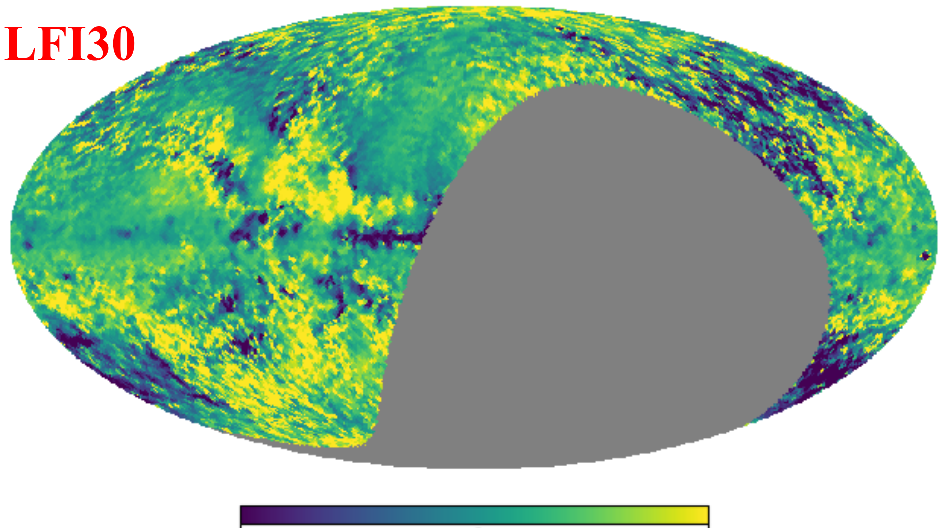
Krachmalnicoff et al. (2018), arXiv: 1802.01145.

Polarized spectral indices 5 - 30 GHz

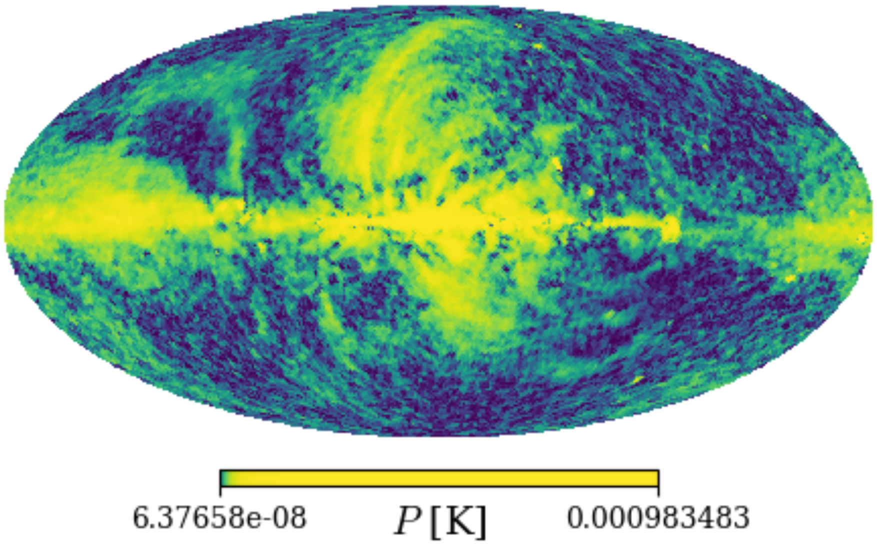
C-BASS & LFI30



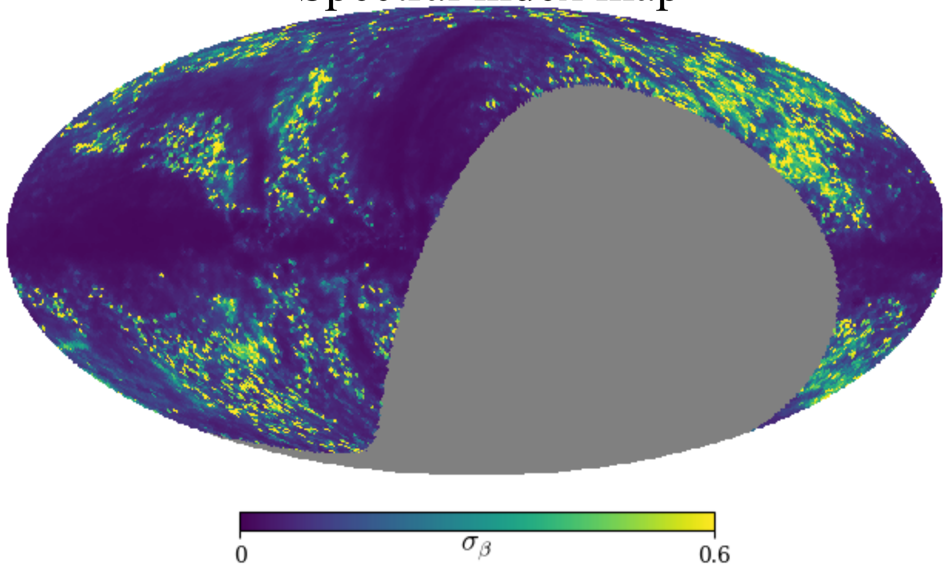
(a) C-BASS P map



Spectral index map



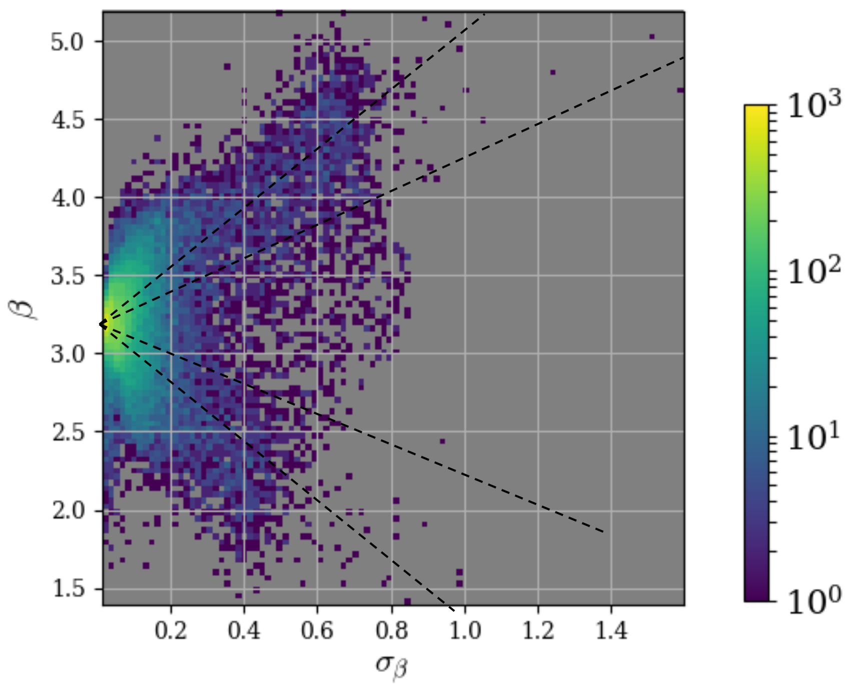
(c) *Planck* 30 GHz P map



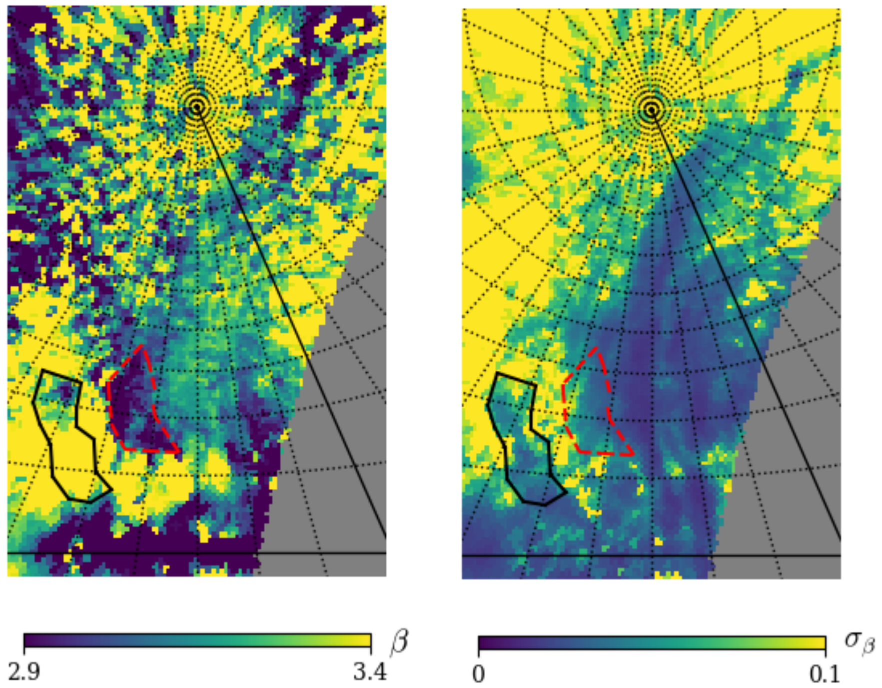
Spectral index error map

(slide from M. Jones)

Real variations in polarized β



Distribution of β vs error on β
- Dashed lines indicate 1-, 2-σ deviations from mean

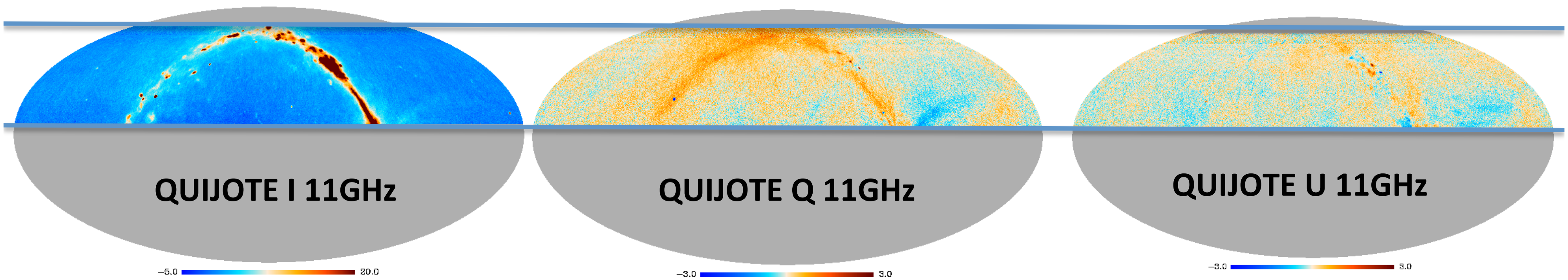


Adjacent regions with low σ_β but very different β

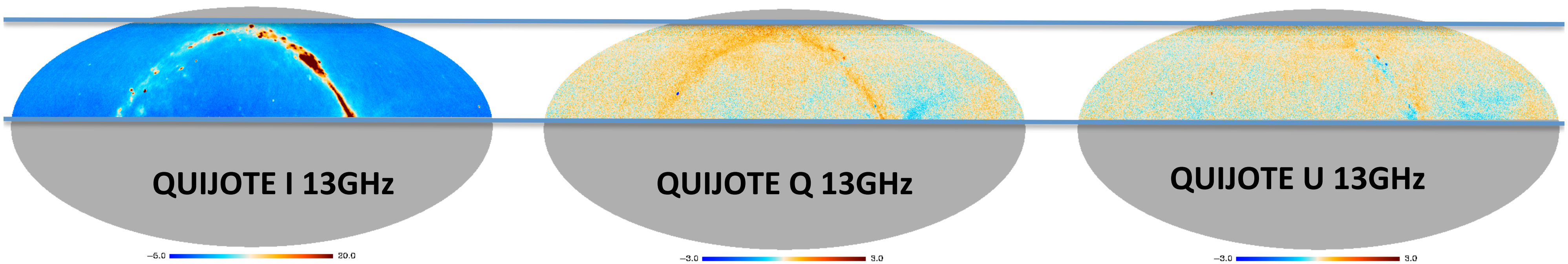
(slide from M. Jones)

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

- 10,000 hrs on a region of 20,000 deg^2 in the northern sky. Still on-going.
- Goal: ~30 μK/beam in Q,U. Current maps: ~60 μK/beam.
- Data release: end of the year.

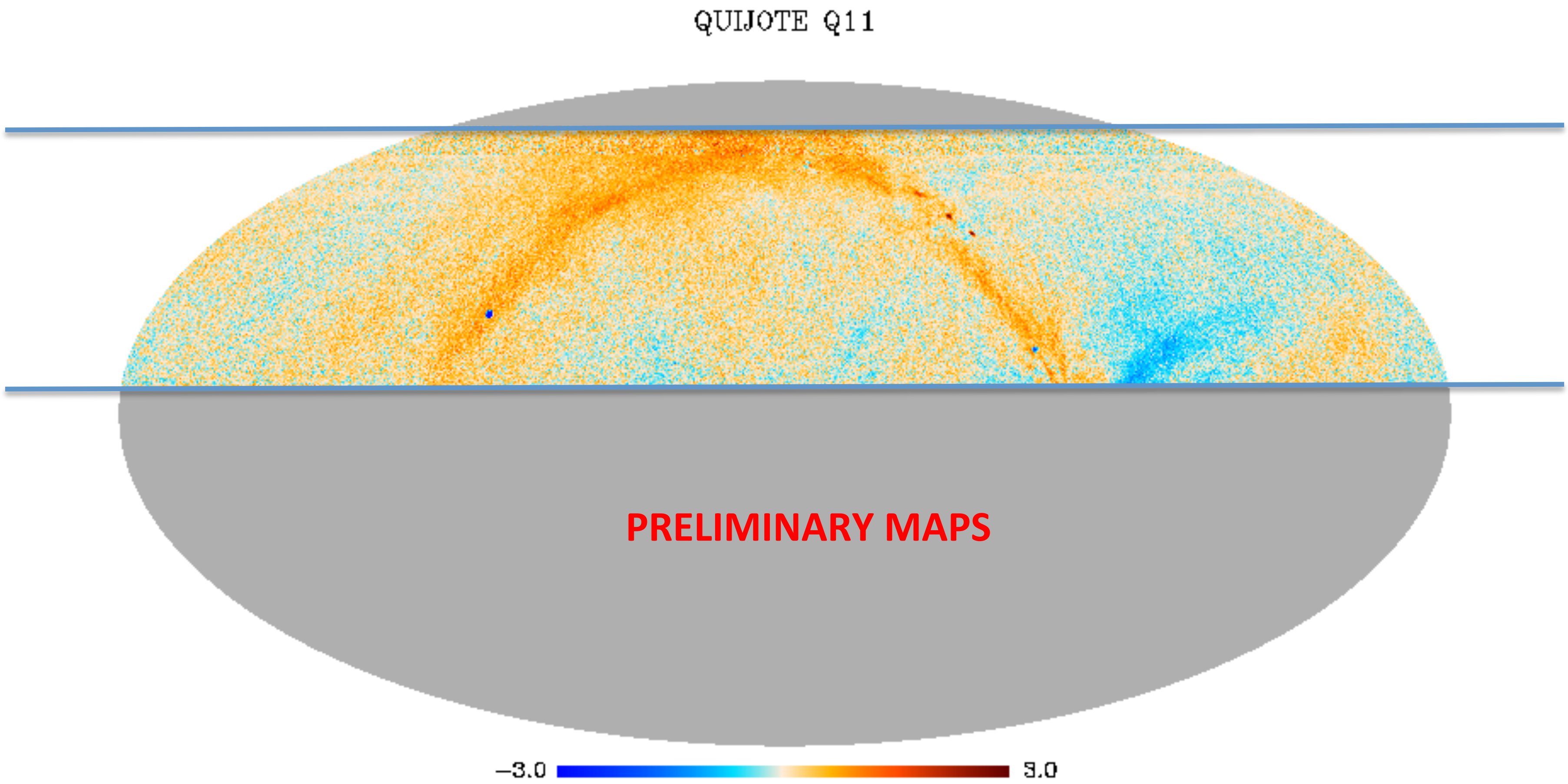


PRELIMINARY MAPS



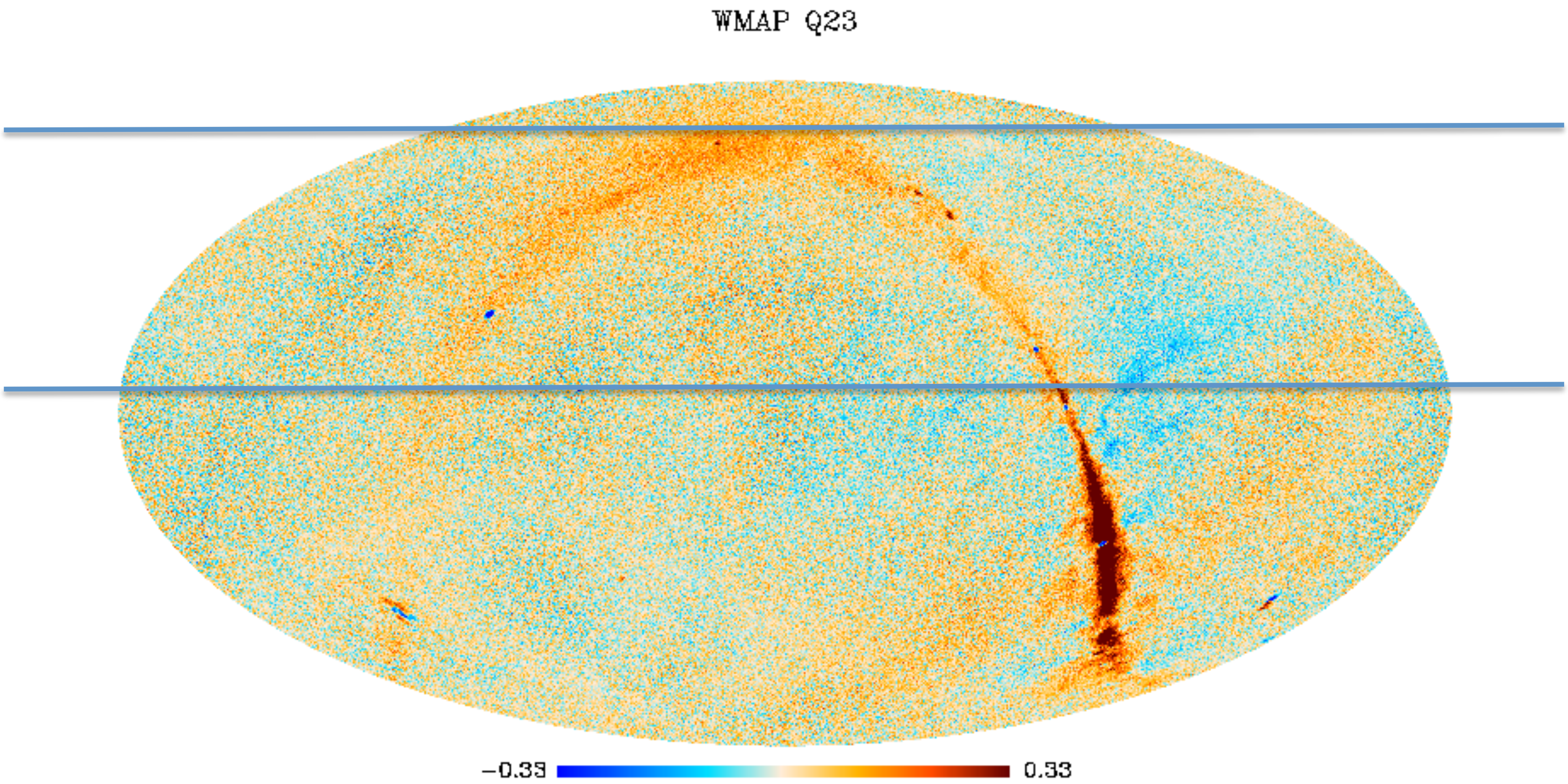
Wide survey with the QUIJOTE MFI (10-20GHz)

- 10,000 hrs on a region of 20,000 deg^2 in the northern sky. Still on-going.
- Goal: ~30 μK/beam in Q,U. Current maps: ~60 μK/beam.
- Data release: end of the year.



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

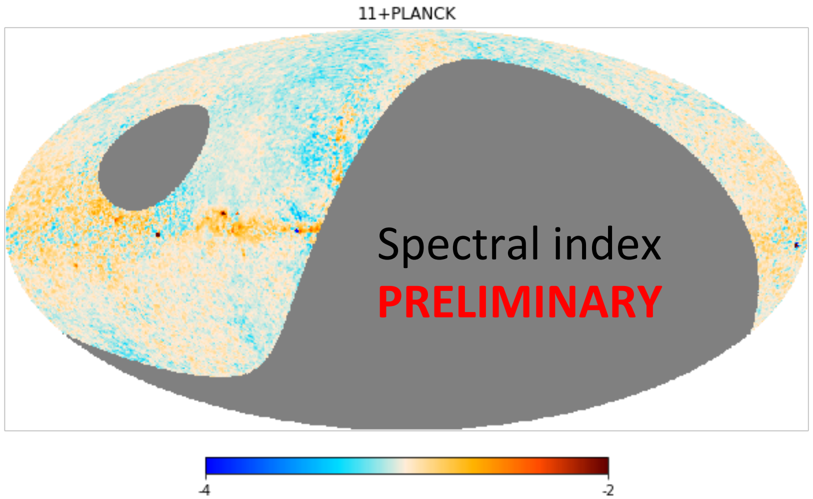
- 10,000 hrs on a region of 20,000 deg^2 in the northern sky. Still on-going.
- Goal: ~30 μK/beam in Q,U. Current maps: ~60 μK/beam.
- Data release: end of the year.

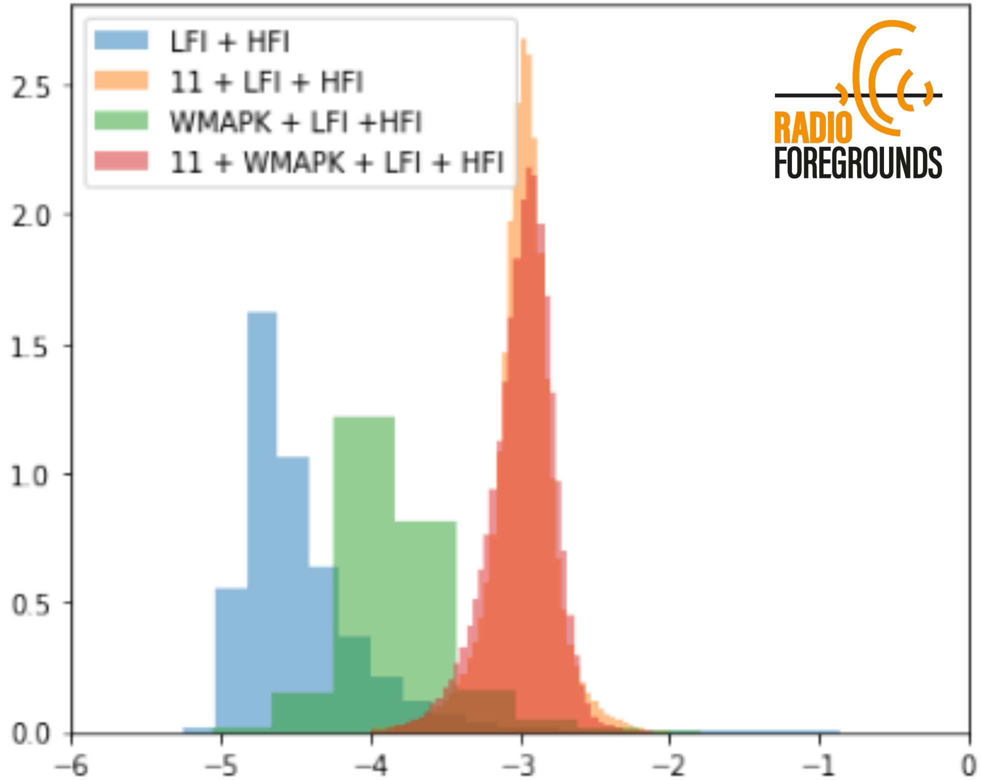


Wide survey with the QUIJOTE MFI (10-20GHz)

PRELIMINARY RESULTS ON:

- Synchrotron spectral index, curvature and correlation with dust at power spectrum level.
- Component separation of the polarised synchrotron, combining PLANCK+WMAP+QUIJOTE. Map of spectral index.
- AME in > 40 regions.

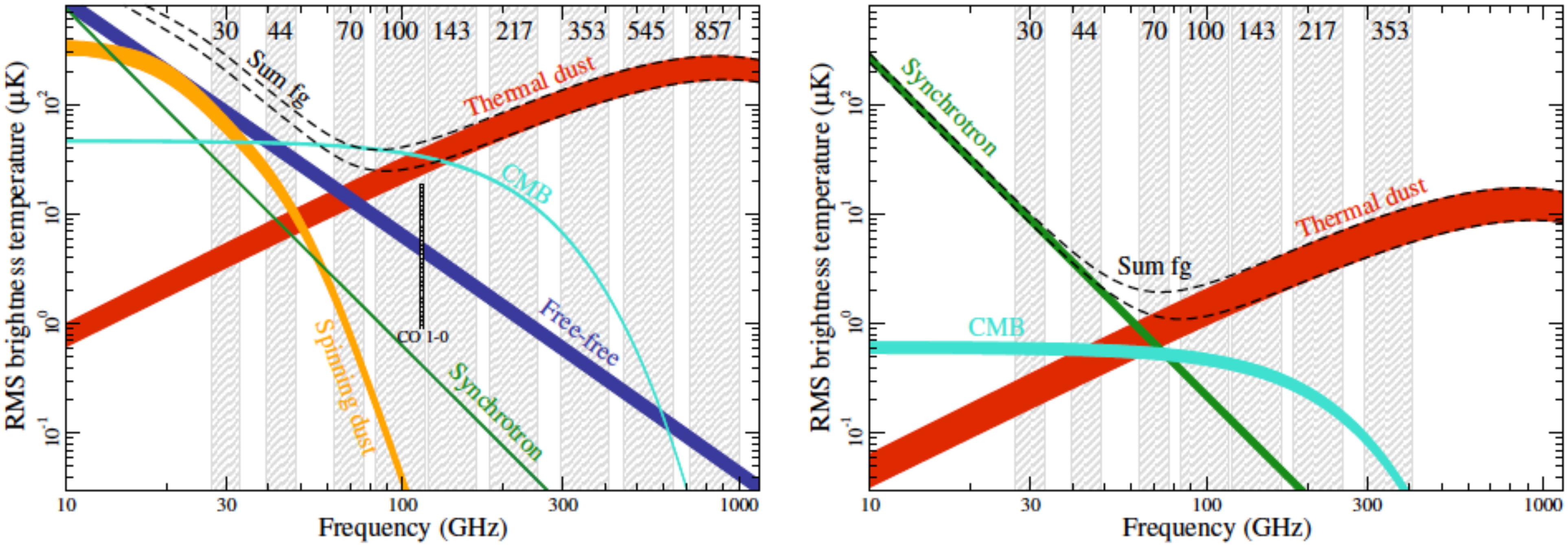




Synchrotron spectral index in polarization. Extraction assumes **no prior information.**

→ **Only when** including the 11GHz data we can constrain the polarization synchrotron spectral index.

Modelling the AME polarization



(Planck Collaboration 2016)

Constraints on AME polarization

★ Compact sources:

- Battistelli et al. (2006) found marginal polarisaiton with $\Pi = 3.4 \pm 1.7$ % at 11 GHz, using COSMOSOMAS
- Upper limits from, $\Pi < 1\%$ (95% CL) from WMAP 23 GHz (López-Caraballo et al. 2011, Dickinson et al. 2011)

★ Diffuse:

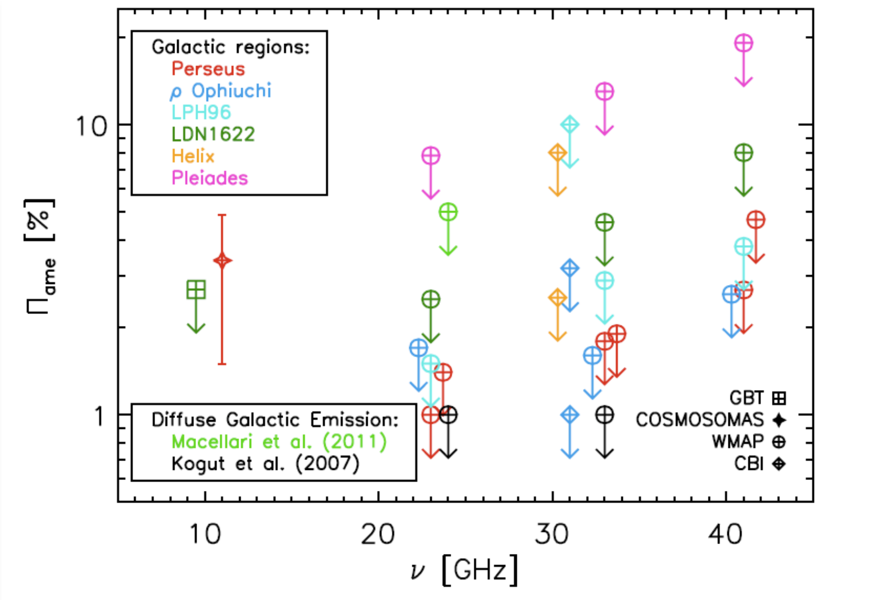
- $\Pi < 5\%$ (Macellari et al. 2011), at 22.8 GHz with WMAP
- $\Pi = 0.6 \pm 0.5$ % (Planck 2015 results, XXV)

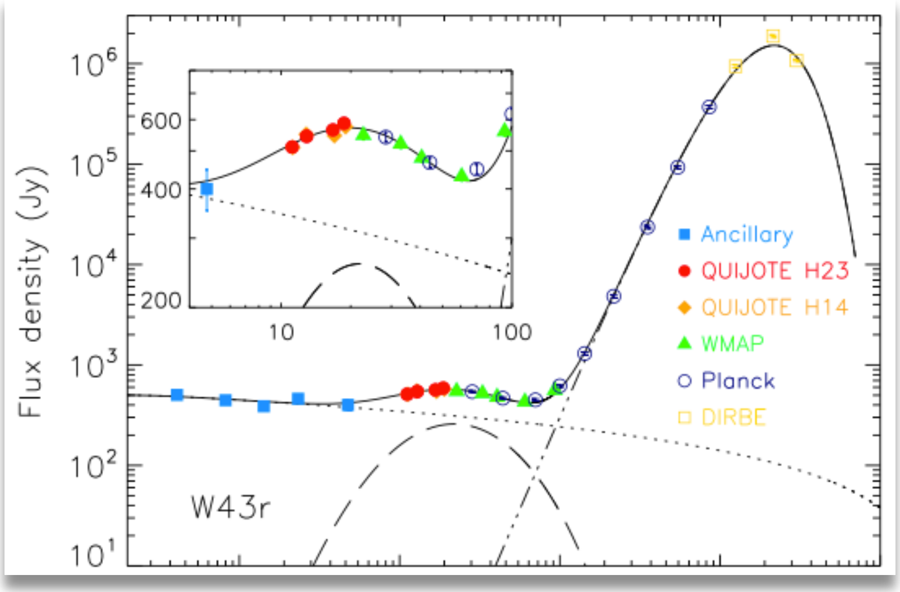
★ QUIJOTE:

- Perseus molecular complex: $\Pi_{AME} < 6.3\%$ at 12 GHz and $\Pi_{AME} < 2.8\%$ at 18 GHz (Génova-Santos et al. 2015)
- W43 molecular complex: $\mathbf{\Pi_{AME} < 0.39\%}$ at 18.7 GHz and **<0.22%** at 40.6 GHz (Génova-Santos et al. 2017)

Best constraints to date! improving previous constraints by a factor 5

Rubiño-Martín et al. (2012)



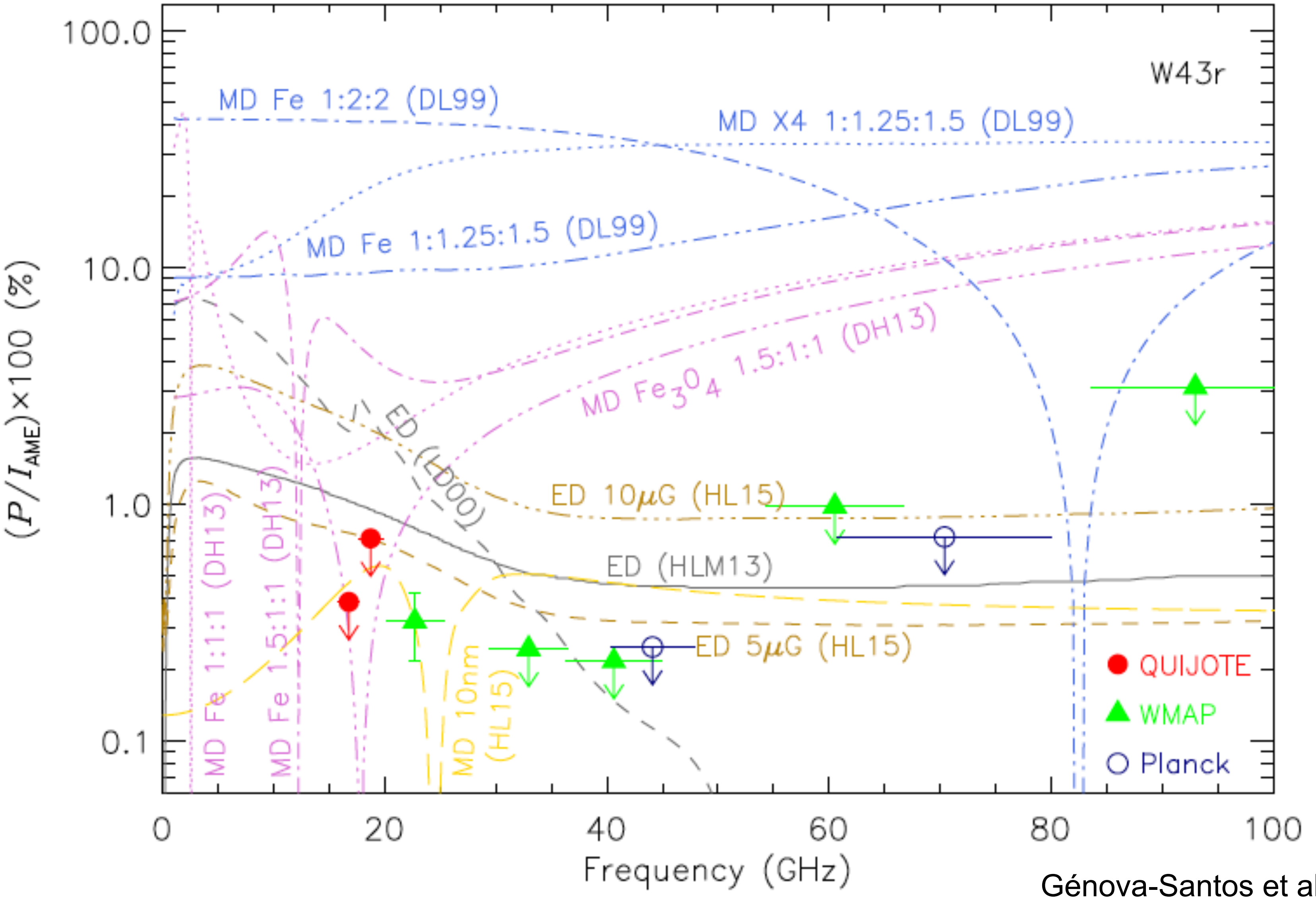


Génova-Santos et al. (2017)

W43 molecular complex: best AME pol constraints

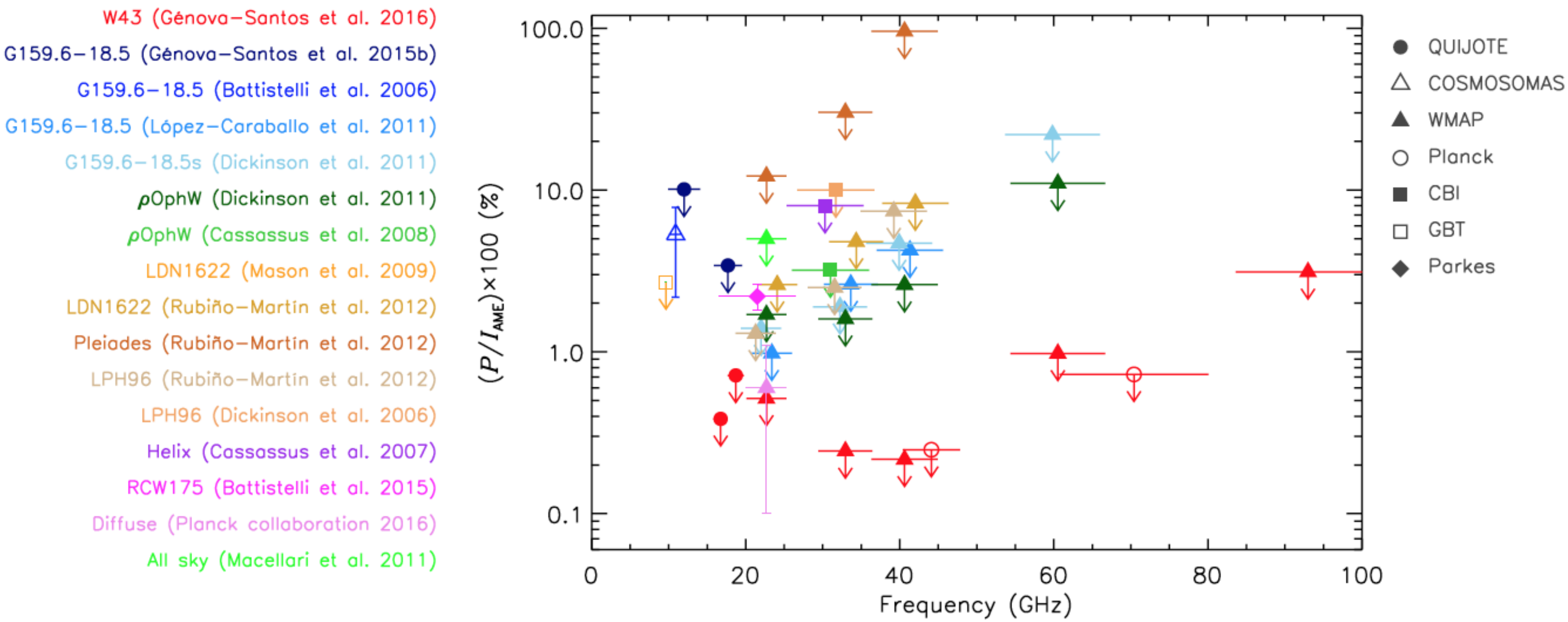
Constraints on AME polarization fraction and comparison with ED and MD models.

Best upper limits to date (< 0.4% at 17GHz from QUIJOTE, and < 0.22% at 23GHz from WMAP).



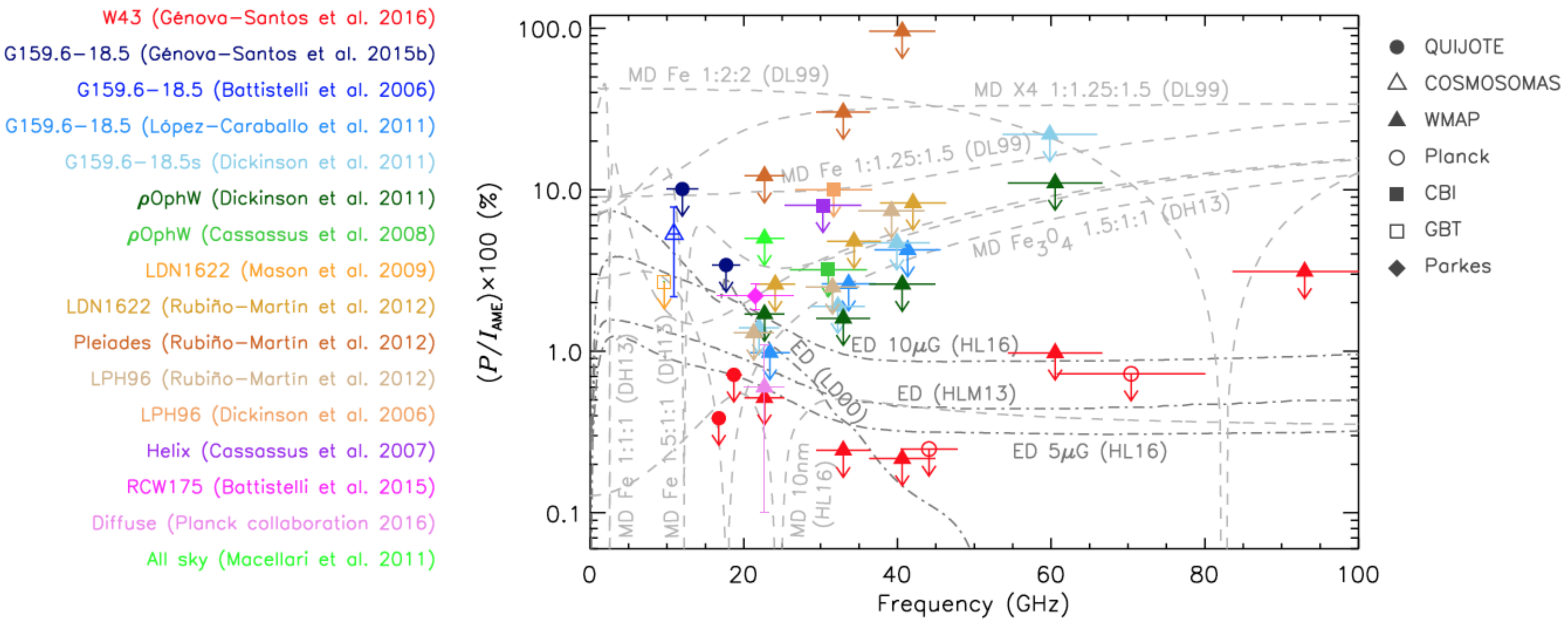
Génova-Santos et al. (2017)

Current constraints on AME polarization



(see Dickinson et al. 2018 for a recent review)

Current constraints on AME polarization

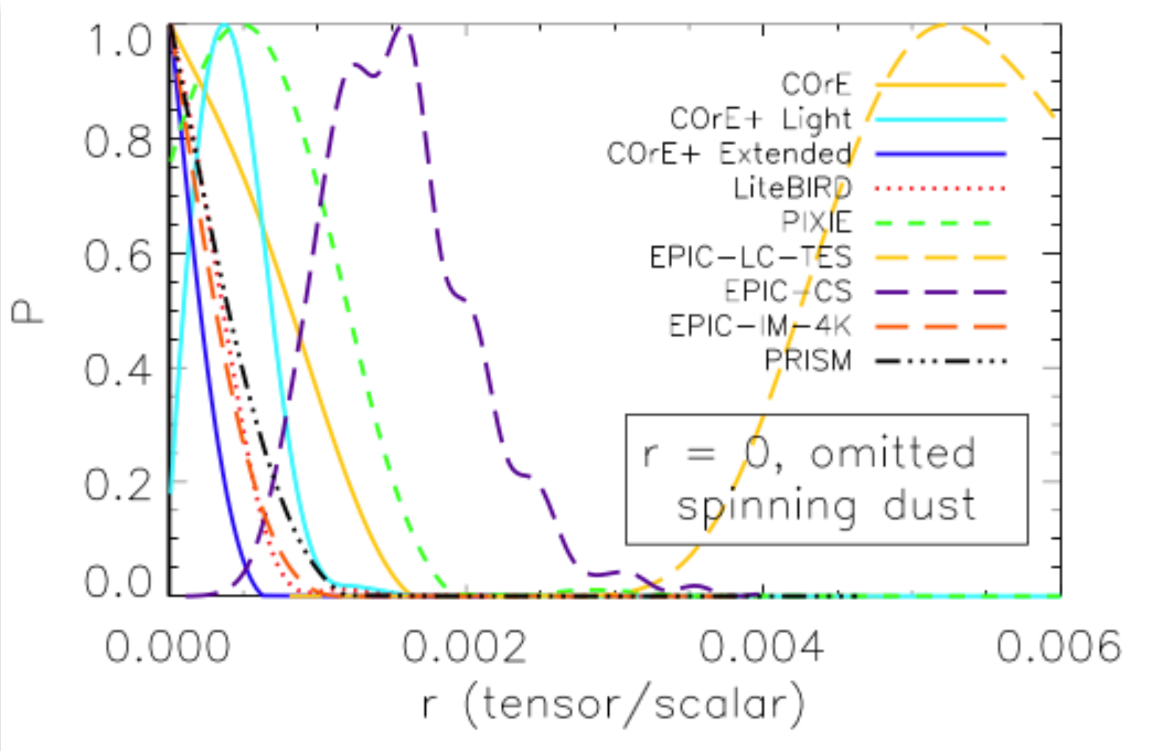


(see Dickinson et al. 2018 for a recent review)

AME polarization?

★ We may not have to worry about AME in polarisation. But:

- Previous upper limits in polarization have been obtained in **individual regions**.
- **Lessons learned with QUIJOTE**: the information in the 10-20GHz range is critical to separate the AME from other astrophysical components.
- Complexity of AME component: wide distribution of “peak frequencies”.
- Ignoring a diffuse AME component with Π=1% may lead to significant biases in r → 10GHz is needed.



(Remazeilles et al. 2016)

RADIOFOREGROUNDS project

http://www.radioforegrounds.eu

H2020-COMPET-2015. Grant agreement **687312:** “Ultimate modelling of Radio Foregrounds” (RADIOFOREGROUNDS).
3-year grant 2016-18 (IAC; IFCA; Cambridge; Manchester; SISSA; Grenoble; TREELOGIC).

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.

http://www.iac.es/congreso/cmbforegrounds18/

Sessions in the meeting will cover these topics:

- Current observational status - CMB polarization experiments.
- Galactic modelling I: thermal dust.
- Galactic modelling II: synchrotron and anomalous microwave emission.
- Extragalactic modelling.
- Component separation methods.
- Sky models and forecast for future missions.

RADIO FOREGROUNDS

A full-sky synchrotron survey

- **Experimental landscape in Europe at low frequencies.**
  - Past experience at low frequencies (pre-Planck, PLANCK).
  - Observing sites.
  - Current Small aperture telescopes at low-frequencies (<100GHz): C-BASS, QUIJOTE, STRIP, KISS, others.

- **Modelling low frequency foregrounds for B-mode studies.**
  - Current view from existing experiments at low frequencies.
  - Synchrotron modeling.
  - AME polarization?

- **On-going mid-term activities.**
  - Towards a full-sky synchrotron survey.
- **Long-term plan.**
  - Full-sky synchrotron survey → next talk by A. Taylor.

A full-sky synchrotron survey: mid-term activities

- **Motivations for full-sky low-frequency survey.**
  - Existing European leadership in northern sky observations.
  - Synergies with existing/planned ground-based CMB efforts.
  - Providing full-sky low-frequency information (< 40GHz) for space missions (LITEBIRD, PICO, CoRE/CMB-Bharat, PRISTINE, PIXIE).

- **Mid-term (2022-2026) on-going and planned activities.**

  Pre-2022
  - S-PASS. Plans to cover northern sky at 2.3 GHz.
  - C-BASS. Completing southern sky at 5 GHz.
  - QUIJOTE. Improved 10-20GHz measurements (new MFI2) and adding 30,40GHz instrument at northern site.
  - LSPE-STRIP (40, 90GHz). From Tenerife.
  - Extension of QUIJOTE (10-20GHz) to southern hemisphere (using current QT-1 telescope + MFI instrument).
  - NextBASS proposal (6-30GHz in a single 2-m class telescope in southern hemisphere). High frequency resolution.

https://wiki.e-cmb.org/uploads/Main/Whitepaper.pdf

A full-sky synchrotron survey: long-term plan

- **Specifications**:
  - To model polarised synchrotron and AME at least to the level of being able to clean angular scales of the second (recombination) bump → minimum frequency of 5-10GHz, and two 6-m class telescopes to obtain the appropriate resolution at low frequencies (~20arcmin at 10GHz).
  - → Complementary to CMB-S4 in southern sky.

- **Full sky survey with 6-m class telescopes.** → next talk by A. Taylor
  - Covering from ~10 to 120GHz.
  - Two sites (north an south). Instrument could be exchanged between the telescopes.
  - Frequency resolution.

Thank you !