Observations of the full Northern sky at 10-20 GHz with the QUIJOTE experiment

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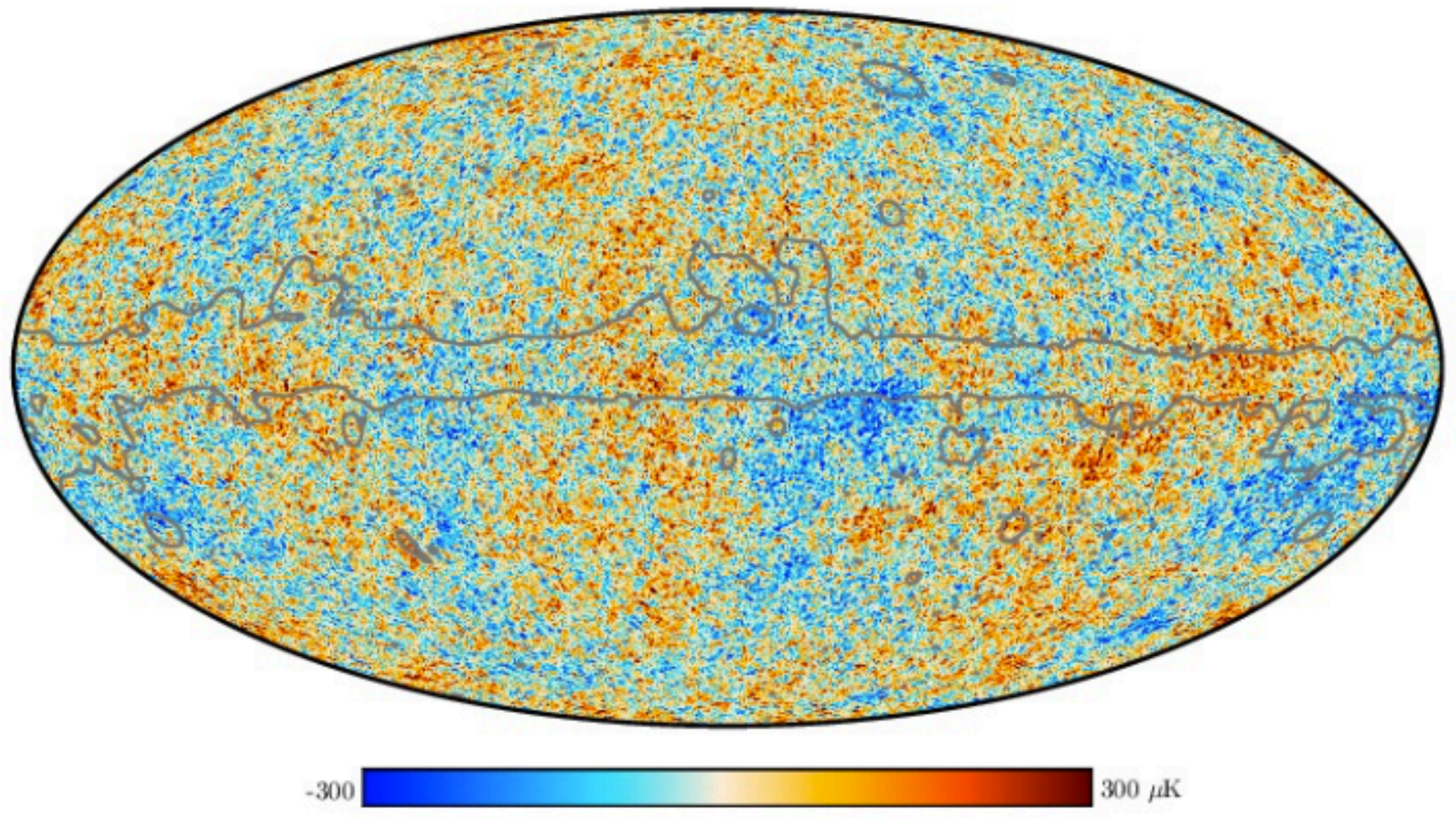
on behalf of the QUIJOTE collaboration

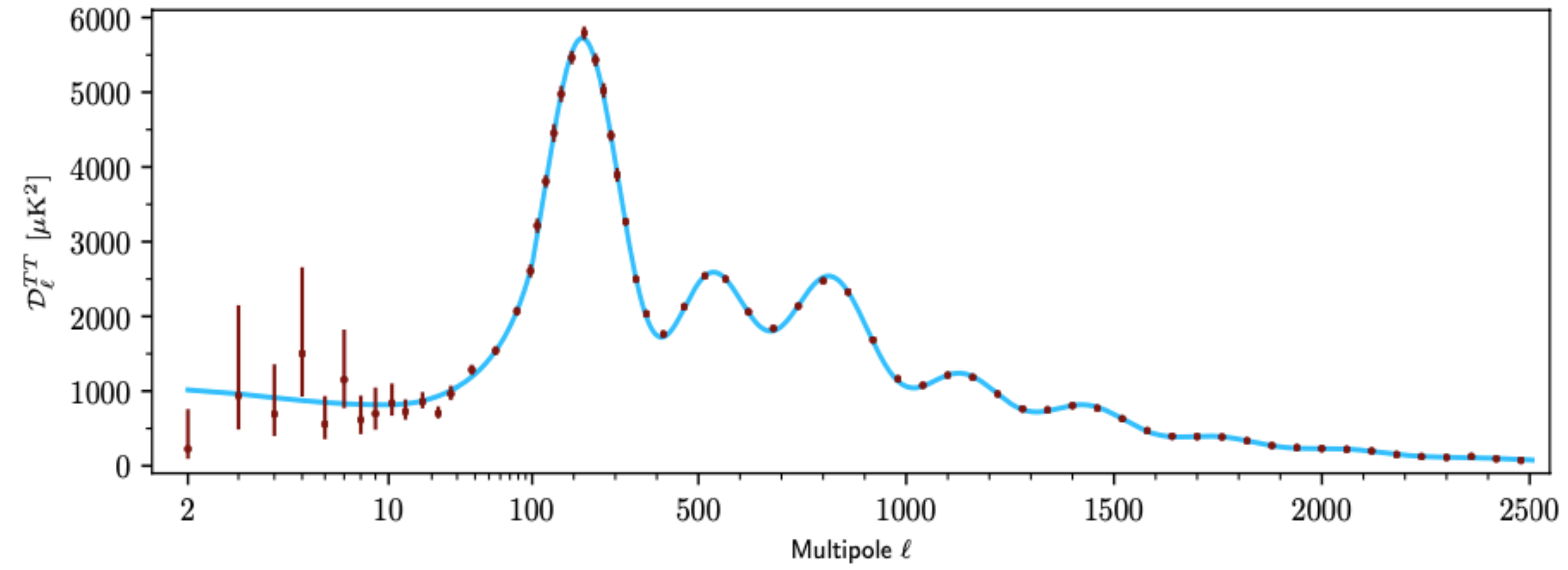
Cosmology/Astroparticle Jamboree, 7 June 2022

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"
Ref. de la ayuda: ICTS-2019-03-IAC-12

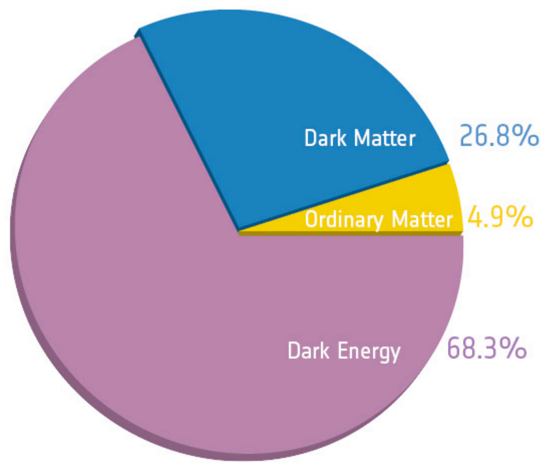
CMB anisotropies

Planck results





Parameter	Plik best fit	Plik [1]
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031
τ	0.0543	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014
n_s	0.96605	0.9649 ± 0.0042



Planck Collaboration, A&A, 641, A1 (2020)

ΛCDM model

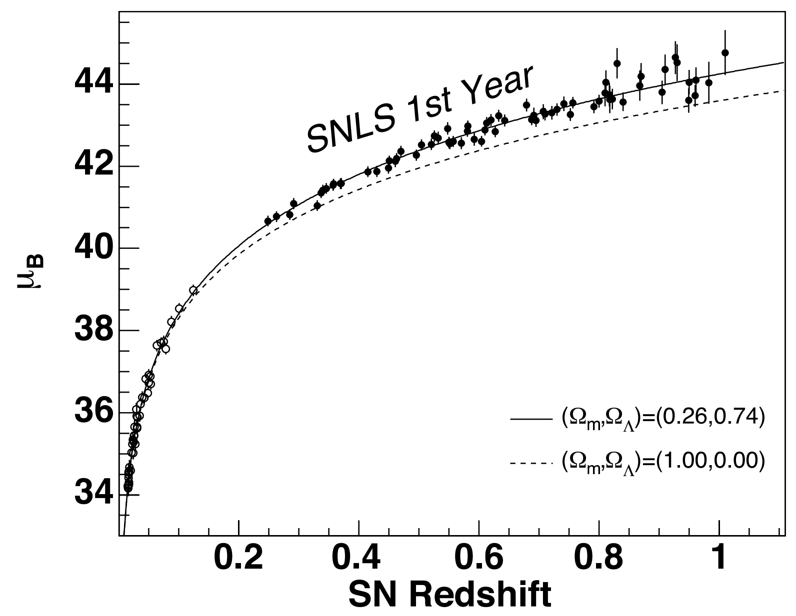
- Two main components: dark energy and dark matter
- 5% or ordinary matter
- Dark matter must be cold
- Universe with flat geometry

Concordance model

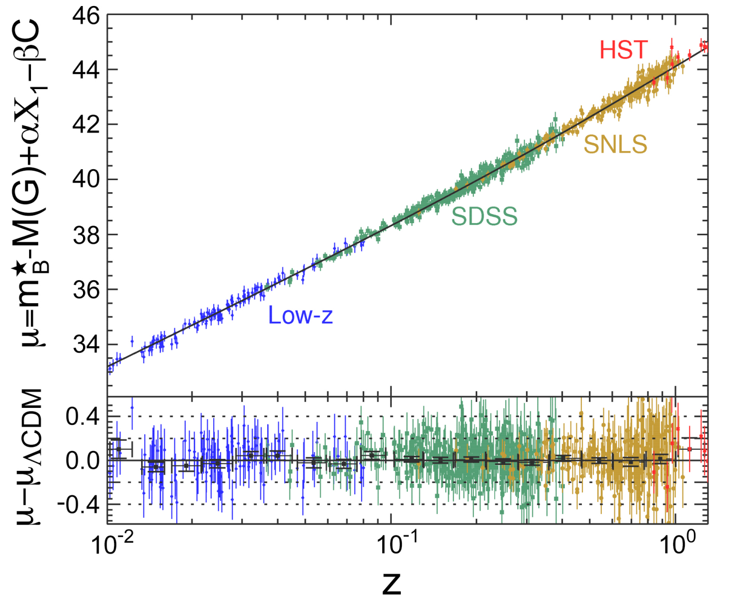
- Astounding agreement with other observables
  - CMB
  - LSS
  - SNe Ia (accelerated expansion)
  - BBN

Type Ia SN observations

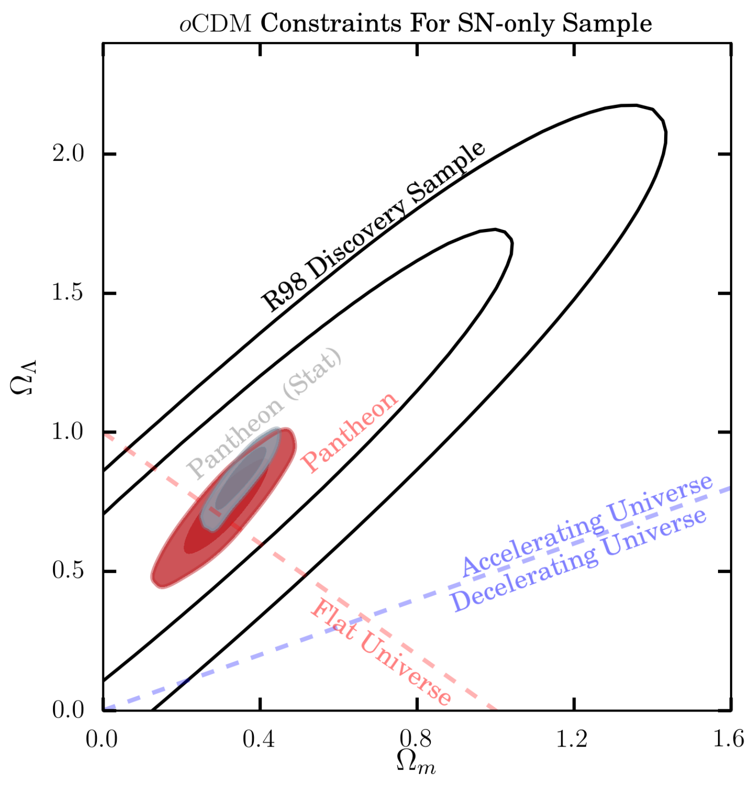
Astier et al. 2006

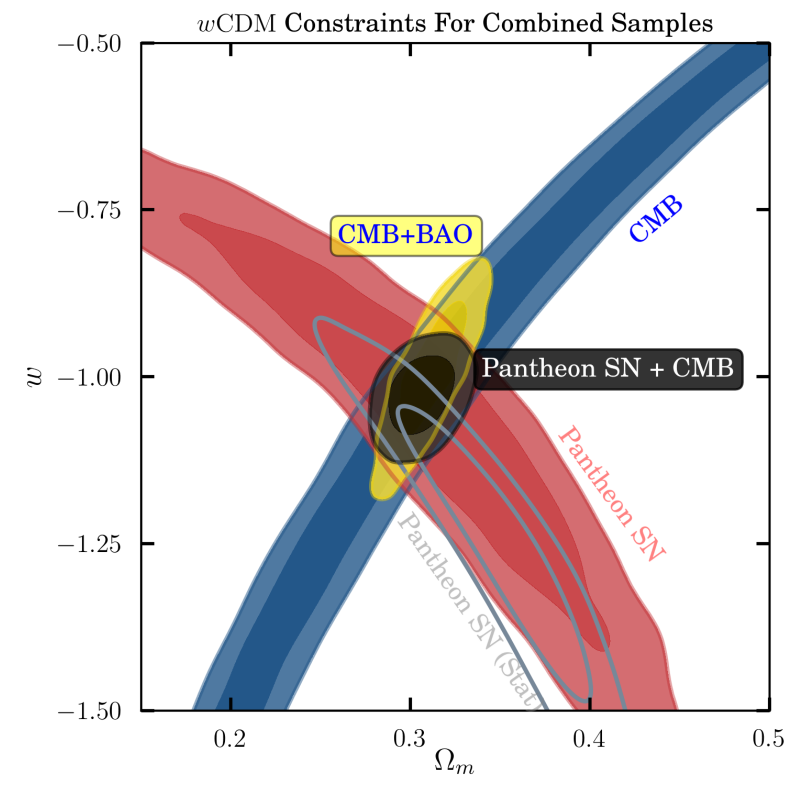


Betoule et al. 2014



Type Ia SN constraints combined with other probes





Scolnic et al. (2018)

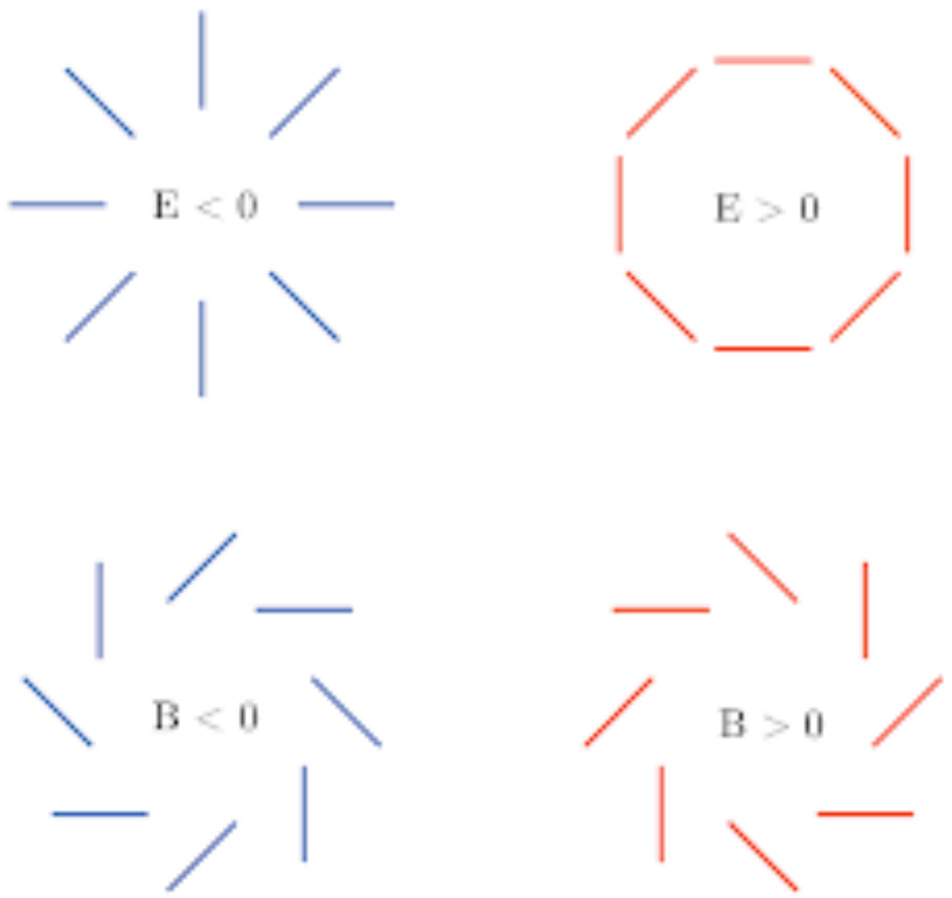
CMB polarisation

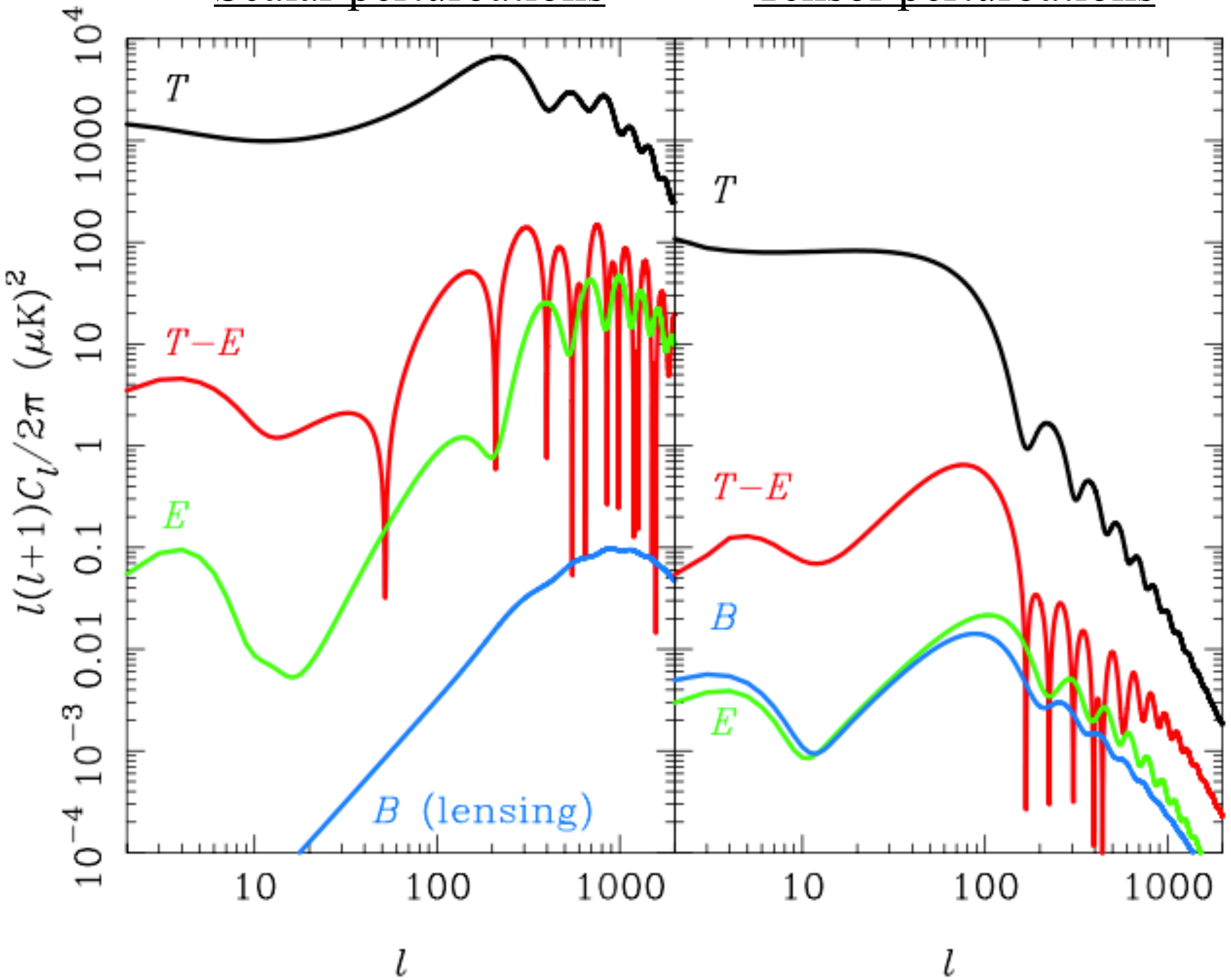
Inflation

- Accelerated expansion in the Early Universe
- Leads to
  - Scalar perturbations ⇒ density perturbations
  - Tensor perturbations ⇒ primordial gravitational waves
- Predictions
  - Flat geometry ✓
  - Nearly scale-invariant perturbations (n_{es}<1 but close to unity) ✓
  - Nearly Gaussian perturbations in all scales ✓
  - Gravitational waves ?

- Gravitational waves may create an specific pattern (**B-mode**) in the CMB polarisation

$$r = \frac{A_t}{A_s} = 0.06\left(\frac{E_{inf}}{10^{16}\ \mathrm{GeV}}\right)^4$$





Challinor, 2013

CMB polarisation

B-modes signal

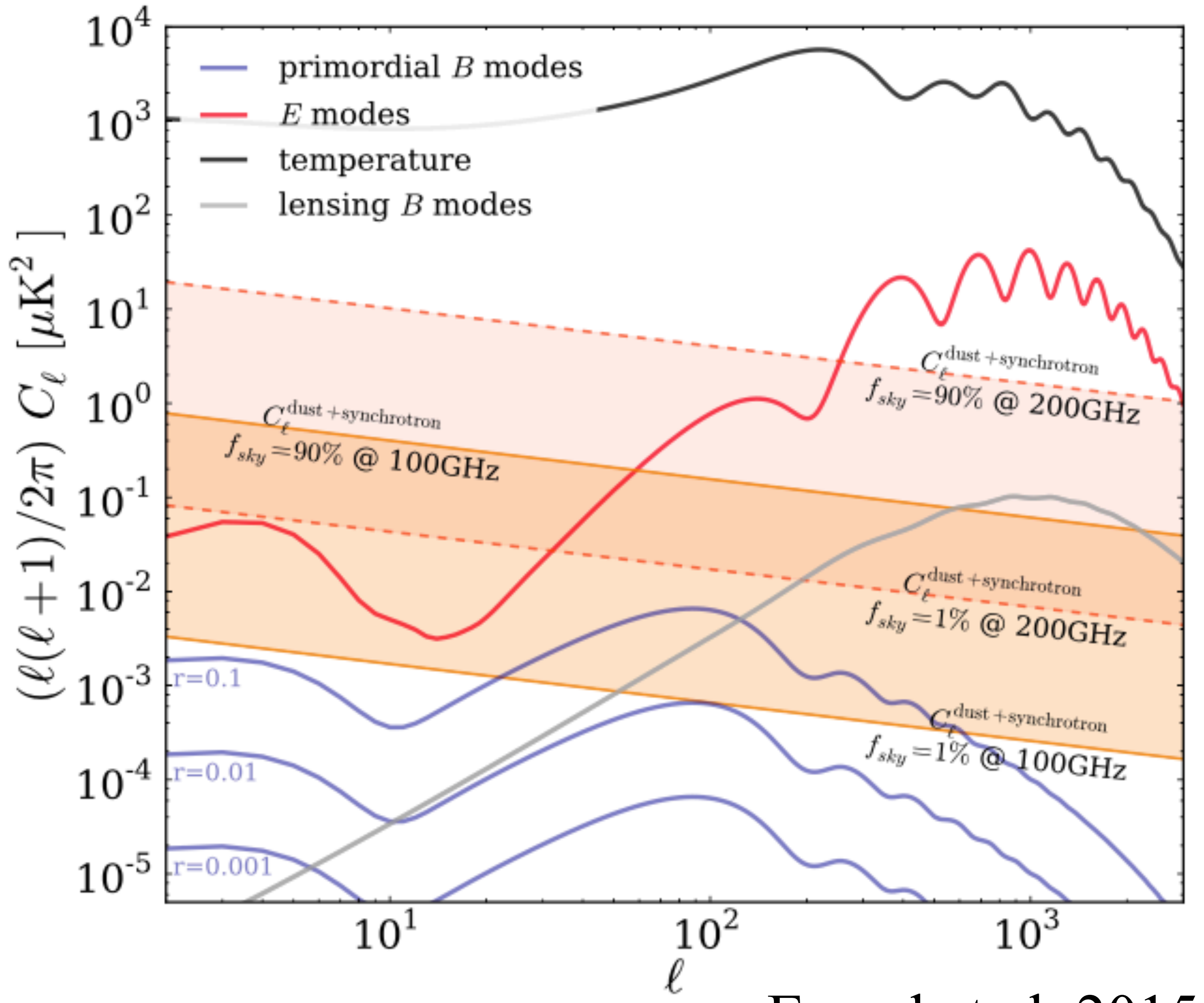
- Extremely faint signal (~nK level) in very large angular scales

⇩

- Extremely high sensitivities
  - Many detectors
  - Large bandwidths
- Exquisite control of instrument systematics (beams, instrumental polarisation, RFI, relative calibration, pointing accuracy….)
- Observations covering very large angular scales (difficult from Earth)
- Careful control characterisation and correction of Galactic foregrounds

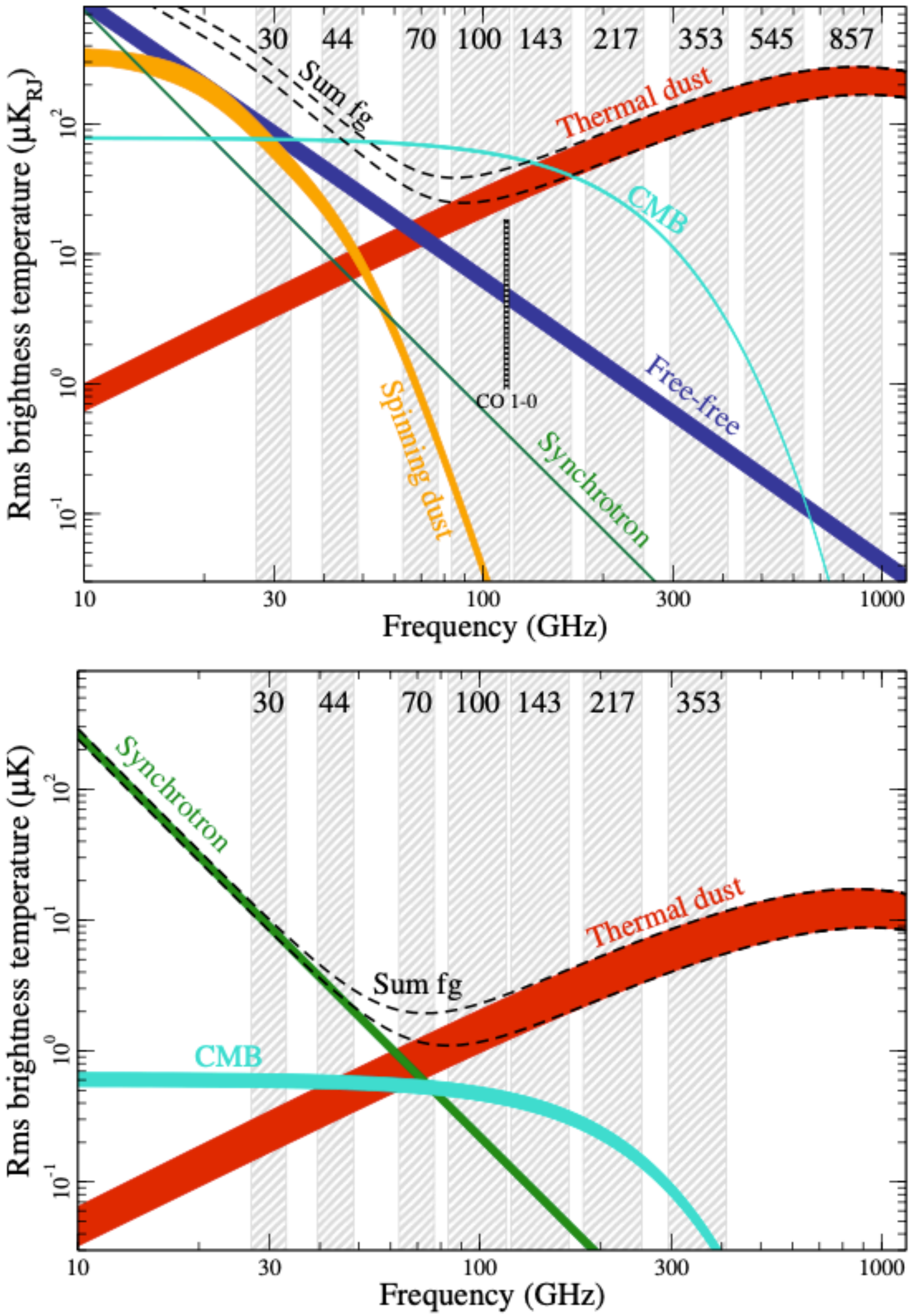
Galactic foregrounds

Foreground	Freq. range	Polarised?
Free-free	low-freq	no
Synchrotron	low-freq	~10%
Anomalous Microwave Emission	intermediate	?
Thermal dust emission	high-freq	~10%



Errard et al. 2015

Planck 2015 results X, 2016

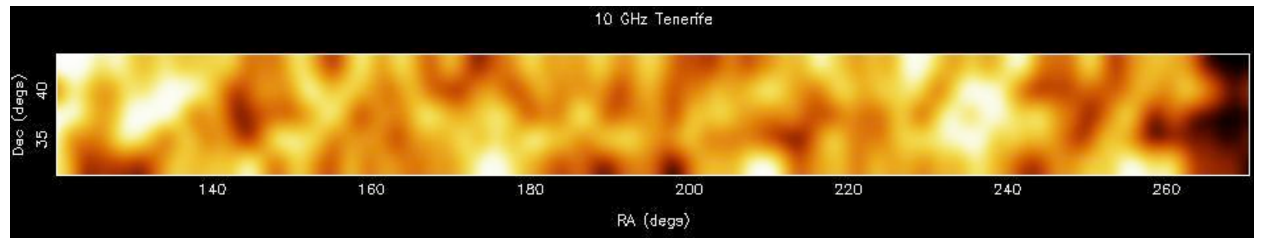



The QUIJOTE experiment
QT1. Instruments
MFI,MFI2
11, 13, 17, 19 GHz
FWHM = 0.93°-0.62°
MFI: 2012-2018
MFI2: 2022-
QT2. Instruments
TGI,FGI
30 and 40 GHz
FWHM = 0.37°-0.28°
Commissioning 2018, 2021-
QT1 and QT2
Crossed-Dragone
telescopes, 2.25m primary,
1.9m secondary
Quijote
Q-U-I Joint Tenerife CMB experiment
RADIO
FOREGROUNDS
UNIÓN EUROPEA
Ref. de la ayuda: ICTS-2019-03-IAC-12
INSTITUTO DE ASTROFISICA DE CANARIAS
IAC
IFCA
Instituto de Física de Cantabria
MANCHESTER
1824
The University of Manchester
DICOM
UNIVERSITY OF
CAMBRIDGE
idom

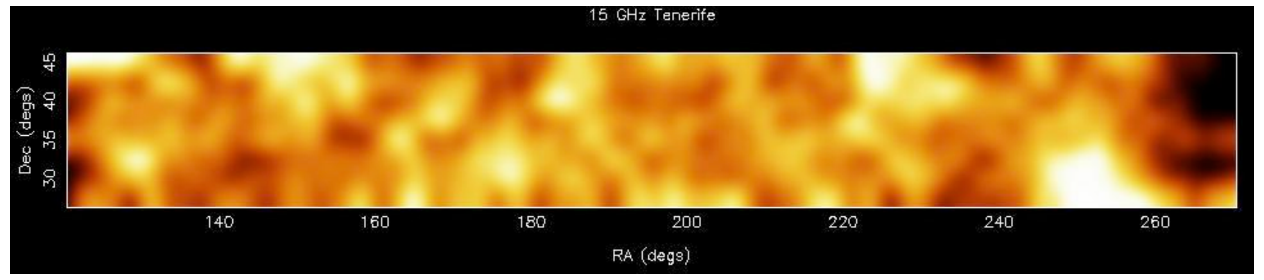
Teide Observatory

Previous CMB experiments

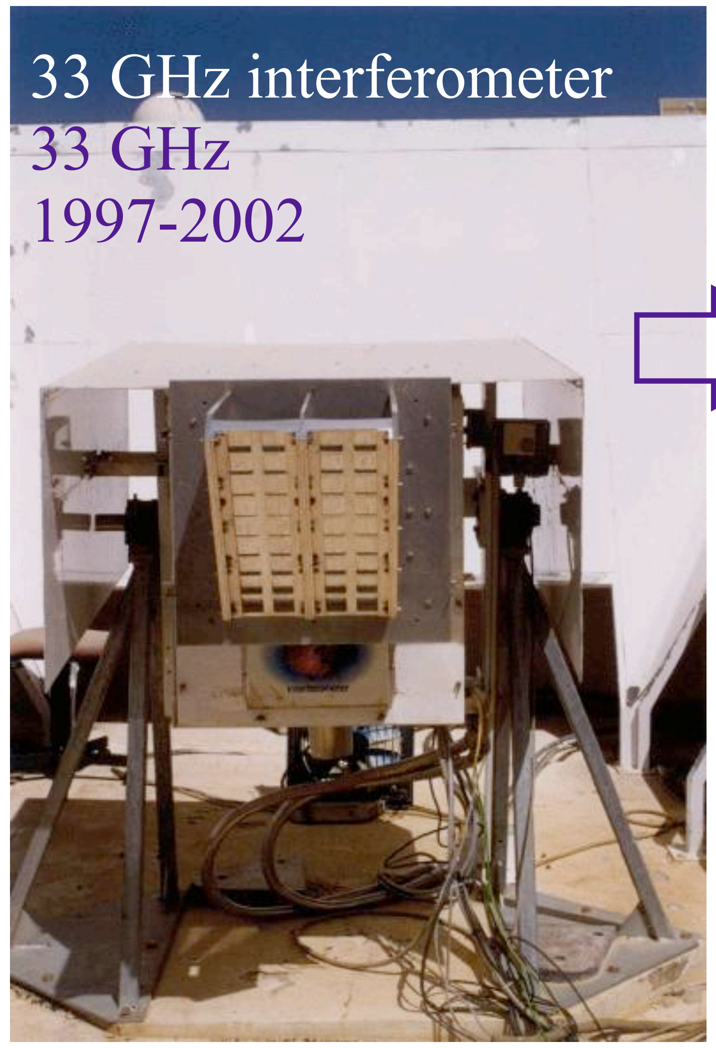
10 GHz Tenerife



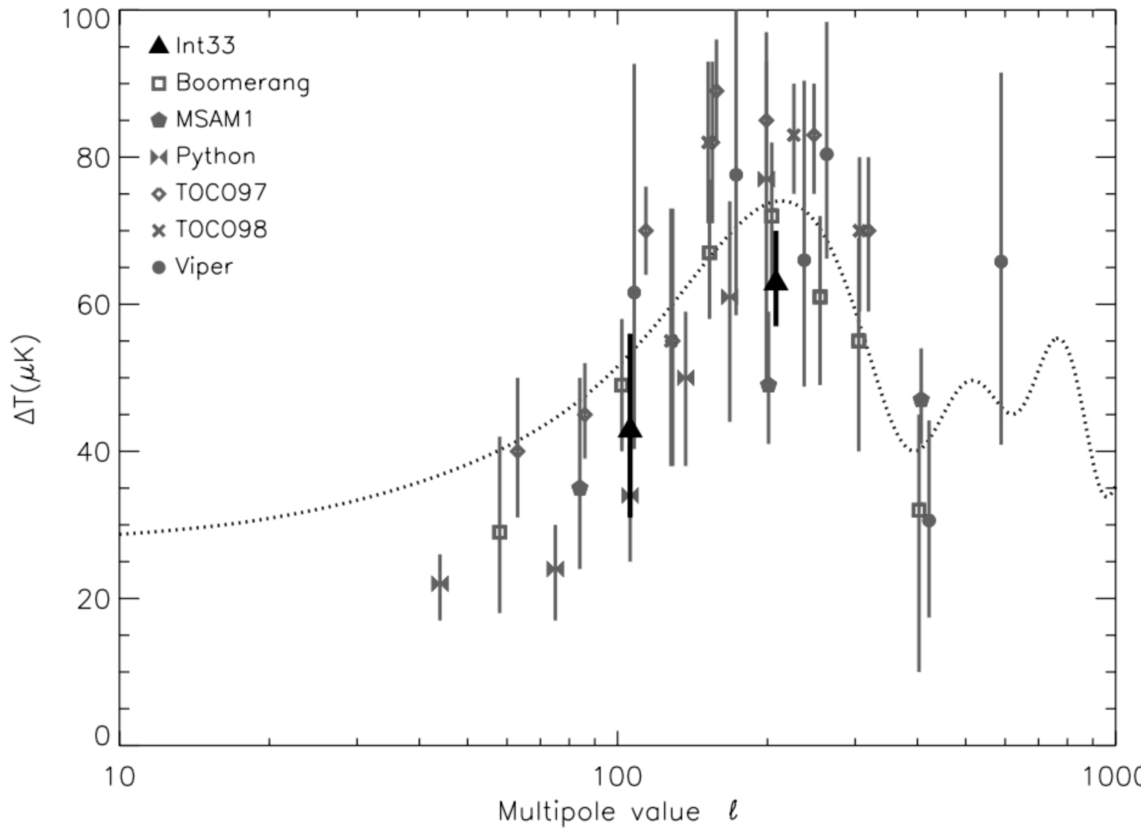
15 GHz Tenerife



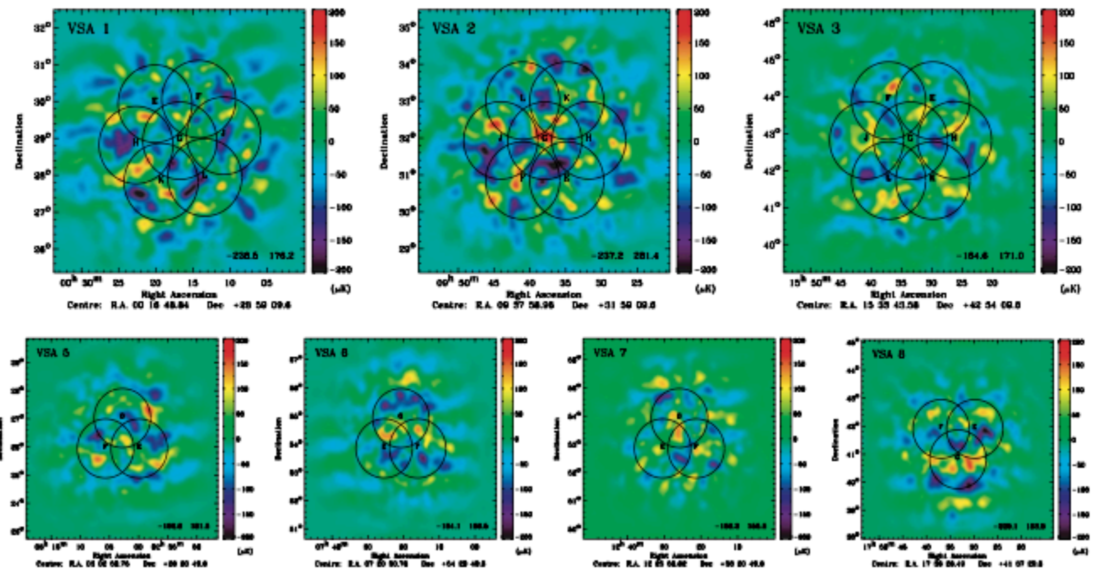
Gutiérrez et al. 2000

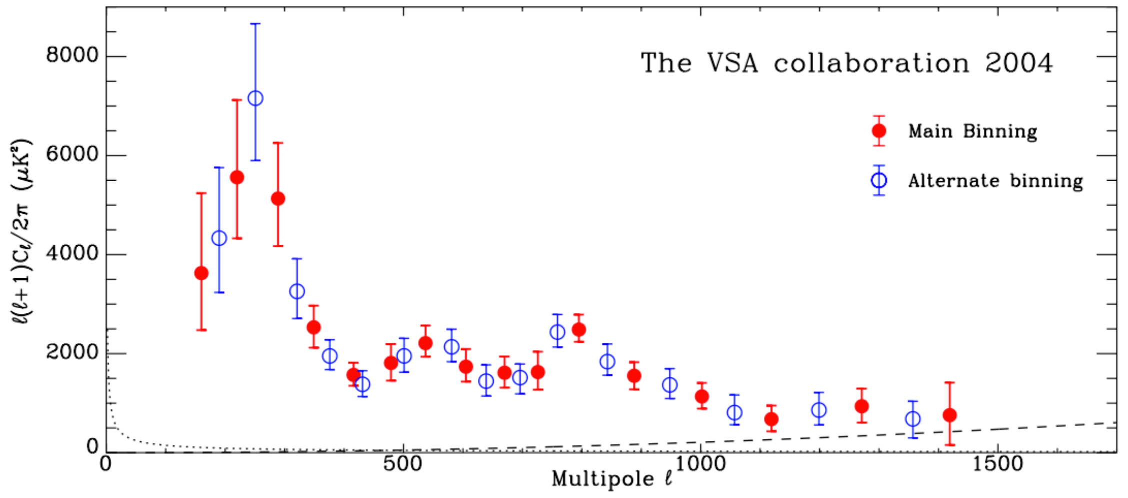


Harrison et al. 2000

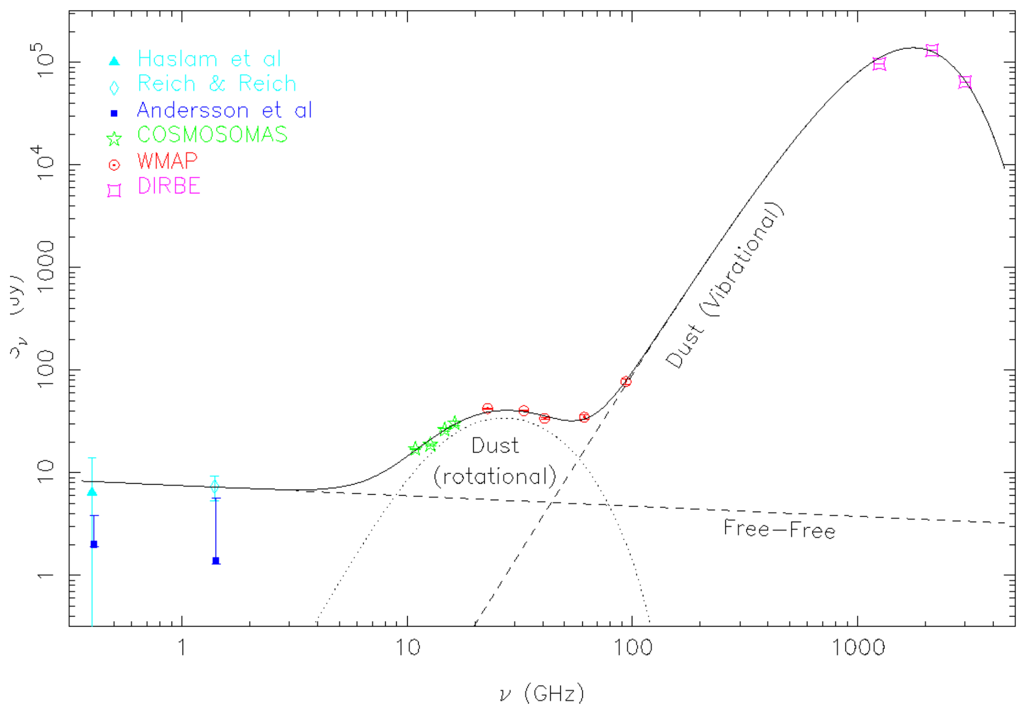


VSA 33 GHz





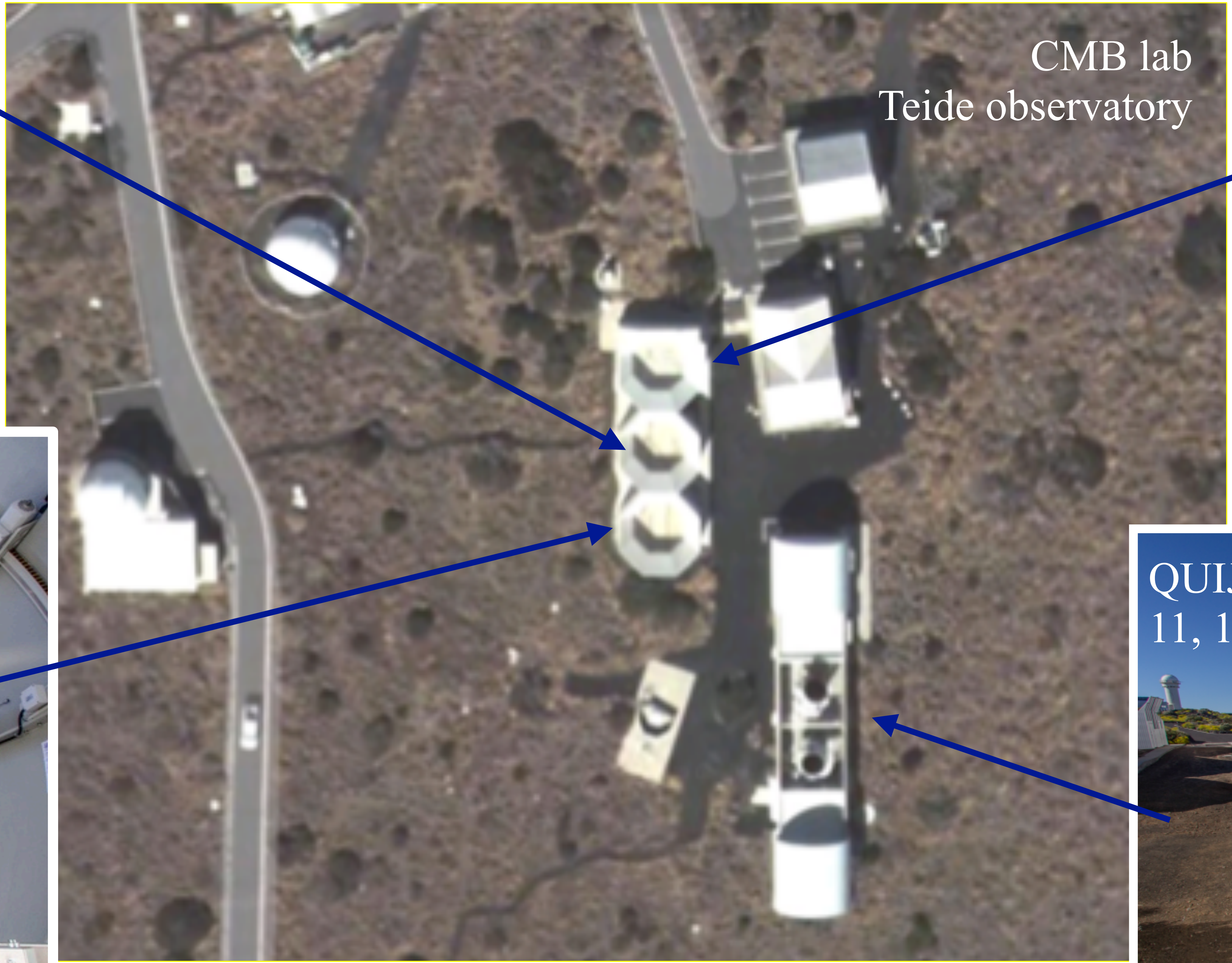
Dickinson et al. 2004

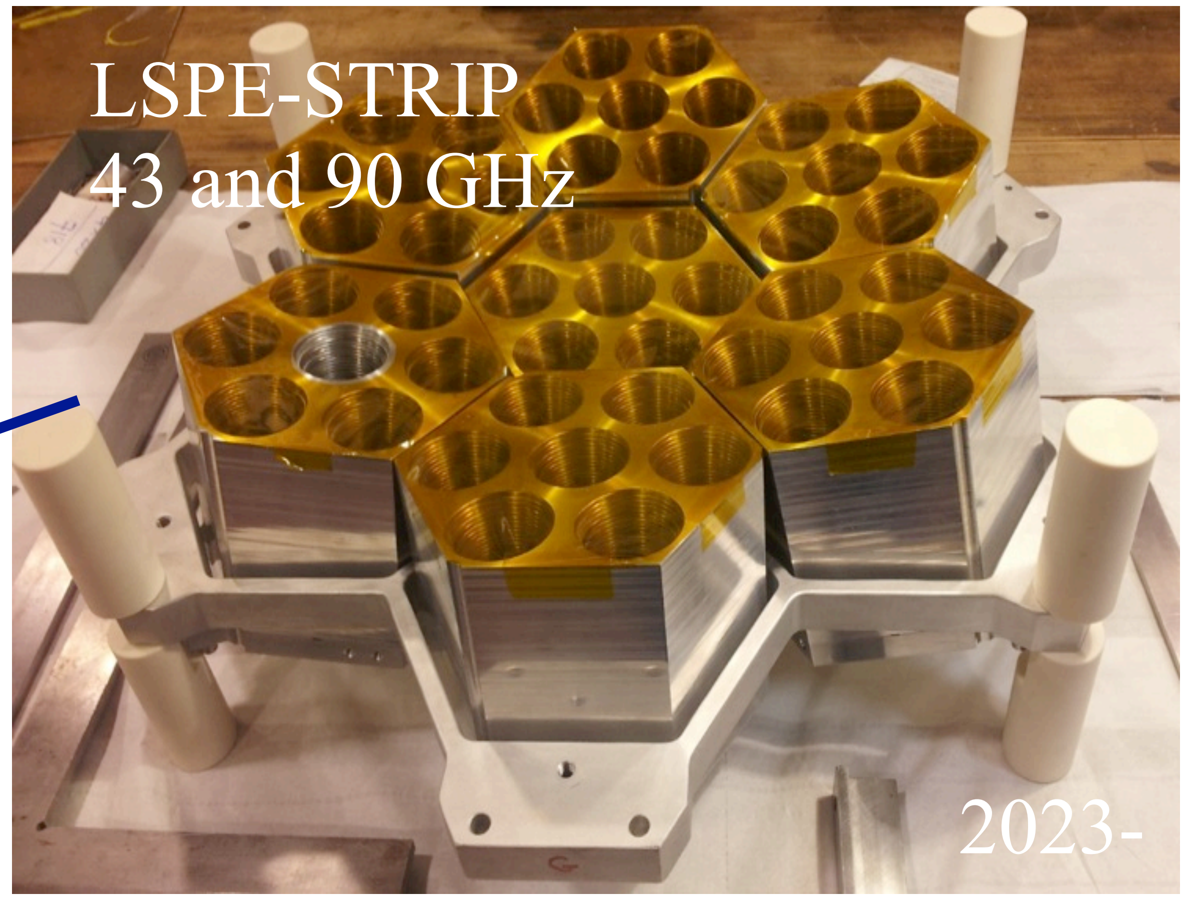


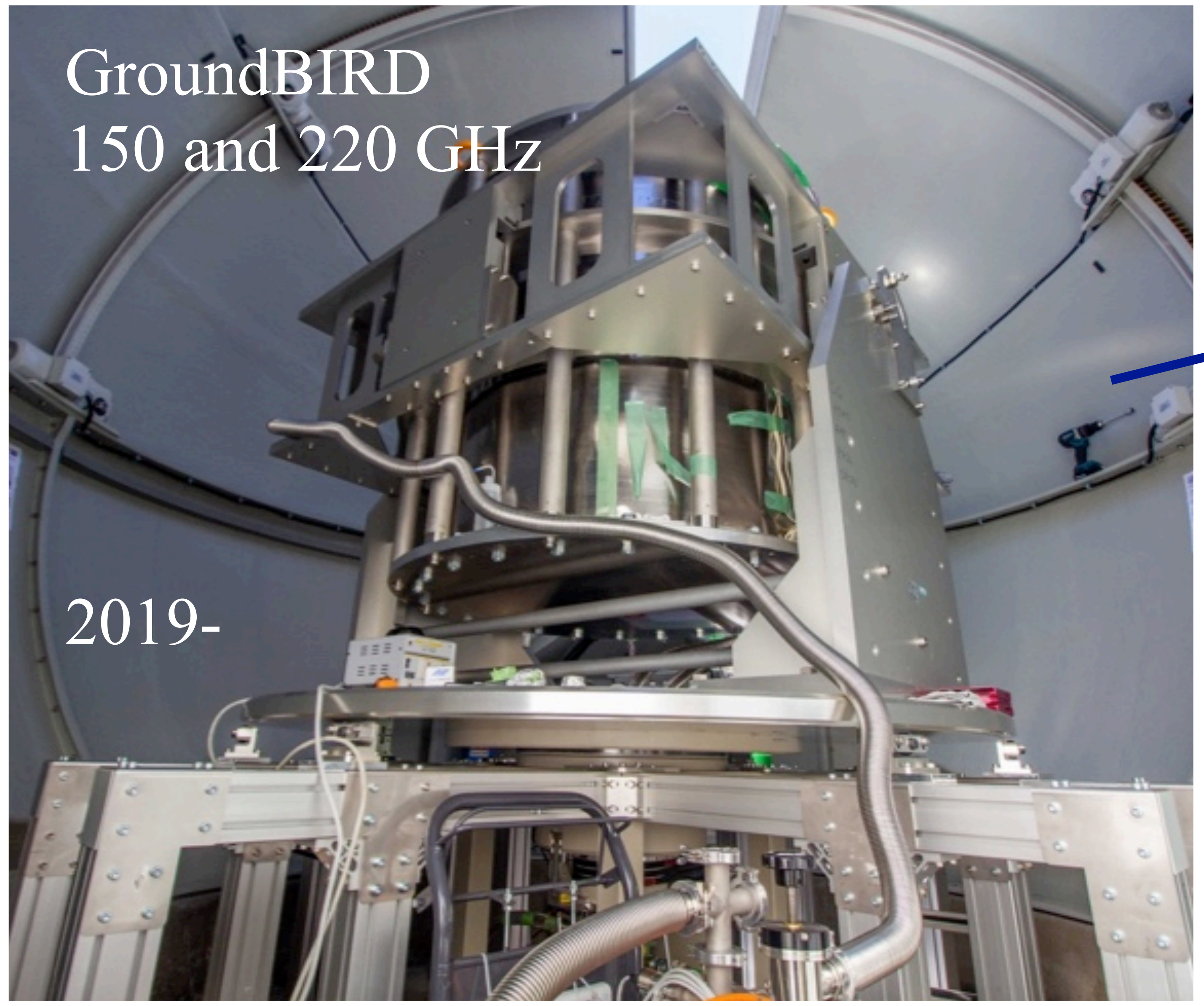
Watson et al. 2005

Teide Observatory

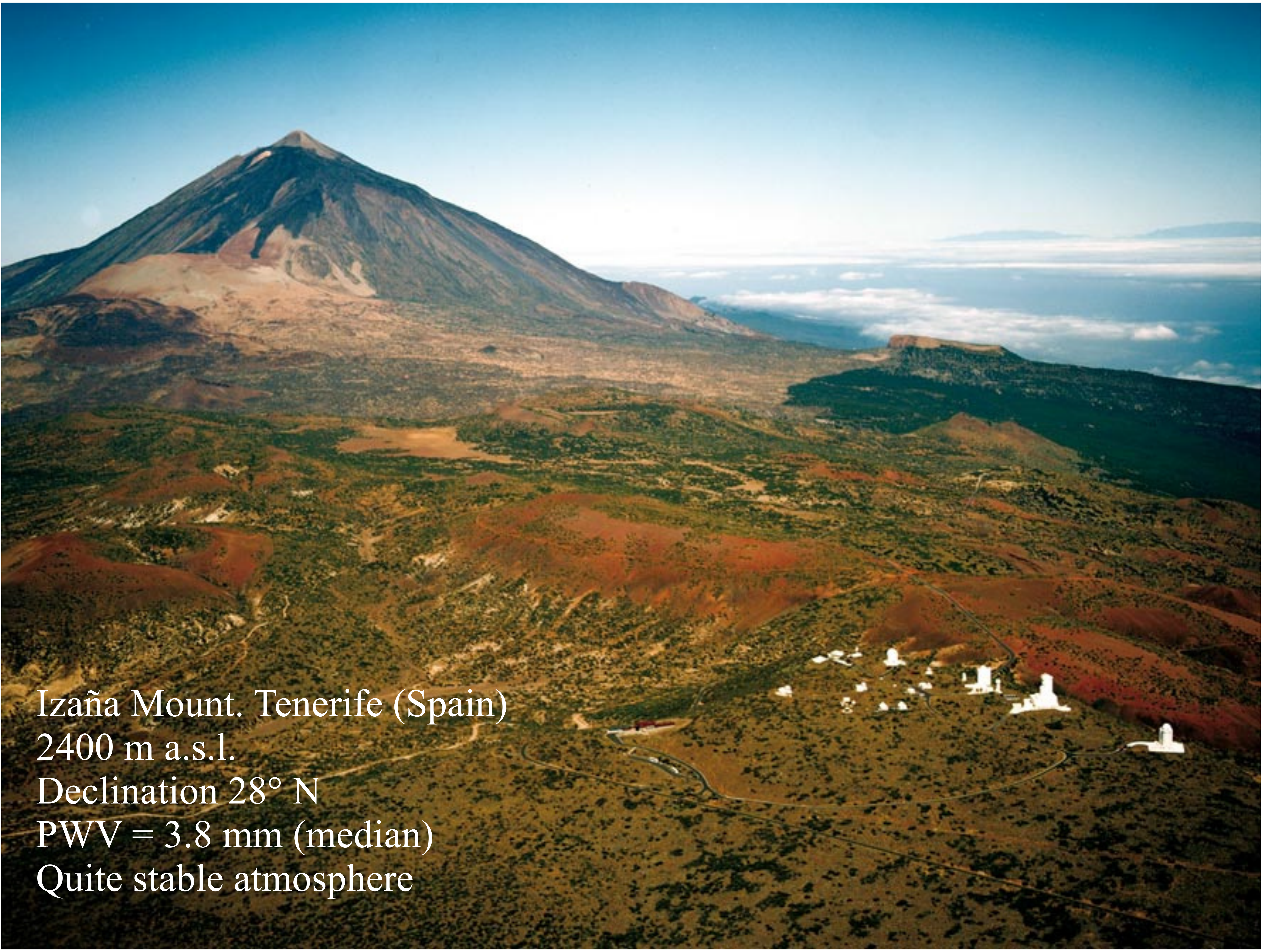
Current and future CMB experiments



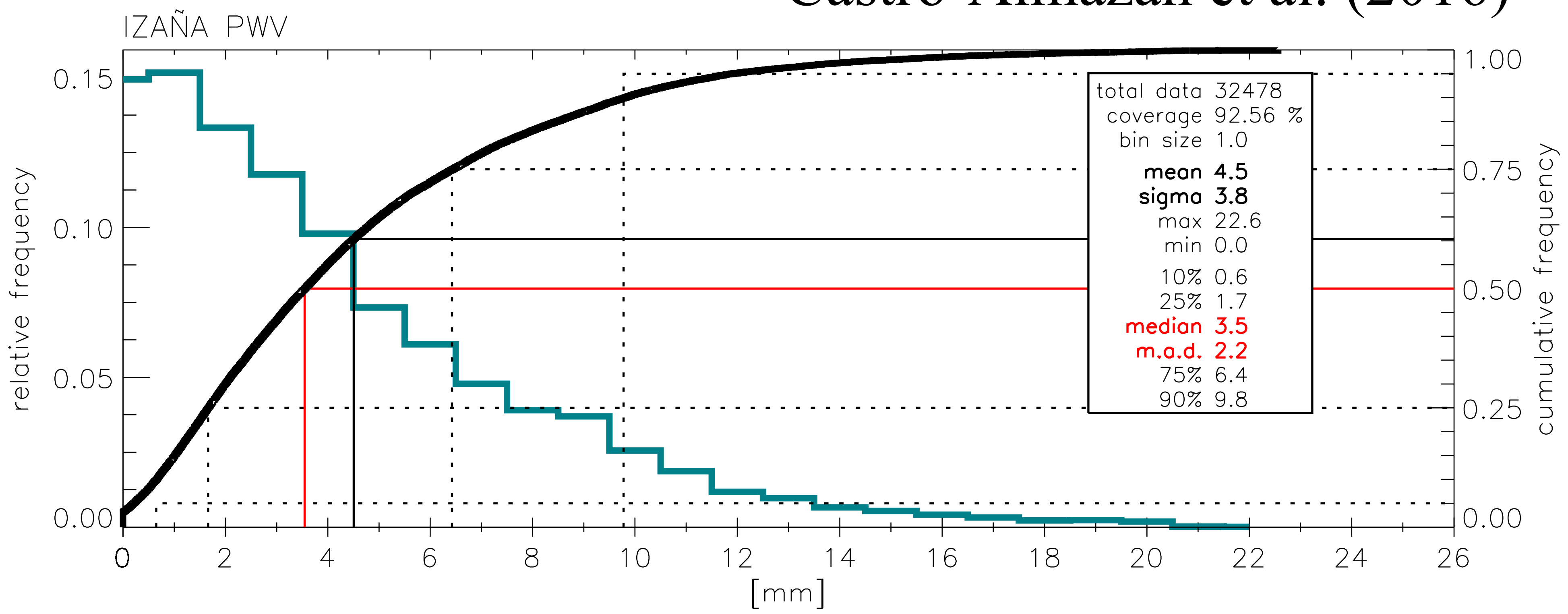


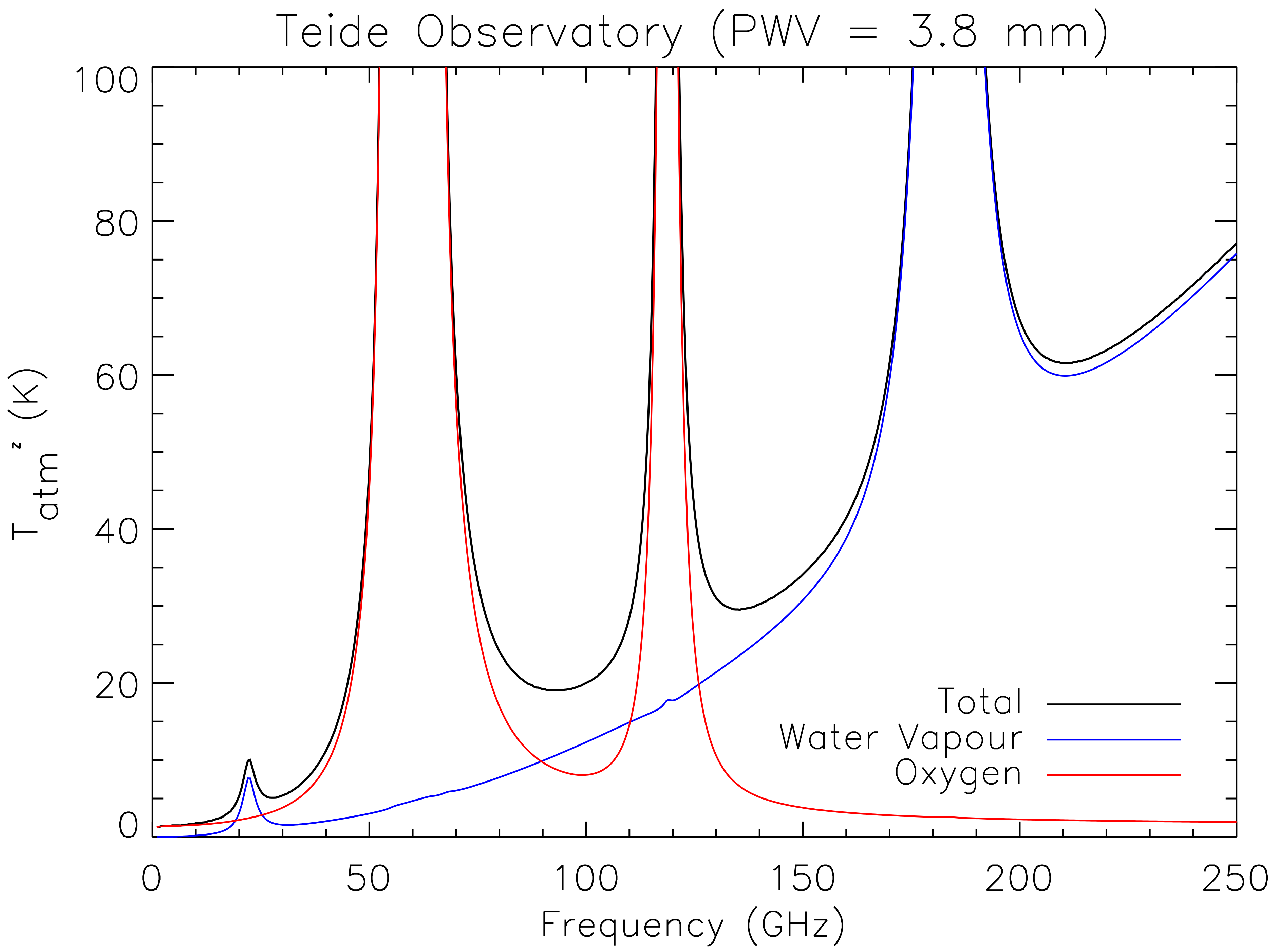


Teide Observatory



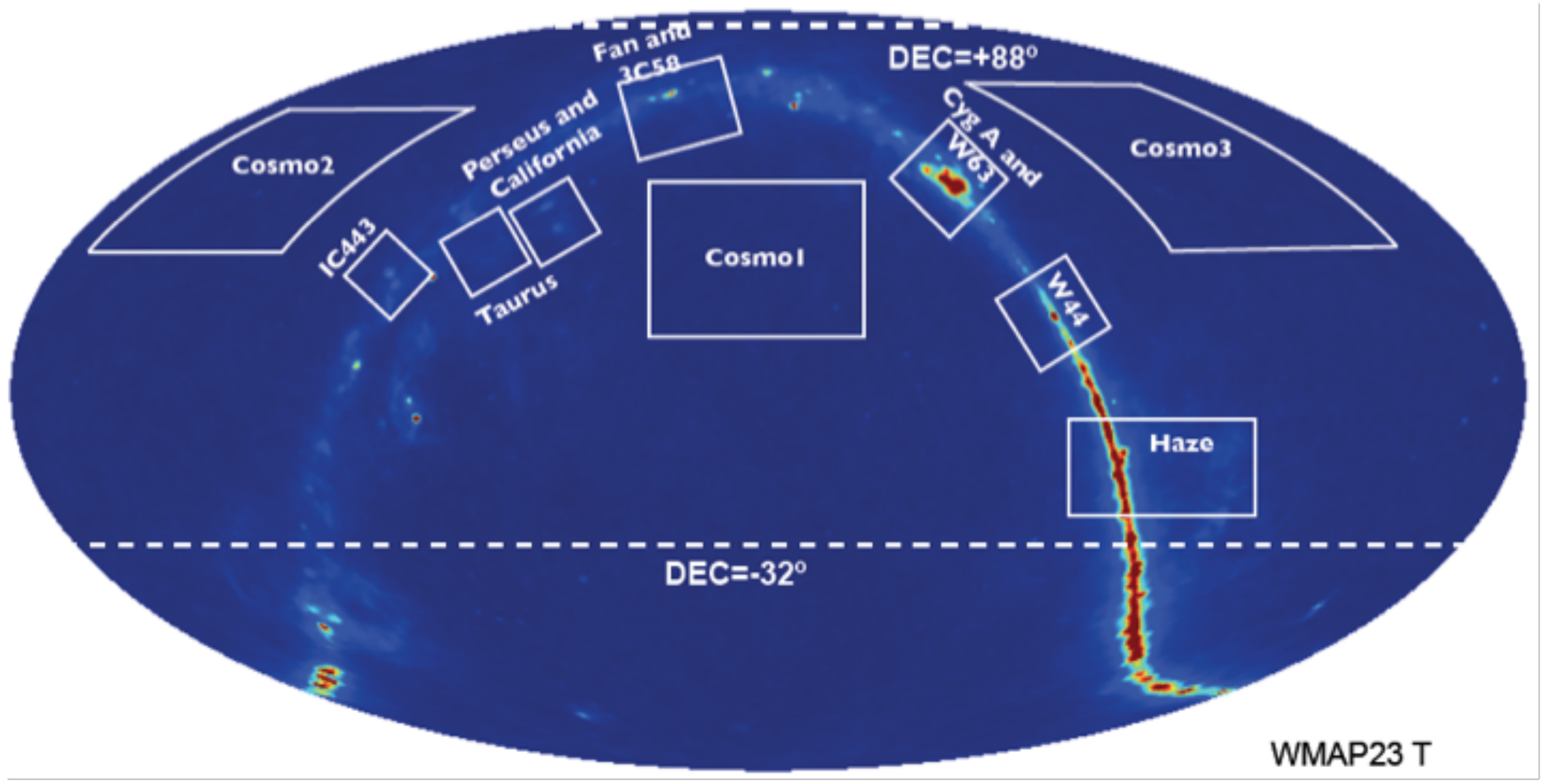
Castro-Almazán et al. (2016)





Science with QUIJOTE-MFI

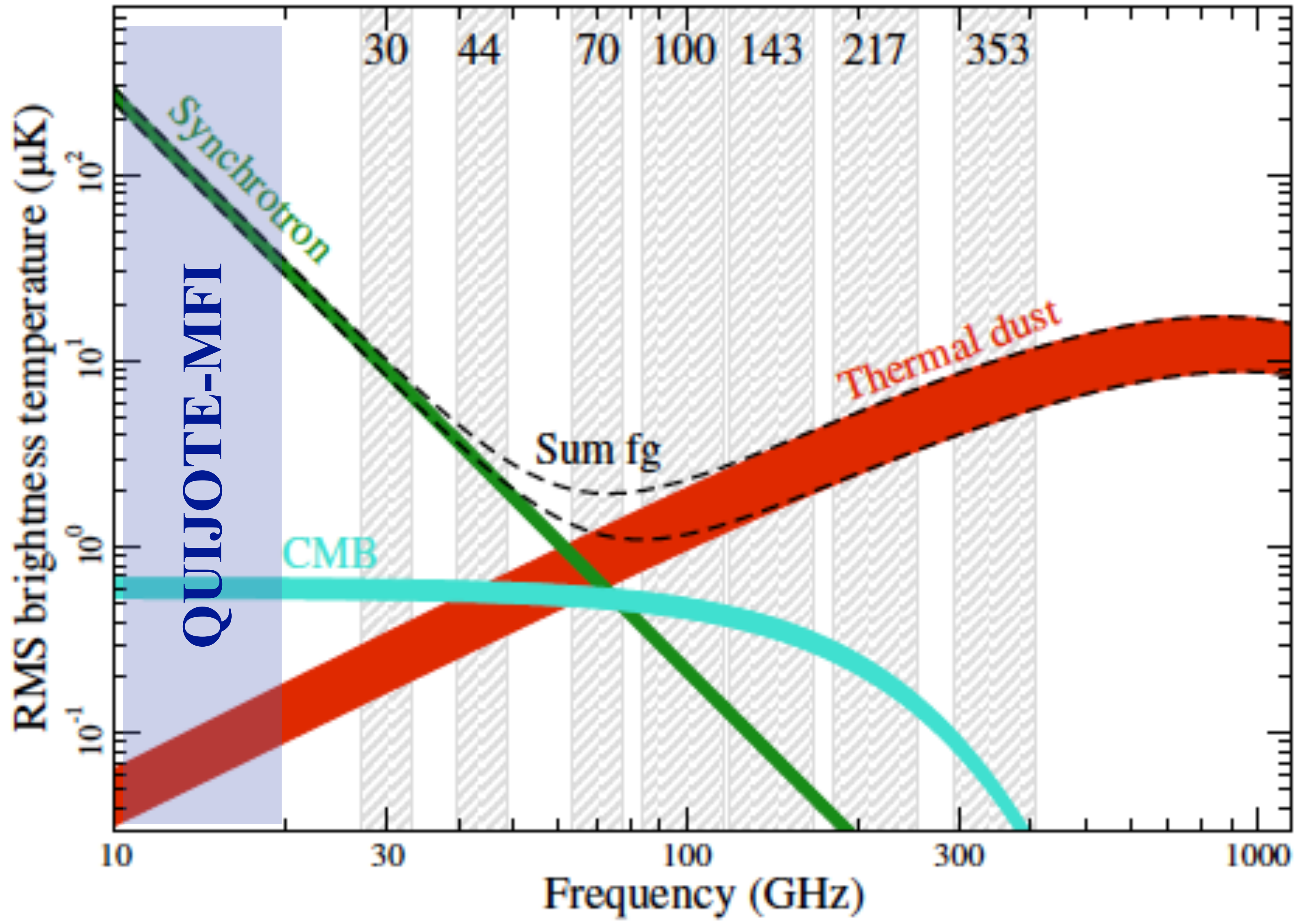
- Excellent complement to Planck/WMAP at low frequencies.
- Fills the gap between WMAP/Planck and low-freqs (C-BASS)
- Legacy value (→LiteBIRD)
- Goal: reach **$\sigma_{Q,U}$ ~ 10 μK/deg** in the full northern-sky (dec>0°)



Observations MFI science phase

- Wide survey (11,000 h) → 10 Tb raw data
- Cosmological fields (~ 3,000 deg^2) (6,500 h)
- Daily calibrators:Tau A, Cas A, Moon, sky dips and also Jupiter, Venus (~1,700 h)
- Galactic centre and the Haze (1,400 h)
- ρ-Ophiuchi molecular cloud (260 h)
- Perseus molecular cloud (750 h) → Génova-Santos et al. (2015)
- Fan and 3C58 (500 h)
- SNRs: W44, W49, W51, W63, IC443 (1,150 h) → Génova-Santos et al. (2017)
- Taurus (450 h) → Poidevin et al. (2019)
- M31 (540 h)

Total: **26,000 hours** of MFI data → **3 effective years**
→ **50% efficiency** between 2013 and 2018



QUIJOTE-MFI scientific results

MFI early results

I. Measurements of the intensity and polarization of the AME in the Perseus molecular complex (Génova-Santos et al. 2015)
II. Polarization measurements of the microwave emission in the Galactic MCs W43 and W47 and SNR W43 (Génova-Santos et al. 2017)
III. Microwave spectrum of intensity and polarization in the Taurus MC complex and L1527 (Poidevin et al. 2019)

MFI wide survey scientific results

IV. A northern sky survey at 10-20 GHz with the Multi-Frequency Instrument (Rubino-Martín et al.)
V. W49, W51 and IC443 SNRs as seen by QUIJOTE-MFI (Tramonte et al.)
VI. The Haze region and the Galactic Centre as seen by QUIJOTE-MFI (Guidi et al.)
VII. Galactic AME sources in the MFI wide survey (Poidevin et al.)
VIII. Component separation in polarization with the QUIJOTE-MFI wide survey. (de la Hoz et al.)
IX. Radio-sources in the QUIJOTE-MFI wide survey (Herranz et al.)
X. Polarised synchrotron loops and spurs. (Peel et al.)
XI. Spatial variability of AME parameters in the Galactic Plane (Fernández-Torreiro et al.)
XII. Analysis of the polarised synchrotron emission at the power spectrum level (Vansyngel et al.)
XIII. Intensity and polarization study of Supernova Remnants (López-Caraballo et al.)
XIV. The FAN region as seen by QUIJOTE-MFI (Ruiz-Granados et al.)
XV. The North Galactic Spur as seen by QUIJOTE-MFI (Watson et al.)
XVI. Component separation in intensity with the QUIJOTE-MFI wide survey (de la Hoz et al.)

Main paper and 5 other papers to be submitted in summer 2022

Maps will be publicly released once these papers are accepted for publication

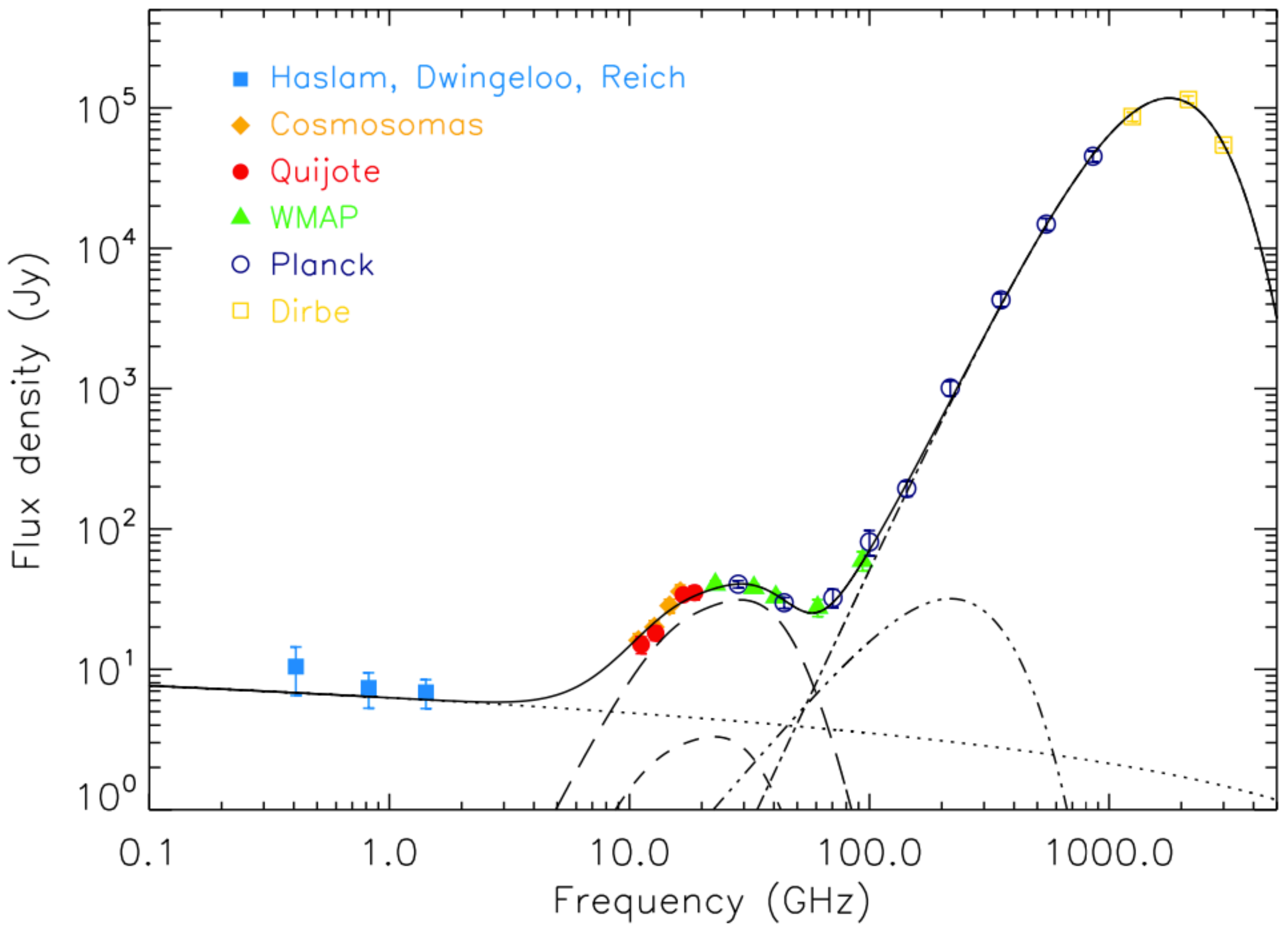
Others

- Detection of spectral variations of AME with QUIJOTE and C-BASS (Cepeda-Arroita al. 2021)
- The PICASSO map-making code: application to a simulation of the QUIJOTE northern sky survey (Guidi et al. 2021)
- MFI data processing pipeline (Génova-Santos et al.)

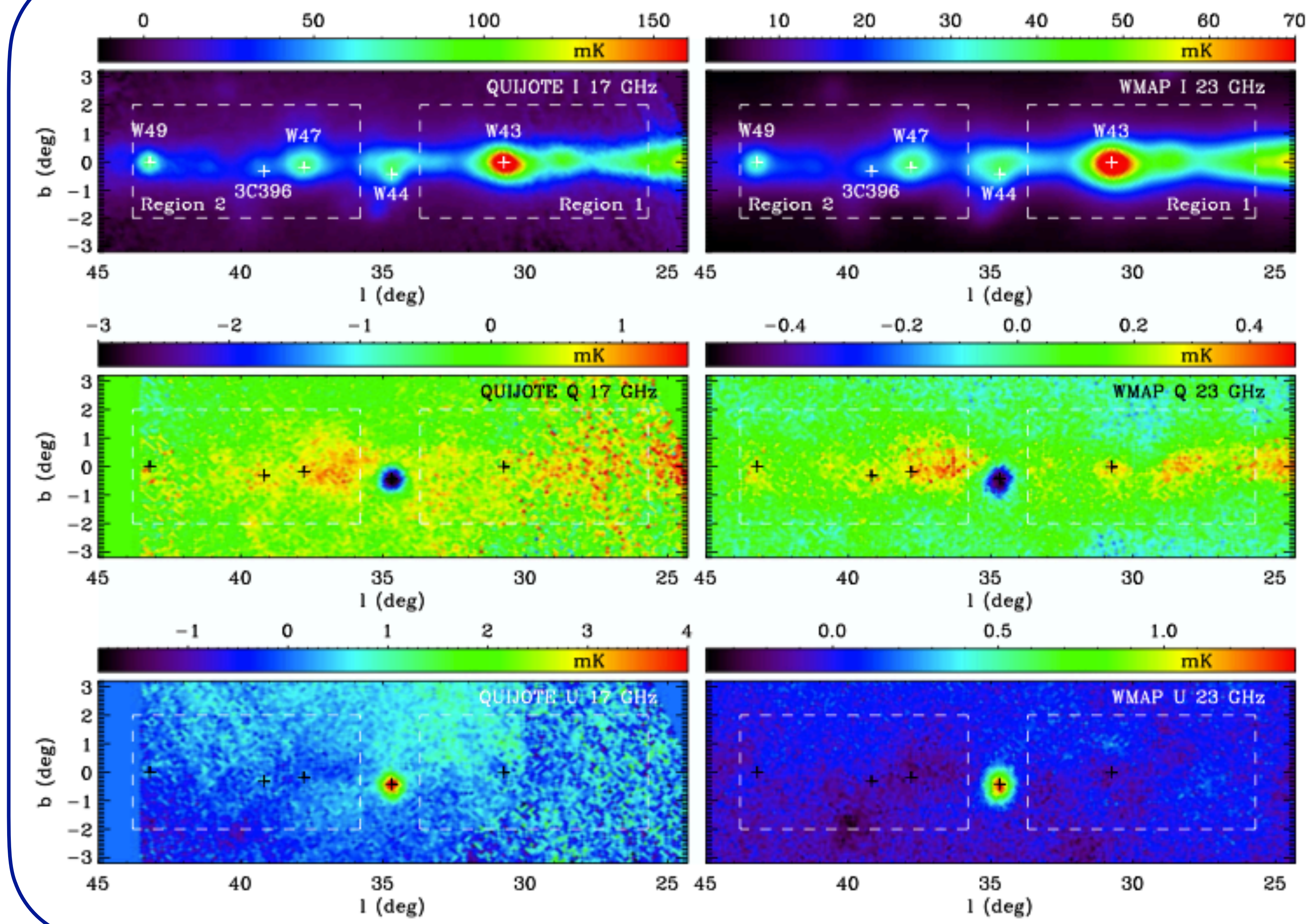
QUIJOTE-MFI early results

Perseus molecular complex

(Génova-Santos et al. 2015)



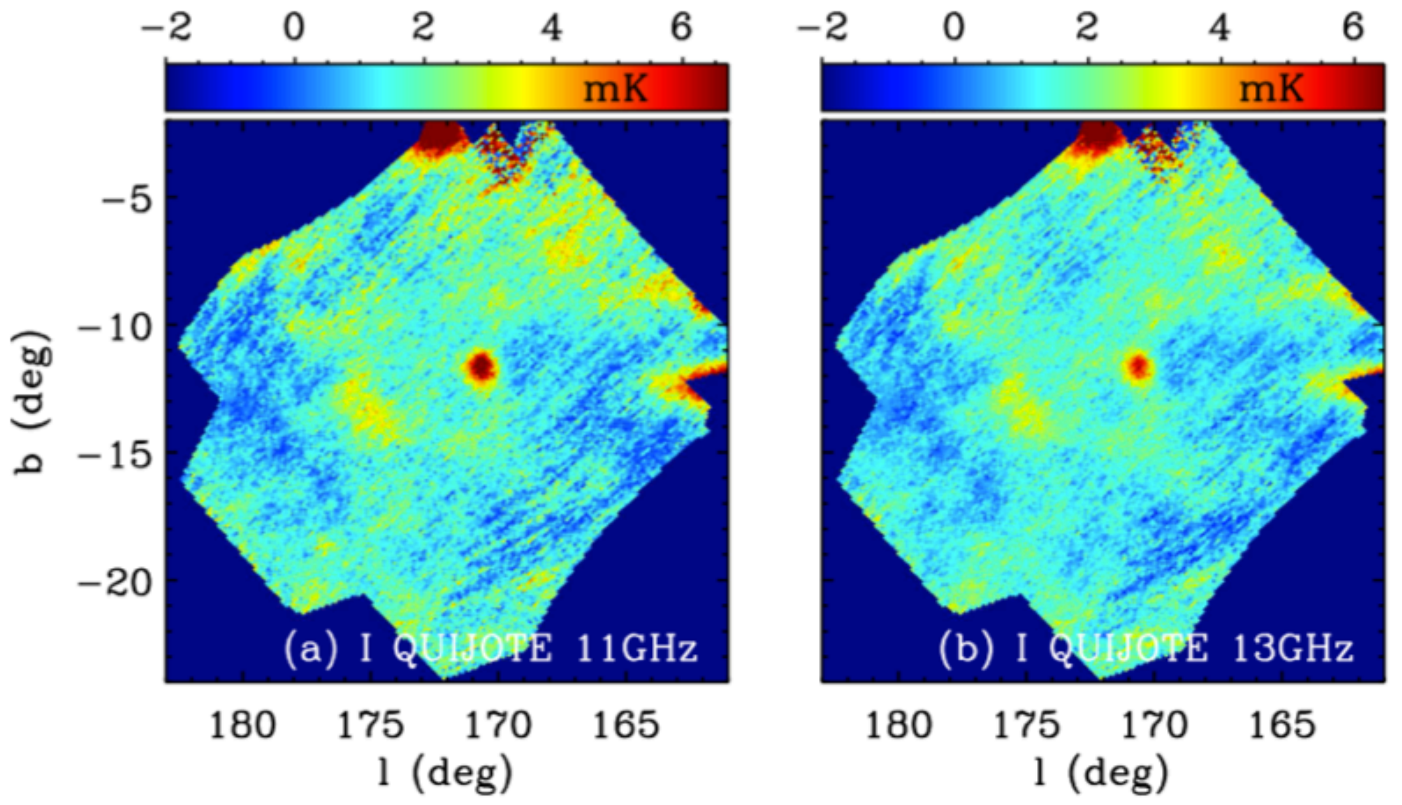
- Survey (194h, ≈250 deg²) on the Perseus MC at 10-20 GHz
- Confirmation of AME intensity downturn at low frequencies
- **Π_{AME}<3.4%** @ 18 GHz



W43, W44, W47

(Génova-Santos et al. 2017)

- 210h, ≈400 deg²
- SNR in W44, both I,Q,U
  - β_{sync}= -0.62± 0.03
- FR in W44
  - RM = -404 ± 49 rad/m²
- Diffuse Galactic emission
  - β_{sync} ~ -1.2
- AME in W43
  - **Π_{AME}<0.39%** @ 17 GHz
  - **Π_{AME}<0.22%** @ 41 GHz



Taurus molecular complex

(Poidevin et al. 2019)

- 451h, ≈289 deg²
- AME detections in the TMC and in L1527
  - Π_{AME}<4.2% @ 28.4 GHz, TMC
  - Π_{AME}<5.3% @ 28.4 GHz, L1527

QUIJOTE-MFI wide survey

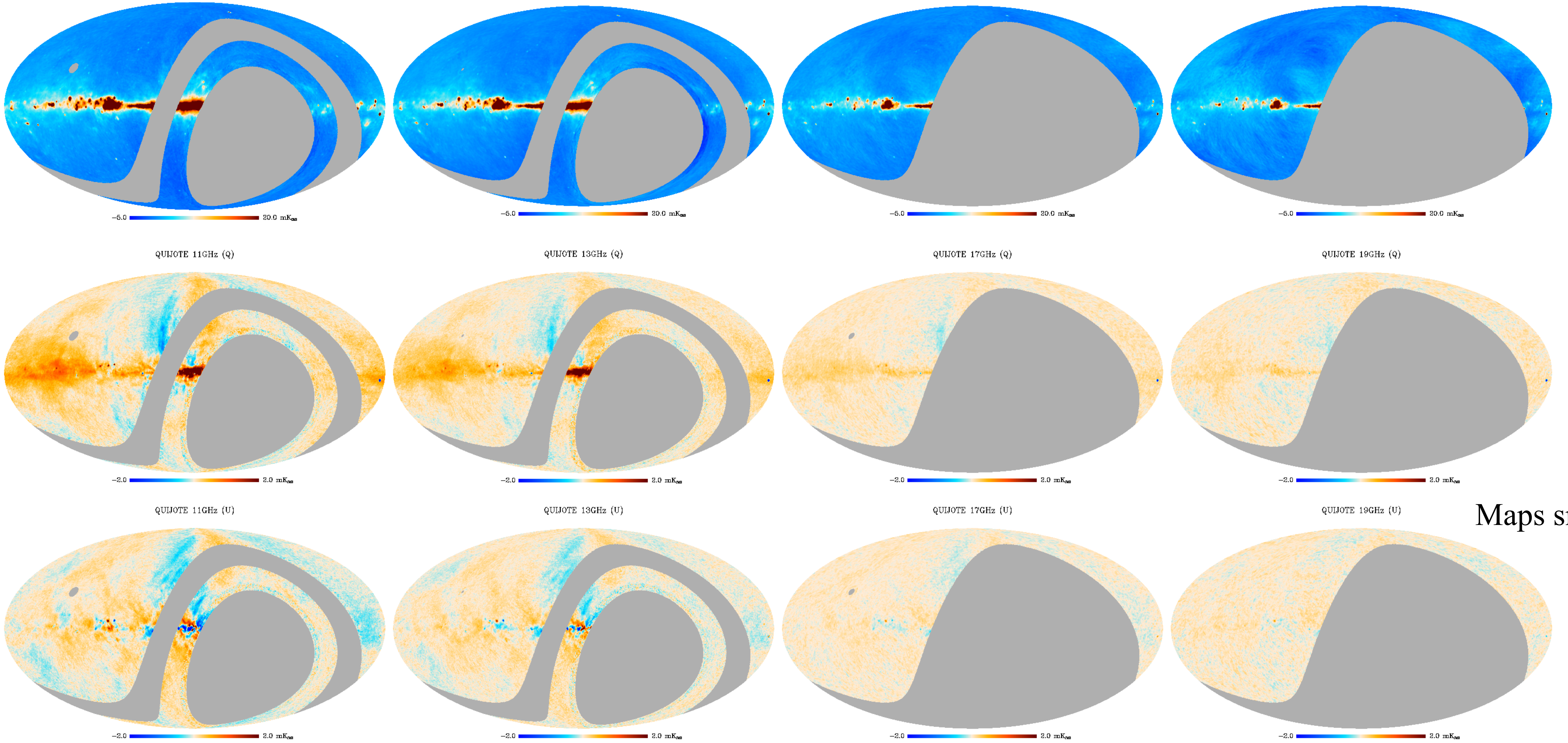
Rubiño-Martín et al. (to be submitted)

QUIJOTE 11 GHz | QUIJOTE 13 GHz | QUIJOTE 17 GHz | QUIJOTE 19 GHz

I

Q

U

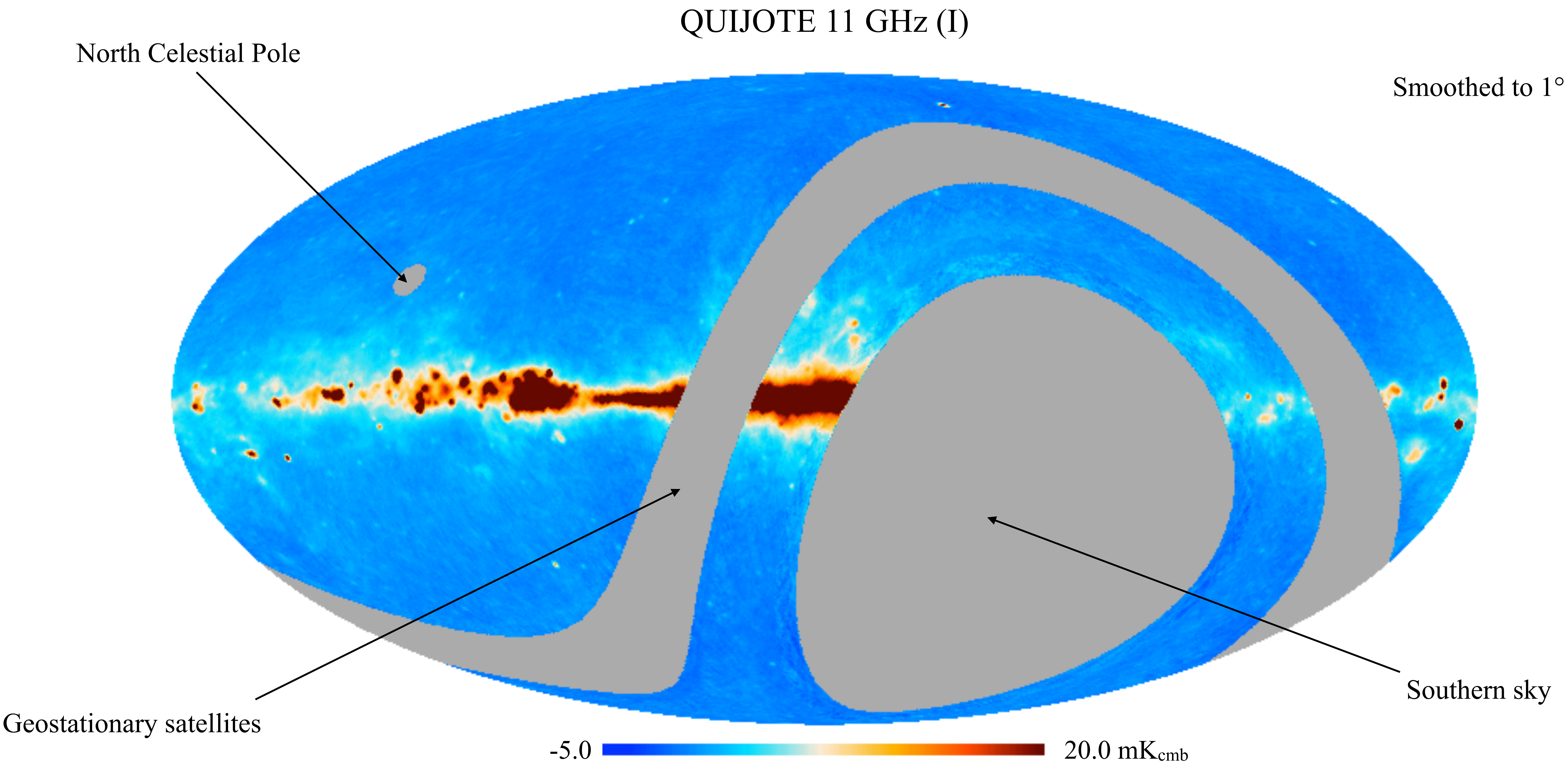


Maps smoothed to 1°

- Full **Northern sky** (~29,000 deg^2)
- Scans at constant elevation (12 deg/s)
- **11,000 hours** (6,000 hours after data flagging)
- **$\sigma_{Q,U}$ ~ 35-40 μK/deg**
- **σ_I ~ 60-150 μK/deg**

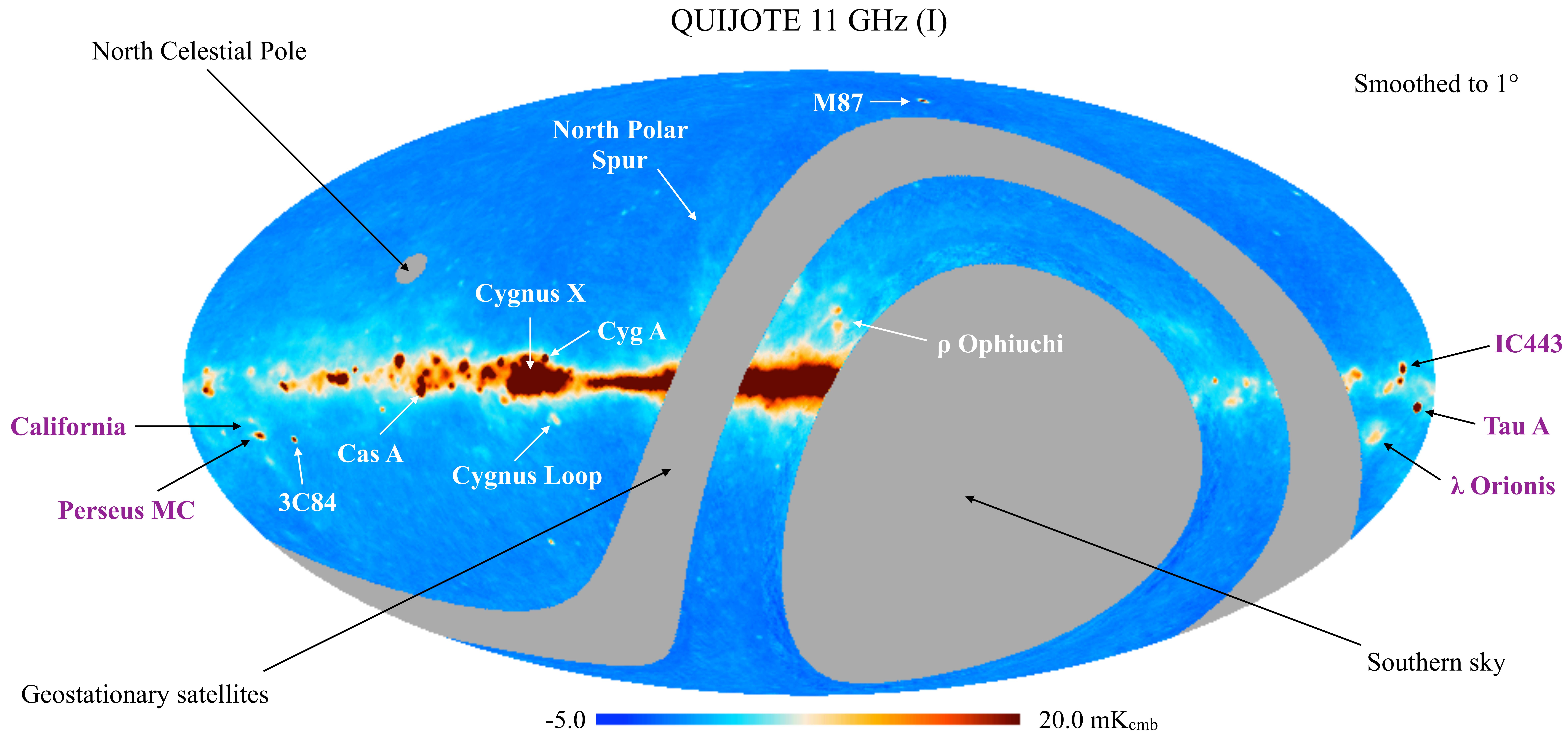
QUIJOTE-MFI wide survey

Rubiño-Martín et al. (to be submitted)



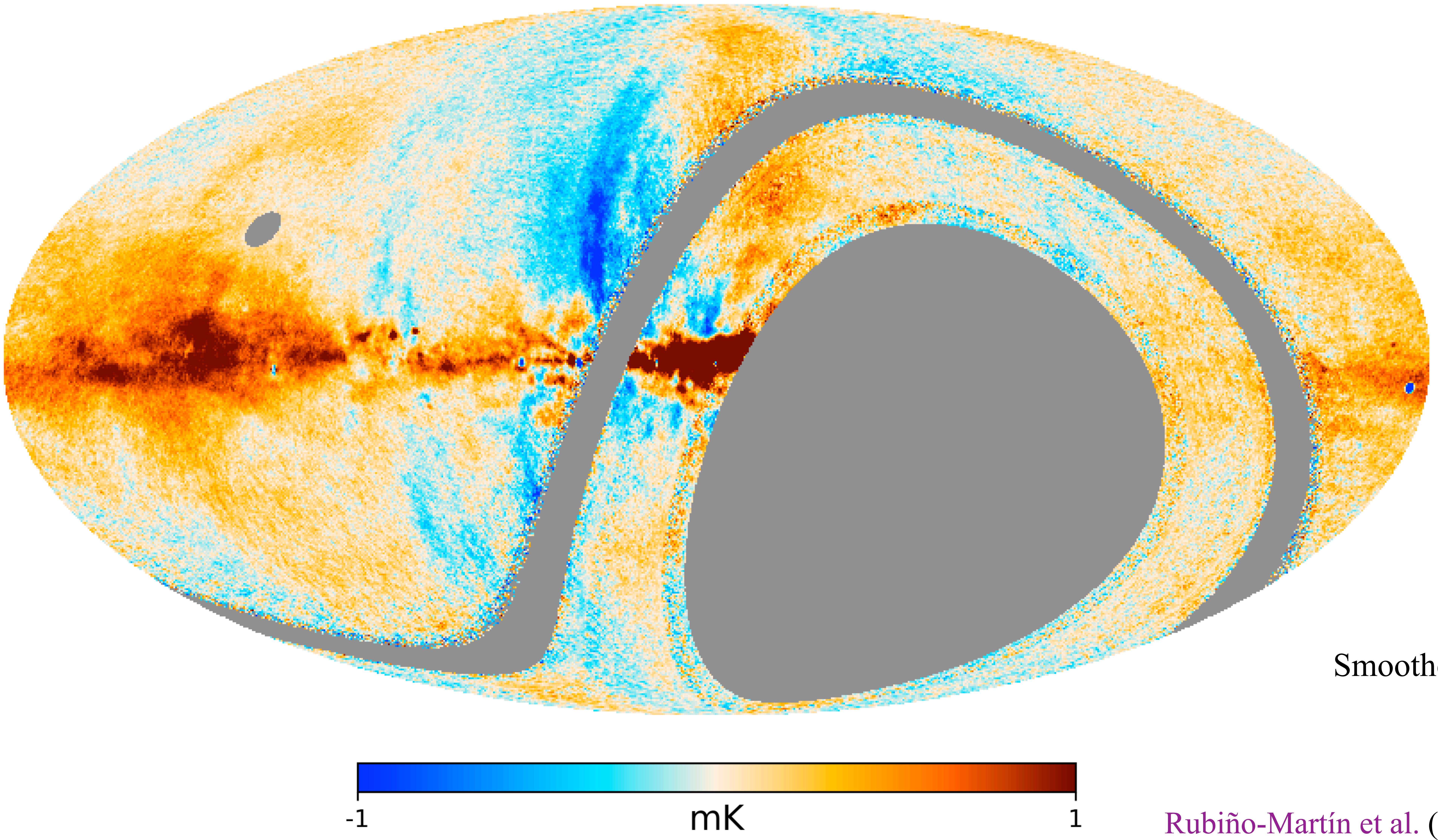
QUIJOTE-MFI wide survey

Rubiño-Martín et al. (to be submitted)



QUIJOTE-MFI wide survey

QUIJOTE 11 GHz (Q)

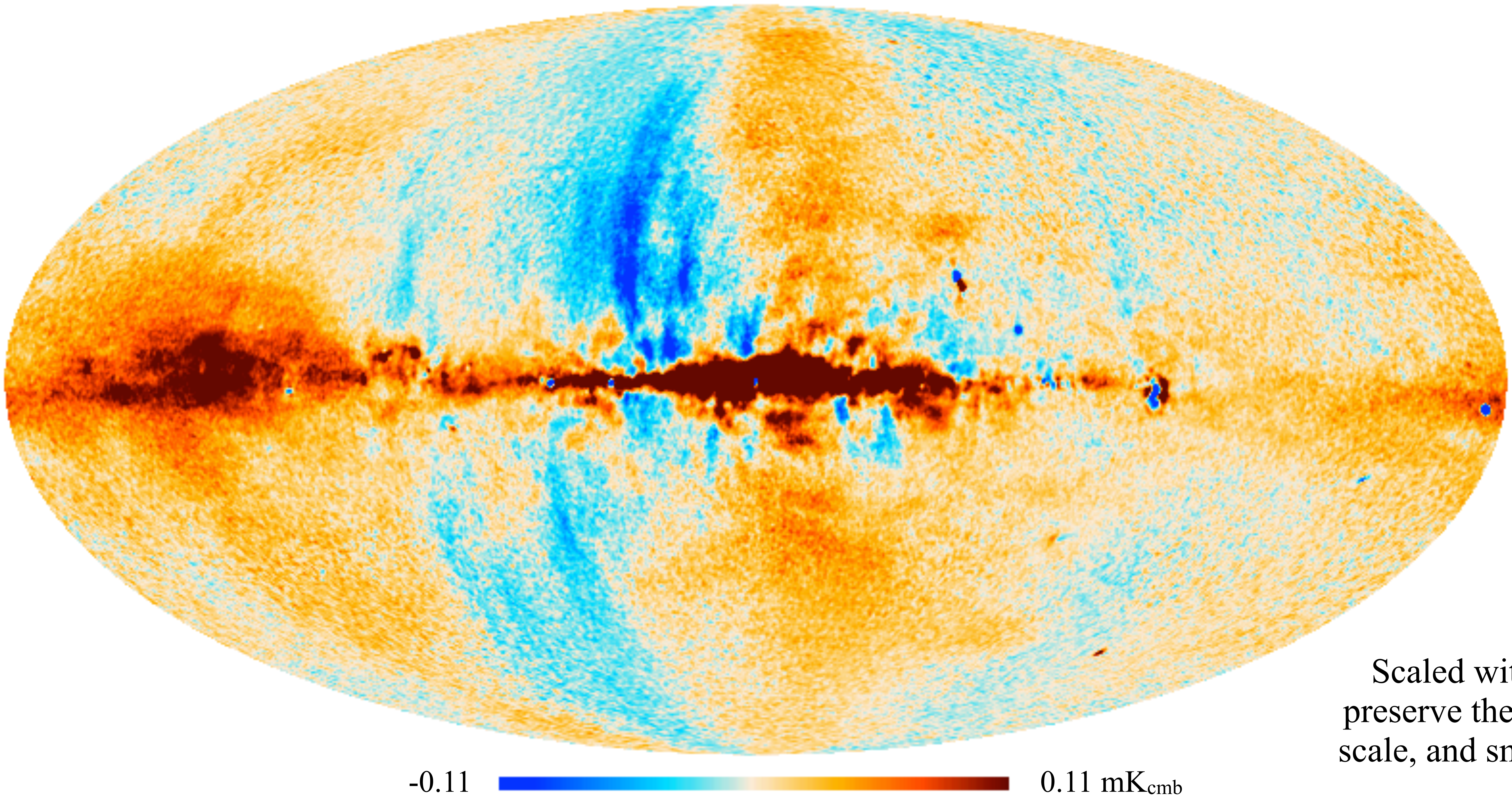


Smoothed to 1°

Rubiño-Martín et al. (to be submitted)

QUIJOTE-MFI wide survey

WMAP 23 GHz (Q)

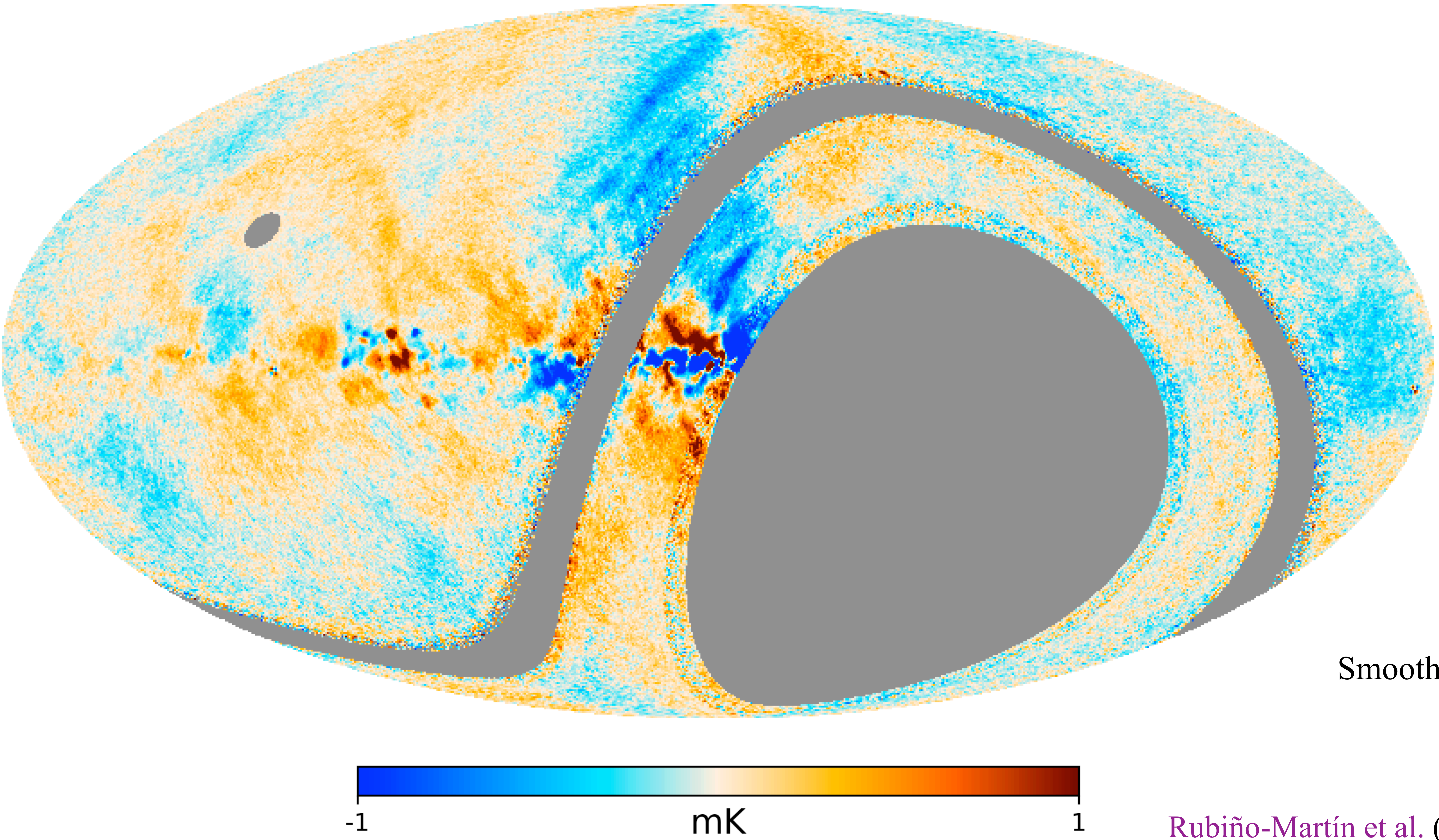


Scaled with β = -3 to preserve the same colour scale, and smoothed to 1°

Rubiño-Martín et al. (to be submitted)

QUIJOTE-MFI wide survey

QUIJOTE 11 GHz (U)

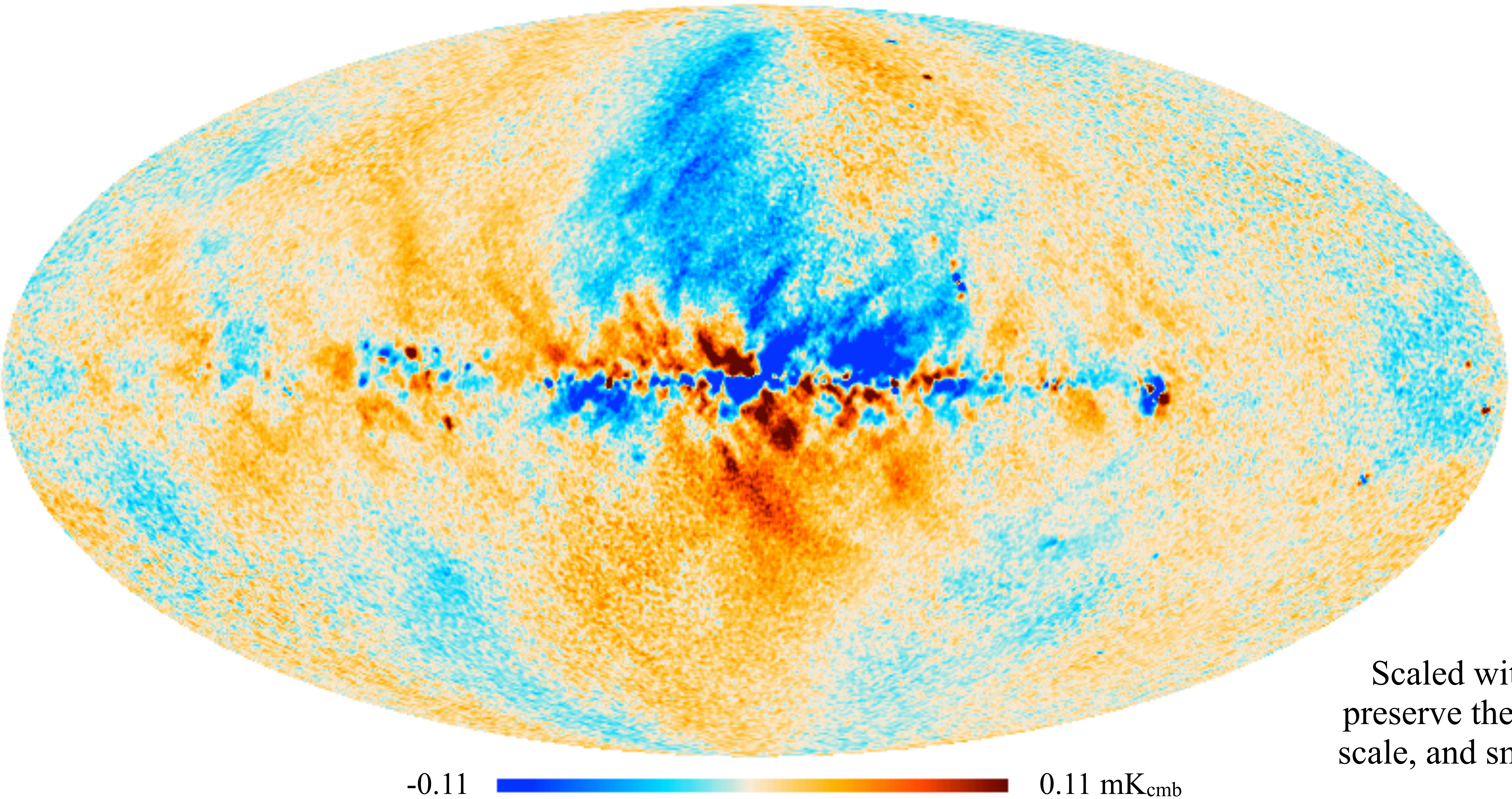


Smoothed to 1°

Rubiño-Martín et al. (to be submitted)

QUIJOTE-MFI wide survey

WMAP 23 GHz (U)



Scaled with β = -3 to preserve the same colour scale, and smoothed to 1°

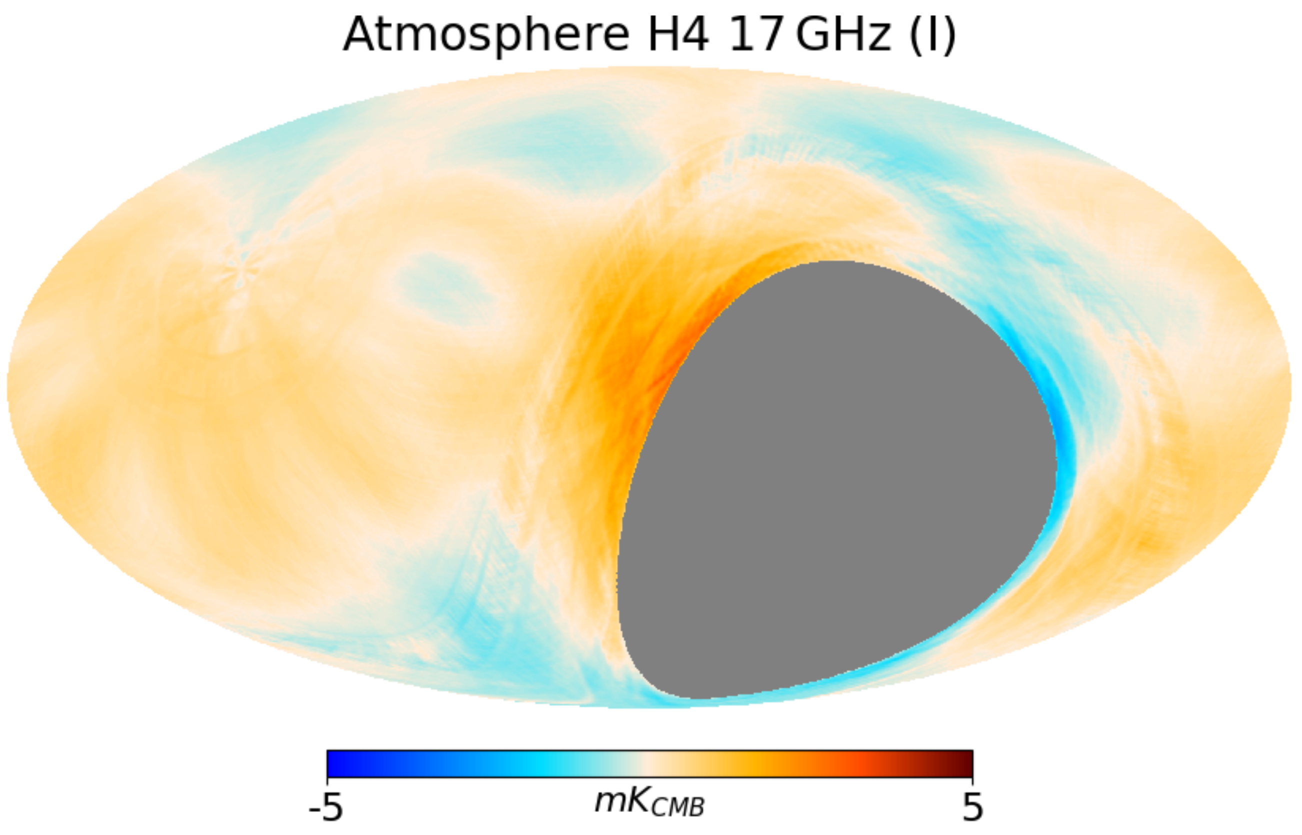
Rubiño-Martín et al. (to be submitted)

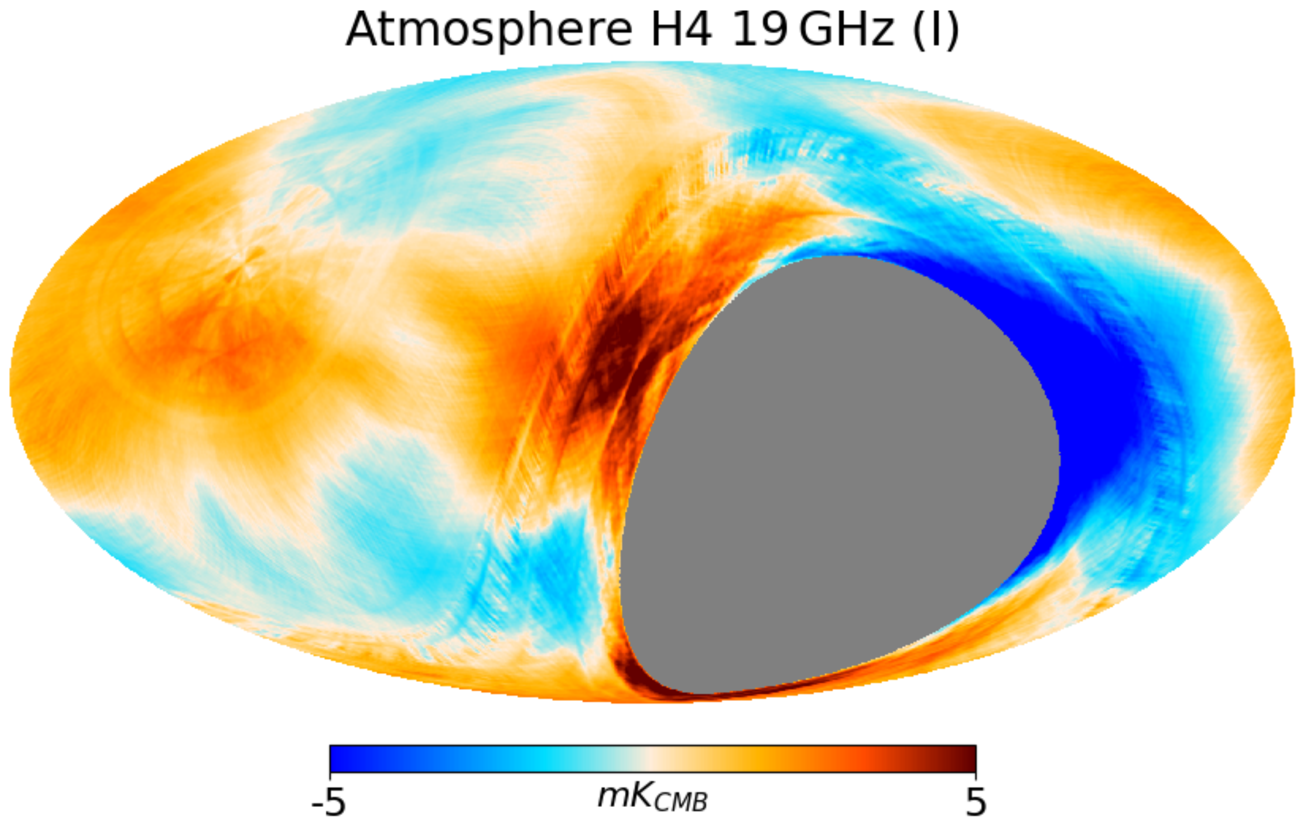
QUIJOTE-MFI wide survey

Pipeline, calibration and systematic effects

Génova-Santos, Rubiño-Martín et al. (in prep.)

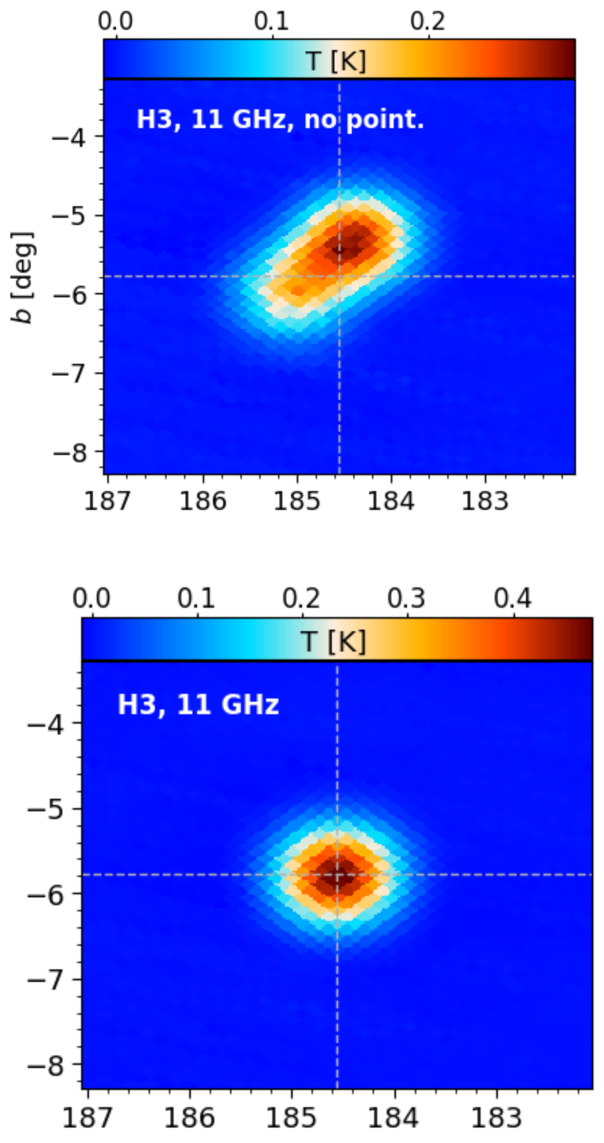
- **Amplitude calibration**
  - External/global. Point sources (Tau A, Cas A) → 5% accuracy
  - Internal gain modelling. Internal calibration diode → **<1%**
- **Polarisation angle calibration**
  - Tau A → accuracy of **0.5°**
- **Beams and window functions**
  - On-sky with bright sources (Tau A, Cas A) and geostationary satellites (~30-40 dB)
  - CST-simulations (agree with on-sky observations down o ~35 dB)
- **Pointing model**
  - Bright sources (Tau A) to fit a 7-parameter model → accuracy better than **1 arcmin**
- **RFI and atmosphere**
  - Masking
  - Mode at constant declination due to scanning strategy (affects l<15)
  - PCA analysis on ~2h to identify commons signal between horns, and remove an atmospheric template.

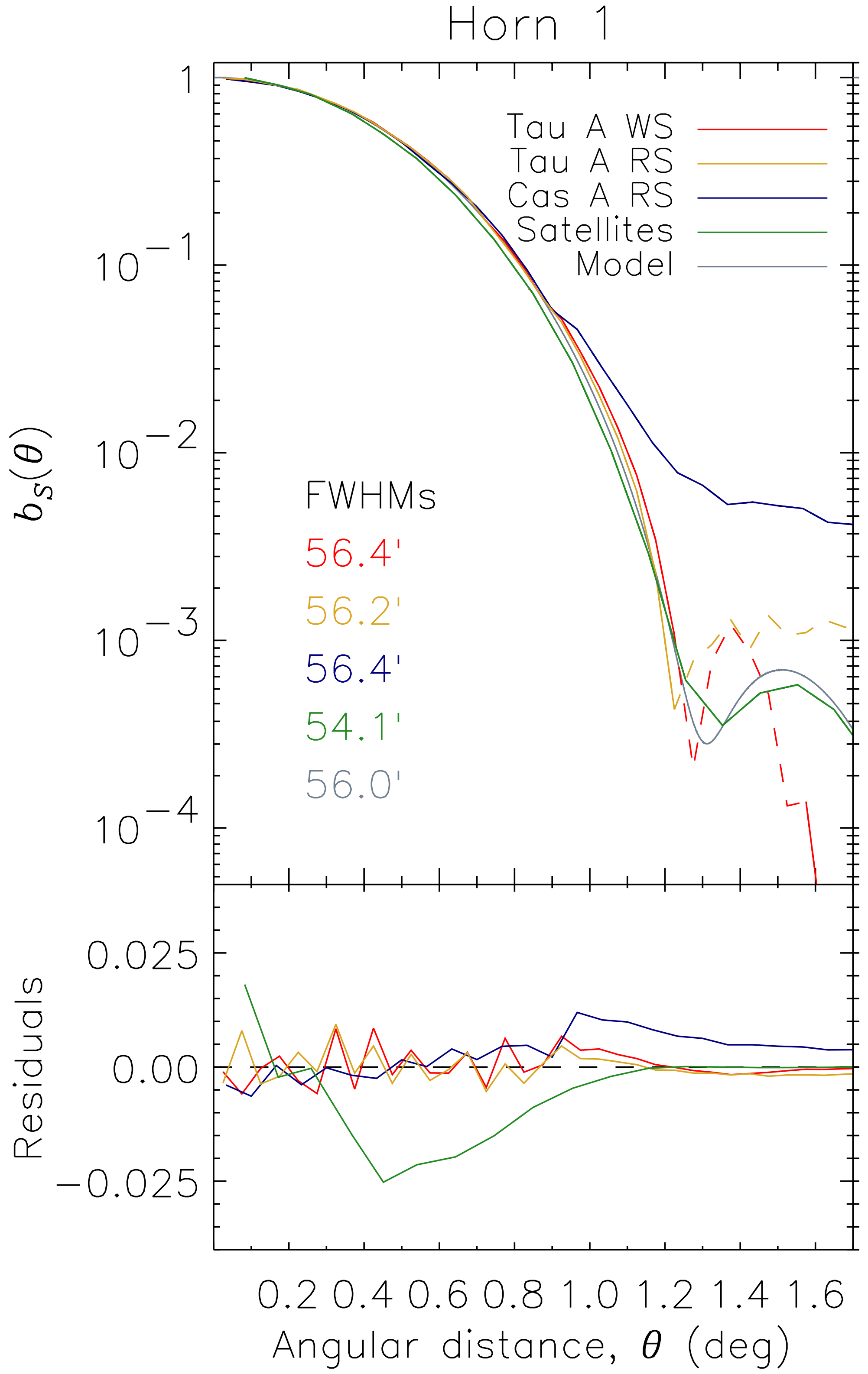




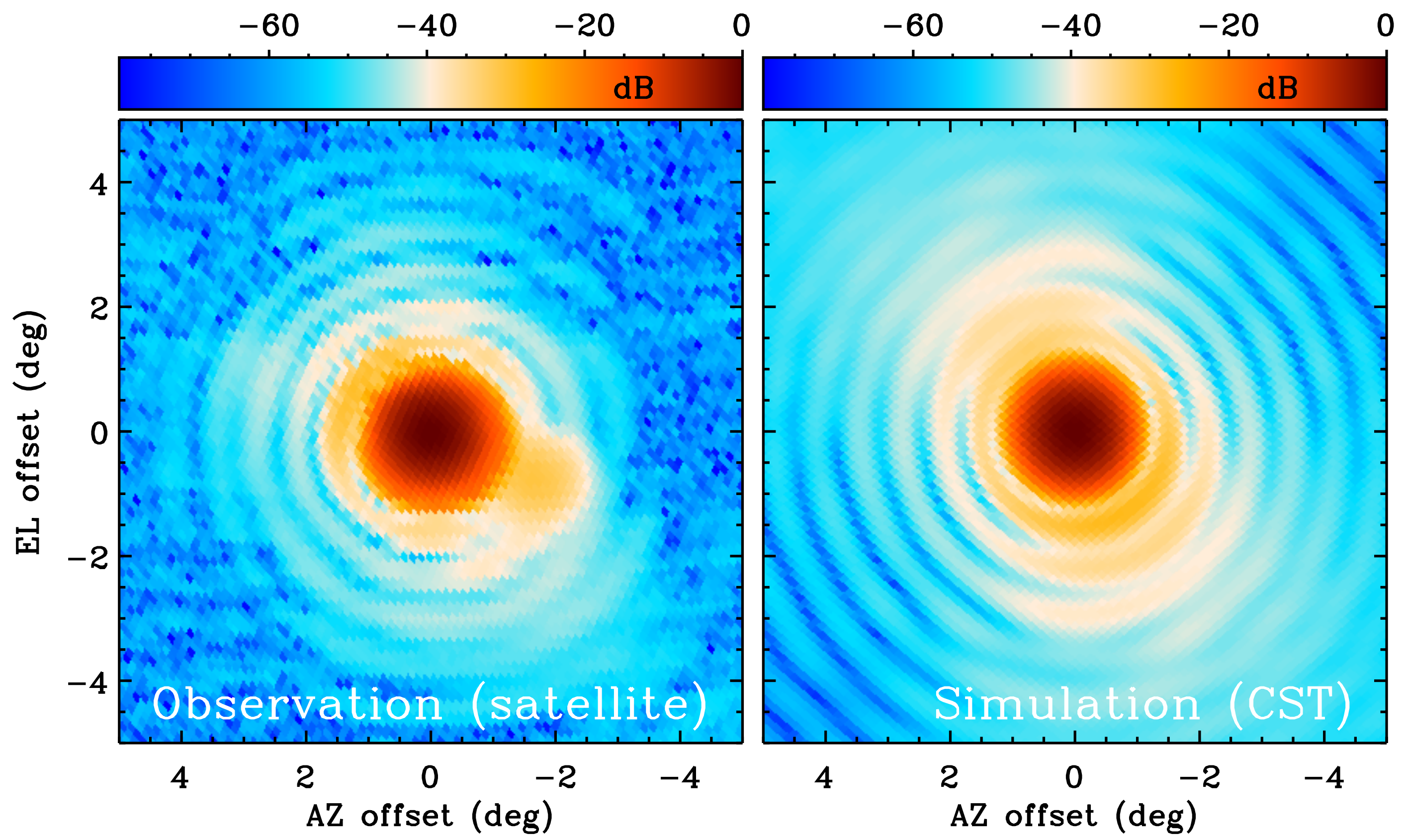
More details in https://indico.ipmu.jp/event/380/contributions/5429/

Pointing model





CST beam modelling

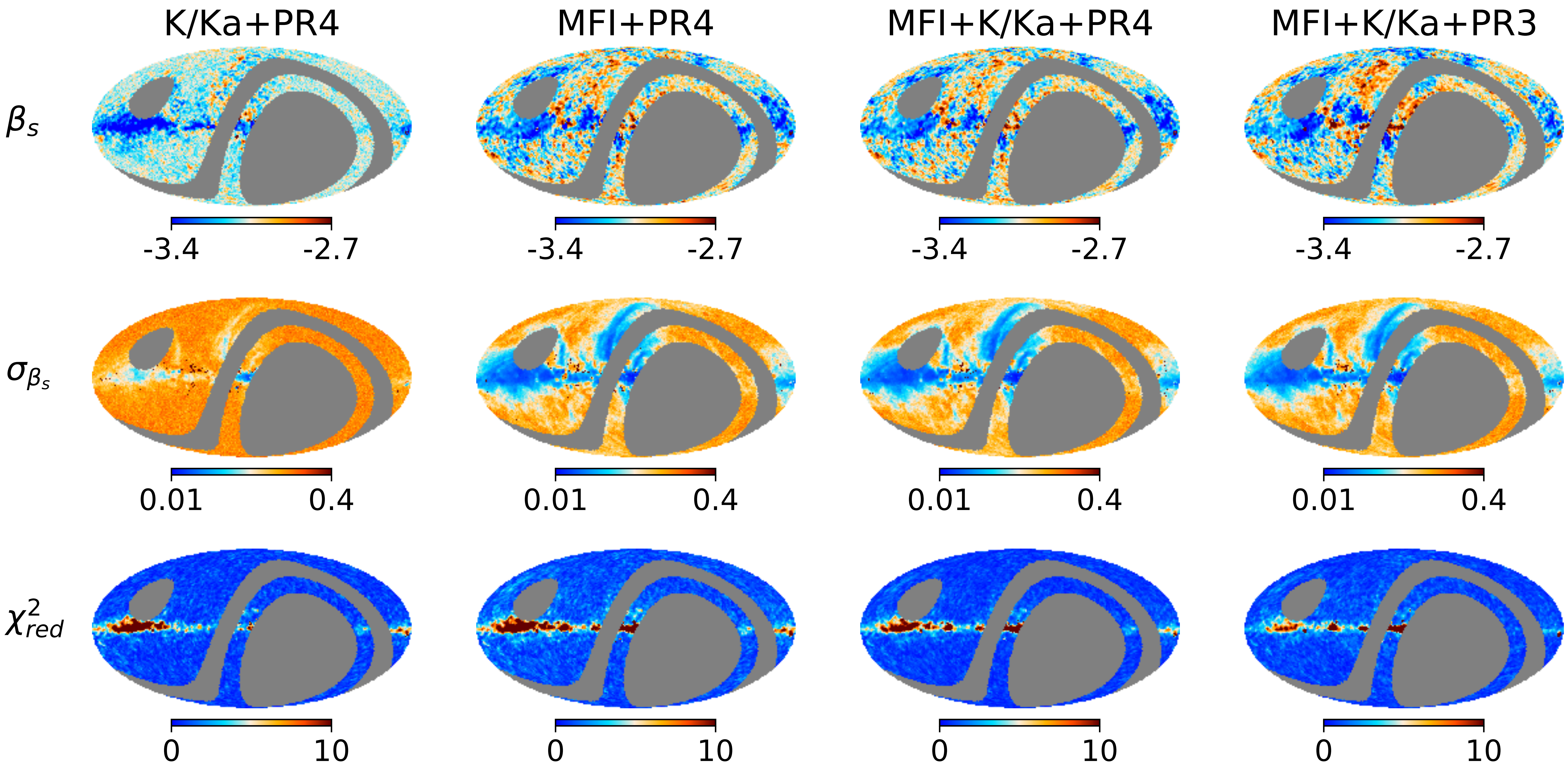


QUIJOTE-MFI wide survey

Scientific results. Polarised synchrotron (map-based)

de la Hoz et al. (to be submitted)

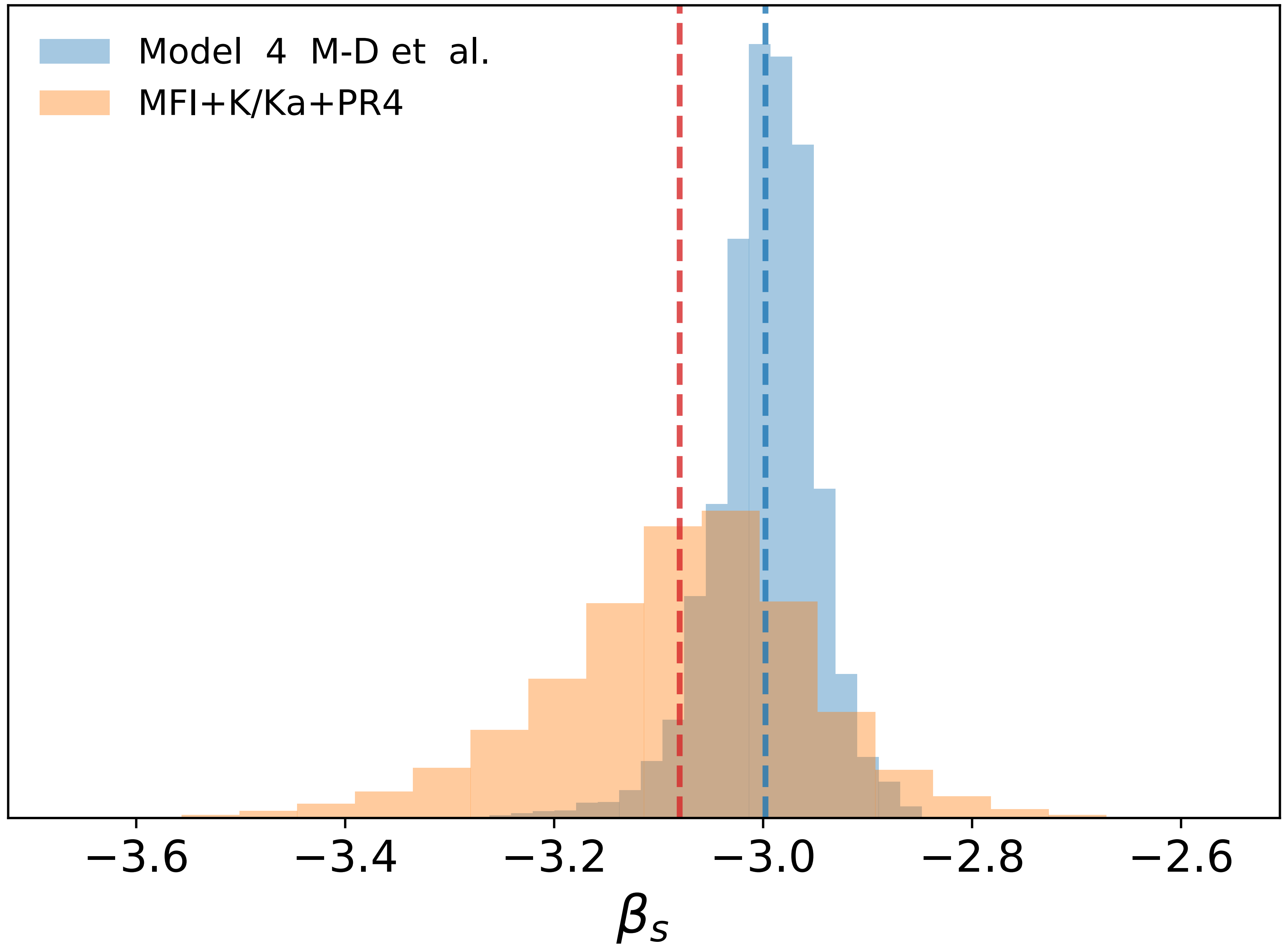
- Parametric component (B-SeCRET) combining QUIJOTE 11, 13 GHz, WMAP 23 and 33 GHz and Planck 30-353 GHz



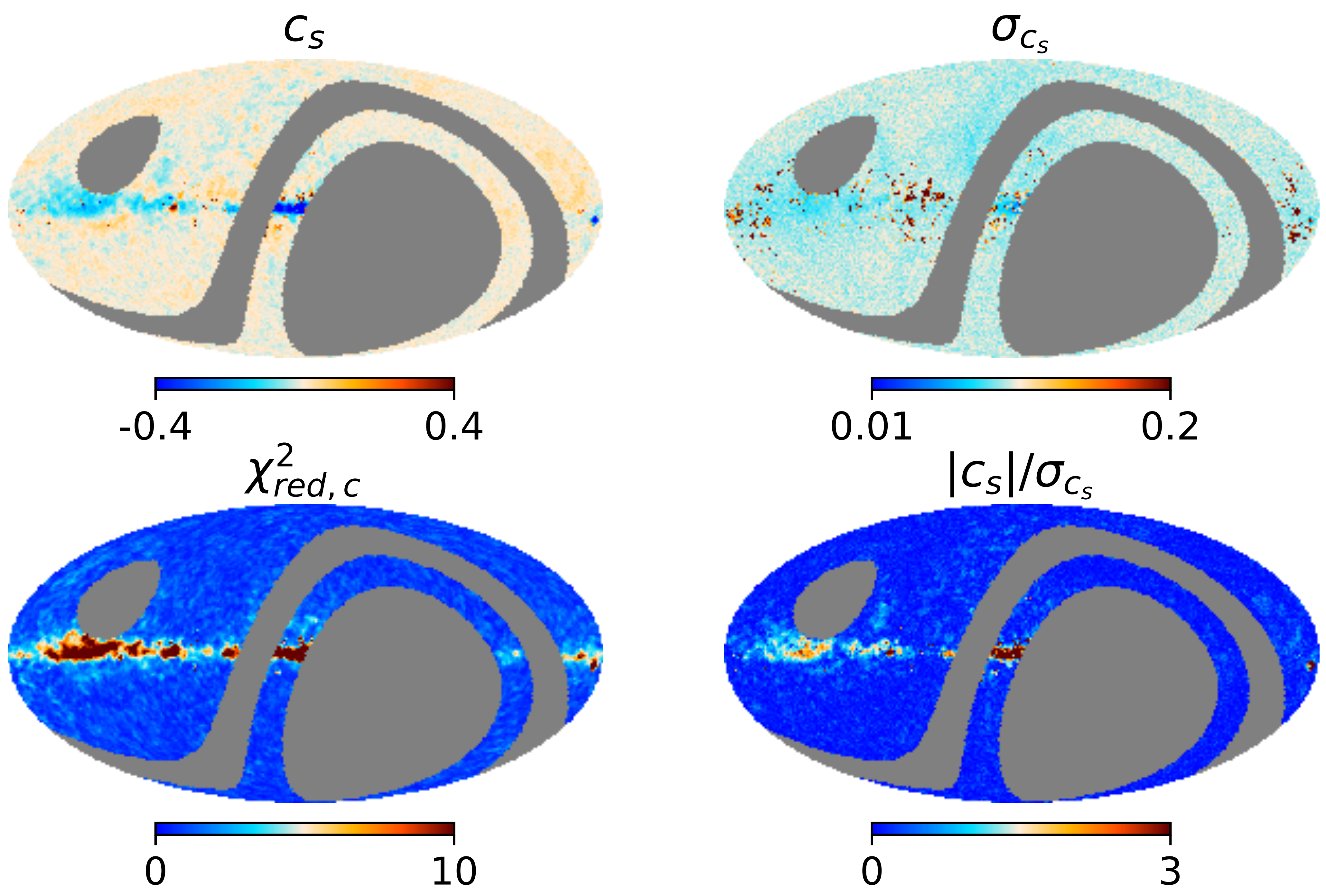
QUIJOTE-MFI wide survey

Scientific results. Polarised synchrotron (map-based)

- Significant detection of **spatial variability of β_s**
  - **$<\beta_s> = -3.08 \pm 0.13$**
  - 2.6 times larger variability than found in Miville-Deschenes et al. (2008), and smaller mean β_s



- The inclusion of QUIJOTE data reduces significantly the uncertainties on β_s
- Detection of **synchrotron curvature** on the Galactic plane:
  - >3σ in some regions of the Galactic plane
  - **$c_s = -0.0797 \pm 0.0012$** (when c_s is assumed to be constant on the sky)



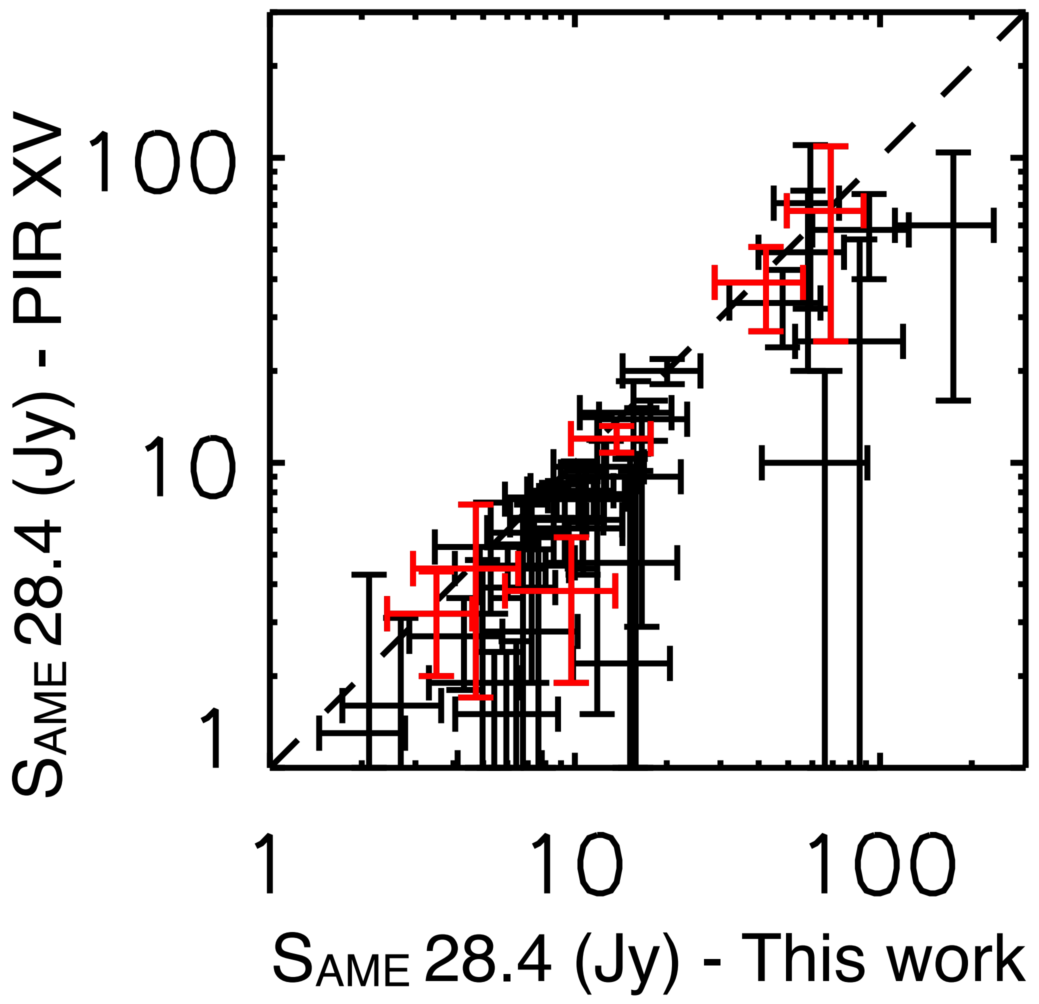
QUIJOTE-MFI wide survey

Scientific results. AME characterisation

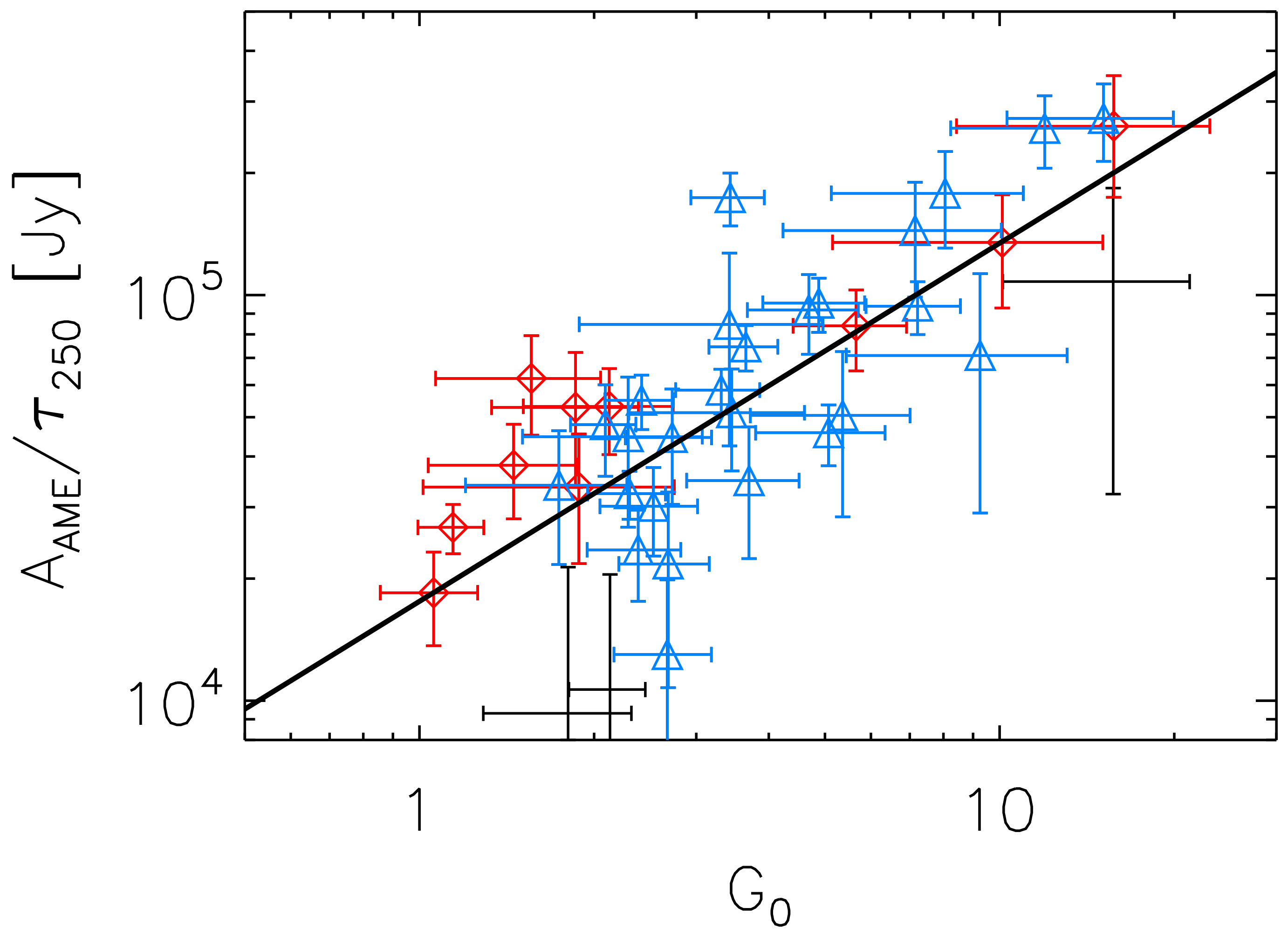
Poidevin et al. (to be submitted)

- Systematic study of 54 AME regions (including targets from Planck Intermediate Results XV 2014)
- Study of AME parameters in an statistical way

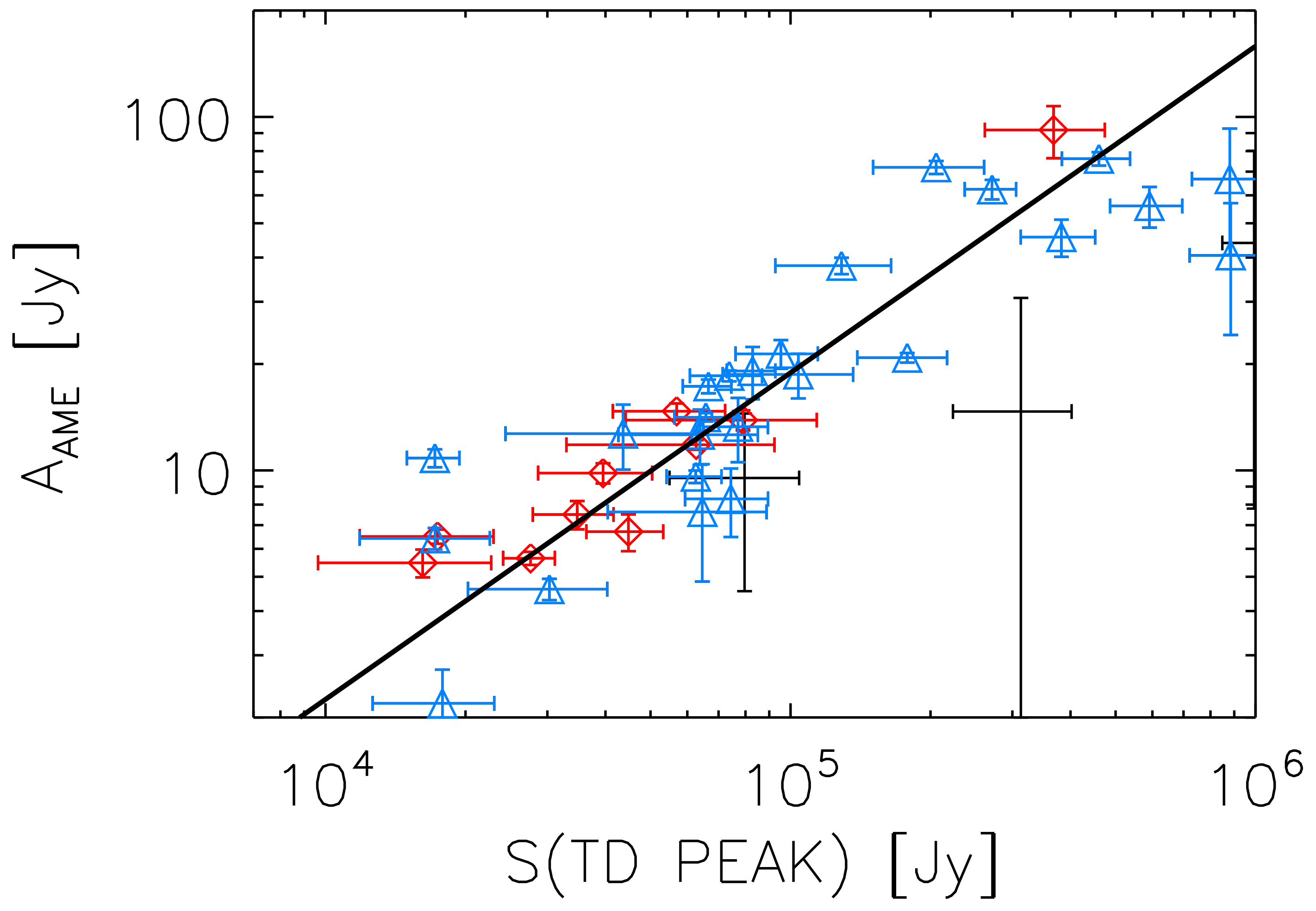
QUIJOTE-MFI improves the separation between AME and free-free leading to more AME

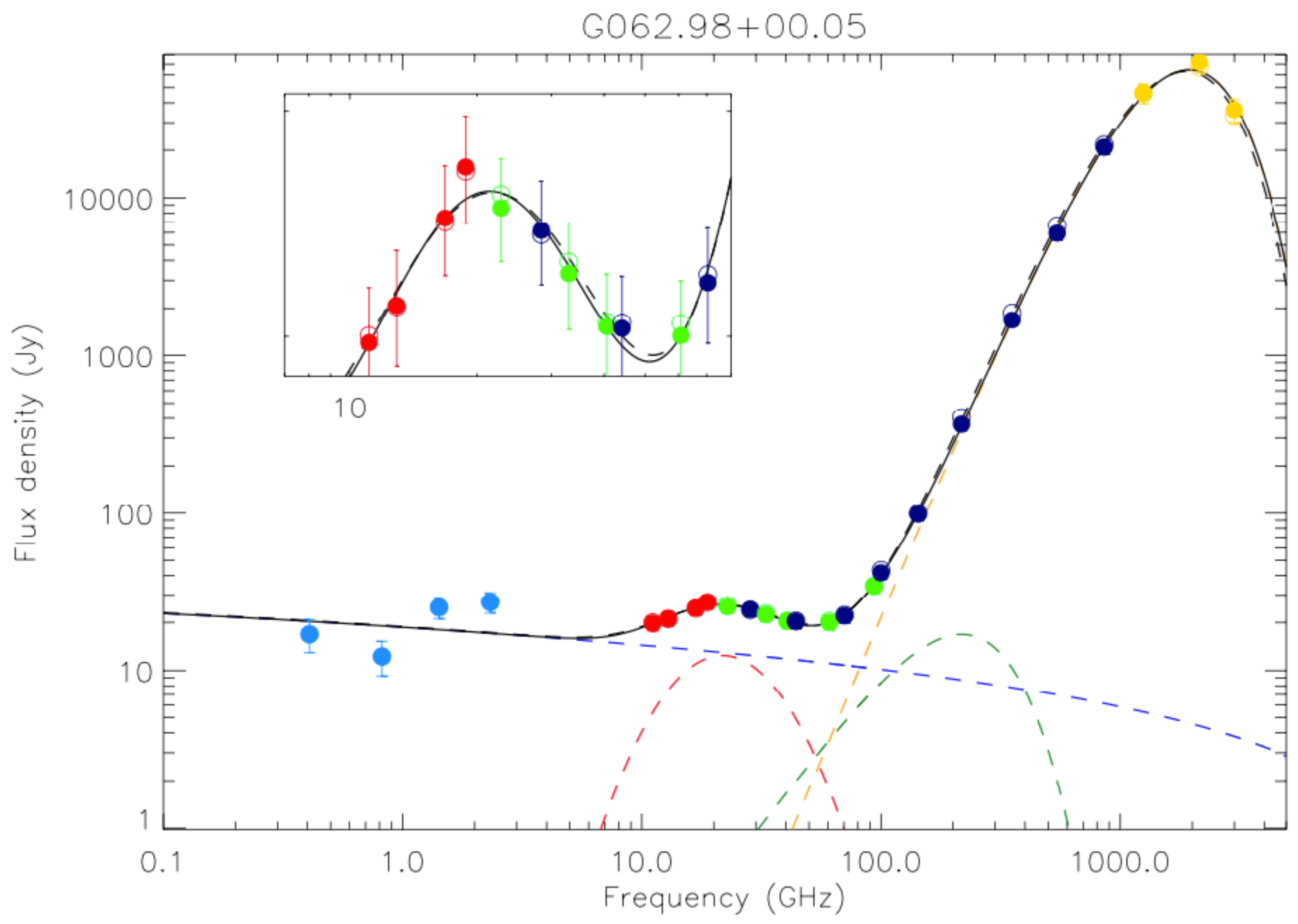


Clear correlation (90%) between AME/τ_{dust} and radiation field G0 - seen in Tibbs et al. (2011, 2012) and in PIR XV (2014)



Clear correlation between the AME and the thermal dust peak amplitudes





QUIJOTE-MFI wide survey

Scientific results. AME characterisation

Fernández-Torreiro et al. (in prep.)

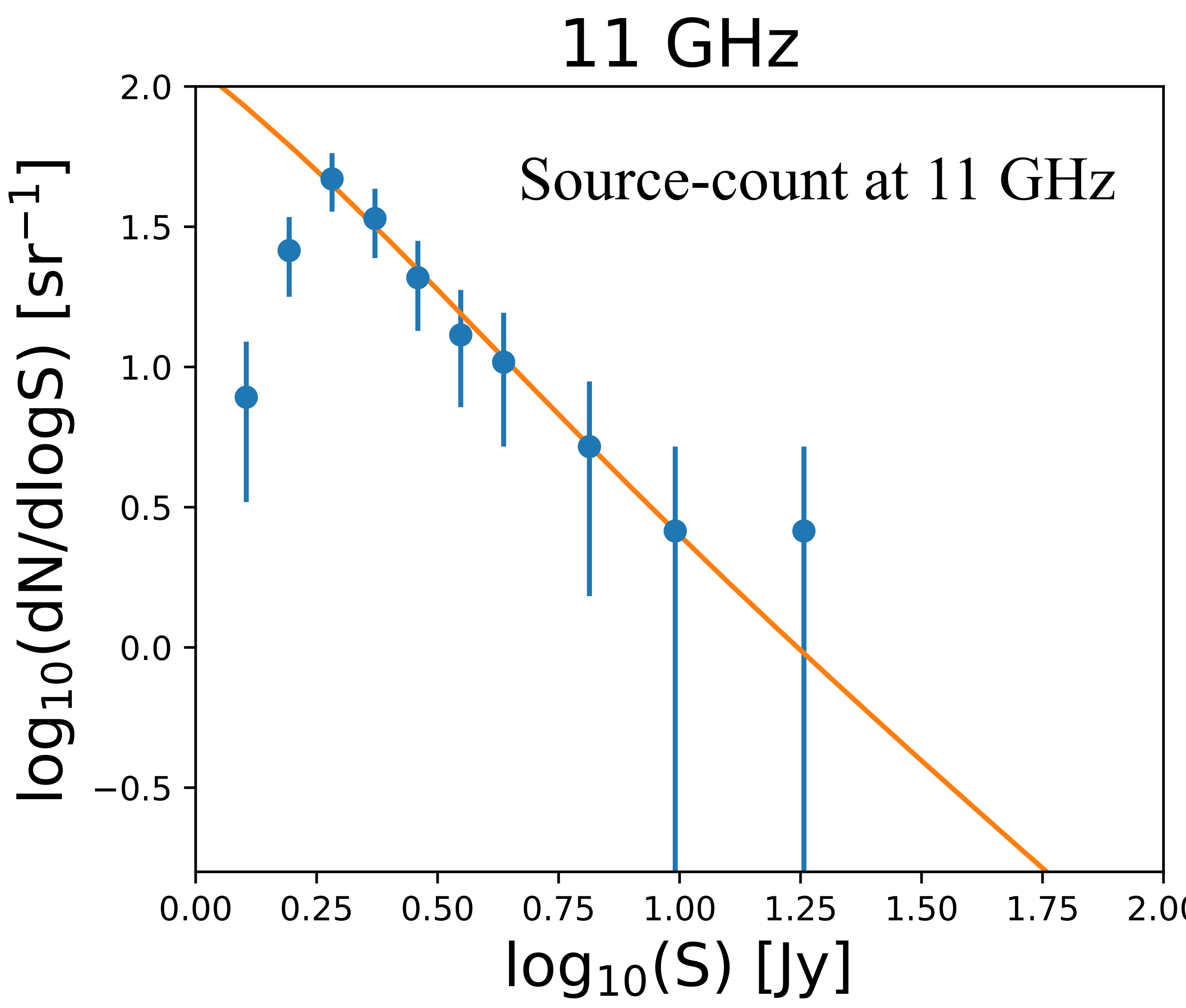
- Extension of the previous work to the full Galactic plane (|b|<10°)
- Detection of spatial variation of AME spectral properties along the Galactic plane

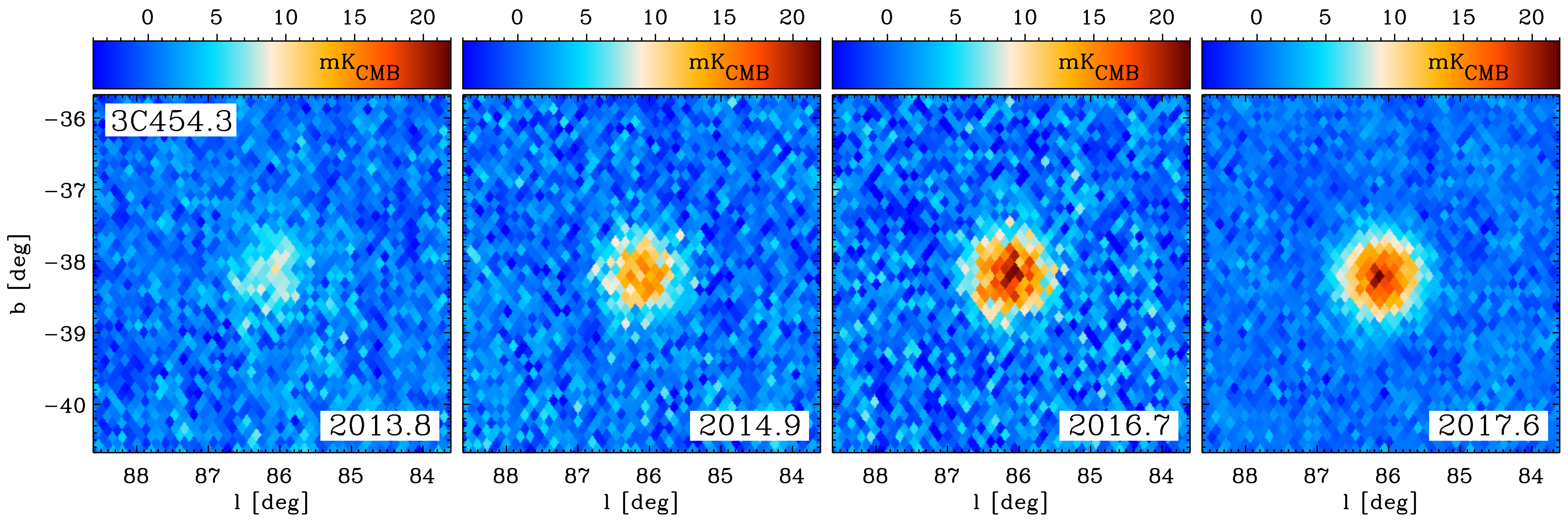
QUIJOTE-MFI wide survey

Scientific results. Point sources

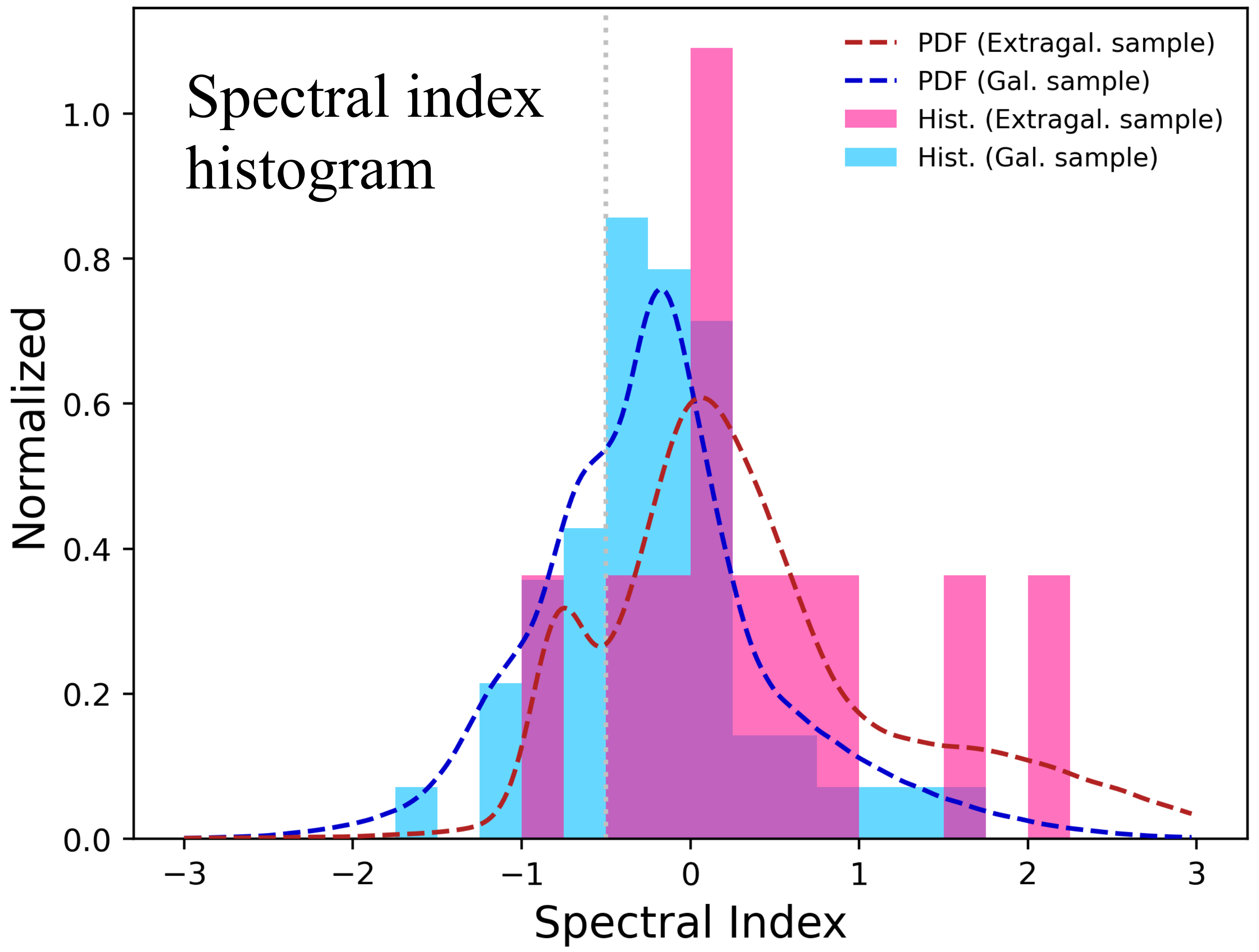
Herranz et al. (to be submitted)

- Systematic study of a catalogue of **782 sources** in the QUIJOTE wide-survey maps
- Completness limit at 11 GHz **~1.8 Jy**
- Study of polarisation properties of ~35 sources **<Π> = [2.8,4.7] %**
- Blind variability search → 7 variable sources, with 3 being strongly variable

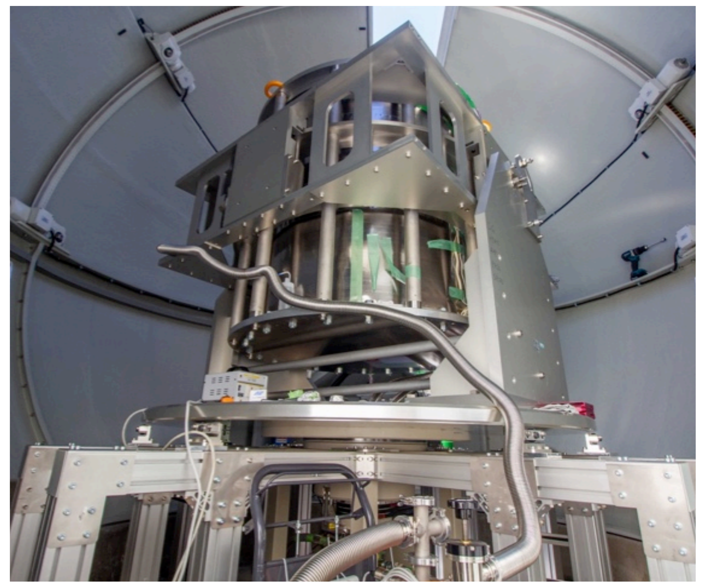




Variability of 3C454.3 in the four-period maps



Conclusions


- CMB observations over the last ~25 years have allowed to consolidate the ΛCDM model
- Excellent agreement with other observables (LSS, SNIa) ⇒ concordance model
- Planck-satellite measured TT anisotropies to cosmic-variance limit
- Next frontier in CMB research is the detection of B-mode anisotropy from cosmic inflation
  - Requieres extremely high sensitivities and control of systematics
  - Exquisite control of Galactic foregrounds

- **QUIJOTE T1 + MFI (10-20 GHz): 2012-2018**
  - Wide survey (Full Northern sky, ~29,000 deg^2, 11,000 h) completed
  - Four maps at 11, 13, 17 and 19 GHz, with **$\sigma_{Q,U}$ ~ 35-40 μK/deg**
  - 13 papers describing main scientific results, 6 to be submitted in ~1-2 months
  - Maps to be released after the acceptance of these 6 paper ⇒ legacy value (LiteBIRD)
  - Implications for foreground studies of QUIJOTE MFI data
    - Synchrotron. Spatial variability of β_s. Curvature. Dust-synchrotron correlation ~20%
    - AME. Improved modelling (better AME/free-free separation). Polarisation constraints (Π_{AME}<0.22%)