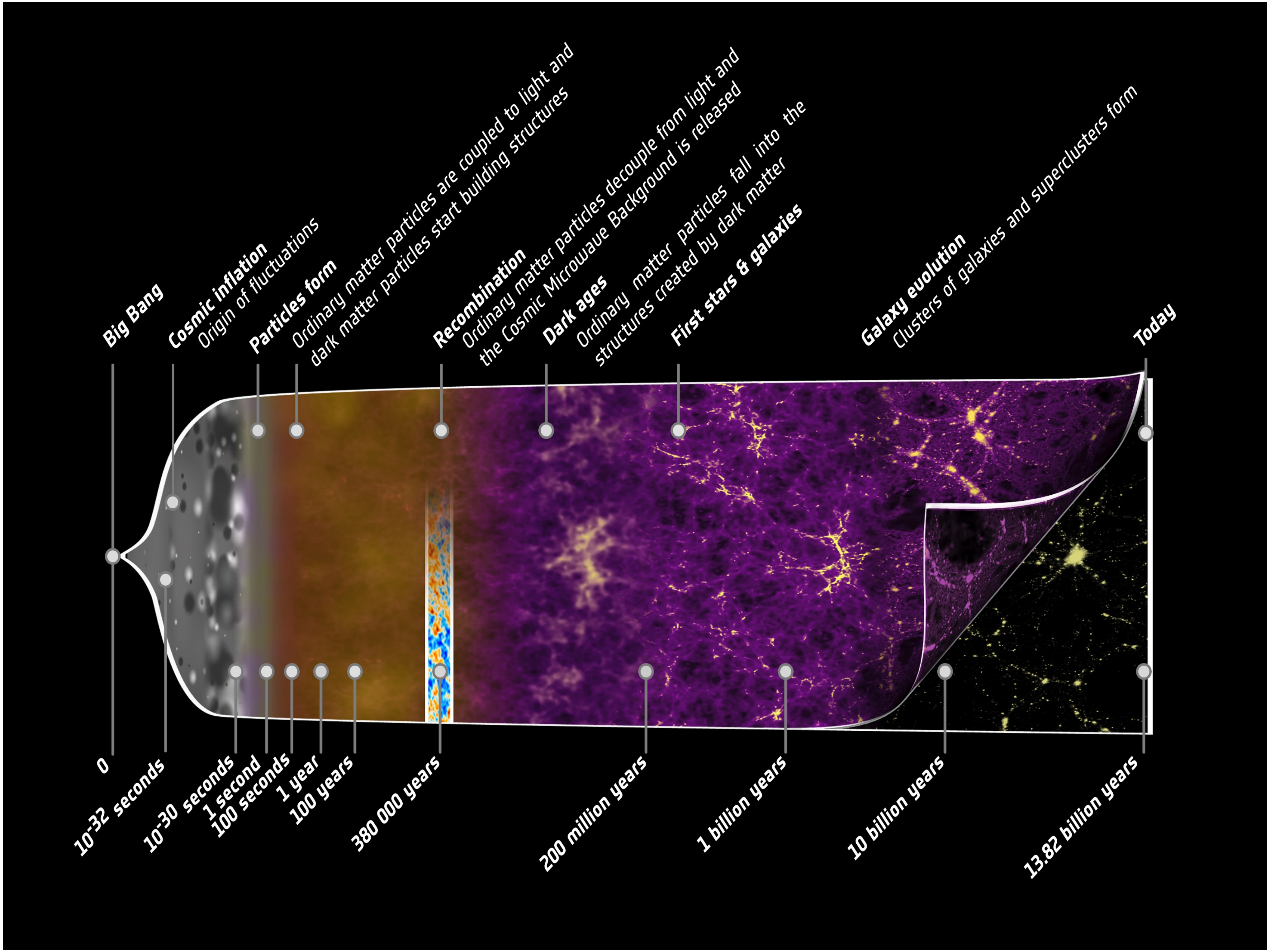
Science at IAC for QUIJOTE and TMS

J.A. Rubiño-Martín (IAC), on behalf of the QUIJOTE and TMS Collaborations

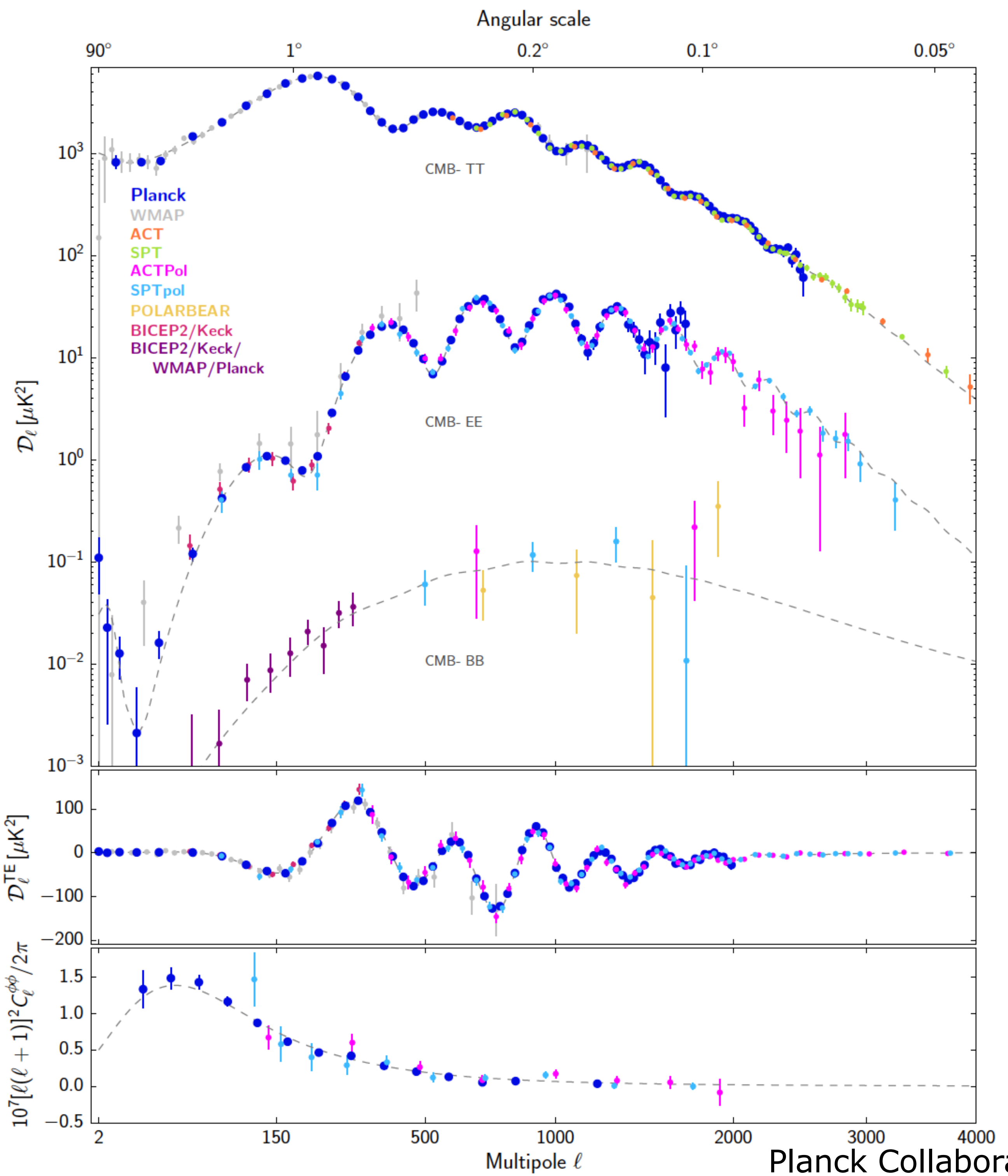
KO meeting UNDARK
8-11 October 2024

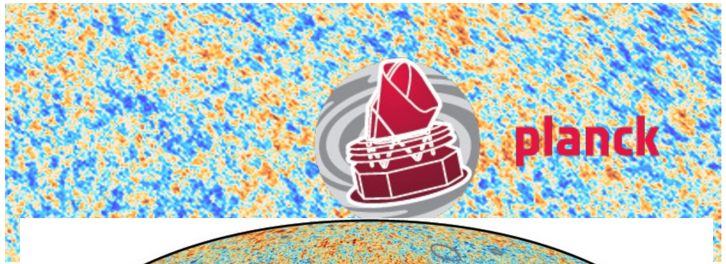
UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"
Ref. de la ayuda: ICTS-2019-03-IAC-12

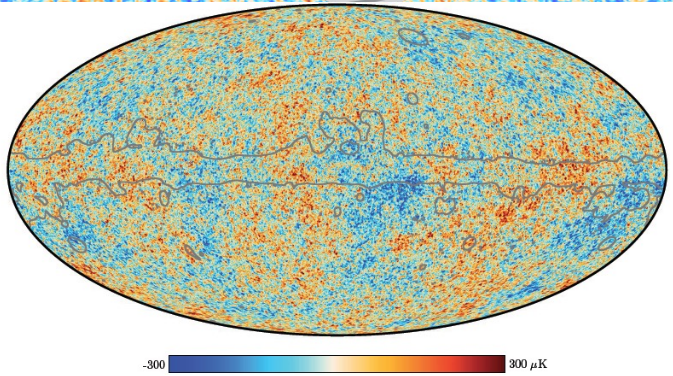
Funded by the European Union

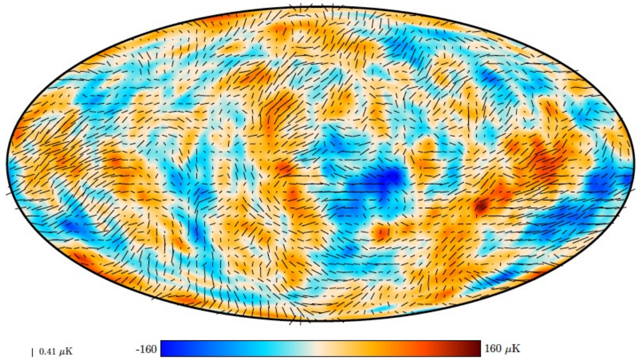


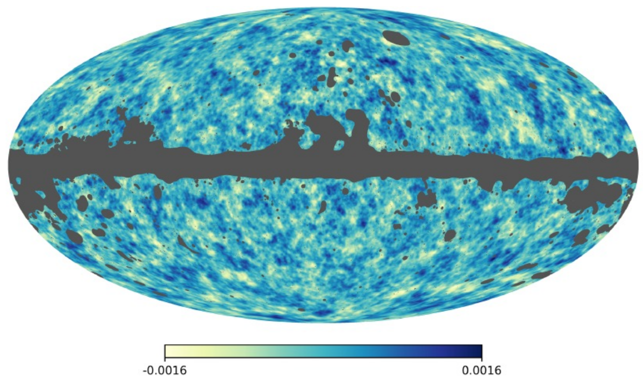
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years











Planck Collaboration I (2020)

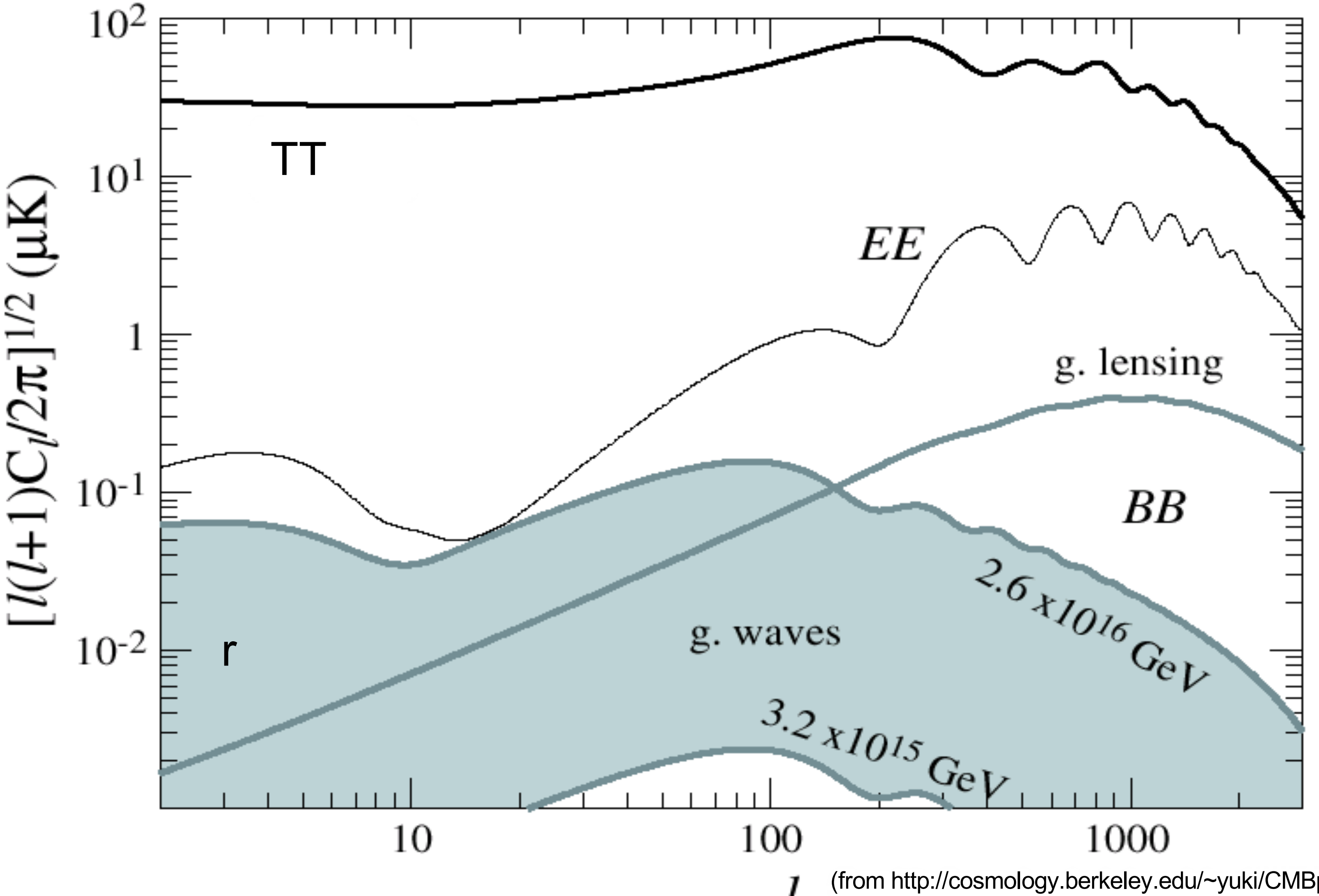
Planck data and base ΛCDM model

- **ΛCDM 6 parameter** model: excellent fit to data!
- Per cent accuracy on all base parameters, but tau.
  - CDM detected at 100σ.
  - Sound horizon 0.03%.
  - n_S is 8σ away from scale-invariance (n_S=1).
- Joint fit to Planck temperature, polarisation and lensing data.

(Planck Collaboration I & VI, 2020)

Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013
z_{re}	7.67 ± 0.73
Age[Gyr]	13.797 ± 0.023
r_*[Mpc]	144.43 ± 0.26
$100\theta_*$	1.04110 ± 0.00031
r_{drag}[Mpc]	147.09 ± 0.26
z_{eq}	3402 ± 26
k_{eq}[Mpc^{-1}]	0.010384 ± 0.000081
Ω_K	-0.0096 ± 0.0061
Σm_ν [eV]	< 0.241
N_{eff}	$2.89^{+0.36}_{-0.38}$
$r_{0.002}$	< 0.101

Primordial gravitational waves and B-modes



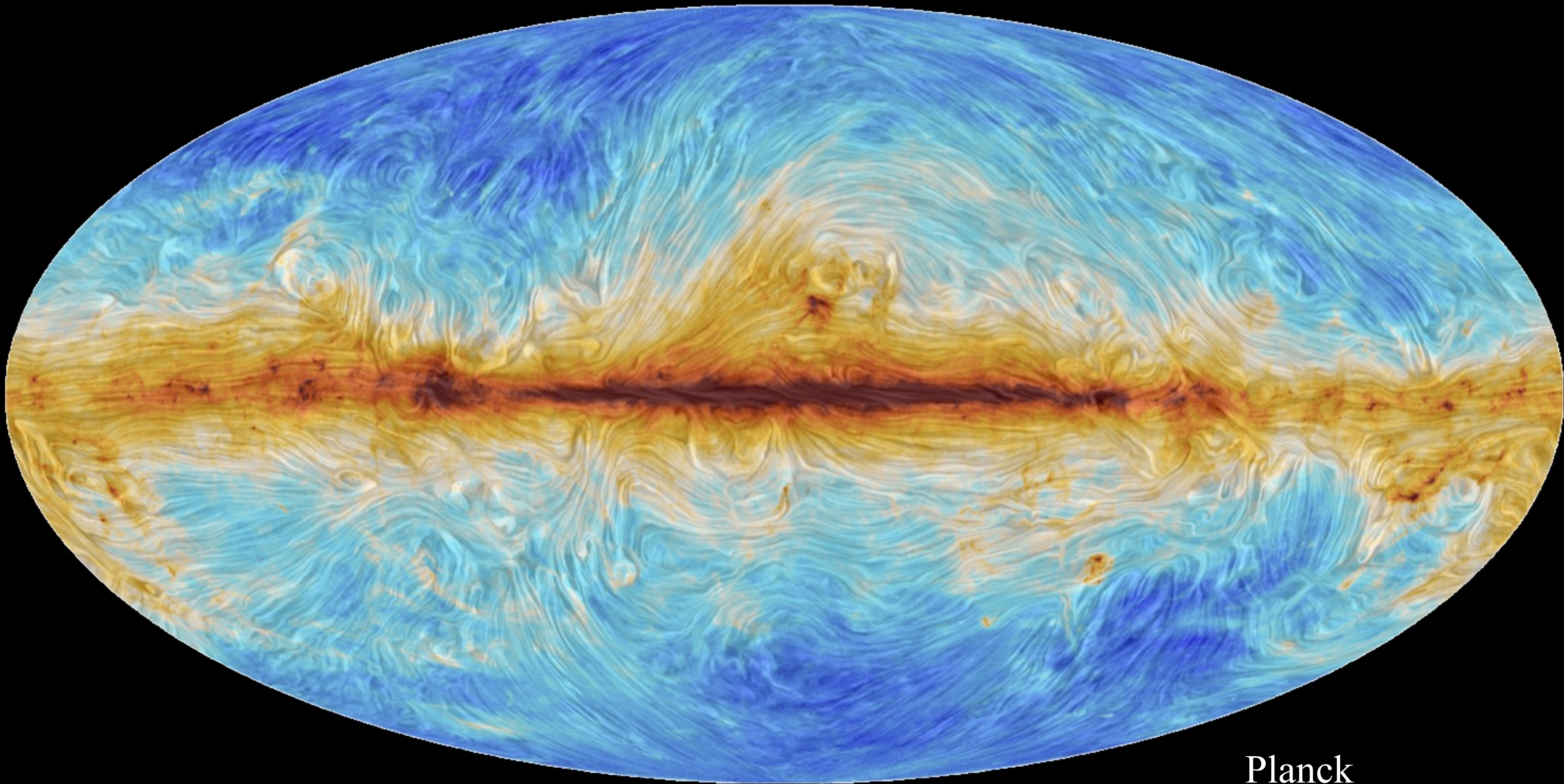
(from http://cosmology.berkeley.edu/~yuki/CMBpol/CMBpol.htm)

Current upper limits: r < 0.032 at 95% C.L

(**BICEP2/Keck + Planck PR4**. Tristram et al. 2022)

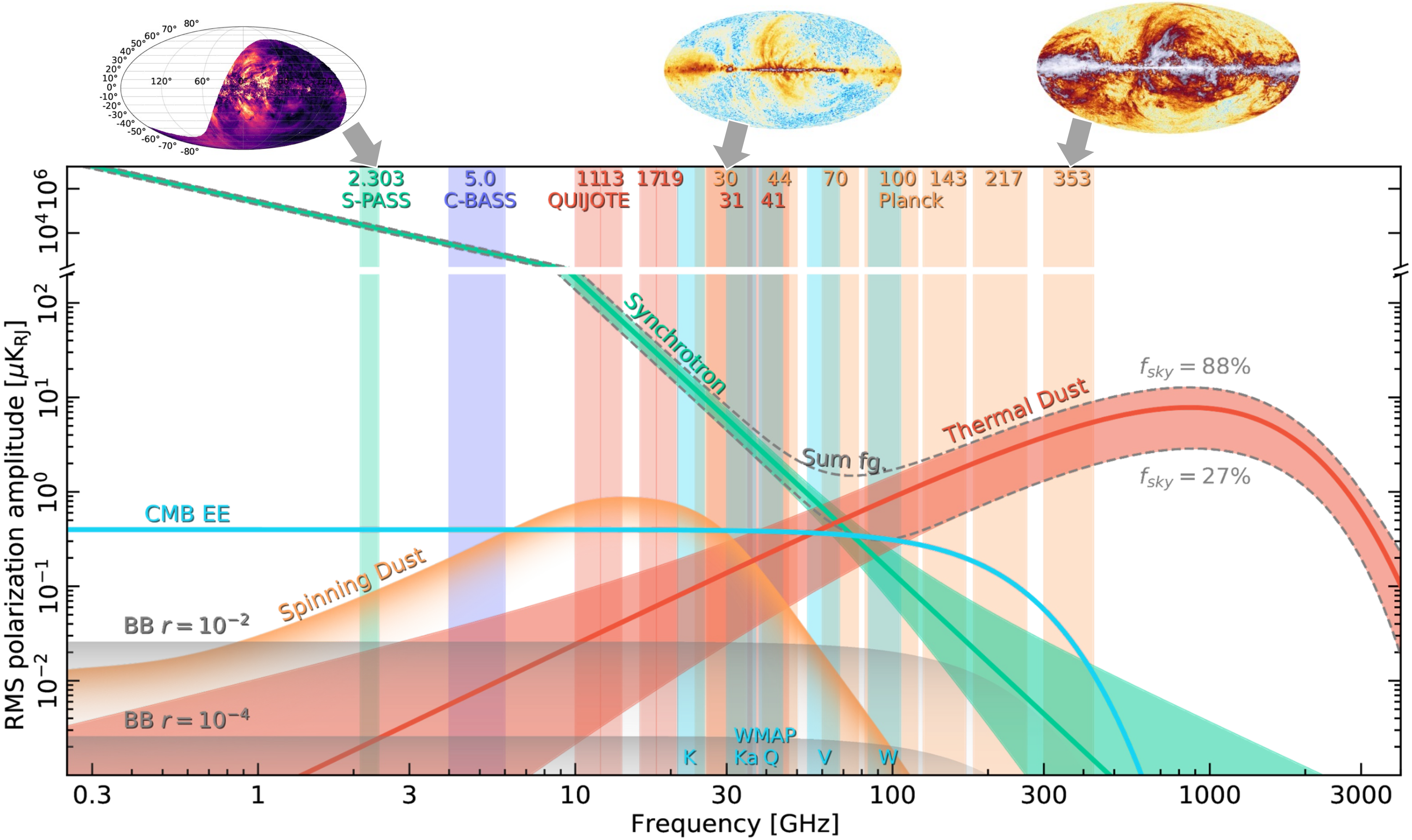
$$V^{1/4} = 1.04 \times 10^{16}\,\mathrm{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

The **polarized Galactic emission** contaminates the microwave observations. At least, two physical mechanisms: thermal dust emission (dust grains) and synchrotron (cosmic rays) → **Galactic Magnetic Field**

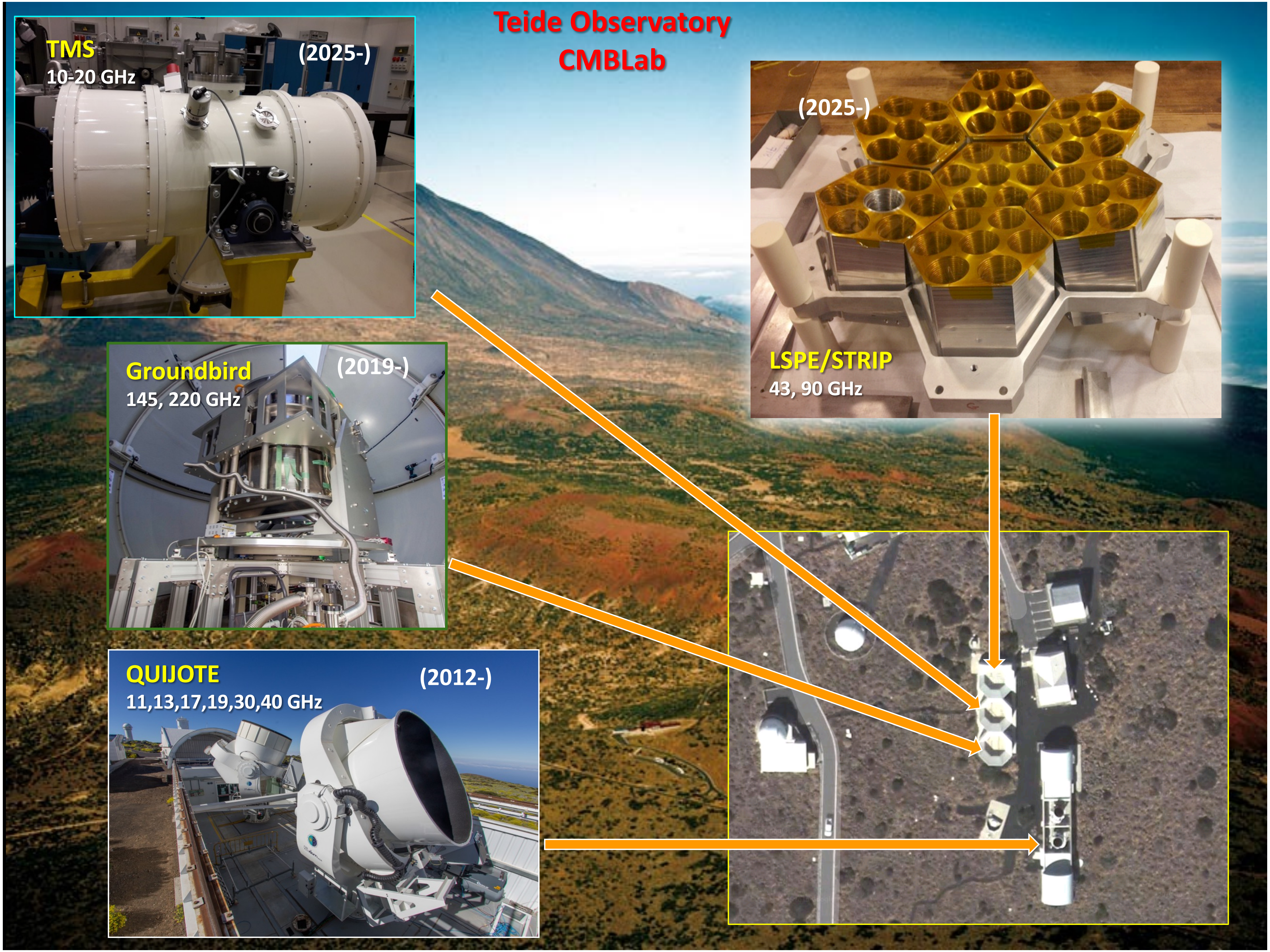


Planck
(thermal dust)

Sky emission in polarization at degree scales



BeyondPlanck Collab. +2023



Teide Observatory
CMBLab
TMS
10-20 GHz
(2025-)
(2025-)
LSPE/STRIP
43, 90 GHz
Groundbird
145, 220 GHz
(2019-)
QUIJOTE
11,13,17,19,30,40 GHz
(2012-)

The QUIJOTE experiment

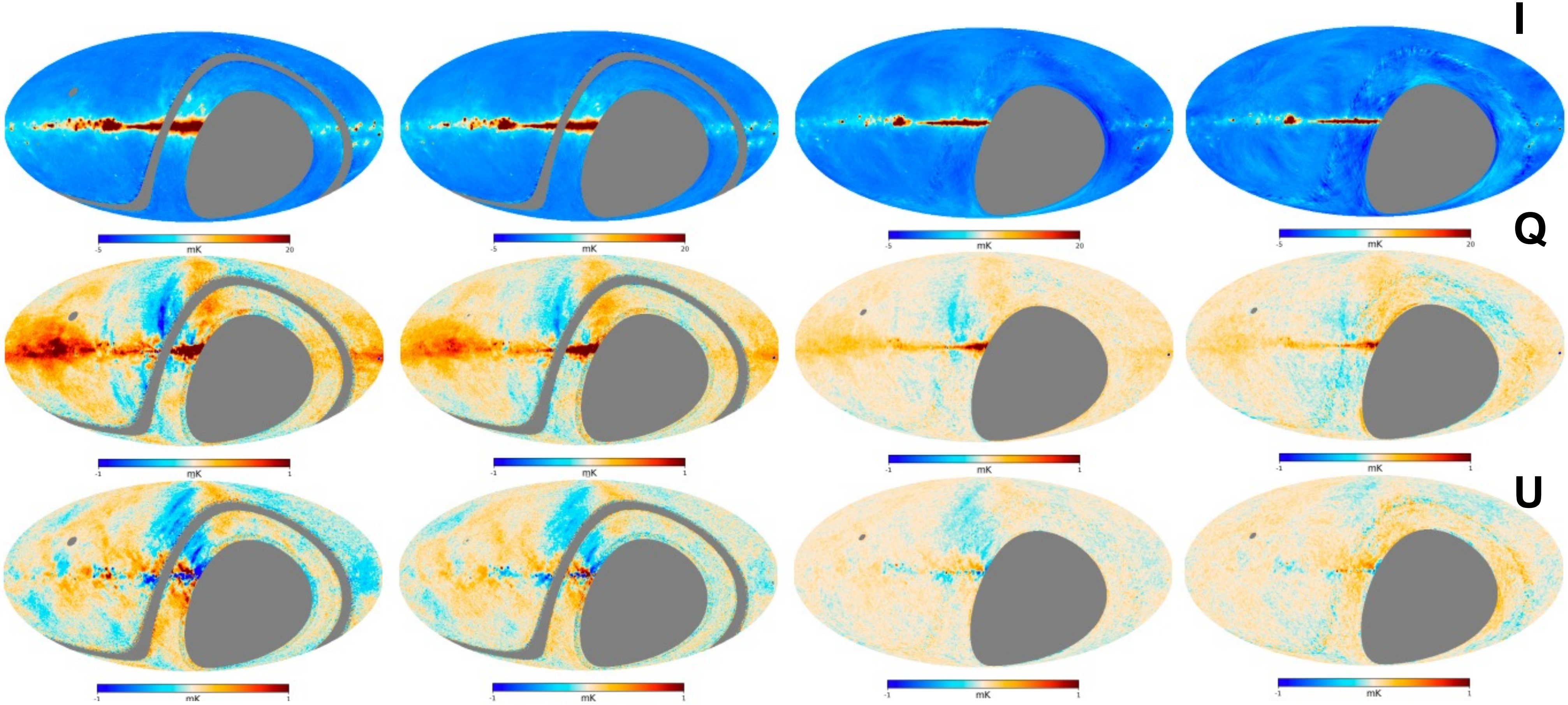
(Q-U-I JOint Tenerife Experiment, http://research.iac.es/project/quijote)

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

Smoothed 1 deg maps

(Rubino-Martin et al. 2023)

(Data release Jan 12th 2023: https://research.iac.es/proyecto/quijote. First six papers)

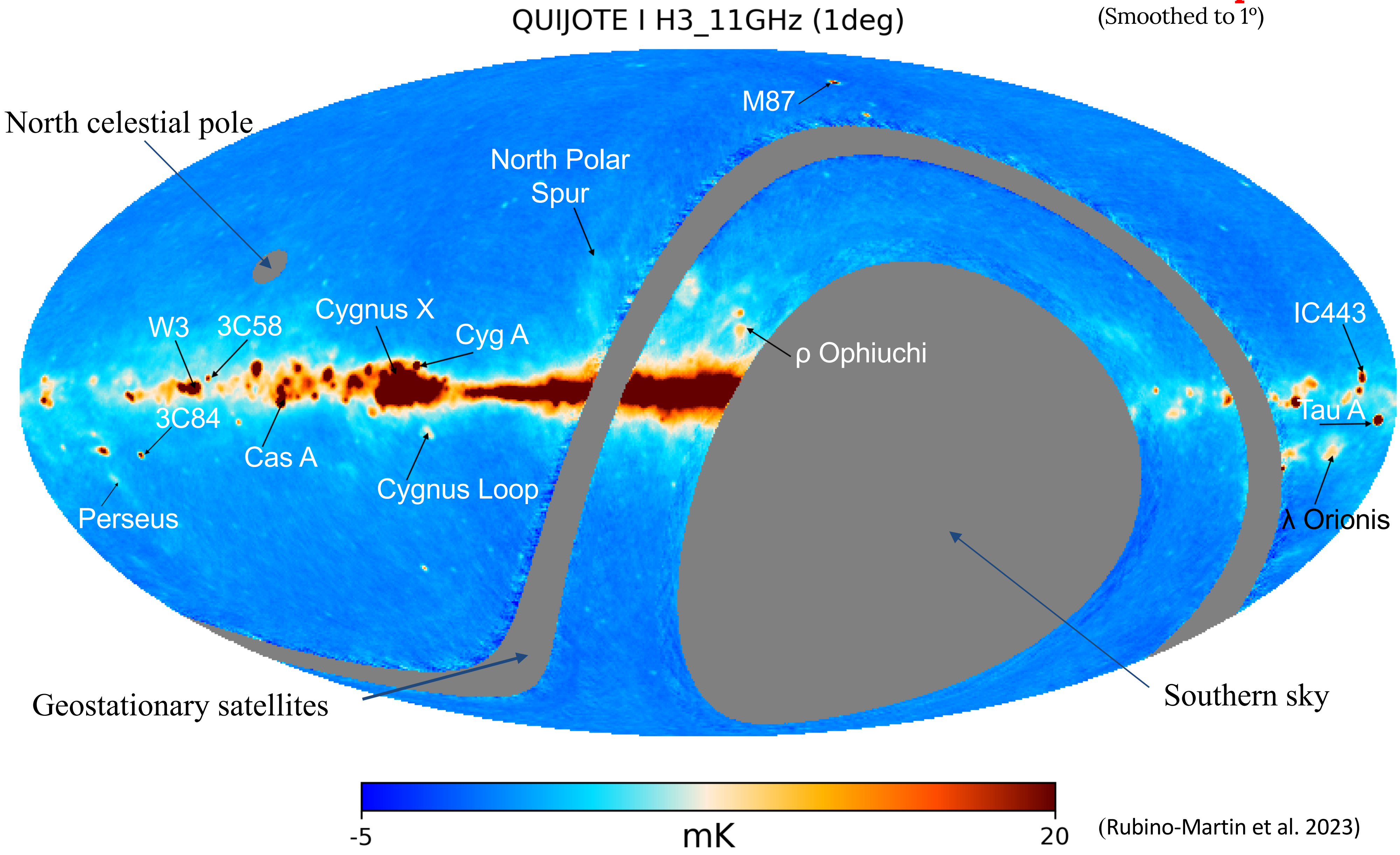


QUIJOTE 11GHz **QUIJOTE 13GHz** **QUIJOTE 17GHz** **QUIJOTE 19GHz**

Approx. 29,000 deg^2. About 10,000 h of observations. Sensitivities in polarization (Q,U): ~35-40 μK/deg → equivalent to 2.4 μK.arcmin @ 100GHz with β=-3.

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

Final maps
(Smoothed to 1º)

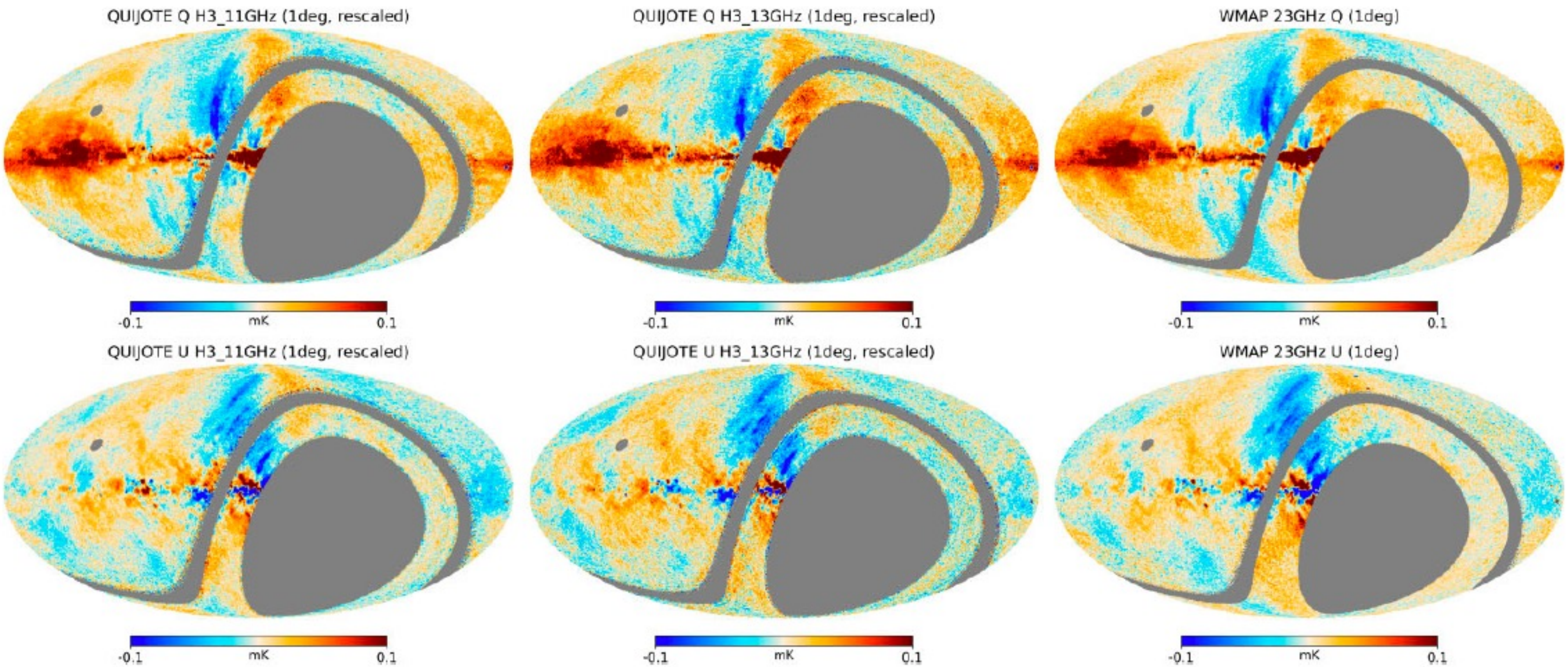


(Rubino-Martin et al. 2023)

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

QUIJOTE | WMAP

11GHz | 13GHz | 23GHz



QUIJOTE maps scaled to 23 GHz using β=-3.1 (for synchrotron). Same colour scale in all maps!
For visualization purposes, the QUIJOTE mask is applied to WMAP 23GHz

(Rubino-Martin et al. 2023)

QUIJOTE MFI wide survey: papers

MFI wide survey papers (associated to the MFI wide survey data release in Jan 2023):

iv. A northern sky survey at 10-20 GHz with the Multi-Frequency Instrument (Rubino-Martín et al. 2023)
v. W49, W51 and IC443 SNRs as seen by QUIJOTE-MFI (Tramonte et al. 2023)
vi. The Haze region and the Galactic Centre as seen by QUIJOTE-MFI (Guidi et al. 2023)
vii. Galactic AME sources in the MFI wide survey (Poidevin et al. 2023)
viii. Component separation in polarization with the QUIJOTE-MFI wide survey. (de la Hoz et al. 2023)
ix. Radio-sources in the QUIJOTE-MFI wide survey (Herranz et al. 2023)

MFI data release Jan 2023

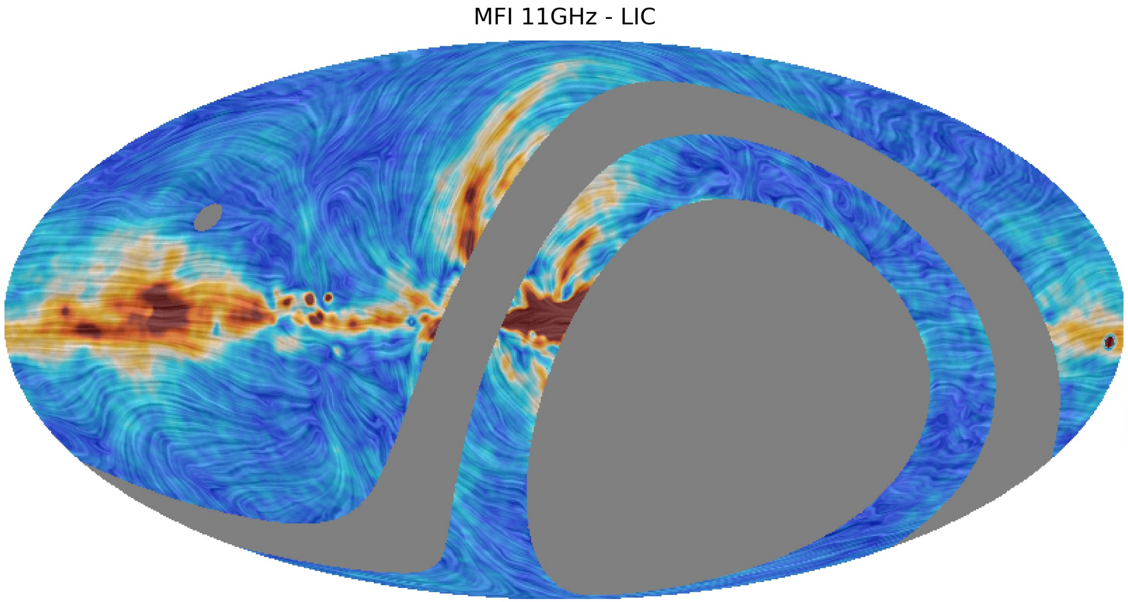
x. Spatial variability of AME parameters in the Galactic Plane (Fernández-Torreiro et al. 2023)
xi. Polarised synchrotron loops and spurs. (Peel et al. in prep)
xii. Analysis of the polarised synchrotron emission at the power spectrum level (Vansyngel et al. in prep)
xiii. Intensity and polarization study of Supernova Remnants (López-Caraballo et al. 2024)
xiv. The FAN region as seen by QUIJOTE-MFI (Ruiz-Granados et al. in prep)
xv. The North Galactic Spur as seen by QUIJOTE-MFI (Watson et al. in prep)
xvi. Component separation in intensity with the QUIJOTE-MFI wide survey (de la Hoz et al. in prep)
xvii. Studying the AME in the Andromeda Galaxy with QUIJOTE-MFI (Fernández-Torreiro et al. 2024)
xviii. New constraints on AME polarization in rho-Ophiucus, Perseus and W44 (González-González et al. A&A subm.)

Other MFI papers:

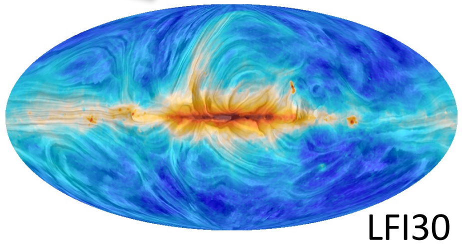
- MFI data processing pipeline (Genova-Santos et al. in prep).

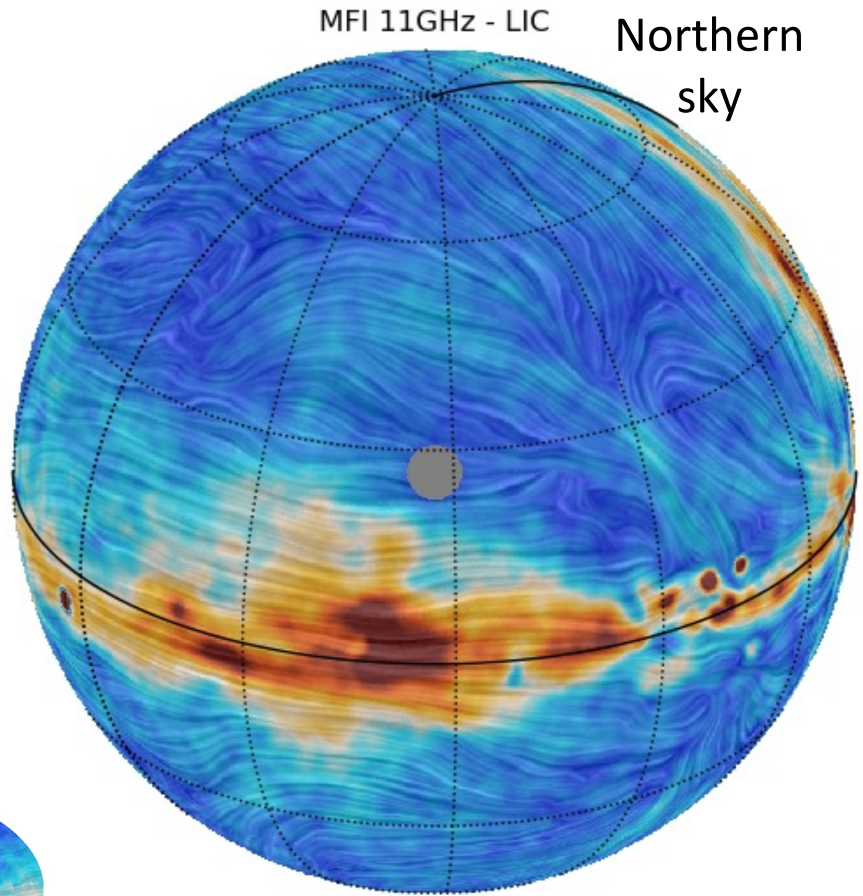
Wide survey with the QUIJOTE MFI (10-20GHz)

Synchrotron and Galactic magnetic field



$$P = \sqrt{Q^2 + U^2}$$





Angles: Comparison to WMAP and PLANCK in high SNR regions, excluding calibrators (CRAB) and high FR regions (galactic center). E.g. the median difference MFI11GHz - LFI30: -0.5º (**error=0.6º**).

Magnetic fields lines (Rubiño-Martin et al. 2023)

QUIJOTE-MFI wide survey results VIII: Component separation in pol.

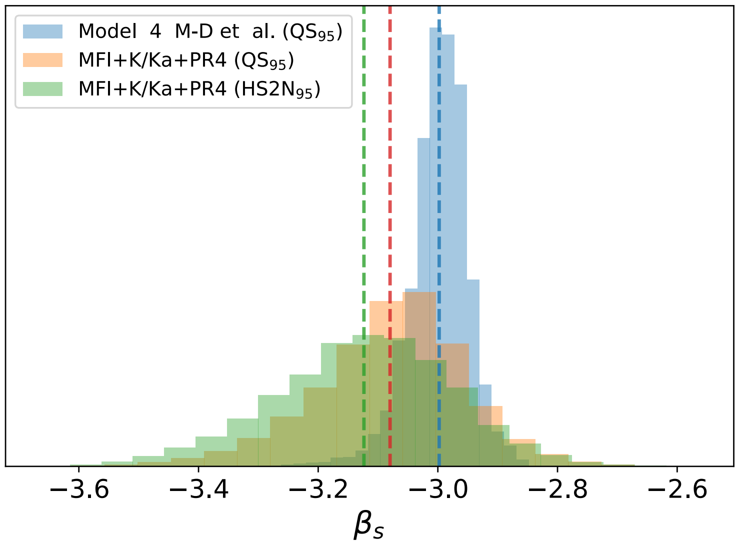
Polarised Synchrotron Spectral index

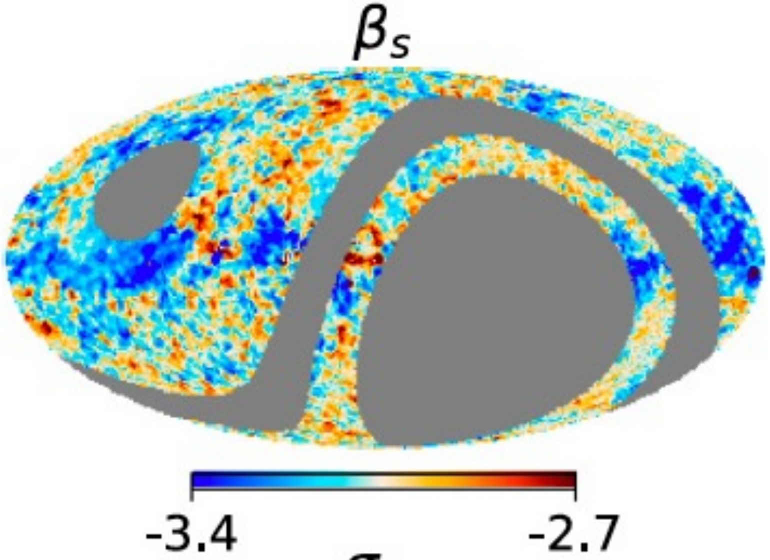
$$T \propto \nu^{\beta_S}$$

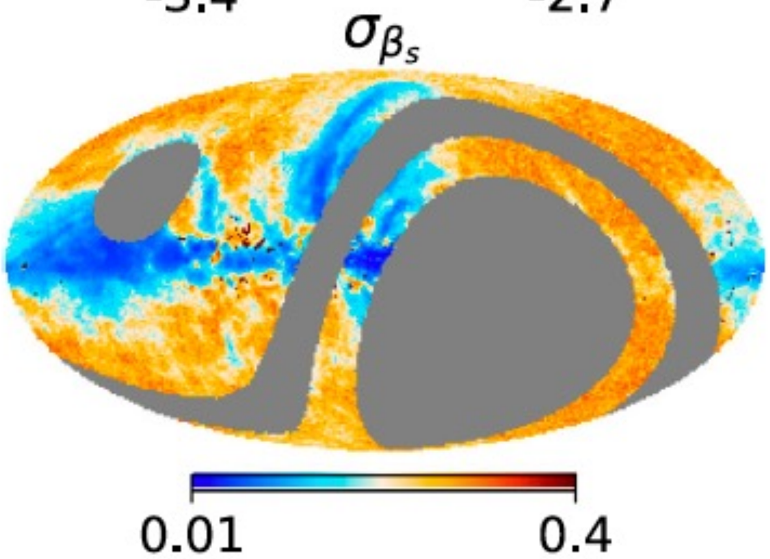
De la Hoz et al. (2023). The first spectral index of the polarized synchrotron in the northern sky. QUIJOTE+WMAP+Planck. Maps at 2º and nside=64, and prior N(-3.1,0.3):

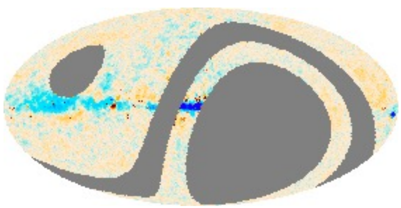
β(11-23GHz) = -3.08 ± 0.13

Significantly broader than existing models!







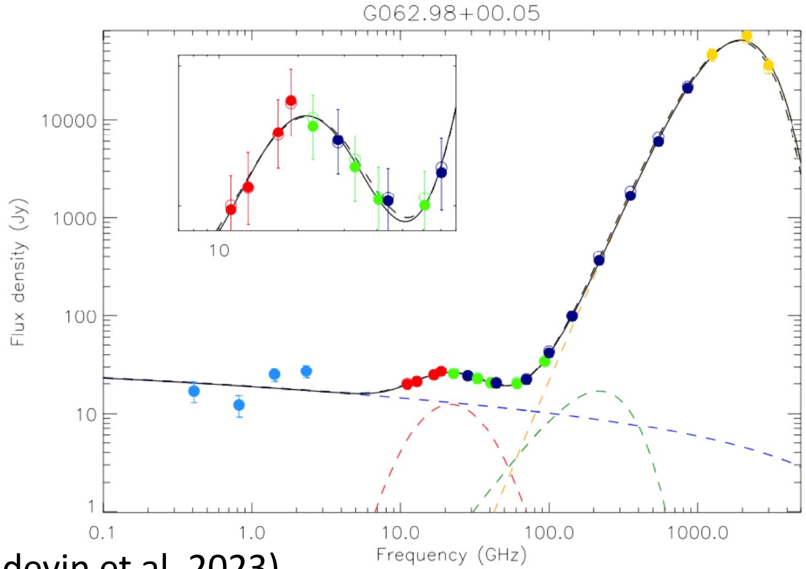


Detection of **uniform curvature, c_s=-0.0797±0.0012**, but not enough statistical significance to distinguish between Power-Law (PL) or curved PL.

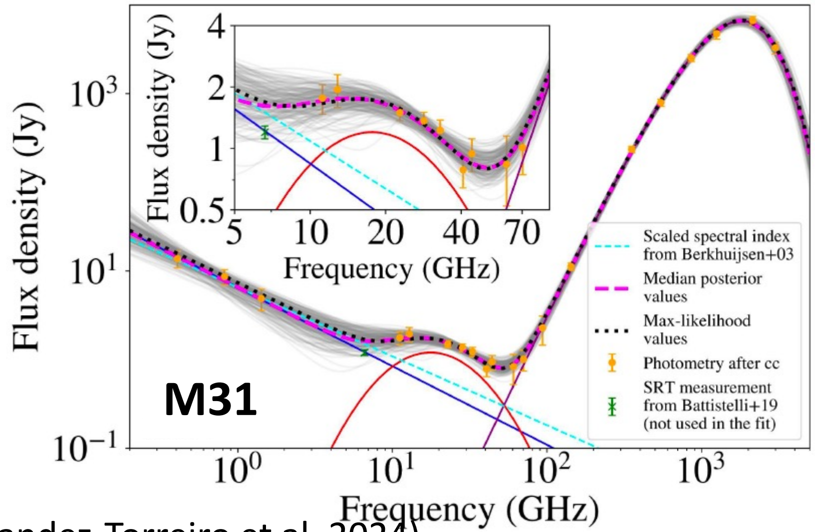
(de la Hoz et al. 2023)

QUIJOTE-MFI results: modelling the Anomalous Microwave Emission

- **AME:** excess emission over free-free, dust and synchrotron in microwaves; spatially correlated with thermal dust. Origin unknown. Probably spinning dust grains. Polarization information is key.
- **QUIJOTE results in compact regions.**
  - **Tramonte et al. (2023)** AME detected in W49 (4.7σ) and W51 (4.0σ).
  - **Poidevin et al. (2023)**: Study of 56 compact AME sources (PIR XV 2014).
  - **Lopez-Caraballo et al. (2024):** CTB80, HB21, Cygnus Loop, CTA1, Tycho and HB9**.**
- **QUIJOTE results for AME diffuse emission in the Galactic plane (|b|<10º).**
  - **Fernandez-Torreiro et al. (2023).** Spatial variability of ν_{AME}. Correlation between AME emissivity – ISRF (G_0) confirmed.
- **Fernandez-Torreiro et al. (2024).** AME detected in M31 (3.5σ). Consistent with SRT (Battistelli+19).
- **Polarization constraints:**
  - Apparently unpolarized. Best upper limits in W44 (< 0.4% at 17GHz from QUIJOTE, and < 0.22% at 41GHz from WMAP). **Génova-Santos et al. (2017), Gonzalez et al. (2024).**



(Poidevin et al. 2023)



(Fernandez-Torreiro et al. 2024)

RadioForegroundsPlus

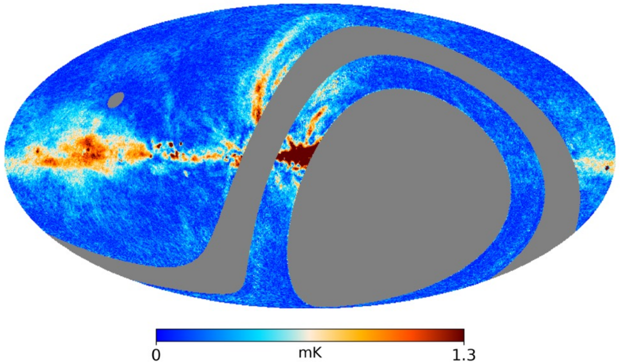
https://research.iac.es/proyecto/radioforegroundsplus

Funded by the European Union

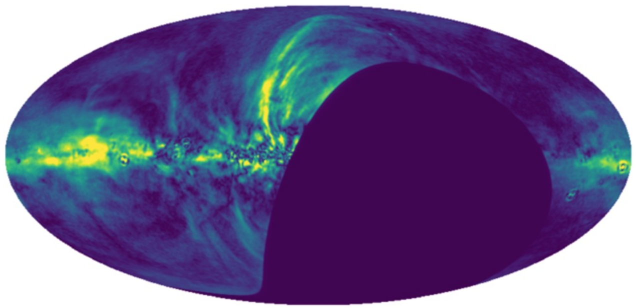
To provide **the best possible characterization of the physical properties of the polarized emissions in the microwave range, by combining Planck** (30-857GHz) **with QUIJOTE** (10-40 GHz), **C-BASS** (at 5 GHz) and **S-PASS** (at 2.3 GHz). The resulting analyses will play a key role in preparing and supporting future international CMB experiments.

Budget ~1.5M€. Period: 2024-2026.

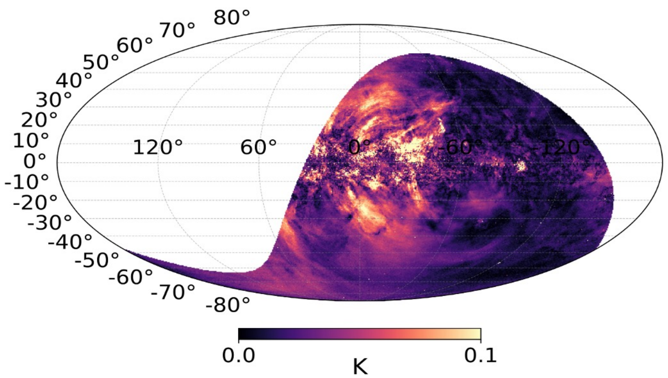
QUIJOTE P 11GHz (1deg)



C-BASS North P



S-PASS



Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Health and Digital Executive Agency (HaDEA). Neither the European Union nor the granting authority can be held responsible for them.

HORIZON-CL4-2023-SPACE-01, GA 101135036

QUIJOTE-MFI wide survey results VI: the Haze emission

Guidi et al. (2023).

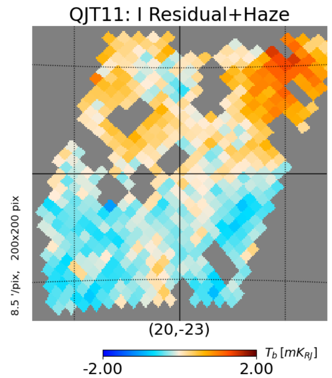
Data: wide-survey + raster scans (1500h)

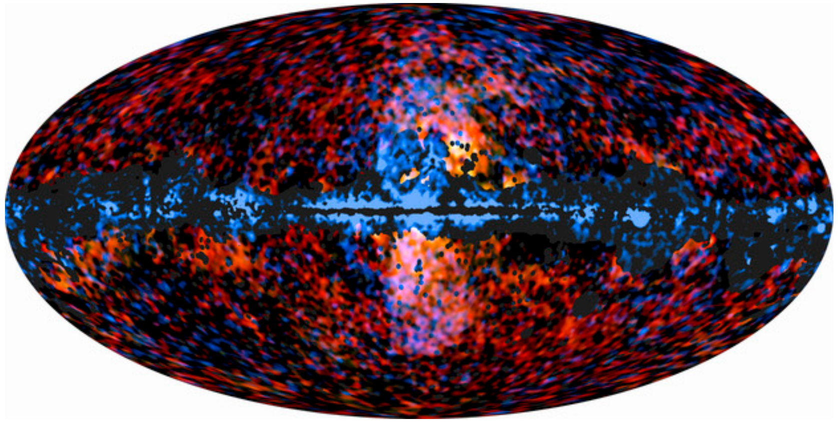
Intensity

- Haze component detected at 9σ, at 11 GHz. Confirmation of WMAP and Planck.
- Spectrum steeper (β=-2.79 ±0.08) than previous results (β=−2.56±0.05, Planck IX, 2013).

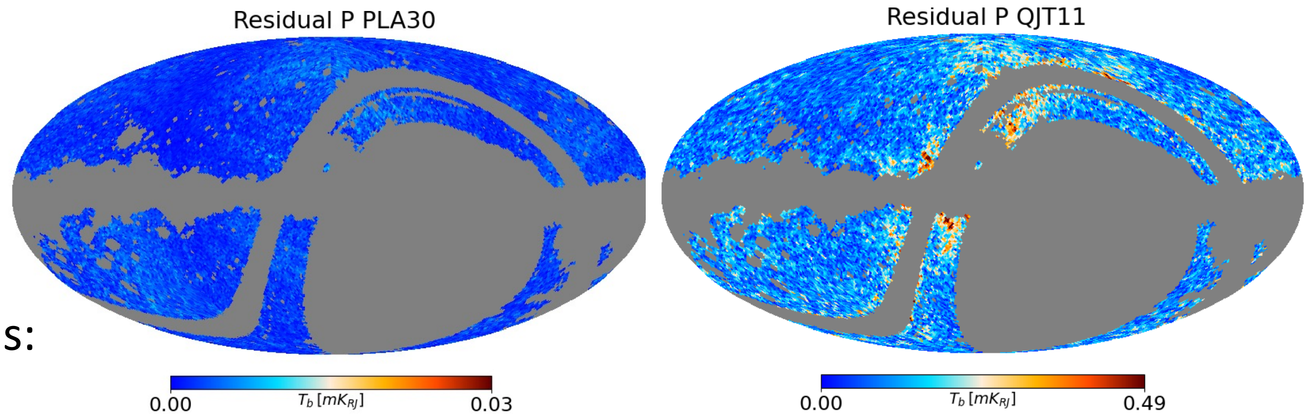
Polarization

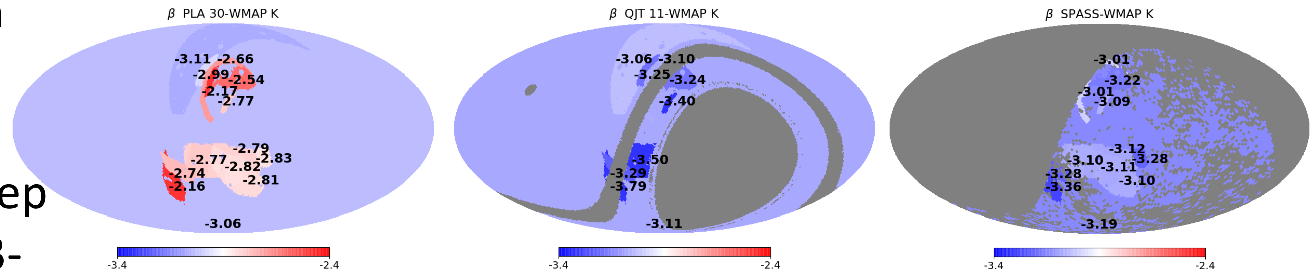
- Sky signal residuals observed in polarization after subtracting other foregrounds: Haze? Possibly due to curvature of the synchrotron spectrum.
- TT-plots show flat spectra indices at 23-30 GHz and steep spectra at 11-23 GHz and 2.3-23 GHz.





Planck (red) and Fermi (blue)

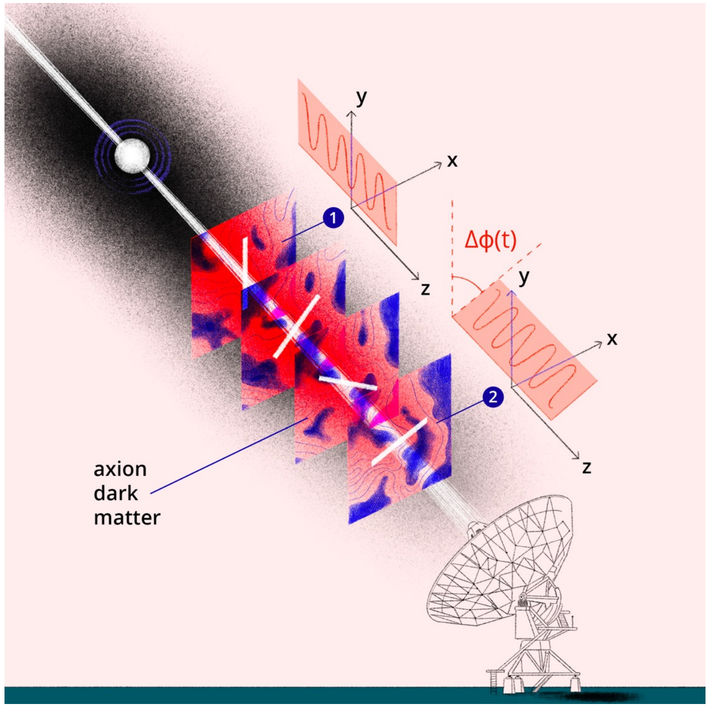


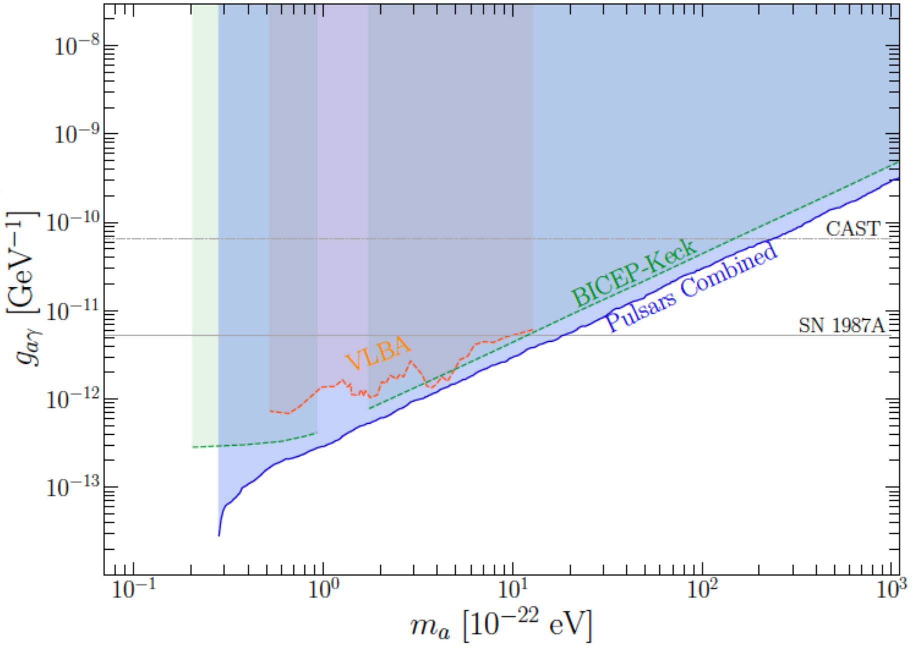


(Guidi et al. 2023)

Searching for DM waves with QUIJOTE

- Coherent oscillations of the ALP background in the galactic halo induce a periodic change on the polarization of the electromagnetic radiation emitted by local sources such as pulsars.
- Methodology: generalised Lomb-Scargle periodogram to search for periodic signals.
- Data: Tau A (Crab) SNR observed by QUIJOTE MFI instrument, and 20 Galactic pulsars from the Parkes Pulsar Timing Array (PPTA) project.
- Result: strongest limits on the axion-photon coupling for a wide range of dark matter masses spanning 10^{-23}eV < m_a < 10^{-19}eV.



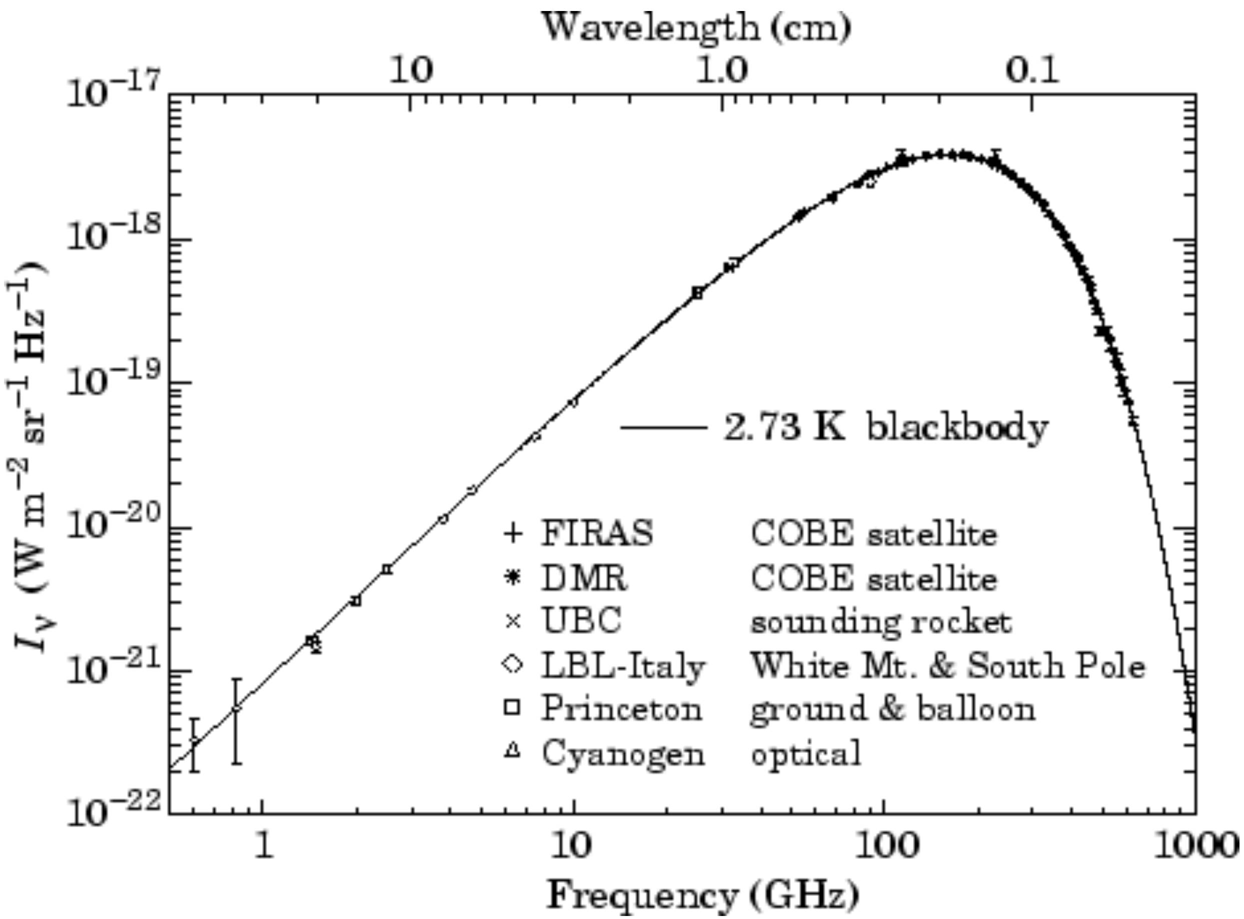


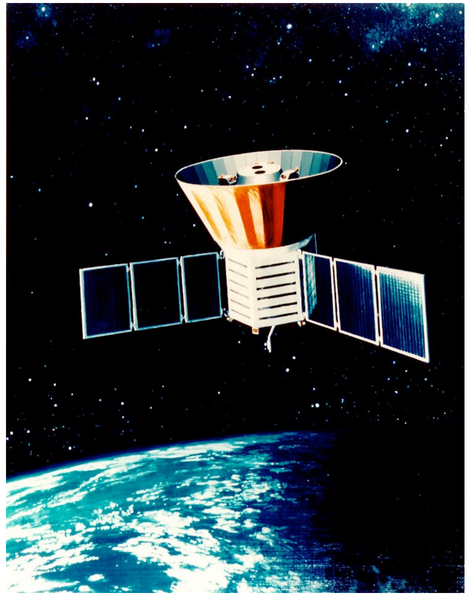
(Castillo et al. 2022)

Tenerife Microwave Spectrometer (TMS)
INSTITUTO DE ASTROFISICA DE CANARIAS · IAC
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
Secondary Mirror
(SM)
Vacuum Window
IR Filter
Sky Feedhorn
(FHs)
Primary Mirror
(PM)
Cryostat
Reference Feedhorn
(FHr)
4K Cold Load
(4KCL)
TMS has Instrumental
participation from :
INAF OAS BOLOGNA
OSSERVATORIO DI ASTROFISICA E
SCIENZA DELLO SPAZIO DI BOLOGNA
Plesso Area della Ricerca CNR
UNIVERSITÀ
DEGLI STUDI
DI MILANO
Universidad
Politécnica
de Cartagena
idom

TMS: scientific motivation

CMB has a blackbody spectrum with extremely high precision
(COBE/FIRAS, Fixsen & Mather 2002)





$T_0 = 2.725 \pm 0.001$ K

$|\mu| < 9 \times 10^{-5}$ (95% CL)

$|y| < 15 \times 10^{-6}$ (95% CL)

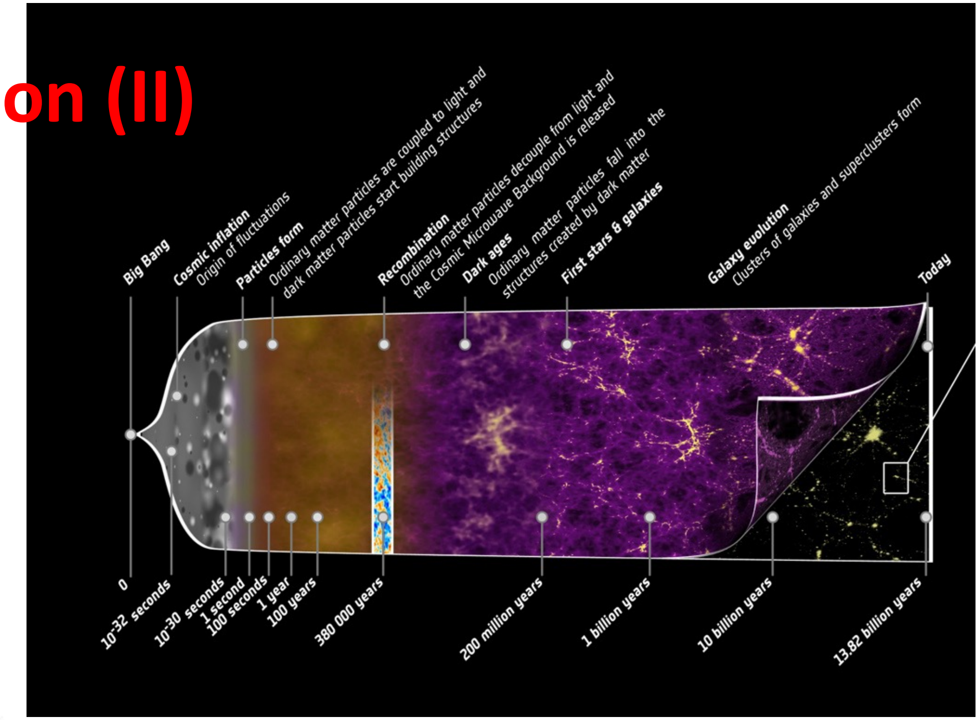
Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen et al., 2003, ApJ, 594, 67

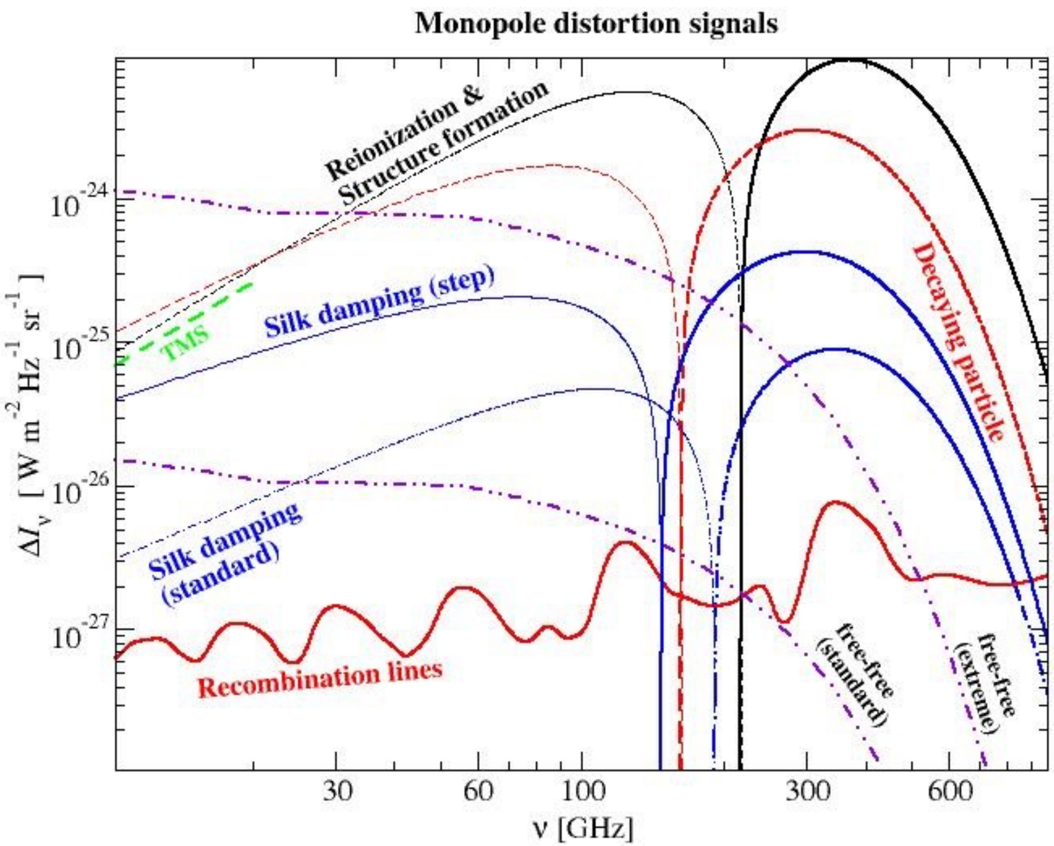
Absolute spectrum in microwaves: encodes information about **energetics** in the Universe (phase transitions in early universe; relic decay DM particles; reionization).

TMS: scientific motivation (II)

CMB spectral distortions probe the thermal history of the Universe at z < few x 10^6.

The standard cosmological model predicts unavoidable spectral distortions (Sunyaev & Khatri 2013; Chluba 2016).



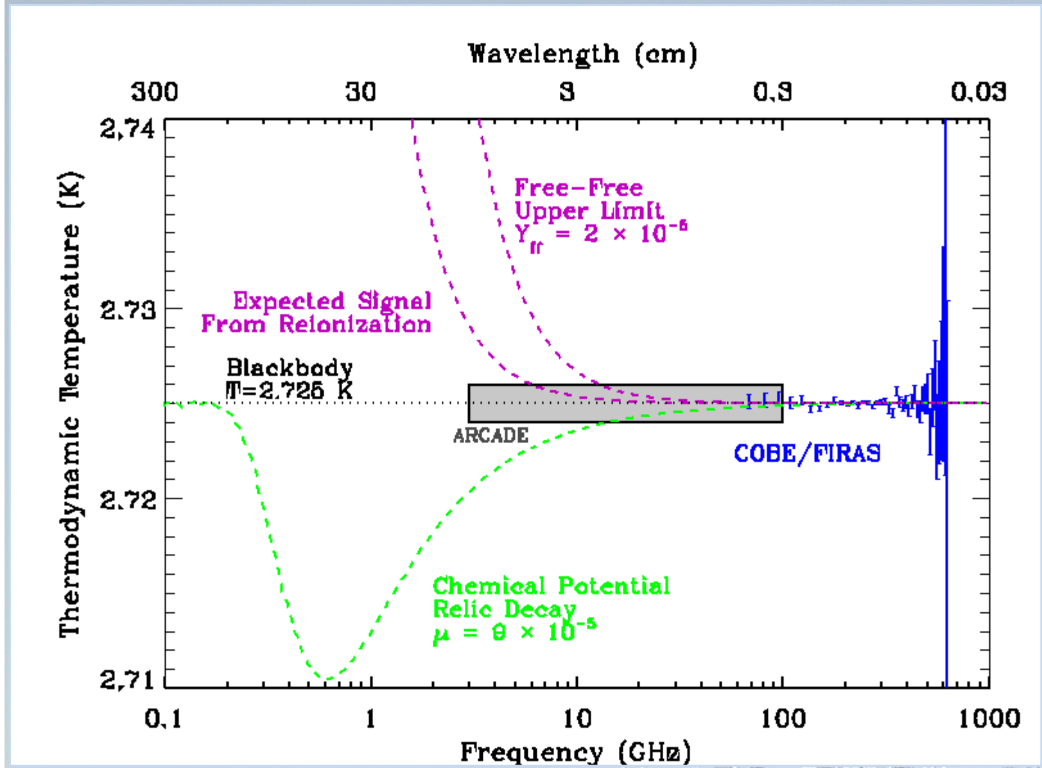


Scientific cases:

- Thermal history from 2 months after BB;
- reionization epoch;
- inflaton at scales well below 1 Mpc;
- decaying and annihilating relics;
- Primordial Black Holes;
- Primordial magnetic fields;
- metals during the dark ages;
- cosmological recombination radiation (→ implications for H_0 tension).

(see Chluba et al. 2021)

TMS: scientific motivation (III). The RSB.



ARCADE2

(Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission)

- Distortion constraints:

$$|\mu| < 6 \times 10^{-4}$$

$$|Y_{\rm ff}| < 10^{-4}$$

- No limit on y-parameter.
- Found low frequency excess.
  - Spectrum:

$$T(\nu) = (18.4 \pm 2.1)\mathrm{K} \left(\frac{\nu}{0.31\,\mathrm{GHz}}\right)^{-2.57\pm0.05}$$

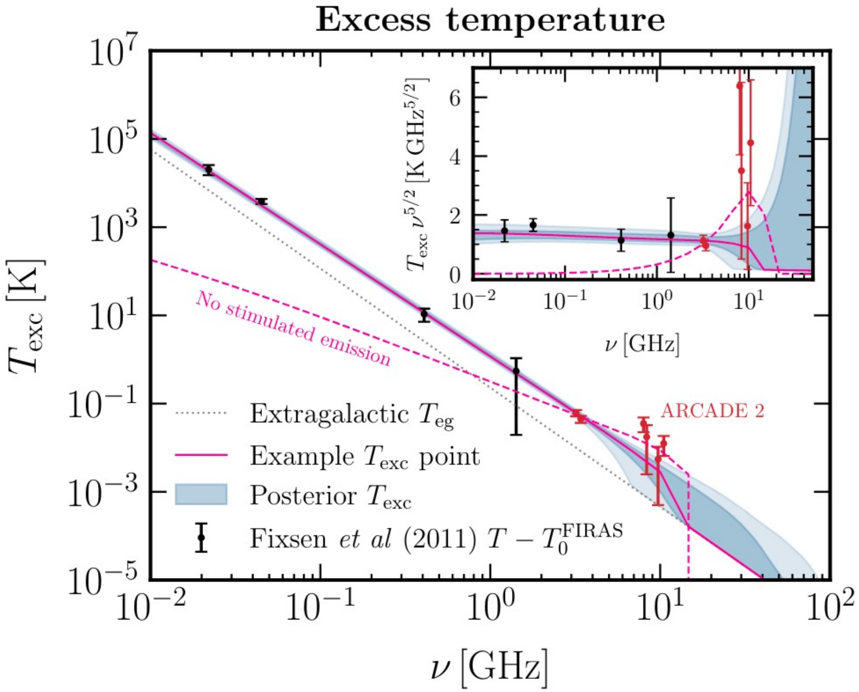
  - Origin of excess (Radio Synchrotron Background) unclear.
  - In tension with TRIS results.

Kogut et al. 2006, New Astronomy Rev., 50, 925
Kogut et al., 2011, ApJ, 734, 9
Fixsen et al., 2011, ApJ, 734, 11
Seiffert et al., 2011, ApJ, 734, 8

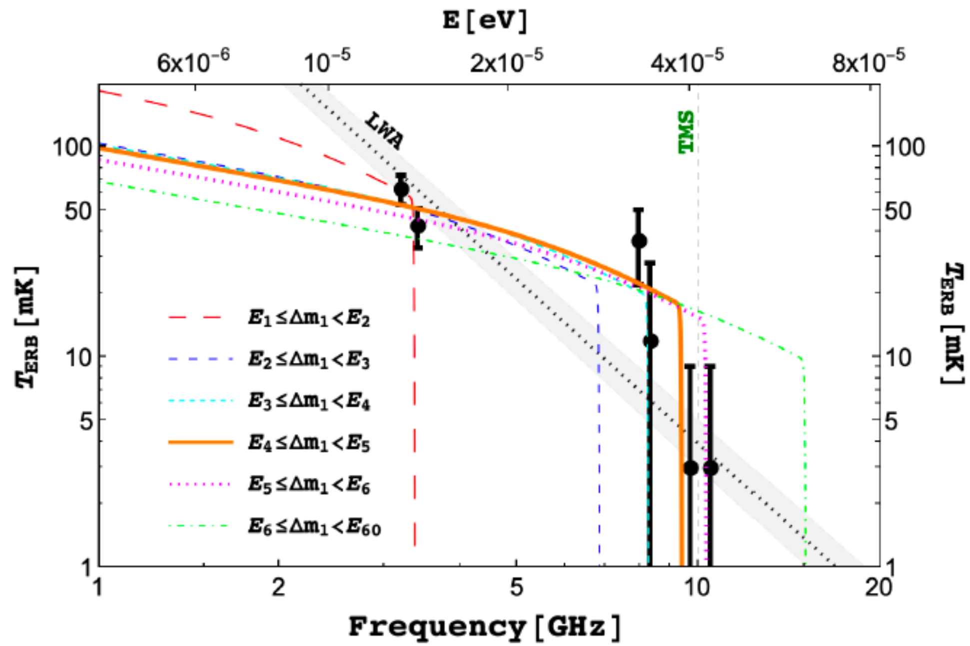
TMS: scientific motivation (IV)

Scientific cases for TMS related to UNDARK:

- **Forecasting the TMS sensitivity to the dark-matter model space**. To develop and adapt the dark-matter phenomenology to the TMS capacities in order to identify the most promising search strategies in the 10-20GHz window.
- **Exploring the origin of the RSB excess**. To test the predictions of DM models that have been proposed to explain the RSB using the upcoming TMS measurements.



Predictions of the frequency dependence of the RSB excess temperature in the ULDM model of Caputo et al. 2023 (stimulated DM decay).



Predictions for the radiative decays of a relic neutrino ν into a sterile neutrino νs, assumed to be quasi-degenerate, to explain the RSB excess (Bhupal Dev et al. 2024).

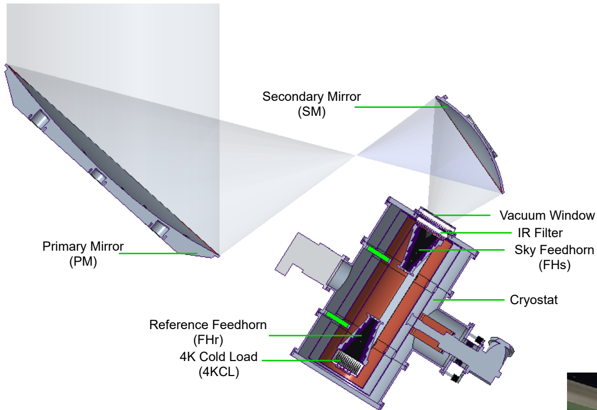
Tenerife Microwave Spectrometer (TMS), 10-20GHz

- **IAC project. Instrumental participation:**

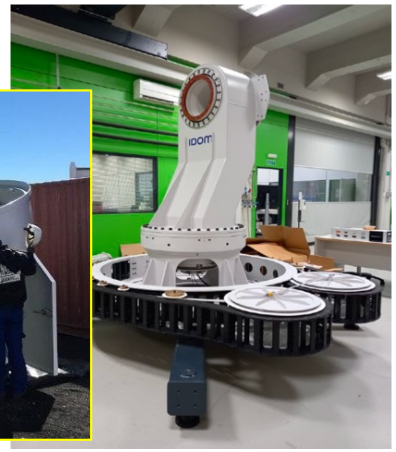
- **Science driver**: Ground-based low resolution spectroscopy observations in the 10-20GHz range to characterize foregrounds and CMB spectral distortions. Provides frequency intercalibration for QUIJOTE-MFI. (Rubino-Martin et al. 2020).
- **Location**: Teide Observatory (former VSA enclosure). Full sky dome.

- **Prototype for future instruments**. **Legacy value (radio synchrotron background).** Complementing future space missions (10-20GHz).

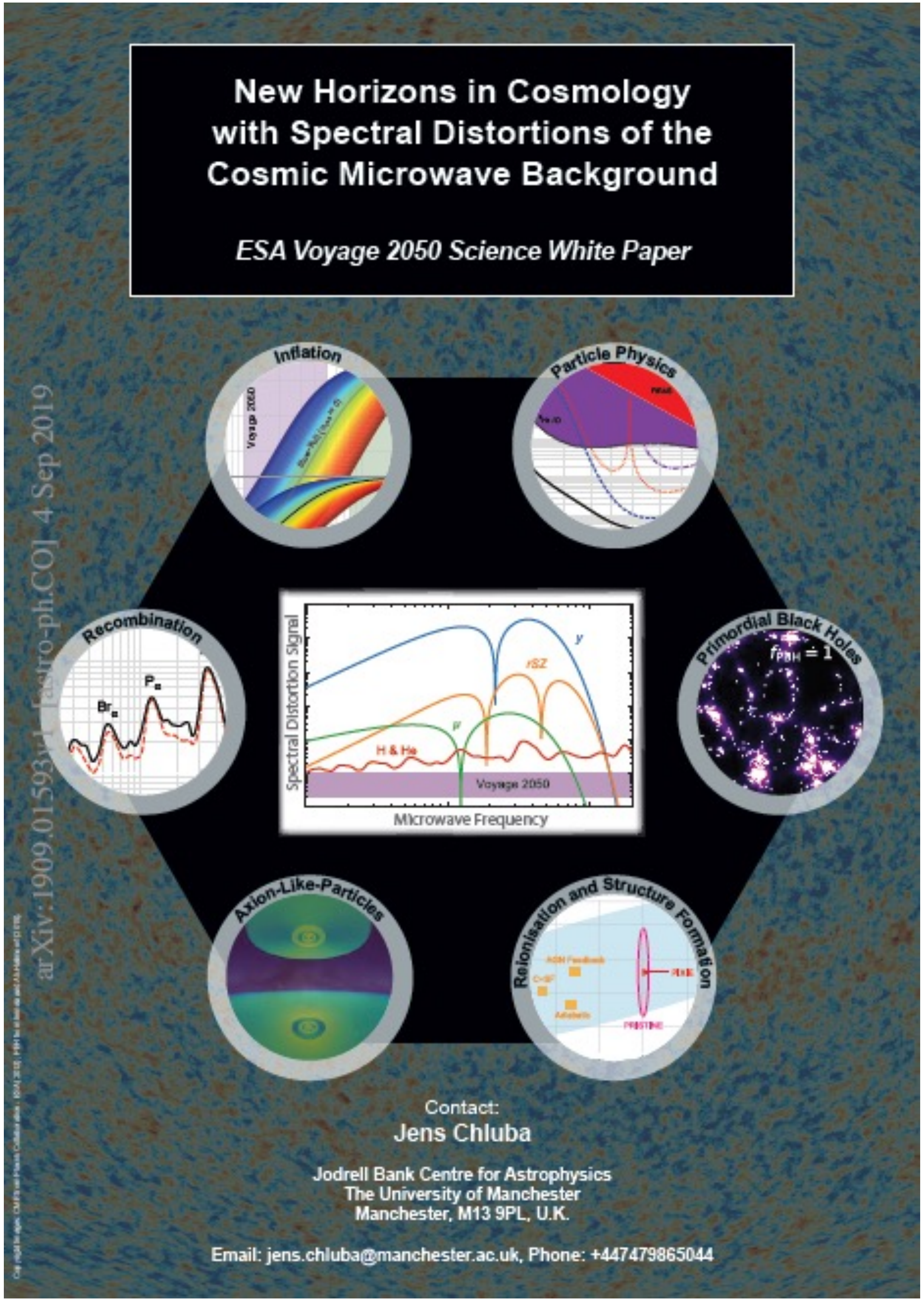
- **Proposed instrument concept**:
  - FEM cooled to 4-10K (HEMTs).
  - Reference 4K cold load.
  - DAS based on FPGAs (Xilinx ZCU208).
  - ~2deg beam, 0.25 GHz spectral resolution (40 bands).



- **Project Status**:
  - Enclosure and dome at the Teide Observatory. ✓
  - Platform fabricated (IDOM). Installation Nov 2022. ✓
  - Cryostat at the IAC since July 2019. ✓
  - 4K load fabricated and tested (Nov 2021). ✓
  - Mirrors designed (Alonso-Arias et al 2022). To be fabricated .
  - Shielding and support structure to be designed and fabricated.
  - DAS based on FPGAs, similar to MFI2.
  - Optomechanics in final fabrication phase (OMTs, hybrids).
  - Commissioning in late 2025.



Ref. de la ayuda: ICTS-2019-03-IAC-12

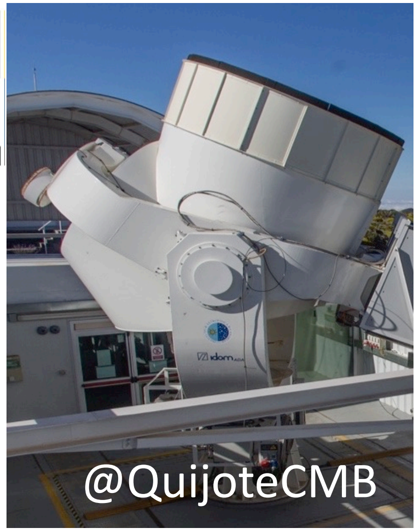


CMB spectral distortions: new window to the Universe

- Almost not experimental progress since COBE/FIRAS (1994).
- Current projects on-going:
  - **TMS** (10-20GHz). HEMTs+FPGAs. Tenerife.
  - **BISOU** (60-1200GHz). FTS. Balloon. (Maffei et al. 2021).
  - **COSMO** (110-300GHz). FTS. Dome-C. (Masi et al. 2021).
- Spectral distortions: one of the three themes selected by ESA for future L-class science mission (Voyage 2050).

Summary & Outlook

Searching for primordial B-modes and DM science



QUIJOTE

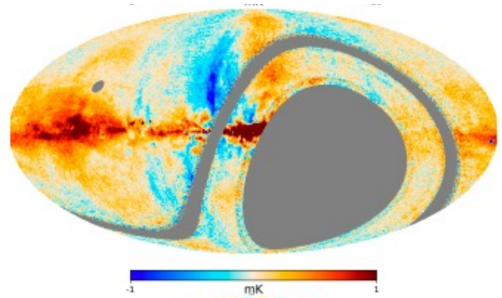
QT1 + MFI 10-20 GHz: 2012-2018.

- **Foreground studies with MFI data (RadioForegroundsPlus)**
  - Synchrotron (spatial variability, curvature, dust-synchrotron correlation).
  - AME modelling (spectral parameters; AME pol. fraction).

QT1 + MFI2 (10-20 GHz): 2024-2027.

QT2 + TGI (30 GHz) and FGI (40 GHz): 2018-2027.

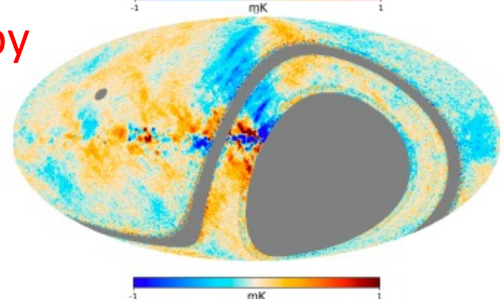
QT2 + NGI (90GHz): 2027-. Design phase.



Combination QUIJOTE with other experiments: 2024-2028.

- **At Teide: Groundbird** (150, 220GHz), **LSPE-STRIP** (43, 90GHz).
- Lower frequencies (CBASS, SPASS). **RadioForegroundsPlus.**

Talk by RGS



TMS

TMS 10-20 GHz: 2025-2030.

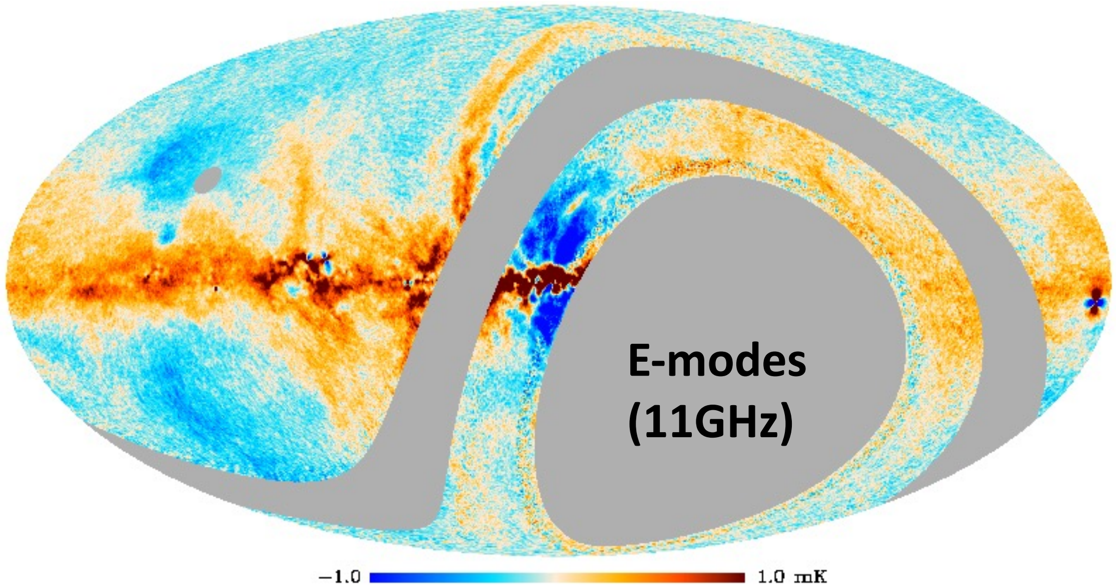
- **Galactic Foregrounds** (monopole).
- **Radio Synchrotron Background (ARCADE2) excess:**
  - Dark matter models (ULDM: axions, dark photons).
- **Instrument design + data analysis pipelines for SD experiments.**

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
RADIO FOREGROUNDS+
Funded by the European Union

Extra slides

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

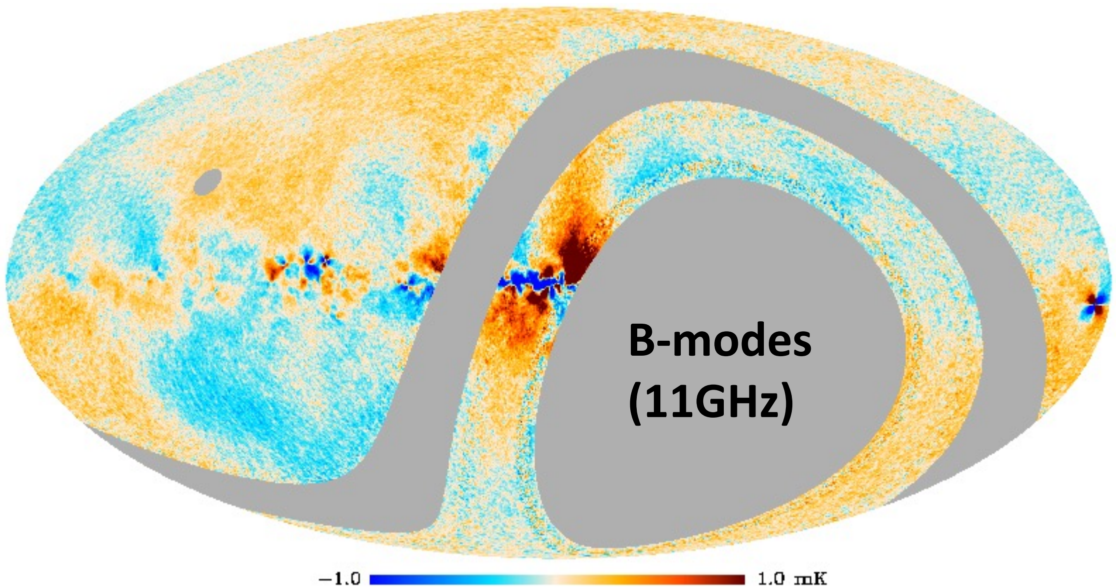
Synchrotron E-B modes and E/B ratio



- Most prominent polarized structures (Fan, NPS, loops) appear in the E-map.
- **EE/BB ratio is approx. 4 at large scales**. Consistent with Martire et al. 2022 (WMAP+Planck).
- Analysis at power spectrum level confirms this result (Vansyngel et al. in prep.)
- For thermal dust, the ratio was closer to 2 (BB/EE~0.5, Planck Collaboration XI 2018).
- We measure **EB and TB consistent with zero**. Positive TE at large angular scales.

$$C_\ell^{XX} = A_{XX}\left(\frac{\ell}{80}\right)^{\alpha_{XX}} + c_{XX}$$

Mask	$\lvert b\rvert > 5°$	$\lvert b\rvert > 10°$	$\lvert b\rvert > 20°$
f_{sky}	0.38	0.34	0.27
EE and BB fitted separately			
A_{EE} [μK^2]	1.52 ± 0.15	1.05 ± 0.18	0.81 ± 0.19
A_{BB} [μK^2]	0.52 ± 0.15	0.20 ± 0.12	0.18 ± 0.13
α_{EE}	−3.00 ± 0.16	−2.72 ± 0.26	−2.96 ± 0.36
α_{BB}	−3.08 ± 0.42	−3.13 ± 0.87	−3.12 ± 1.03
c_{EE} [μK^2]	0.07 ± 0.09	−0.13 ± 0.11	−0.09 ± 0.12
c_{BB} [μK^2]	0.10 ± 0.09	−0.06 ± 0.09	−0.09 ± 0.09
A_{BB}/A_{EE}	0.34 ± 0.10	0.19 ± 0.12	0.22 ± 0.18
Joint EE and BB analysis			
A_{EE} [μK^2]	1.49 ± 0.12	0.97 ± 0.13	0.78 ± 0.14
α_{EE} (=α_{BB})	−3.04 ± 0.13	−2.83 ± 0.21	−3.03 ± 0.29
c_{EE} (=c_{BB}) [μK^2]	0.09 ± 0.06	−0.08 ± 0.06	−0.08 ± 0.07
A_{BB}/A_{EE}	0.36 ± 0.04	0.26 ± 0.07	0.26 ± 0.08



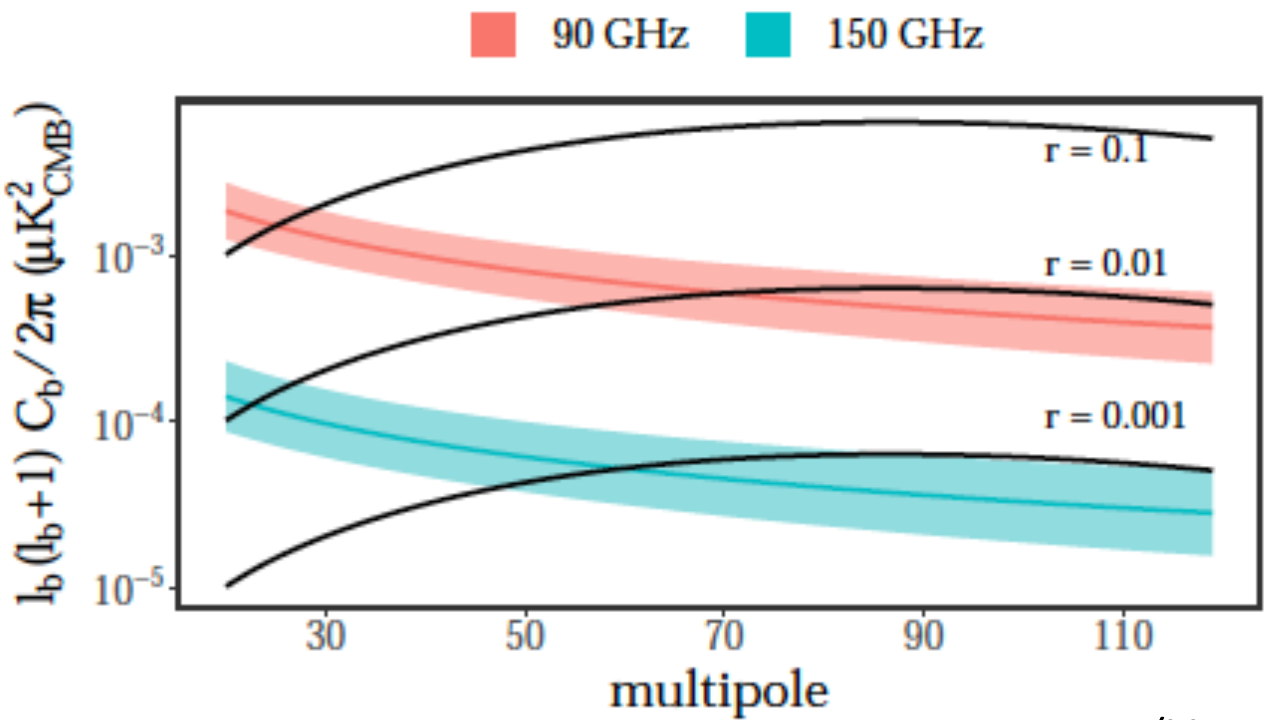
(Rubiño-Martin et al. 2023)

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

Synchrotron properties and B-mode detectability

- Auto- and cross-spectra of QUIJOTE, WMAP, PLANCK maps in northern sky (|b|>10º).
- Dust-synchrotron correlation: ~ 0.18±0.06.
- Variability on sky (compared to other results: Planck Col. XI 2018, Krachmalnikoff et al. 2018).

Contamination of the CMB at 90 and 150GHz by the synchrotron B-modes. Regions at 95% C.L. :



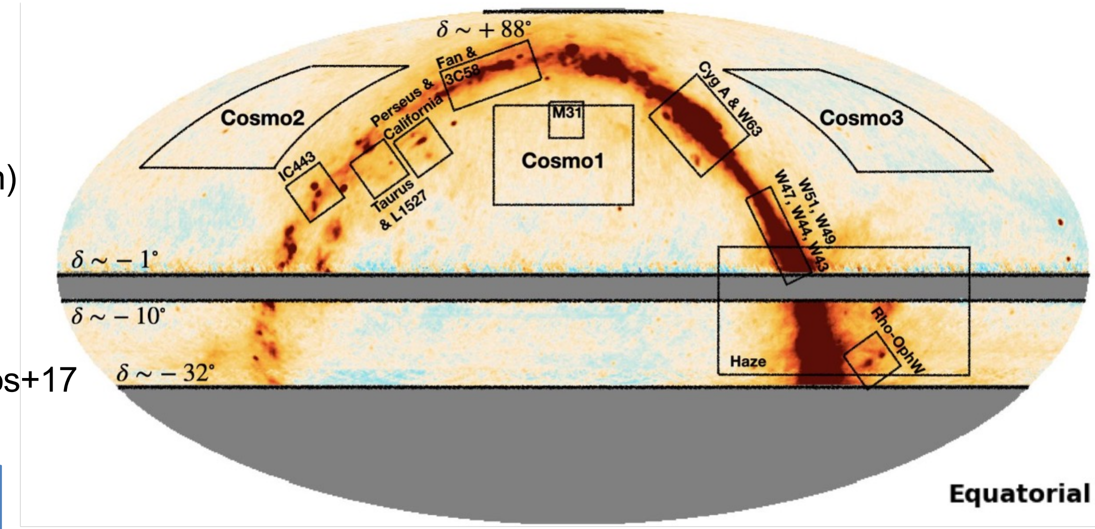
(Vansyngel et al. in prep)

Science with QUIJOTE first instrument (MFI)

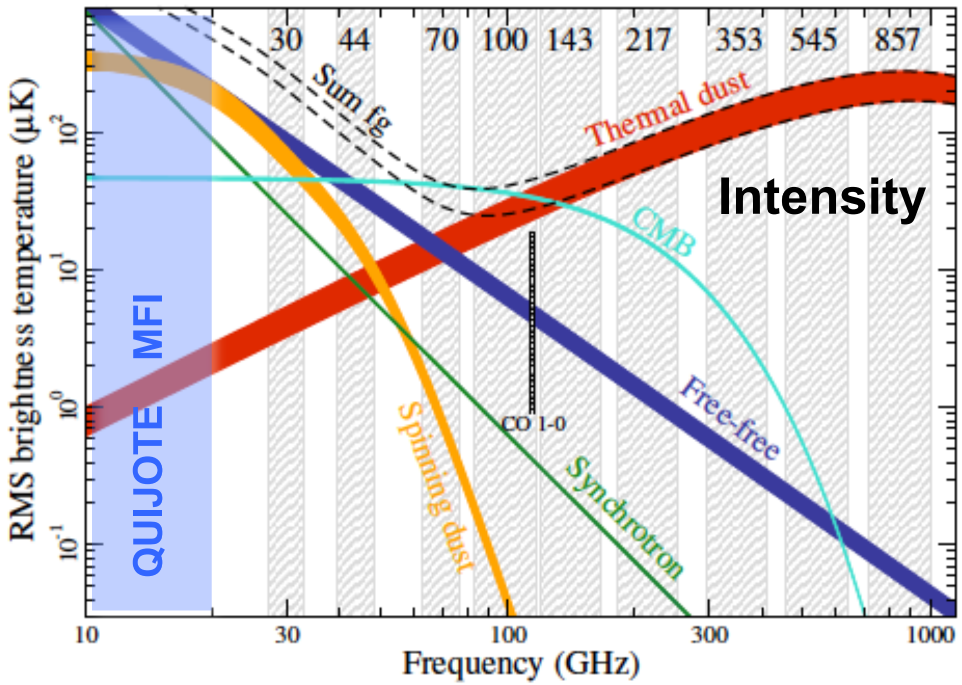
Excellent complement to PLANCK at low frequencies. Legacy for future experiments (→LiteBIRD)

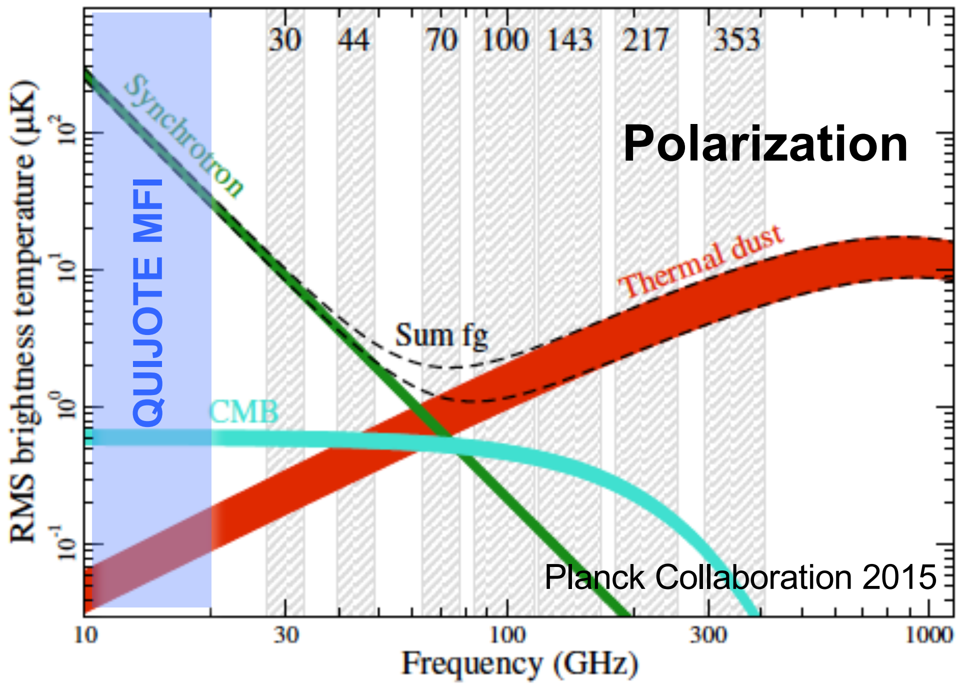
MFI Science phase (Nov 2012- Dec 2018)

- Wide survey (10,800h) → **main data release 2023**.
- Cosmological fields (~3,000 deg^2) (6,500h)
- Daily calibrators (Crab, Cass A, Jupiter, sky dips,..) (1,700h)
- Galactic centre and Haze (1,400h)
- Perseus molecular cloud (750h) → Genova-Santos+15
- Fan region and 3C58 (500h)
- Taurus region (450h) → Poidevin+19
- SNRs (W44, W47, IC443, W63) (1,150h) → Genova-Santos+17
- M31 (540h)



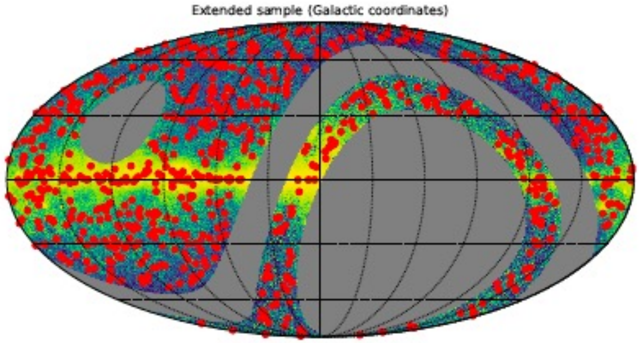
Total: ~**26,000 h** of MFI data (3 effective years).
→ ~50% efficiency during science phase.

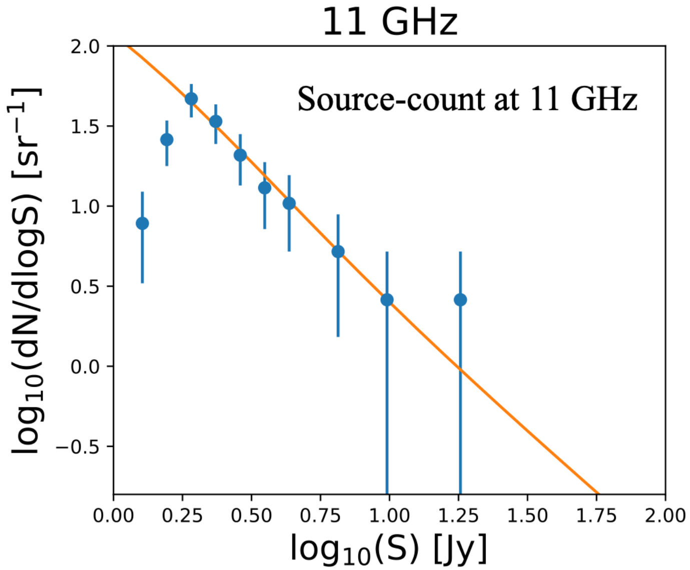




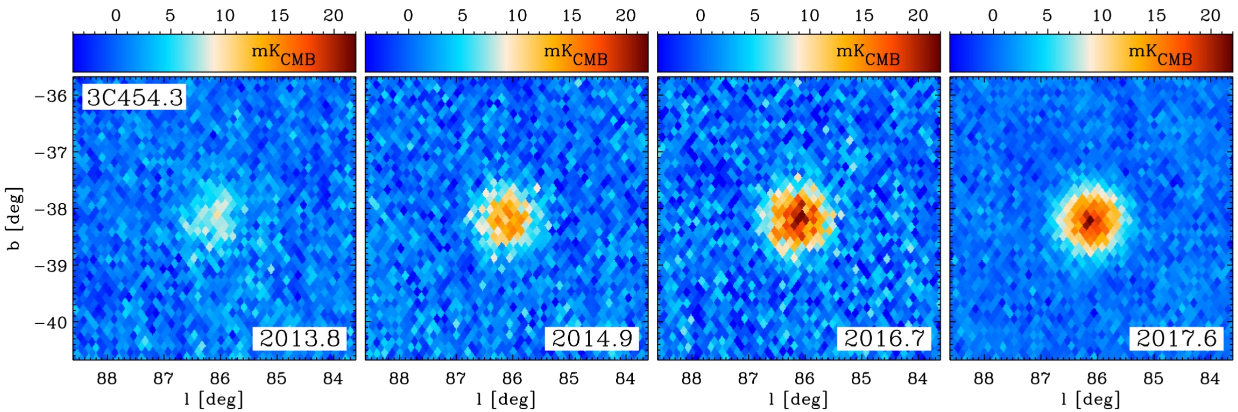
QUIJOTE-MFI wide survey results IX: radiosources

- Systematic study of a catalogue of **782 sources** in the QUIJOTE wide-survey maps. → included in data release.
- Completeness limit at 11 GHz **~1.8 Jy**
- Study of polarisation properties of ~35 sources **<Π> = [2.8,4.7] %**

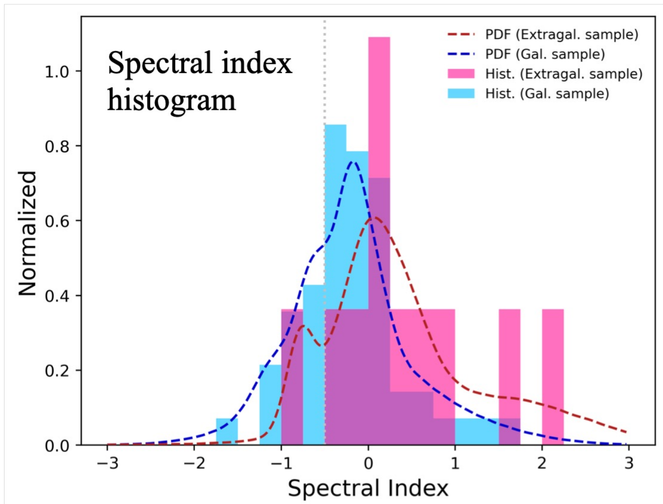




- Blind variability search → 7 variable sources, with 3 being strongly variable:



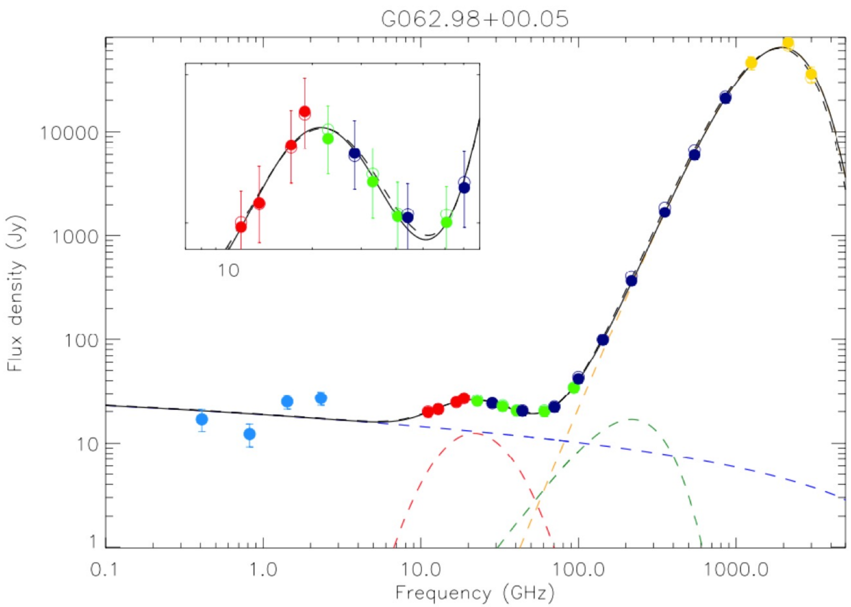
Variability of 3C454.3 in the four-period maps

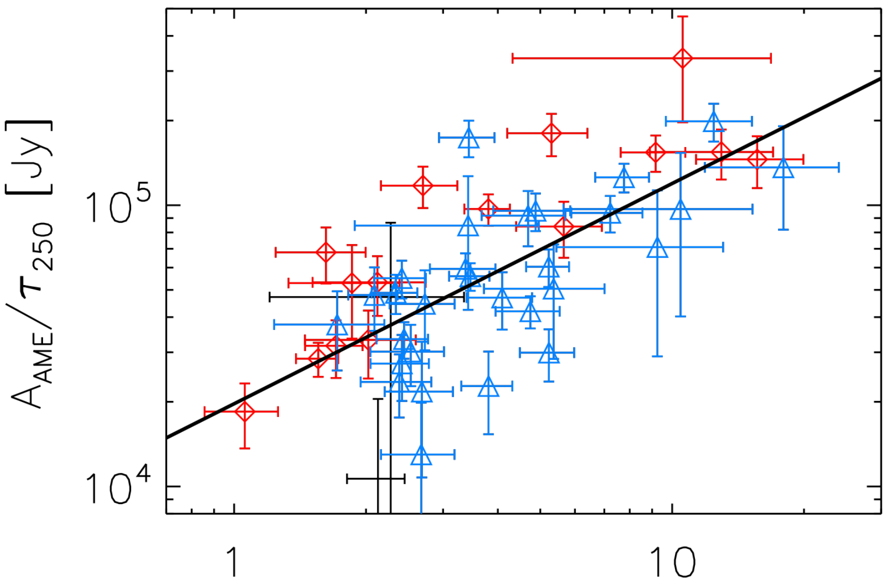


(Herranz et al. 2023)

QUIJOTE-MFI wide survey results: modelling the AME

- **Génova-Santos et al. (2017):** Best upper limits on AME polarization to date , from W44 region (< 0.4% at 17GHz from QUIJOTE, and < 0.22% at 41GHz from WMAP).
- **Tramonte et al. (2023), V.** : AME detected in W49 (4.7σ) and W51 (4.0σ).
- **Poidevin et al. (2023), VII** : Study of 56 compact AME sources (includes targets from PIR XV 2014). Main results:
  - QUIJOTE-MFI provides a cleaner separation of the AME, free-free and synchrotron components. Generally, higher AME and lower free-free. We find ν_{AME}= 23.6±3.6 GHz.
  - Clear correlation (90%) of AME/tau_{dust} with radiation field G_0 (T_d). Seen in Tibbs et al. (2011, 2012), and PIR XV (2014).
  - Clear correlation between AME and dust peak. Poor correlation between G_0 and EM.



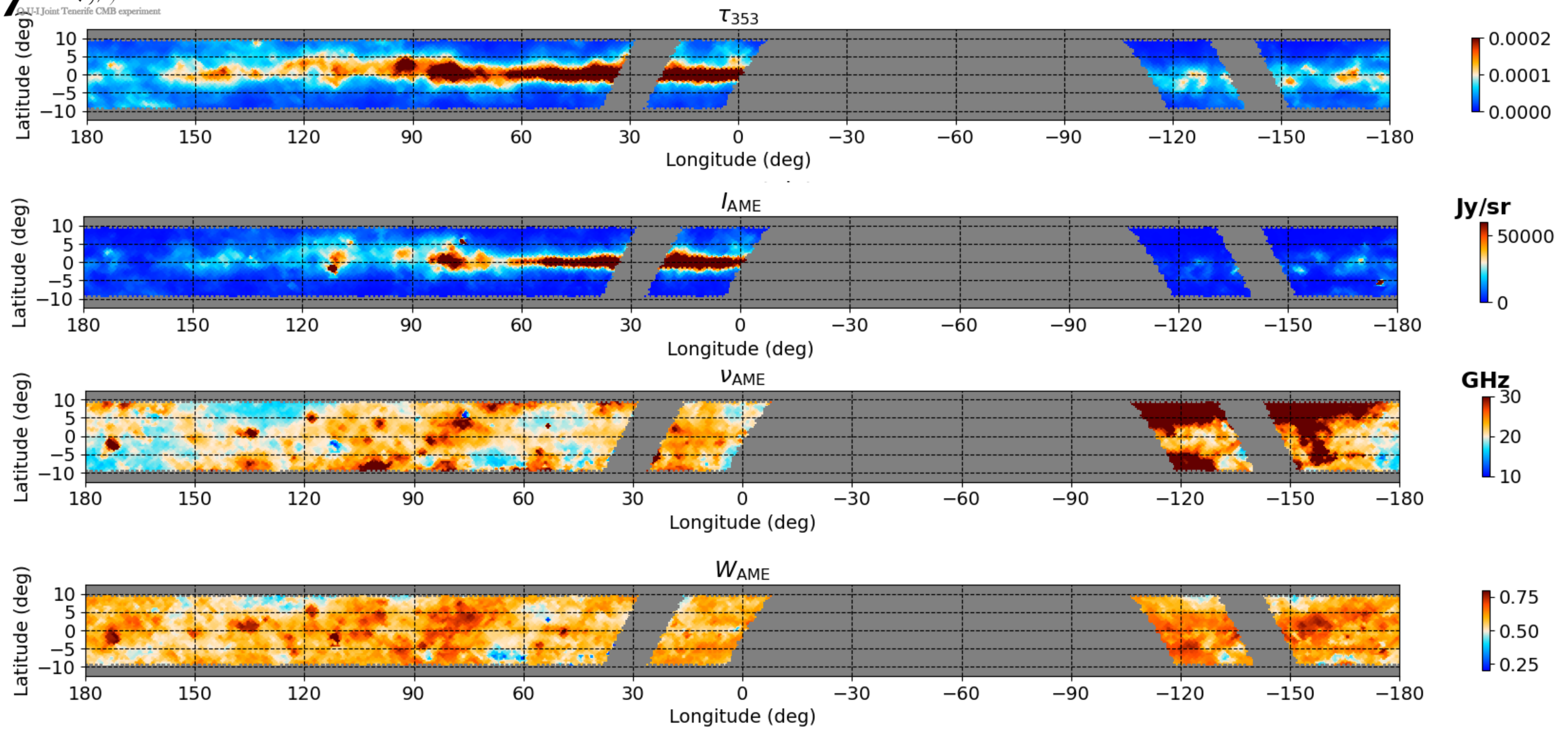


(Poidevin et al. 2023)

G_0

QUIJOTE-MFI wide survey results X: AME variations along the plane |b|<10º

(Fernández-Torreiro et al. 2023)



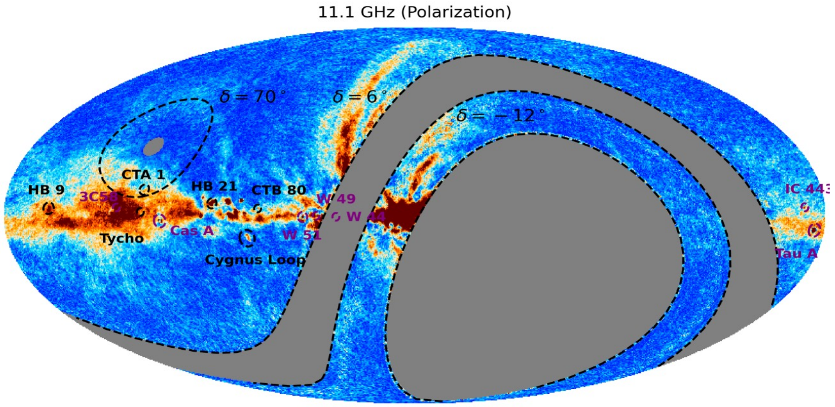
- Extending previous works to the Galactic plane (|b|<10º) seen by QUIJOTE MFI.
- AME parameterization: parabola in log S – log ν plane, three params (A, ν_{AME}, width).

$$\nu_{\rm AME} = 20.7^{+2.0}_{-1.9}\,{\rm GHz} \qquad W_{\rm AME} = 0.560^{+0.059}_{-0.050}$$

- Spatial variability of ν_{AME}. Correlation AME emissivity – ISRF (G_0) confirmed if using tau_{353}.
- Rather uniform AME emissivity: ϵ(28.4 GHz/100μm)= 11.6 ± 3.5 μK/(MJy/sr).

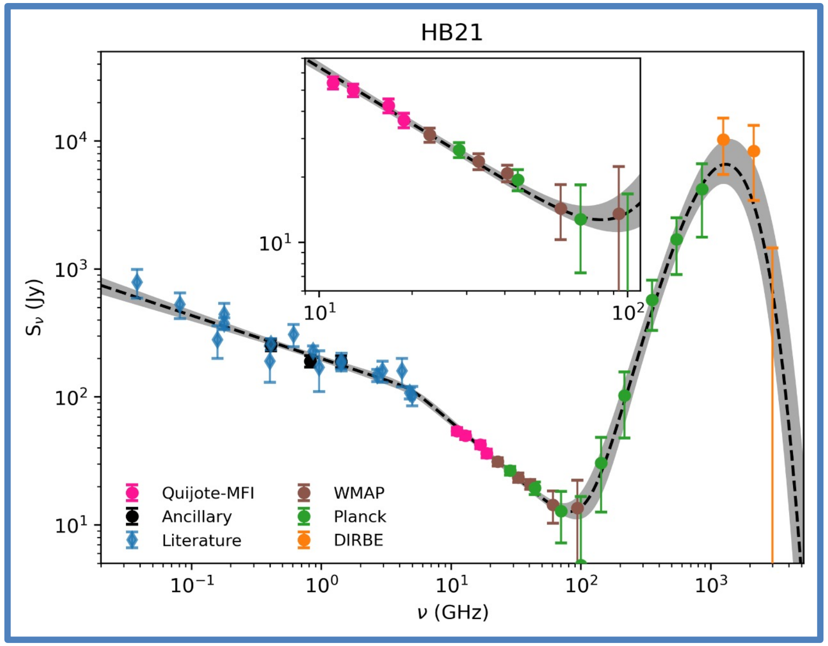
QUIJOTE-MFI wide survey results XIII: AME in SNRs

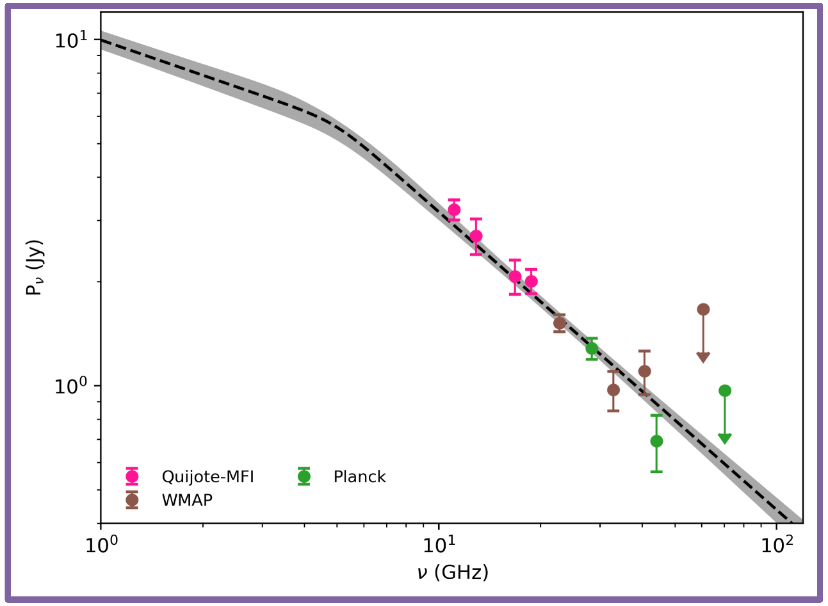
- **SNRs:** CTB80, HB21, Cygnus Loop, CTA1, Tycho and HB9 (López-Caraballo+24)**.** Our previous studies: Tau A and Cas A (main calibrators, Rubino-Martin+23); W44 (Genova-Santos+17), W49 and W51 (Tramonte+23).



- **Results: synchrotron**. We confirm the spectral break of the synchrotron emission for CTB80 and HB21. Polarization levels are lower than 10%.
- **Results: AME**. Detected in W49 at 4.7sigma. Not seen in other regions. Derived upper limits on polarization:

SNR	$A_{\rm AME}$ at 95% C.L. [Jy]	[%]
CTB 80	≤ 2.8	≤ 19.7
Cygnus Loop	≤ 2.4	≤ 7.0
HB 21	≤ 3.9	≤ 11.3
CTA 1	≤ 1.4	≤ 20.3
Tycho	≤ 2.2	≤ 14.6
HB 9	≤ 1.5	≤ 9.7



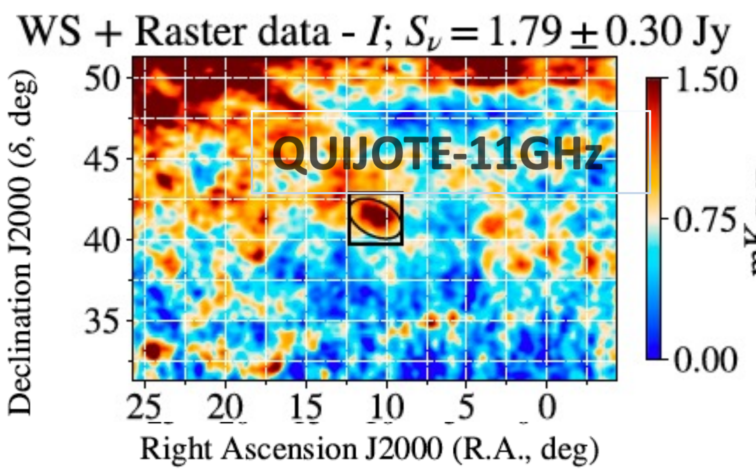


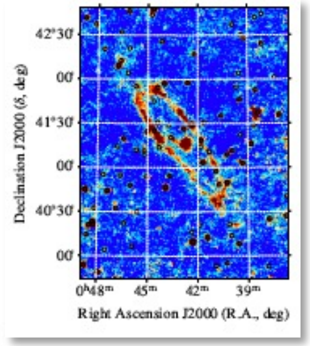
(López-Caraballo et al. 2024)

QUIJOTE-MFI wide survey results XVII: AME in M31

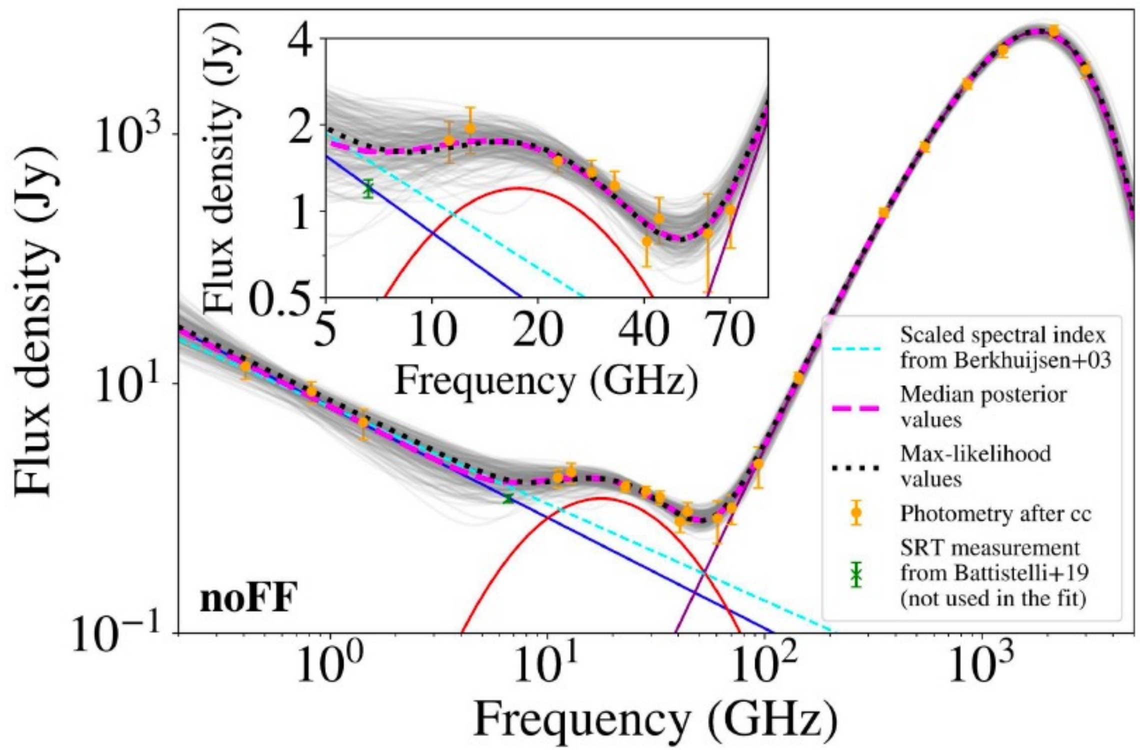
- **AME detected in M31 at 3.5-sigma level** using QUIJOTE-MFI in combination with Planck, WMAP and ancillary data. Consistent with SRT (Battistelli +19).
- The selection of the aperture has an impact on the significance of the AME detection (CBASS: Harper+23).
- The recovered **AME emissivity** in M31, ϵ(28.4 GHz/100μm)= 9.1 ± 2.9 μK/(MJy/sr), is **similar to that found for the Milky Way** (paper X).

Parameter	Case 1 (all components)
$S_{1\,\mathrm{GHz}}$ (Jy)	5.91 ± 1.01
α_{syn}	-0.97 ± 0.21
EM (pc cm^{-6})	2.72 ± 1.64
A_{AME} (Jy)	1.03 ± 0.32
ν_{AME} (GHz)	17.15 ± 3.17
W_{AME}	0.58 ± 0.16
τ_{353}	3.79 ± 0.34
β_{d}	1.71 ± 0.08
T_{d} [K]	18.49 ± 0.79
$S^{\mathrm{ff}}_{1\,\mathrm{GHz}}$ (Jy)	0.39 ± 0.24
S^{AME} @ 25 GHz (Jy)	0.83 ± 0.32
$S^{\mathrm{dust}}_{3000\,\mathrm{GHz}}$ (Jy)	3255 ± 1130
χ^2_{red}	0.61





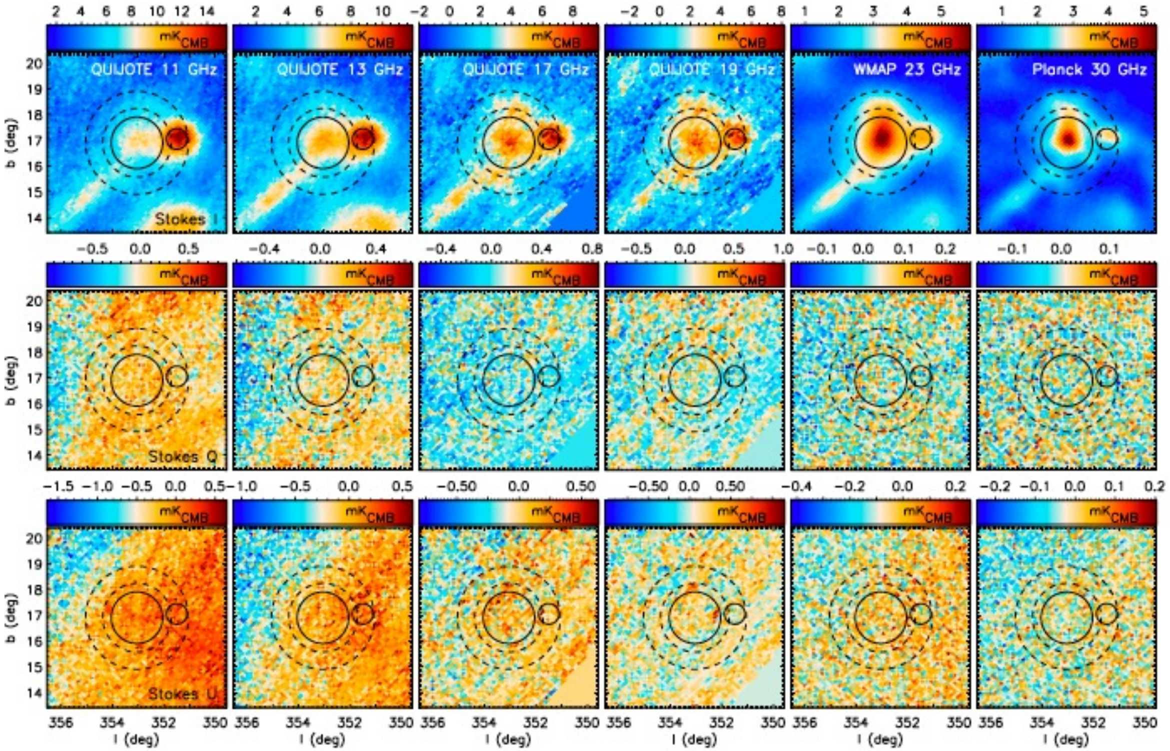
SRT@6.6GHz

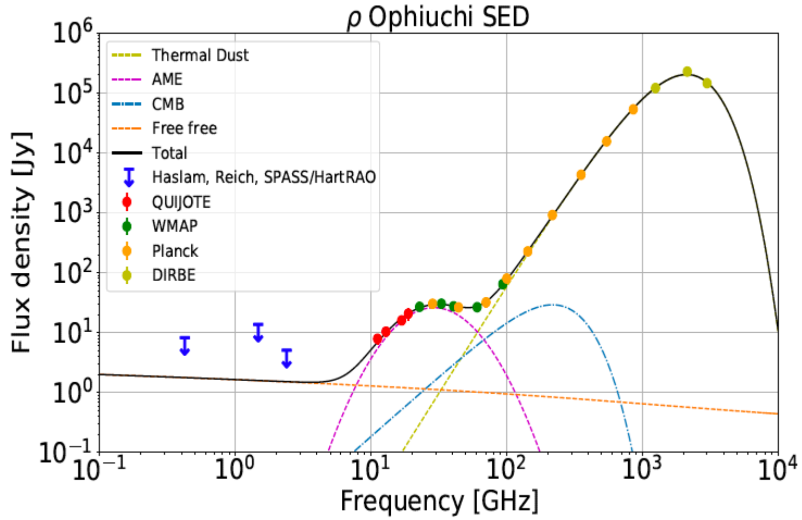


(Fernández-Torreiro et al. 2024)

QUIJOTE-MFI wide survey results XVIII: AME in ρ Ophiuchi, Perseus and W43

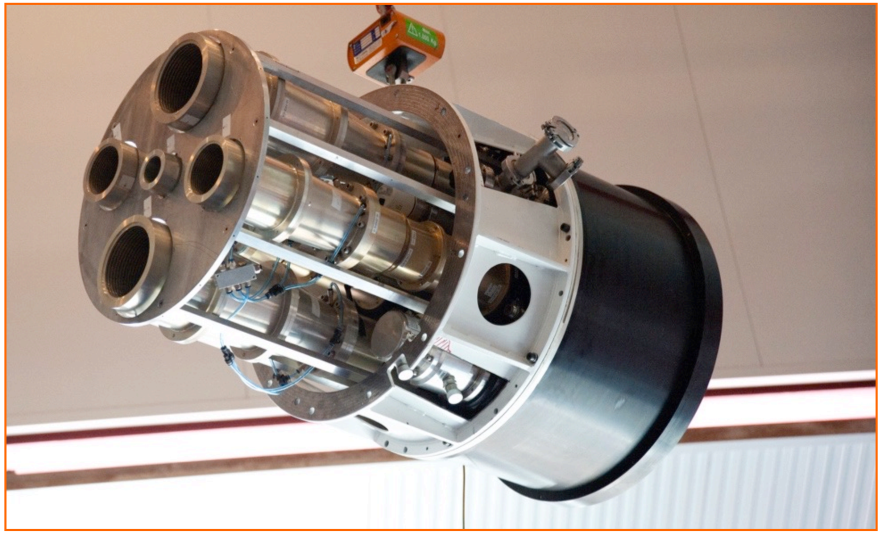
- **QUIJOTE-MFI** wide survey data plus additional 1800 hours of dedicated raster scan observations.
- **Upper limits on AME polarization fraction of order ≲ 1%** (95% confidence level) **for the three regions**.
- Π_{AME} < 1.1% (at 28.4 GHz), Π_{AME} < 1.1% (at 22.8 GHz) and Π_{AME} < 0.28% (at 33 GHz) in ρ Ophiuchi, Perseus and W43 respectively.
- At QUIJOTE 17 GHz: Π_{AME} < 5.13% for ρ Ophiuchi, Π_{AME} < 3.47% for Perseus and Π_{AME} < 0.88% for W43.
- Improved intensity-to-polarization leakage correction that has allowed for the first time to derive reliable polarization constraints from the Planck-LFI data. Residuals at 0.2% level.



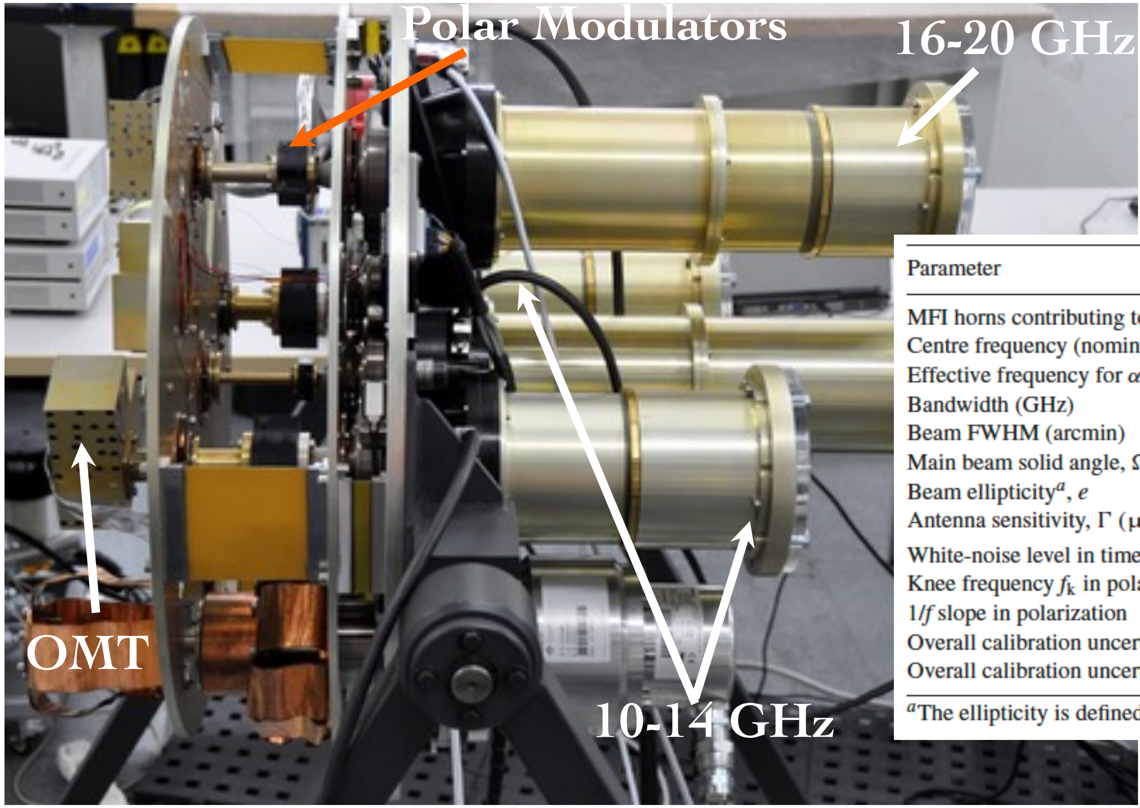


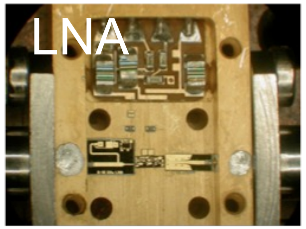
(Gonzalez-Gonzalez et al. 2024, A&A submitted)

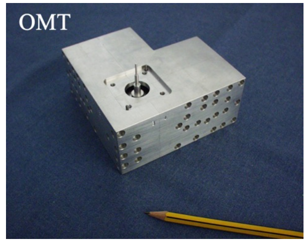
MFI Instrument (10-20 GHz)



- **Operations**: Nov 2012 – Dec 2018, 50% efficiency
- 4 horns, 32 channels. Four frequency bands: 11, 13, 17 and 19 GHz. Bandwidth: 2 GHz.
- **Sensitivities**: ~700-800 μK $s^{1/2}$ in timelines.
- Near sidelobes ~ 35 dB, far-sidelobes < 80 dB
- f_{knee} ~ **250 mHz** (pol), ~**50 Hz** (int)
- "**HWP**": steeping polar modulator (RL<-20dB, IL< -0.15dB, I<-40 dB)







Parameter	11 GHz	13 GHz	17 GHz	19 GHz
MFI horns contributing to these bands	3	3	2, 4	2, 4
Centre frequency (nominal), ν_0 (GHz)	11.1	12.9	16.8	18.8
Effective frequency for $\alpha = -1$, $\nu_e(\alpha = -1)$ (GHz)	10.98	12.89	16.85	18.85
Bandwidth (GHz)	2.17	2.20	2.24	2.34
Beam FWHM (arcmin)	55.38	55.84	38.95	40.32
Main beam solid angle, Ω_{mb} (10^{-4}sr)	2.748	2.781	1.362	1.428
Beam ellipticity[a], e	0.013	0.040	0.034	0.035
Antenna sensitivity, Γ (μK_{CMB} Jy^{-1})	961.9	703.8	847.0	645.2
White-noise level in timelines (μK_{CMB} $s^{1/2}$)	858	697	773	866
Knee frequency f_k in polarization (mHz)	254	198	223	556
$1/f$ slope in polarization	1.95	1.86	1.73	1.34
Overall calibration uncertainty I (per cent)	5	5	5	5
Overall calibration uncertainty Q, U (per cent)	5	5	6	6

[a]The ellipticity is defined here as $e = 1 - FWHM_{min}/FWHM_{max}$.

(Rubiño-Martin et al. 2023)

*** New Physical Probes of the Early Universe.**

How did the Universe begin? How did the first cosmic structures and black holes form and evolve? These are outstanding questions in fundamental physics and astrophysics, and we now have new astronomical messengers that can address them. Our recommendation is for a Large mission deploying gravitational wave detectors or precision microwave spectrometers to explore the early Universe at large redshifts. This theme follows the breakthrough science from Planck and the expected scientific return from LISA. [Executive summary, page iii].

2.3.4 Recommendation

The Senior Committee recommend that ESA should develop a Large mission capable of deploying new instrumental techniques such as gravitational wave detectors or precision microwave spectrometers to explore the early Universe (say $z > 8$). Such a mission would shed light on outstanding questions in fundamental physics and astrophysics, such as how inflation occurred and the Universe became hot and then transparent, how the initial cosmic structures grew, how the first black holes formed and how supermassive black holes came to exist less than a billion years after the Big Bang. [page 18].