Low-Frequency Foregrounds

Main Research Topics, Key Goals, Experiments and Perspectives

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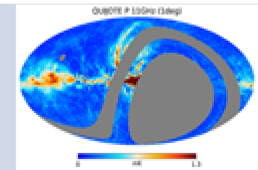
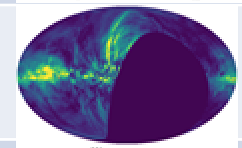
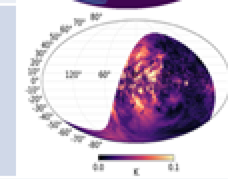
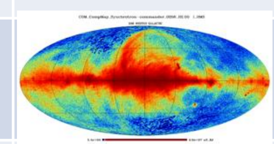
1.Basic Properties of Galactic Emission Mechanisms (1–90 GHz)

Emission Type	Frequency Peak	Spectral Index (Iν)	Polarization	Origin
Synchrotron	<10 GHz	$\beta \approx -2.7$ to -3.2	10–40%	Relativistic electrons in magnetic fields
Free-Free	Rather Flat across 1–100 GHz	$\beta \approx -2.1$	≈ 0%	Electron-ion scattering in ionized gas
Anomalous Microwave Emission (AME)	20–40 GHz	β varies	<1%	Spinning dust grains (e.g., PAHs)

2. Polarization Experiments with Low Freq. Bands

(active in the decade 2020-30)

Name	Freq Range (GHz)	Type	Key Focus	Freq Range (MHz)
QUIJOTE	10-40 (+ 90)	Northern sky survey, polarization	Synchrotron, AME, CMB foregrounds	
C-BASS	5	All-sky survey, polarization	Synchrotron template for CMB cleaning	
S-PASS	2.3	Southern sky survey	Galactic magnetic field and synchrotron polarization	
LOFAR	nan	Low-frequency array	Faraday rotation, ISM structure	30-240
Planck	30-857	CMB satellite	All-sky polarization, dust and synchrotron	
LSPE / STRIP	43,90	North sky survey (+ future south)	Focused on synchrotron foregrounds	
SKA	nan	Next-gen radio array (southern sky)	Galactic magnetism, polarization tomography	50-1500

Polarization Experiments with low Freq. Bands (cont.)

Experiment	Freq. Range (GHz)	Location	Key Focus
SPTpol / SPT-3G	90, 150, 220	South Pole	High-resolution, B-mode cosmology
CLASS	40, 90, 150, 220	Atacama, Chile	Large-scale polarization
QUBIC	150 (90 future)	Salta, Argentina	Bolometric interferometry
BICEP / Keck / BICEP Array	30–270	South Pole	Multiband, precision B-mode search
AdvACT	28.4, 90, 150, 220,277	Atacama, Chile	Multiband precisión B-mode search
Simons Obs.	27,39,93,145,225, 280	Atacama, Chile	Multiband precisión B-mode search
LiteBIRD	40–400	Future CMB satellite @ L2	Primordial B-modes, precise foreground subtraction

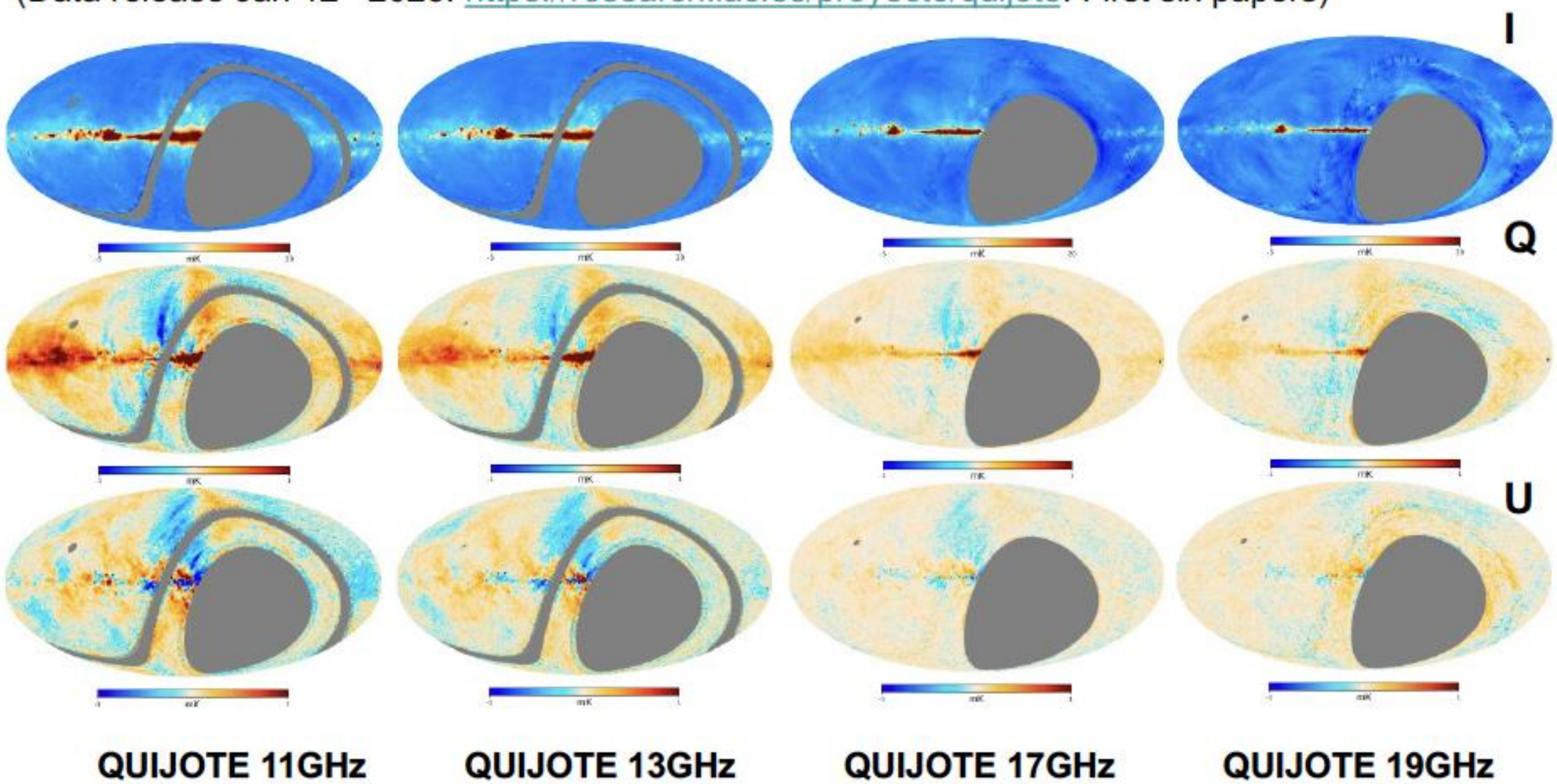
Data example

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

Smoothed 1 deg maps

(Rubino-Martin et al. 2023)

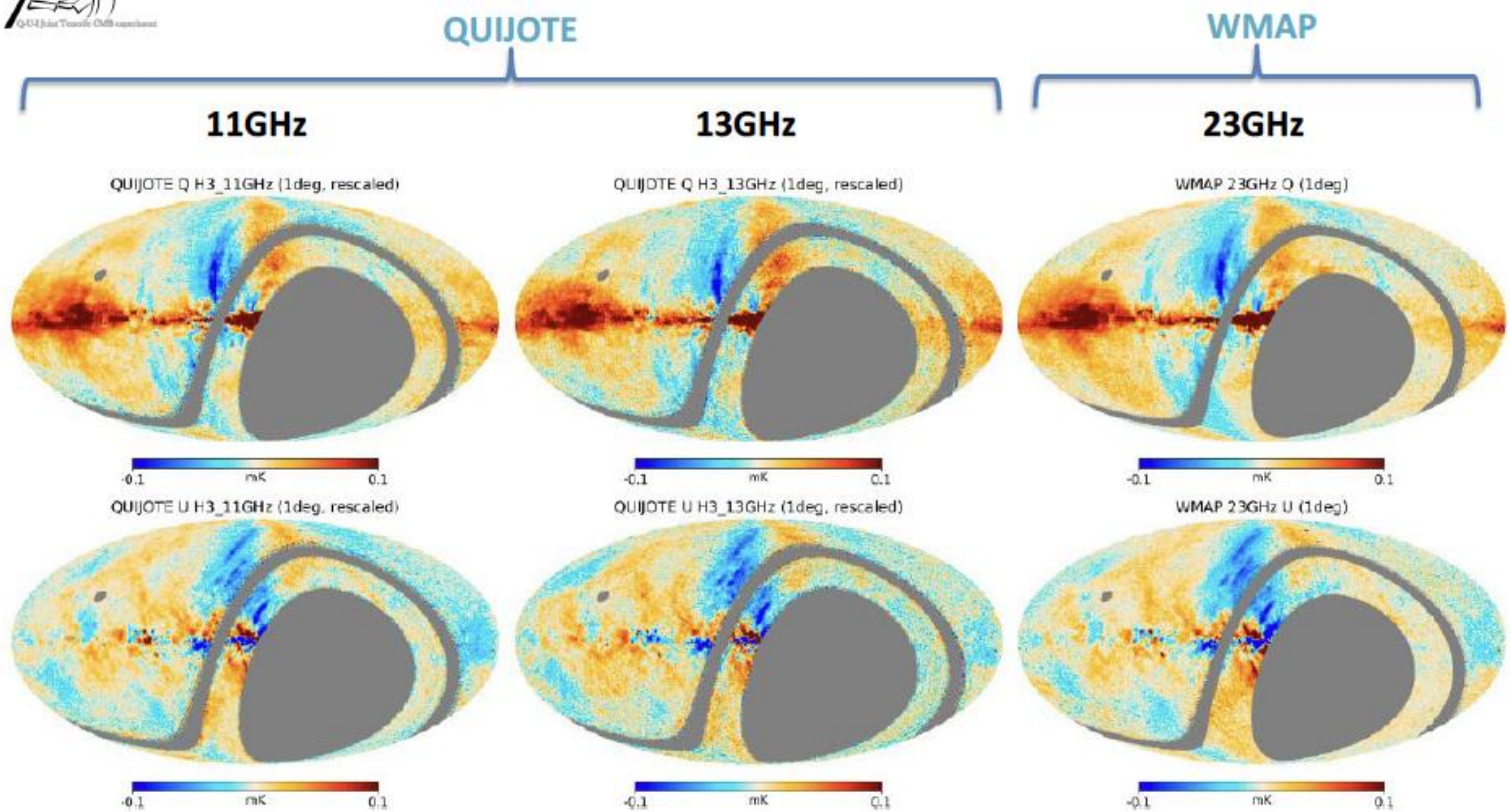
(Data release Jan 12th 2023: https://research.iac.es/proyecto/quijote. First six papers)



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.

QUIJOTE vs. WMAP

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



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)

3. Characterization of Galactic Synchrotron Emission

- Key Goals :
  - • Measure polarization fraction, spectral index, and angular power spectrum.
  - • Understand spatial variations in synchrotron spectral index.
  - • Study frequency dependence of polarization angle and depolarization.

3.1 Synchrotron Spectral Index and Polarization Fraction

Region	Spectral Index (β)	Freq Range (GHz)	Reference	Polarization Fraction (%)
High Galactic latitudes	-3.0 ± 0.1	0.4–30	Kogut et al. (2007), ApJ, 665, 355	10–20
North Galactic Spur	-2.8 ± 0.1	1–23	Gold et al. (2011), ApJS, 192, 15	20–30
Galactic plane (|b|<5°)	-2.7 ± 0.1	0.4–2.3	Carretti et al. (2019), MNRAS, 489, 2330	10–15
Full sky (Planck Commander)	-3.1 ± 0.1	30–70	Planck Collaboration (2016), A&A, 594, A10	10–20
Fan Region	-2.9 ± 0.1	0.6–2.3	Bernardi et al. (2009), A&A, 500, 965	30–40
Northern sky (QUIJOTE Wide Survey)	-2.90± 0.20 -3.09 ± 0.13	11–19	Rubiño-Martín et al. (2023), MNRAS, 518, 4355	10–25

3.2 Average Angular Power Spectrum of Galactic Synchrotron Emission

Multipole Range (ℓ)	Cl ∝	Reference
1–10	ℓ^(-2.5)	Wolleben et al. (2006), A&A, 448, 411
10–100	ℓ^(-2.8)	La Porta et al. (2008), A&A, 479, 641
100–300	ℓ^(-3.0)	Gold et al. (2011), ApJS, 192, 15
300–600	ℓ^(-3.1)	Carretti et al. (2010), MNRAS, 405, 1670
600–1000	ℓ^(-3.3)	Planck Collaboration (2016), A&A, 594, A10

3.3 EE and BB Modes in Galactic Polarized Synchrotron Emission

- The angular power spectra of Galactic synchrotron polarization can be decomposed into:
  - EE modes: associated with ordered magnetic fields, symmetric patterns.
  - BB modes: associated with turbulent magnetic structures, asymmetric patterns.

- These components are critical foregrounds for CMB B-mode studies.
- Martire et al. (2022) present one of the most complete analyses of the angular power spectrum of polarized Galactic synchrotron emission using Planck and WMAP data.

  Main results:
  - EE and BB angular spectra follow power laws: $\alpha\_EE = -2.95 \pm 0.04$, $\alpha\_BB = -2.85 \pm 0.14$ for $30 \leq \ell \leq 300$
  - B/E power ratio ≈ 0.22 ± 0.02 (B-modes are subdominant)
  - EB cross-correlation: compatible with 0, with <1.2% limit relative to EE at 2σ
  - Frequency spectral indices: $\beta\_EE = -3.00 \pm 0.10$, $\beta\_BB = -3.05 \pm 0.36$

- Reference: Martire et al. (2022), A&A 660, A87 – https://arxiv.org/abs/2203.06724

3.3 EE/BB Power Spectrum Measurements in Synchrotron Studies

Study	ℓ Range	α_EE	α_BB	BB/EE	Freq (GHz)
Martire et al. (2022)	30–300	-2.95 ± 0.04	-2.85 ± 0.14	0.22 ± 0.02	23–30
Planck Collaboration (2016)	10–600	-2.9±0.1	-2.9±0.1	0.35	30
Rubiño et al. (2023)	10-100	-2.96±0.29	-3.12±0.89	0.26 ± 0.07	11–19

3.3 Statistical Properties of Polarized Synchrotron

- Key Goals:
  - • Analyze E/B asymmetry to distinguish foregrounds from B-modes.
  - • Study non-Gaussianity and coherence of polarization patterns.
  - • Use simulations to test B-mode recovery pipelines.

3.4 Frequency Dependence of Synchrotron Polarization Angle

- The polarization angle of Galactic synchrotron emission changes with frequency due to Faraday rotation:

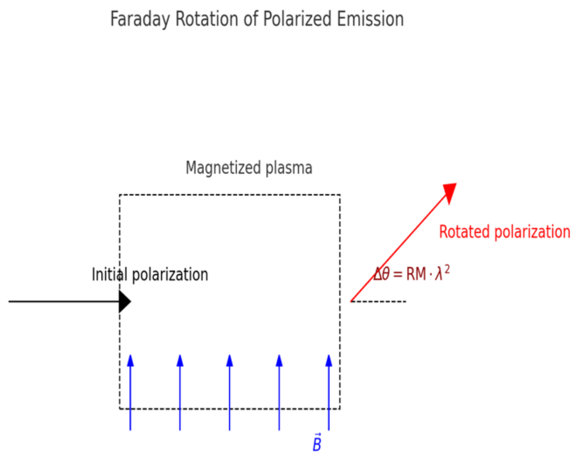
- • Faraday Rotation Law:
- $\theta(\lambda) = \theta_0 + RM \times \lambda^2$
- - θ: observed polarization angle
- - λ: wavelength
- - RM: Rotation Measure, sensitive to electron density and line-of-sight magnetic field

- • Effects:
- - Strong at low frequencies (MHz–GHz): causes depolarization
- - Negligible at high frequencies (>30 GHz): intrinsic polarization angle recovered

- • Applications:
- - Mapping Galactic magnetic fields
- - Faraday tomography (e.g. RM synthesis)
- - Foreground characterization for CMB B-mode detection

- References:

- • Brentjens & de Bruyn (2005), A&A 441, 1217
- • Jelić et al. (2015), A&A 583, A137
- • Planck Collab. XLII (2016), A&A 596, A103



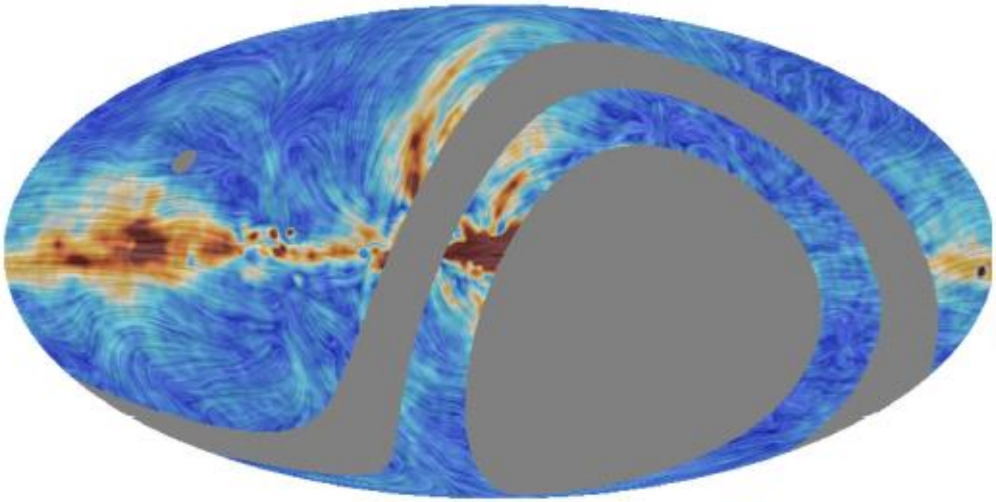
4. Magnetic Field Structure of the Milky Way

- Key Goals:
  - • Model the 3D structure of large-scale and turbulent magnetic fields.
  - • Use Faraday rotation maps to constrain magnetic field coherence.
  - • Correlate radio surveys with synchrotron polarization data.

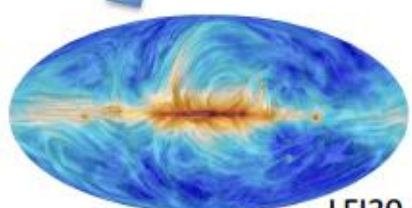
Wide survey with the QUIJOTE MFI (10-20GHz)

Synchrotron and Galactic magnetic field

MFI 11GHz - LIC

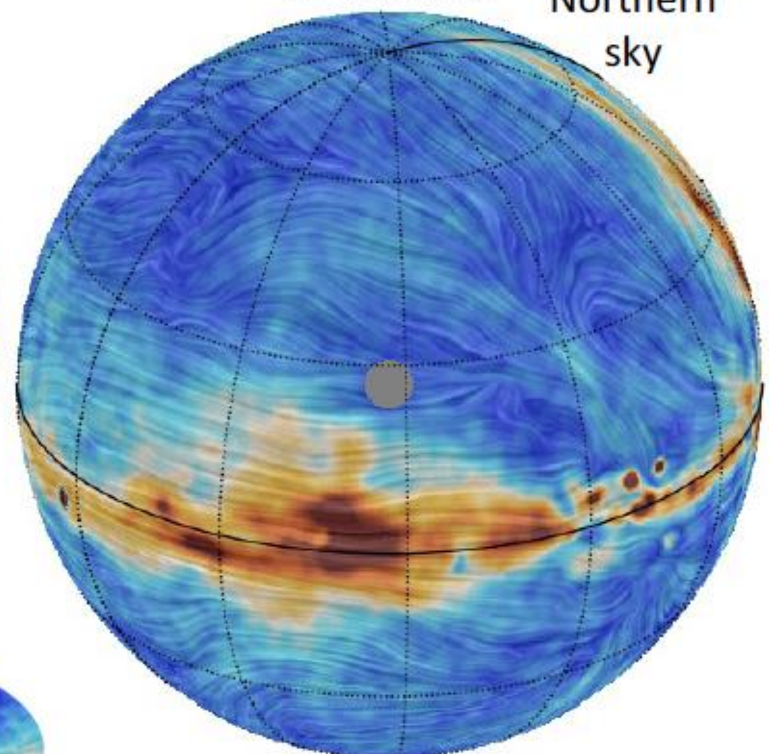


$$P = \sqrt{Q^2 + U^2}$$



LFI30

MFI 11GHz - LIC



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)

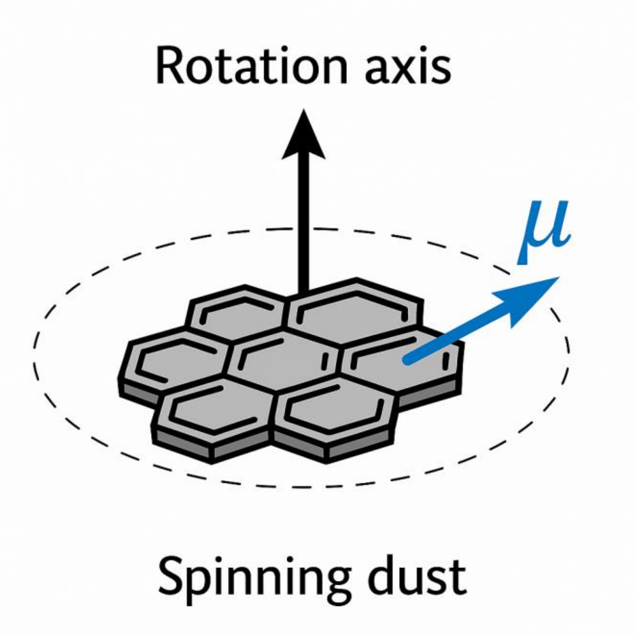
5. Anomalous Microwave Emission

- Spinning dust emission is attributed to electric dipole radiation from small, rapidly rotating dust grains, such as PAHs (polycyclic aromatic hydrocarbons), in the interstellar medium.

- 1. Power Radiated by a Rotating Electric Dipole:
- $P(\nu) \propto \mu^2 \nu^2 f(\nu)$
- - μ: electric dipole moment of the grain
- - ν: rotational frequency
- - $f(\nu)$: distribution function of rotation rates

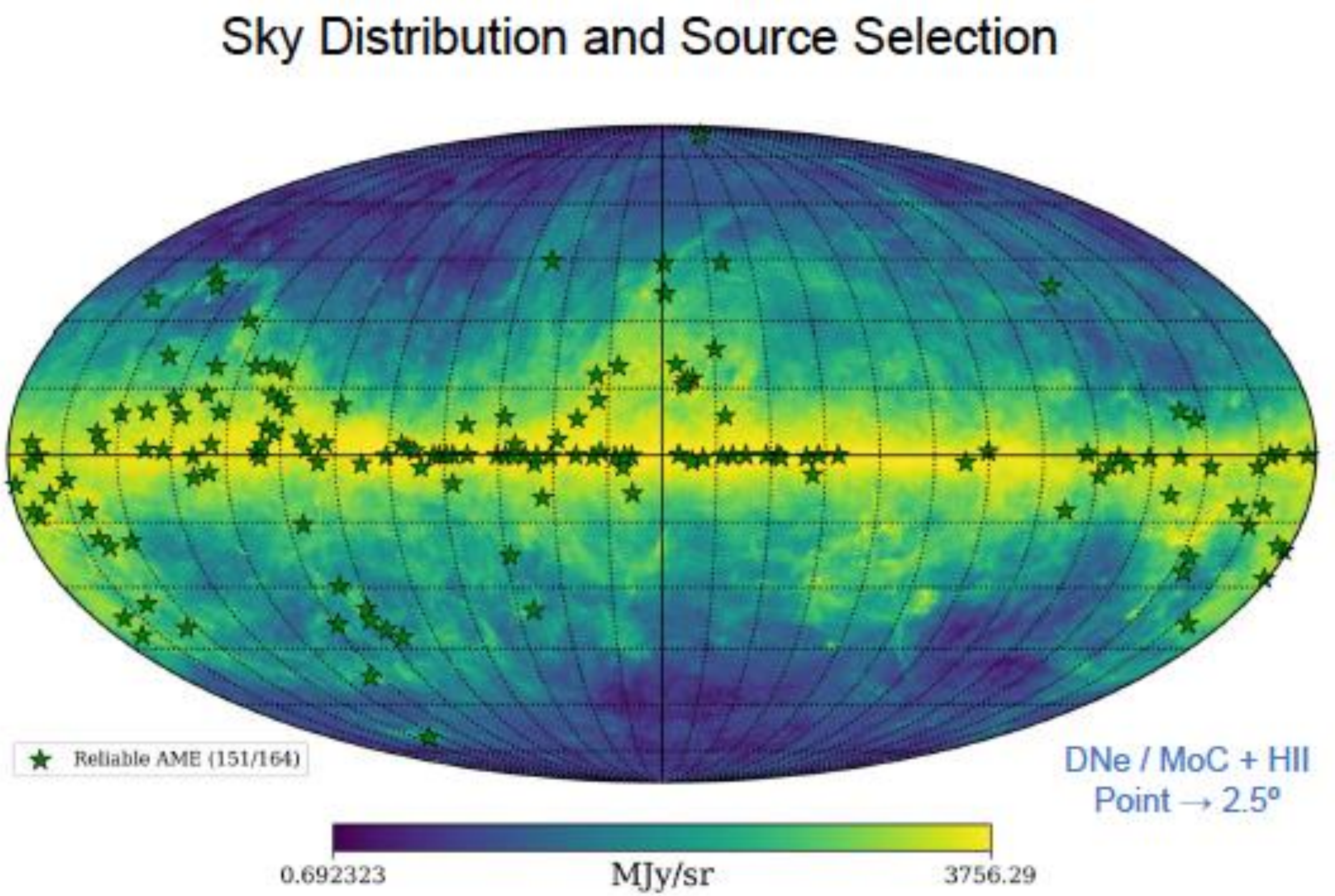
- 2. Grain Rotation Rate Distribution:
- $f(\nu) \propto \exp[-(\nu - \nu_0)^2 / 2\sigma^2]$
- - ν_0: peak rotation rate
- - σ: dispersion due to gas-grain interactions

- 3. Emissivity (per H atom):
- $j(\nu) = \int n(a) P(\nu, a) da$
- - $n(a)$: size distribution of dust grains
- - $P(\nu, a)$: power emitted by grain of size a



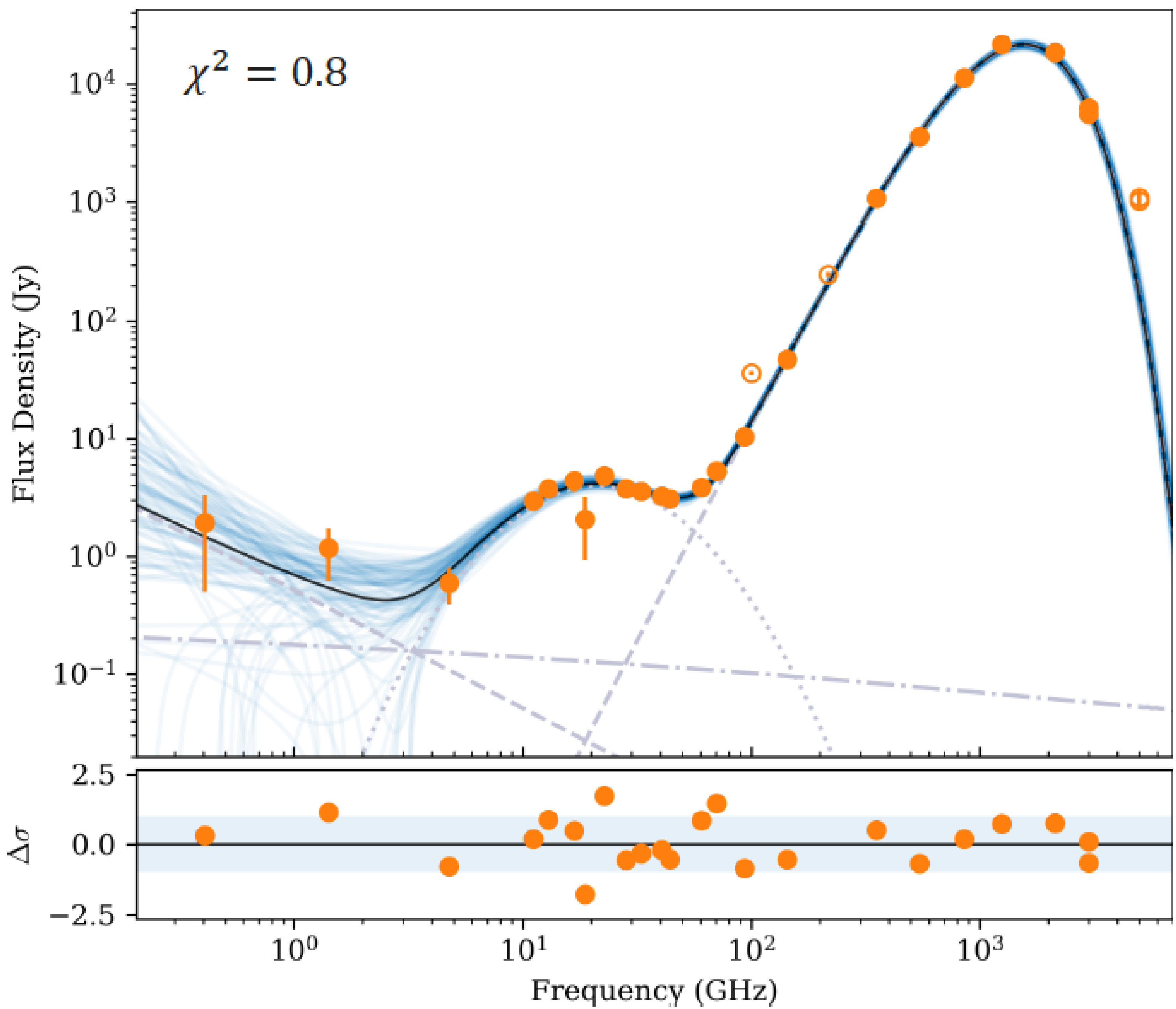
- References:
- • Draine & Lazarian (1998), ApJ, 508, 157
- • Ali-Haïmoud et al. (2009), MNRAS, 395, 1055

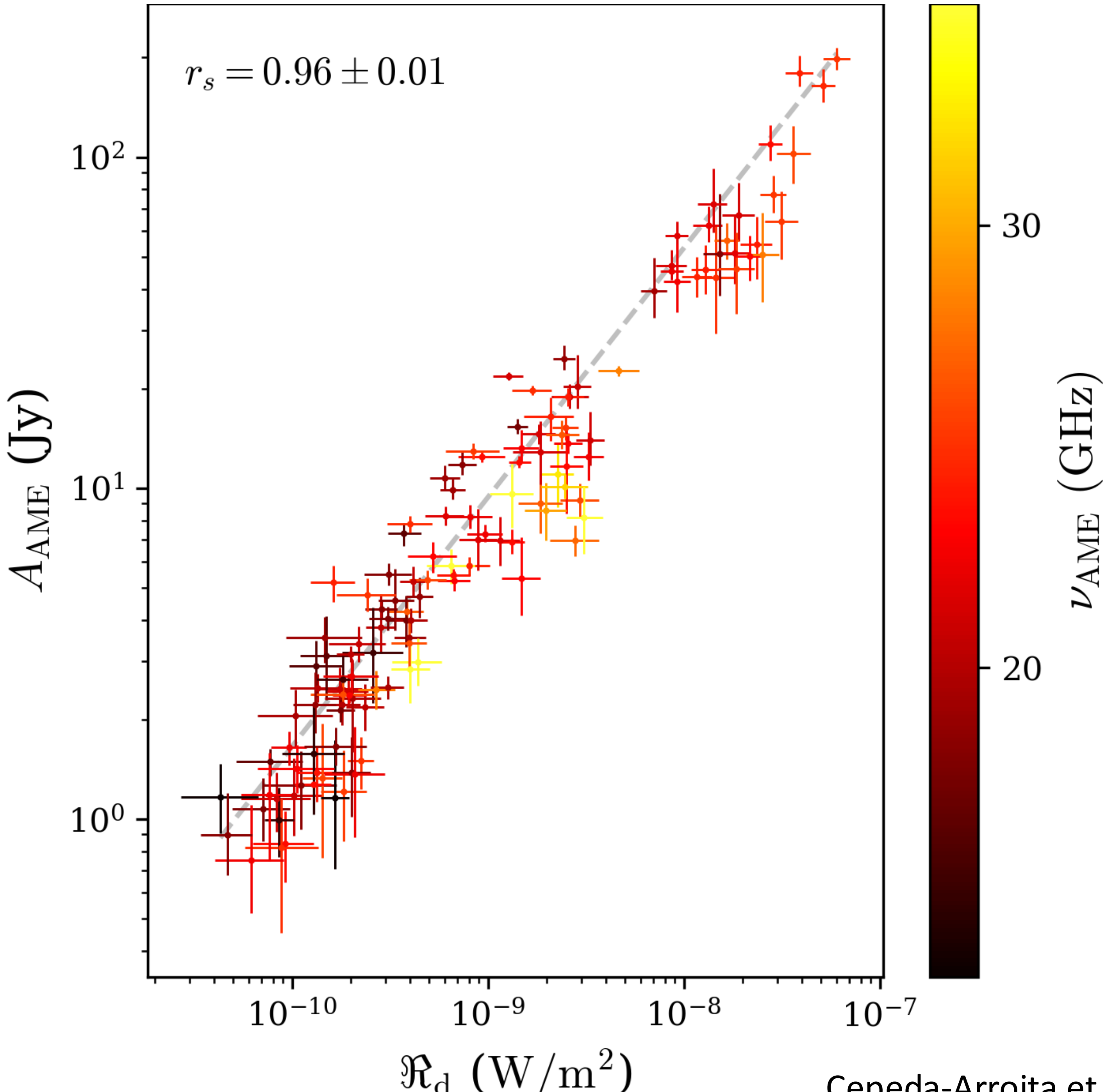
Anomalous Microwave Emission



Cepeda-Arroita et al. Iin preparation)

Typical High Latitude Source: *G159.02-33.88*



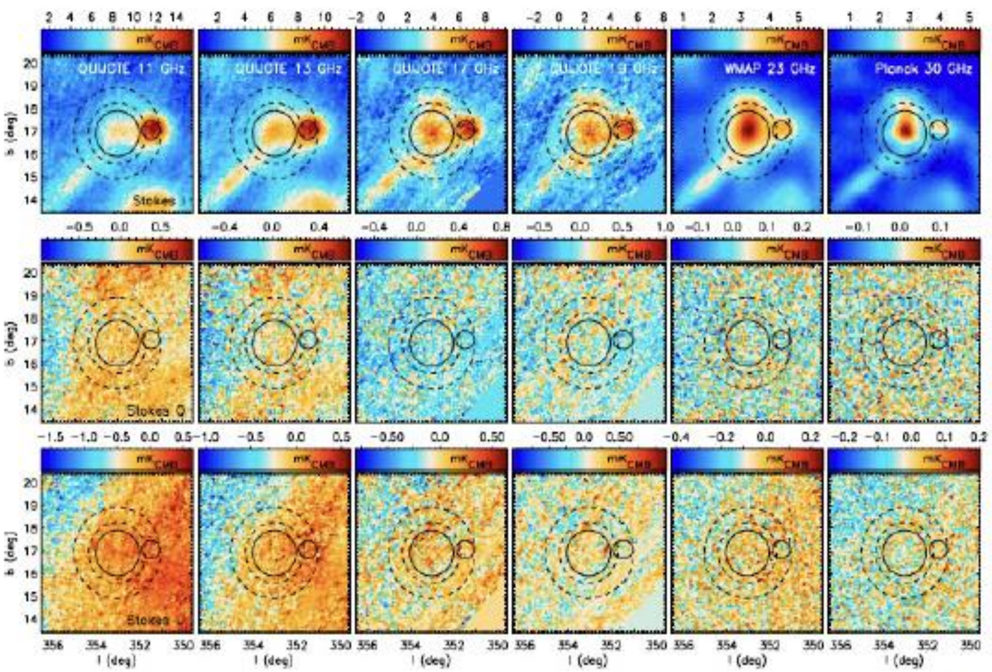


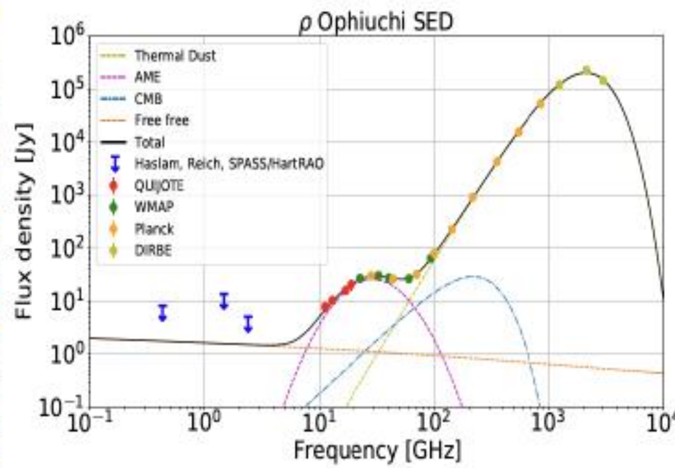
Cepeda-Arroita et al.

5.1 Polarization Measurements of Anomalous Microwave Emission (AME)

Region	Freq (GHz)	Polarization (%)	Reference
Perseus (COSMOSOMAS)	11–17	<1.0	Battistelli et al. (2006), ApJ, 645, L141
Perseus (QUIJOTE)	11–19	<0.22	Génova-Santos et al. (2015), MNRAS, 452, 4169
Taurus (QUIJOTE)	11–19	<0.39	Poidevin et al. (2019), MNRAS, 487, 1729
Rho Ophiuchi (Planck)	30	<1.6	Planck Collaboration (2016), A&A, 594, A10
W43 (QUIJOTE)	11–19	<0.09	Génova-Santos et al. (2017), MNRAS, 464, 4107

Upper limits on the polarization of the Anomalous Microwave Emission in rho Oph p<0.28%





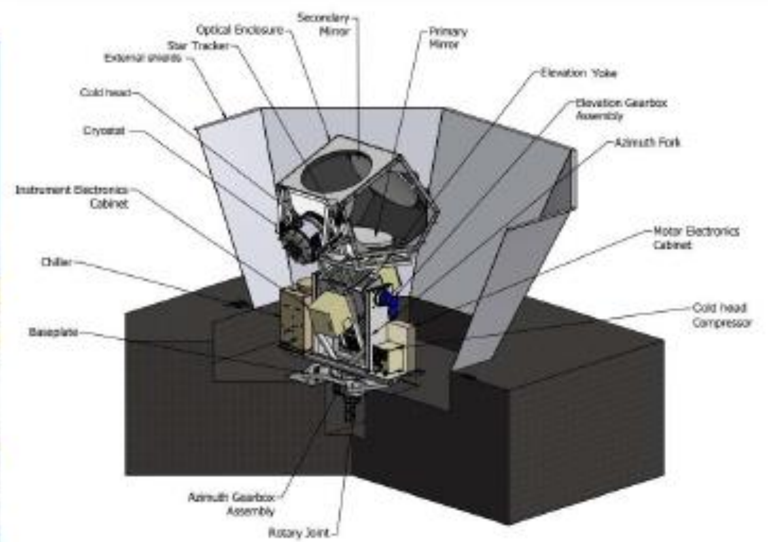
Gonzalez-Gonzalez et al. 2025 Astron. Astrophys 695, 245

5.2 Anomalous Microwave Emission (AME)

- Key Goals:
  - • Quantify the polarization fraction of AME.
  - • Separate AME from synchrotron and thermal dust in multifrequency data.
  - • Evaluate AME contamination for CMB B-mode searches.

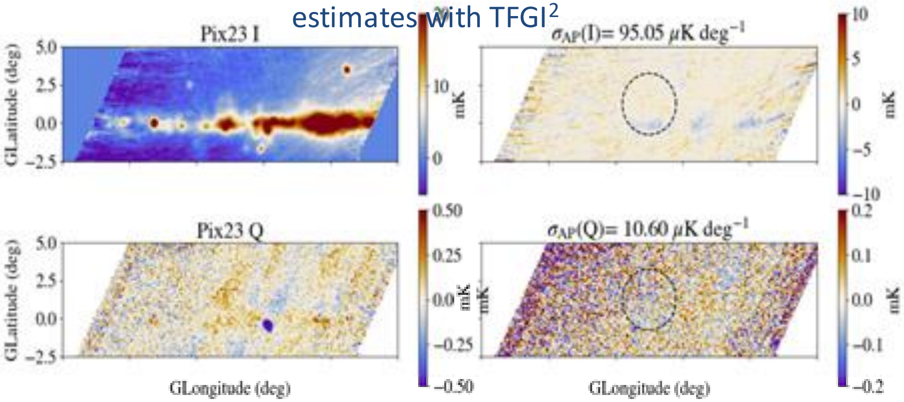
6. New developments: QUIJOTE and STRIP telescopes at Teide Observatory (10-90 GHz)

QUIJOTE Telescopes

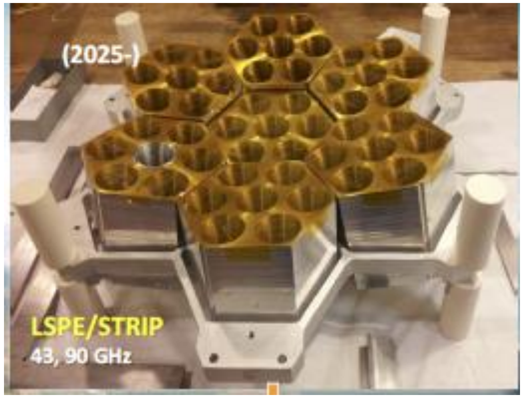


Render for STRIP (Paonessa et al. 2025, JINST subm)

Observations of Galactic regions + sensitivity estimates with TFGI[2]



Sensitivity Goal:
1 μK/deg
In sky area
3000 sq. deg

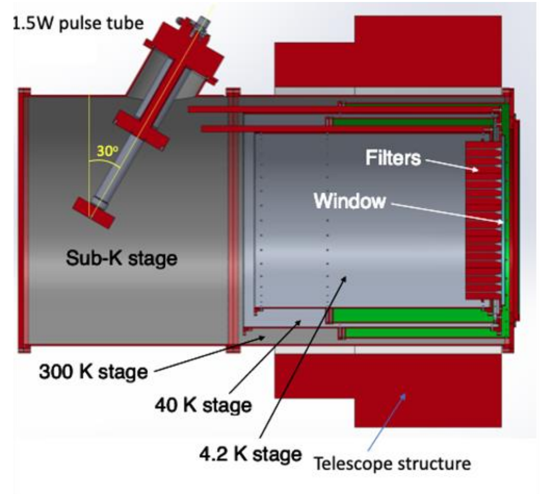


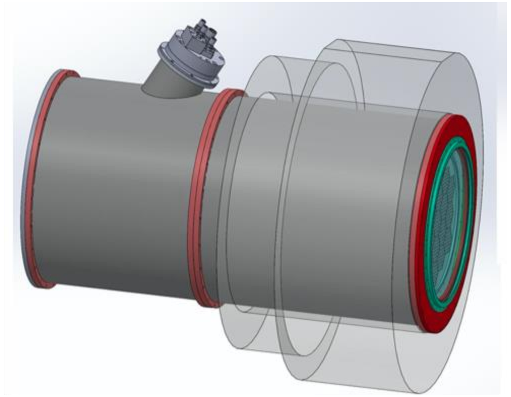
equivalent 2 μK.arcmin @ 100 GHz with β = -3

Experimental Perspectives 10-90 GHz Teide Obs.
QUIJOTE: MFI, TFGI, NGI+ STRIP 40 GHz

Ninety-GHz instrument (NGI)

- 90-GHz instrument for the QUIJOTE telescope 2
- Scientific collaboration: two QUIJOTE nodes (IAC, IFCA) and University of Rome La Sapienza and Univ. Tokyo
- Baseline design based on MISTRAL@SRT (Paiella et al. 2022)
  - Cryostat: pulse-tube refrigerator combined with an absorption refrigerator to reach a final temperature of 150 mK
  - Polarization modulation unit: ∅ 60-cm HWP coupled to a rotation unit based on magnetic levitation
  - Detectors: 350 KIDs with dual polarization at 150 mK
- Scientific goals:
  - Survey of 3,000 deg^2 down to a sensitivity of 6 μK·arcmin
  - Survey of synchrotron regions to sensitivity of 2 μK·arcmin
  - Comparable sensitivity to synchrotron to the QUIJOTE/MFI2 (10-20 GHz) and the TFGI (30-40 GHz)
  - Constrain the frequency dependence of the spectral index of polarized synchrotron
- Status:
  - Conceptual design finished
  - Call for tender for the detailed design and fabrication of the cryostat and cold structure to be opened in June/July





Conclusions

- Need to provide **the best possible characterization of the physical properties of the polarized emissions in the 5-90 GHz range**
- Establish the statistical Properties of Polarized Synchrotron and the Magnetic Field of our Galaxy
- Understand the physics of the Anomalous Microwave Emission in different environments and angular scales and determine its polarization properties
- The coming years will also focus on improving statistical models, integrating cross-tracer data, and supporting upcoming missions like LiteBIRD, Simons Observatory and CMB-S4.

Thanks