Measuring the polarization of the CMB with QUIJOTE and LiteBIRD

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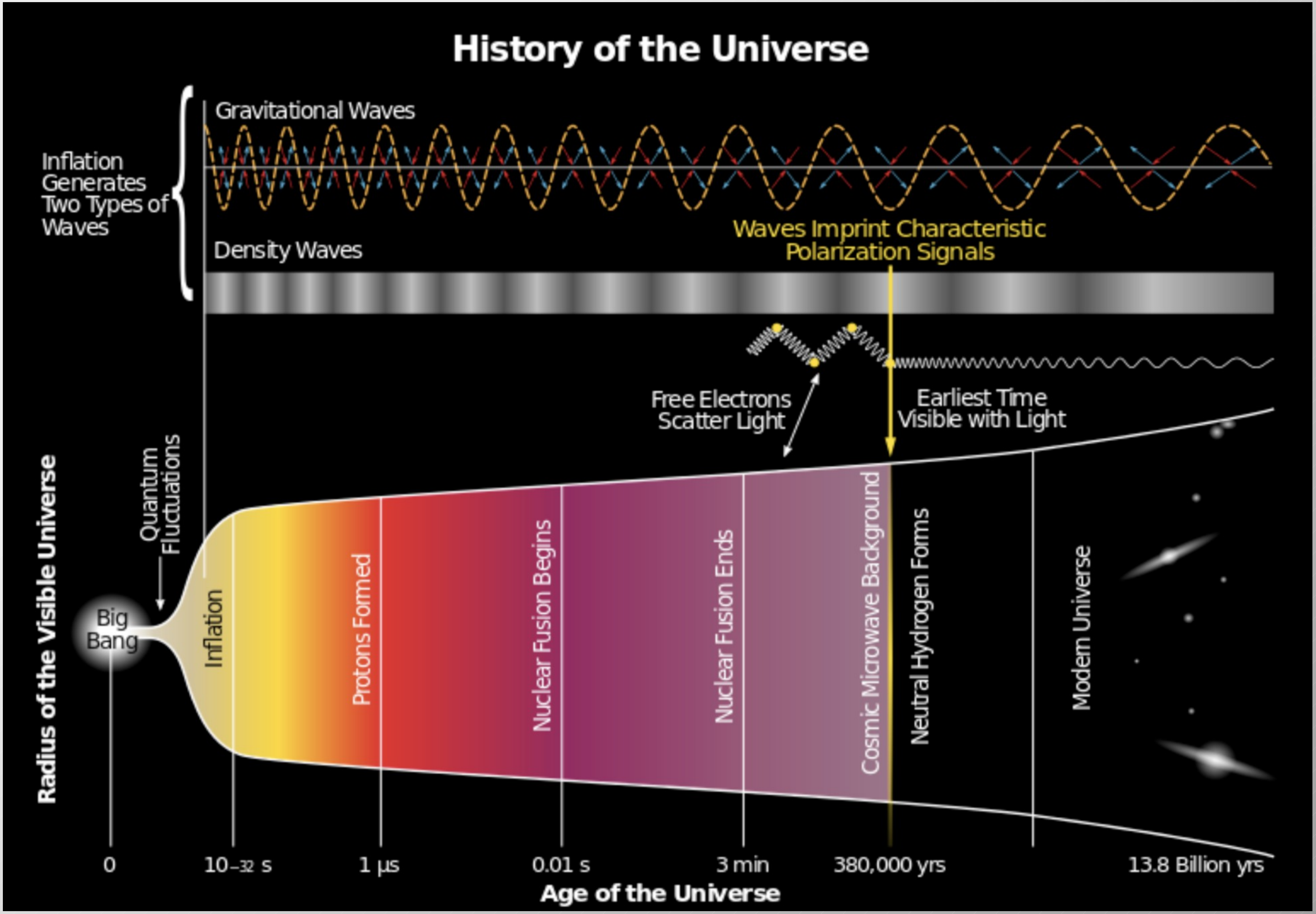
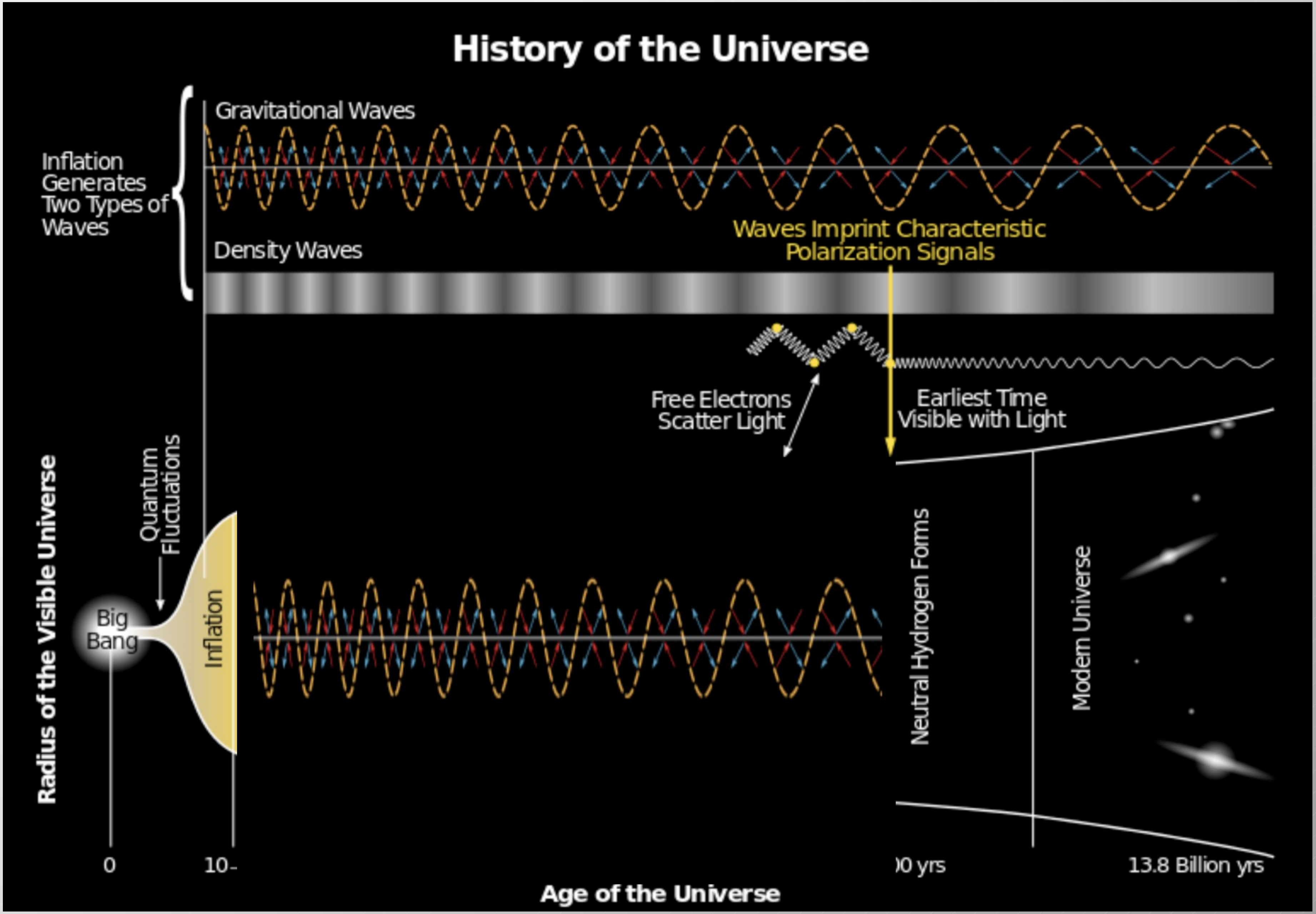
XXXIII - Canary Island Winter School - 2022

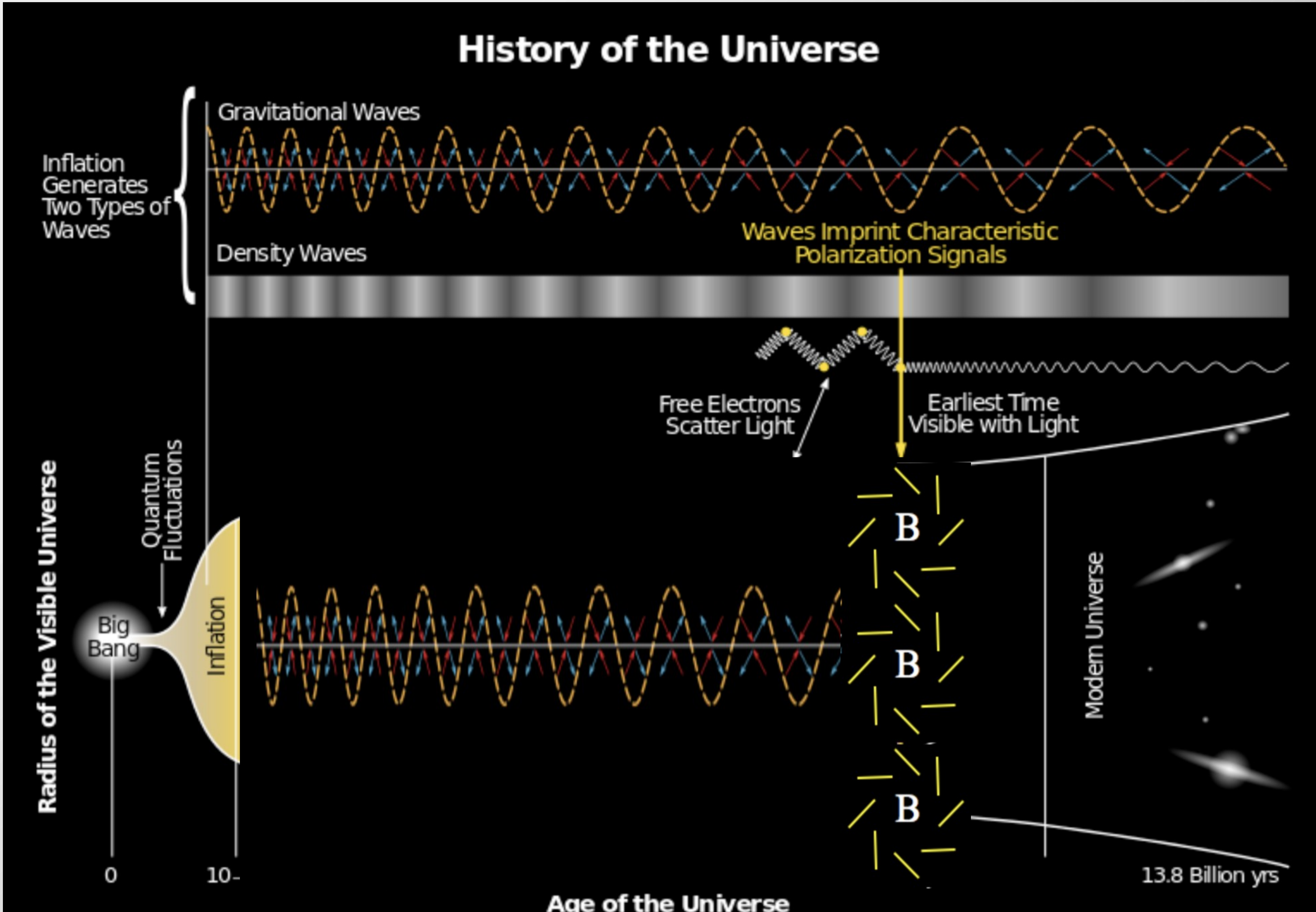
Big Bang and Inflation



Big Bang and Inflation

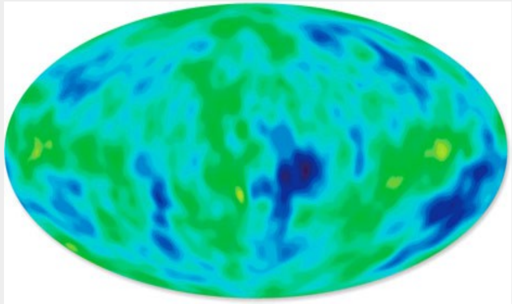


Big Bang and Inflation

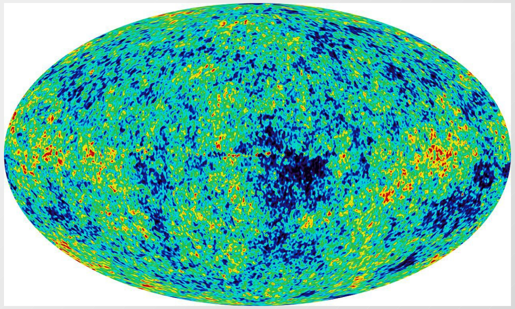


Past and future space missions

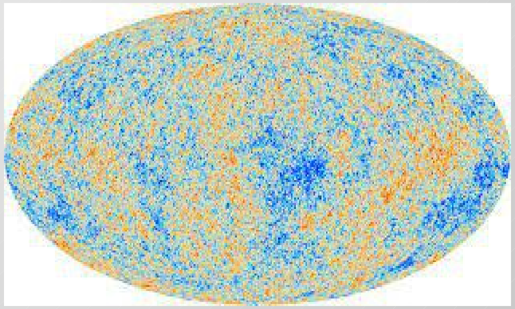
COBE 1989-1993

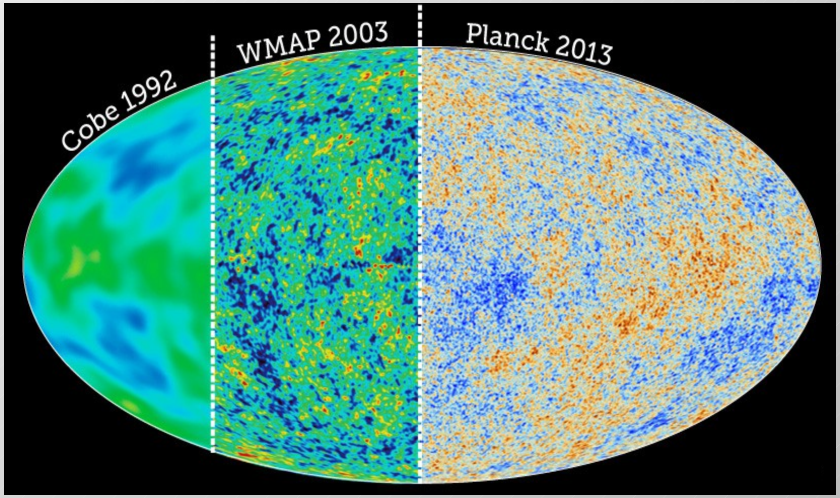


WMAP 2001 - 2010

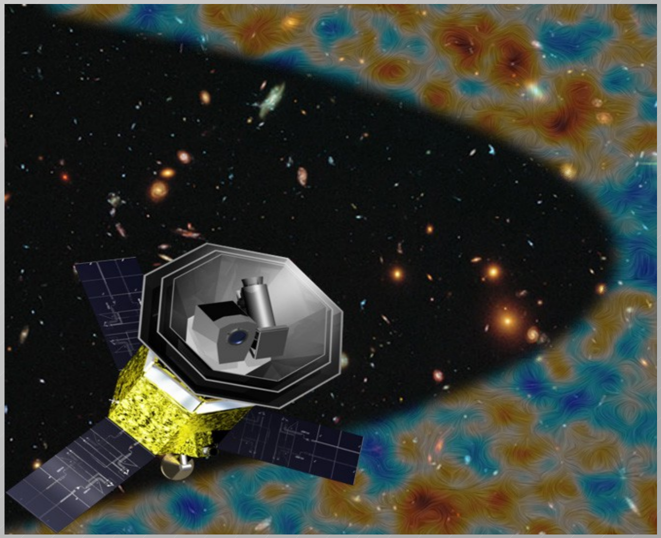


Planck 2009 - 2013





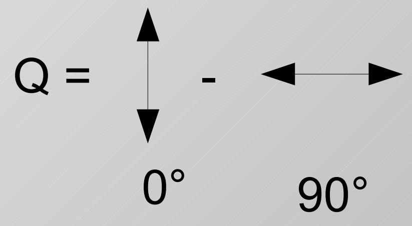
Future space mission: LiteBIRD (JAXA-2029)

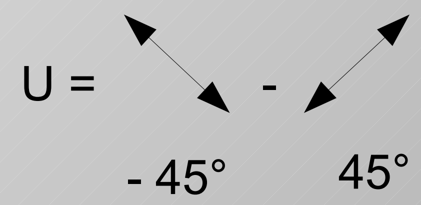


Stokes parameters, E-modes and B-modes

Stokes parameters

- We can measure the polarization of the CMB the same way as for light
- The Stokes parameters quantify polarization of a light ray:
  - I = no filter at all
  - Q = linear polarized at 0° and 90°
  - U = linear polarized at -45° and 45°
  - V = circular polaraized
- I is just the temperature.
- Q and U combine to form E-modes and B-modes.
- No known physical process can generate V-polarised CMB radiation.





Linear combination of Q and U invariant under rotation as a spin-2 quantity

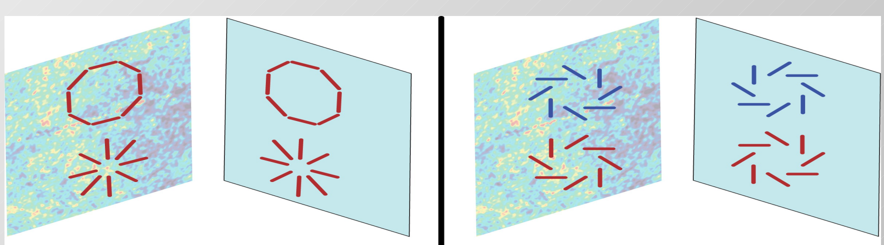
$$Q'\pm iU' = e^{\pm 2i\psi}(Q\pm iU)$$

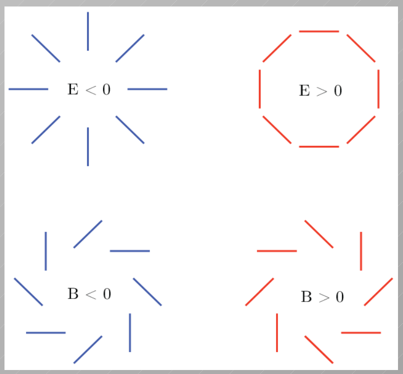
Spin-2 armonic decomposition on the sky:

$$Q'\pm iU'(\vec{n}) = \sum_{l=2}^{\infty}\sum_{m=-l}^{+l} a_{lm}^{\pm 2}\,{}_{\pm 2}Y_{lm}(\vec{n})$$

E-modes and B-modes

$$\sum_{l=2}^{\infty}\sum_{m=-l}^{+l} a_{lm}^{\pm 2}\,{}_{\pm 2}Y_{lm}(\vec{n}) = \sum_{l=2}^{\infty}\sum_{m=-l}^{+l} (a_{E,lm}+ia_{B,lm})\,{}_{\pm 2}Y_{lm}(\vec{n})$$





$$a_{E,lm} = \frac{1}{2}(a_{lm}^{+2}+a_{lm}^{-2})$$

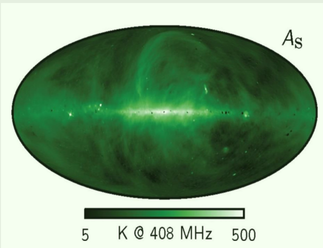
Invariant under parity trasformation

$$a_{B,lm} = \frac{-i}{2}(a_{lm}^{+2}-a_{lm}^{-2})$$

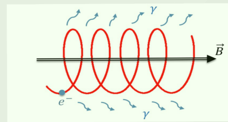
NOT invariant under parity trasformation

Foregrounds

SYNCHROTRON

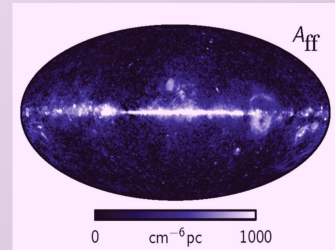


Cosmic ray electrons emits photos spiralizing around the galactic magnetic field (B).

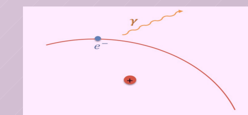


$$S_{sync} = A_{sync} \left(\frac{\nu}{\nu_0} \right)^{\beta_s}$$

FREE-FREE

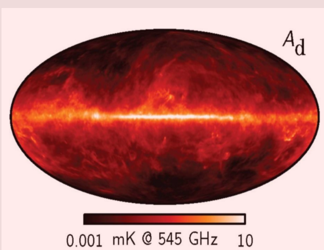


Thermal electron – ion interaction in the instersllar plasma (thermal bremmstrahlung)



$$S_{ff} = \frac{2 K_B \nu^2}{c^2} \Omega T_{ff}$$

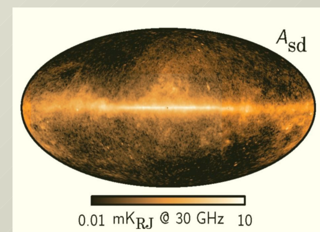
THERMAL DUST



Interstellar dust grains absorb the interstellar radiation and are heated up. In the cooling process it emits radiation

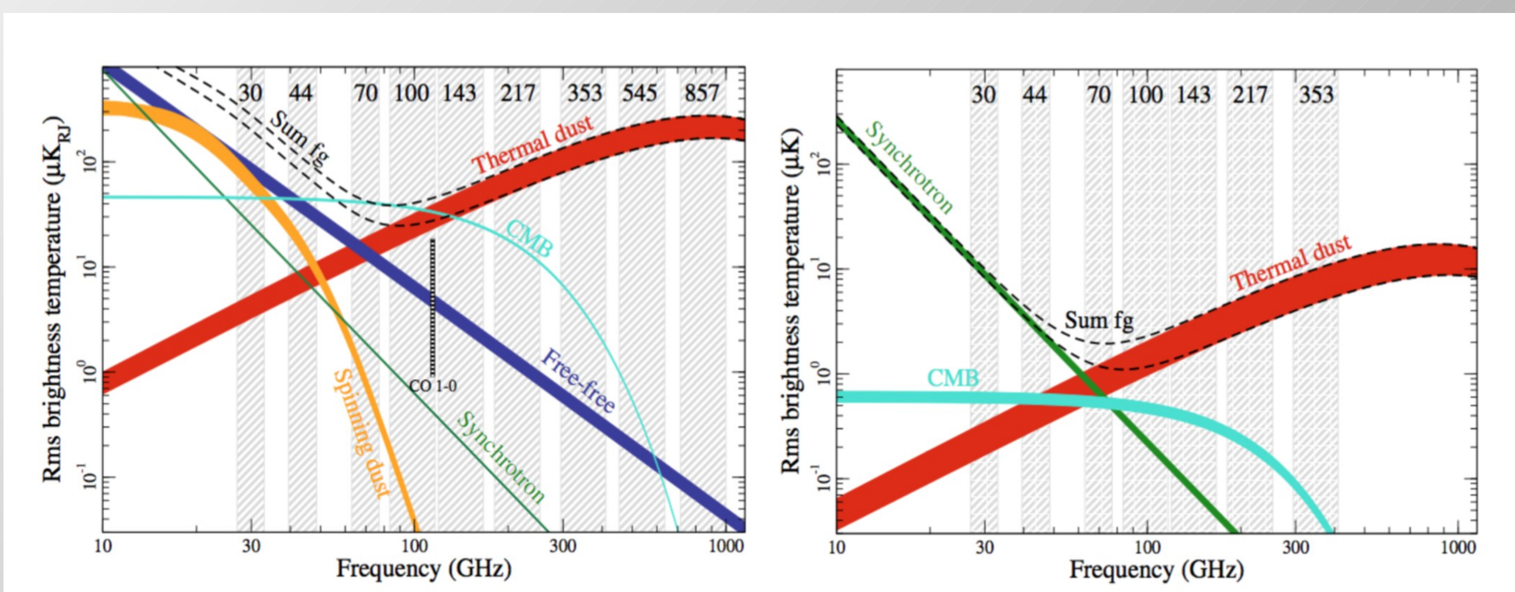
$$S_{TD} = \tau_{\nu 0} \left(\frac{\nu}{\nu_0} \right)^{\beta_d} B_\nu(T_d)$$

ANOMALOUS MICROWAVE EMISSION



Radiation produced (most propably) by spinning small dust grains with an electric dipole moment

$$S_{AME} = A_{AME} \exp\left[\frac{-1}{2 W_{AME}^2} \ln^2 \left(\frac{\nu}{\nu_{AME}} \right) \right]$$



Foregrounds vs. B-modes

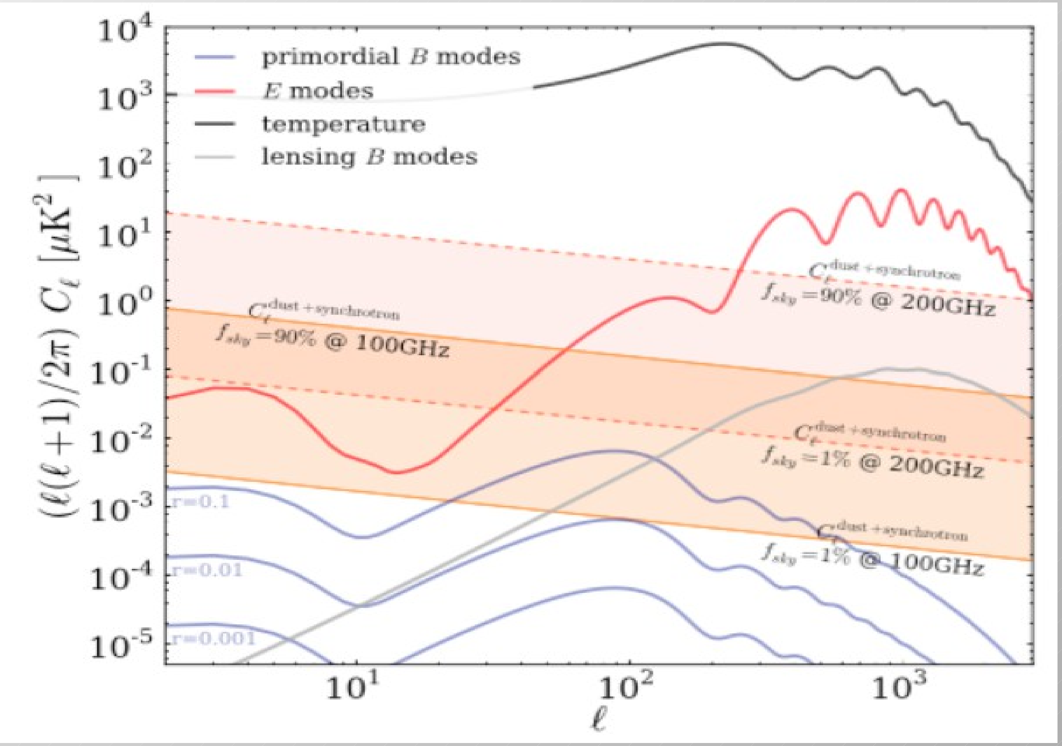
Foregrounds. B-mode signal is subdominant over Galactic foregrounds

Tensor to scalar ratio

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

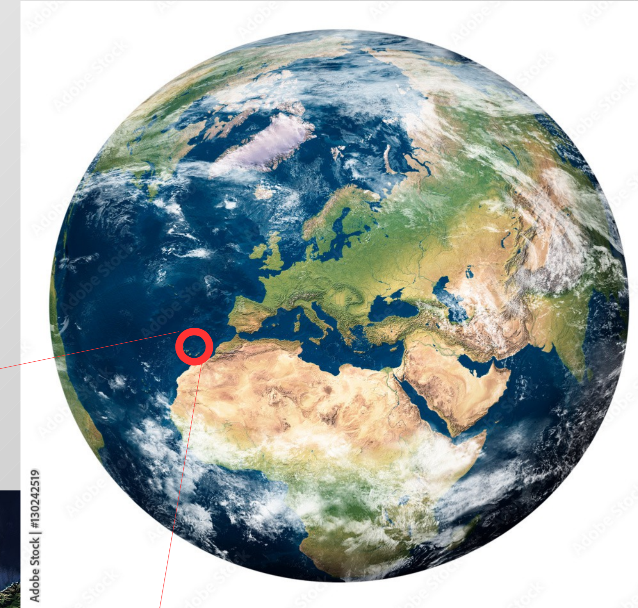
Upper limit at the moment

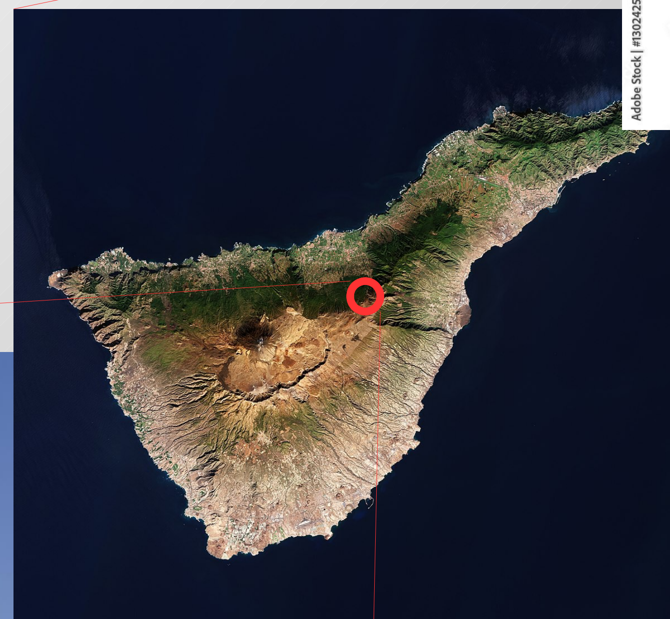
r < 0.032

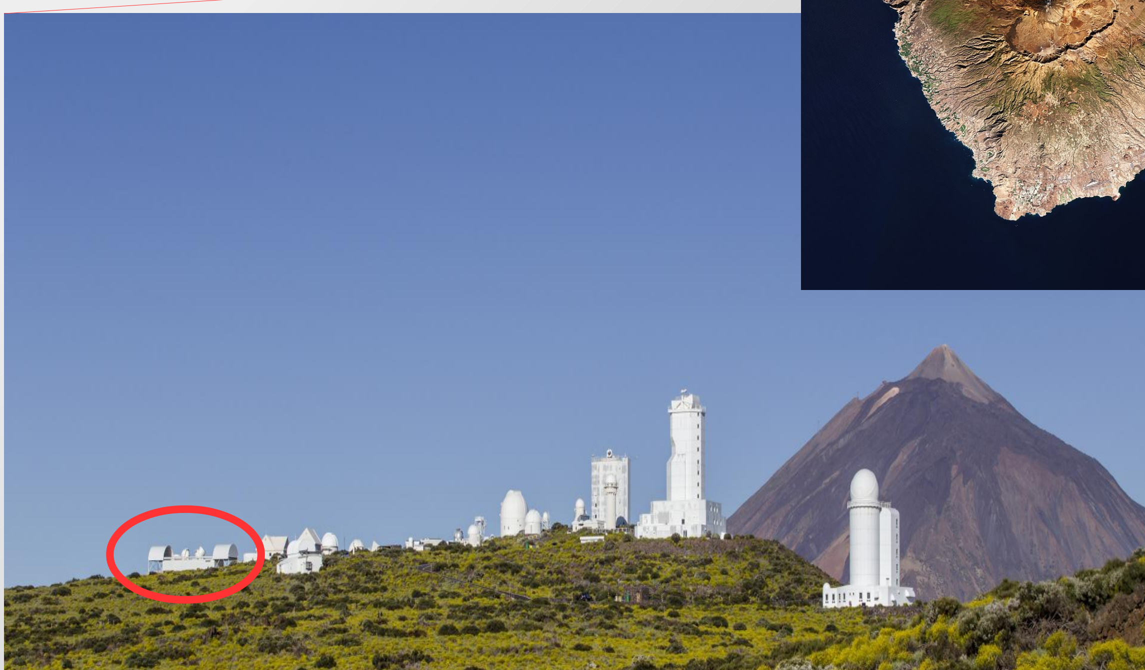


Teide observatory

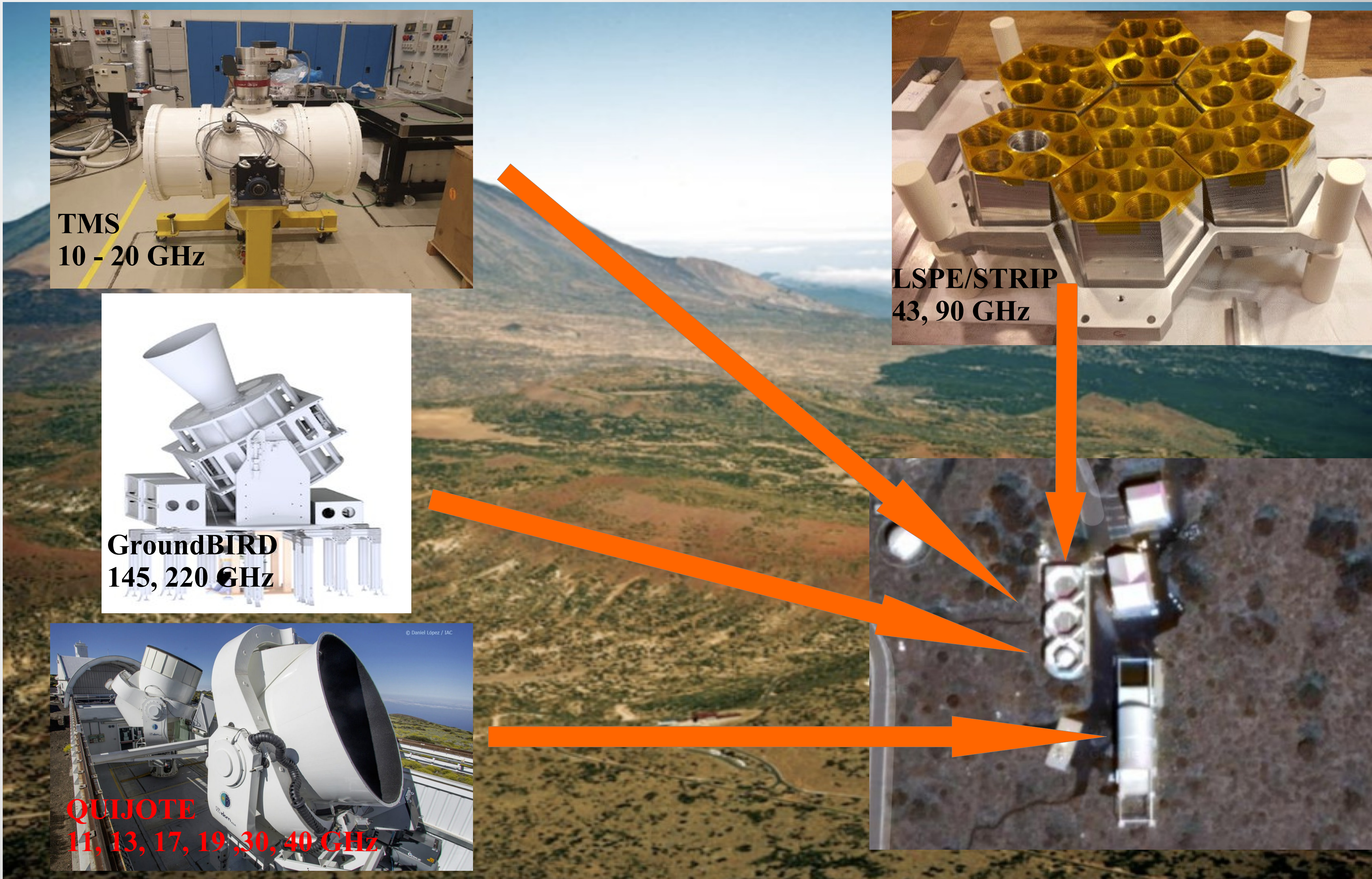
Altitude 2400 m; 28.3° N, 16.5° W



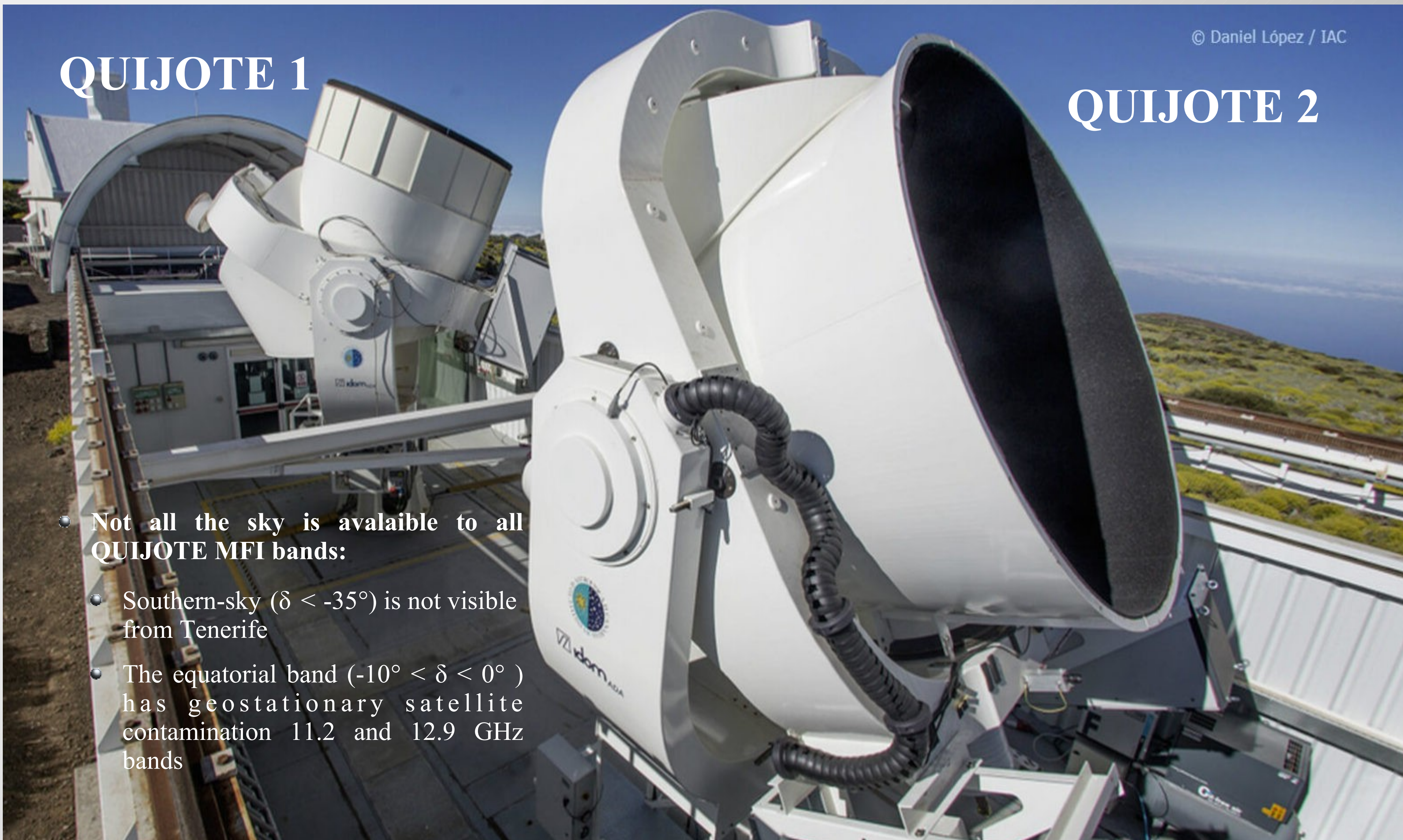




Teide observatory (Cosmology)



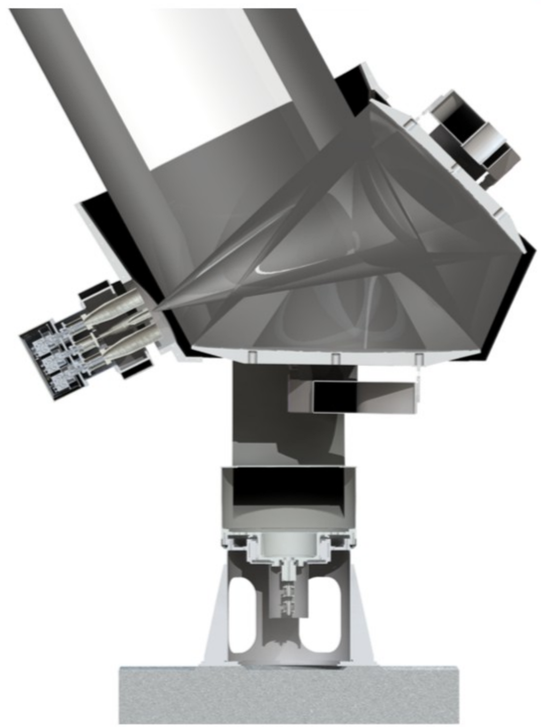
QUIJOTE telescopes



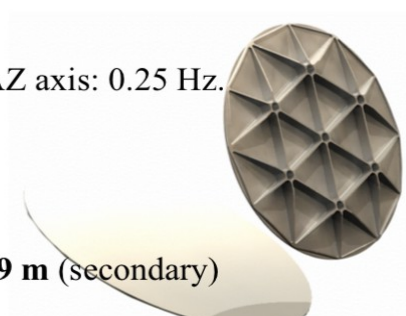
- **Not all the sky is avalaible to all QUIJOTE MFI bands:**
  - Southern-sky ($\delta < -35°$) is not visible from Tenerife
  - The equatorial band ($-10° < \delta < 0°$) has geostationary satellite contamination 11.2 and 12.9 GHz bands

QUIJOTE telescopes

QUIJOTE. Telescope

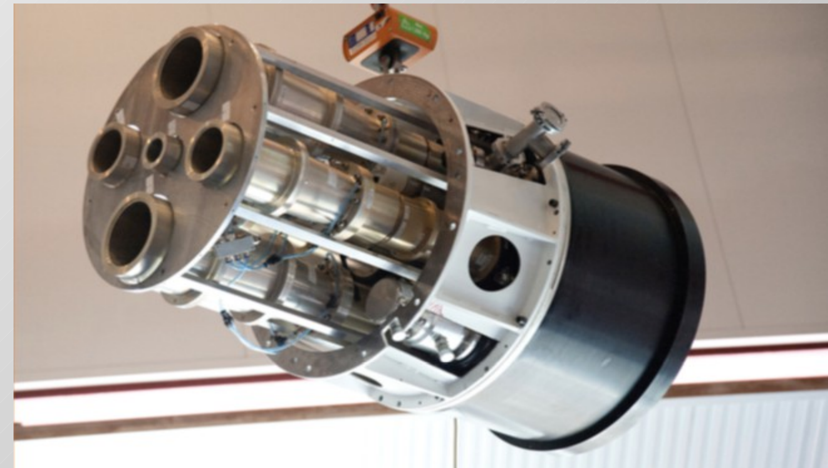


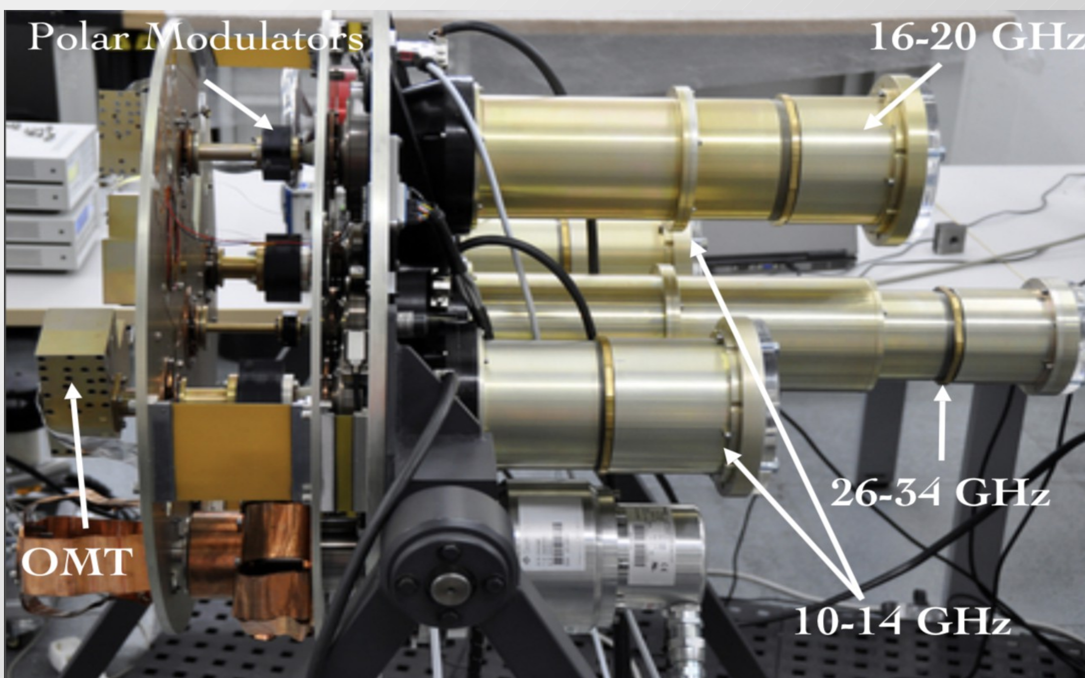
- **Alto-azimutal mount**
- Maximum rotation speed around AZ axis: 0.25 Hz.
- Maximum zenith angle**: 60º**
- **Cross-Dragonian design.**
- Aperture: **2.25 m** (primary) and **1.9 m** (secondary)



QUIJOTE-1 MFI (Multi frequency instrument)

- 4 horns, 32 channels, 4 frequency bands: 11,13,17 and 19 Ghz
- Angular resolution: 0.92° - 0.63°
- Sensitivity: 400 – 600 $\mu K \cdot s^{1/2}$ per channel
- Stepping modulator (HWP) for polarization
- HEMT technology
- Observing from November 2012 to November 2018



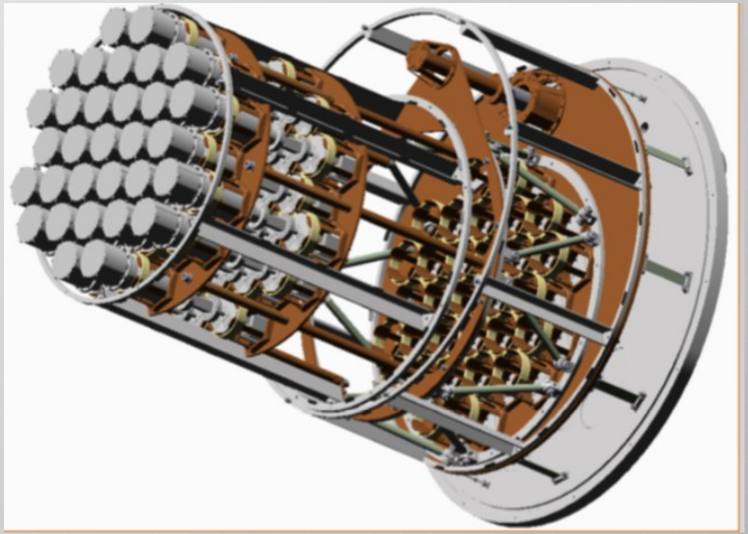


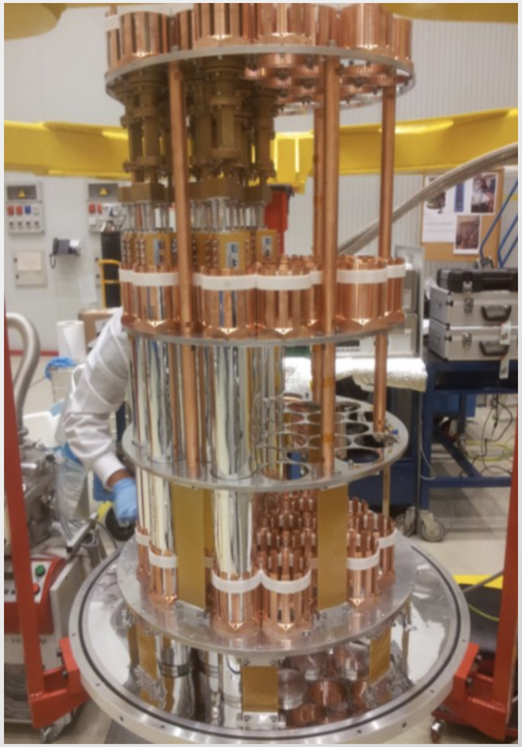
QUIJOTE-1 MFI 2 (10-20 GHz)

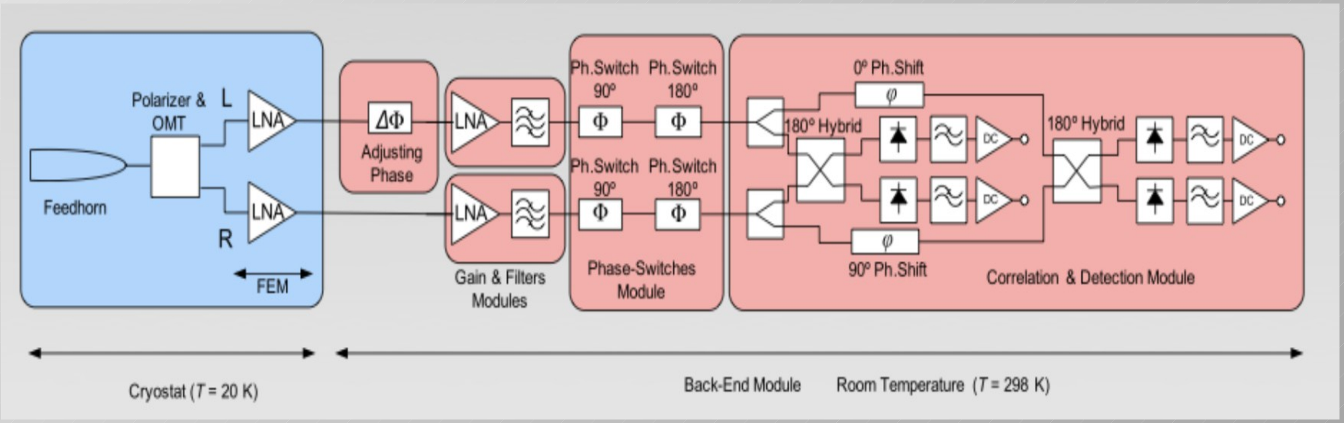
- **MFI upgrade (MFI2 @ QT1).** Aim: to increase the integration speed of the MFI by a factor 3 (mainly coming from the new LNAs) → Sensitivity of ~ 10 μK/deg @ 11 Ghz in wide survey.
- **5 horns.** Two covering the 10-14 Ghz band, and three covering 16-20 GHz
- **Full digital back-end (FPGAs)** → RFI removal.
- **Status:** Cryostat fabricated and tested. Opto-mechanical components fabricated. Now in assembly phase.
- **Operations:** 3 effective years, starting beginning 2023.

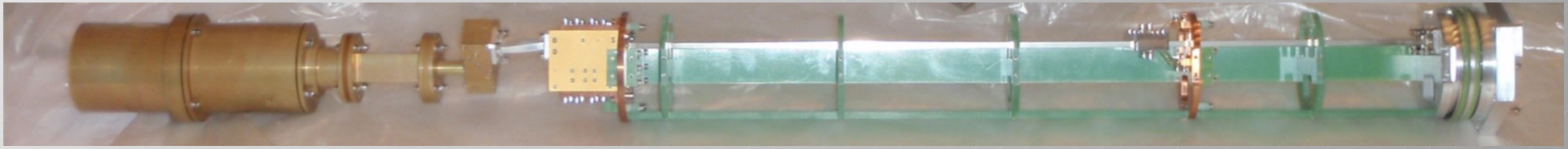
QUIJOTE-2 TFGI (Thirty-Forty GHz Instrument)

- 14 pixels at 30 GHz, 15 pixel at 40 GHz
- Angular resolution: 0.32° - 0.26°
- Sensitivity: ~ 100 $\mu K \cdot s^{1/2}$
- First light in 2018 but stopped. Now restarted, in phase of calibration (started in november 2021)

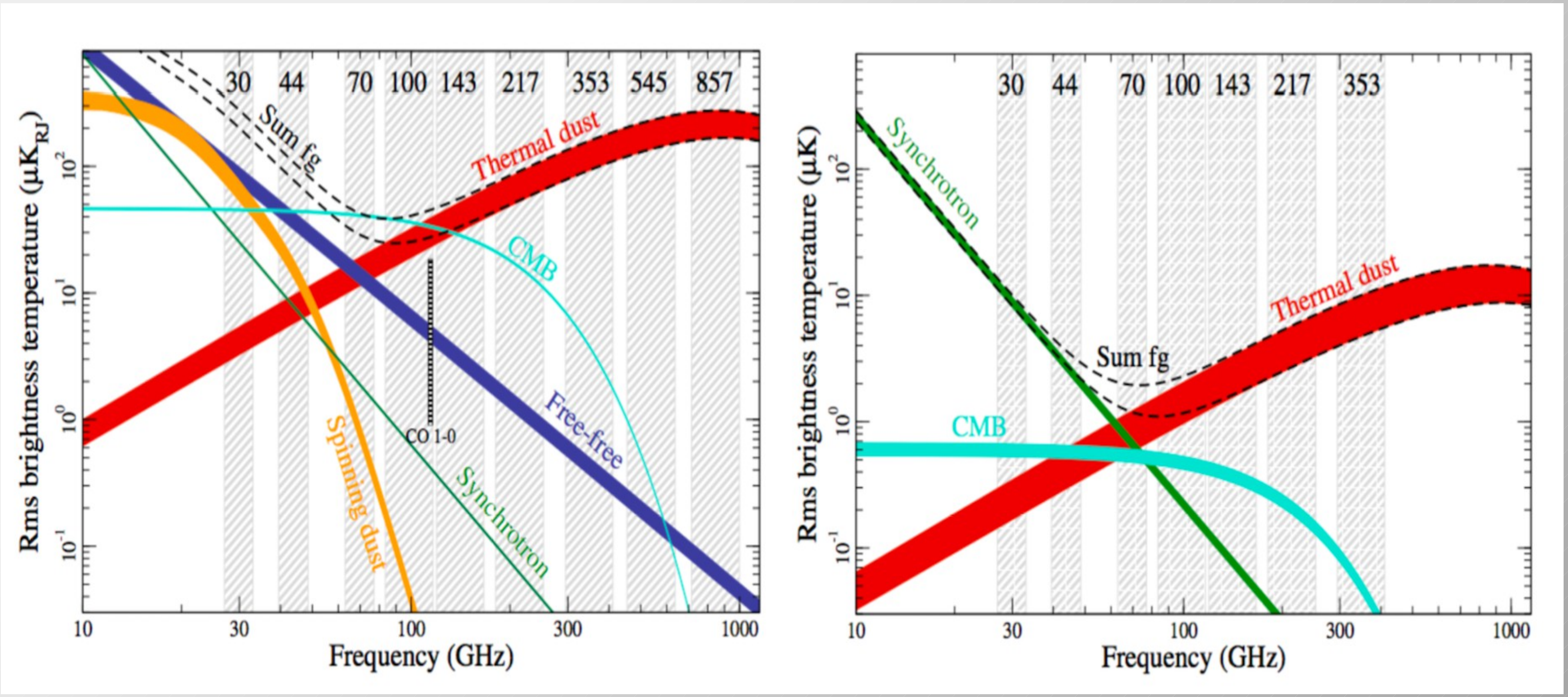




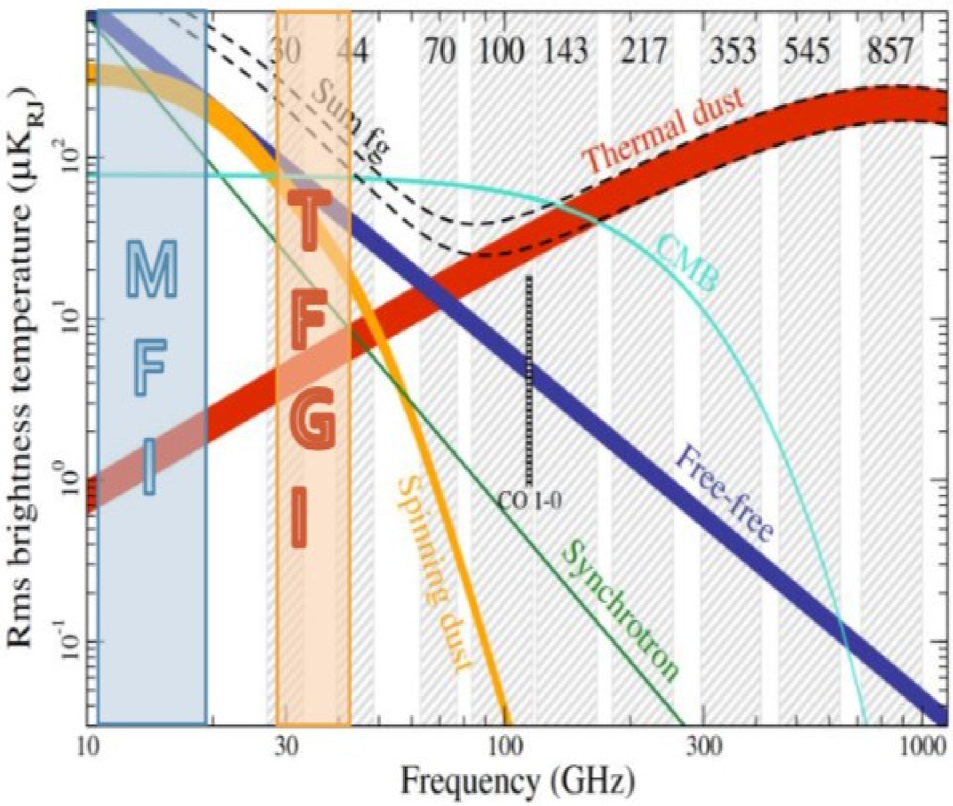


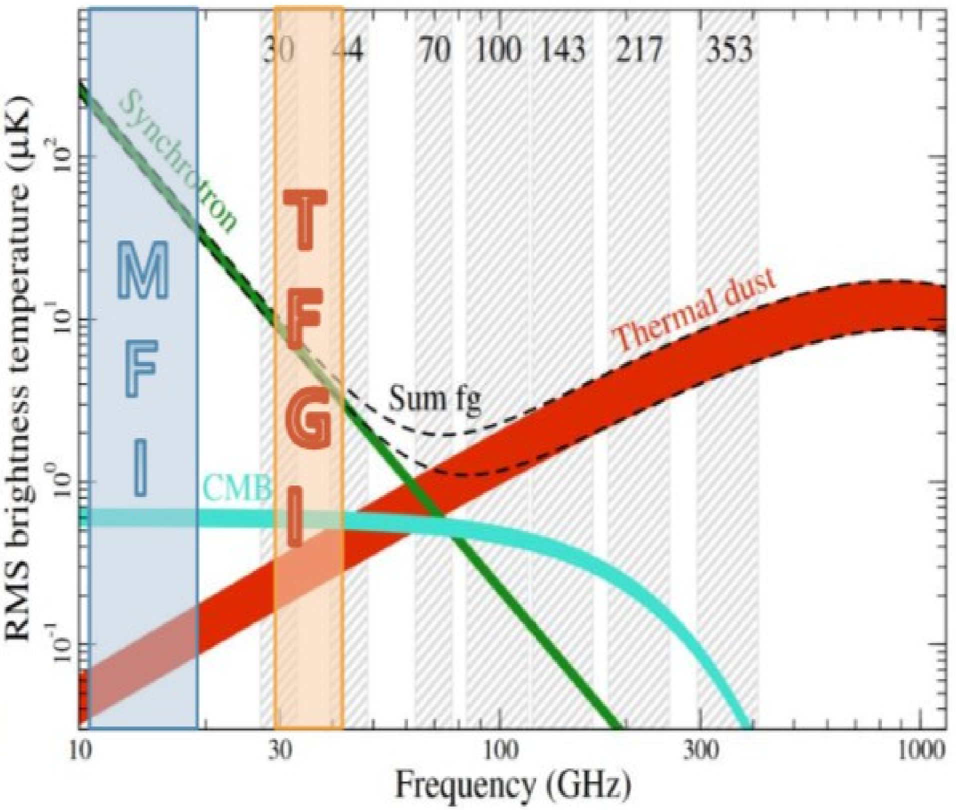


Foregrounds

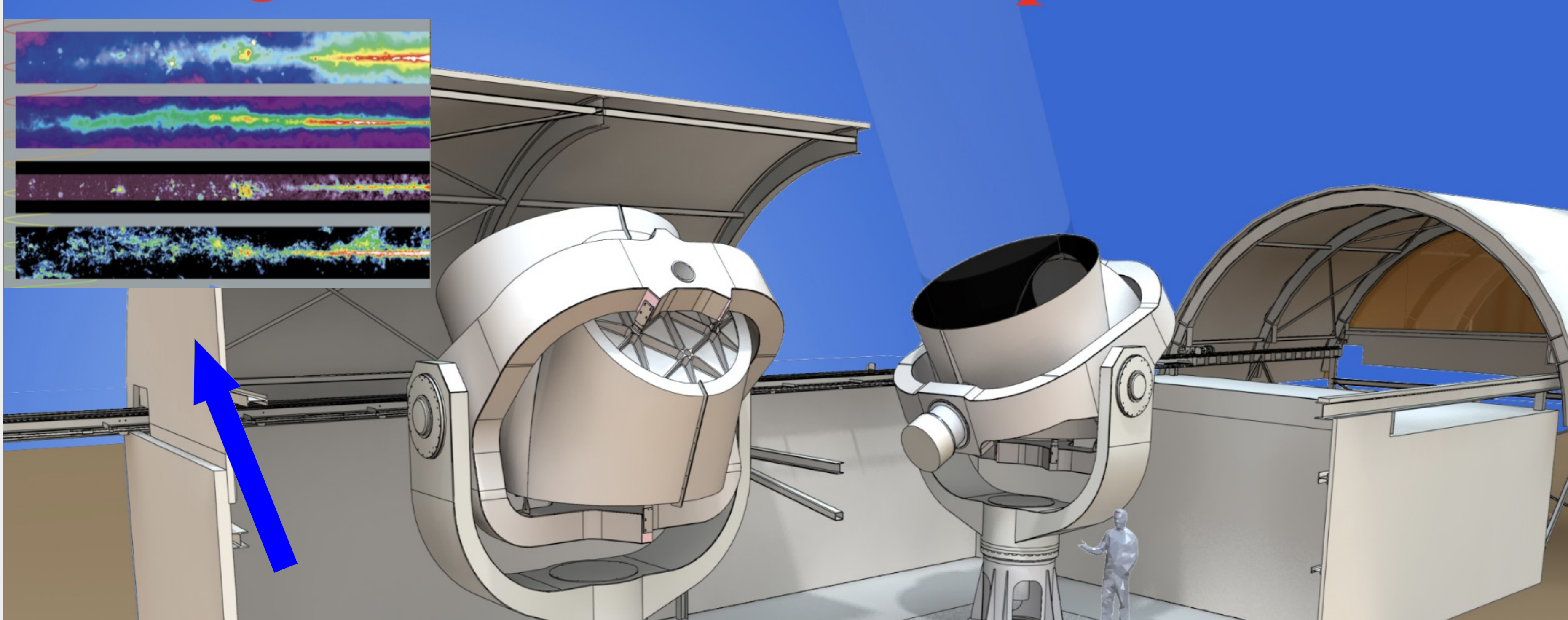


QUIJOTE frequency range





QUIJOTE CMB experiment



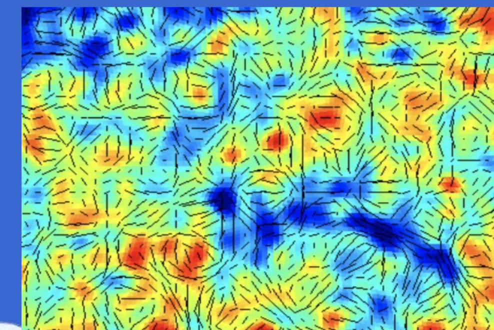
Phase I (2012 - 2018)

MFI two principal objective (in upcoming publication):

- detailed study of selected Galactic regions (e.g. sources with a strong AME component).
- characterization of low frequency Galactic foregrounds in intensity and polarization.
  - Synchrotron: main emission mecanism at QUIJOTE's frequencies.
  - Anomalous microwave emission (spinning dust?): current best upper limits of polarization fraction are ~ 0.22% (Genova-Santos et al. 2017).

allowing to achieve a more accurate component separation for present and future CMB experiments.To correct them in future space missions aiming to reach r = 0.001 (LiteBIRD satellite telescope). **Excellent complement to Planck at low frequencies**

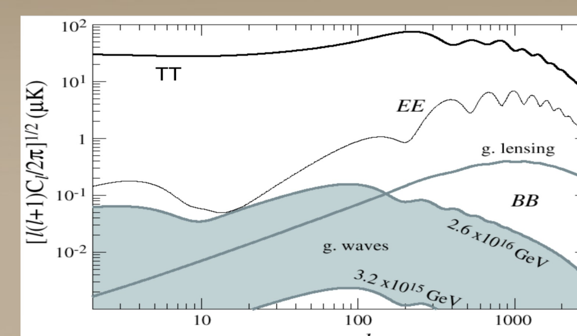
QUIJOTE CMB experiment



Phase II (2023 - ...)

Future objectives:

- Combined FGI/TGI data should allow to reach r = 0.05 after 3 years of operation
- GroundBIRD will start operations in 2023, at 145 GHz and 220 GHz, and will have sensitivity to r = 0.01, after three years.
- Joint QUIJOTE + GroundBIRD (same angular resolution, different frequencies) analysis could potentially allow for even more stringent r constraints, and simultaneous correction for synchrotron+dust for possible future experiments operating at intermediate frequencies (~90 Ghz).



QUIJOTE MFI fields

- **Wide survey**: 20.000 deg^2 of sky covered, more that 21.000 hours of observations, sensitivity of 30 μK/1°beam.

  Nominal observation: 8h azimuth scans at fixed elevation (30°, 35°, 40°, 50°, 60°, 65°, 70°, 75°, 80°)

  Goal: **mostly foreground studies**

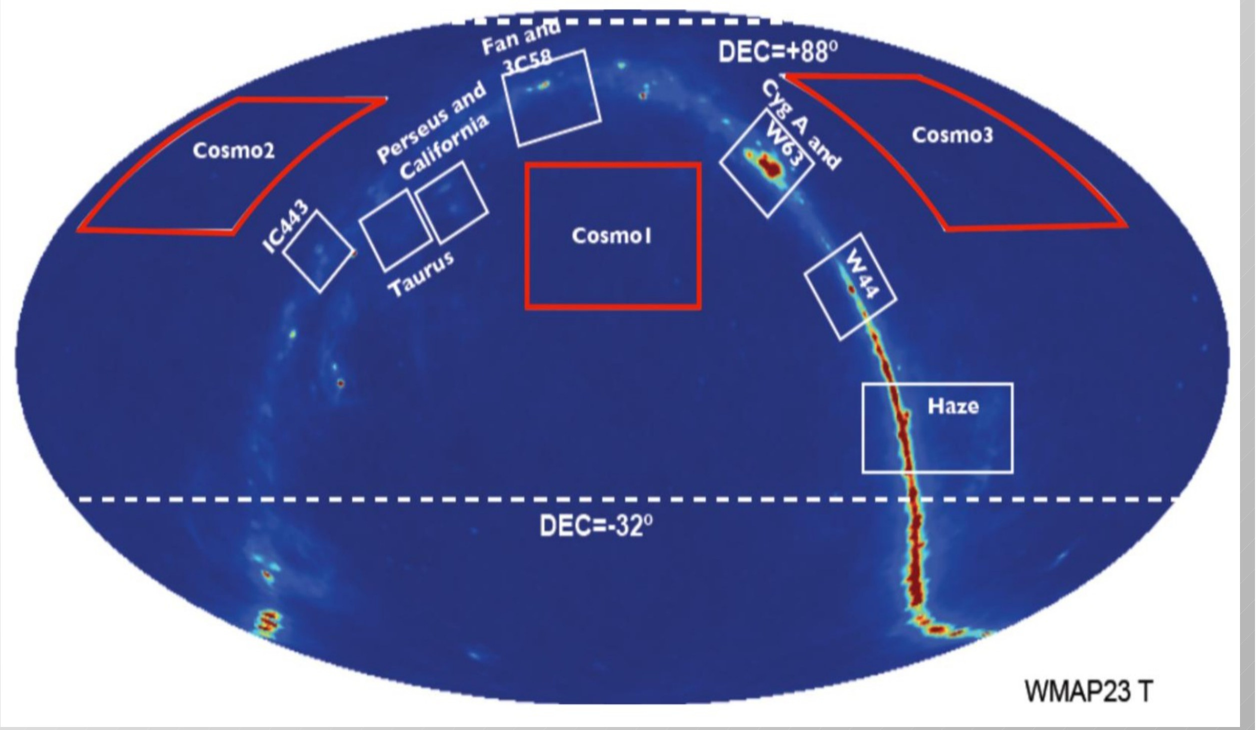
- **Deep cosmological survey**: 3.000 deg^2 in 3 separated fields. Sensitivity 10μK/1°beam after 1 year with the MFI (@11,13,17,19 Ghz) and 1μK/1°beam after 1 year with TFGI (@ 30, 40 Ghz).

  Goal: reach r ~ 0.05 in three years of operation of the TFGI in **B_modes studies for l ~ 18°**

- **Galactic regions**: covering few hundred deg^2 sensitivity 30 - 40 μK/1°beam

  Raster observation: scans in a azimuth interval and fixed elevation

  Goal: **radio foregrounds characterization in those regions**



QUIJOTE papers already published:

- Perseus molecular complex (Genova-Santos et al. (2015))
- W44, supernova remnant, W43 and W47 molecular complexes (Genova-Santos et al. (2017))
- Taurus molecular cloud (Poidevin et al. 2019)

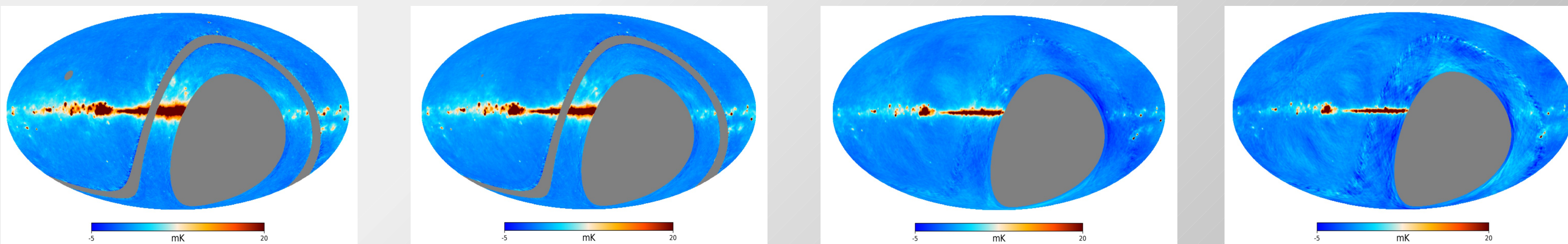
...but also:

- 3C58 and the fan region (561.4h)
- Galactic haze (930h)
- SNRs: IC443 (270h), W63 (250h)
- ….

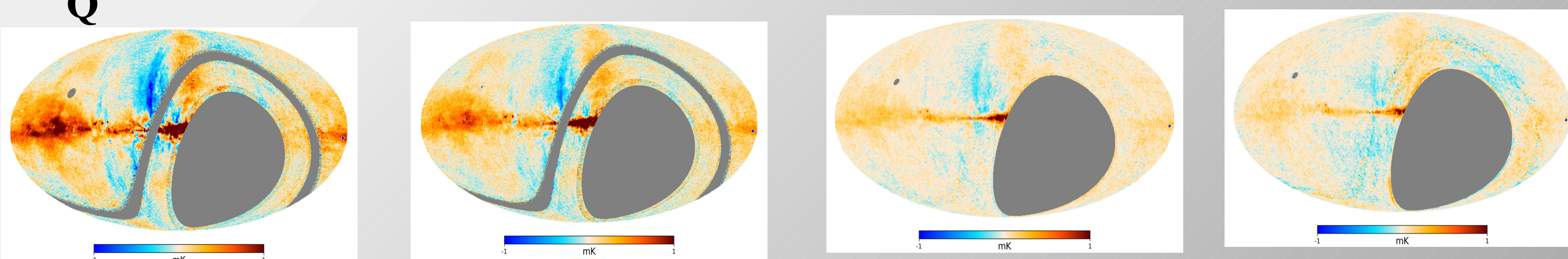
QUIJOTE MFI wide survey (10-20 GHz)

Smoothed 1 deg maps

I



Q



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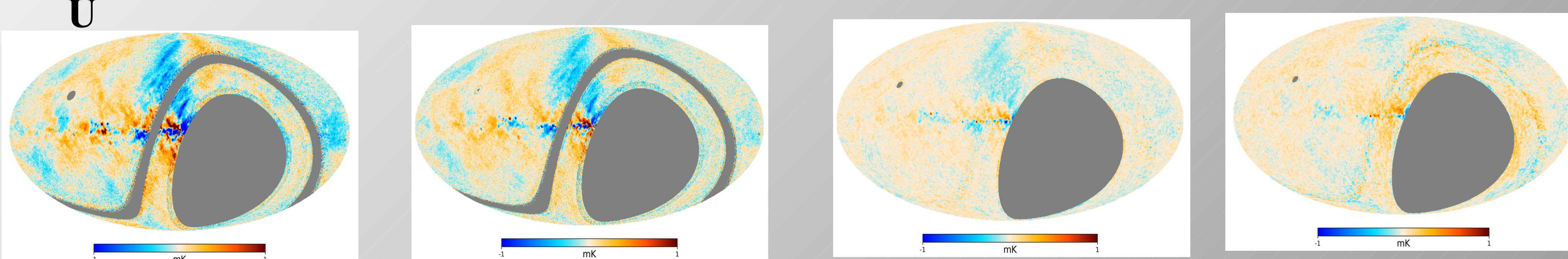
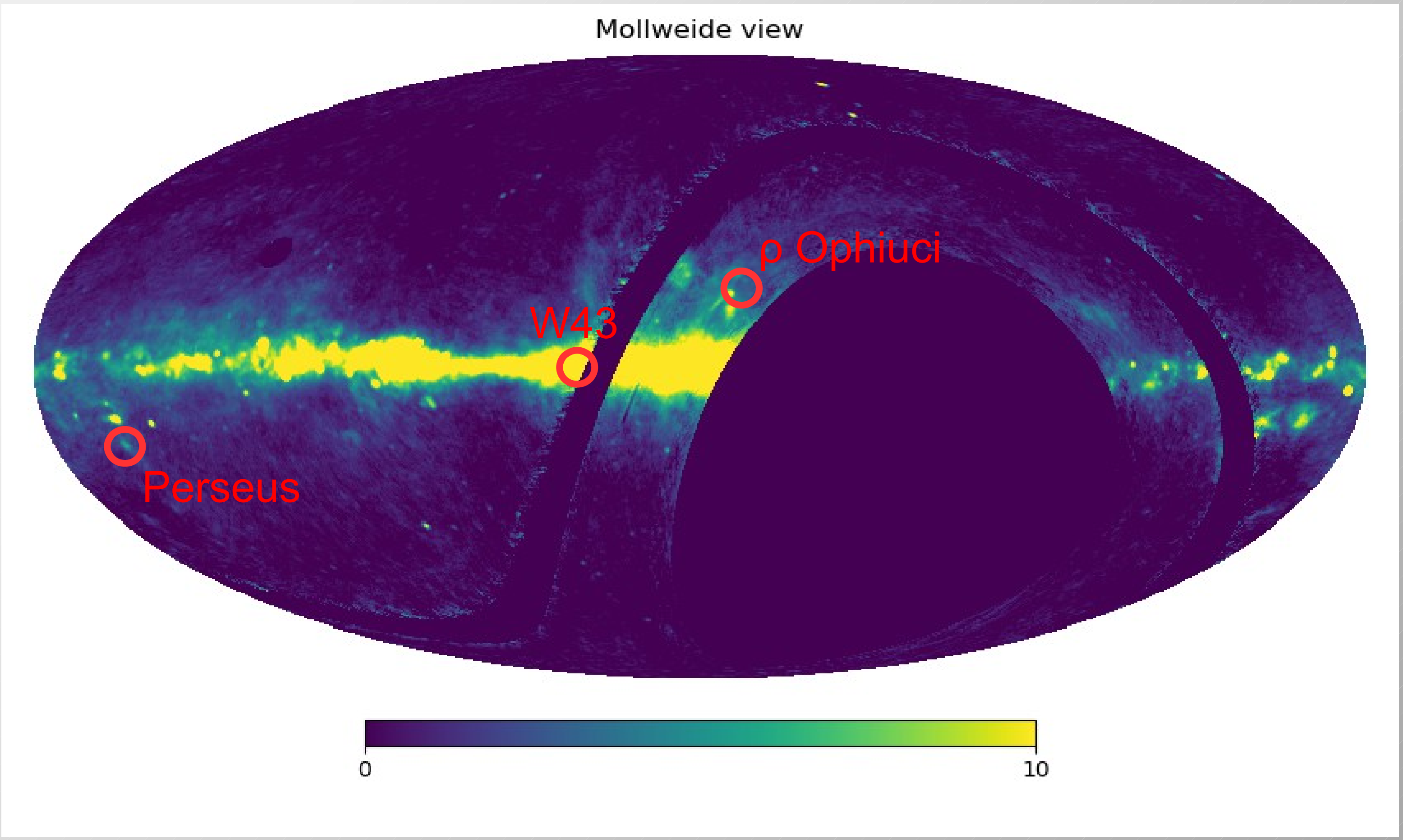


11 GHz **13 GHz** **17 GHz** **19 GHz**

My activity with MFI
Anomalous Microwave Emission (AME) analysis

Main purpose of my activity:

- To measure the polarization and upper limits, or to improve it, for the AME radiation in some galactic region.
- 3 of the brightest and best studied regions as been chosen: **ρ Ophiuchi, W43, Perseus.**

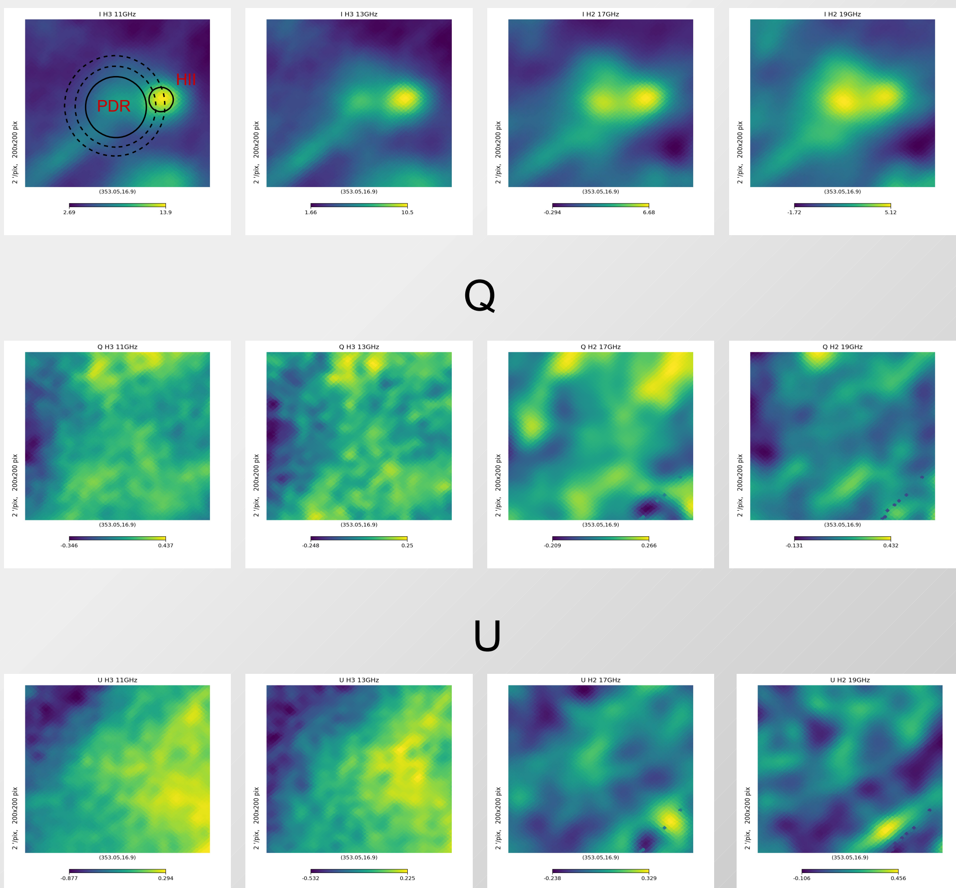


ρ Ophiuchi

Intensity

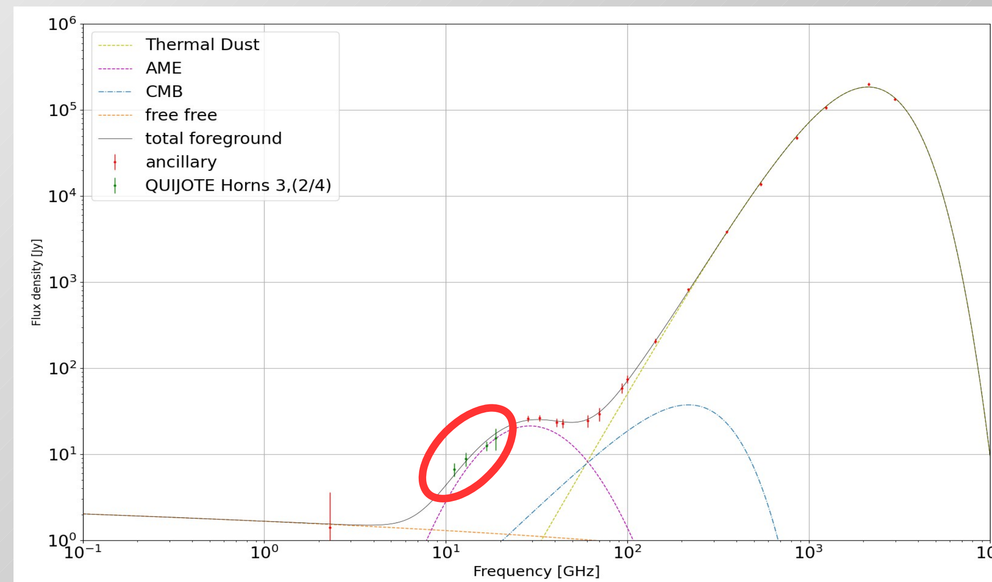
Q

U



11 GHz | 13 GHz | 17 GHz | 19 GHz

Spectral Energy Distribution



SED parameters

Foreground	Free free	Thermal dust			CMB	AME		
Parameter	EM (cm^{-6} pc)	τ_{250} ($x10^{-5}$)	T_d(K)	β_d	ΔT_{cmb} (μK)	A_{ame}	ν_{ame} (GHz)	W_{ame}
Values	16 ± 21	53.0 ± 3.3	22.1 ± 0.3	1.66 ± 0.04	81.0 ± 28.0	21.3 ± 1.8	29.1 ± 1.9	0.53 ± 0.08

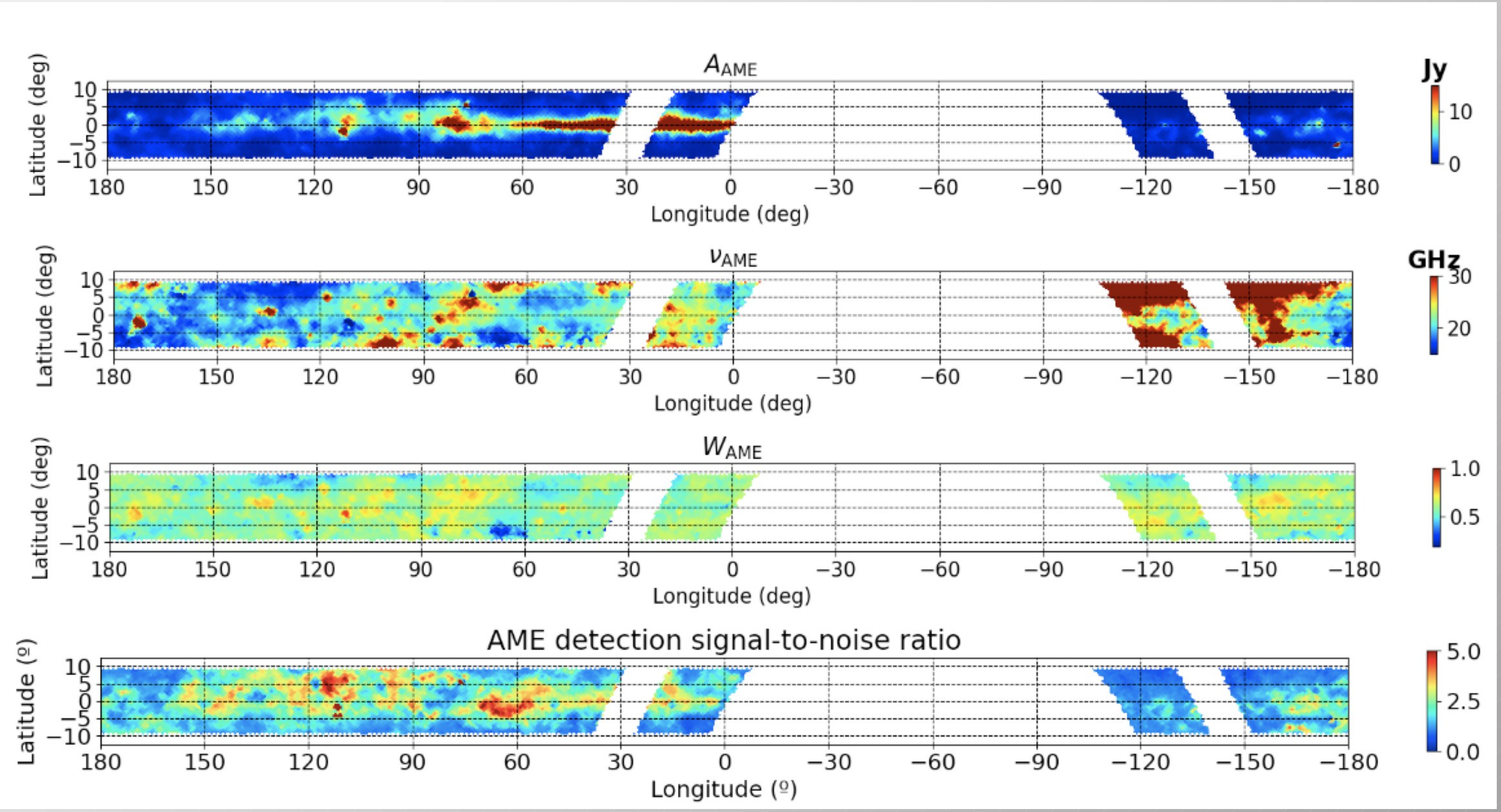
Polarization parameters

Freq. [Ghz]	Iame (Jy)	Q (Jy)	U (Jy)	P (Jy)	Πame (%)
QUIJOTE - 11	6.2 ± 1.4	0.080 ± 0.189	0.445 ± 0.206	0.452 ± 0.205	6.71 ± 3.91
QUIJOTE - 13	8.7 ± 1.6	0.176 ± 0.149	0.369 ± 0.198	0.409 ± 0.189	4.52 ± 2.55
QUIJOTE - 17	14.0 ± 1.7	- 0.076 ± 0.184	0.377 ± 0.280	0.385 ± 0.277	< 5.19
QUIJOTE - 19	18.6 ± 4.4	0.316 ± 0.458	0.456 ± 0.621	0.554 ± 0.57[illegible]	< 7.41
WMAP K - 23	24.3 ± 2.5	0.111 ± 0.129	0.351 ± 0.092	0.368 ± 0.96[illegible]	1.44 ± 0.50
Planck - 28	26.7 ± 2.5	- 0.055 ± 0.133	0.137 ± 0.108	0.147 ± 0.112	< 1.20
WMAP Ka - 33	25.8 ± 2.7	- 0.263 ± 0.137	0.034 ± 0.138	0.265 ± 0.137	0.83 ± 0.67
WMAP Q - 40	20.5 ± 3.2	0.067 ± 0.238	- 0.103 ± 0.232	0.122 ± 0.231	< 2.49
Planck - 44	18.0 ± 3.6	0.137 ± 0.146	0.137 ± 0.221	0.193 ± 0.188	< 2.35

Galactic AME variations

Maps for the amplitude, peak and width of the parable fitting the AME

Poster from Mateo Fernandez Torreiro



List of pubblications

MFI early results (3 papers, published):

I. Intensity and polarization of the AME in the Perseus molecular complex (Génova-Santos et al. 2015)
II. Polarization measurements 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 (13 papers, associated to MFI wide survey data release):

IV. A northern sky survey at 10-20 GHz with the Multi-Frequency Instrument (Rubino-Martín et al. submitted)
V. W49, W51 and IC443 SNRs as seen by QUIJOTE-MFI (Tramonte et al. submitted)
VI. The Haze region and the Galactic Centre as seen by QUIJOTE-MFI (Guidi et al. submitted)
VII. Galactic AME sources in the MFI wide survey (Poidevin et al. Submitted): the detection of AME in various compact sources, allowing to perform a statistical study over the AME parameters and the correlation with other foregrounds
VIII. Component separation in polarization with the QUIJOTE-MFI wide survey. (de la Hoz et al. Submitted): the production of new foregrounds maps in intensity and polarization, providing a particularly accurate separation of polarized synchrotron and AME
IX. Radio-sources in the QUIJOTE-MFI wide survey (Herranz et al. Submitted): the production of a catalog of radio-sources at the MFI frequencies
X. Polarised synchrotron loops and spurs. (Peel et al. in prep)
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.): the characterization of the polarized diffuse synchrotron with cross-correlations
XIII. Intensity and polarization study of Supernova Remnants (López-Caraballo et al. in prep)
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): the study of the brightest polarized loop in the sky, the North Polar Spur
XVI. Component separation in intensity with the QUIJOTE-MFI wide survey (de la Hoz et al. in prep)

Other MFI papers (3 papers, 2 published):,

- 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 MFI survey (Guidi et al. 2021)
- MFI data processing pipeline (Genova-Santos et al. in prep)
- Measeurement of the intensity and polarization of the AME in ρ Ophiuci molecular complex. Update measurement for Perseus, W43, W44, W47 (Gonzalez Gonzalez et al.)

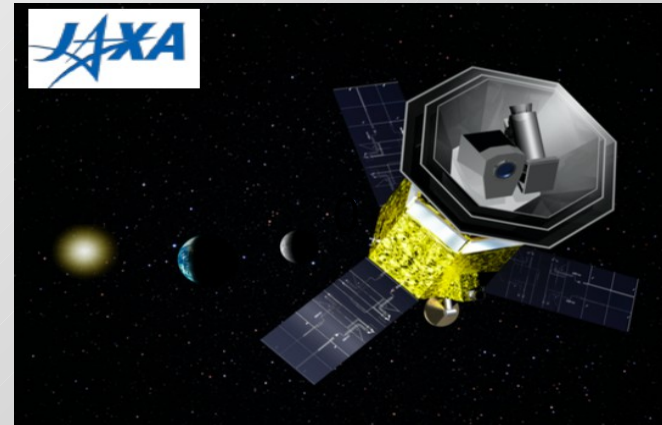
LiteBIRD (2029)

Member of simulation of In-flight calibration group

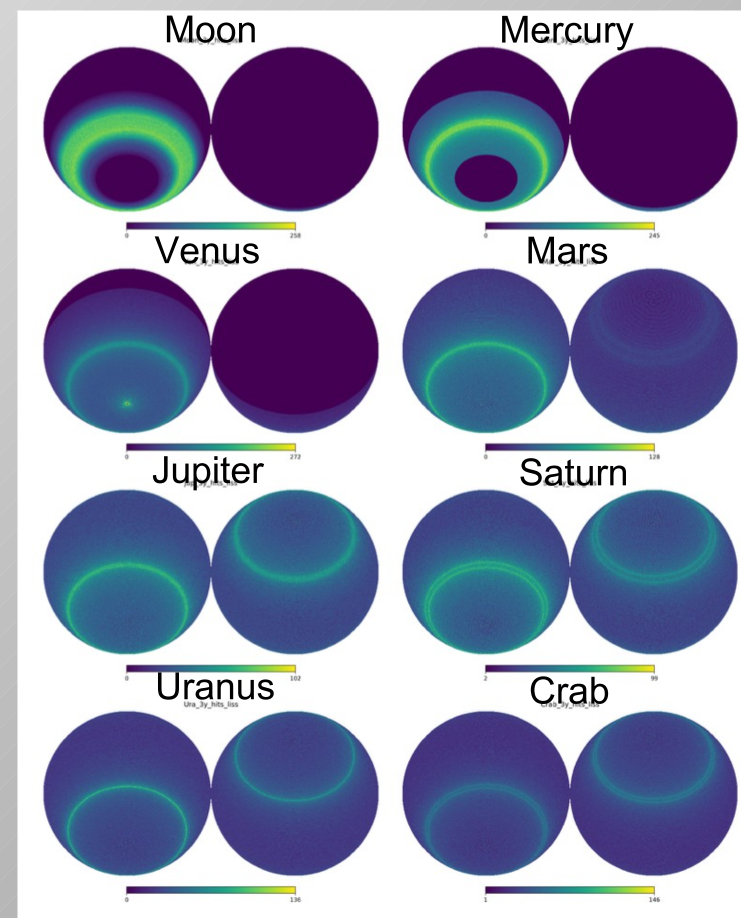
- Over 300 researchers from Japan, North America and Europe
- All-sky 3-y survey, from Sun-Earth Lagrangian point L2
- Large frequency coverage (34-448 GHz, 15 bands)

Definitive search for the **B-mode signal from cosmic inflation** in the CMB polarization

- Making a discovery or ruling out well-motivated inflationary models
- Aim to detect inflationary B-mode polarization with total uncertainty of $\delta r < 0.001$
- Insight into the quantum nature of gravity
- **Reionization** (improve $\sigma(\tau)$ by a factor of 3)
- **Neutrino mass** ($\sigma(\sum m_\nu) = 15$ meV)
- Constraints on **cosmic birefringence**
- ....



Simulation of some celestial objects as observed by LiteBIRD



Thank You for Your attention!