Tenerife Microwave Spectrometer (TMS): absolute spectral measurements in the 10-20GHz range

J.A. Rubiño-Martín (IAC)

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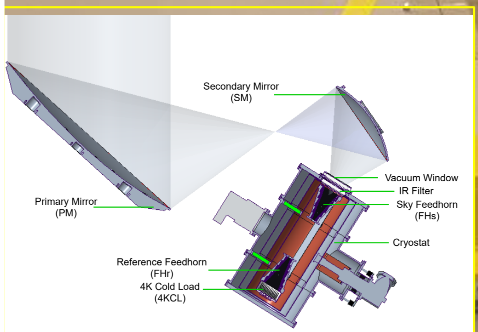
GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"
Ref. de la ayuda: ICTS-2019-03-IAC-12

CMB-CAL @ BICOCCA



TMS has Instrumental participation from :

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UNIVERSITÀ DEGLI STUDI DI MILANO

Universidad Politécnica de Cartagena

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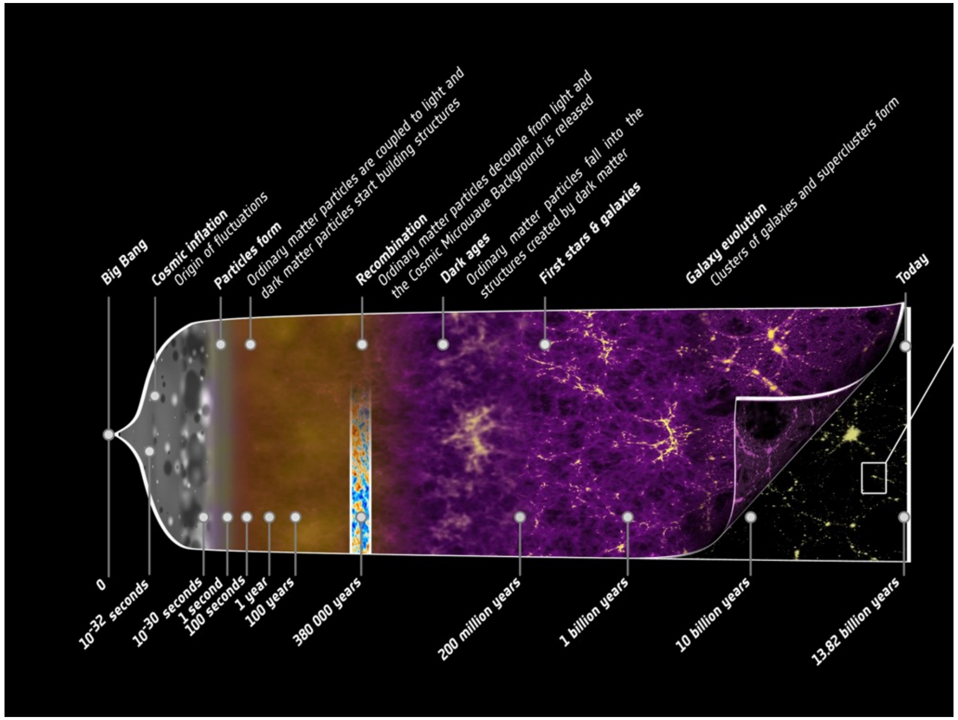
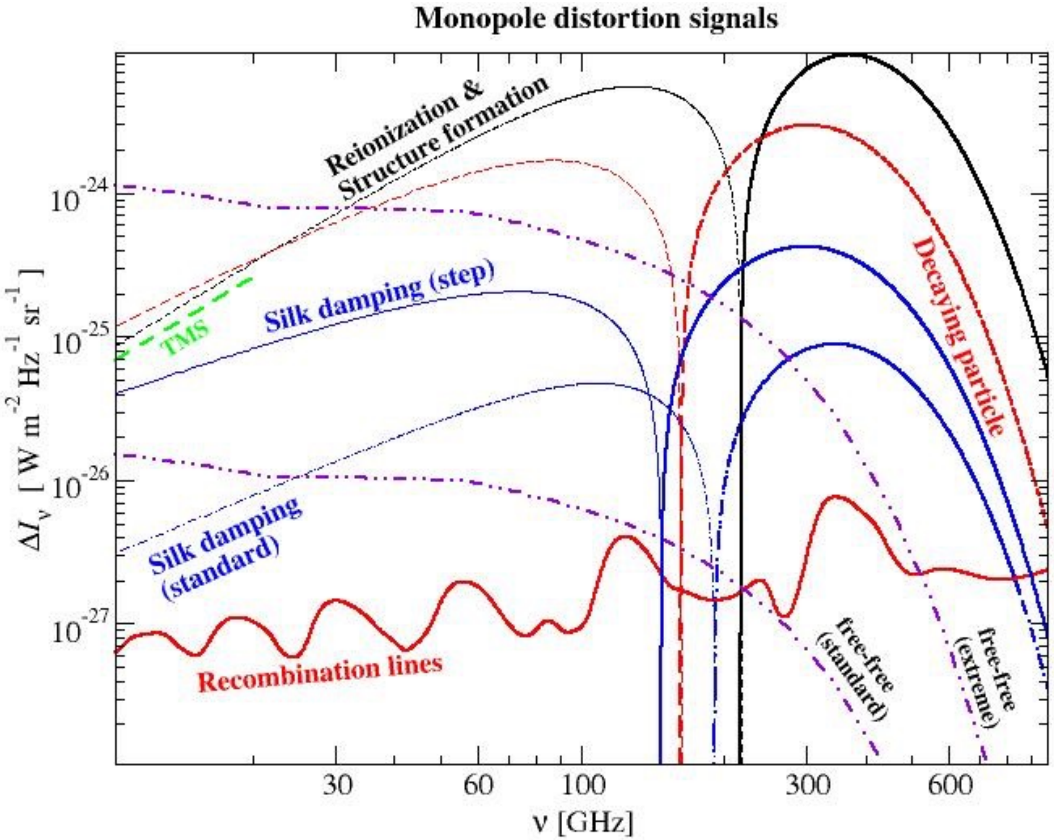
TMS: scientific motivation

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).



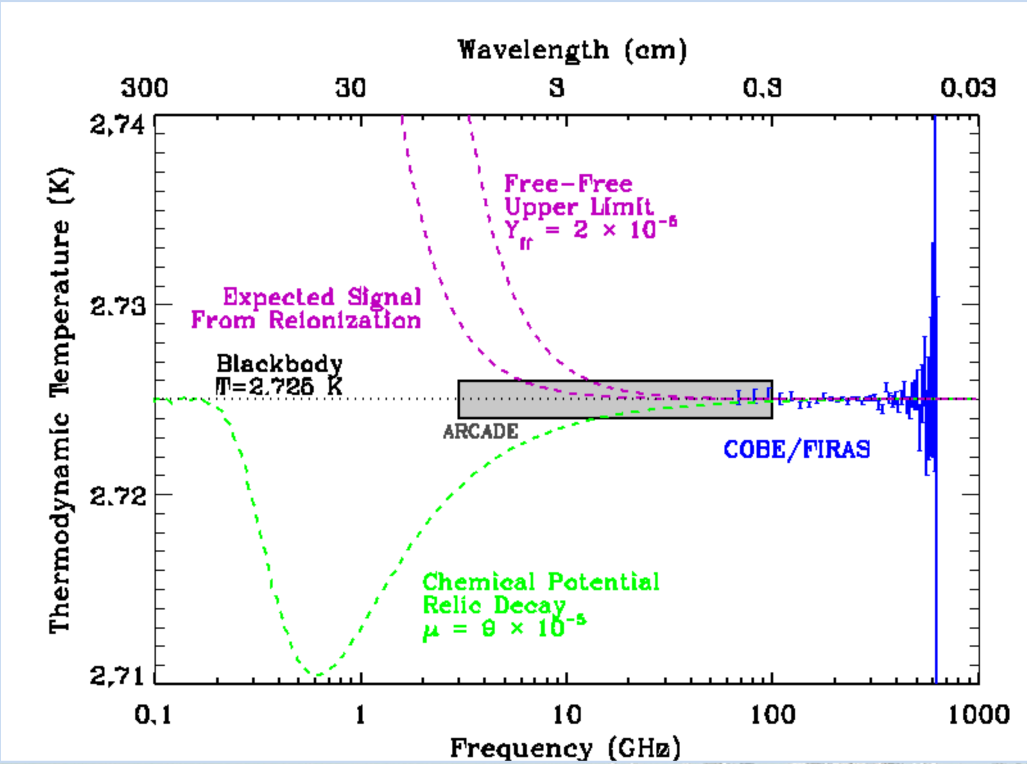


Scientific cases:

- 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 (II). Radio Synch. Bckg



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:

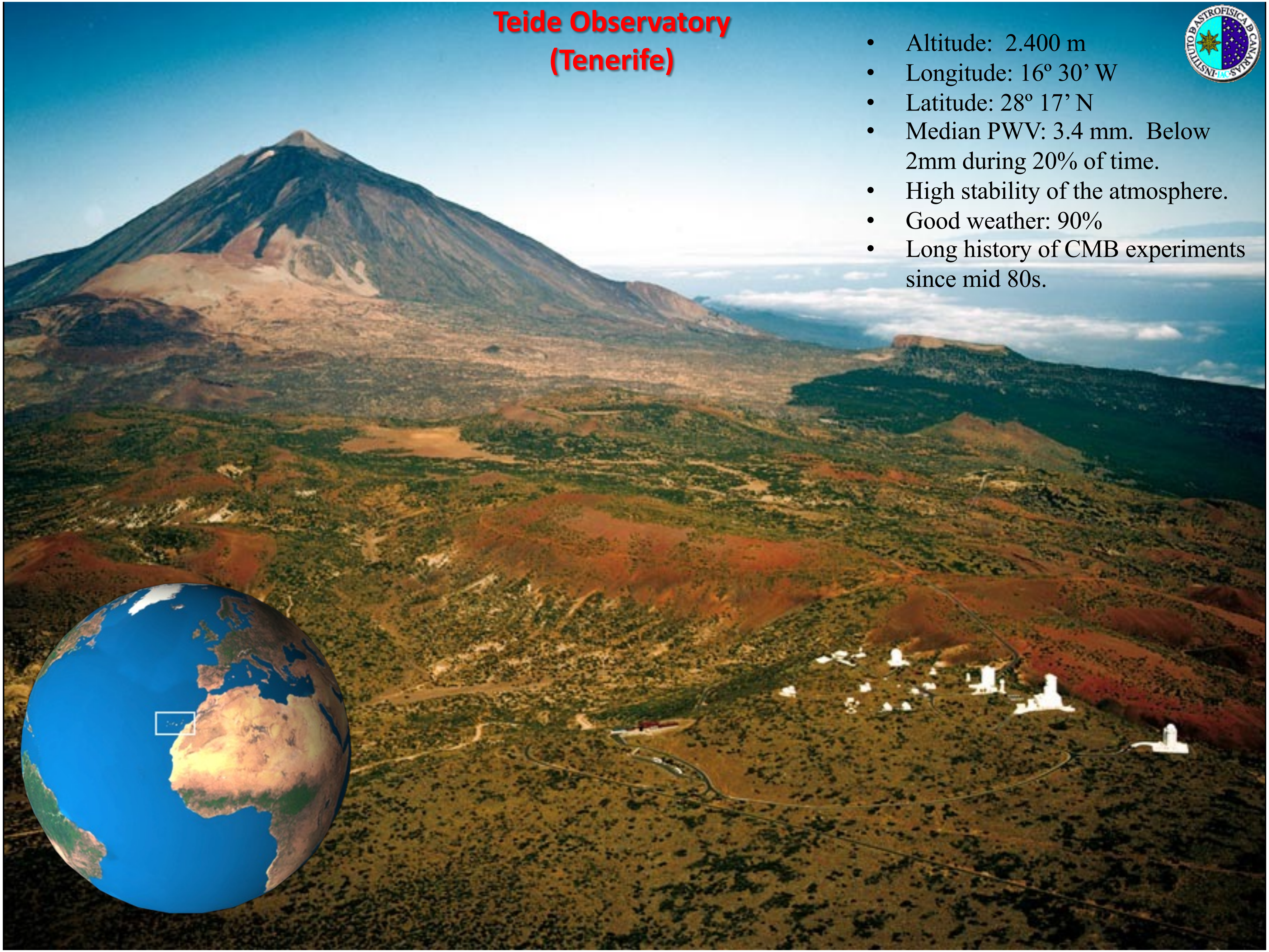
$$T(\nu) = (18.4 \pm 2.1)\mathrm{K} \left(\frac{\nu}{0.31\,\mathrm{GHz}}\right)^{-2.57\pm0.05}$$

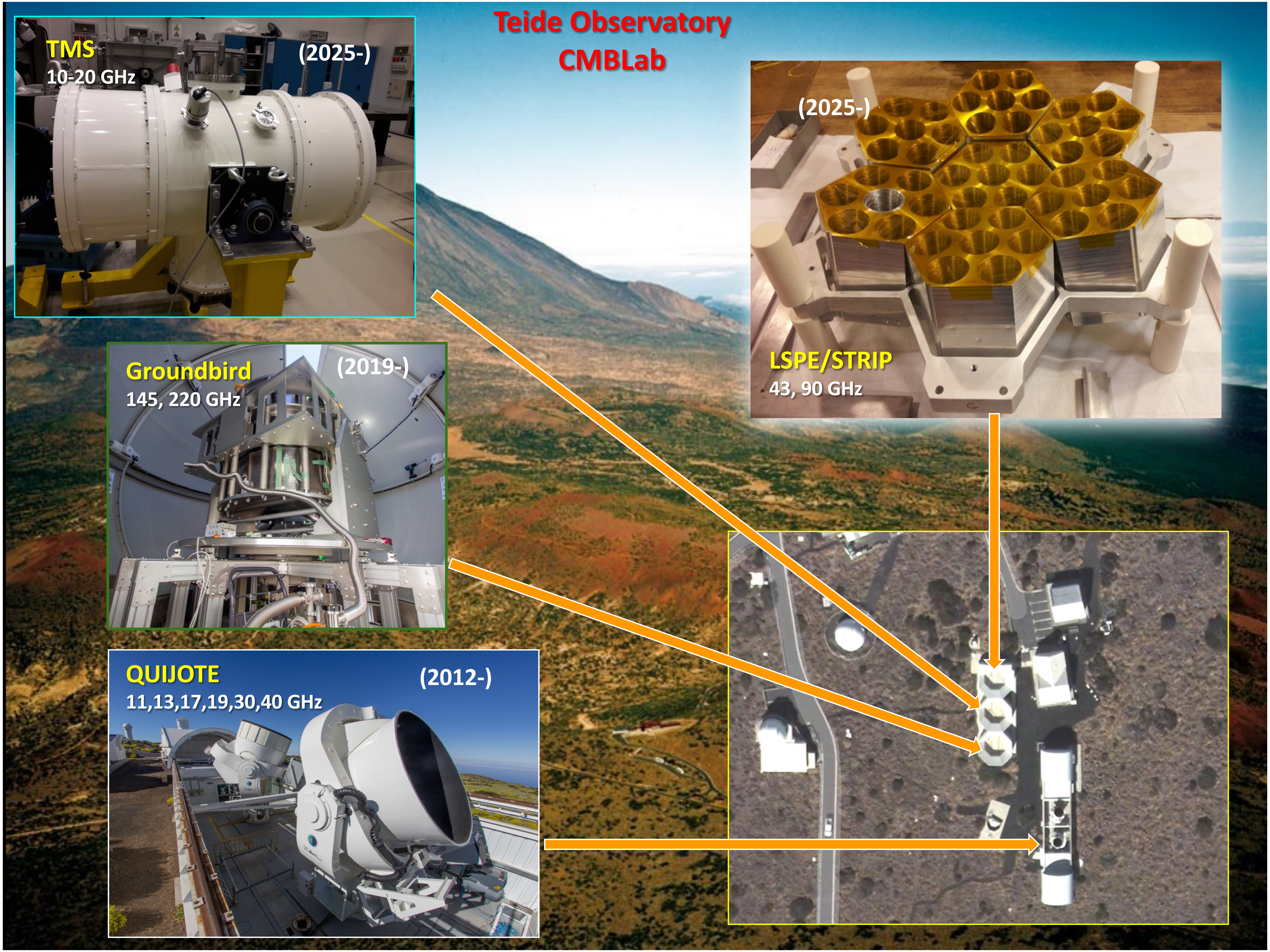
  - **Confirmed with LWA1** between 35-80MHz (Dowell & Taylor 2018).
  - Origin of excess (Radio Synchrotron Background) unclear.
  - Status of the field described in two conferences (see Singal et al. 2018; 2023).

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

Teide Observatory
(Tenerife)

- Altitude: 2.400 m
- Longitude: 16º 30’ W
- Latitude: 28º 17’ N
- Median PWV: 3.4 mm. Below 2mm during 20% of time.
- High stability of the atmosphere.
- Good weather: 90%
- Long history of CMB experiments since mid 80s.

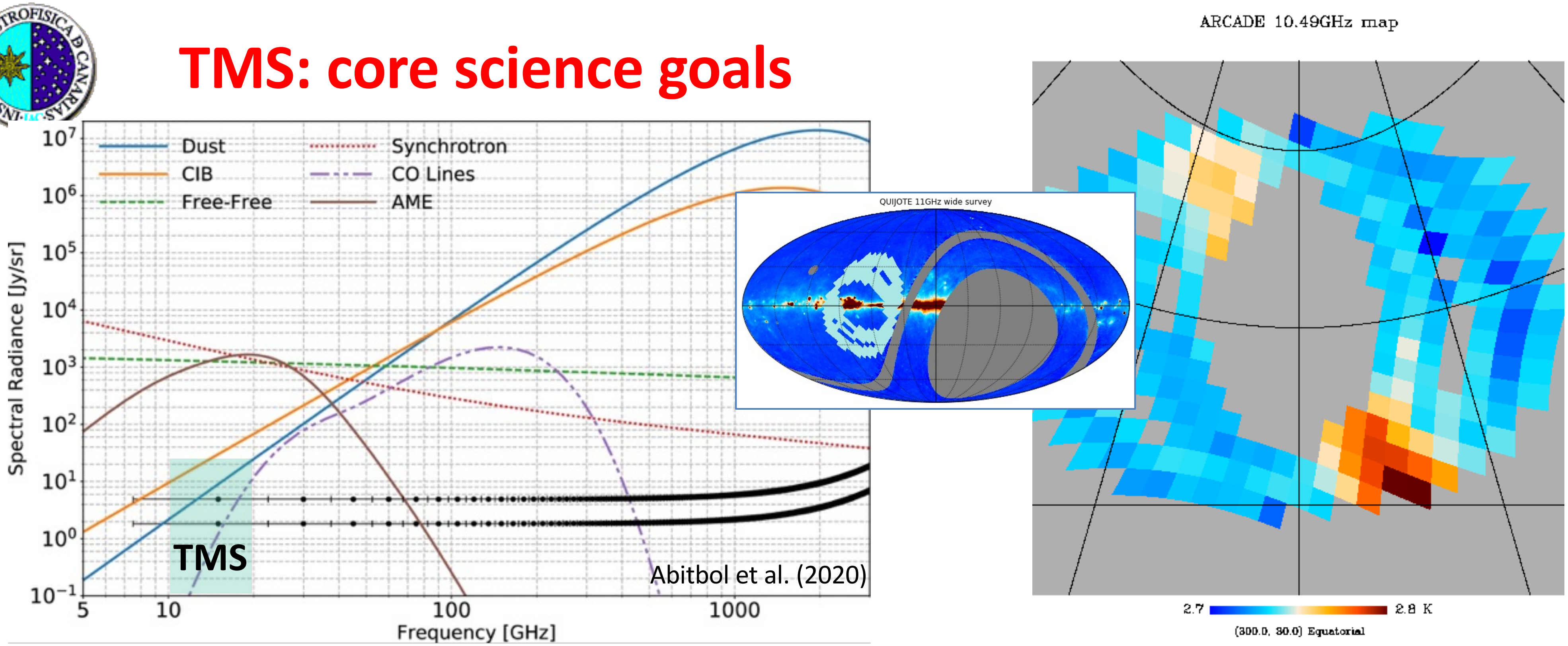




Teide Observatory
CMBLab
TMS
10-20 GHz
(2025-)
(2025-)
LSPE/STRIP
43, 90 GHz
Groundbird
145, 220 GHz
(2019-)
QUIJOTE
11,13,17,19,30,40 GHz
(2012-)

CMB team @ IAC (http://research.iac.es/proyecto/cmb/)

TMS: core science goals

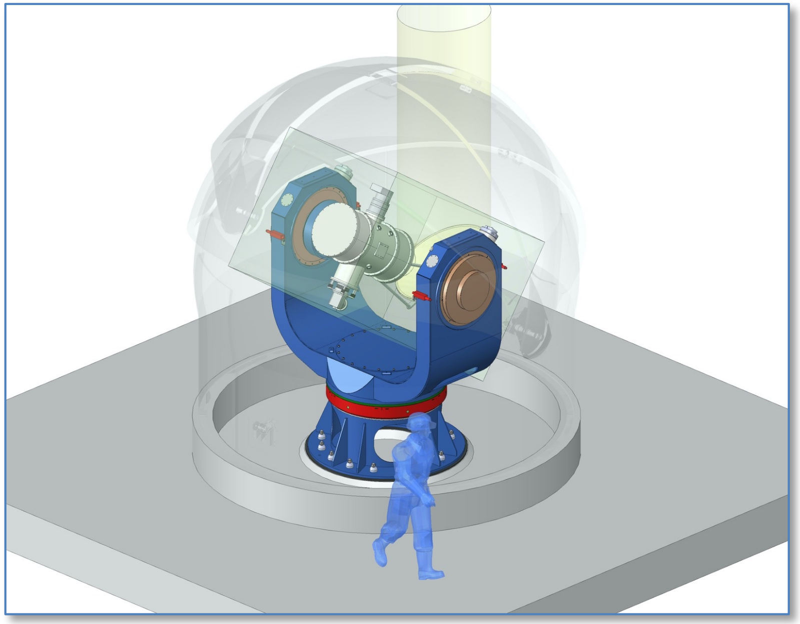


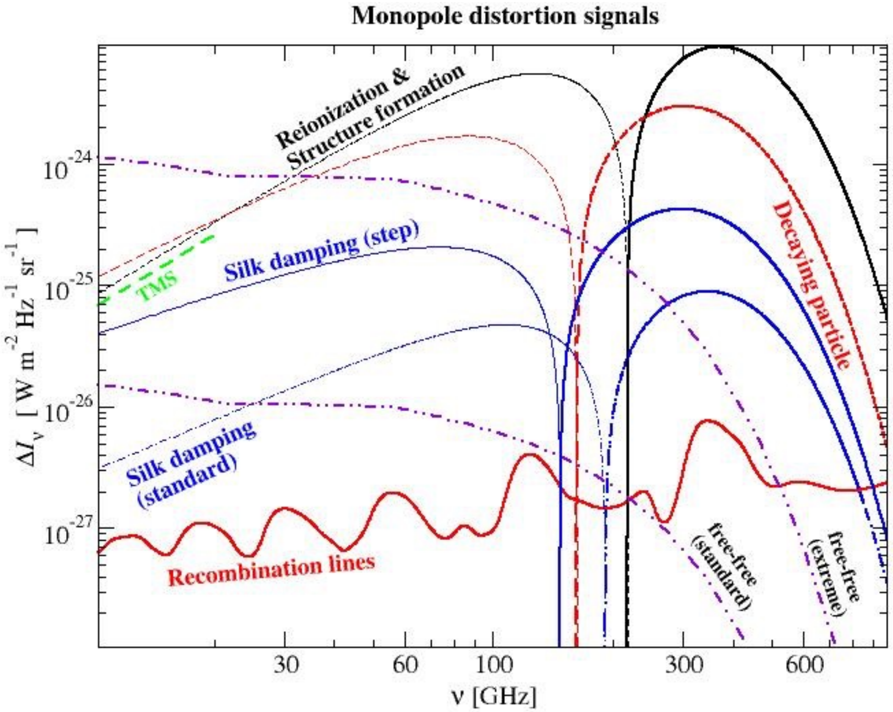
Three main primary goals:

- To measure the **absolute sky spectrum in the 10-20 GHz range**, searching for possible deviations from a pure blackbody at the level of 10-20 Jy/sr (expected level of distortion signal due to reionization and structure formation in our Universe).
- To provide accurate information of the **spectral properties of the synchrotron and anomalous microwave emission from our Galaxy,** and to constrain the emission properties of the **extragalactic emission**, both in the range 10-20 GHz (→ characterize the excess of emission detected by ARCADE 2). **Legacy value** (Voyage 2050).
- To provide an **absolute calibration scale for the QUIJOTE experiment**, as well as an accurate (sub-percent) relative calibration scale for the four QUIJOTE MFI frequencies (11, 13, 17 and 19 GHz).

TMS: project baseline

- **Low resolution spectroscopy in the 10-20GHz band.**
- Location: Teide Observatory.
- FEM cooled to 4-10K (HEMTs), reference load at 6K.
- DAS FPGAs: Band divided in 4 sub-bands, acquired through ZCU208 RFSoC Ultrascale boards (Xilinx)
- ~2 deg beam, 0.25 GHz spectral resolution (40 bands).

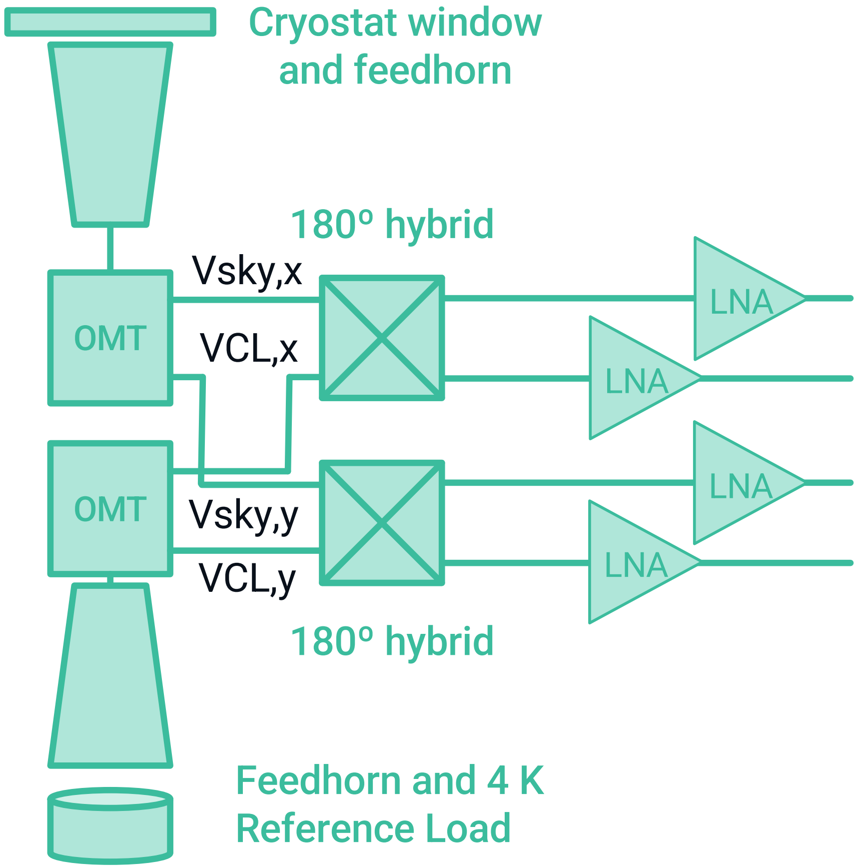




(adapted from Andre et al. 2014)

Frequency range [GHz]	10.0–20.0
Frequency resolution [GHz]	0.25
Spectral resolution, $R = \lambda/\Delta\lambda$	60.0
Tsys [K]	22.0
Beam FWHM [deg]	2.0
Cross-polarization (whole band)	$< -30\,\mathrm{dB}$
Sidelobe levels (whole band)	$< -25\,\mathrm{dB}$
NEP per frequency channel [$\mathrm{mK\,s^{1/2}}$]	1.97
Average sensitivity in 100 h integration at 10 GHz [Jy/sr]	23.0

(Rubino-Martin et al. 2020, SPIE)


Cryostat window
and feedhorn
180º hybrid
Vsky,x
VCL,x
OMT
OMT
Vsky,y
VCL,y
LNA
LNA
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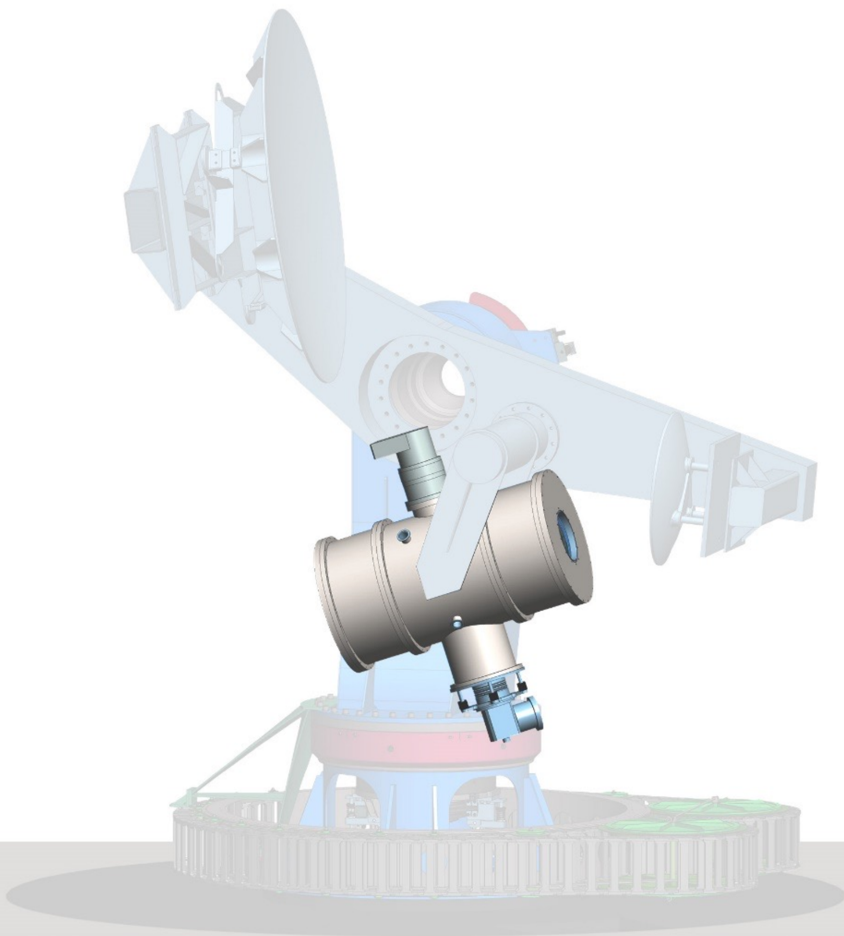
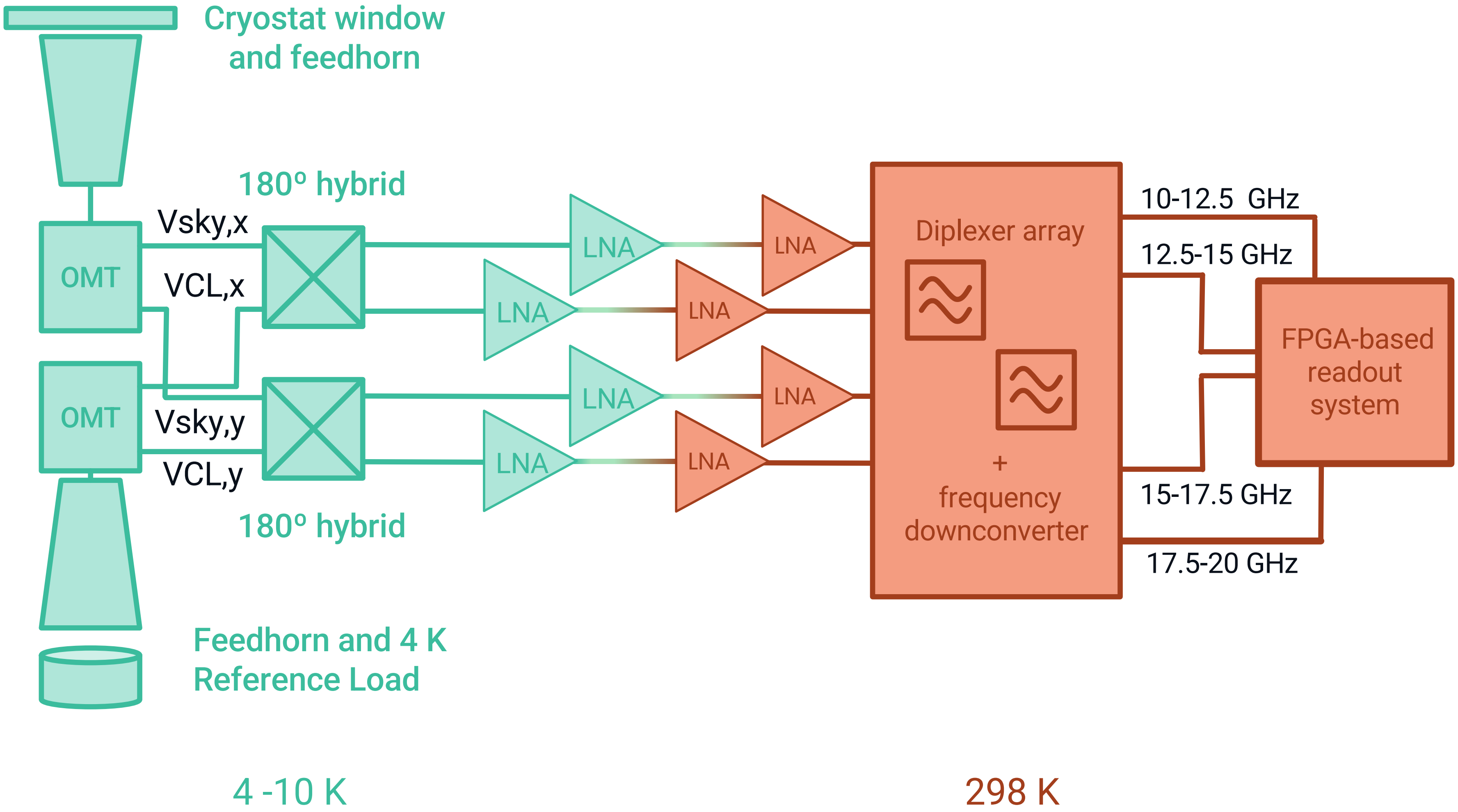
LNA
180º hybrid
Feedhorn and 4 K
Reference Load

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180º hybrid
LNA
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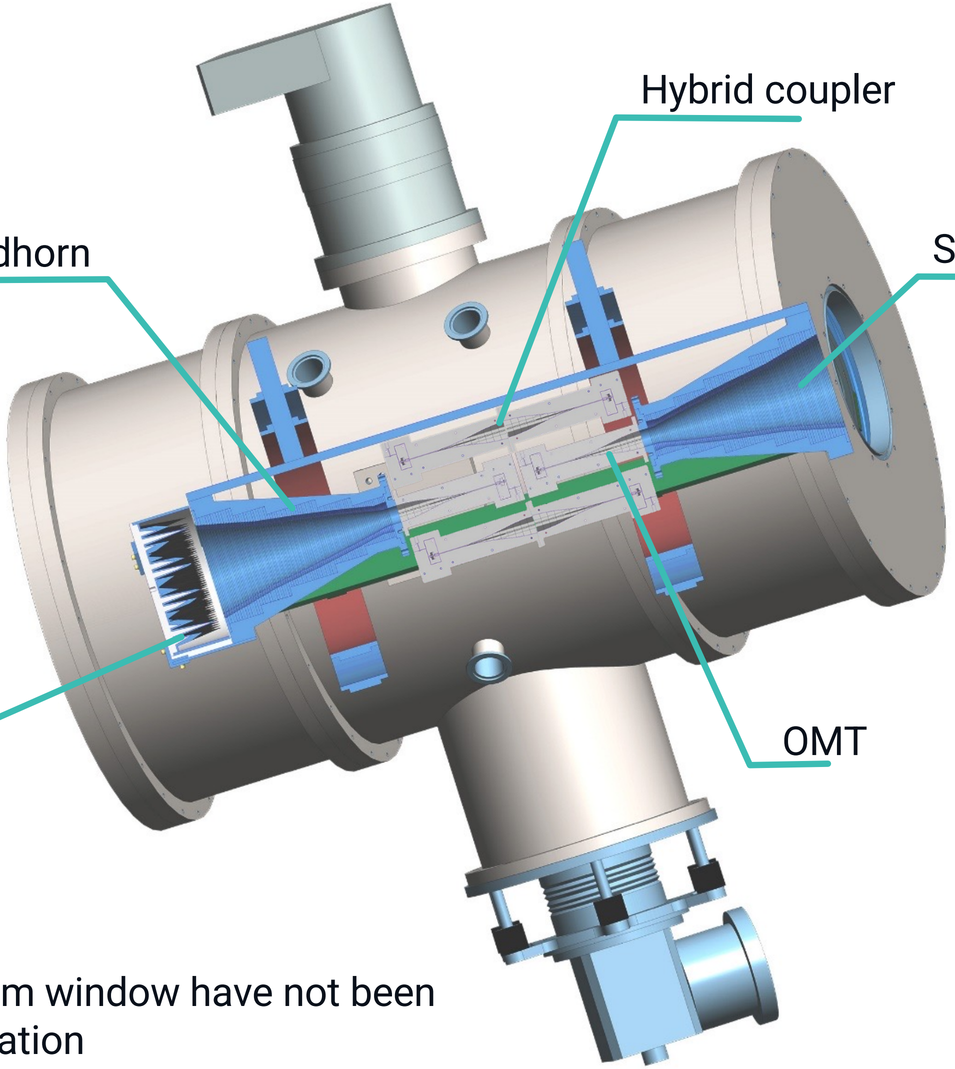
LNA
LNA
LNA
LNA
LNA
LNA
Diplexer array
+
frequency
downconverter
10-12.5 GHz
12.5-15 GHz
15-17.5 GHz
17.5-20 GHz
FPGA-based
readout
system
Feedhorn and 4 K
Reference Load
4 -10 K
298 K

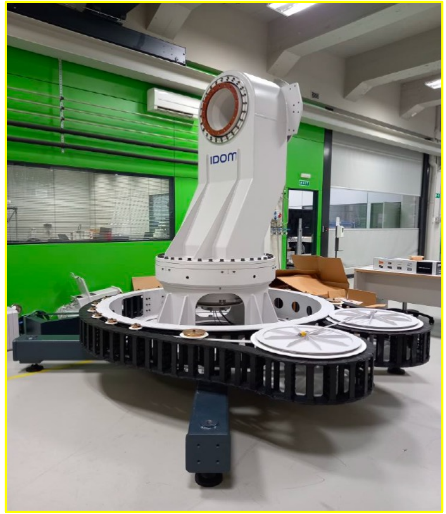


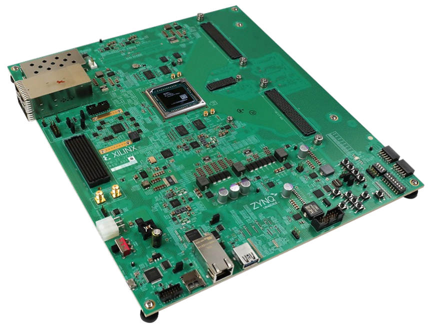
(*) The IR filter and vacuum window have not been included in this representation

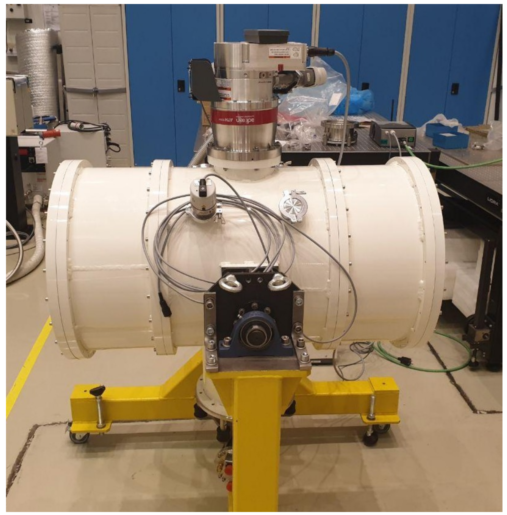
(see details in Alonso-Arias et al. 2020, SPIE paper 11447-63)

TMS: project status (Nov 2024)

- **Dome and shielding.** Installed at Teide Observatory.
- **Platform.** Fabrication during 2022. Installed at Teide Obs.
- **Mirrors.** 1.49m primary and 0.6m ellipsoidal secondary (Alonso-Arias et al 2022), designed. To be fabricated.
- **Cryostat (vacuum chamber).** Fabricated in 2019. Made of aluminium (AA6061-T6), 970mm length, 490mm diameter.
- **Horns**: covering the full 10-20 GHz band (1 octave) already manufactured. Measured at University of Milano.
- **OMT**. Designed. Octave bandwidth. In fabrication.
- **180º Hybrid**. Designed. Octave bandwidth, based on OMT.
- **Reference Cold Load**. Fabricated and tested.
- **DAS (FPGAs).** Four ZCU208 RFSoC Ultrascale board (Xilinx) purchased. Programming software.







TMS: reference cold load

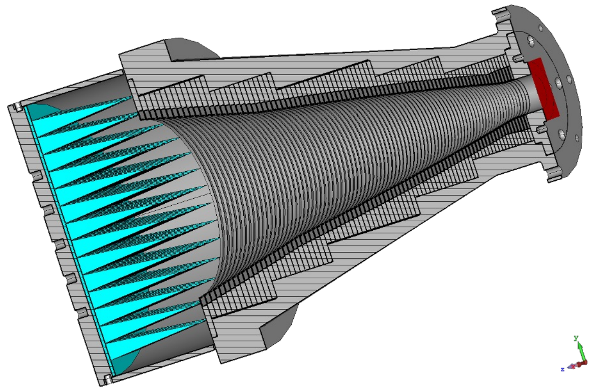
Specs: Emissivity > 0.999 (RL<-30dB), and stable in temperature (within 1mK during 1h observation).

Implementation (INAF OAS Bologna):

- **Aluminium + pyramidal elements.** Enhancing of thermal conductivity and emissivity
- **Coating of Eccosorb CR117** to increase absorption.
- **Radiation shield in Aluminium** to avoid stray constributions

EM modelling. CST Studio Suite and HFSS. Stand-alone and with TMS feedhorn. **Computation of the dissipated power distribution**

EM tests (UniMi). Room temperature measurements of reflectivity.



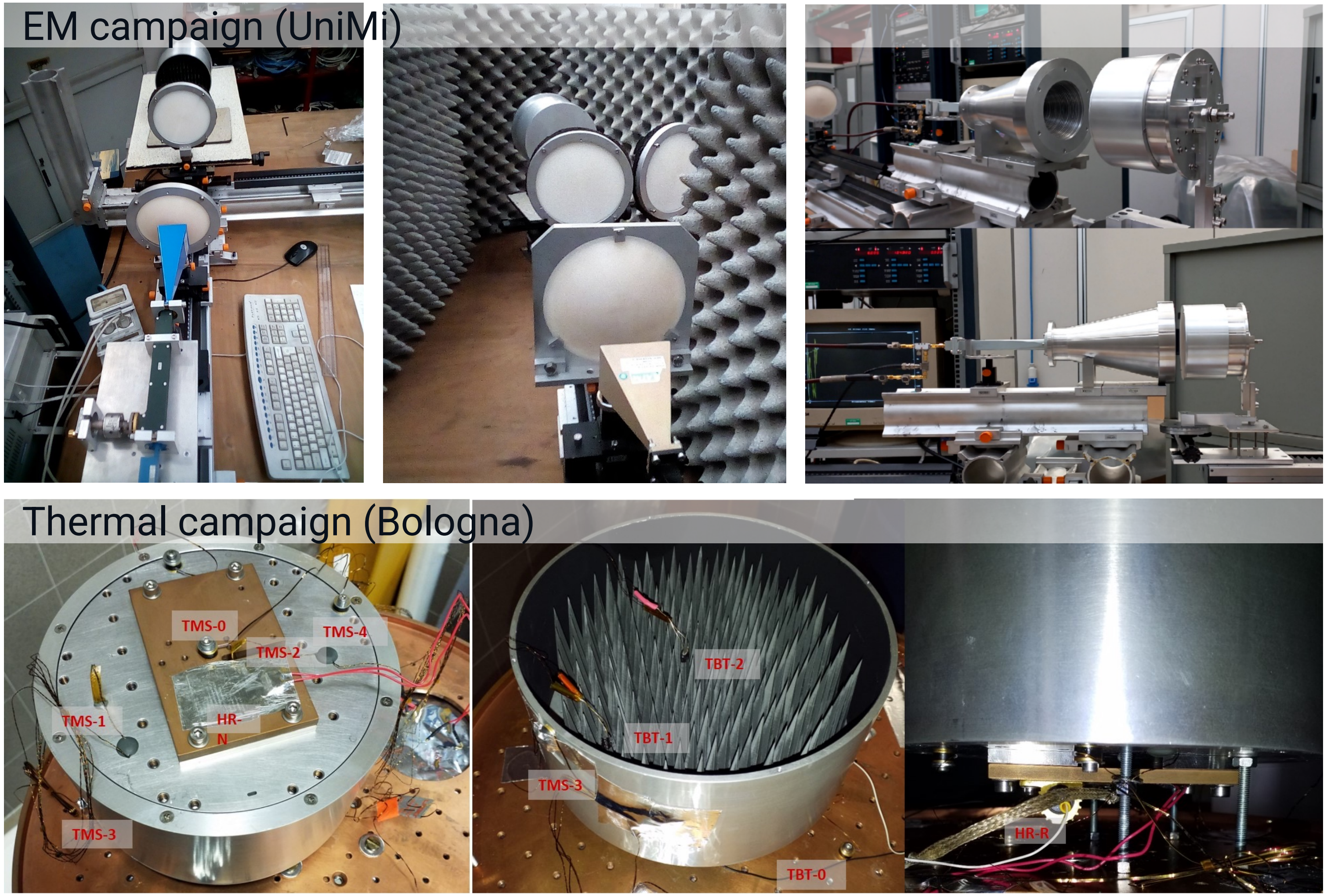
Thermal modelling. ESATAN-TMS software. Computation of **thermal gradients.** Thermal stability.

Thermal tests (Bologna). 20 complete cycles – thermal stress. Steady state tests -- gradients + balance. Transient tests -- validation of model.

Alonso-Arias, Cuttaia, Terenzi, Simonetto, Fuerte-Rodríguez, Hoyland & Rubiño-Martín (2024)

TMS: reference cold load

Testing campaigns



(Alonso-Arias et al. 2024)

TMS: reference cold load

EM tests results.

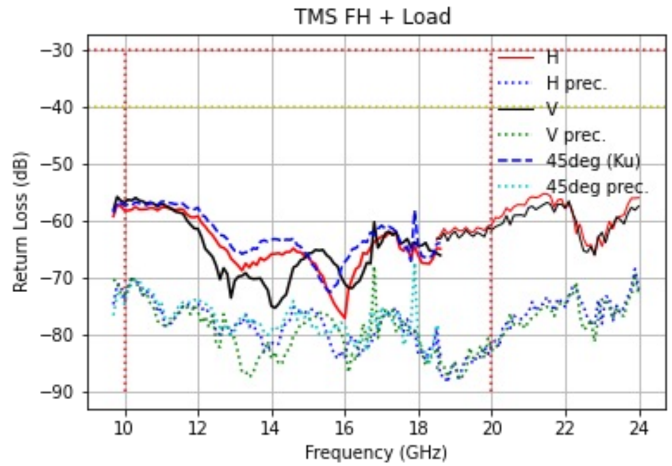
- Return loss much better than -30 dB requirement, better than -40 dB goal for most of band.

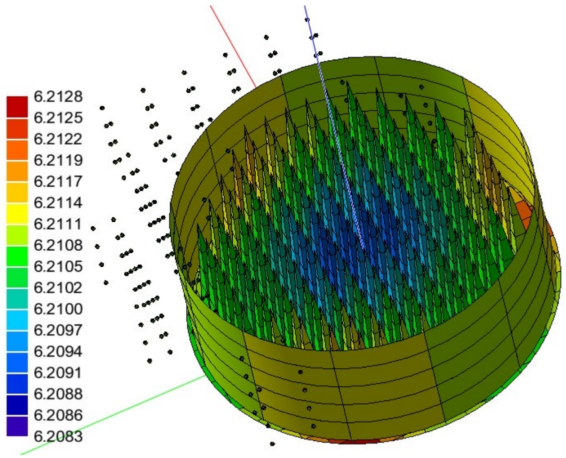
Thermal tests results.

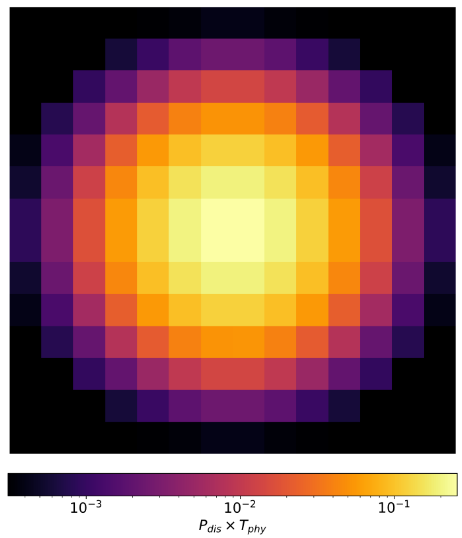
- Measured thermal gradients in operational conditions ~25 mK.
- Mesurable effect of thermal imbalance for environment temperatures > 20 K

Load model: Equivalent emissivity model.

- Brightness temperature seen by TMS horn derived from EM and thermal models (not including the shield contribution).
- Higher contribution from central pyramids → Central sensor gives a reference value for the load brightness temperature.
- **6.2 K** blackbody emitter, precision of sub-μK across the band 10-20GHz.







(Alonso-Arias et al. 2024)

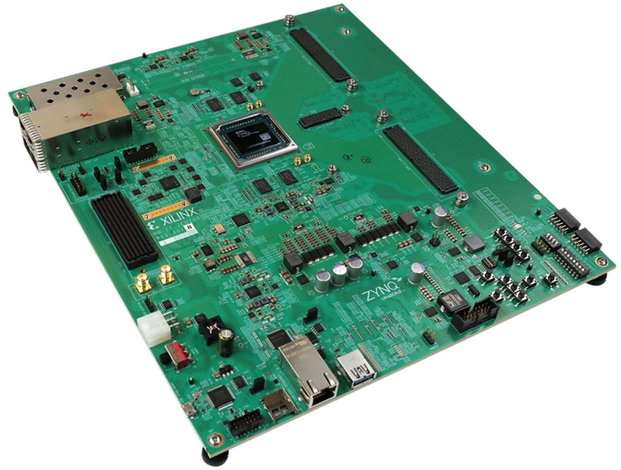
TMS: DAS

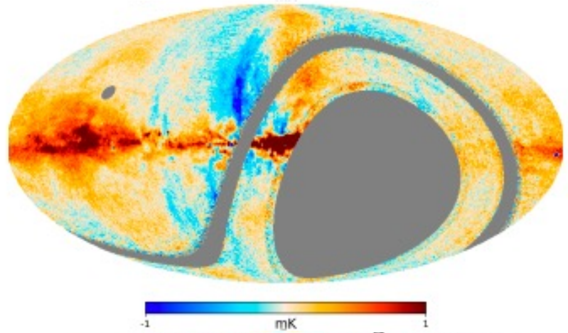
Data Acquisition System (DAS) based on a SoC-FPGA:

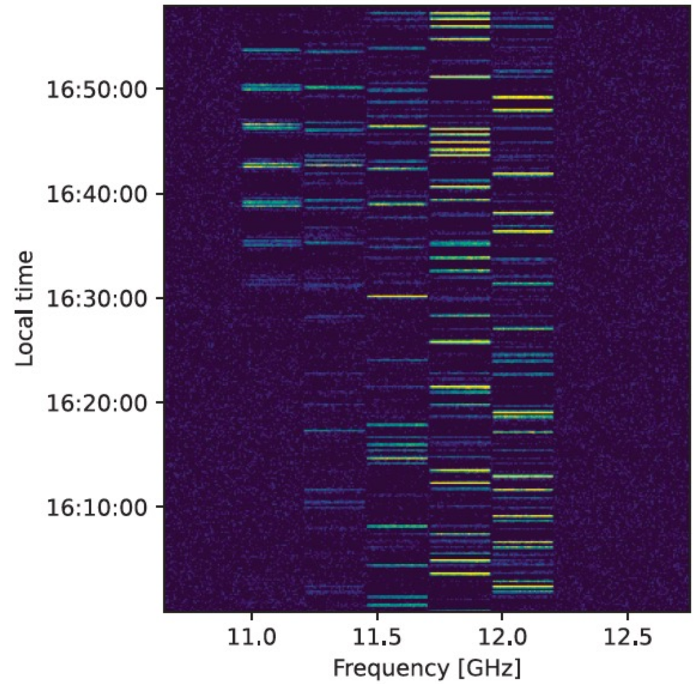
- ZCU208 RFSoC Ultrascale board (Xilinx).
- Sampling frequency 5.0 Gsps
- Maximum bandwidth of 2.5 GHz at each RF input.
- Down-conversion modules and LO distribution blocks provide the down conversion to the baseband.
- The backend implements a hard programmed polyphase filterbank (PFB) and a Fast Fourier Transform (FFT) in order to retrieve the spectral information from the digitised samples of the fast onboard ADCs in the time domain.

Same DAS will be used in new MFI2 instrument for QUIJOTE (Hoyland et al. 2022, SPIE).

Digital systems are essential due to their capability to **filter out unwanted RFI signals**, particularly in this band (geostationary satellites, satellite constellations).







The QUIJOTE experiment

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

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

QT-1. Instruments: MFI, MFI2.
11, 13, 17, 19 GHz. Δv=2GHz.
FWHM=0.93º-0.62º
MFI: 2012-18.
MFI2: 2023-

QT-2. Instruments: TGI & FGI
30 and 40 GHz. Δv =10GHz
FWHM=0.37º-0.28º
Commissioning 2018.
Observations re-started 2021.

NGI: 90GHz camera.
1000 detectors (KIDs).

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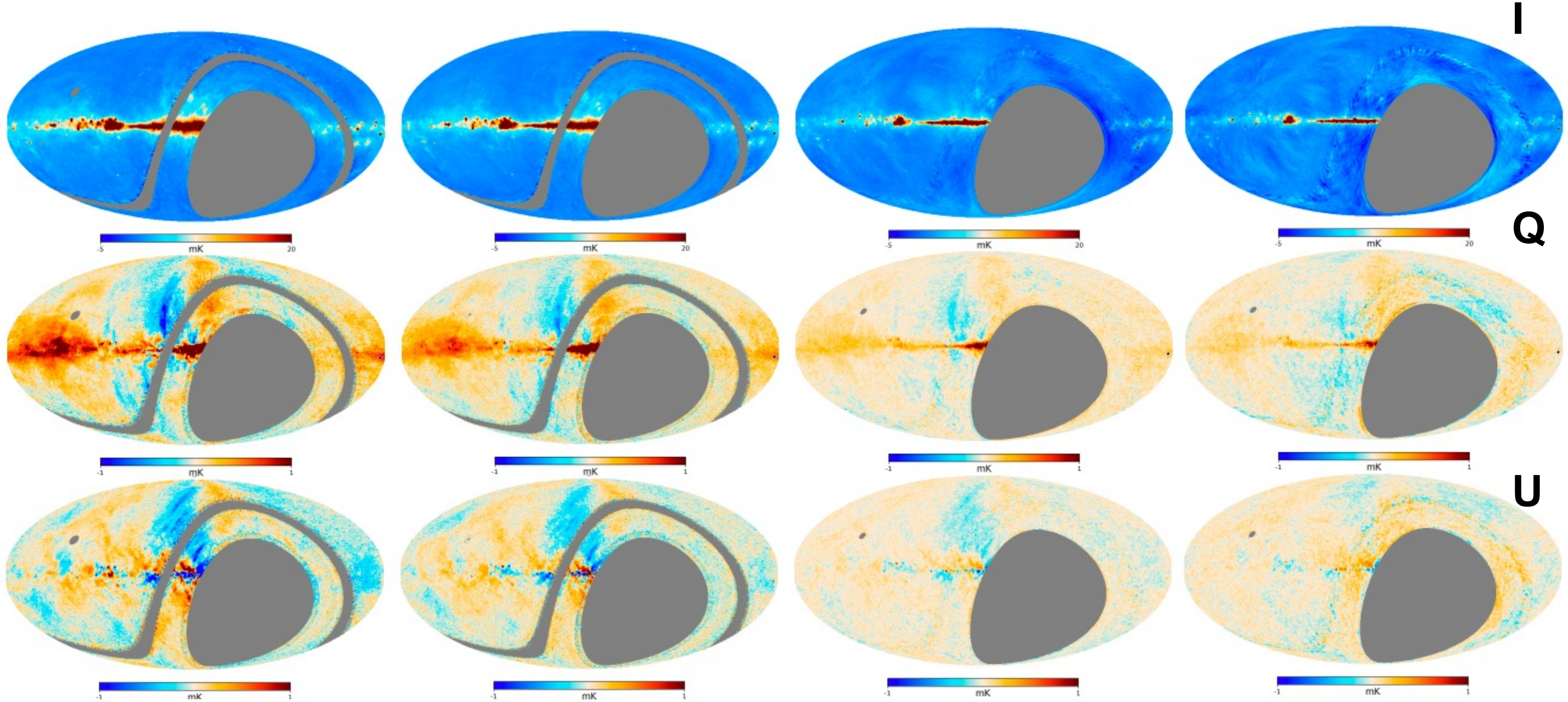
Wide survey with the QUIJOTE MFI (10-20 GHz)

Smoothed 1 deg maps

(Rubino-Martin et al. 2023)

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

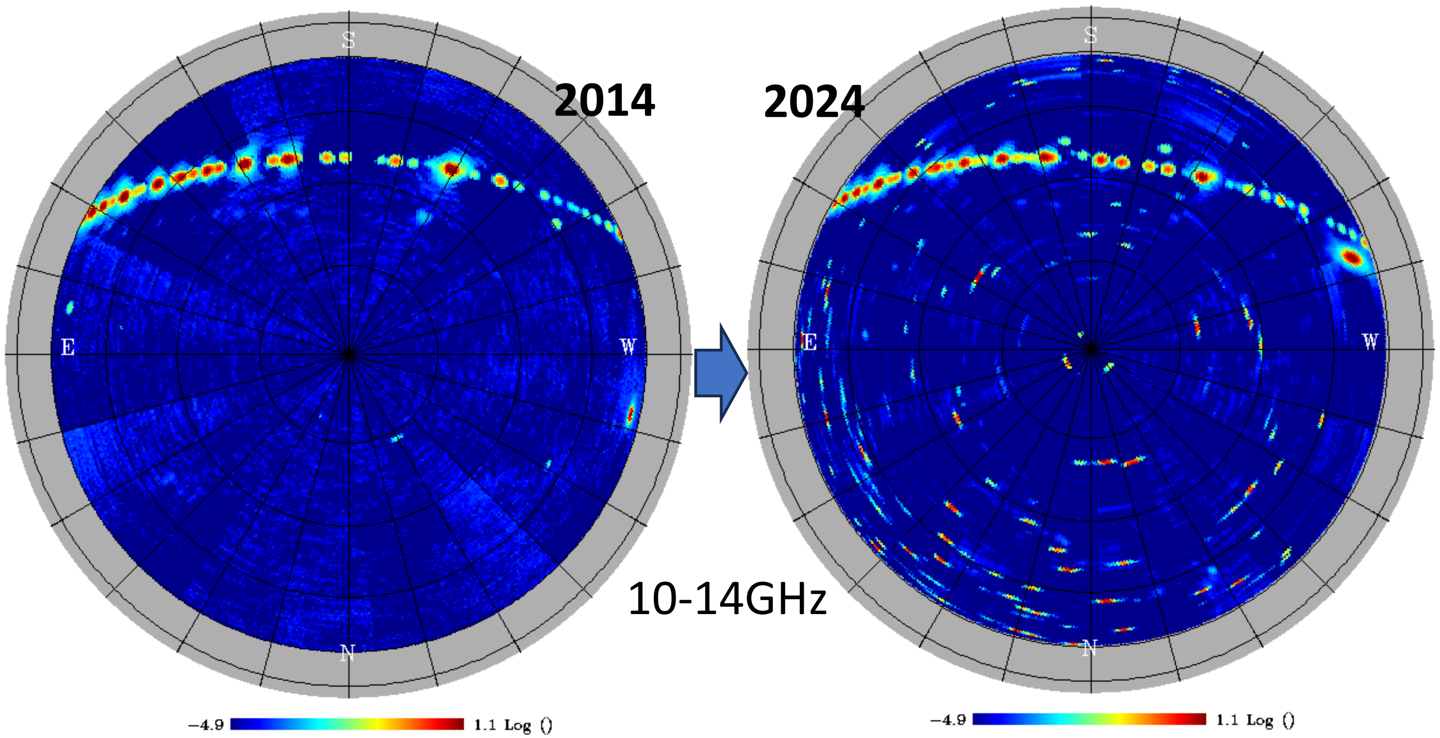


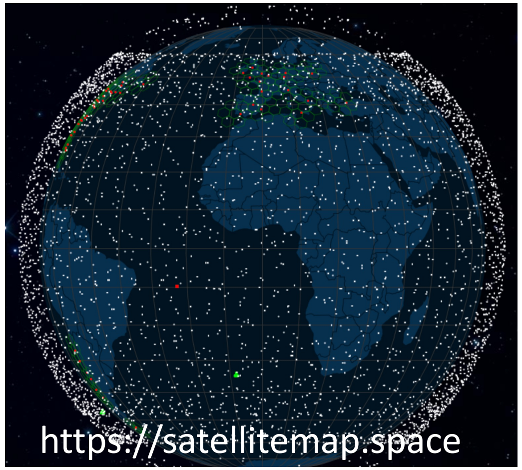
QUIJOTE 11GHz **QUIJOTE 13GHz** **QUIJOTE 17GHz** **QUIJOTE 19GHz**

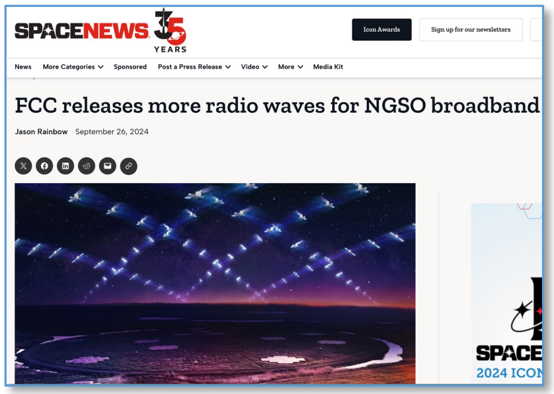
Approx. 29,000 deg^2. About 10,000 h of observations. Sensitivities in polarization (Q,U): ~35-40 μK/deg → equivalent to 2.4 μK.arcmin @ 100GHz with β=-3.

QUIJOTE MFI2 instrument – commissioning & RFI

- **First light: March 15th, 2024.** Using old MFI DAS (no polarization measurements yet).
- **Noise levels**. Significant improvement wrt MFI. New Tsys values a factor of 2 better. Better correlated noise properties (fknee~1.6Hz, compared to 50Hz for MFI).
- **RFI contamination**: Significant impact of megaconstellations at 10.7-12.7GHz (Starlink, OneWeb). New geostationary satellites in the high frequency bands (17-19GHz).
- RFI problem getting worse (17GHz, Ka band for TV: 37.5-42.5GHz).
- **Digital DAS are needed at these frequencies!**







17.3-17.7GHz

TMS and QUIJOTE-MFI2 DAS: list of tasks to complete

Tasks	HW status Acquired/not yet acquired	Design phase	Design verified Proof of concept
Down-converter	Acquired	Concept	No
Local Oscillators	Acquired	Concept	No
BEM Amplifiers	Acquired	Concept	No
Diplexer	Acquired	Concept	No
Baluns	Acquired	Implemented	Yes
FPGA (ZCU208)	Acquired	implemented	yes
Base overlay		implemented	yes
FIR FILTER		implemented	yes
FFT		implemented	yes
Averaging		Implemented	yes
1/10Gbit ethernet		Implemented	Yes
1588 Time stamping		?	No
Calibration signal		?	No
Plotly Graphics Interface		Concept	No

IAC team involved in the development: R. Hoyland. D. Diaz-Martin

TMS analytic response and syst. errors

Angela Arriero

Systematic error characterization: Jones matrices

$$\mathbf{J}_{\mathrm{OMT}} = \begin{pmatrix} (1+O_x^k) & O_a^k \cdot e^{i(\theta_2+\theta_3)} \\ O_a^k \cdot e^{i\theta_2} & (1+O_y^k)\cdot e^{i\theta_3} \end{pmatrix} \qquad \mathbf{J}_{\mathrm{hyb}} = \frac{1}{\sqrt{2}} \begin{pmatrix} (1+B_1^k) & (1+B_a^k)e^{i(\beta_1+\beta_2)} \\ e^{i\beta_1}(1+B_a^k) & -e^{i\beta_2}(1+B_4^k) \end{pmatrix} \qquad \mathbf{J}_{\mathrm{LNA}} = \begin{pmatrix} g_1 & 0 \\ 0 & g_2 e^{i\psi} \end{pmatrix}$$

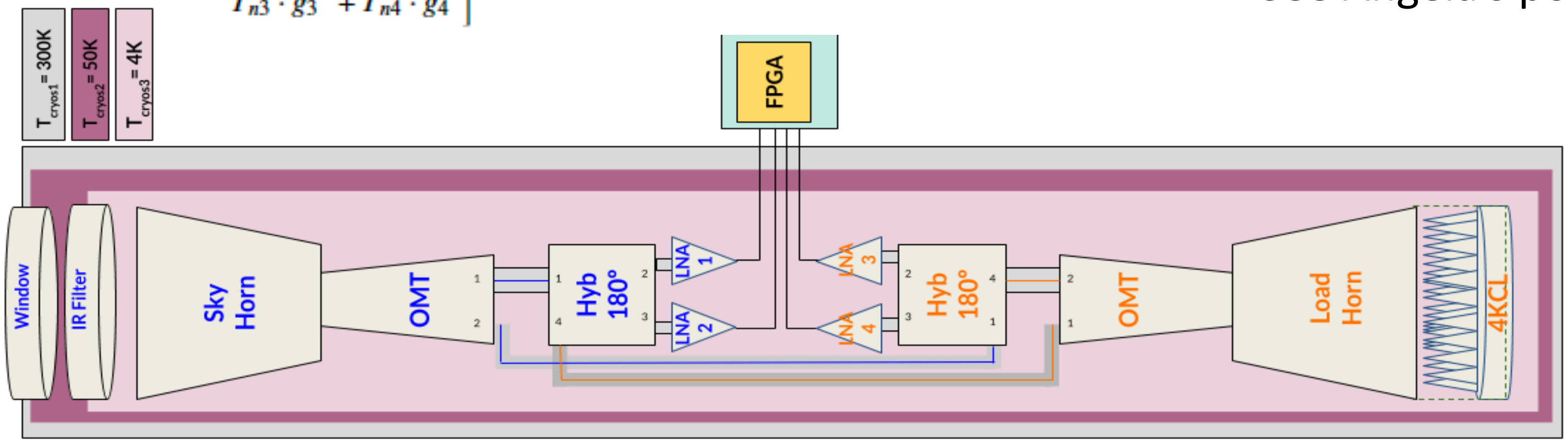
Detailed modeling of the non-ideal behavior of the components → **calibration.**

- **OMTs**. Non-ideal terms impact on polarization leakage.
- **Hybrids**. Non-ideal terms produce sky←→load mixing.
- **LNAs**. Gain imbalace also leads to sky – load mixing.

$$I1 = \frac{I_{\mathrm{sky}}}{8}\left[B_{11}(B_{11}+4) + B_{21}(B_{21}+4) + 1\right] + \frac{I_{\mathrm{load}}}{8}\left[B_{14}^2 + B_{24}^2\right] + \frac{Q_{\mathrm{load}}}{8}\left[B_{14}^2 - B_{24}^2\right] + \frac{Q_{\mathrm{sky}}}{8}\left[B_{11}(B_{11}+4) - B_{21}(B_{21}+4)\right]$$

$$I1 = \frac{I_{\mathrm{sky}}}{8}\left[(g_1+g_2)^2 + (g_3+g_4)^2\right] + \frac{I_{\mathrm{load}}}{8}\left[(g_1-g_2)^2 + (g_3-g_4)^2\right] + \frac{Q_{\mathrm{load}}}{8}\left[(g_1-g_2)^2 - (g_3-g_4)^2\right] + \frac{Q_{\mathrm{sky}}}{8}\left[(g_1+g_2)^2 - (g_3+g_4)^2\right] + \frac{1}{2}\left[T_{n1}\cdot g_1{}^2 + T_{n2}\cdot g_2{}^2 + T_{n3}\cdot g_3{}^2 + T_{n4}\cdot g_4{}^2\right]$$

See Angela’s poster

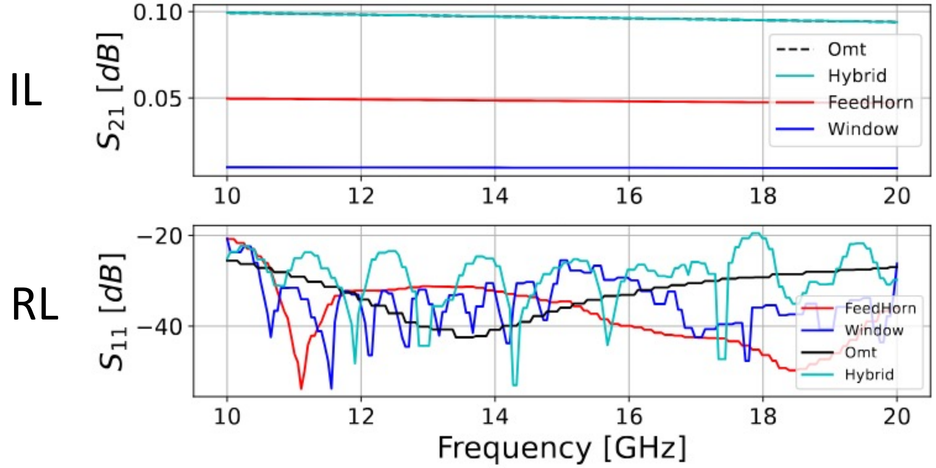


TMS: systematics and thermal model

Angela Arriero

Lossy response of passive and active RF components:

Component	T [K]	Factor	ΔT[K]
Window	300	0.002	0.68
IRF	50	0.001	0.04
FH_s	6	0.012	0.07
OMT_s	6	0.023	0.14
Hs_{180}	6	0.022	0.13
LNA1	6		3.8
Cum. G1	-		4.86
LNA3	6		3.8
Cum. G3	-		4.86
Load	8		
FH_l	6	0.011	0.07
OMT_l	6	0.023	0.14
Hl_{180}	6	0.022	0.13
LNA2	6		3.8
Cum. G2	-		4.14
LNA4	6		3.8
Cum. G4	-		4.14

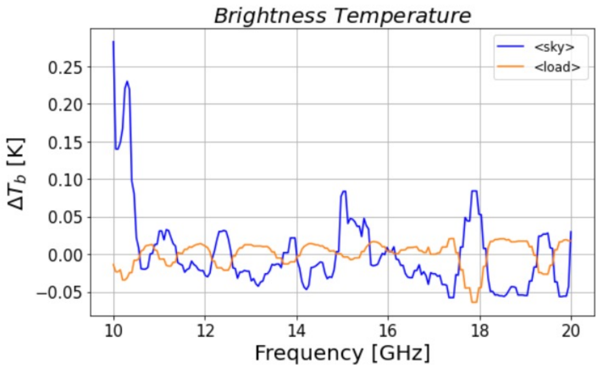


S21 or Insertion Loss (IL): Values in literature.
S11 or Return Loss (RL): Values taken from Alonso-Arias (PhD thesis)

Component initial values for TMS simulation:
Physical temperatures, losses, spillover, environment and cryostat temperatures.

Friss equations:

$$S_{TMS} = T_{inp} \cdot L_{eff1} + \sum^{i} T_i \cdot L_{eff2} + T_{noise} + T_{\mathrm{env1}} \cdot L_{eff3}$$



Stability: impact of thermal variations of absolute measurements, response to 1mK change.

Component	$\Delta Ts_o[\mu K]$	$\Delta Tl_o[\mu K]$
FH_s	10.5	0
OMT_s	43	0
Hs_{180}	88.2	0
FH_l	0	10.5
OMT_l	0	43
Hl_{180}	0	0

Values to be calibrated and corrected in the data analysis.

Conclusions
TMS absolute calibration

- **IAC project. Instrumental participation:**

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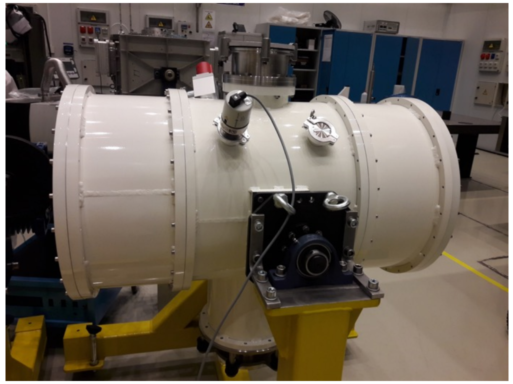
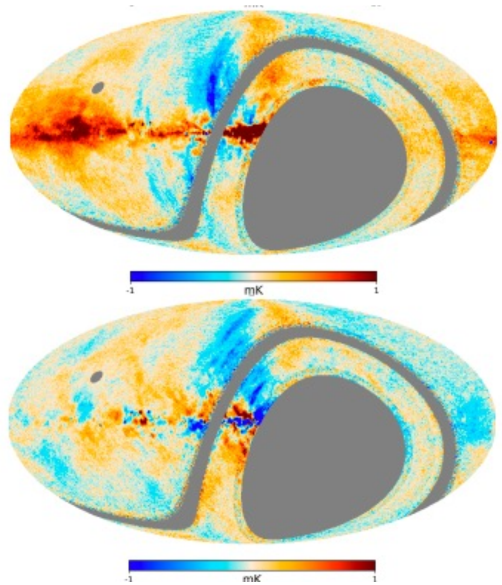


- **Science driver**: Ground-based low resolution spectroscopy observations in the 10-20GHz range to characterize foregrounds and CMB spectral distortions. Provides absolute calibration for QUIJOTE-MFI.

- **Prototype for future instruments. Legacy value (Radio Synchrotron Background).** Complementing future space missions (10-20GHz).

- **Absolute calibration.** Three aspects discussed in this talk:
  - **Design of the reference load.**
    - **6.2 K** blackbody emitter, precision of sub-μK across the band 10-20GHz.
    - Instantaneous comparison sky-load (1/f suppression).
  - **Digital DAS (FPGAs).**
    - Needed for RFI removal! (megaconstellations)
    - Additional advantages for calibration (bandpass response) to be investigated.
  - **Modelling instrumental response / thermal response.**
    - Gain calibration / balanced radiometer.
    - Thermal contribution of passive and active components → to be calibrated (temperature sensors & thermal model).

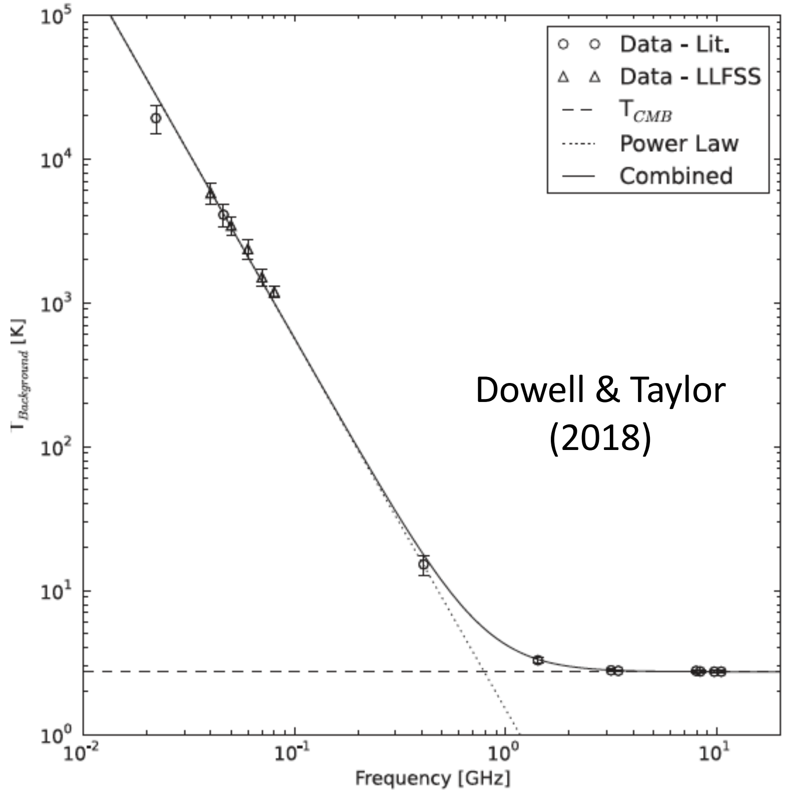


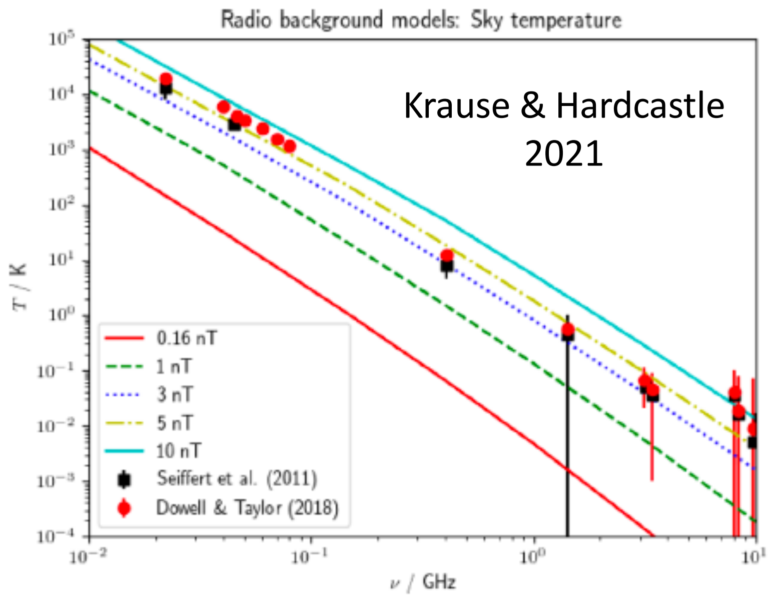
Extra slides

RSB - current status

Status of the field described in two conferences (see Singal et al. 2018; 2023).

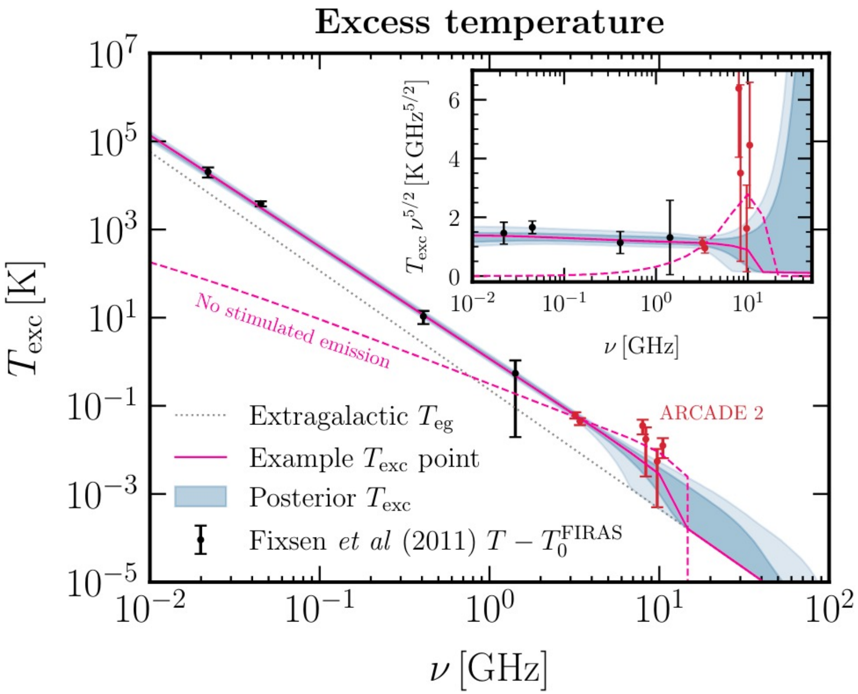
- **Confirmed with LWA1 measurements** between 35-80MHz. See Dowell & Taylor (2018).
- Detected emission is much larger than the expected **radiosource contribution at these frequencies**:
  - Gervasi et al. 2008; Vernstrom et al. 2011.
  - Vernstrom et al. (2014). P(D) analysis provide estimates at 3GHz of ~14mK, well below the ARCADE excess (>80mK).
  - Contribution of cosmic web does not explain the excess (Brown et al. 2017).
- **Local origin?**
  - Subrahmanyan & Cowsik 2013 – plane parallel model is not appropriate. But large halo required.
  - Synchrotron from local bubble: requires high magnetic field strengths in the halo (3-5 nT). Krause & Hardcastle (2021).



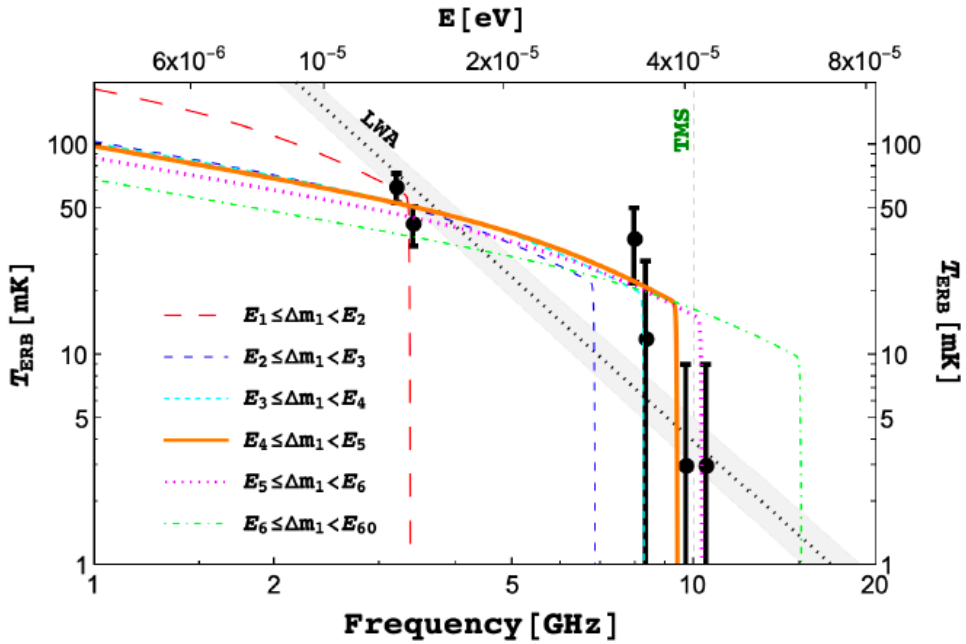


RSB - current status (II)

- Extragalactic origin and other explanations:



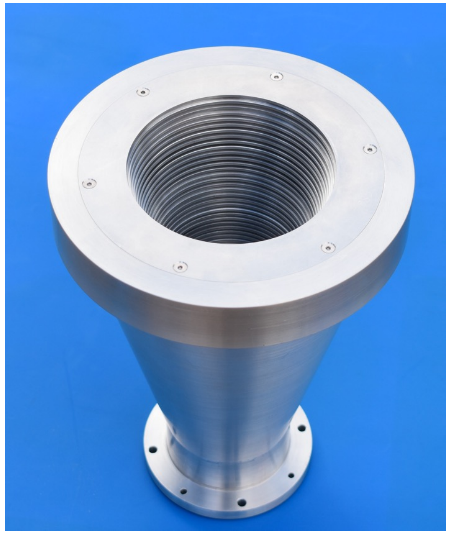
Predictions of the frequency dependence of the RSB excess temperature in the ULDM model of Caputo et al. 2023 (stimulated DM decay).

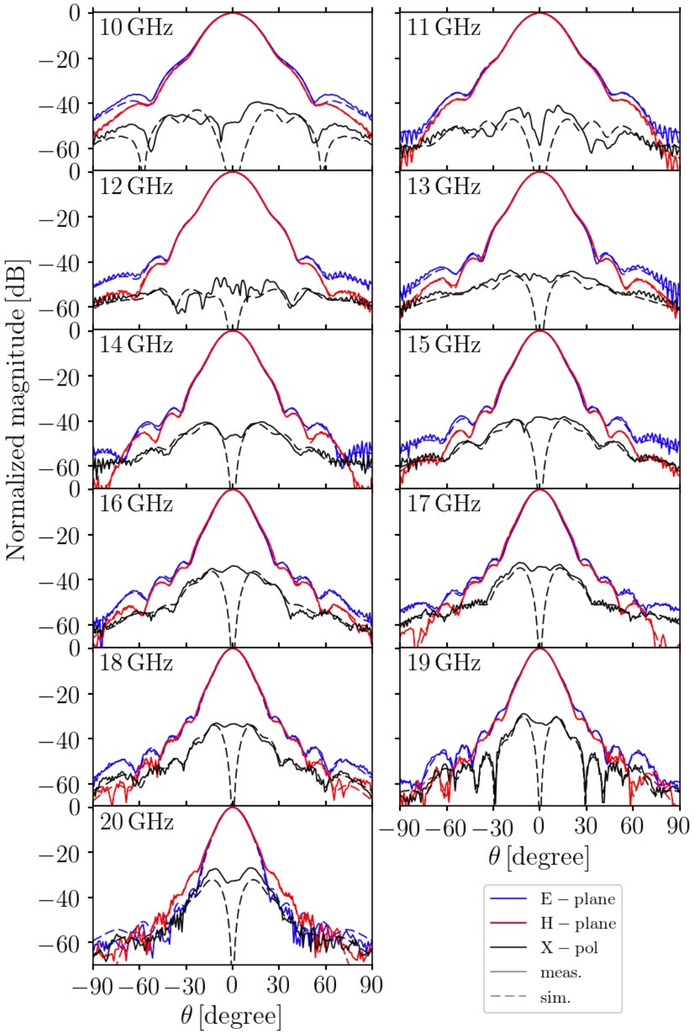


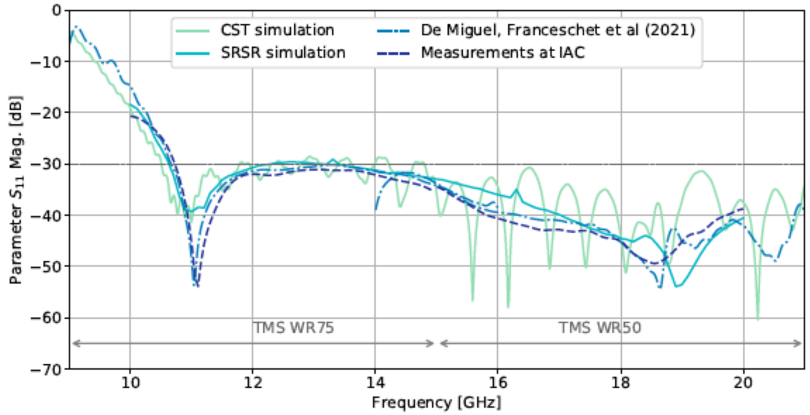
Predictions for the radiative decays of a relic neutrino ν into a sterile neutrino νs, assumed to be quasi-degenerate, to explain the RSB excess (Bhupal Dev et al. 2024).

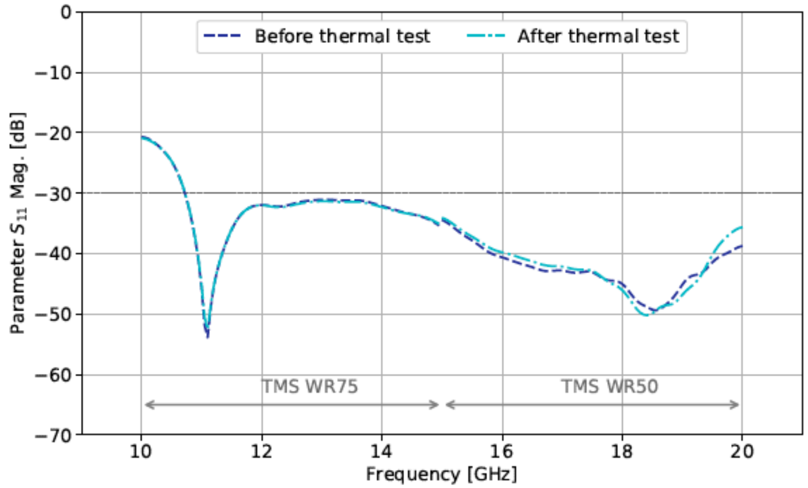
TMS: horns

Meta-horn antenna formed of meta-rings, to ensure 2:1 operation (De Miguel et al. 2021).
Return loss < -30dB, **Xpol** < -30dB (Alonso Arias et al. 2024).









TMS: OMT and 180º hybrid covering one octave

Paz Alonso

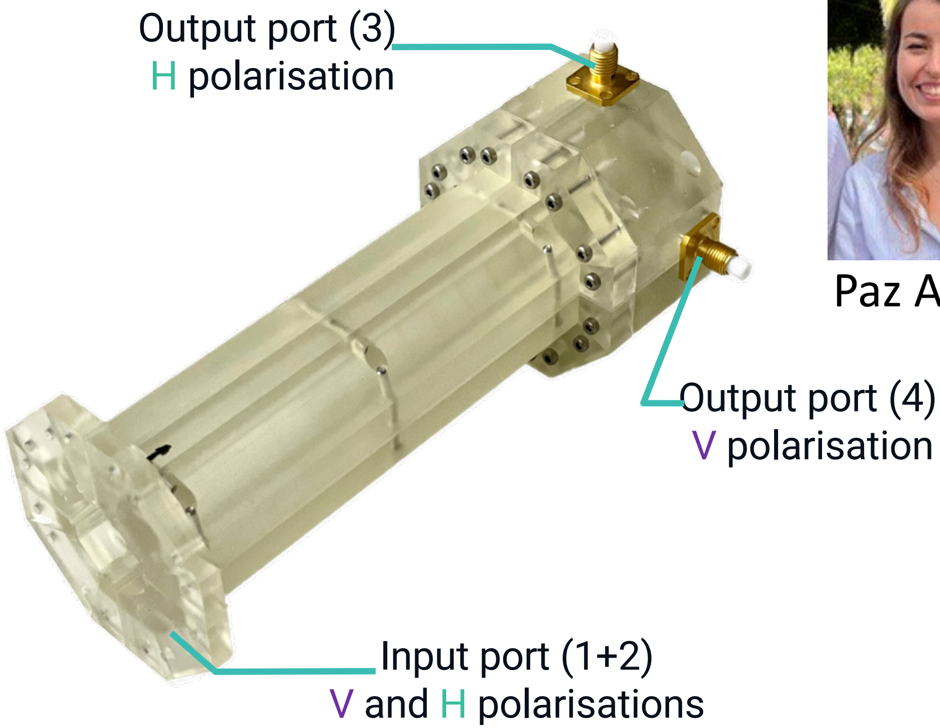
OMT (2:1)

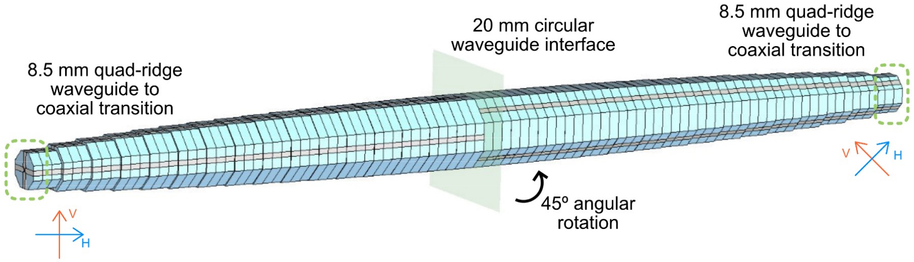
- **Quad-ridge waveguide technology** to ensure 2:1 operation
- **Highly symmetric design** to avoid resonating high-order modes.

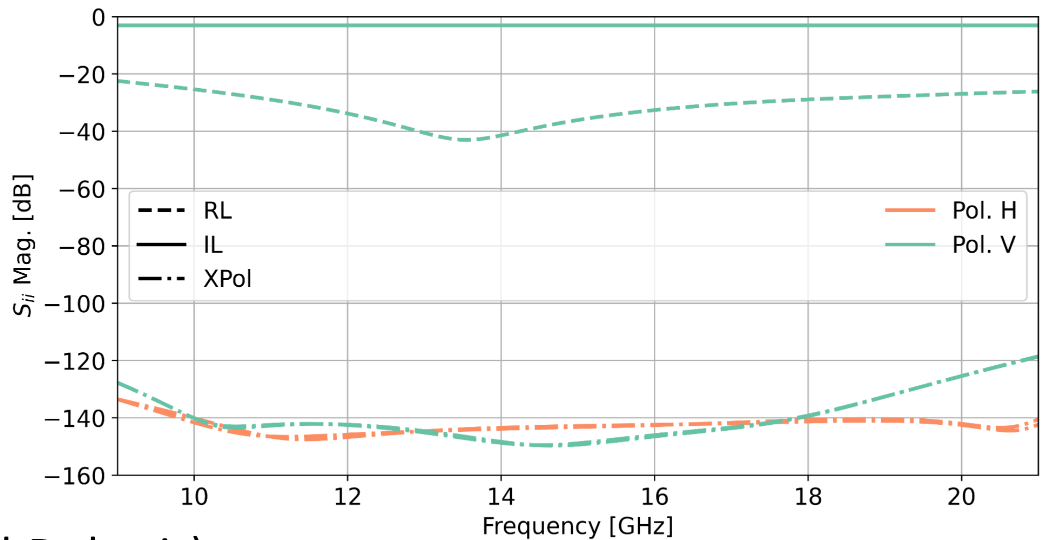
- RL < -25 dB (worst value at 10 GHz)
- Xpol < -30 dB expected
- Output phase imbalance < 3º

180º hybrid coupler (2:1)

- Novel concept for 180º hybrid coupler based on OMT design.







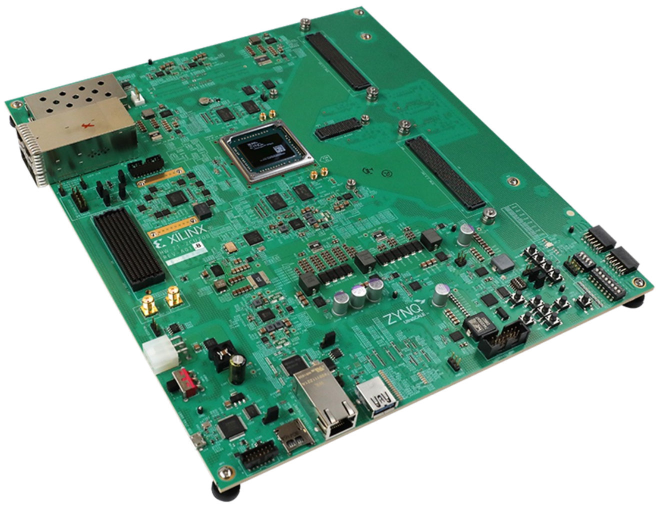
(P. Alonso-Arias PhD thesis)

Our methodology
(PYNQ, VIVADO,VITIS Model Composer)

- PYNQ is an open-source project from AMD® that makes it easier to use Adaptive Computing platforms.

- Using the Python language and libraries, designers can exploit the benefits of programmable logic and microprocessors to build more capable and exciting electronic systems.

- PYNQ can be used with Zynq, Zynq UltraScale+, Zynq RFSoC, Alveo accelerator boards and AWS-F1 to create high performance applications.

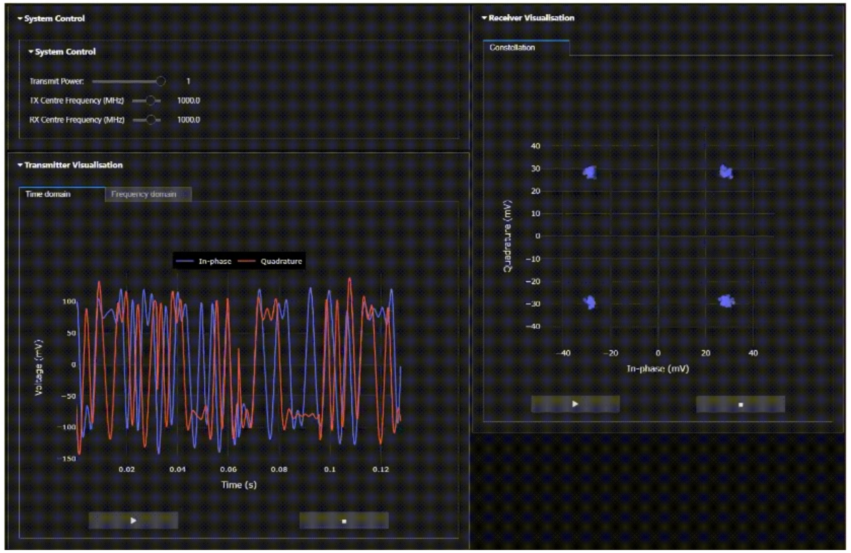


Zynq UltraScale+ RFSoCZCU208

- Onboard ADC Sample rate: 5GSPS
- Channels: 8 x 14 bits ADC
- FPGA: Gen 3 with Arm® Cortex®-A53 supporting ZYNC interface

Lab testing and final implementation: FPGA self testing

Since the FPGA boards have RF output as well as RF input only one board is necessary to test out designs



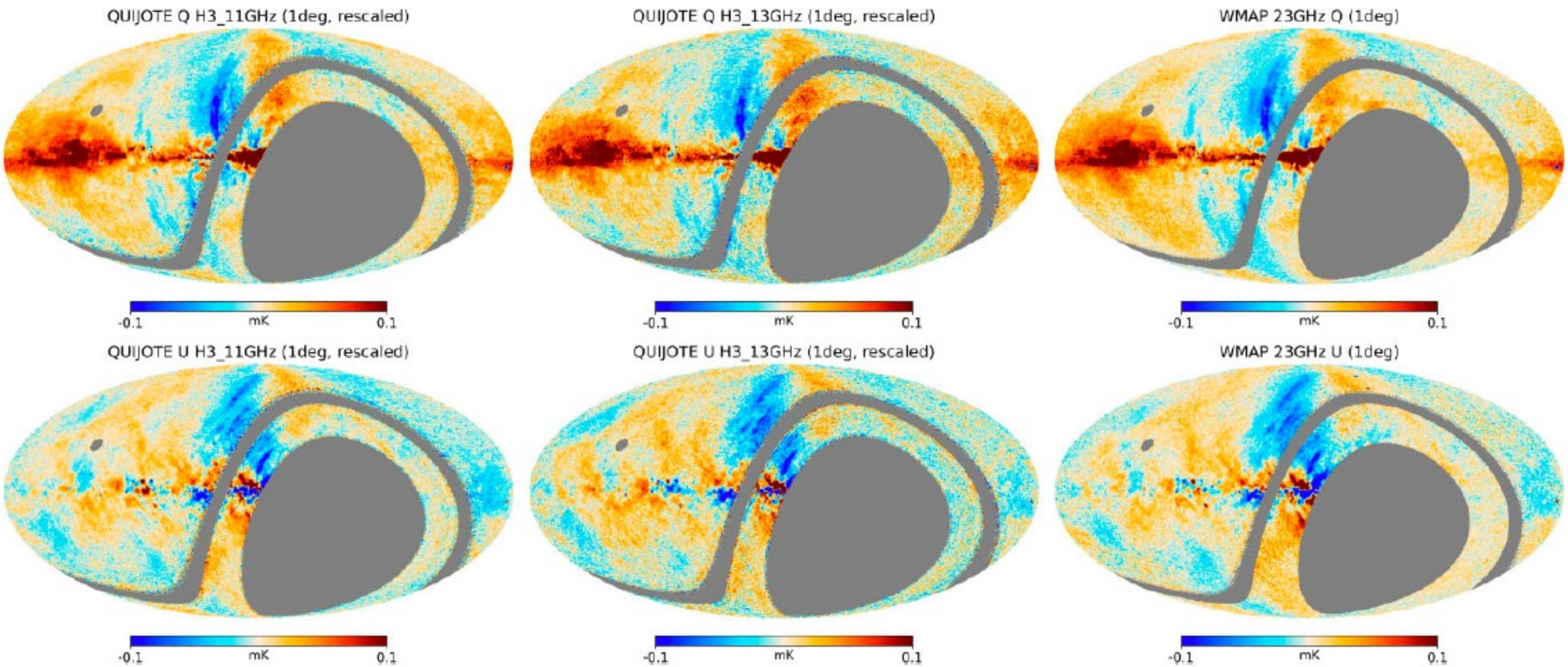
Python has a versatile web based graphics interface in Plotly

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

Quijote
Q-U-I Joint Tenerife CMB experiment

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)