The QUIJOTE experiment

and its polar modulaton techniques

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On behalf of the QUIJOTE collaboration

B-mode from space, IMPU, Tokyo, December 10-16, 2015

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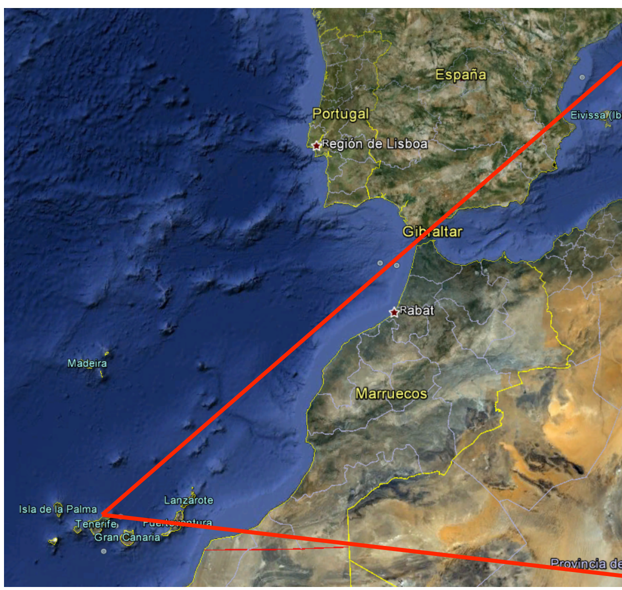
- Overview of the QUIJOTE experiment
- Radiometer instrumentation
- Polar modulaton techniques
- Beyond QUIJOTE

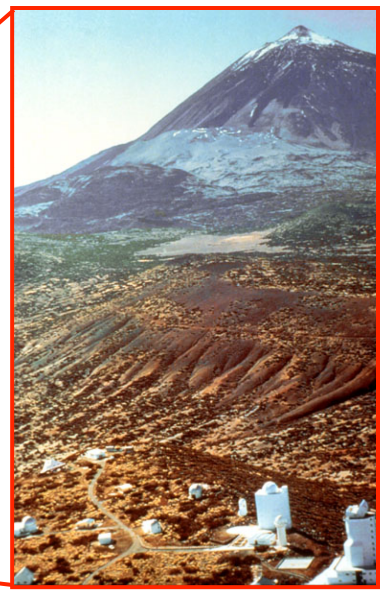
The QUIJOTE collaboration

http://www.iac.es/project/cmb/quijote
http://www.epi-consolider.es/

The QUIJOTE experiment

- QUIJOTE (Q U I JOint Tenerife Experiment) is a ground-based radio astronomy project aimed to characterize the polarization of the Cosmic Microwave Background (CMB).
- The instruments are installed and operated at El Teide Observatory, Tenerife, Spain.





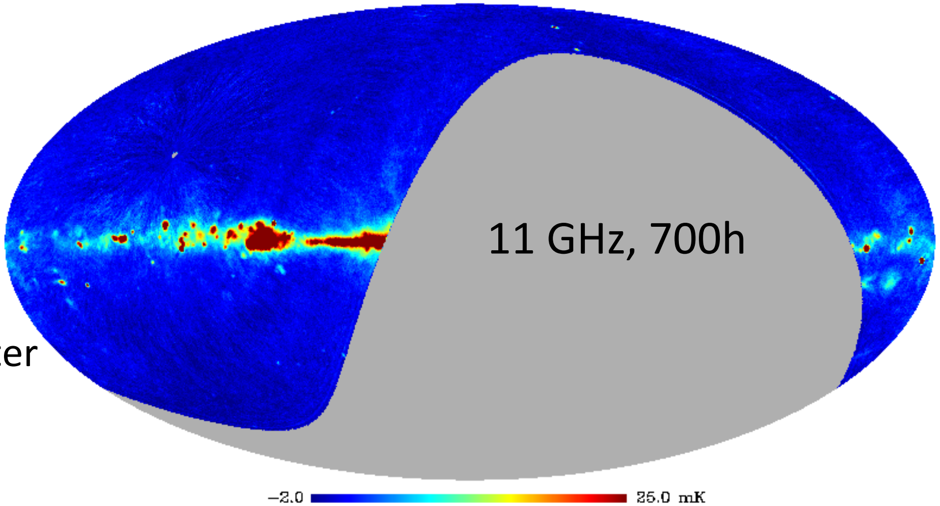
El Teide Observatory
2390 m

Dome & telescopes

Quijote
Q-U-I Joint Tenerife CMB experiment

QUIJOTE: project baseline

- **Two telescopes** (both operative) and **three instruments**: MFI (10-20 GHz) -operative-, TGI (30 GHz) –commissioning Dec 2015- and FGI (40 GHz) -2016-
- 1-deg angular resolution.
- **Surveys**:
  - Wide survey: 20,000 deg^2, ≈15 μK/deg^2 @ 11, 13, 17 and 19 GHz, ≤3 μK/deg^2 @ 30, 40 GHz
  - Deep cosmological survey: 3×1,000 deg^2, ≈4 μK/deg^2 @ 11, 13, 17 and 19 GHz, ≤1 μK/deg^2 @ 30, 40 GHz (after 1 year)
- **Scientific goals**:
  - B-modes down to r=0.05 (after 3 years), r=0.1 (after 1 year).
  - Characterization of the synchrotron and AME polarization.

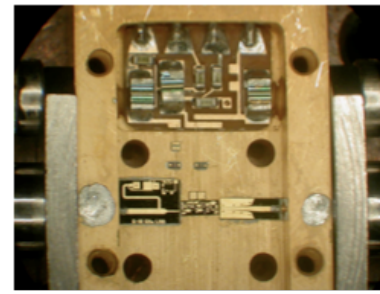


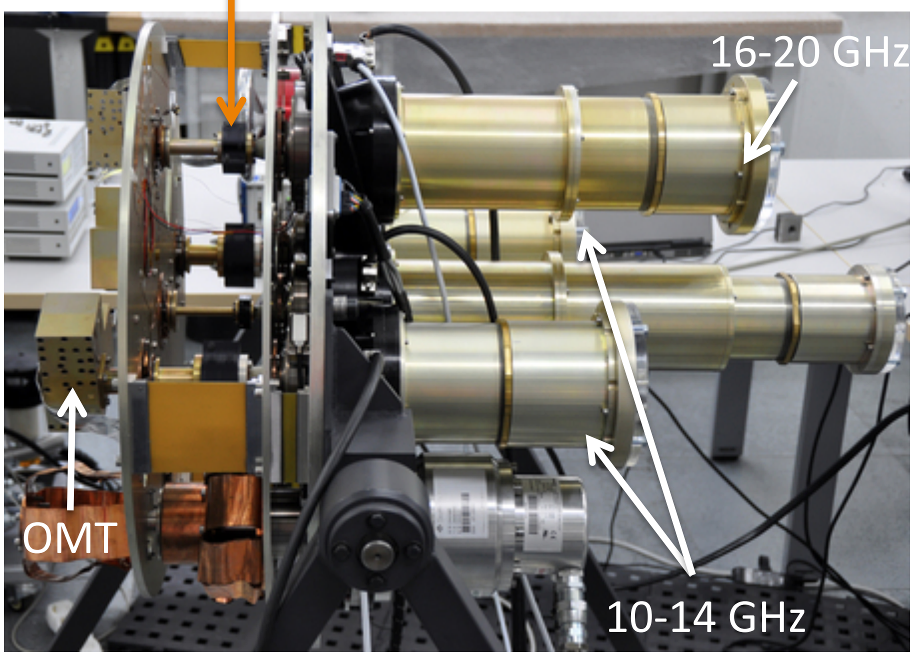
QUIJOTE dome with the two telescopes (Teide Observatory)

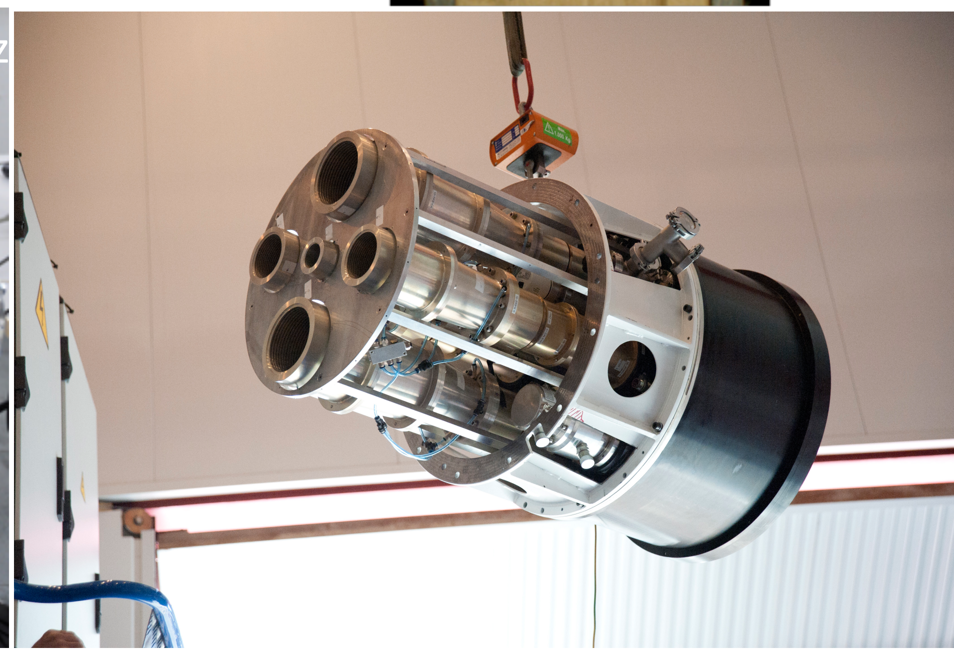
Quijote
Q-U-I Joint Tenerife CMB experiment

Multi-Frequency Instrument (MFI), 10-20 GHz

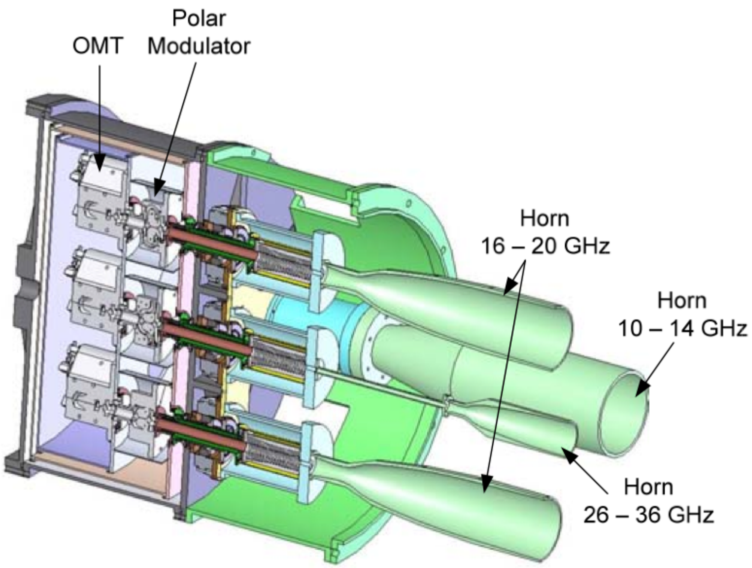
- In operation since Nov. 2012
- 4 horns, covering 4 frequencies of 2 GHz bandwidth: 11, 13, 17, 19 GHz
- Sensitivities: ~400-600 μK $s^{1/2}$ per channel







Multi-Frequency Instrument (MFI), 10-20 GHz



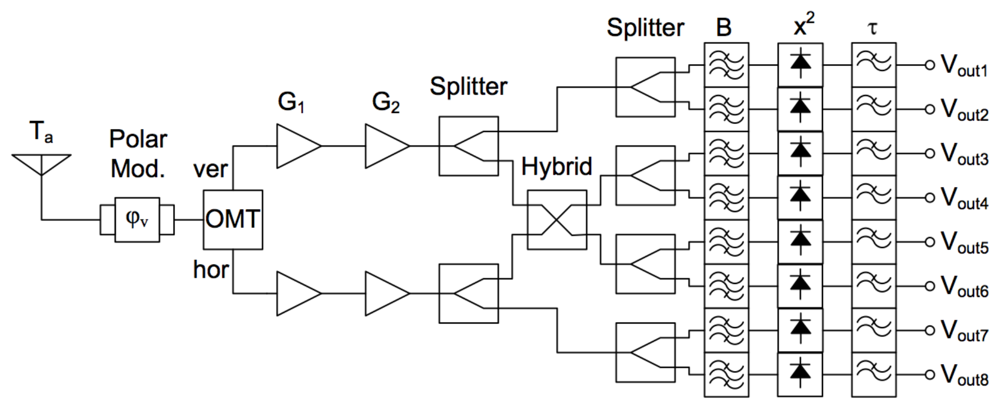
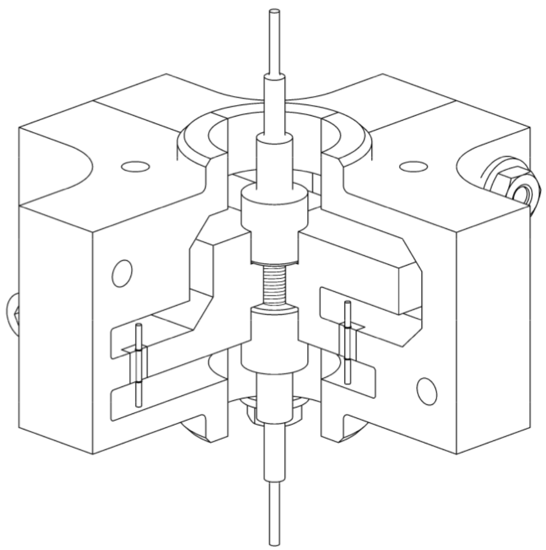


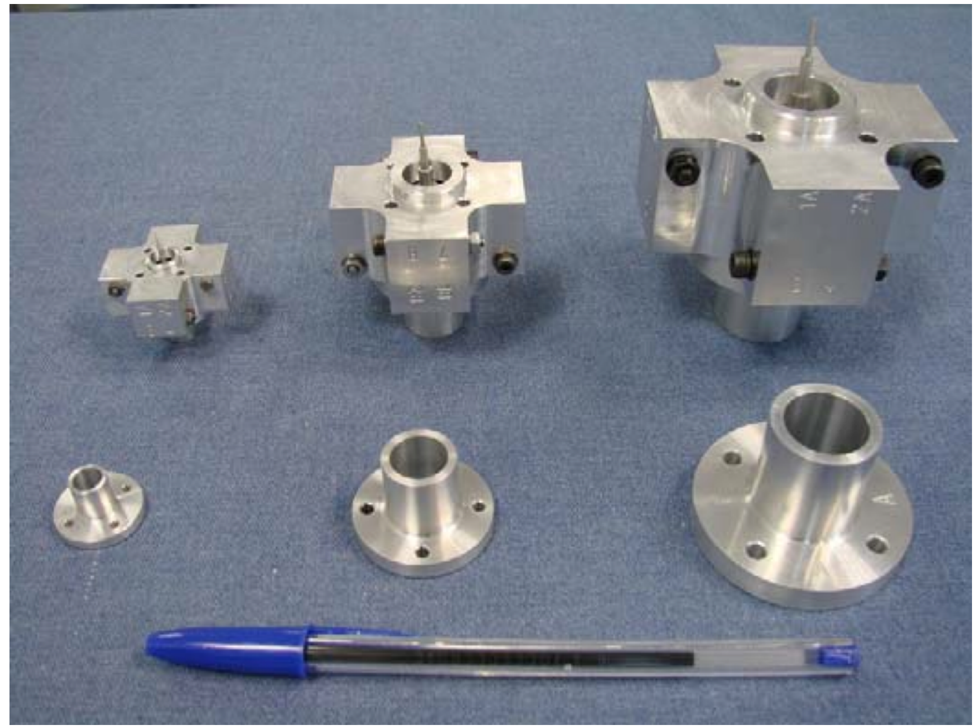
Fig. 7.5. Radiometer block diagram of the QUIJOTE project for the 10 – 14 GHz and 16 – 20 GHz bands. Each band is sub-divided into two subbands at the filter stage.

The polar modulator spins at a programmable frequency in the range 10-40 Hz and produces the modulation of the polarization. The sum of the channels gives I while the subtraction of pairs of channels gives the polarization modulation:

$$V_{\mathrm{sub}} = Q\sin(4\varphi_{\mathrm{pm}} + 2\varphi_{\mathrm{p}}) + U\cos(4\varphi_{\mathrm{pm}} + 2\varphi_{\mathrm{p}})$$

MFI polar modulator





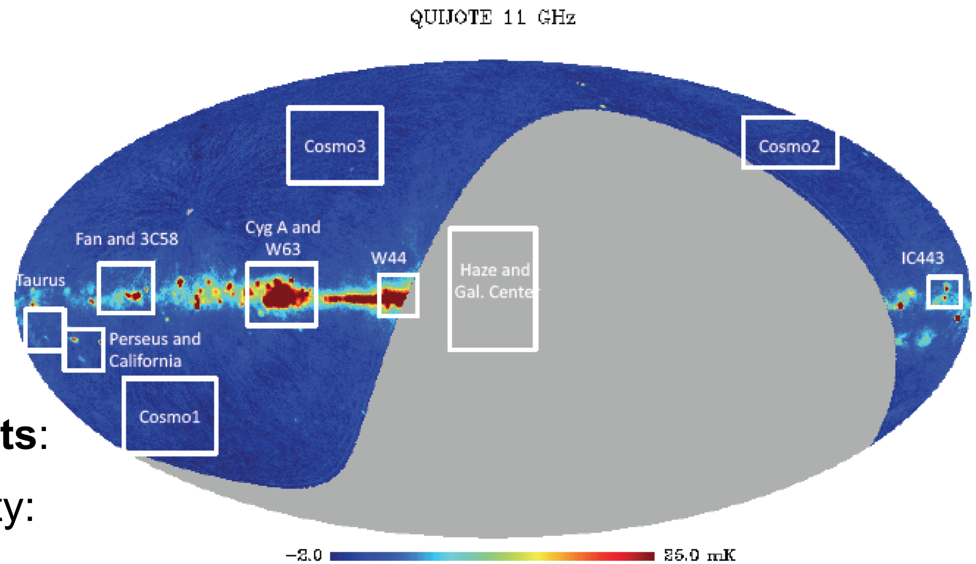
Due to problems with the degradation of the bearings (rotor and bearings work at 80 K) when performing observations the modulator is positioned at 4 discrete values.

MFI polar modulator

QUIJOTE-science

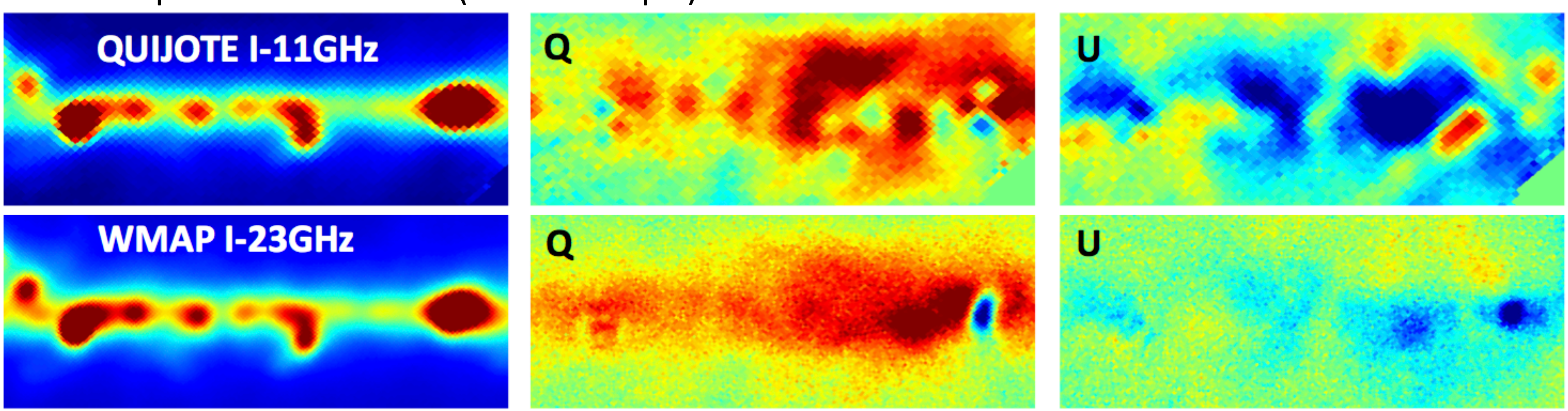
- **MFI Instrument (10-20 GHz).**
  - In operation since Nov. 2012.
  - 4 horns, covering 4 frequency bands:

  11, 13, 17 and 19 GHz.
  - Sensitivities: ~400-600 μK $s^{1/2}$ per channel.



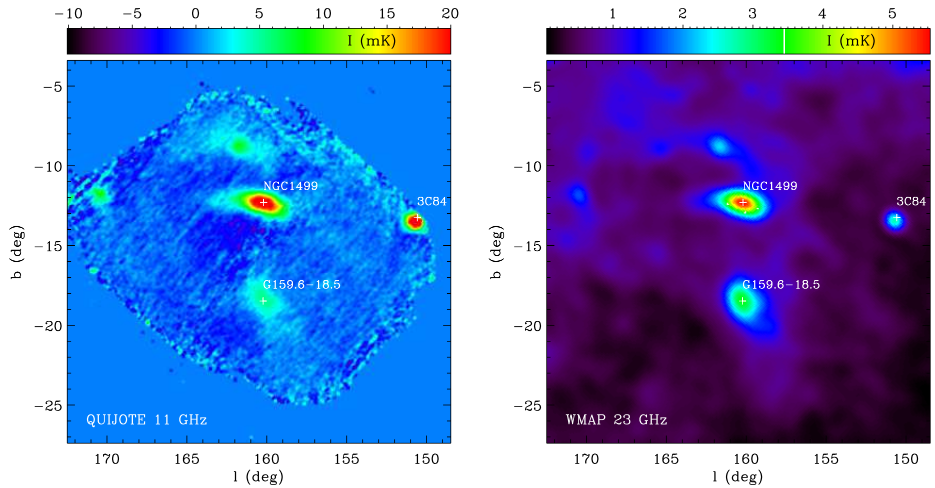
- **TGI (30 GHz) and FGI (40GHz) instruments**:
  - TGI: 31 pixels at 30GHz. Expected sensitivity: 50 μK $s^{1/2}$ for the full array.
  - FGI: 31 pixels at 40GHz. Expected sensitivity: 60 μK $s^{1/2}$ for the full array.

Galactic plane around l=8º (20ºx6º maps):

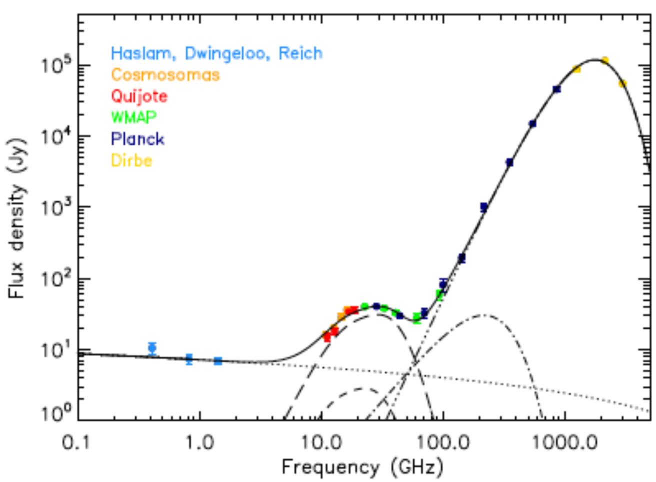


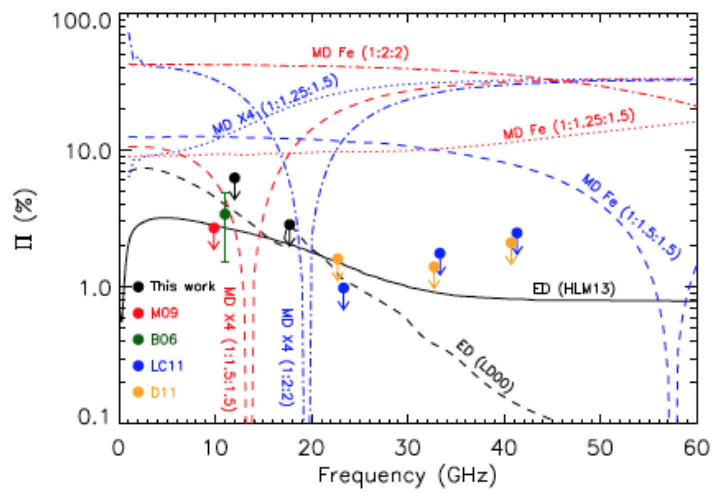
Perseus molecular complex

Génova-Santos et al. (2015), arXiv:150104491



200 hours



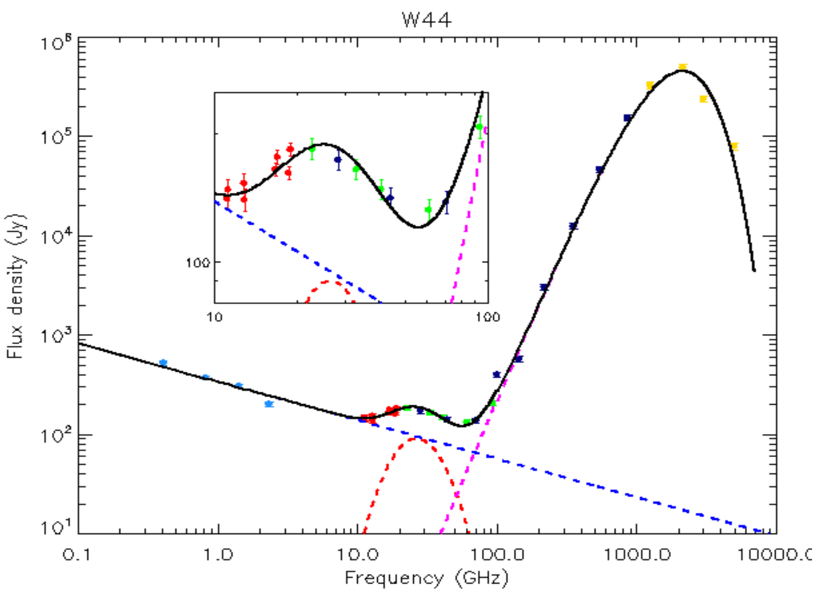


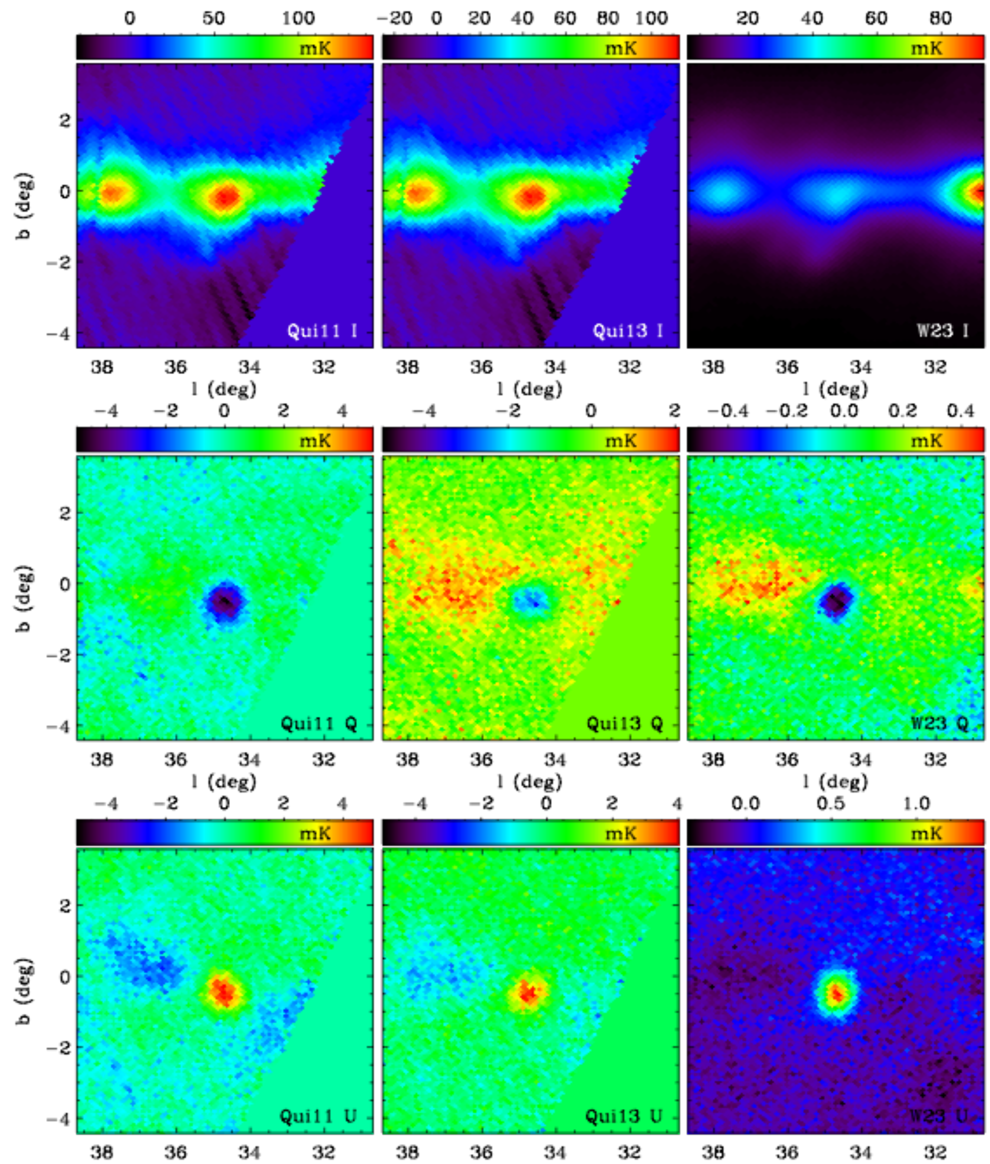
- QUIJOTE intensity provides the **first** independent confirmation of the spectral downturn
- **No polarization detection**: Π_{AME} < 10.1% at 12 GHz and < 3.4% at 18 GHz
- **TGI** observations should provide a sensitivity of $\mathbf{\Pi_{AME}}$ **~ 0.1% at 30 GHz**

Observations of AME W44

MFI results. W44

- Bright SNR on the Galactic plane showing AME (Planck collaboration et al. 2014)
- Confirmed with Quijote (50hrs)
- Possibility of getting tight polarization constraints on the AME, after subtracting out the polarized synchrotron component.



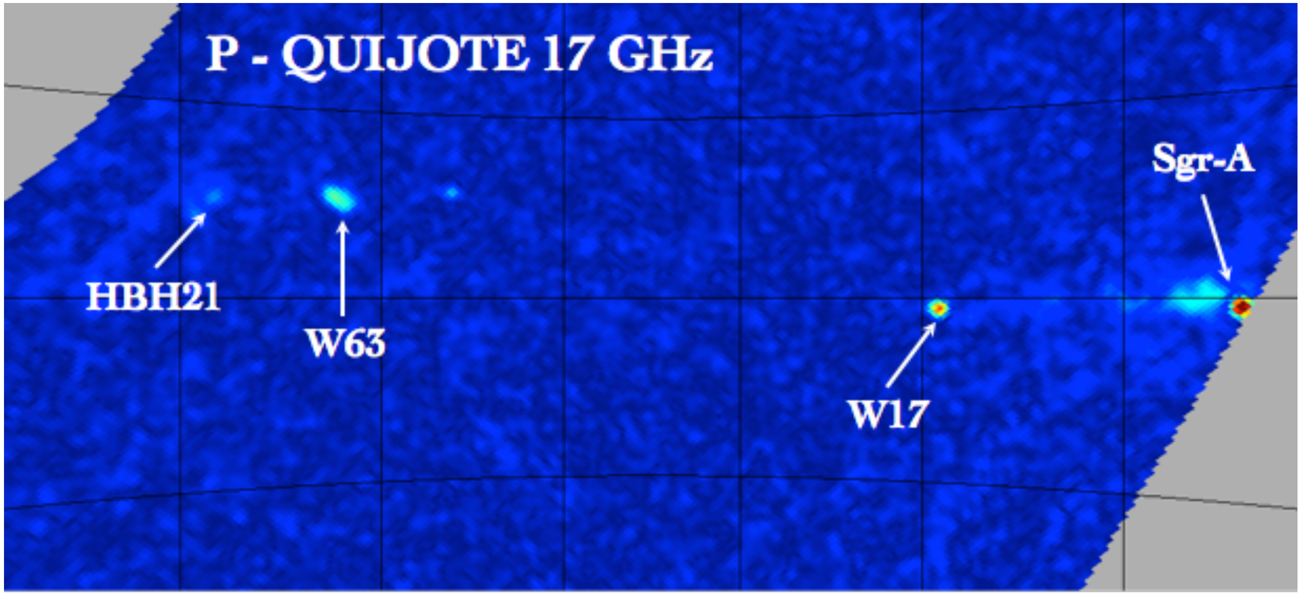


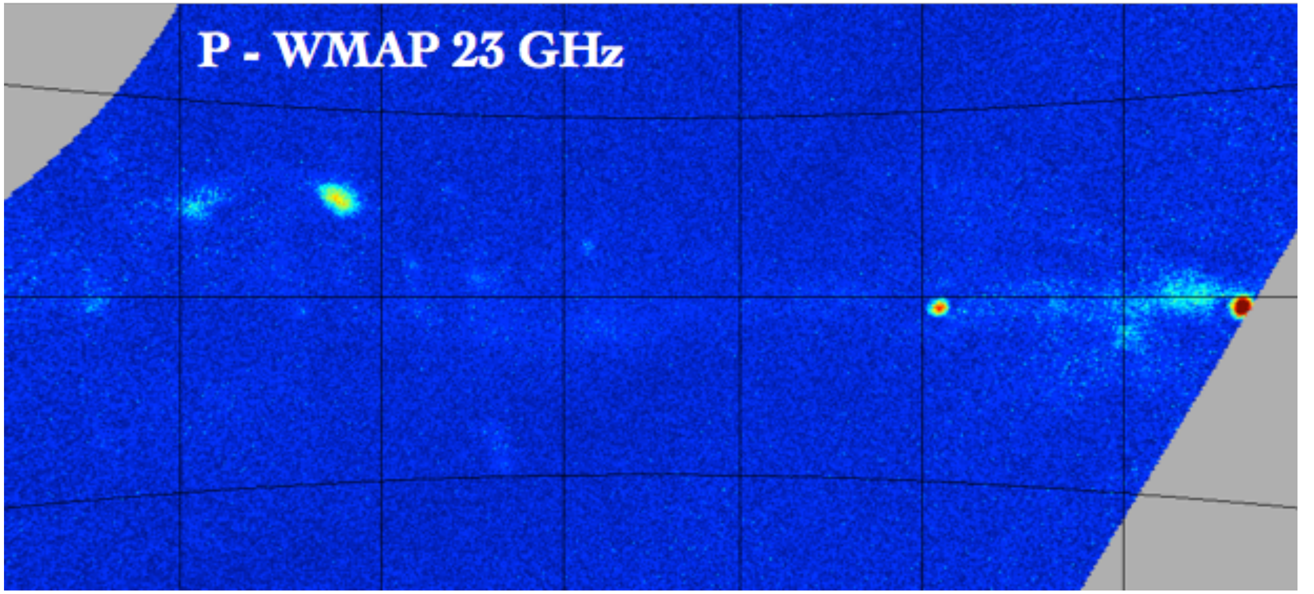
QUIJOTE Wide Survey

MFI results. Wide survey

○ Polarized intensity at 17GHz (wide survey, 700hr), compared to WMAP 23 GHz.

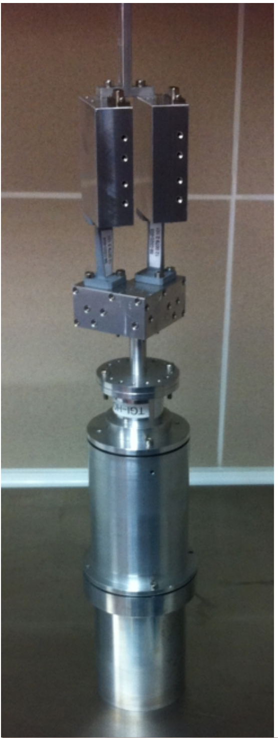
○ Even with a preliminary map-making, compact objects and diffuse emission is starting to be seen.

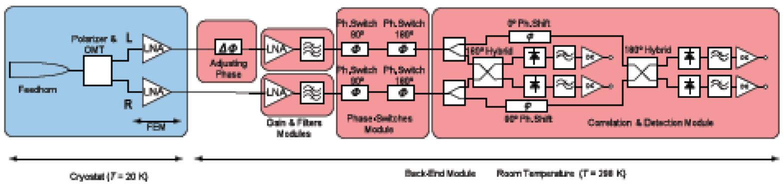


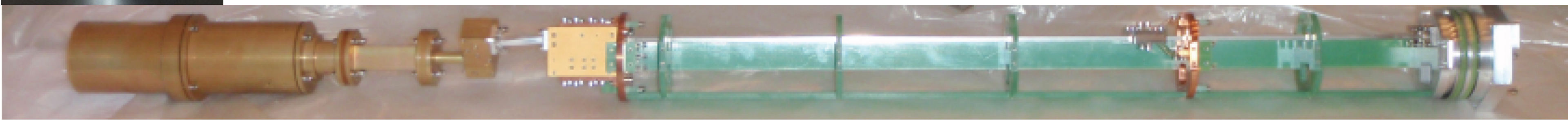


Thirty GHz Instrument (TGI)

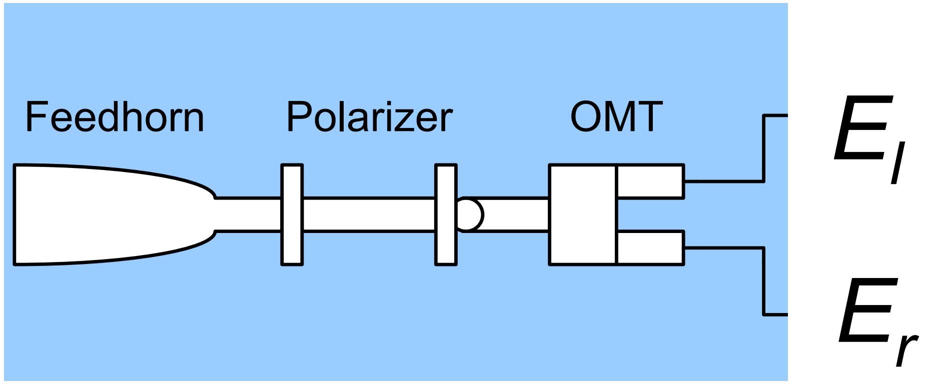
Cryostat internal structure
31 pixels







TGI Receiver: principle of operation

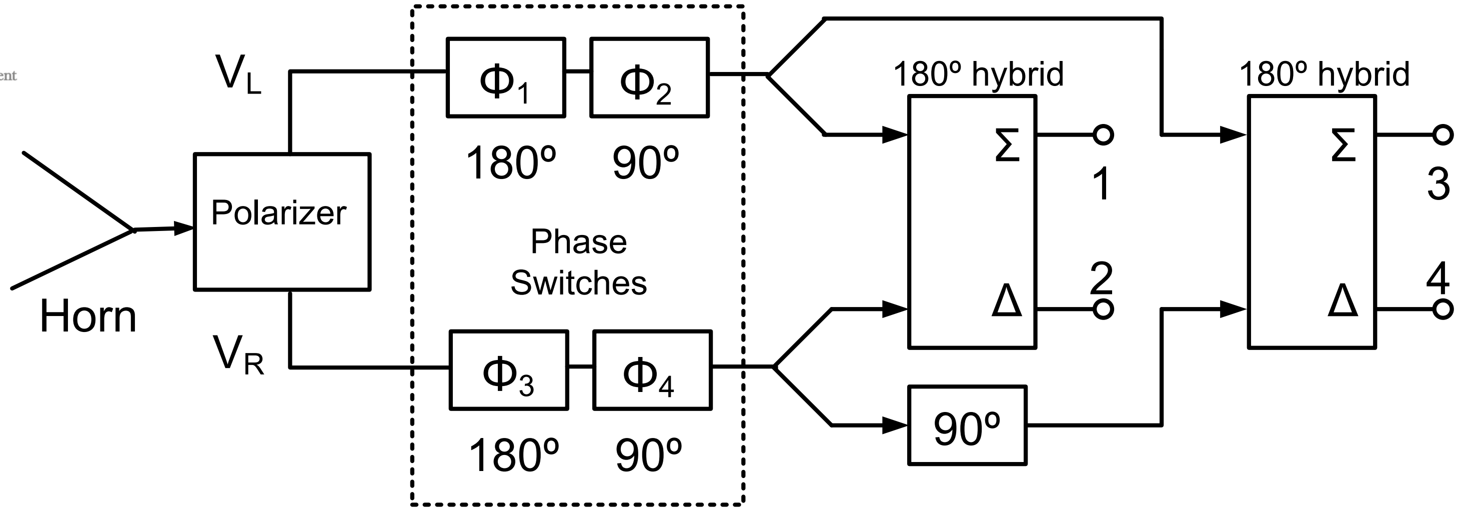


Circular components of electric fields

$$\begin{pmatrix} I \\ Q \\ U \end{pmatrix} \equiv \begin{pmatrix} |E_l|^2 + |E_r|^2 \\ 2\,\mathrm{Re}\left(E_l^* E_r\right) \\ -2\,\mathrm{Im}\left(E_l^* E_r\right) \end{pmatrix}$$

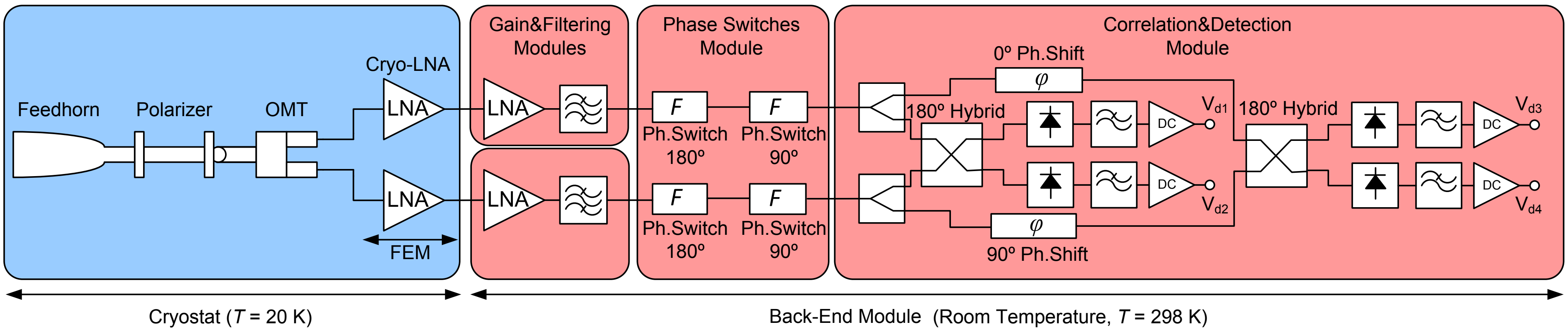
Stokes parameters

Stokes parameters



Φ	I	Q	U
0º	Vd1 + Vd2 = Vd3 + Vd4	Vd1 – Vd2	Vd3 – Vd4
90º	Vd1 + Vd2 = Vd3 + Vd4	Vd3 – Vd4	Vd2 – Vd1
180º	Vd1 + Vd2 = Vd3 + Vd4	Vd2 – Vd1	Vd4 – Vd3
270º	Vd1 + Vd2 = Vd3 + Vd4	Vd4 – Vd3	Vd1 – Vd2

QUIJOTE 30 GHz Instrument (TGI)

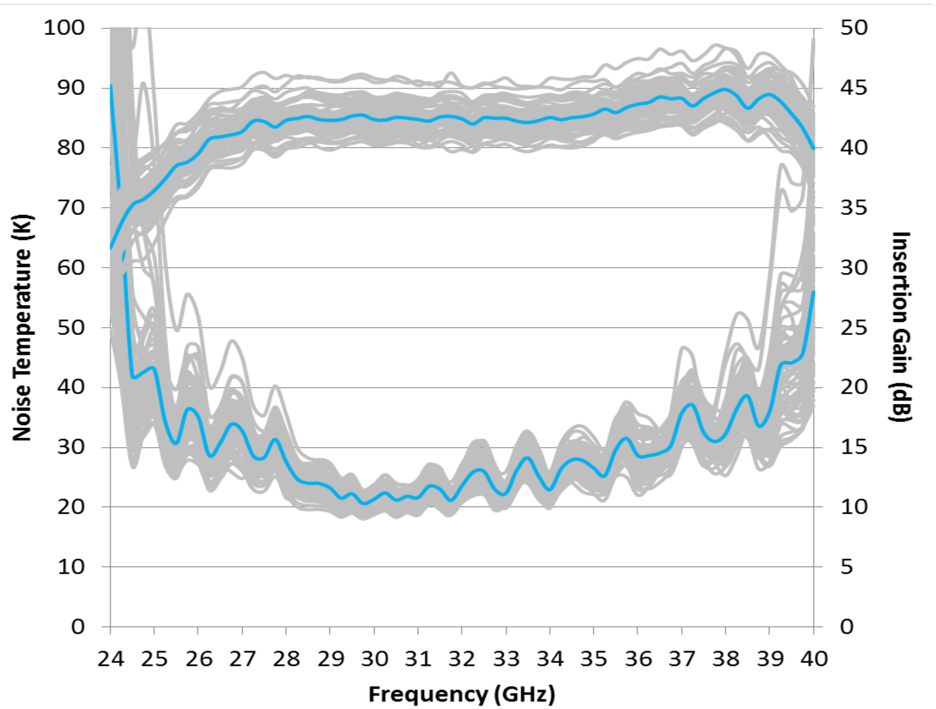


- Phase switches in two balanced branches
- Microwave Correlation (180º hybrids)
- Direct detection (Schottky diode)
- Simultaneous measurement of Stokes parameters (I, Q, U)

$$I \propto V_{d1} + V_{d2} \ \text{ or } \ V_{d3} + V_{d4}$$

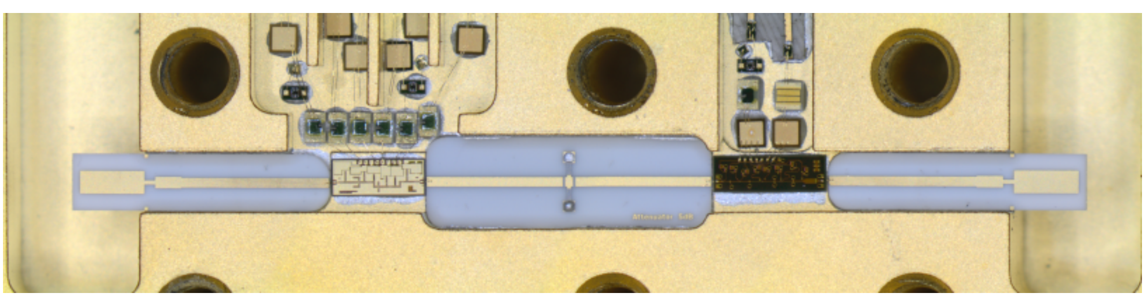
$$Q \propto V_{d1} - V_{d2} \qquad U \propto V_{d3} - V_{d4}$$

Cryo-LNA (FEM) 26-36 GHz – IAF MMIC Ka V2 BA



Performance of the 62 cryogenic-Low Noise Amplifier (LNA) units at 12 K
(Gain and Noise Temperature)

Average values (26-36 GHz):
Gain ≈ 43 dB
Noise temperature ≈ 25 K

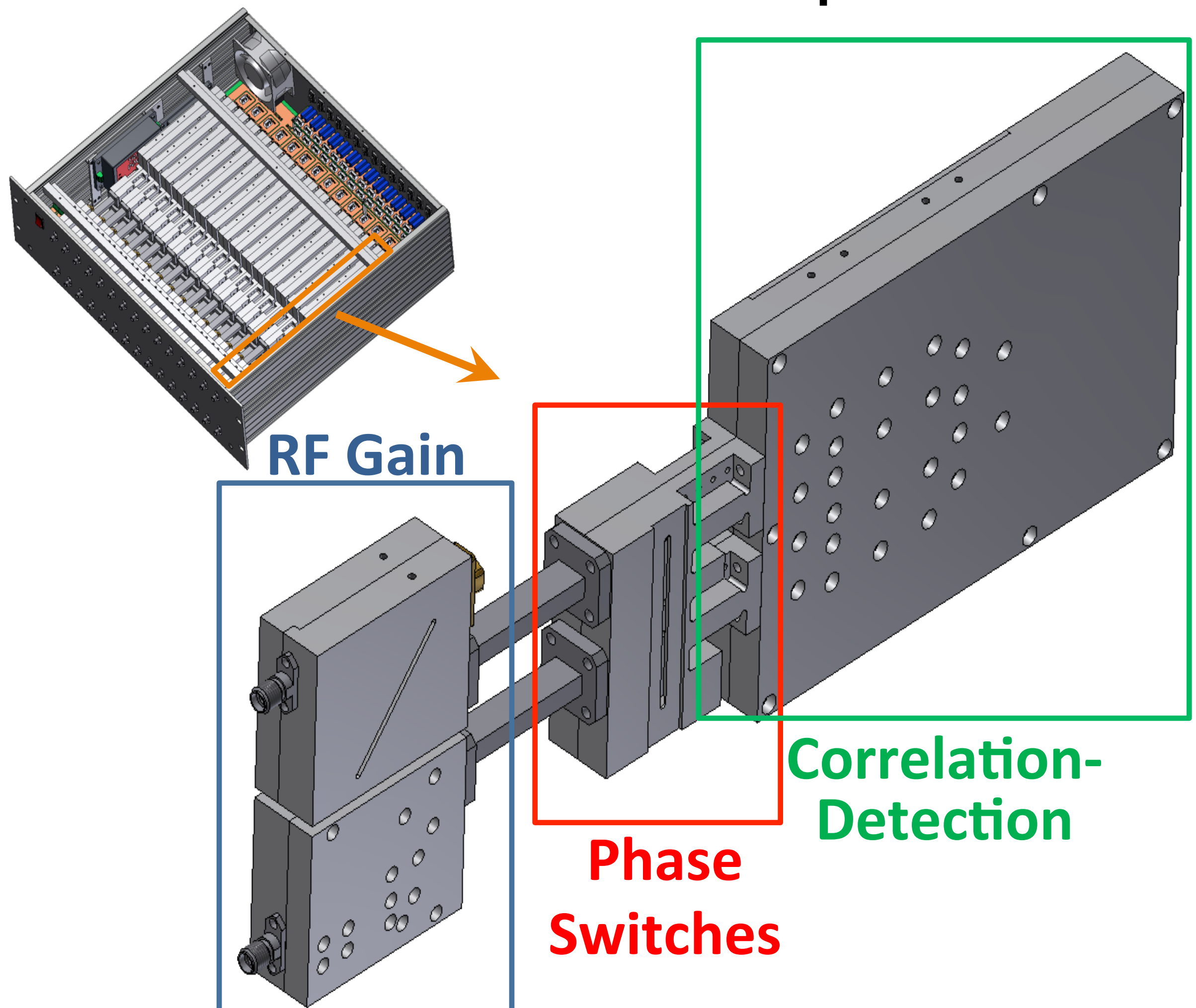


Internal view:
Two MMIC chips

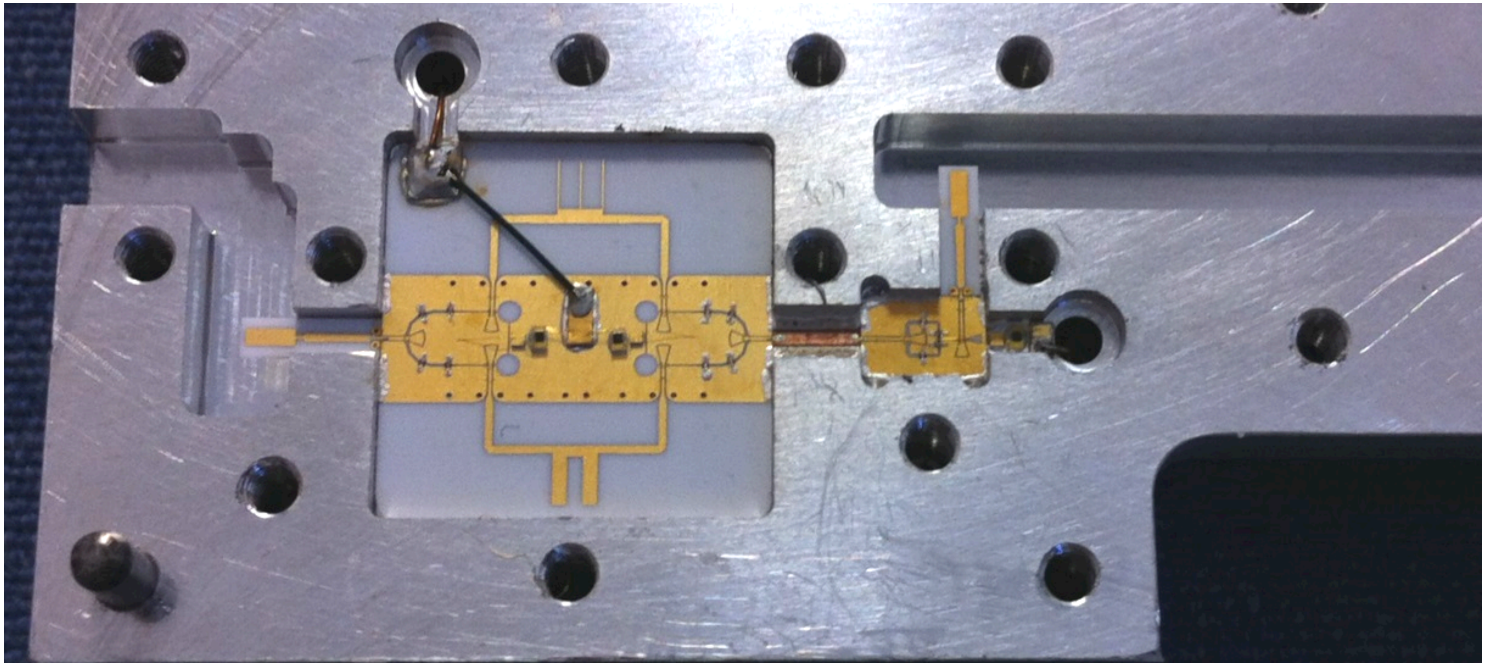
TGI BEM rack assembly

BEM rack TGI (16 pixels)

BEM for 1 pixel



Phase Switches - QUIJOTE TGI

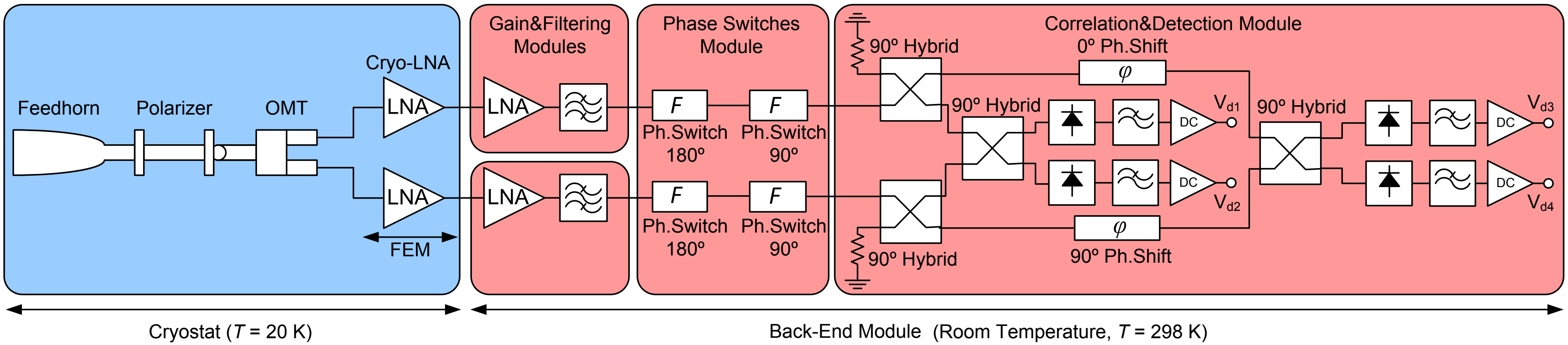


View of the 90° (left part) and 180° (right part) phase switches, only one branch.

Coplanar waveguide, slotline and microstrip transmission lines

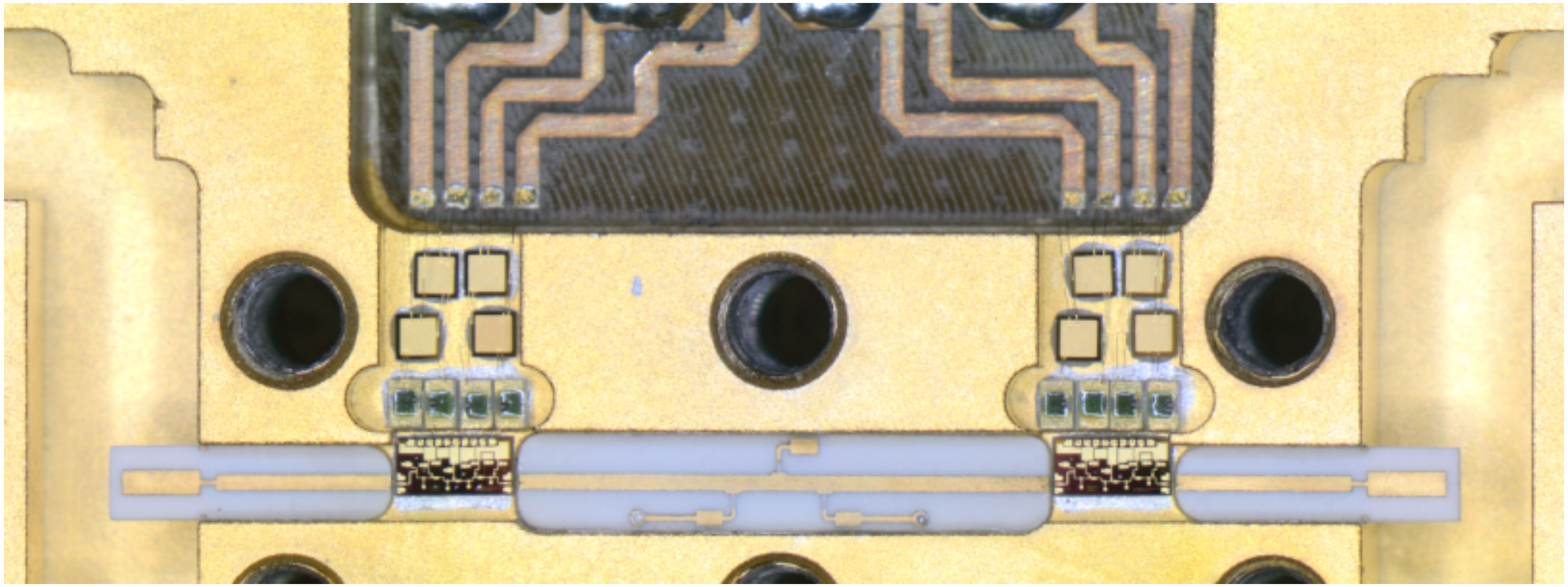
Switching devices: PIN diodes

Receiver scheme QUIJOTE 40 GHz (35-47 GHz) Forty GHz Instrument (FGI)



Same main architecture as 30 GHz receiver

Cryogenic Low-Noise Amplifier (FGI) (35-47 GHz)



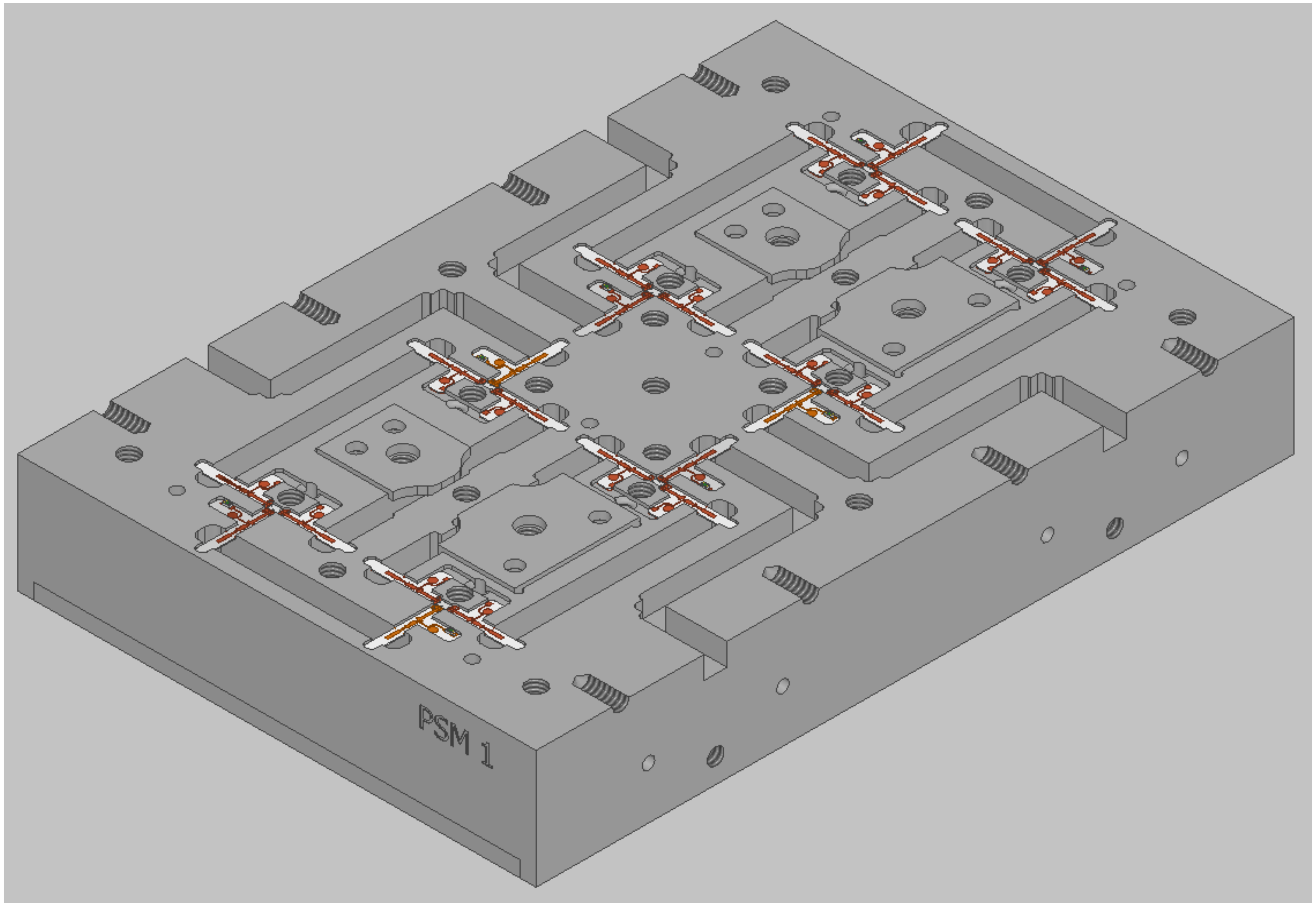
Cryo-Q-Band LNA MMIC (two units) from IAF-Fraunhofer + gain equalizer

Prototype results:

Gain ≈ 41 dB at 15 K

Noise temperature ≈ 22 K at 15 K

Phase Switches - QUIJOTE FGI



FGI phase-switches module (180 and 90 degrees). Two branches.
Based on SPDT MMIC chips and waveguide phase-shifters.

Beyond QUIJOTE:
IR Electro-Optical Correlator for a Large Format Interferometer

Preliminaries

- **Goal:** Develop instruments to measure polarization with high sensitivity at the QUIJOTE frequency bands: 10-20, 30 and 40 GHz**.**

- **Detection Technology:** Bolometers are not optimal in this frequency range. Ultra Low Noise receiver-based polarimeters can be used.

- **Opto-Mechanics:** Size limiting factor for direct imaging instruments due to the restricted focal plane area of the required telescope.

- **Large Format Interferometer**: Not limited by the focal plane area. Potentially hundreds or even thousands of receivers to have optimal sensitivity**.**

Preliminaries

- **<u>Main Challenge</u>:** Develop a correlator for hundreds of wideband microwave (MW) signals. The routing, combination and detection result complex and very expensive.

- **<u>Proposal</u>:** Use Electro-Optical (EO) modulators to up-convert MW signals to the Infra Red (IR) wavelength (1550 nm).

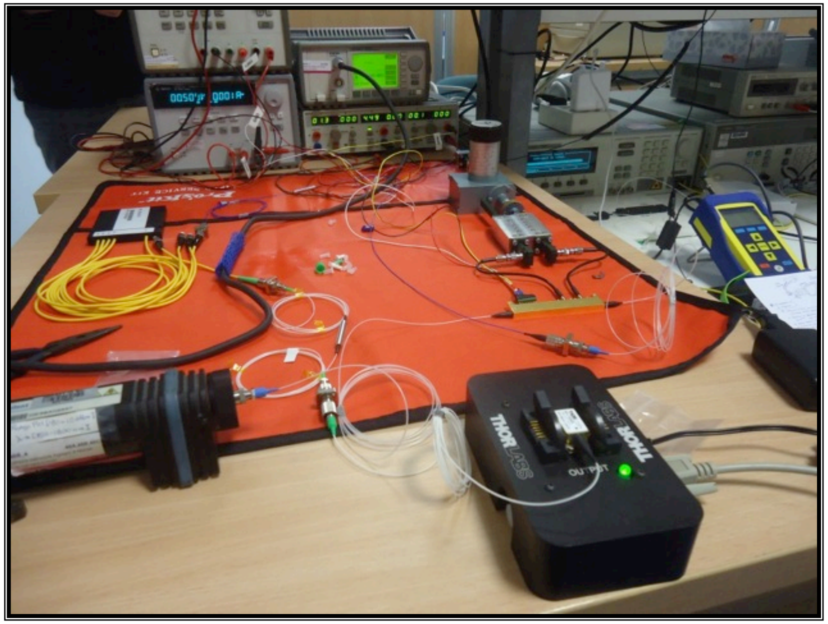
- The correlation and detection can be performed using optical fibers, lenses and IR cameras.

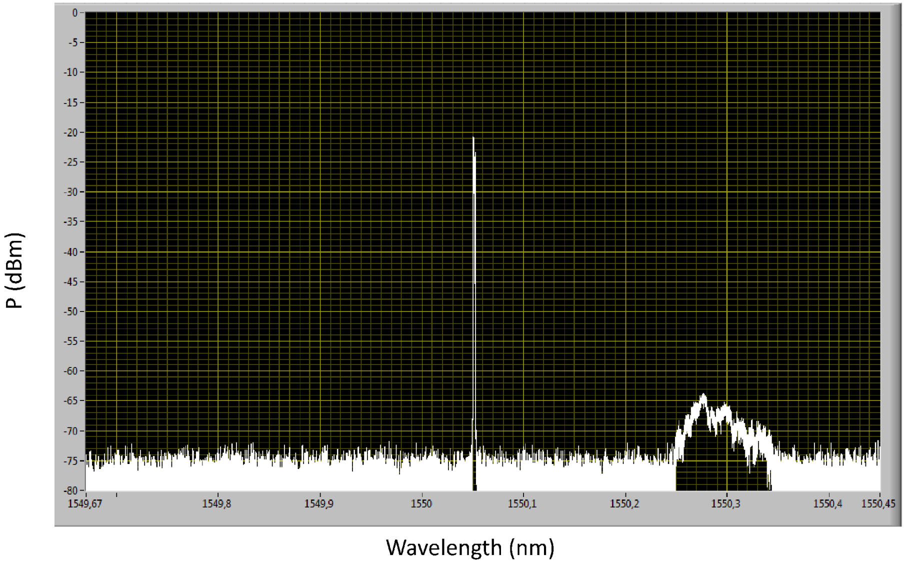
- High density detection and low cost.

- Very well understood technology to implement a synthesized imager.

MZM-Based Optical Correlator

Up-conversion of MW Signals to the IR



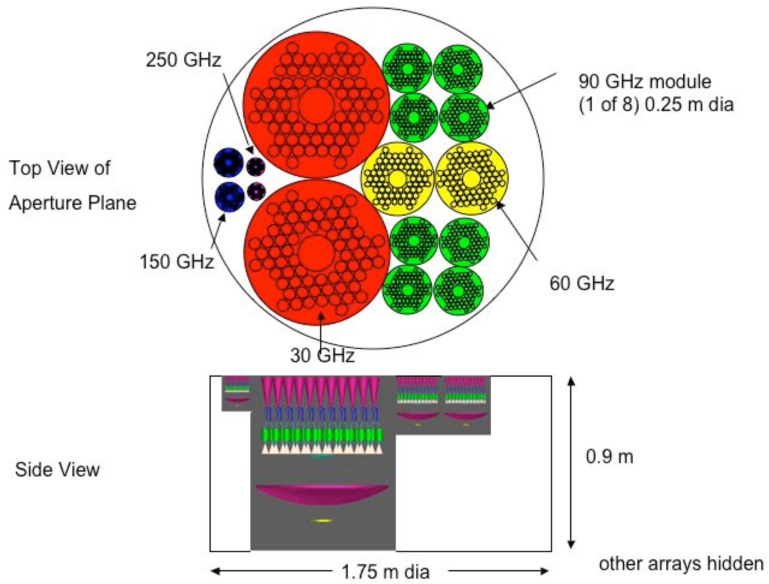


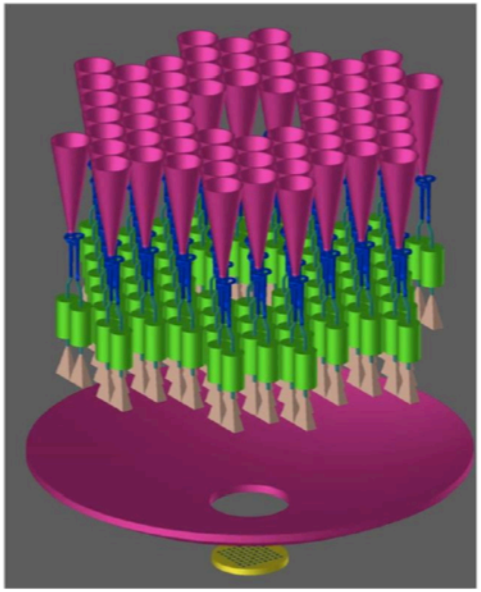
- Use of Mach-Zehnder Optical Modulator to perform the frequency range conversion.

- Optical carrier needs to be filtered.

Instrumental Precedents

EPIC: Space mission concept





The Einstein Polarization Interferometer for Cosmology or EPIC is a proposed space probe to measure the B-modes of the CMB Polarization. It consists of a series of interferometric arrays tuned to various frequencies to precisely measure the CMB and to remove galactic foregrounds from infrared dust emission and syncrotron radiation. Each array as shown below has a set of 64 conical

- From 30 to 300 GHz.

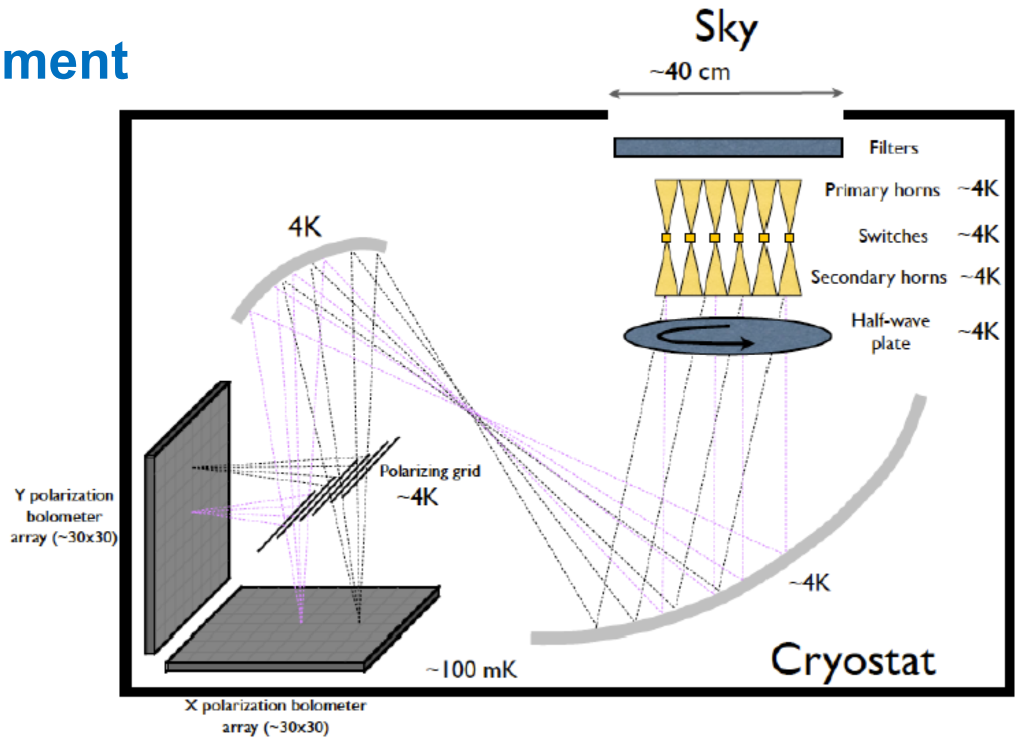
- Bolometric Interferometer

- Fizzeau Beam Combiner

Instrumental Precedents

QUBIC: Ground-based Instrument

- Synthetized Imager
- 97, 150 and 220 GHz
- Antarctica Concordia Station
- Fizzeau Beam Combiner



The signal on the bolometers as a function of time is[2]:

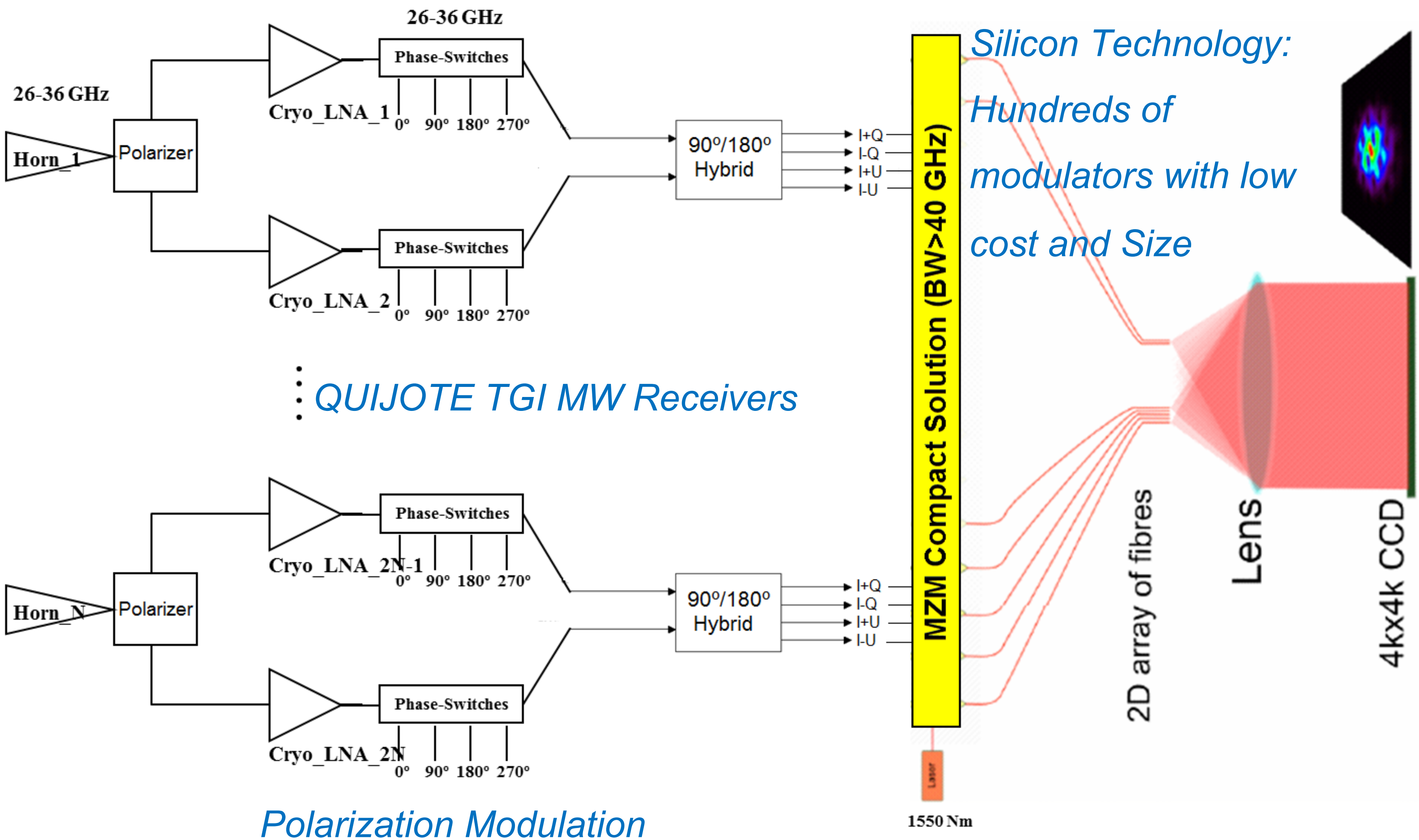
$$R(\vec{d}_p, t) = S_I(\vec{d}_p) \pm \cos(4\omega t) S_Q(\vec{d}_p) \pm \sin(4\omega t) S_U(\vec{d}_p)$$

where the $\pm$ is + for one of the focal planes (polarized in one direction) and − for the other one polarized in the other direction.

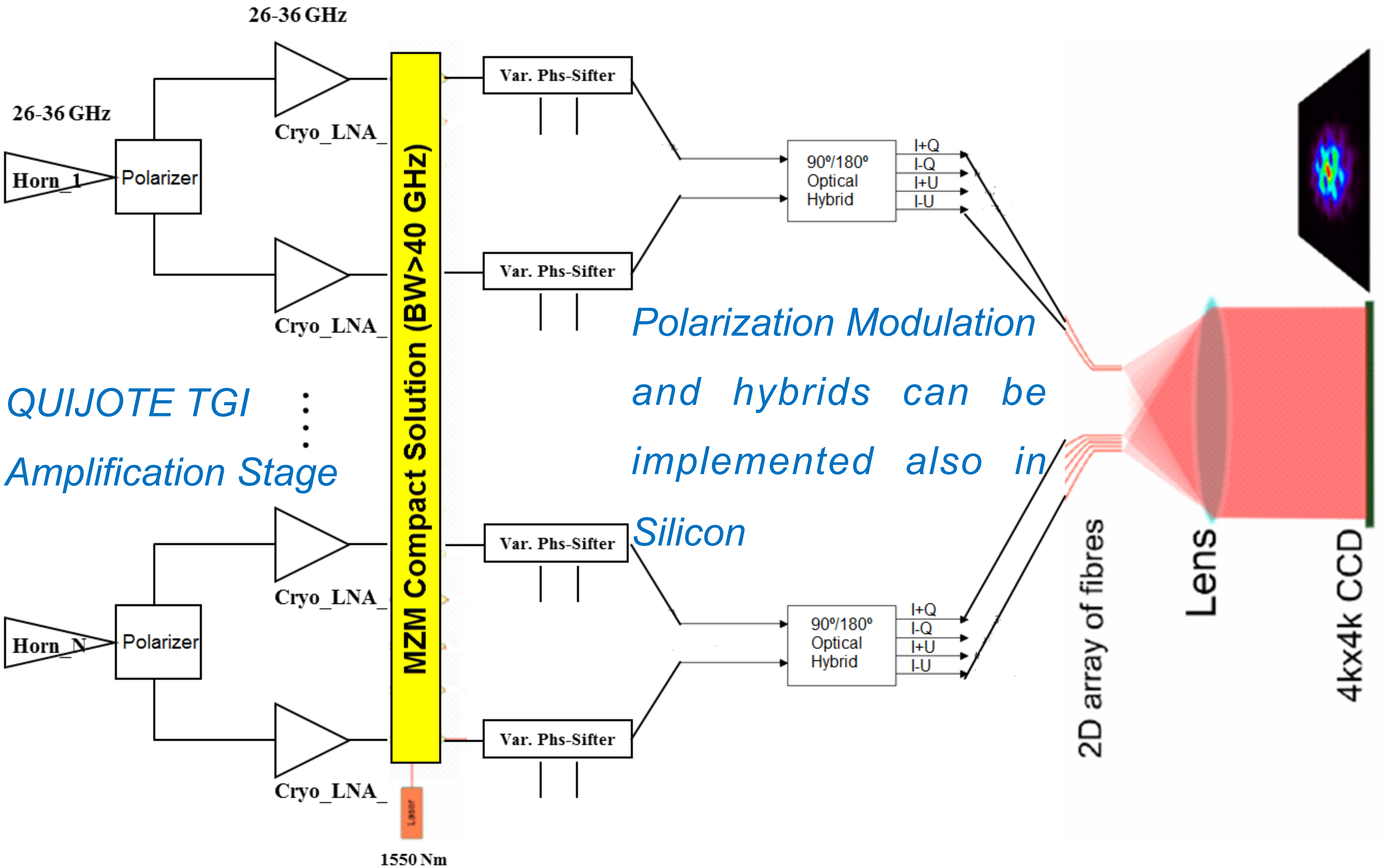
This kind of interferometers act as imagers

(Battistelli et al., Astroparticle Physics 34, 2011, 705-716)

Interferometer Implementation Proposal



Interferometer Implementation Proposal



QUIJOTE TGI Amplification Stage

Polarization Modulation and hybrids can be implemented also in Silicon

CONCLUSIONS

- QUIJOTE is a polarization experiment designed to reach a level of sensitivity of **r=0.05**.
- QUIJOTE can measure the **synchrotron and AME** polarized emissions with unprecedented sensitivity in a unique frequency band no covered by other experiments. In particular is an excellent complement to Planck at low frequencies.
- First light of **MFI (10-20 GHz)** on QT1 in Nov. 2012. Routine observations on selected Galactic regions and cosmological fields have been done since then, producing intensity and polarization maps at 4 frequencies.
- **Polar modulation** techniques allow an instantaneous measurement of the Q and U Stokes parameters with a good control of systematics. This has been proven with real measurements for the MFI and at the lab level for the TGI.
- **TGI (30 GHz)** is being installed in the second telescope (QT2) and commissioning is expected in the next weeks. One year of observation with the TGI should provide a sensitivity of r=0.01. **Sensitivity in the degree of polarization of AME regions** should reach **0.1%** in a relatively short time.
- **FGI (40 GHz)** is presently under construction and is expected to be finished by the end of 2016. Combined FGI/TGI data should reach r=0.05 after 3 years of observations.
- **Legacy polarization maps** (10-40 GHz) and derived products will be made publicly available.
- A **large-format interferometer** based on an electro-optical correlator is being planned for polarization observations at the QUIJOTE frequencies. The expected improvement in sensitivity will allow to reach values of r=0.01 or below. A 9 pixels interferometer at 10-20 GHz is expected to be developed as a first step.