CMB roadmap in Spain

I. Existing infraestructures, current ground based experiments and European projects.
II. Instrumental developments and technologies.
III. Spanish CMB Roadmap: ground based experiments, synergies with space.
IV. Views on European roadmap.

Authors: E. Martínez-Gonzalez, J.A. Rubiño-Martín, L. Verde.
With contributions from: E. Artal, F. Casas, R. Génova-Santos, A. Gómez, R. Hoyland, R. Rebolo, P. Vielva

I. Existing infraestructures, current ground based experiments and European projects.

- Teide Observatory.
- QUIJOTE experiment.
- IAC instrumentation division (AIV rooms, workshops, etc)
- DICOM lab for design, fabrication and tests of LNAs.
- CAB lab for fabrication and test of KIDs.
- H2020-COMPET-2015: RADIOFOREGROUNDS

The Izaña Site

Observatorio del Teide
(http://www.iac.es)

Altitude: 2400 m

Longitude: 16º 30' W

Latitude: 28º 17' N

Typical PWV: 3 mm, and below 2mm during 20% of time.

Good weather: 90%

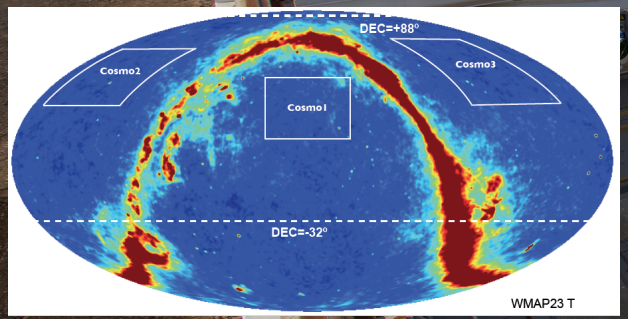
Easy access: 40 km road journey from IAC

The QUIJOTE experiment

Q-U-I Joint Tenerife CMB experiment

QT1.
Instrument: MFI.
11, 13, 17, 19 GHz.
FWHM=0.92º-0.6º
In operations since 2012

QT2.
Instruments: TGI and FGI
30 and 40 GHz.
FWHM=0.37º-0.26º
In operations since 2016



Instituto de Física de Cantabria

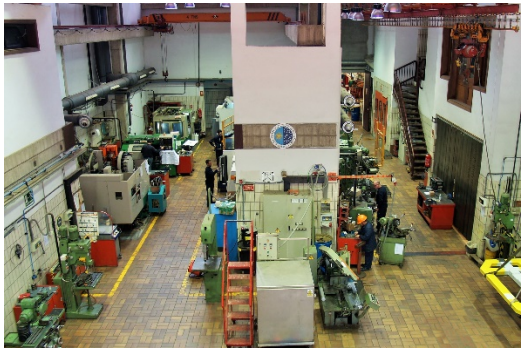
DICOM

UNIVERSITY OF CAMBRIDGE

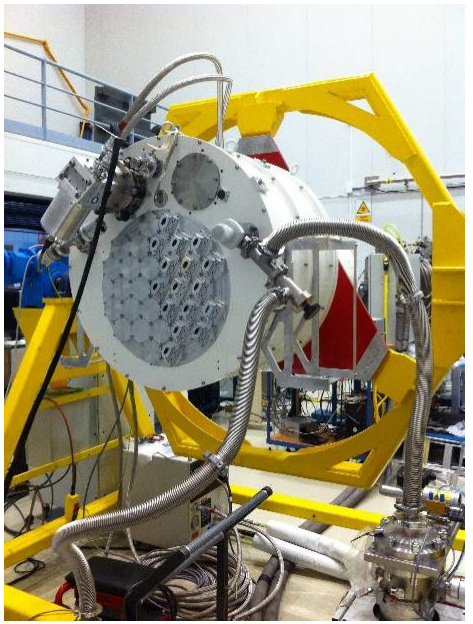
MANCHESTER 1824
The University of Manchester

idom

IAC Facilities



Mechanical Workshop
Dimensional Metrology Lab.
Microwave Laboratory 1-50GHz
Electronics Workshop
Technical Drawing
Mechanical Design
Cryogenic Design
AIV class 100,000 cleanroom
Software
3D printing



UC-DICOM capabilities

Design, testing and manufacturing of:

Radiofrequency and microwave systems for radio astronomy.

- Cryogenic LNA Monolithic Microwave Integrated Circuits (MMIC):
  - IAF-Fraunhofer 100 nm and 50 nm mHEMT technologies (two collaboration projects since 2008 with Observatorio de Yebes), cryo-LNA in several bands from 2 to 110 GHz
  - OMMIC (France) mHEMT 70 nm, Ka and Q-band LNA
- Horn antennas, Orthomode Transducers (OMT), Polarizers, Couplers:
  - Several frequency bands, from 10 to 110 GHz
  - Broadband performance (10-14 GHz, 14-20 GHz, 26-36 GHz, 35-47 GHz, 81-99 GHz)
- Radiometers and polarimeters:
  - Planck-LFI: 30 and 44 GHz Back End Modules
  - QUIJOTE TGI and FGI (30 and 40 GHz): horns, OMT, polarizers, receivers (Front End and Back End Modules) (31 pixels)
  - Polarimeter demonstrator at 90 GHz: horns, OMT, polarizers, receivers (Front End and Back End Modules) (2 pixels)
- Broadband subsystems:
  - Cryogenic and ambient LNA
  - Phase-switches, microwave correlators, filters, Schottky diode detectors, …

NANOFABRICATION OF KINETIC INDUCTANCE DETECTORS FOR FAR INFRARED RADIATION

Alicia Gomez, et al.

Centro de Astrobiología (INTA-CSIC)

CENTRO DE ASTROBIOLOGÍA
Asociado al NASA Astrobiology Institute

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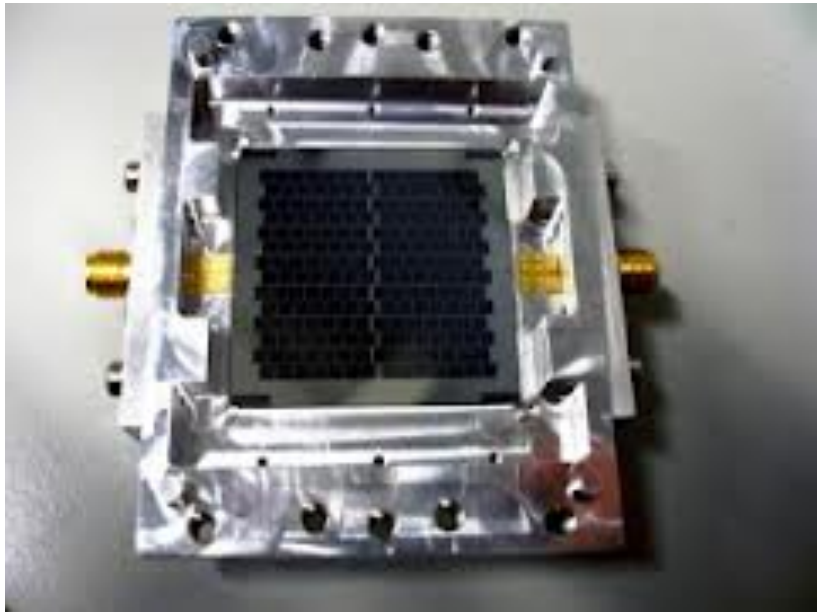

RADIOFOREGROUNDS project

http://www.radioforegrounds.eu

H2020-COMPET-2015. Grant agreement **687312:** "Ultimate modelling of Radio Foregrounds" (RADIOFOREGROUNDS).
3-year grant (IAC; IFCA; Cambridge; Manchester; SISSA; Grenoble; TREELOGIC).

This project will provide specific products:

a) state-of-the-art legacy maps of the synchrotron and the anomalous microwave emission (AME) in the Northern sky;
b) a detailed characterization of the synchrotron spectral index, and the implications for cosmic-rays electron physics;
c) a model of the large-scale properties of the Galactic magnetic field;
d) a detailed characterization of the AME, including its contribution in polarization; and
e) a complete and statistically significant multi-frequency catalogue of radio sources in both temperature and polarization.
f) specific (open source) software tools for data processing, data visualization and public information.

II. Instrumental developments and technologies

- Detectors.
  - KIDs (CAB)
  - LNAs (DICOM)
- Microwave components. Optimization of HWPs (extension of the MFI).
- Optical interferometers.
  - A preliminar study done within the Spanish EPI Consolider project.
  - The technological demonstration and fabrication of a prototype of a few elements funded by two Spanish national projects.
  - Important synergy with QUBIC.
- High-performance data processing pipelines (Gaia, Planck) and compression algorithms (FAPEC). Grid computing capacity (EGI). Spanish supercomputing network (BSC, Altamira, LaPalma) and other resources (IEEC, DAPCOM, TeideHPC).

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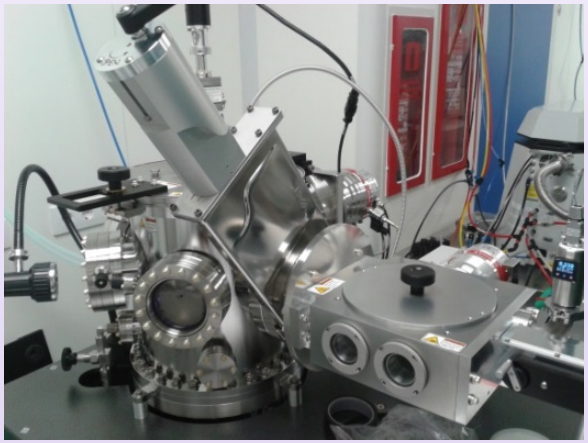
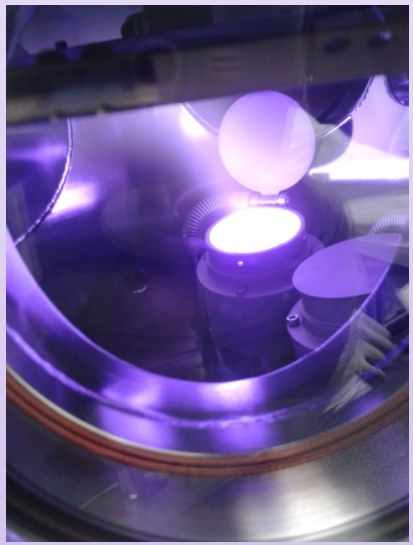
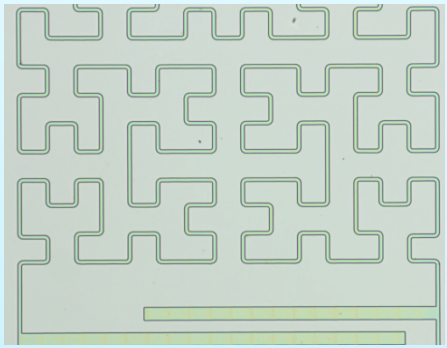
KIDs: Fabrication

Sputtering:
Deposition of superconducting films

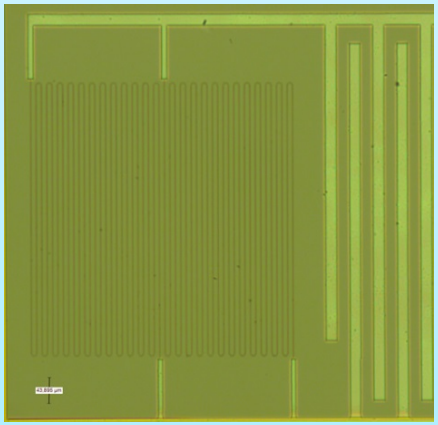




Nano and micro lithography

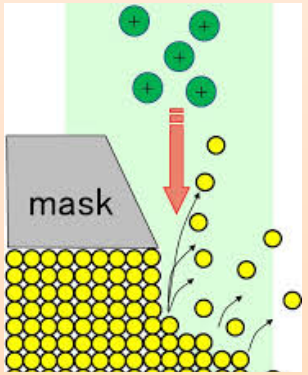


Laser writer



e-beam lithography

Etching:
Wet etching, ion milling and RIE



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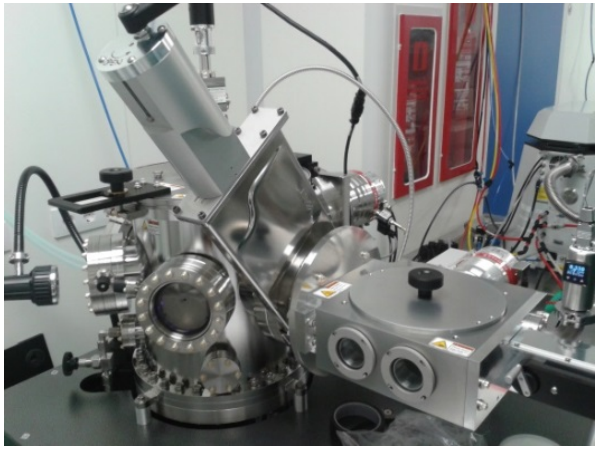
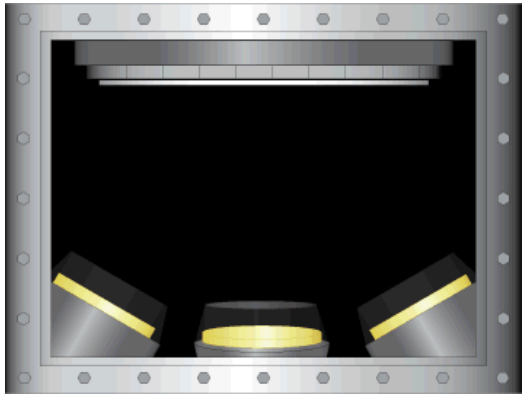
KIDs: Fabrication

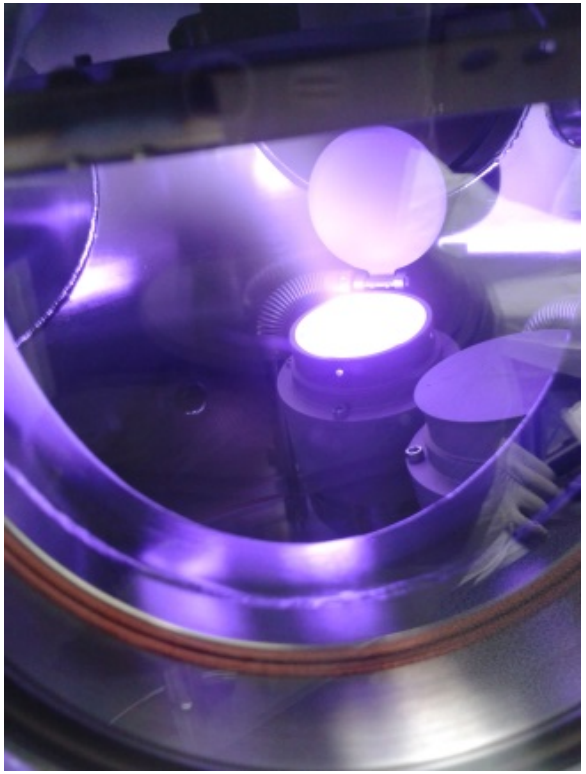
4 inch wafers →Scaling number of pixels…

Very high homogeneity is necessary for scaling the number of pixels (cross-coupling ,…)

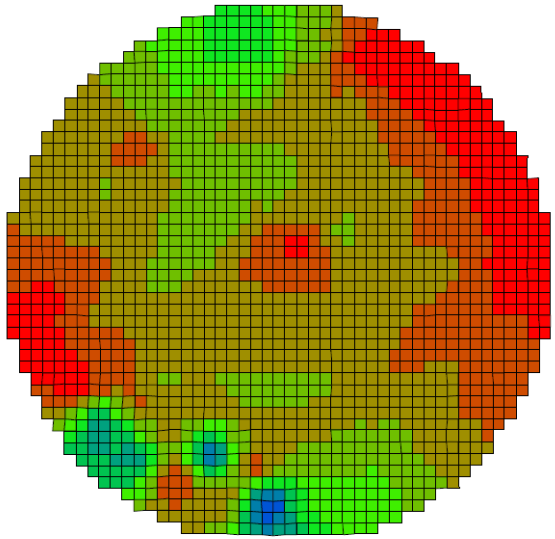
Installation of Confocal Sputtering (Al, Nb, Ti)







Homogeneity ≈ 1.5 %



KIDs: Characterization

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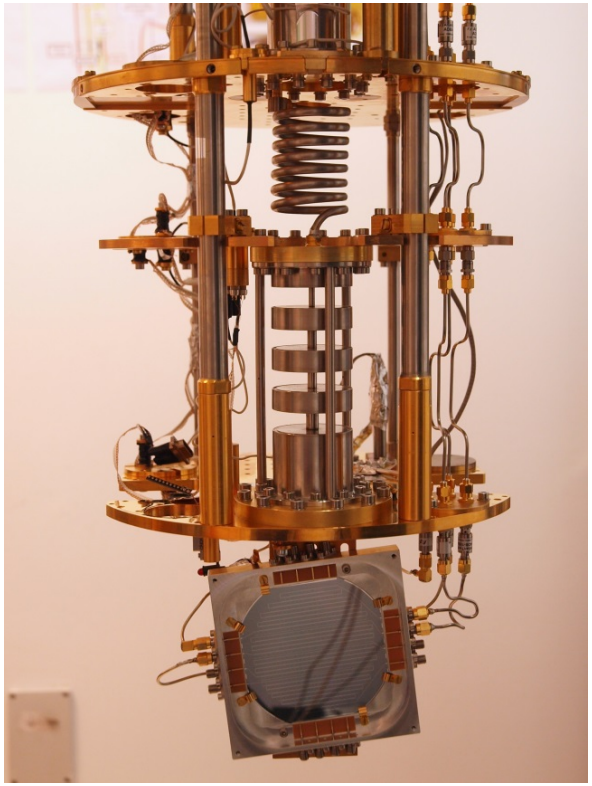
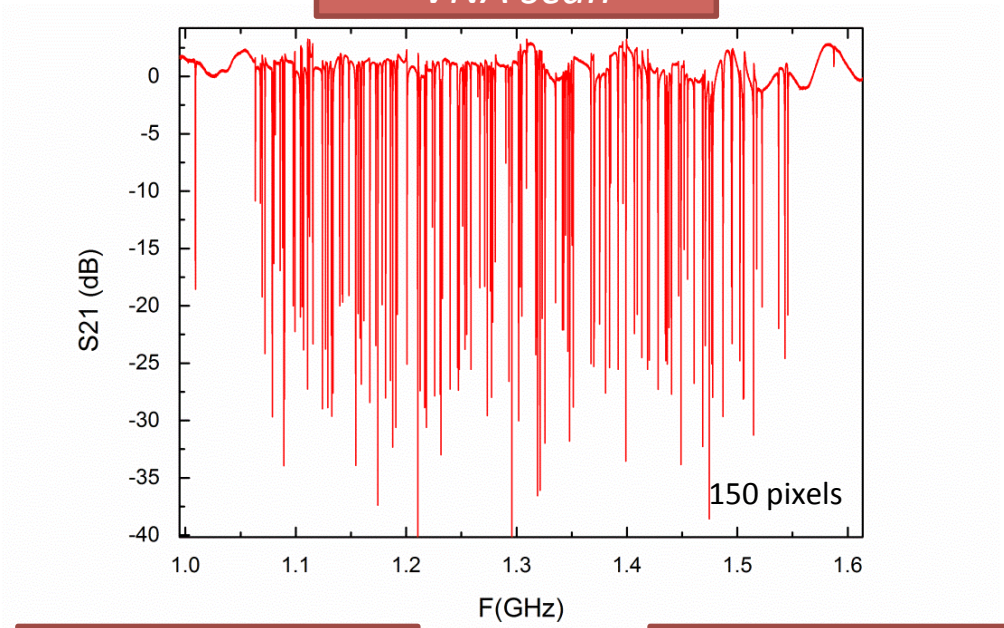
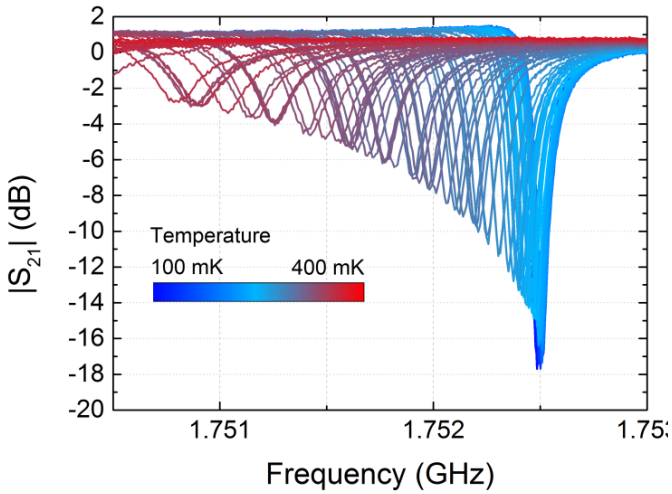


Dilution cryostat
for testing (10mK)

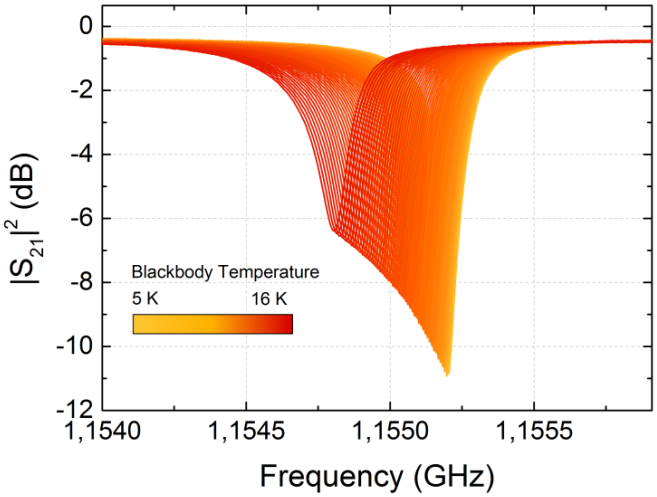
VNA scan



Dark response



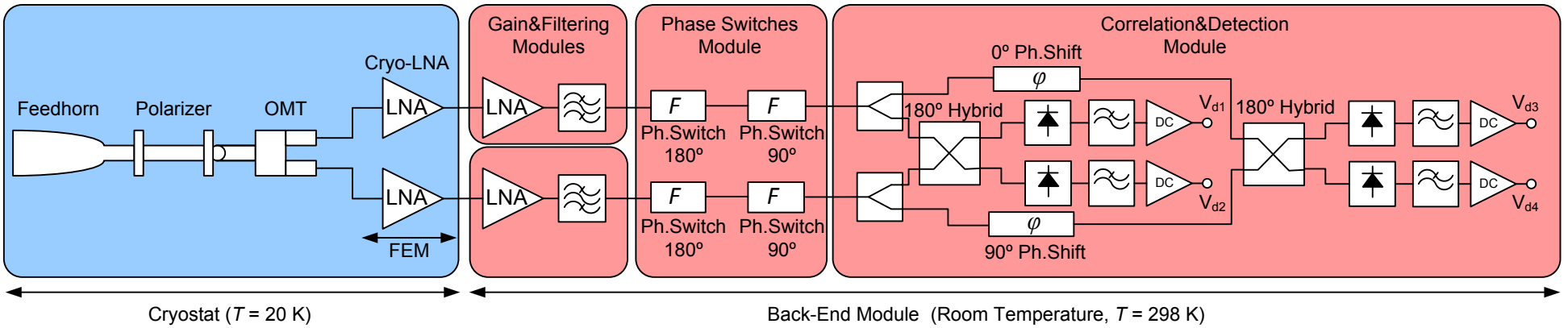
Optical response



Radiometer instrumentation

Eduardo Artal et al.
(Dpt. Communications Engineering, DICOM)

QUIJOTE 30 and 40 GHz Instrument (TGI, FGI)

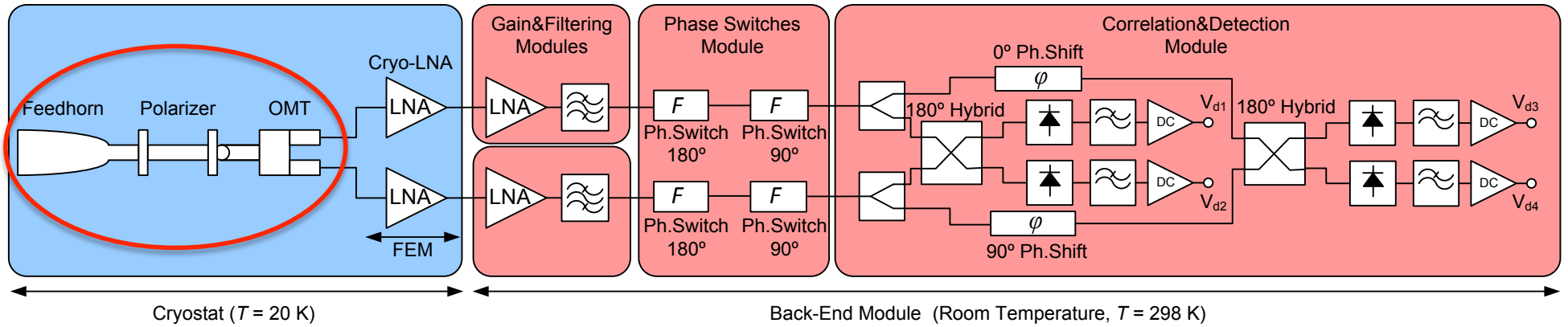


Wave-guide components (Coupling signals to detectors)

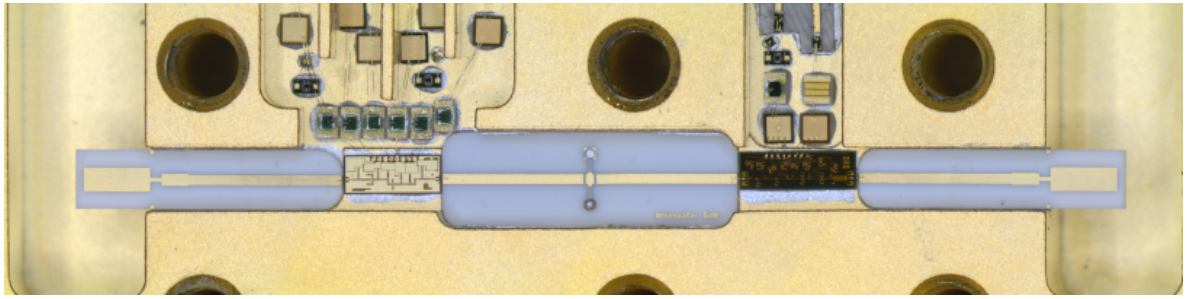
-Feedhorn

-Polarizer

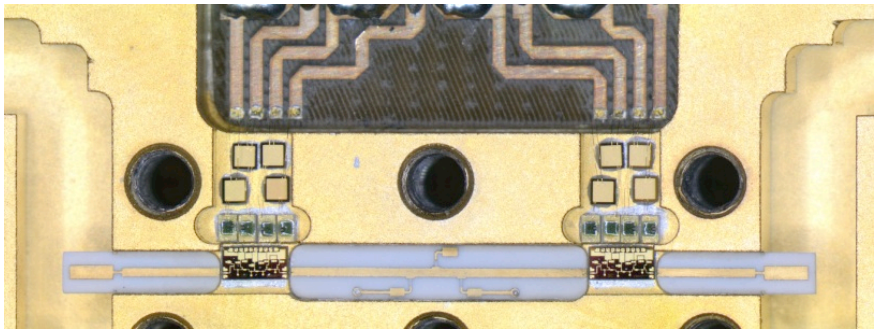
-OMT



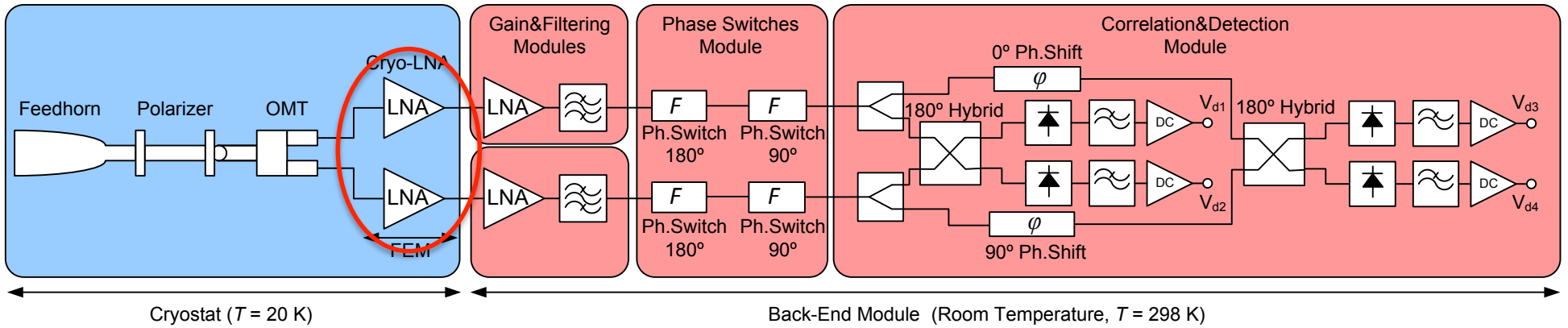
Cryogenic Low-Noise Amplifier



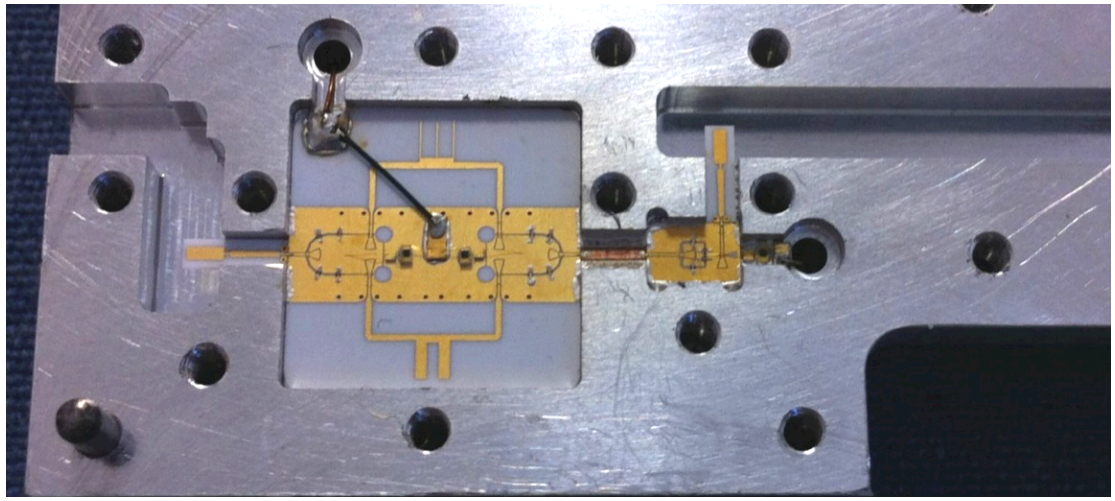
TGI: 26-36 GHz
Gain ≈ 43 dB
Noise temperature ≈ 25 K



FGI: 35-47 GHz
Gain ≈ 41 dB at 15 K
Noise temperature ≈ 22 K at 15 K



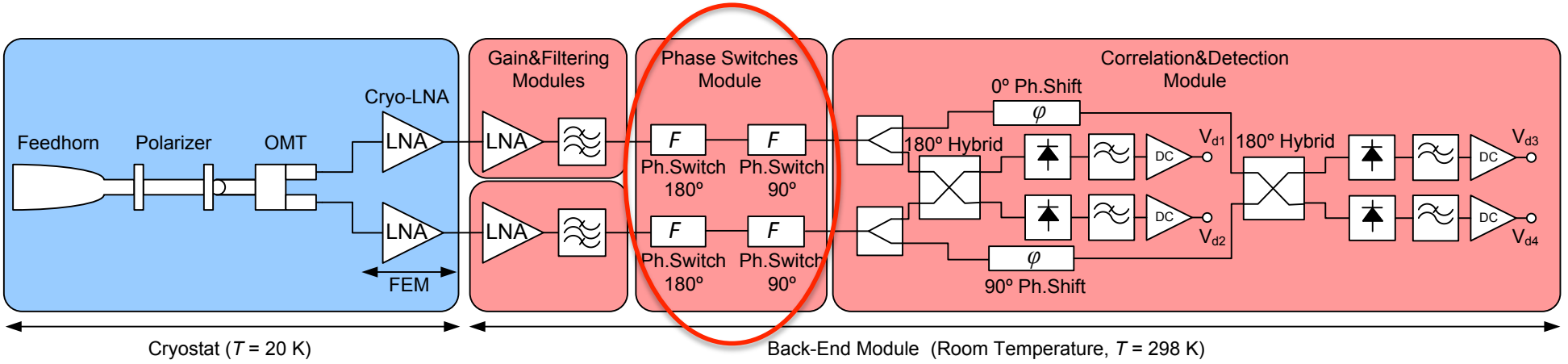
Discrete Polar Modulation: Phase Switches - QUIJOTE TGI / FGI



Coplanar waveguide, slotline and microstrip transmission lines

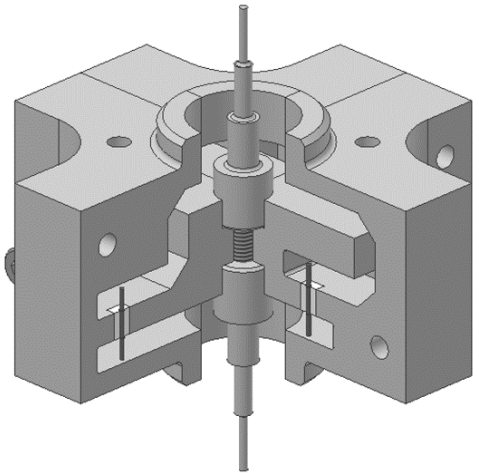
Switching devices: PIN diodes

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

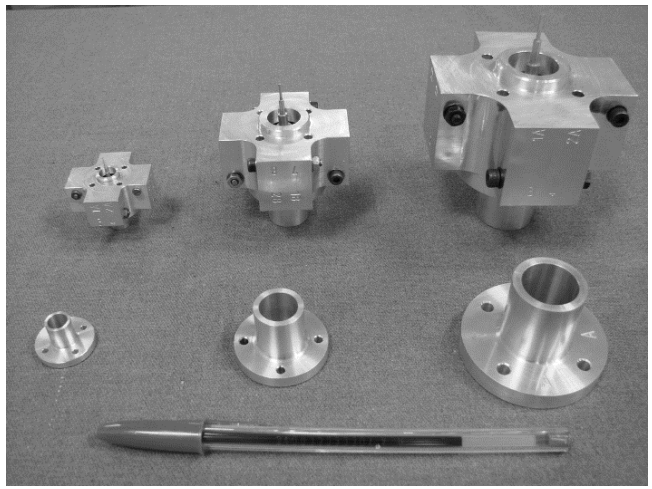


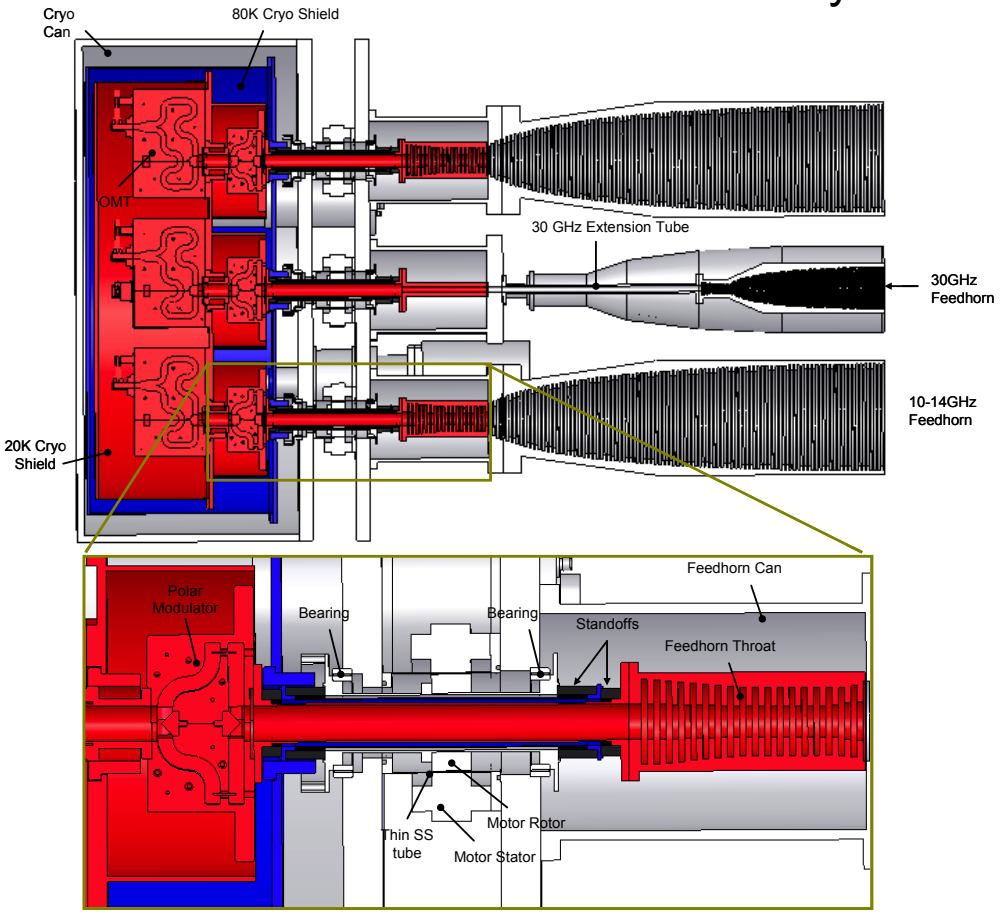
In-line Continuous/Discrete Polar Modulation 10-40GHz

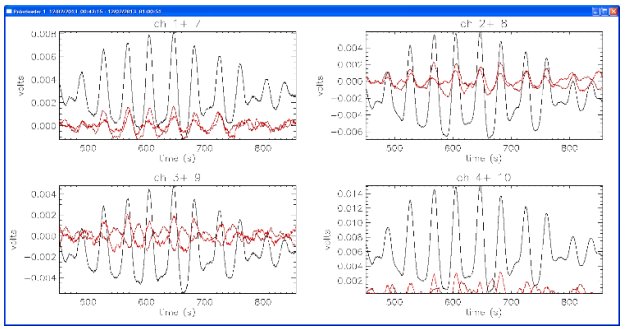
R. Hoyland et al.



Scalable In-line Polar Modulator







III. Spanish roadmap for CMB experiments.

- **Contributions to CORE.**
- **Ground-based low frequency observations**.
  - QUIJOTE. Extension of QUIJOTE to southern hemisphere.
  - Optical interferometer at low frequencies (10-50GHz).
  - STRIP-LSPE.
  - Short duration balloon flights for calibration.
- **Ground-based high frequencies observations**, large angular scales.
  - GroundBird.
- **CMB spectral distortions.**
  - KISS.
  - Microwave spectrometer 10-20GHz.
- H2020-FETOPEN-2016-2017: Ultrasensitive Bolometers for Cosmology (rUBiCOn) (submitted)

Spanish contribution to CORE.

- CORE is a priority for the Spanish CMB community.

- Spanish interests expressed in the letter of intent: detectors and detector readout, on-board electronics, opto-mechanical components (horns, OMTs, lenses, etc.).

- Estimated contribution: about 7% of the cost (salaries not included).

- Priorities on contributions to:
  - **Focal Plane Array**: potential contribution to KIDs fabrication and testing, orthomodes/ lenses, KID coupling, read-out amplification.
  - **DPU and on-board electronics**. Previous experience with REBA (Planck), and currently with NISP (EUCLID). On-board data compression (experience in Gaia and Euclid).
  - **Data Processing Center**. Experience in Planck, and Gaia. DPC of QUIJOTE.

QUIJOTE project: Timescales

QT2

- **TGI**: commissioning phase: on-going. Science phase: October 2016.
- **FGI**: commissioning early next 2017.
- Observing plan for TGI/FGI science phase:
  - Cosmological survey. 3 years effective. Results after one year (effective).

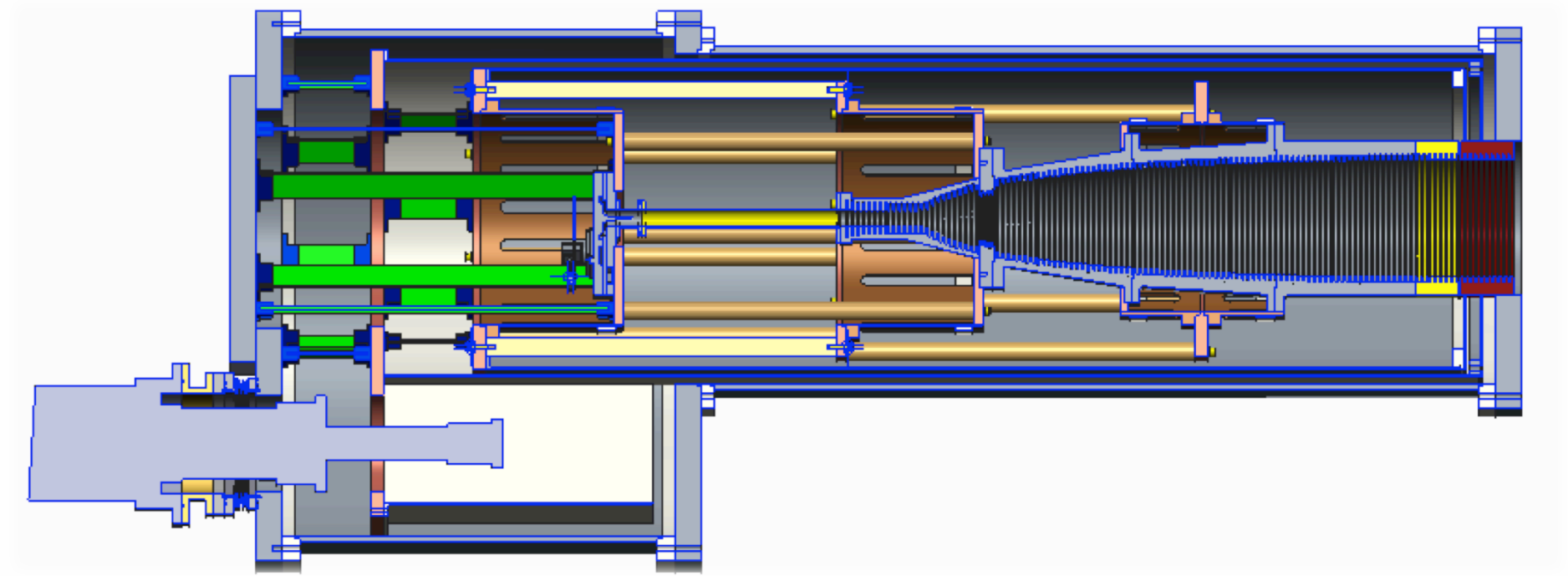
QT1

- **MFI**. In science phase.
  - Cosmological fields. Three years effective.
  - Wide survey. One year effective (first results to appear soon).
- **MFI upgraded**. Funds secured. Aim: to increase the speed by at least a factor of 3. 2-yr for development. On telescope by end 2018.

Legacy polarization maps (10-40GHz) **and derived products will be publicly available**.

QUIJOTE: Plans for full sky coverage

- We are exploring the possibility of building a replica of QUIJOTE in the southern hemisphere (South Africa).
- In collaboration with Wits University (ZA) , a prototype of a MFI pixel is already funded.
- **MFI-S** in fabrication now, and will be tested at the 7.6m telescope at HartRAO early 2017.
- A complete MFI instrument and a full replica of a QUIJOTE telescope will come later, if observations with the prototype instrument are successful (funds not approved yet).

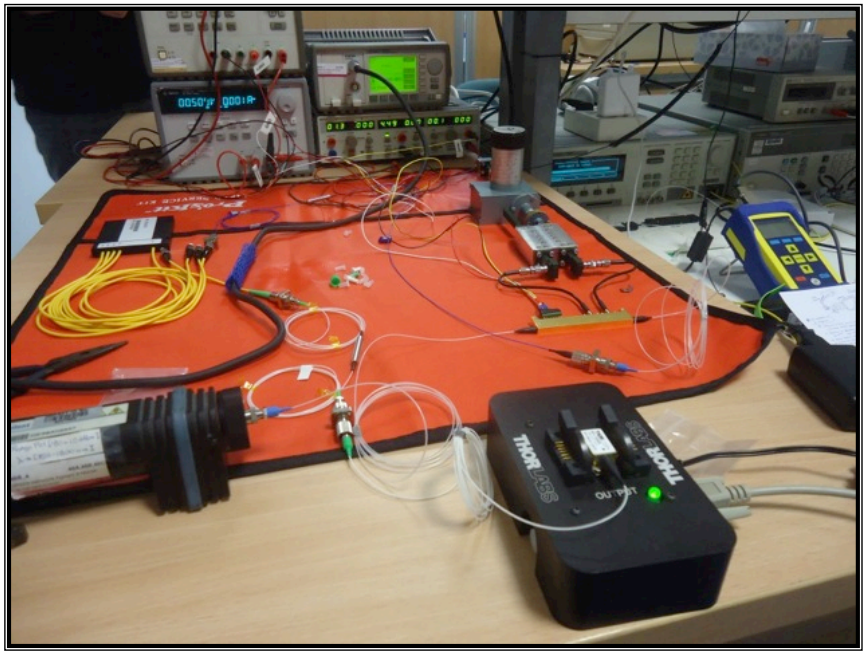


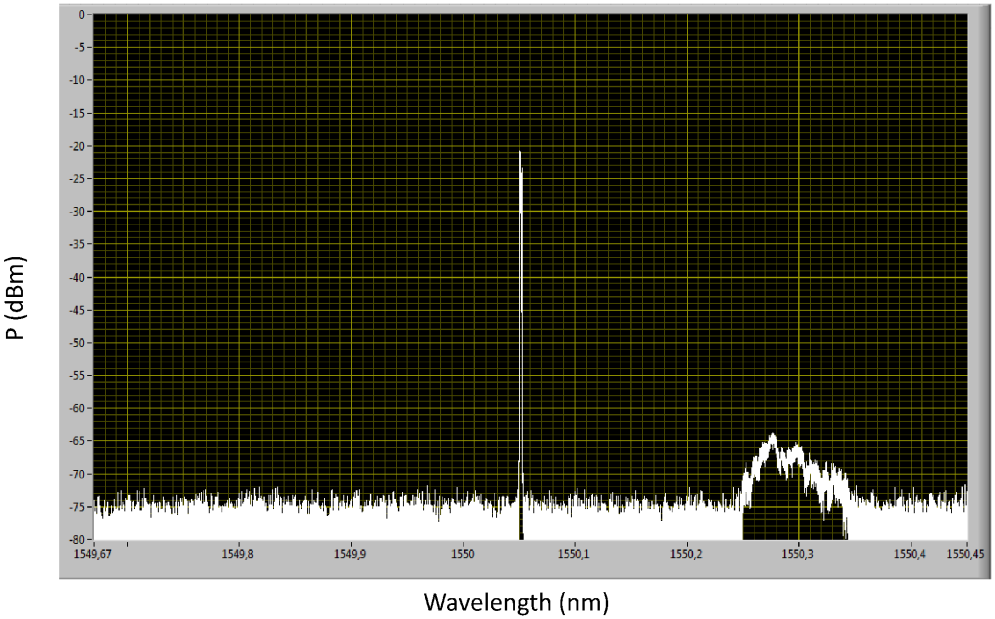
Plans for the Optical Interferometer

- A preliminar study done within the Spanish EPI Consolider project.
- The technological demonstration and fabrication of a prototype of a few elements already funded by two Spanish national projects.
- **Timescales**: 1 year to produce the prototype at 10-20GHz.

- Planned location: Teide Observatory.

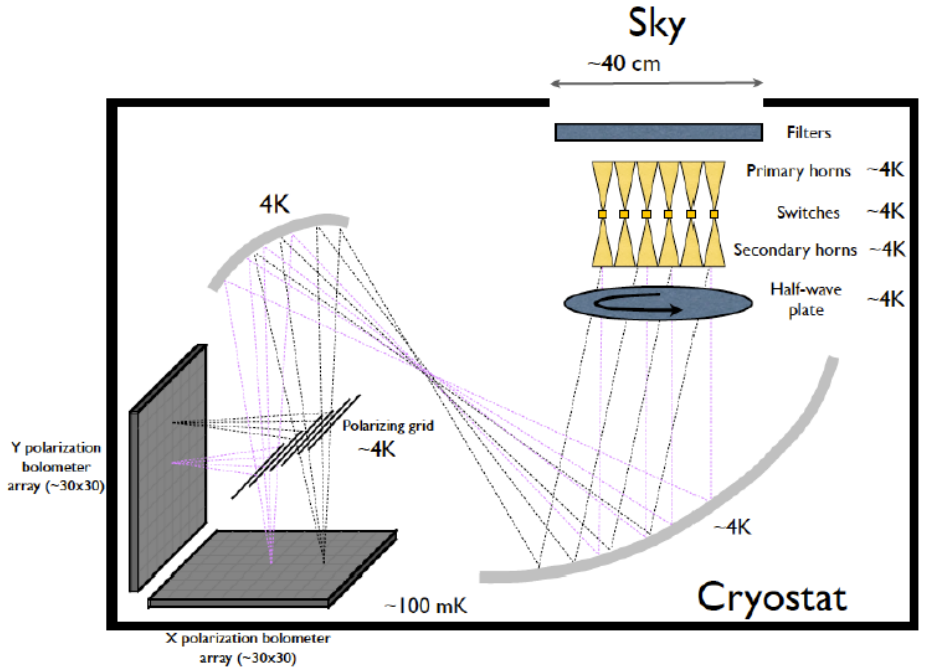
Up-conversion of MW Signals to the IR





Synergy with the QUBIC experiment

- *Synthetized Imager*
- *97, 150 and 220 GHz*
- *Atacama Observatory*
- *Fizzeau Beam Combiner*



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

$$R(\vec{d}_p, t) = S_I(\vec{d}_p) \pm \cos(4\omega t) S_Q(\vec{d}_p) \pm \sin(4\omega t) S_U(\vec{d}_p) \quad (1)$$

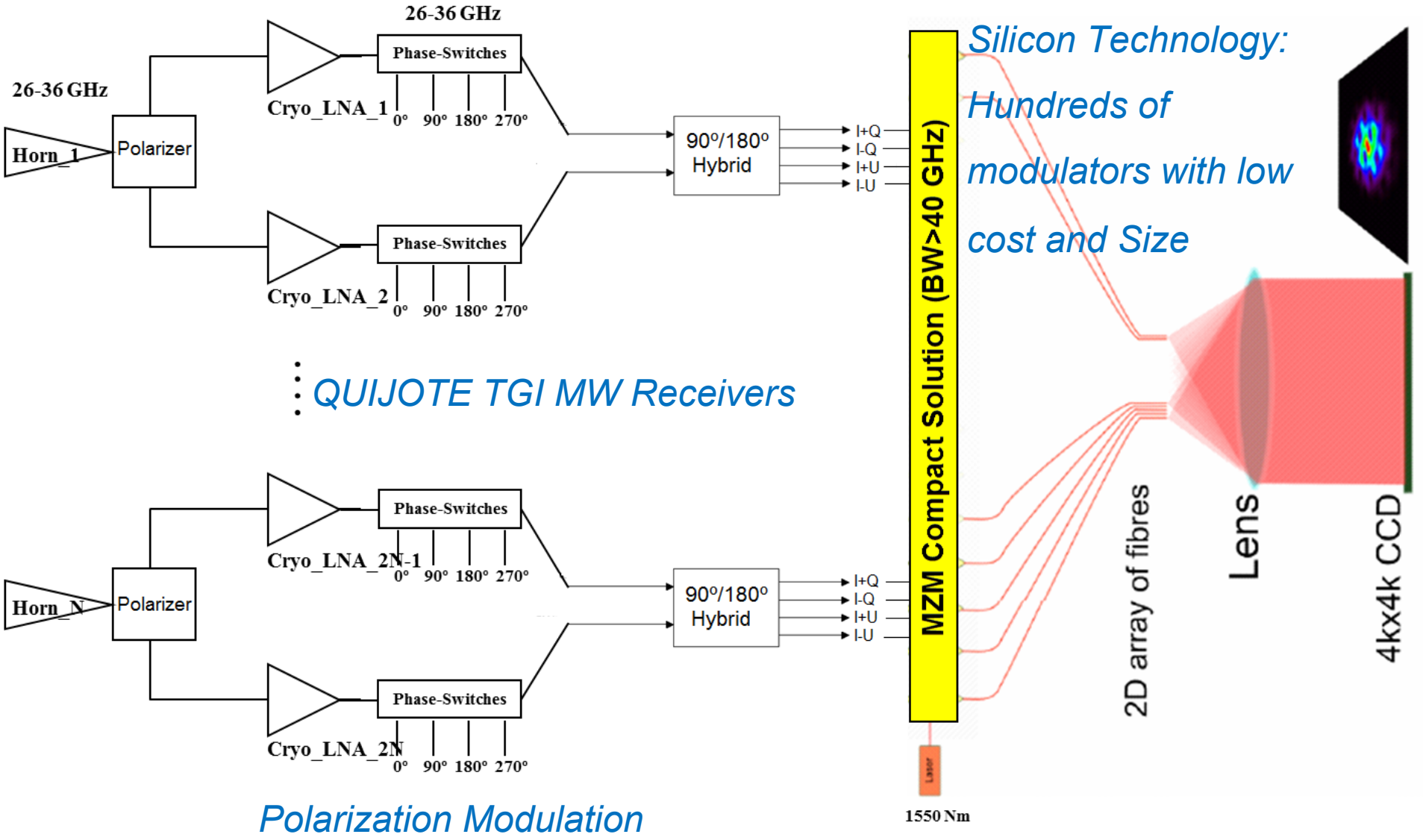
where the ± is + for one of the focal planes (polarized in one direction) and − for the other one polarized in the other direction.

This kind of interferometers act as imagers

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

- Our proposal is theoretically equivalent to QUBIC but using a different wavelength in the correlation and detection stage (NIR vs MW).

Interferometer Implementation Proposal



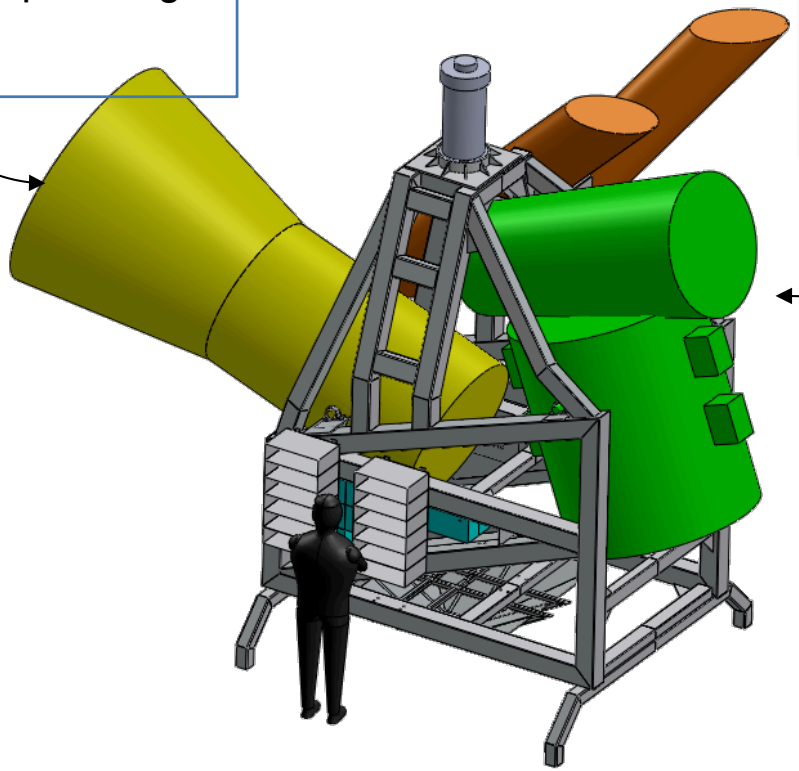
LSPE in a nutshell

SWIPE

- 140, 220, 240 GHz
- Multi-moded bolometers
- Rotating half-wave plate + grid polarizer

STRIP was previously intended to fly on the same gondola with SWIPE

Now being modified for ground observations (telescope and mount)



STRIP

- 43, (90) GHz
- QUIET coherent polarimeters
- Dragone side-fed telescope (~ 0.5° - 1° angular res.)

Goal: Constrain $r < 0.03$ with 99.7 % confidence level (3σ).

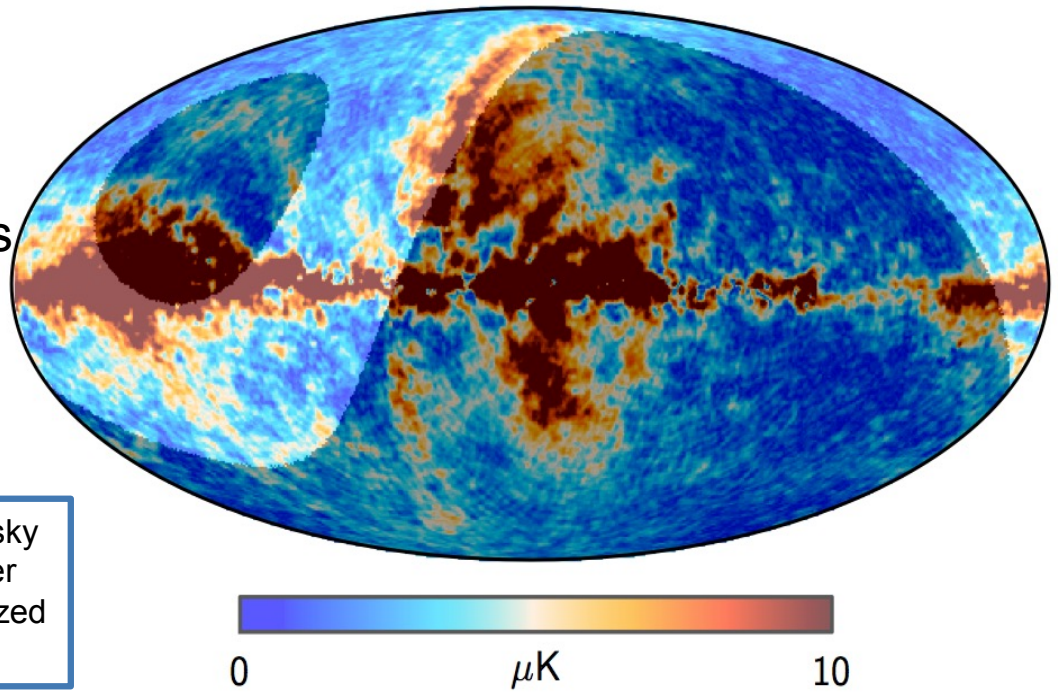
STRIP /LSPE

STRIP is the STRatospheric Italian Polarimeter, aimed at accurate measurements of the low-frequency (43 and 95 GHz) polarized emission, dominated by Galactic synchrotron.

STRIP was previously intended to fly on the same gondola with SWIPE. Now being modified for ground observations (telescope and mount).

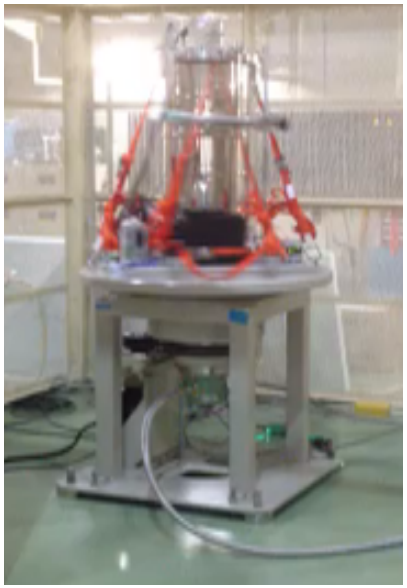
Planed to be installed in Tenerife (former VSA enclosure). **Timescale**: 2 years.

Maps of ¼ of the sky with high sensitivity. Overlaps with QUIJOTE wide survey and cosmological fields → synergy.



~ 23% of the sky available after masking polarized emission

GroundBIRD



❖ Japan (KEK, Riken, NAOJ, Universities of Tohoku, Saitama and Tokio), Korea (University of Korea), Spain (IAC)

❖ 145 GHz (660 KIDs) and 220 GHz (224 KIDs)

❖ At Teide observatory, at former VSA enclosure (possible future extension to Atacama).

❖ High-speed rotation scans of 20 rpm

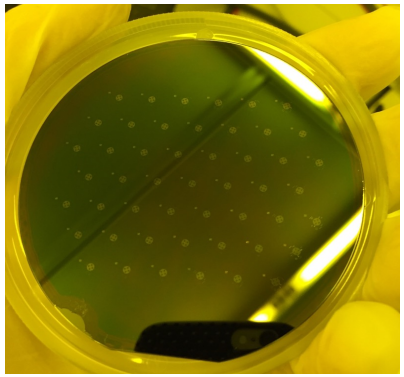
❖ 20-deg FOV with angular resolution of 0.6 deg (@ 145 GHz)

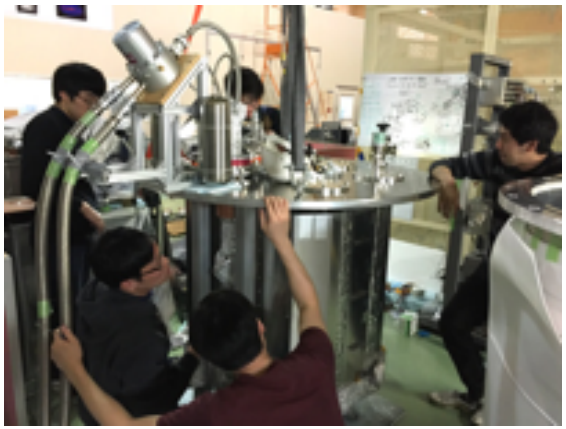
❖ AZ scans + Earth rotation provides very large-scale fields

❖ Memorandum of Understanding signed on 13 May 2016. Formal (more detailed) Agreement to be signed soon.

❖ Planned installation: summer 2017

❖ Operation plan: 3 years (2017-2020)





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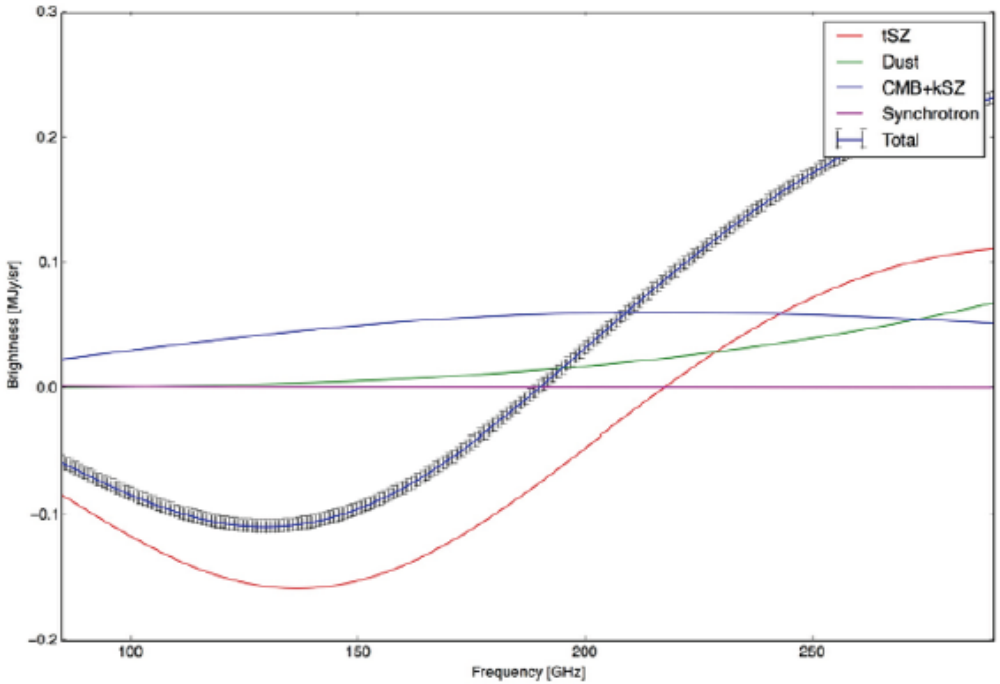
KIDs Interferogram Spectrometer Survey (KISS)

- LPSC and Institut Néel (Grenoble), and IAC (Tenerife).
- **Science driver**: Ground-based low resolution spectroscopy observations of known low redshift galaxy clusters at mm wavelengths to map cluster physical properties from spectral distortions.
- **KISS instrument**:
  - NIKA-like KIDs based camera + Martin Puplett interferometer (few GHz resolution) + QUIJOTE telescope (few arcmin resolution).
  - 80-280GHz, 500 detectors, 2-3 deg FOV.
- **Timescale**: start operations in 2 years



$y = 3.3 \times 10^{-5}$

24 hours integration time

Microwave Spectrometer in the 10-20GHz band

- IAC project. Already funded.
- **Science driver**: Ground-based low resolution spectroscopy observations in the 10-20GHz range to characterize foregrounds (monopole signals; spectral dependence of monopole signals; ARCADE results) and CMB spectral distortions. Provides frequency cross-calibration for QUIJOTE.
- **Proposed instrument**:
  - FEM cooled to 4-10K, reference load to 4K.
  - Switched stabilized filter-bank.
  - ~2deg beam, 0.25 GHz spectral resolution (40 bands).
- **Timescale**: two years.
- **Location**: Teide Observatory (former VSA enclosure).

Instituto de Física de Cantabria

European Commission

Title of Proposal:	**U**ltrasensitive **B**olometers for **CO**smology
Acronym:	**rUBiCOn**

H2020-FETOPEN-2016-2017 (submitted)

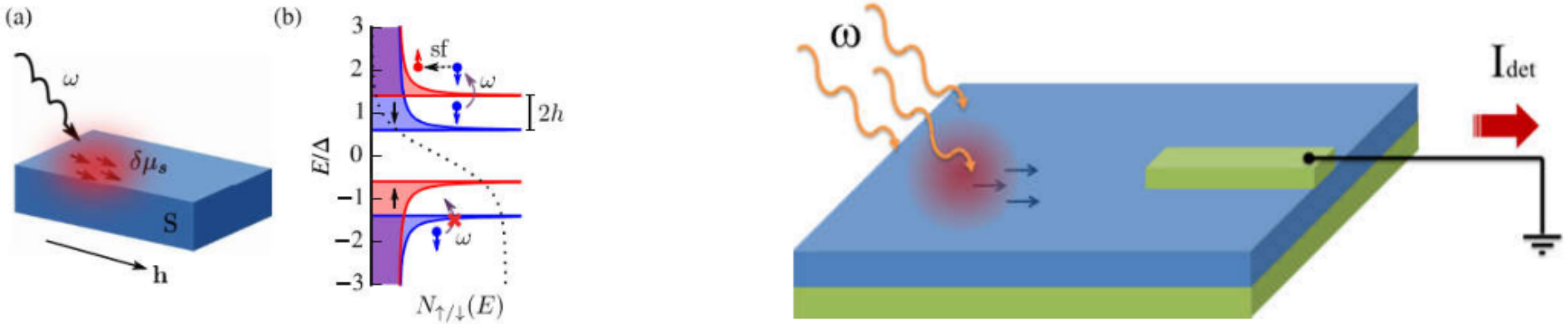


Figure 2: When a superconductor is placed in contact with a ferromagnetic insulator, the density of states shows spin-splitting. This property converts the incoming radiation energy to spin imbalance, which can be read out with a spin filter junction realized with another ferromagnetic insulator. The detector current is then directly proportional to the power in the incoming radiation, allowing for a measurement of the latter.

IV. Views on the European roadmap

- European roadmap: observations on the low frequency range 10-50 GHz
- Present and future needs for all-sky observations
- Spectral distortions
- European coordination
- Participation in S4

Ideas for an European roadmap

- The European bet is now a high resolution mission of the CORE type.
- CORE will cover a relatively wide frequency range with a minimum frequency at around 60 GHz.
- **Frequencies below 50 GHz are needed to control the synchrotron emission to the required precision,** and have to be observed from the ground with experiments like QUIJOTE.
- Natural synergy with existing efforts in Europe (e.g. STRIP/LSPE, QUBIC).

- **Present and future needs to complement CORE at low frequencies:**
  - In the short term, place a QUIJOTE-like telescope in the Southern hemisphere in order to cover all-sky.
  - In the longer term, construct sensitive experiments in the range 10-50 GHz with thousands of detectors and cover both hemispheres → Interferometer?
  - The cost and operation of the future experiments (large-format interferometers, experiments in the south) will require most probably an international consortium with contributions from several countries.

- **Spectral distortions measurements** from the ground, balloons and space. Multiple efforts in Europe (e.g. OLIMPO, KISS, IAC-Spectrometer), and also the old PRISM proposal. This could complement PIXIE at frequencies below 30GHz.

European coordination and contributions to S4

- Coordinated contribution at European level. Needs to be organised for ground and balloon experiments, extending the current organization for space missions (Planck, CORE).

- Participation to S4 is desirable, and should be based on our present and future experiments and expertise.
- In Spain, the present low frequency QUIJOTE and specially the future interferometers with thousands detectors could provide a necessary complement to the hundred of thousands detectors expected for S4 at frequencies 40-300 GHz.
- Our infrastructures in Observatories and Labs can also complement the S4 ones with respect to observations, KIDs and LNAs fabrication, …
- Other contributions can be based on our expertise in data processing and analysis, in particular in relation to combined analyses involving low and high frequency data.