QUBIC: Laboratory Characterization

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on behalf of the QUBIC Collaboration

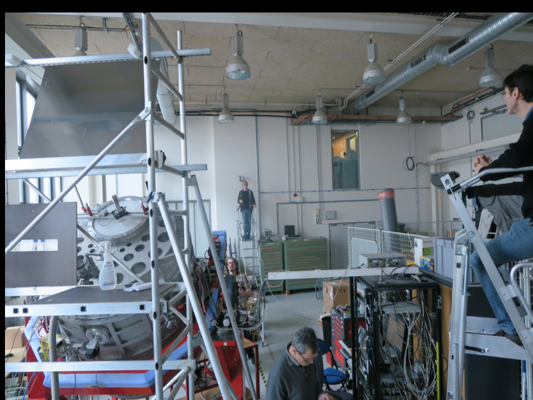
Upcoming special issue of JCAP
arXiv:2008.10056

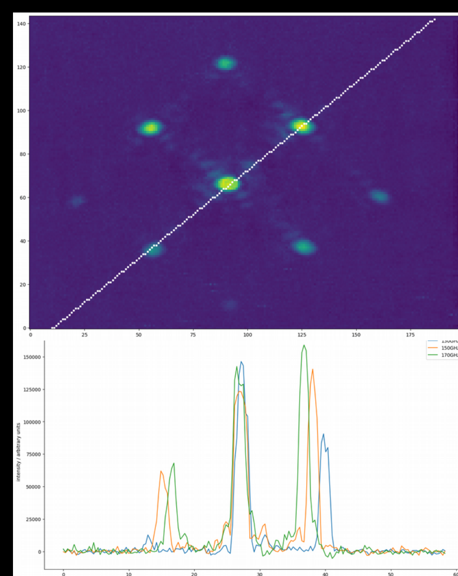
Laboratory Characterization: Summary

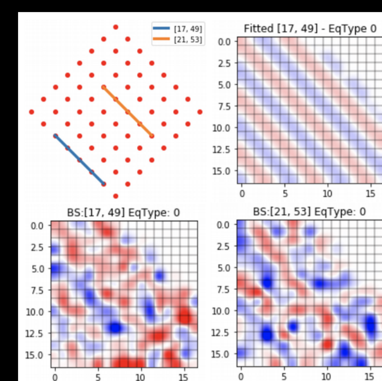
arXiv:2008.10056

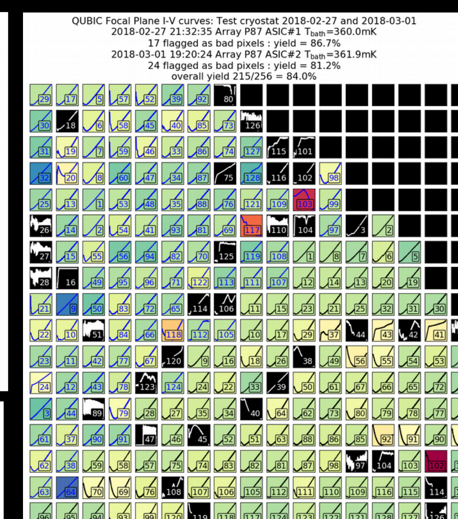
- Measurement of the synthesized beam pattern matching well simulations
- Measurement of the synthesized beam at different frequencies demonstrating that spectral imaging is feasible.
- Measurement of fringes on the focal plane demonstrating that Self Calibration is feasible.
- Measurement of the millimetre calibration source with very high signal-to-noise ratio showing that calibration with an external source is feasible.
- Mapmaking with the synthesized beam which demonstrates a complete end-to-end checkout of the QUBIC system.
- Measurement of polarization modulation with the Half Wave Plate rotation.

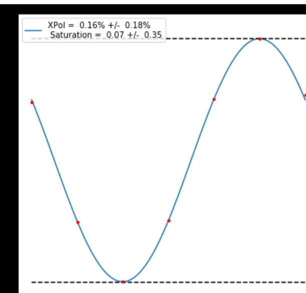
- Cryogenic cooldown to sub-Kelvin temperature demonstrating that the cryostat architecture is well designed and executed.
- Cryogenic recycling showing that the sub-Kelvin temperature can be maintained for approximately 24 hours, and is easily recycled with an autonomous program and takes only several hours before sub-Kelvin temperature is re-achieved.
- Measurement of TES I-V curves showing the high yield of 84% and the homogenous characteristics of the 256 bolometers in the TES array.
- Measurement of TES phonon Noise Equivalent Power of 4.7×10^{-17} W/Hz.
- Measurement of TES critical temperature of 412 mK.
- Mechanical/Electronic functionality of subsystems.









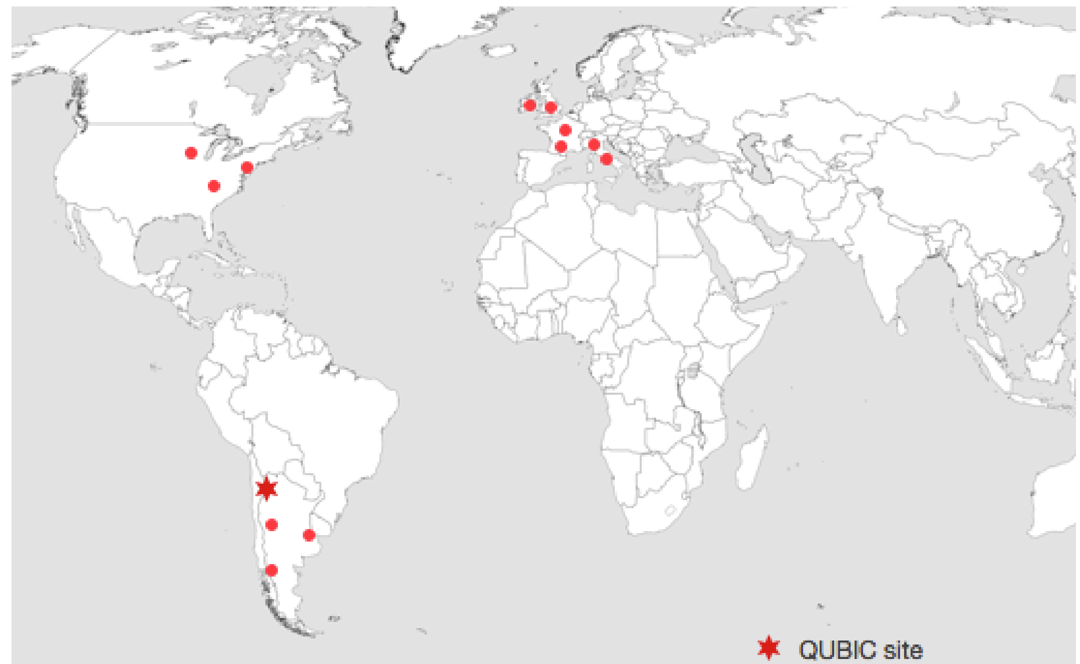


Bolometric Interferometry
control of instrument systematic effects using self calibration
control of foreground contamination using spectral imaging

QUBIC

a Q&U Bolometric Interferometer for Cosmology

APC Paris, France
C2N Orsay, France
CSNSM Orsay, France
IAS Orsay, France
IRAP Toulouse, France
LAL Orsay, France
Universita di Milano-Bicocca, Italy
Universita degli studi di Milano, Italy
Universita La Sapienza, Roma, Italy
Maynooth University, Ireland
Cardiff University, UK
University of Manchester, UK
Brown University, USA
Richmond University, USA
University of Wisconsin, USA
Centro Atómico Constituyentes, Argentina
GEMA, Argentina
Comisión Nacional de Energía Atómica, Argentina
Facultad de Cs Astronómicas y Geofísicas, Argentina
Centro Atómico Bariloche and Instituto Balseiro, Argentina
Instituto de Tecnologías en Detección y Astropartículas, Argentina
Instituto Argentino de Radioastronomía, Argentina



Control of Systematics

- QUBIC proposes an innovative solution to the problem of foreground and systematic effects:

  Bolometric Interferometry

  - control of instrument systematic effects using self calibration
  - control of foreground contamination using spectral imaging

Primordial B-modes with QUBIC

Very weak signal

Focal Plane:
- 2048 TES with NEP ~ 4×10^{-17} $W.Hz^{-1/2}$
- 128:1 SQUIDs+ASIC Mux Readout
- End-To-End Sims. show σ(r)=0.015 with 3 years (Hamilton et al arXiv:2011.02213)

Instrumental systematics

Cryogenic Optics after HWP and Polarizer + Full power detectors
- Instrumental Polarization has no effect

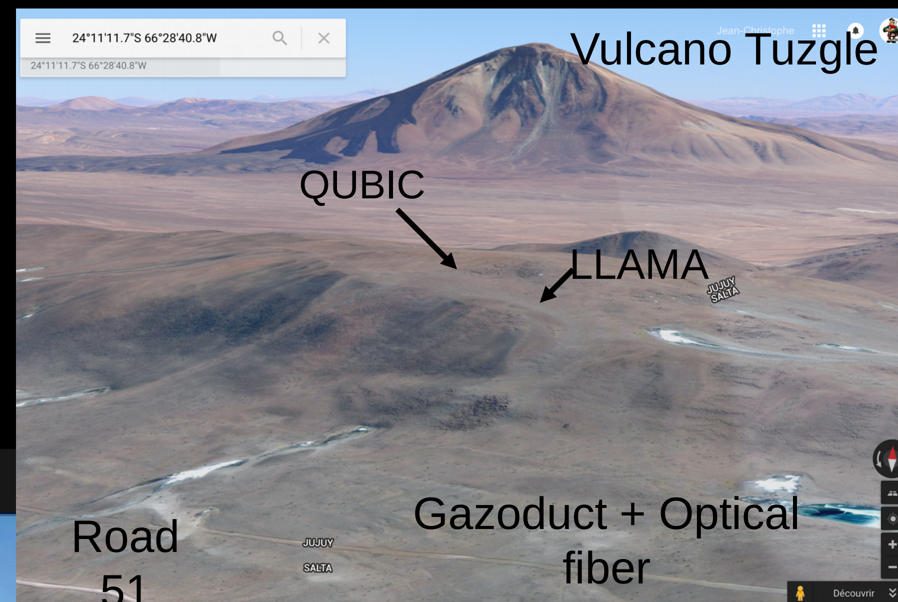
400 elements Interferometer
- Synthesized Imaging (well controlled beam) – angular resolution 23.5 arcmin
- **Self-Calibration** using switches + active source

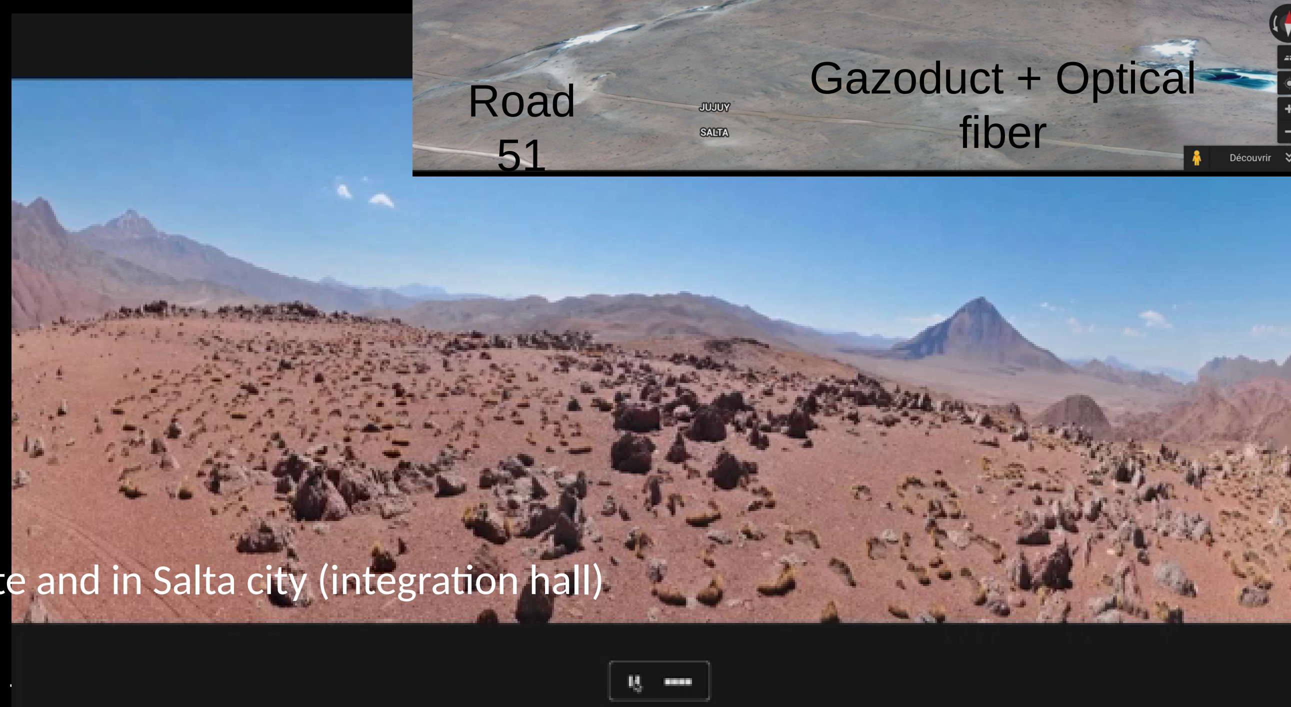
Polarized foregrounds

Two wide bands: 150 and 220 GHz
- 1 focal plane for each channel

Spectro-Imaging allows to form ≳ 2+3 bands
- Increased Frequency Resolution
- More Complex dust models can be constrained

QUBIC Site: near San Antonio de los Cobres (Salta, Argentina)

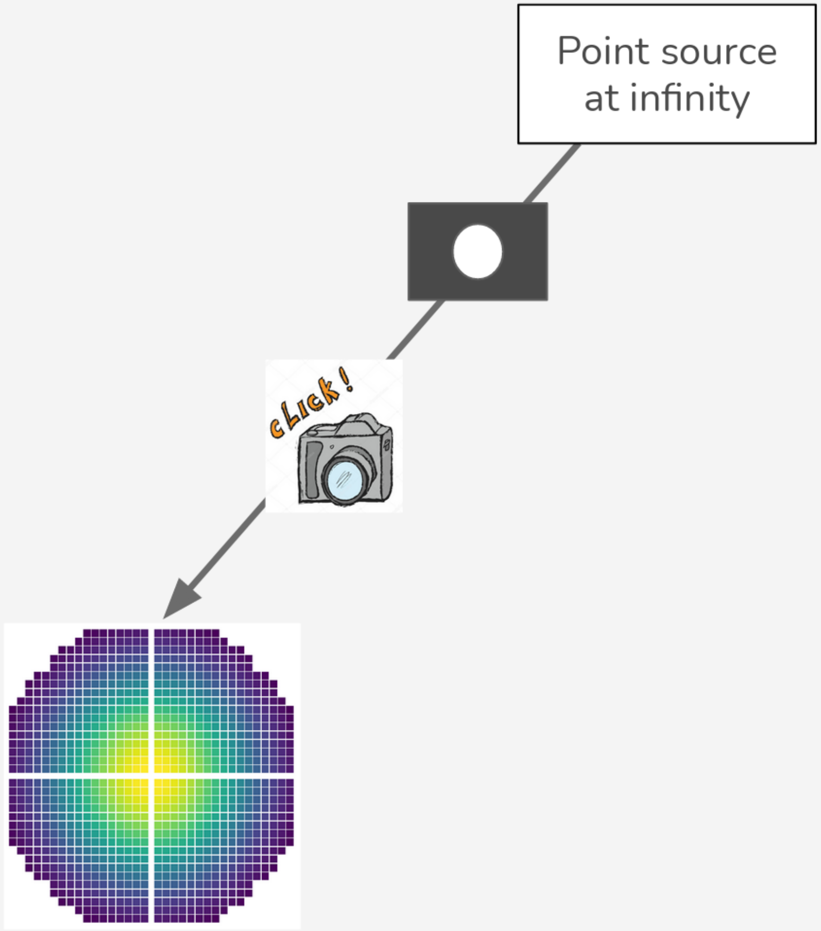




5000m a.s.l.
Logistics + mount : Argentina
Access road built, works started on site and in Salta city (integration hall)

Imaging Interferometer

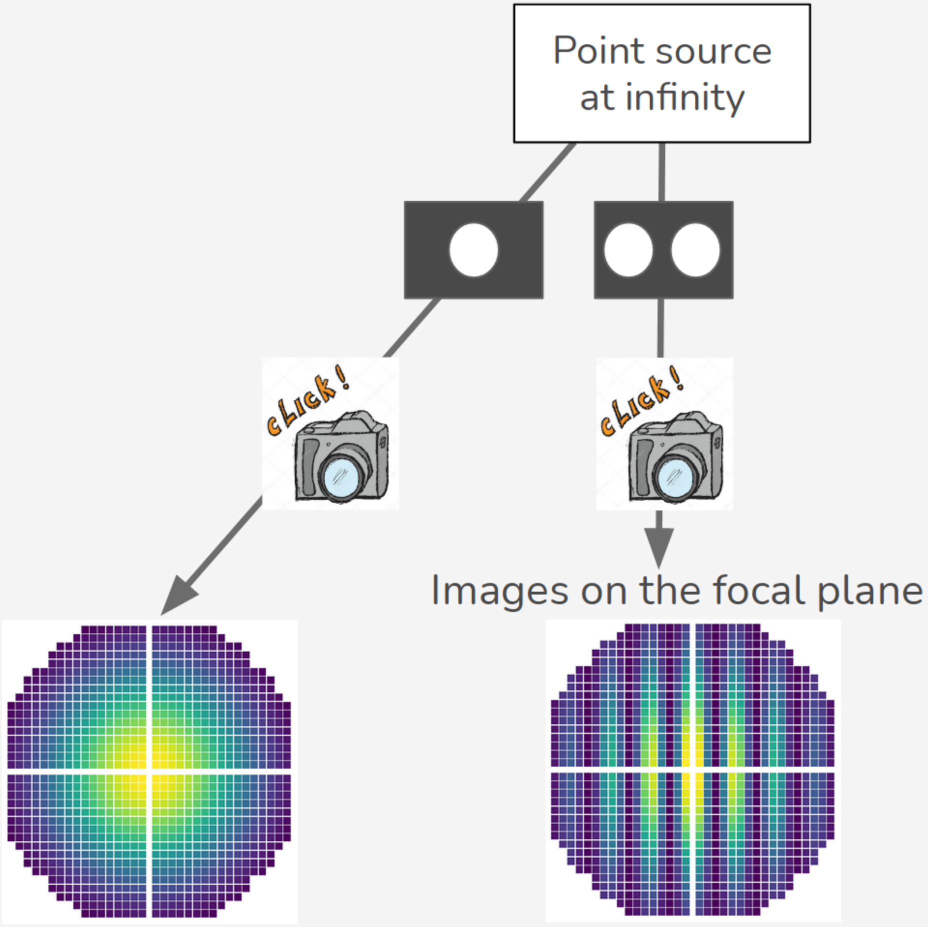
An imaging interferometer



L. Mousset

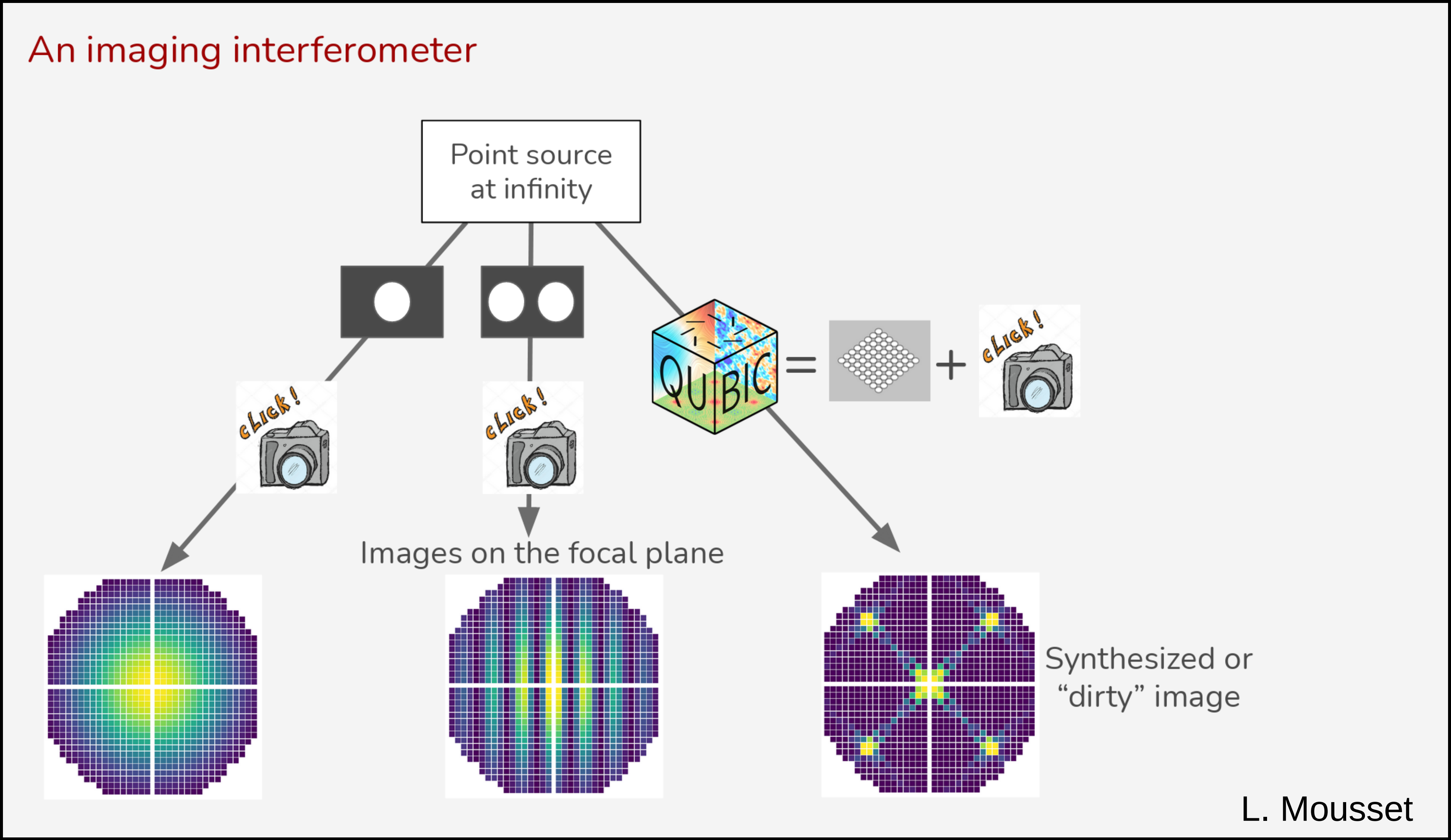
Imaging Interferometer

An imaging interferometer

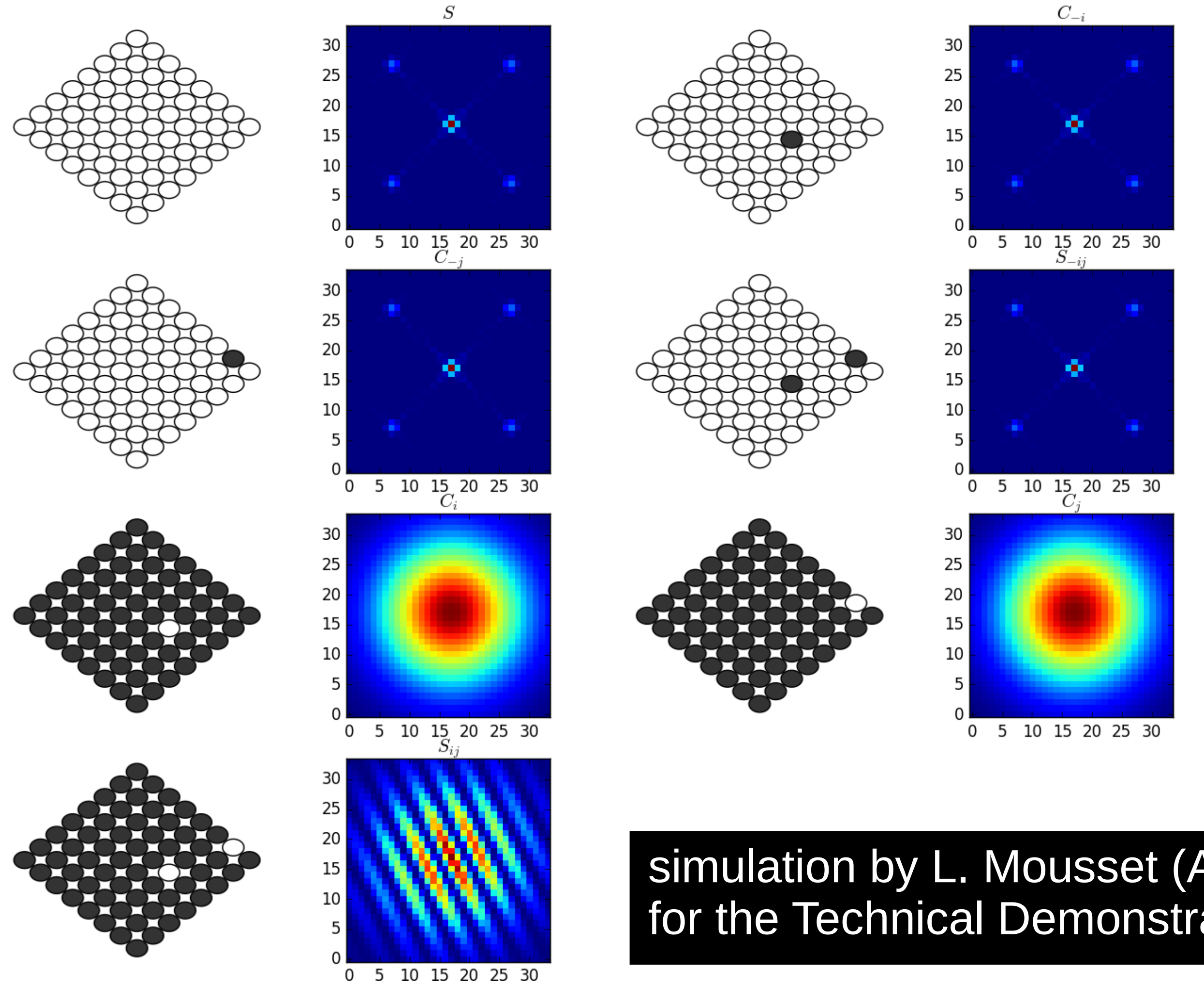


L. Mousset

Imaging Interferometer



Recover Baselines by switching off selected horns



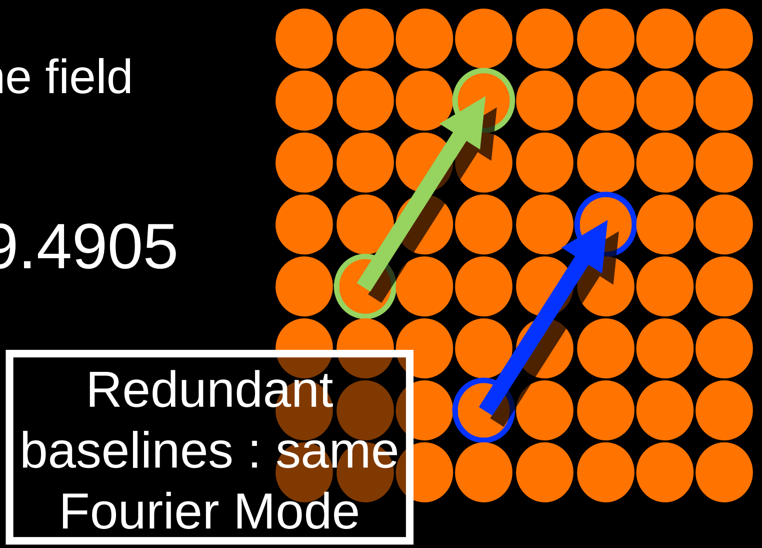
simulation by L. Mousset (APC)
for the Technical Demonstrator

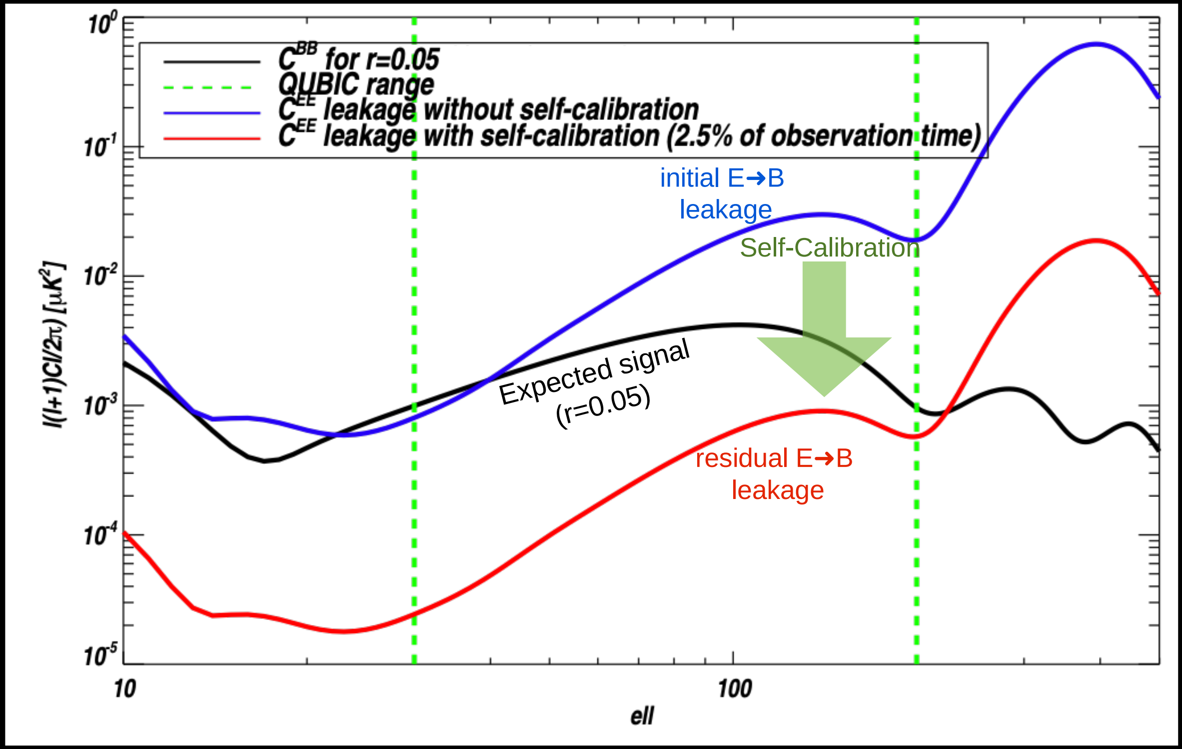
Self Calibration

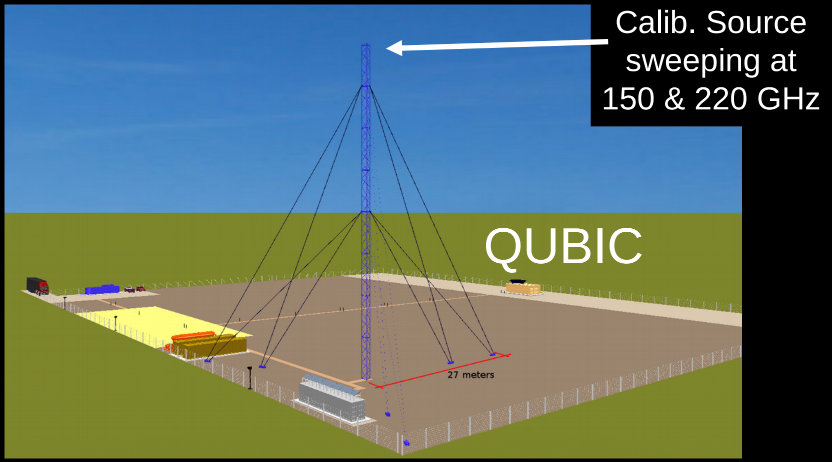
Unique possibility to handle systematic errors

- Use horn array redundancy to calibrate systematics
- In a perfect instrument redundant baselines should see the same signal
- Differences due to systematics
- Allow to fit systematics with an external source on the field

Bigot-Sazy et al., A&A 2013, arXiv:1209.4905



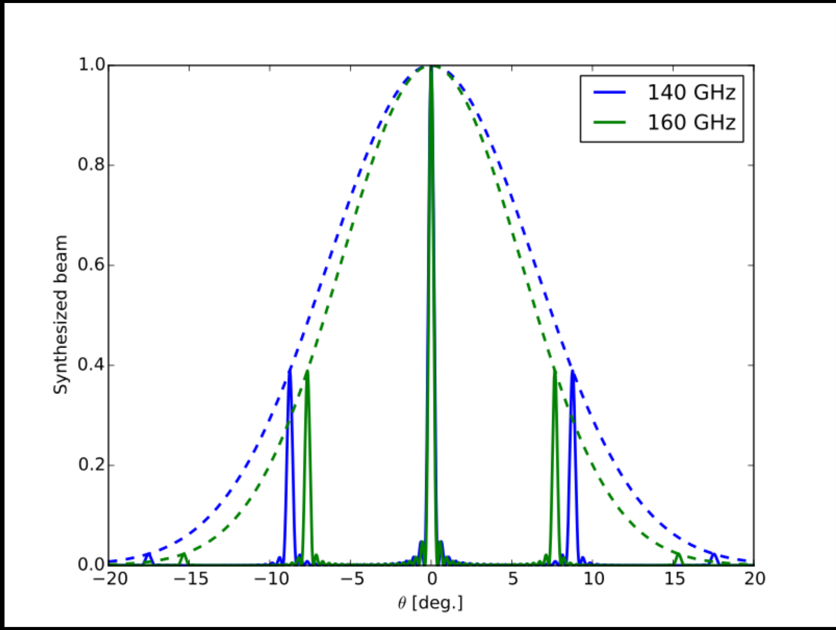




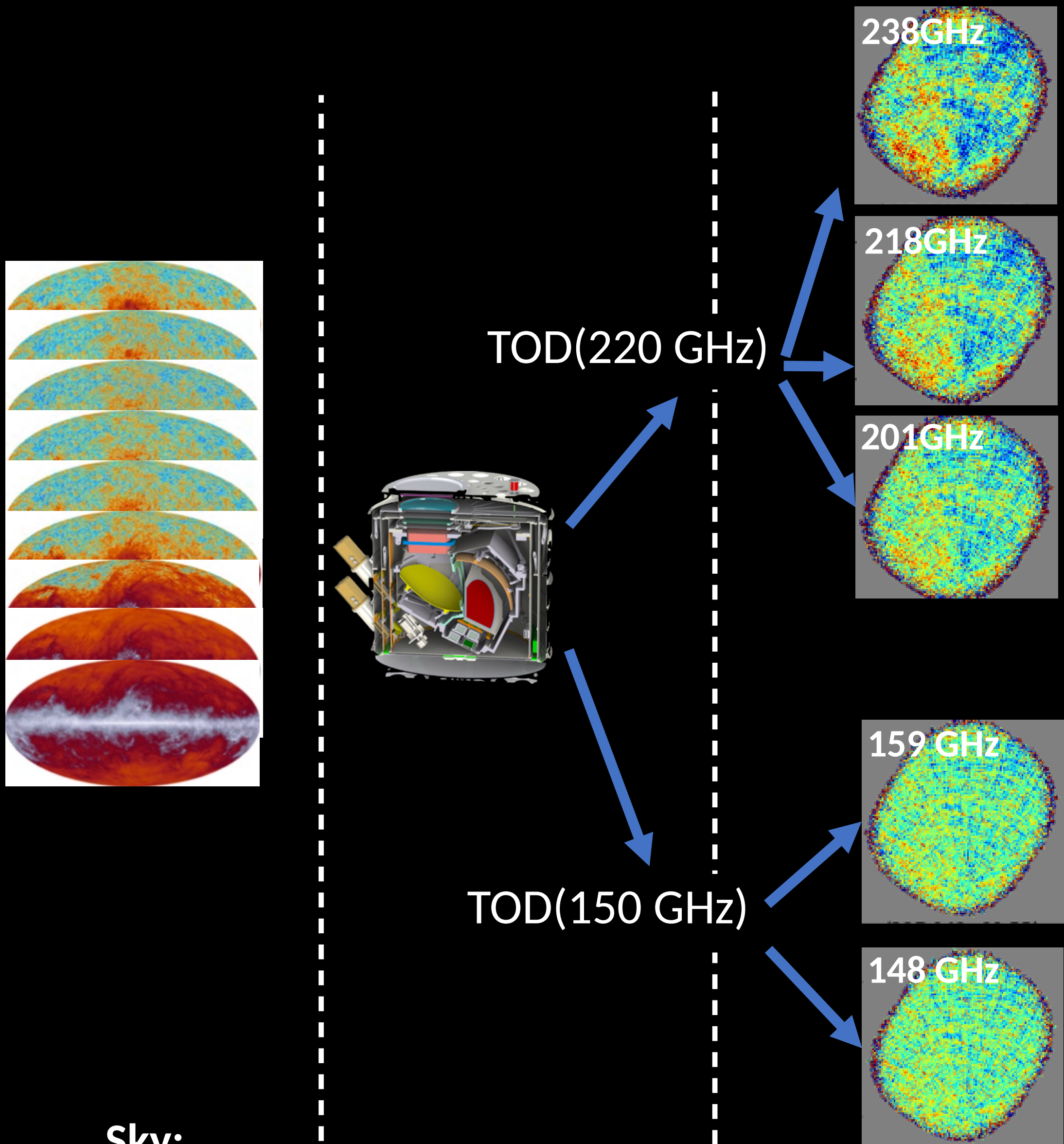
Spectro Imaging

- Synthesized beam:
  - ★ Depends on horns configuration
  - ★ AND on frequency !
    - ex: a point source emitting at 140 and 160 GHz
- There is spatial + frequency information
- Multi-frequency map-making with the same TOD
  - ★ Spectral resolution $\Delta\nu/\nu \sim 0.05$
  - ★ Shown to be quasi-optimal with simulations

Mousset et al arXiv:2010.15119



QUBIC Spectro Imaging



Sky: Infinite bands

Instrument: 2 wide bands

Data Analysis: 5 narrow bands

=> Increased Spectral Resolution

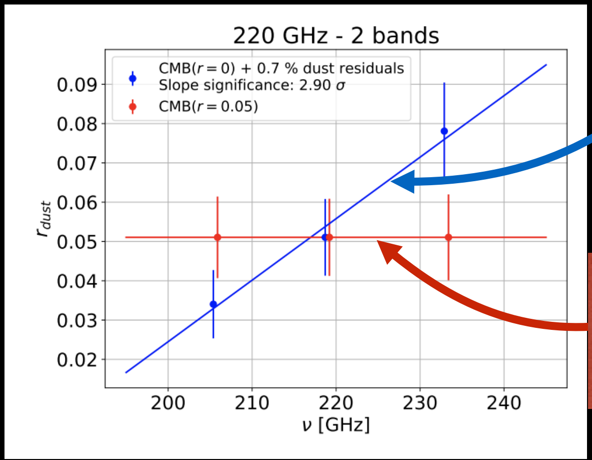
=> Dust subtraction

=> More complex models can be constrained

Effective tensor-to-scalar ratio (can originate from CMB and from dust) measured in μK²

Assumed to be from a map **after imperfect component separation**

⇒ Dust residuals remain



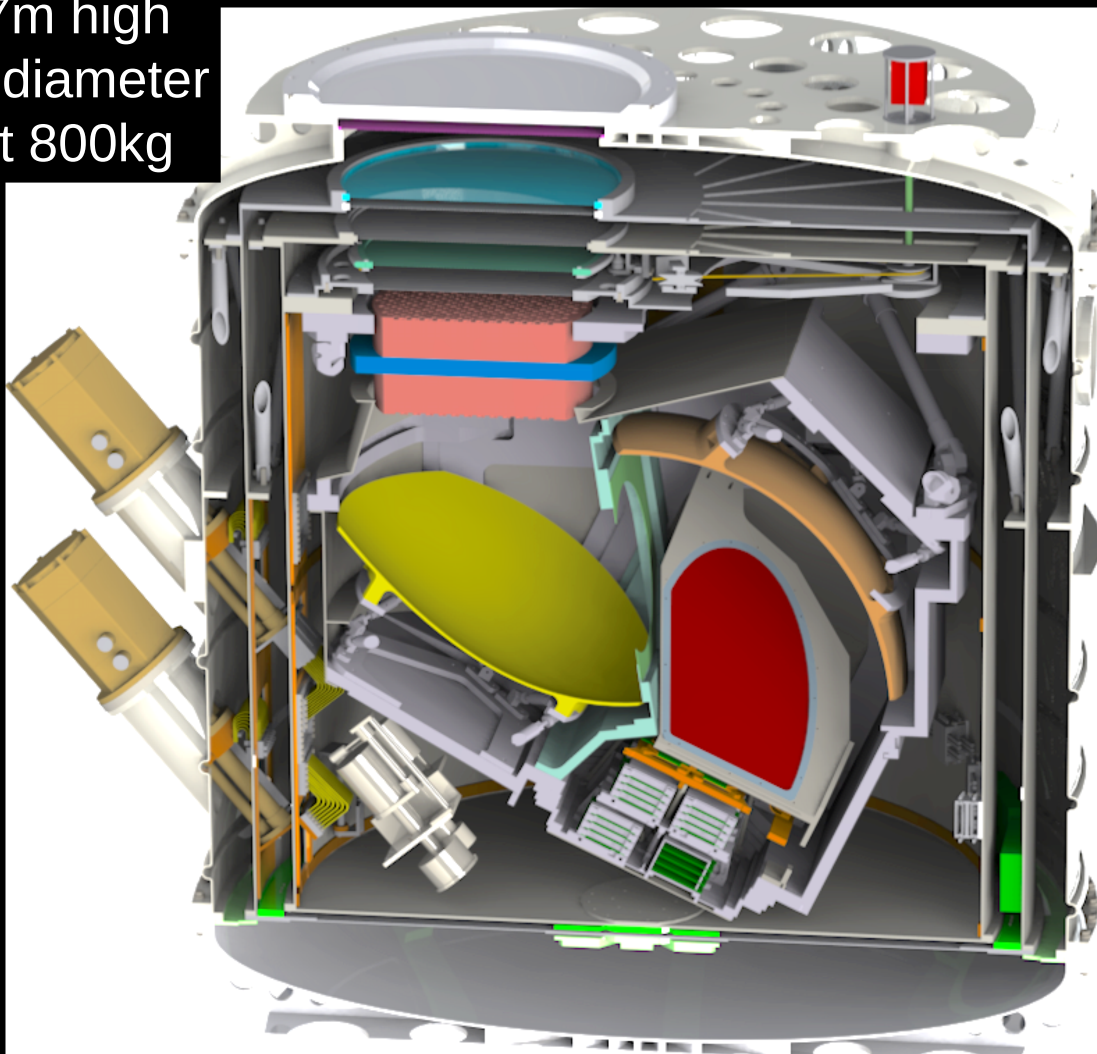
Dust is not a Blackbody

CMB is a Blackbody: Constant T

Hamilton et al, 2020, arXiv:2011.02213

QUBIC Layout

1.547m high
1.42m diameter
About 800kg

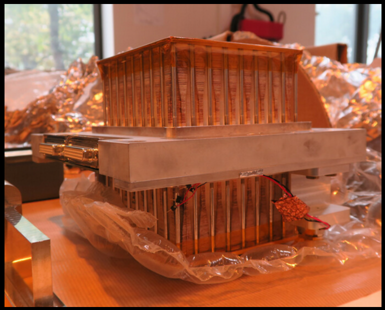


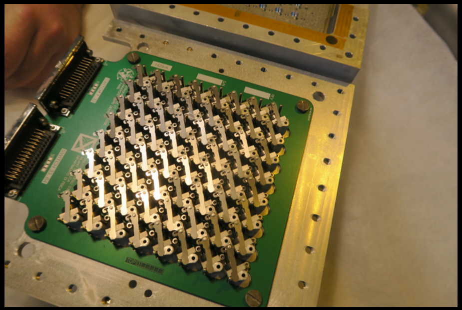
- Outer cryostat: Roma
- 1K Box / detectors: APC, CSNSM / IRAP
- Fridges: Manchester
- Optics: Roma / Maynooth / Cardiff

Currently cold
and under test at APC

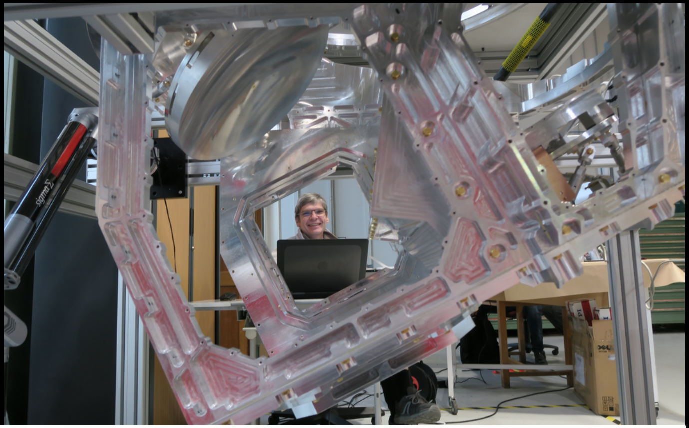
QUBIC Hardware

cryostat manufactured by Roma La Sapienza
Masi et al, 2020, arXiv:2008.10659

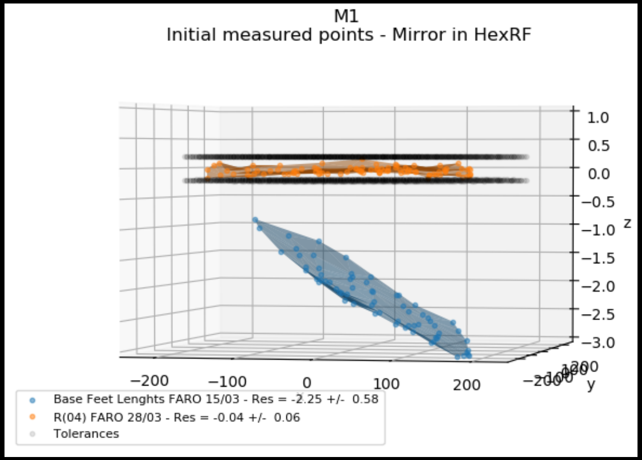


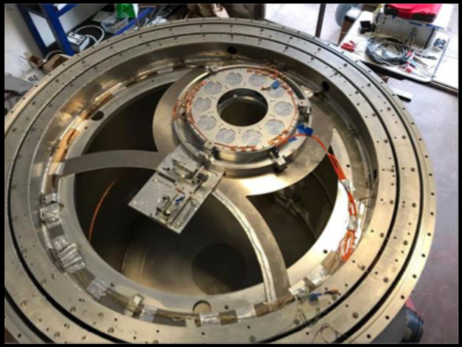


Back-to-back platelet horn array: Milano Statale (INFN)
Switches: Milano Bicocca (INFN)
Cavaliere et al, 2020, arXiv:2008.12721



1K Optics box: APC
Mirrors + alignment: Milano, Roma, APC
Design: Maynooth, Milan
O'Sullivan et al, 2020, arXiv:2008.10119

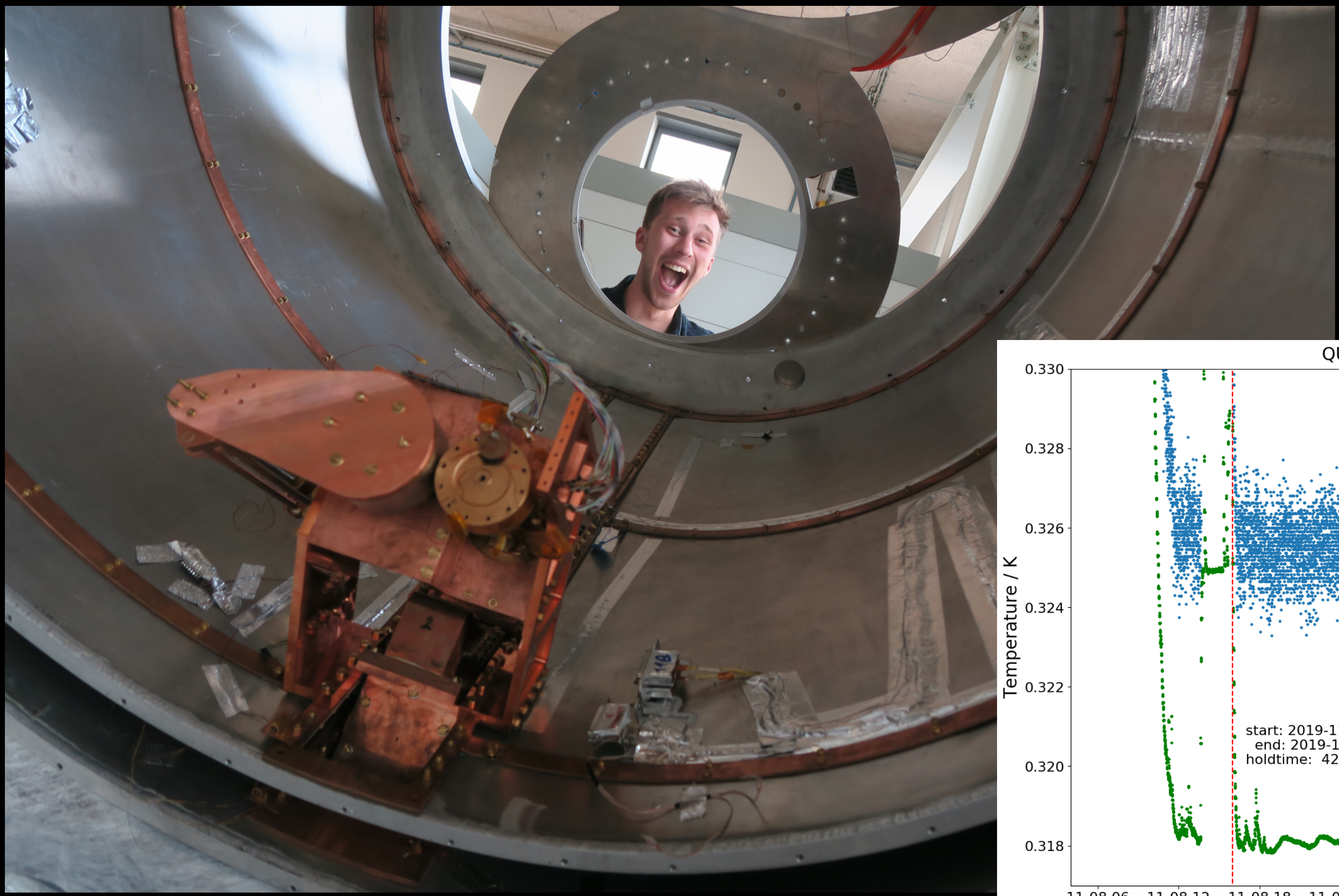


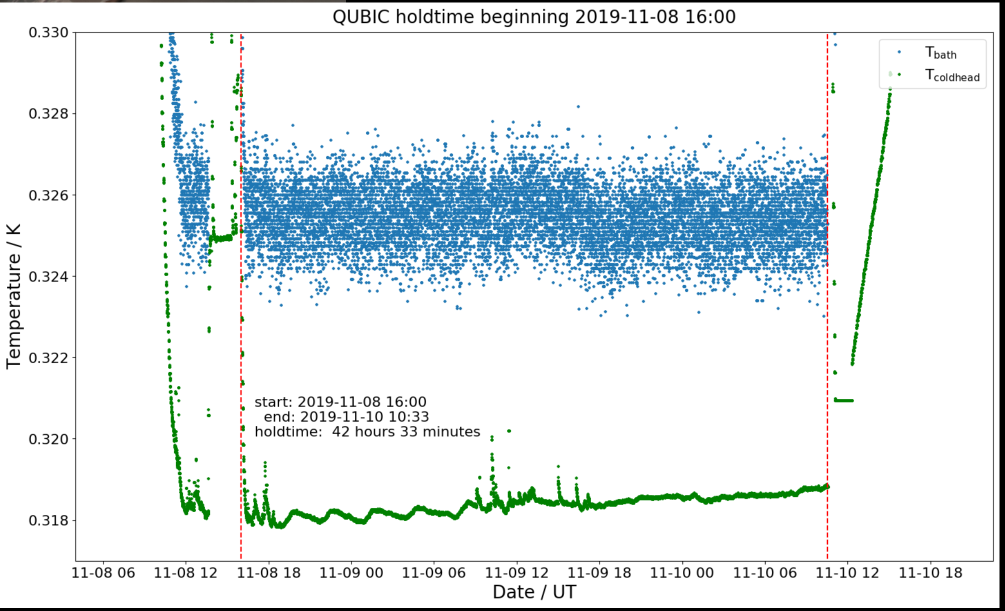


Half Wave Plate rotator: Roma La Sapienza (INFN)
D'Alessandro et al, 2020, arXiv:2008.10667

Cryo system

1K and 300mK He4 fridges: U. Manchester



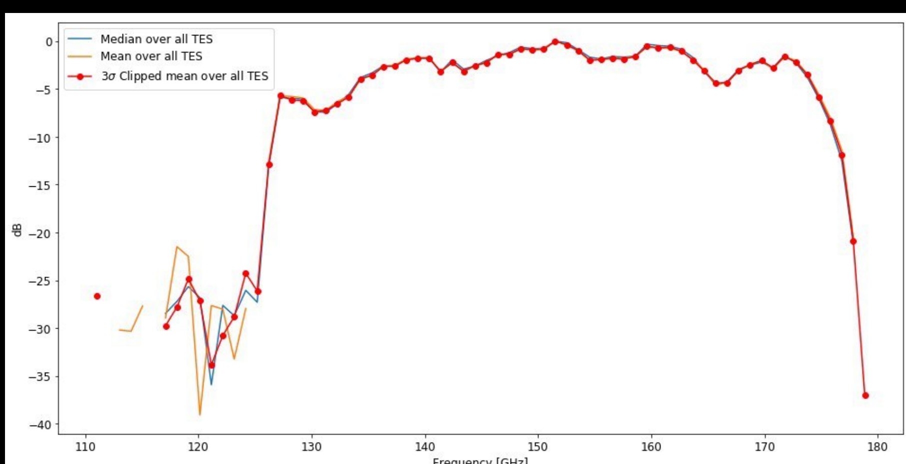


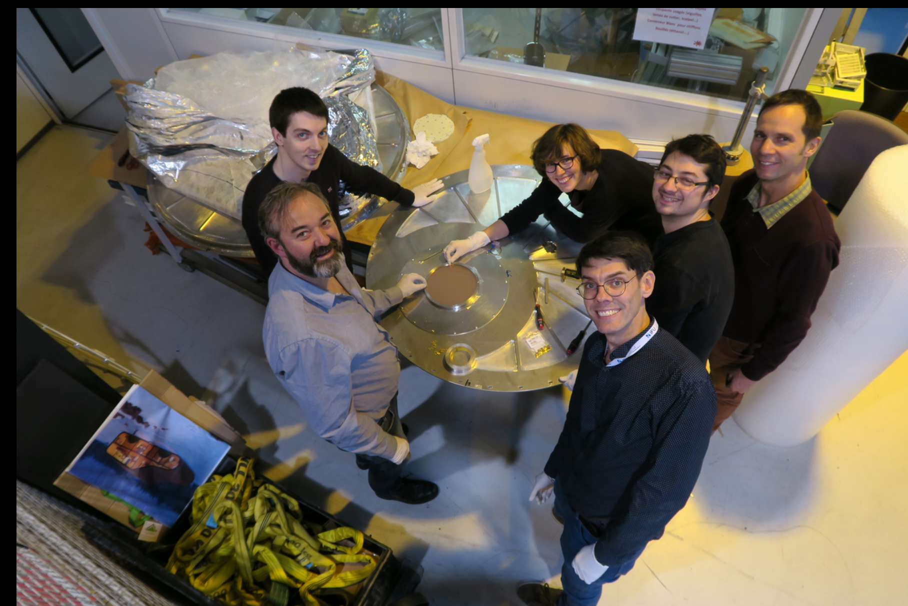
Sub-Kelvin temperature can be maintained for well over 24 hours, and the 300 mK fridge is easily recycled with an autonomous program. It takes only several hours before sub-Kelvin temperature is re-achieved.

Cryo Optical Components

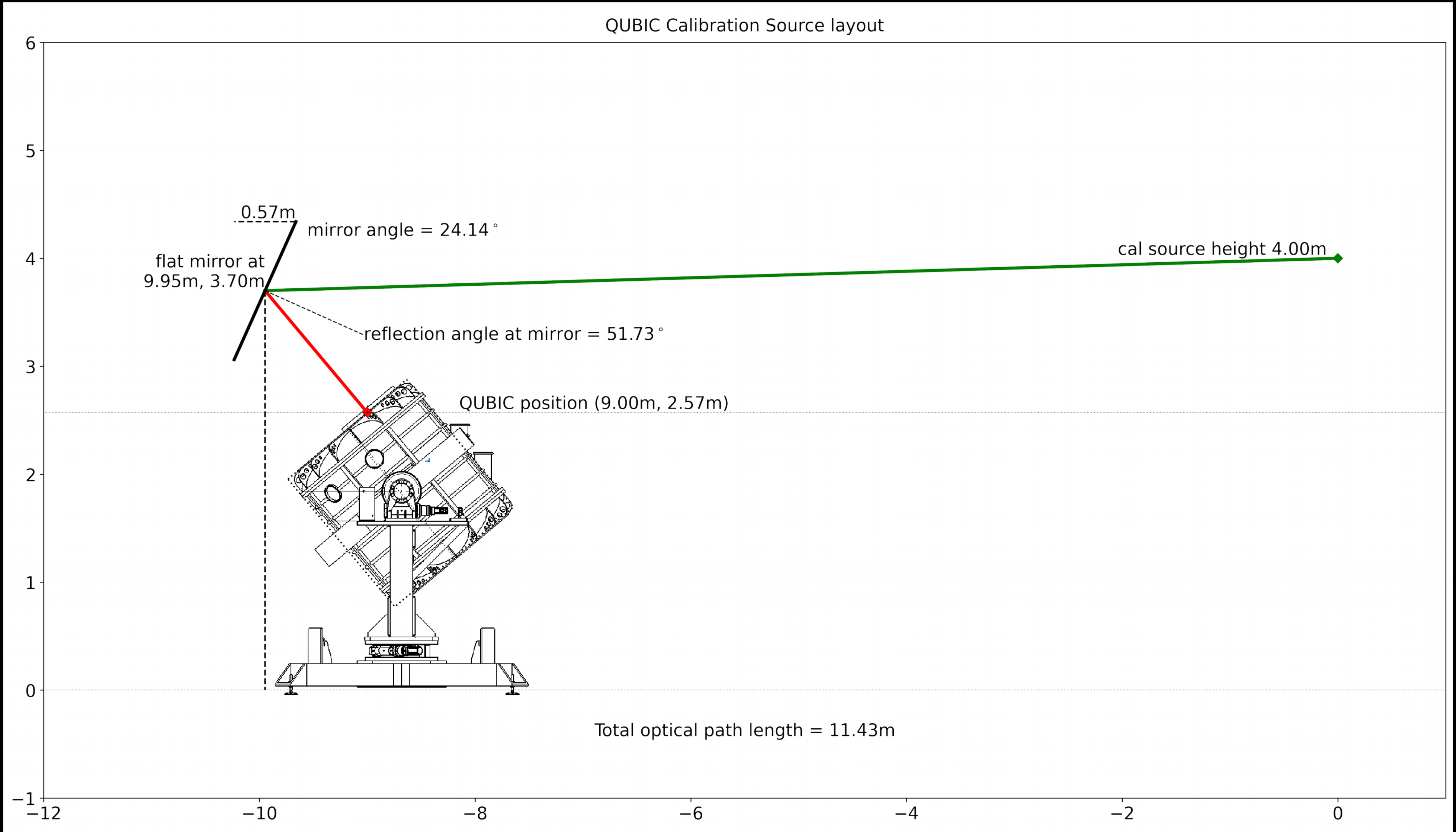
Filters, HWP, Polarizer: Cardiff

30cm diameter hot-pressed and AR-coated mesh HWP – To be cut





Calibration Setup

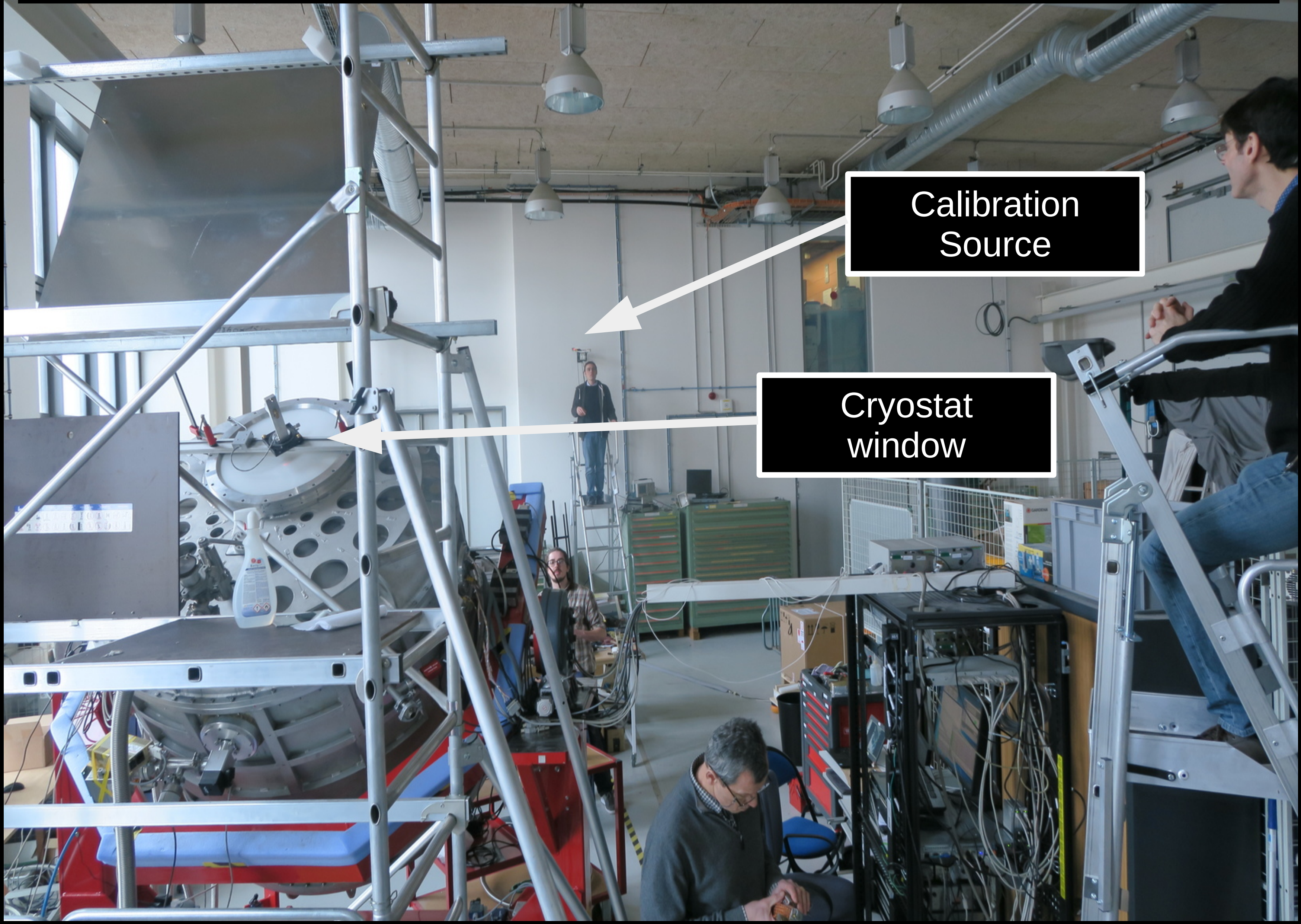


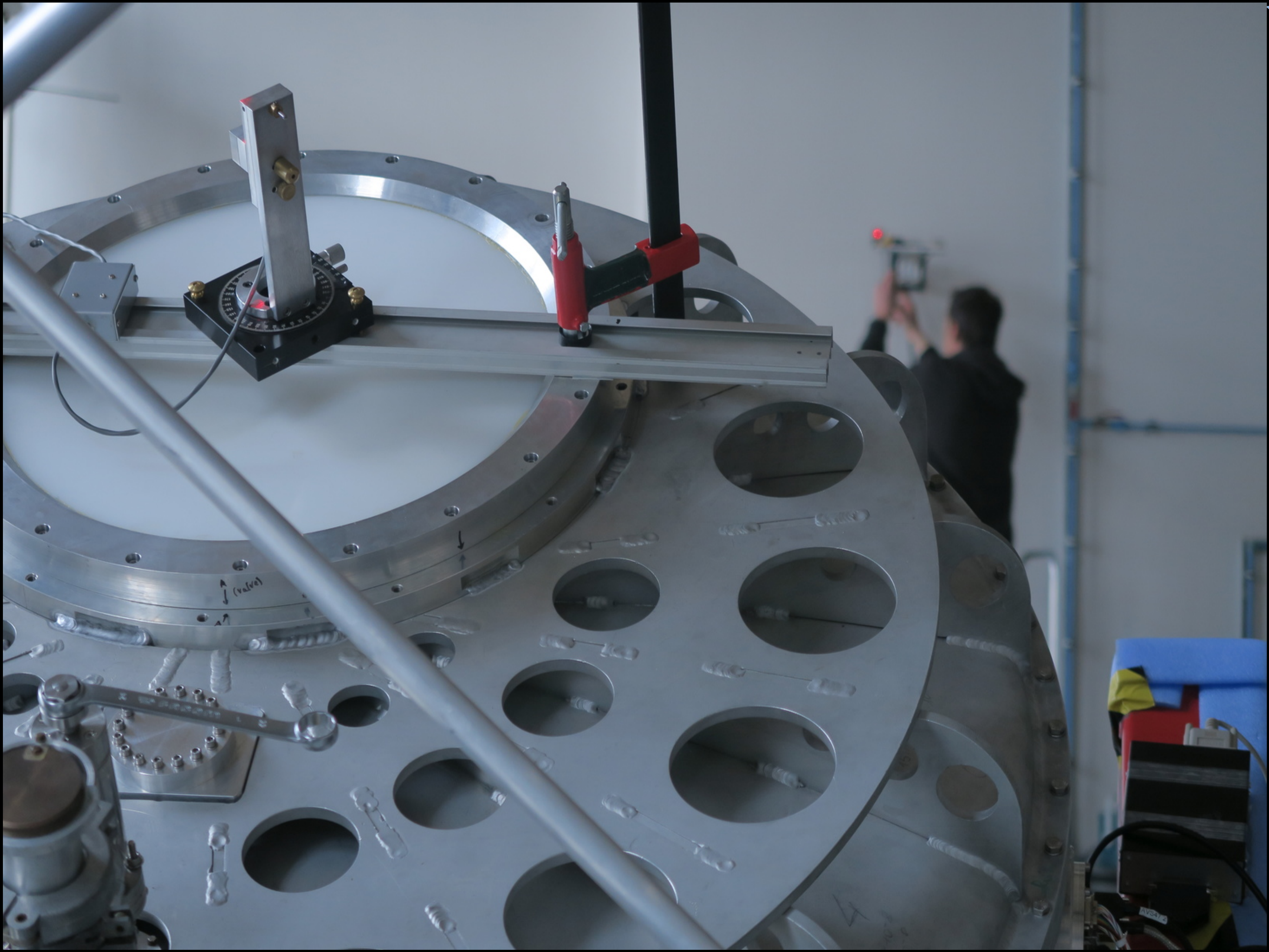
QUBIC as seen from the Calibration Source

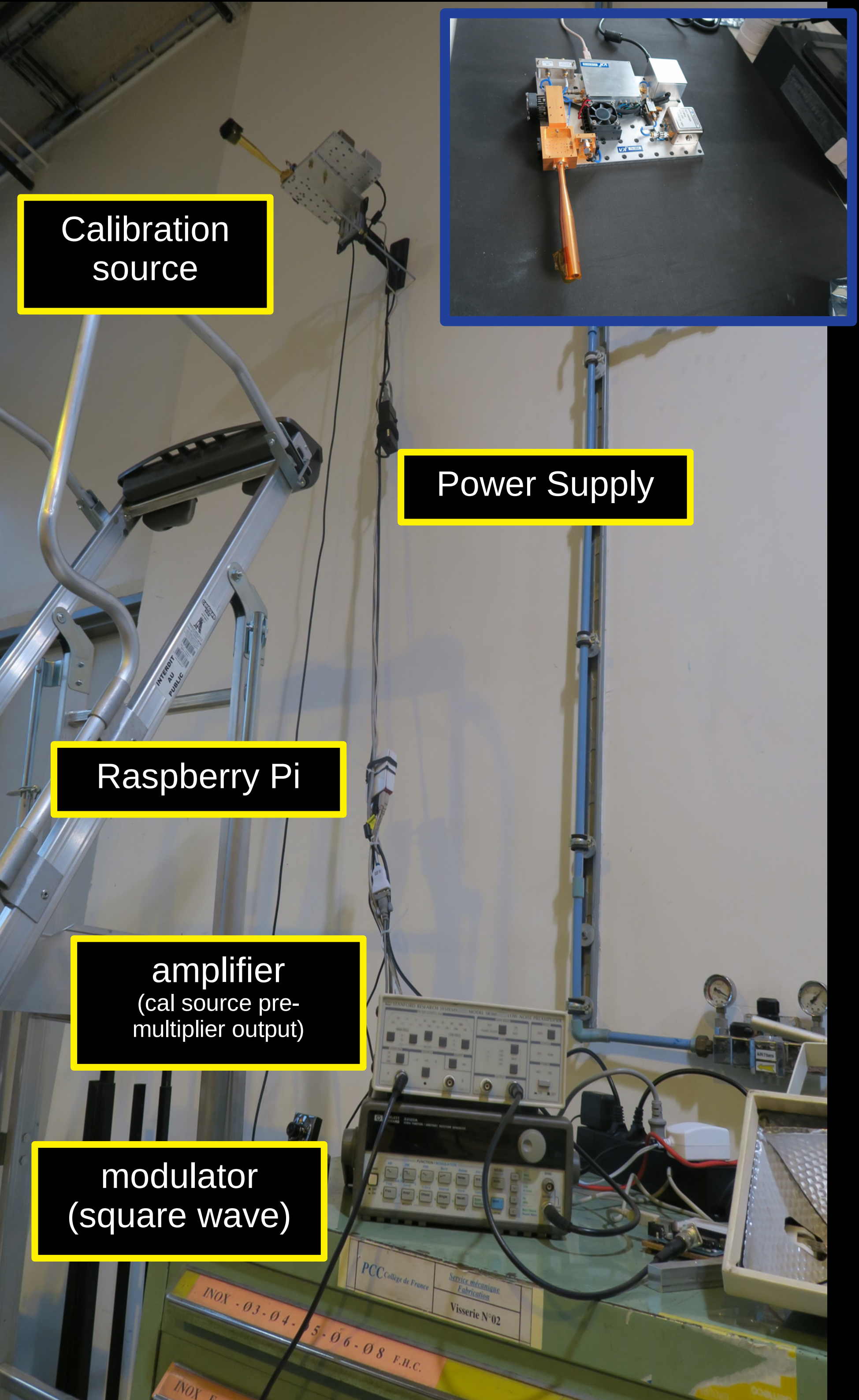
reflection of window in flat mirror

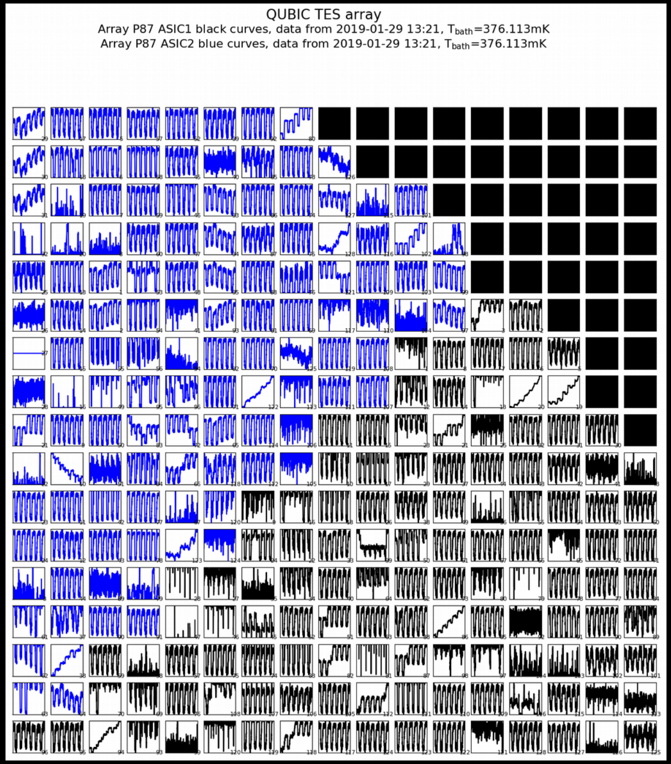
QUBIC cryostat

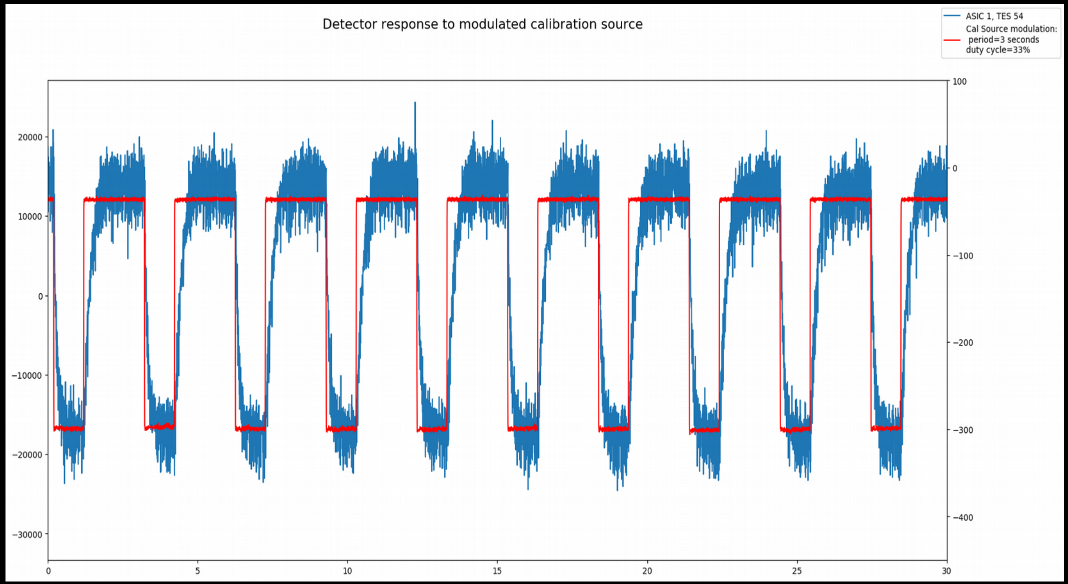
Calibration Setup



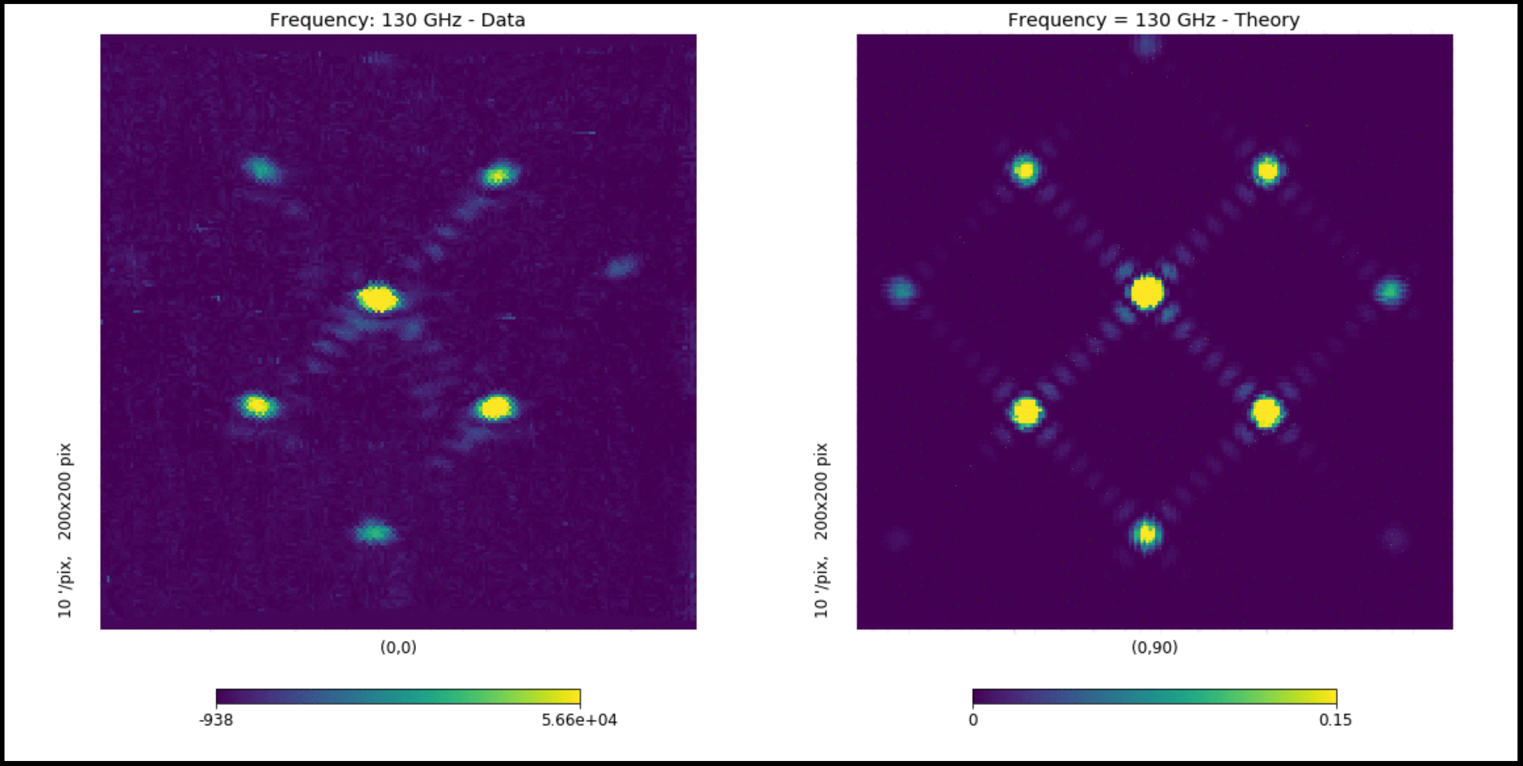



Calibration source
Power Supply
Raspberry Pi
amplifier
(cal source pre-multiplier output)
modulator
(square wave)


QUBIC TES array
Array P87 ASIC1 black curves, data from 2019-01-29 13:21, T_{bath}=376.113mK
Array P87 ASIC2 blue curves, data from 2019-01-29 13:21, T_{bath}=376.113mK

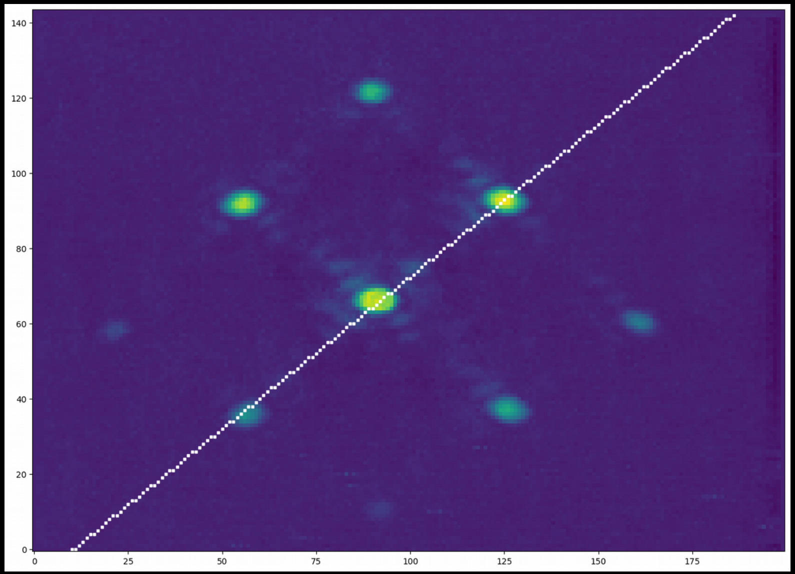

Detector response to modulated calibration source
ASIC 1, TES 54
Cal Source modulation:
period=3 seconds
duty cycle=33%

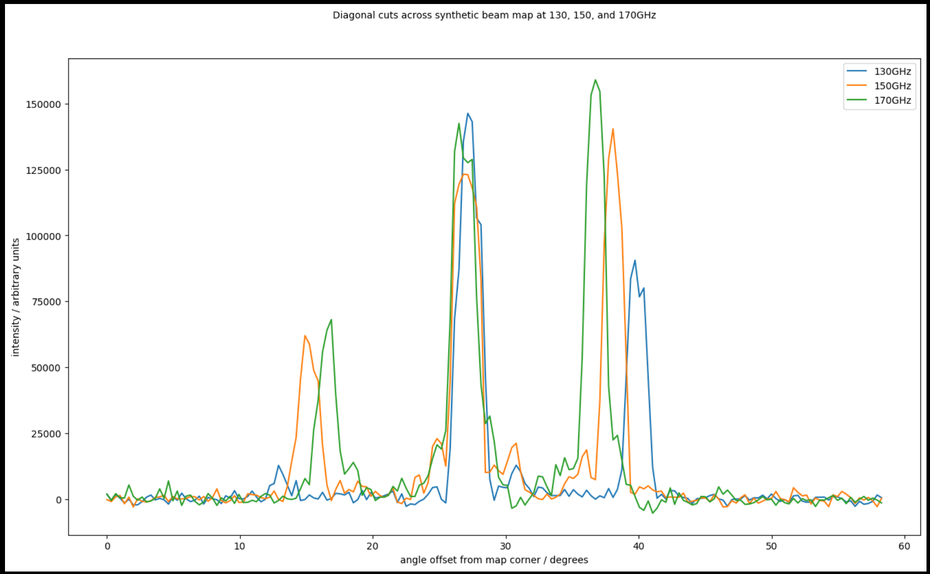
Synthesized Beam



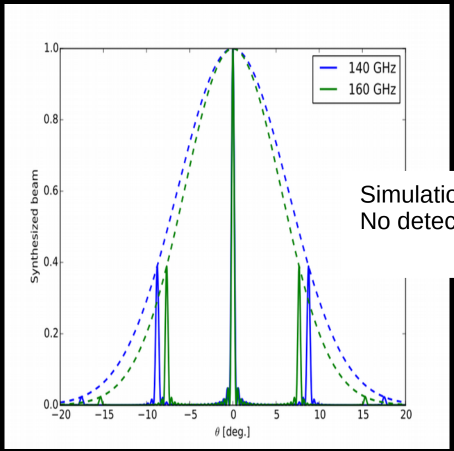
QUBIC has the synthesized beam expected from simulations of bolometric interferometry.

Synthesized Beam as a function of Frequency





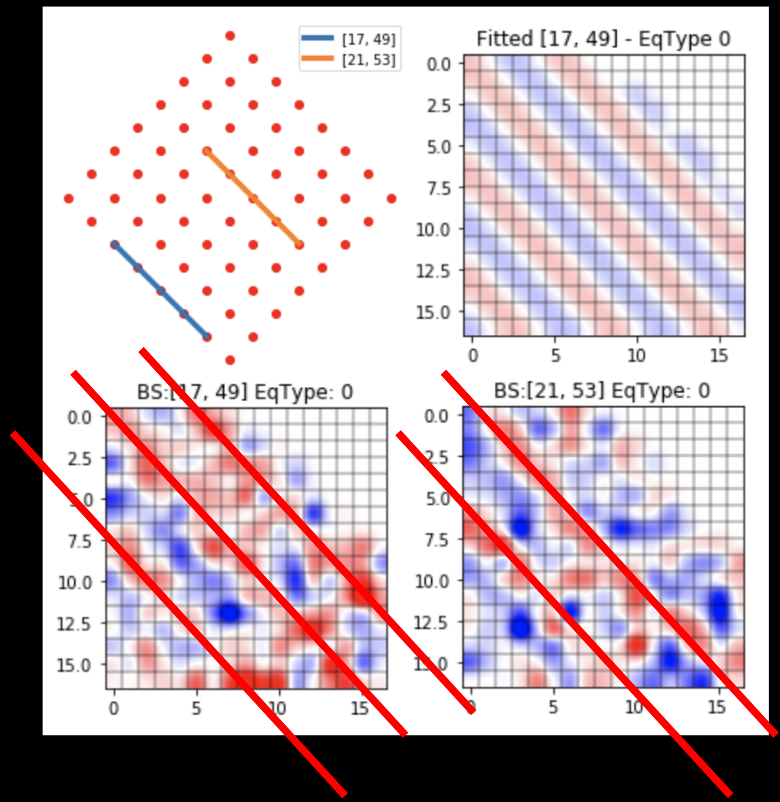
The synthesized beam with different profiles at different frequencies allows us to do spectral imaging with multiple bands imaged simultaneously.



Simulation for 20x20 horn array.
No detector saturation

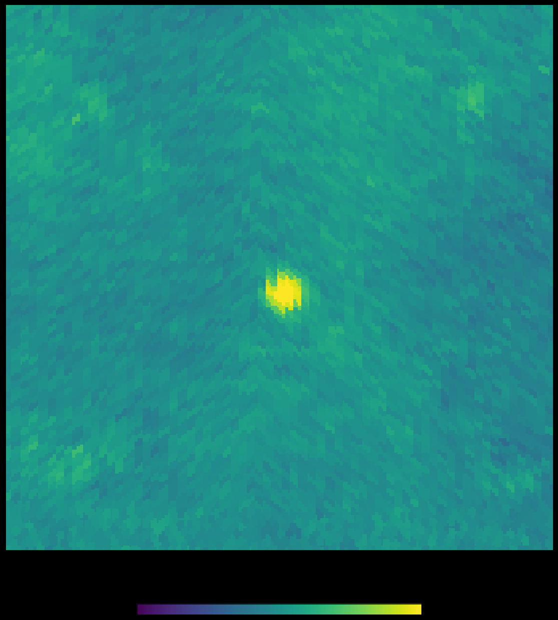
Fringes

Equivalent Baselines



Imaging fringes with different baselines is fundamental to performing “Self Calibration”

Mapmaking



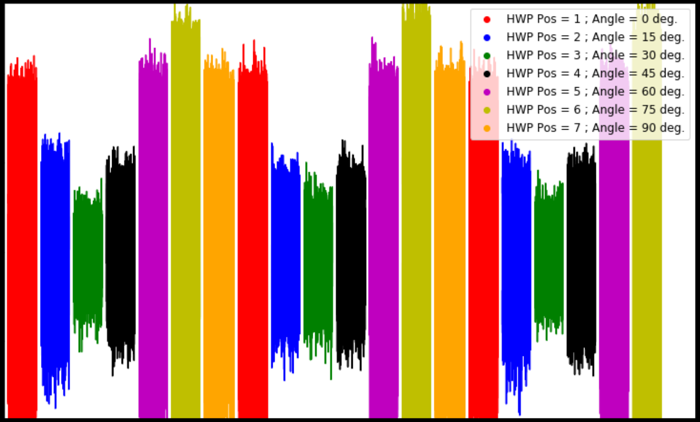
Mapmaking with the synthesized beam demonstrates a complete end-to-end checkout of the QUBIC system.

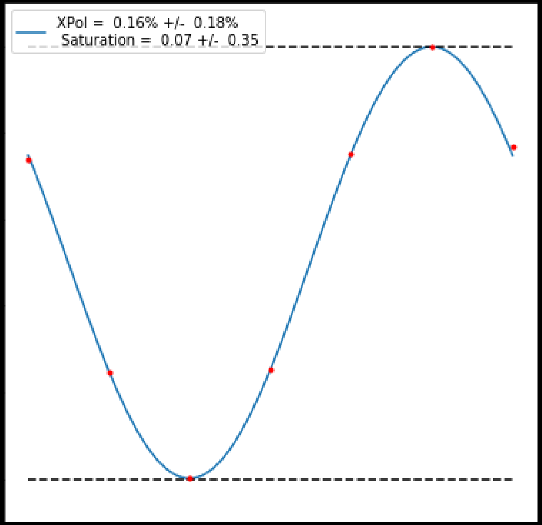
This is an image of the source at 150 GHz projected on the sky using our map-making software to deconvolve from the multiple peaked synthesized beam.

All subsystems must work correctly individually and as a system in order to create this map.

- Hardware components
- Hardware interfaces between components
- Control software
- Software interfaces between components
- Data acquisition, archiving, reading, and data analysis software

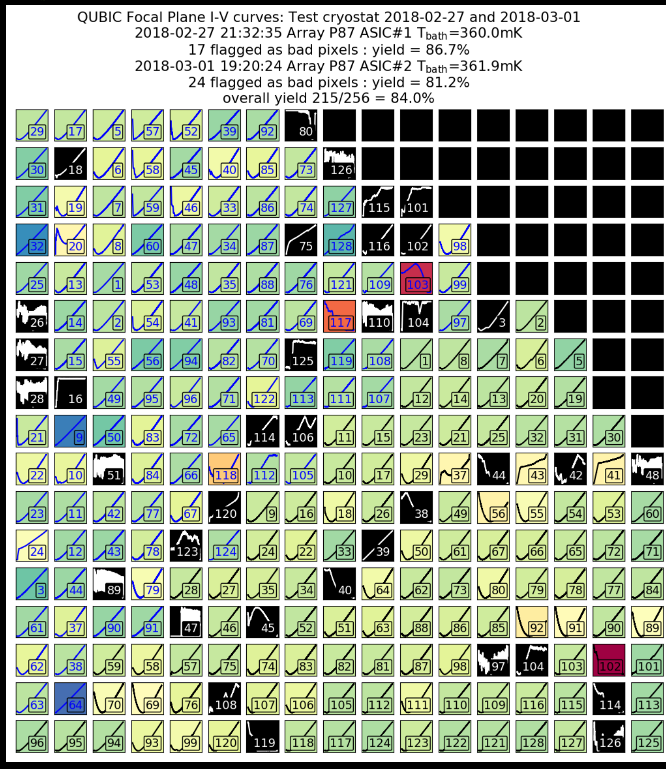
Polarization Modulation



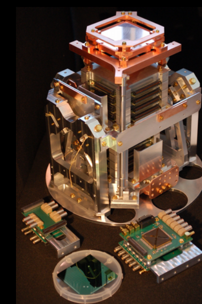


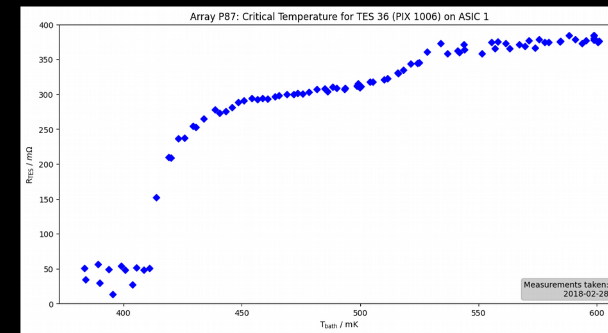
The rotating Half Wave Plate allows QUBIC to modulate the polarization angle on the sky. Cross-polarization contamination is less then 0.3%. This capability is essential to detect the CMB polarization.

TES I-V response and Detector Yield



I-V curves of the 244 TES bolometers in the QUBIC Technical Demonstrator focal plane measured simultaneously. The measurement takes one minute.



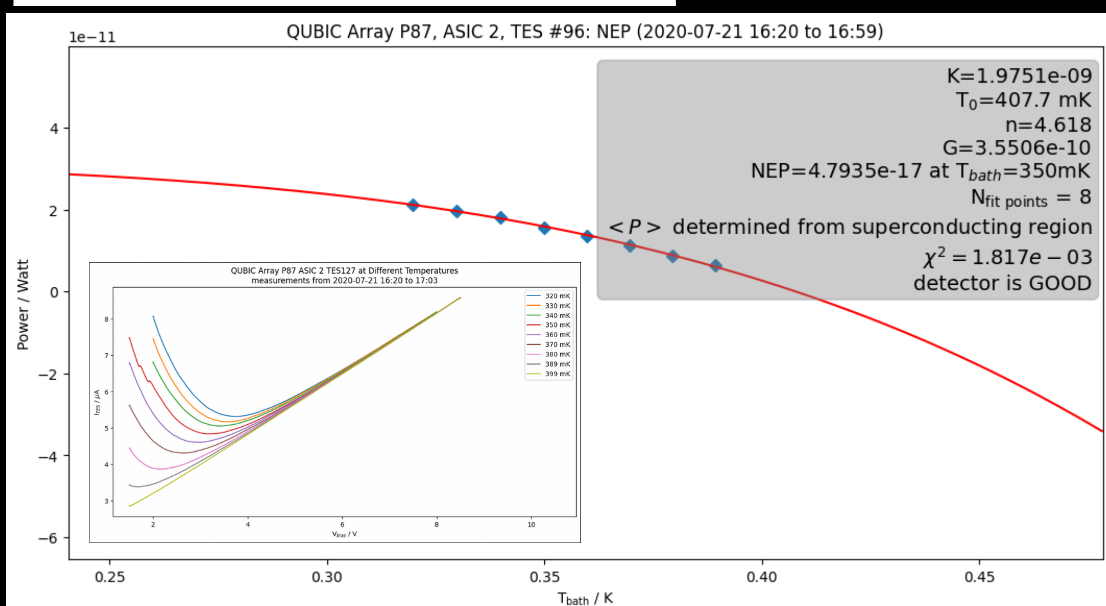


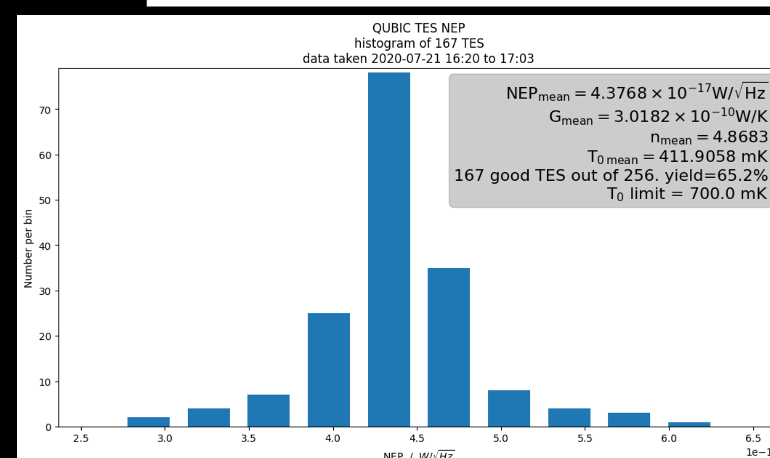
TES detector array CSNSM (now IJCLAB)
Electronics: APC & IRAP
Marnieros et al 2020, JLTP 199, p.955
Piat et al 2019, arxiv:1911.12418

TES phonon Noise Equivalent Power is calculated by measuring the I-V response at different bath temperatures.

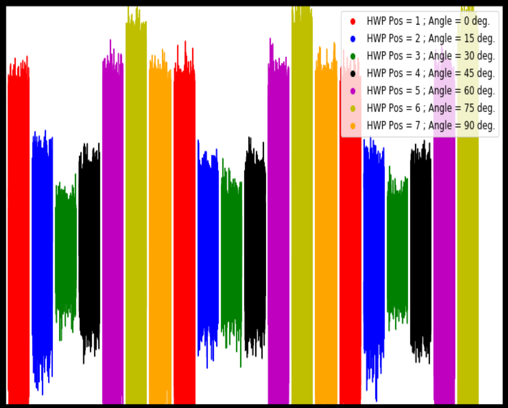
This example shows
$NEP_{phonon} = 4.8 \times 10^{-17}$ W/√Hz

The mean value is
$NEP_{phonon} = 4.4 \times 10^{-17}$ W/√Hz

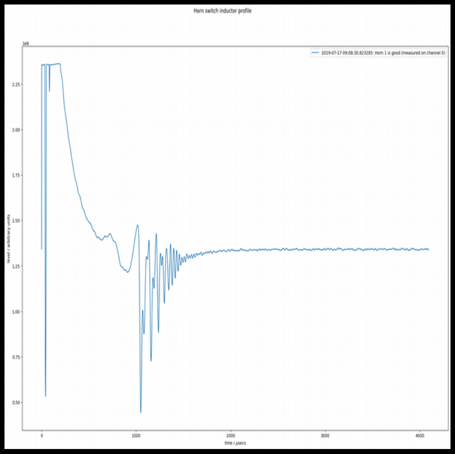




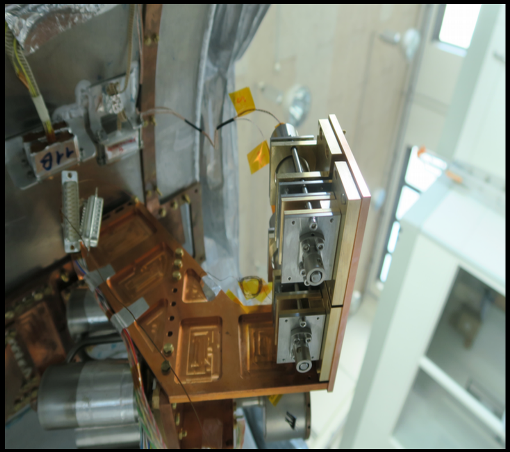
Mechanical/Electronic Functionality of Subsystems



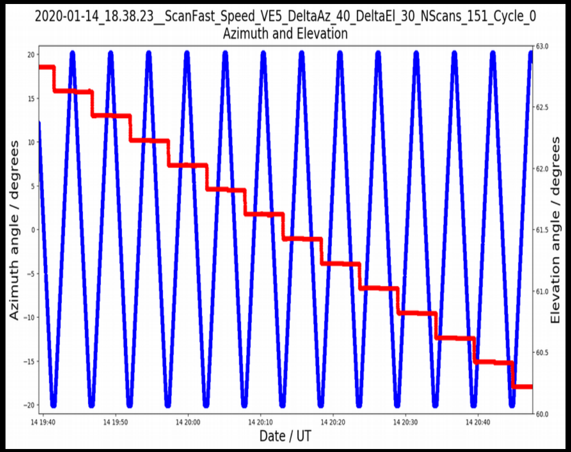
Half Wave Plate rotator



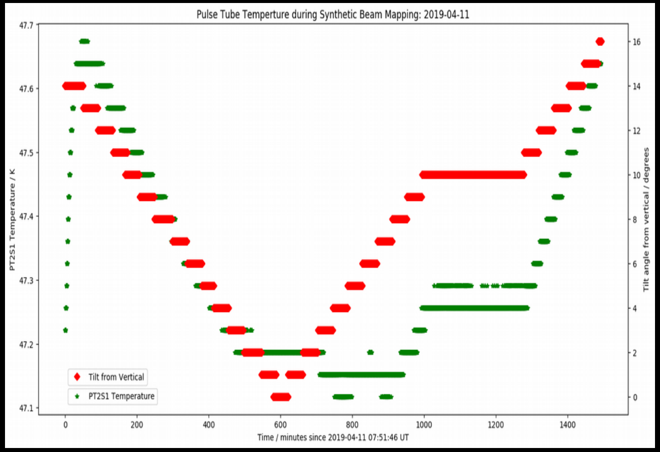
Horn switches



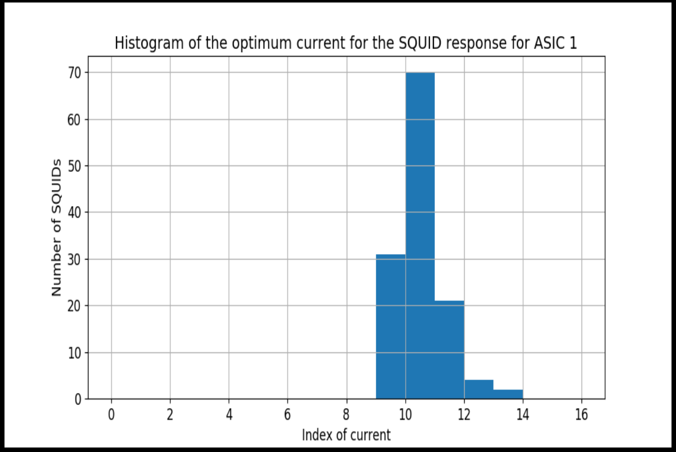
Mechanical heat switches



Platform positioning



Pulse Tube inclination



SQUIDs

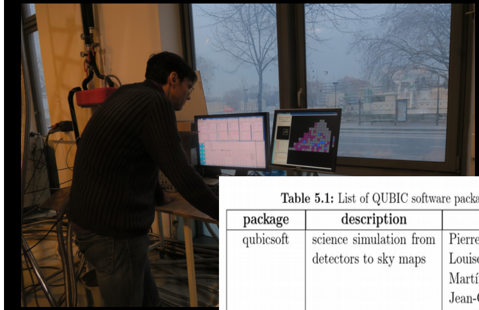


Table 5.1: List of QUBIC software packages developed by QUBIC collaborators

package	description	developer	repository/website
qubicsoft	science simulation from detectors to sky maps	Pierre Chanial (original) Louise Mousset (maintainer) Martín Gamboa Jean-Christophe Hamilton Jean Kaplan Aniello Mennella Steve Torchinsky	github:mousset/qubic
pyoperators	simulation framework for qubicsoft	Pierre Chanial Steve Torchinsky (maintainer)	github:satorchi/pyoperators
pysimulators	simulation framework for qubicsoft	Pierre Chanial Steve Torchinsky (maintainer)	github:satorchi/pysimulators
qubichw	hardware control and housekeeping	Steve Torchinsky Manuel Gonzalez Michel Piat	github:satorchi/qubichw
qubicpack	quicklook data visualization and analysis	Steve Torchinsky Michel Piat	github:satorchi/qubicpack
QuTeDB	data archive with web interface	Maurizio Tomasi	U.Milano:QuTeDB
MODAL	Optics simulation	Marcin Gradziel	Maynooth Physics

Software and software interoperability

QUBIC Overview

- QUBIC proposes an innovative solution to the problem of foreground and systematic effects:

  <u>Bolometric Interferometry</u>

  - control of instrument systematic effects using self calibration
  - control of foreground contamination using spectral imaging

Articles submitted to JCAP for a special issue on QUBIC:

- QUBIC I: Overview and Science Program
  arXiv:2011.02213
- QUBIC II: Spectro-Polarimetry with Bolometric Interferometry
  arXiv:2010.15119
- QUBIC III: Laboratory Characterization
  arXiv:2008.10056
- QUBIC IV: Performance of TES Bolometers and Readout Electronics
  (to be released soon)
- QUBIC V: Cryogenic system design and performance
  arXiv:2008.10659
- QUBIC VI: Cryogenic half wave plate rotator, design and performance
  arXiv:2008.10667
- QUBIC VII: The feedhorn-switch system of the technological demonstrator
  arXiv:2008.12721
- QUBIC VIII: Optical design and performance
  arXiv:2008.10119