Probing the Early Universe with QUBIC

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KSETA workshop, March 15 2022

Talk Outline

1) Cosmic Microwave Background Measurement Techniques
2) The QUBIC Instrument
3) Metallic Magnetic Bolometers
4) QUBIC new Read Out Electronics

Cosmic Microwave Background (CMB) Measurement Techniques

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CMB Detection Techniques

Radiometers Vs. Bolometers

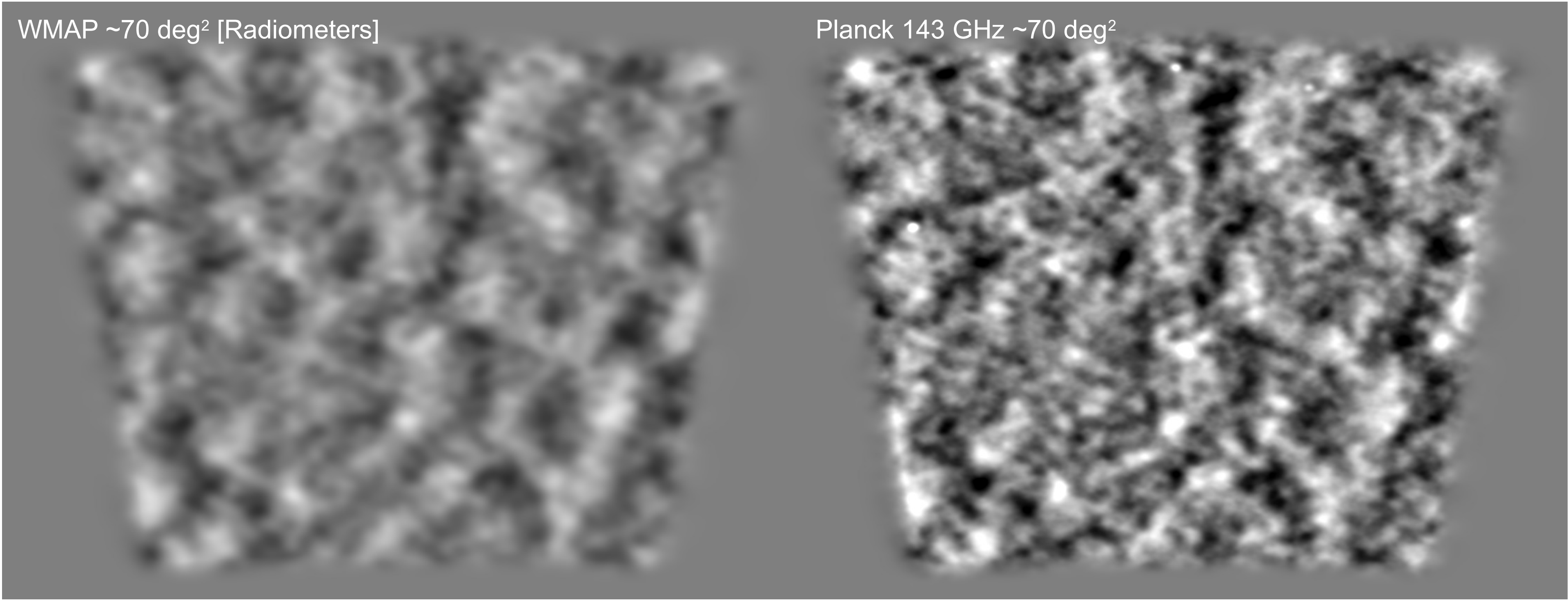
Radiometers:

- Coherent receivers: an antenna detect *E(t)* at the wavelength of the radiation
- Needs an amplifier at the wavelength of the radiation
- OK up to ~ 90 GHz but amplifier adds noise to the input signal

Bolometers:

- Incoherent receiver: A thermistor detects the temperature increase of an absorber due to the power deposited
- Bolometer arrays can be large, polarization sensitive, multichroic, also use Antenna-Coupled technology
- Needs aggressive cryogenics for detectors (~0.3K or below) in order to have them less noisy (thermal noise) than incoming radiation
- Needs multiplexed readout if using a large number of channels
- Transition Edge Sensor use the normal-to-superconducting transition to have large dynamics
- Not so good below ~90 GHz due to large dimensions of the absorber

CMB Measurement Strategy



Space based measurement
Full sky scanned, no issues with atmospheric interference

CMB Measurement Strategy

Ground based measurement

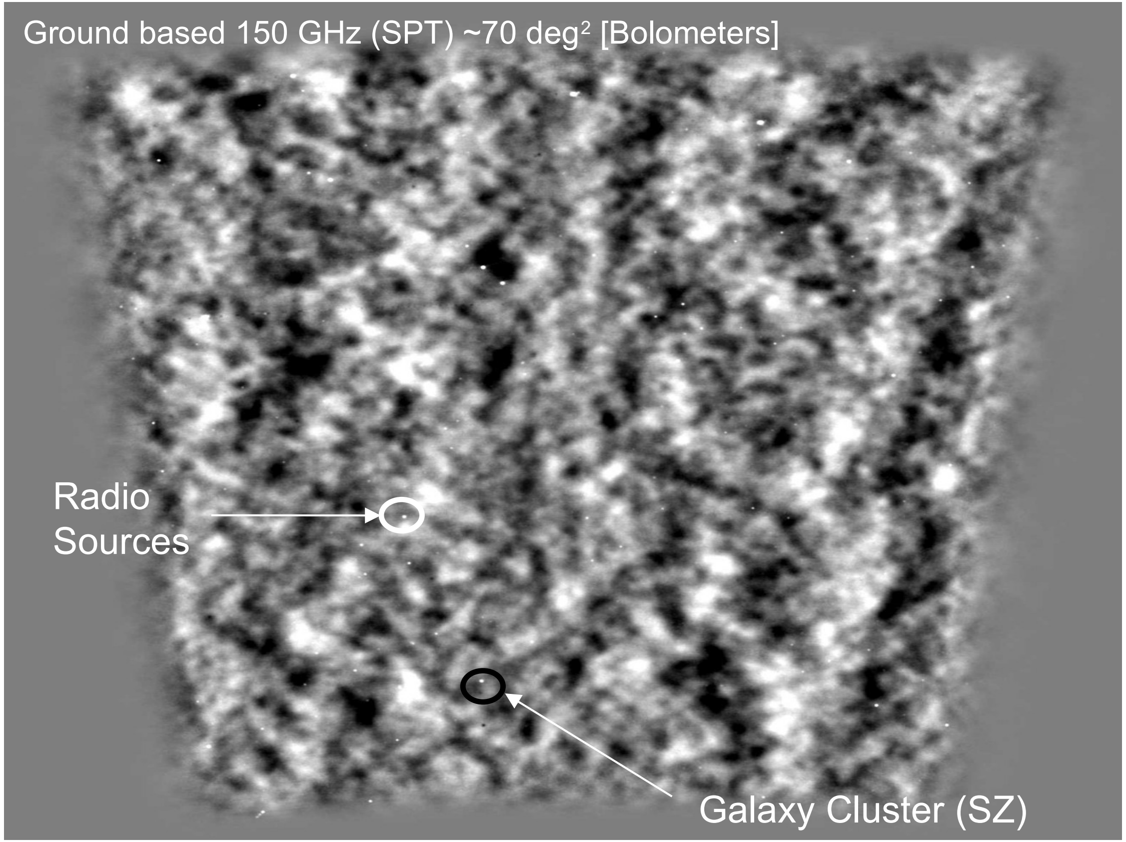
- In a given band: Power received related to temperature
- Generally needs a power receiver at the focal plane of a telescope
- Sky is scanned back and forth over the observed region to gain redundancy and remove electronic/cryogenic/atmospheric drifts of the signal

Scanning strategy is a big issue and is the subject of refined optimization

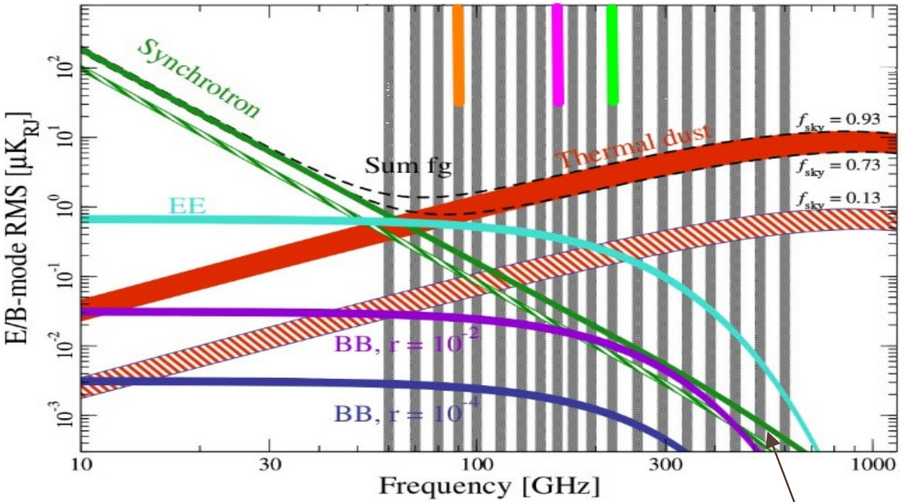
E.g. South Pole Telescope (SPT):

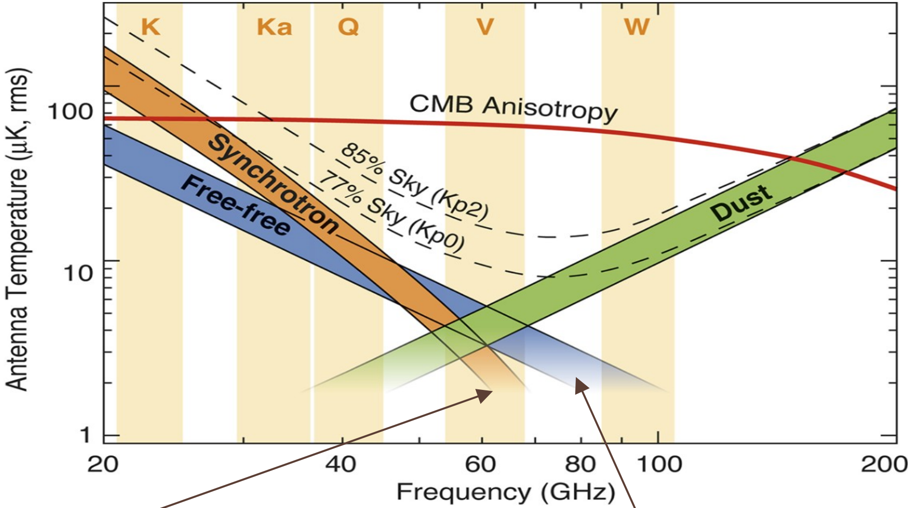
- 13x higher resolution and 60x deeper than WMAP

- 7x higher resolution and 9x deeper than Planck

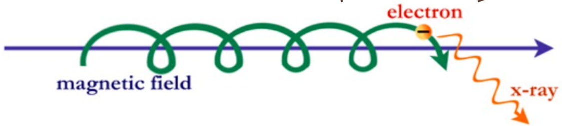


Foreground Interference Spectrum

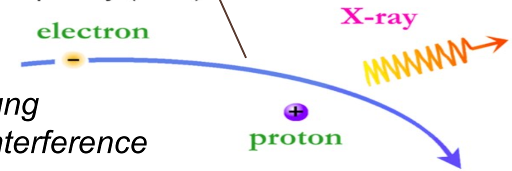




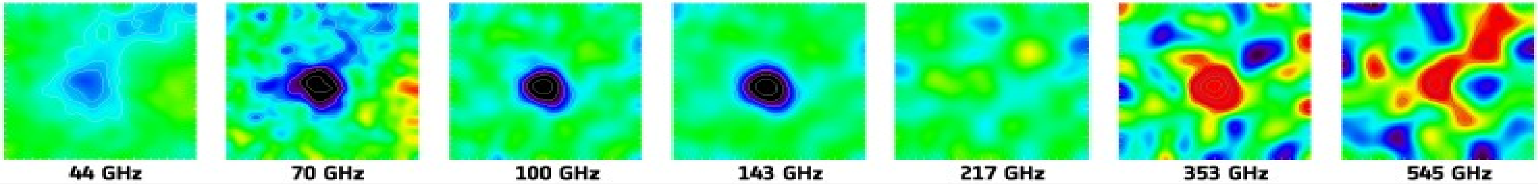
Foreground Synchrotron Interference



Foreground Bremsstrahlung (Free-free) Interference

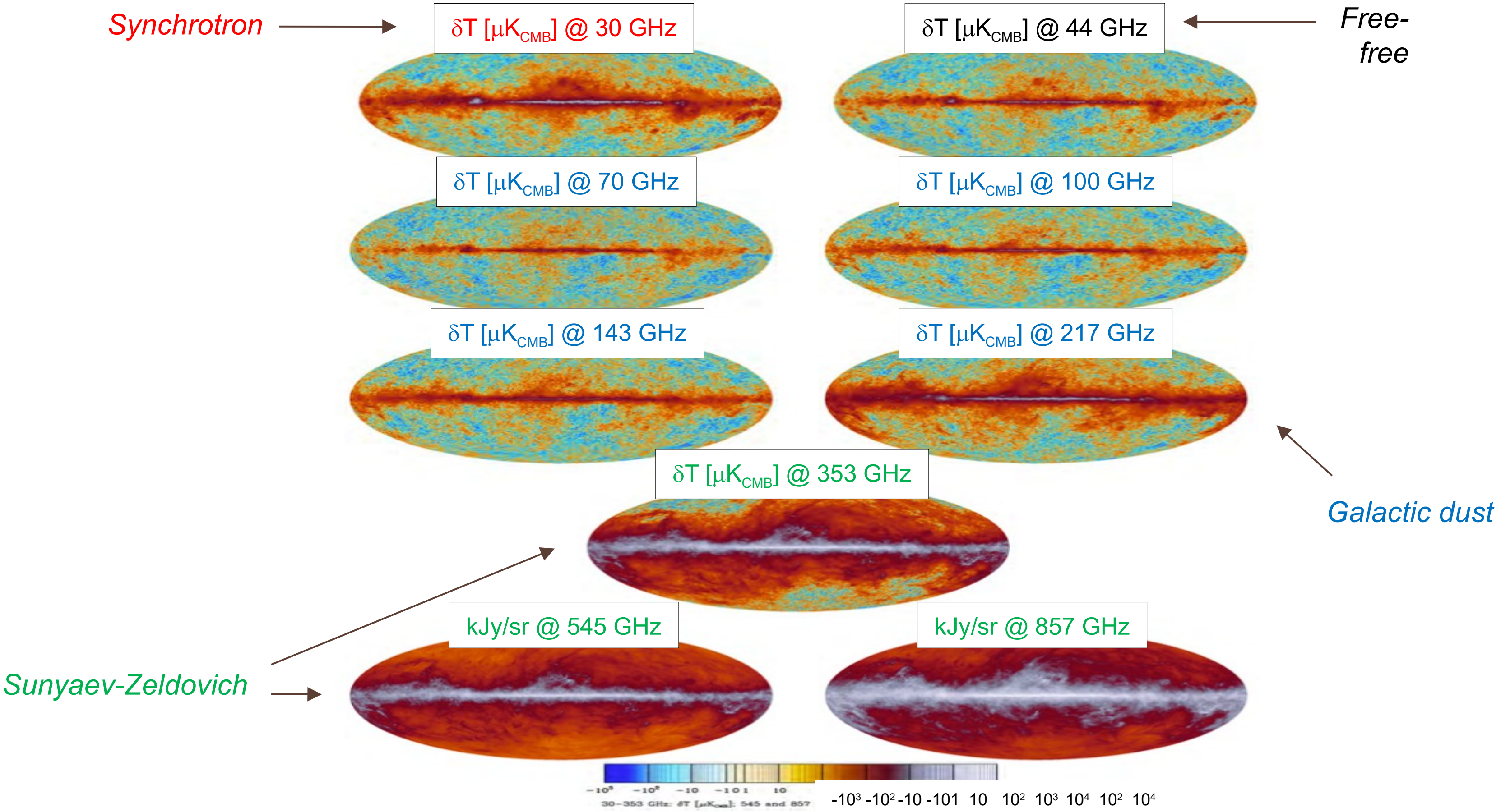


Sunyaev-Zeldovich effect



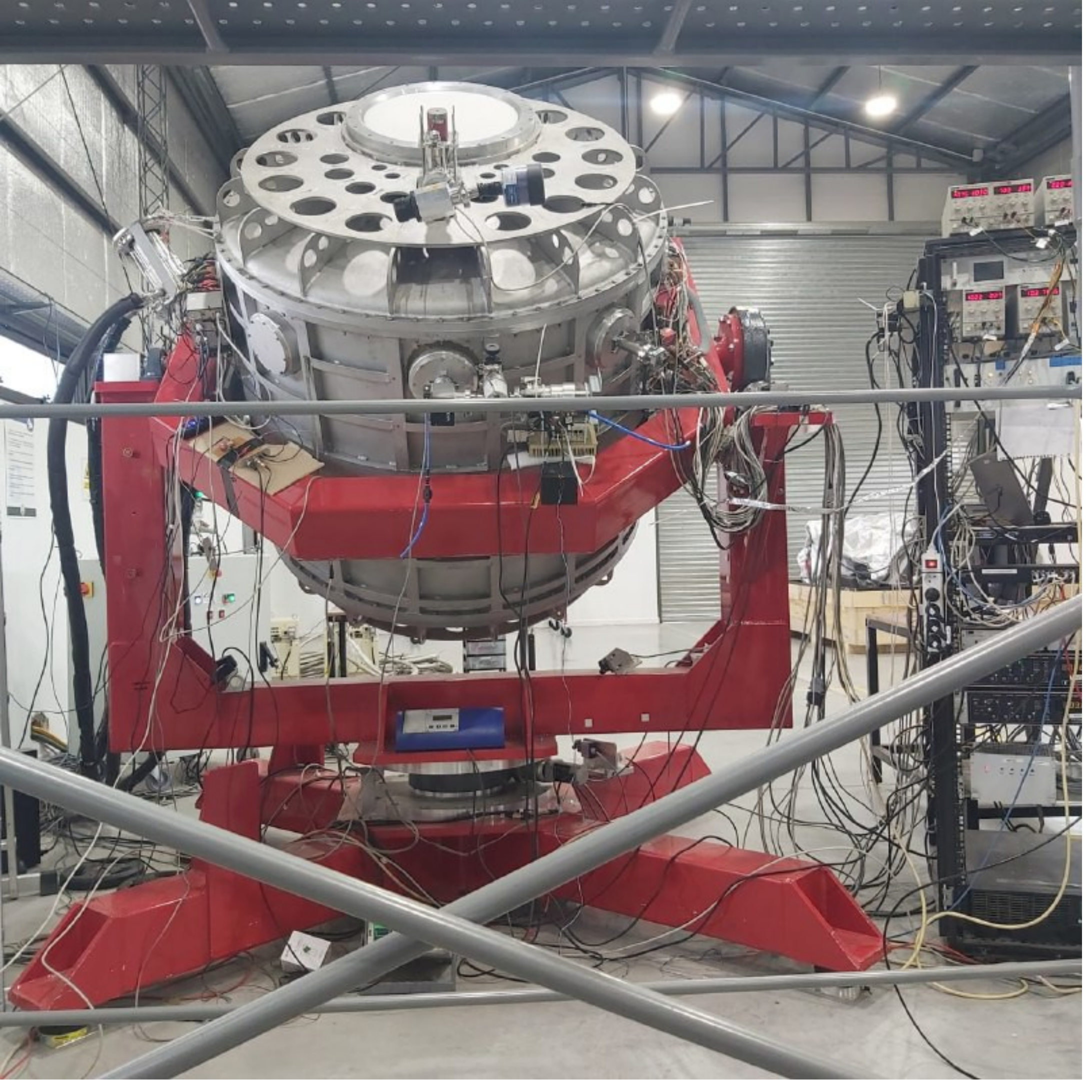
Abell 2319 with Planck

Foreground Interference Spectrum @ Planck



CMB Observation Stages

Year	Stage	Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	Stage 4 CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO $+\tau_e$ prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**



The QUBIC Instrument

Q & U Bolometric Interferometer for Cosmology

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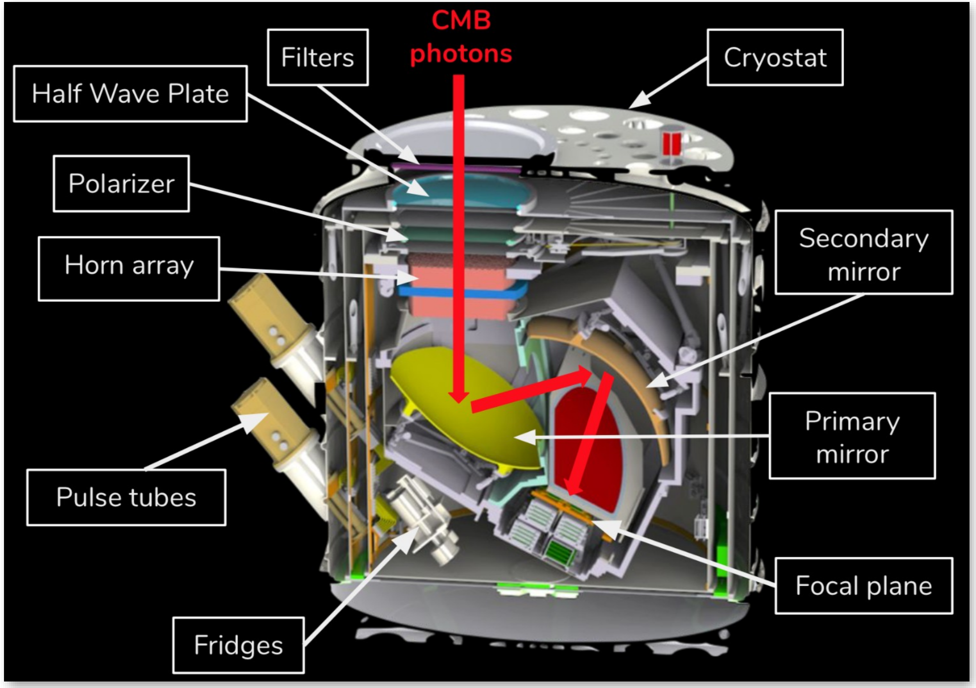
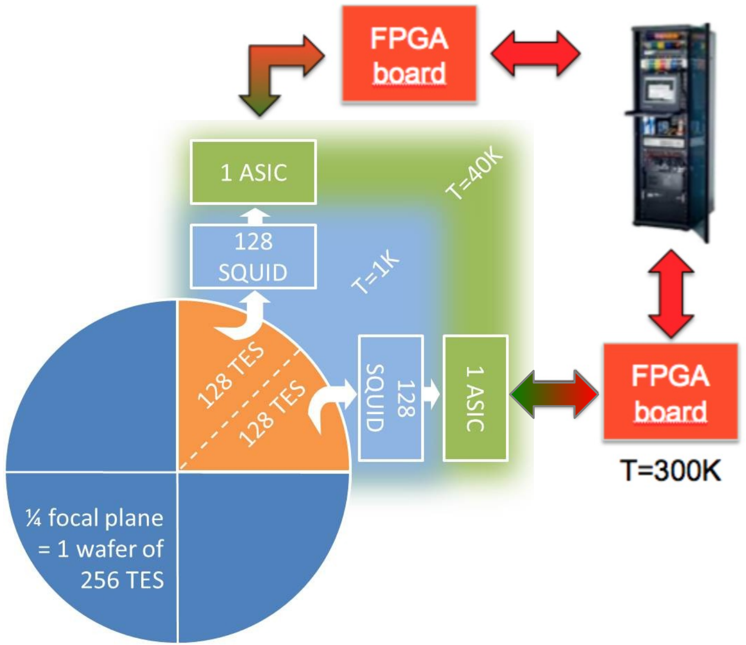
QUBIC Outline

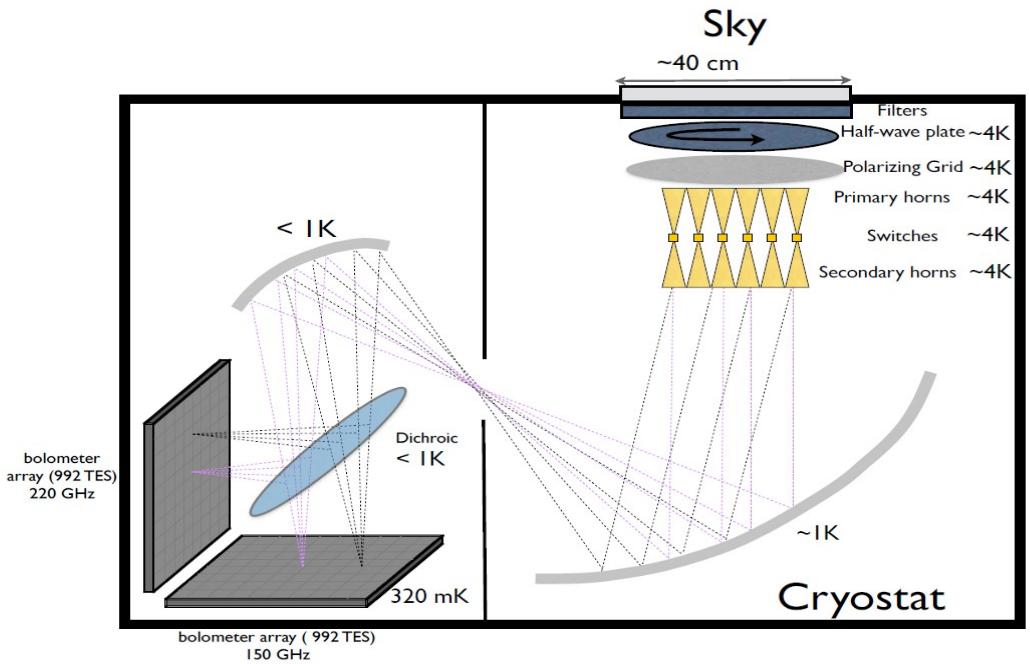
1) QUBIC as an interferometric bolometer
2) Bolometers
3) Transition Edge Sensors
4) Read Out Electronics for TES

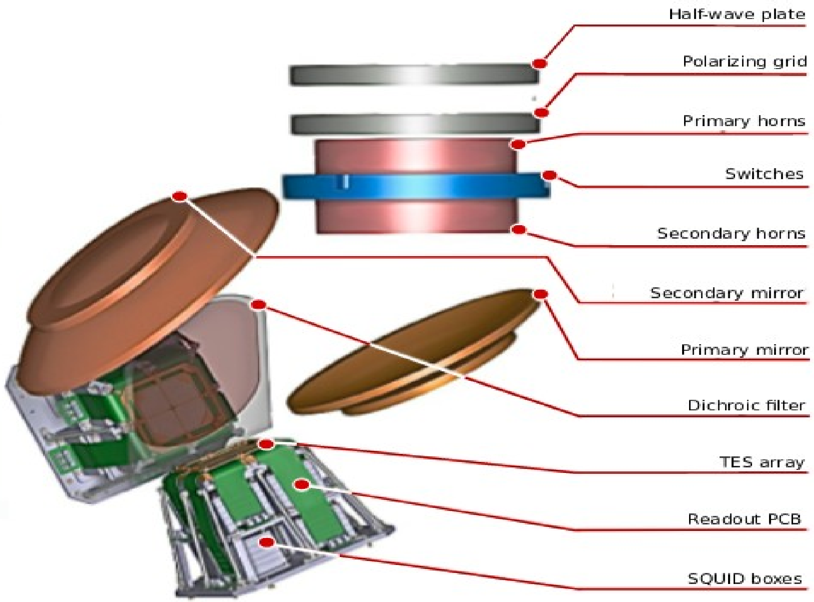
The QUBIC Instrument





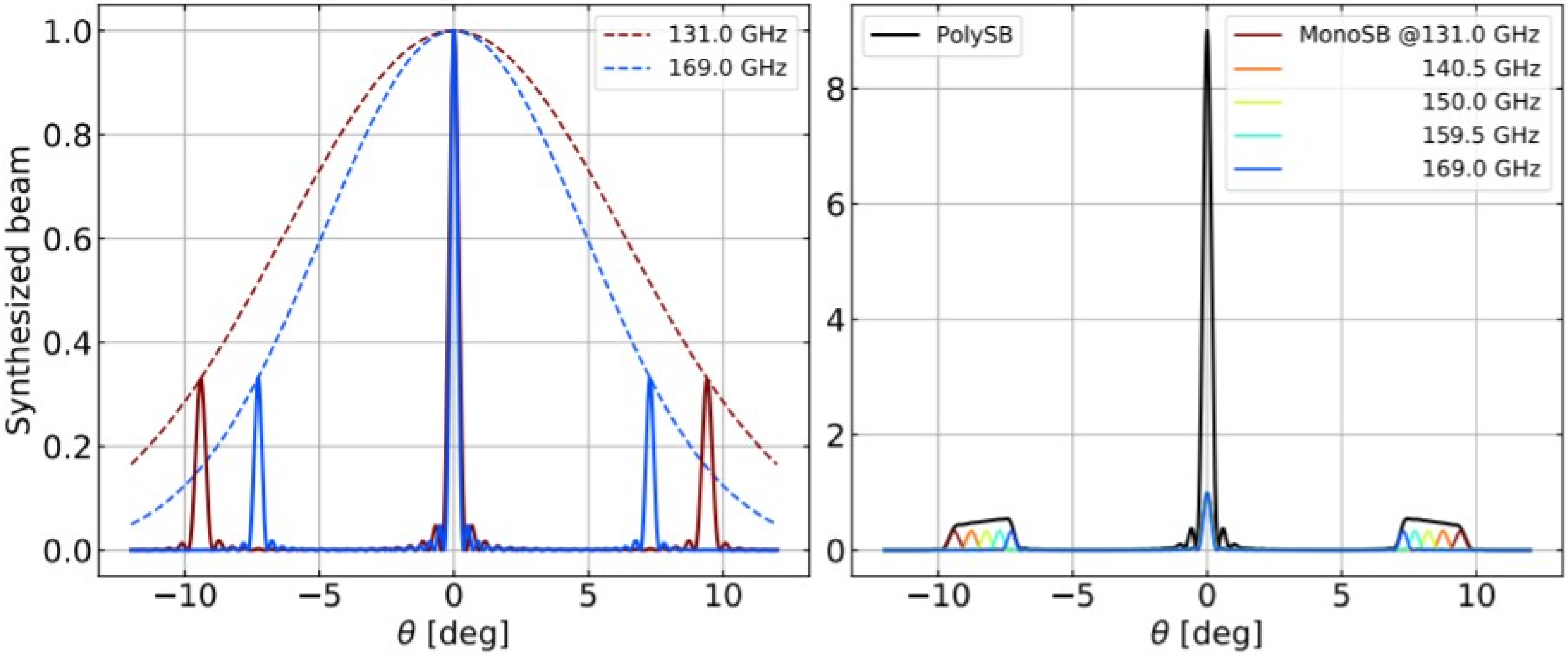
A Bolometric Interferometer





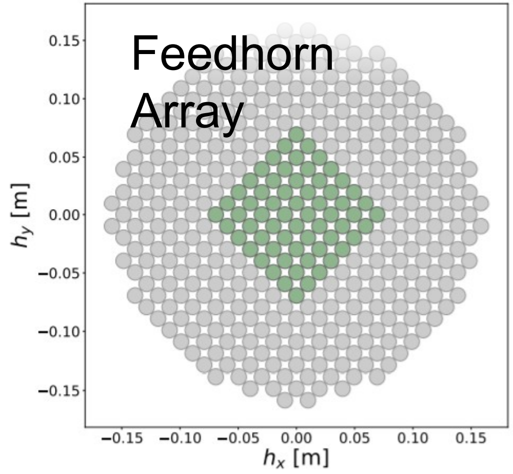
QUBIC works as a bolometer with a cryostat at the detector working at 150 GHz and 220 GHz to separate the CMB from the galactic dust. Light absorption is achieved using a Palladium metallic grid placed in a quarter wave cavity in order to optimize the absorption efficiency. A distance of 400 µm between the grid and the rear reflector is a good compromise for both 150 GHz and 220 GHz photons. The array is not intrinsically sensitive to polarization.

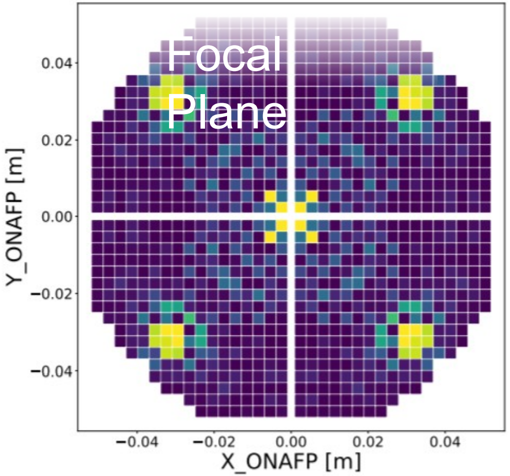
Interferometry: The Synthetic Beam

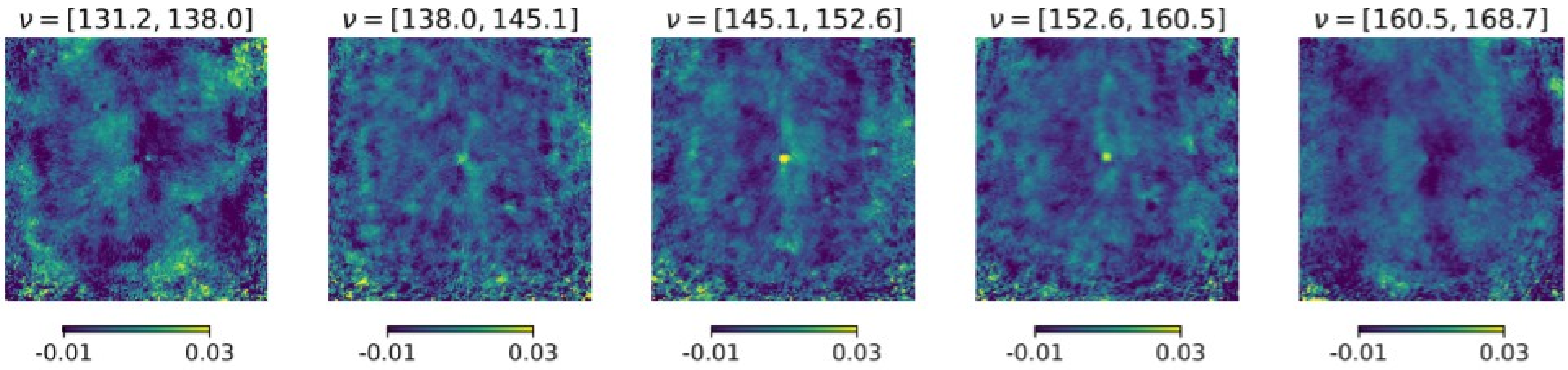


The Monochromatic synthesized beam (MonoSB) for 131 and 169 GHz primary beam at each frequency is shown by a dashed line. The Polychromatic beam (PolySB, black line) as result of the addition of 9 monochromatic synthesized beams (5 of them are shown in colored lines) spanning the 150 GHz band (131 to 169 GHz) is shown on the left. The continuous frequency band is sampled in discrete frequencies thanks to the interferometric technique.

Interferometry: Calibration

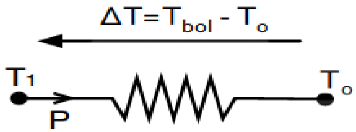




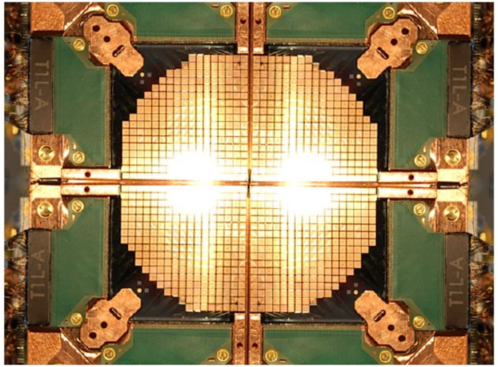


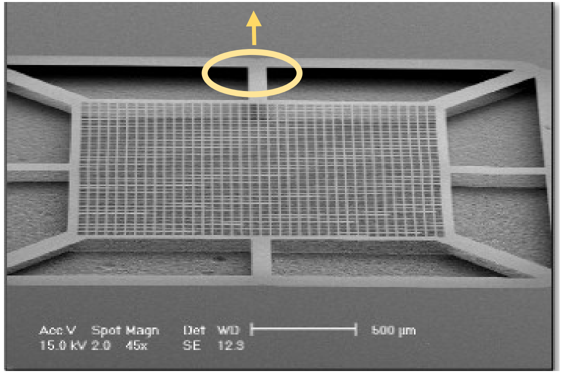
Calibration data with the source at 150 GHz projected on the sky using our map-making software to deconvolve from the multiple peaked synthesized beam and split the physical band of the instrument into 5 sub-bands.

Bolometers: Absorber

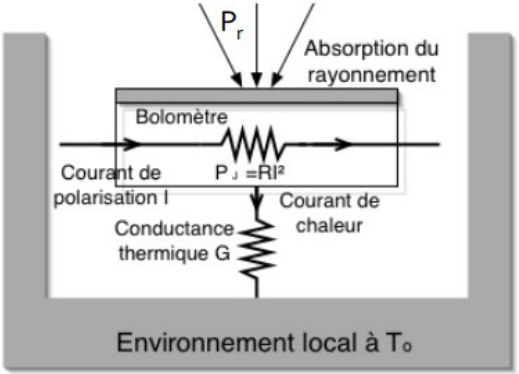


Focal Plane





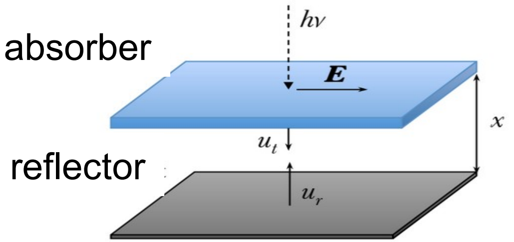
$$\left\{ \begin{aligned} \frac{\tilde{T}}{\tilde{P}_{sig}} &= \frac{1}{G_{eff}\left(1 + j\omega\tau_{eff}\right)} \\ \tau_{eff} &= \frac{C}{G_{eff}} \end{aligned} \right\}$$



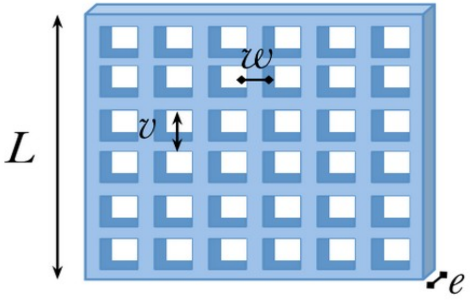
Given the expected background power of the QUBIC setup (5-50 pW in the 150-220 GHz range) an extremely low thermal coupling between the sensors and the cryostat is needed to optimize signal to noise ratio. This is obtained using 500 nm thin SiN suspended membranes, which exhibit thermal conductivities between 50 and 500 pW/K depending on the precise pixel geometry.

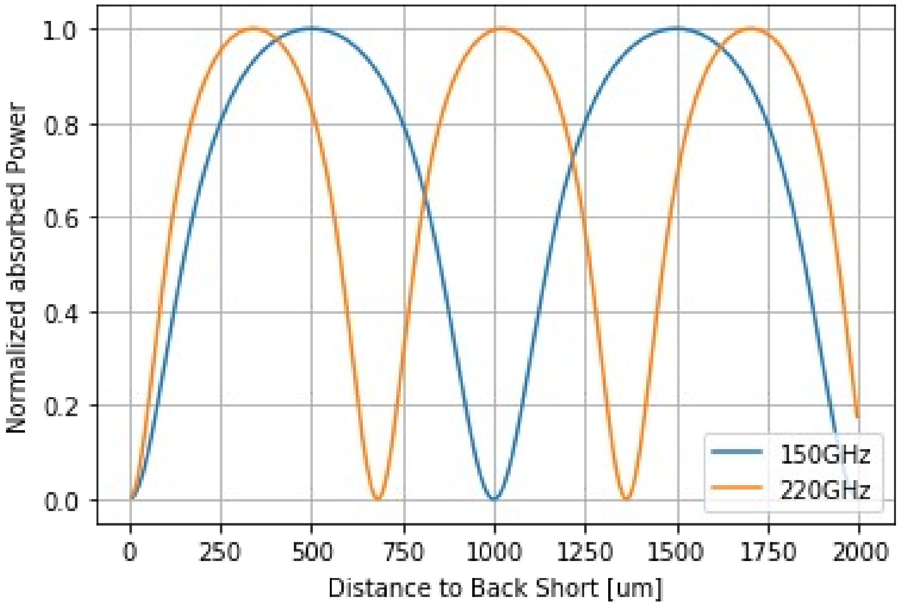
C: bolometer heat capacity [J/K]
G_{eff}: bolometer effective thermal conductance [W/K]

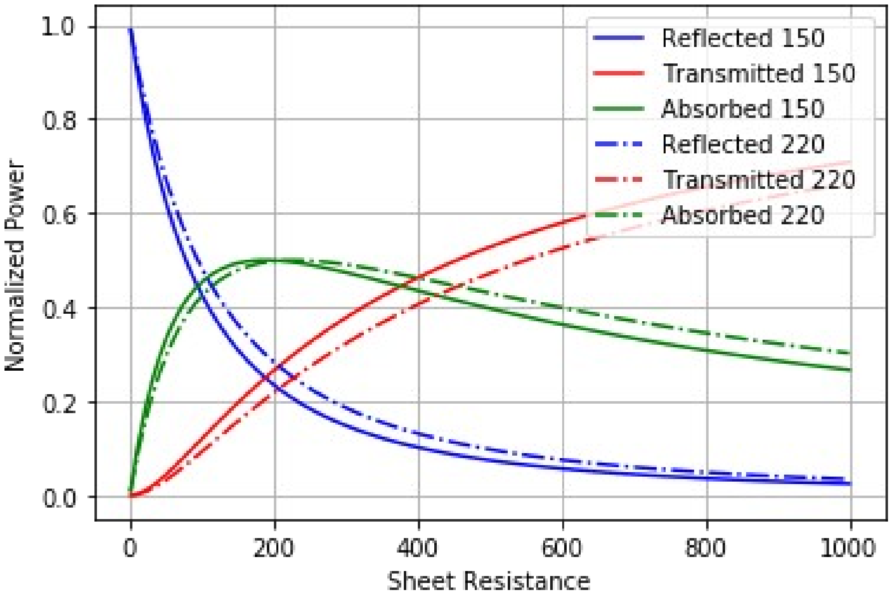
Bolometers: Absorber



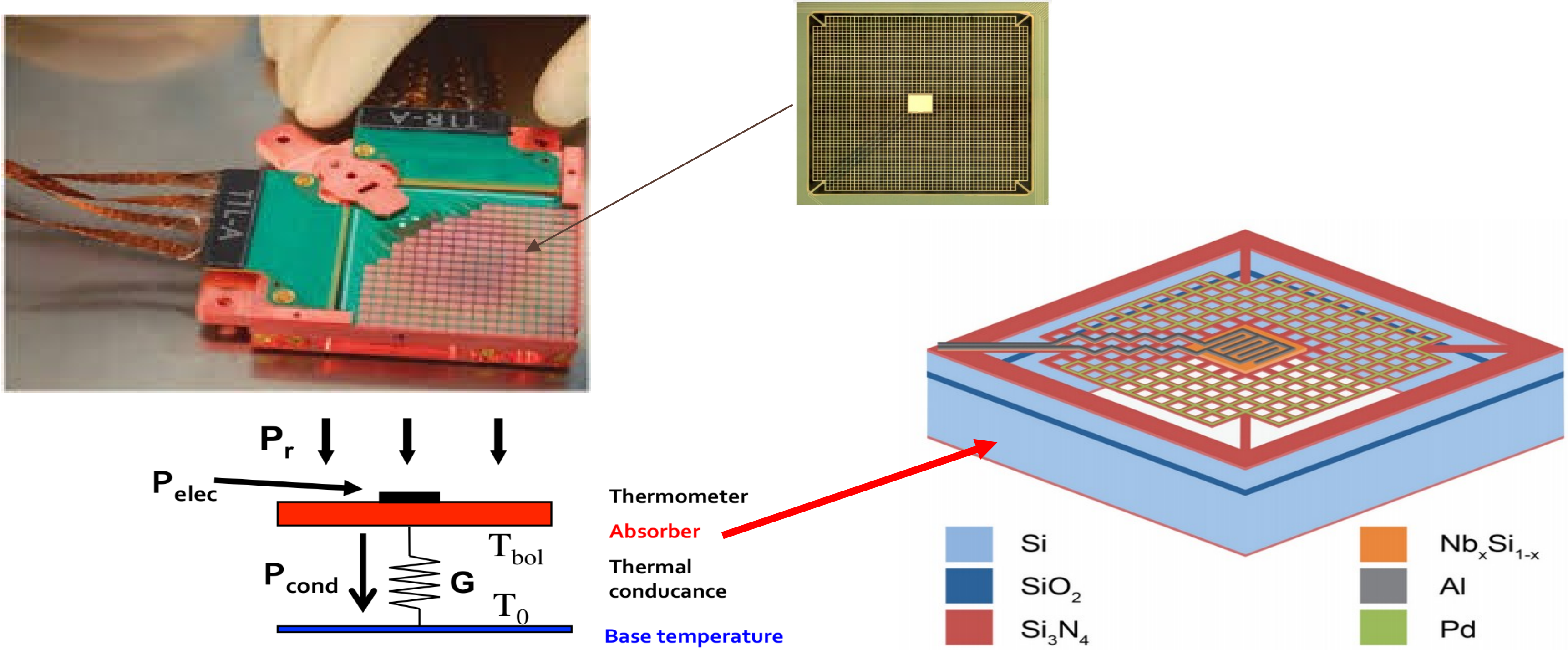
Max absorption = 100% for $R_C = Z_0$
with a reflective layer at $x = \lambda/4$



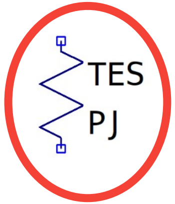


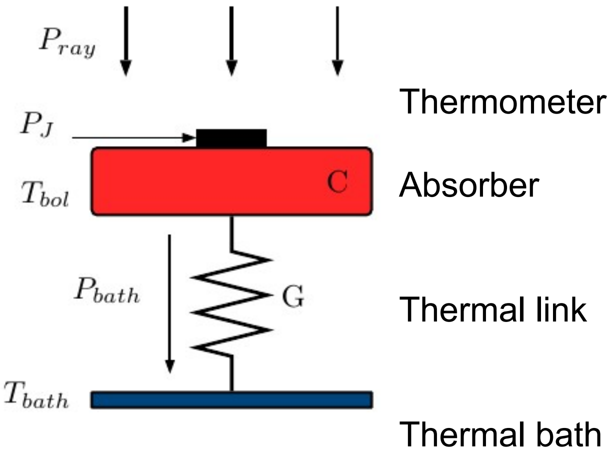


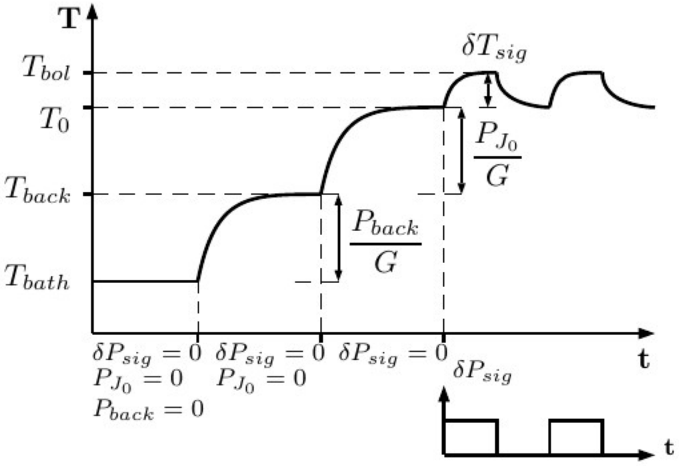
Bolometers:
Transition Edge Sensors (TES)

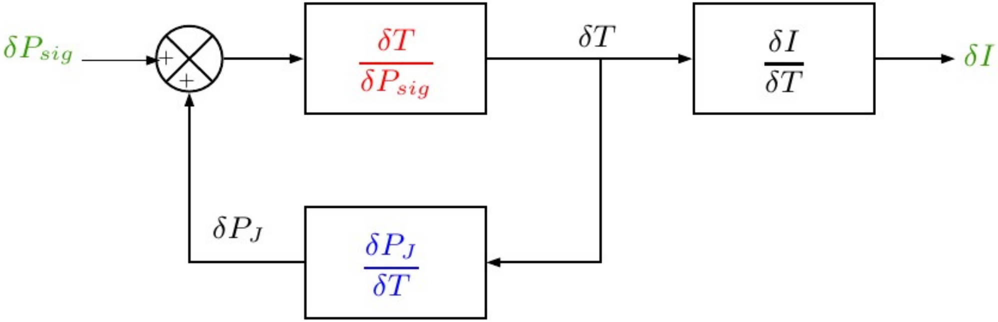


Transition Edge Sensors as Thermometers







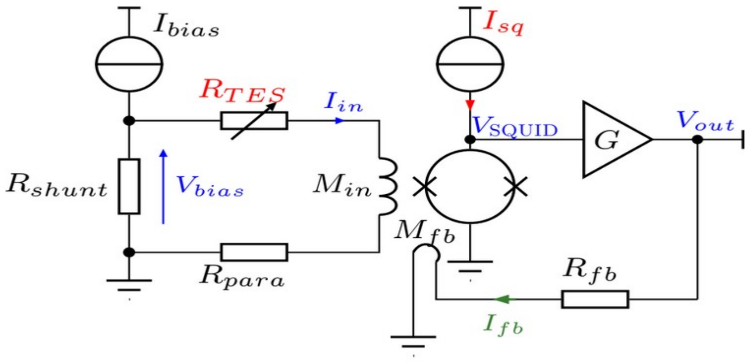


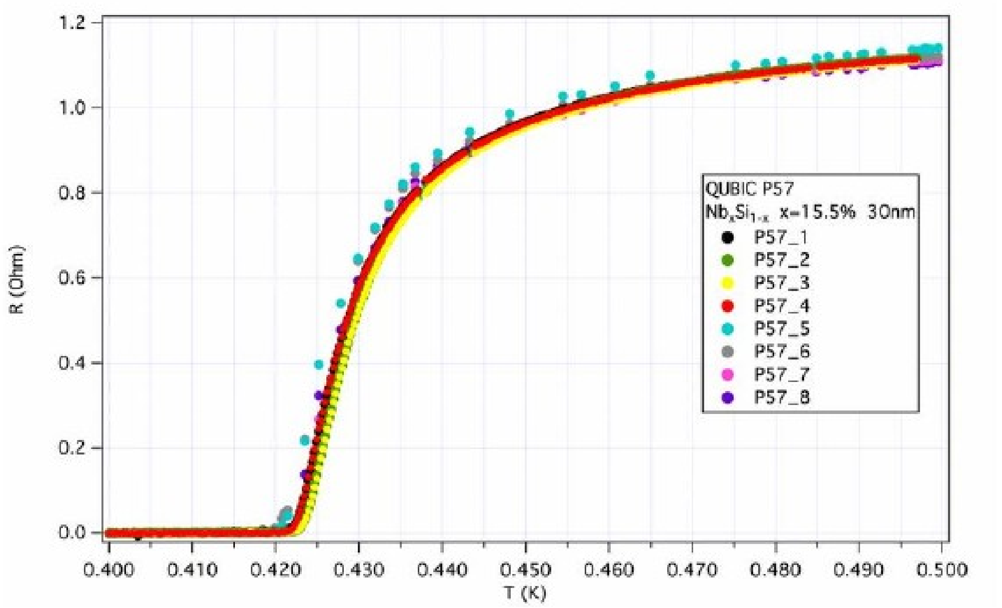
$$S_I(\omega) = \frac{\delta I_{in}}{\delta P_{sig}} = \frac{-1}{V_{bias}} \frac{\mathscr{L}}{\mathscr{L}+1}$$

Detection System for TES

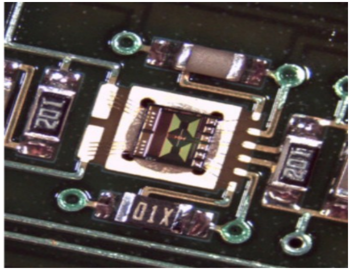
Detector stage temperature spec.	350 mºK
Detector stage temperature goal	320 mºK
Bolometers NEP	5.10^{-17}W $Hz^{-1/2}$
Bolometers time constant	< 10 ms
Number of bolometers / focal plane	1024
Number of 256 TES wafers	4
Scientific Data sampling rate	100 Hz

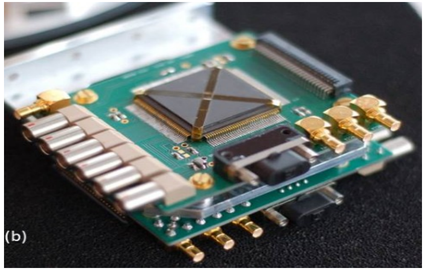
The total Noise Equivalent Power (NEP) is of the order of 5.10^{-17} $WHz^{-1/2}$ at 150 GHz, with a time constant in the 10-100 ms range. The pixels have 3 mm spacing while the membranes structure is 2.7mm wide.

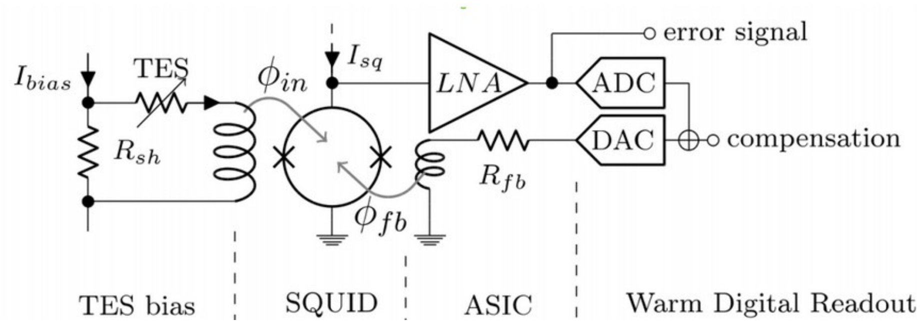


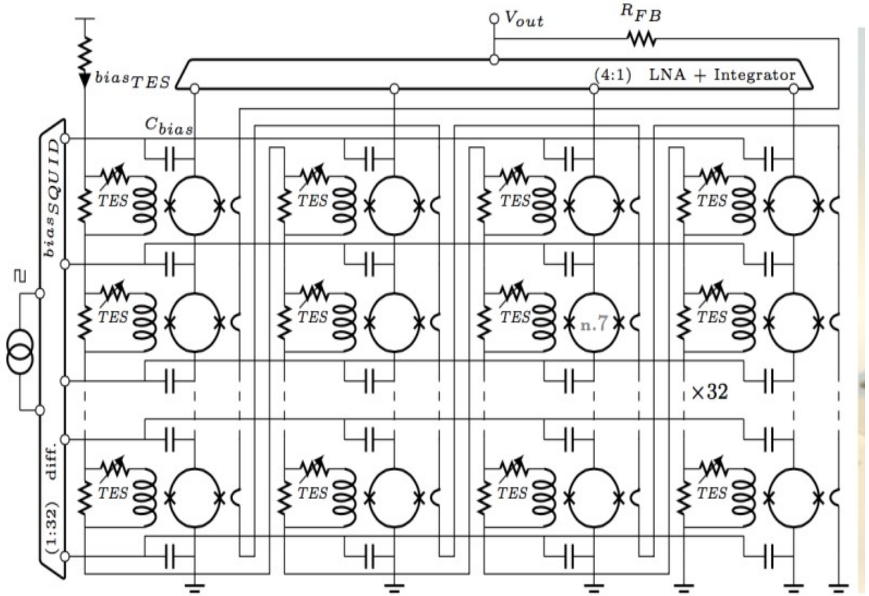


µMUX SQUIDS and Read-Out for TES









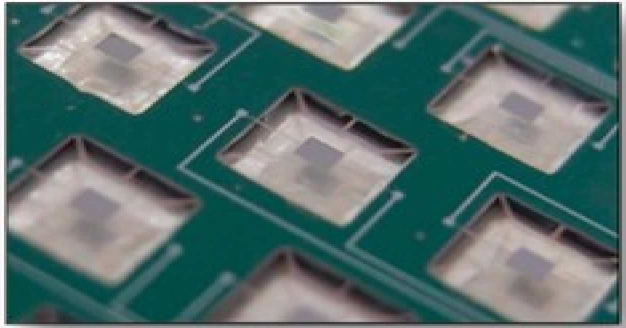
TES work as thermometers that change resistance in the transition from conductor to superconductor at a given frequency. They use Superconducting Quantum Interference Device (SQUID) couple to the Low Noise Amplifier on the Front End. Most of the Front End electronic works at cryogenic temperatures.

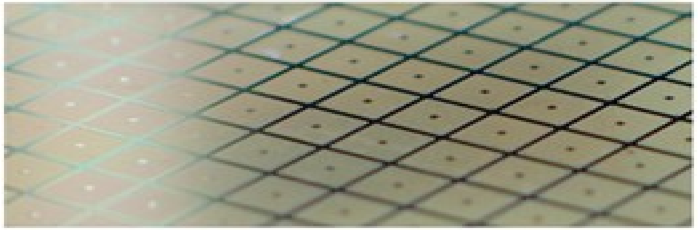
TES Summary

TES characteristics:
- Increase in Speed Response
- Response linearization

Advantages:
- Sensitivity
- High Technology Readiness Level (mainly in the USA)

Disadvantages:
- Fabrication Complexity
- Time multiplexed readout with feedback loop
- Very low temperatures required for the Read Out Electronics





Metallic Magnetic Bolometers (MMBs)

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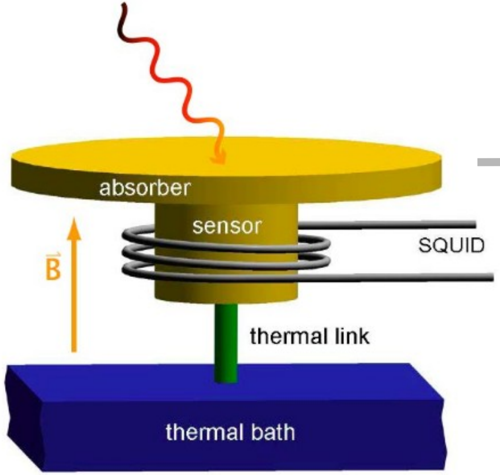
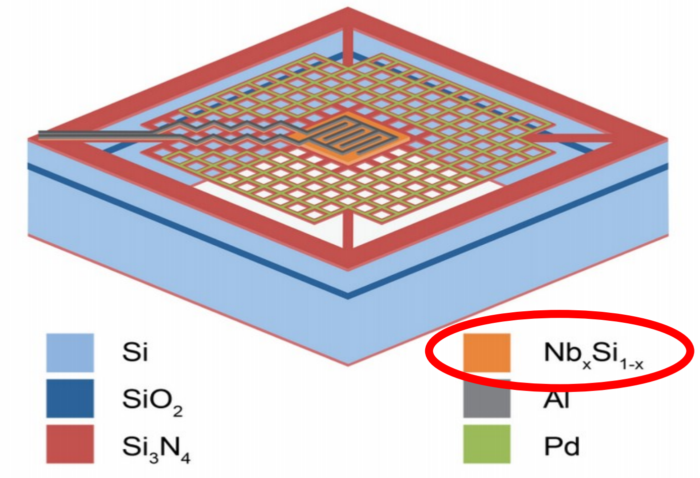
MMBs Outline

1) Metallic Magnetic Sensor and Absorber
2) μMUX SQUID resonators
3) Read Out Electronics

Bolometers: Metallic Magnetic (MMB)

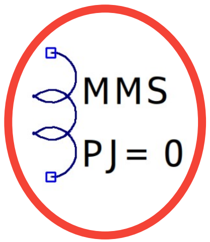


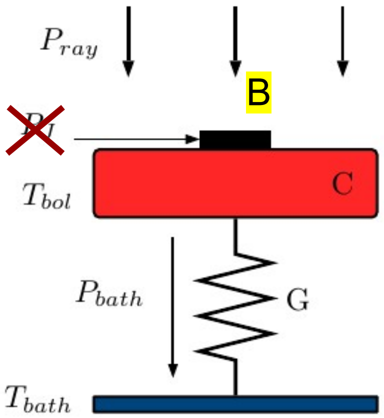


The TES are made with a Nb_xSi_{1-x} amorphous thin film. Its transition temperature and normal state resistivity can be easily adjusted to meet the QUBIC requirements for optimum performances and multiplexed read-out. The routing of the signal between the TES and the bonding pads at the edge of the array is realized by superconducting aluminum lines. These lines are patterned at the front of the array, on the silicon frame supporting the membranes.

The proposed MMB aims to replace that membrane with a MMC used as a thermometer.

Metallic Magnetic Sensor as a Thermometer



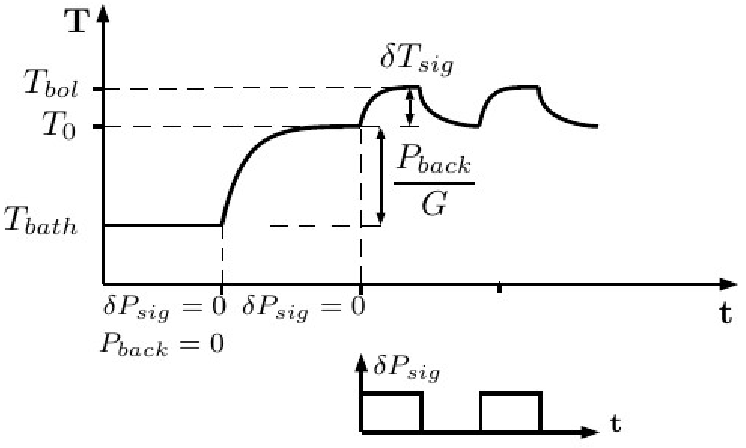


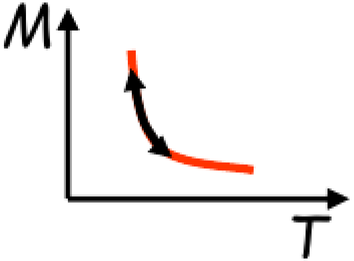
Thermometer

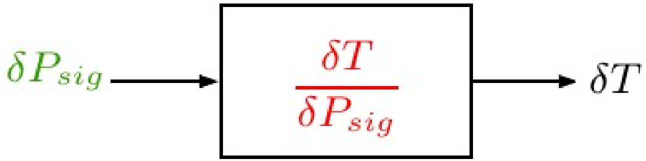
Absorber

Thermal link

Thermal bath



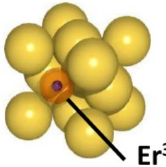


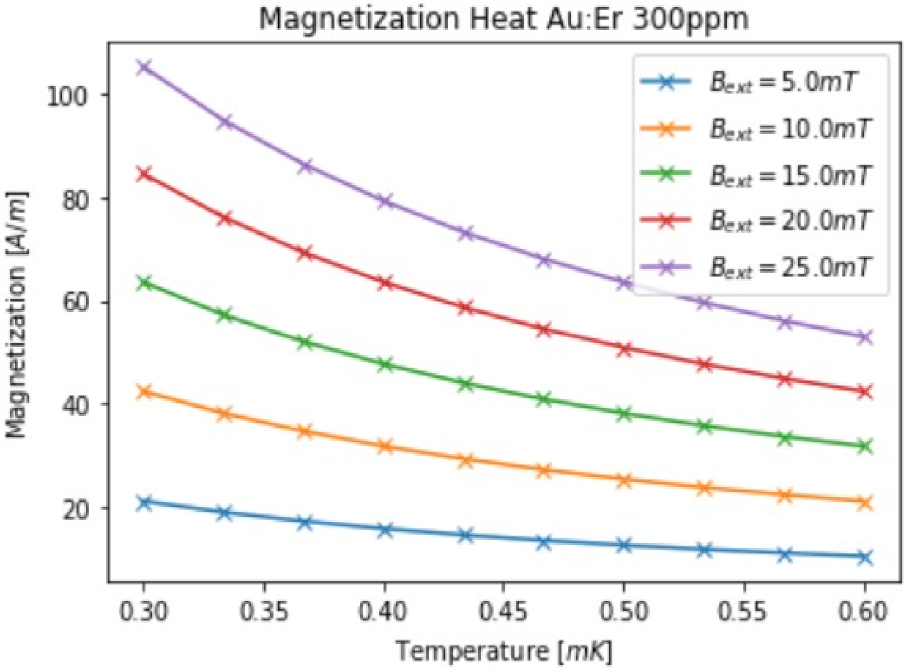


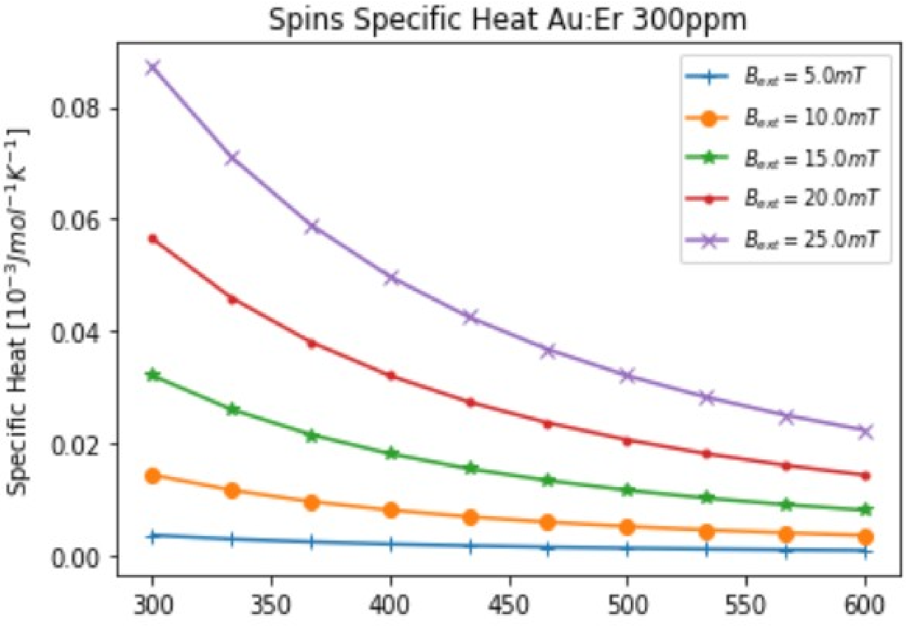
$$\delta M = \frac{\partial M}{\partial T} \delta T$$

Thesis work of Juan Bonaparte and Juan Manuel Geria

Au:Er Parametric range < 1K





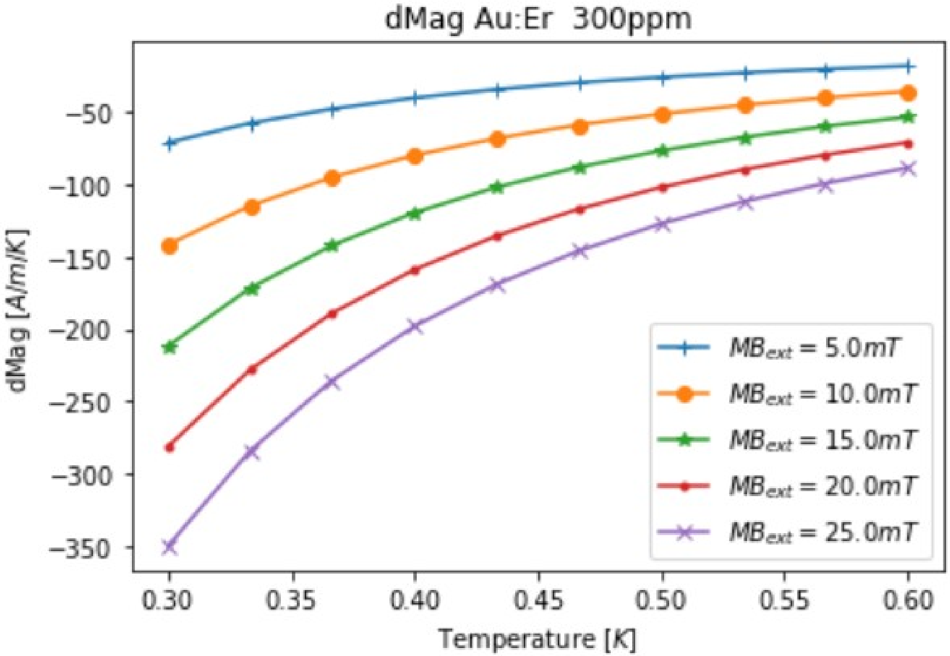


$$M = N \frac{\tilde{g}^2 \tilde{S}(\tilde{S}+1)\mu_B^2}{3k_b} \frac{B}{T}$$

$$c_s = N k_B \left(\frac{E}{k_B T}\right)^2 \frac{e^{\frac{E}{k_B T}}}{\left(e^{\frac{E}{k_B T}}+1\right)^2}$$

Transfer function

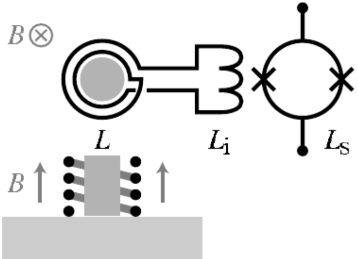
$$M = \frac{N g^2 J(J+1)\mu_B^2}{3k_B}\frac{B}{T}$$



$$\frac{\partial M}{\partial T} = -\frac{M}{T}$$

$$\delta m = \left(\frac{\partial M}{\partial T}\right)\delta T$$

Detection System for MMBs



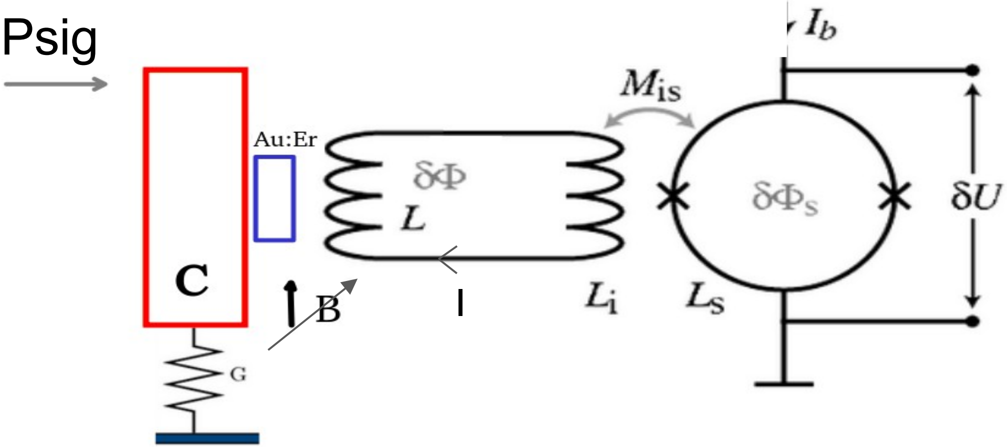
$$\delta\Phi = -\frac{\mu_0}{2r}\frac{M}{T}V\,\delta T$$

$$\delta\Phi_s = \frac{k\sqrt{L_i L_s}}{L+2L_i}\delta\Phi$$

$$S_{\phi_{in}} = -\frac{\mu_0}{2r}V\frac{M}{T_0}\frac{1}{G_{ab}}\frac{M_{in}}{L+L_i}$$

δPsig → **δ**T → **δ**M → **δΦ** → **δΦ**s

δPsig



Detectors Noise Comparison

Thermal Fluctuations Noise MMB

$$\sqrt{S_{\Phi_{TFN}}} = \Re_{MMB} \cdot \sqrt{4k_B T_0^2 G_{ab}}$$

Photon Noise MMB

$$\sqrt{S_{\Phi_{h\nu}}} = \Re_{MMB} \cdot NEP_{h\nu}$$

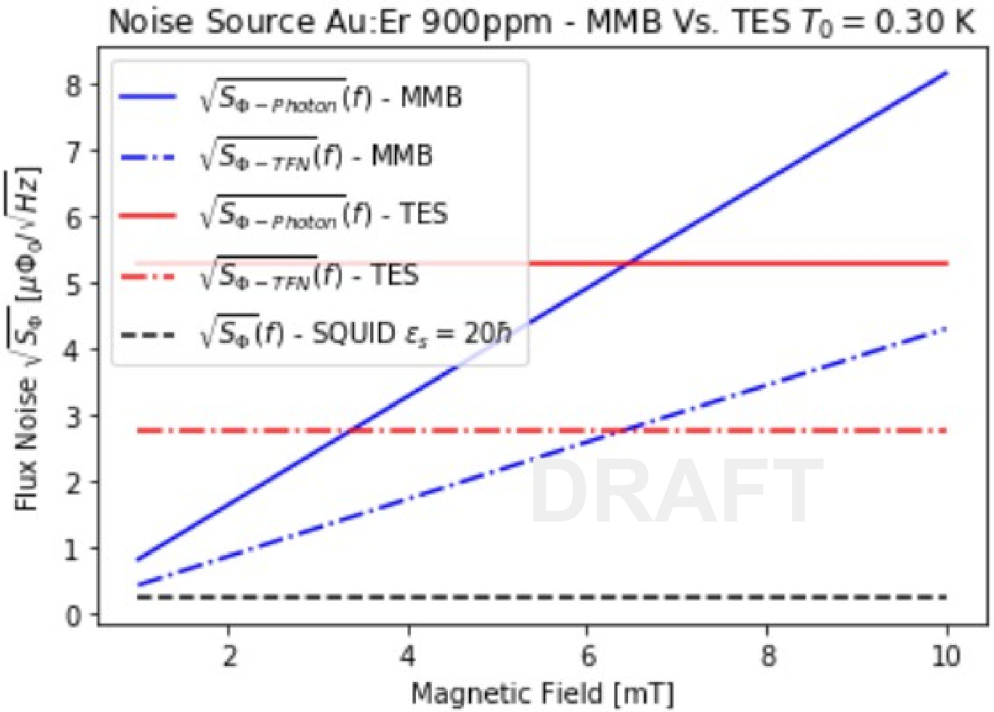
Thermal Fluctuations Noise TES

$$\sqrt{S_{\Phi_{TFN}}} = \Re_{TES} \cdot \sqrt{4k_B T_0^2 G_{ab}}$$

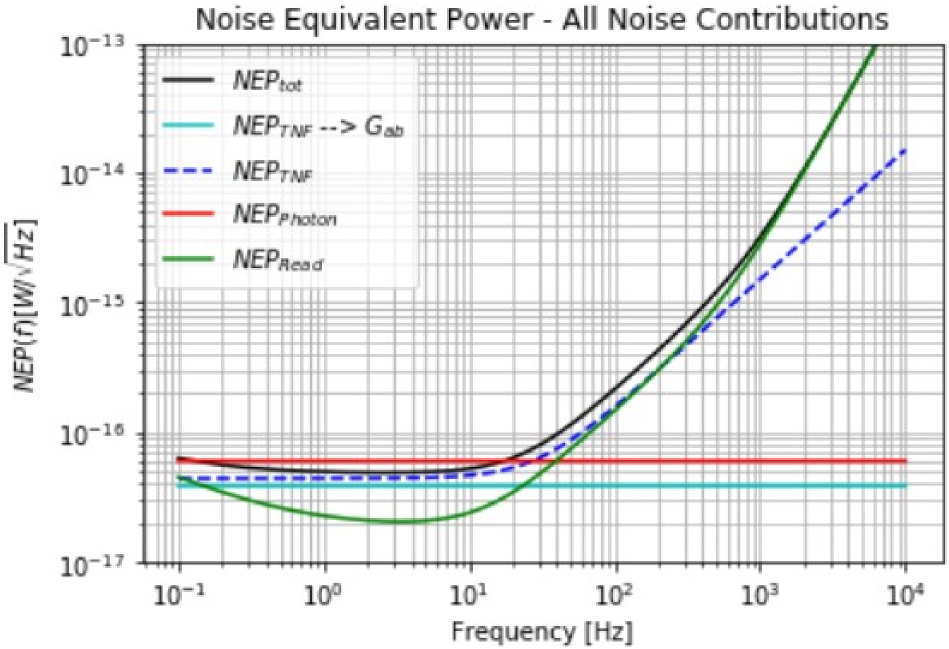
Photon Noise TES

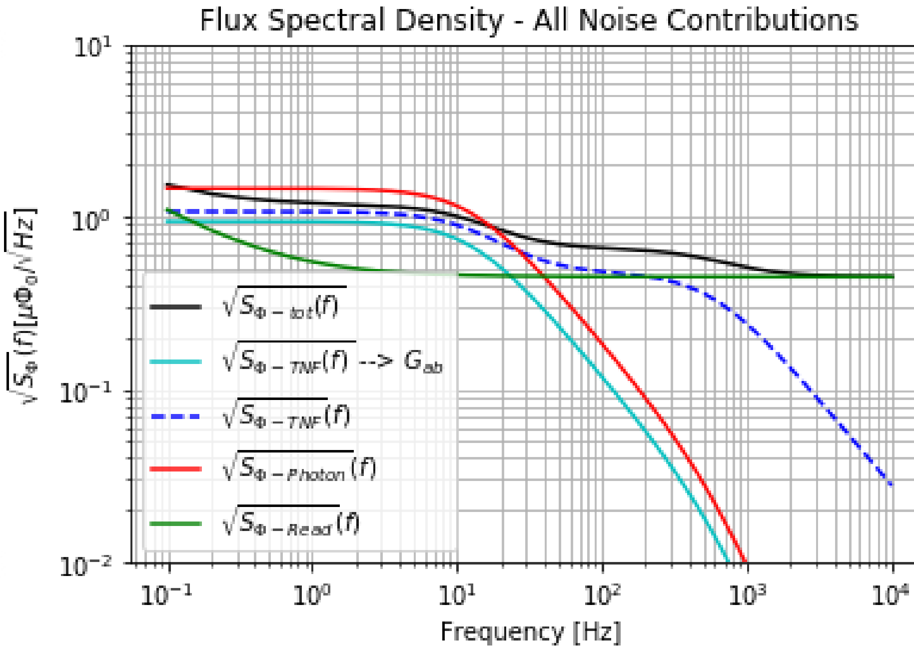
$$\sqrt{S_{\Phi_{h\nu}}} = \Re_{TES} \cdot NEP_{h\nu}$$

$$\sqrt{S_{\Phi_{SQUID}}} = \sqrt{2L_s \epsilon_s}$$



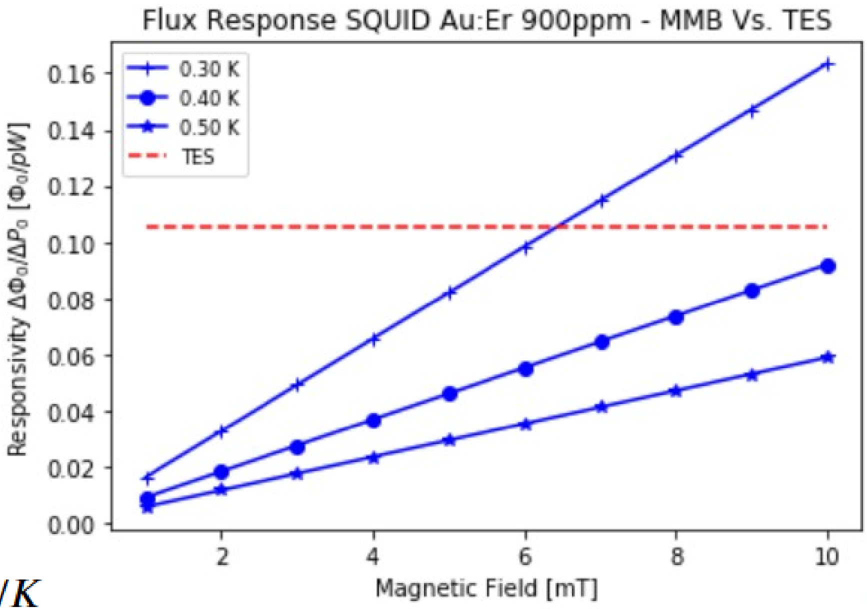
Noise Spectral Density





Detectors Responsivity Comparison

$$\Re_{MMB} \leq -\frac{\mu_0}{2r}\frac{C_s}{B}\frac{1}{G_{ab}}\frac{1}{2}\sqrt{\frac{L_s}{L}}$$



$$\Re_{TES} = \frac{-1}{V_b}\frac{\mathscr{L}}{\mathscr{L}+1}$$

$G_{ab} = 140pW/K \,;\, C_s < 0.1pJ/K$

$r = 50\mu m \,;\, h = 4\mu m$

$L_s = 60pHy \,;\, L = 100pHy$

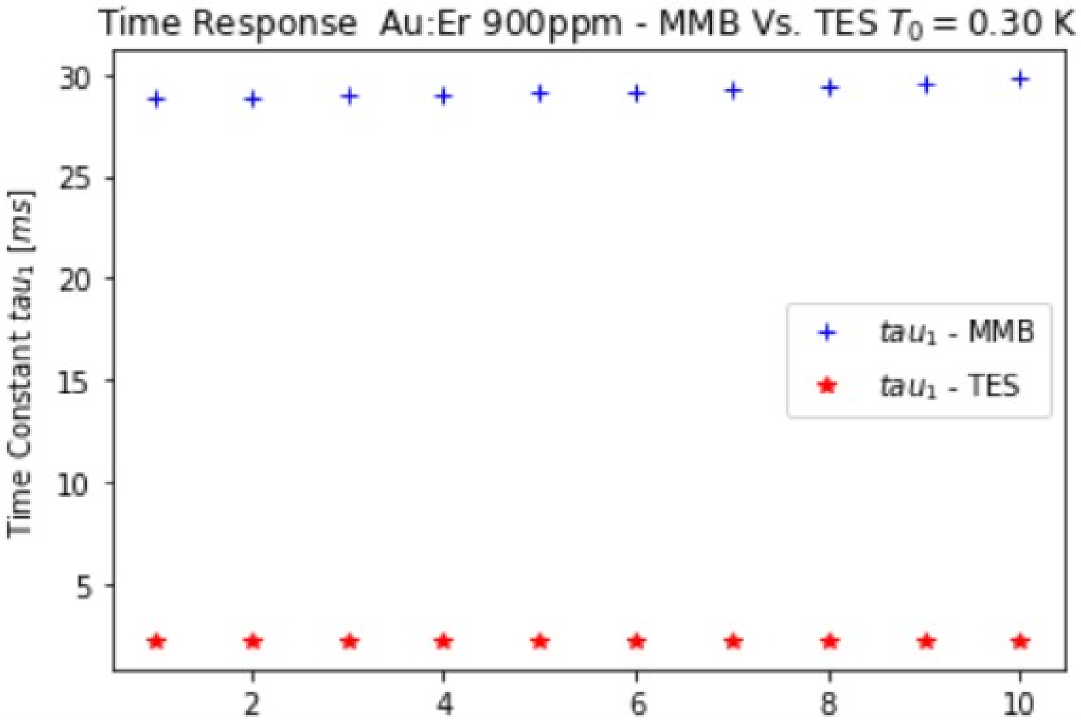
$V_b = 1\mu V \,;\, \mathscr{L} = 10$

$M_i = 242pHy$

Detectors Time Constants Comparison

$$\tau_{MMB} = \frac{C_{total}}{G_{ab}}$$

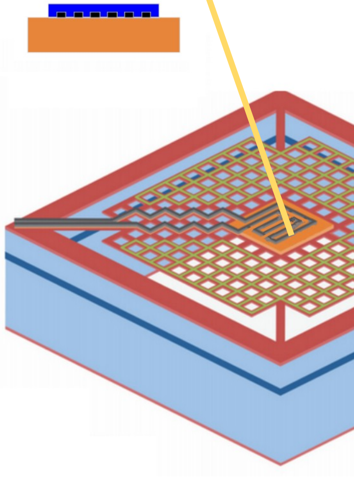
$$\tau_{TES} = \frac{C_{total}}{G_{ab}(\mathscr{L} + 1)}$$

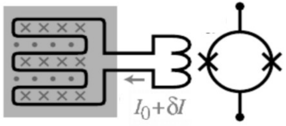


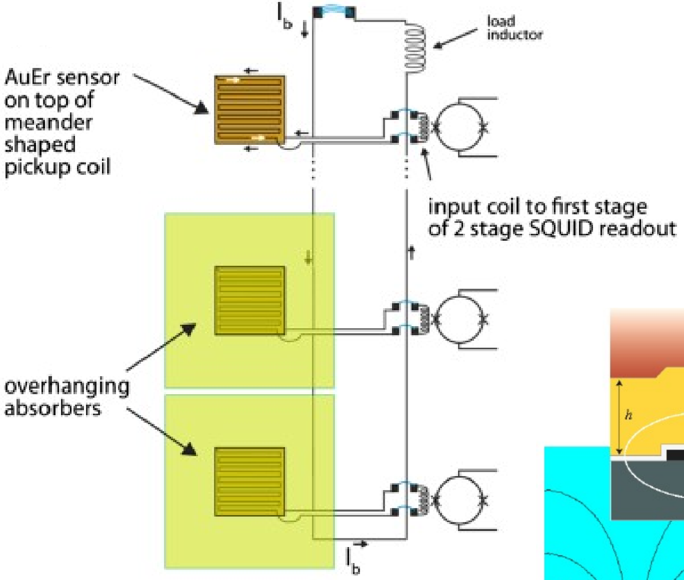
Magnetic field
[mT]

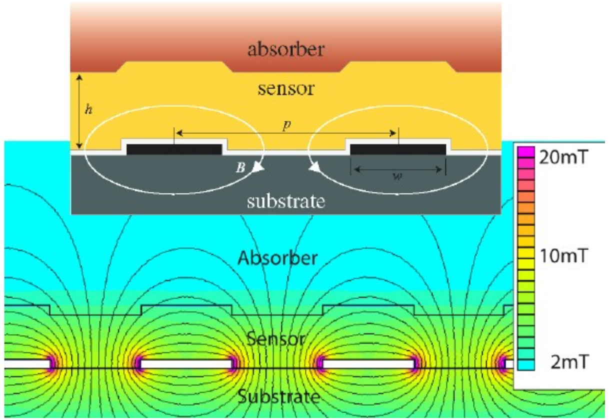
MMB Challenges

Thermometer
(Au:Er)



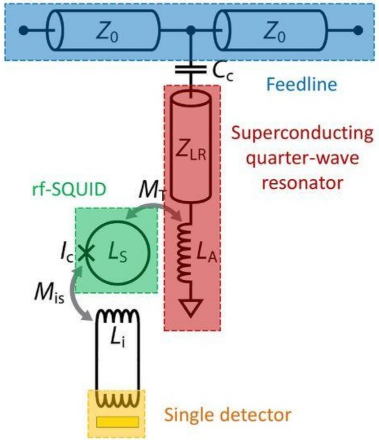


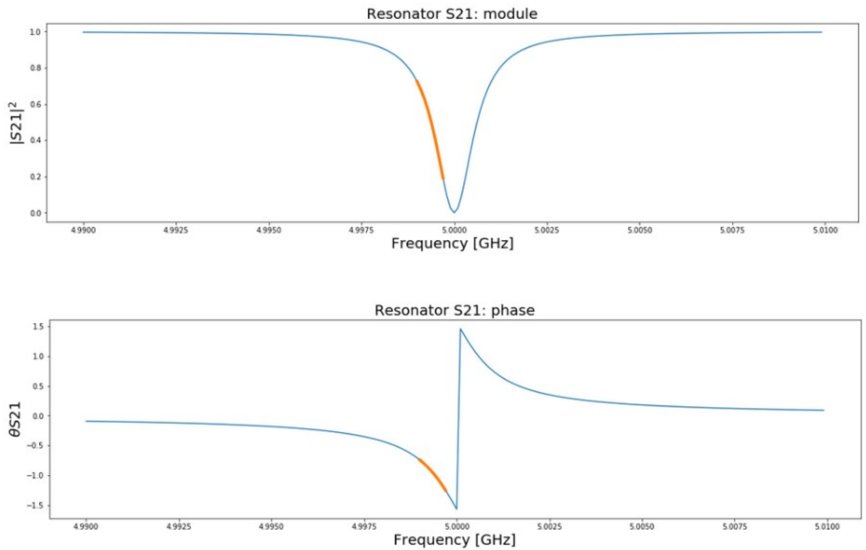


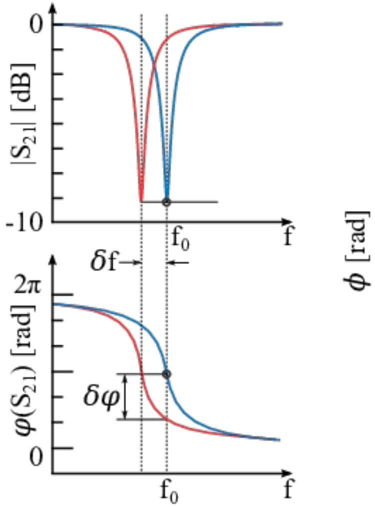


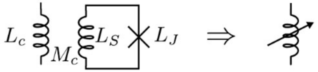
µMUX RF SQUID

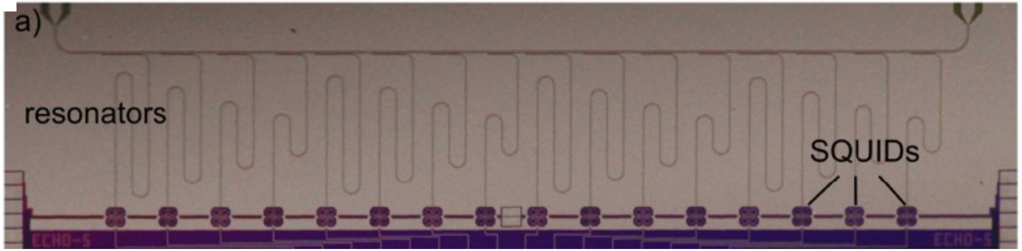
Thesis work of Nahuel Müller and Jesús David Bonilla

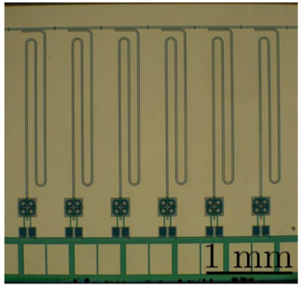




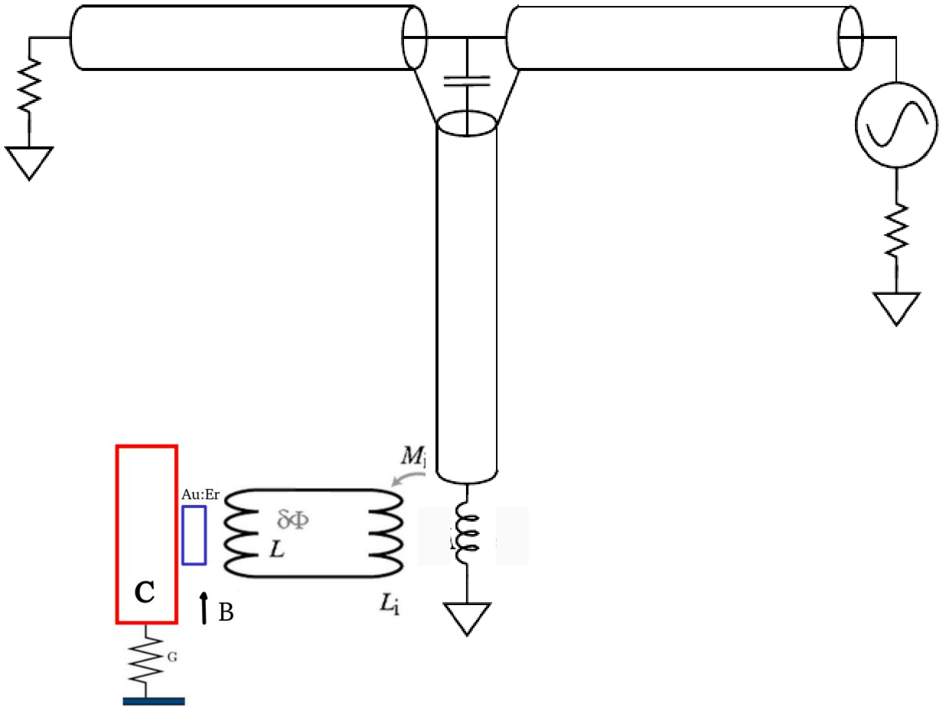


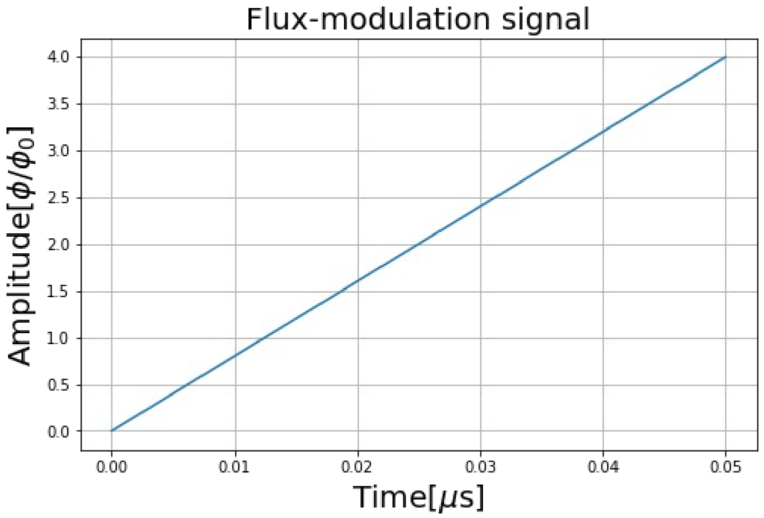


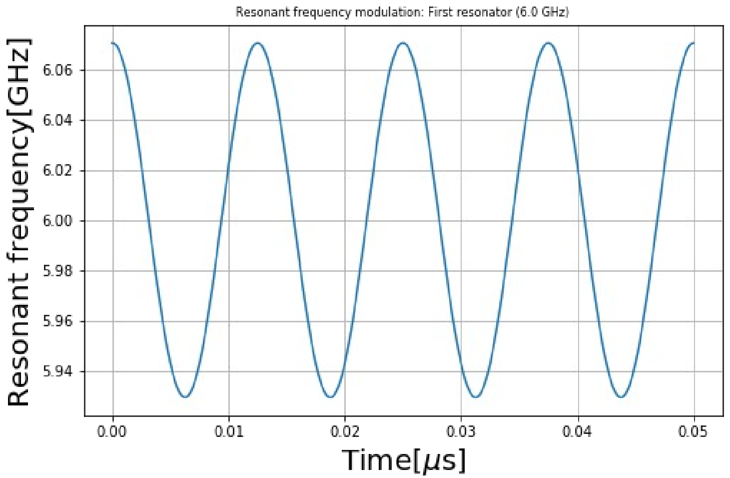




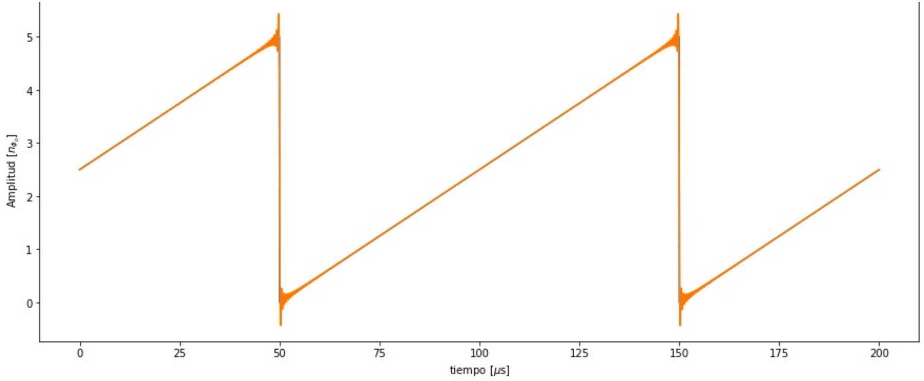
µMUX RF SQUID

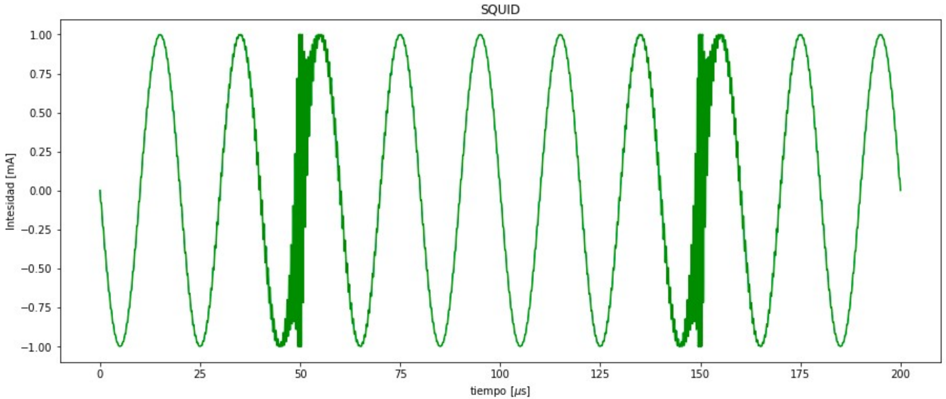


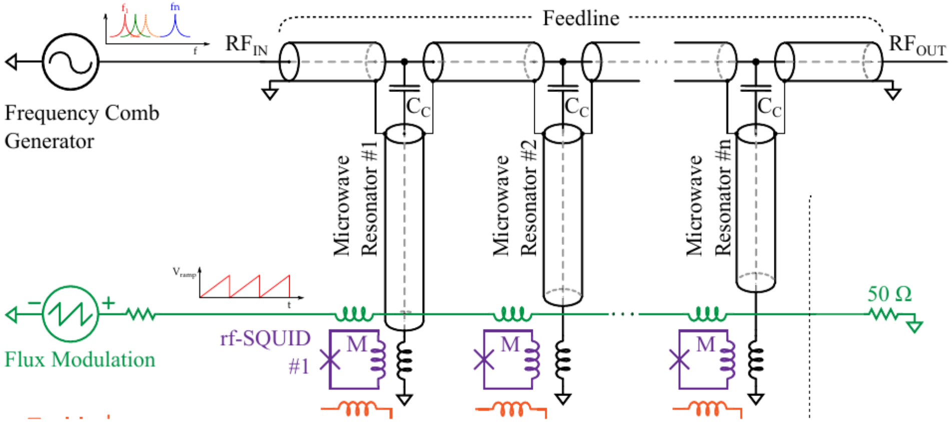




µMUX RF SQUID: Flux ramp modulation





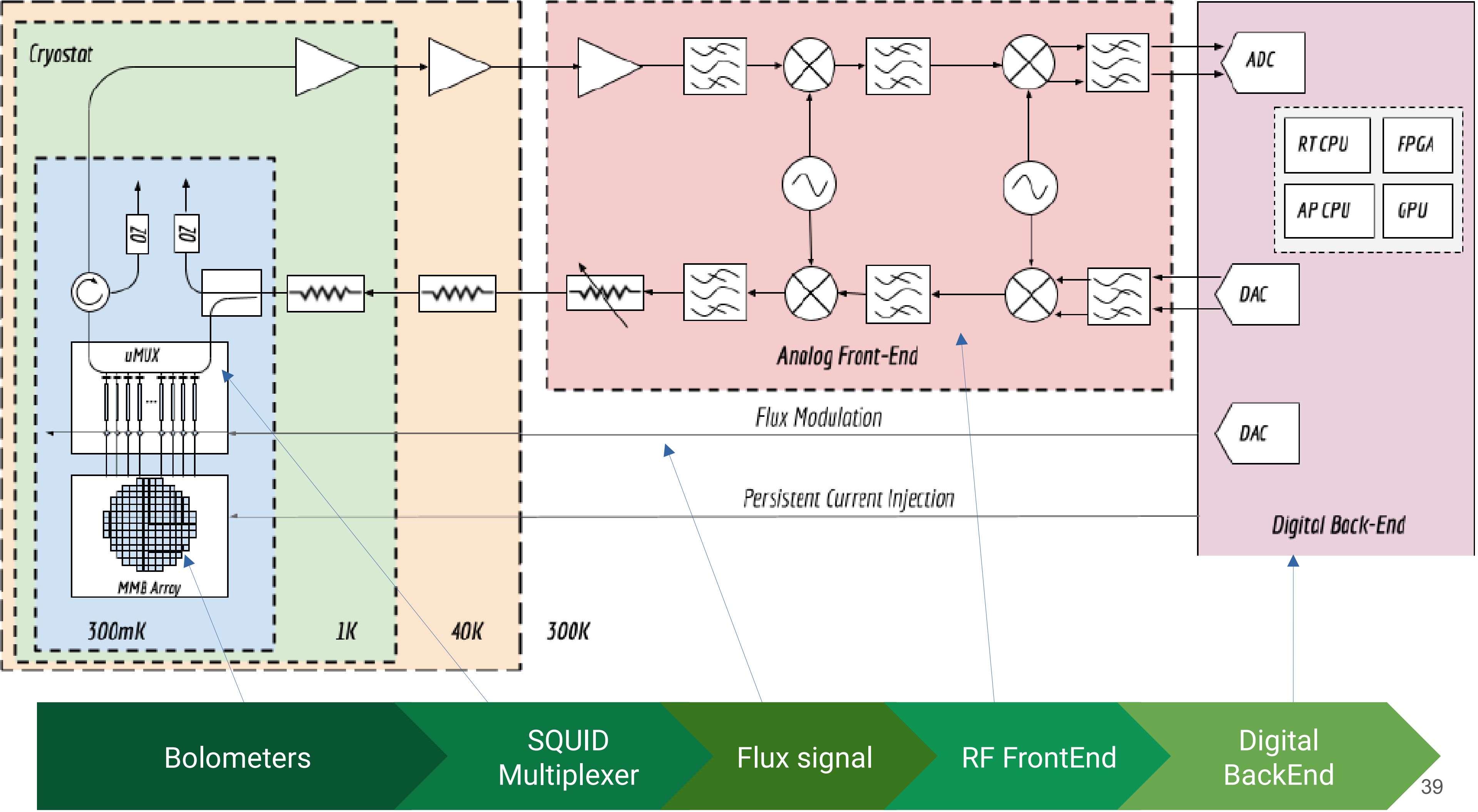


Thesis work of Juan Manuel Salum

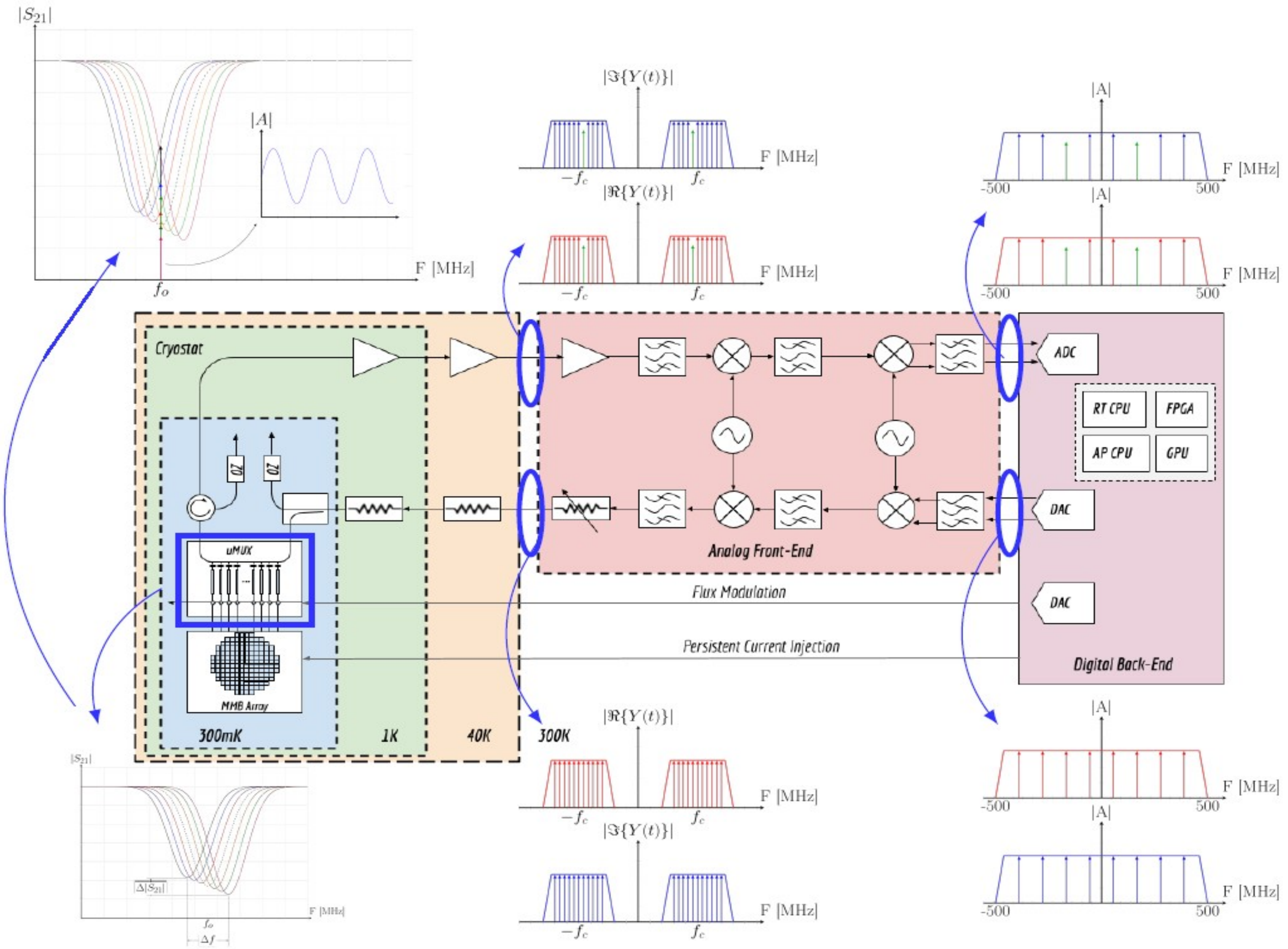
QUBIC new Read-Out Electronics

UNSAM
UNIVERSIDAD NACIONAL DE SAN MARTÍN

Karlsruher Institut für Technologie


Cryostat
ZO
ZO
uMUX
MMB Array
300mK
1K
40K
300K
Analog Front-End
Flux Modulation
Persistent Current Injection
ADC
RT CPU
FPGA
AP CPU
GPU
DAC
DAC
Digital Back-End
Bolometers
SQUID Multiplexer
Flux signal
RF FrontEnd
Digital BackEnd

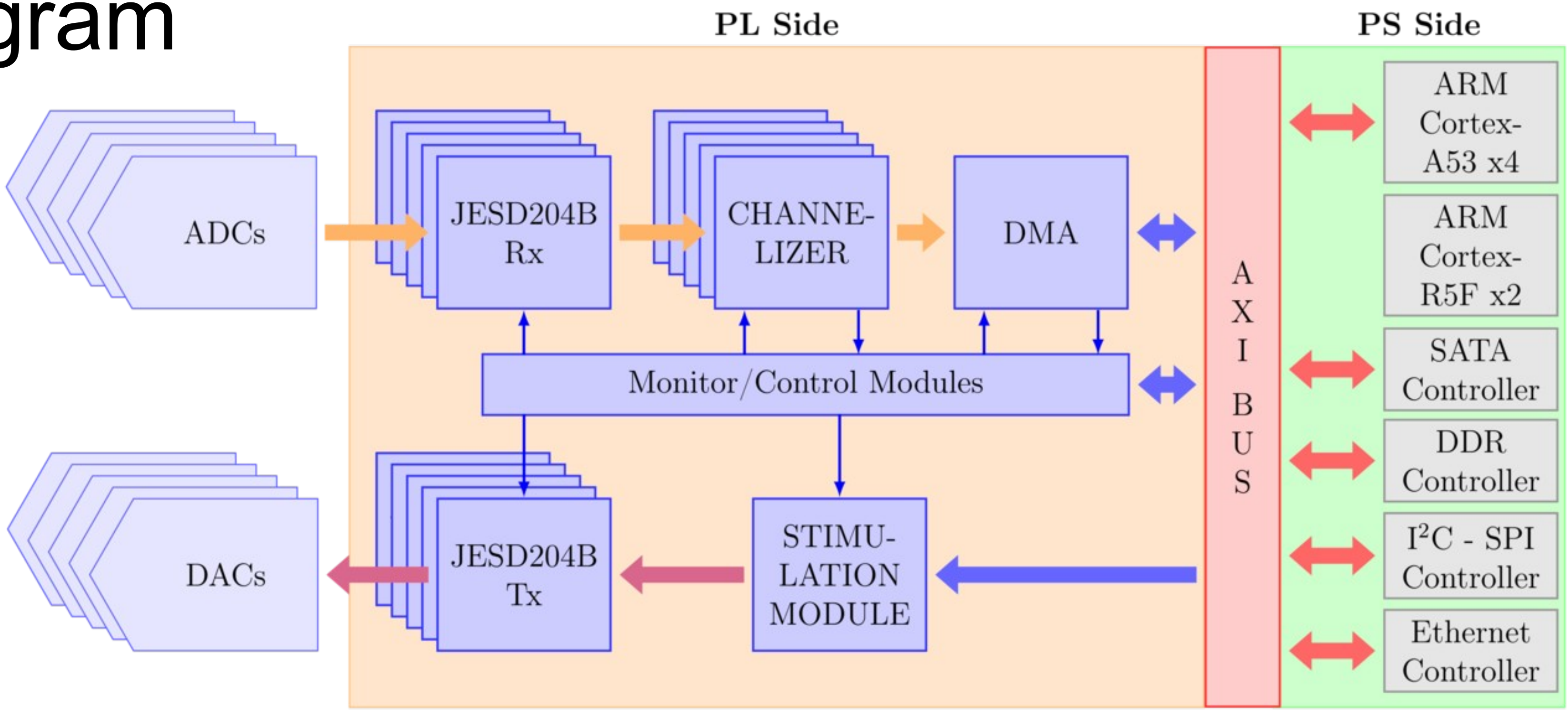
Read-Out System: Signal Path



QUBIC Read-Out electronics specifications

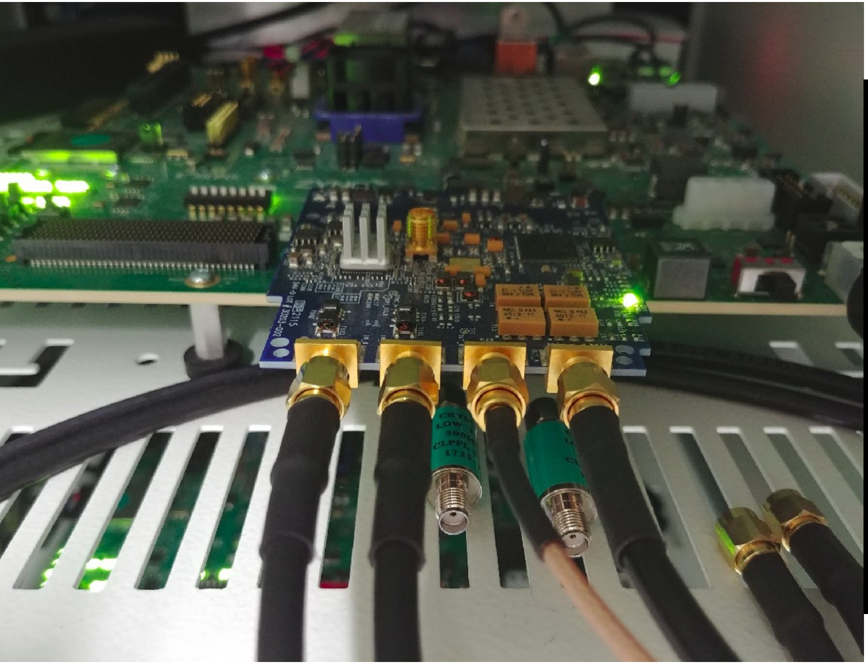
Requirement	Value	Description
Total Bandwidth	4GHz to 8GHz	Limited by the LNA bandwidth and the µSQUID Mux
Input signal power	-90dBm to -60dBm	Read-out power per pixel
Number of channels	400	Limited by the µSQUID Mux
Number of ADCs	5	80 channels per ADC
ADC SNR	> 65 dB	At least 10*log(number of tones) bigger tan the LNA SNR
Number of channels per ADC	80	
Sampling frequency of ADC	800Msps	Limited by the SNR
Number of DACs	5	To cover the LNA bandwidth
DAC SNR	> 75 dB	At least 10 dB higher than the ADC SNR
Total power per block	-30dBm to -0dBm	At the cryostat Input
Type of Modulation	I+Q	800 MHz of complex bandwidth, limited by SNR
Number of I+Q mixers	10	5 for up and 5 for down-conversion
Number of local oscillators	5	5 for up and down-conversion
Range of LO frequencies	4GHz to 8GHz	
Reference clock Jitter	< 150 fps	SNR due to jitter 10dB bigger tan the intrinsic ADC SNR
Phase noise in the LOs	< -80dB/Hz	@1KHz offset

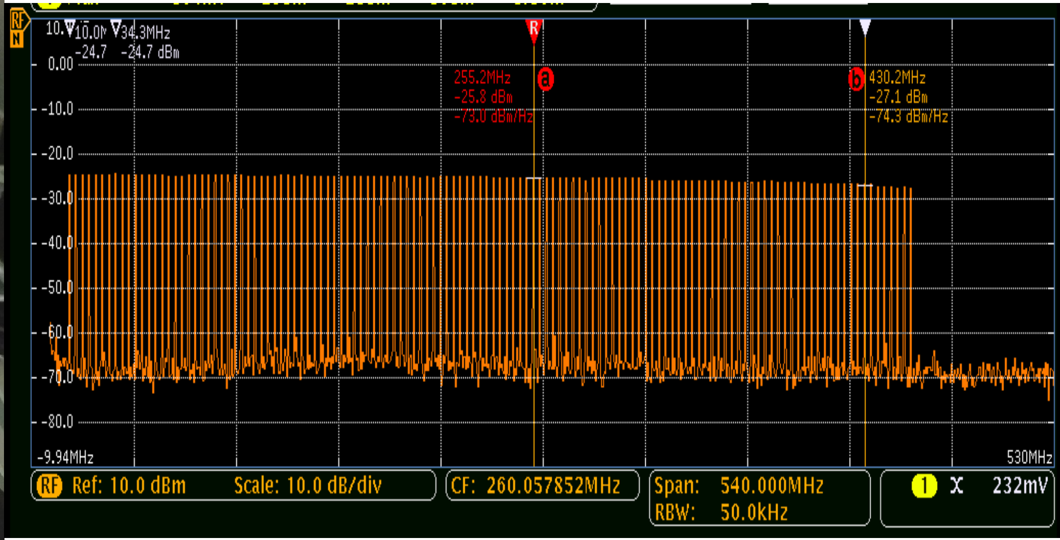
Back-End Diagram



Thesis work of Luciano Ferreyro

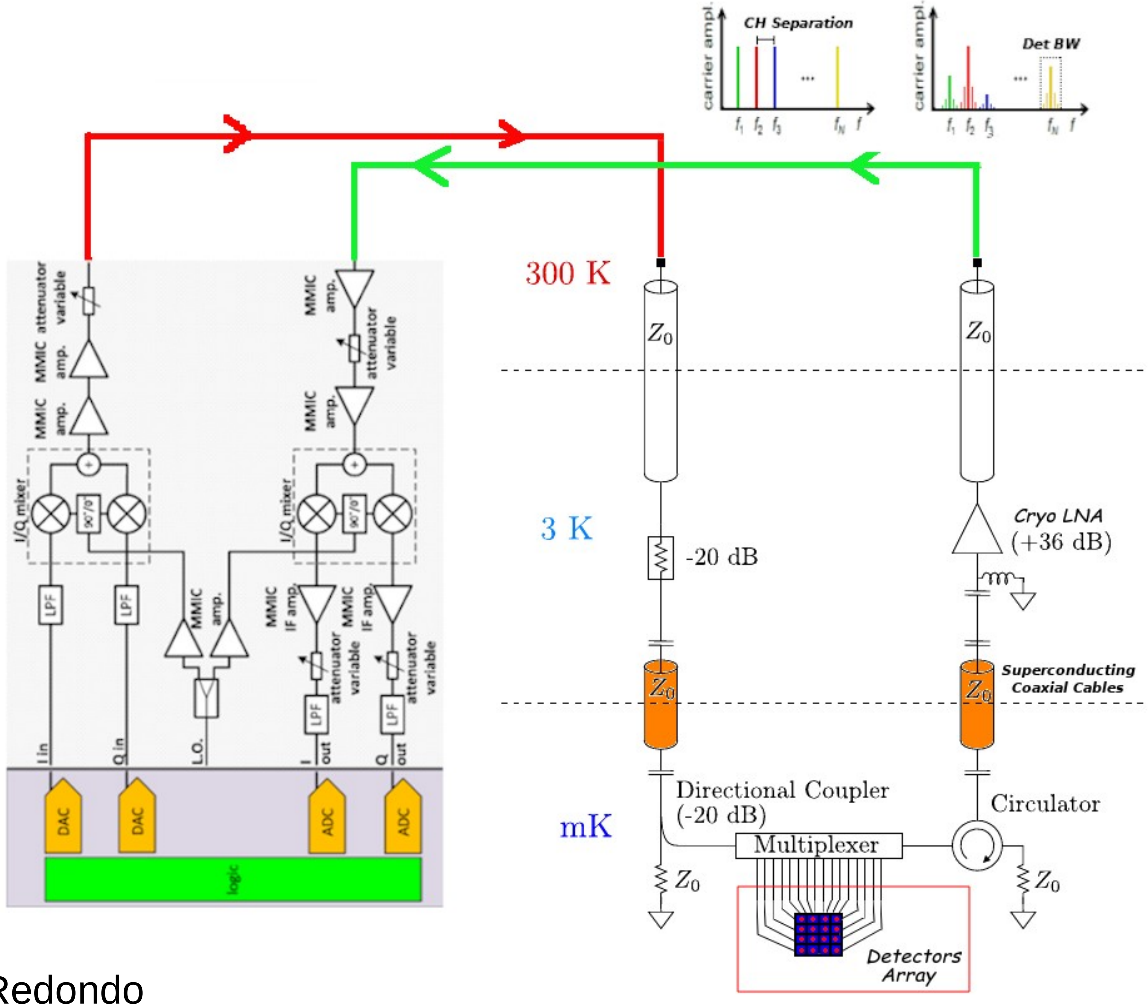
Back-End Implementation





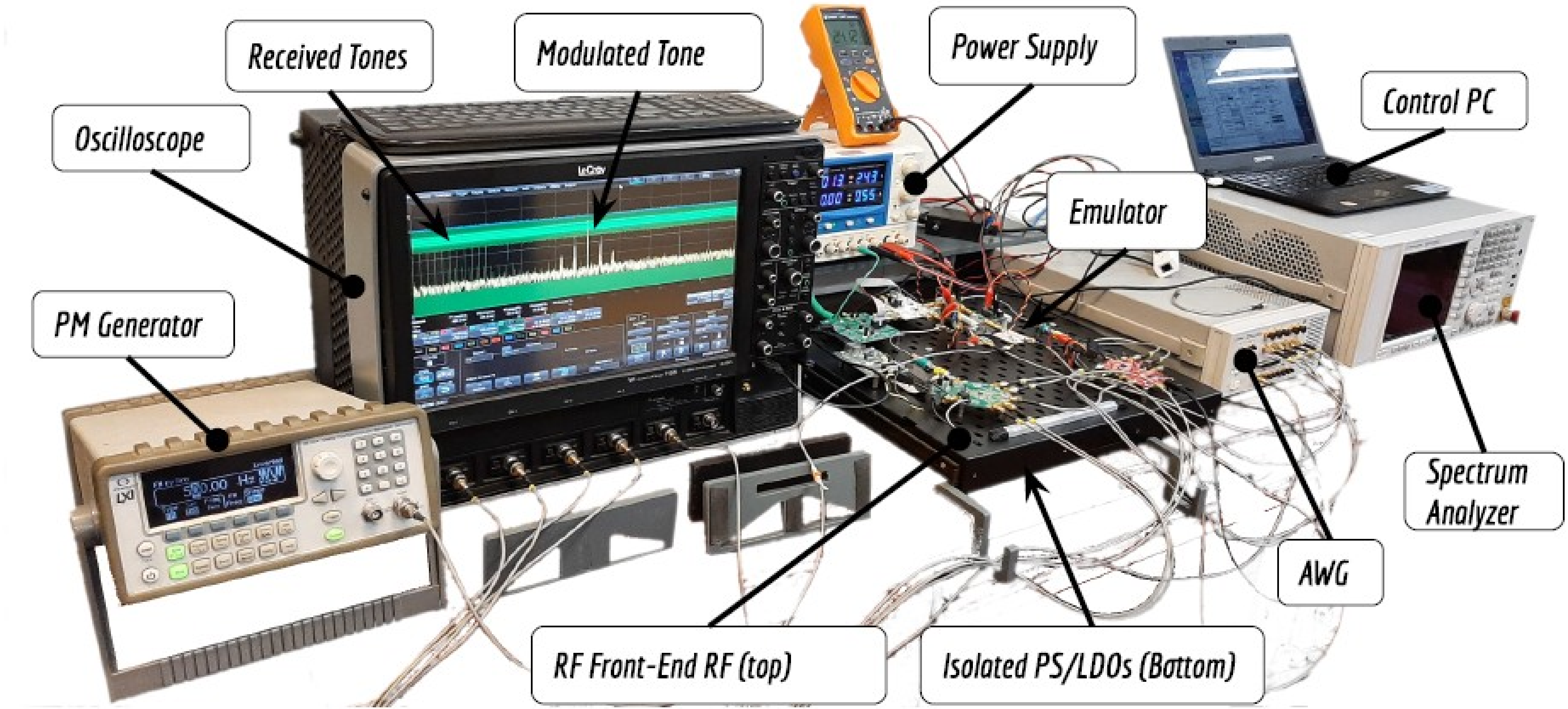
An implementation of 1000 tones with a Goertzel filter in a ZCU102 FPGA evaluation board by Xilinx uses a total of 56.14% of the BRAM and 82.2% of the DSP Slices.
The spectrum analyser shows a measurement of 256 tones demodulated successfully

Front-End Diagram

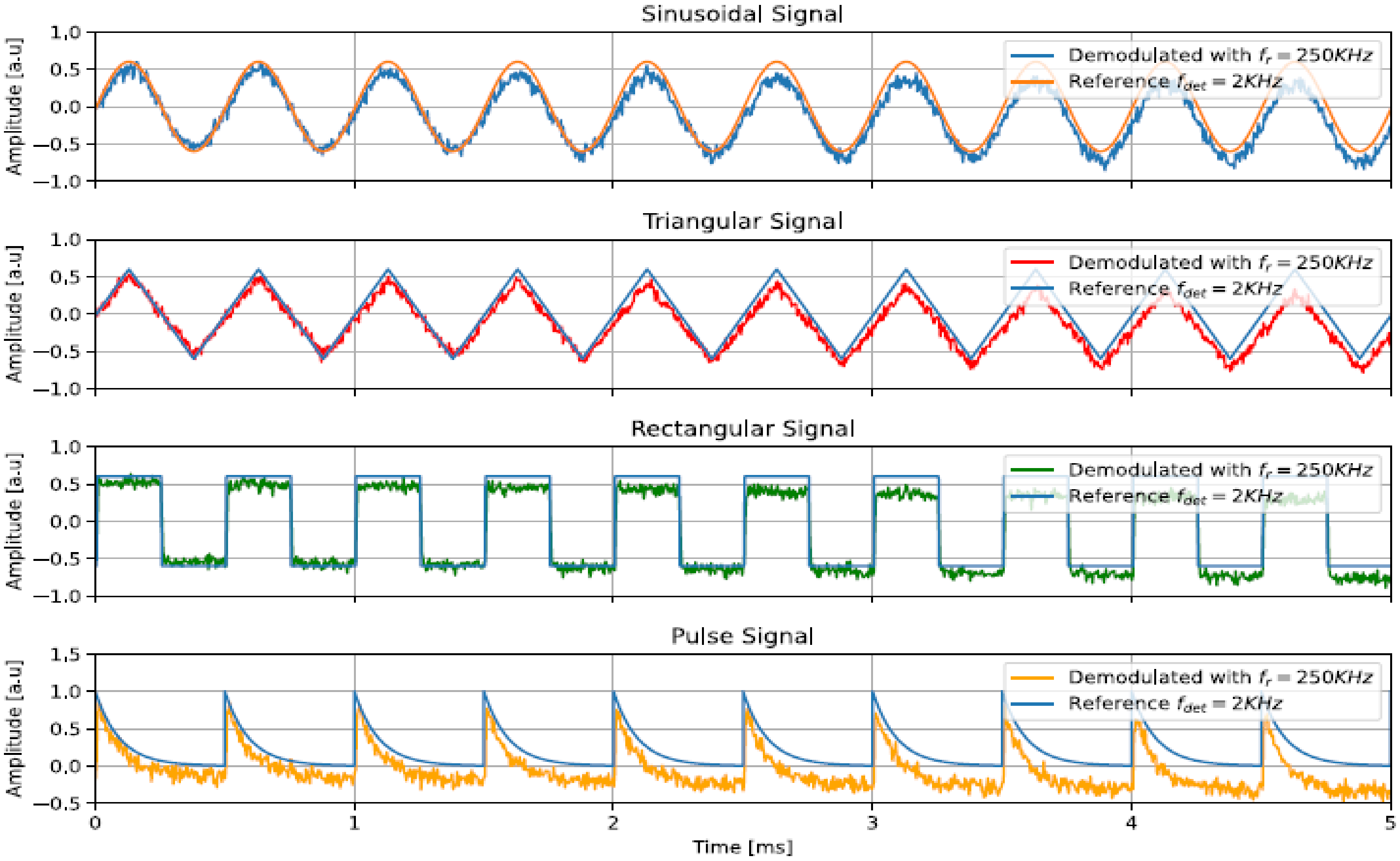


Thesis work of Manuel García Redondo

Front-End Implementation



Front-End I+Q modulation results



MMBs Summary

MMB characteristics:

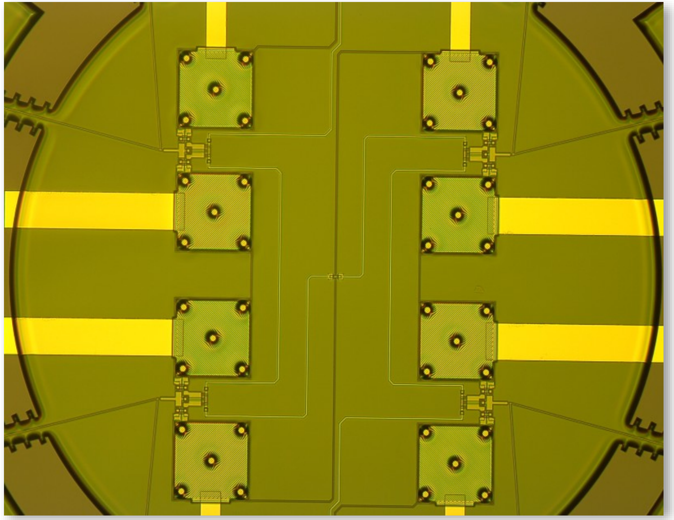
- Low detector noise (photon limited)
- No power dissipated by the thermometer
- Higher sensitivity & responsivity
- Requires a SQUID μMUX

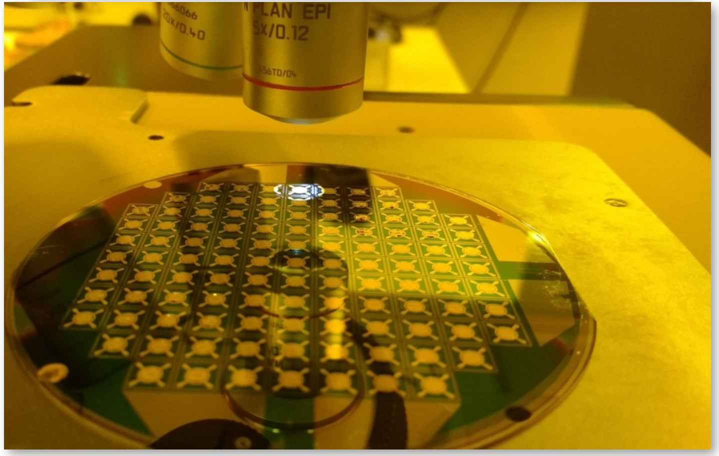
Advantages:

- Easier Read Out (no feedback loop inside the cryostat)
- Well tested as a calorimeter (ECHo @ KIT (IPE))
- Technology readiness available @ KIT (IMS) & Heidelberg

Disadvantages:

- Fabrication complexity
- Needs to be tested as a bolometer (as a new enabling technology)





MMBs for QUBIC Project Status

- **Metallic Magnetic Bolometers:**
  - Conceptual study by means of simulations of the responsivity, noise and temporal response of the sensor based on publications for the QUBIC design working temperature of 300 mK. Made in collaboration between KIT (IMS) & UNSAM.
  - Design of the coupling system absorbers and SQUIDs.

- **μMUX multiplexer:**
  - Research of the characteristic parameters based on the design of the QUBIC sensors.
  - Study of the flow signal for the SQUIDs Read Out.

- **Read Out system:**
  - Design and implementation of the RF stage in collaboration between KIT (IPE) & UNSAM.
  - Assembly of a digital system, programming for the tones generation and reading of the state of the multiplexer resonators via I+Q mixing.

Conclusions

1) QUBIC prioritizes bolometry over radiometry as a better way to observe the 150 GHz band (corresponding to the 2.7K photons of the CMB) and remove the foregrounds in post processing in the 220 GHz band (corresponding mostly to galactic dust).
2) QUBIC uses interferometry to generate a synthetic bean which, in conjunction with the polarizer can split the band in 5 sub-bands improving the resolution.
3) QUBIC currently uses TES as bolometers which performance can be improved using MMBs which do not dissipate power in the superconducting state, therefore allowing to reduce the cryogenic temperature even further (at least 1 order of magnitude).
4) QUBIC uses currently a TDM read out system that requires an ASIC inside the 4K stage. The proposed Read Out electronics for MMBs uses FDM, which allows to place all active electronics (except the LNA) outside the cryostat, reducing the power dissipated inside it and reducing the number of cables going inside it. The flux ramp modulation avoids the need of a feedback loop. This multiplexing system also is expandable allowing QUBIC to increase the number of pixels if desired to reach stage 3 or even 4 of CMB measurement in the future.

Vielen Dank
Muchas Gracias