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Karlsruher Institut für Technologie

Micromachined Sensors and Electronics for QUBIC

HIRSAP meeting, Sept. 23 2019

ITeDA

Outline

› Introduction to Cosmic Microwave Background (CMB) Radiation Measurement
› CMB Polarization
› CMB Measurements techniques
› The QUBIC Bolometer
› Micromachined Sensors and Electronics for Stage 3 QUBIC

Introduction to Cosmic Microwave Background (CMB) Radiation Measurement

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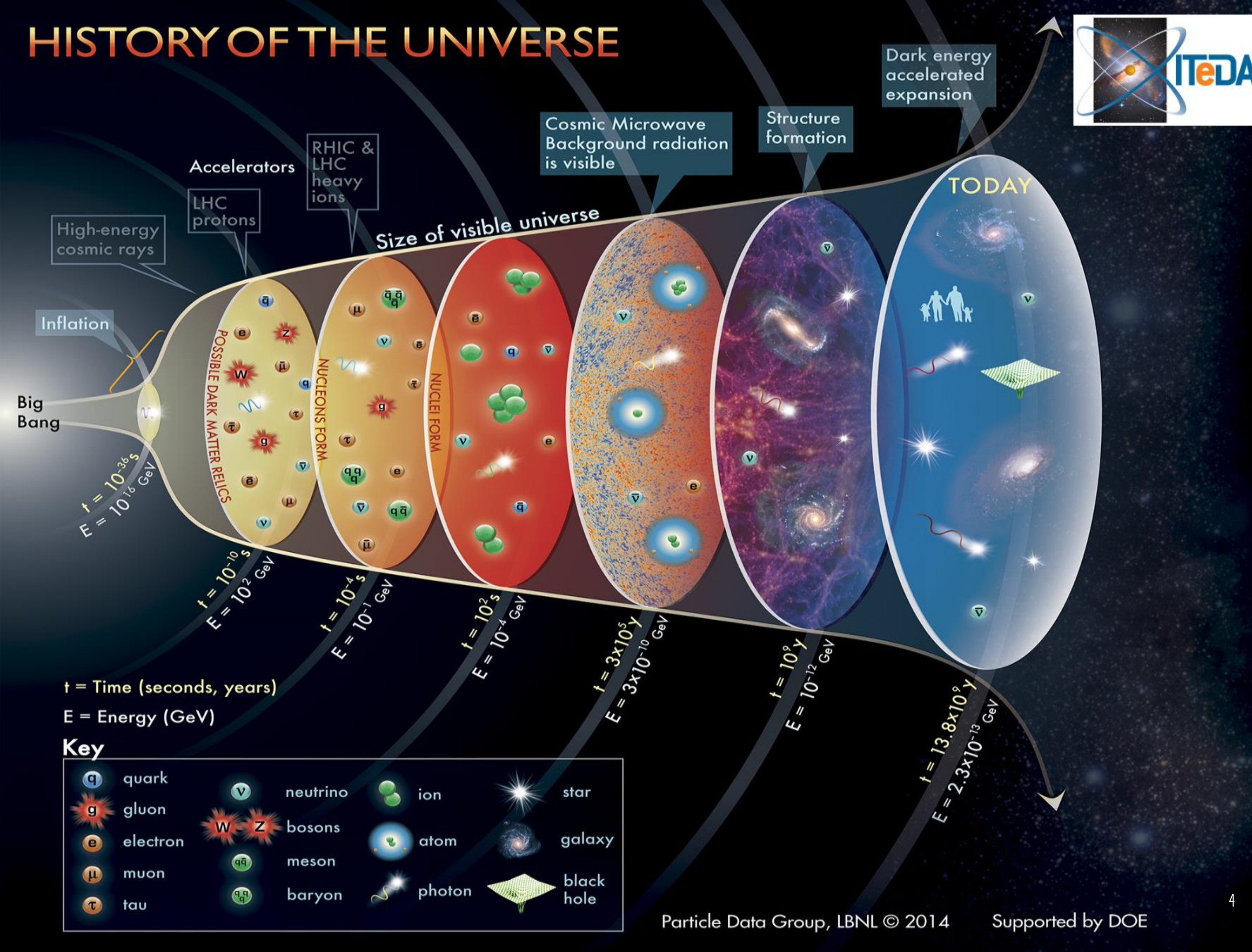
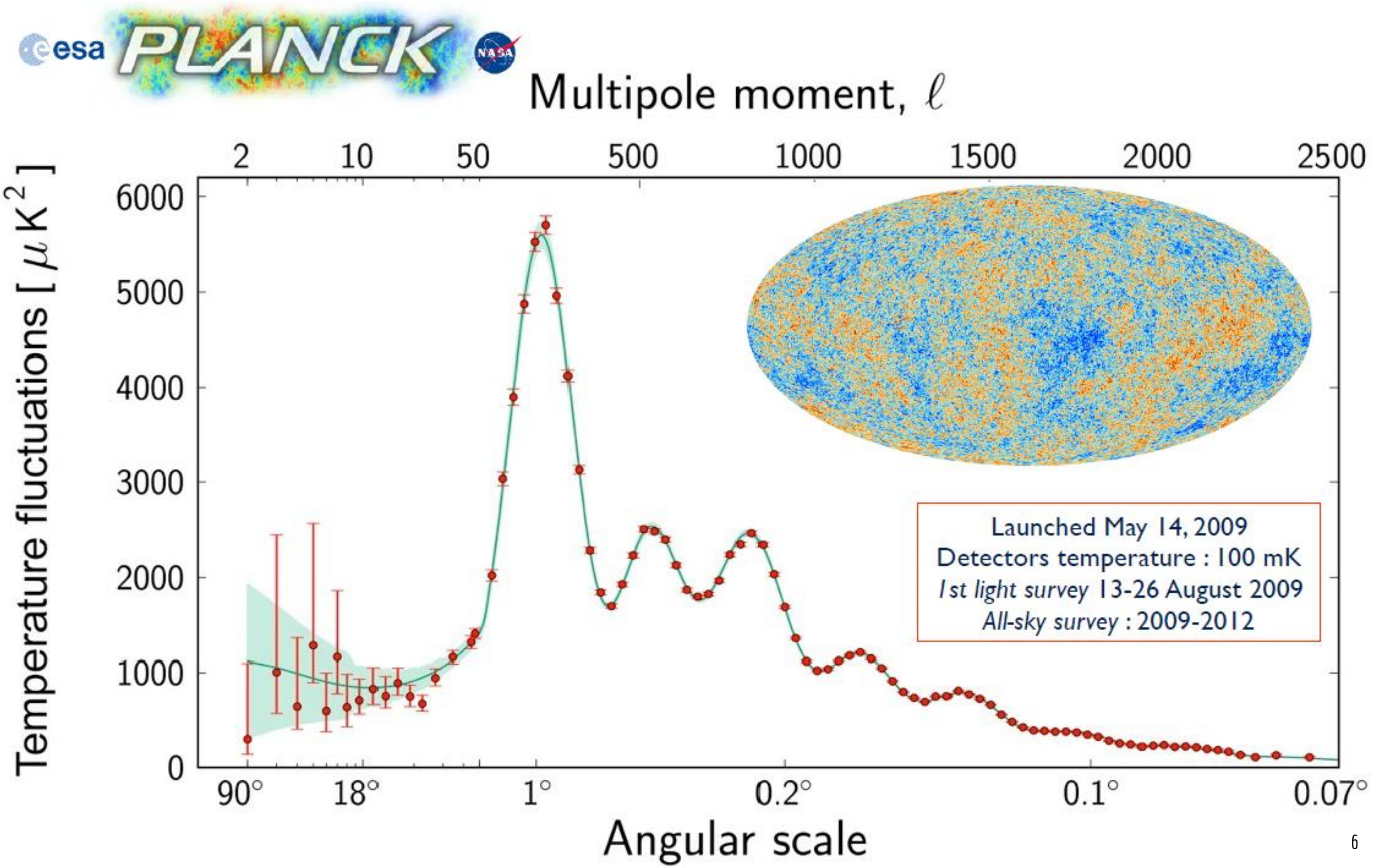

HISTORY OF THE UNIVERSE
ITeDA
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^{-36} s
E = 10^{16} GeV
t = 10^{-10} s
E = 10^{2} GeV
t = 10^{-4} s
E = 10^{-1} GeV
t = 10^{2} s
E = 10^{-4} GeV
t = $3x10^{5}$ y
E = $3x10^{-10}$ GeV
t = 10^{9} y
E = 10^{-12} GeV
t = $13.8x10^{9}$ y
E = $2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

CMB Measurement History

- 1965: Discovery by Penzias & Wilson → *Big-Bang confirmed. Where are the anisotropies?*
  - Isotropic black-body radiation at T~3K
- 1992: COBE → *Cold Dark Matter strongly favored*
  - Anisotropies discovered $\Delta T/T=10^{-5}$
  - Black-body confirmed
- 1999: Boomerang and Maxima → *Topological defects excluded. Inflation favored. Evidence for flatness*
  - First acoustic peak discovered
- 2001: DASI & CBI → *Major prediction confirmed*
  - Polarization detection
- 2003: WMAP → *Confirmation of adiabatic primordial perturbations. Precision cosmology*
  - Full-sky measurement of T and E
- 2013: Planck → *Ultimate T and E spectra factor 3 gain on cosmological parameters, flatness confirmed*
  - Ultimate measurements of T and E
- 20XX: B-mode experiments (QUBIC, SPT) → *Exploration of inflationary physics*
  - Primordial gravitational waves

CMB Radiation: Angular distribution



CMB Polarization

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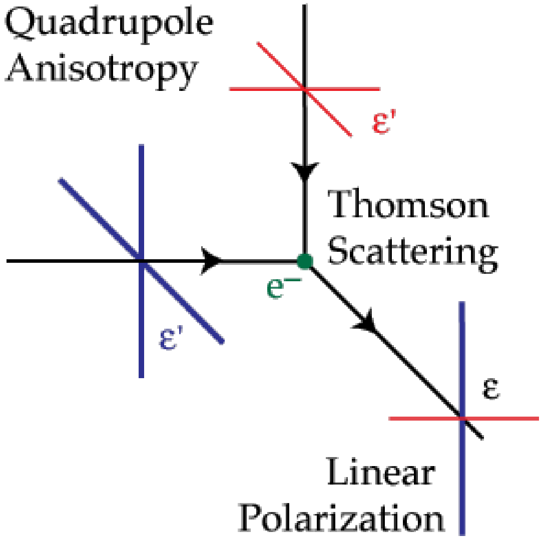
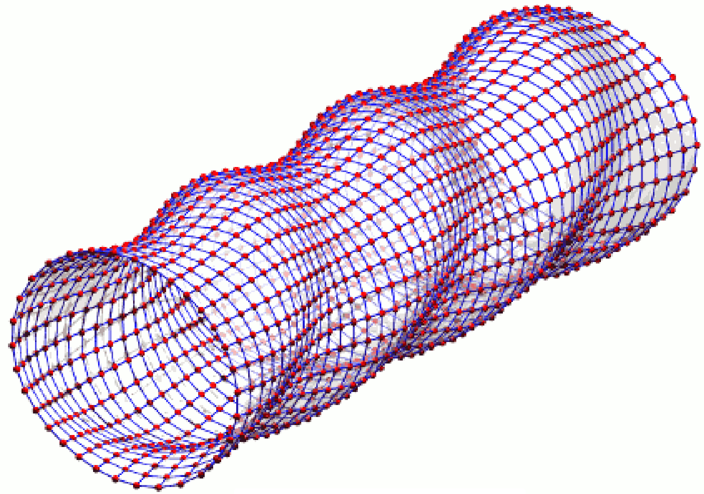
CMB Polarization





Stokes Parameters

$$I(\vec{n}) = \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle + \langle |E_{\perp}(\vec{n})|^2 \rangle$$ Scalar

$$Q(\vec{n}) = \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle - \langle |E_{\perp}(\vec{n})|^2 \rangle$$ Spin 2

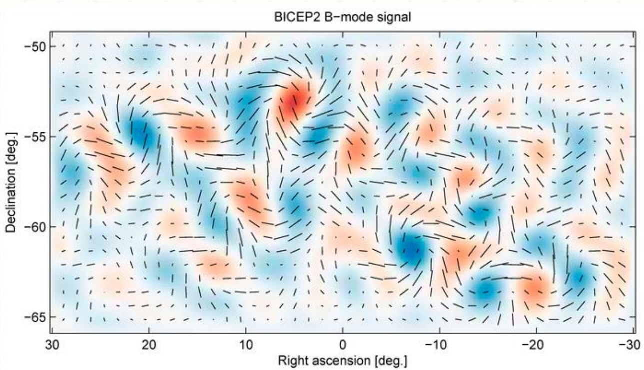
$$U(\vec{n}) = \langle E_{\parallel}(\vec{n}) E_{\perp}^*(\vec{n}) \rangle + \langle E_{\perp}(\vec{n}) E_{\parallel}^*(\vec{n}) \rangle$$ Spin 2

CMB Polarization Modes E and B

Spin-2 Spherical Harmonics expansion

$$Q(\vec{n}) + iU(\vec{n}) = \sum_{lm} a_{2,lm\ 2}Y_{lm}(\vec{n})$$

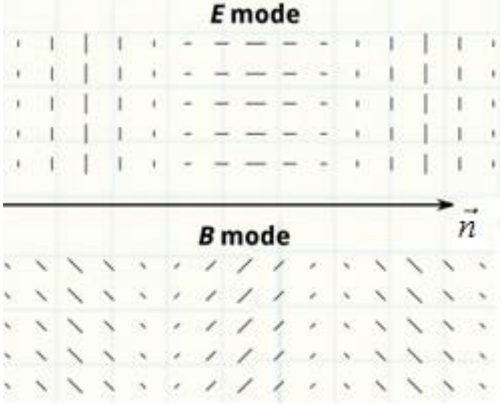
$$Q(\vec{n}) - iU(\vec{n}) = \sum_{lm} a_{2,lm\ -2}Y_{lm}(\vec{n})$$



Any polarization field can be decomposed into 2 scalar fields E and B

$$a_{E,lm} = -\frac{a_{2,lm} + a_{-2,lm}}{2} \quad \text{(even)}$$

$$a_{B,lm} = i\,\frac{a_{2,lm} - a_{-2,lm}}{2} \quad \text{(odd)}$$



$$C_l^{TT} \quad C_l^{TE}$$
$$C_l^{EE} \quad C_l^{BB}$$

CMB Polarization Modes E and B

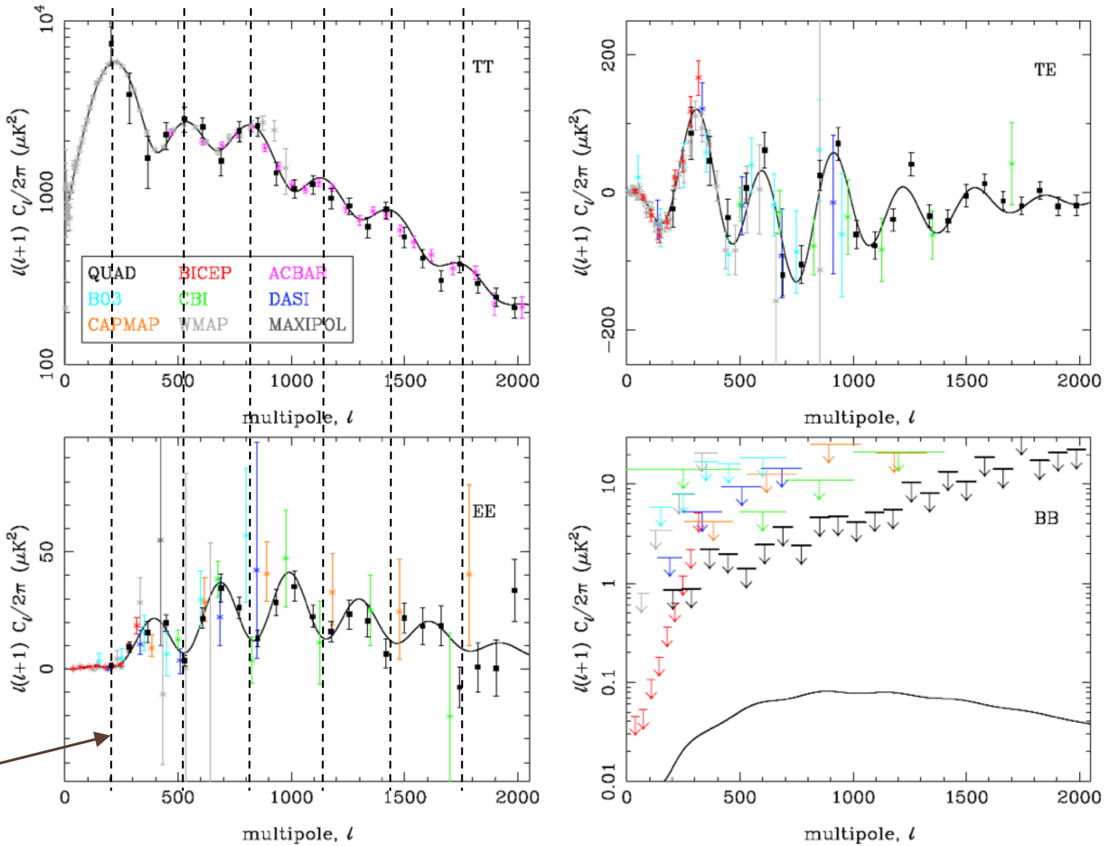
- Predicted long ago: electrons/photons scattering before decoupling

- Detection 2001: DASI and CBI (interferometers)

- Later measurements:

WMAP, QUAD, BICEP. Perfect agreement with temperature measurements.

Coincidence between TT peaks and EE troughs, Typical of adiabatic primordial fluctuations (generated by inflation for instance).



CMB Measurements Techniques

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CMB Detection Techniques

Radiometers Vs. Bolometers

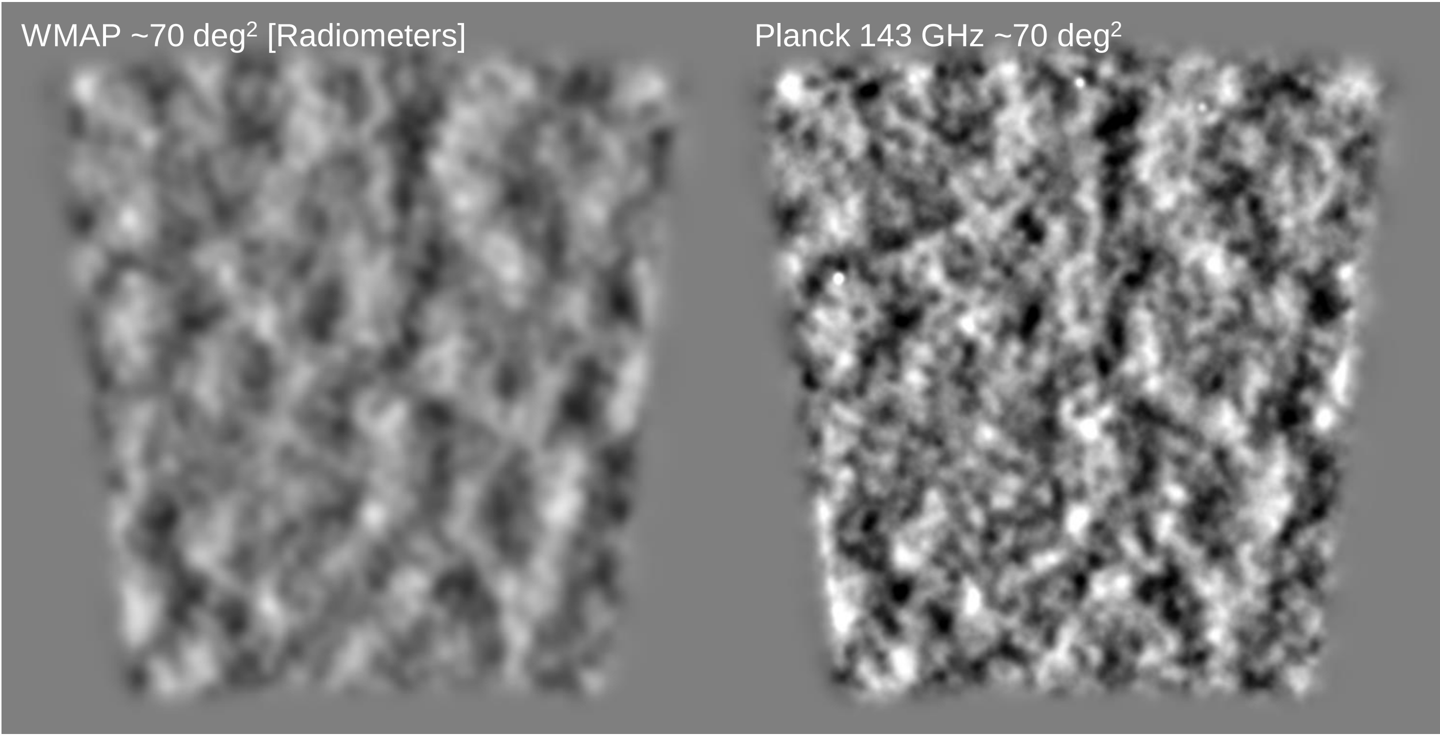
Radiometers:

- 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

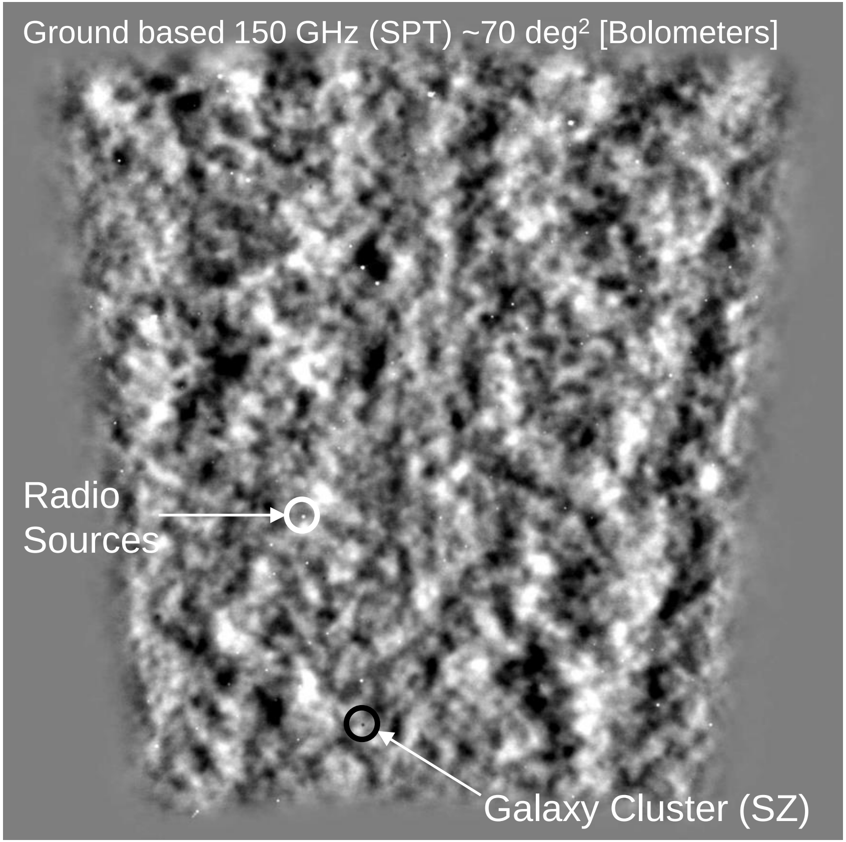
CMB Measurement Strategy

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

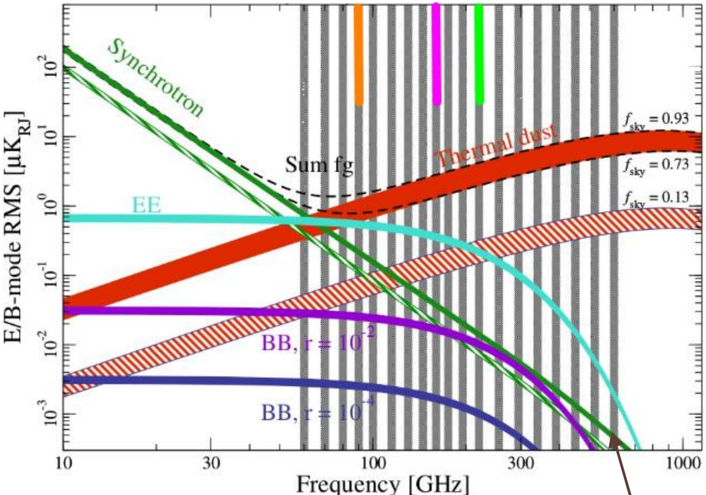
Scanning strategy is a big issue and is the subject of refined optimization

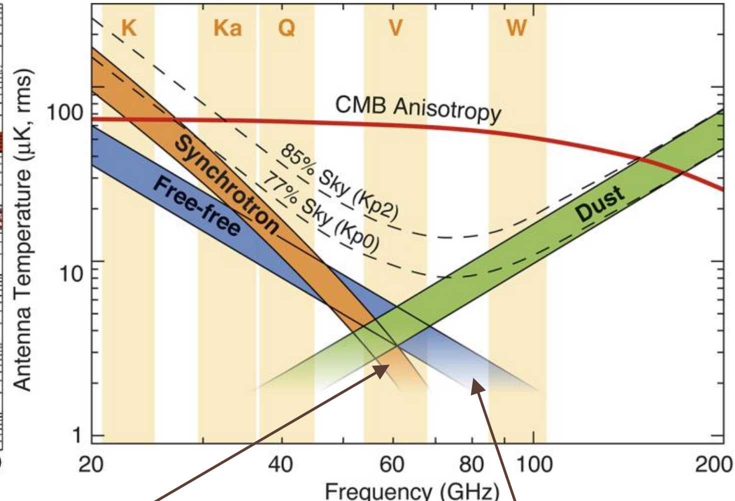
E.g. South Pole Telescope (SPT):
- 13x higher resolution and 60x deeper than WMAP

- 7x higher resolution and 9x deeper than Planck

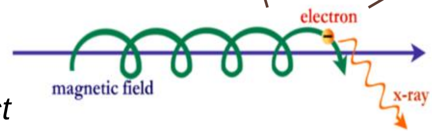


Interference Spectrum

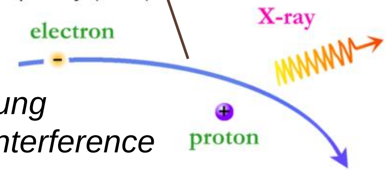




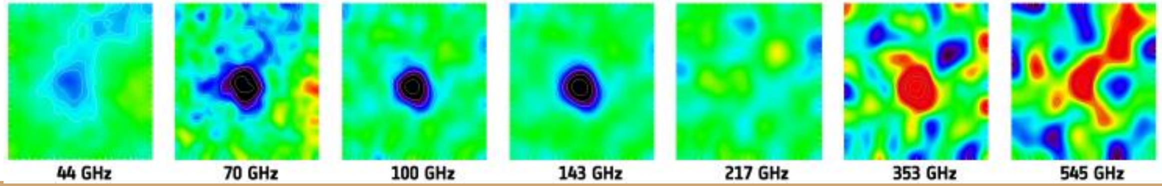
Foreground Synchrotron Interference



Foreground Bremsstrahlung (Free-free) Interference

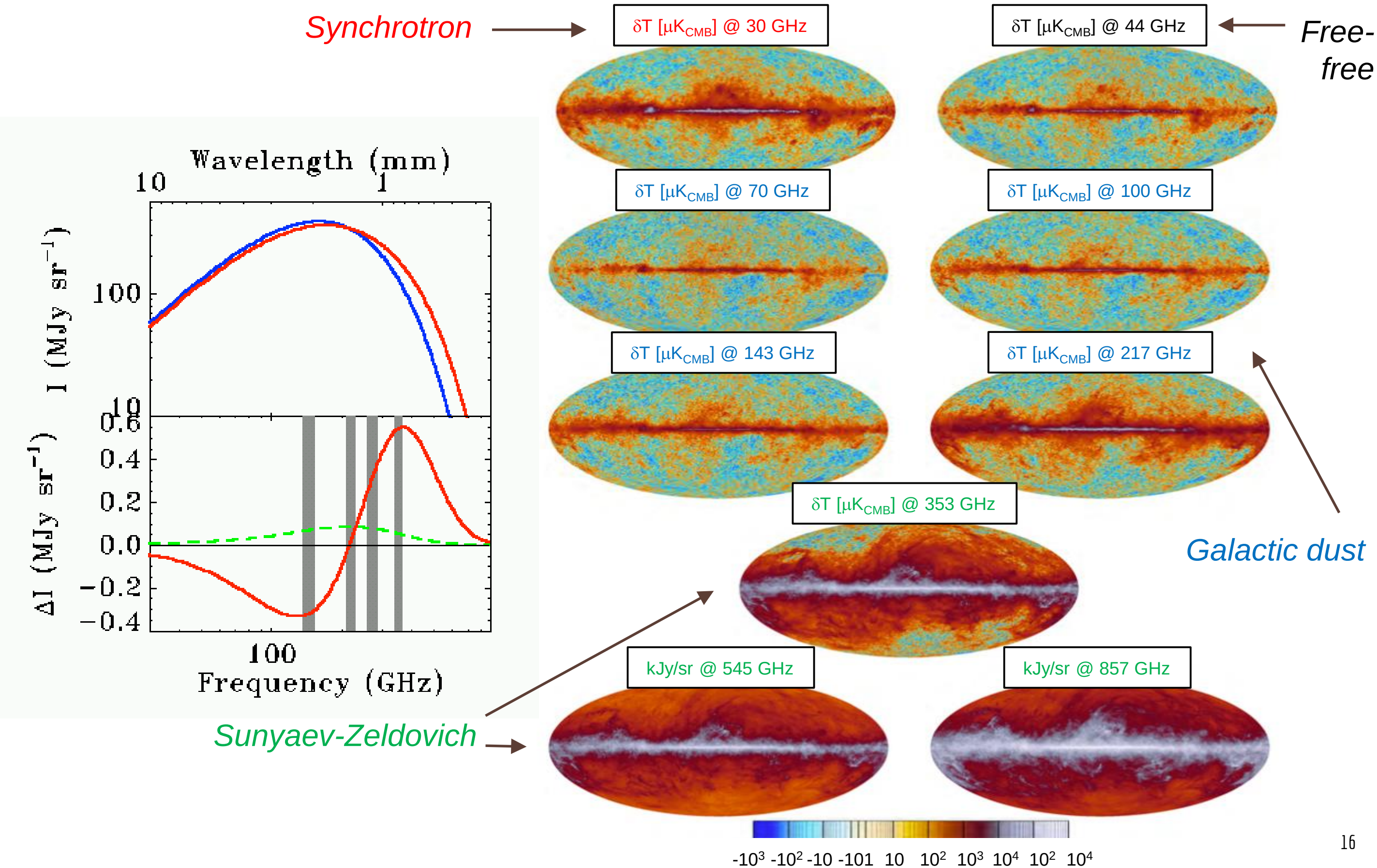


Sunyaev-Zeldovich effect



Abell 2319 with Planck

Interference Spectrum at Planck



CMB Observation Stages

		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 Bolometer

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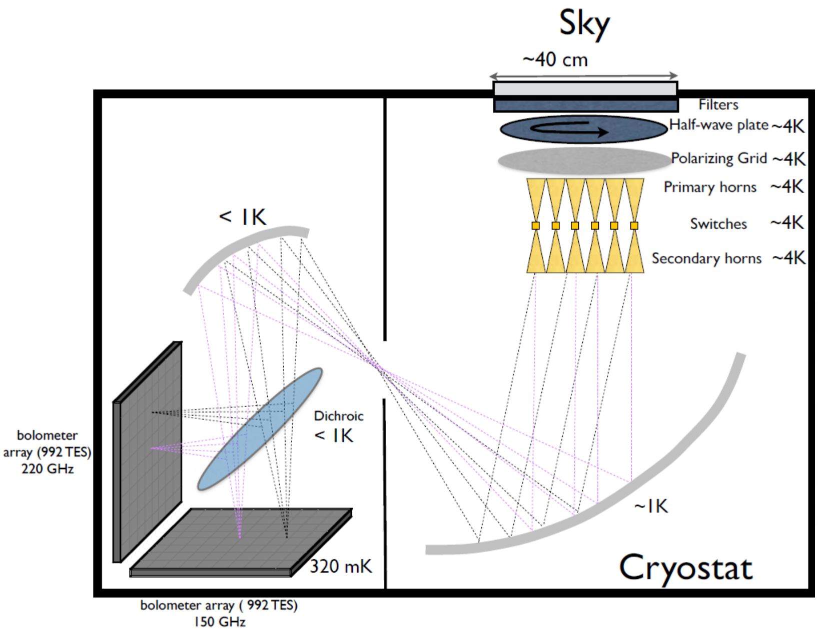
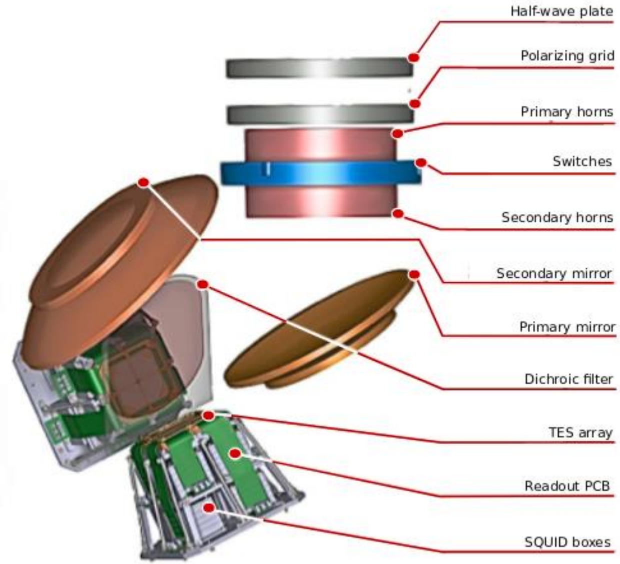
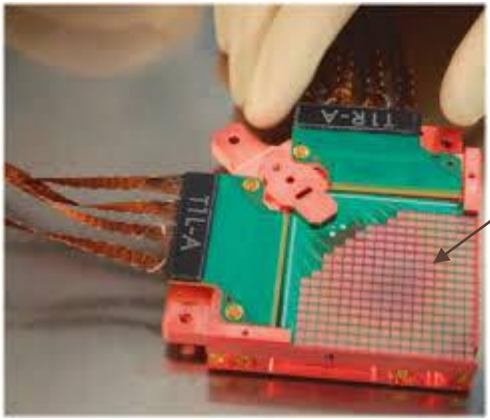
The QUBIC Telescope

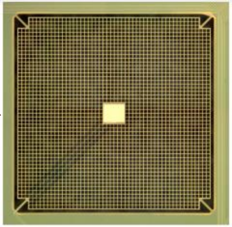


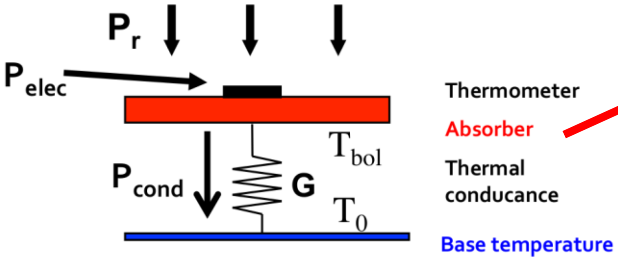


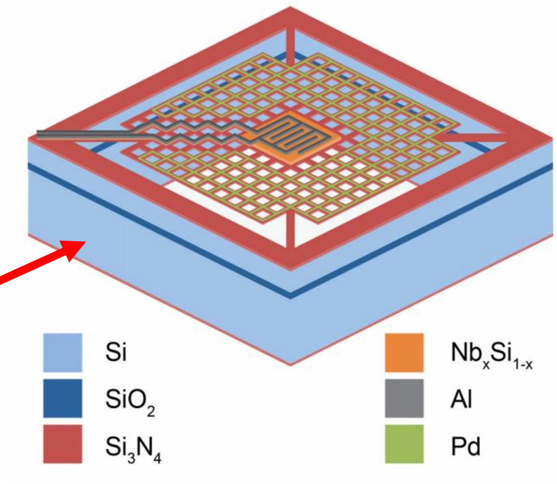
QUBIC works as a bolometer with a cryostat at the detector working at 150 GHz and 220 GHz to separate the CMB from the galactic dust. Light absorption is achieved using a Palladium metallic grid placed in a quarter wave cavity in order to optimize the absorption efficiency. A distance of 400 μm between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

QUBIC Bolometers for CMB Transition Edge Sensors (TES)





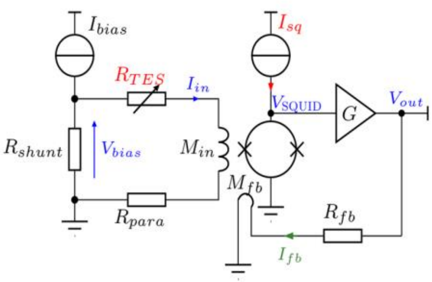


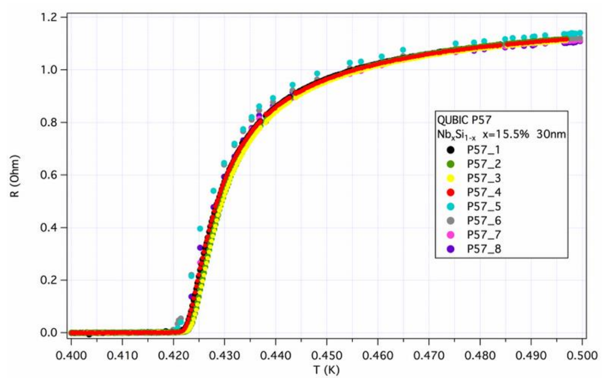


Transition Edge Sensor (TES)

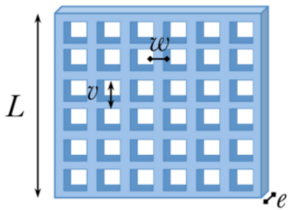
Detector stage temperature spec.	350 mºK
Detector stage temperature goal	320 mºK
Bolometers NEP	5.10^{-17}W.Hz$^{-1/2}$
Bolometers time constant	< 10 ms
Number of bolometers / focal plane	1024
Number of 256 TES wafers	4
Scientific Data sampling rate	100 Hz

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.

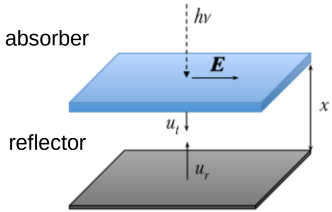


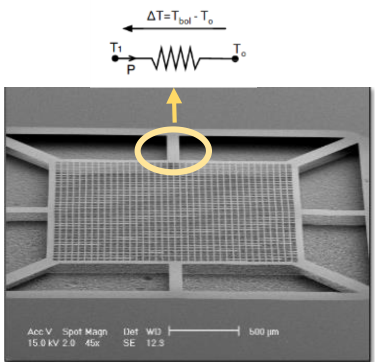


Bolometer Absorber

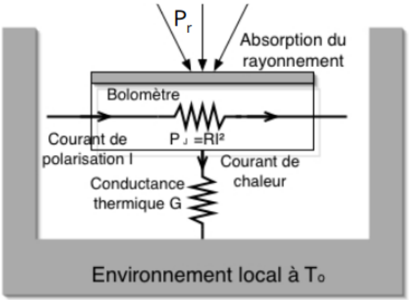


Max absorption = 100% for $R_c = Z_0$ with a reflective layer at $x=\lambda/4$





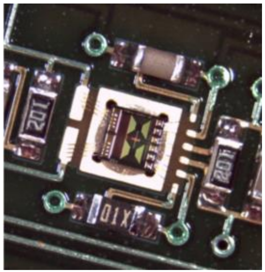
$$\left\{ \begin{aligned} \frac{\tilde{T}}{\tilde{P}_{sig}} &= \frac{1}{G_{eff}\left(1 + j\omega\tau_{eff}\right)} \\ \tau_{eff} &= \frac{C}{G_{eff}} \end{aligned} \right\}$$

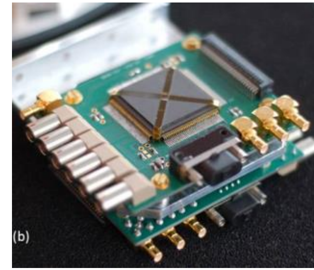


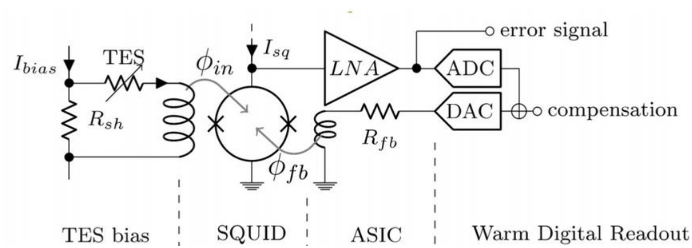
C: bolometer heat capacity [J/K]
G_{eff}: bolometer effective thermal conductance [W/K]

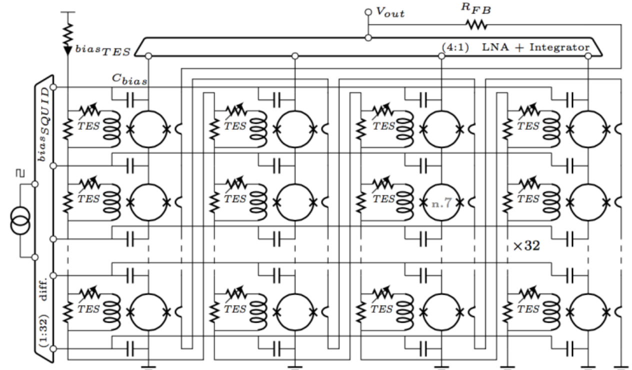
Given the expected background power of the QUBIC setup (5-50 pW in the 150-220 GHz range) an extremely low thermal coupling between the sensors and the cryostat is needed to optimize signal to noise ratio. This is obtained using 500 nm thin SiN suspended membranes, which exhibit thermal conductivities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

Mux and ReadOut 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:

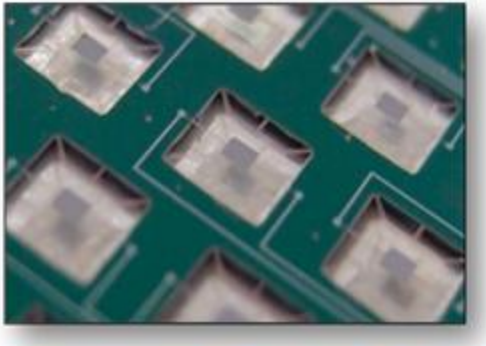
- Increase in Speed Response
- Response linearization

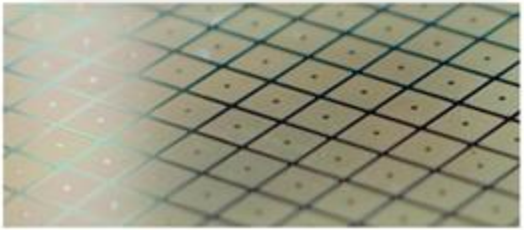
Advantages:

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

Disadvantages:

- Fabrication Complexity
- Multiplexed readout
- Very low temperatures required for the Read Out Electronics





Micromachined Sensors and Electronics for Stage 3 QUBIC

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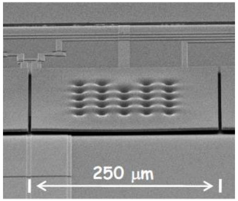
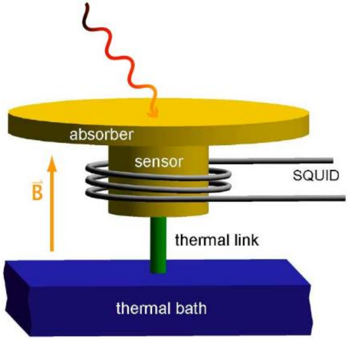
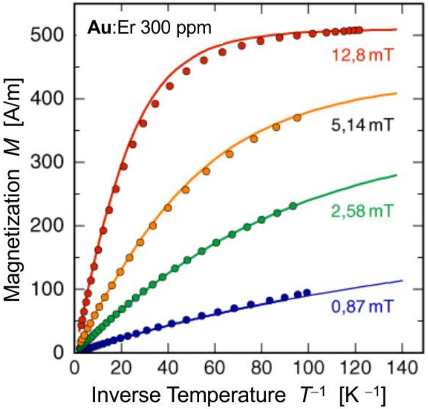
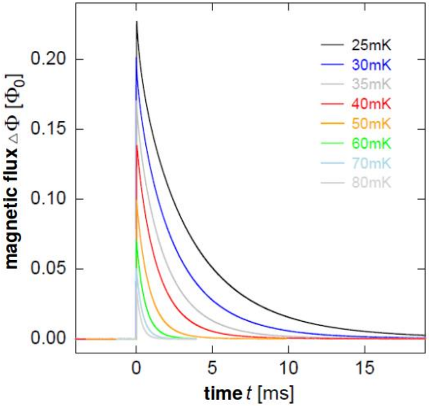
Metallic Magnetic Calorimeters (MMC) for X-Rays measurements with ECHo









MMCs work as calorimeters that change their magnetic characteristics and therefore, their resonance frequency with temperature. Therefore they require a SQUID to transform the variations in magnetic flux to variations in signal power. The transient response is very similar to the TES.

MMCs Read Out with ECHo

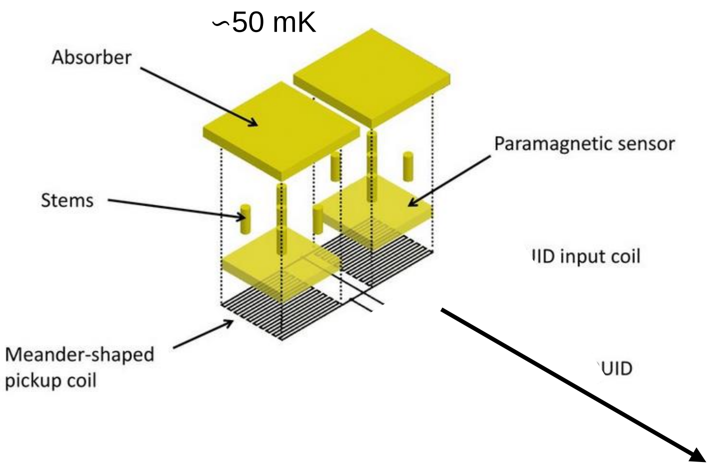
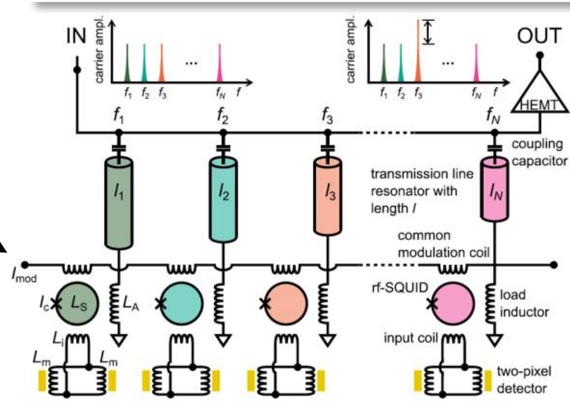
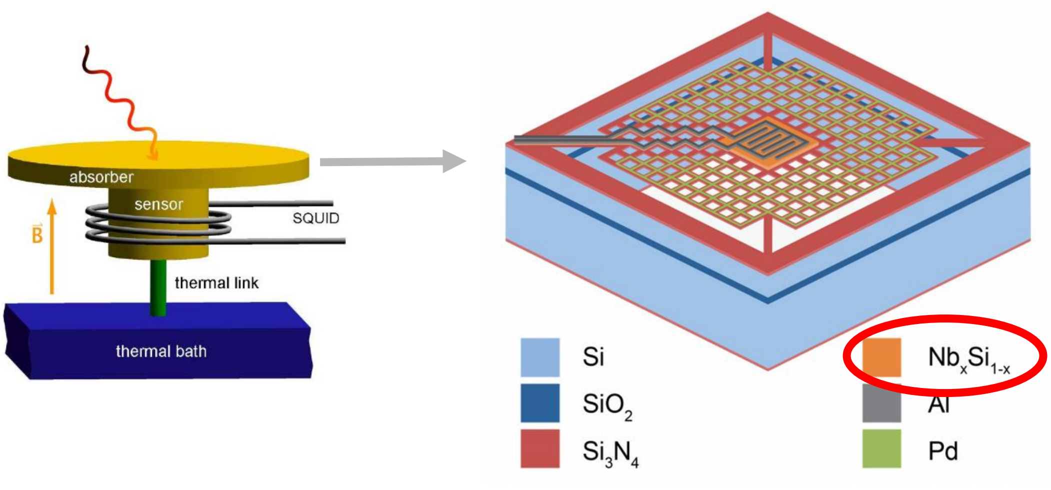


TABLE 1. Estimated Shannon Limits on readout of the Fiducial LTD (a 150 GHz polarimeter)			
	B	**Achieved (planned) MUX factor**	**Shannon Limit**
TDM	5 MHz	40	$\sim 10^4$
MHz FDM	5 MHz	8 (32)	$\sim 10^4$
GHz FDM	5 GHz	4(144) (~1000)	$\sim 10^7$
CDM	5 MHz	(256)	$\sim 10^4$
CDM + FDM	5 GHz	(65536)	$\sim 10^7$



MMCs also work a extremely low temperatures, therefore requiring a dilution cryostat. The multiplexer also work at cryogenic temperatures, but the read out system can work at room temperature.

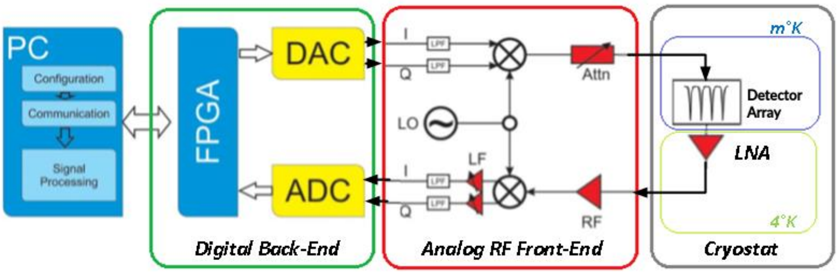
Metallic Magnetic Bolometers (MMB)



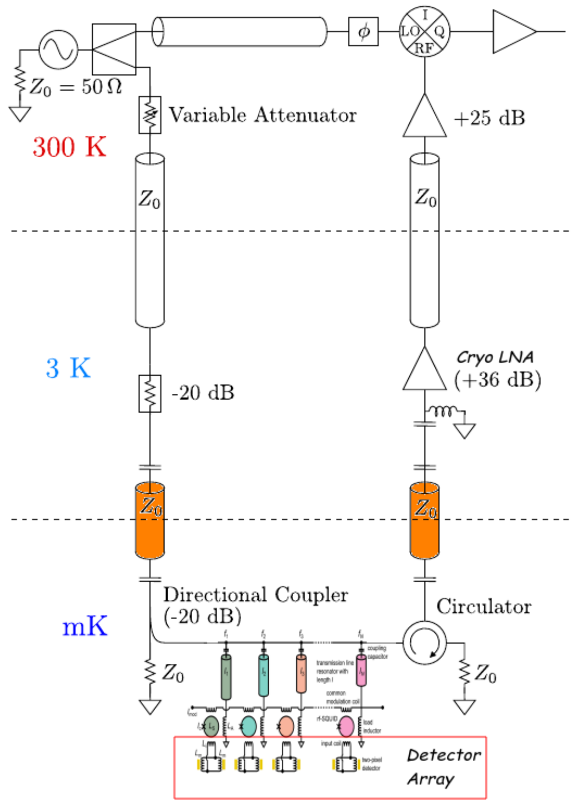
The TES are made with a Nb_xSi_{1-x} amorphous thin film. Its transition temperature and normal state resistivity can be easily adjusted to meet the QUBIC requirements for optimum performances and multiplexed read-out. The routing of the signal between the TES and the bonding pads at the edge of the 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.

QUBIC Detector electronics with MMBs



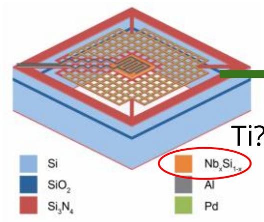
The whole Read Out Electronics for QUBIC using MMBs can increase the number of channels by a factor of 10, moving the detector into the Stage 3 category

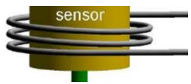


QUBIC detector electronics specifications

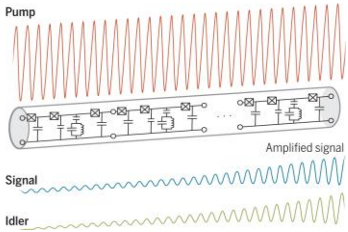
Requirement	Value	Description
Total Bandwidth	4GHz to 8GHz	Limited by the LNA bandwidth and the μSQUIDmux
Input signal power	-90dBm to -60dBm	Read-out power per pixel
Number of channels	400	Limited by the μSQUIDmux
Number of ADCs	5	80 channels per ADC
ADC SNR	> 65 dB	At least 10*log(number of tones) 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	IQ	800 MHz of complex bandwidth, limited by SNR
Number of IQ 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

Metallic Magnetic Bolometers for CMB
Complete electronics layout design

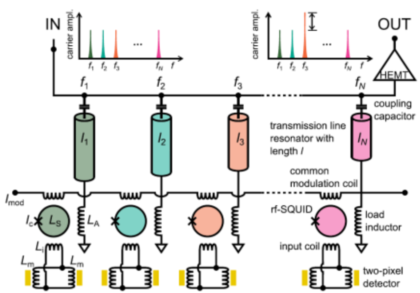


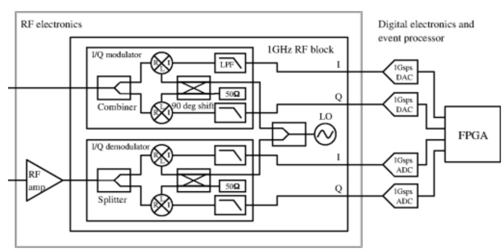


Thermometer:
Metallic
Magnetic



Absorber (ITeDA)	Thermometer (Heidelberg-ITeDA)	SQUID Multiplexer (Heidelberg)	LNA (TWPA) (KIT-ITeDA)	RF FrontEnd (KIT-ITeDA)	Digital BackEnd (KIT-ITeDA)





MMBs Summary

MMB characteristics:

- Fast response
- High sensitivity
- Requires a SQUID

Advantages:

- Easier Read Out
- Well tested (ECHo @ KIT)
- Technology readiness available in Germany (Heidelberg)

Disadvantages:

- Fabrication complexity (less than TES though)
- Very low temperatures required but only for the LNA