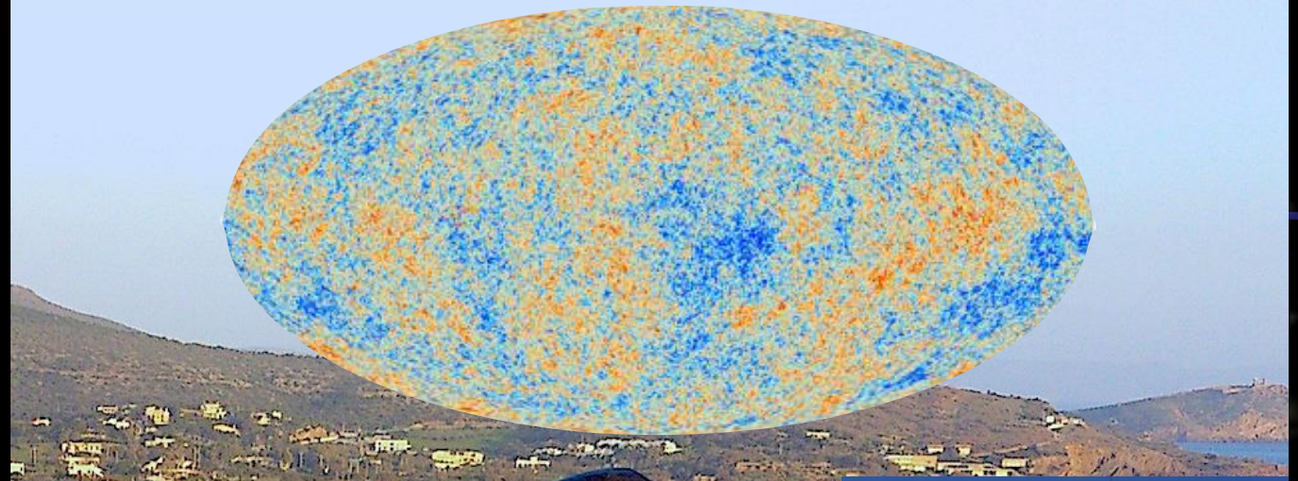


*Polar Bear*

# Cosmological inflation and the QUBIC mm-telescope

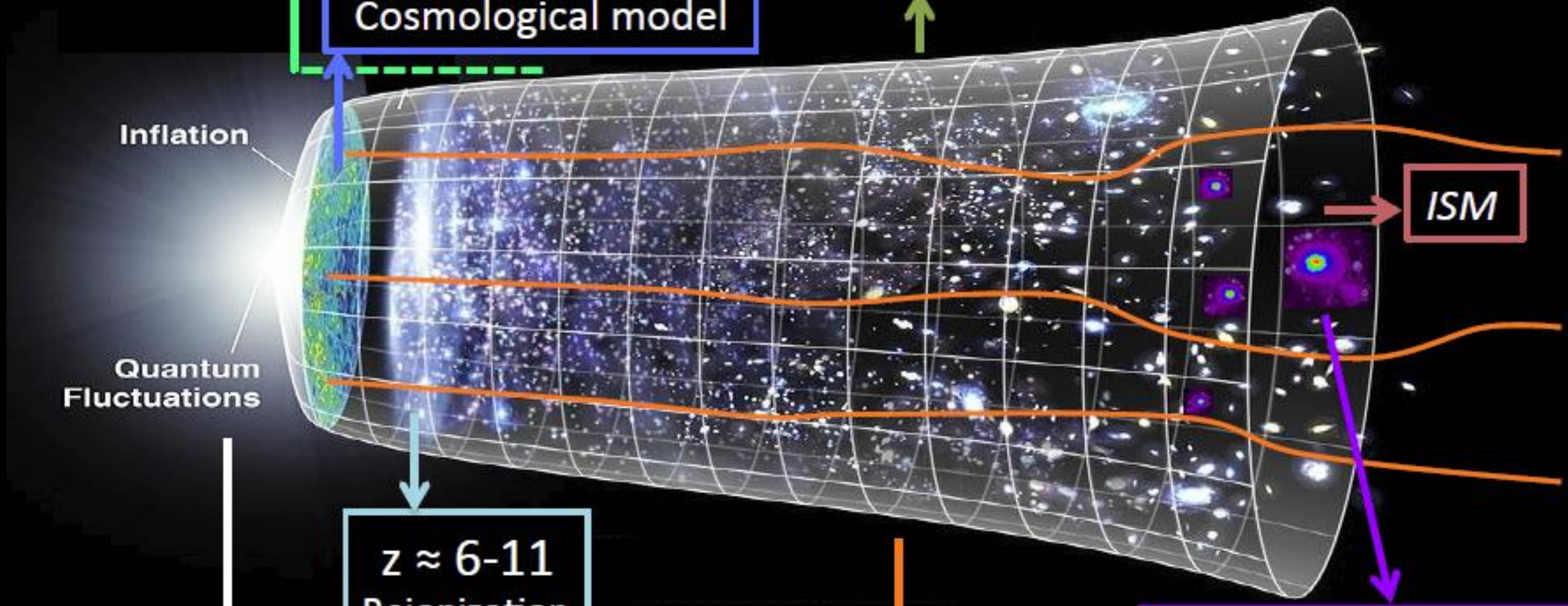
**S. Loucatos**
**APC Paris and**
**Irfu CEA-Saclay**

***2017***

$z < 2 \times 10^6$
Thermal history
(energy injection into the CMB)

CMB T,E (B)
Cosmological model

*CIB, cosmological astrophysics*



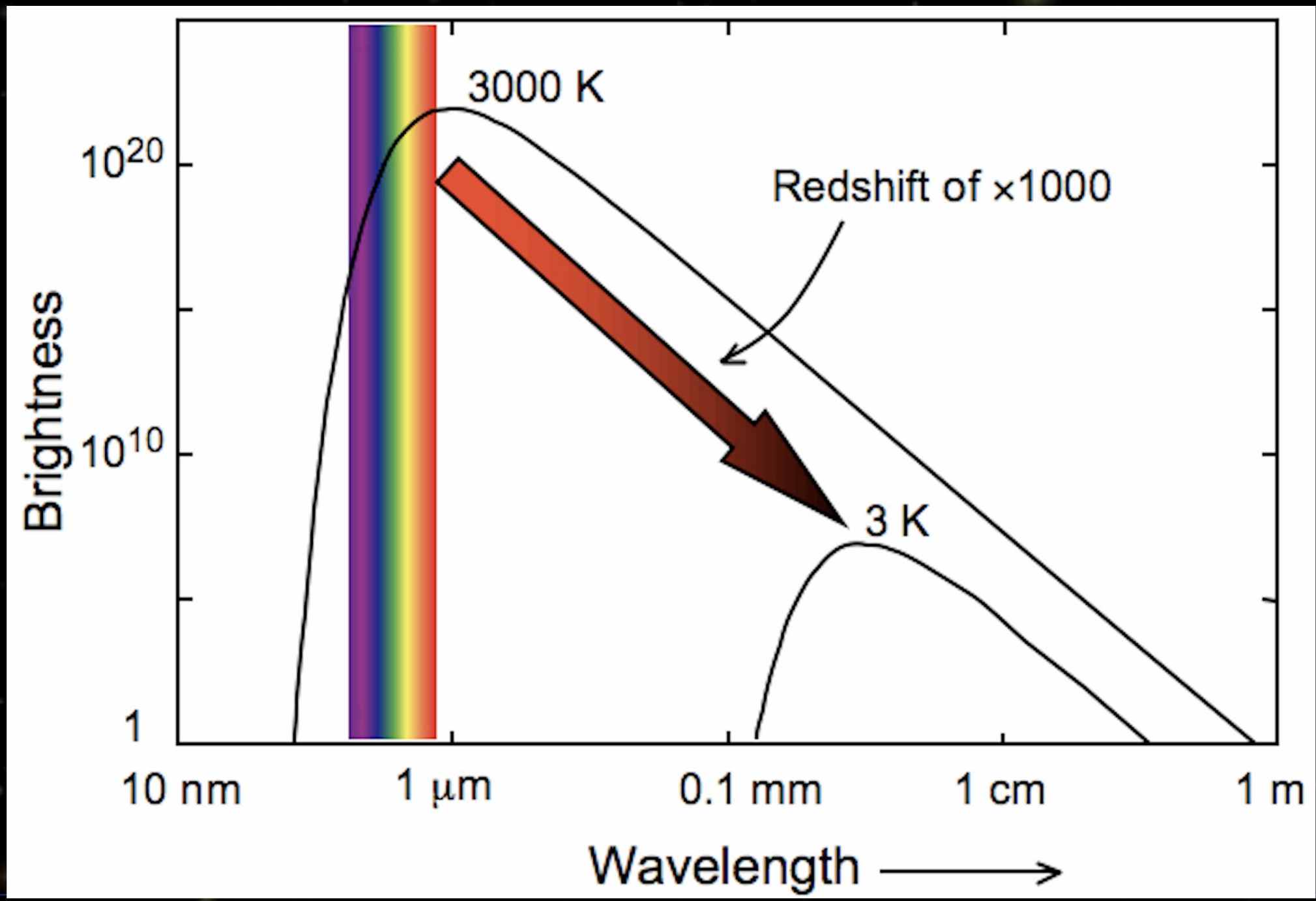

Inflation
Physics at ≈ $10^{16}$ GeV
$E > 10^{12} \times E_{LHC}$

$z \approx 6\text{-}11$
Reionization

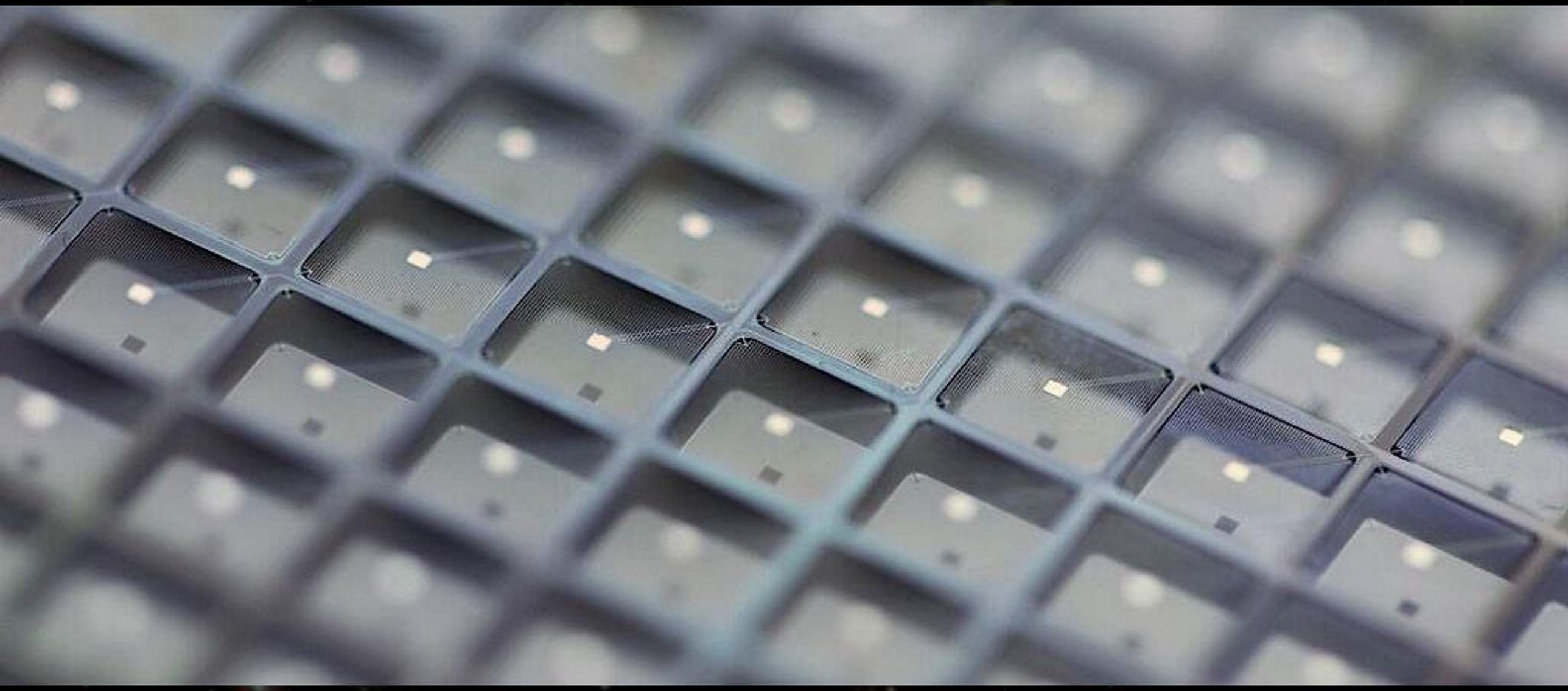
$z \approx 1\text{-}3$
Gravitational lensing
Dark matter distribution

$z \approx 0\text{-}2$
Sunyaev-Zeldovich effect:
Distribution of the hot gas and velocity field

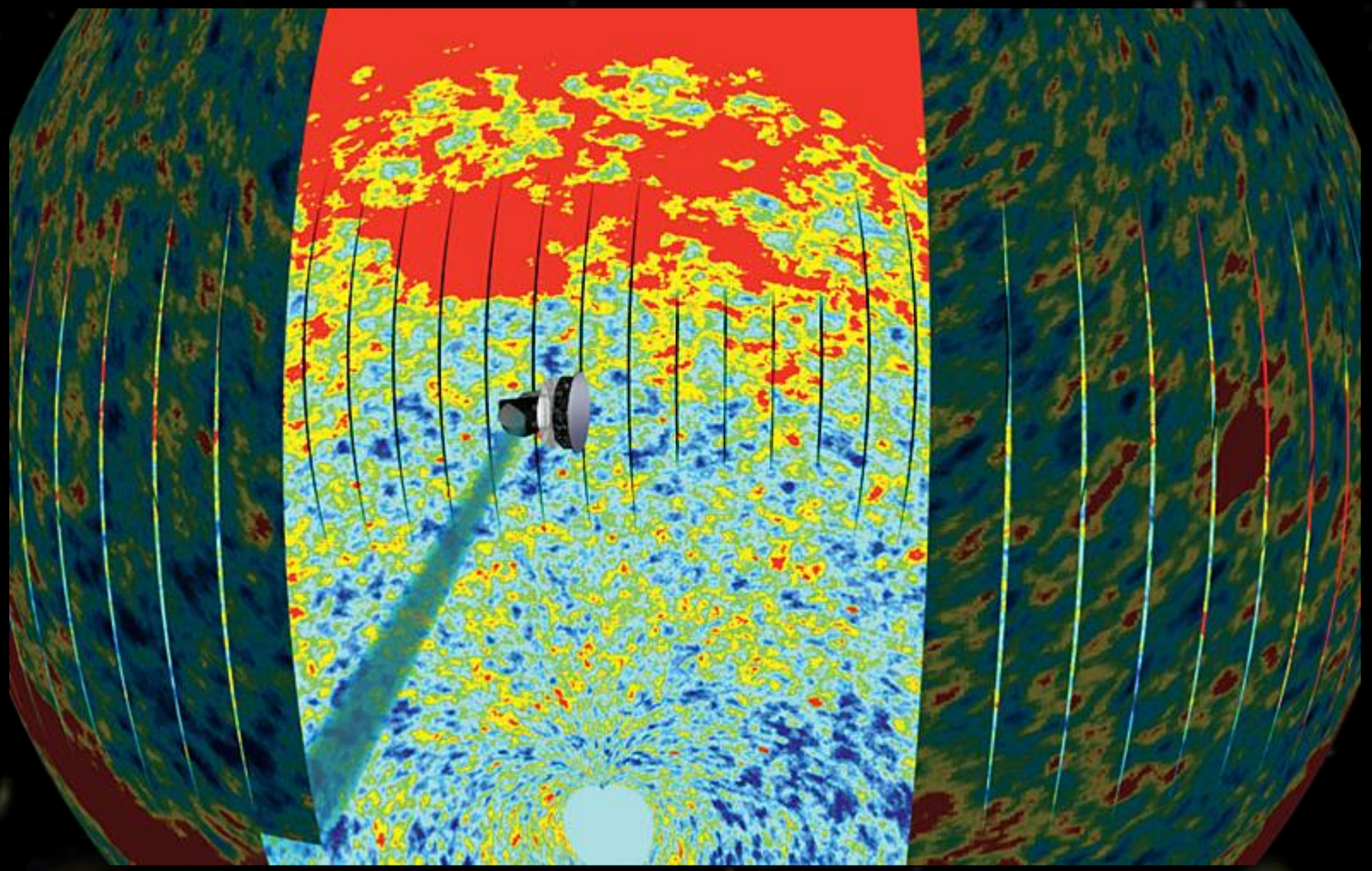
Radiation emitted at 3000K → cooled by universe expansion to 2.77 K



Environmet of the detectors < $T_{CMB}$
Thermometers (bolometers) cooled at 100 -300 mK
→ minimize the thermal noise (phonons)

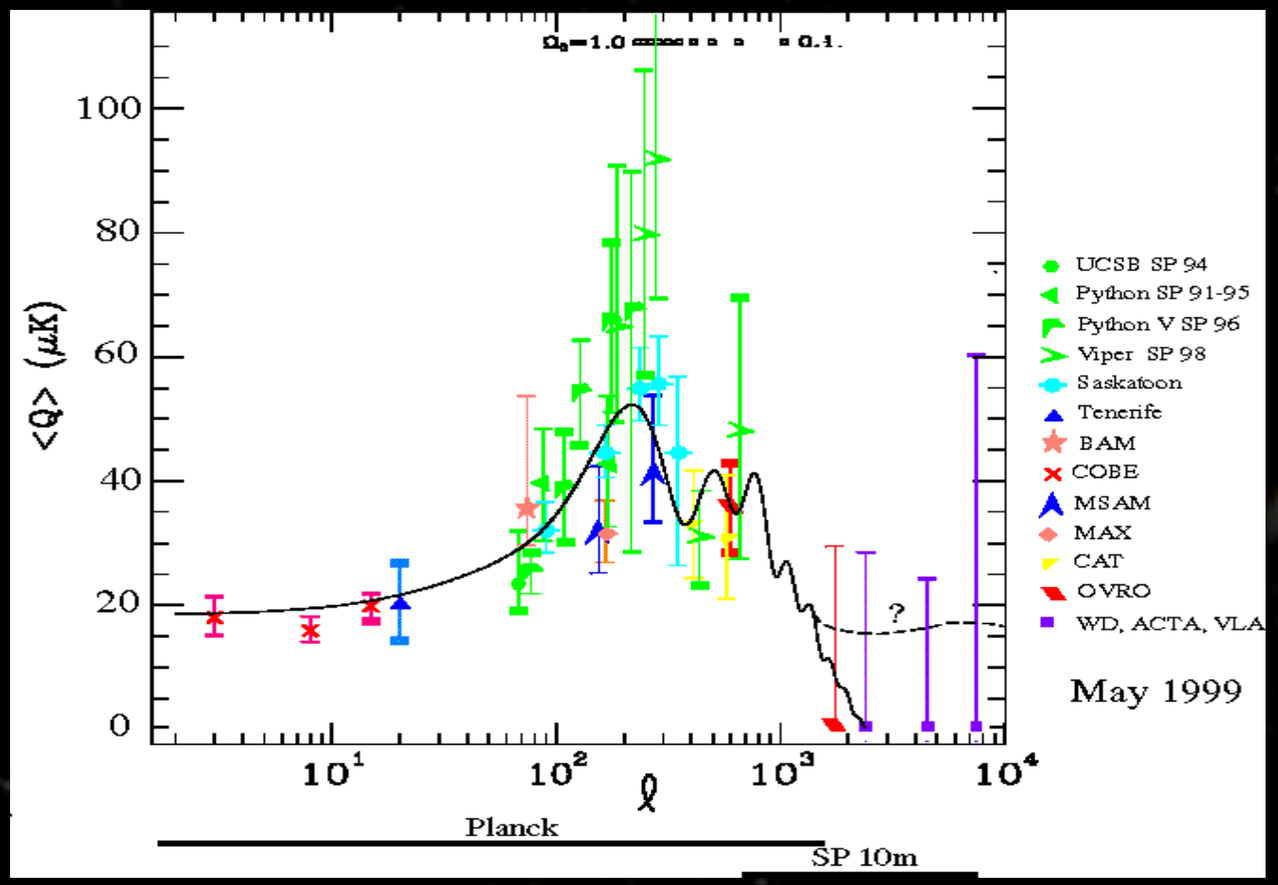


# Many pixels = imager

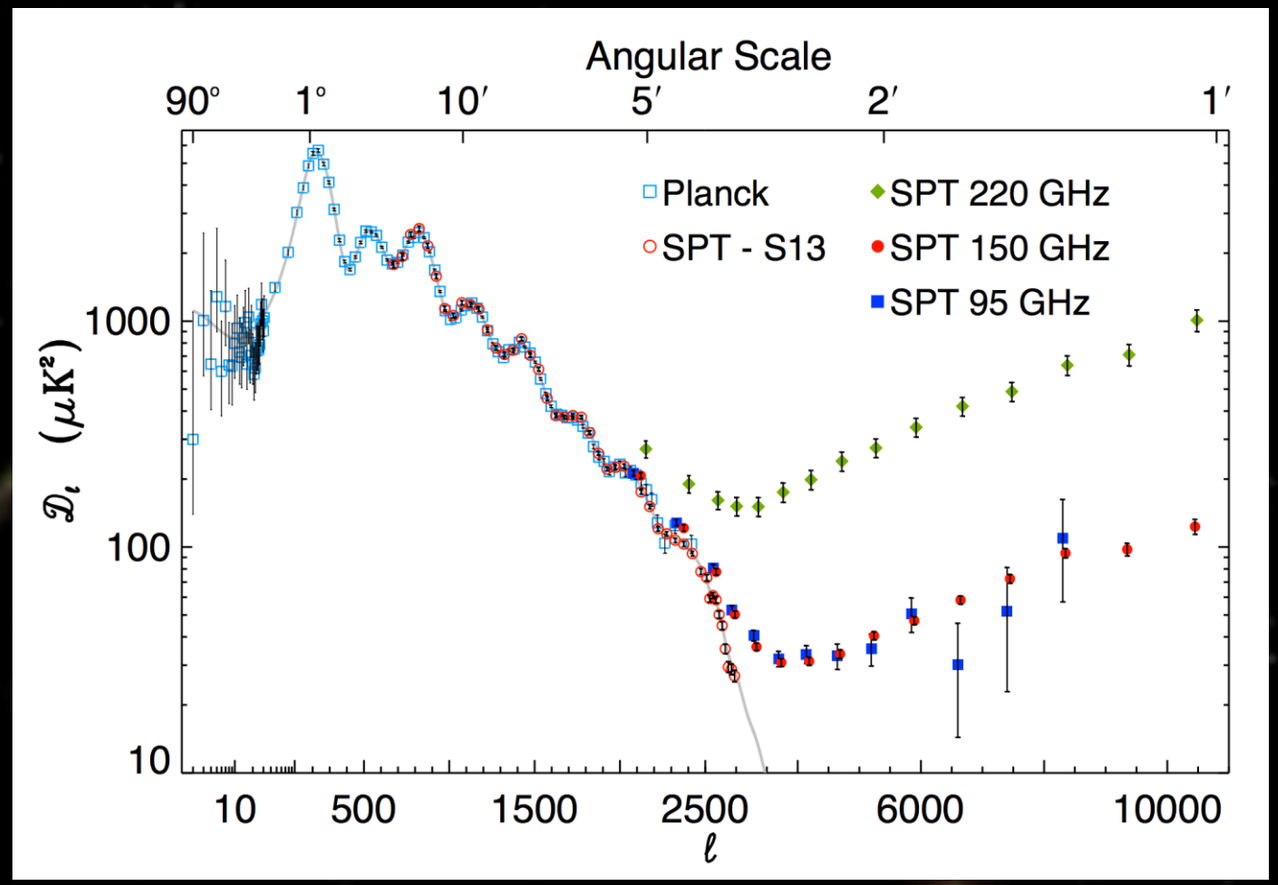


Planck sky scan

# CMB: Tremendous progress over the last 15 years




1999

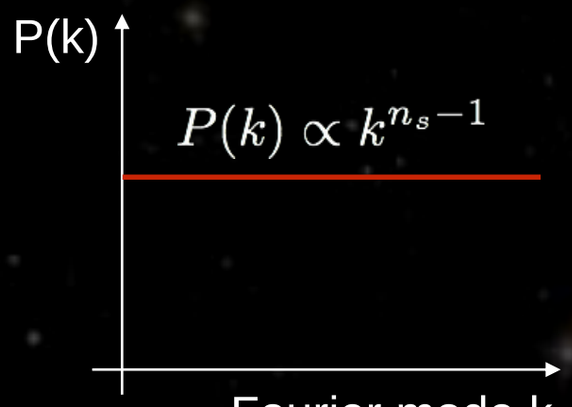


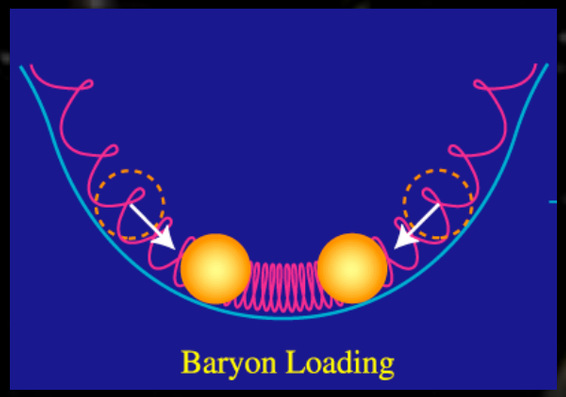

2016

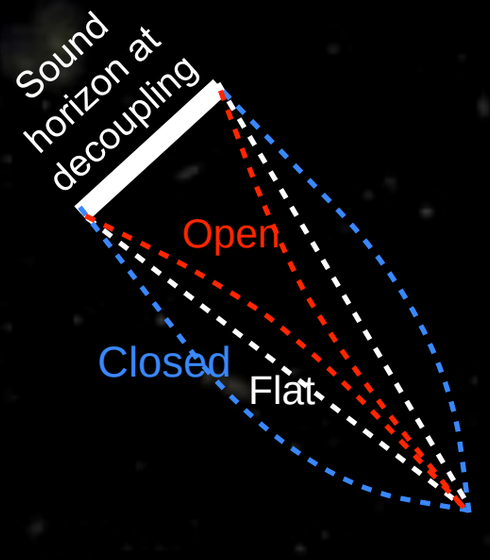
Huge success : thousands of independent points fitted with less than 10 parameters and a $\chi^2$/ndf about 1
Theoretical curve predicted in 1987 [Bond & Efstathiou] without any data. [Also by Zeldovitch, Sunyaev et al. in 1972 !!!]

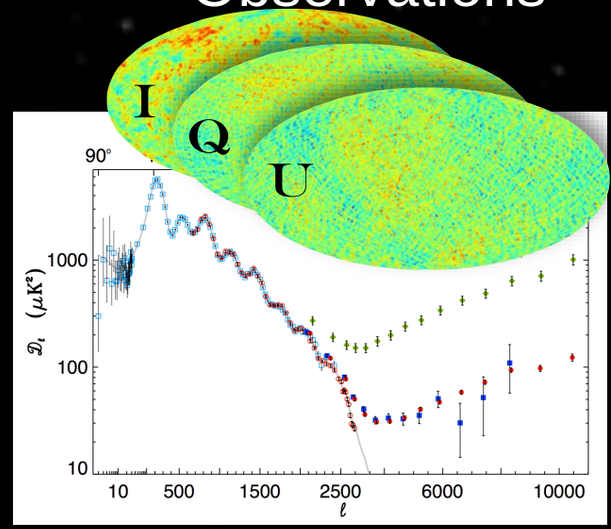
# Density Field Transfer Function

Early Universe Primordial Density Fluctuations → Acoustic Oscillations → Geometry → CMB Observations

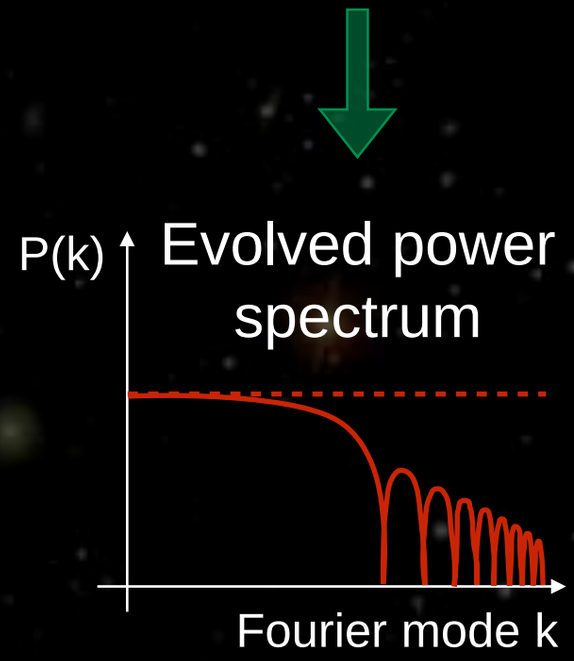


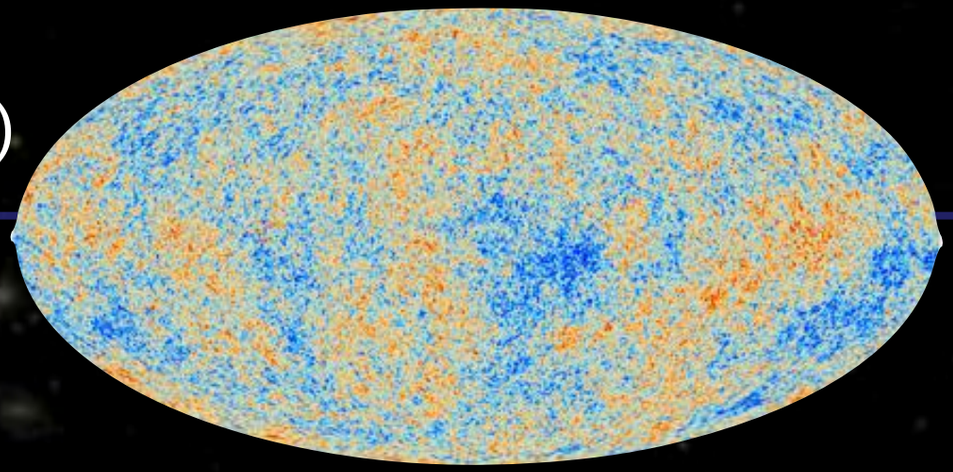



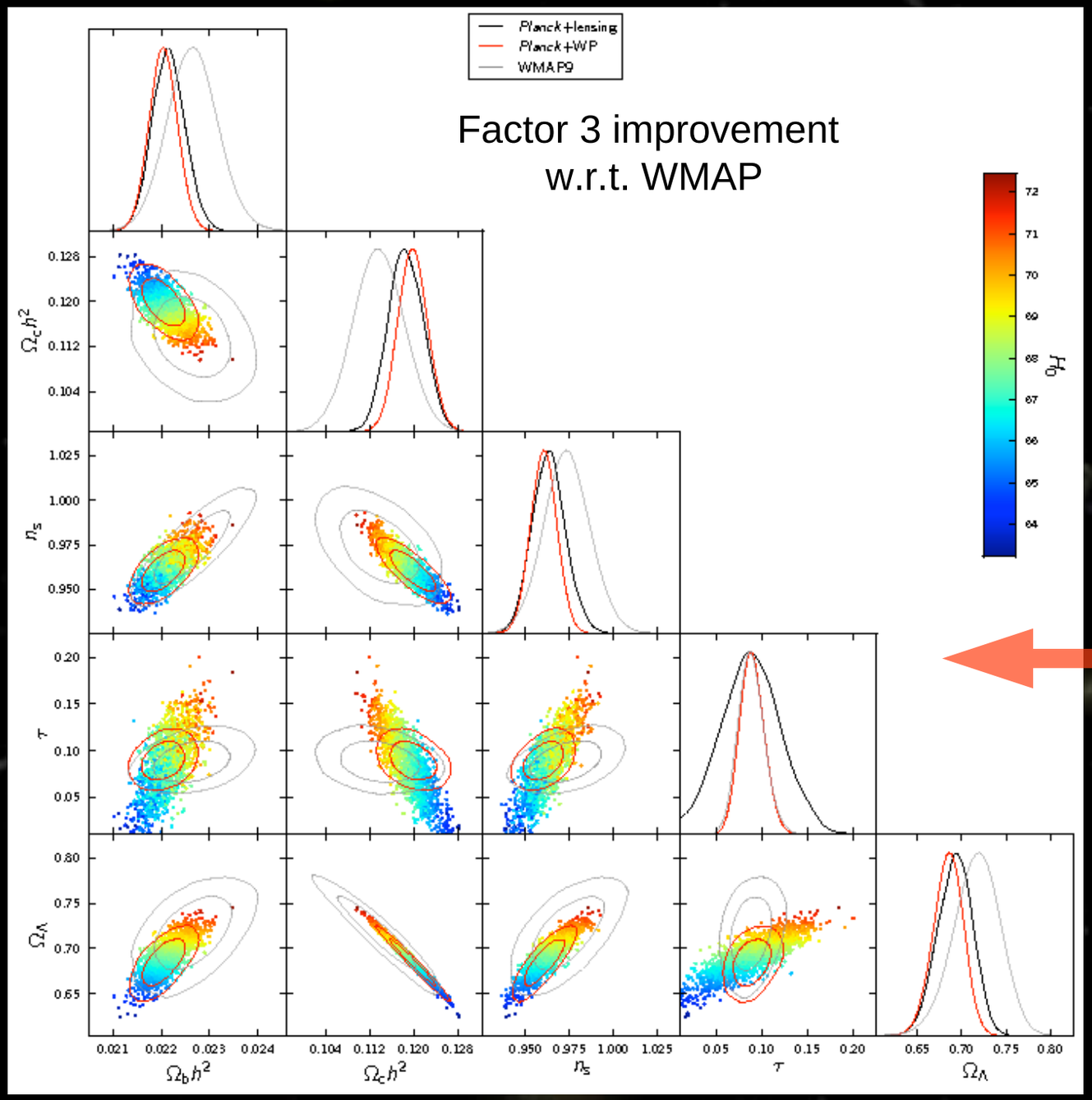

- Perturbations evolve from end of inflation to decoupling due to matter-radiation oscillations.
- The transfer function depends upon « simple physics » and cosmological parameters
- Allows to fit both cosmology and primordial spectra (including inflationary physics)

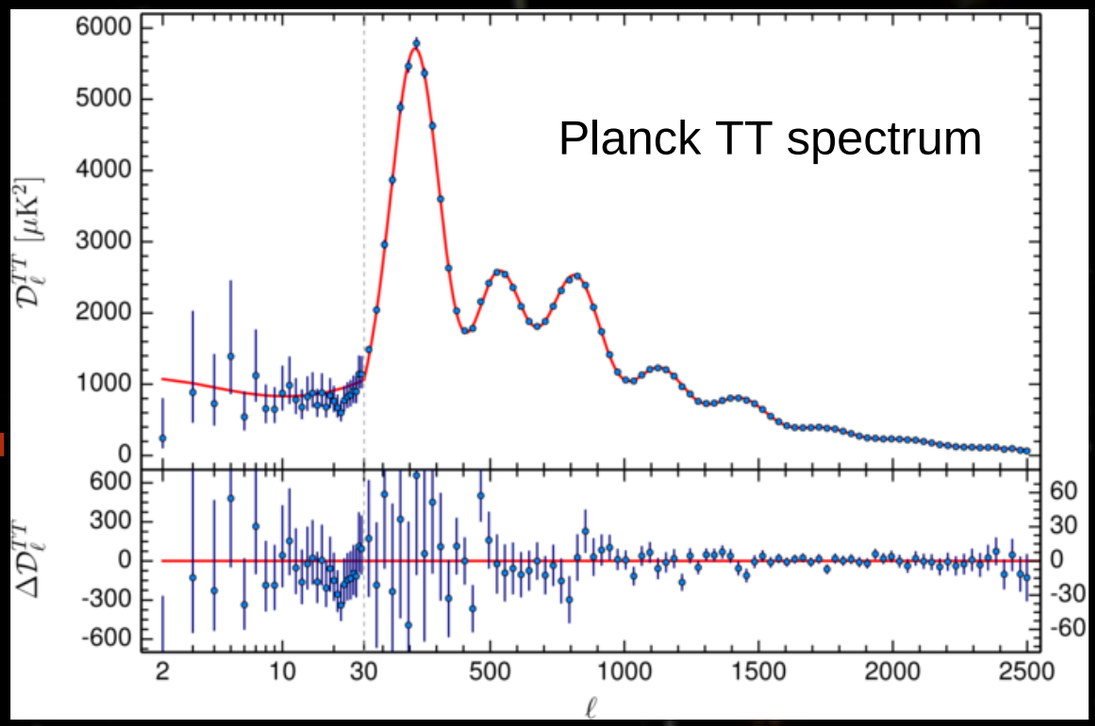


# Planck Results: ΛCDM firmly Established

Planck
(ESA Mission)



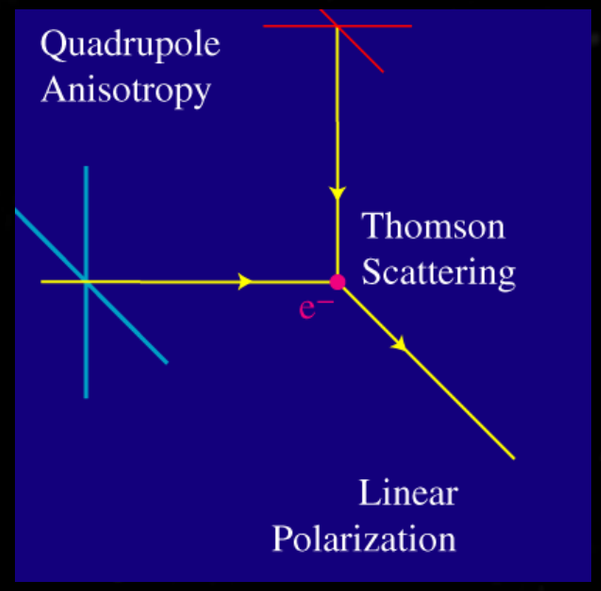



## Current step: Inflation Physics through CMB Polarization

# CMB Polarization (~10%)

- Generated by Thomson scattering
  - ★ electrons in quadrupolar motion falling into Dark Matter potential wells before decoupling




W. Hu

- Stokes Parameters (linear pol.)

$$I = \left\langle |E_x|^2 \right\rangle + \left\langle |E_y|^2 \right\rangle$$

$$Q = \left\langle |E_x|^2 \right\rangle - \left\langle |E_y|^2 \right\rangle$$

$$U = 2\left\langle \mathrm{Re}[E_x E_y^\star] \right\rangle$$

- Scalar E and B fields

$$a_{E,\ell m} = -\frac{a_{2,\ell m} + a_{-2,\ell m}}{2}$$

$$a_{B,\ell m} = i\frac{a_{2,\ell m} - a_{-2,\ell m}}{2}$$

(even) E-modes

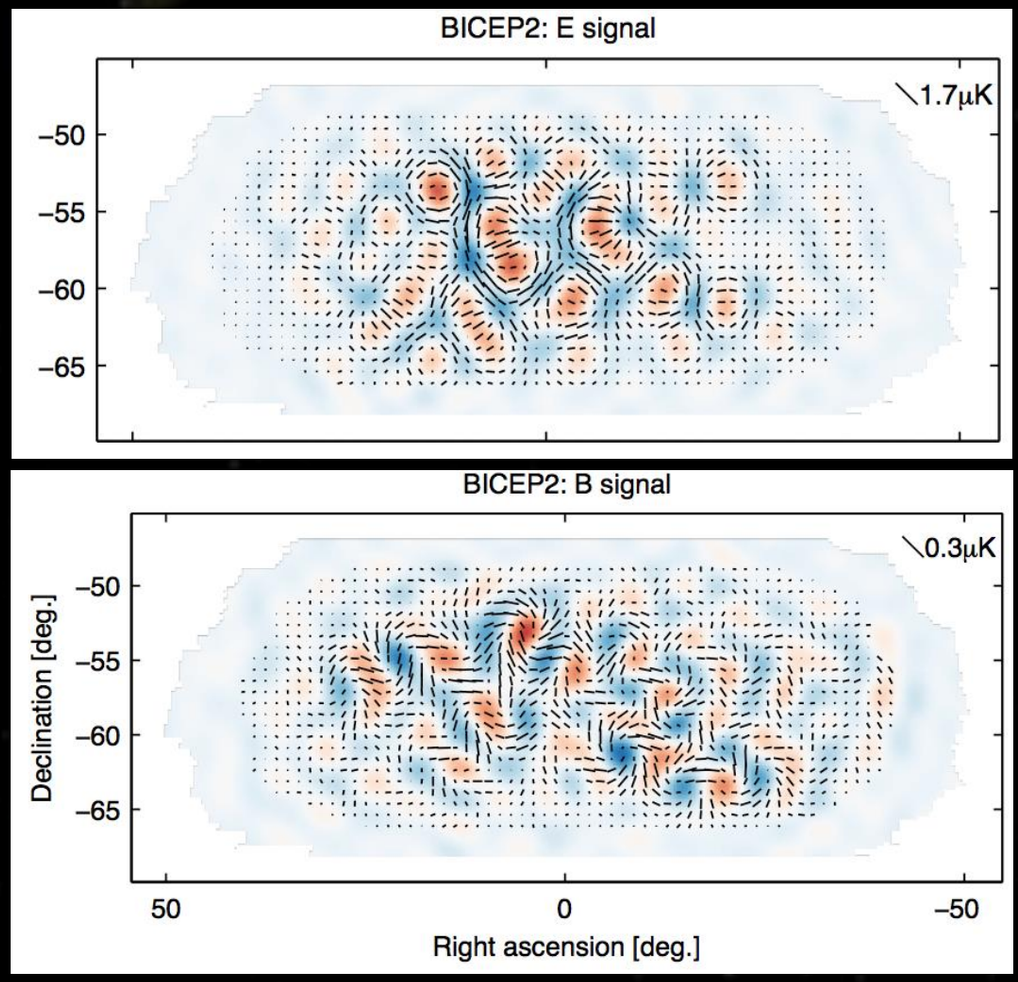
(odd) B-modes

$$\left.\begin{matrix} C_\ell^{TT} & C_\ell^{TE} \\ C_\ell^{EE} & C_\ell^{BB} \end{matrix}\right\}$$

# Scalar and tensor modes - E & B polarization

- Scalar perturbations: $P_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$
  - Density fluctuations
    - Temperature
    - E polarization
    - No B polarization

- Tensor perturbations: $P_t(k) = A_t \left(\frac{k}{k_0}\right)^{n_t}$
  - Specific prediction from inflation!
  - = Primordial gravitational waves
    - Temperature
    - E polarization
    - B Polarization



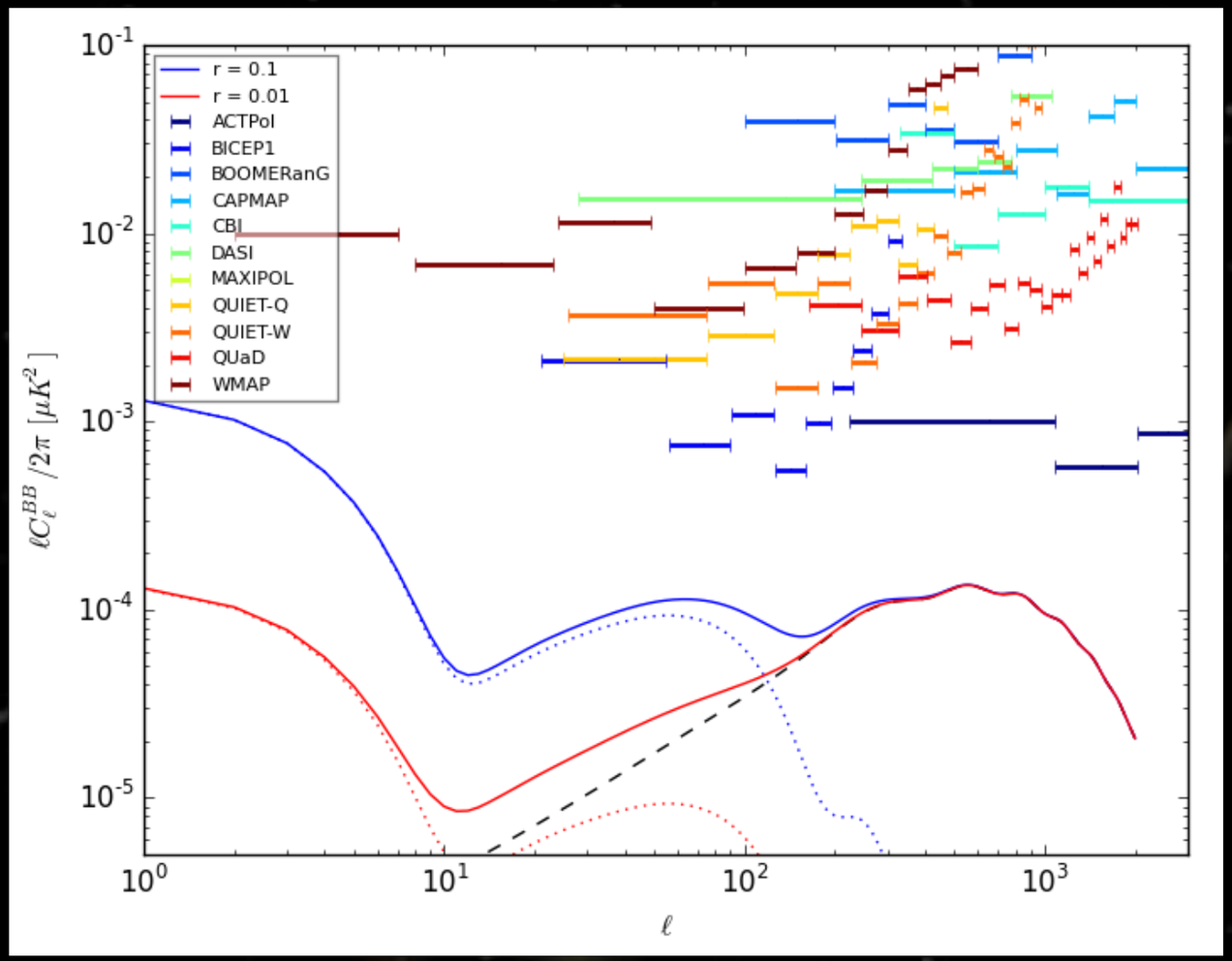

⇒ detecting primordial B-modes: $r = \frac{P_t(k_0)}{P_s(k_0)}$ *~ ratio between E and B modes*

- Direct detection of tensor modes
- «smoking gun» for inflation
- Measurement of its energy scale $V^{1/4} = 1.06 \times 10^{16} \mathrm{GeV} \left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/4}$

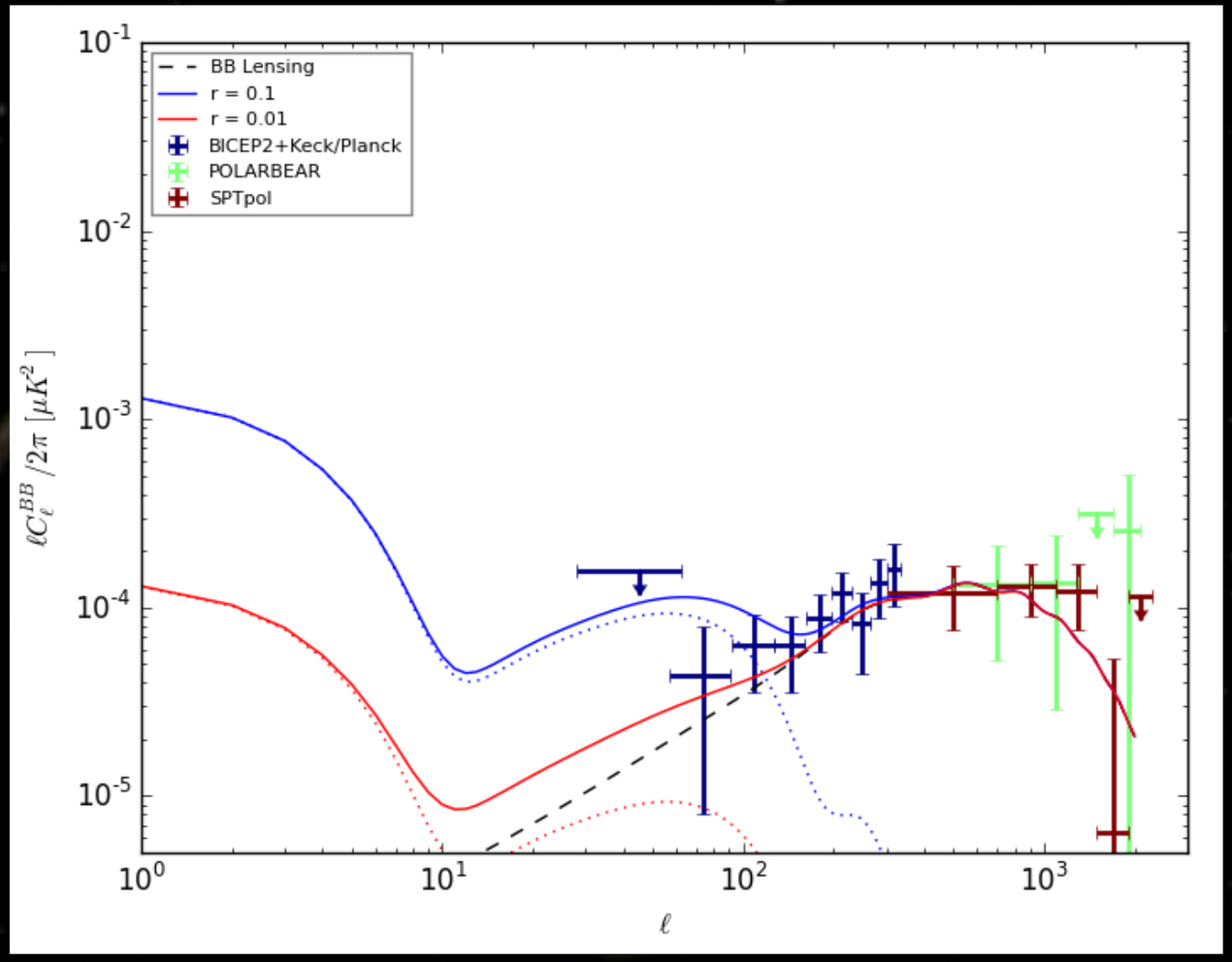
# New landscape for B-modes

## We have entered into the measurement era

Before




Today




Detected signal is Dust + Lensing [Planck+BICEP2]

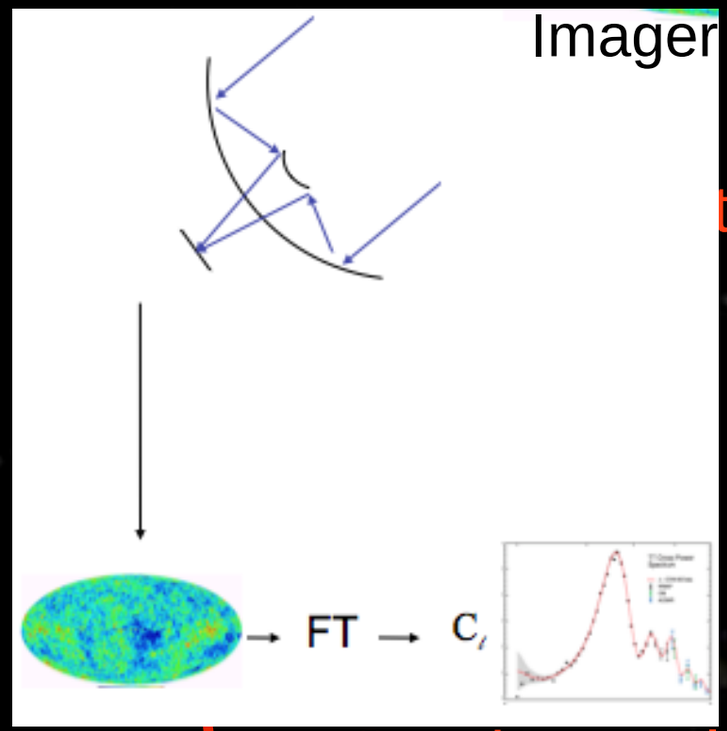
Let’s go deeper & cleaner !

# Possible instruments

- **Imagers with bolometers:**
  - ★ No doubt they are nice detectors for CMB:
    - wide band
    - low noise
  - ★ Diffraction on external optical elements, ground pickup, Polarization, … may be an issue
- **Interferometers:**
  - ★ Long history in CMB
    - CMB anisotropies in the late 90s (CAT: 1st detection of subdegrees anisotropies, VSA)
    - CMB polarization 1st detection (DASI, CBI)
  - ★ Clean systematics:
    - No telescope (lower ground-pickup & cross-polarization)
    - Angular resolution set by receivers geometry (well known)
  - ★ Technology used so far
    - Antennas + HEMTs : higher noise
    - Correlators : hard to scale to large #channels
- **Can these two devices be combined ?**
  **→ Bolometric Interferometry**

P. Timbie

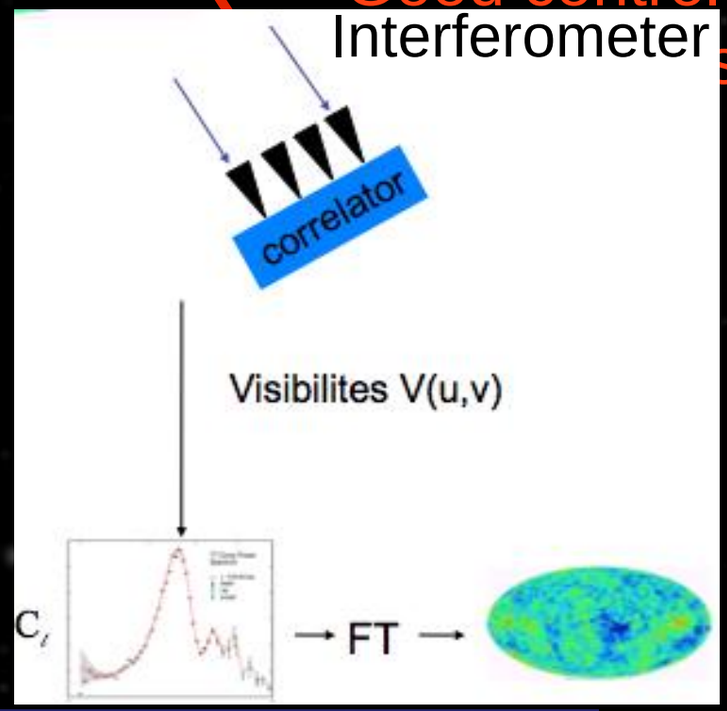
Imager




ty

Good control

Interferometer




s

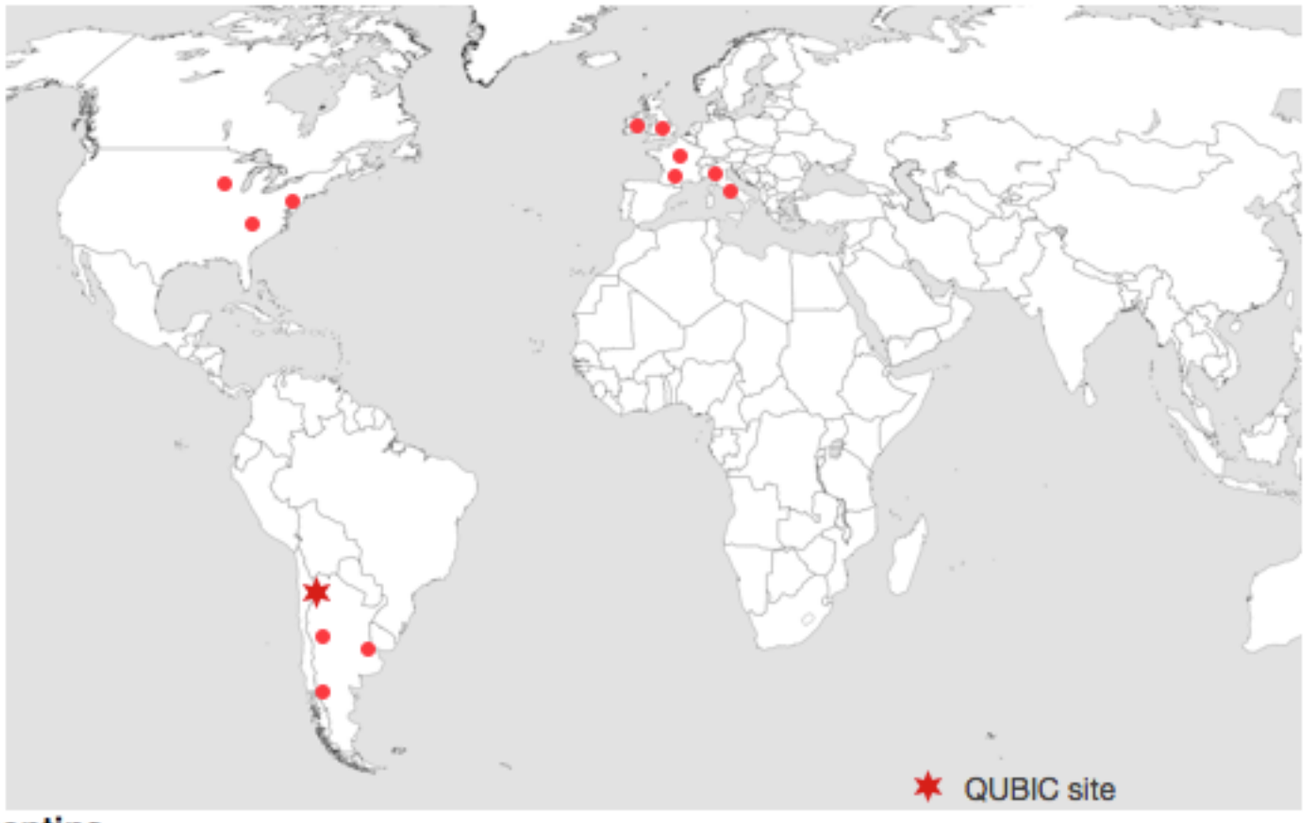
# QUBIC Collaboration

a Q&U Bolometric Interferometer for Cosmology

More than 130 members

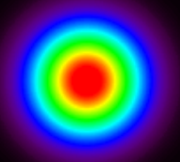
6 countries
22 labs

**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**



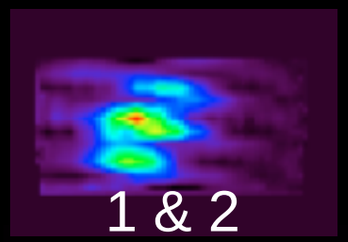
# QUBIC concept: Quasi optical correlator

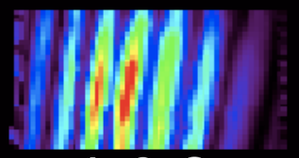
Fringes successfuly observed in 2009 with MBI-4 [Timbie et al. 2006]



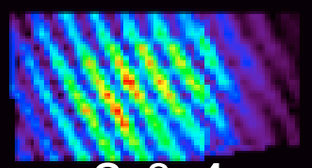
1 horn open

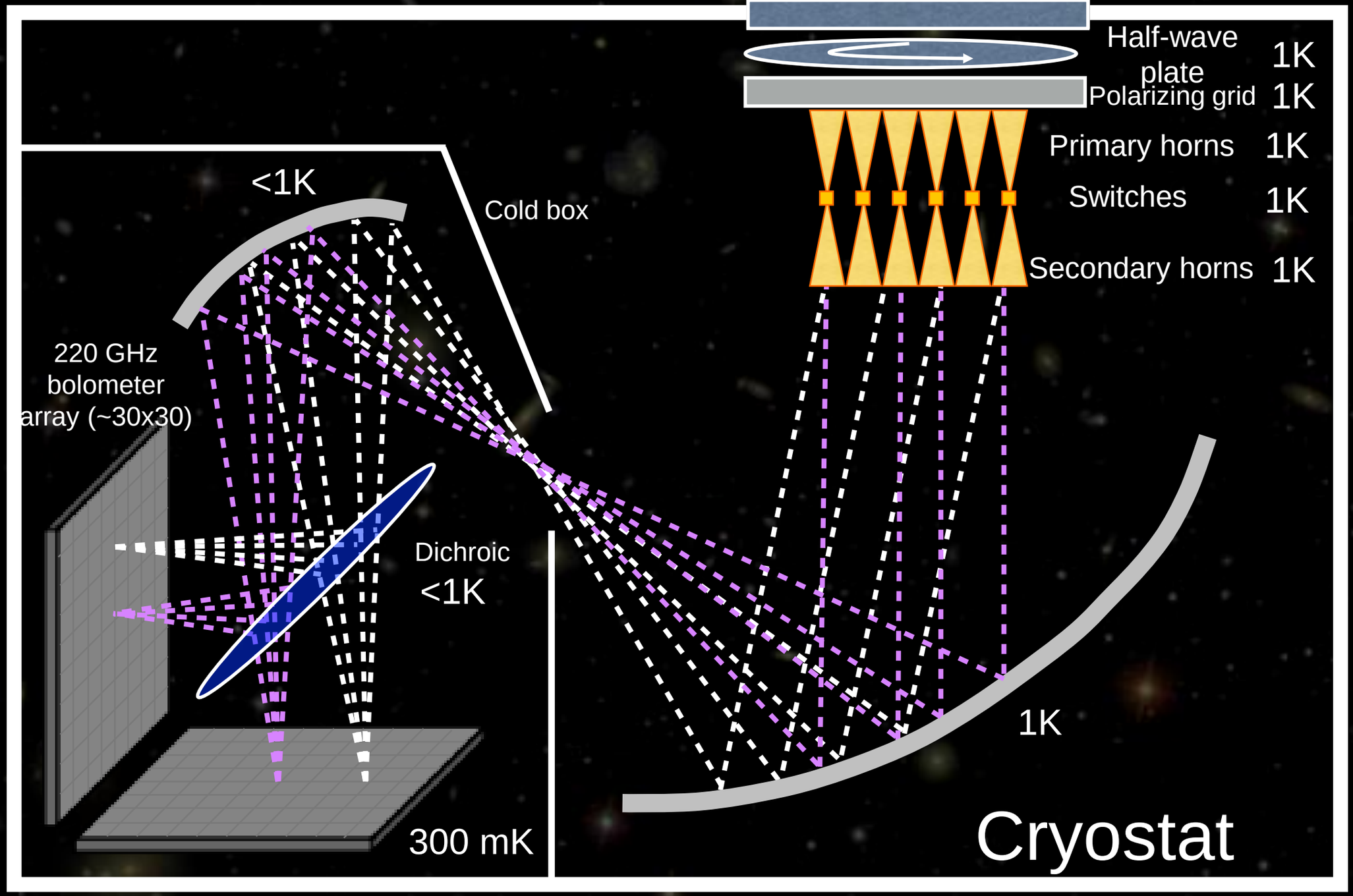
MBI-4 data
2009 campaign (PBO-Wisc.)








150 GHz bolometer array

# QUBIC Main Features

- TES Focal planes
  - ★ 2048 TES with NEP ~ $4x10^{-17}$ $W.Hz^{-1/2}$
  - ★ 128:1 SQUIDs+ASIC Mux Readout

→ High Sensitivity
r < 0.01 @ 95%C.L.(No foregrounds) r < 0.02 @ 95%C.L.(inc. foregrounds)

- 400 Elements Bolometric Interf.
  - ★ Synthesized imaging on focal planes
  - ★ 23.5 arcmin FWHM

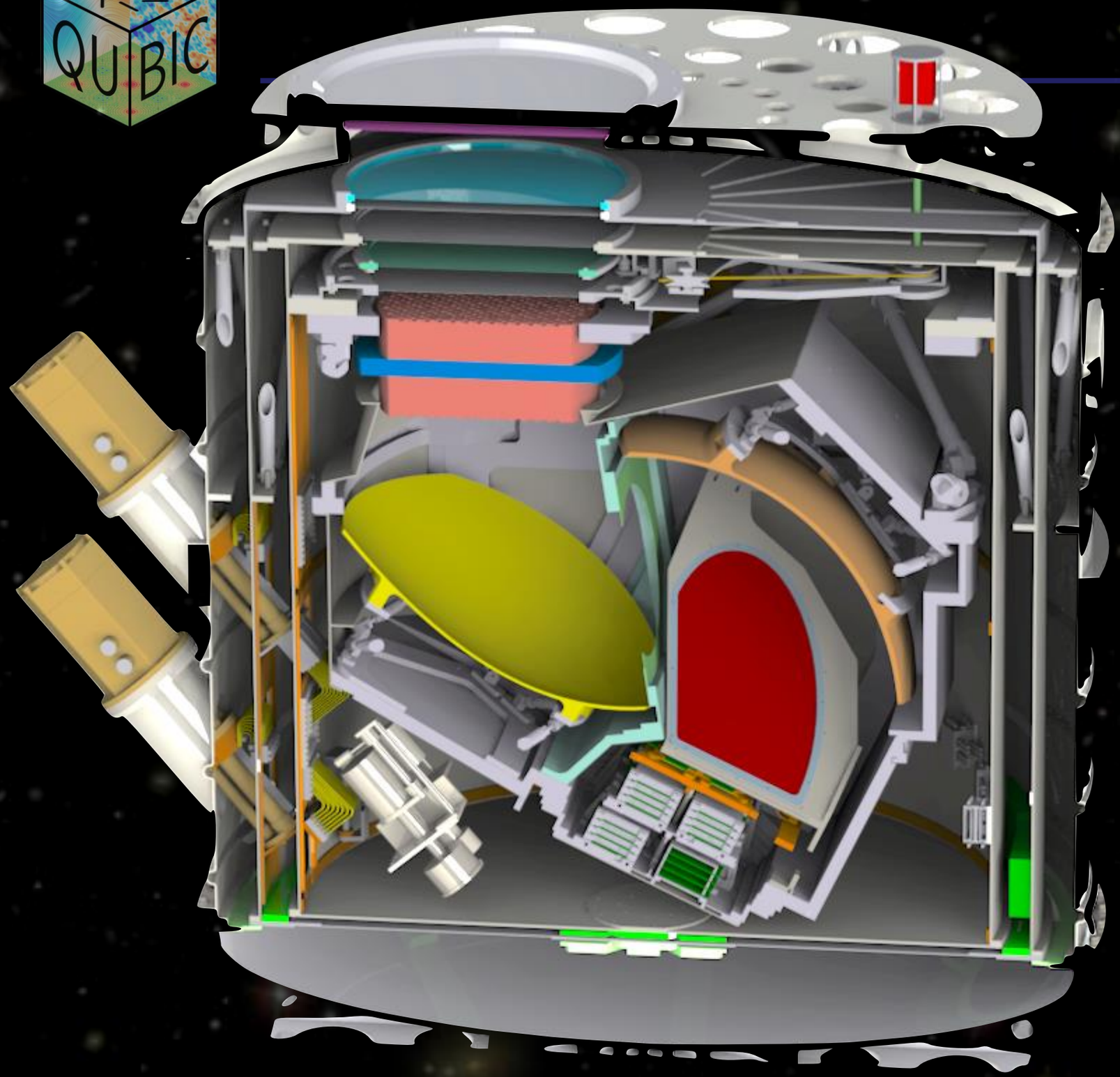
→ Synthesized imager scanning the sky Perfect beam control

- Dual Band operations
  - ★ One focal plane for each band
  - ★ 150 and 220 GHz

→ Dust Polarisation contamination removal

- Switches on each horn
  - ★ Ability to reconstruct baselines individually
  - ★ Self-Calibration like an interferometer

→ Unprecedented control of systematics with Self-Calibration



# Instrument fully designed

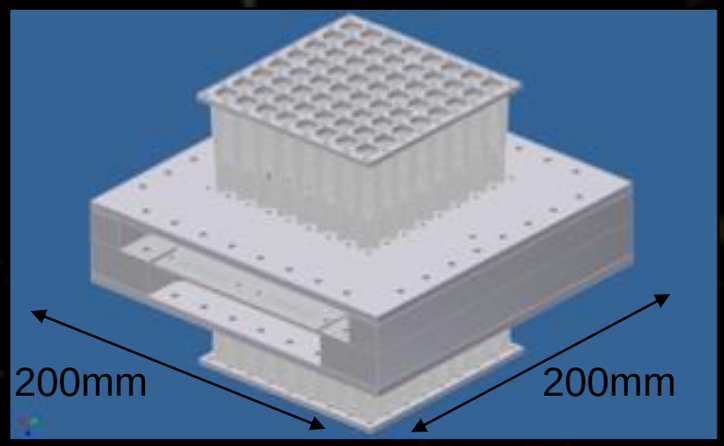
- Outer cryostat: Roma
- 1K Box / detectors: APC
- Fridges: Manchester
- Optics: Roma / Maynooth

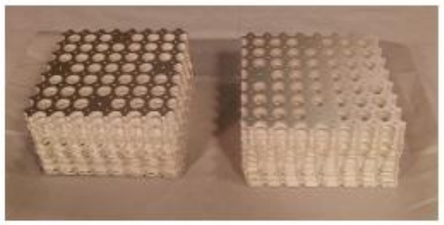
1.547m high
1.42m diameter
About 800kg

# Integration has started

# Optics

- Horn and switch assembly:
  - ★ Al platelets horns: single moded at 150GHz, few moded at 220GHz (A. Mennella, University of Milano)
  - ★ Electromagnet controlled mechanical RF switch (M. Zannoni, Milano Bicocca)
  - ★ Status
    - 8x8 prototype built



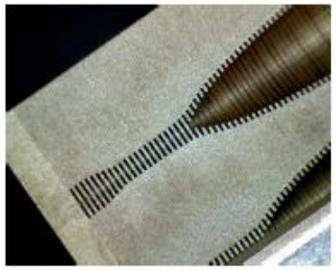
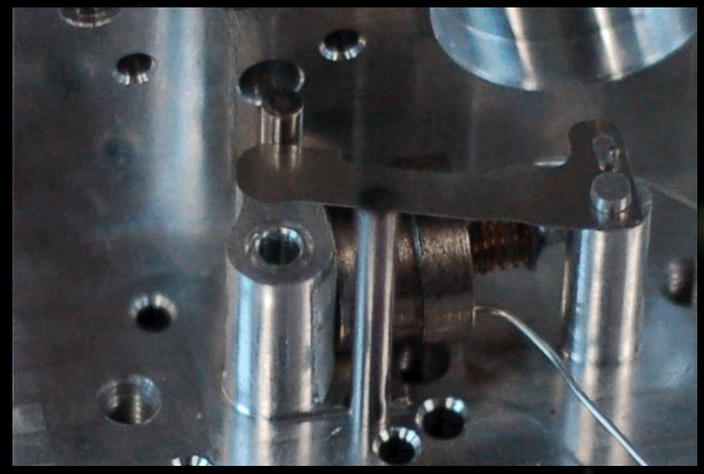
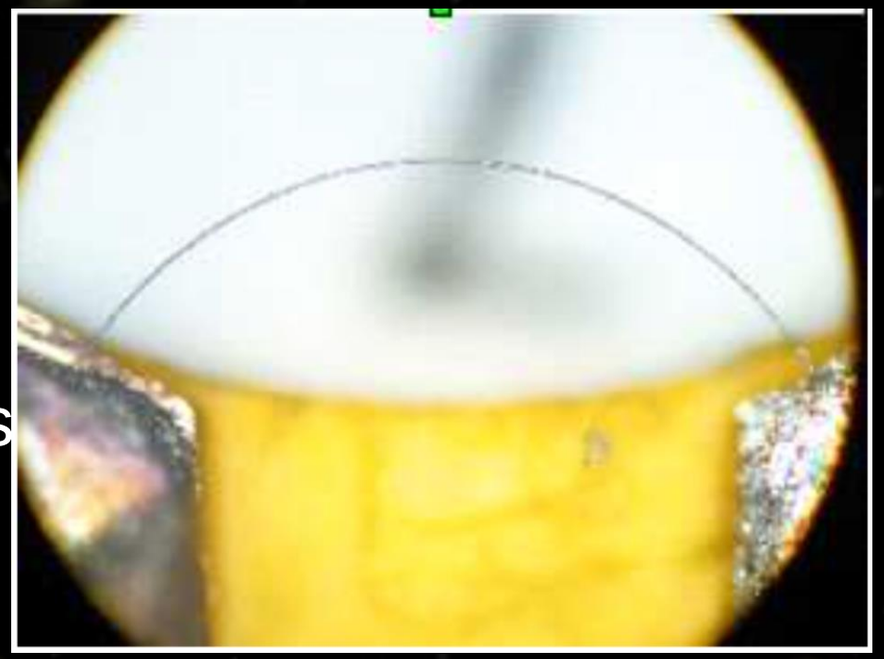


FIGURE 3.6: Picture of the horn array, produced for the technological demonstrator of QUBIC (left). Close picture of a horn cut (center). Mirror, produced for the technological demonstrator (right).



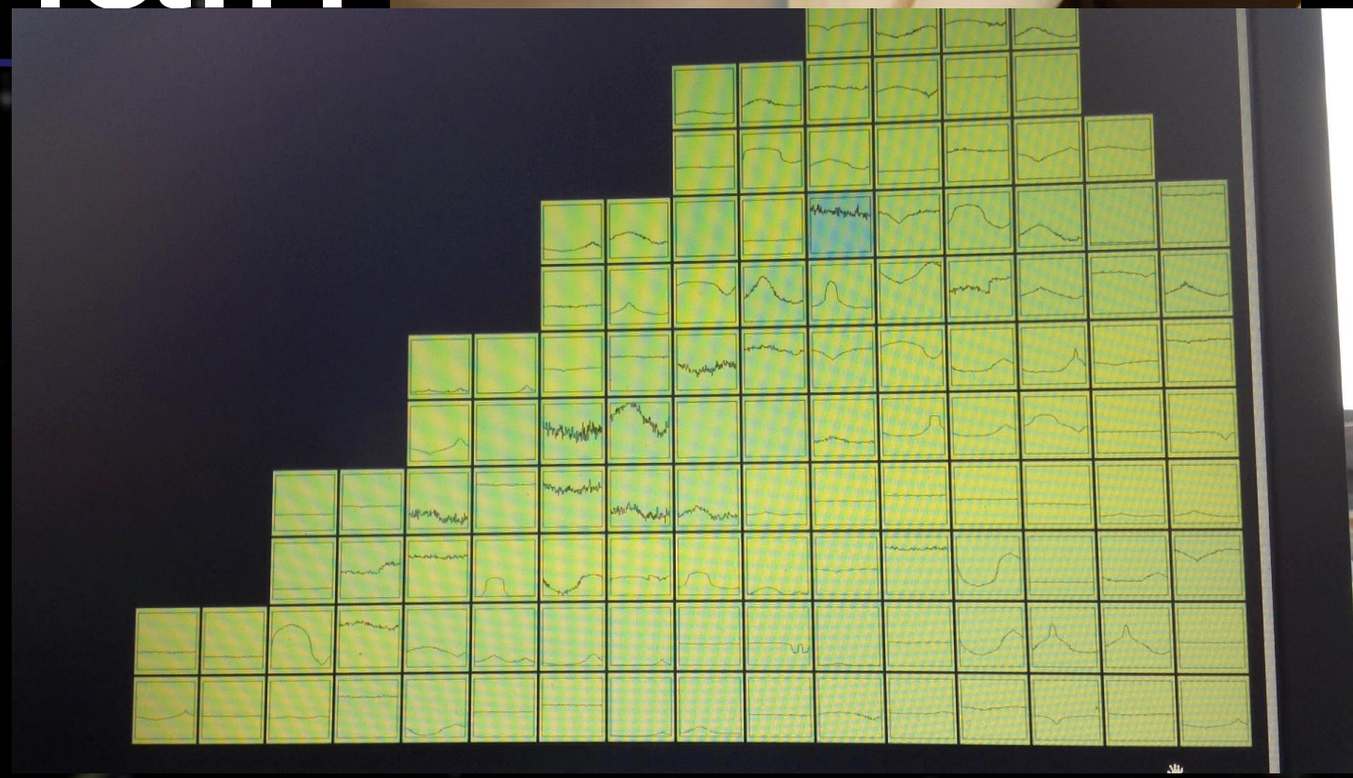
# Optics

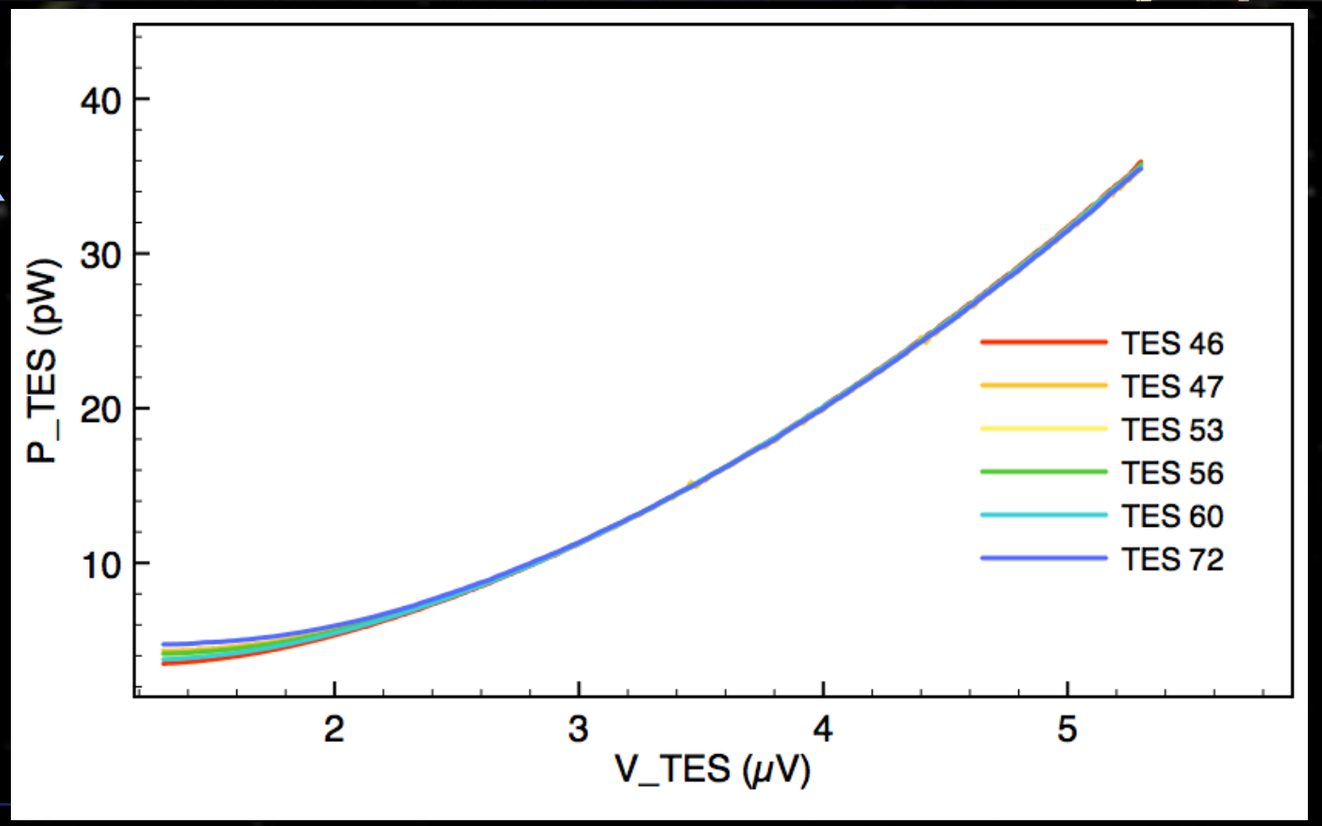
- Carbon fibre sources (LAL)
  - ★ Used on Planck-HFI calibration
  - ★ To allow regular intercalibration of detectors



# Detection Chain

- French responsibility
  - ★ APC + CSNSM / IEF / IRAP
- 2 arrays of 992 NbSi TES
  - ★ Each array : 4x248 elements
  - ★ 300 mK bath ($^3$He-$^4$He evaporation cooler)
  - ★ 3 mm size
  - ★ **Measured NEP ~ 4.10$^{-17}$ W.Hz$^{-1/2}$**
  - ★ time constant ~ 10 ms
- 4K SQUIDs + SiGe ASIC Mux
  - ★ SQUIDs pre-amplifier+mux
    - 32:1 multiplexing
  - ★ 4K SiGe ASIC (amp+mux)
    - 4:1 multiplexing
  - ★ 128 channels / ASIC
  - ★ Low noise: ~200 pV.Hz$^{-1/2}$
  - ★ low power: ~ few mW





# Detection chain

- 1 focal plane = 4 wafers of

  256 TESs @300mK

  ★ Readout: Time Domain Multiplexing 128:1

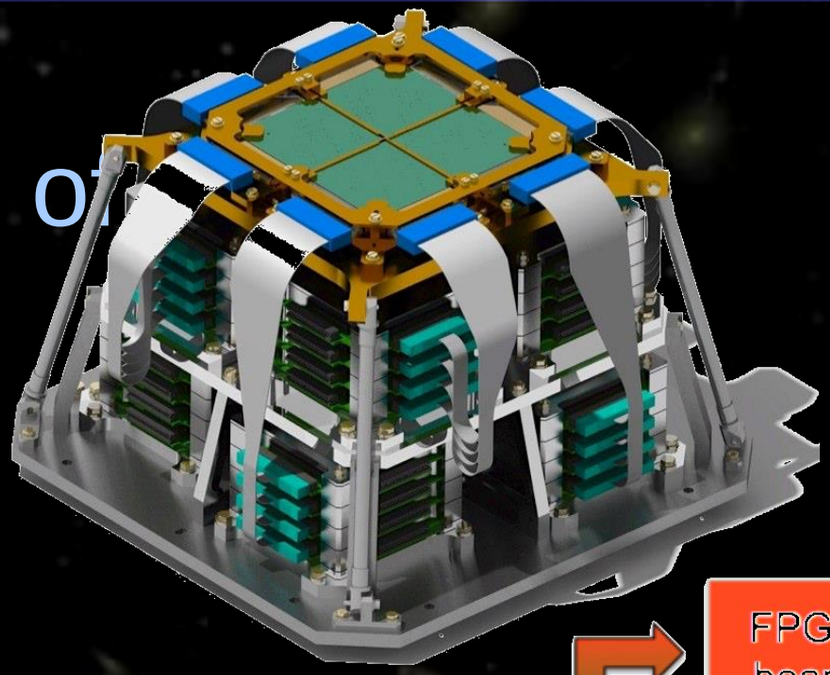
  ★ 128 SQUIDs @ 1K+

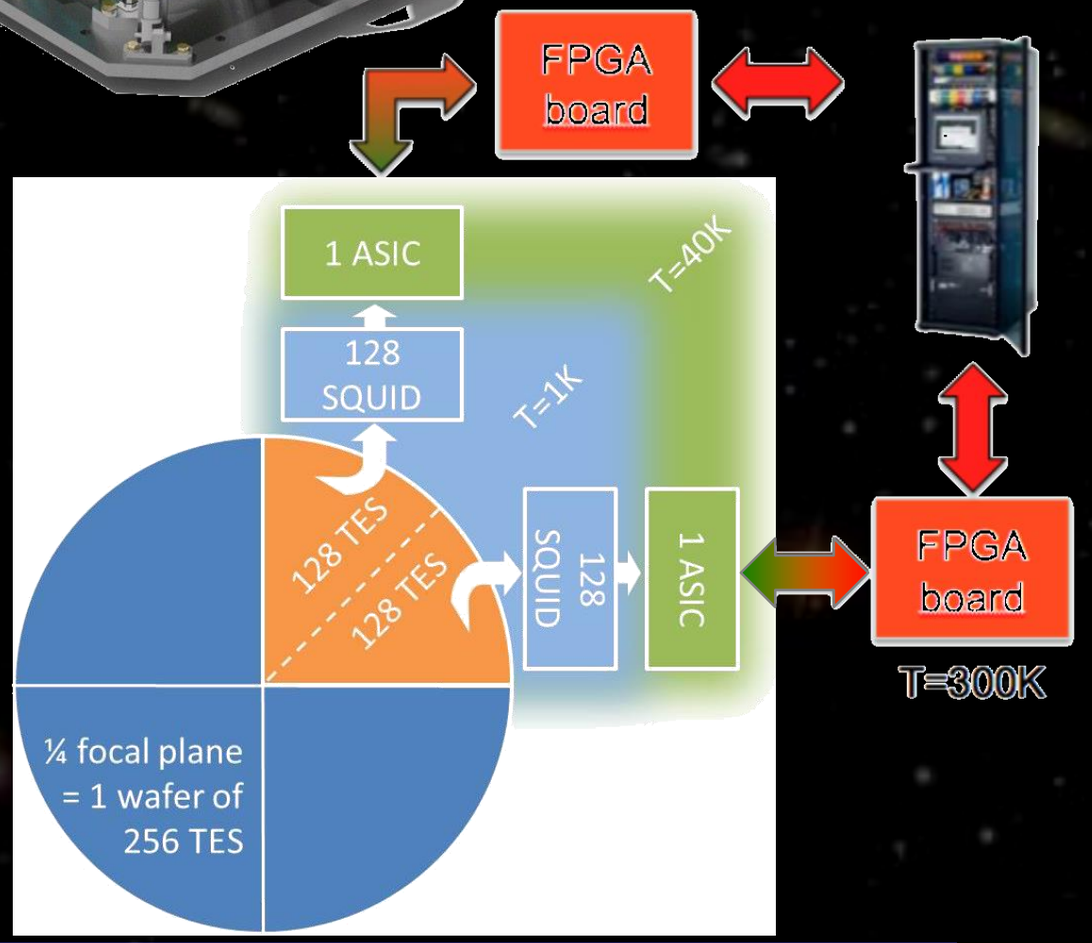
  1 ASIC @ 40 K for ⅛ focal plane

  ★ Specifications:

  - NEP < $5.10^{-17}$ W.Hz$^{-0.5}$
  - $\tau$ < 10ms

- 2 focal planes: 150GHz and 220GHz





# Detection chain

- Focal plane:
  - ★ TD: 2x256 NbSi TESs (CSNSM, IEF)
  - ★ Support structure and readout (APC)

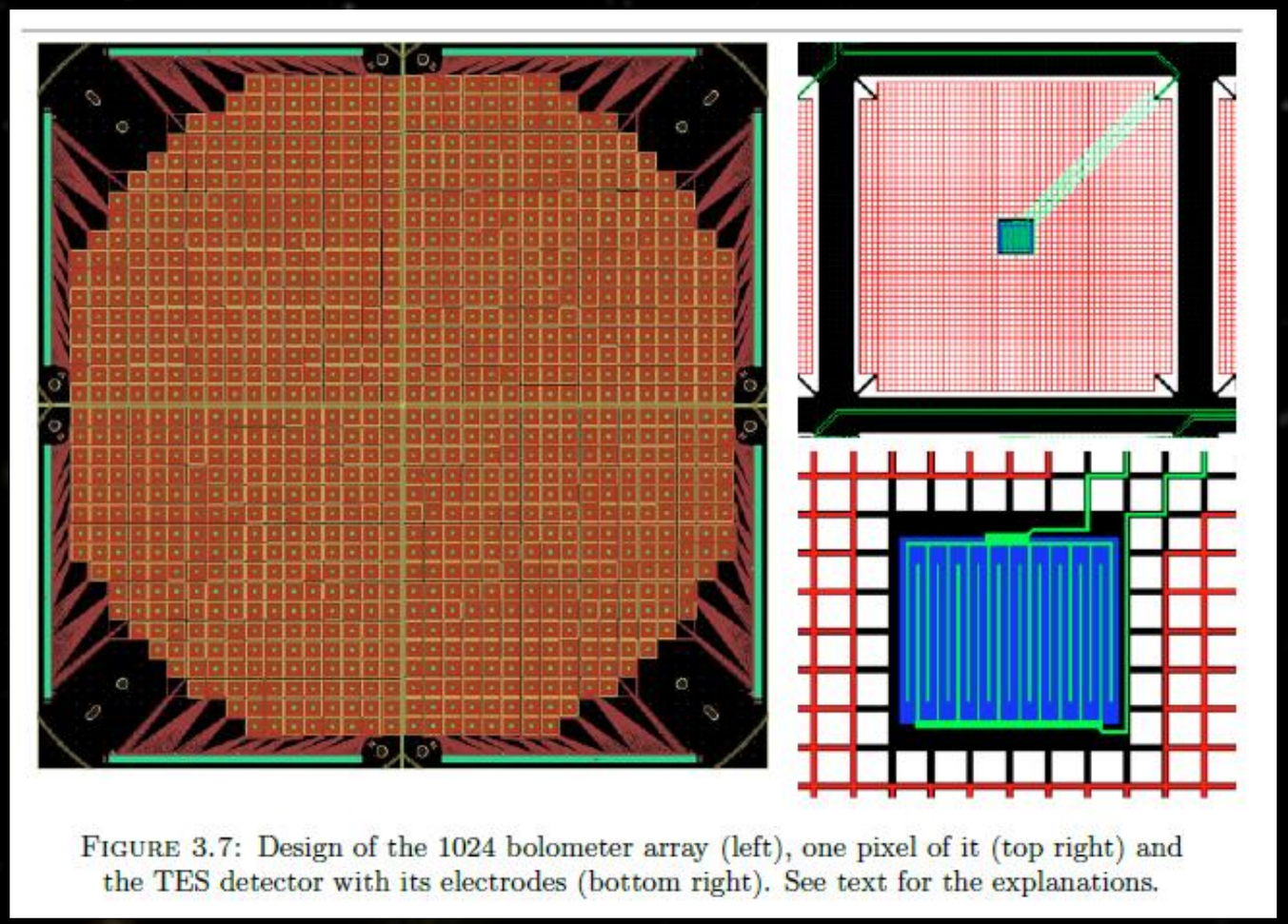
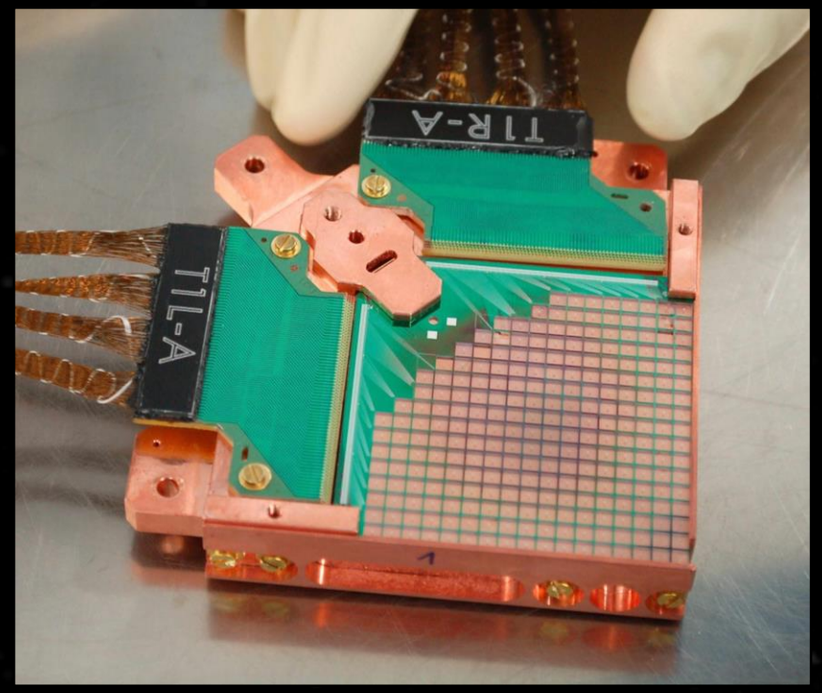
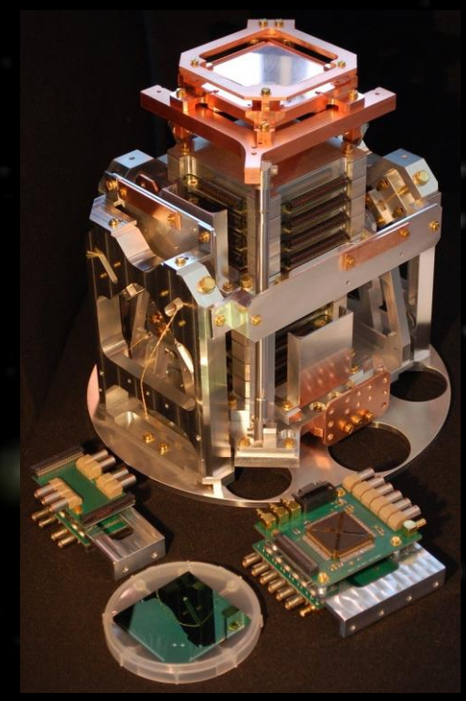


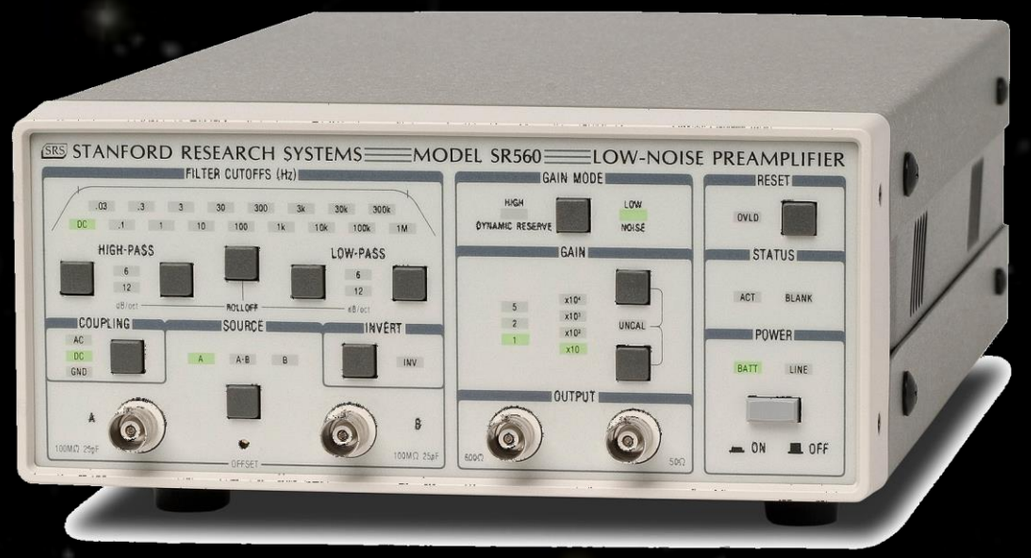
FIGURE 3.7: Design of the 1024 bolometer array (left), one pixel of it (top right) and the TES detector with its electrodes (bottom right). See text for the explanations.

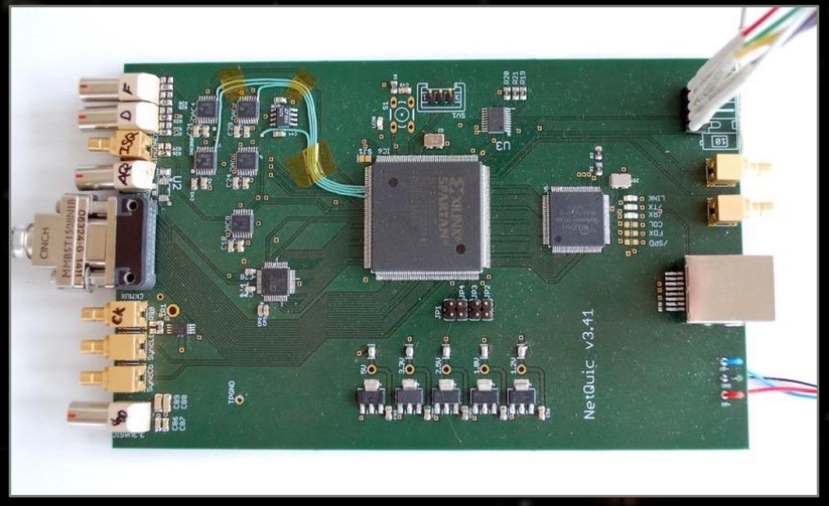


# Detection chain

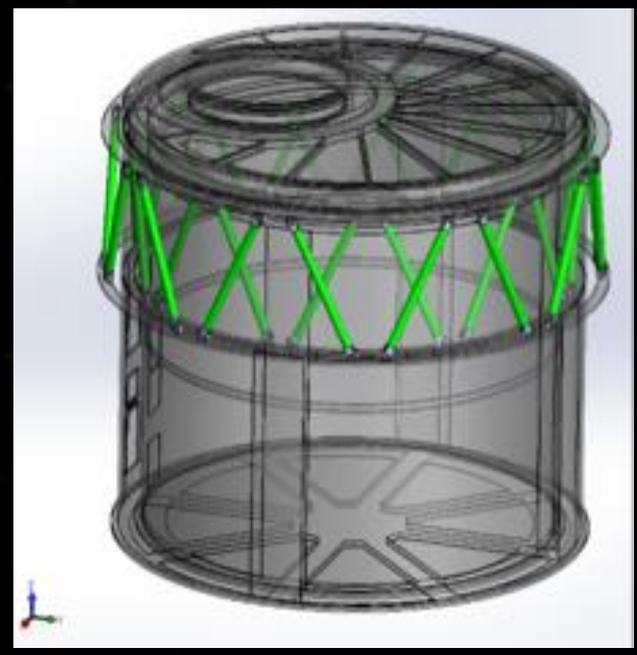
- Warm electronics
  - ★ Amplifier (APC): SR560
  - ★ FPGA board (IRAP)
  - ★ Status:
    - 4x SR 560 available for TD
    - FPGA board available and functional
    - Being done: increasing acquisition speed, FLL in FPGA
    - Schedule: fast FLL with TESs end of February



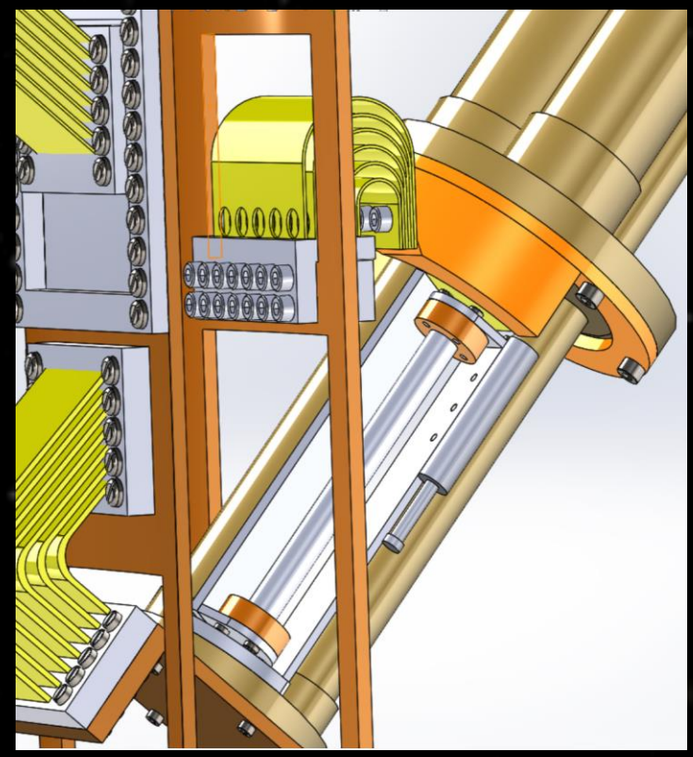
# Cryostat and cryogenics

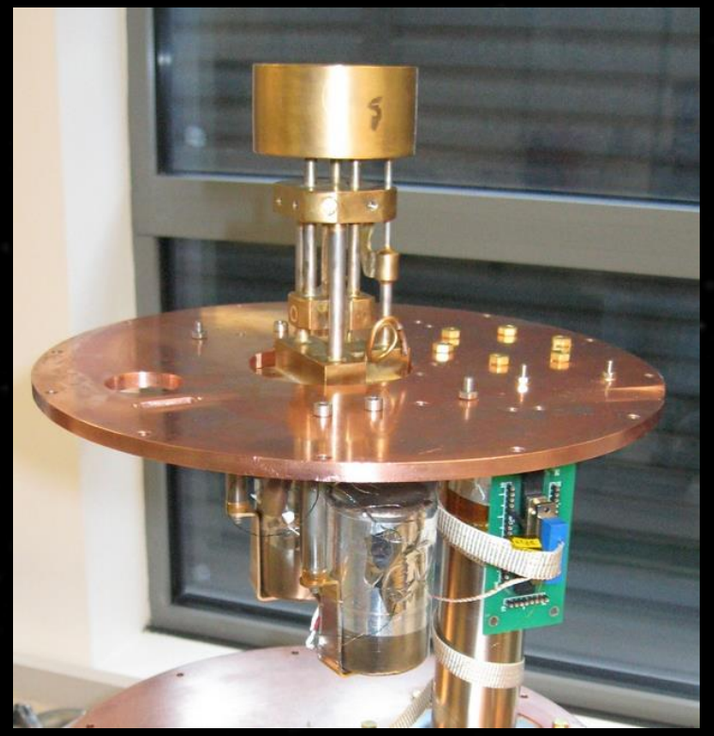
- Cryostat (Roma Sapienza: Silvia Masi, Paolo de Bernardis)
  - ★ Shields at 300K, 40K and 4K supported by fiberglass tubes



# Cryostat and cryogenics

- Cryogenic system
  - ★ 2x1W pulse tubes (to buy by Roma Sapienza)
  - ★ 40K-4K and 4K-1K heat switches (Manchester)
    - Status: prototypes built, being integrated for tests
    - Schedule: manufacture in April, assembly and tests until end of June, **delivery in July**
  - ★ 1K adsorption fridge (Manchester)
    - Status: prototypes built, to integrate and test
    - Schedule: manufacture in May, assembly and tests until end of August, **delivery in September**
  - ★ 300mK adsorption fridges (Manchester)
    - Status: fridge tested and available
    - Schedule: **delivery in September**

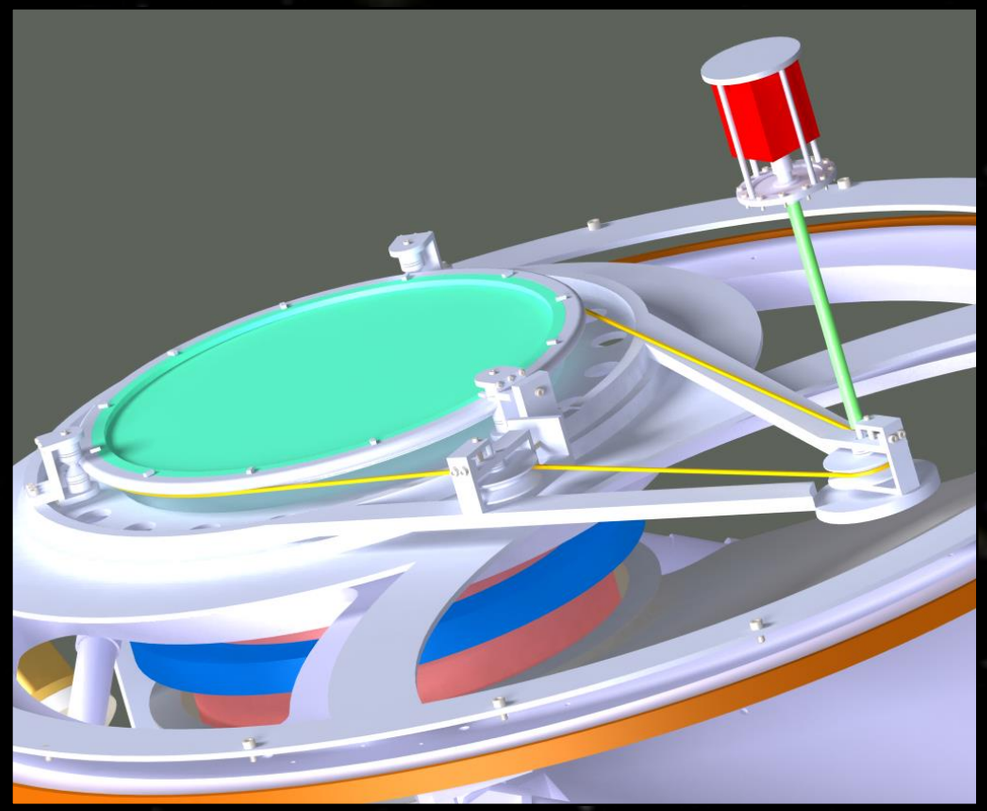




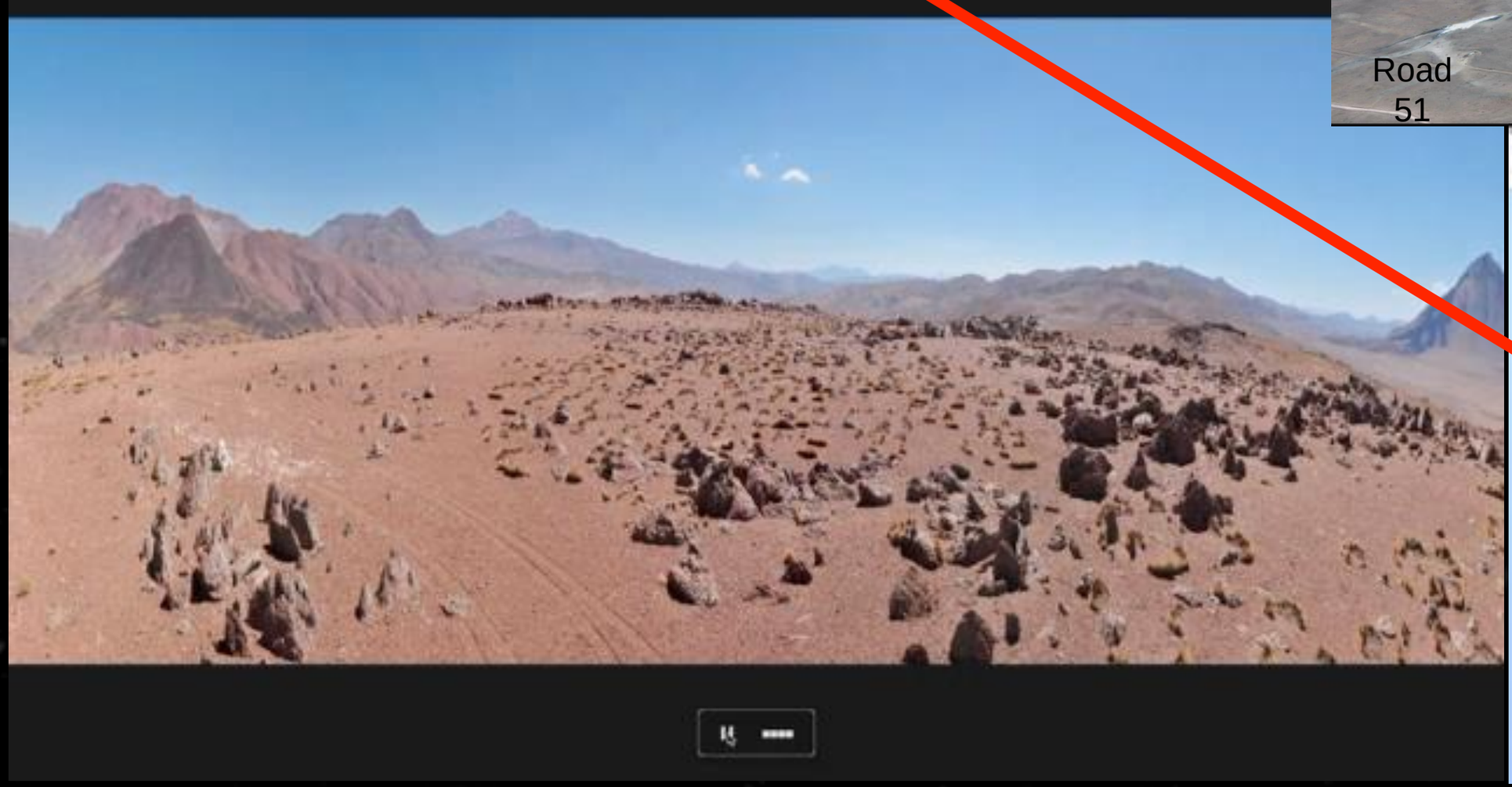
# Cryostat and cryogenics

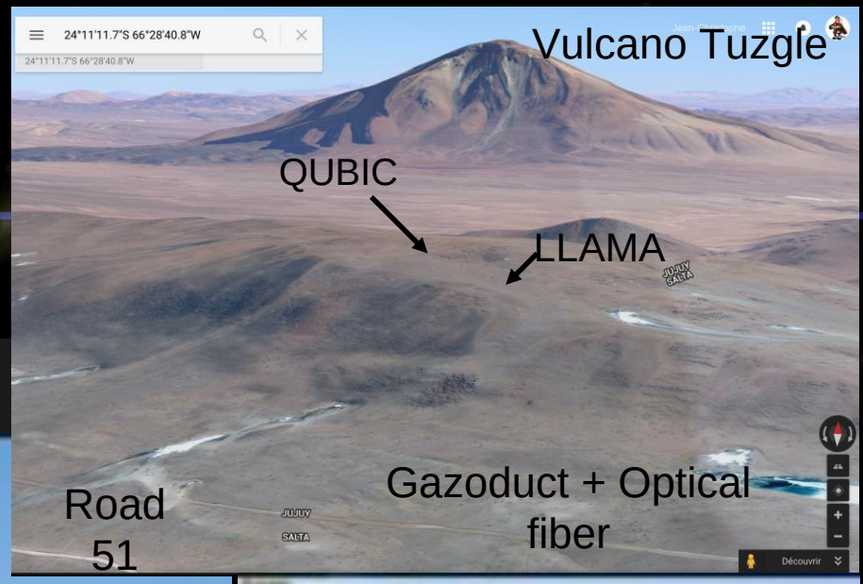
- HWP rotator (Rome Sapienza):

★ Equivalent to the PILOT one: warm motor, shaft, kevlar belt, HWP on ball-bearings and optical fibres to control the position



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






- 5000m a.s.l.
- Logistics + mount : Argentina
- NEW: Access road built up to LLAMA (800m remaining)

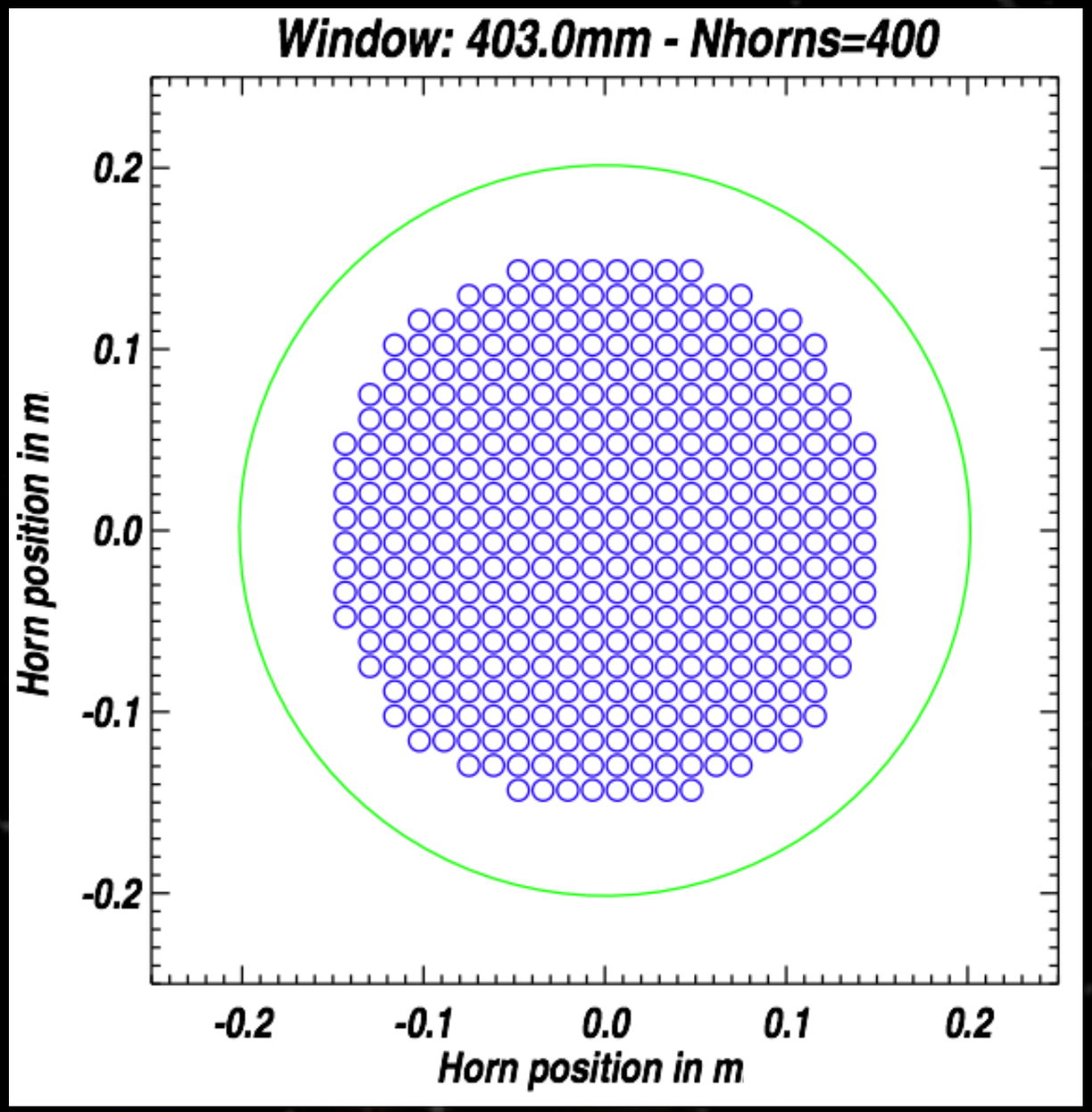
# Possible site for QUBIC: large, flat, few stones at 4869m a.s.l.

South

# San Antonio de los Cobres (3775m a.s.l. - 5000 habitants)

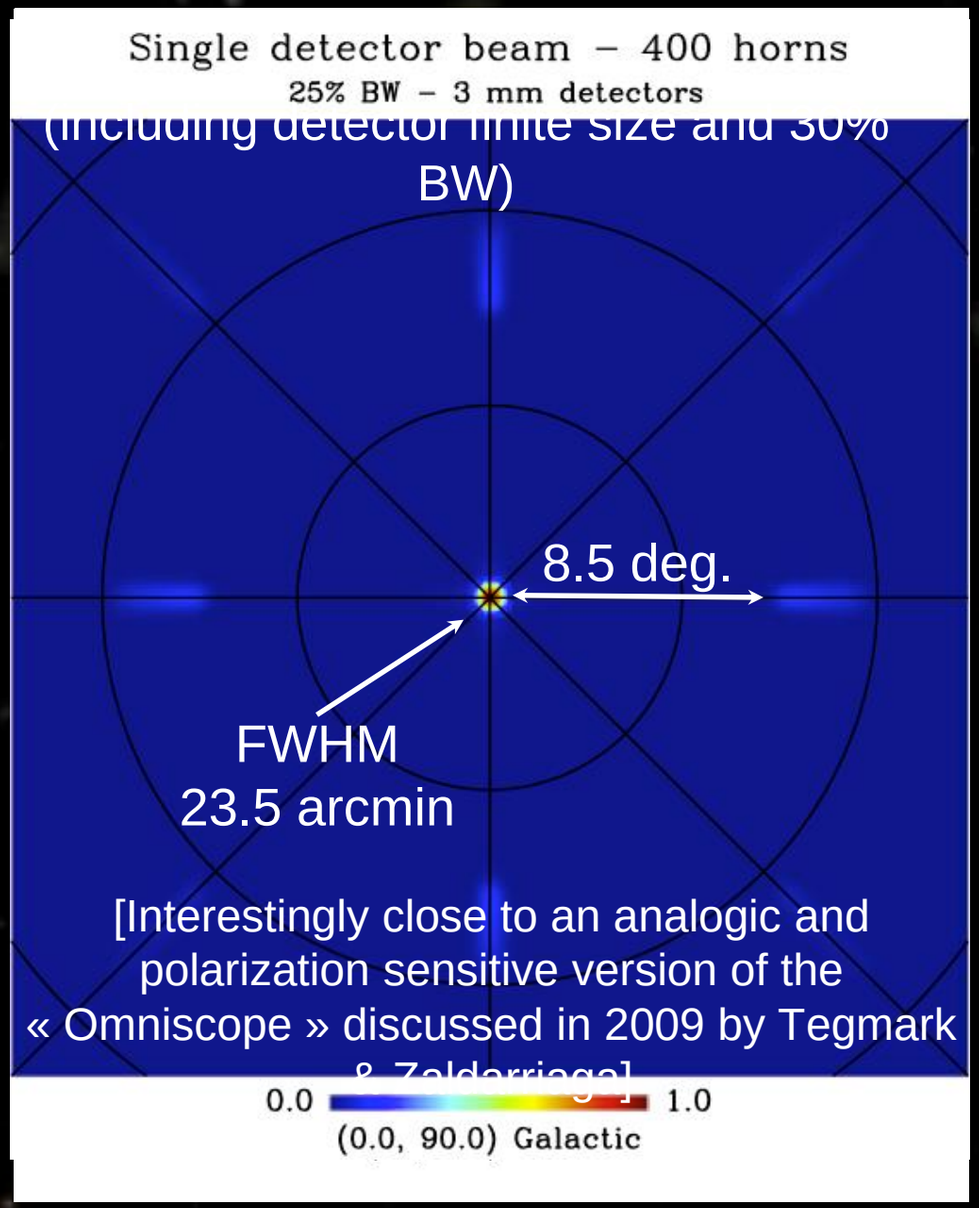
# B.I. = Synthesized imager

## Primary horns array




150-220 GHz, 20x20 horns,
13 deg. FWHM, D=1.2 cm

## Synthesized beam (on the sky)




Synthesized beam used to
scan the sky as with an imager

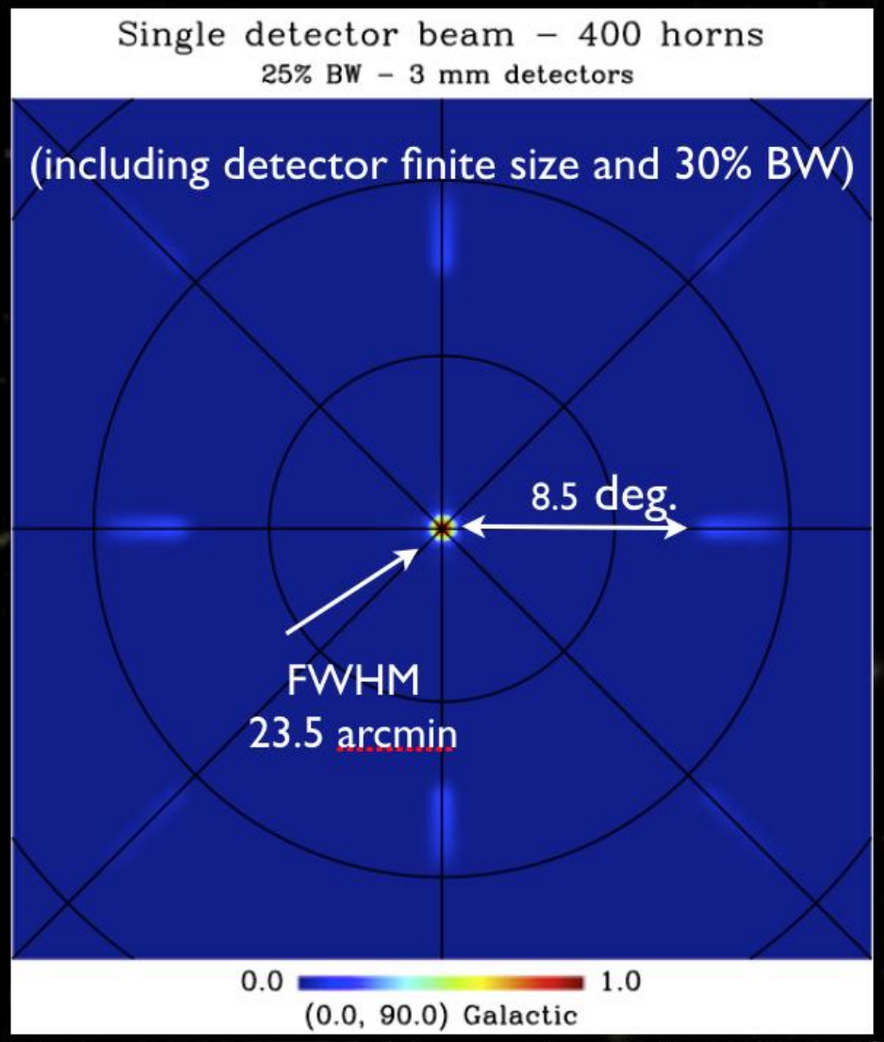
# Map-making with QUBIC synthesized beam

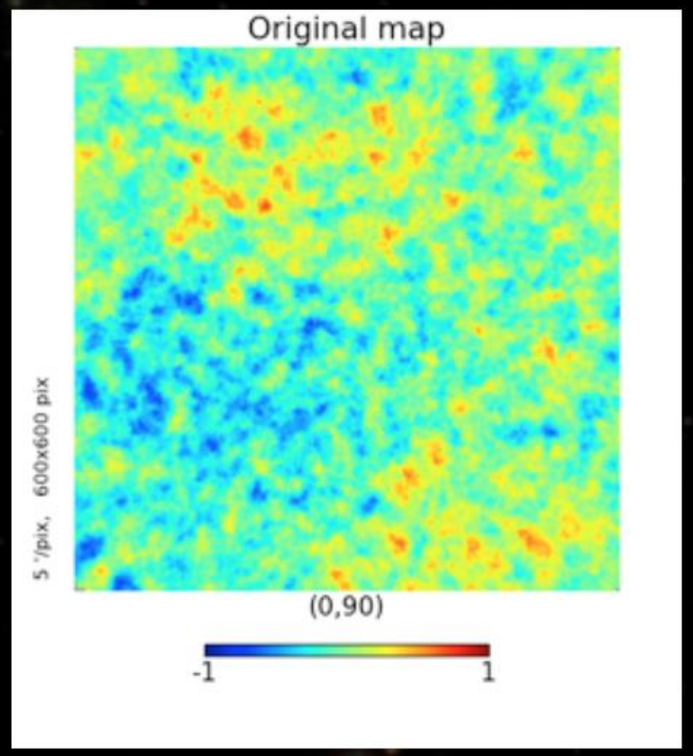
- Signal on bolometer $d_p$ at frequency ν (HWP modulation) :

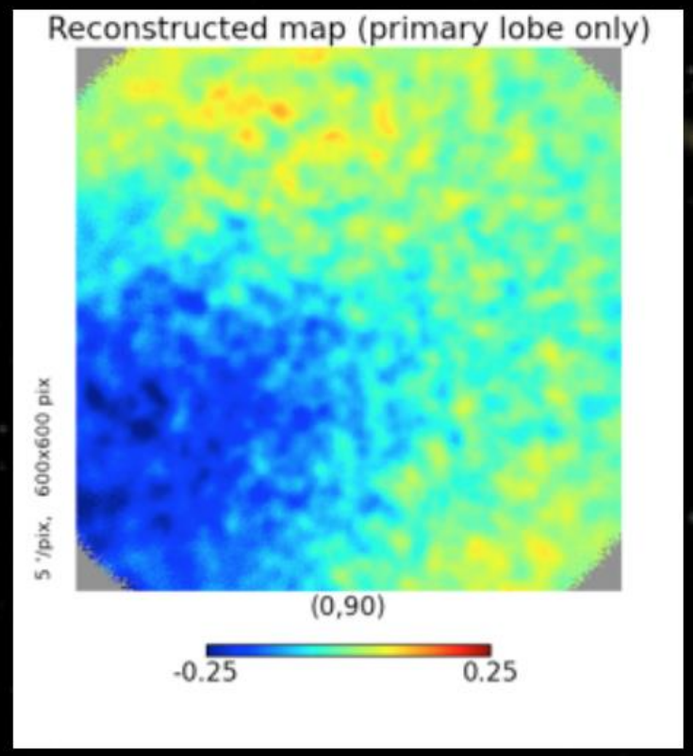
$$R(\vec{d}_p, \nu, t) = S_I(\vec{d}_p, \nu) + S_Q(\vec{d}_p, \nu) \times \cos\left[4\phi_{HWP}(t)\right] + S_U(\vec{d}_p, \nu) \times \sin\left[4\phi_{HWP}(t)\right]$$

- where $S_X$ is the «synthesized image» : our observable
  - FFT of visibilities in traditional interferometry
  - Sky convolved with the «synthetic beam»

$$S_X(\vec{d}_p, \nu) = \int X(\vec{n}, \nu) B_s(\vec{d}_p, \vec{n}, \nu) \mathrm{d}\vec{n}$$

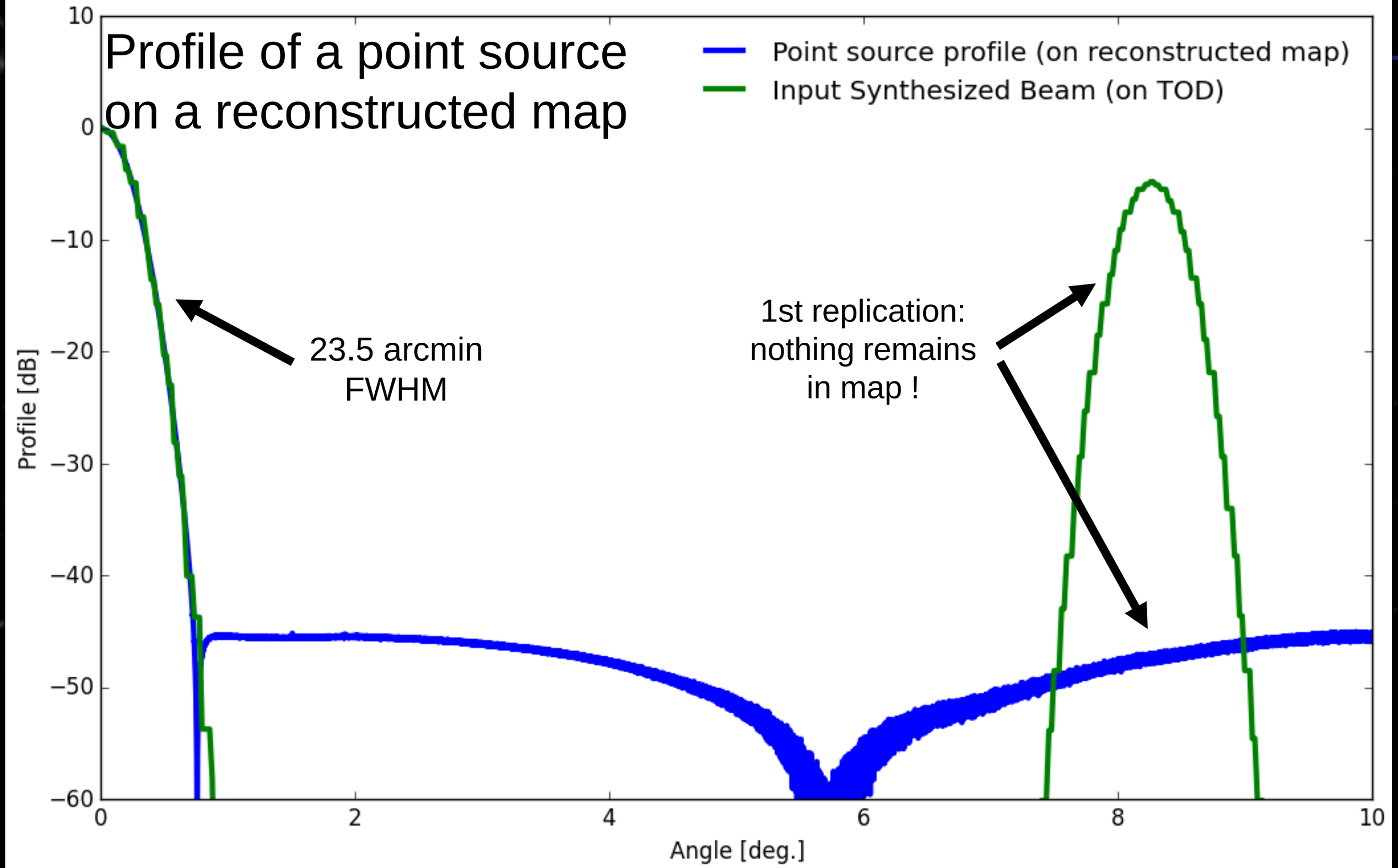



Mapmaking needs to account for precisely-known but multiply-peaked synthesized beam

# Profile of a point source on a reconstructed map



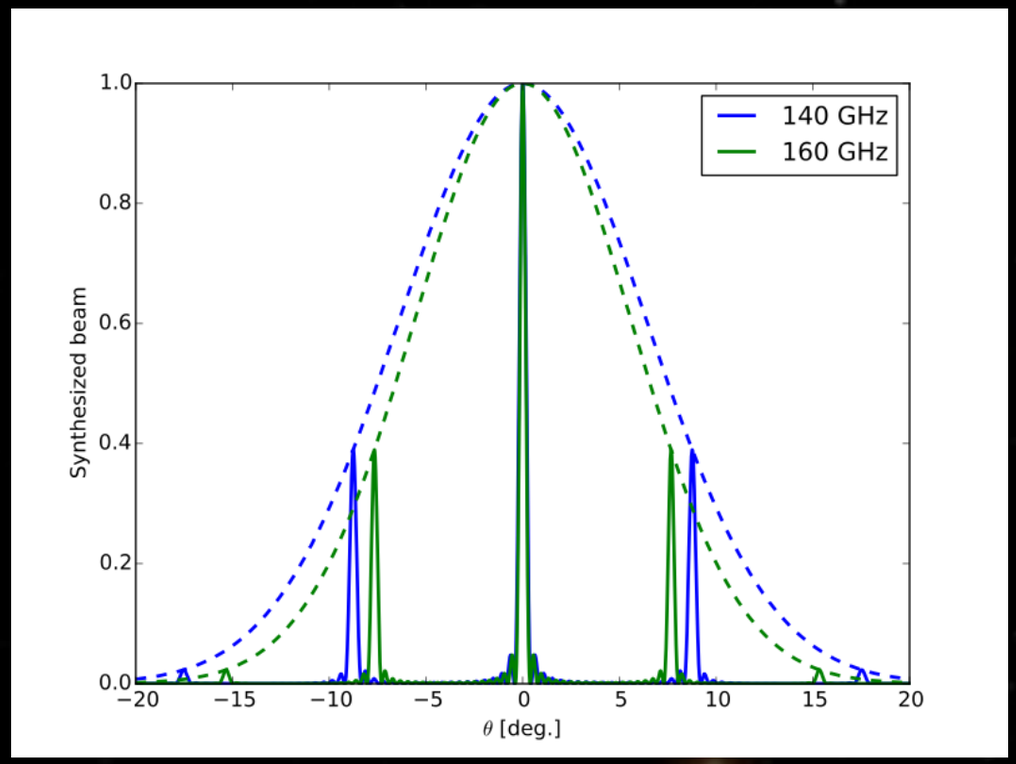

QUBIC

QU Bolometric Interferometer for Cosmology

# Data Analysis more complex but richer than with a classical imager

Complex shape of synthesized beam

Frequency dependence of synthesized beam



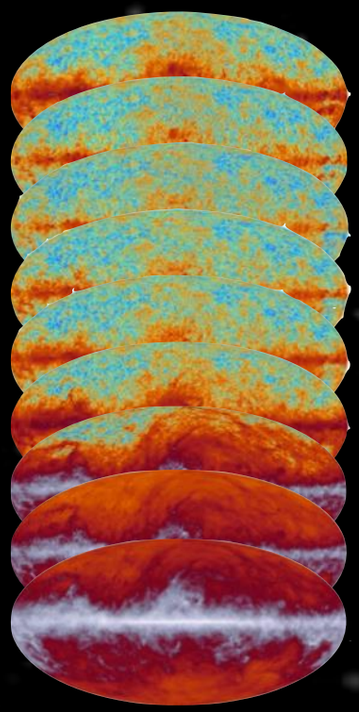

Map-making more complex

Spectro-Imaging

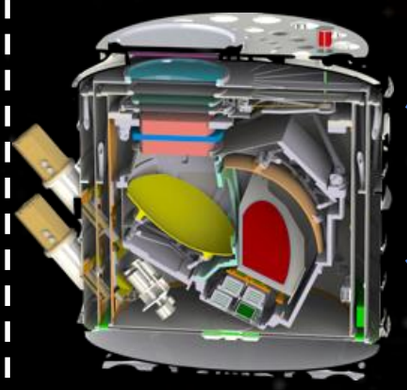
CPU…

Foregrounds!

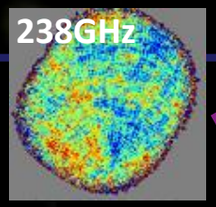
# QUBIC Spectro-Imaging



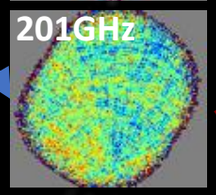
TOD(220 GHz)

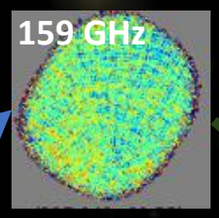


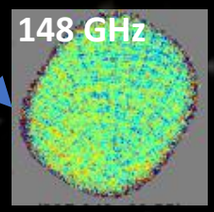
TOD(150 GHz)

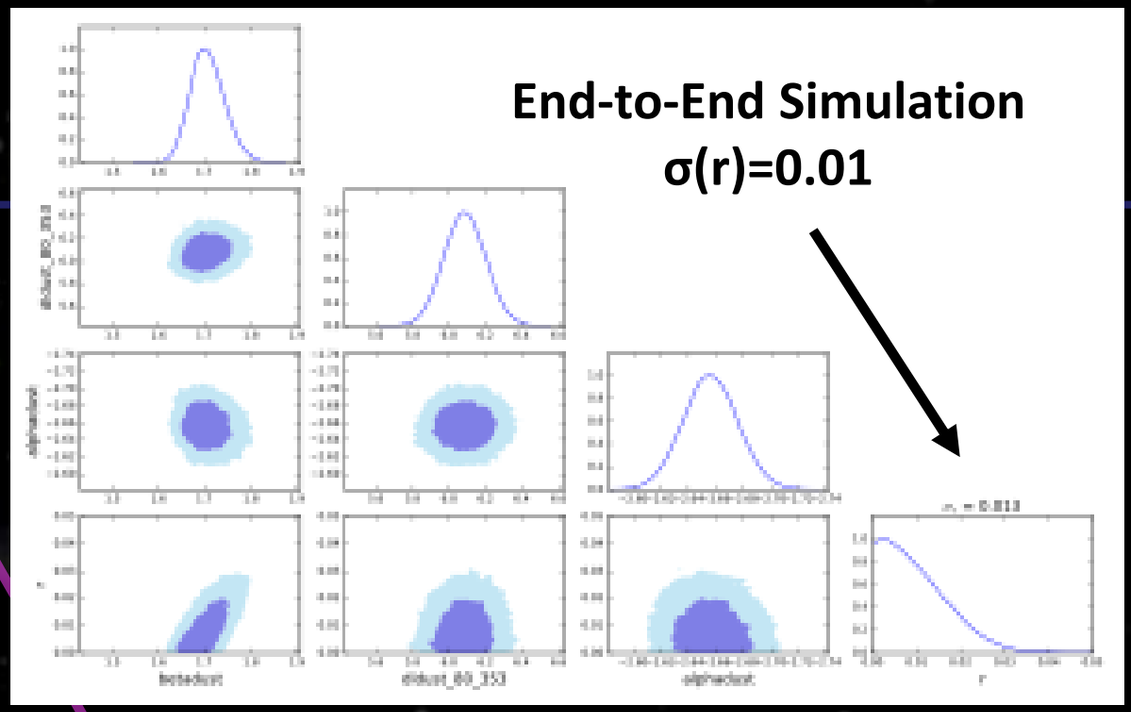


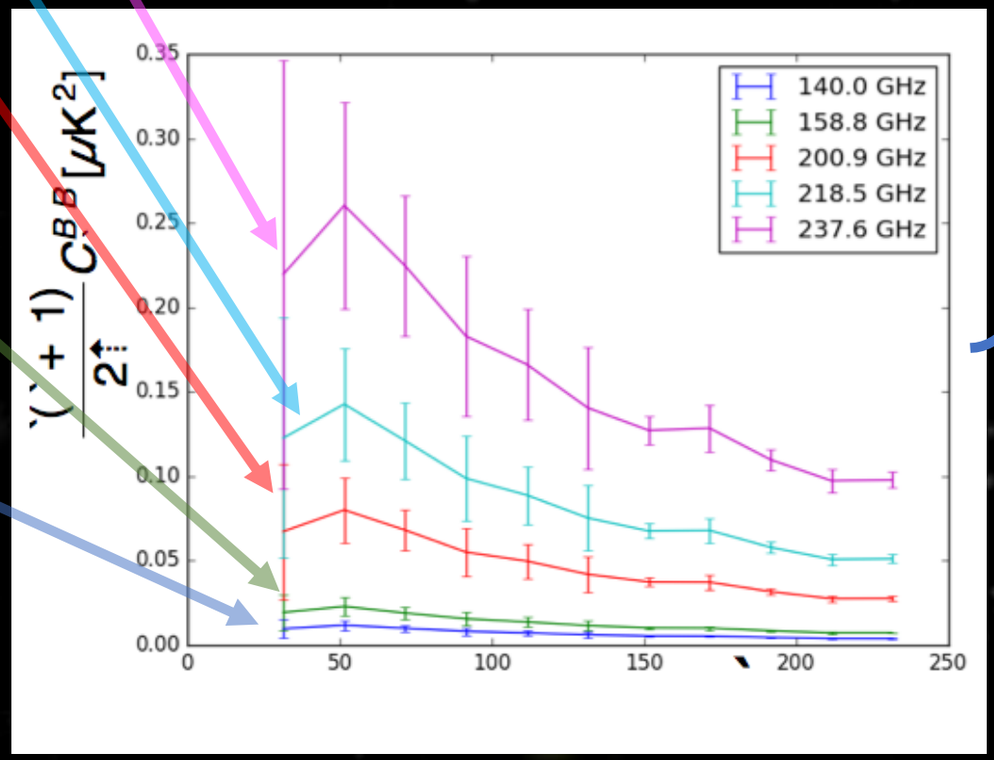





**Sky:**
**« Infinite # bands »**

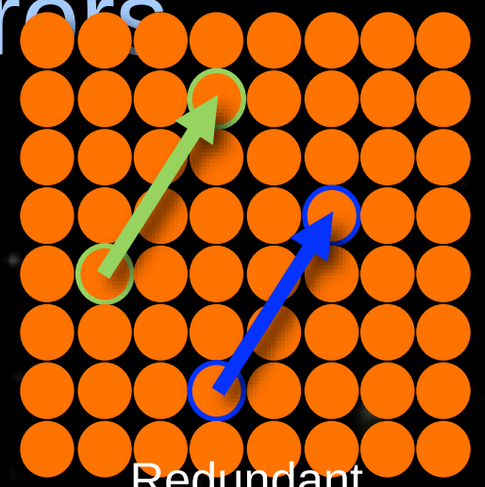
**Instrument:**
**2 wide bands**

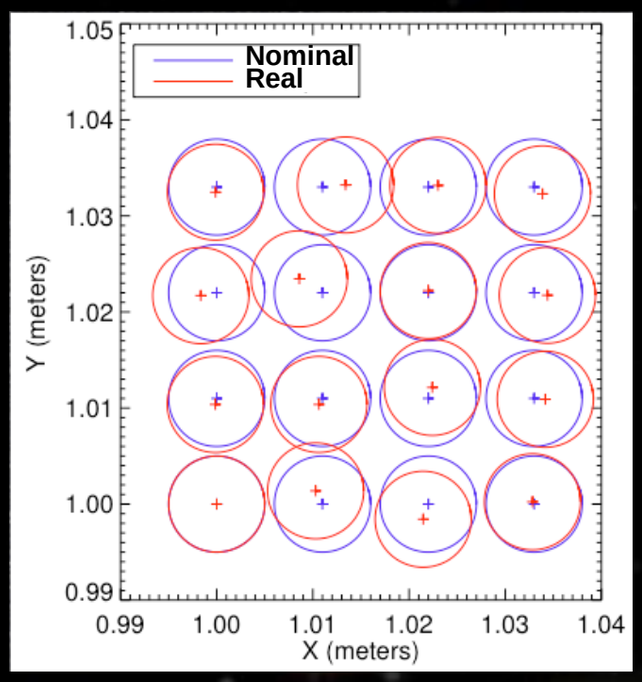
**Data Analysis:**
**5 narrow bands**

**=> Increased Spectral Resolution**
**=> Dust subtraction**

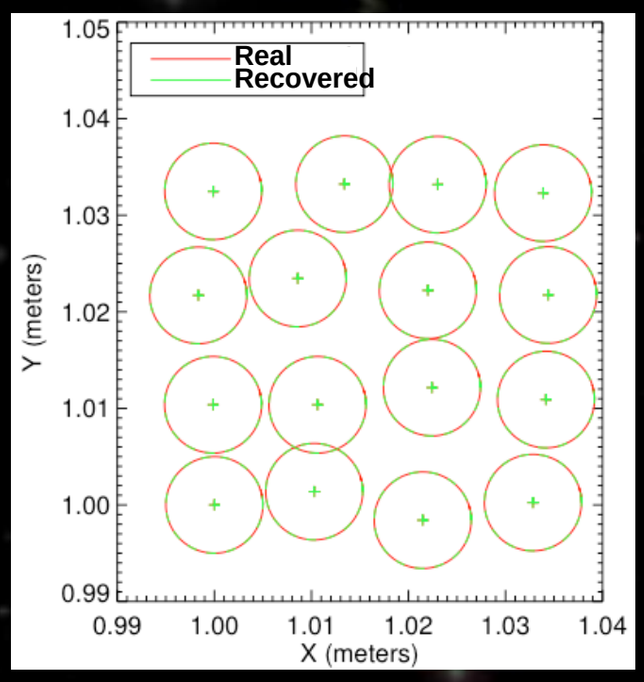
# Systematics: Self Calibration

- 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
  - ★ Unique specificity of Bolometric Interferometry ! [Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]
  - ★ Example: exact horns locations (figure exagerated !!)

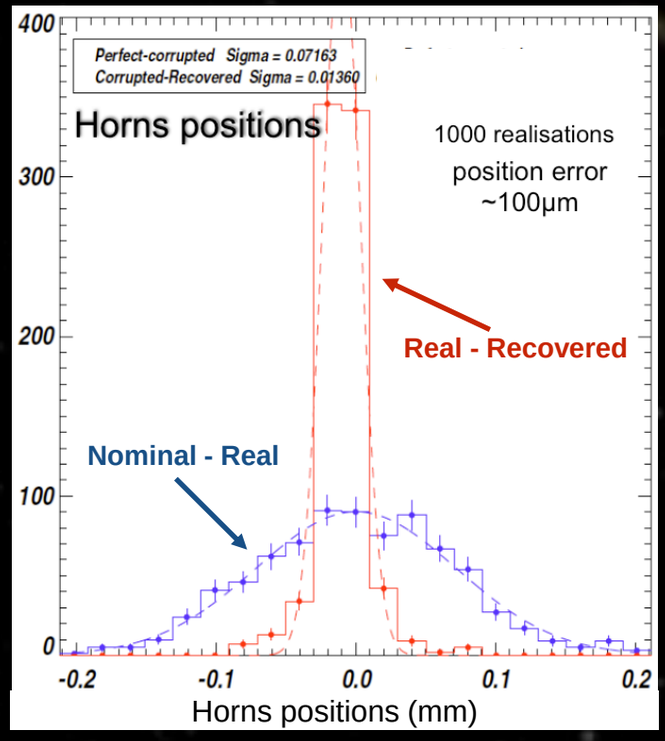



Actual horn positions (red) are not well know
One uses ideal ones (blue) in map reconstruction
⇒ Systematics in maps, E/B leakage

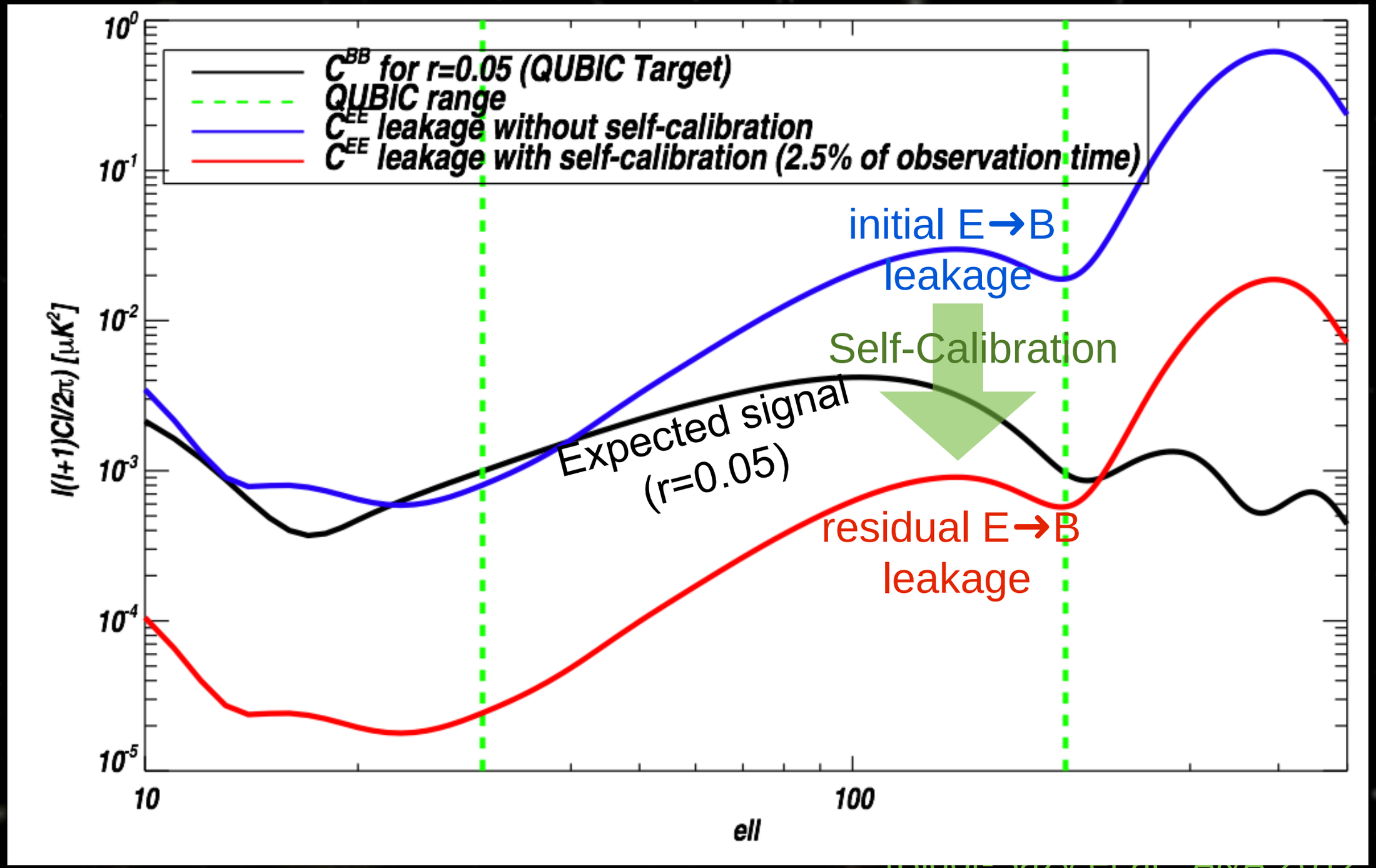



Actual horn positions (red) are recovered
thanks to self calibration (green)
⇒ E/B leakage is reduced




Horn position knowledge improvement

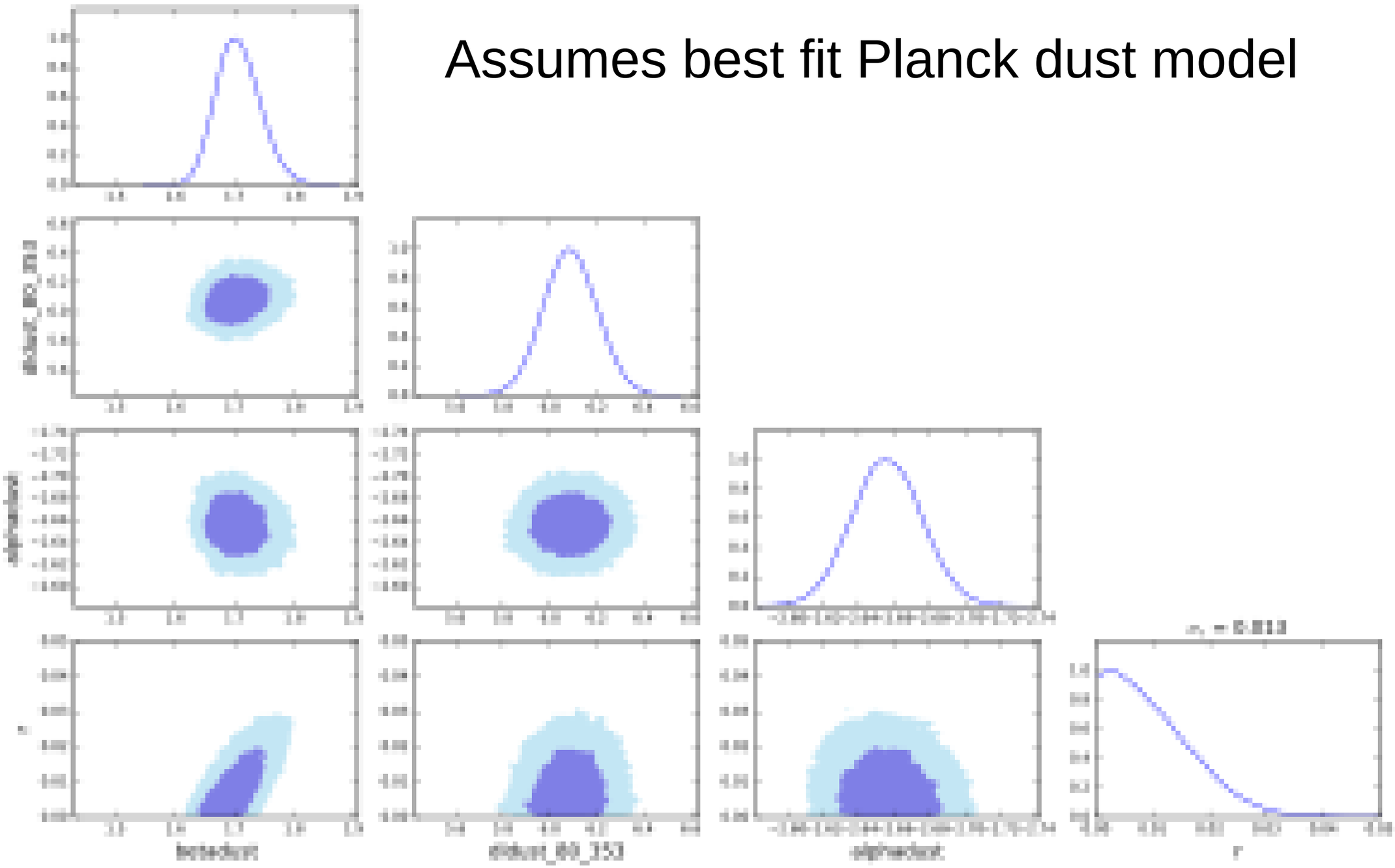
# Self-Calibration results




[Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]

# Expected Sensitivity: σ(r)~0.01

Assumes best fit Planck dust model



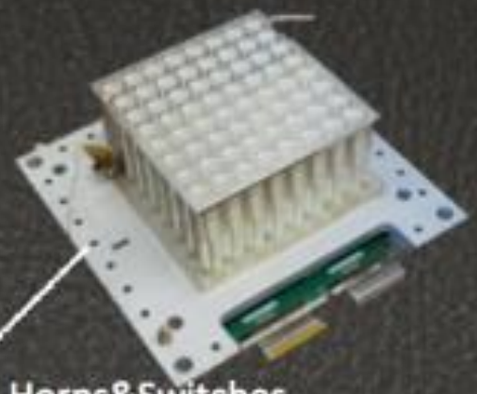
# QUBIC Deployment Plan

**2017-2018 : at APC**

- Integration started
- Early 2018: Technological Demonstrator (reduced QUBIC)
  - 1/4 focal plane, 64 horns, small mirrors
- April 2018: Upgrade to full size mirrors and 400 horns

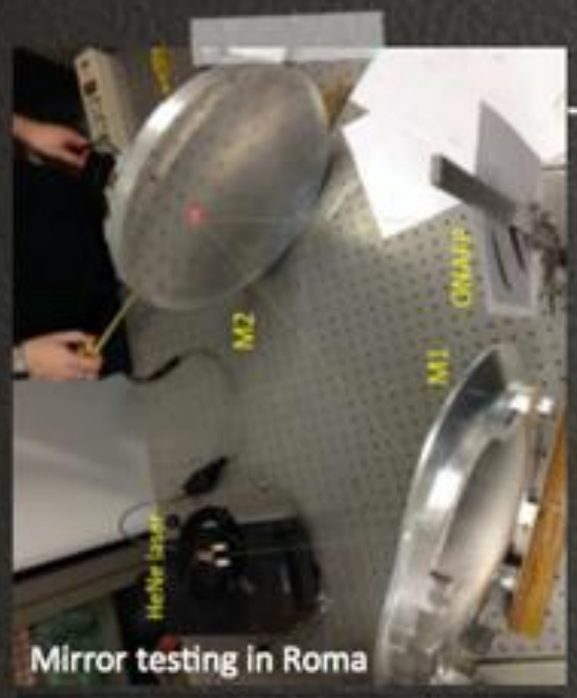
→

In-Lab demonstration of Bolometric Interferometry

Horns&Switches
(Milano)

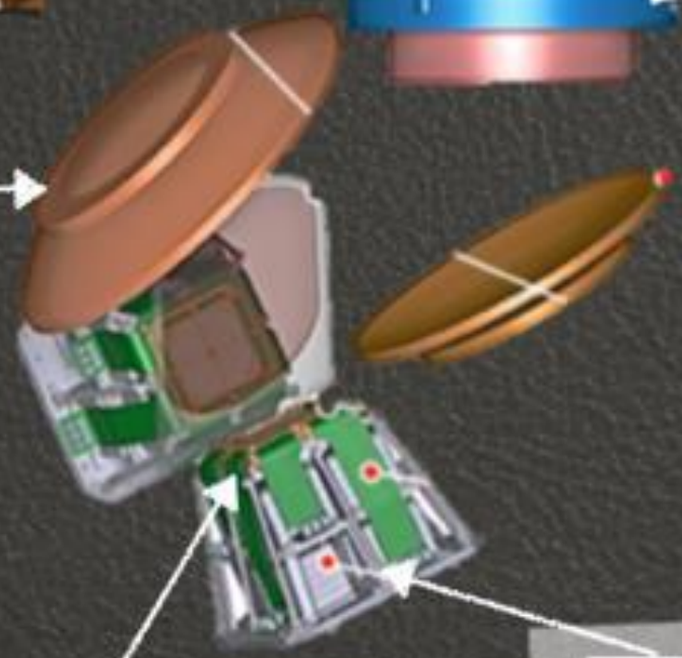
Cryostat@Roma



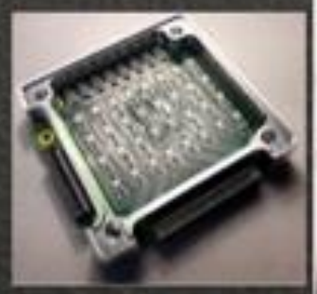

Mirror testing in Roma

1K Box
integration@APC

Calibration mount
(LAL/Orsay)



TES array ready
(CSNSM/Orsay)



Squid Board
+ ASIC (APC/Paris)

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- April 2018: Upgrade to full size mirrors and 400 horns

→ In-Lab demonstration of Bolometric Interferometry

**2018 : Argentina**
- mid-2018: Integration with mount, Installation on site
- First Light Sept. 2018 with ¼ focal plane

→ On-Sky demonstration of Bolometric Interferometry

**2019 : Argentina**
- Upgrade to QUBIC 1st module (2 focal planes 150 and 220 GHz)
- First Light March 2019
- Data taking: 2-3 years σ(r)=0.01

→ Stage III
σ(r) = 0.01

**2020-… : QUBIC evolves towards Stage-IV**
- European extension of the collaboration
- Improved designs already being investigated
- Excellent quality site open to development

→ Evolution to Stage IV
σ(r) = 0.001

# Summary

- QUBIC is a novel instrumental concept

★ Dedicated to CMB polarimetry and inflationary physics

★ High sensitivity with ~2000 TES bolometers
★ High Control of Instrumental Systematics thanks to Interferometry
★ Spectro-Imaging within 2 bands (150 and 220 GHz) thanks to Interferometry

★ Target :
- First module (150 & 220 GHz): σ(r)=0.01 (incl. dust)
- QUBIC Full (more modules) (90, 150, 220 GHz) : σ(r)=0.001 around 2025 ?
- A possible contribution to CMB-S4 or CMB-E4 ?

★ Status :
- Instrument being Integrated at APC - Tests at APC
- On-Sky in Argentina with 256 TES Late 2018
- On-Sky in Argentina with 2048 TES in 2019

# Ευχαριστώ για την προσοχή σας