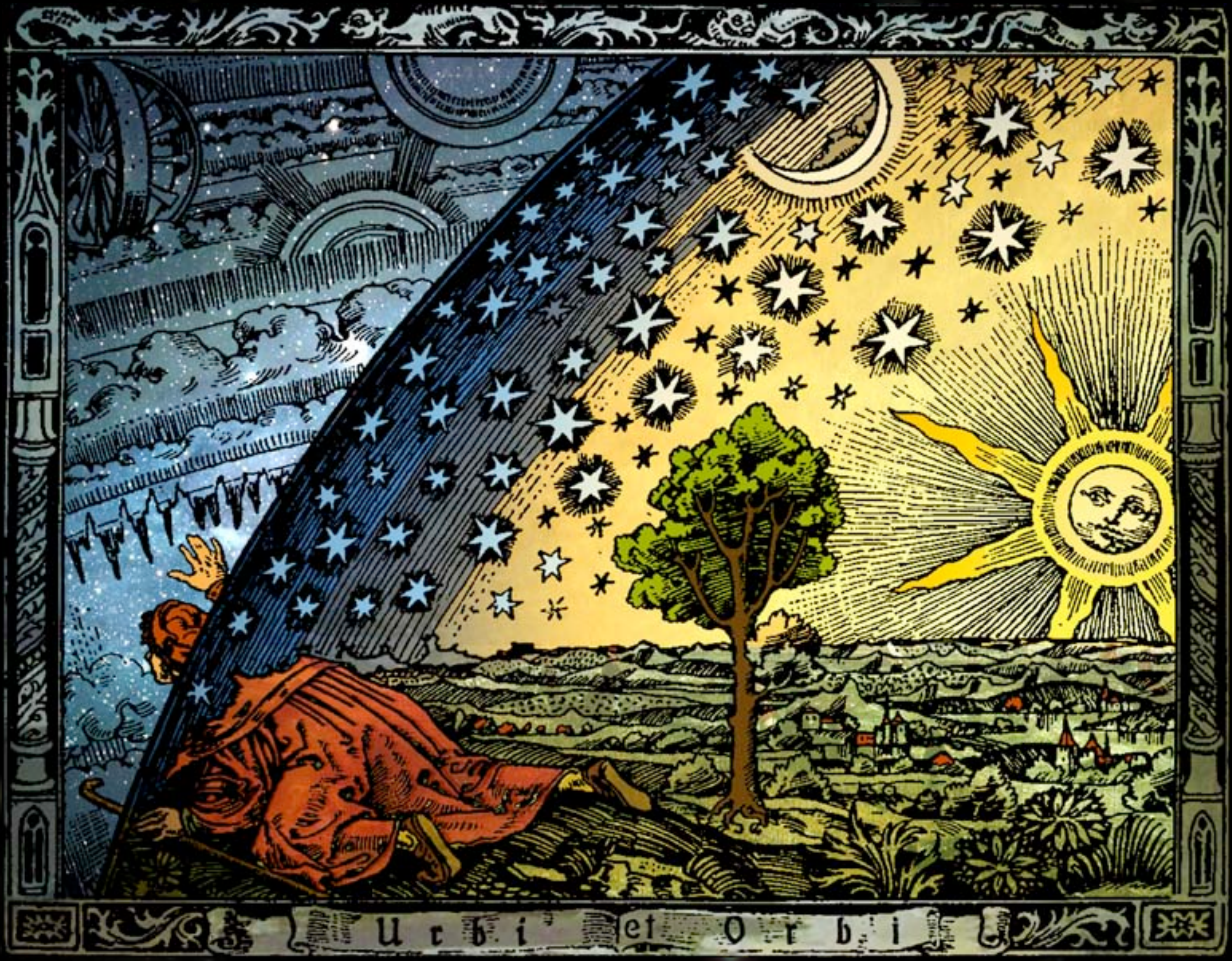
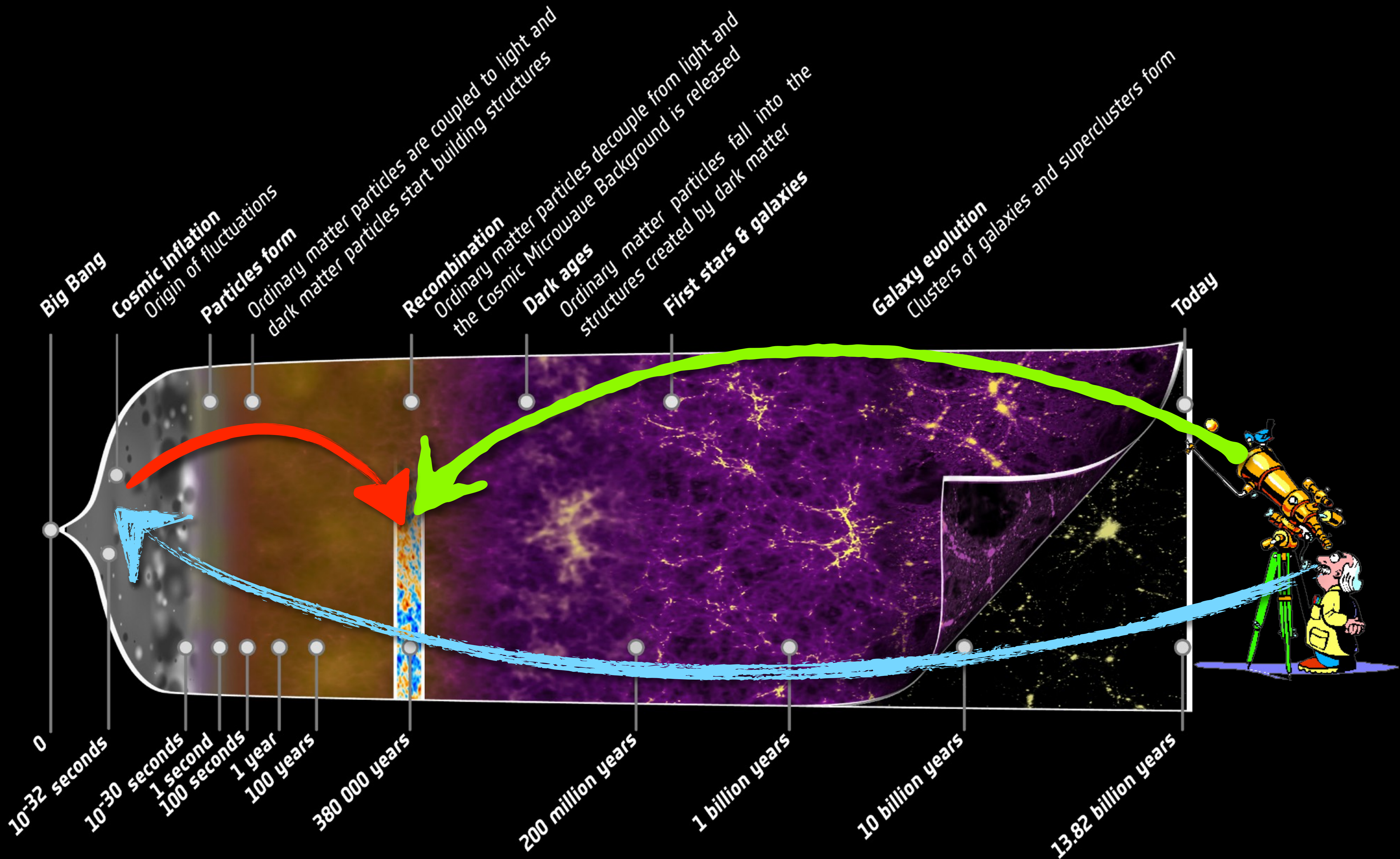
# Exploring the primordial Universe with QUBIC

## the Q U Bolometric Interferometer for Cosmology

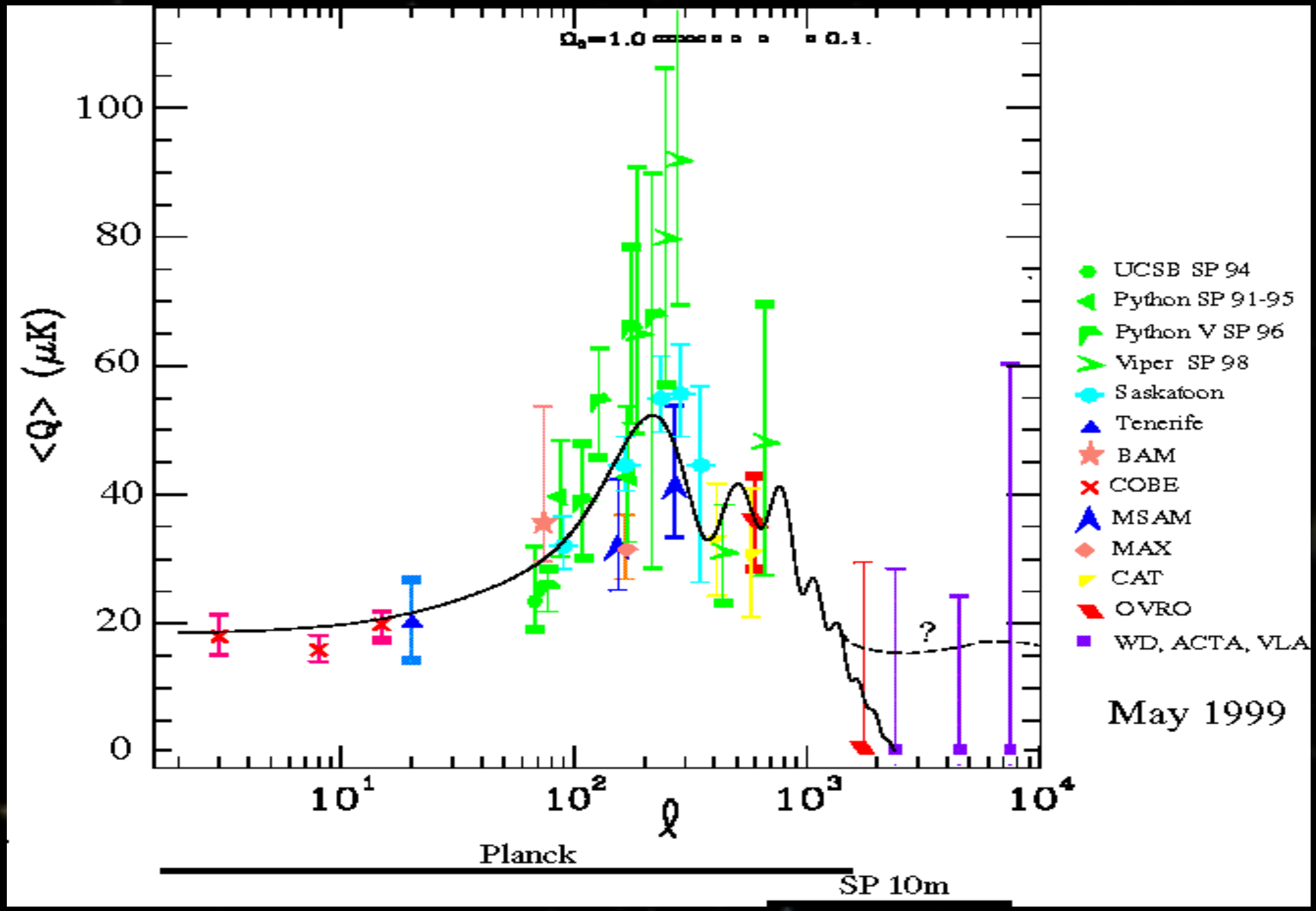



J.-Ch. Hamilton (APC - Paris, CNRS/IN2P3)

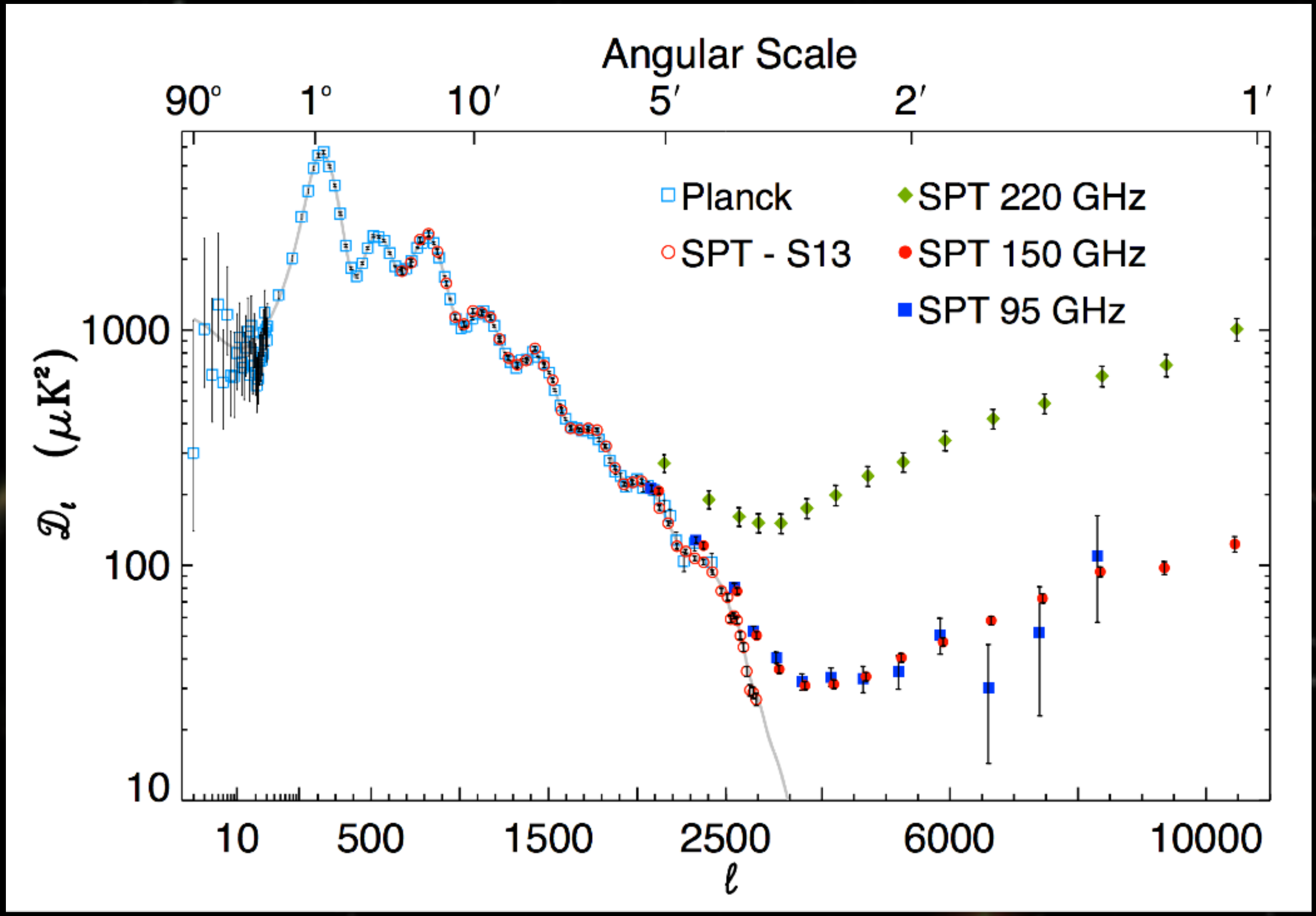



# Observing the CMB polarization gives access to the Primordial Universe physics (inflation epoch)

# CMB: Tremendous progress over the last 15 years




1999

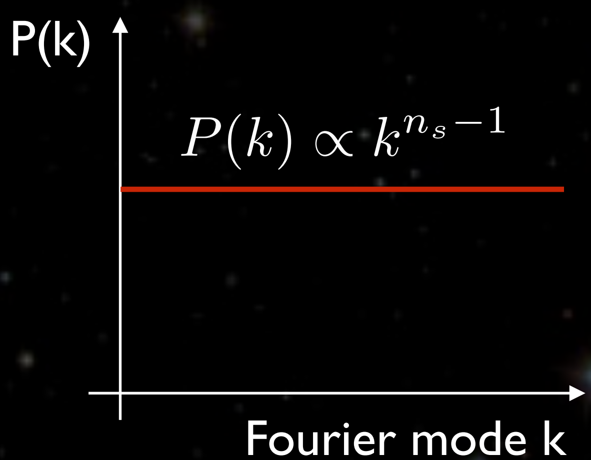


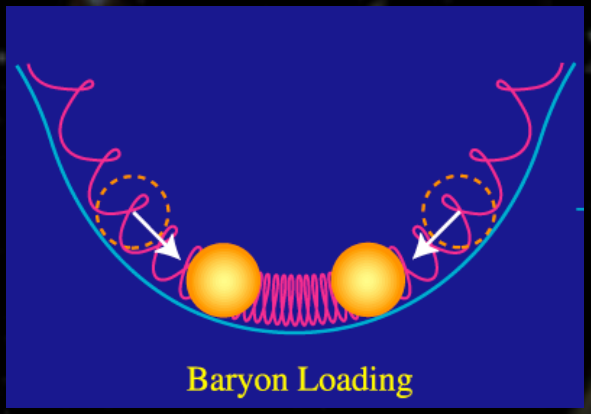

2016

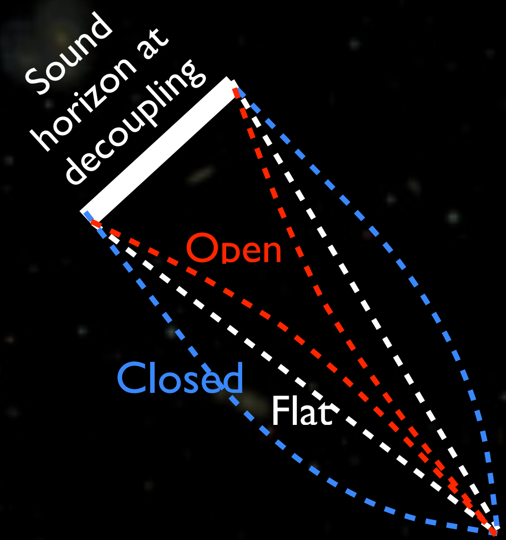
**<u>Huge success :</u>** thousands of independent points fitted with less than 10 parameters and a $\chi^2$/ndf about 1
Theoretical curve predicted in 1987 [Bond & Efstathiou] without any data. [Also by Zeldovitch, Sunyaev et al. in 1972 !!!]

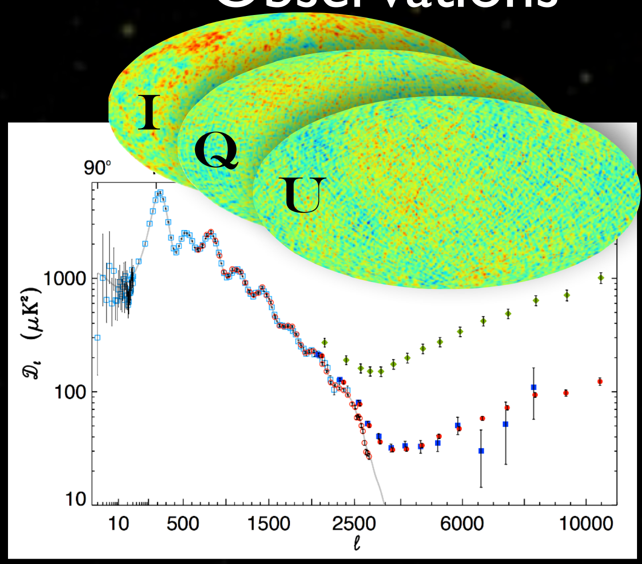
# Density Field Transfer Function

Early Universe Primordial Density Fluctuations (inflation) → Acoustic Oscillations → Geometry → CMB Observations

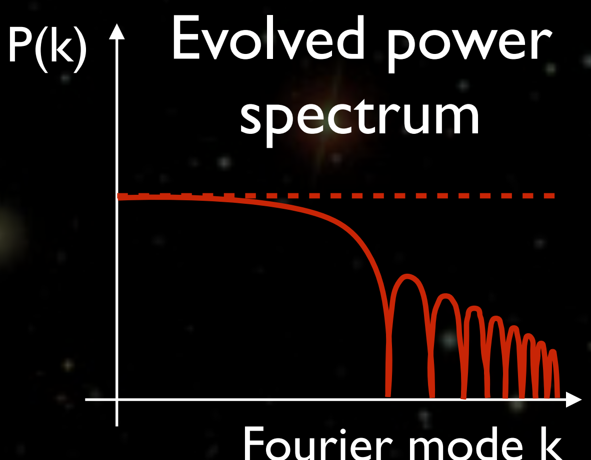


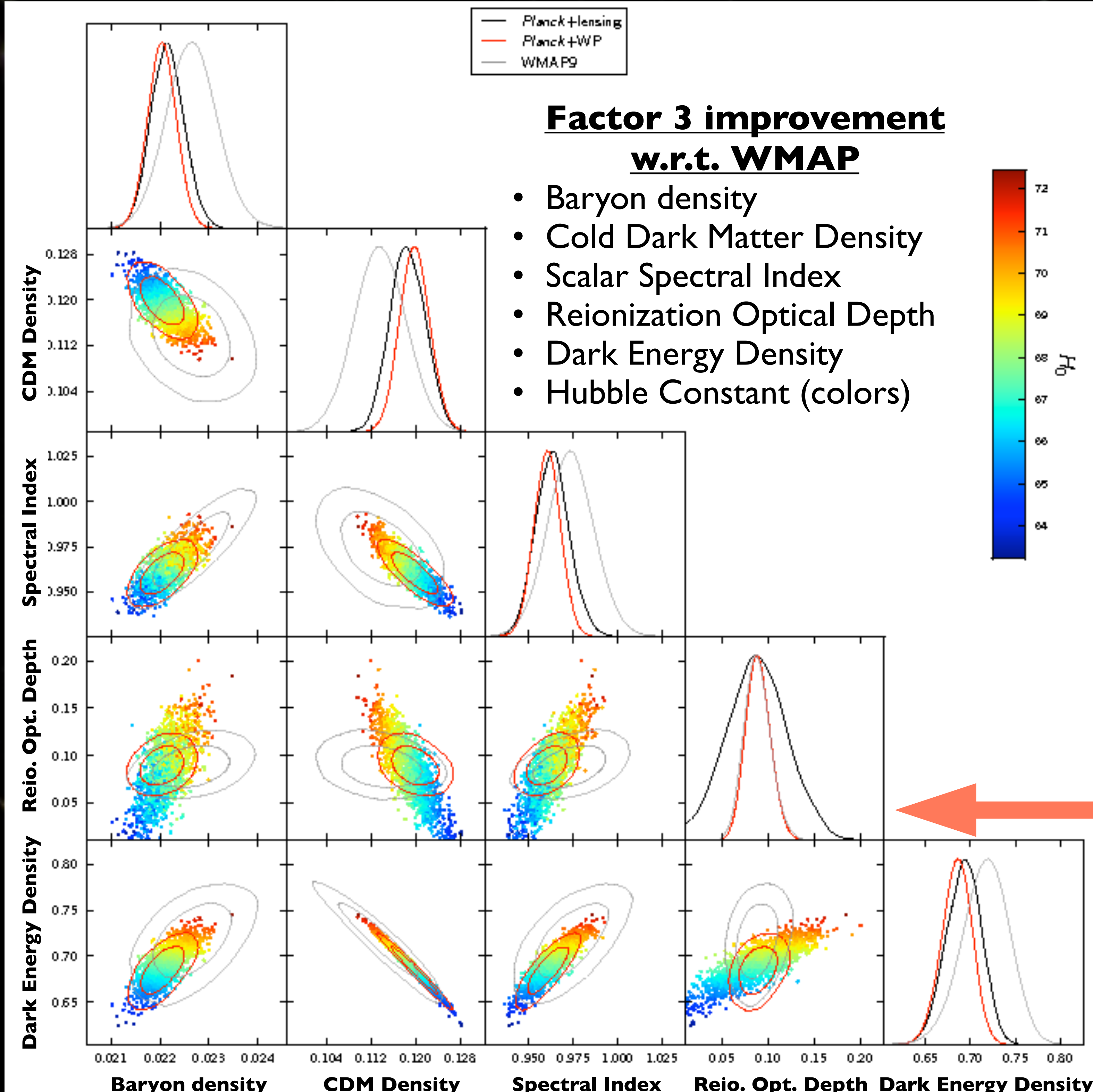




- Perturbations evolve from end of inflation to decoupling due to matter-radiation oscillations.
- The **transfert function** depends upon « simple physics » and cosmological parameters
- Allows to fit both cosmology and primordial spectra (including inflationary physics)

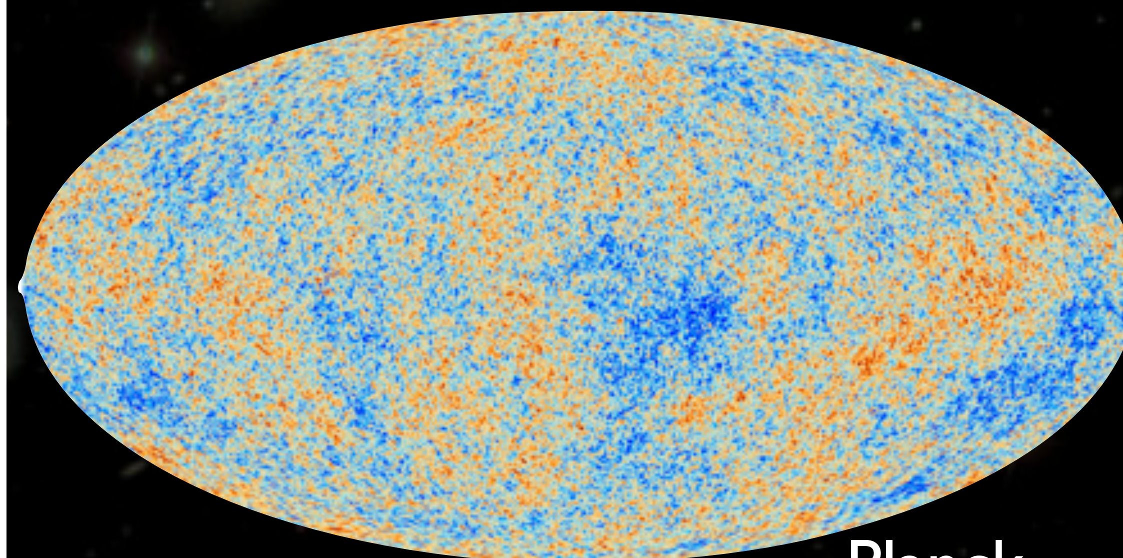


# Planck Results: ΛCDM firmly Established

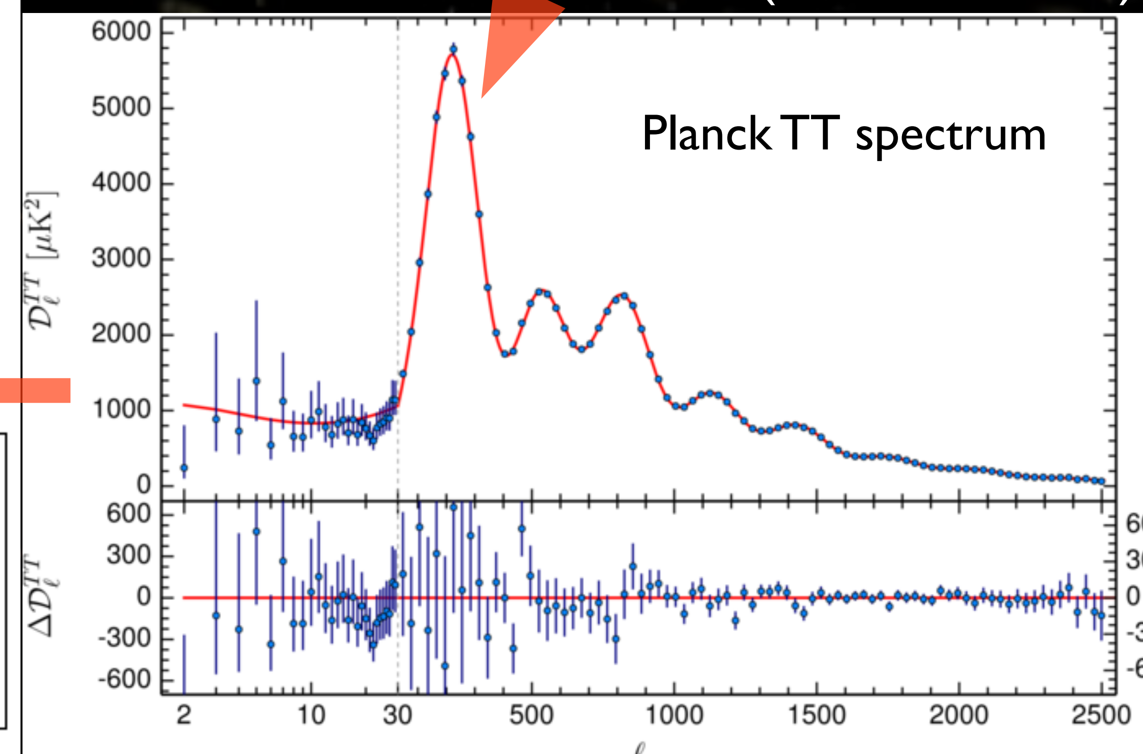



**Factor 3 improvement w.r.t. WMAP**

- Baryon density
- Cold Dark Matter Density
- Scalar Spectral Index
- Reionization Optical Depth
- Dark Energy Density
- Hubble Constant (colors)



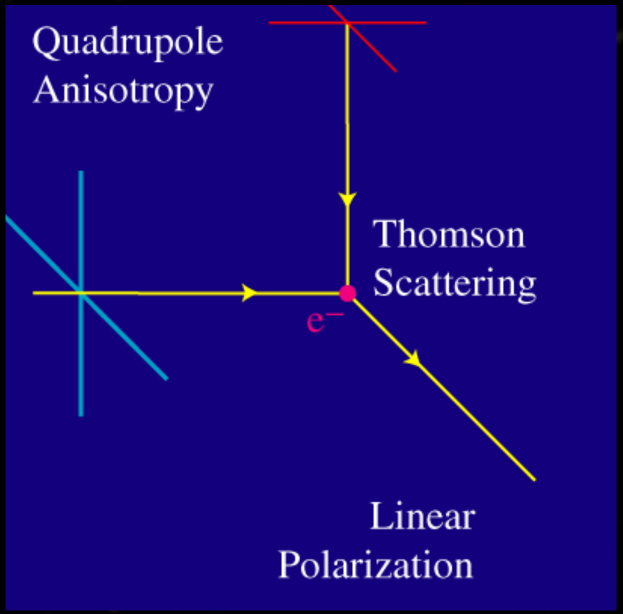
Planck (ESA Mission)




Next (current actually !) 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.)

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

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

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

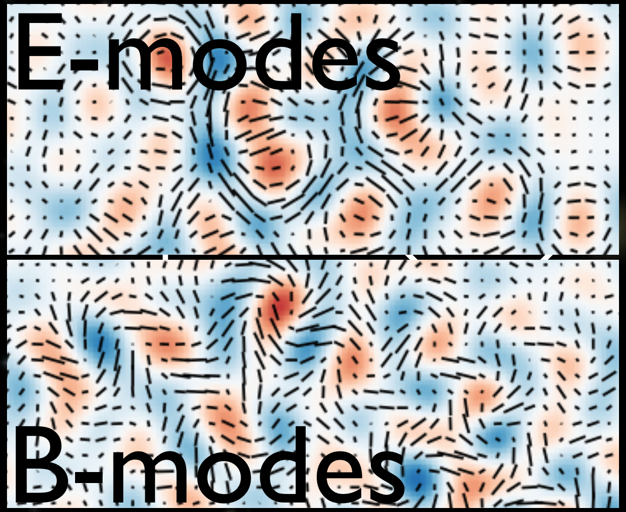
- Scalar E and B fields

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

(even)

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

(odd)

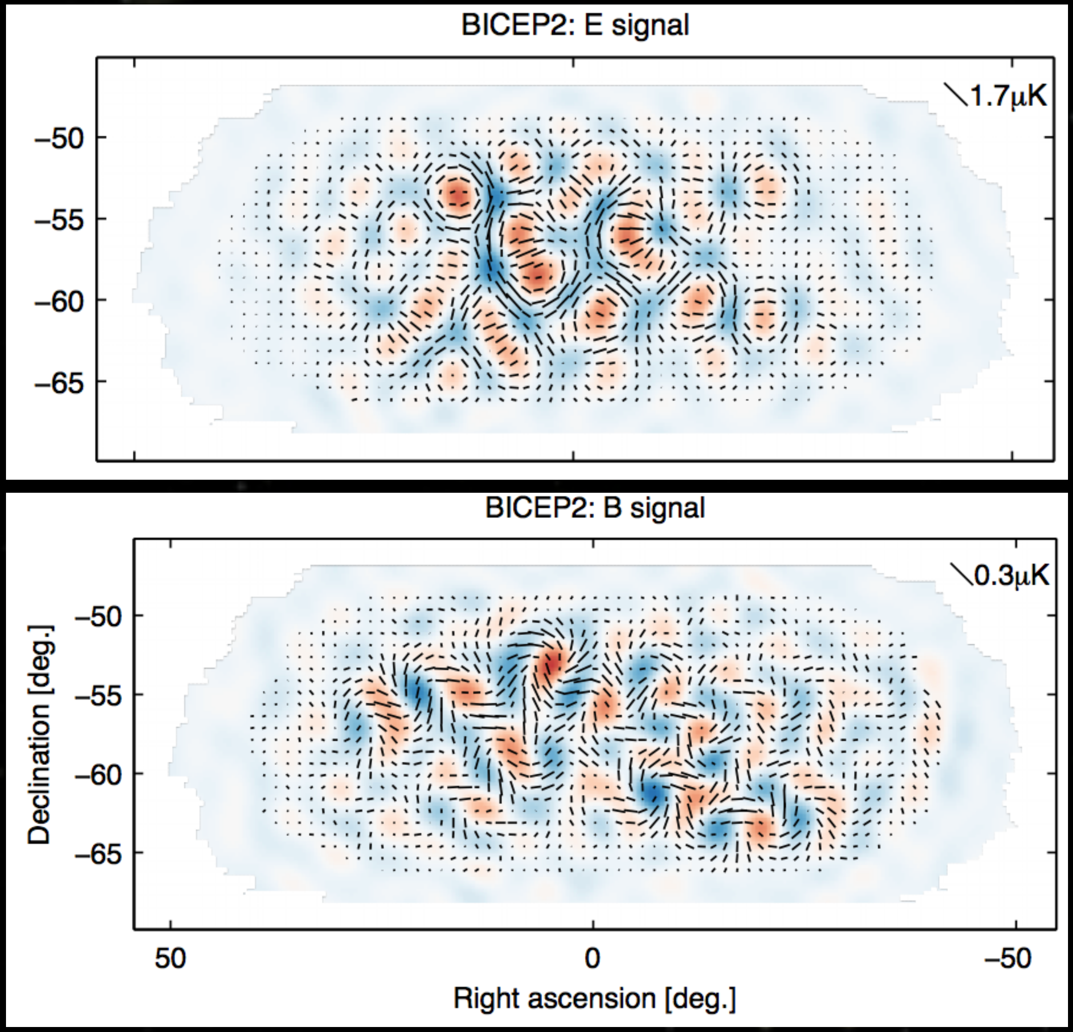



$$\left.\right\} \quad C_\ell^{TT} \quad C_\ell^{TE} \quad C_\ell^{EE} \quad C_\ell^{BB}$$

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




⇒ **detecting primordial B-modes:**
- Direct detection of tensor modes
- «smoking gun» for inflation
- Measurement of its energy scale

$$r = \frac{P_t(k_0)}{P_s(k_0)}$$

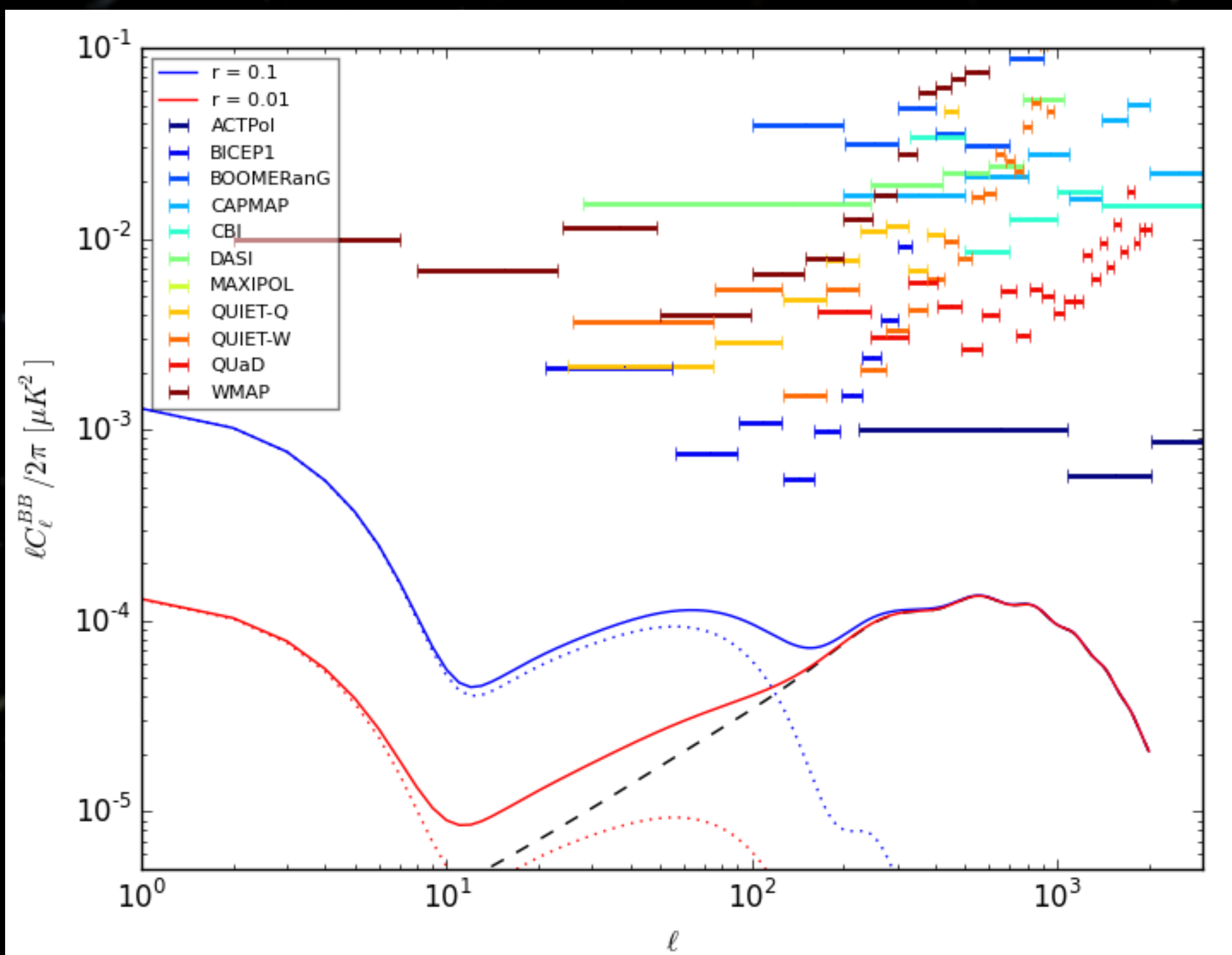
*~ ratio between E and B modes*

$$V^{1/4} = 1.06 \times 10^{16}\,\mathrm{GeV} \left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/4}$$

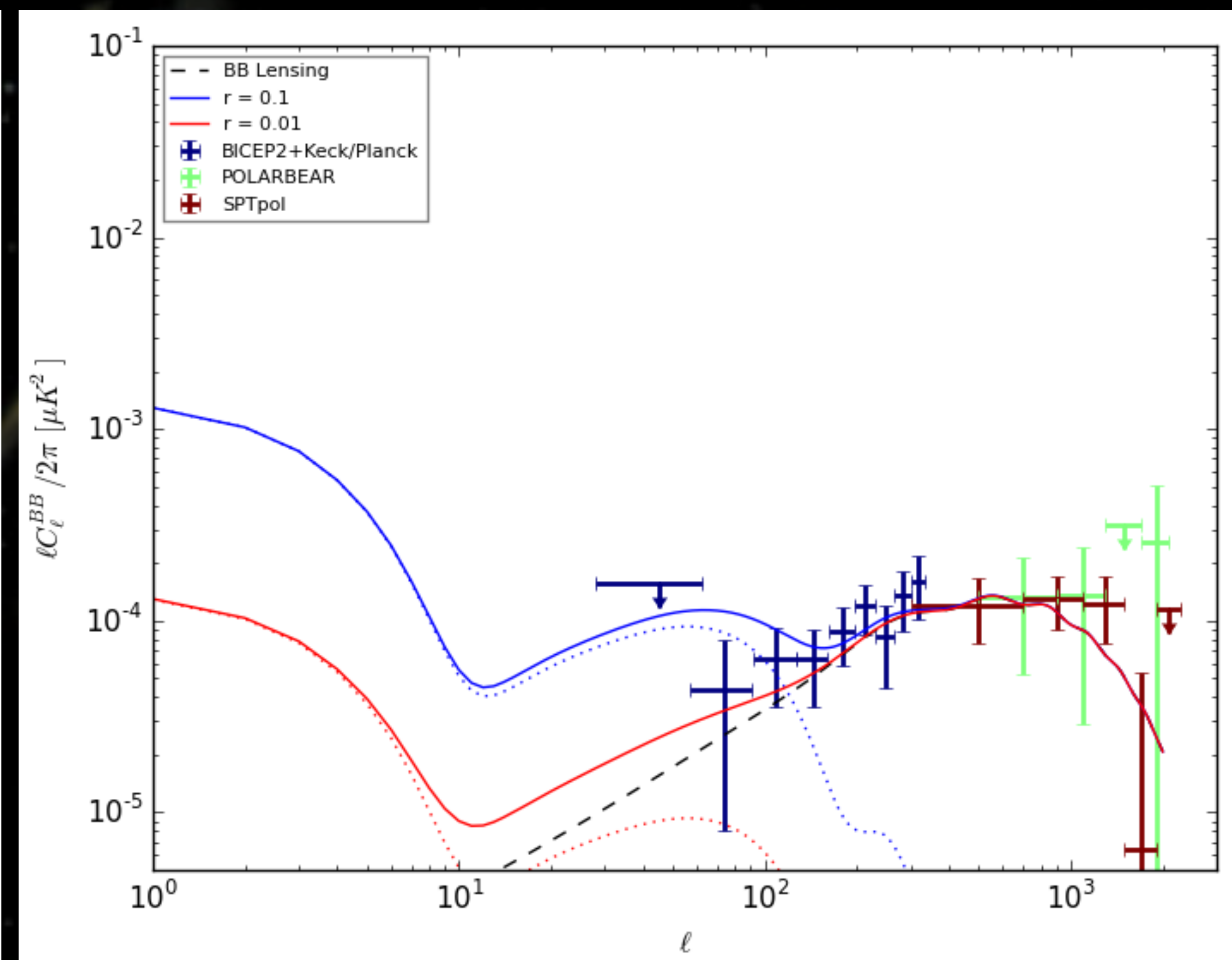
# Take home message:

# 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 !

# Why B-modes are so hard ?

- Sensitivity :
  - ★ Signal amplitude ~ 70 nK on a 3K background
  - ➡ Need extremely sensitive and stable detectors at ~150 GHz

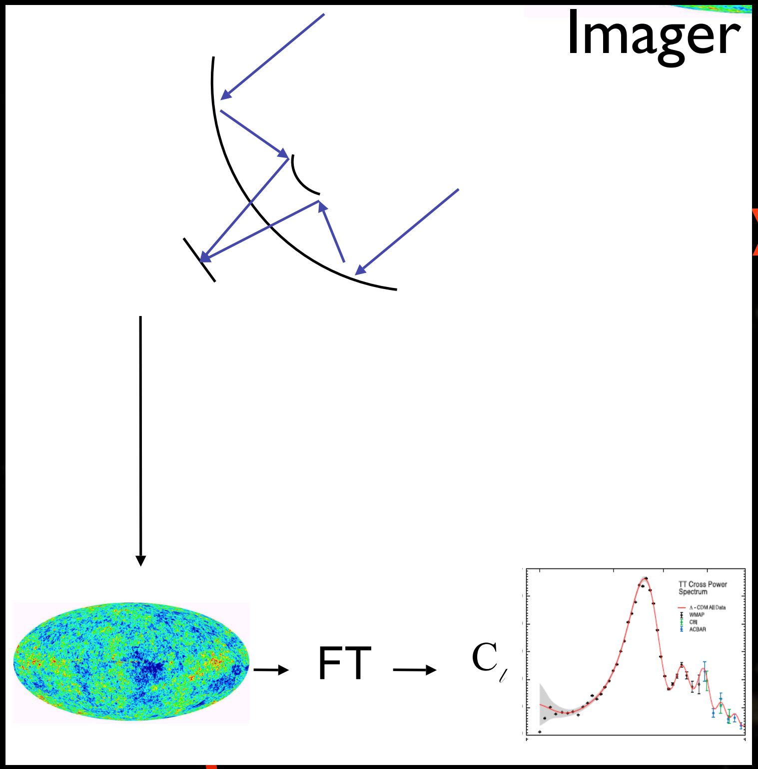
- Astrophysical Foregrounds :
  - ★ BICEP2 false alert has shown their importance
  - ★ Interstellar Dust is already known to be high
    - ➡ Need high frequency detectors at > 150 GHz
  - ★ Synchrotron emission might become an issue
    - ➡ Observations at < 70 GHz will be important in a few years

- Systematic effects :
  - ➡ Need for accurate polarization modulation and detailed knowledge of instrument properties

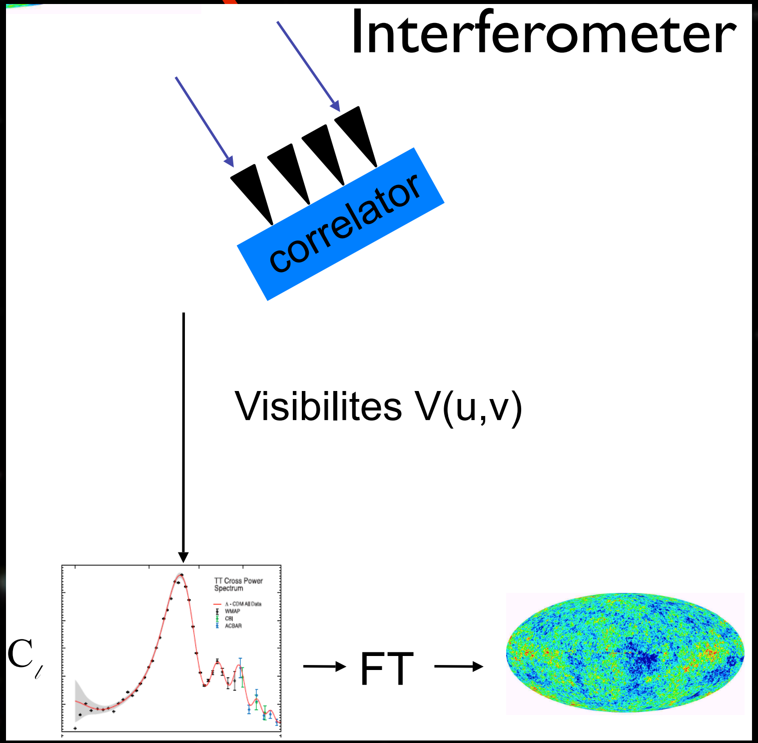
# Possible instruments

- 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 nice devices be combined ?
  - ➡ Bolometric Interferometry !

P. Timbie




Good control



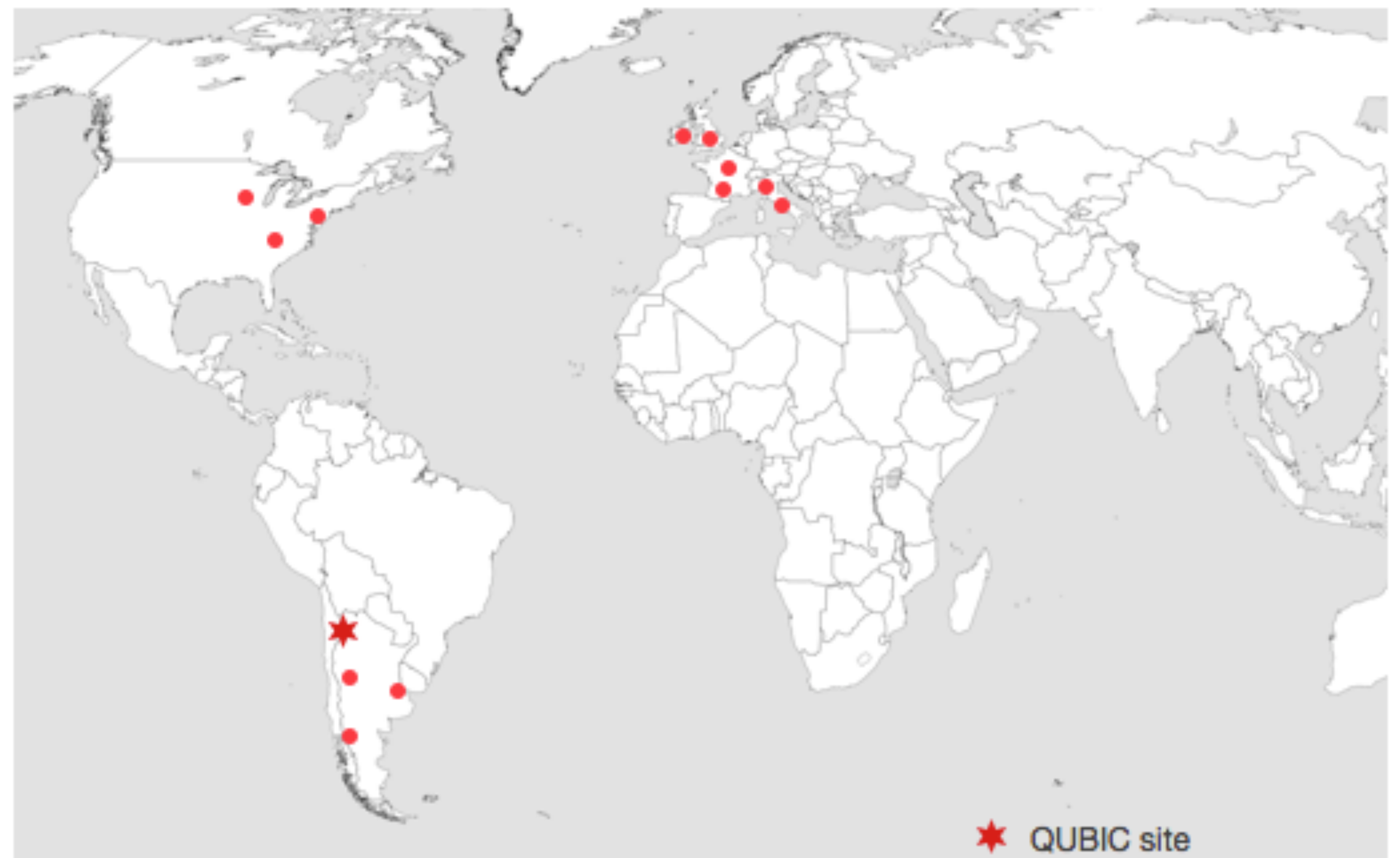
# The QUBIC Collaboration

QUBIC
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



# Primordial B-modes with QUBIC

**Very weak signal** →

- Focal Plane: TES (APC-CSNSM-C2N-IRAP)
  - 2048 TES with NEP ~ $4 \times 10^{-17}$ $W.Hz^{-1/2}$
  - 128:1 SQUIDs+ASIC Mux Readout

**Polarized foregrounds** →

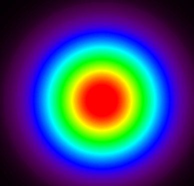
- Two wide bands: 150 and 220 GHz
  - 1 focal plane for each channel
- Spectro-Imaging 2+3 bands

**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

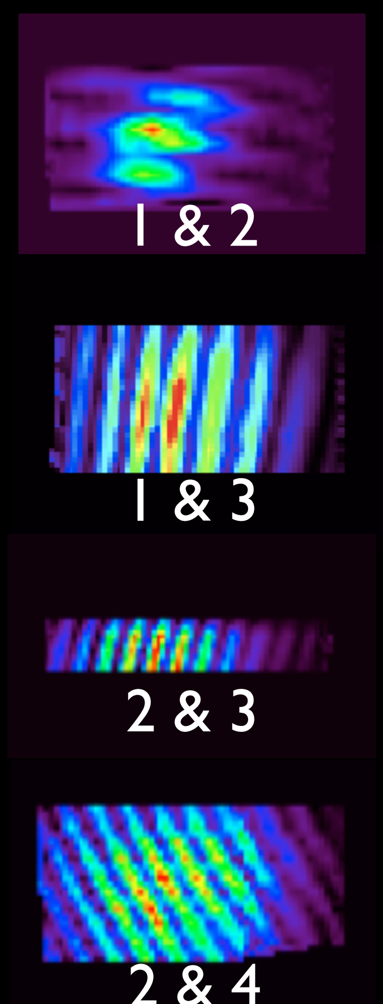
# QUBIC concept: Quasi optical correlator

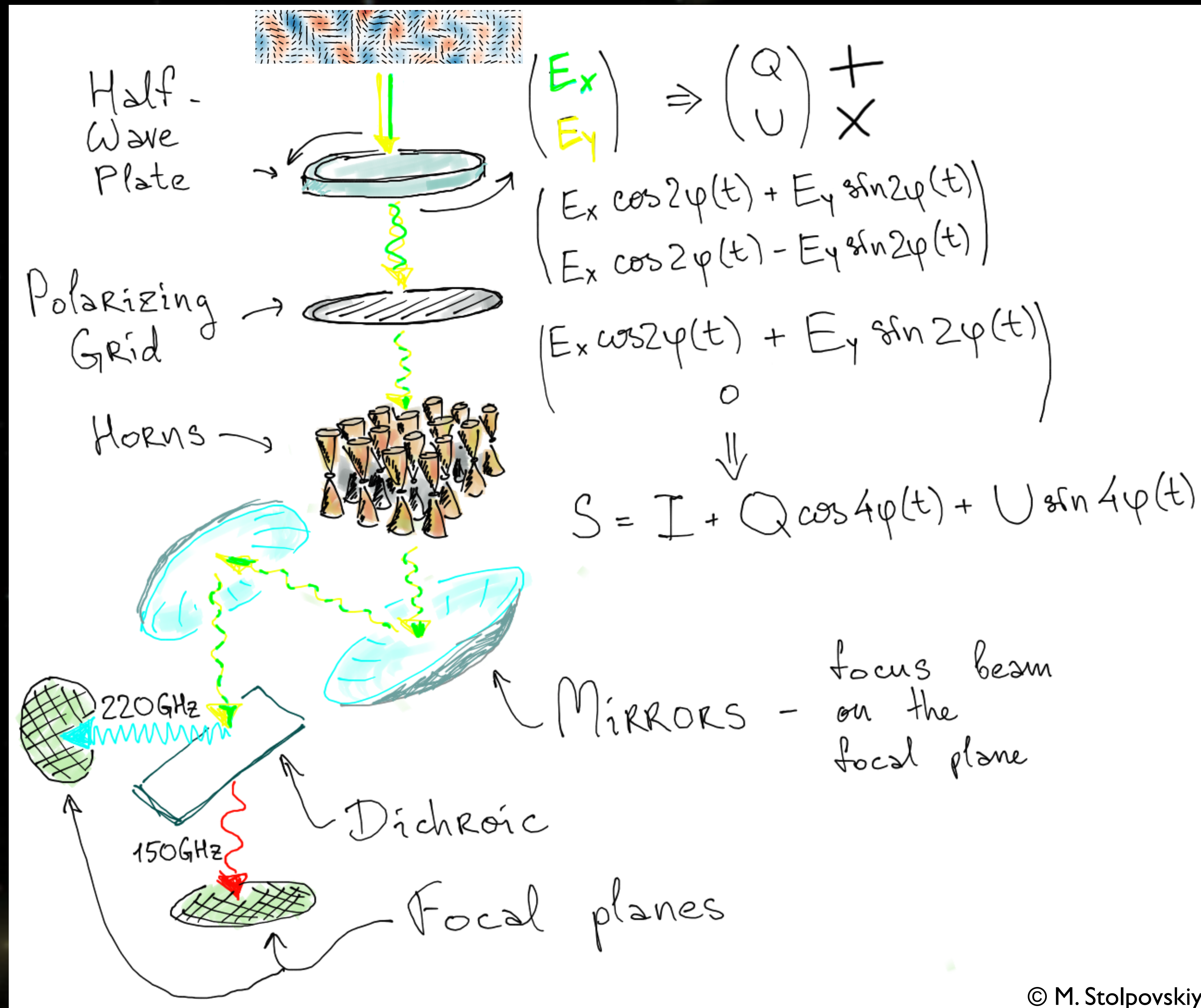
fringes successfuly observed in 2009 with MBI-4 [Timbie et al. 2006]

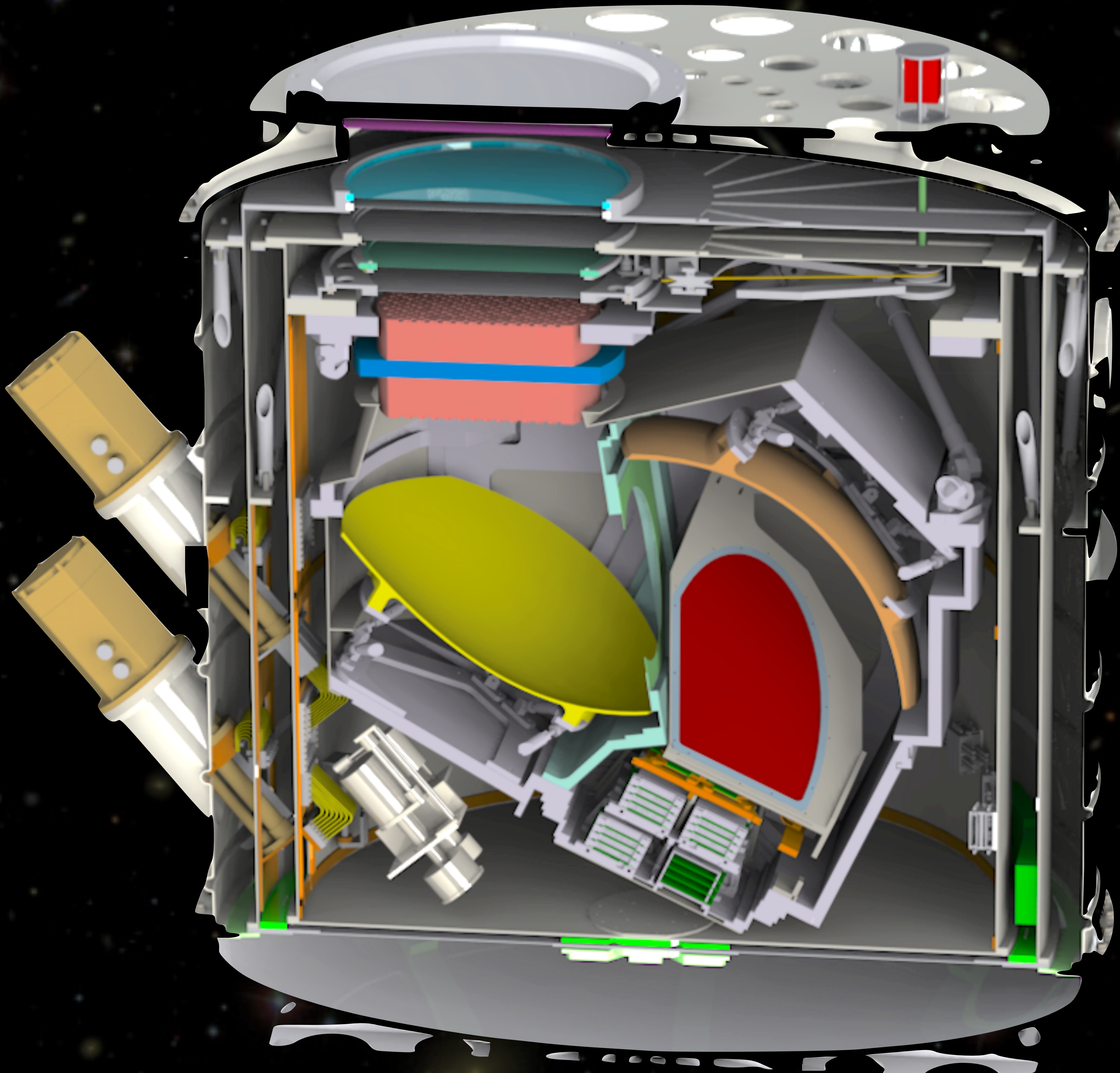


1 horn open

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





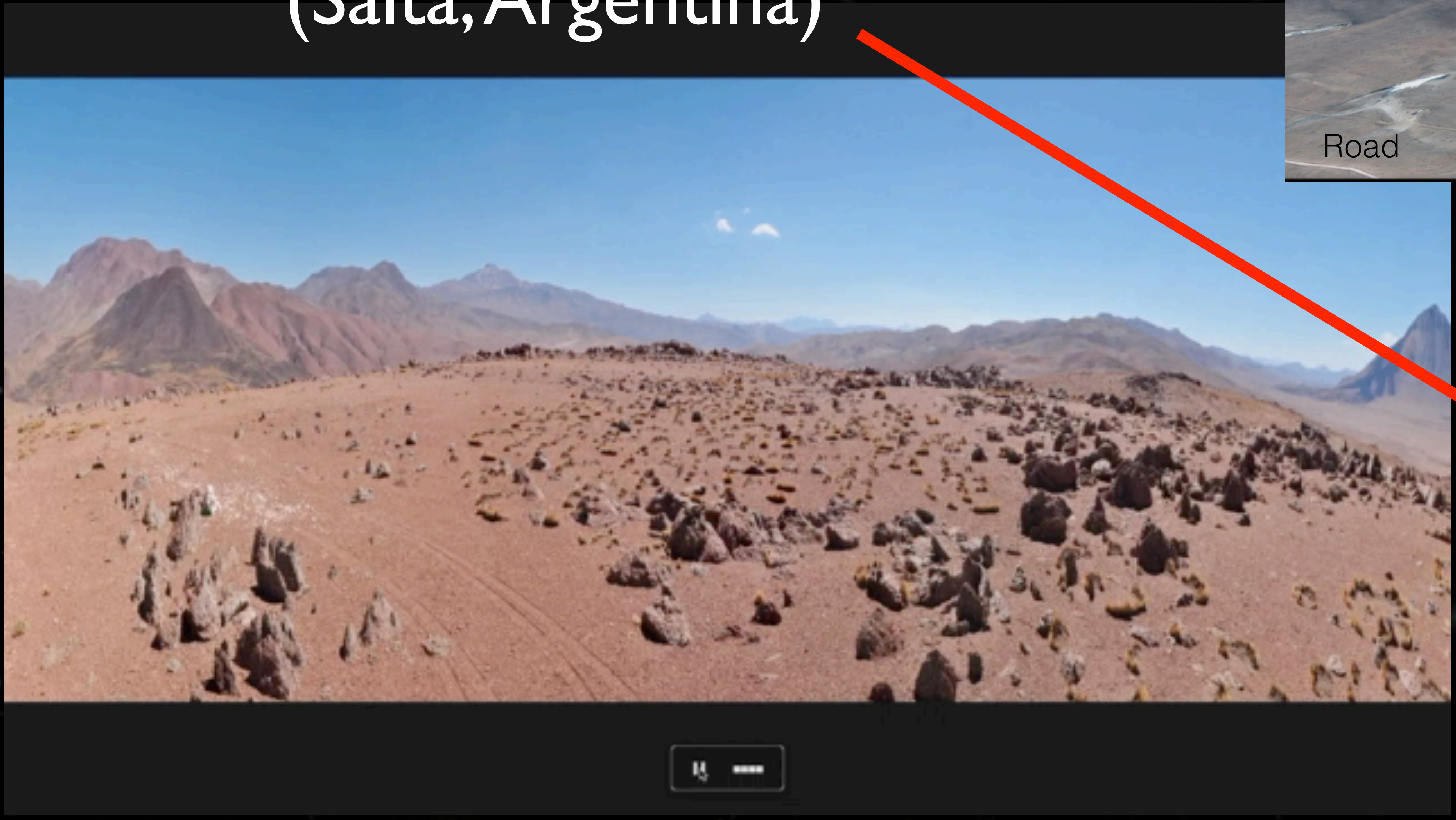
# Instrument fully designed

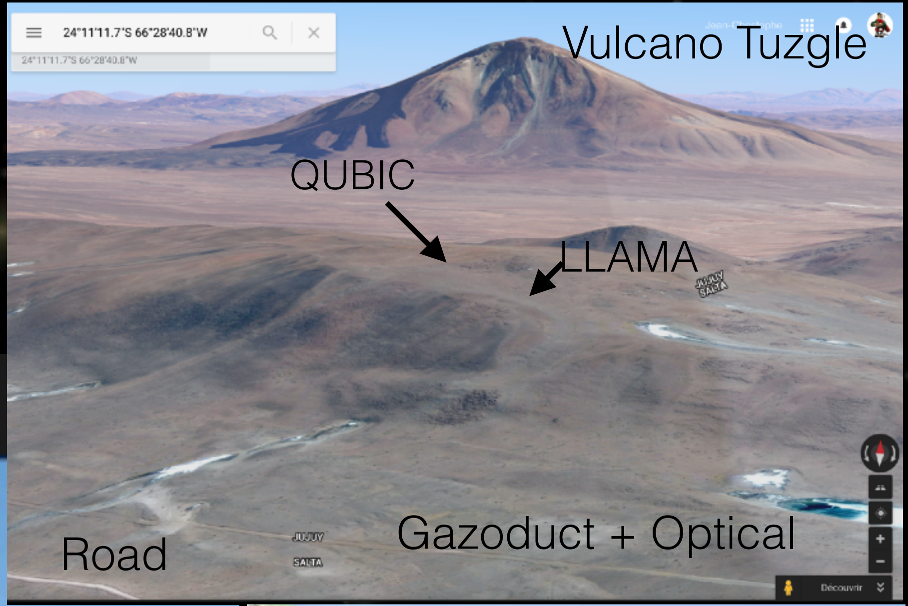
- Outer cryostat: Roma
- 1K Box / detectors: APC
- Fridges: Manchester
- Optics: Roma / Maynooth

1.547m high
1.42m diameter
About 800kg

# Integration has started

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



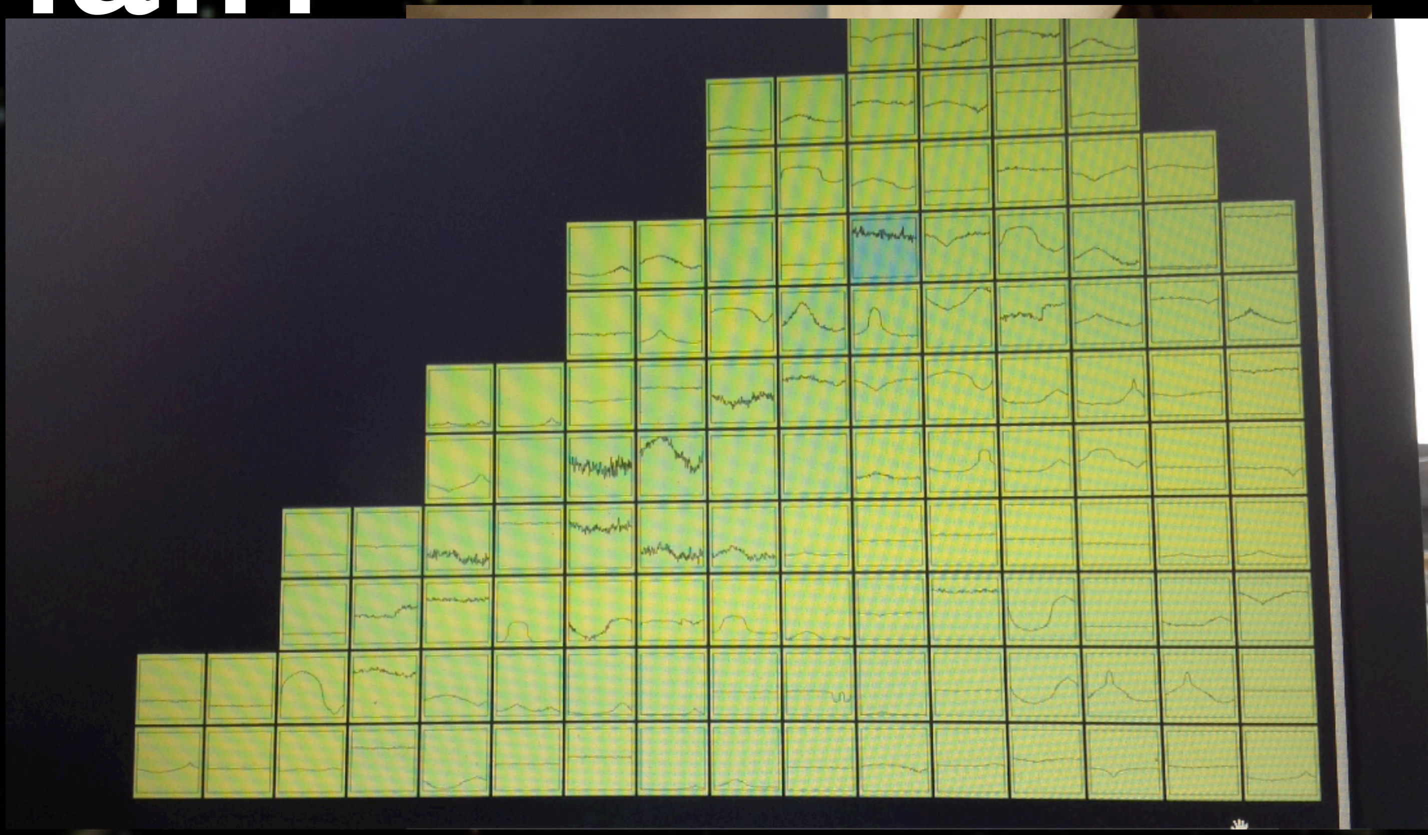


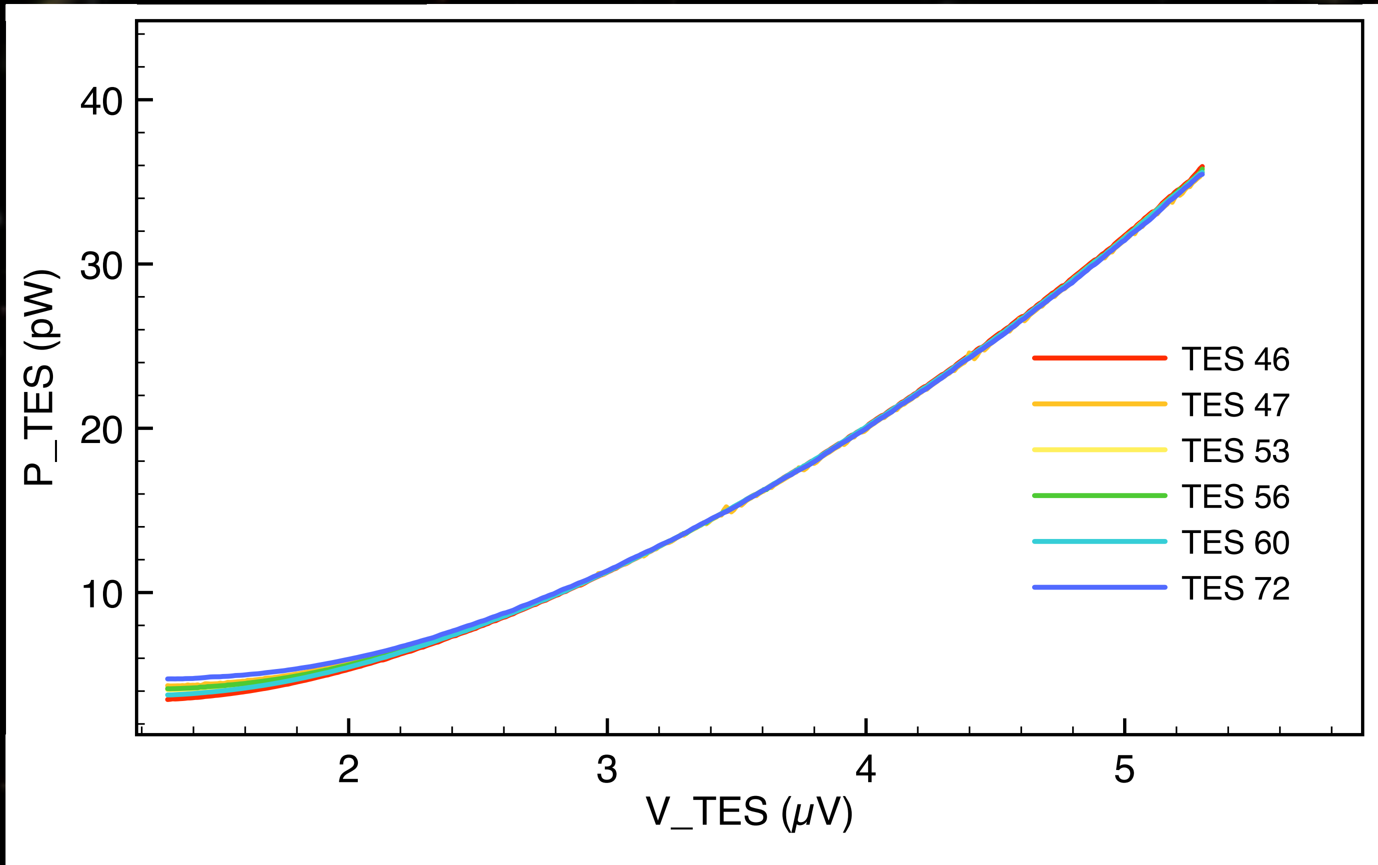


- 5000m a.s.l.
- Logistics + mount : Argentina
- NEW: Access road built up to LLAMA (800m remaining)

# Detection Chain

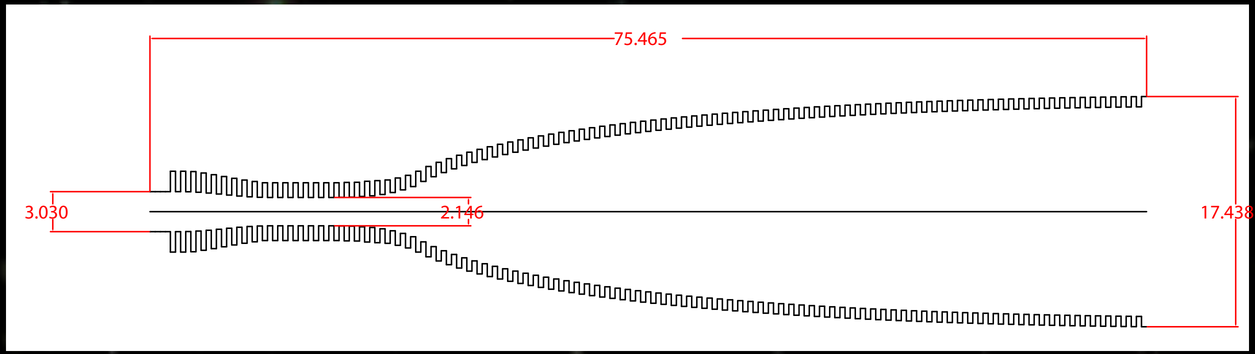
- French responsibility
  - ★ APC + CSNSM / IEF / IRAP
- 2 arrays of 992 NbSi TES
  - ★ Each array : 4x248 elements
  - ★ 300 mK bath ($^3$He-$^4$He evaporation cooler)
  - ★ 3 mm size
  - ★ **Measured NEP ~ 4.10$^{-17}$ W.Hz$^{-1/2}$**
  - ★ time constant ~ 10 ms
- 4K SQUIDs + SiGe ASIC Mux
  - ★ SQUIDs 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

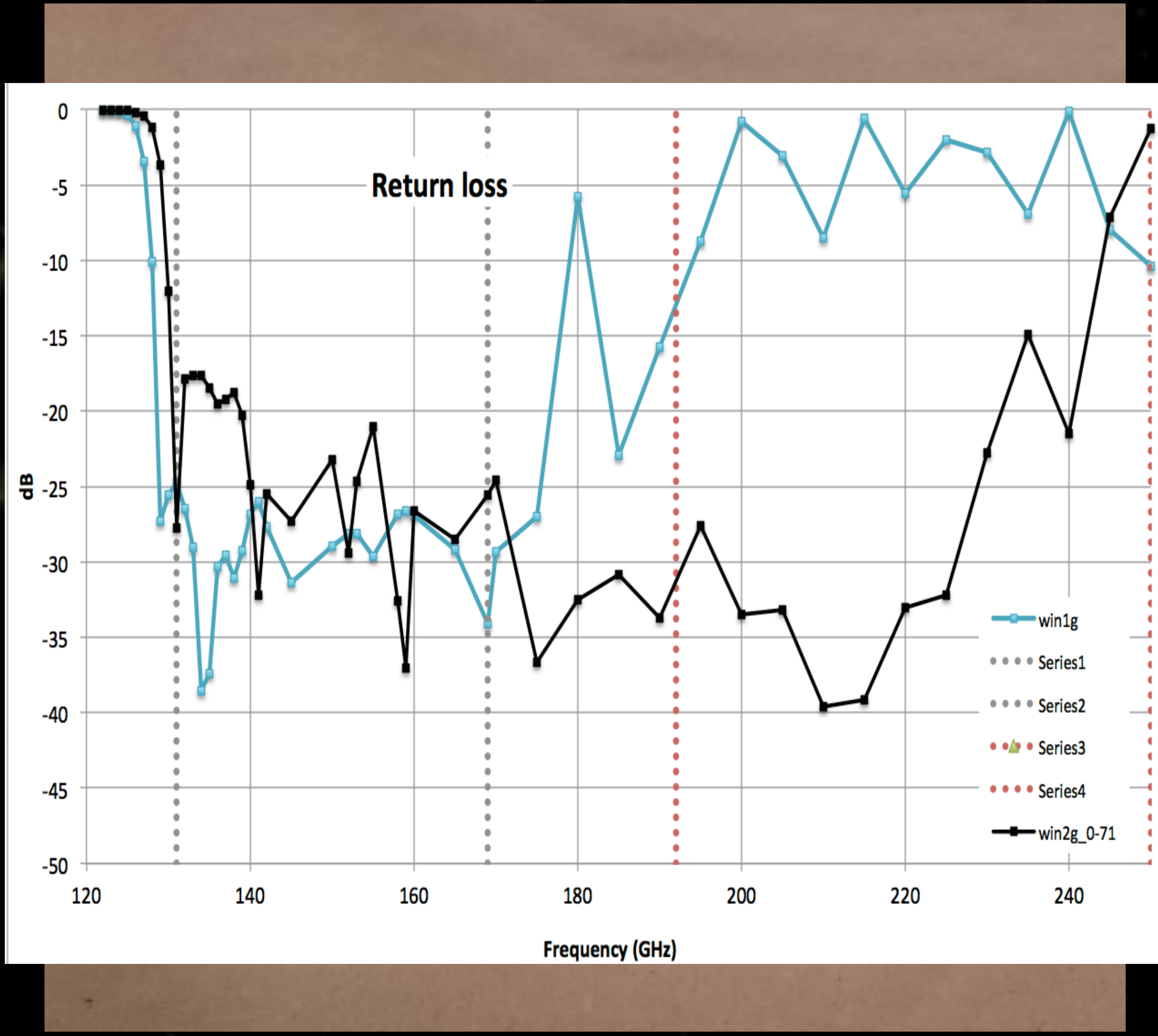




# Dual Band Platelet Horns

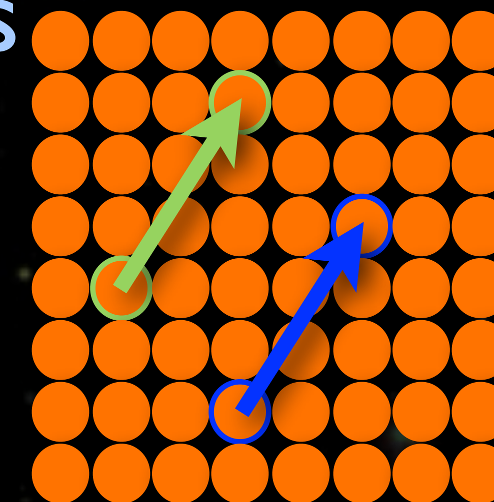
- Conception / Realisation
  - ★ Milano / APC / Manchester
- Platelet fabrication
  - ★ Cheap arrays
  - ★ Milano
- Exquisite beam and Xpol
  - ★ based on Clover design
- Wide band
  - ★ Single model at 150 GHz
  - ★ Few model at 220 GHz



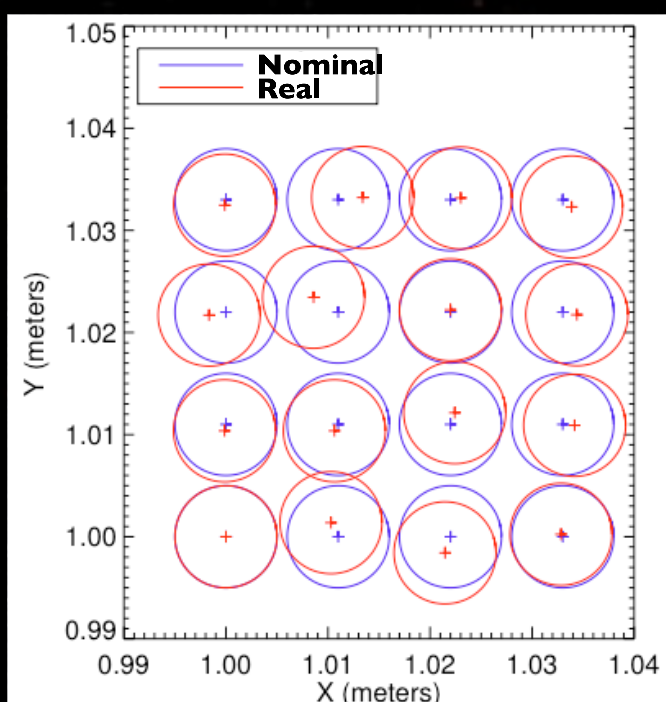



# Systematics: Self-Calibration

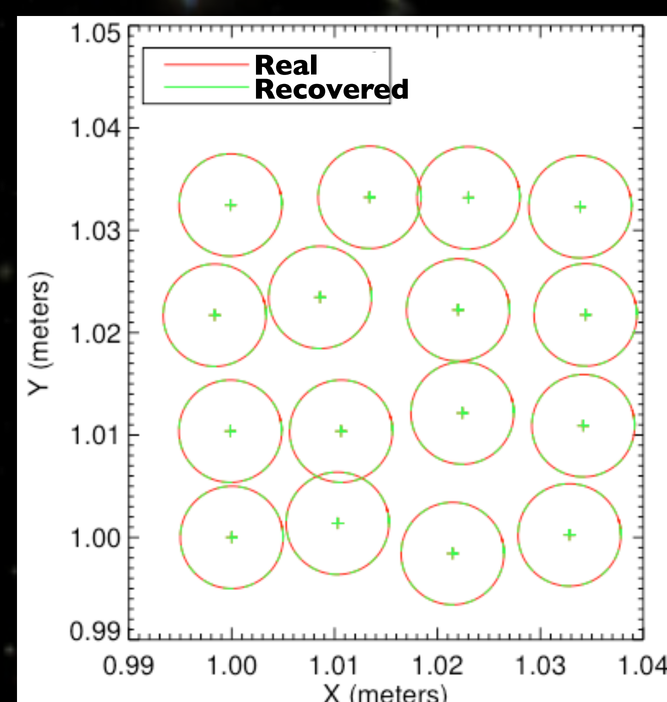
- Unique possibility to handle systematic errors
  - ★ Use horn array redundancy to calibrate systematics
    - In a perfect instrument redundant baselines should see the same signal
    - Differences due to systematics
    - Allow to fit systematics with an external source on the field
  - ★ Unique specificity of Bolometric Interferometry !
    [Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]
  - ★ Example: exact horns locations (figure exagerated !!)



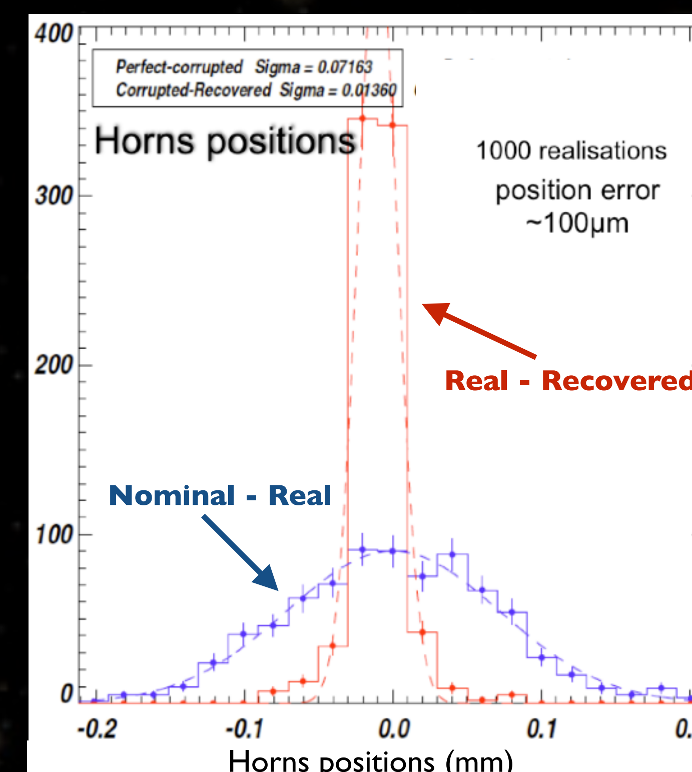
Redundant baselines : same Fourier Mode




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

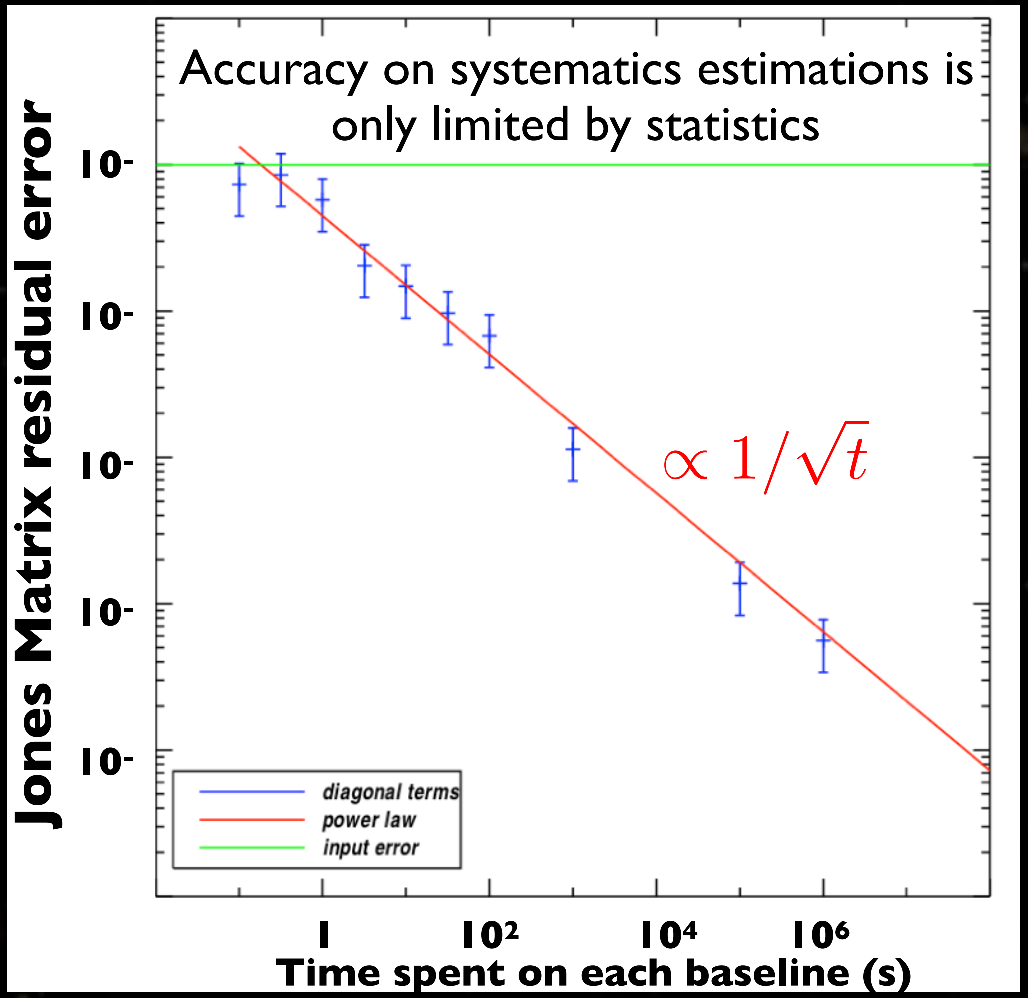



Horn position knowledge improvement

# Self-Calibration Simulation

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

- Simulate instrument with systematics
- Perform Self-Calibration
  - ★ done for various amounts of time spent on calibration
- Check improvement on systematic parameters



# Self-Calibration Simulation

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

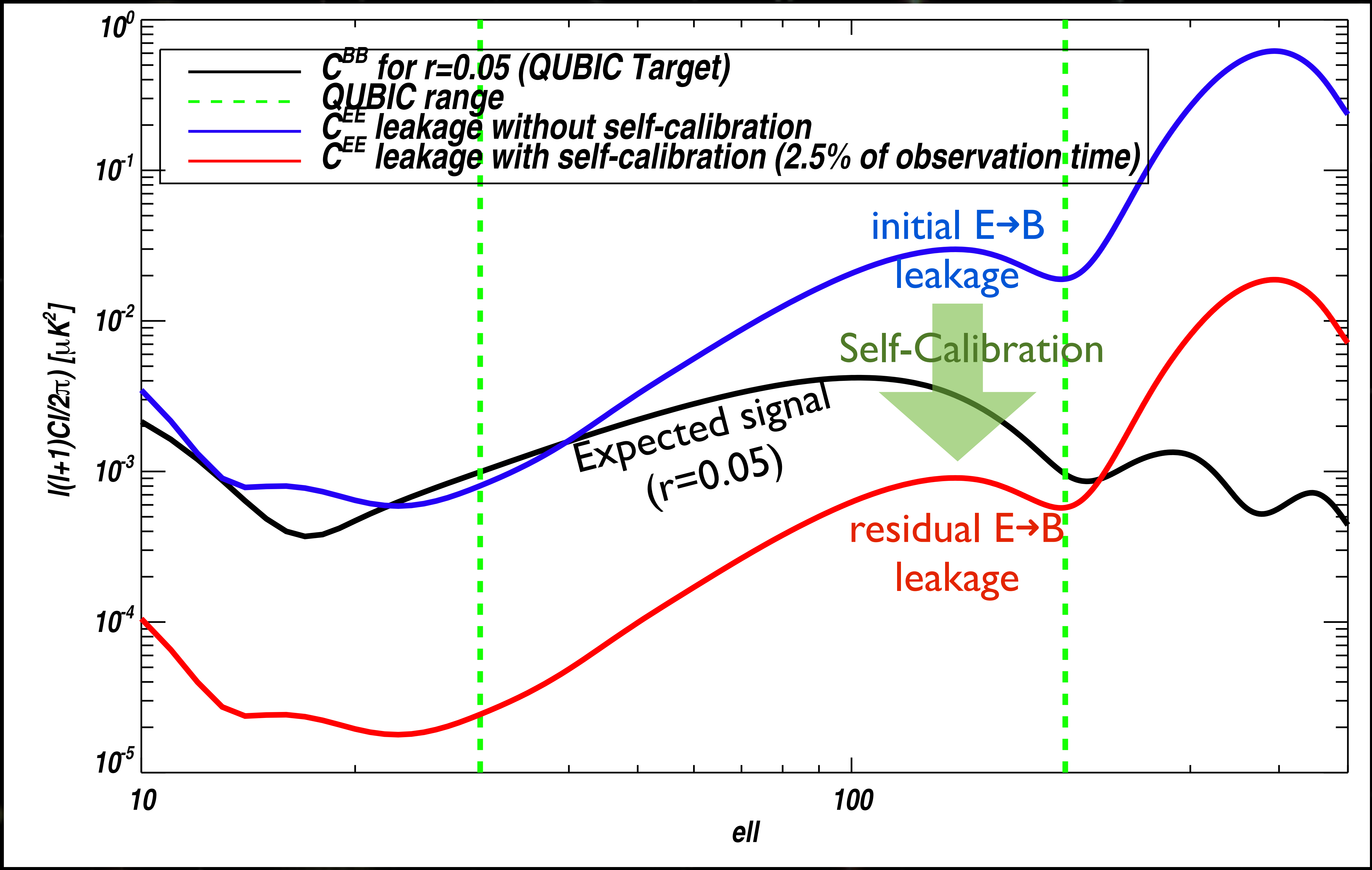
- Simulate instrument with systematics
- Perform Self-Calibration
  - ★ done for various amounts of time spent on calibration
- Check improvement on systematics parameters

List is not exhaustive: Horn location error, Horn transmission, Horn CrossPol, HWP transmission, HWP CrossPol

| parameters | No Self Cal. | 1 day / year | | 100 days/year | |
|---|---|---|---|---|---|
| | $\sigma_{nominal-real}$ | $\sigma_{real-recovered}$ | ratio | $\sigma_{real-recovered}$ | ratio |
| $\overrightarrow{x_i}$ | $100. \times 10^{-6}$ | $5.86 \times 10^{-5}$ | 17 | $2.27 \times 10^{-8}$ | 4402 |
| $g_\eta(\overrightarrow{x_i})$ | 0.0001 | $1.36 \times 10^{-6}$ | 73 | $1.22 \times 10^{-8}$ | 8182 |
| $e_\eta(\overrightarrow{x_i})$ | 0.0001 | $1.09 \times 10^{-6}$ | 92 | $1.20 \times 10^{-8}$ | 8280 |
| $h_\eta$ | 0.01 | $1.18 \times 10^{-4}$ | 84 | $7.27 \times 10^{-6}$ | 1375 |
| $\xi_\eta$ | 0.01 | $1.24 \times 10^{-4}$ | 80 | $5.81 \times 10^{-6}$ | 1722 |

  - ★ Improvement allows to improve maps by having a better synthesized beam model
- Deduce amount of leakage from E to B
  - ★ NB: Sources of T,E leakage are different in interferometry (see Bunn 2006)

# Self-Calibration results



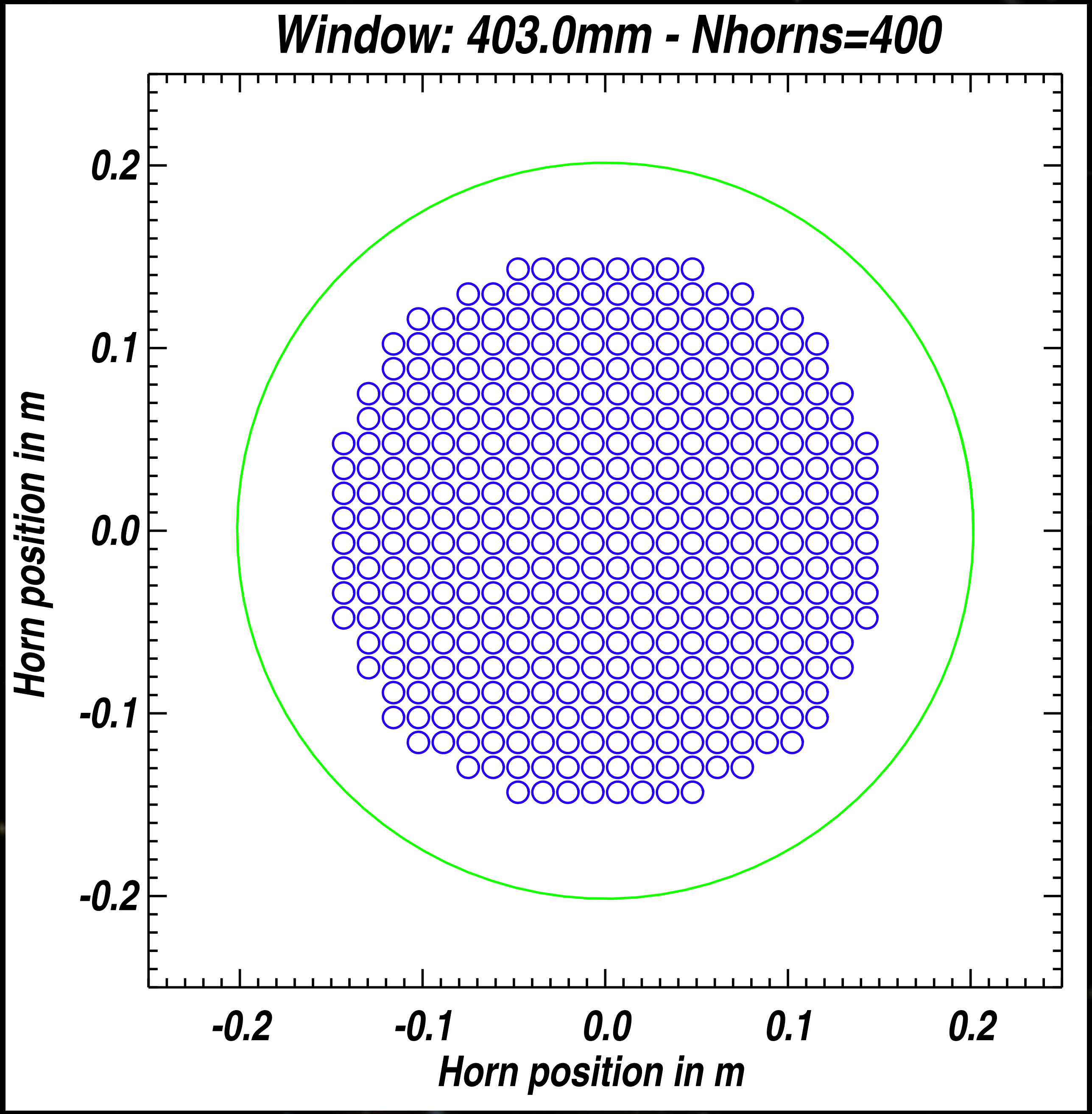

[Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]

# Self-Calibration summary

- Complicated synthesized beam but can be known to exquisite accuracy
- Specific feature of Bolometric Interferometry
- Adjustable handling of systematics - limited by:
  - amount of time spent on self-calibration
  - systematics modeling can be complexified if needed (constraints $\propto N_h^2$, unknowns $\propto N_h$)
  - Possibility to improve on systematics when they become the limitation
- Calibration source:
  - ★ In the far-field ~50 m: need for a ~45m calibration tower
  - ★ Large power ~10-100 mW
  - ★ Polarized (but no need to know its actual polarization)

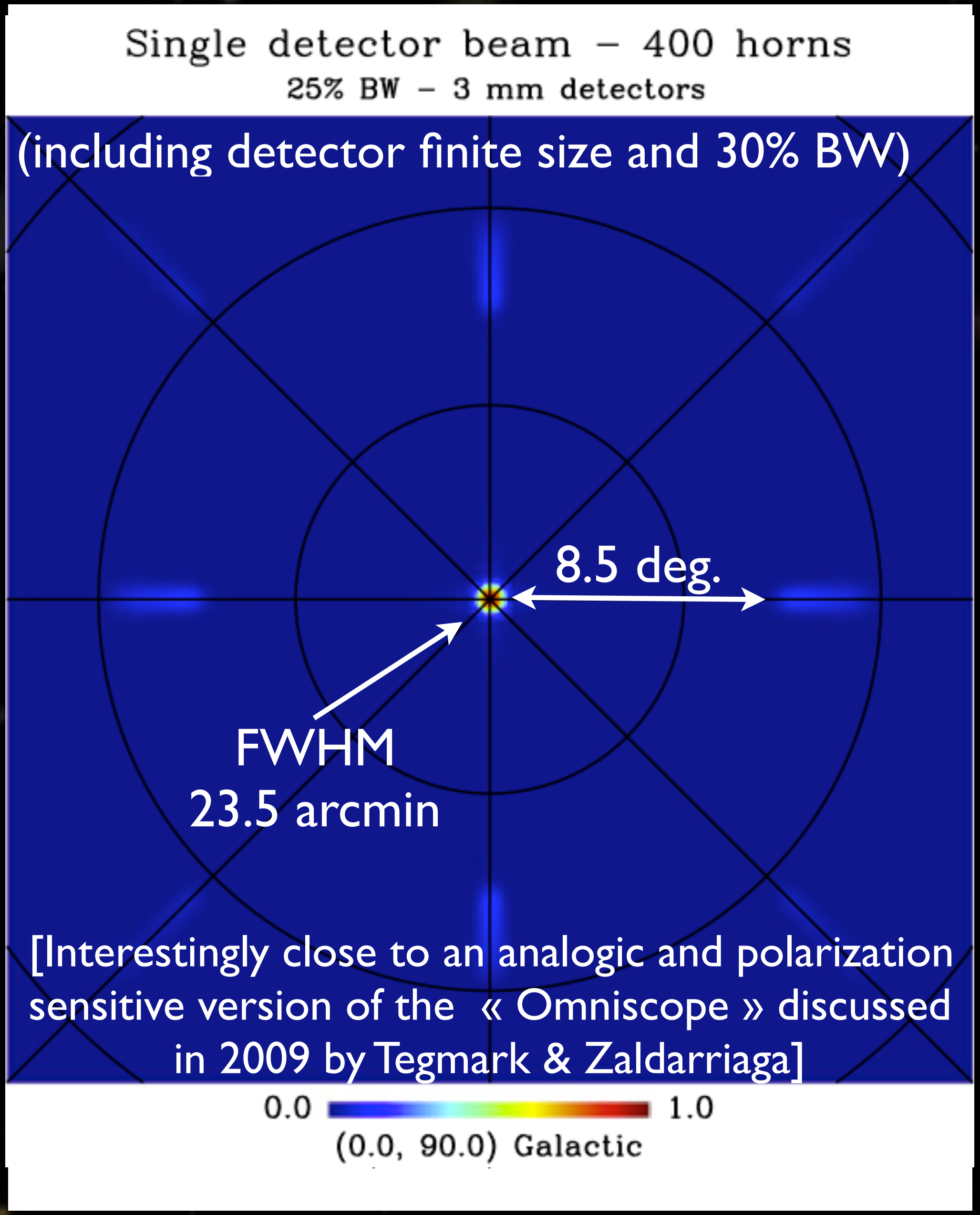
# B.I. = Synthesized imager

## Primary horns array

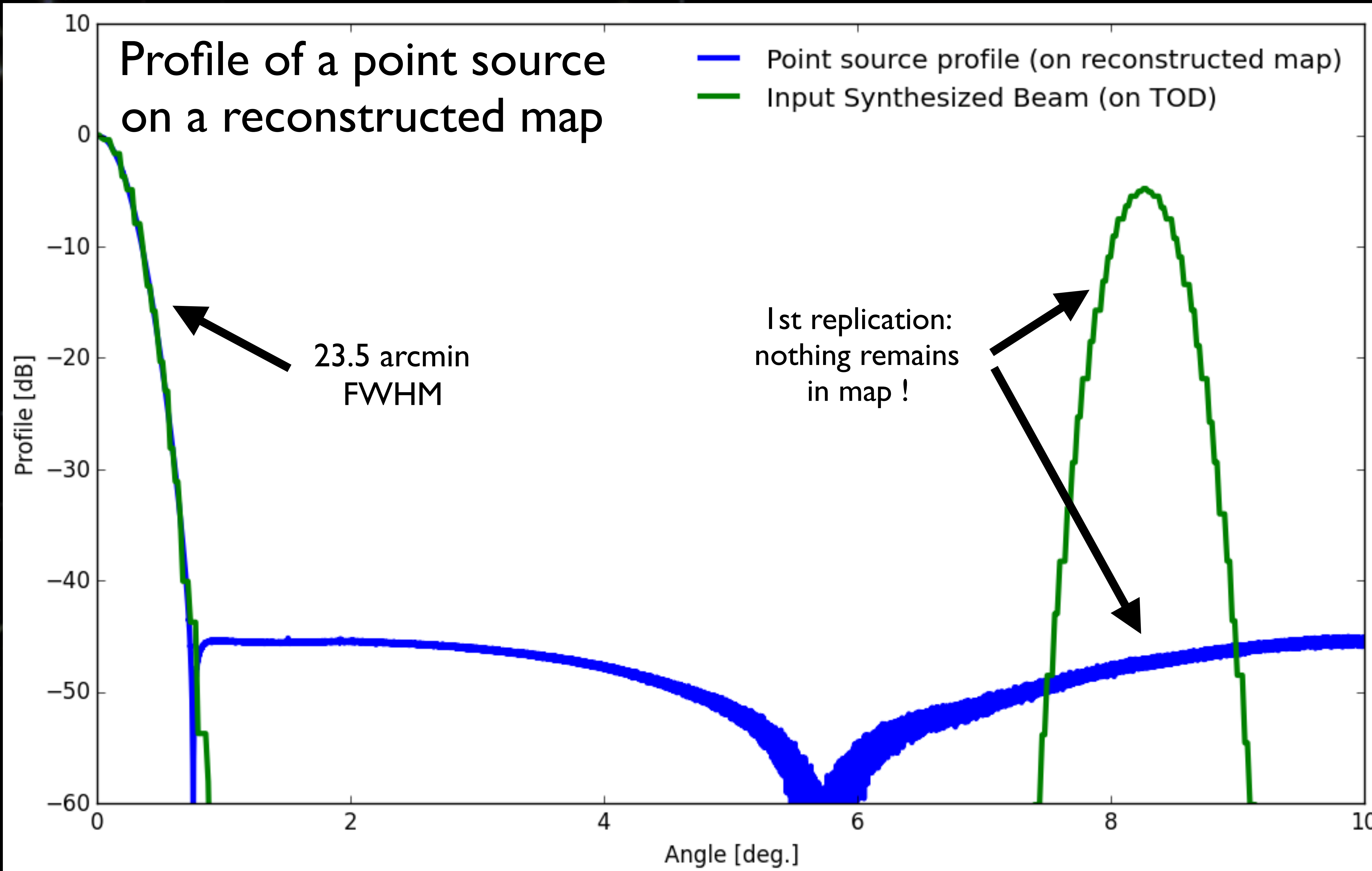



150-220 GHz, 20x20 horns,
13 deg. FWHM, D=1.2 cm

## Synthesized beam (on the sky)




Synthesized beam used to scan the sky as with an imager



Profile of a point source on a reconstructed map
Point source profile (on reconstructed map)
Input Synthesized Beam (on TOD)
23.5 arcmin FWHM
1st replication: nothing remains in map !
Profile [dB]
Angle [deg.]
10
0
−10
−20
−30
−40
−50
−60
0
2
4
6
8
10

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

Complex shape of synthesized beam

↓

Map-making more complex

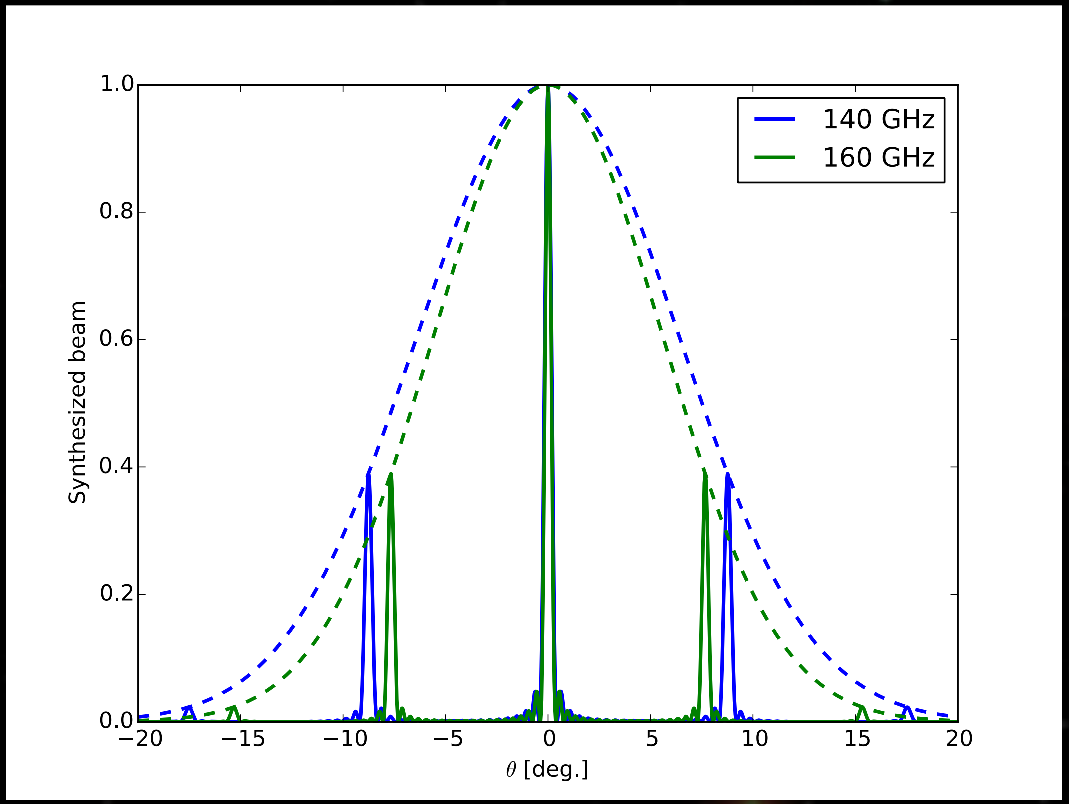
CPU…

Frequency dependence of synthesized beam

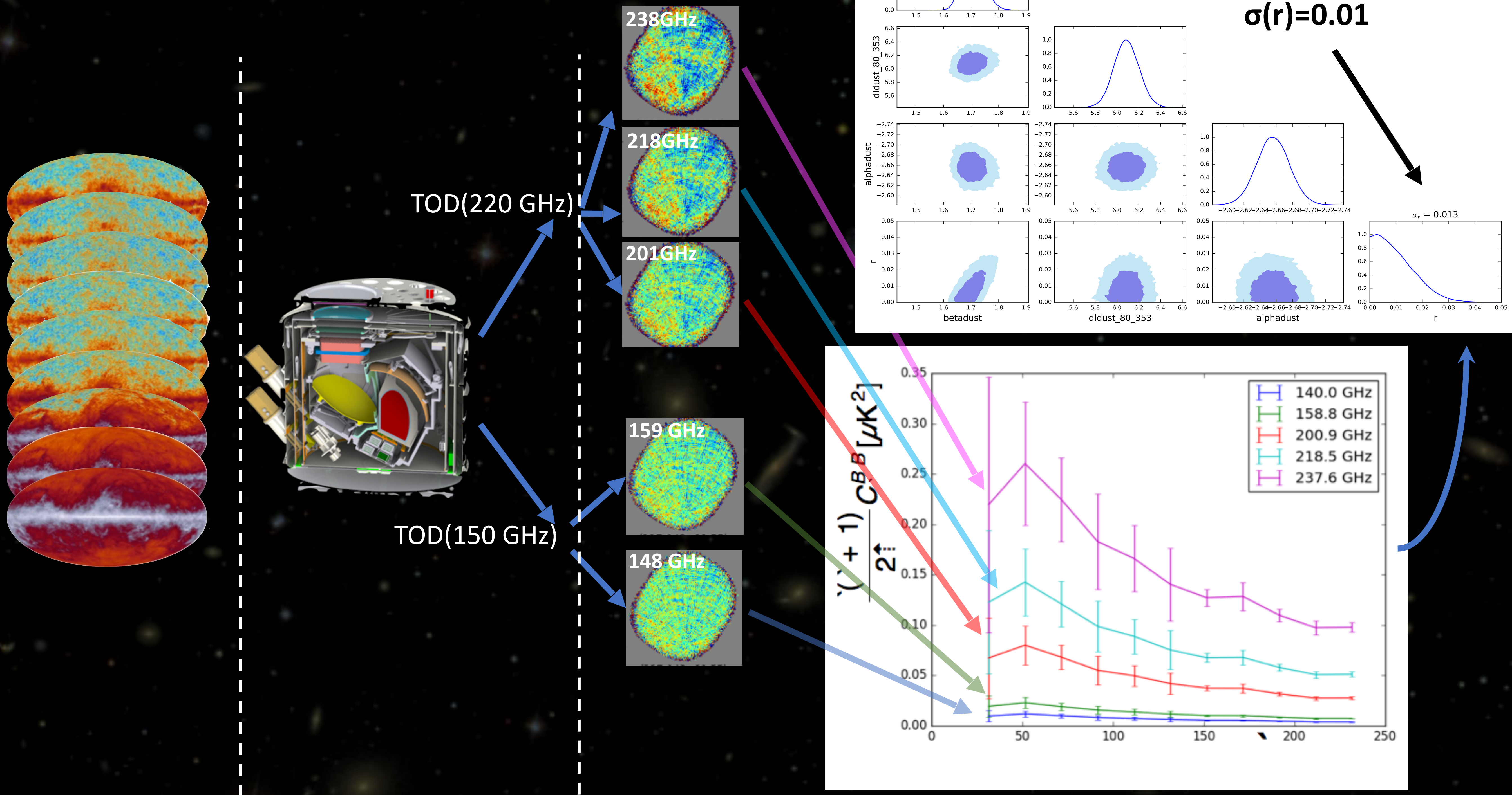
↓

Spectro-Imaging

Foregrounds!



# QUBIC Spectro-Imaging




**Sky:**
**« Infinite # bands »**

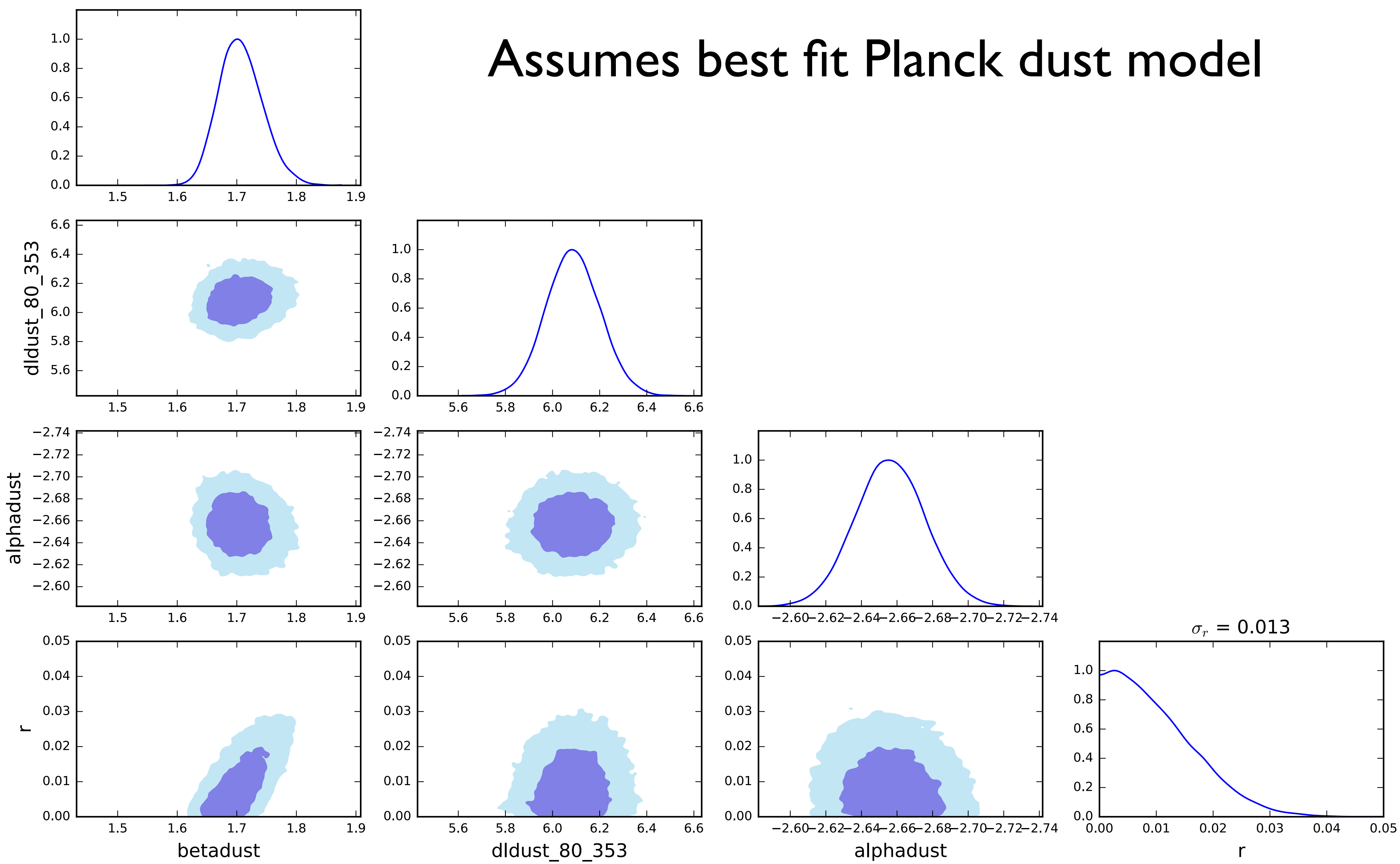
**Instrument:**
**2 wide bands**

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

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

# Expected Sensitivity: σ(r)~0.01

Assumes best fit Planck dust model

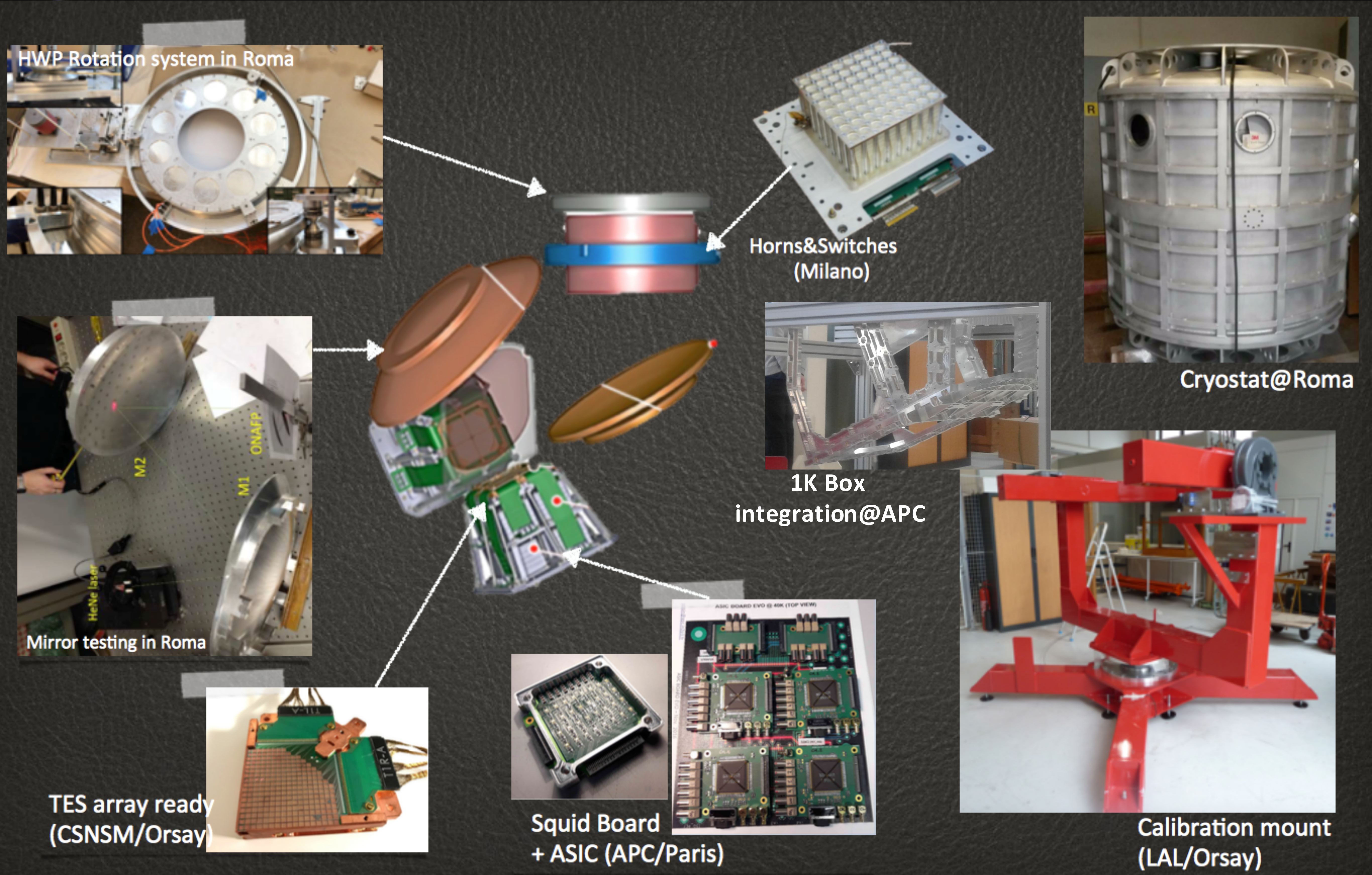


# QUBIC Deployment Plan

**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


HWP Rotation system in Roma
Horns&Switches
(Milano)
Cryostat@Roma
1K Box
integration@APC
M2
M1
ONAFP
HeNe laser
Mirror testing in Roma
TES array ready
(CSNSM/Orsay)
Squid Board
+ ASIC (APC/Paris)
Calibration mount
(LAL/Orsay)

# 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

**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 $\sigma(r)=0.01$

→ Stage III $\sigma(r) = 0.01$

**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 $\sigma(r) = 0.001$

# 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): $\sigma(r)=0.01$ (incl. dust)
- QUBIC Full (more modules) (90, 150, 220 GHz) : $\sigma(r)=0.001$ around 2025 ?
- A possible contribution to CMB-S4 or CMB-E4 ?

★ Status :

- Instrument being Integrated at APC - First cool-down January 2018 - Tests at APC
- On-Sky in Argentina with 256 TES Late 2018
- On-Sky in Argentina with 2048 TES in 2019

# Thank you

Exciting times ahead !!!