# Exploring the primordial Universe with QUBIC

## the Q U Bolometric Interferometer for Cosmology


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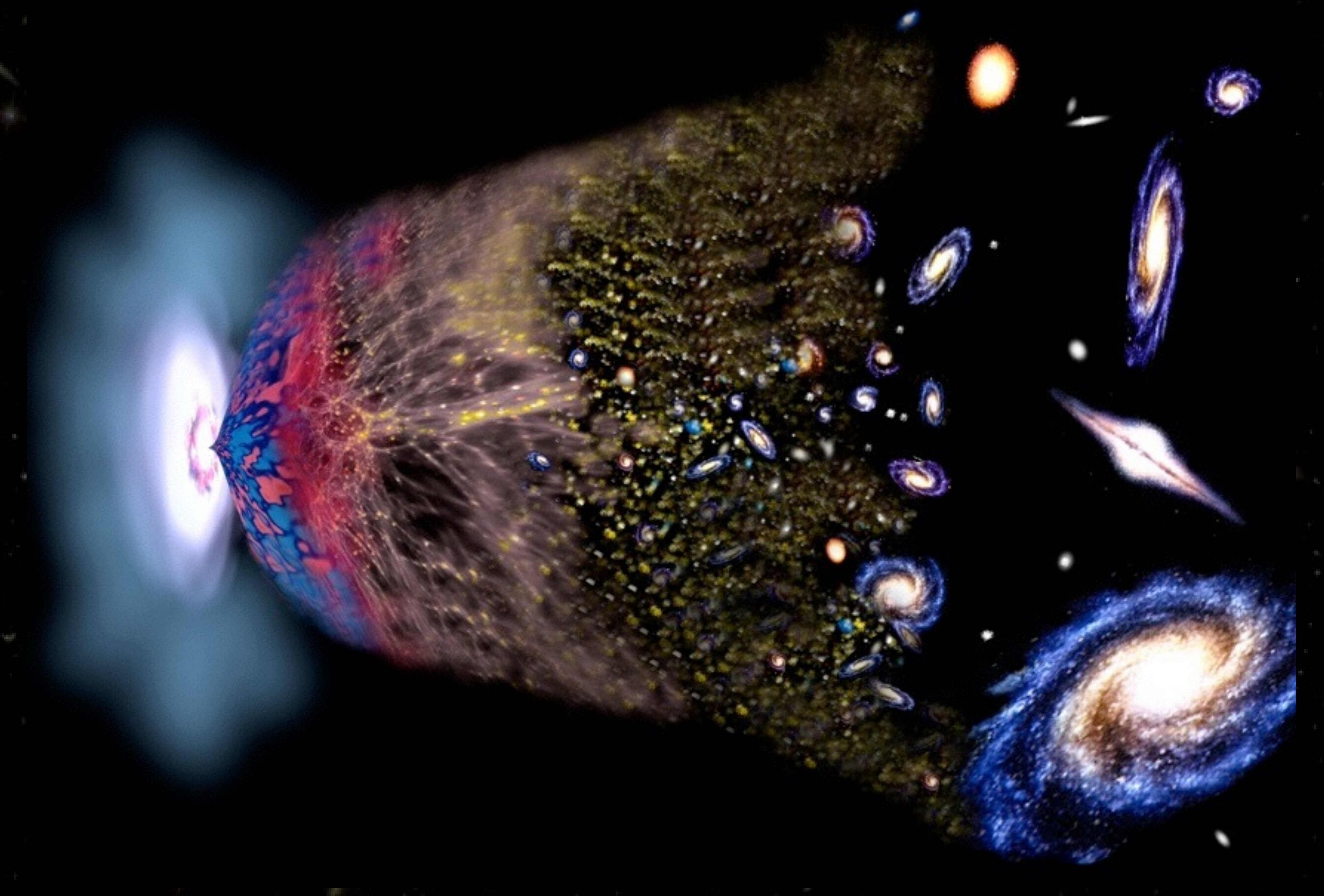


# Inflation

- Phase of accelerated expansion in the Early Universe
- Initially invented to solve some issues in Big-Bang theory
  - ★ Horizon
  - ★ Flatness
  - ★ Monopoles
- Predicts the shape of the primordial density perturbations
  - ★ Seeds for Structure formation
  - ★ Gaussianity
  - ★ Generation of both scalar and tensor perturbations
  - ★ Nearly scale invariant power spectrum (spectral index slightly lower than 1)
- All the models that are fitted to observations (CMB or Large Scale Structure) implicitly assume inflation
  - ★ One would feel more confortable checking this detail ...

# Scalar and tensor modes - E & B polarization

- Scalar perturbations:
  - Density fluctuations
    - Temperature
    - E polarization
    - No B polarization

$$P_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

$$\sigma^T_{scal} \simeq 100\mu\mathrm{K}$$
$$\sigma^E_{scal} \simeq 4\mu\mathrm{K}$$

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

*~ ratio between E and B modes*

- Tensor perturbations:
  - Specific prediction from inflation!
  - = Primordial gravitational waves
    - Temperature
    - E polarization
    - B Polarization

$$P_r(k) = A_t \left(\frac{k}{k_0}\right)^{n_t}$$

$$\sigma^T_{tens} \leq 30\mu\mathrm{K}$$
$$\sigma^E_{tens} \leq 1\mu\mathrm{K}$$
$$\sigma^B_{tens} \leq 0.3\mu\mathrm{K}$$

$\Rightarrow$ detect B-modes is :

- Direct detection of tensor modes
- «smoking gun» for inflation
- Measurement of its energy scale

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

# Primordial Fluctuations Origin ?

## Inflation Predictions

| | |
|---|---|
| • Flatness, Homogeneity | ✔ |
| • Nature of the perturbations:<br>★ TT peaks at same scales as EE troughs<br>➡ Adiabatic perturbations | ✔ |
| • Spectral index $P(k) \propto k^{n_s - 1}$<br>★ Planck TT + WMAP Pol + High $\ell$ + BAO<br>$n_s = 0.9608 \pm 0.0054 \; (7.2\sigma \text{ from } 1)$<br>➡ Almost scale invariant spectrum | ✔ |
| • Gaussianity<br>★ No hint for non-Gaussianity (despite impressive efforts) | ✔ |
| • Tensor perturbations of the metric<br>★ BICEP2 detection ? to be confirmed… |  |

# The QUBIC Collaboration

- APC Paris, France
- IAS Orsay, France
- CSNSM Orsay, France
- IRAP Toulouse, France
- Maynooth University, Ireland
- Università di Milano-Bicocca, Italy
- Università degli studi, Milano, Italy
- Università La Sapienza, Roma, Italy
- University of Manchester, UK
- IHEP, Beijing, China
- Tsinghua University, Beijing, China
- NIAOT, Nanjing, China
- PMO, Nanjing, China
- Richmond University, USA
- Brown University, USA
- University of Wisconsin, USA

E. Battistelli [e], A. Baú [f], D. Bennett [l], L. Bergé [c], J.-Ph. Bernard [b], P. de Bernardis [e], G. Bordier [a], A. Bounab [b], É. Bréelle [a], E.F. Bunn [j], M. Calvo [e], R. Charlassier [a], S. Collin [c], A. Coppolecchia [e], A. Cruciani [e], G. Curran [l], M. de Petris [e], L. Dumoulin [c], A. Gault [i], M. Gervasi [f], A. Ghribi [a], M. Giard [b], C. Giordano [e], Y. Giraud-Héraud [a], M. Gradziel [l], L. Guglielmi [a], J.-Ch. Hamilton [a,*], V. Haynes [g], J. Kaplan [a], A. Korotkov [h], J. Landé [b], B. Maffei [g], M. Maiello [m], S. Malu [k], S. Marnieros [c], J. Martino [a], S. Masi [e], A. Murphy [l], F. Nati [e], C. O'Sullivan [l], F. Pajot [d], A. Passerini [f], S. Peterzen [e], F. Piacentini [e], M. Piat [a], L. Piccirillo [g], G. Pisano [g], G. Polenta [e,n,o], D. Prêle [a], D. Romano [e], C. Rosset [a], M. Salatino [e], A. Schillaci [e], G. Sironi [f], R. Sordini [e], S. Spinelli [f], A. Tartari [f], P. Timbie [i], G. Tucker [h], L. Vibert [d], F. Voisin [a], R.A. Watson [g], M. Zannoni [f], The QUBIC collaboration

Currently trying to build a collaboration with China (IHEP: J. Xia, H. Li, X. Zhang):
- Procurement of the Mount NIAOT)
- Participation to data analysis and scientific exploitation

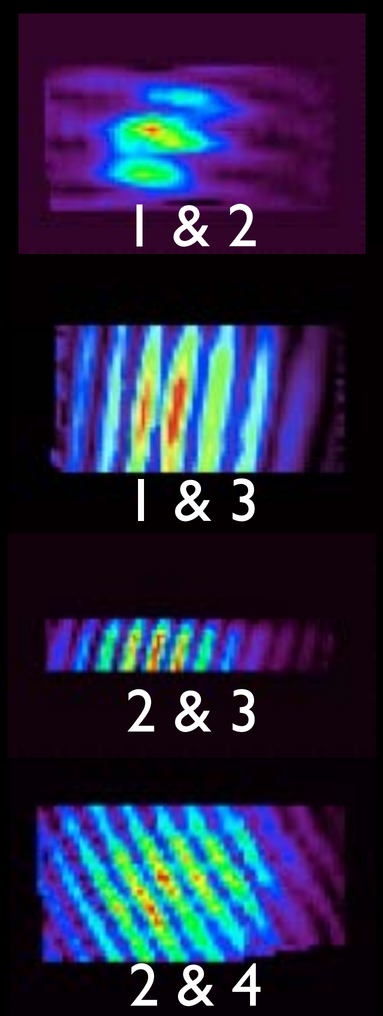
arXiv:1010.0645 ~ Astroparticle Physics 34 (2011) 705–71

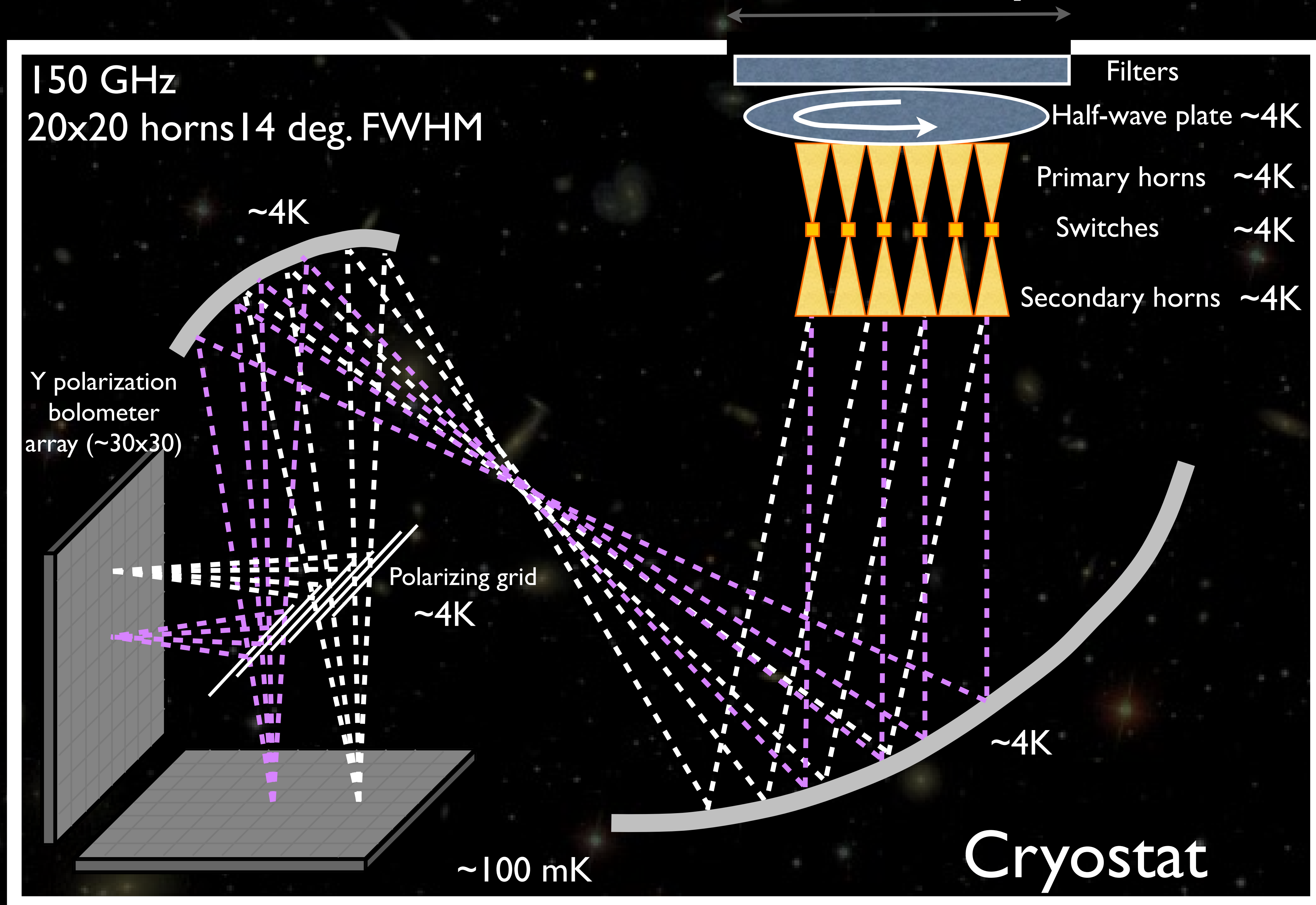
# QUBIC design

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

1 horn open

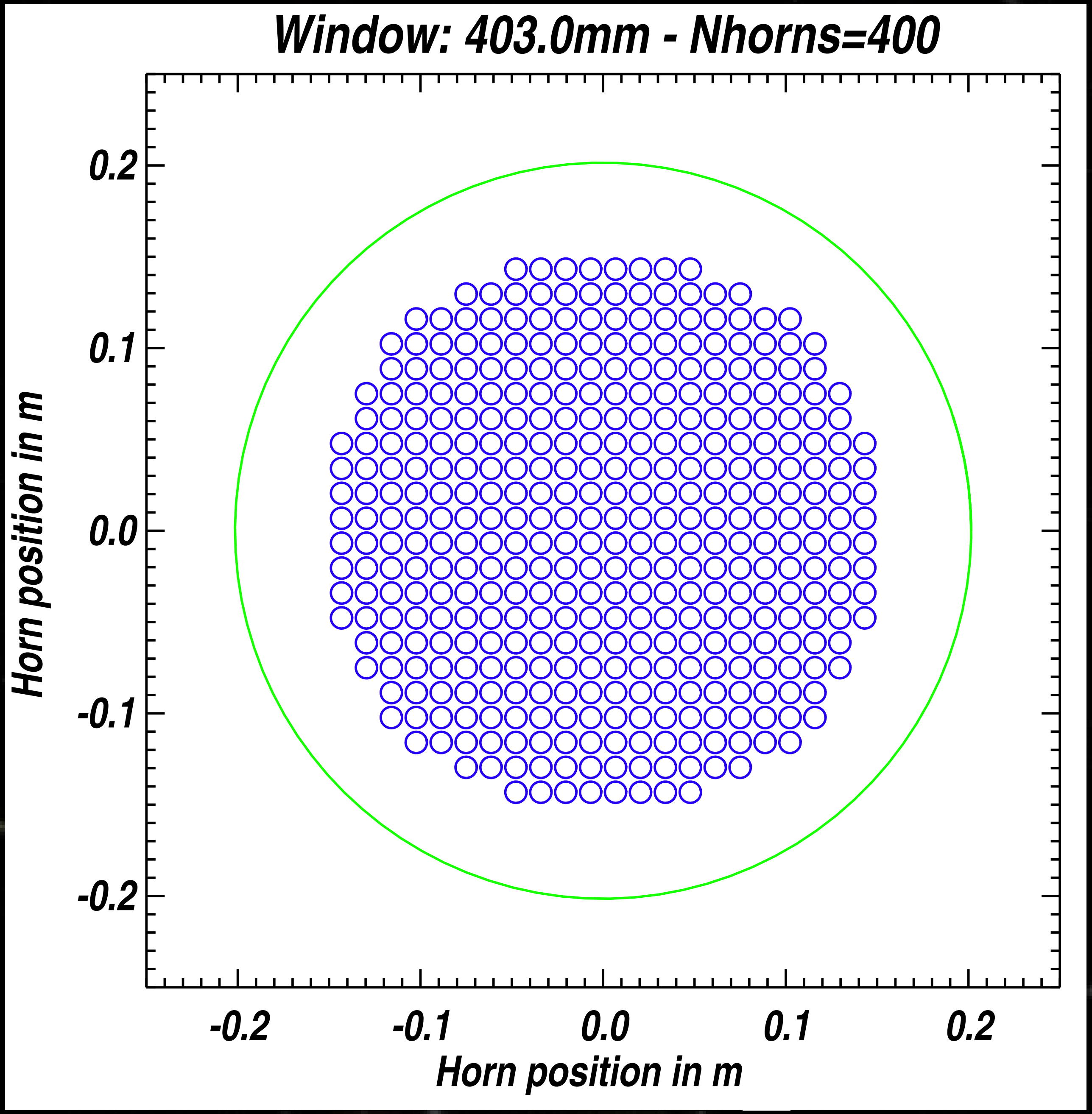
MBI-4 data
2009 campaign
(PBO- Wisc.)



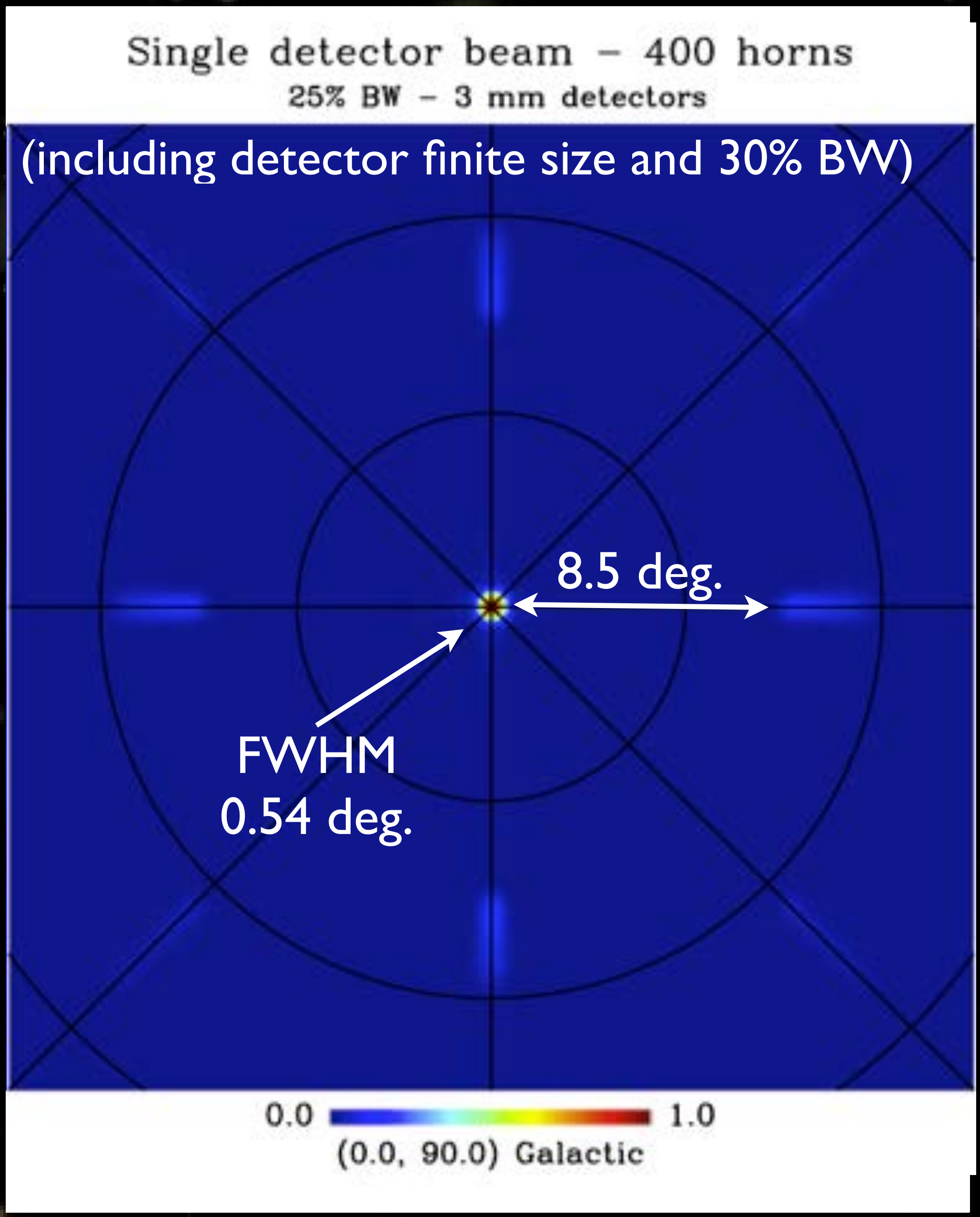
# B.I. = Synthesized imager

## Primary horns array




150 GHz, 20x20 horns,
14 deg. FWHM, D=1.2 cm

## Synthesized beam



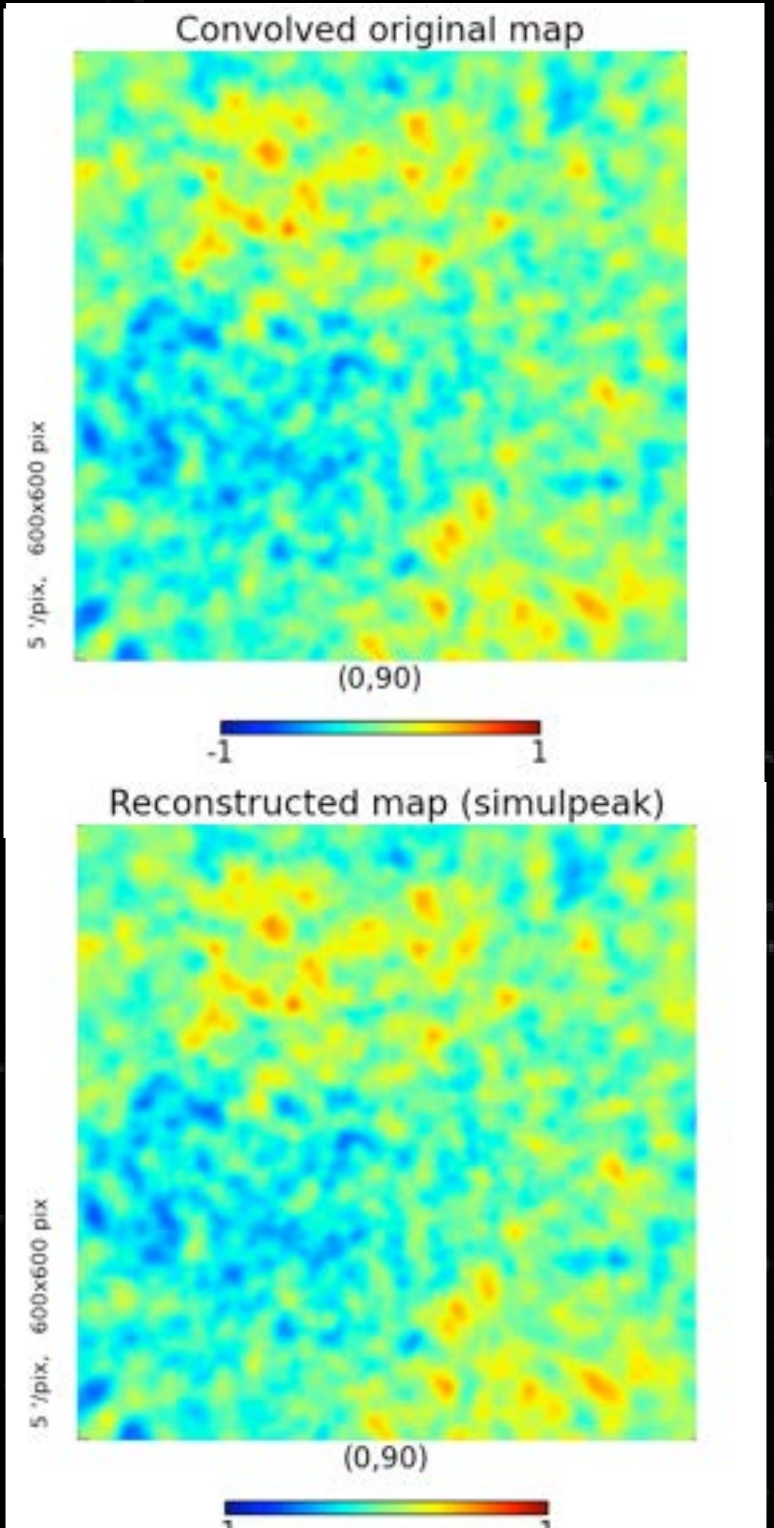

Synthesized beam used to
scan the sky as with an imager

# Map Making ~ as an imager

- Scan the sky with synthesized beam
  - ★ Az. scans at constant elevation following a single field
  - ★ Phi rotation around optical axis
- Reproject data on the sky

$$\hat{T} = \left(A^t \cdot N^{-1} \cdot A\right)^{-1} \cdot A^t \cdot N^{-1} \cdot \vec{d}$$

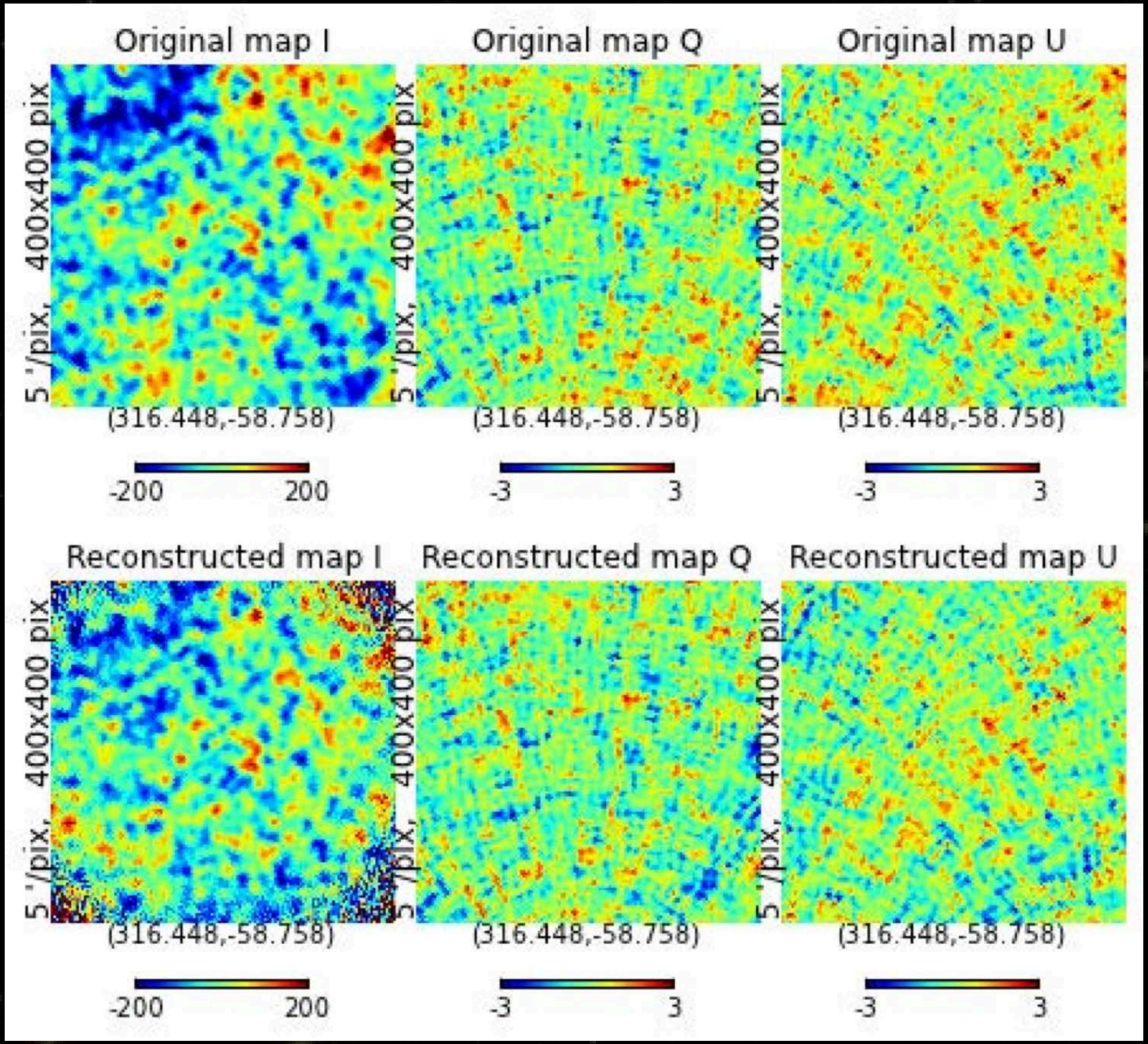
- QUBIC Synthesized beam has multiple peaks
  - ★ Usual map making assumes *A* has a single non zero element in each column
    - Does not lead to good results
  - ★ Improved method with better beam approximation
    - Sparse matrices helps fast convergence of CG
    - First results on simulations are promising

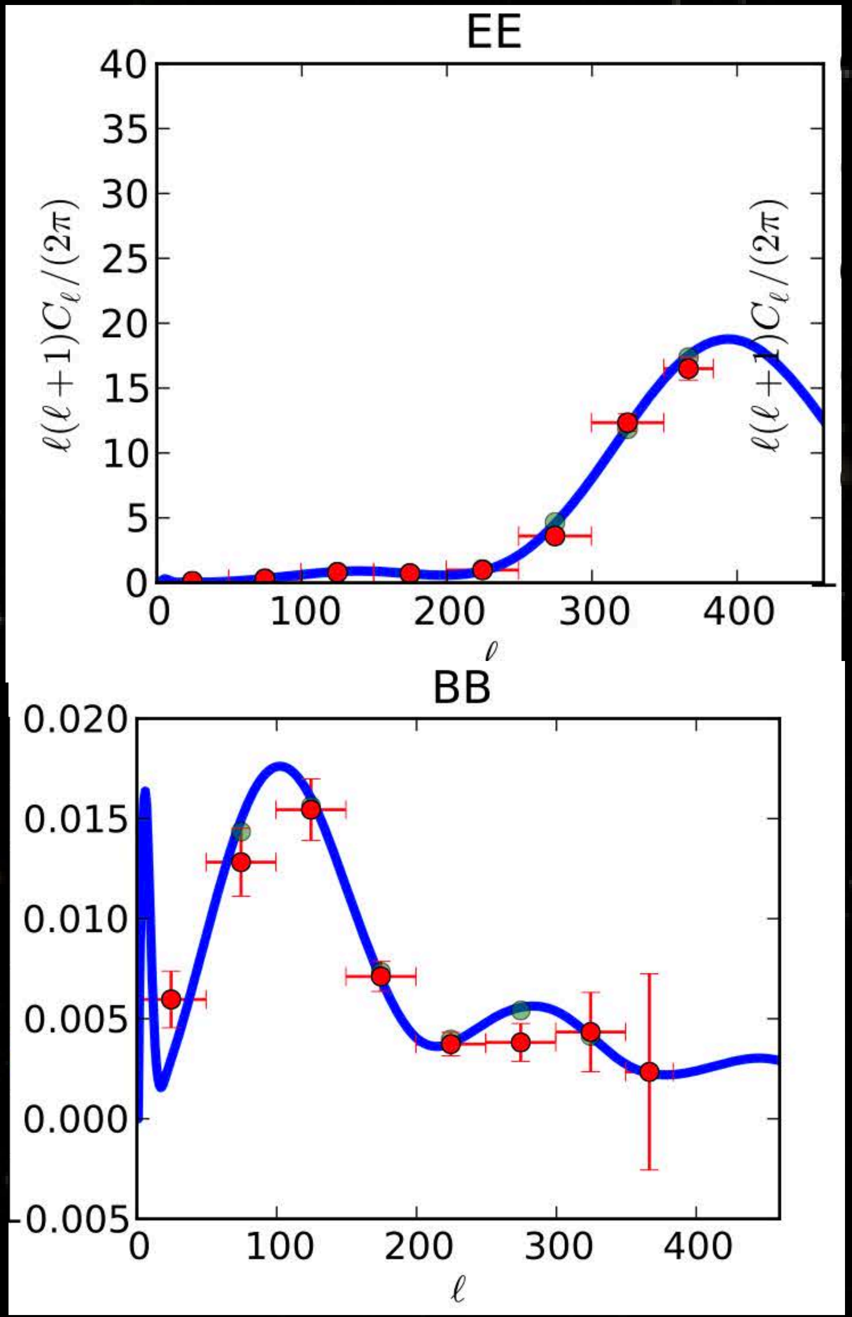



[Pierre Chanial @ APC]

# « End-to-end » simulations

TOD → Maps → E & B power spectra



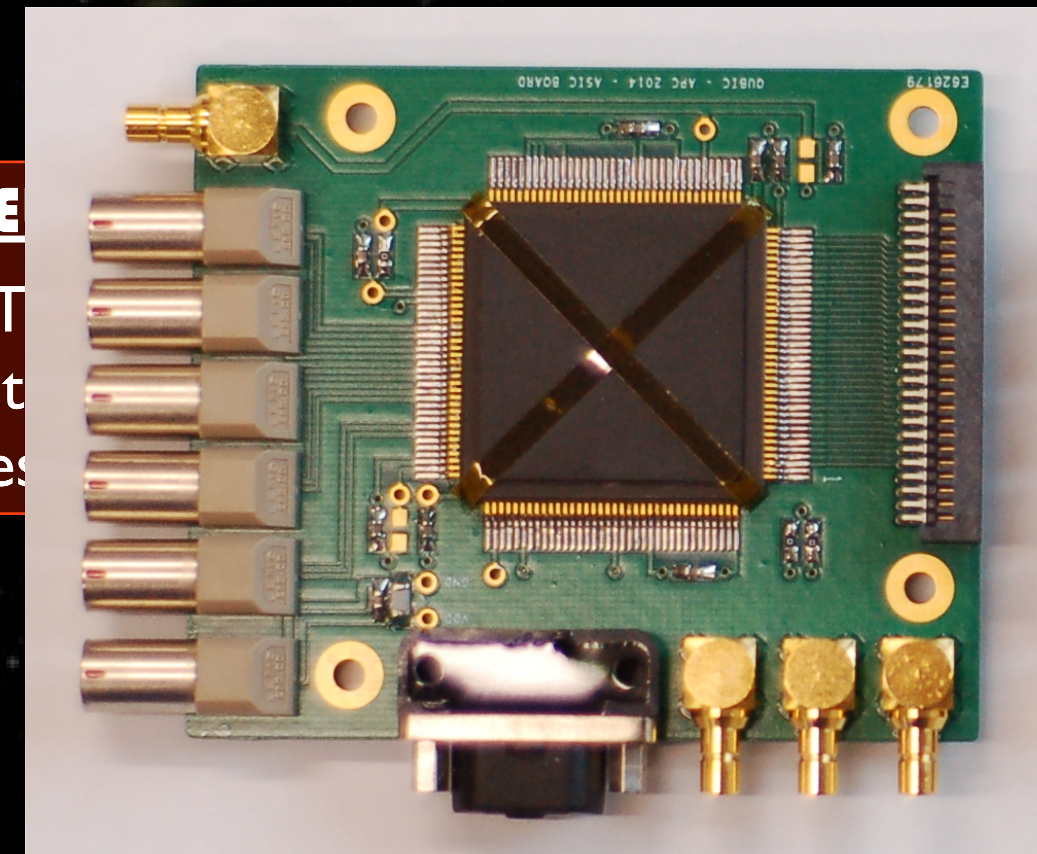
# QUBIC Site: Dome C, Antarctica

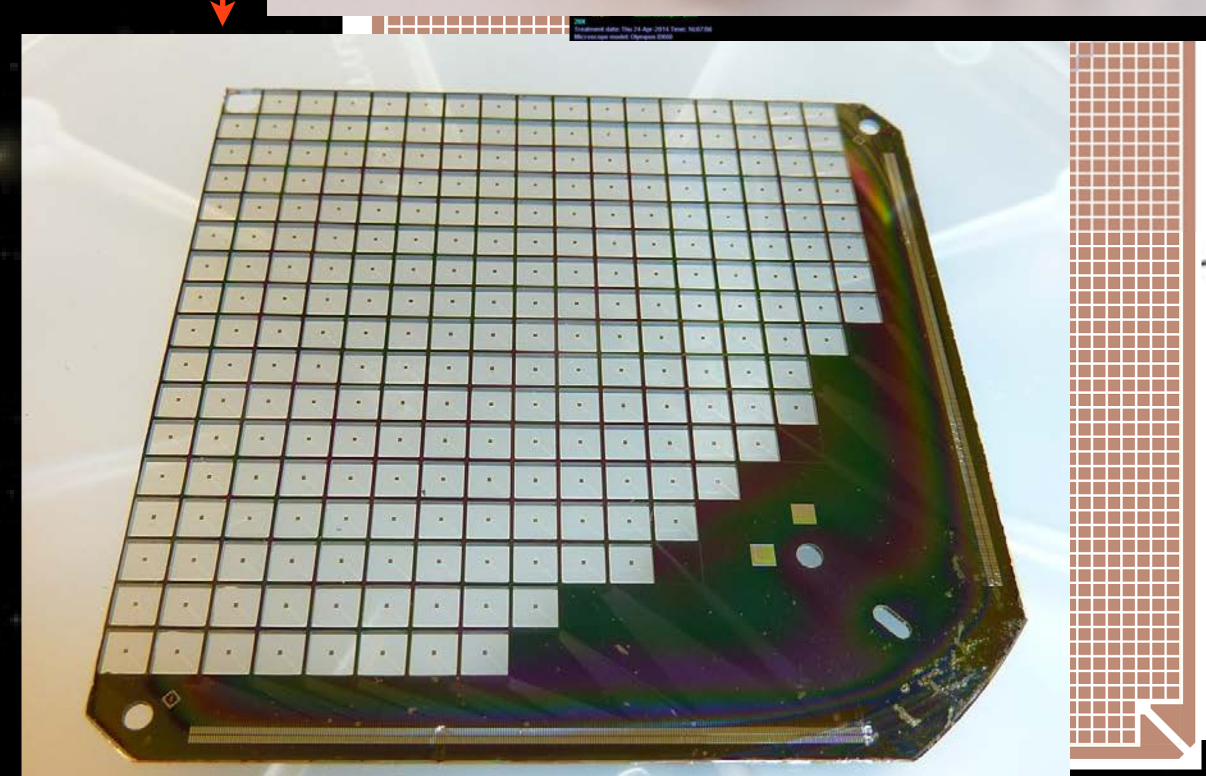


# Detection Chain

- TES + SQUIDs + 4K SiGe ASIC Mux
  - ★ CSNSM: Stefanos Marnieros
  - ★ APC: Michel Piat
  - ★ IRAP: Ludovic Montier
- 2 arrays of 992 NbSi TES
  - ★ Each array : 4x248 elements
  - ★ 300 mK bath ($^3$He-$^4$He)
  - ★ 3 mm size
  - ★ Measured NEP ~ $4.10^{-17}$ $W.Hz^{-1/2}$
  - ★ time constant ~ 10 ms
- 4K Multiplexed Readout
  - ★ 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

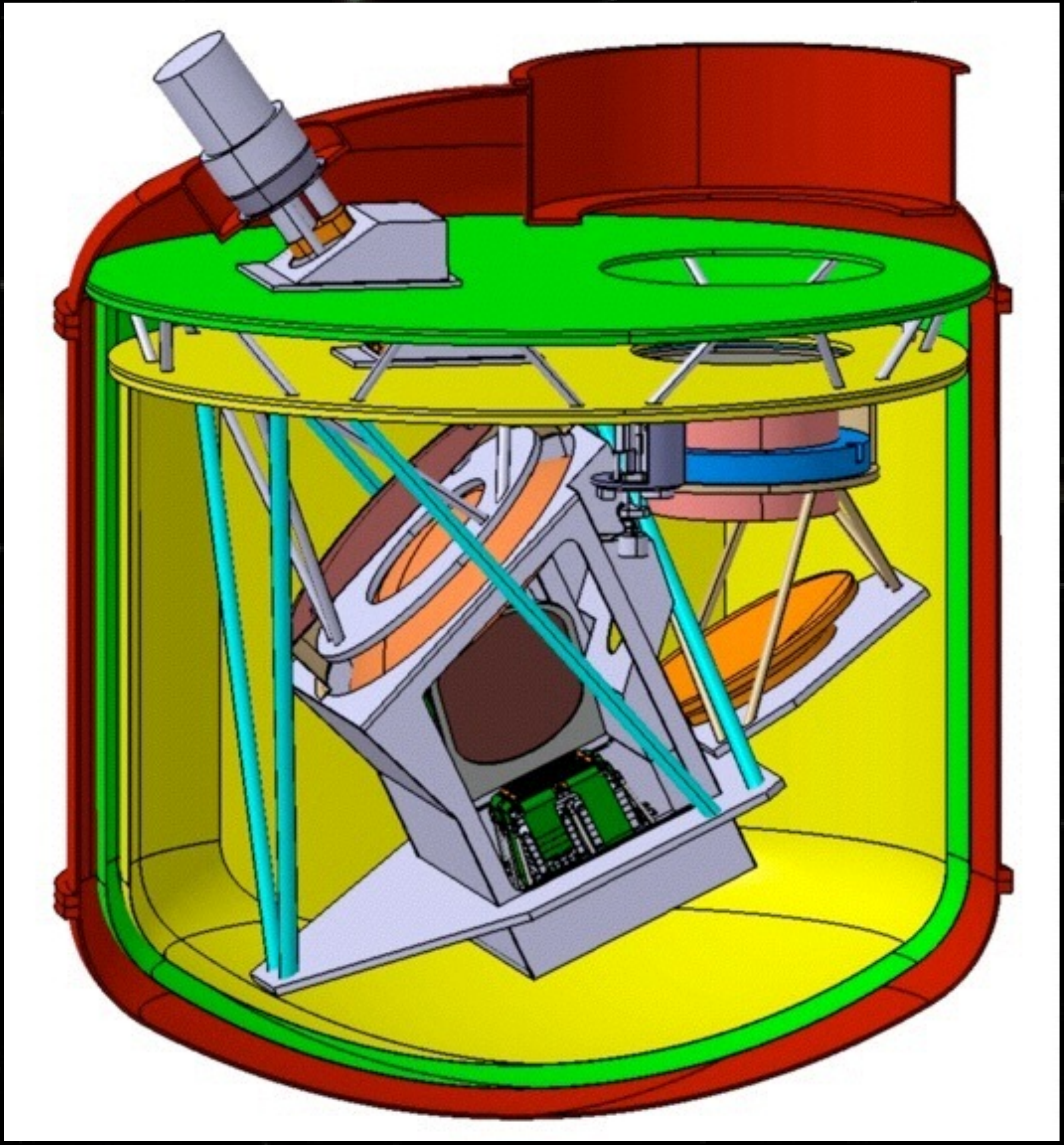
NE
1st 248 T
Current
tes





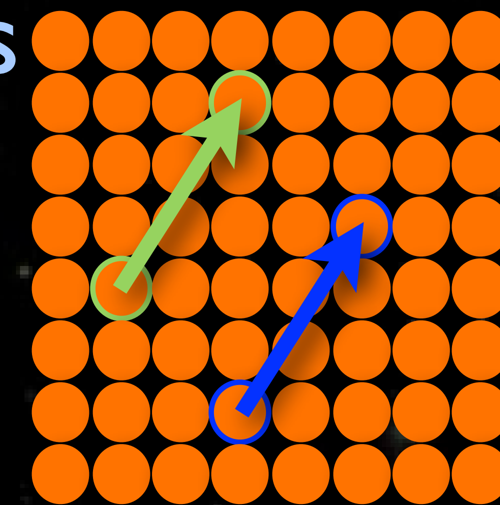
# QUBIC Cryostat

- Designed in Roma
  - ★ P. de Bernardis / S. Masi
- 45 cm window
  - ★ Stack (~20 cm) of zotefoam layers
- 1st stage: 4K: Pulse-Tube
  - ★ Filters, horns, switches, HWP, 1st mirror
- 2nd stage: 300 mK: $^7$He evaporation cooler
  - ★ 2nd mirror, polarizing grid, detectors

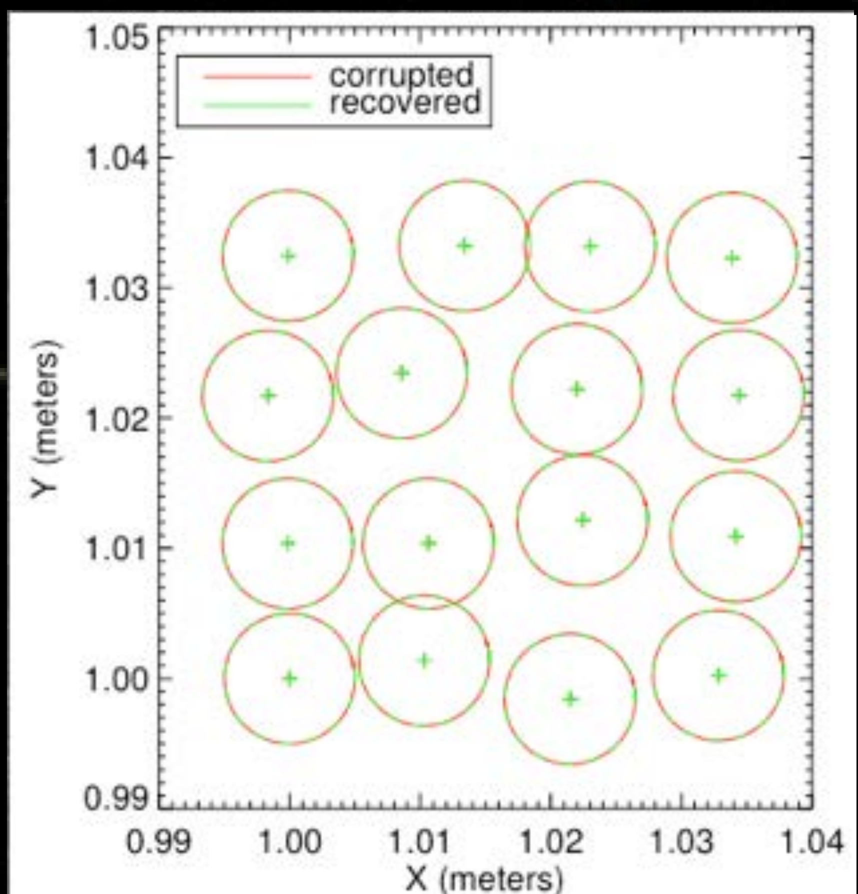


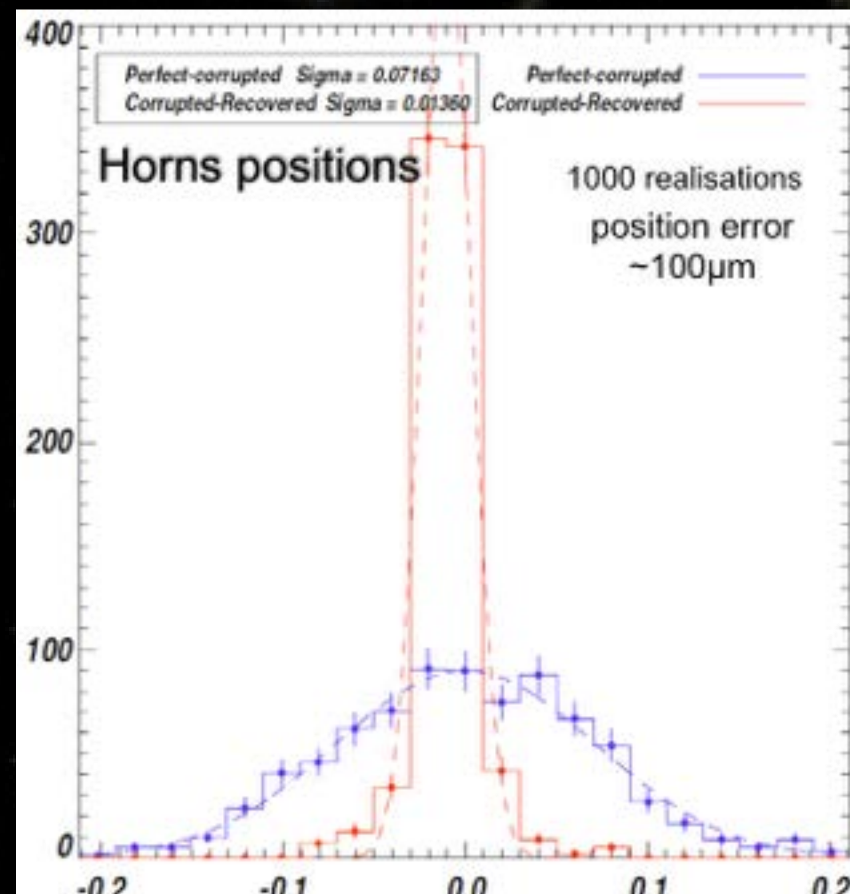
# Systematics: Self-Calibration

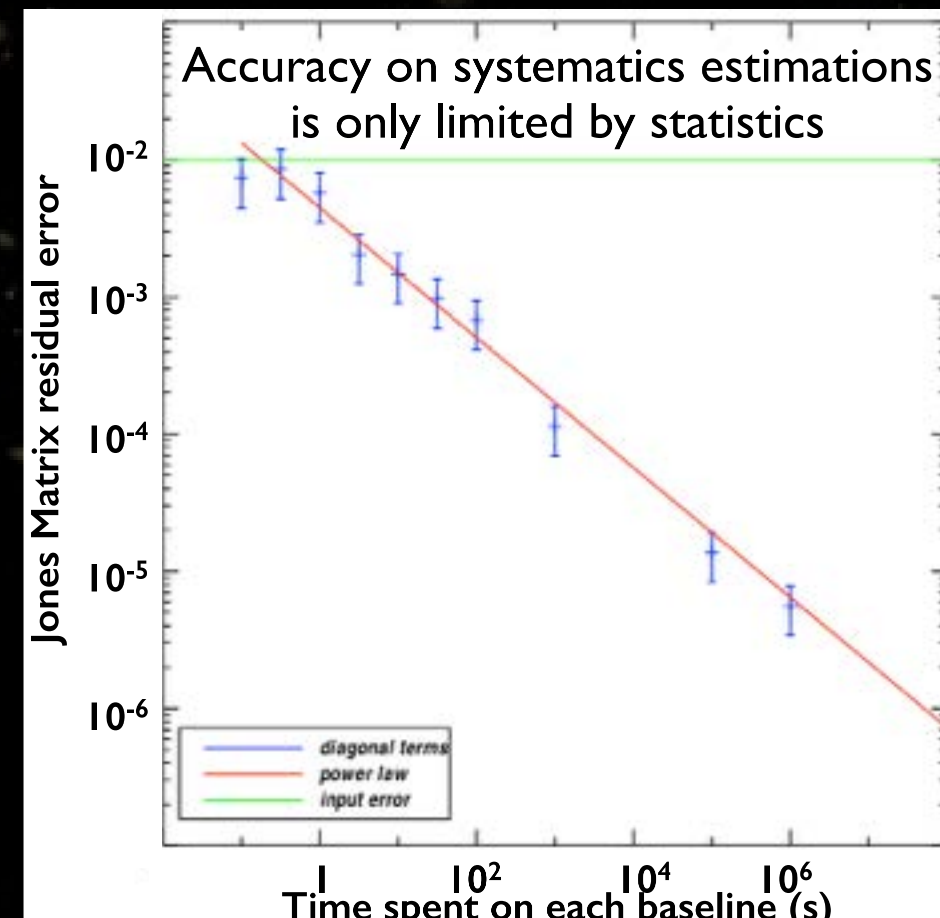
- Unique possibility to handle systematic errors
  - ★ Use horn array redundancy to calibrate systematics
    - In a perfect instrument redundant baselines should see the same signal
    - Differences due to systematics
    - Allow to fit systematics with an external source on the field
  - ★ Unique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



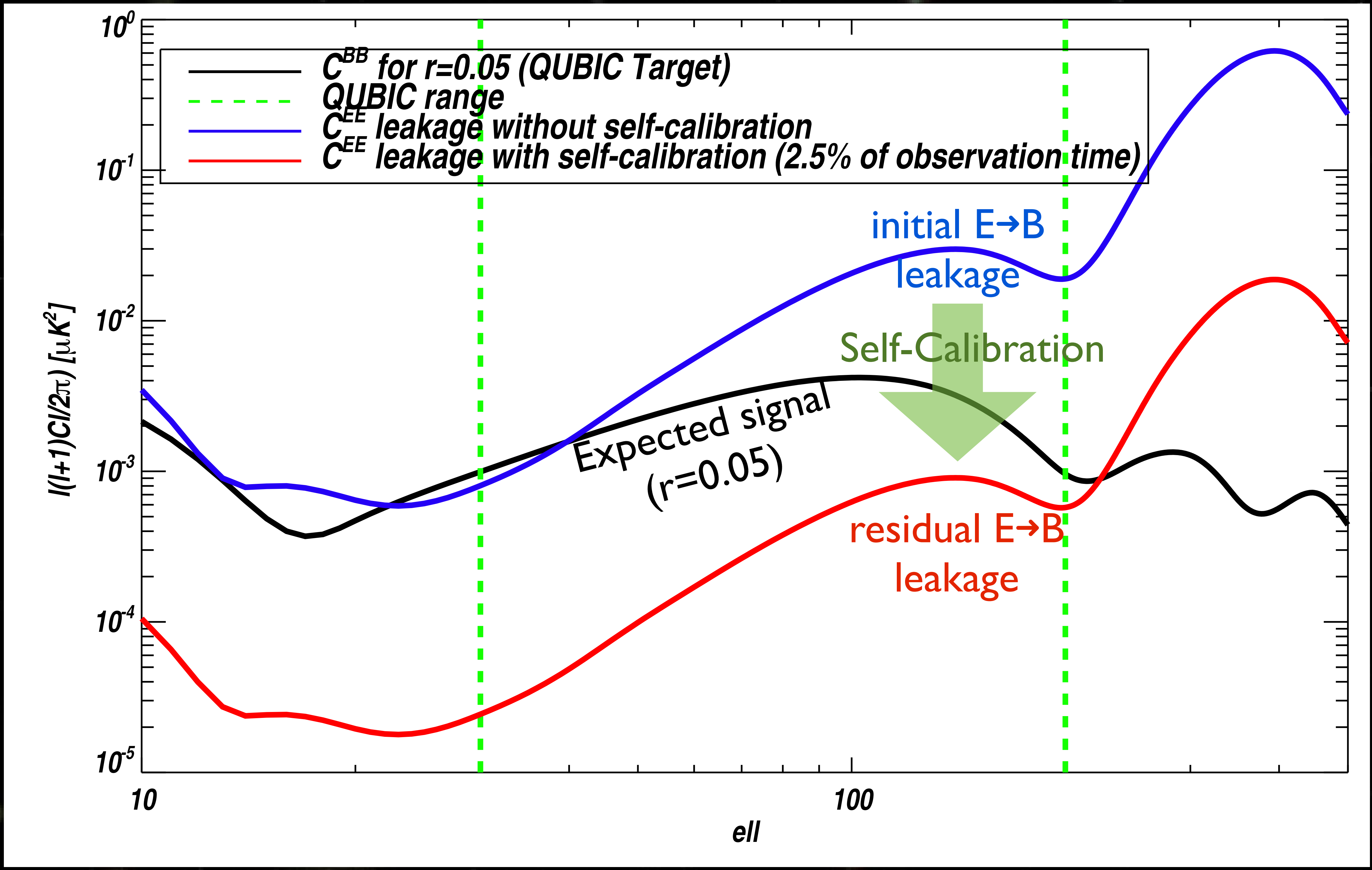
Redundant baselines : same Fourier Mode



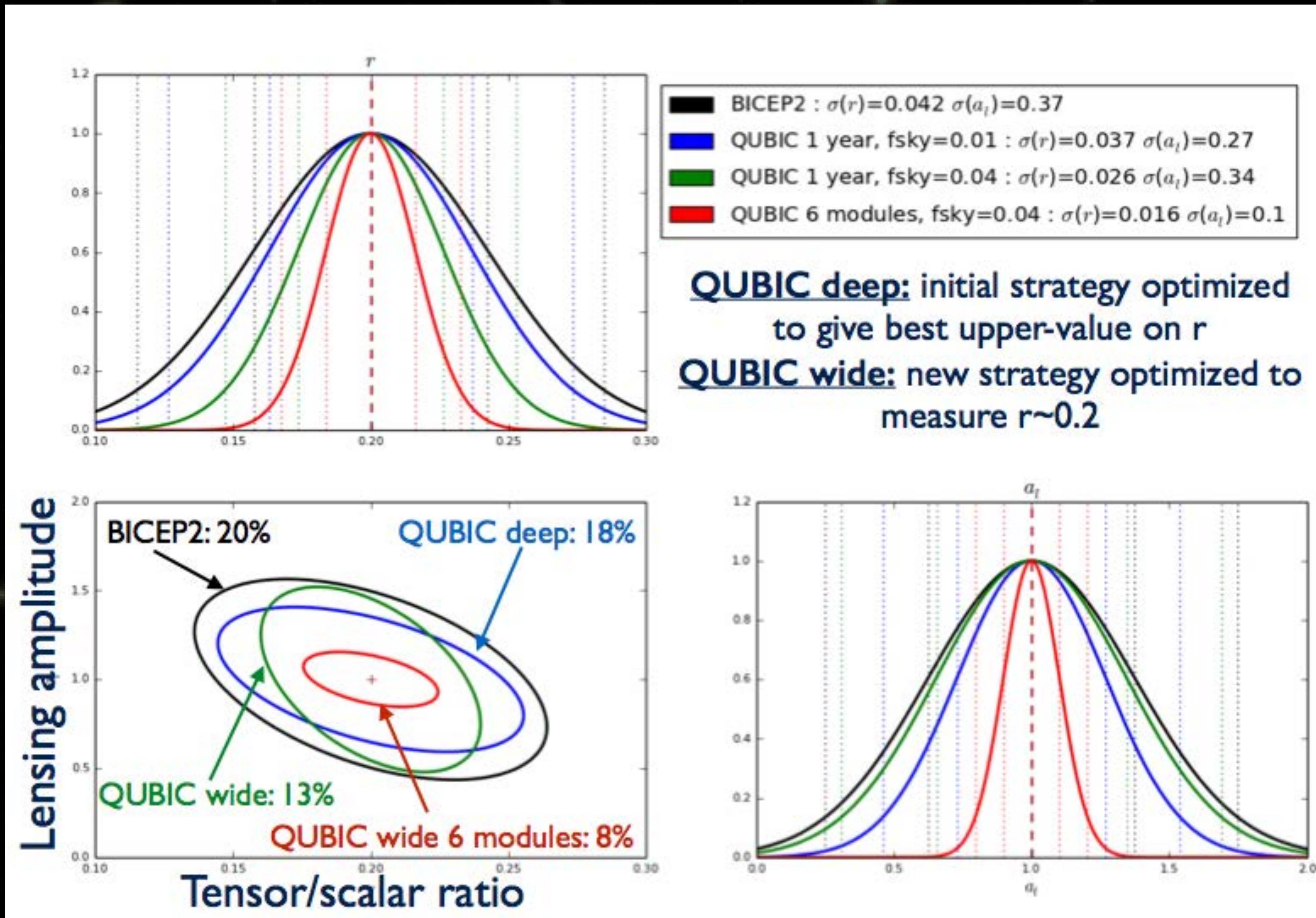



# Self-Calibration results



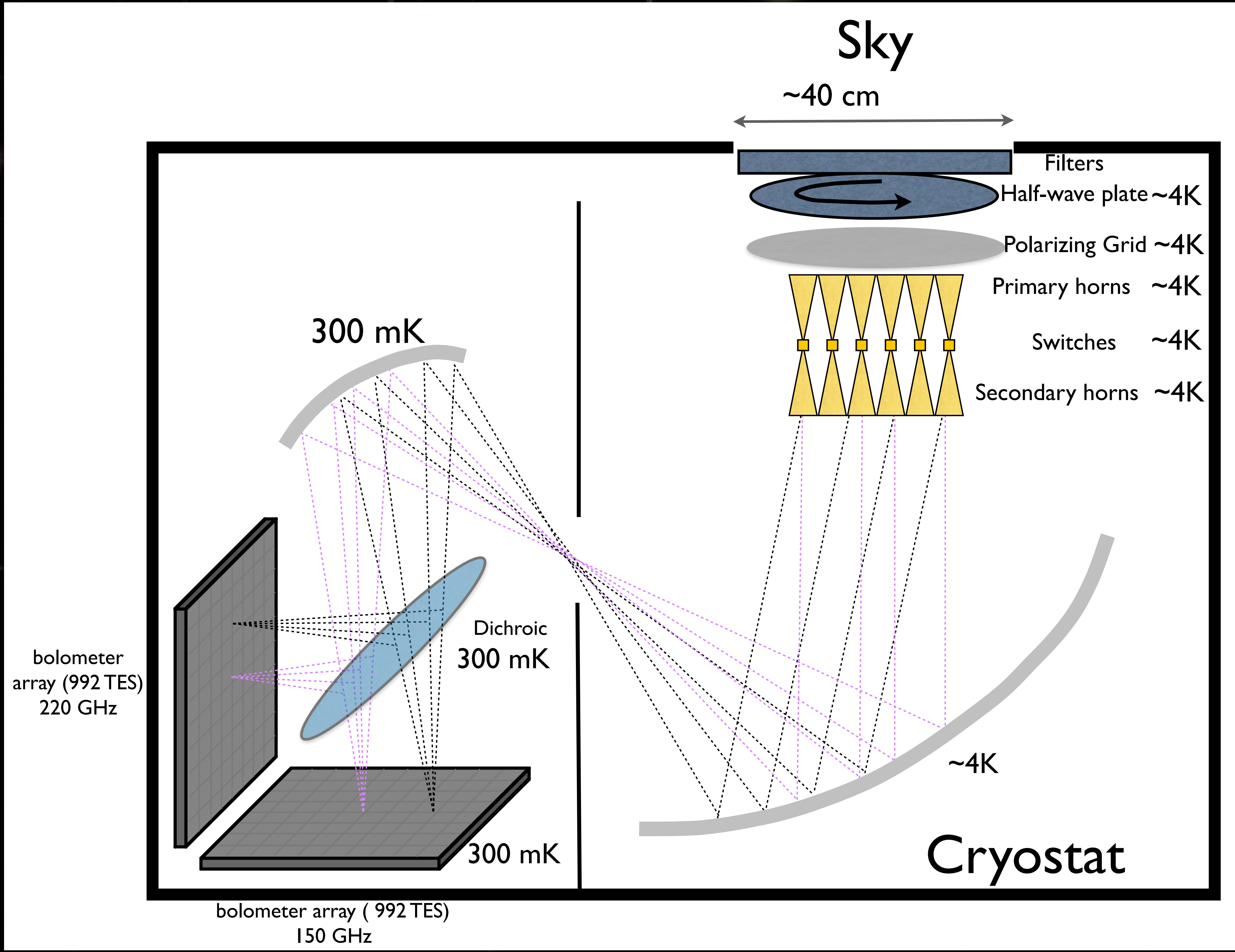

[Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]

# Expected sensitivity



# Currently Assessing the possibility of a dual band QUBIC 150 / 220 GHz for the first module

Replace Polarizing grid by a Dichroic, add polarizing grid after Half Wave Plate
=> Completely immune to XPol
=> need large bandwidth horns




**Anticipated sensitivity:**
4.3 µK.arcmin @ 150 GHz
12.5 µK.arcmin @ 220 GHz

(5-10 x deeper than Planck)

# QUBIC Timeline

- First Module (150 GHz or 150/220 GHz T.B.D.)
  - ★ Elements construction phase has started
  - ★ Construction, Integration and tests at APC, Paris : 1st semester 2015
  - ★ Transportation to Dome C: mid-2016
  - ★ First light on site: End 2016
  - ★ Data Taking: 2017-2018
- Future modules (100 GHz, 150 GHz, 220 GHz)
  - ★ Depend on results with first module
  - ★ Start design studies in 2016
  - ★ 3 frequencies for a clean foreground control
  - ★ Some of them could be at Dome A…

# Conclusions

- QUBIC is a novel instrumental concept
  - ★ High sensitivity
  - ★ High control of instrumental systematics
  - ★ Possibility to run at two frequencies 150 and 220 GHz
  - ★ Operations to start in late 2016 at Dome C
- QUBIC is in a very good position to check / challenge the BICEP2 result - and to detect lower B-modes
  - ★ Higher sensitivity
  - ★ Optimized for large scale B-modes
  - ★ 220 GHz would allow for controlling Galactic dust contamination
  - ★ No other ground-based competitors seem to have plans for the « golden » 220 GHz channel (usually target 100 and 150 GHz)
- Trying to build a collaboration with China
  - ★ Led by IHEP members (J. Xia, H. Li, X. Zhang)
  - ★ Mount to be designed and manufactured by NIAOT
  - ★ Contribution to data analysis and simulations