Exploring the primordial Universe with QUBIC

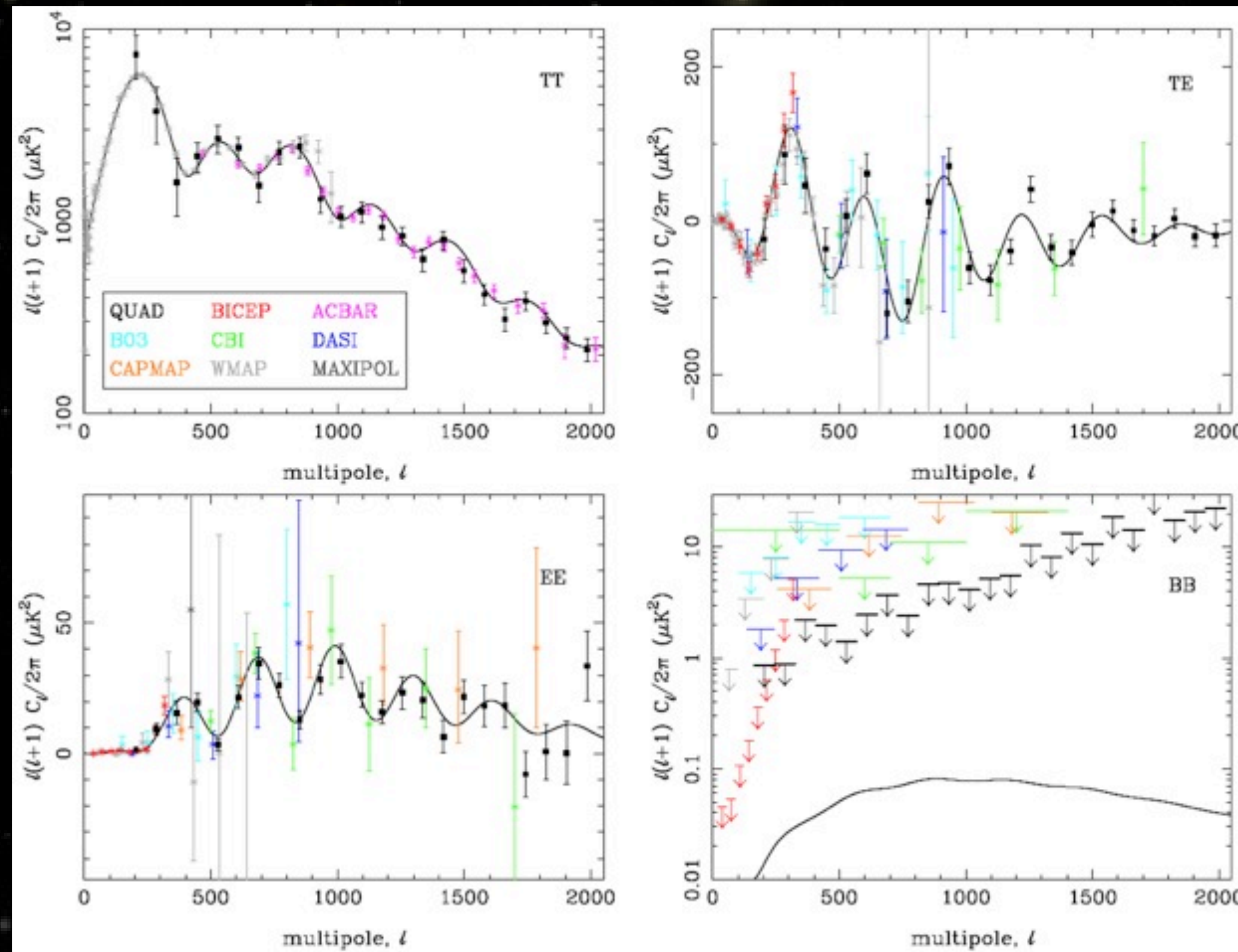
the Q U Bolometric Interferometer for Cosmology

J.-Ch. Hamilton, APC

CNRS, IN2P3, Université Paris-Diderot

Recent CMB measurements

- Pol. detection 2001
  - ★ DASI et CBI (interferometers)
- Later measurements:
  - ★ WMAP, QUAD, BICEP ...
  - ★ Perfect agreement with temperature measurements
- Correspondance between TT peaks and EE troughs
  - ★ Typical of adiabatic primordial fluctuations (generated by inflation for instance ...)
- Last week : Planck Temperature results !
  - ★ + sample polarization measurements



[QUAD Collaboration: Arxiv:0906.1003]

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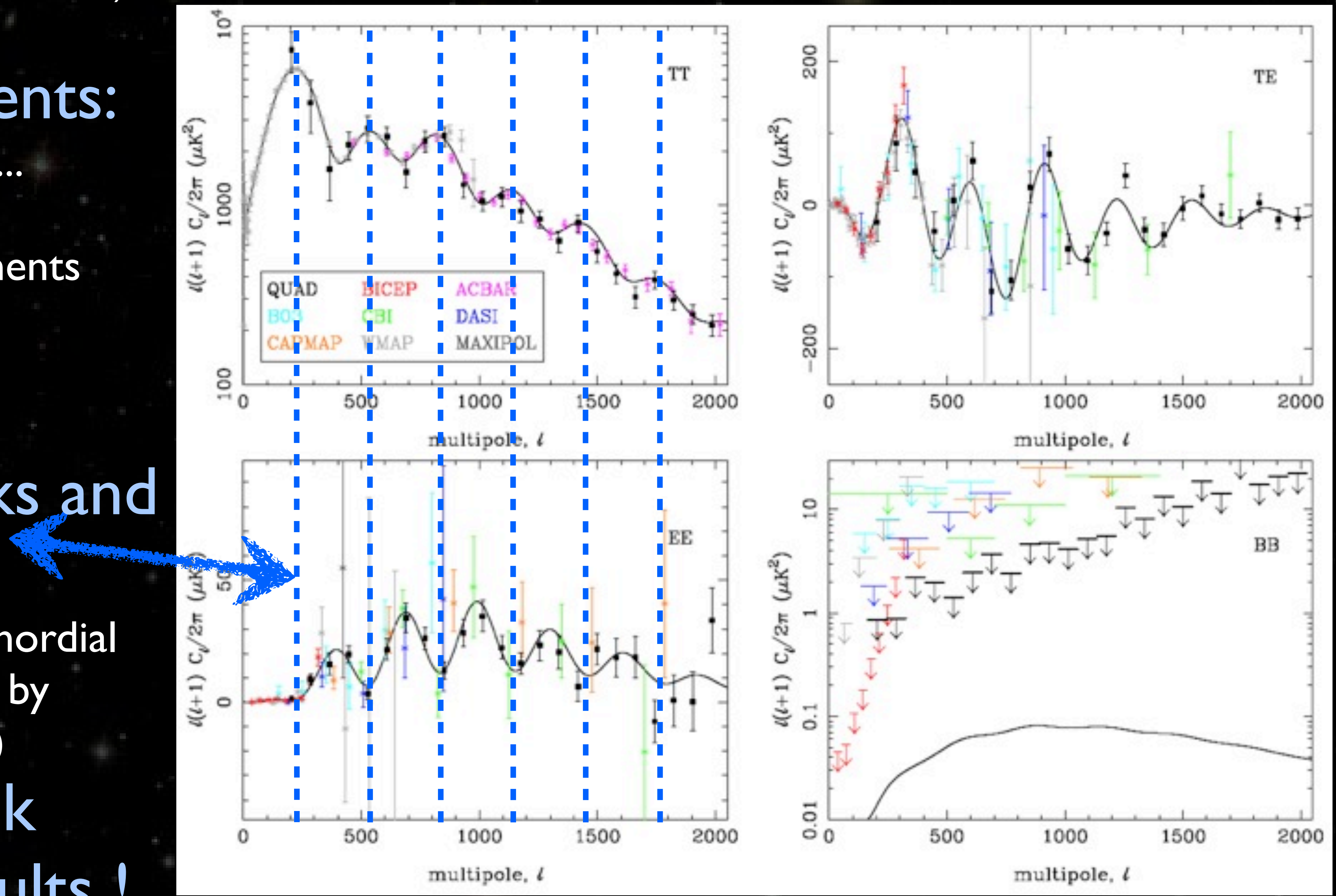

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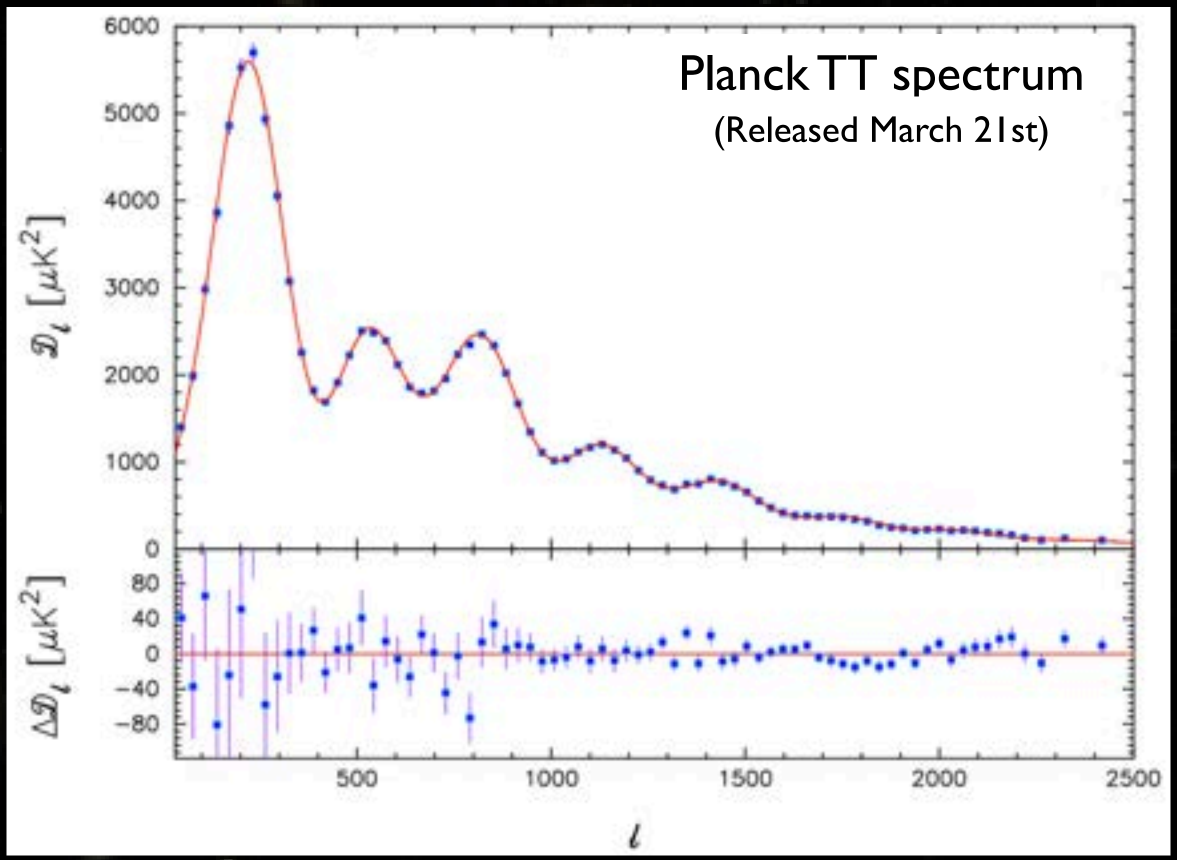

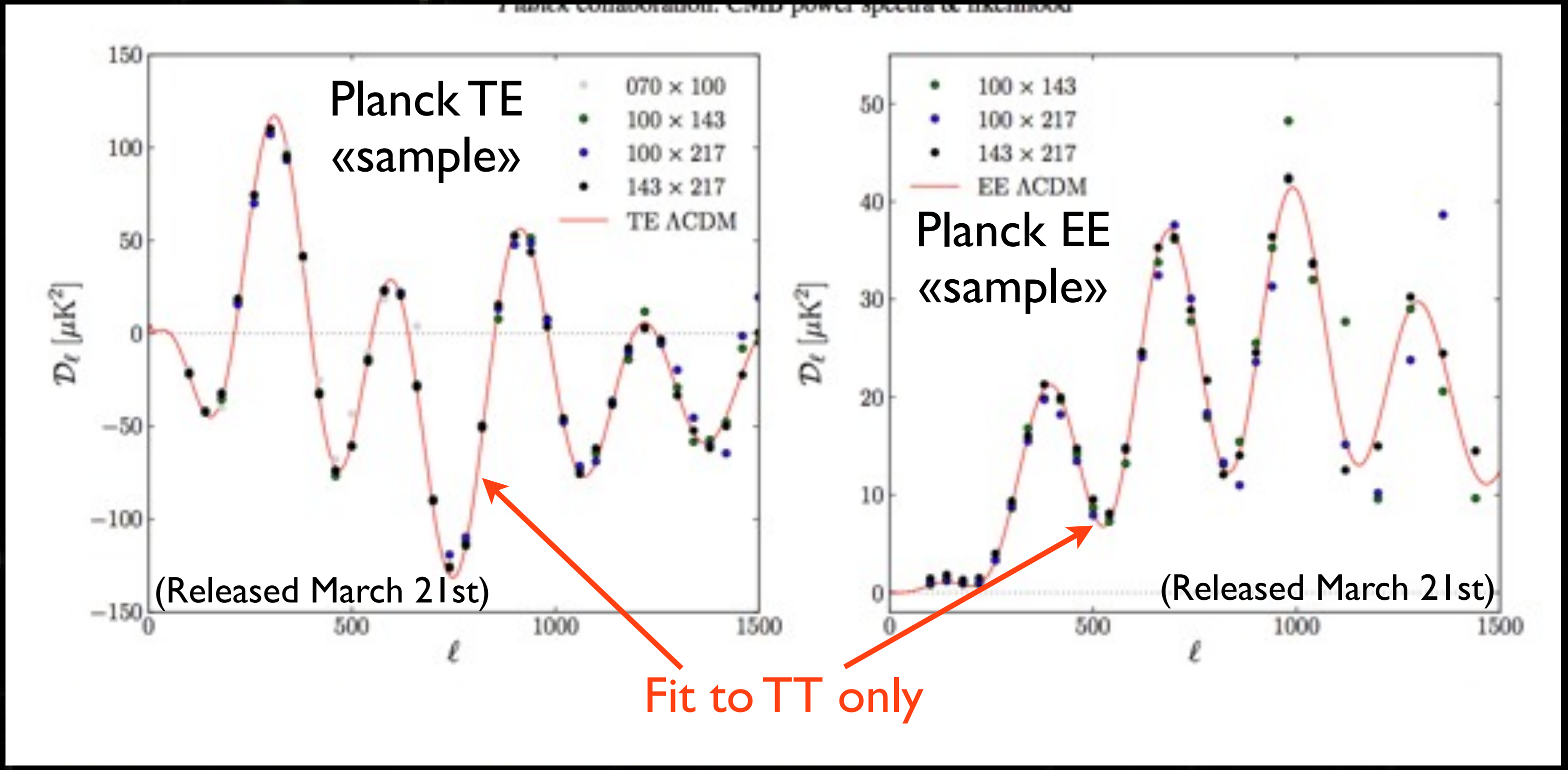

Primordial fluctuations: where are we standing ?

Inflation predictions

• Flatness, Homogeneity	✔
• Nature of perturbations: ★ TT peaks at the same location as EE troughs ➡ Adiabatic perturbations	✔
• Spectral index $P(k) \propto k^{n_s-1}$ ★ Planck TT + WMAP Pol + High ℓ + BAO $n_s = 0.9608 \pm 0.0054$ (7.2σ from 1) ➡ Almost scale invariant spectrum	✔
• Gaussianity ★ No convincing evidence for non-gaussianity (despite impressive efforts)	✔
• Tensor perturbations of the metric ★ No B-mode detection (yet ...)	?

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B-modes: Holy Grail for cosmology

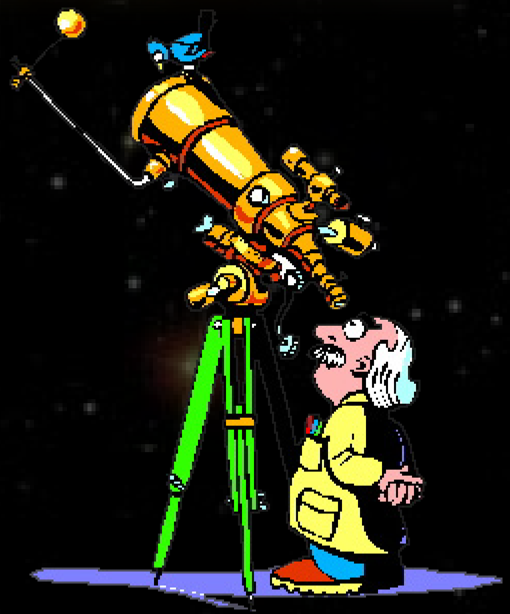
- Smoking gun for inflation
  - T/S ratio:
    - < 0.11 [95% C.L. from Planck TT + WMAP Pol + BAO]
    - > 0.01 for simplest inflationary models
    - might be much lower for more complex models
- Cosmic strings and other defects
  - Produces distinctive B polarization
    - [Bevis et al. (2007), Phys.Rev.D76:043005]
    - [Urrestilla et al. (2008), astro-ph/0803.2059]
    - [Pogosian et Wyman (2007), astro-ph/0711.0747]
- Superstrings ?
  - most (all ?) string inspired inflation theories predict r << 1
  - Unique opportunity to falsify string theory !
    - [Kallosh & Linde (2007), JCAP 0704:017]
- CPT symetry testing
  - CPT violations may induce cosmological birefringence
  - linear polarization rotation : non vanishing TB and EB CMB spectra
    - [Feng et al. (2006), PRL 96, 221302]
    - [Xia et al., (2009), Phys. Lett. B687, 129]
    - [Gluscevic et al., (2012), arXiv:1206.5546v1]

Inflation
↙ ↘
Scalar perturbations → TT, TE, EE
Tensor perturbations → TT, TE, EE, BB

Expected difficulties in the Holy Grail Quest

- Sensitivity :
  - ★ B polarization is at best 10 times weaker than E
  - ★ Amplitude could be **very** small ...
  - ★ 1 year of Planck is ~ S/N=1 for T/S=0.01
  - ★ A dedicated space mission might not be for tomorrow.

- Foregrounds :
  - ★ Need to remove them accurately (can't just mask)
    - ➡ Multiwavelength detectors
  - ★ Observe an ultra-clean region
    - ➡ can't be too small as primordial B modes are mainly on large scales



- Systematic effects :
  - ★ Instrument induces leakage of T into E and B (and T>>E>>B)
    - ➡ Cross-polarization and ground pickup are major issues
  - ★ Atmospheric polarization ...
  - ➡ Need for accurate polarization modulation

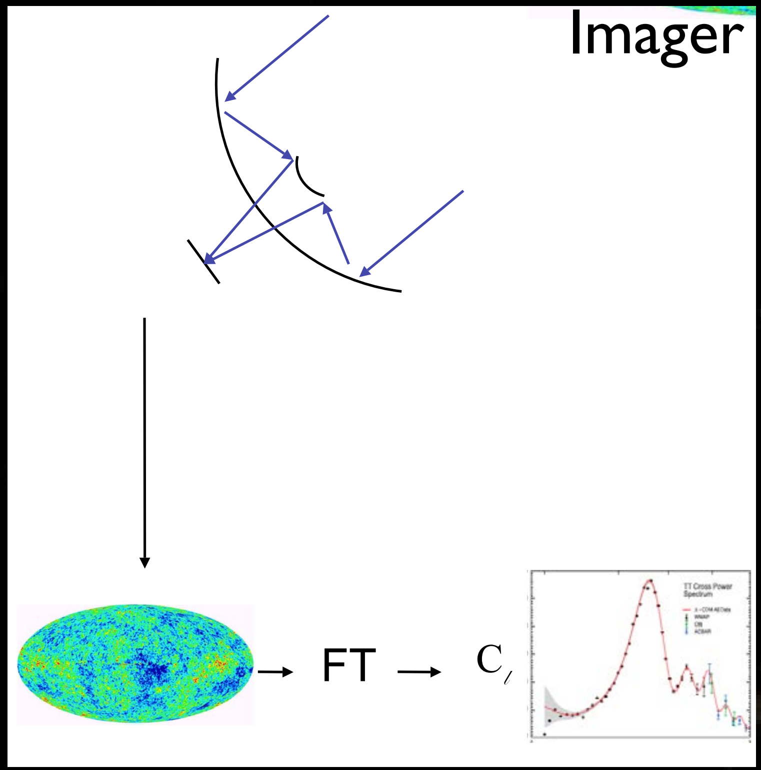
Possible instruments

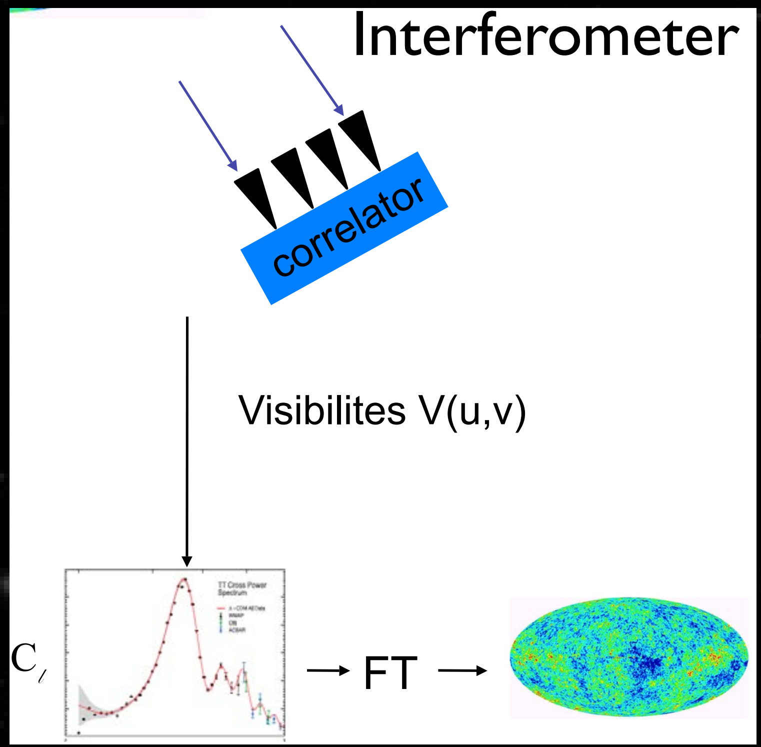
- Imagers with bolometers:
  - ★ No doubt they are nice detectors for CMB:
    - wide band
    - low noise
  - ★ Especially true for a satellite (small background)

- Interferometers:
  - ★ Long history in CMB
    - CMB anisotropies in the late 90s (CAT: 1st detection of subdegrees anisotropies, VSA)
    - CMB polarization 1st detection (DASI, CBI)
  - ★ Technology used so far
    - Antennas + HEMTs : higher noise
    - Correlators : hard to scale to large #channels
  - ★ Clean systematics:
    - No telescope (lower ground-pickup & cross-polarization)
    - Angular resolution set by receivers geometry (well known)

- Can these two nice devices be combined ?
  - ➡ Bolometric Interferometry !

P. Timbie





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Good control of systematics

- Can these two nice devices be combined ?

➡ Bolometric Interferometry !

Both

The QUBIC collaboration

- APC Paris, France
- IAS Orsay, France
- CSNSM Orsay, France
- IRAP Toulouse, France
- Institut Néel, Grenoble, France
- Maynooth University, Ireland
- Universita di Milano-Bicocca, Italy
- Universita La Sapienza, Roma, Italy
- University of Manchester, UK
- 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

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

QUBIC Site: Dome C, Antarctica

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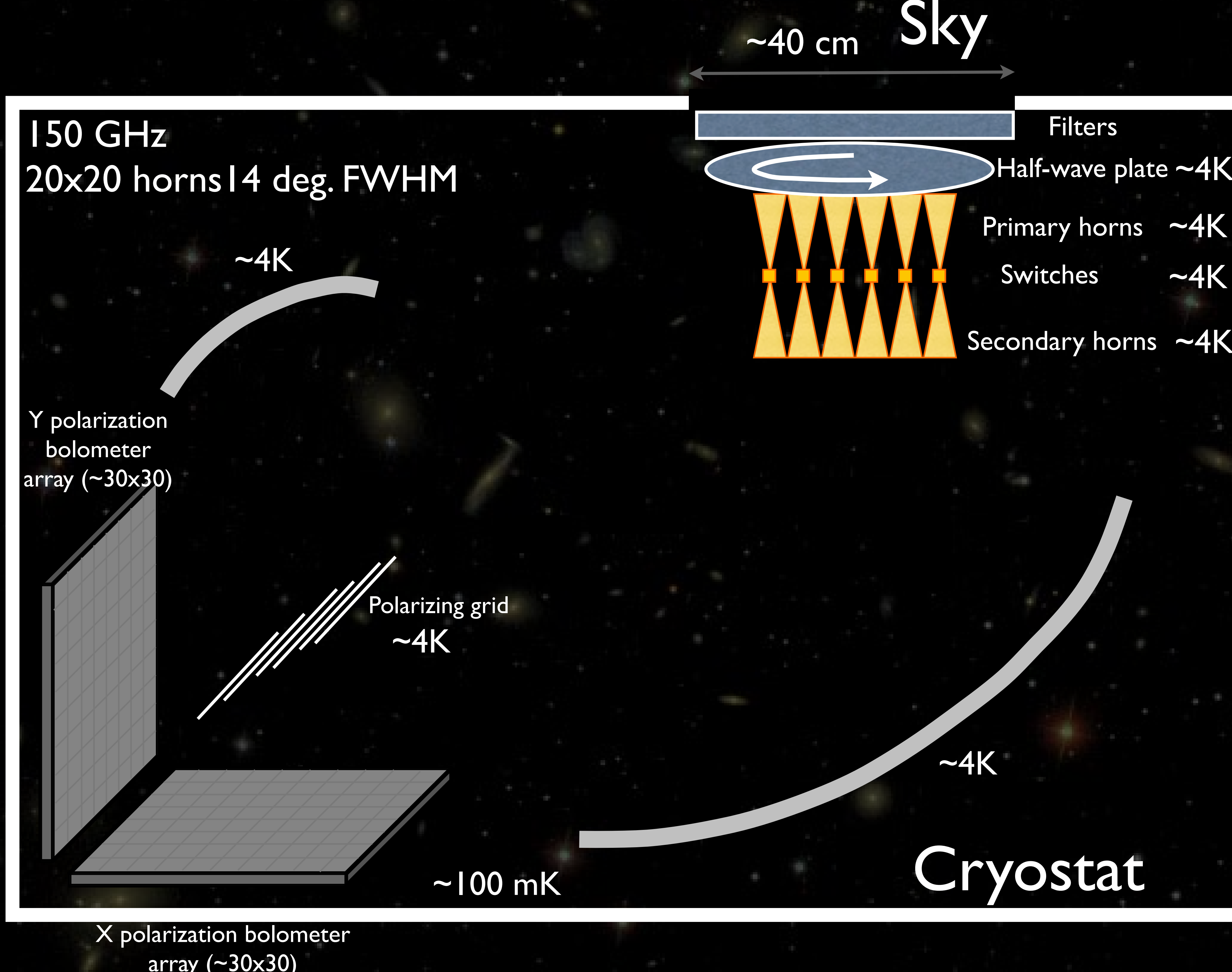
QUBIC design



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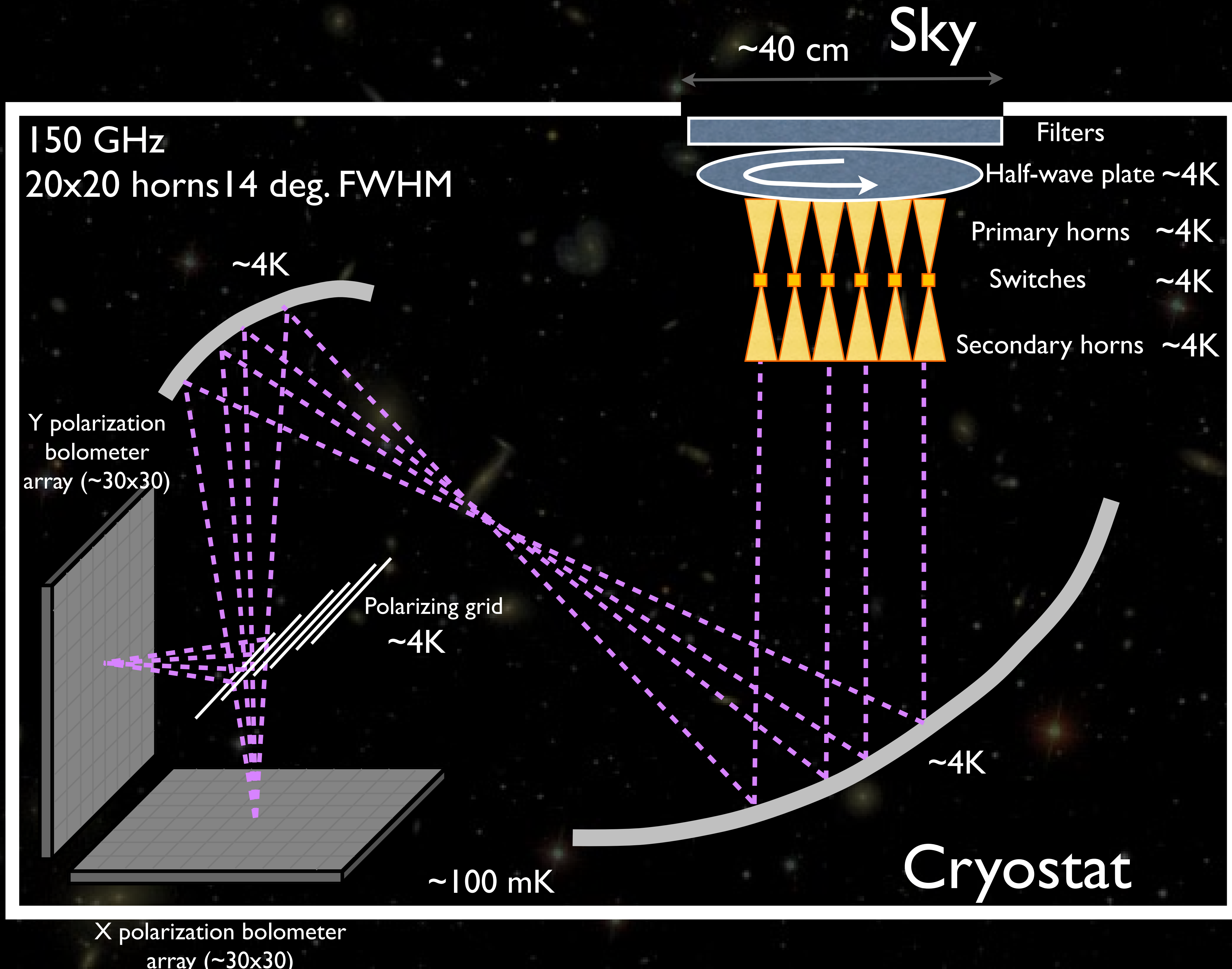

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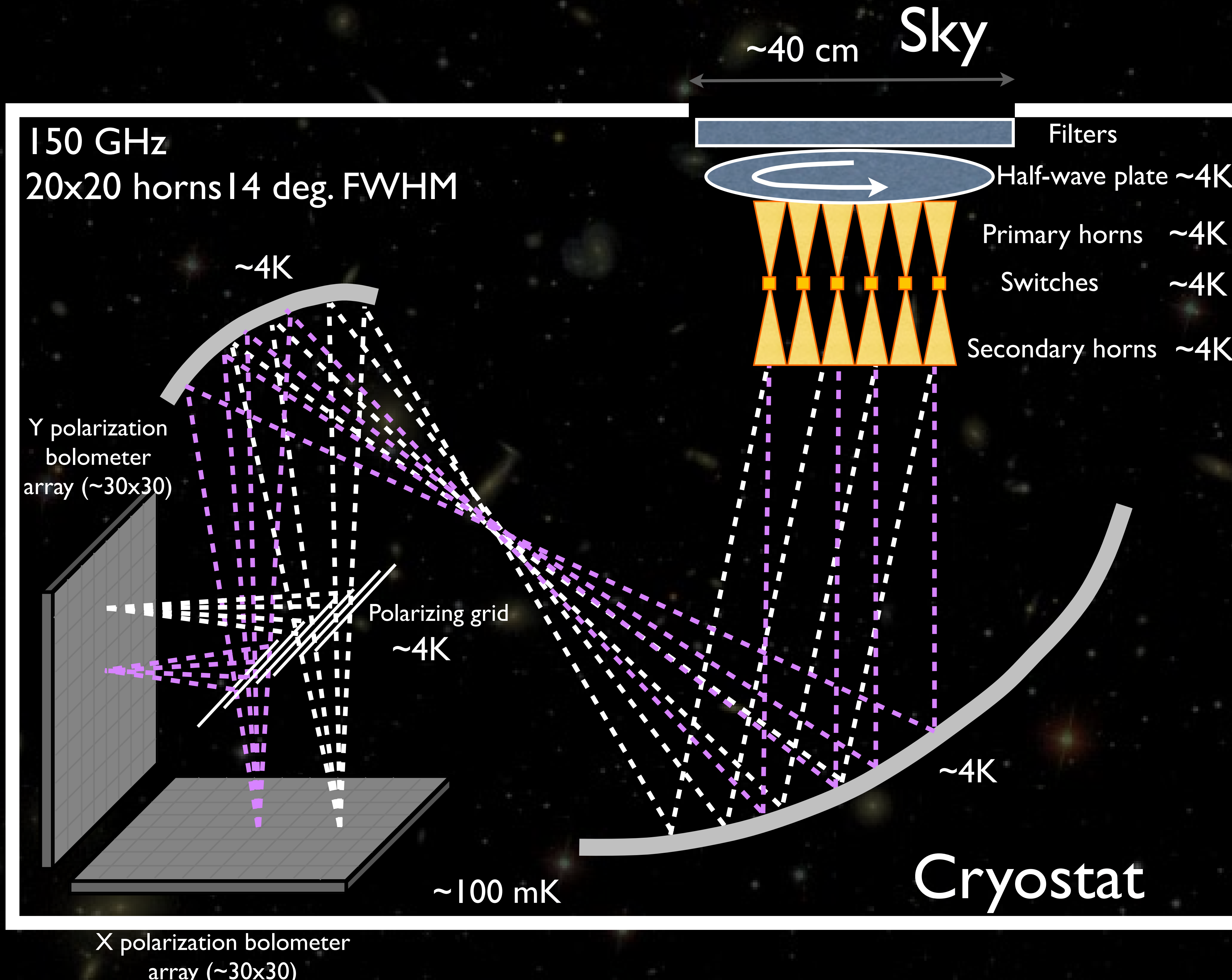

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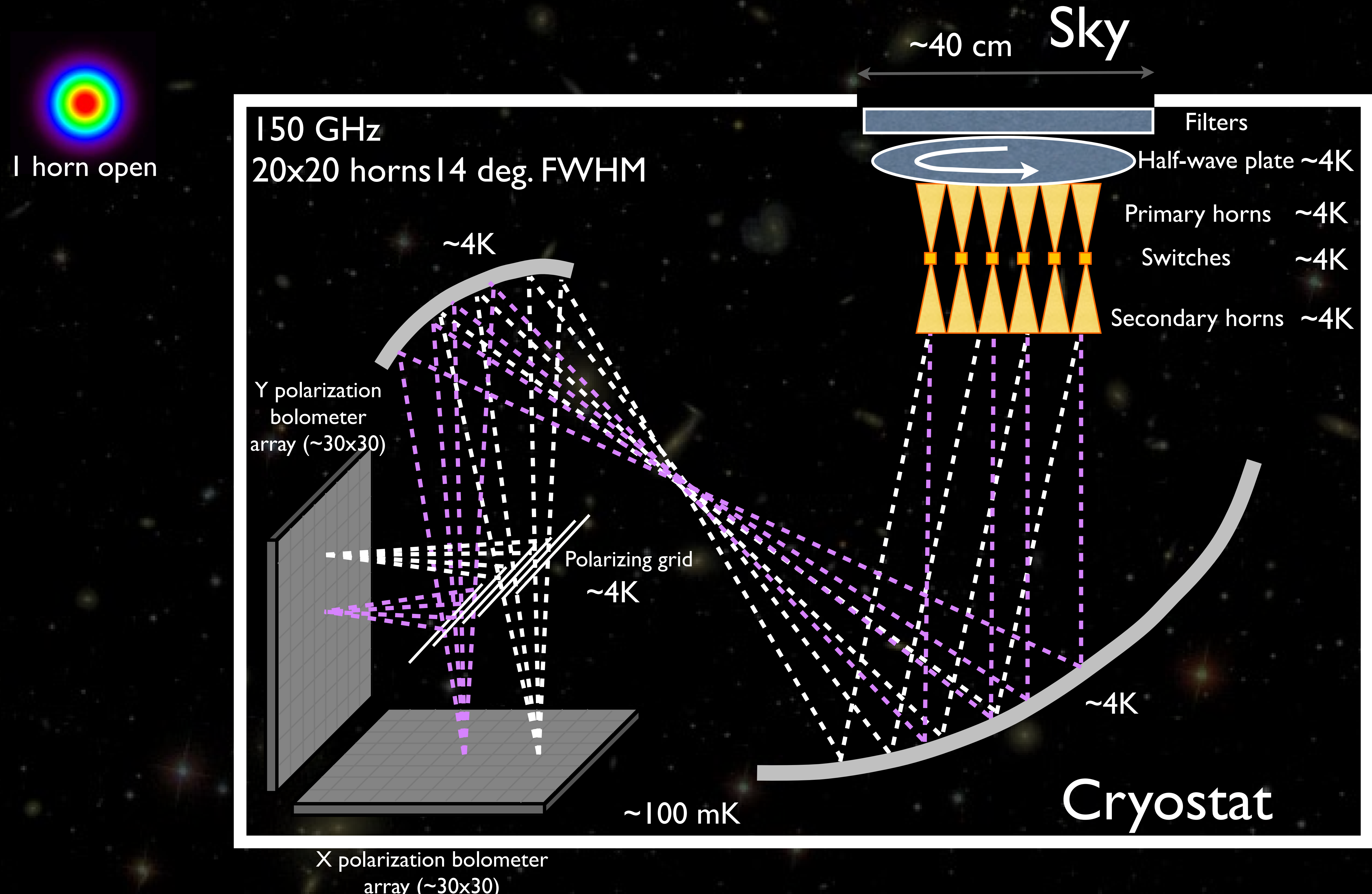

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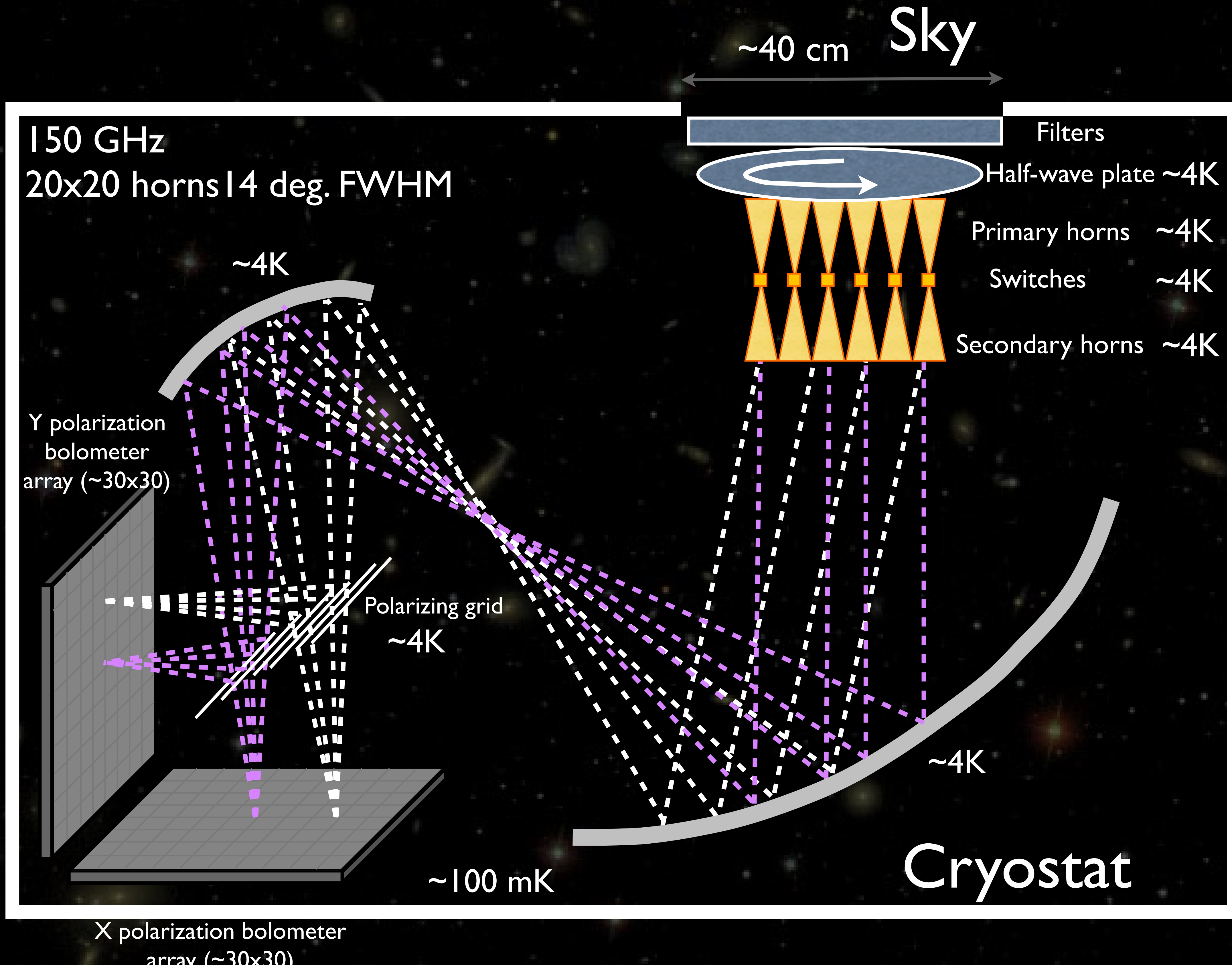
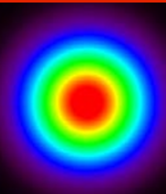


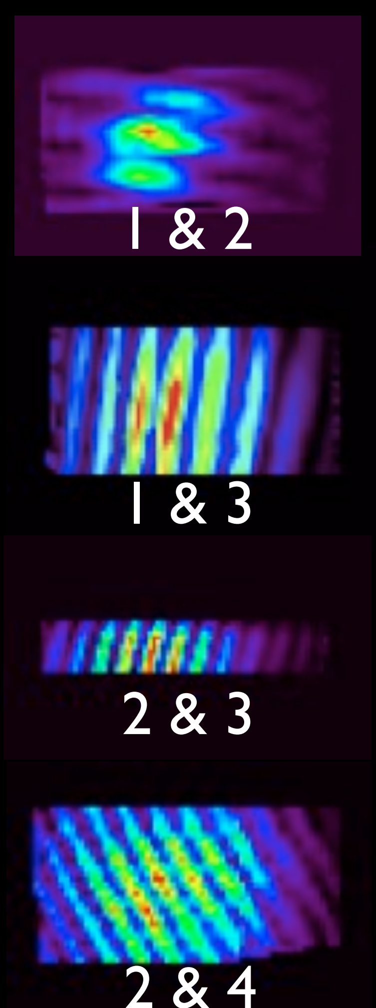
QUBIC design

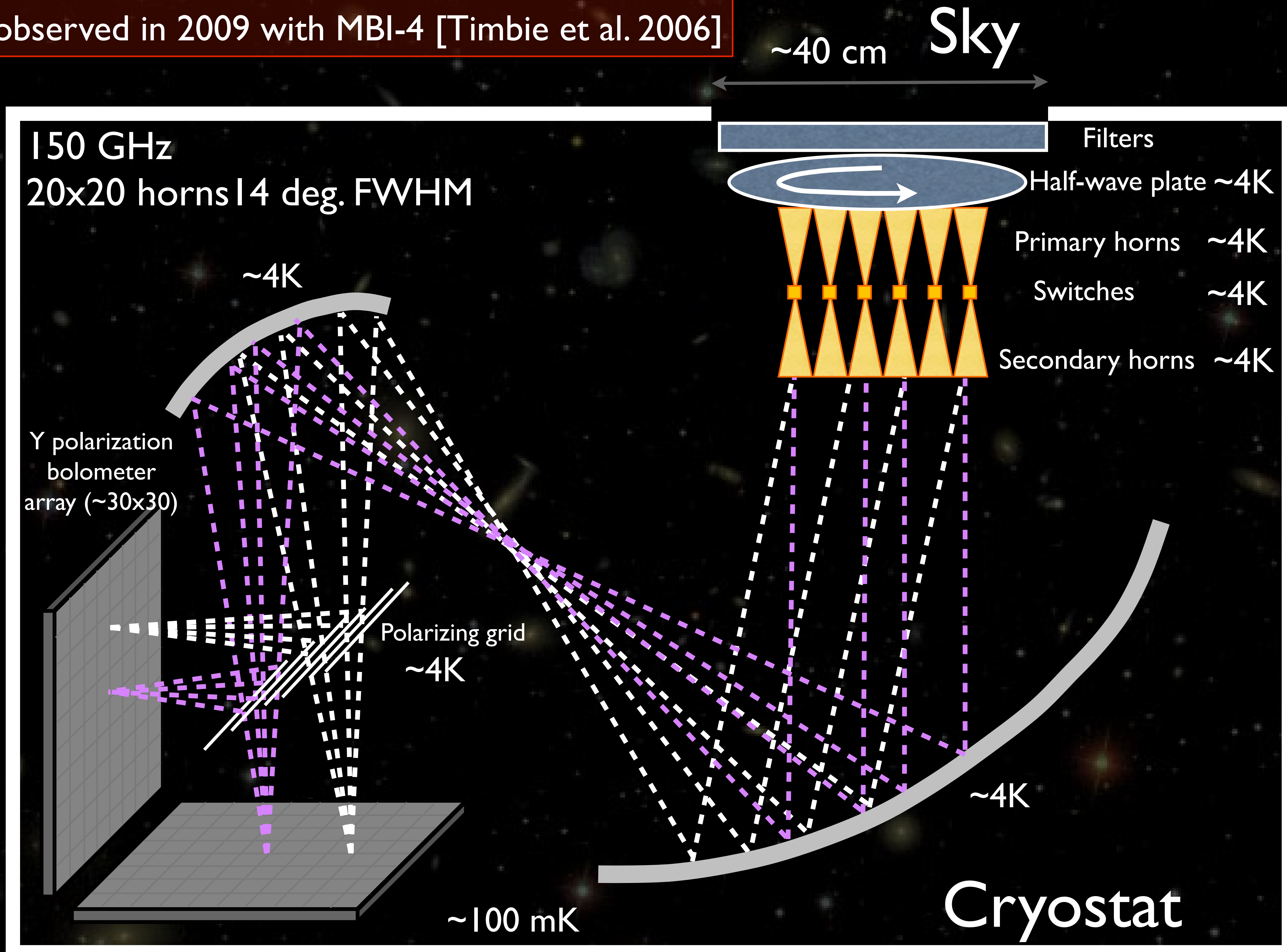
fringes successfuly observed in 2009 with MBI-4 [Timbie et al. 2006]



1 horn open

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





X polarization bolometer
array (~30x30)

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Signal in QUBIC

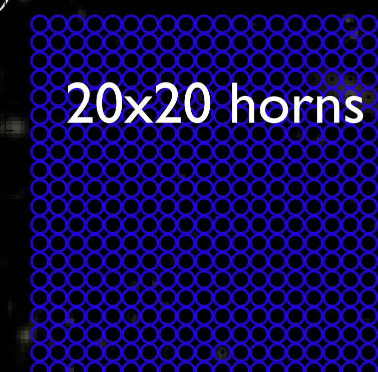
- Signal on bolometer d_p (HWP modulation) :

$$R(\vec{d}_p, t) = S_I(\vec{d}_p) \pm \cos(4\omega t) S_Q(\vec{d}_p) \pm \sin(4\omega t) S_U(\vec{d}_p)$$

+ for X focal plane
- for Y focal plane

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

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



- Synthetic beam formed by the set of baselines
  - ★ (x_i = locations of primary horns, D_f = focal length of the combiner)

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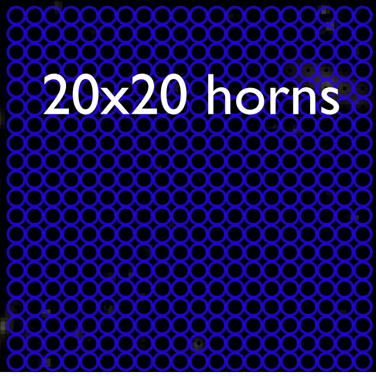

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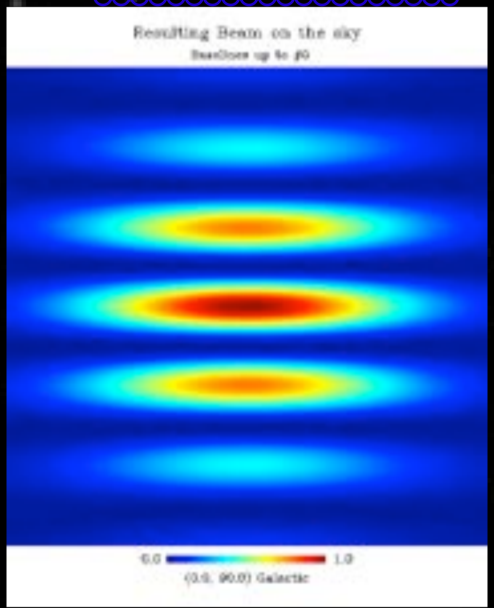

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⇔ An imager with the synthesized beam

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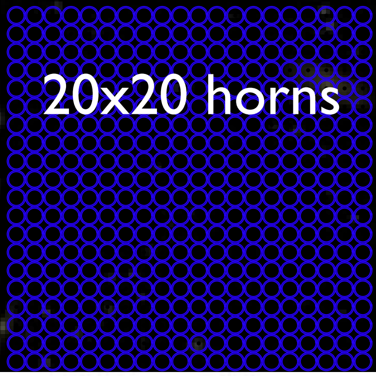

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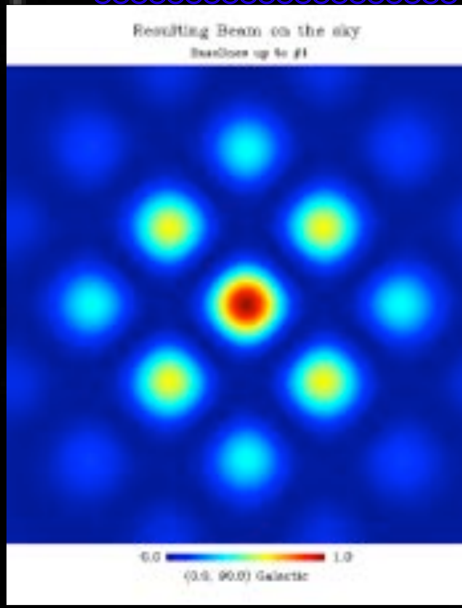

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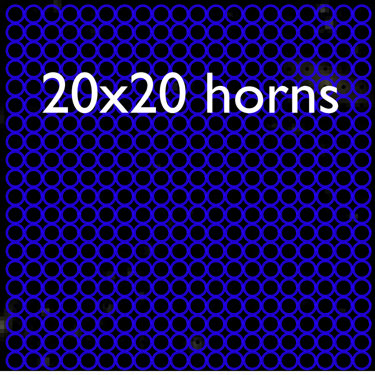

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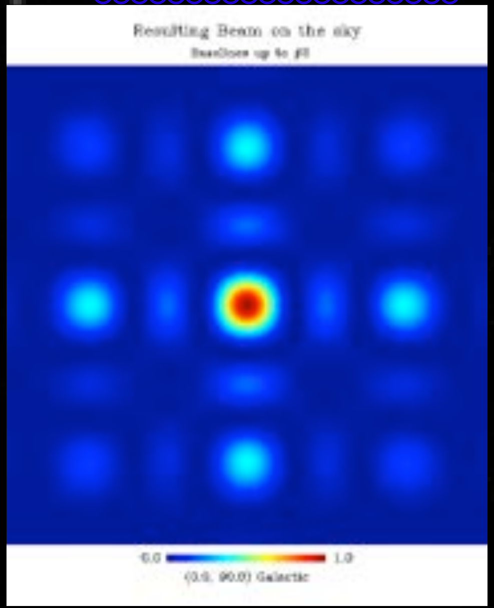

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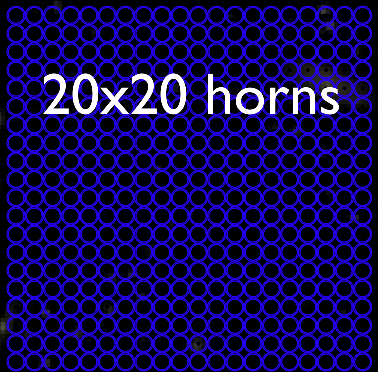

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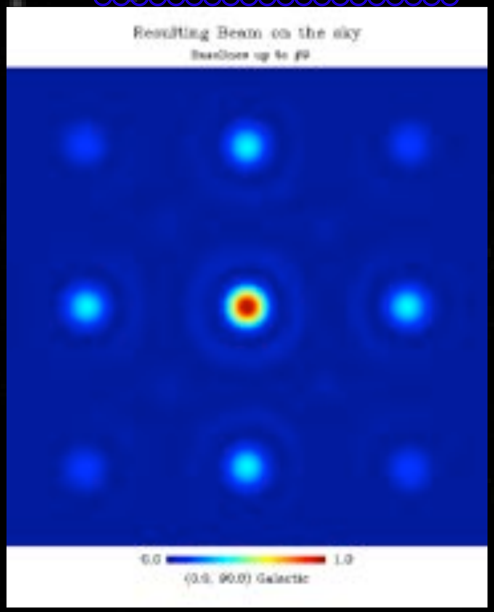

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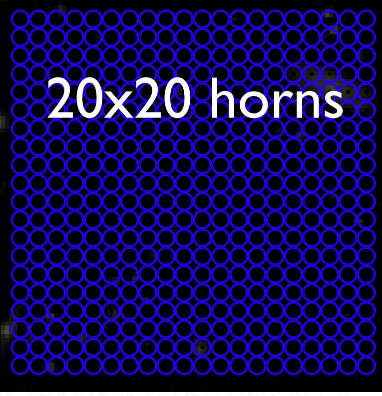

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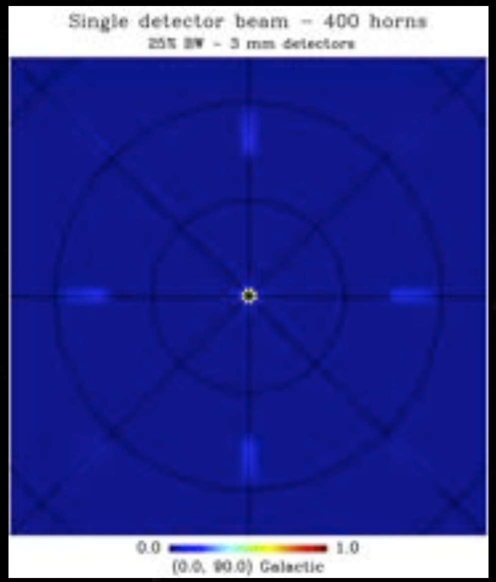

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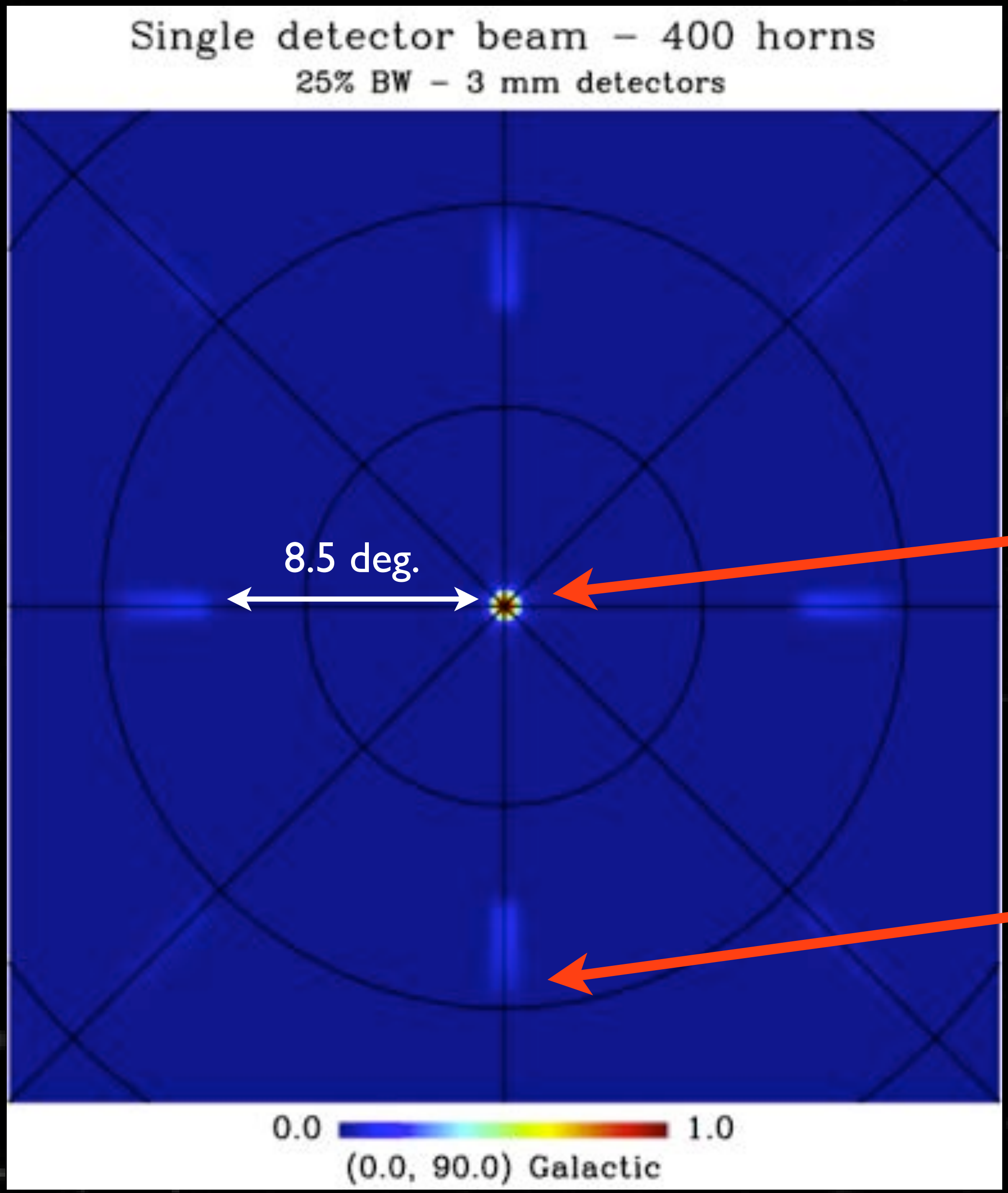
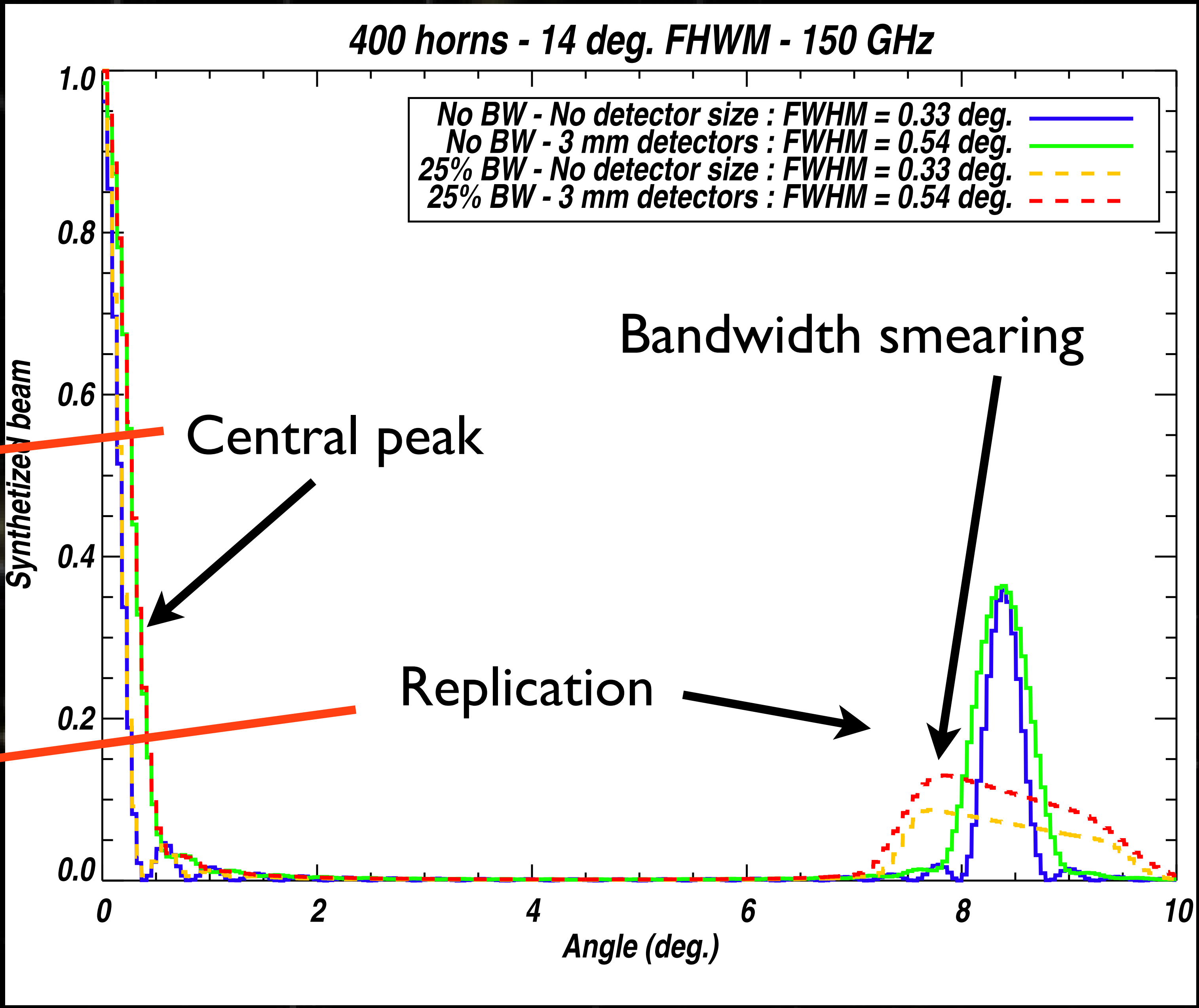
Synthesized beam





Replicated peaks **are not** (uncontrolled) sidelobes:

- Extremely well known (as much as the main peak)
- The structure of the synthesized beam gives us spatial sensitivity
- Optimal map-making for B.I. in progress

Map Making

- Scan the sky and store TOIs for each detector
- Reproject data on the sky

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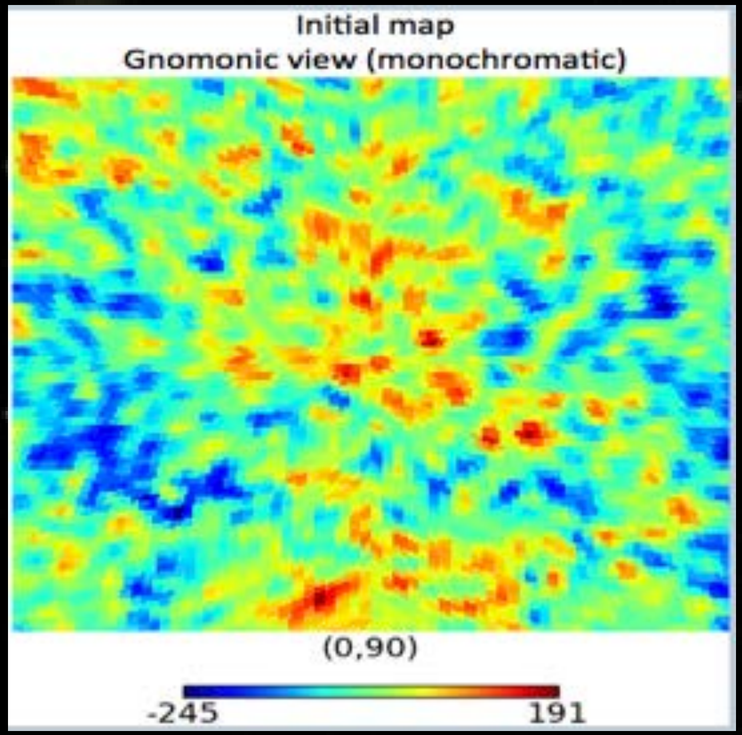
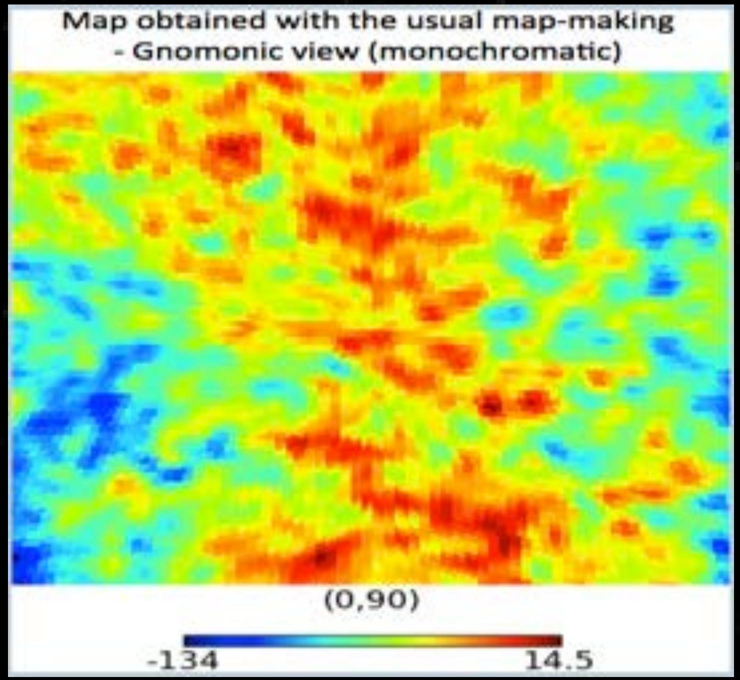
- QUBIC Synthesized beam has multiple peaks
  - ★ Usual map making assumes *A* has a single non zero element in each column
    - Does not lead to good results
  - ★ Improved method with better beam approximation
    - Sparse matrices helps fast convergence of CG
    - First results on simulations are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





Map Making

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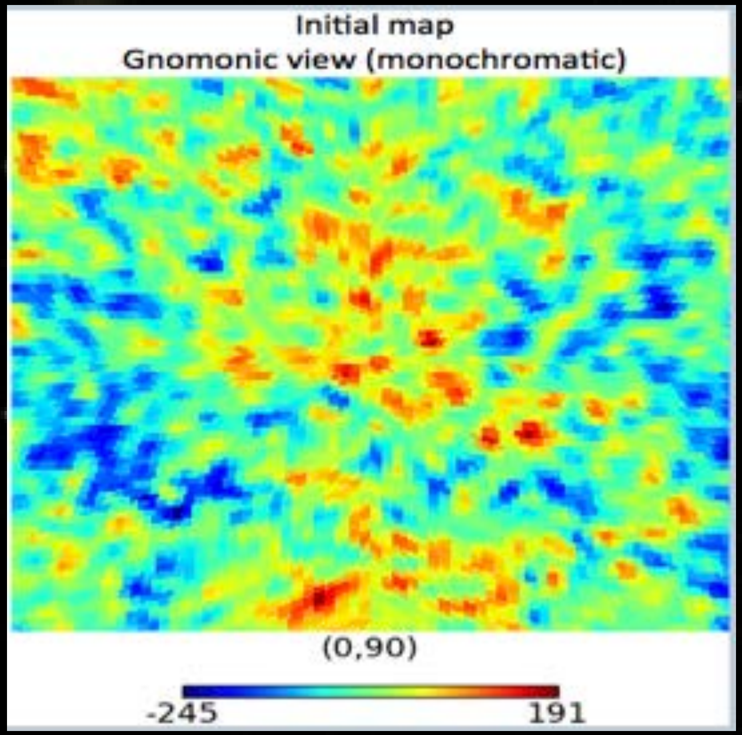

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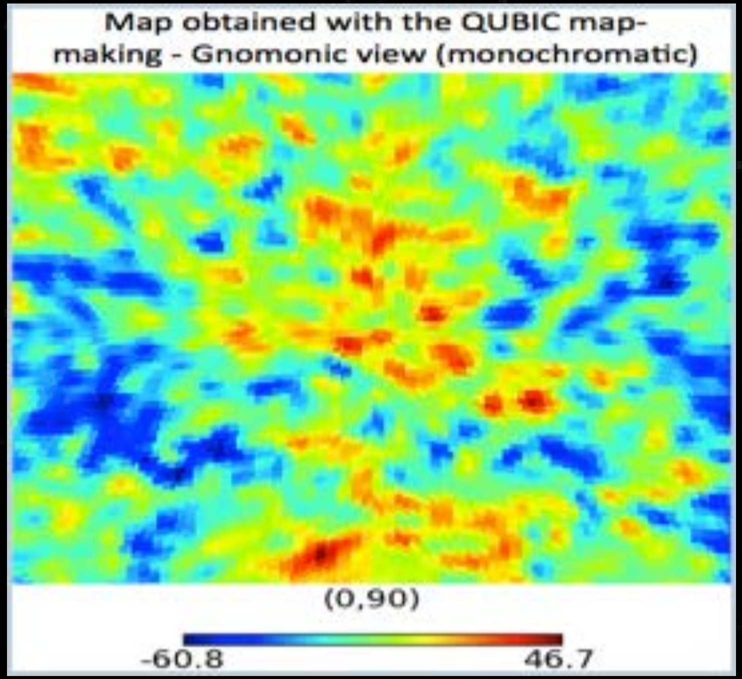
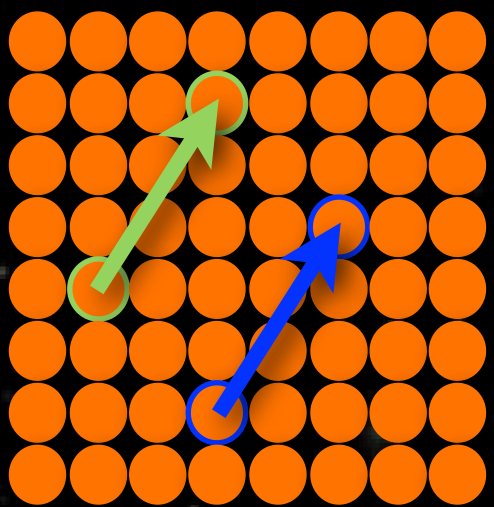


Self-Calibration

- 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 !
  - ★ Example: exact horns locations (figure exagerated !!)



Redundant baselines : same Fourier Mode

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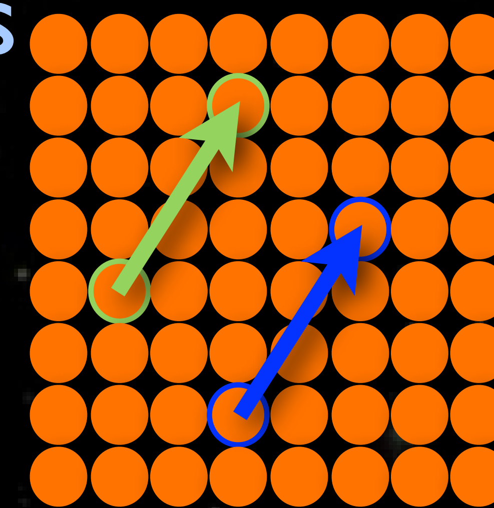

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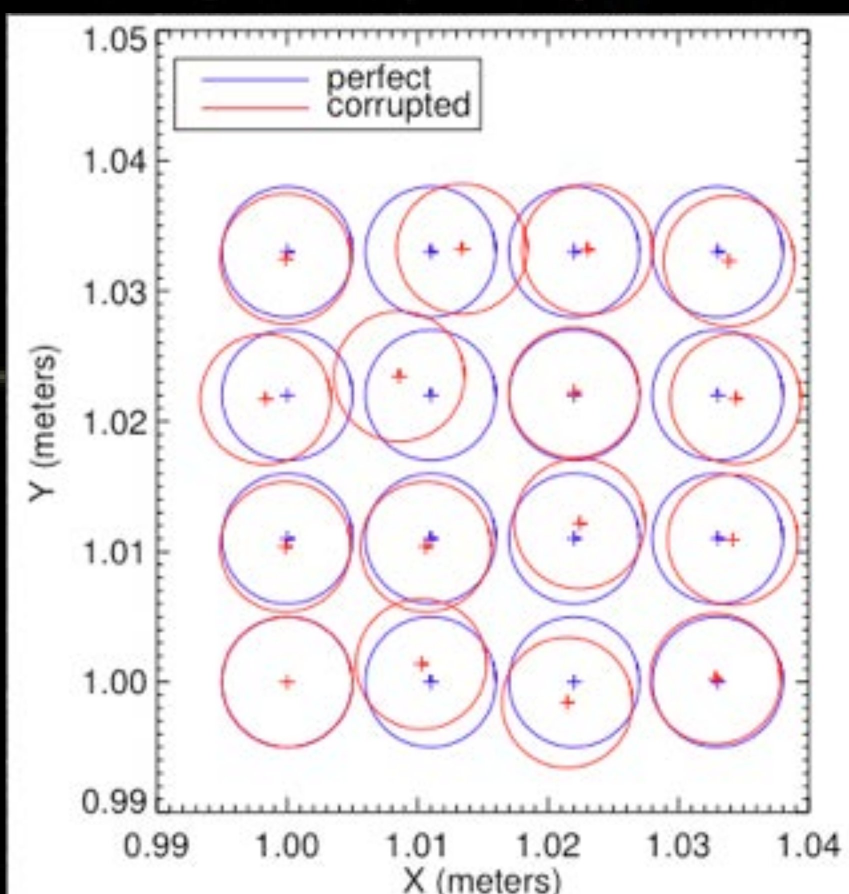

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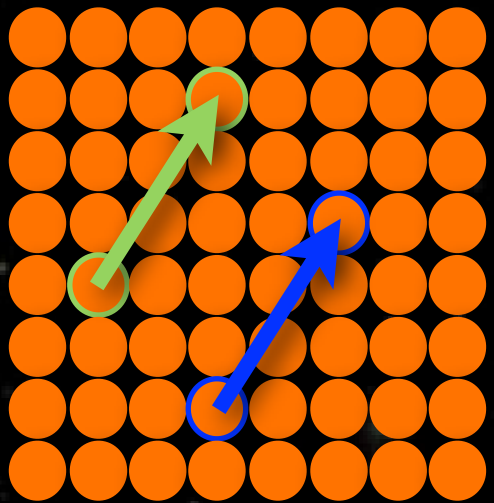

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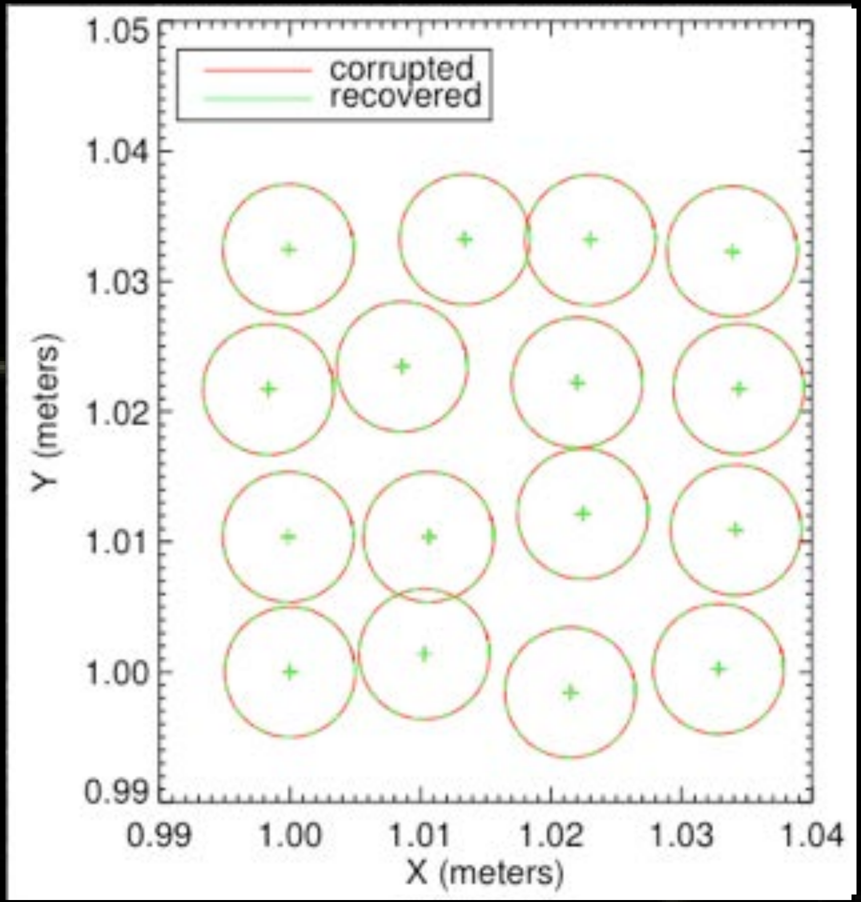

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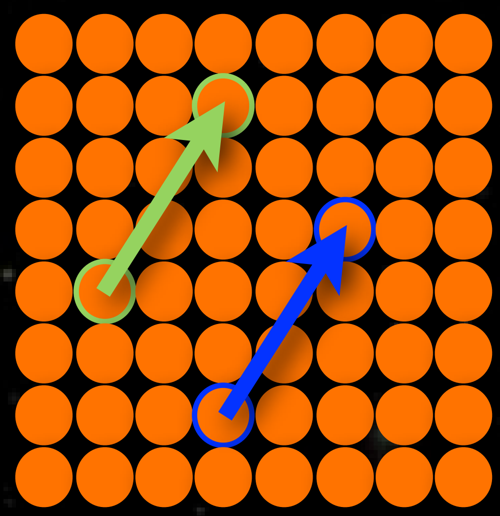
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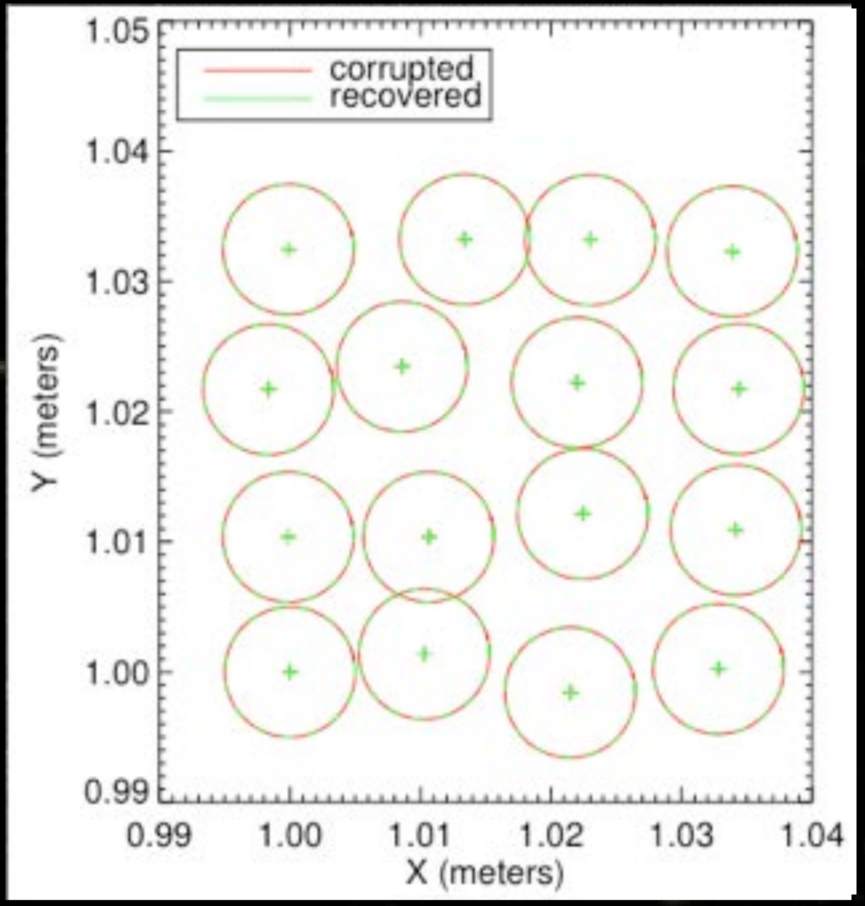

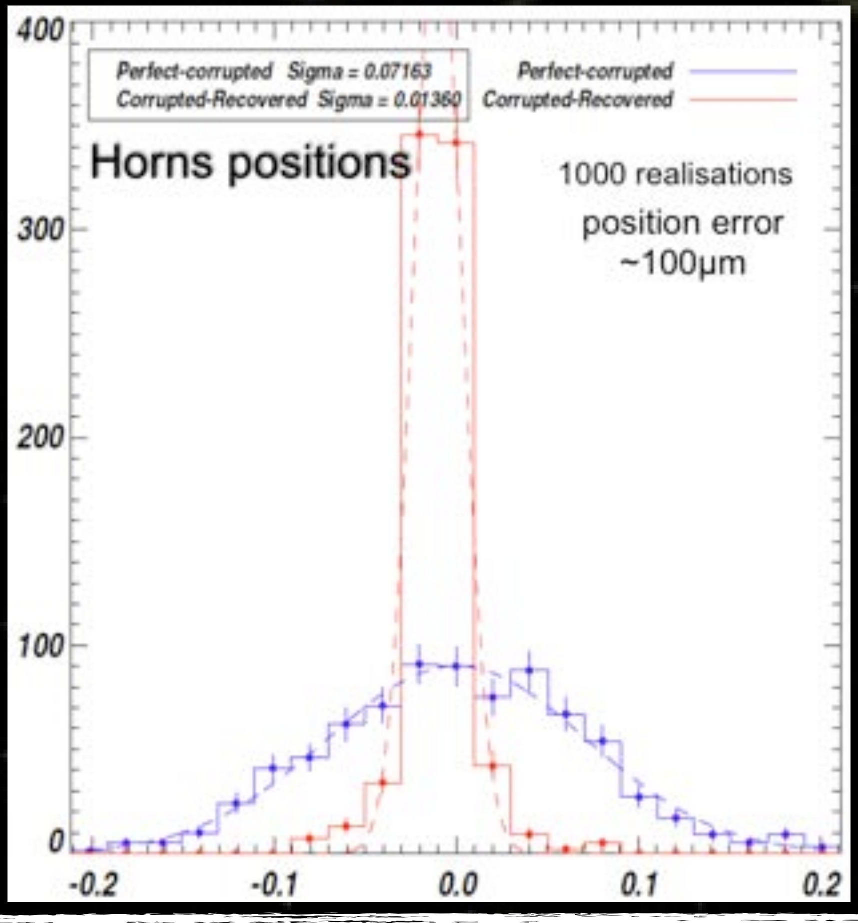

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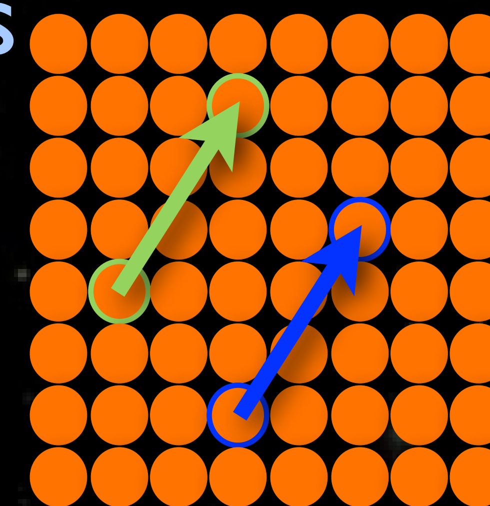

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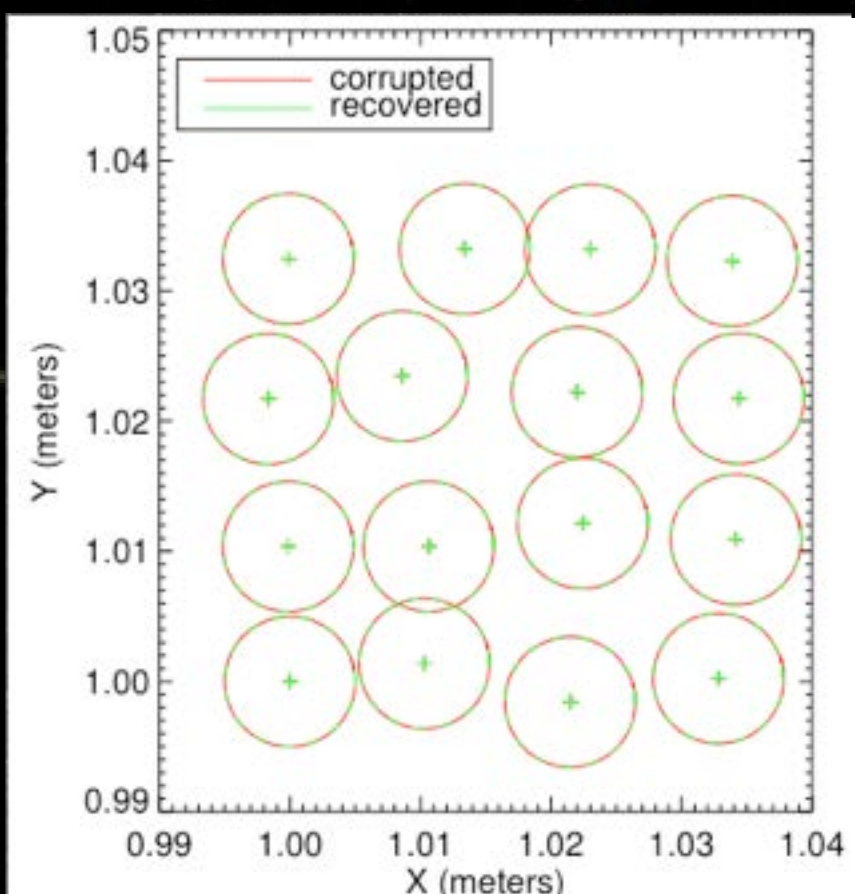

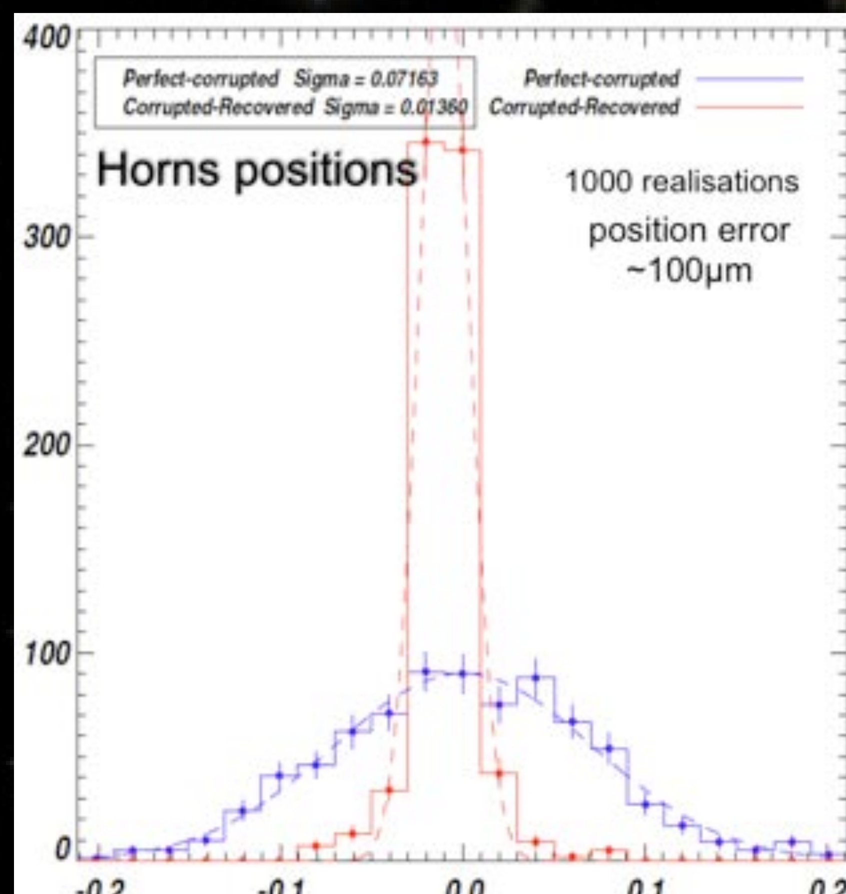

	RMS before	RMS after
Horns location	0.072	0.011
Individual beams	0.090	0.005
TES Intercalibration	0.029	0.007
pointing error, instrument effective Jones matrix	...	...

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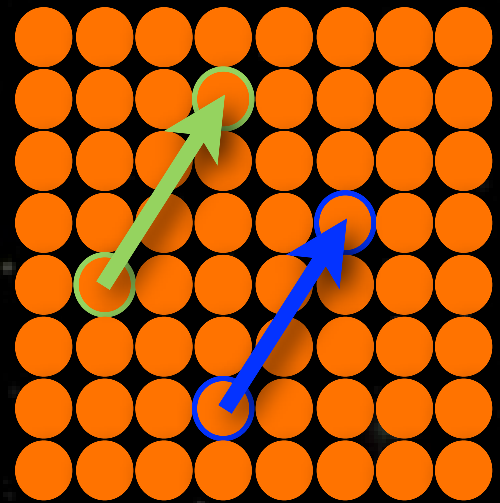

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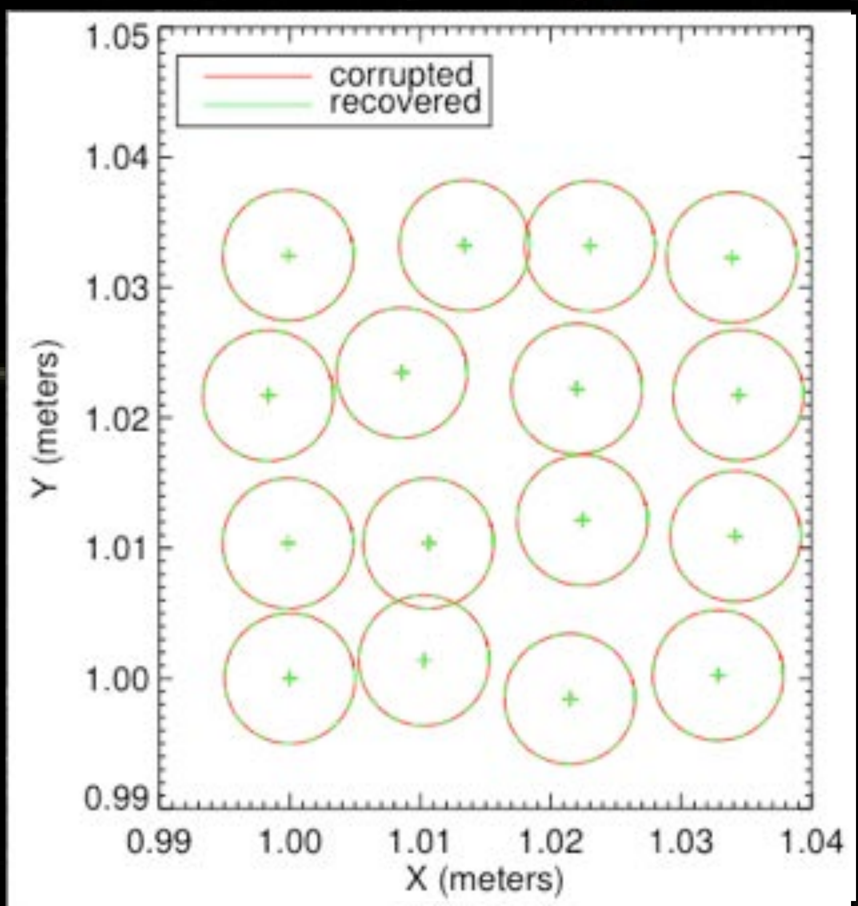

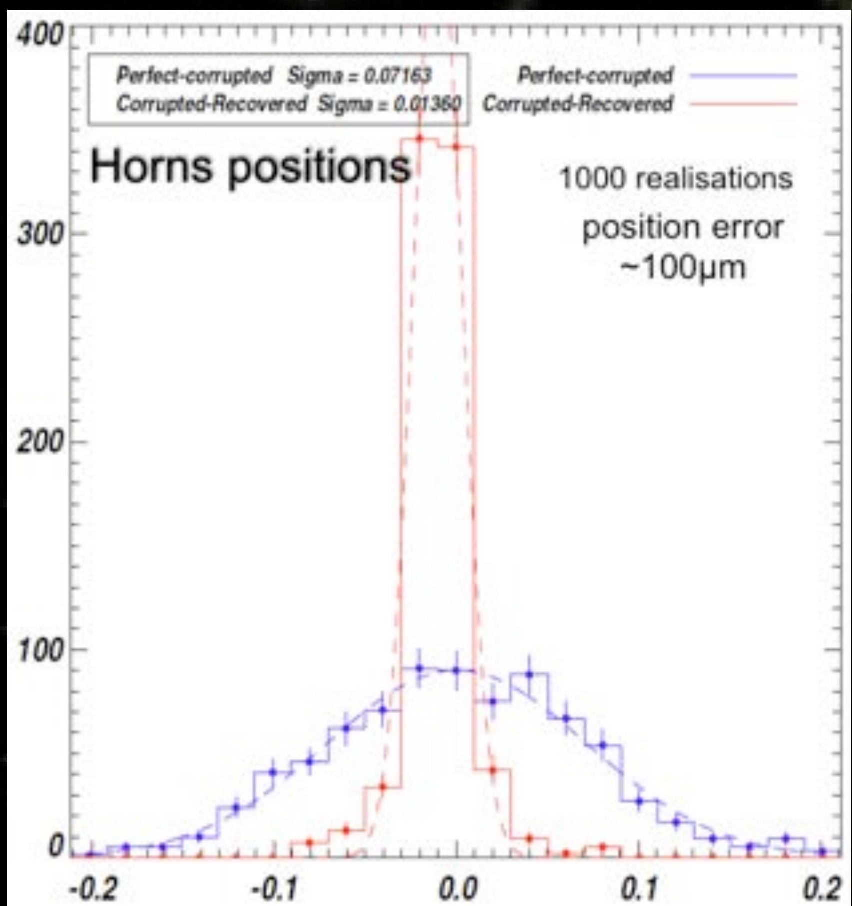

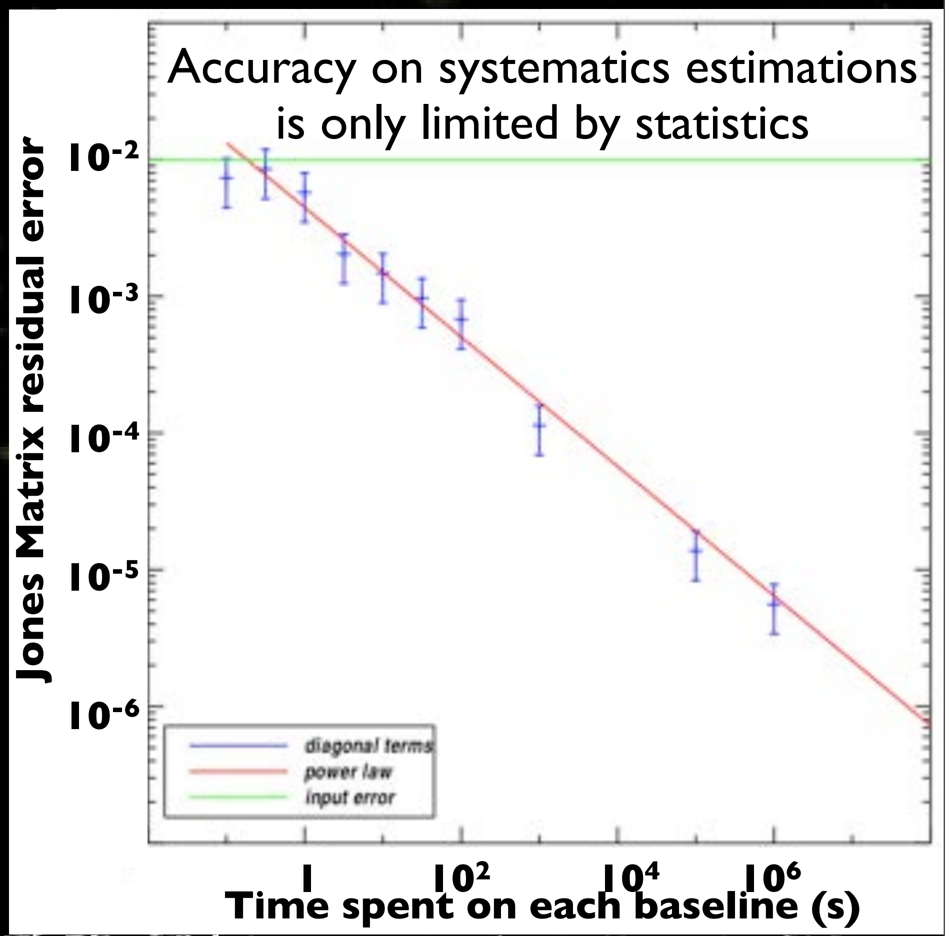

Real size Self-Calibration

- We simulate self-calibration for a real-sized QUBIC for various «time spent per baseline» [Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]

	parameters	$t_b = 0s$	$t_b = 1s$		$t_b = 100s$	
		$\sigma_{id-corr}$	$\sigma_{corr-rec}$	ratio	$\sigma_{corr-rec}$	ratio
Synthesized beam	α^{η}_{iq}	0.004	8.48×10^{-5}	47	1.87×10^{-6}	2140
Horns location	$\widehat{n}_p$	0.15	1.41×10^{-3}	106	3.26×10^{-5}	4596
Source position	$\overrightarrow{x_i}$	$100. \times 10^{-6}$	5.86×10^{-5}	17	2.27×10^{-8}	4402
Channels Jones Matrix {	$g_\eta(\overrightarrow{x_i})$	0.0001	1.36×10^{-6}	73	1.22×10^{-8}	8182
	$e_\eta(\overrightarrow{x_i})$	0.0001	1.09×10^{-6}	92	1.20×10^{-8}	8280
HWP Jones Matrix {	h_η	0.01	1.18×10^{-4}	84	7.27×10^{-6}	1375
	ξ_η	0.01	1.24×10^{-4}	80	5.81×10^{-6}	1722

➡ Reduce uncontrolled systematics to a level that can be adjusted by spending a larger fraction of the time on calibration

➡ We can achieve systematics below statistical errors

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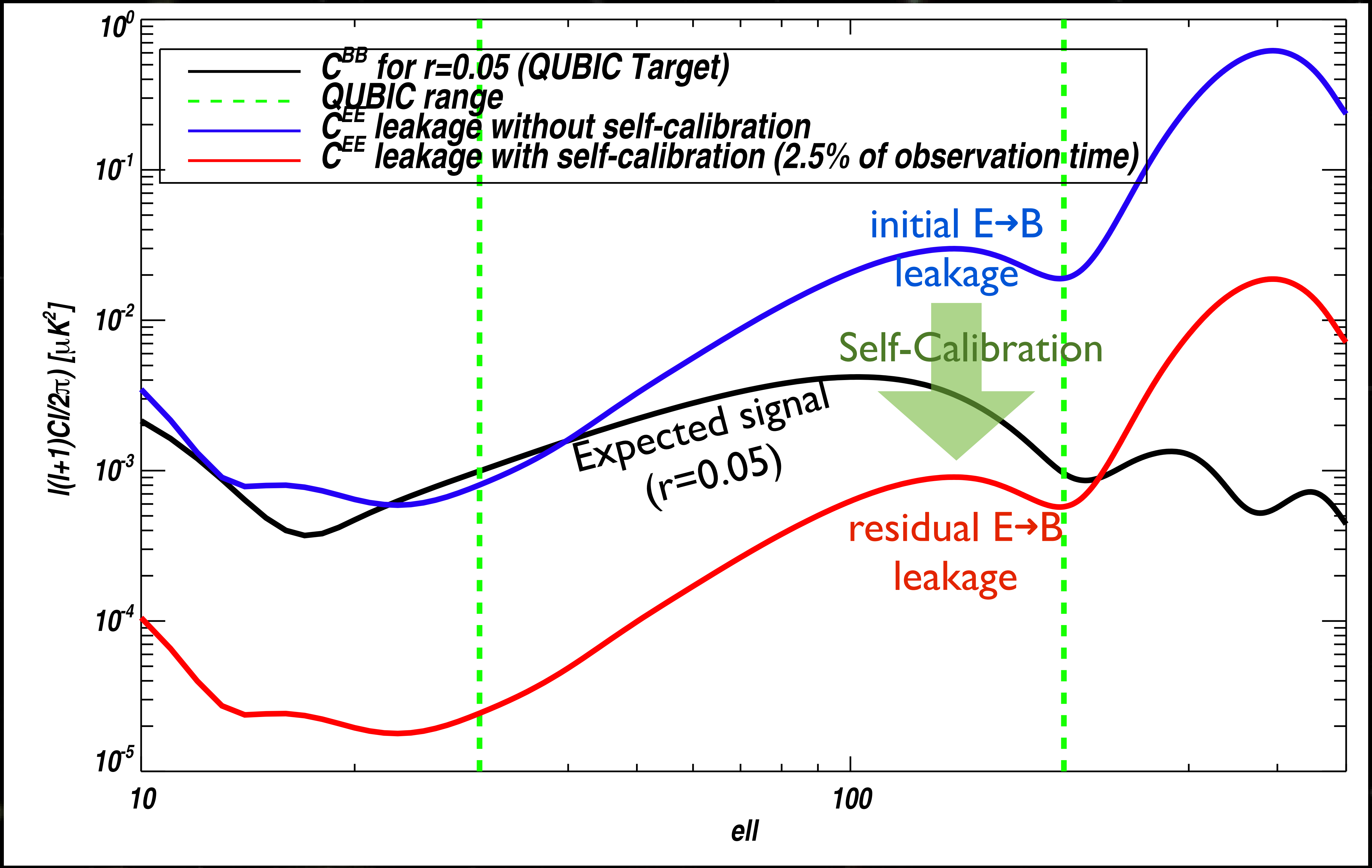
Self-Calibration results



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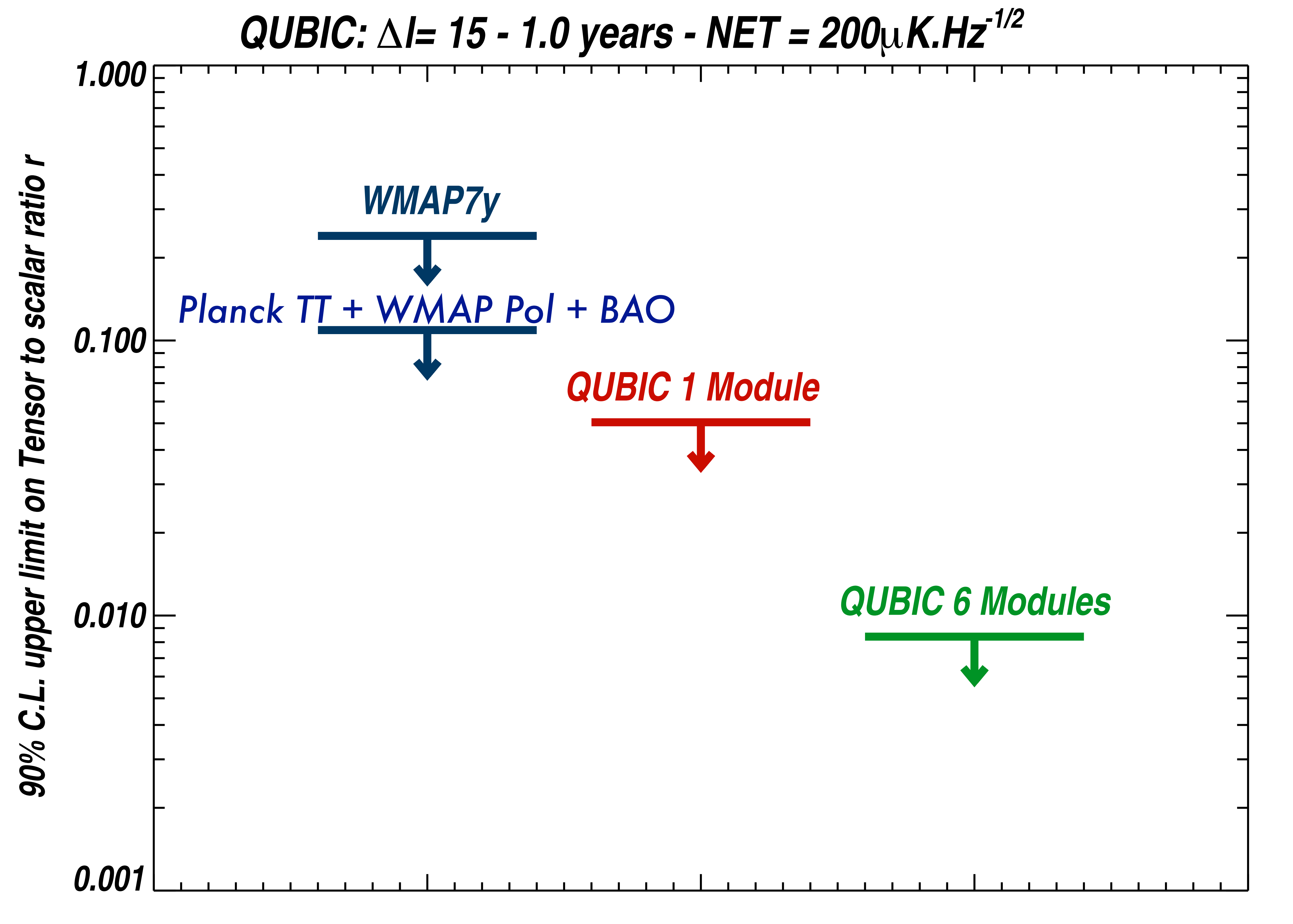
QUBIC timeline

- 2012: Partially funded by french ANR
  - ★ Construction starts for the 1st module
    - 400 horns - 150 GHz - 2048 TES bolometers
- 2013-2014: Integration of the 1st module at APC
- late 2014: First light at Dôme C, Antarctica
  - ★ Data taking : one to two years (incl. winter) with one module
- 2016...: Full QUBIC construction
  - ★ 6 modules at 90, 150 and 250 GHz

tensor/scalar ratio sensitivity



Summary

- QUBIC is a novel instrumental concept
  - ★ Dedicated to CMB polarimetry and inflationary physics
  - ★ High sensitivity with TES bolometers
  - ★ Interferometer optimized to handle systematics (self calibration)
  - ★ Target :
    - First module: $r < 0.05$ at 90% C.L. in one year
    - Six modules: $r < 0.01$ at 90% C.L. in one year

- Working towards a collaboration with China
  - ★ with IHEP (XinMin Zhang, JunQin Xia, Hong Li, ...) and PMO (ShengCai Shi)
  - ★ Huge need for data analysis and simulations
  - ★ Some aspects still need to be covered for the 1st module
  - ★ Dome A site would be as good as Dome C for future modules
  - ➡ Nice opportunity to get involved in such a hot topic

谢谢

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