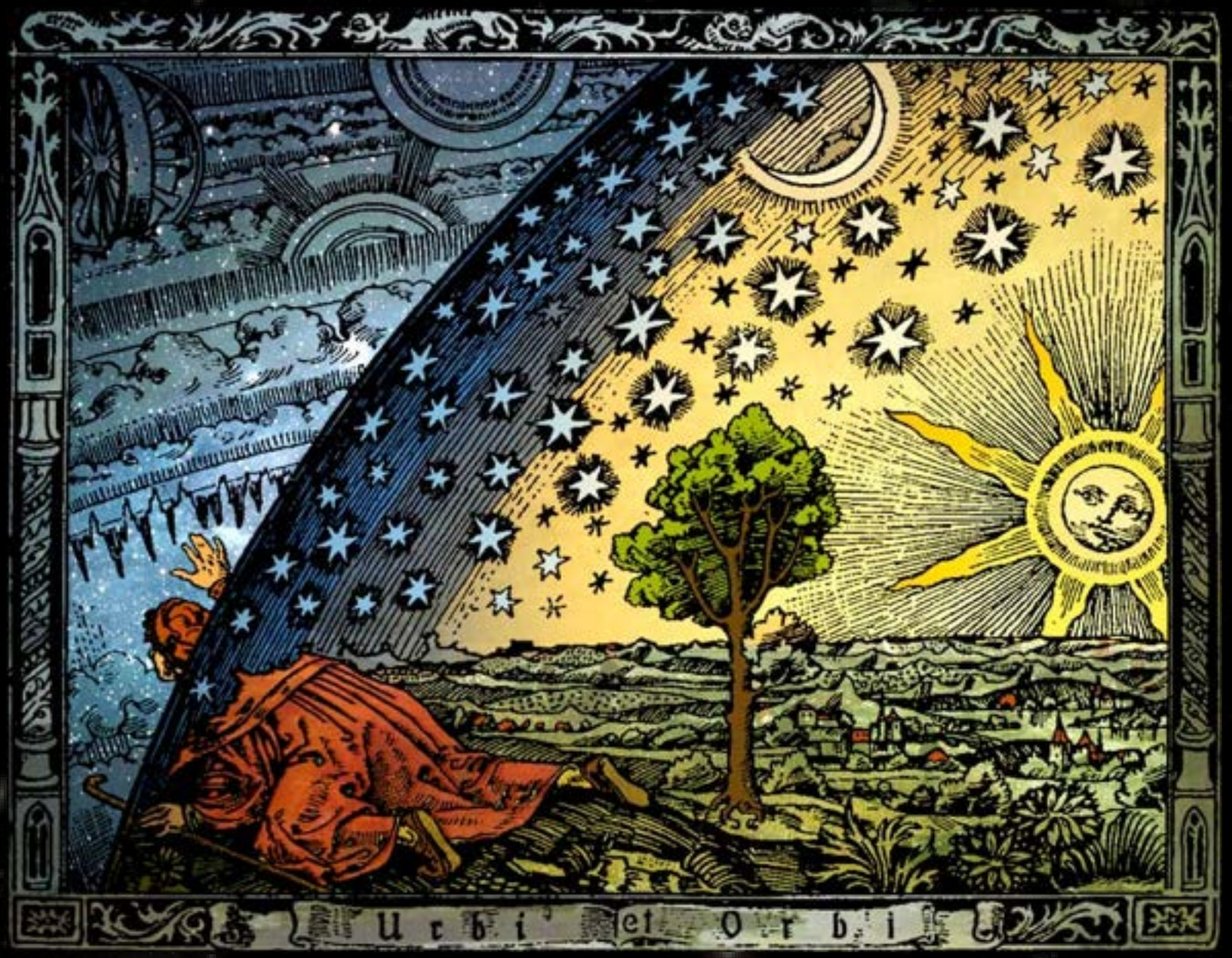
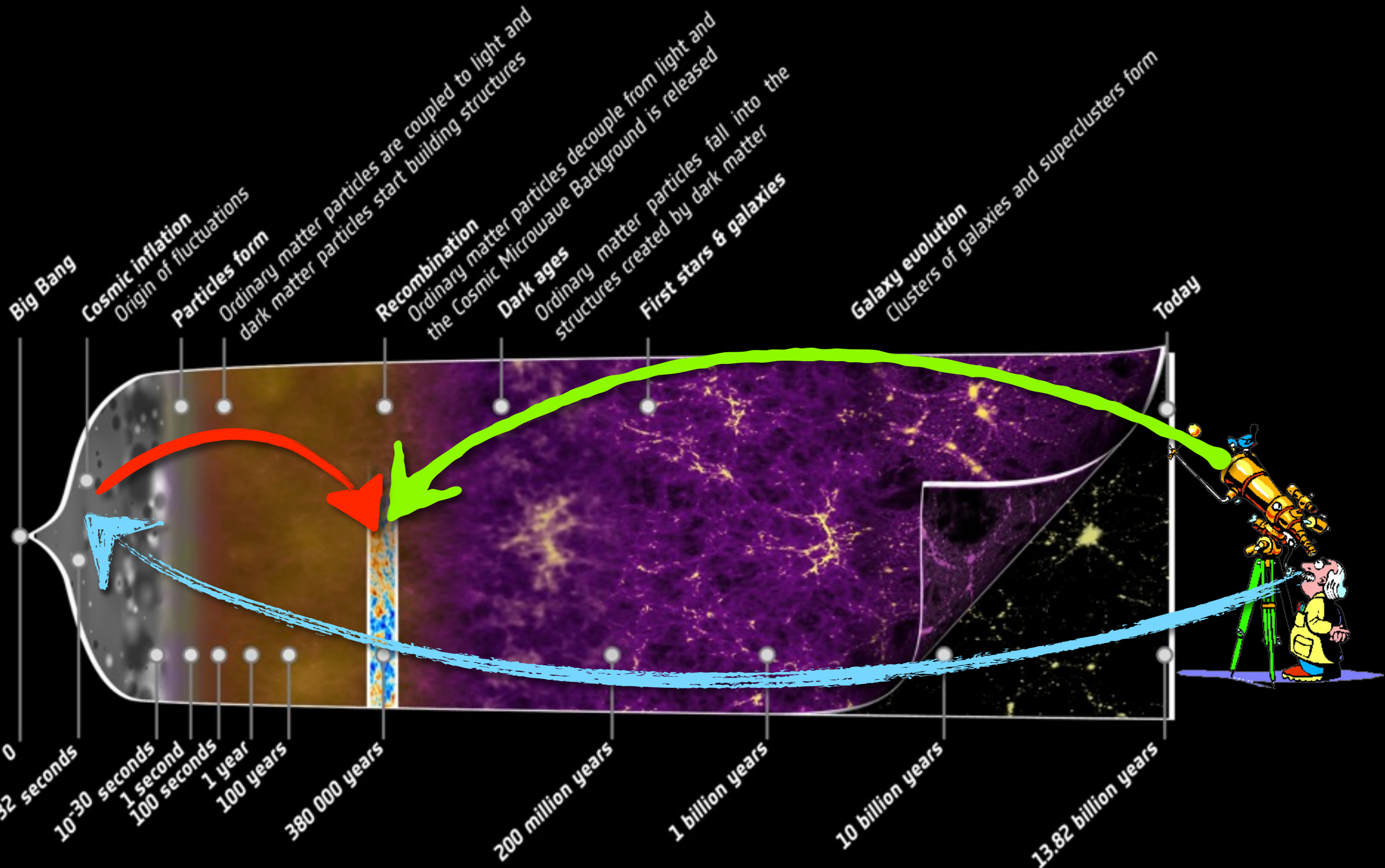
Exploring the primordial Universe with QUBIC

the Q U Bolometric Interferometer for Cosmology



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



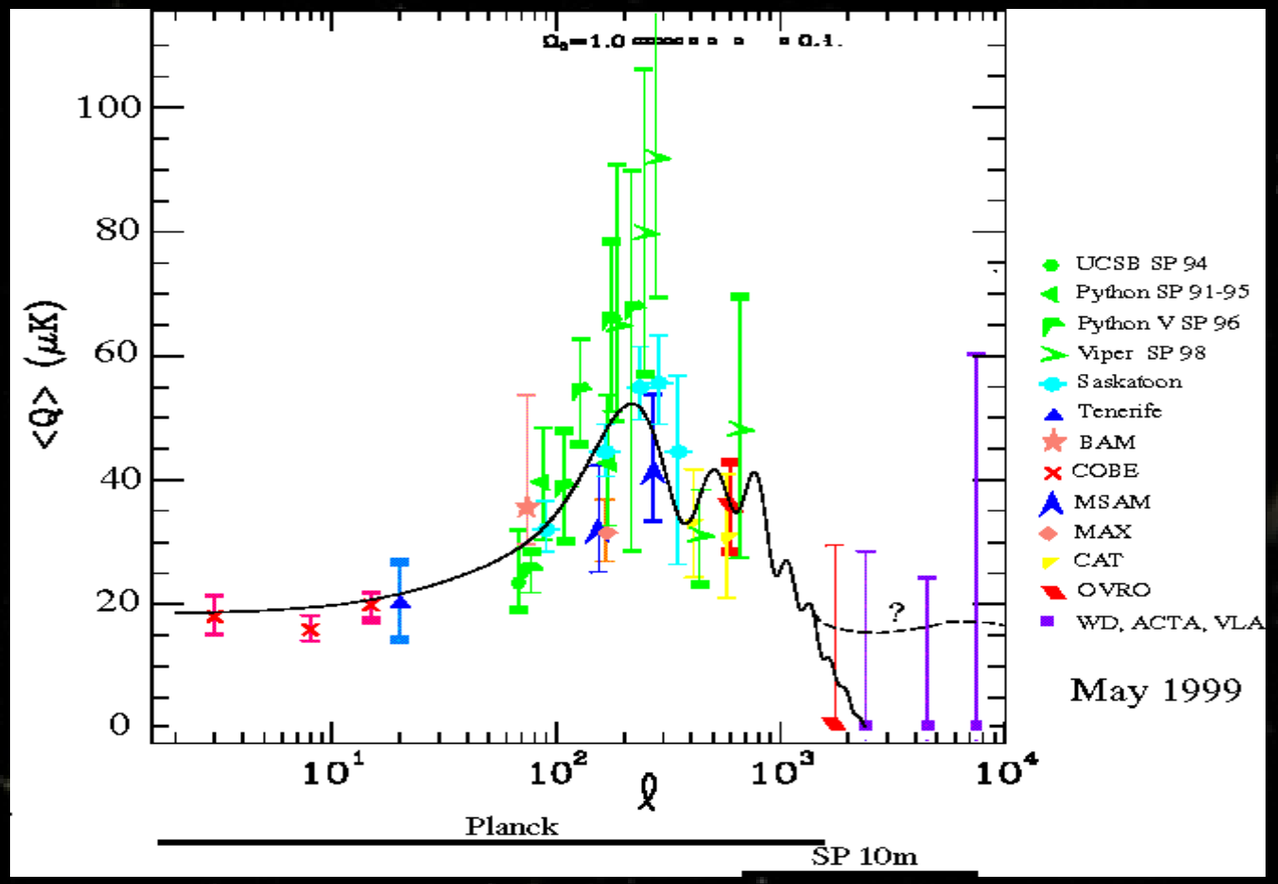
Observing the CMB polarization gives access to the Primordial Universe physics (inflation epoch)

QUBIC

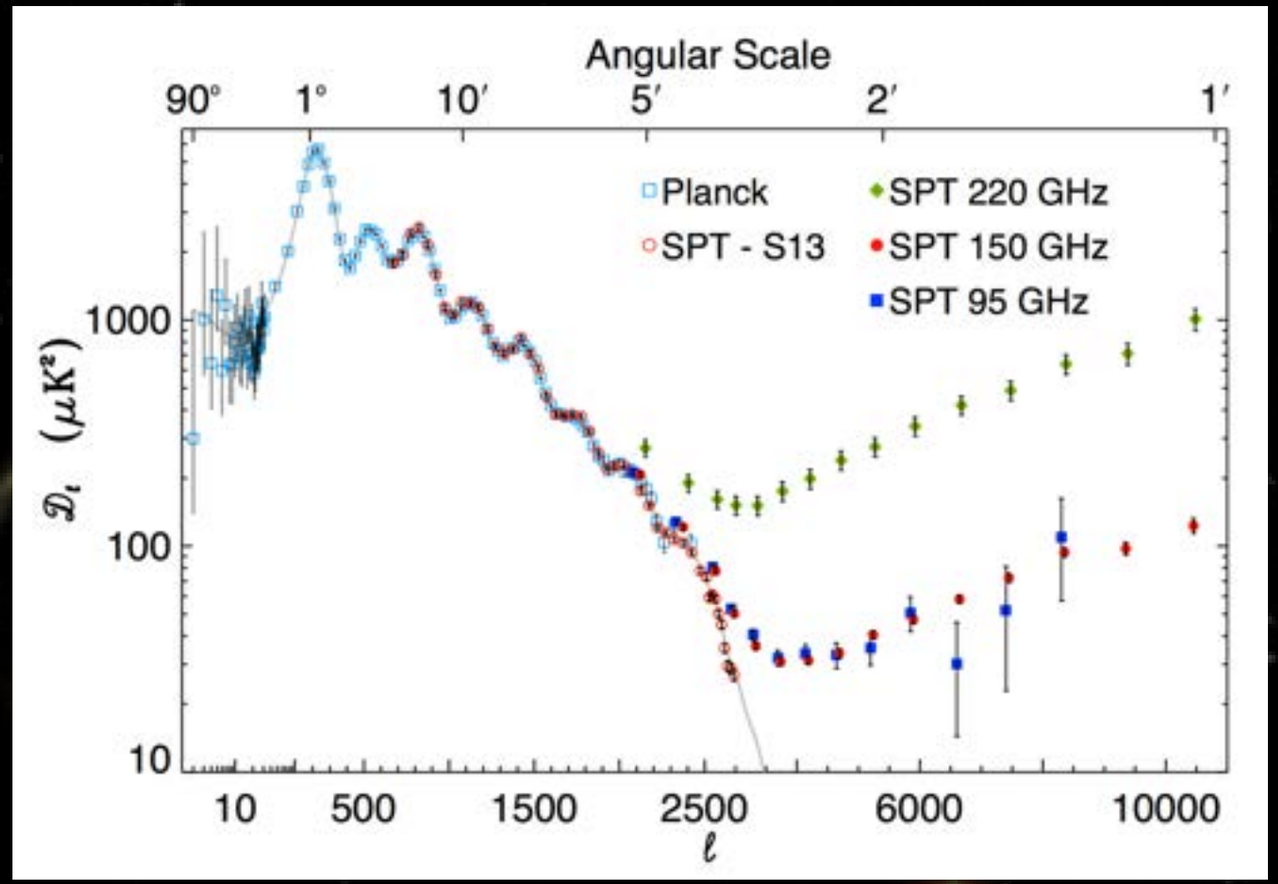
QU Bolometric Interferometer for Cosmology

J.-Ch. Hamilton
INFN, Pisa, March 2nd 2016

CMB: Tremendous progress over the last 15 years



1999

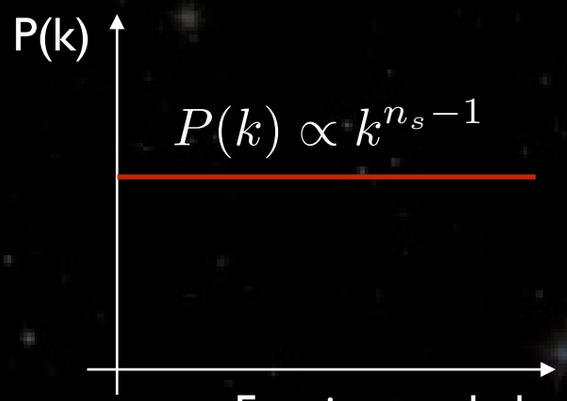


2016

Huge success : thousands of independent points fitted with less than 10 parameters and a χ^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



Density Field Transfer Function

Early Universe
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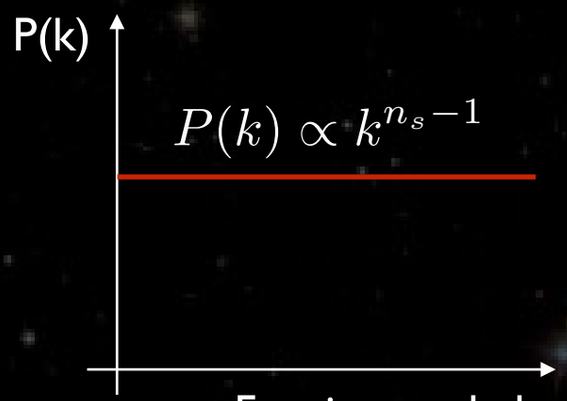
Acoustic
Oscillations



Density Field Transfer Function

Early Universe
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→

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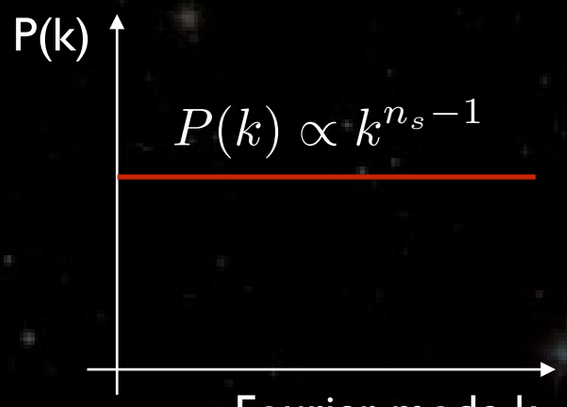
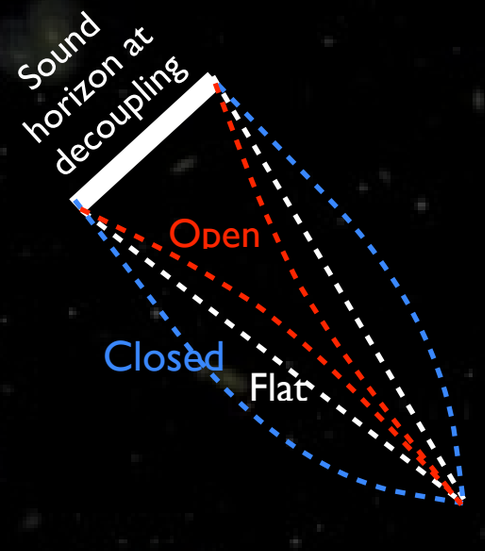
Geometry





Density Field Transfer Function

Early Universe
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Geometry

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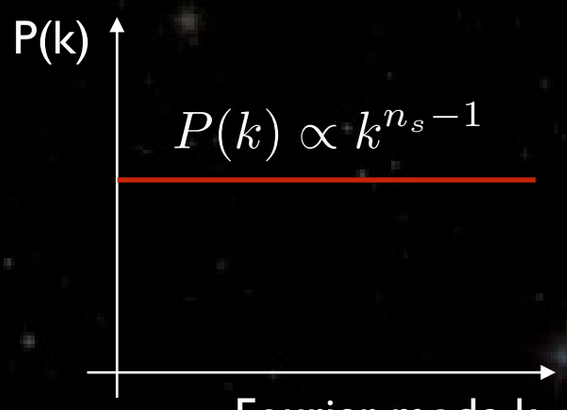
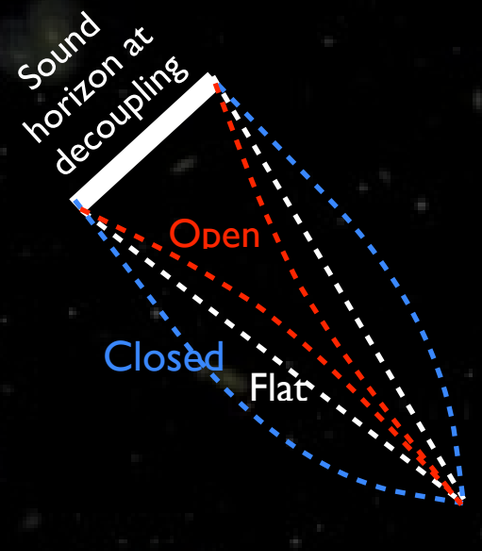
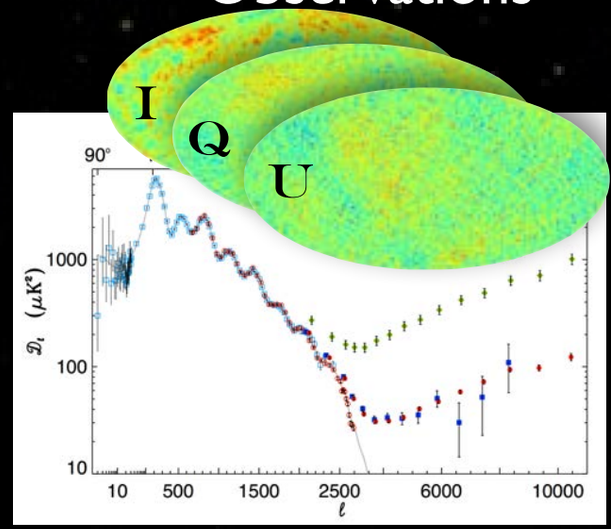
CMB
Observations

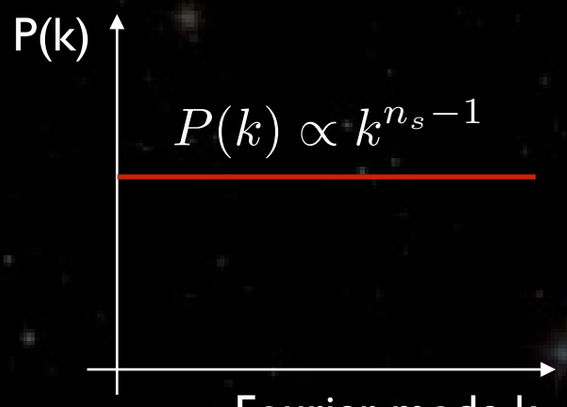


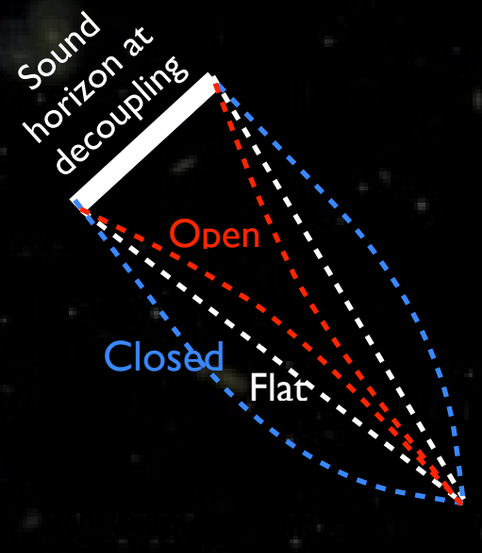


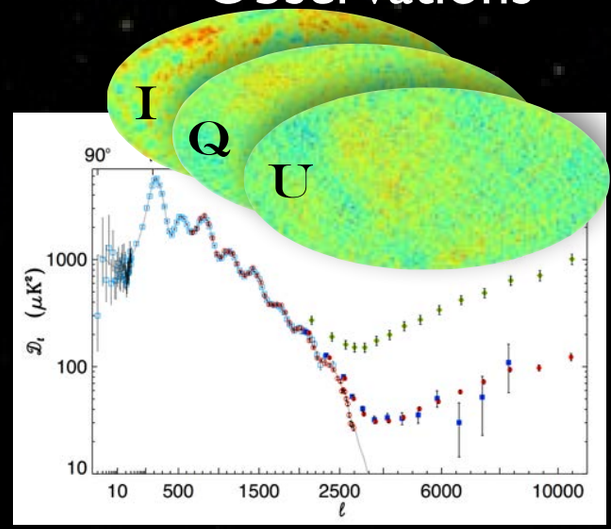


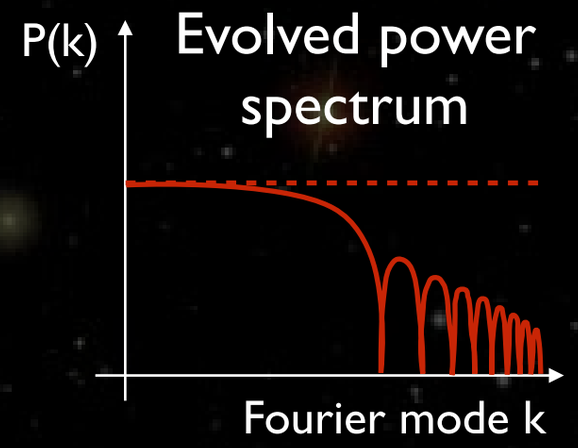
Density Field Transfer Function

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









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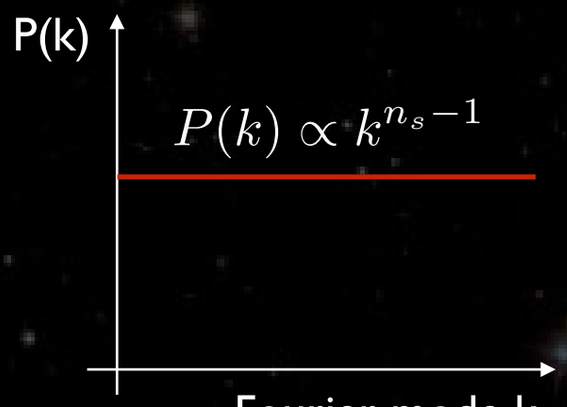
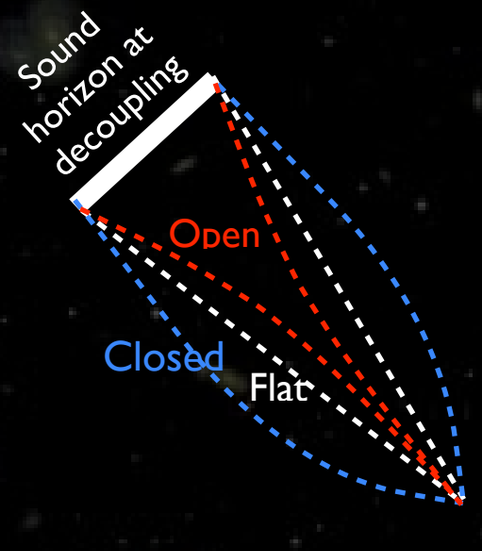
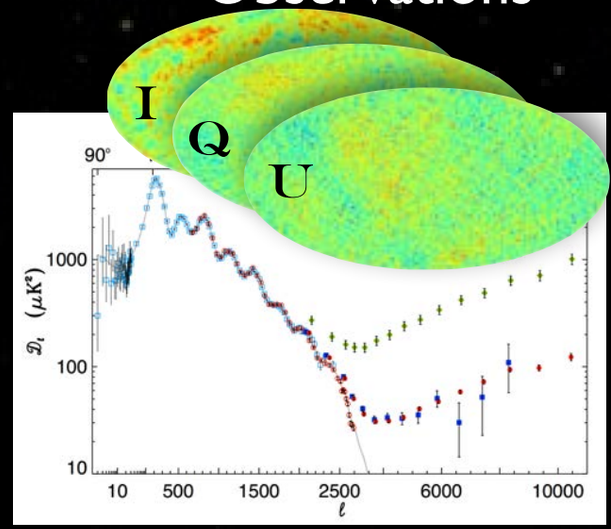
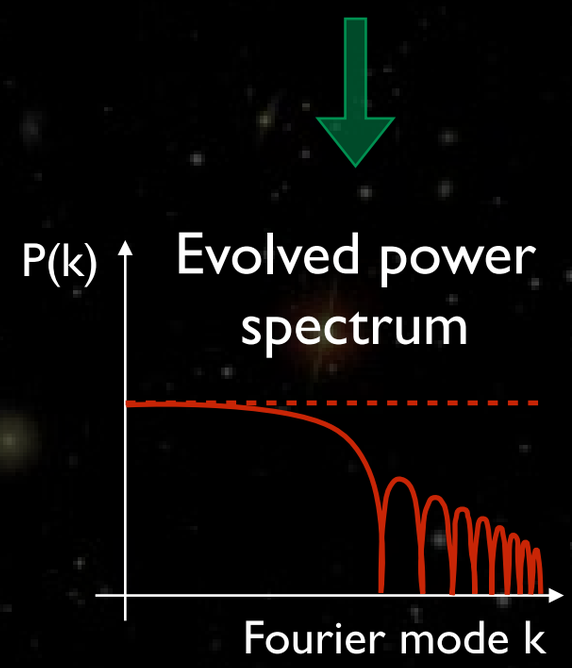




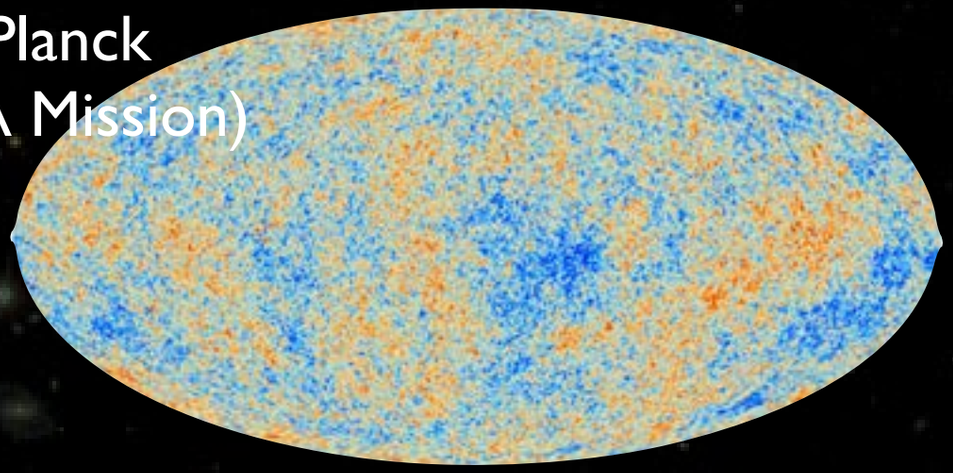


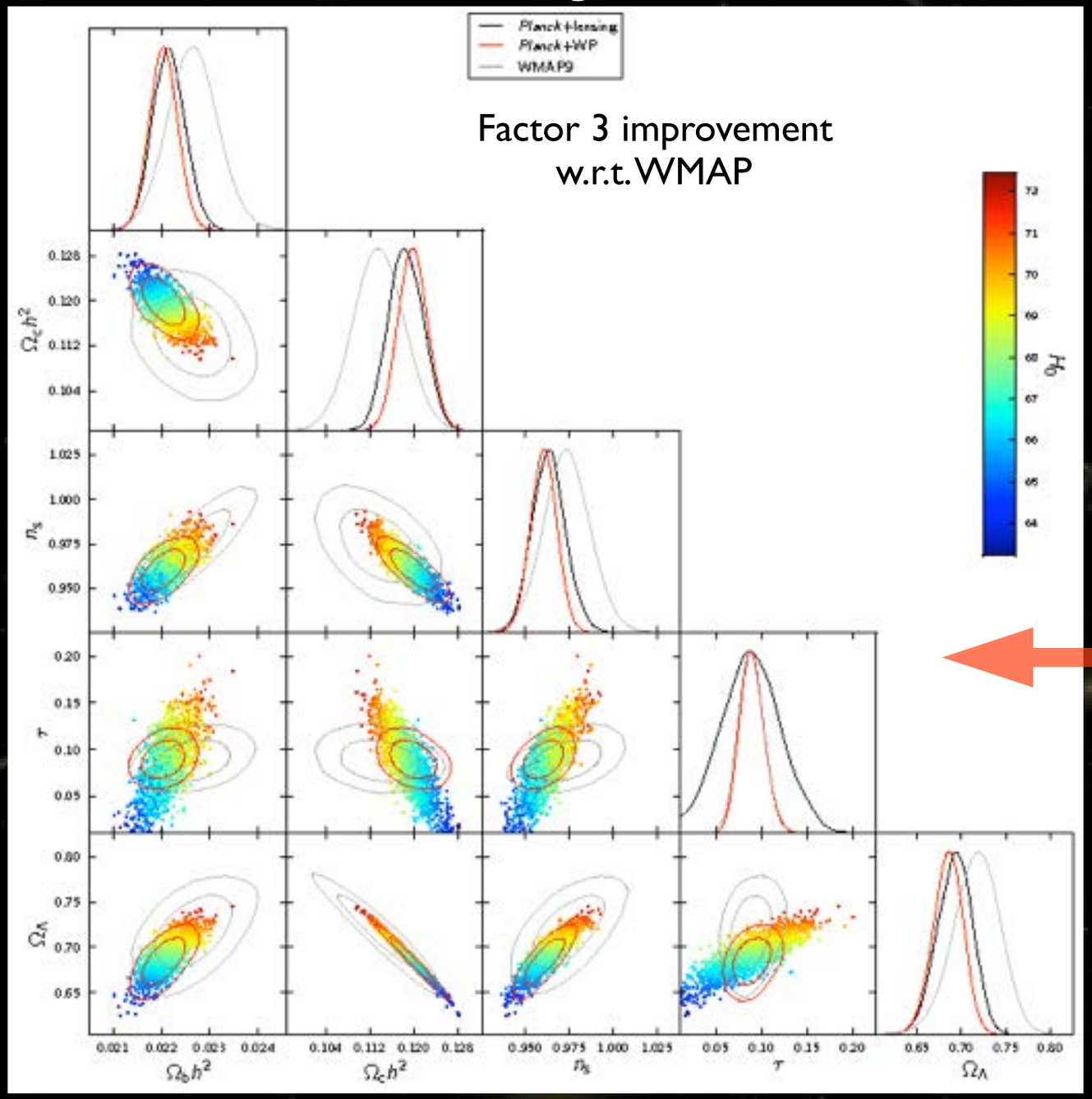
- Perturbations evolve from end of inflation to decoupling due to matter-radiation oscillations.
- The **transfert function** depends upon « simple physics » and cosmological parameters
- Allows to fit both cosmology and primordial spectra (including inflationary physics)



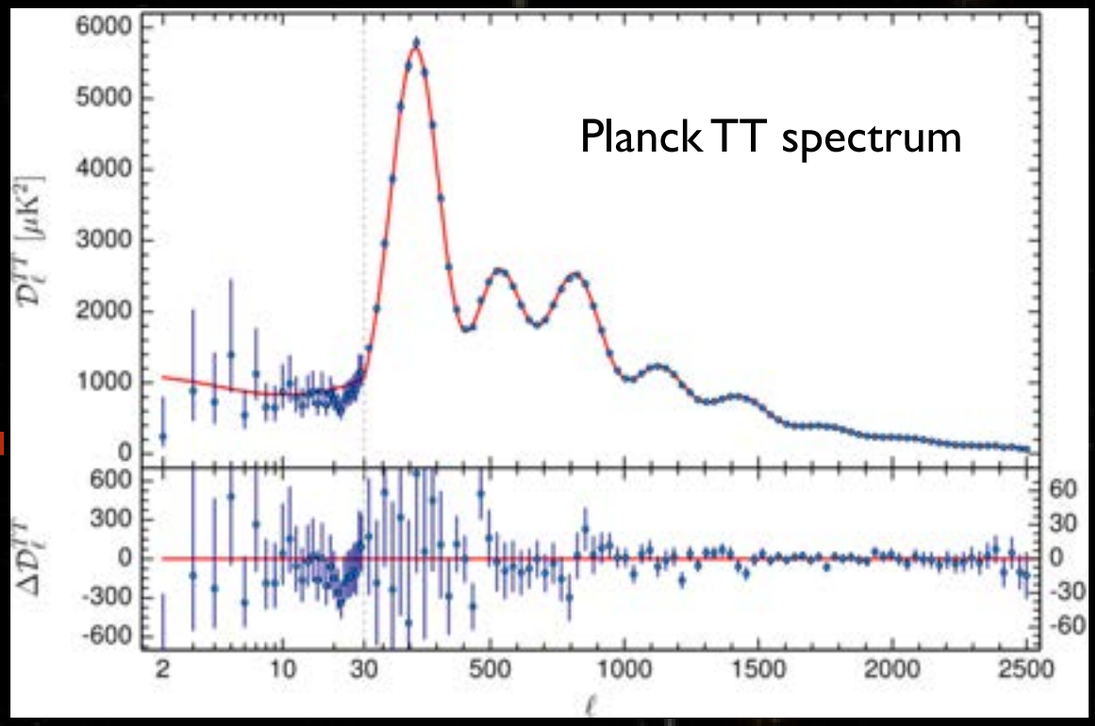
Planck Results: ΛCDM firmly Established

Planck
(ESA Mission)





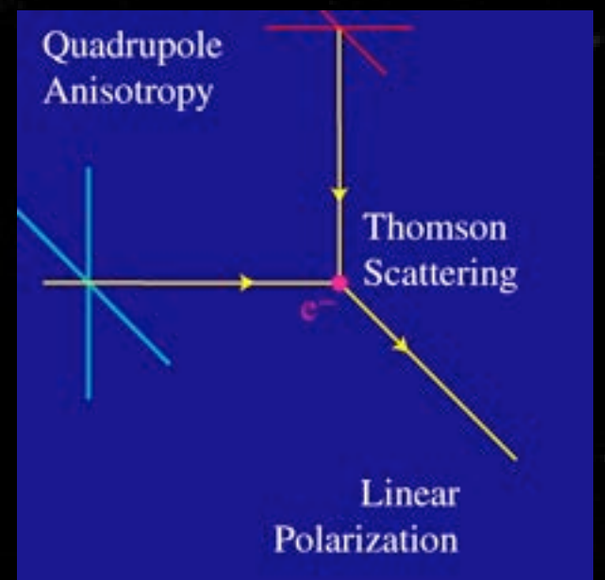
Factor 3 improvement
w.r.t. WMAP



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.)

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

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

- 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

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

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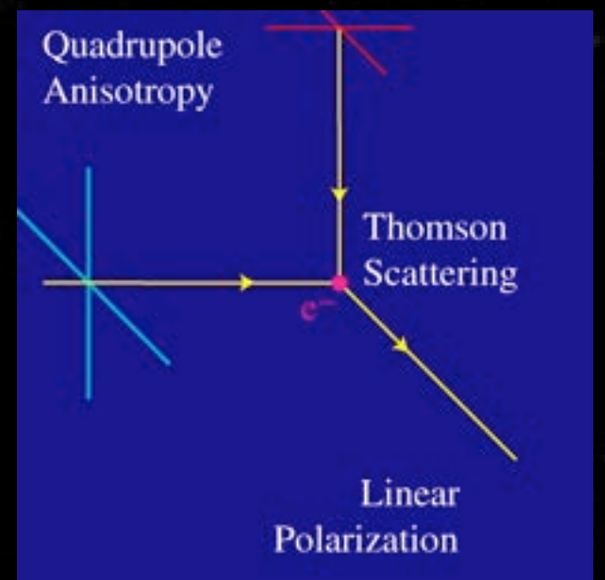

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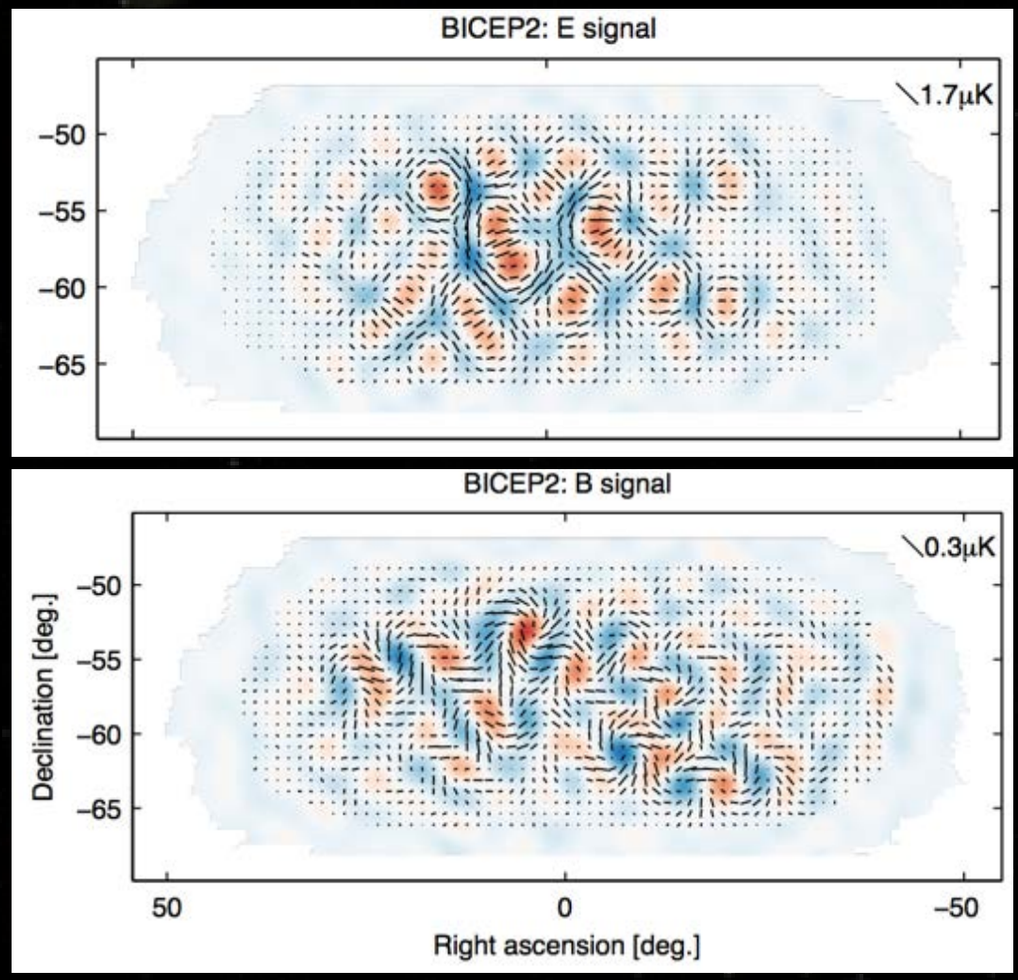
Scalar and tensor modes - E & B polarization

- **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

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

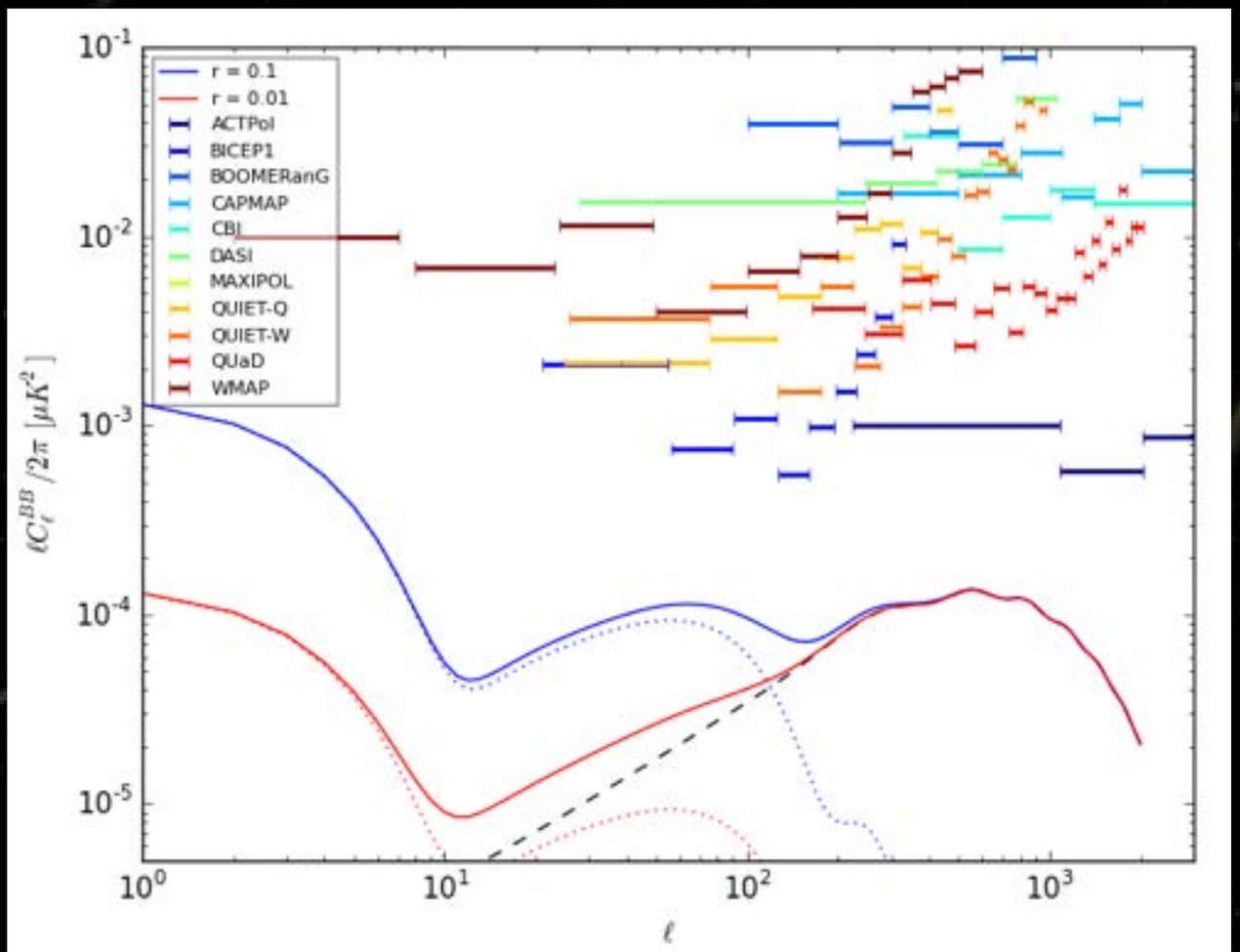
~ ratio between E and B modes

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

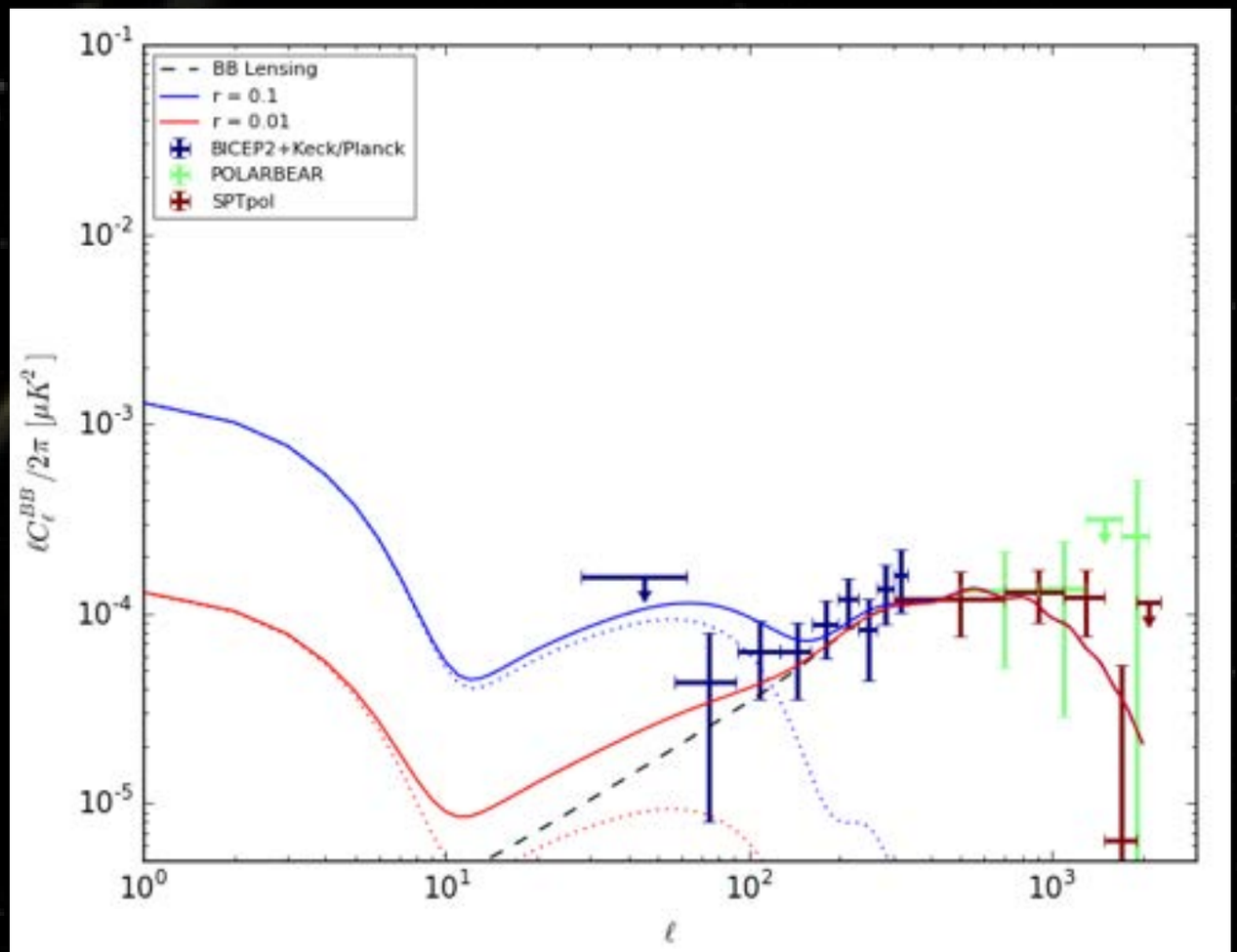
Take home message:

New landscape for B-modes
We have entered into the measurement era

Before



Today

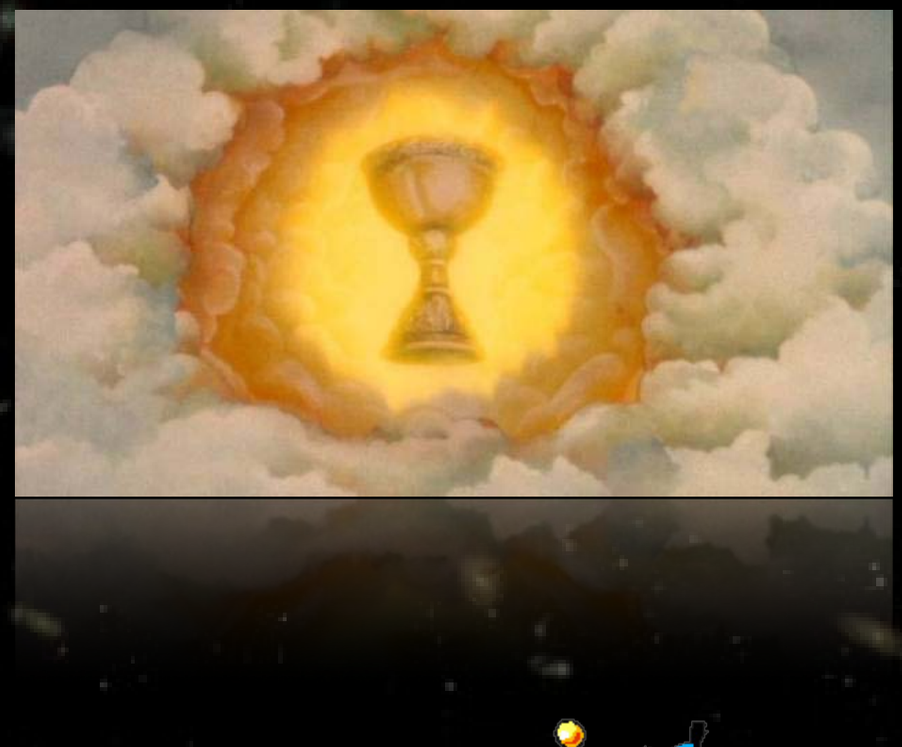


Detected signal is Dust + Lensing [Planck+BICEP2]

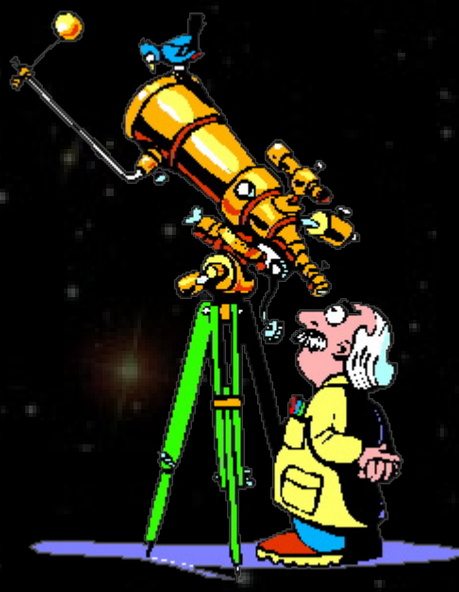
Let's go deeper & cleaner !

Why B-modes are so hard ?

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



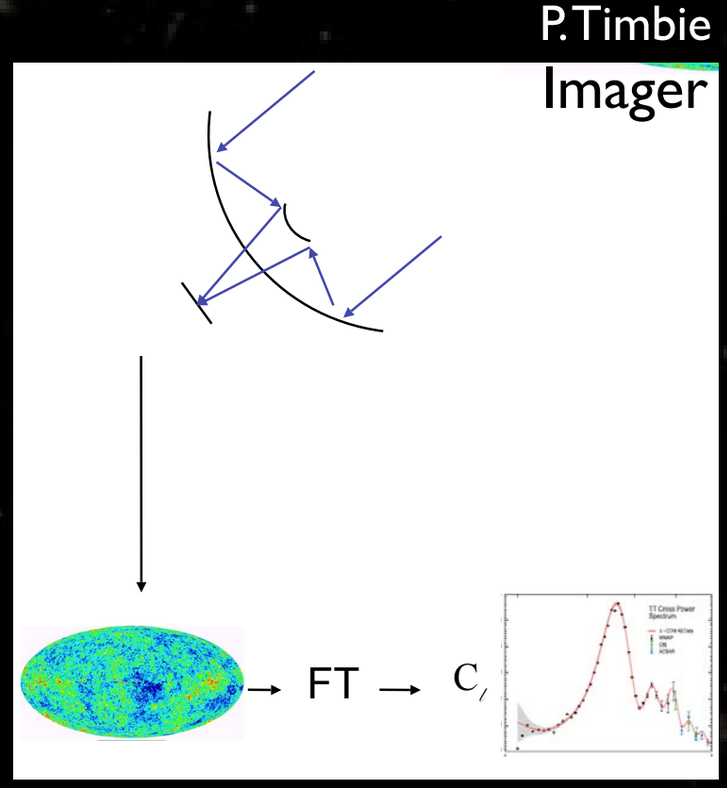
- Astrophysical Foregrounds :
  - ★ BICEP2 false alert has shown their importance
  - ★ Interstellar Dust is already known to be high
    - ➡ Need high frequency detectors at > 150 GHz
  - ★ Synchrotron emission might become an issue
    - ➡ Observations at < 70 GHz will be important in a few years

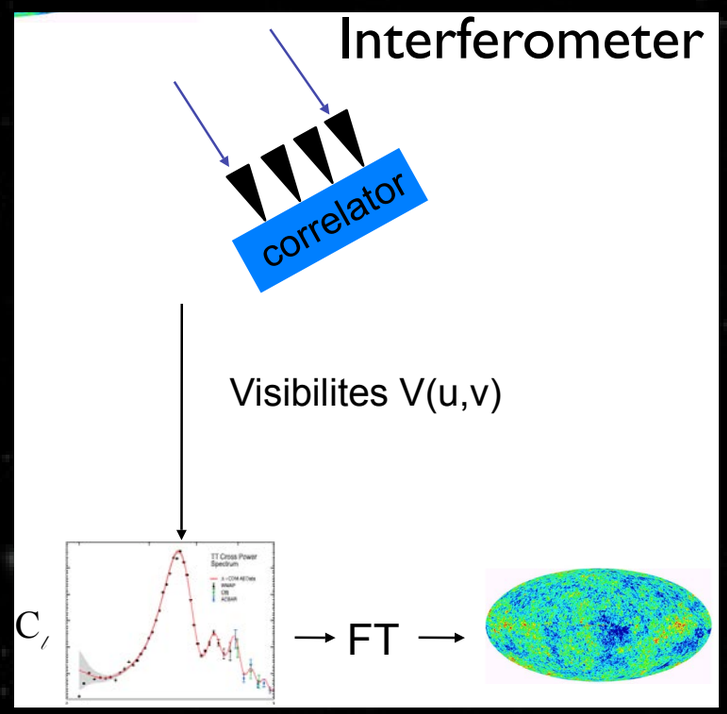


- Systematic effects :
  - ➡ Need for accurate polarization modulation and detailed knowledge of instrument properties

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 !





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Good control of systematics

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  - ➡ Bolometric Interferometry !

Both

The QUBIC Collaboration

1) APC Paris, France
2) Brown University, USA
3) Cardiff University, UK
4) CSNSM Orsay, France
5) IAS Orsay, France
6) IEF, Orsay, France
7) IRAP Toulouse, France
8) LAL Orsay, France
9) University of Manchester, UK
10) Università di Milano-Bicocca, Italy
11) Università degli studi, Milano, Italy
12) Maynooth University, Ireland
13) Richmond University, USA
14) Università La Sapienza, Roma, Italy
15) University of Wisconsin, USA

81 collaborators:

J. Aumont[5], S. Banfi[10], P. Battaglia[11], E.S. Battistelli[14], A. Baù[10], B. Bélier[6], D.Bennett[12], L. Bergé[4], J.Ph. Bernard[7], M. Bersanelli[11], M.A. Bigot-Sazy[1], N. Bleurvacq[1], G. Bordier[1], J. Brossard[1], E.F. Bunn[13], D. Buzi[14], D. Cammilleri[1], F. Cavaliere[11], P. Chanial[1], C. Chapron[1], A. Coppolecchia[14], F. Couchot[8], G. D'Alessandro[14], P. De Bernardis[14], M. de Petris[14], T. Decourcelle[1], F. Del Torto[11], L. Dumoulin[4], C. Franceschet[10], A. Gault[15], D. Gayer[12], M. Gervasi[10], A. Ghribi[1], M. Giard[7], Y. Giraud-Héraud[1], M. Gradziel[12], L. Grandsire[1], J.Ch. Hamilton[1], V. Haynes[9], S. Henrot-Versillé[8], N. Holtzer[4], J. Kaplan[1], A. Korotkov[2], J. Lande[4], A. Lowitz[15], B. Maffei[5], S. Marnieros[4], J. Martino[5], S. Masi[14], M. McCulloch[9], S. Melhuish[9], A. Mennella[11], L. Montier[7], A. Murphy[12], D.Néel[4], M.W. Ng[9], C. O'Sullivan[12], F.Pajot[7], A. Passerini[10], C. Perbost[1], O. Perdereau[8], F. Piacentini[14], M. Piat[1], L. Piccirillo[9], G. Pisano[3], D. Prêle[1], D. Rambaud[7], O. Rigaut[4], M. Salatino[14], A. Schillaci[14], S. Scully[12], M. Stolpovskiy[1], A. Tartari[1], P. Timbie[15], M. Tristram[8], G. Tucker[2], D. Viganò[11], F. Voisin[1], B. Watson[9] and M. Zannoni[10]

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

+ Pisa / INFN ?

QUBIC Main Features

- **TES Focal planes**
  - ★ 2048 TES with NEP ~ 4×10^{-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

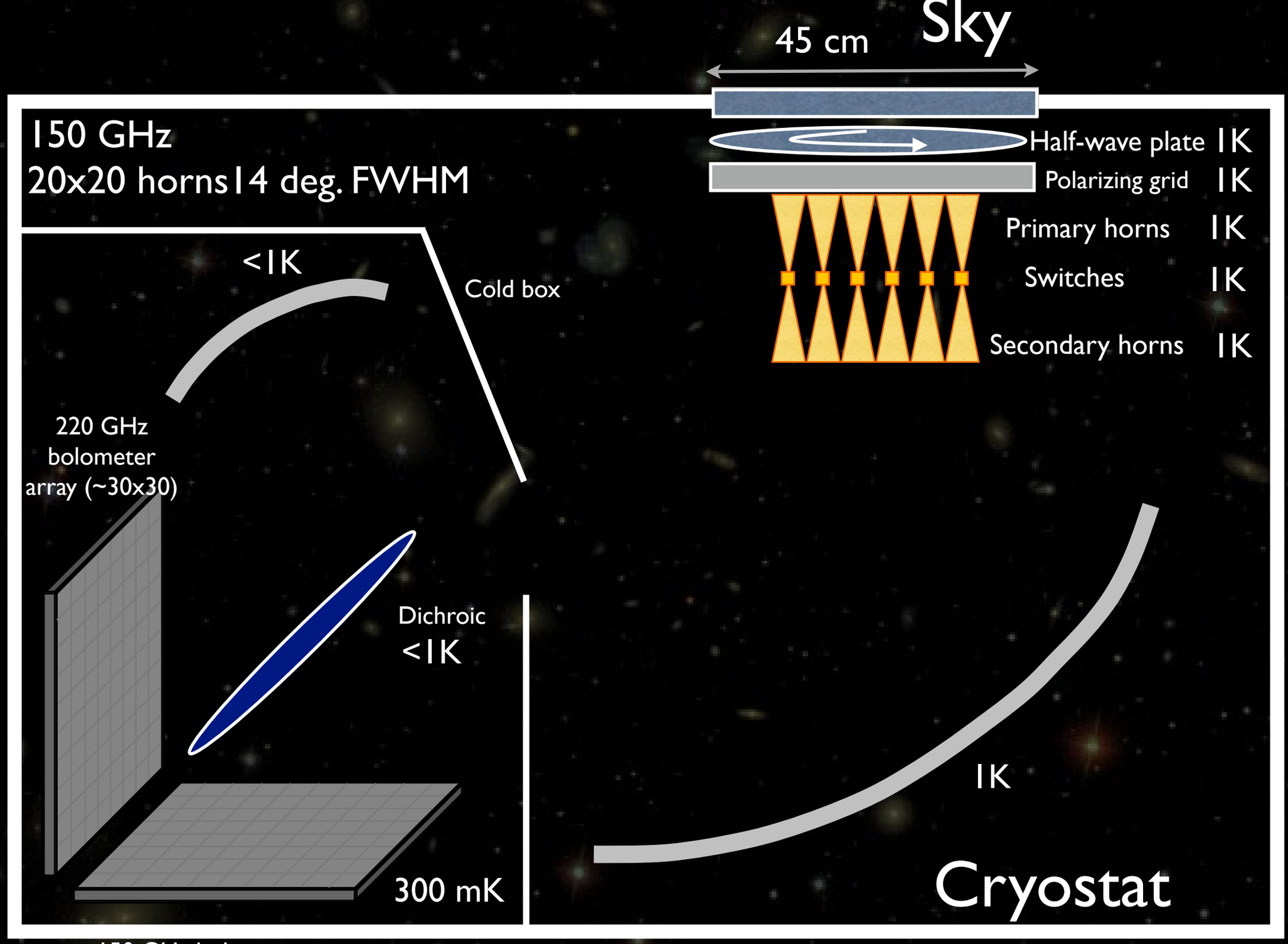
- **Dual Band operations**
  - ★ One focal plane for each band
  - ★ 150 and 220 GHz

→ Dust Polarisation contamination removal

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

→ Unprecedented control of systematics with Self-Calibration

QUBIC concept: Quasi optical correlator



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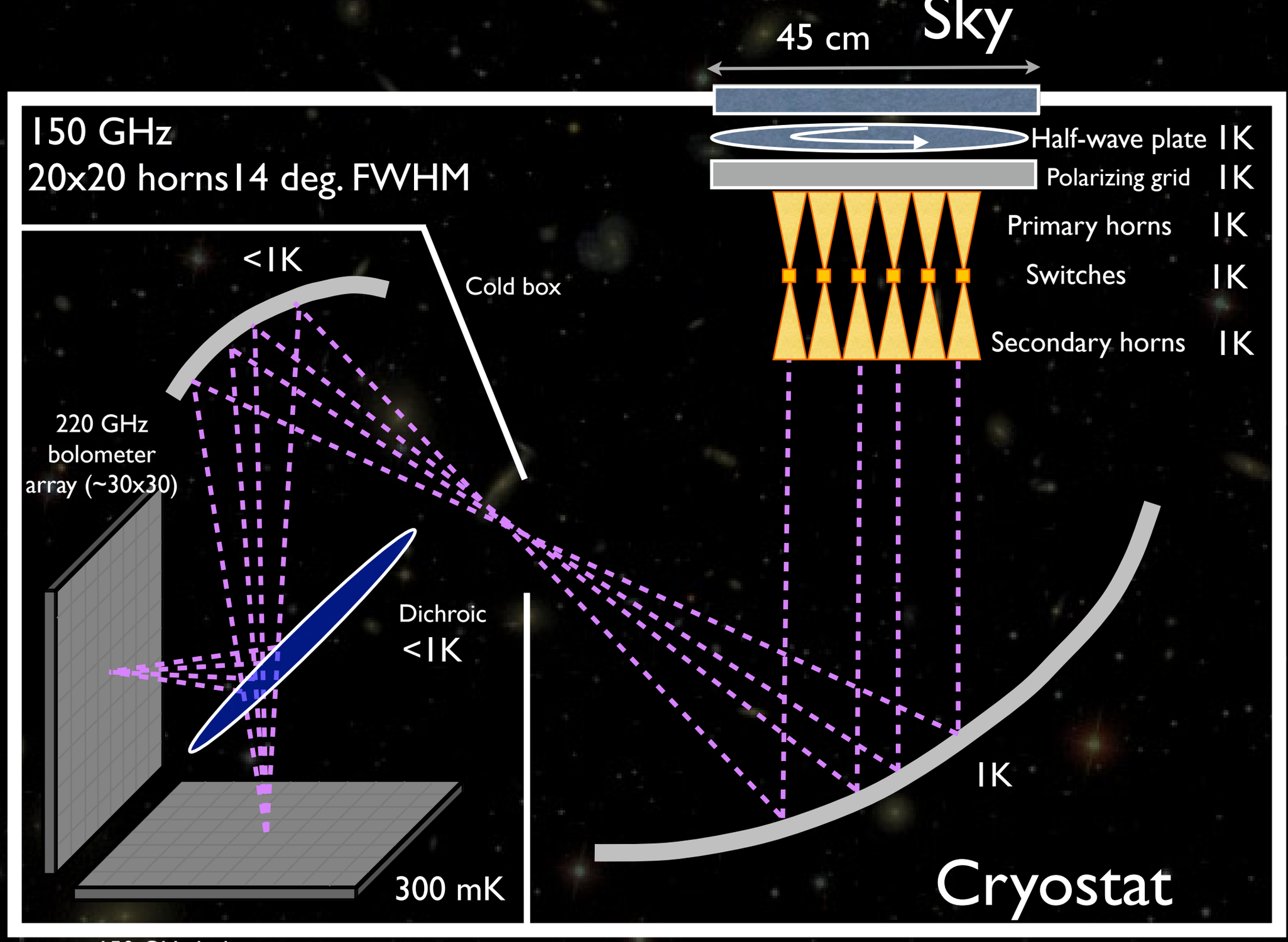

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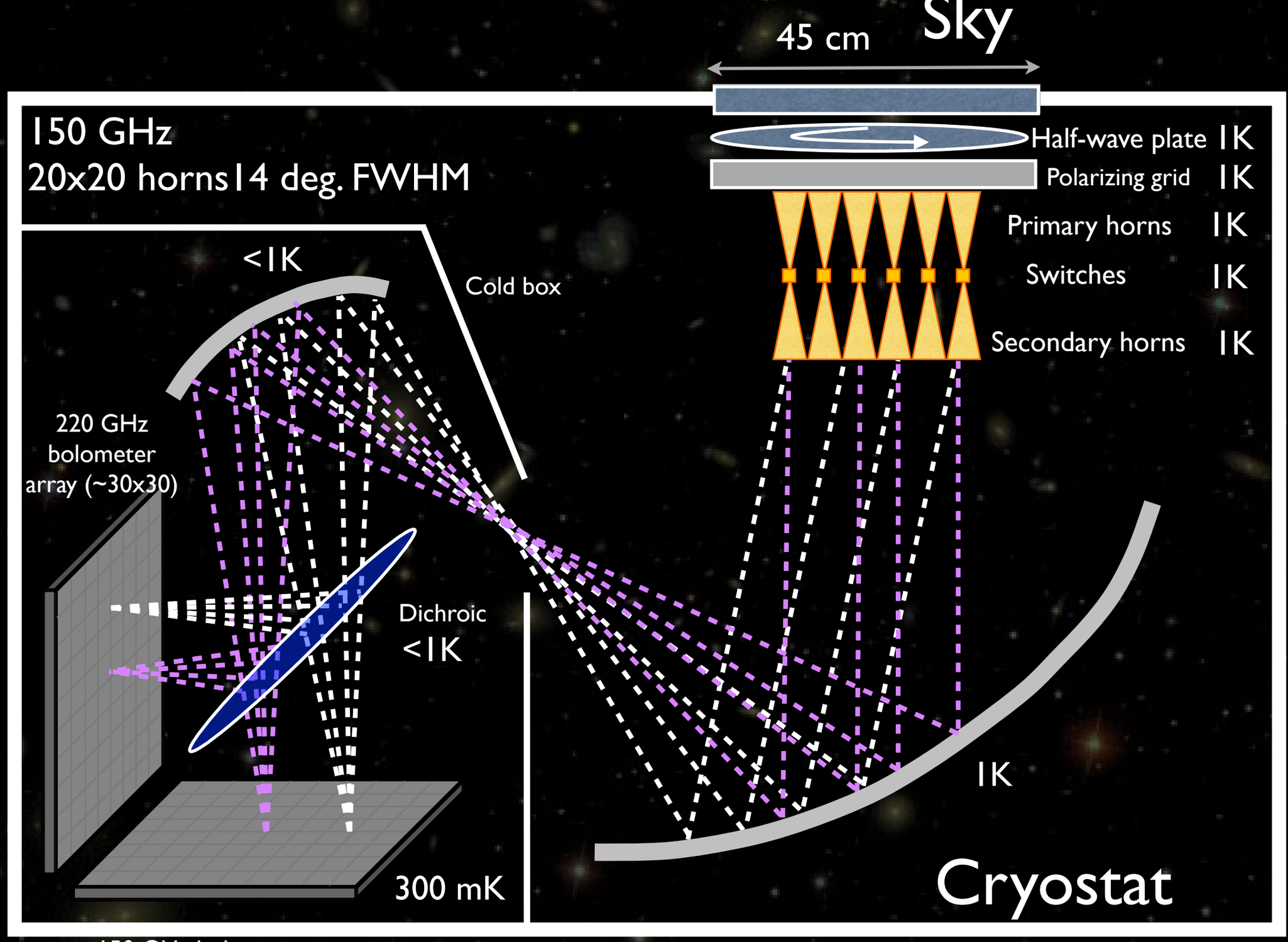

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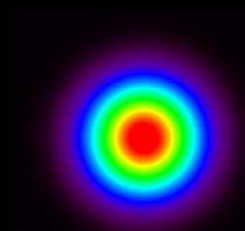
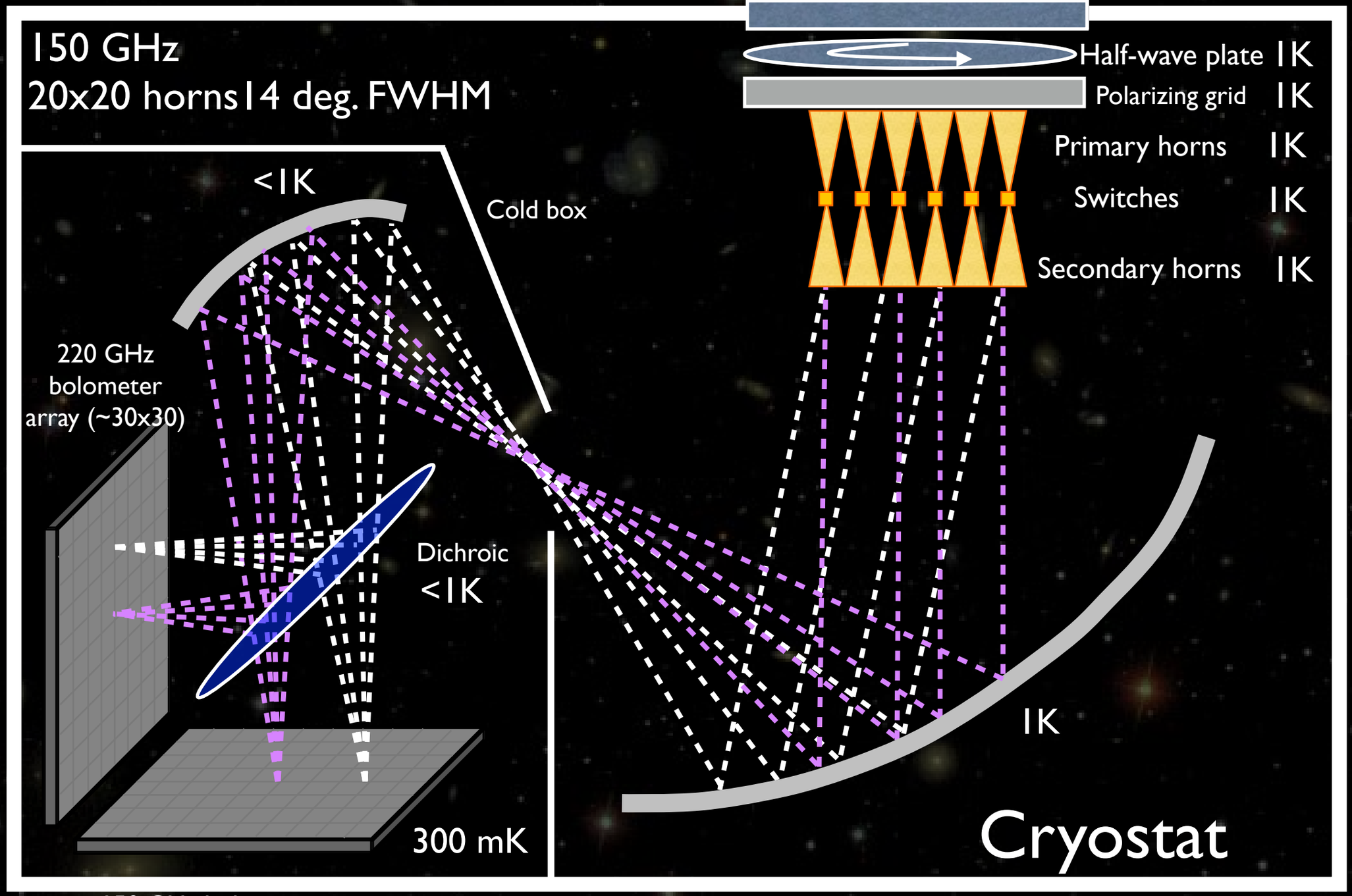


1 horn open



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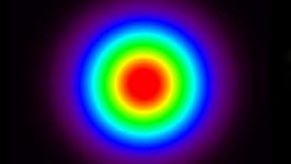

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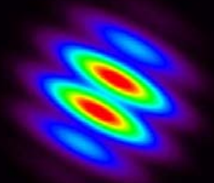
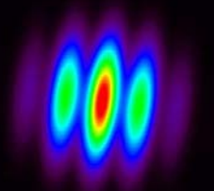
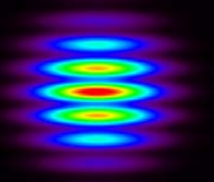


1 baseline



1 baseline



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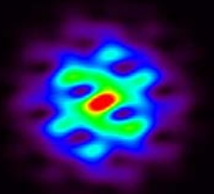
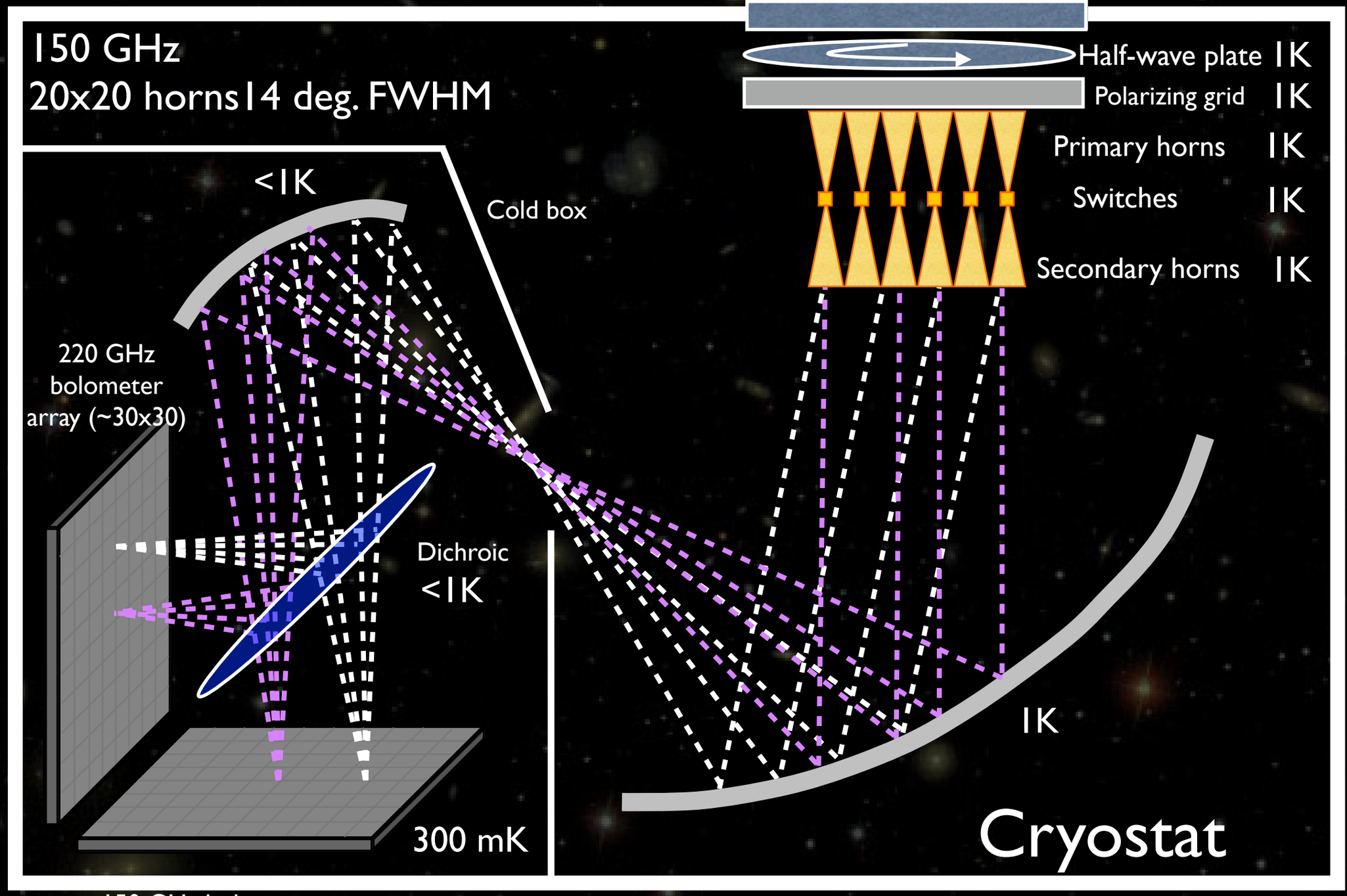
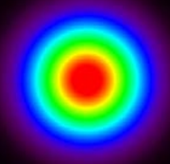


total signal
(all baselines)



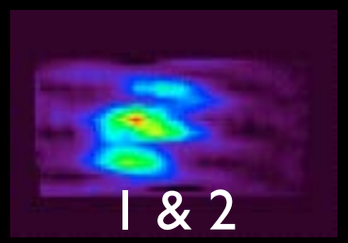
QUBIC concept: Quasi optical correlator

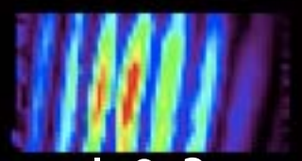
fringes successfuly observed in 2009 with MBI-4 [Timbie et al. 2006]

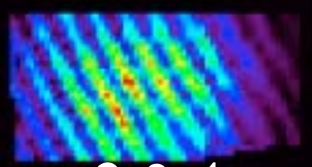


1 horn open

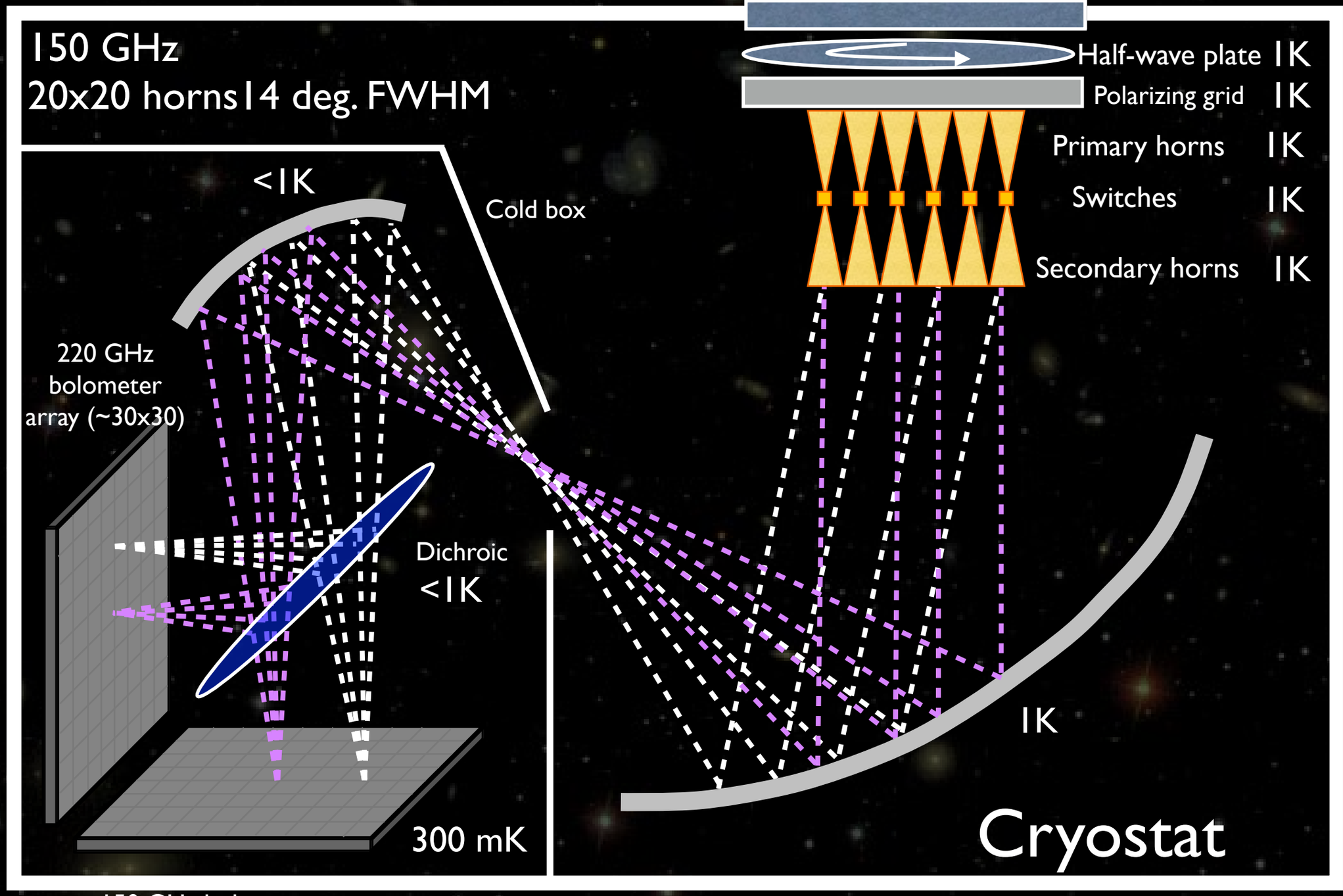
MBI-4 data
2009 campaign
(PBO- Wisc.)







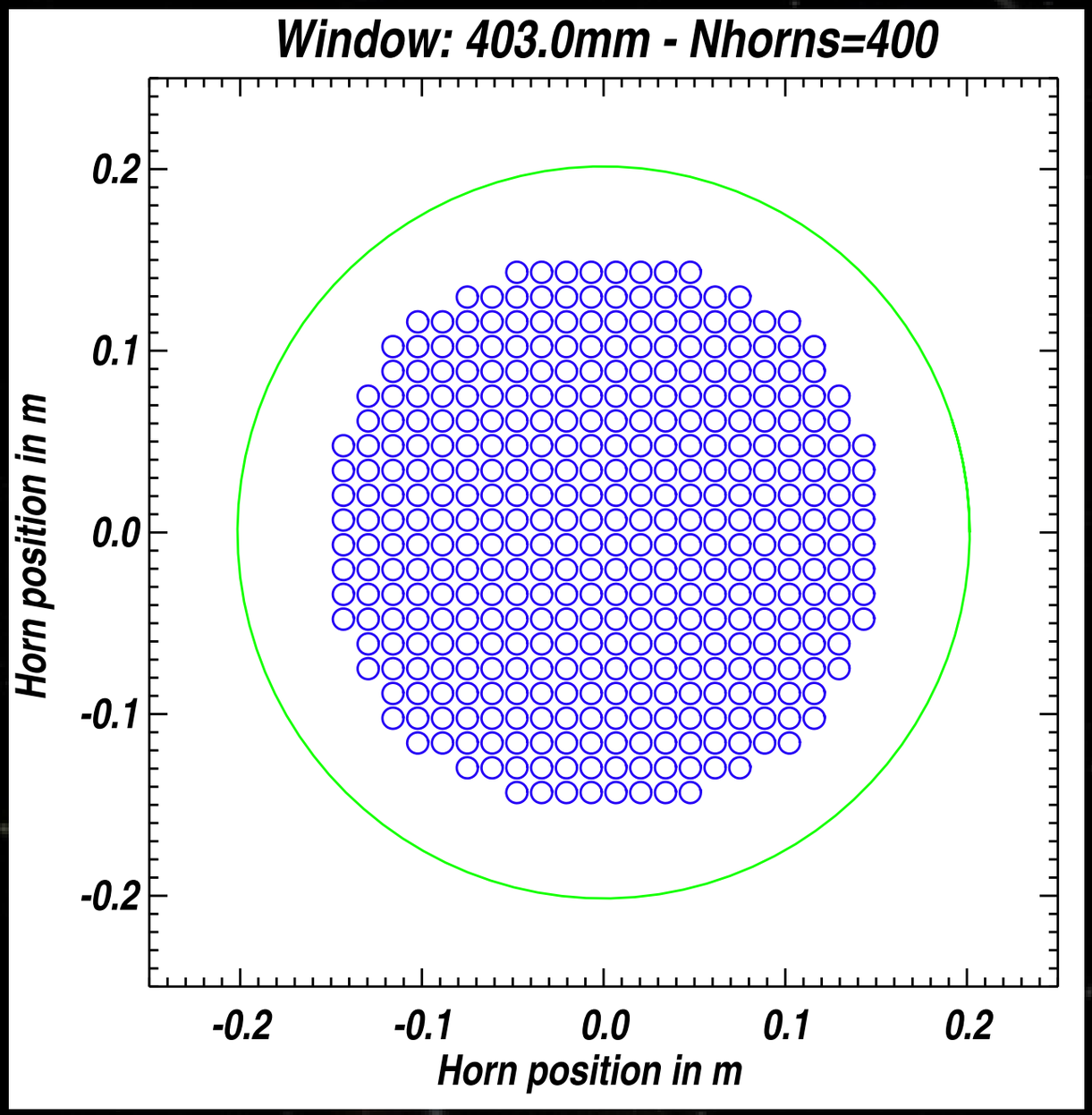
150 GHz
20x20 horns14 deg. FWHM



150 GHz bolometer array
(~30x30)

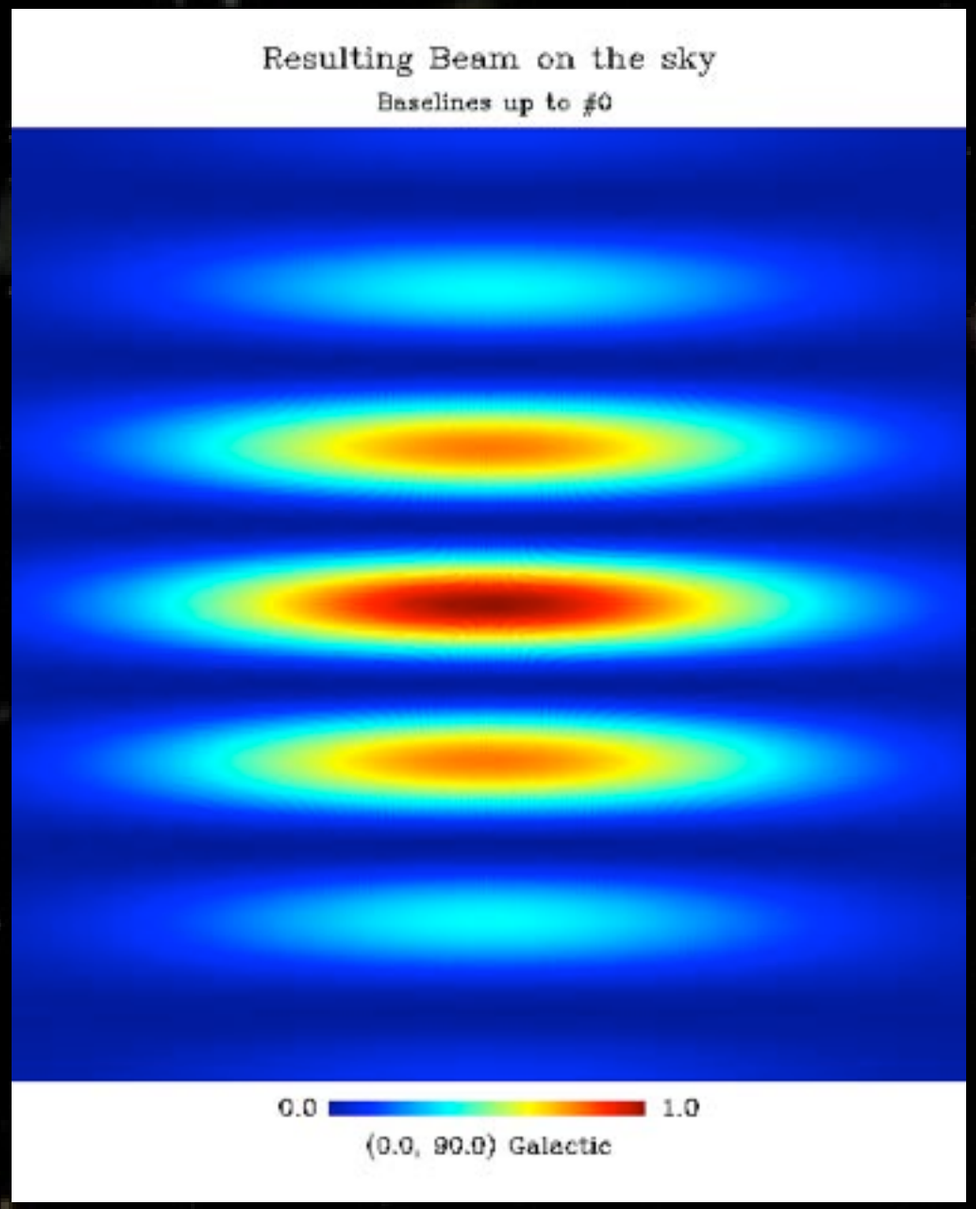
B.I. = Synthesized imager

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

B.I. = Synthesized imager

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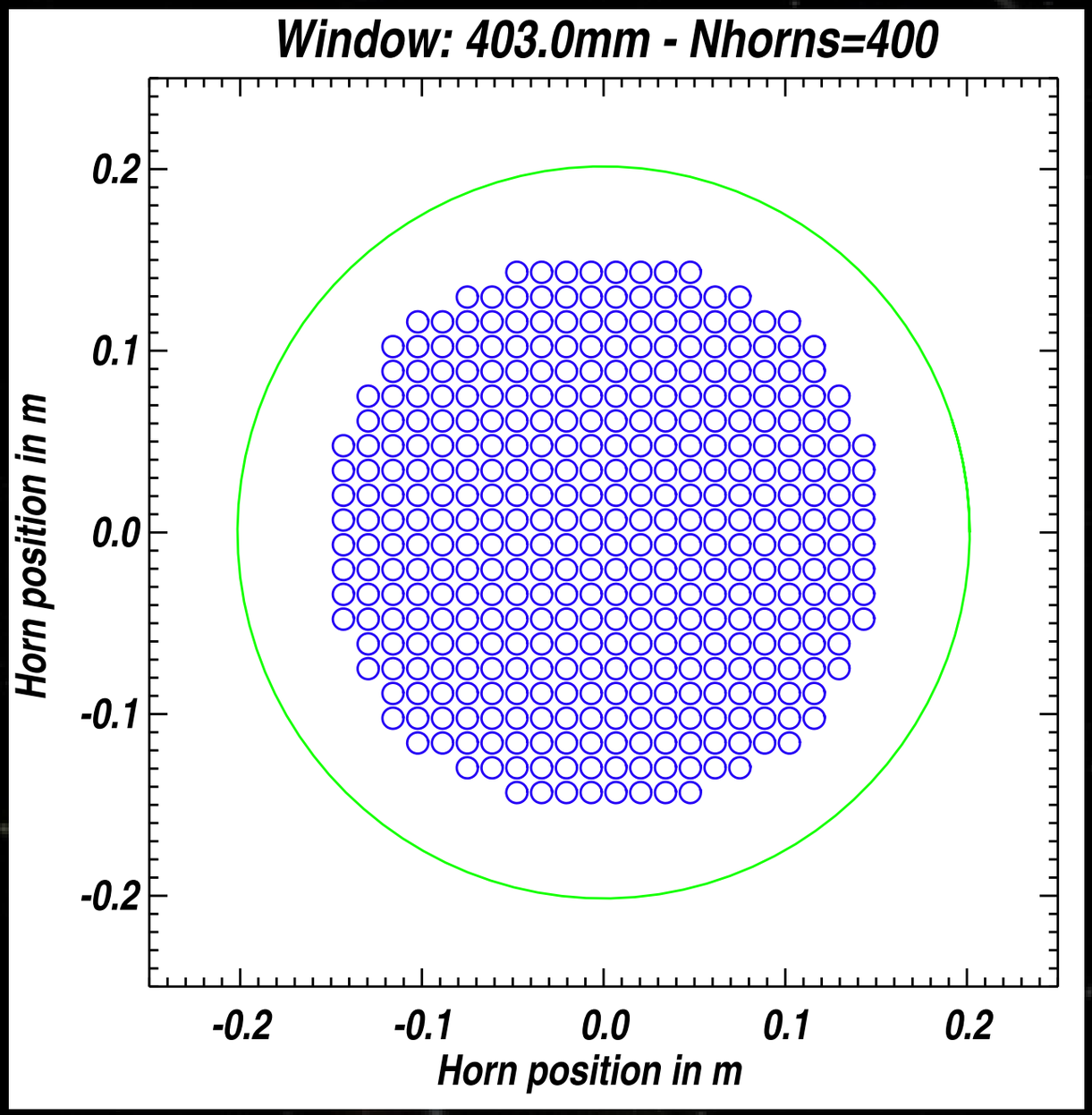

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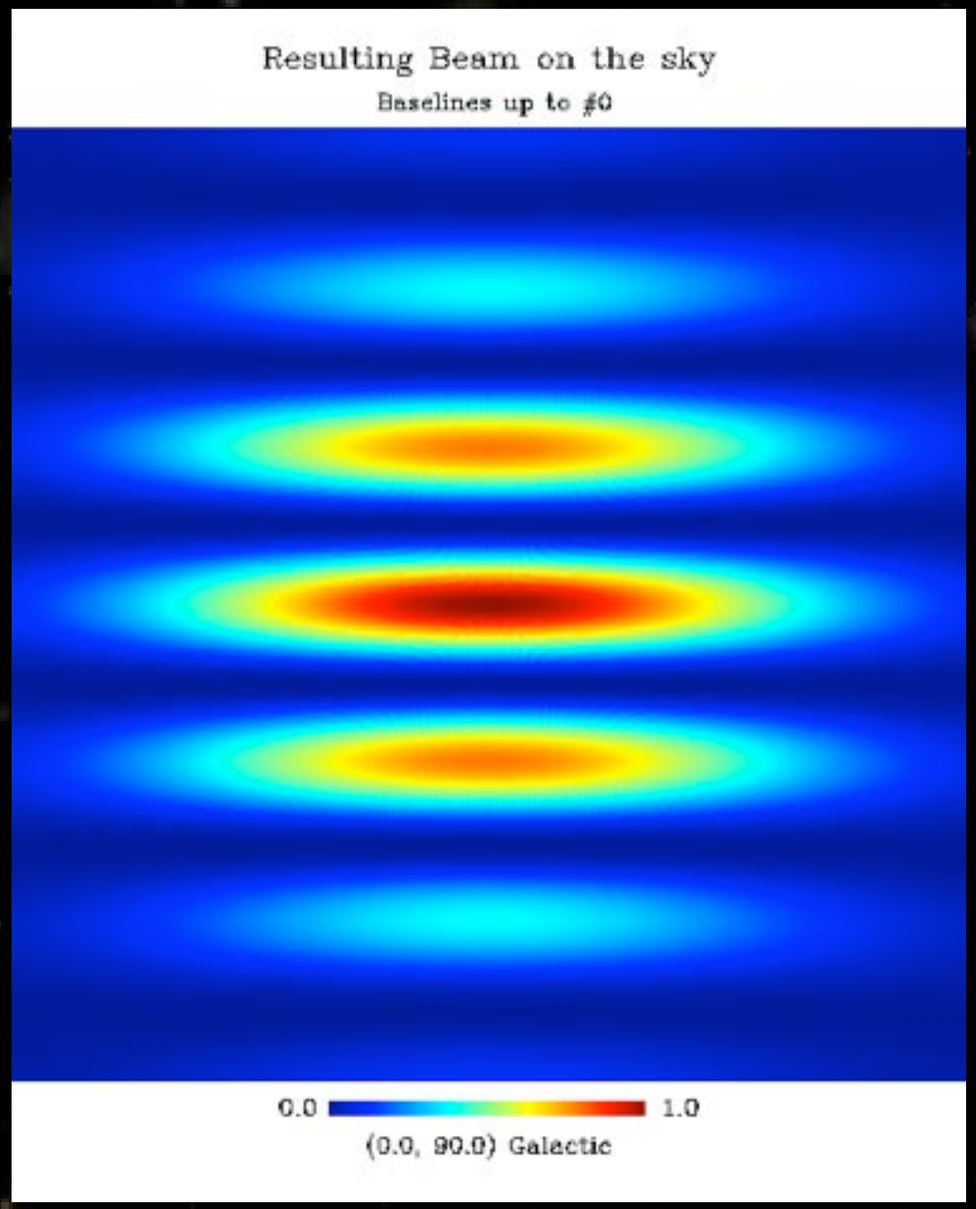

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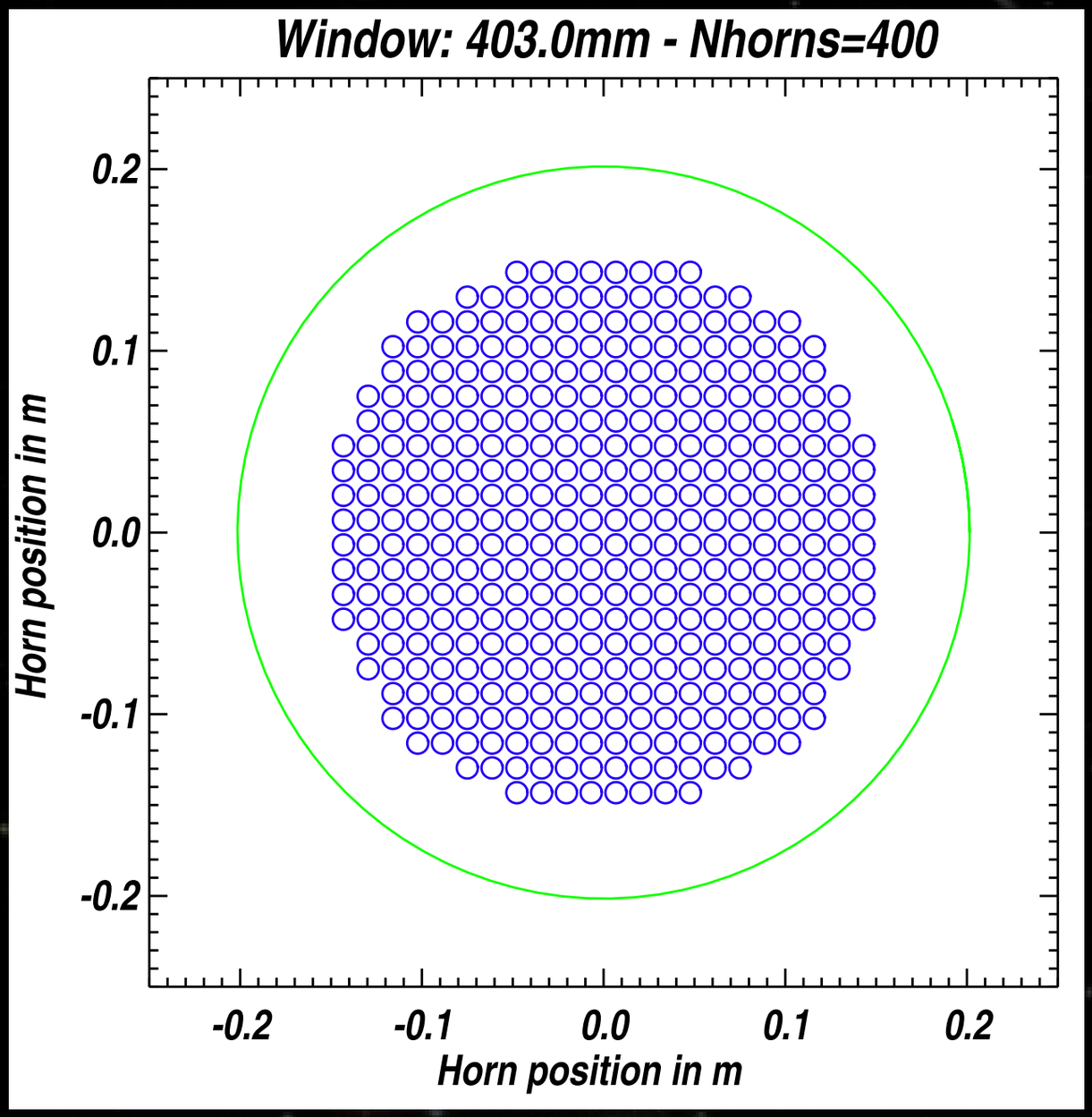

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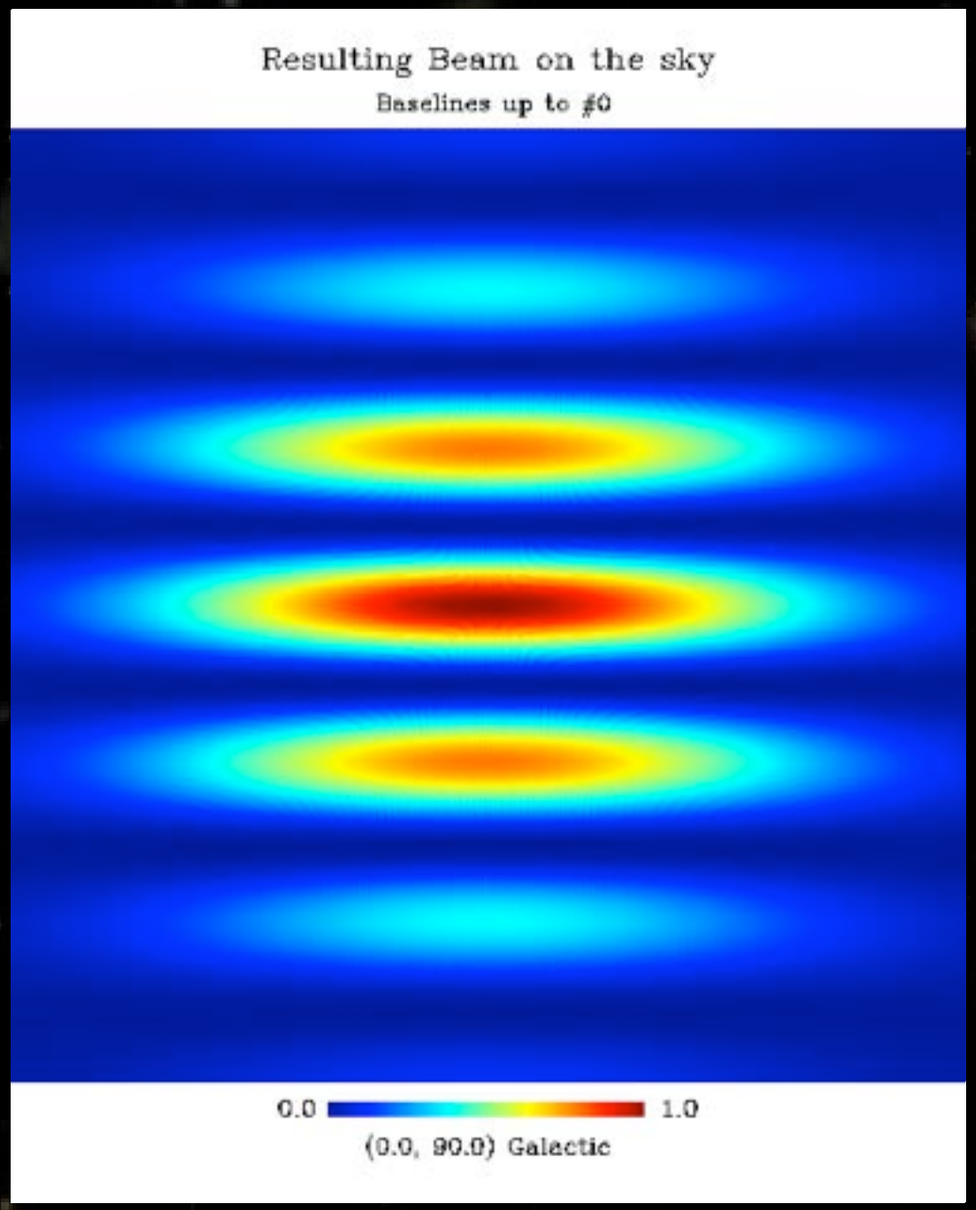

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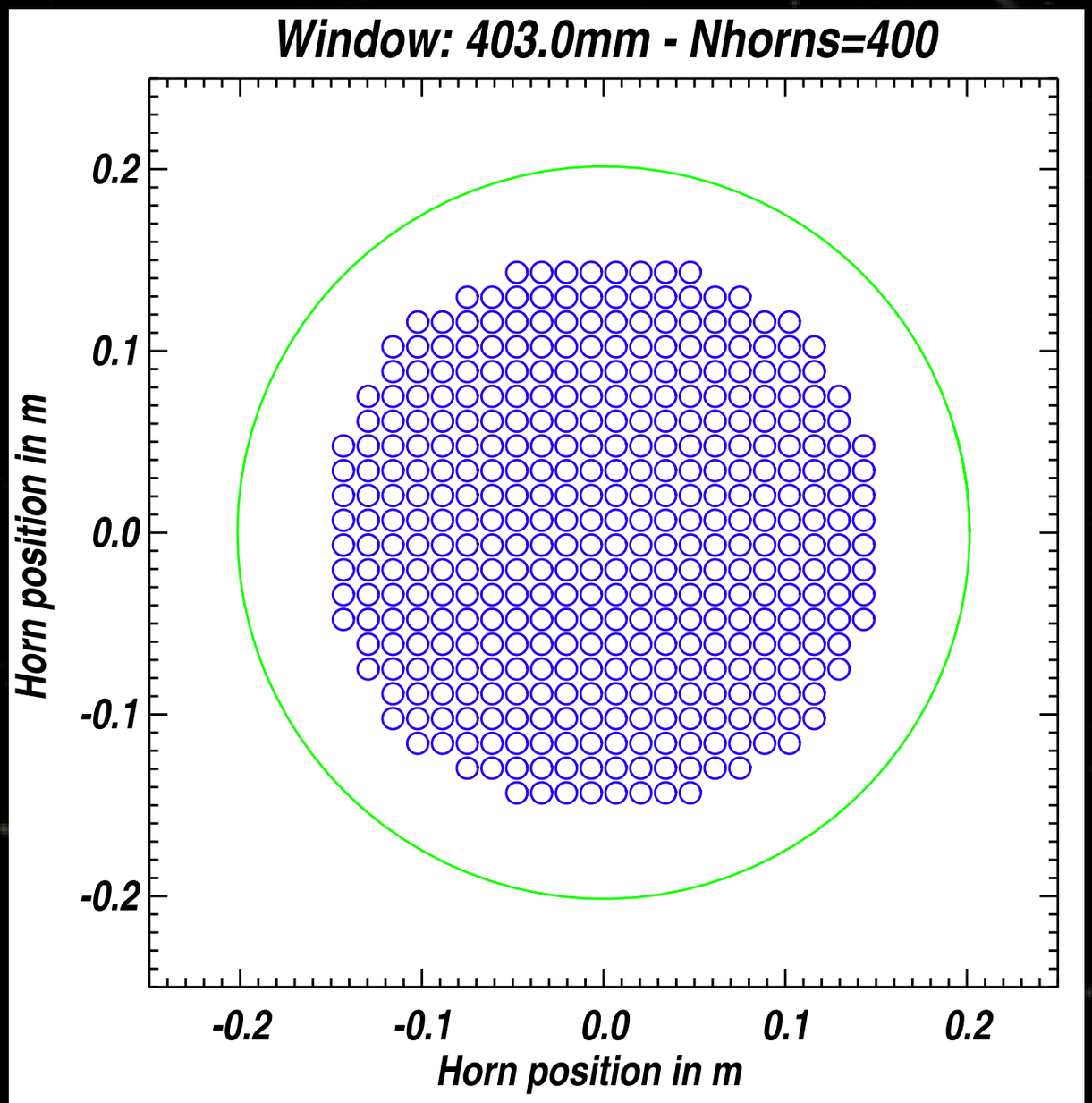

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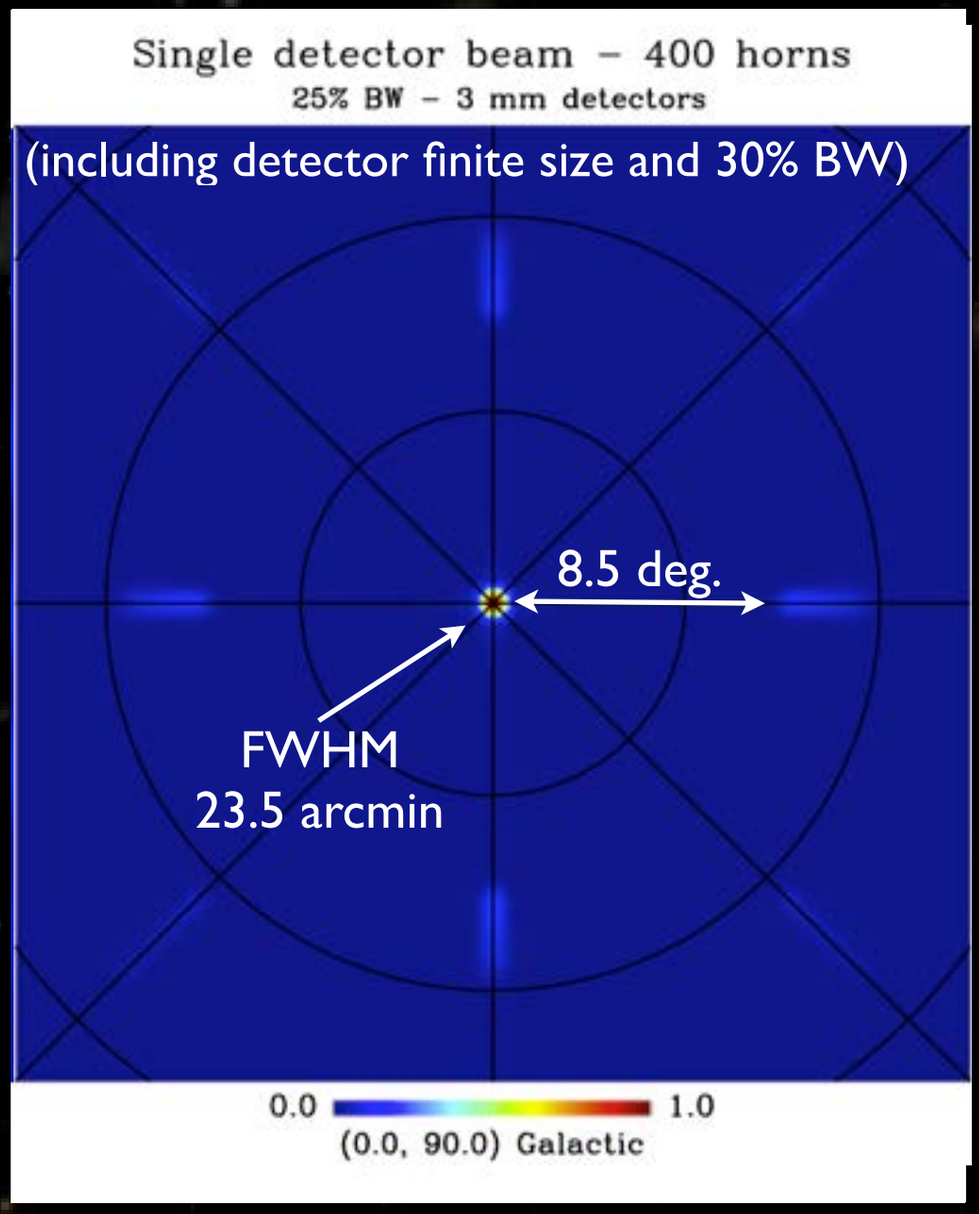

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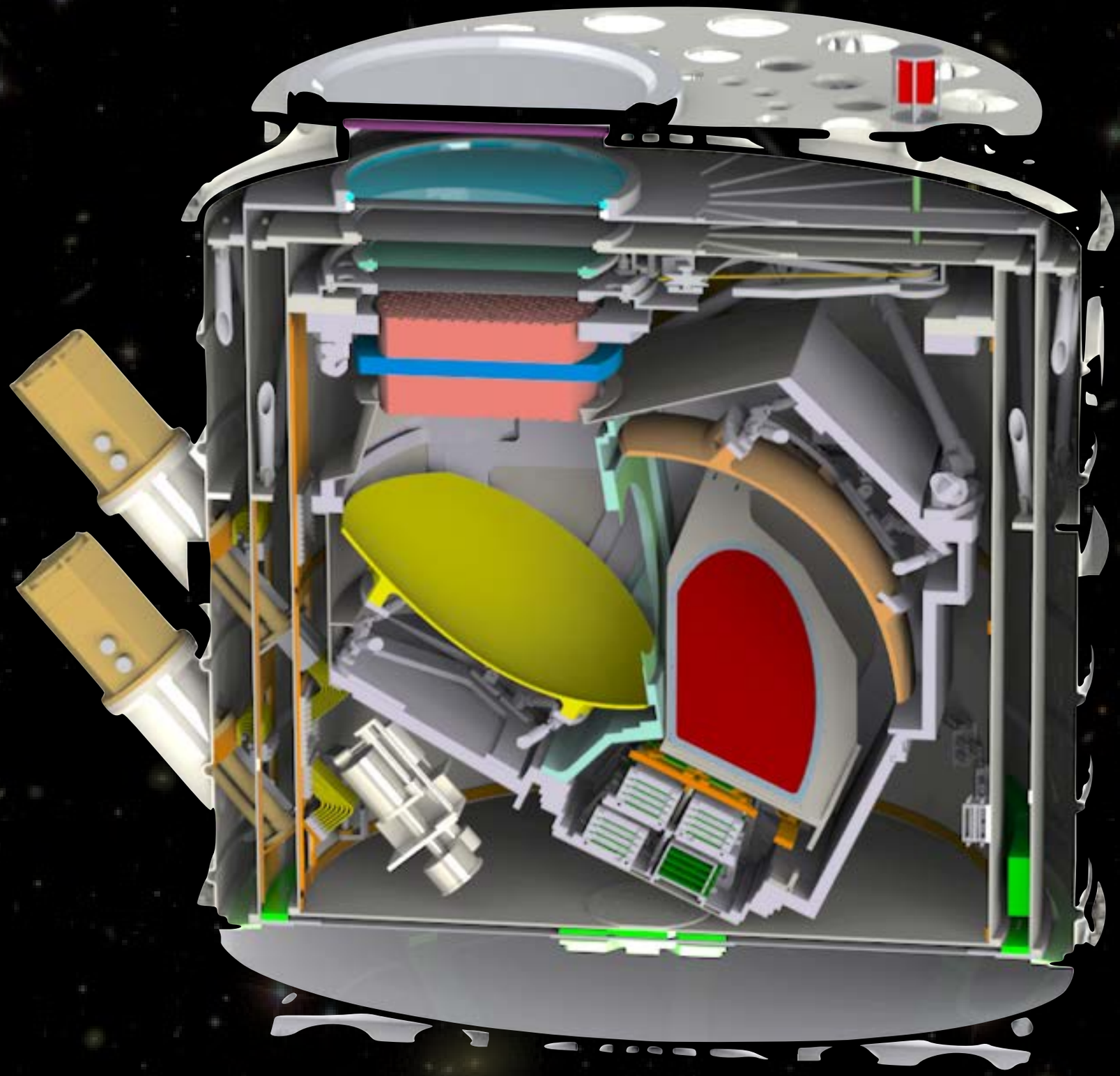

Instrument fully designed

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

1.547m high
1.42m diameter
About 800kg

Parts being constructed

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)
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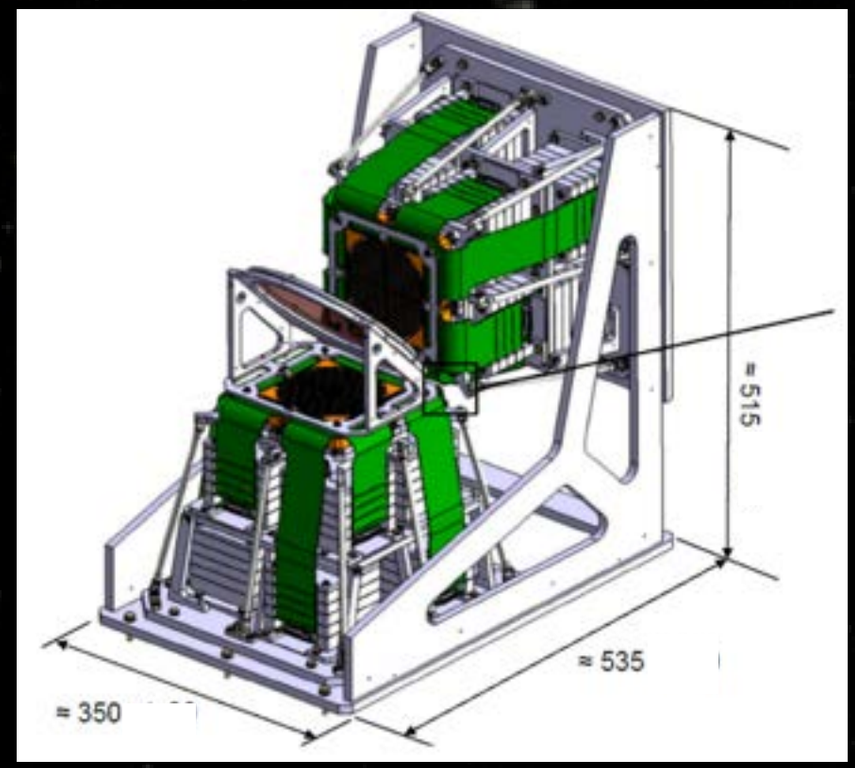
  - ★ 128 channels / ASIC
  - ★ Low noise: ~200 pV.Hz$^{-1/2}$
  - ★ low power: ~ few mW



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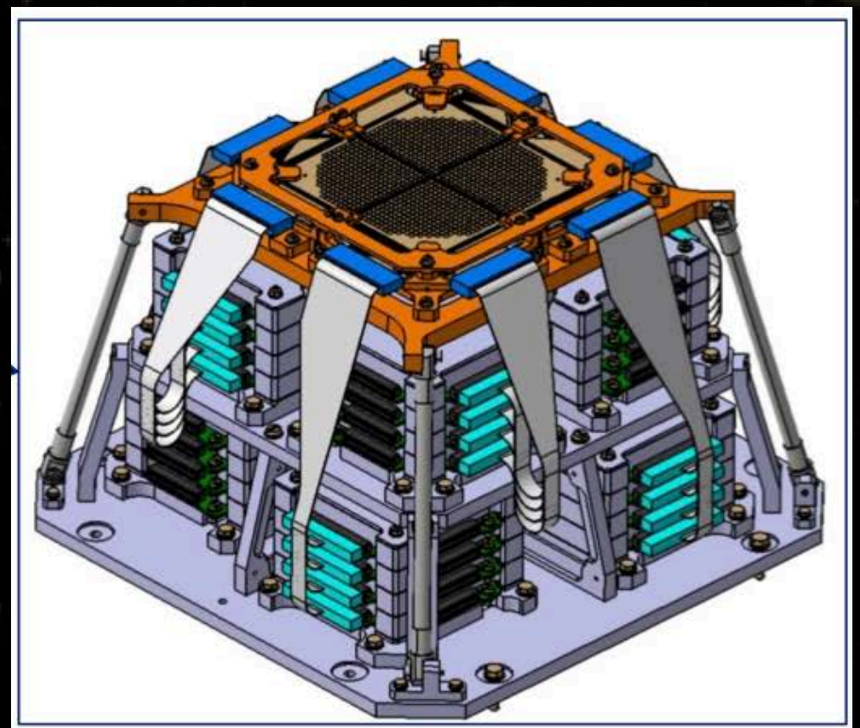

Half focal plane

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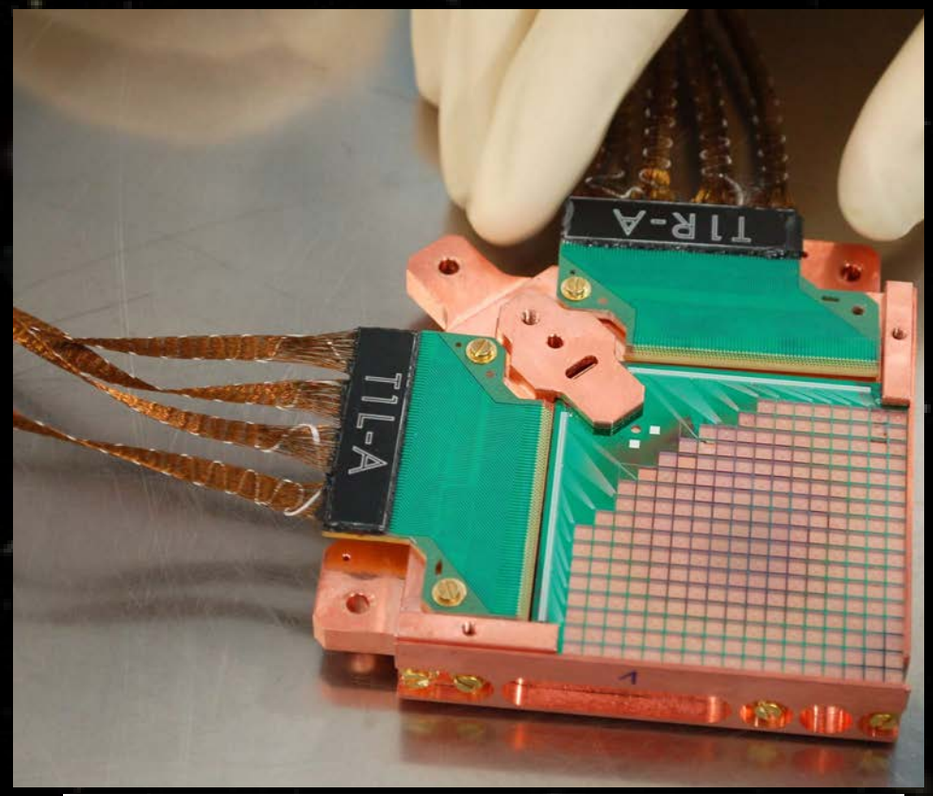

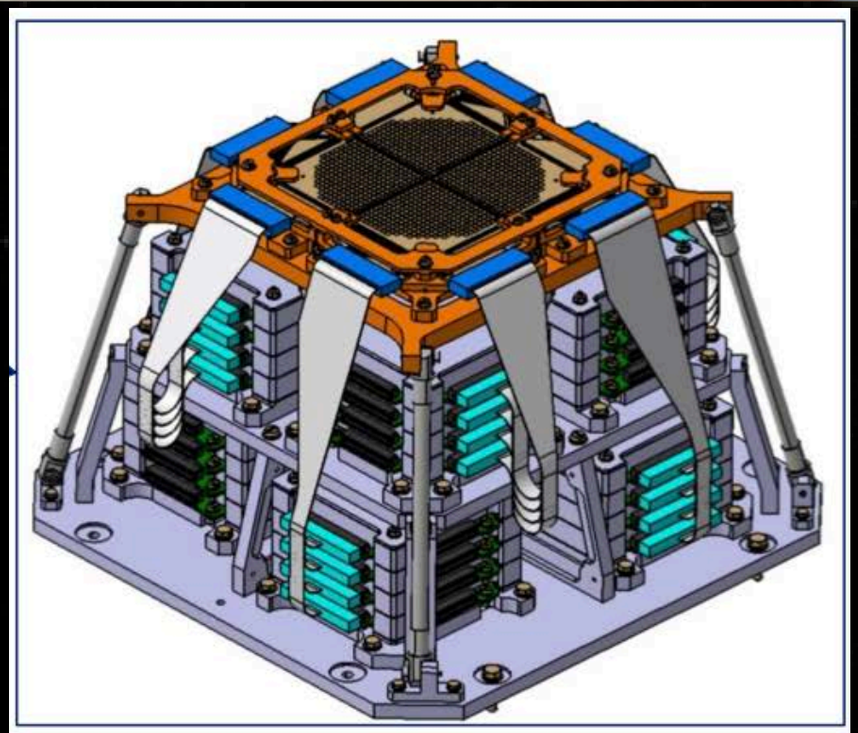

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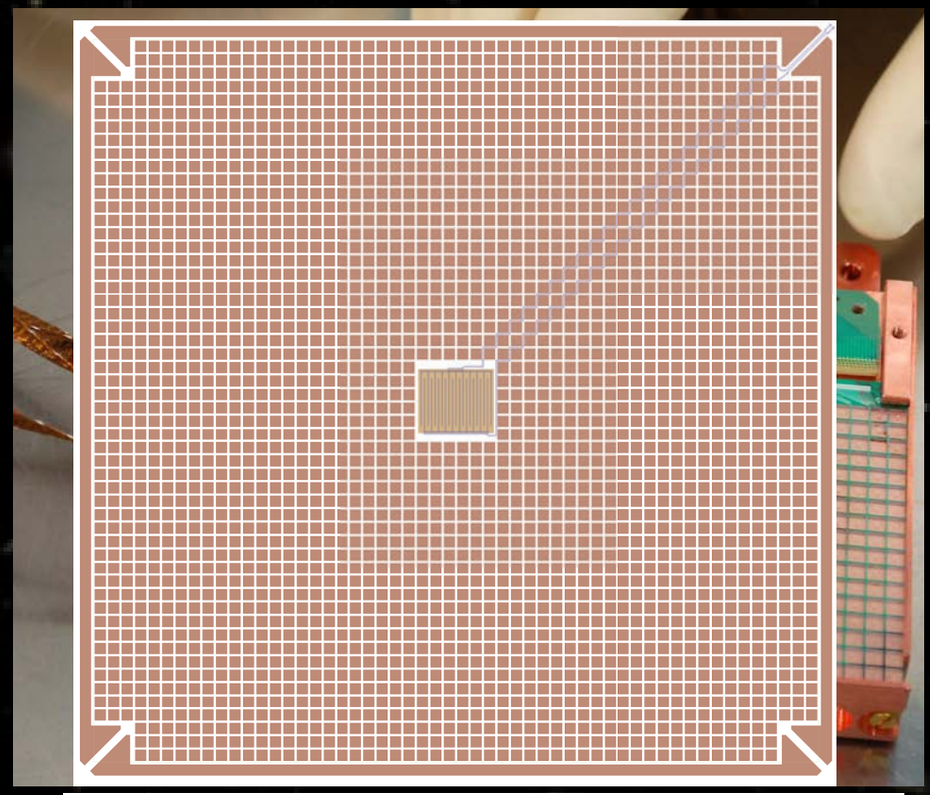

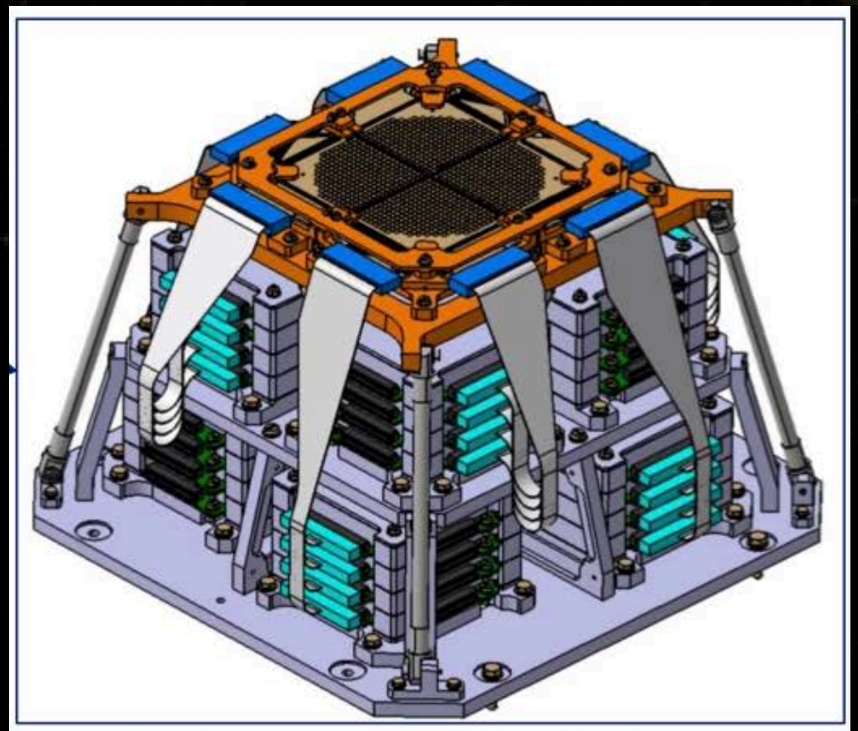

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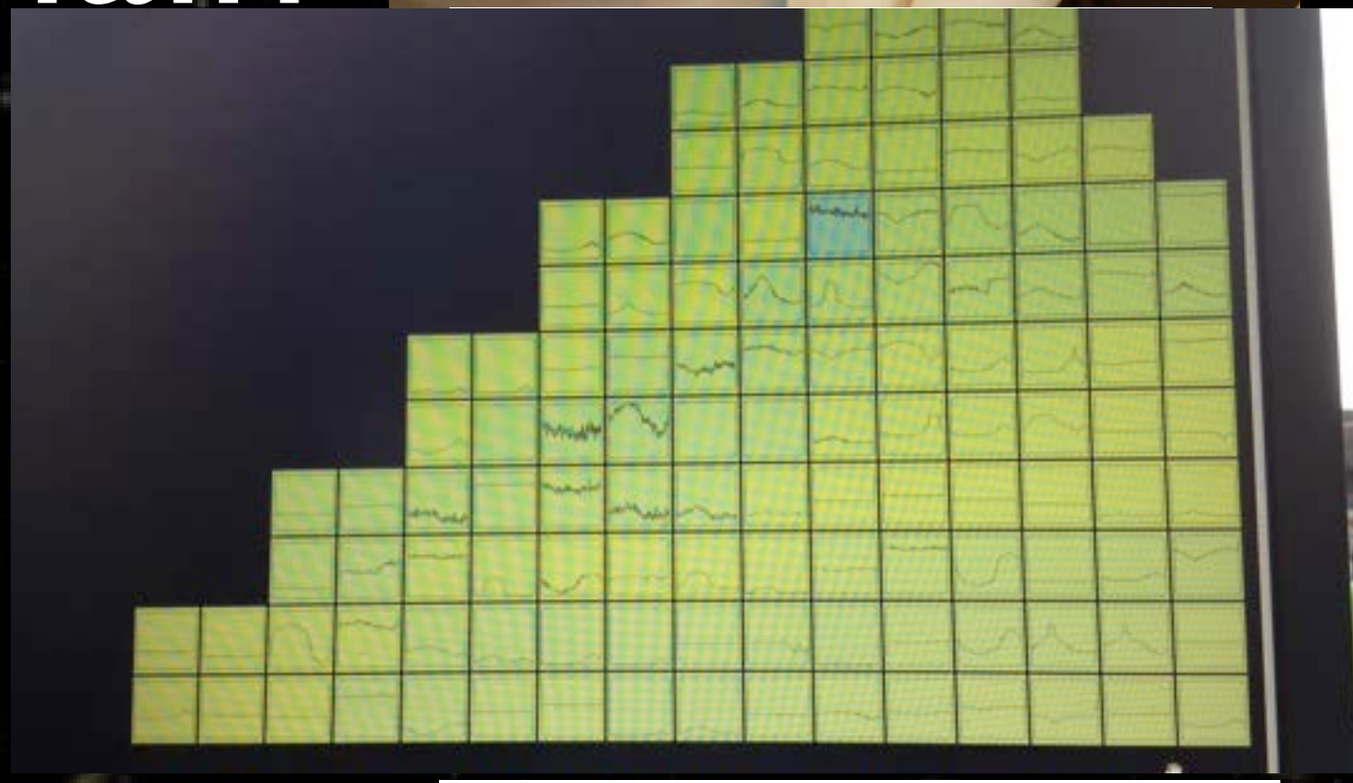

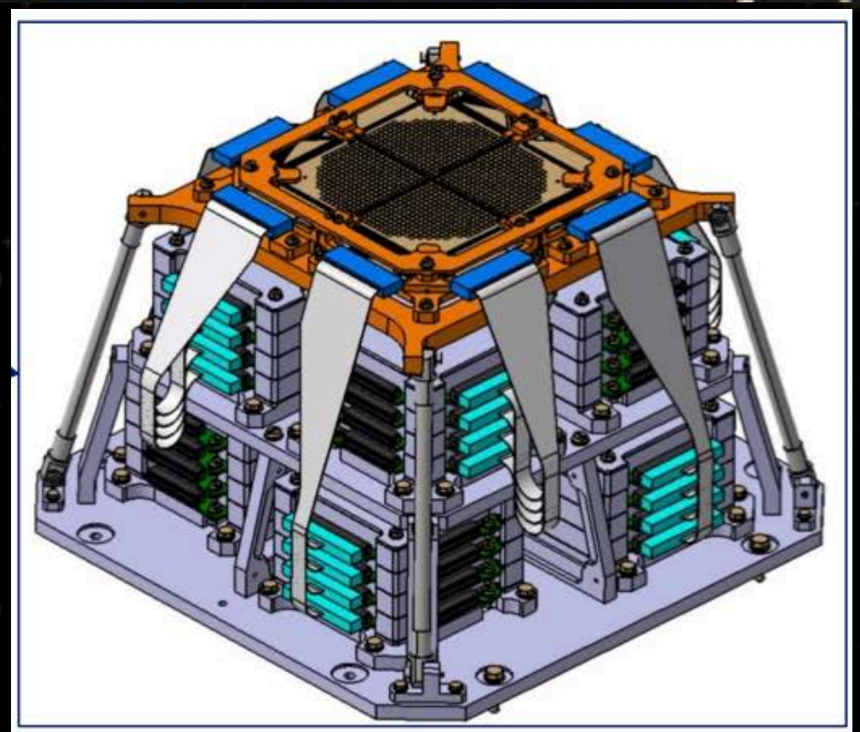

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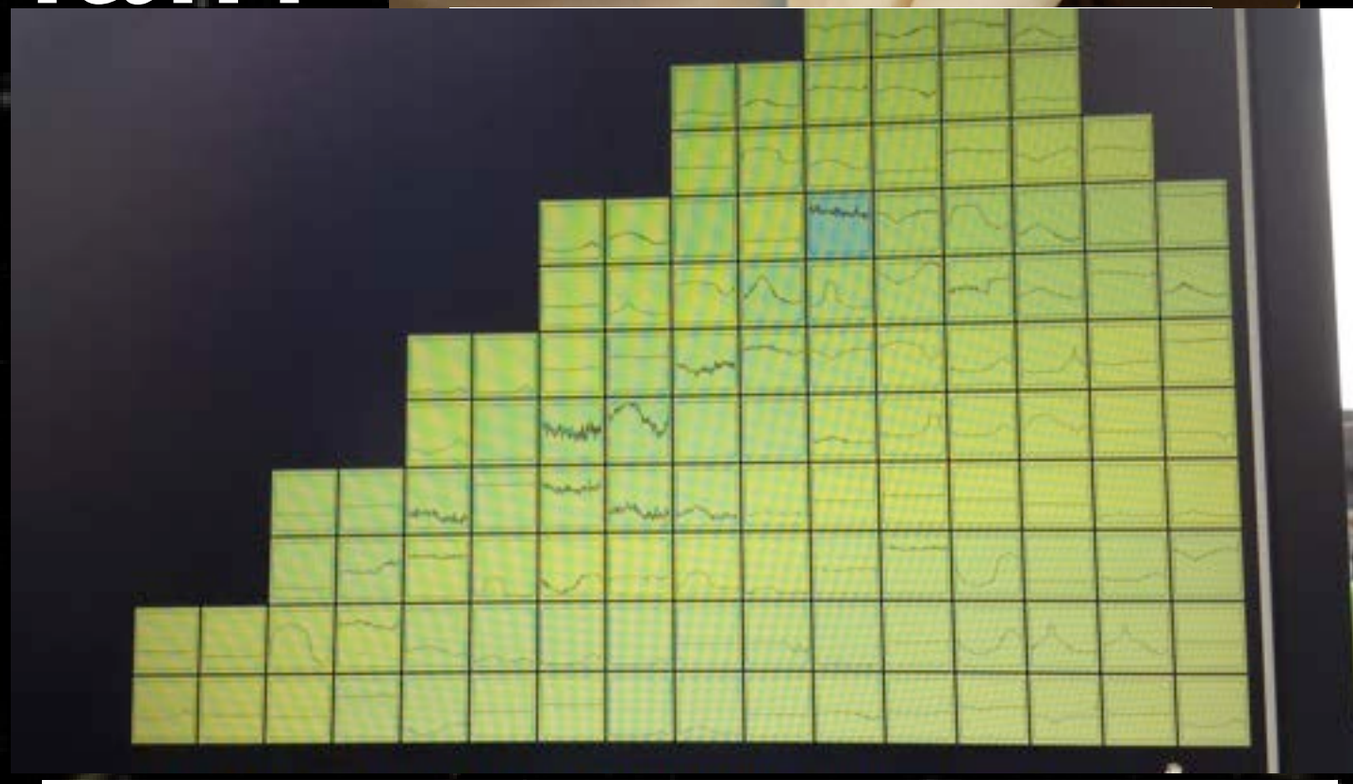
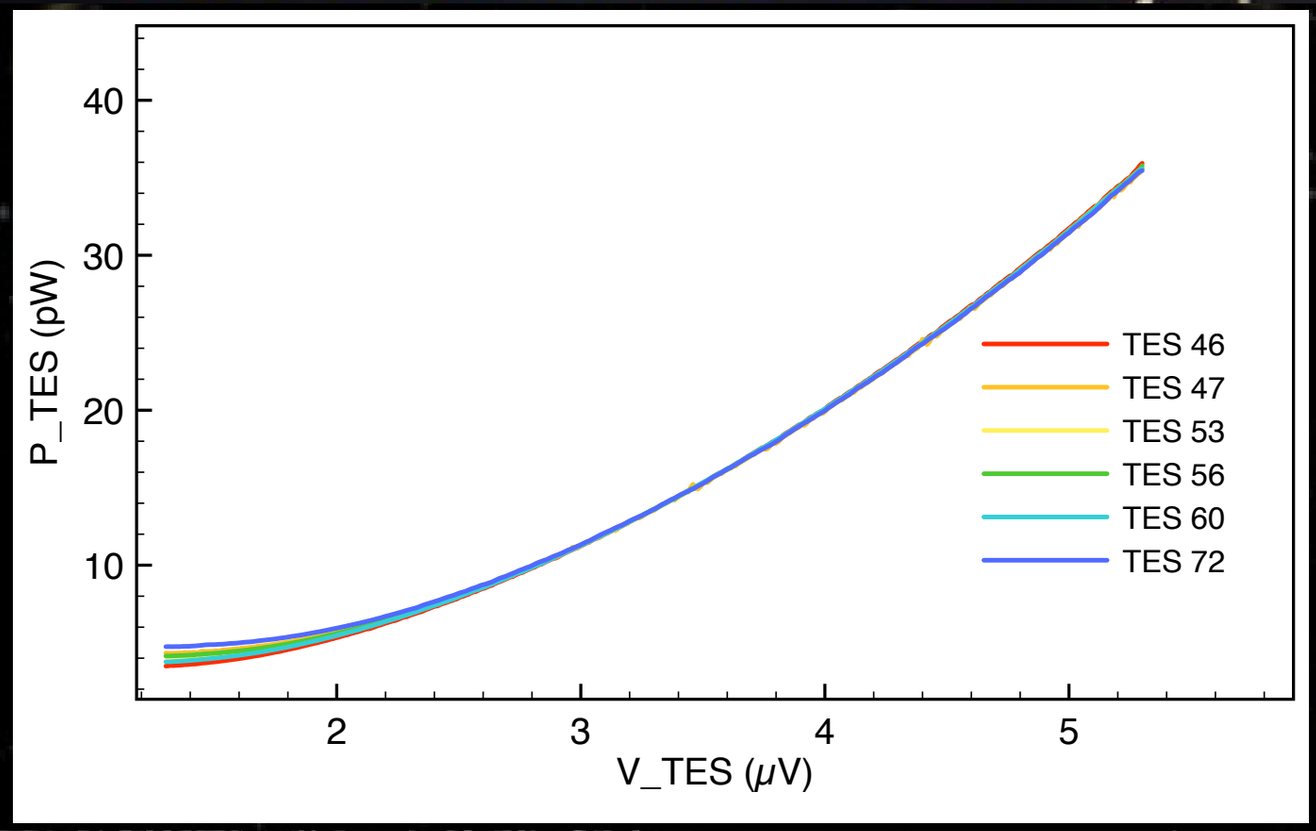
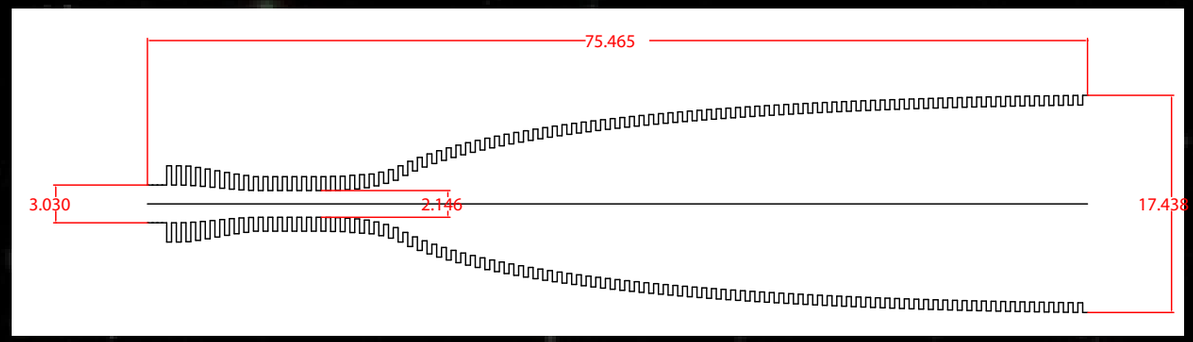




Dual Band Platelet Horns



- 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

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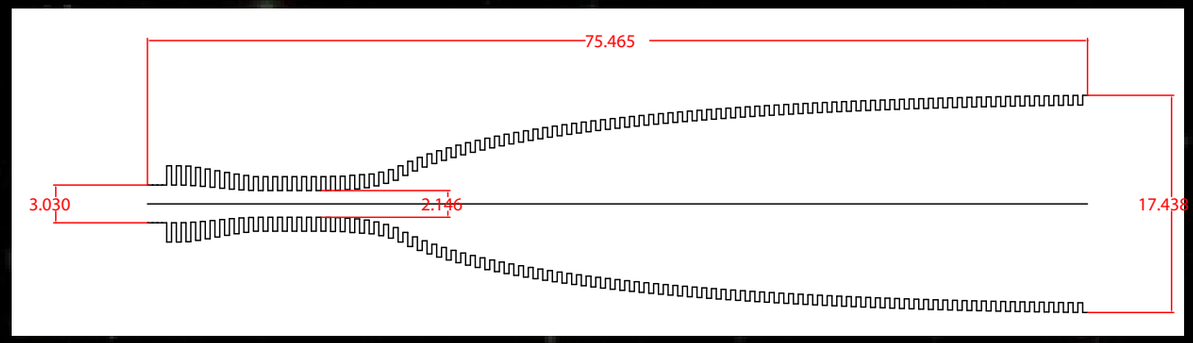

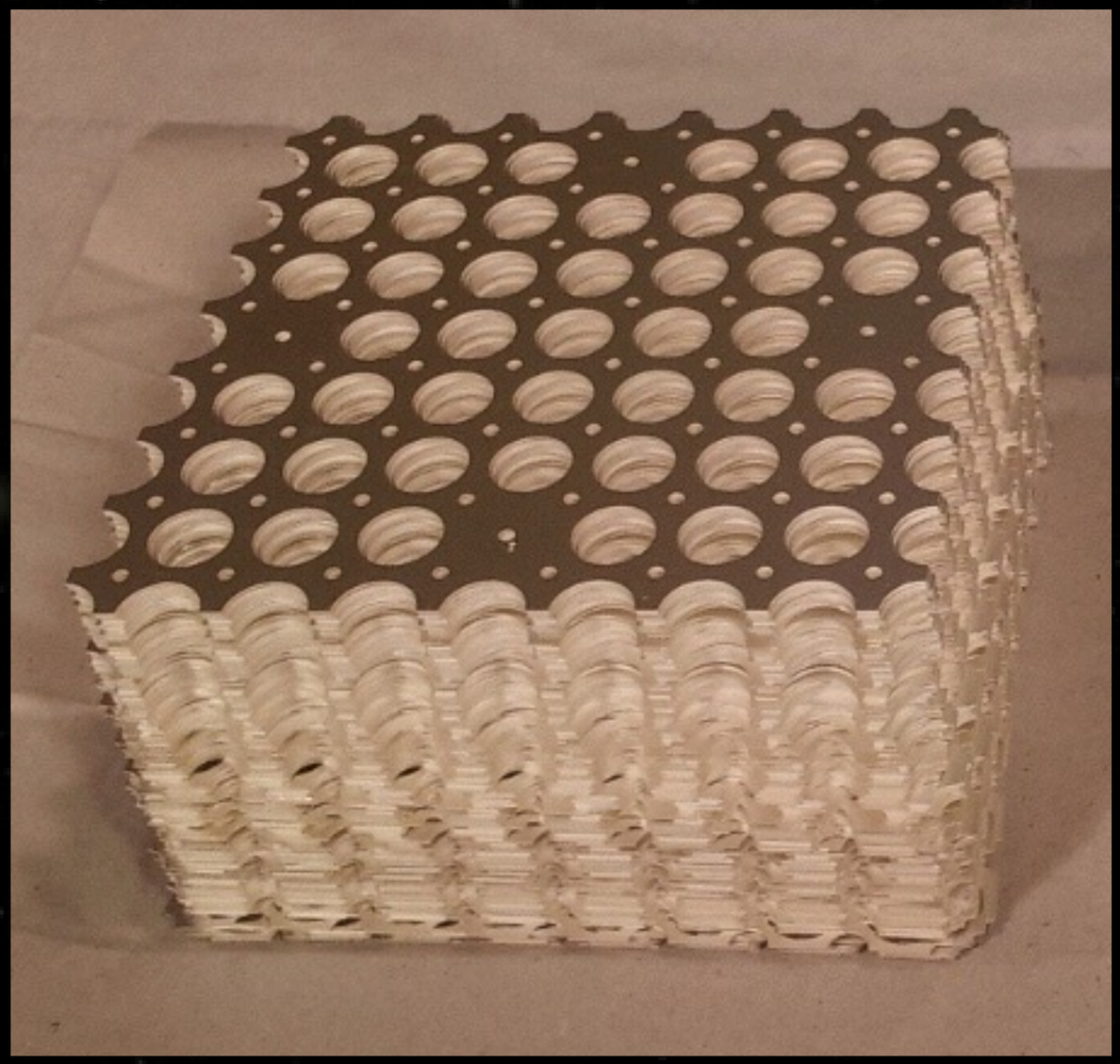

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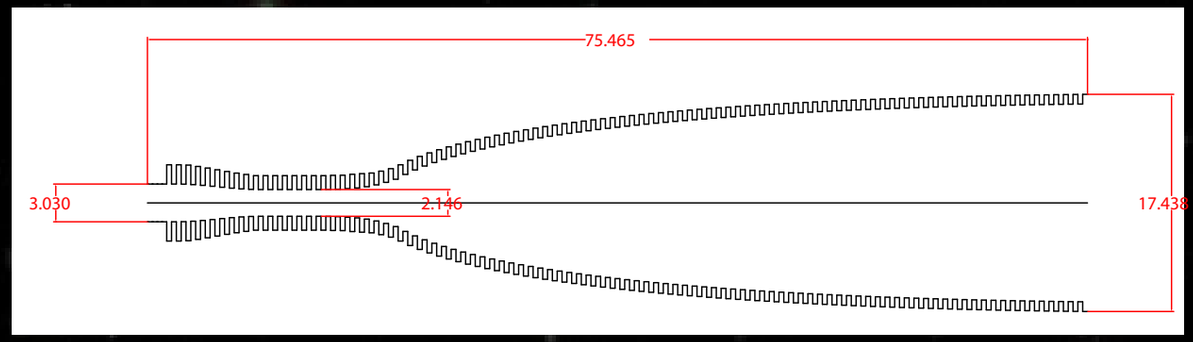

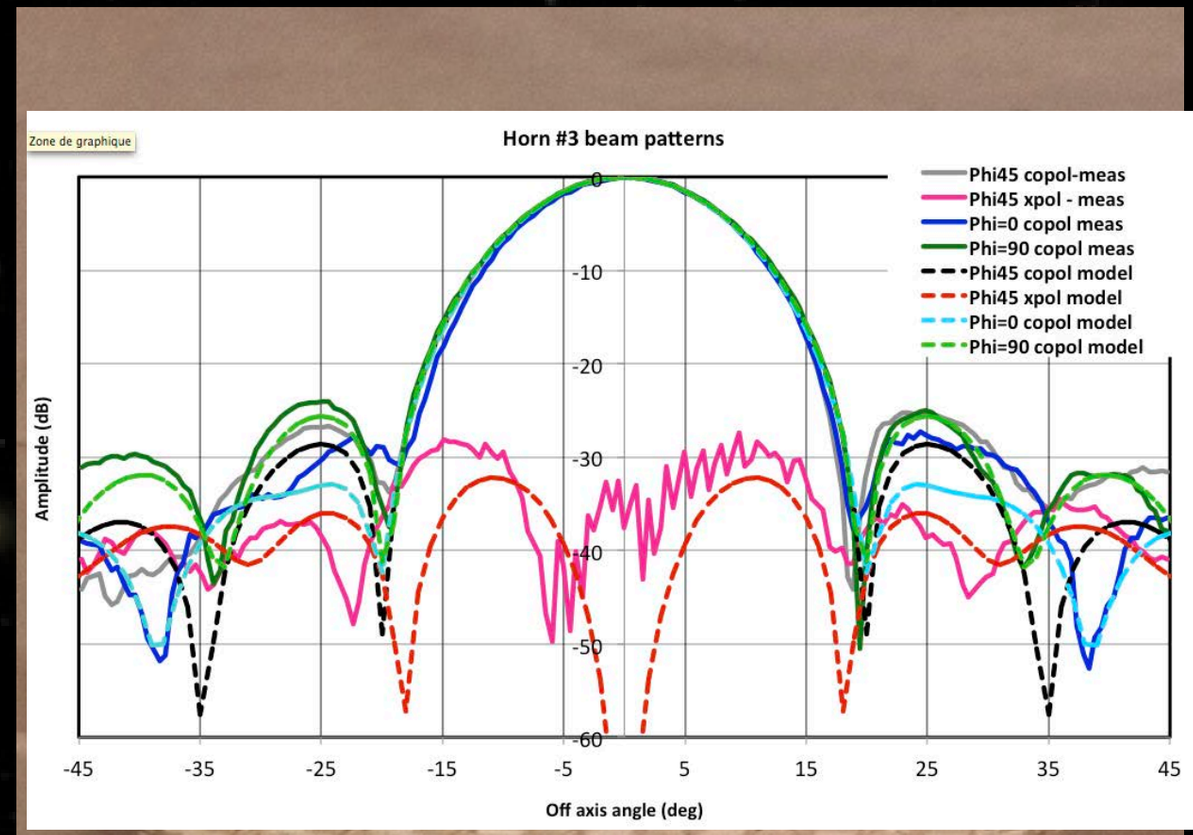

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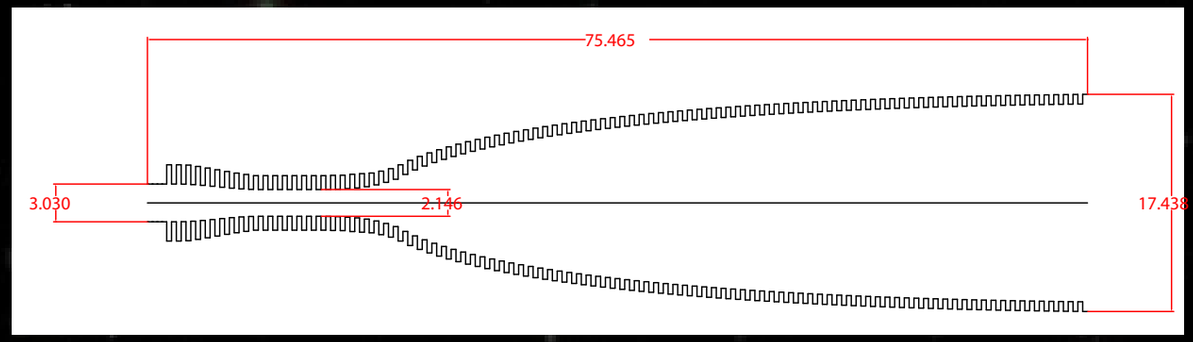
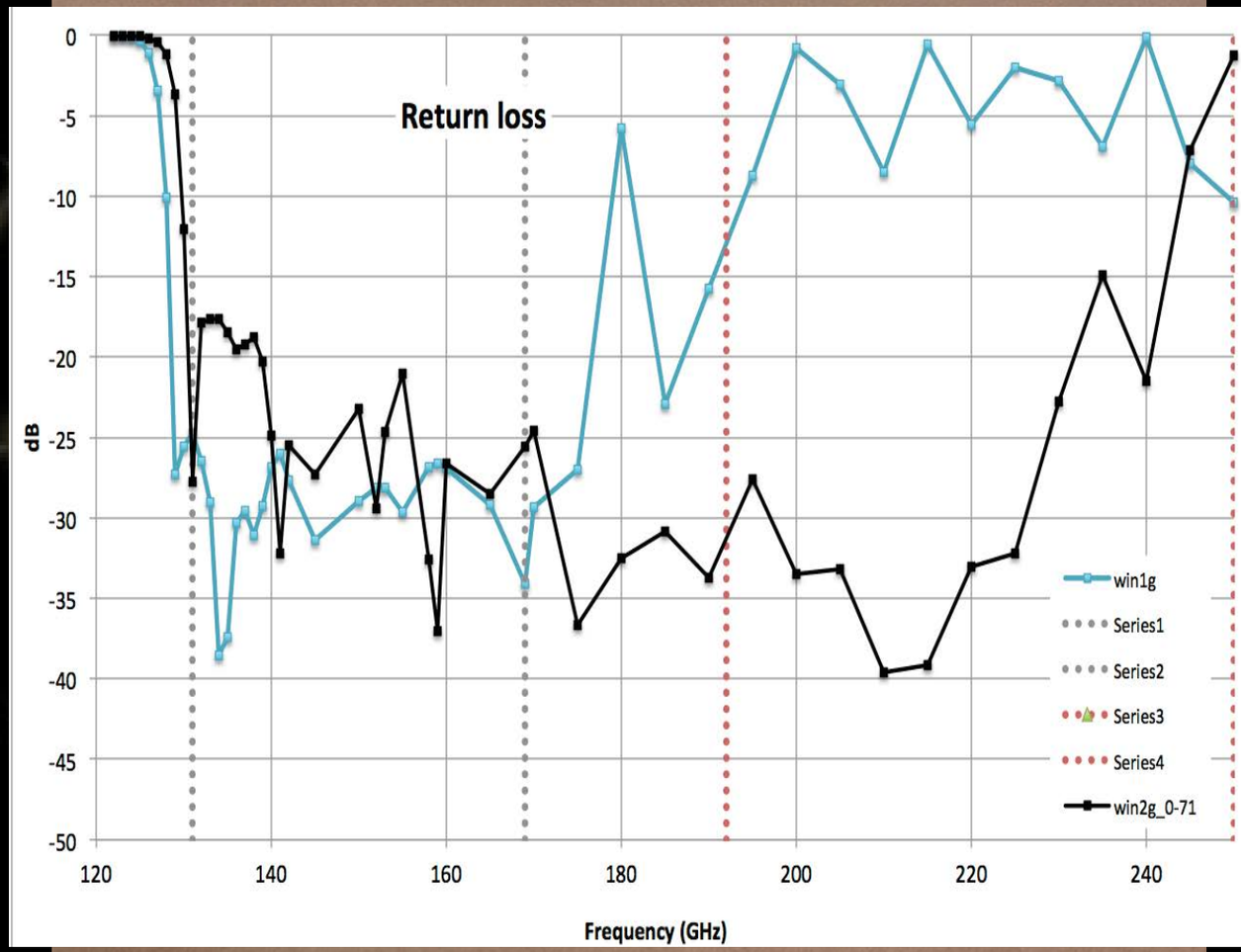
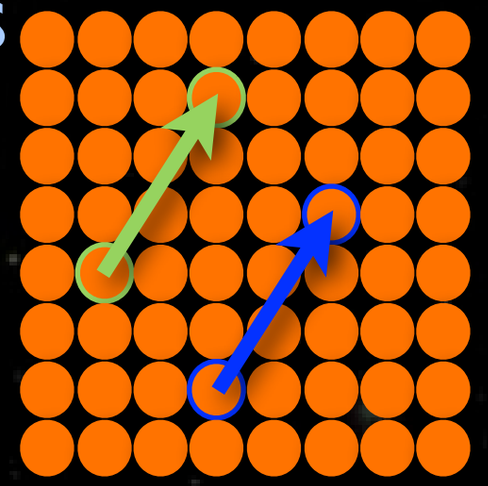


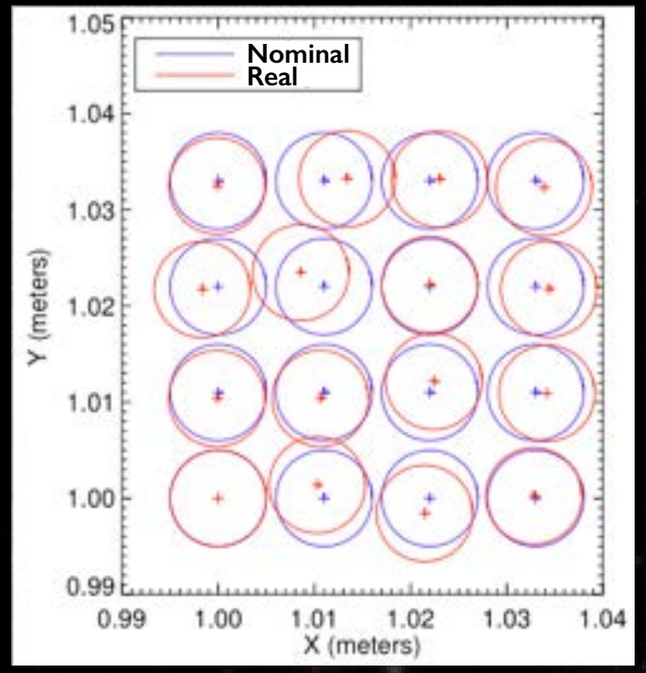


Systematics: Self-Calibration

- 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

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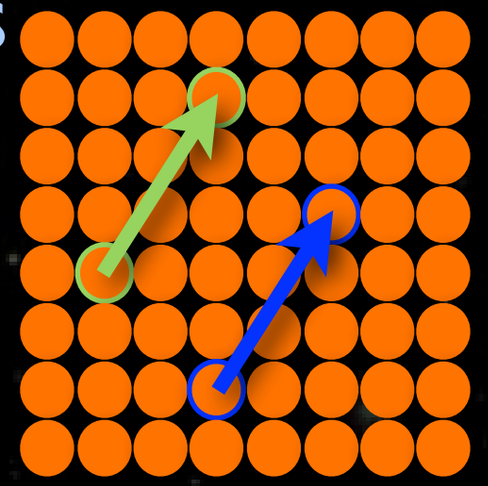

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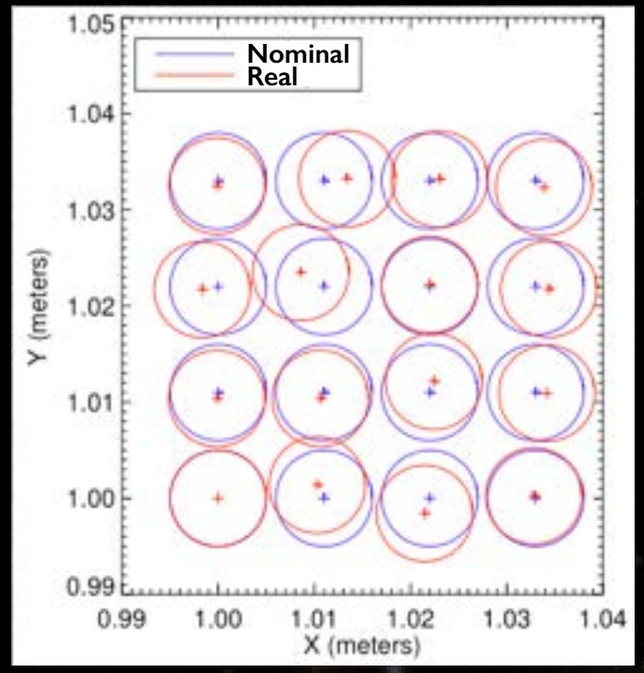

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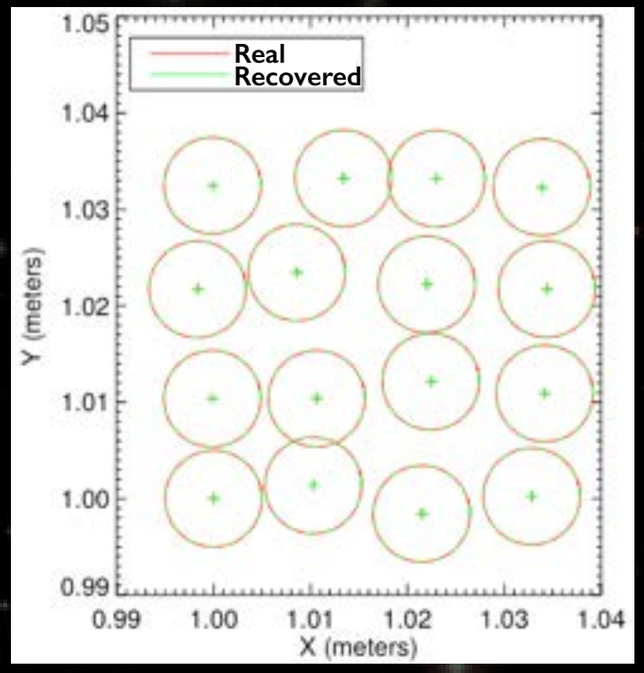

Actual horn positions (red) are recovered
thanks to self calibration (green)
⇒ E/B leakage is reduced

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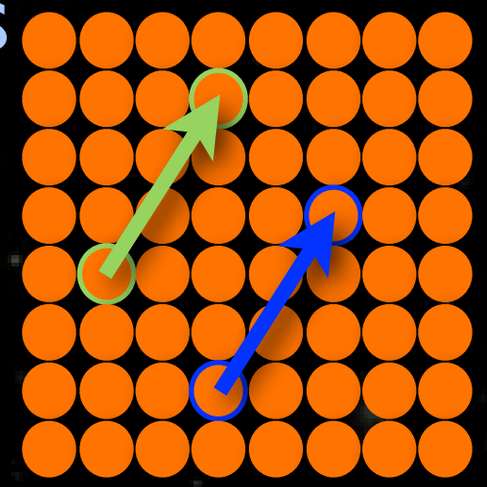
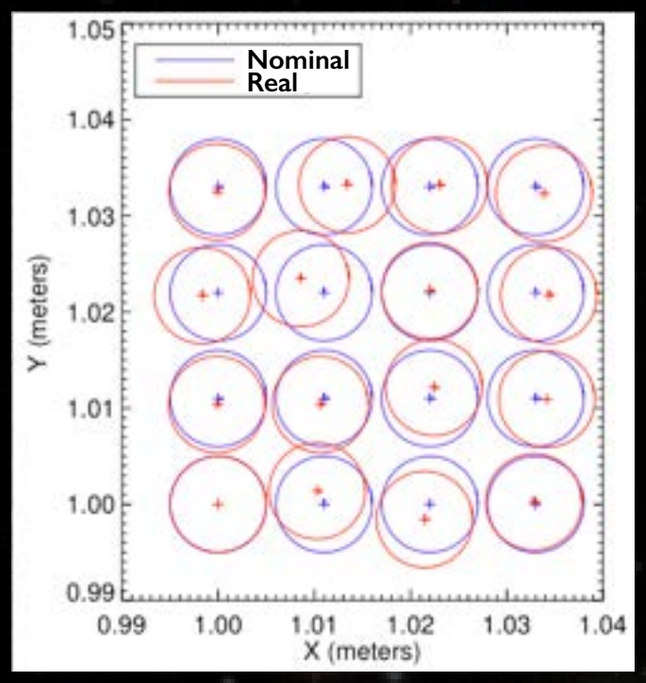
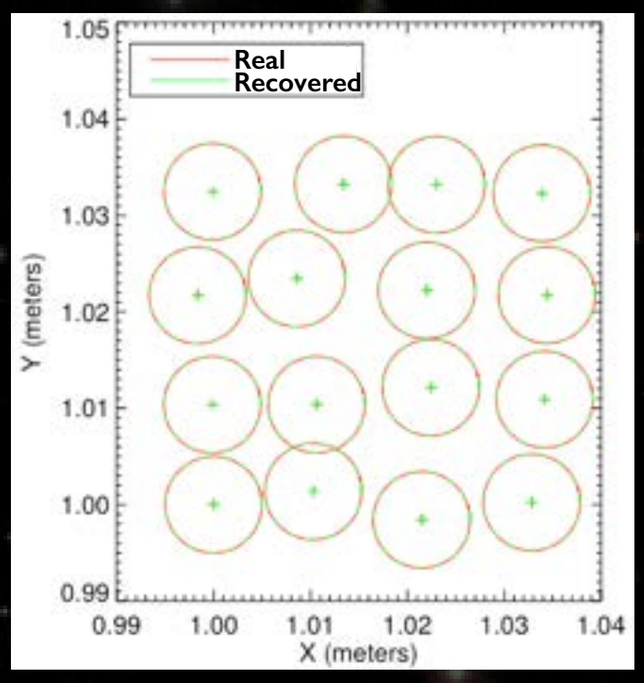
  - ★ Unique specificity of Bolometric Interferometry !
    [Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]
  - ★ Example: exact horns locations (figure exagerated !!)



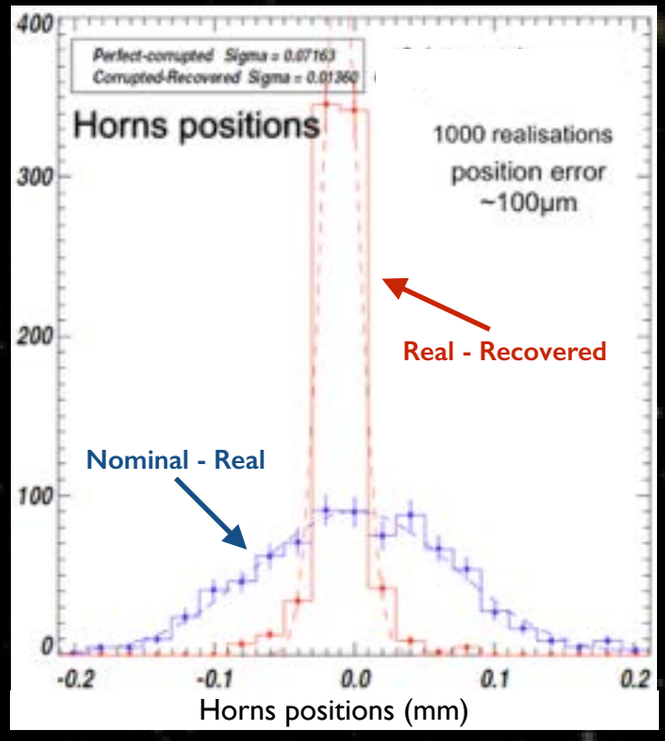
Redundant baselines : same Fourier Mode



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

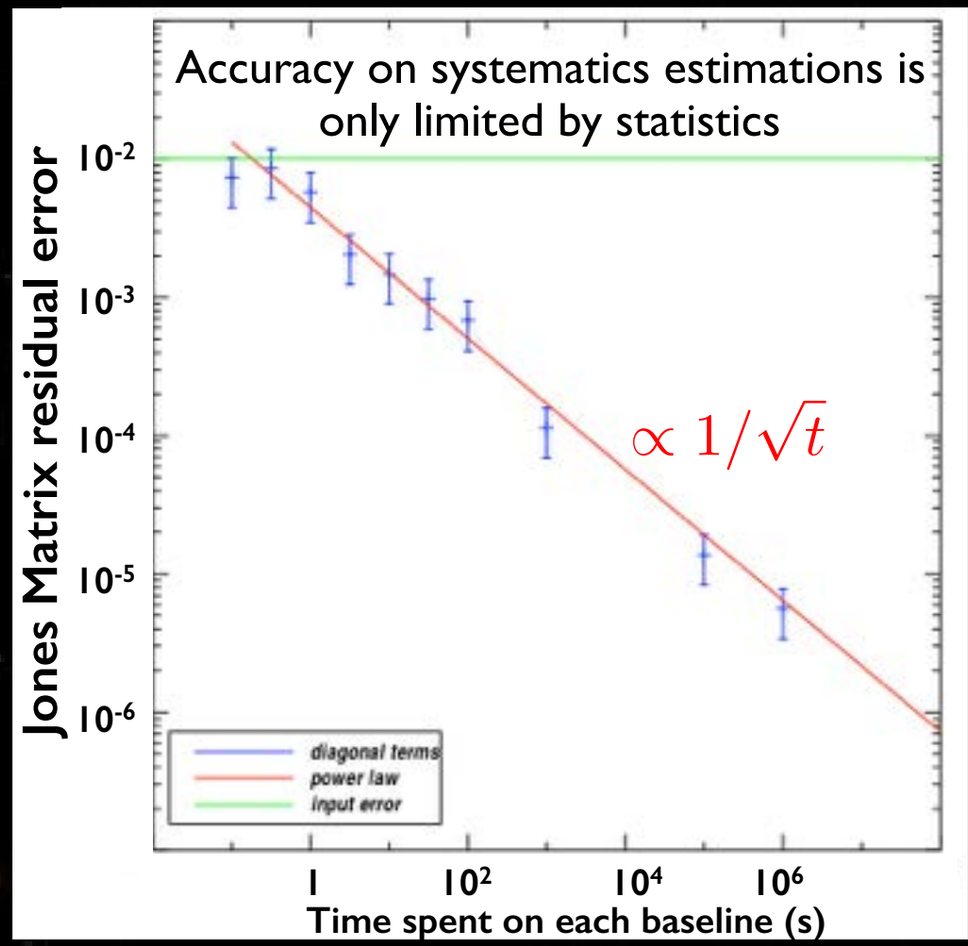


Horn position knowledge improvement

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



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- Simulate instrument with systematics
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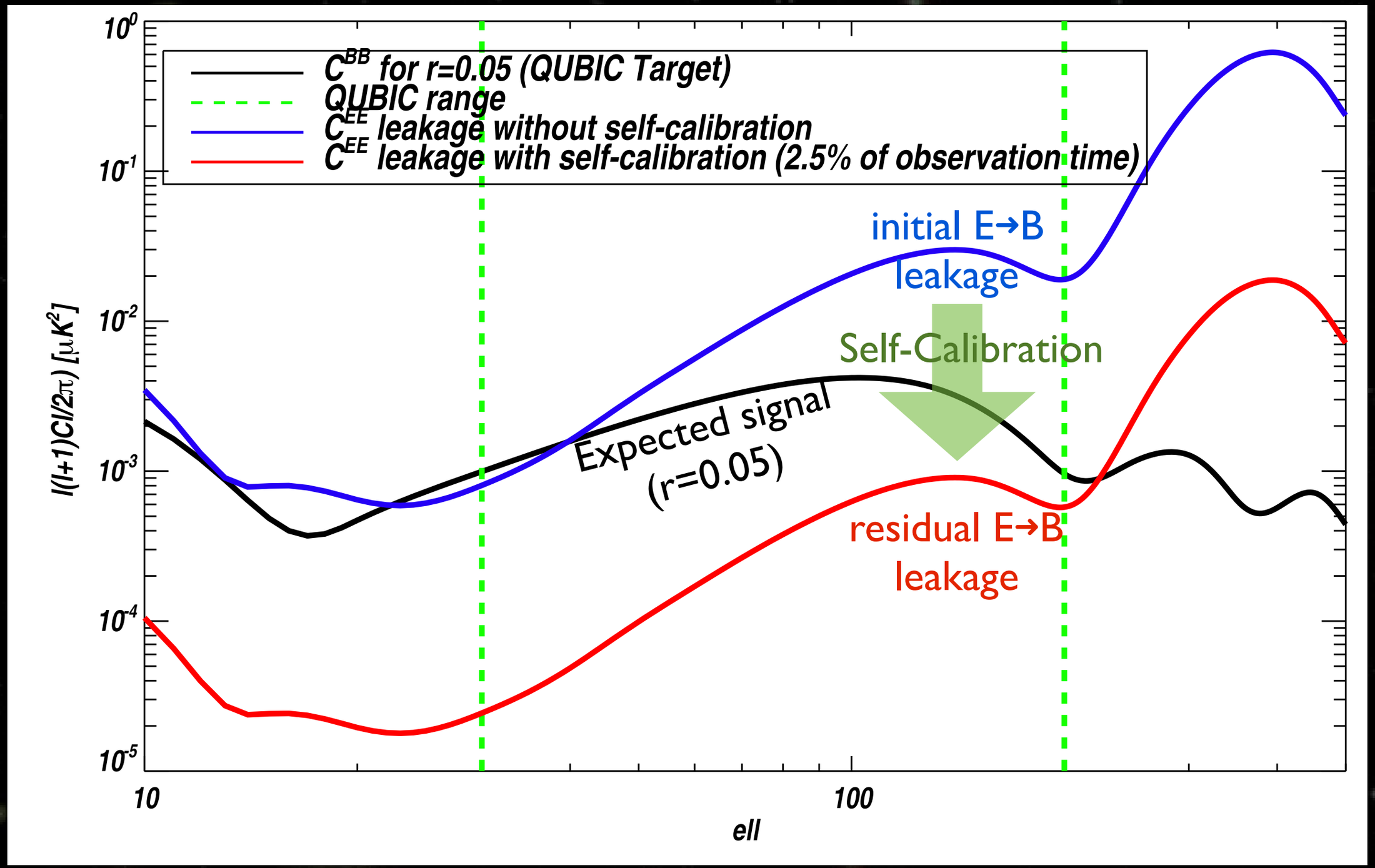
- Check improvement on systematics parameters

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
$\overrightarrow{x_i}$	$100. \times 10^{-6}$	5.86×10^{-5}	17	2.27×10^{-8}	4402
$g_\eta(\overrightarrow{x_i})$	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
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

- ★ 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

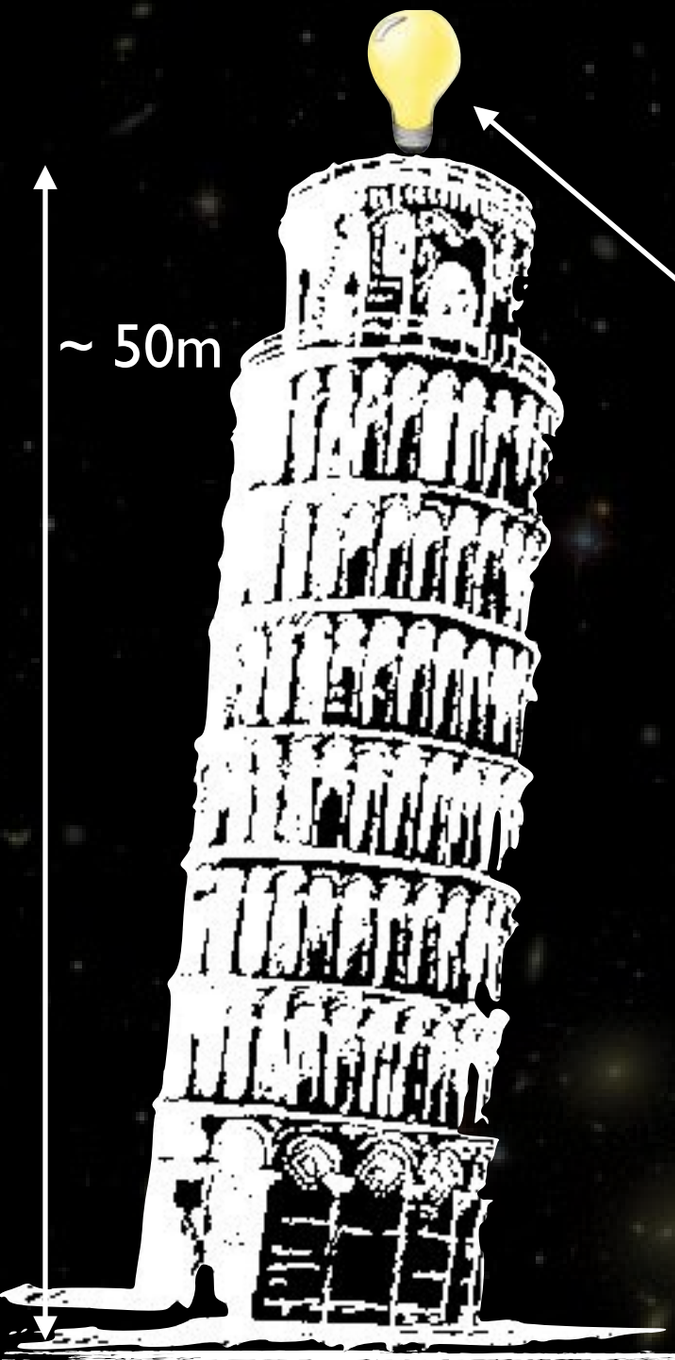


[Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]

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)

Self-Calibration summary



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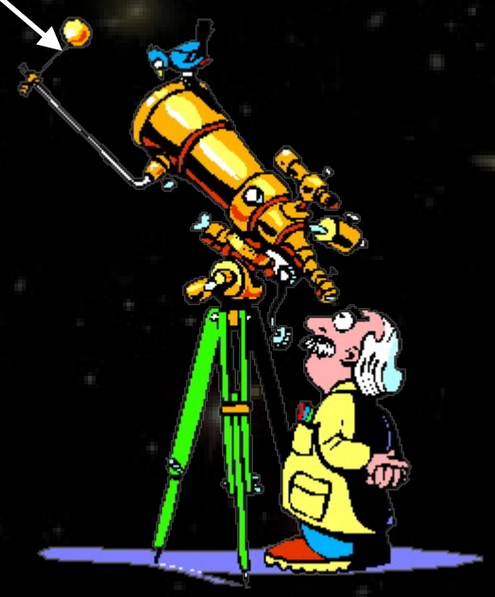
~ 50m



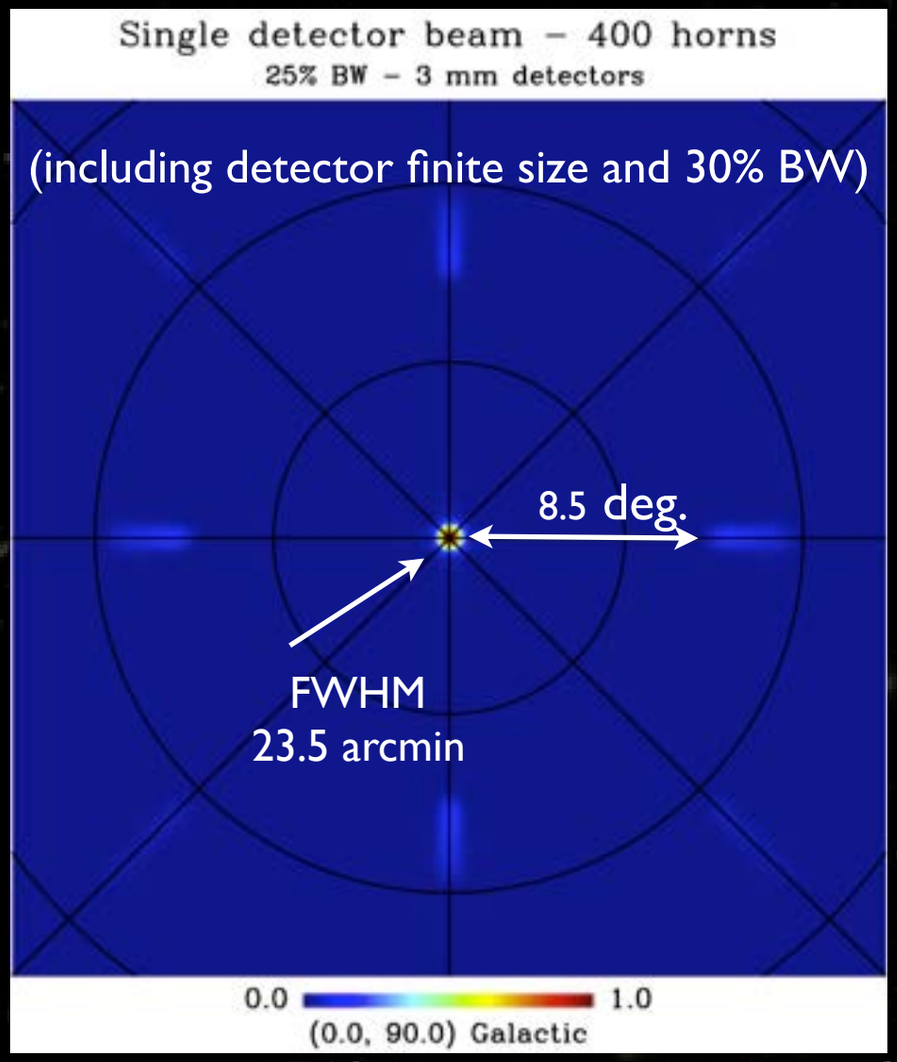
Map-making with QUBIC synthesized beam

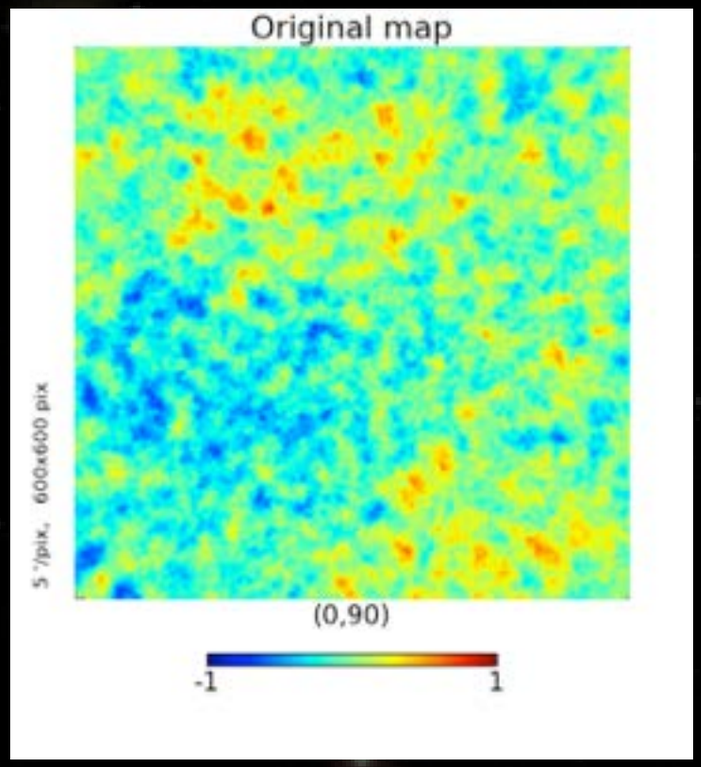
- Signal on bolometer d_p at frequency ν (HWP modulation) :

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

- 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

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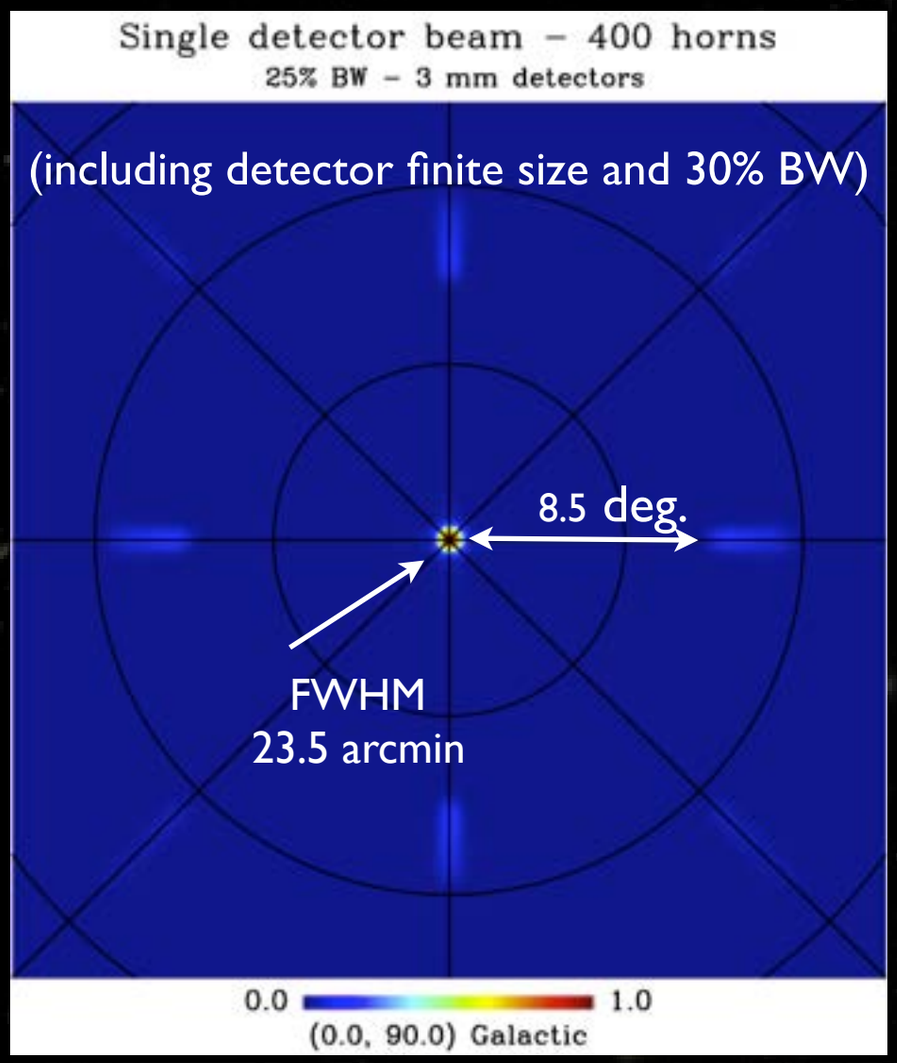
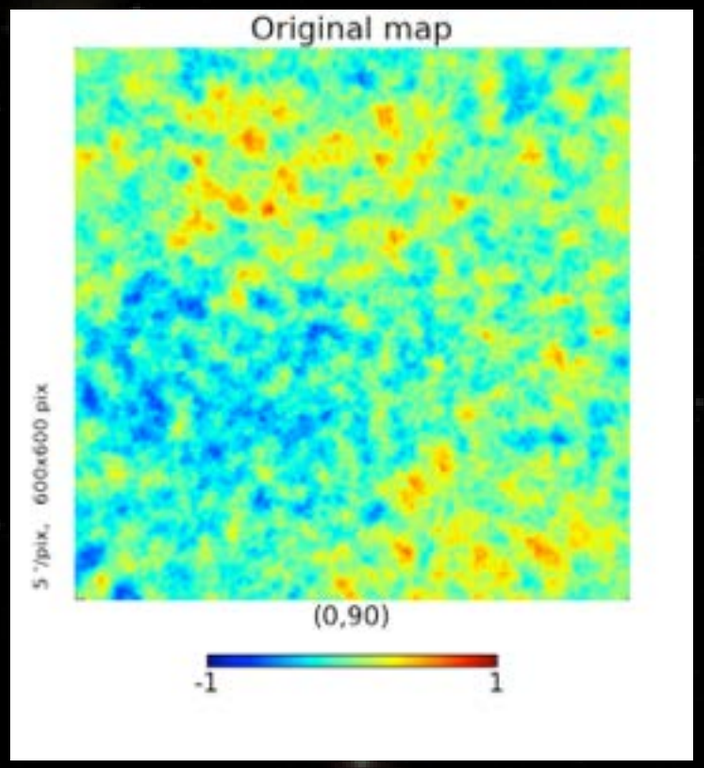
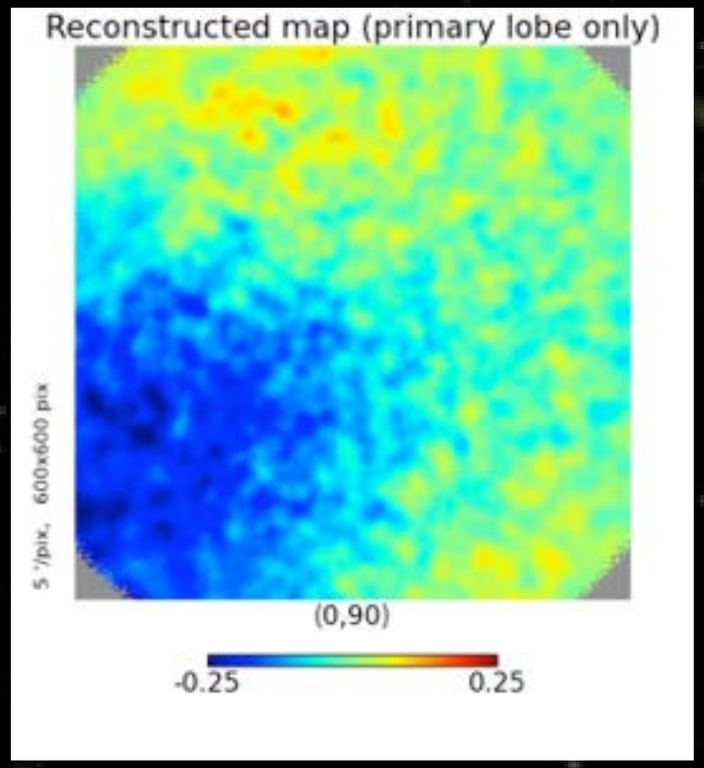


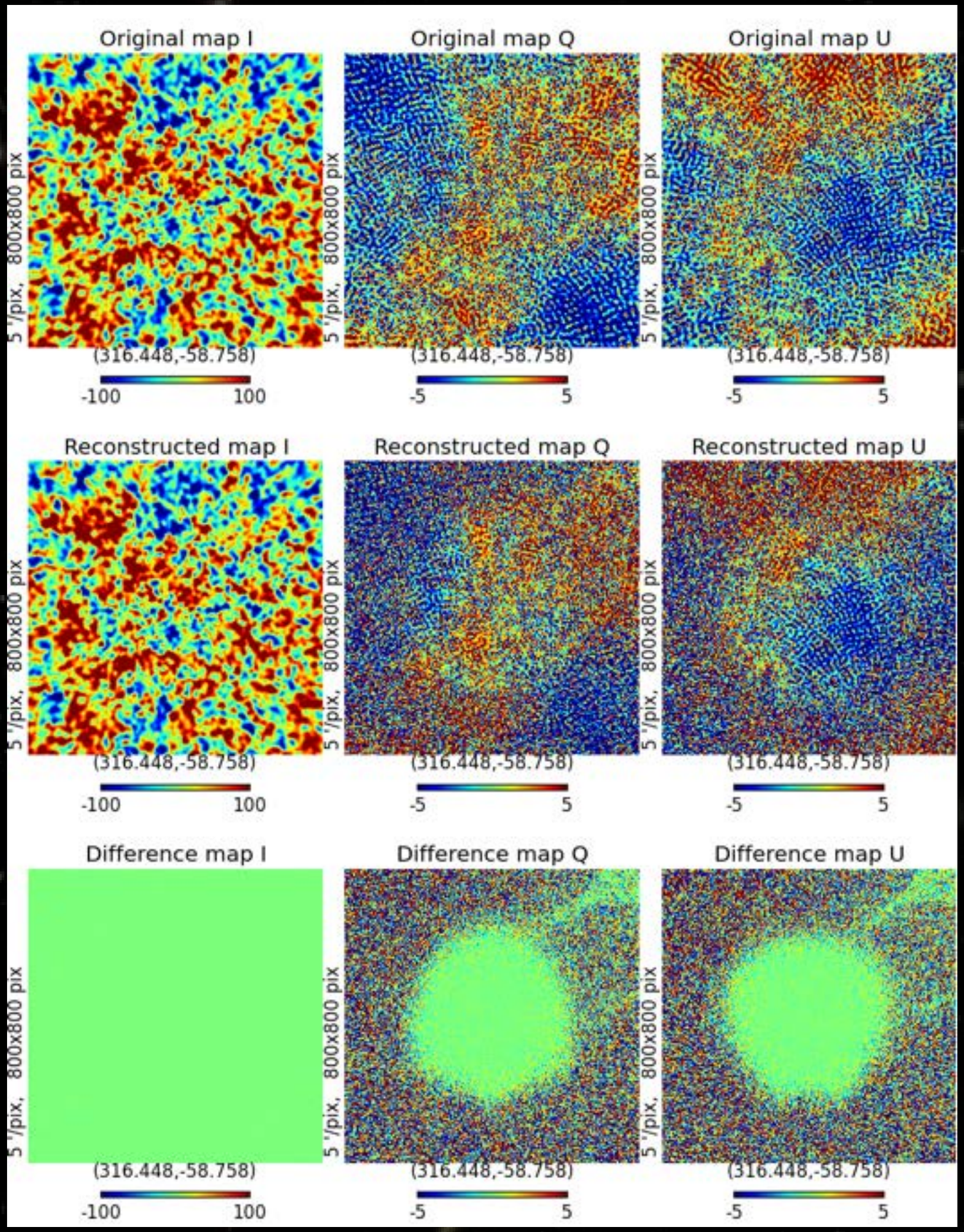


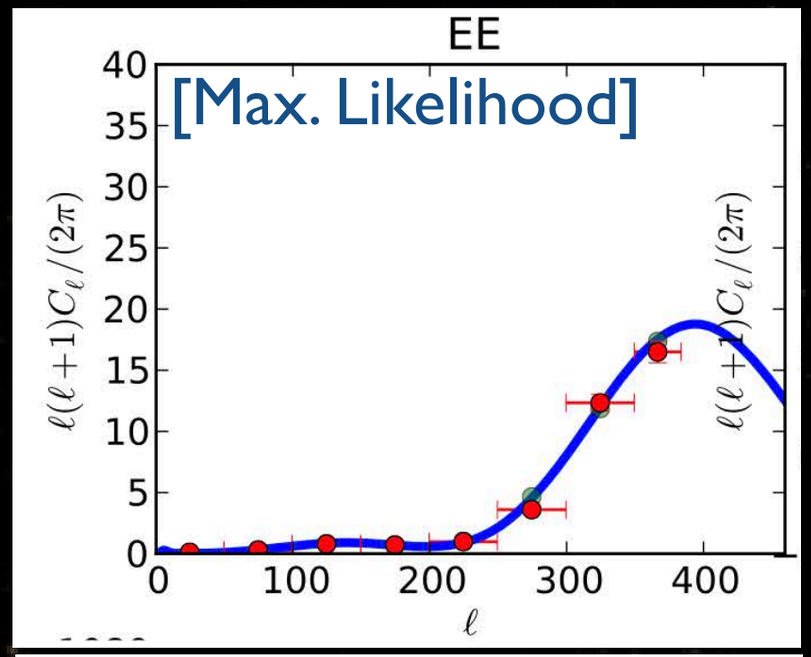


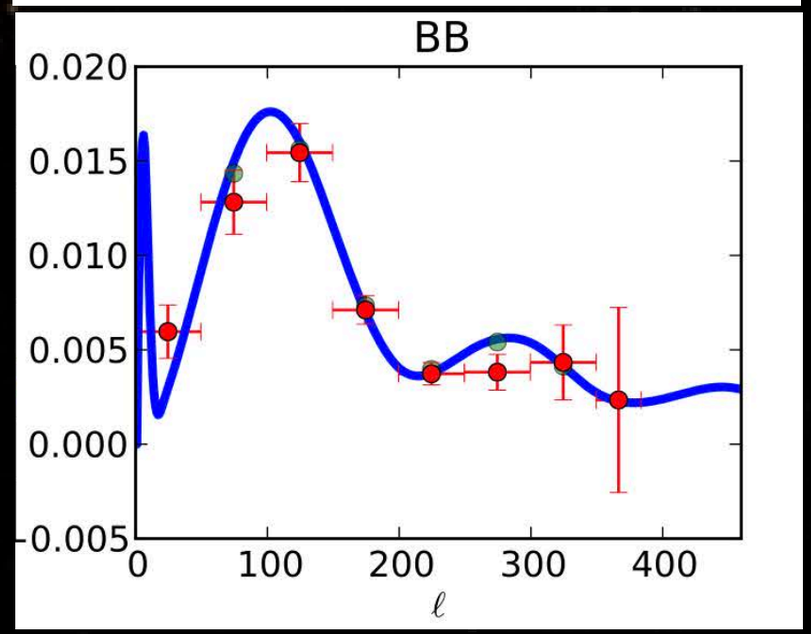
Mapmaking needs to account for precisely-known but multiply-peaked synthesized beam

QUBIC specific Map Making & CI

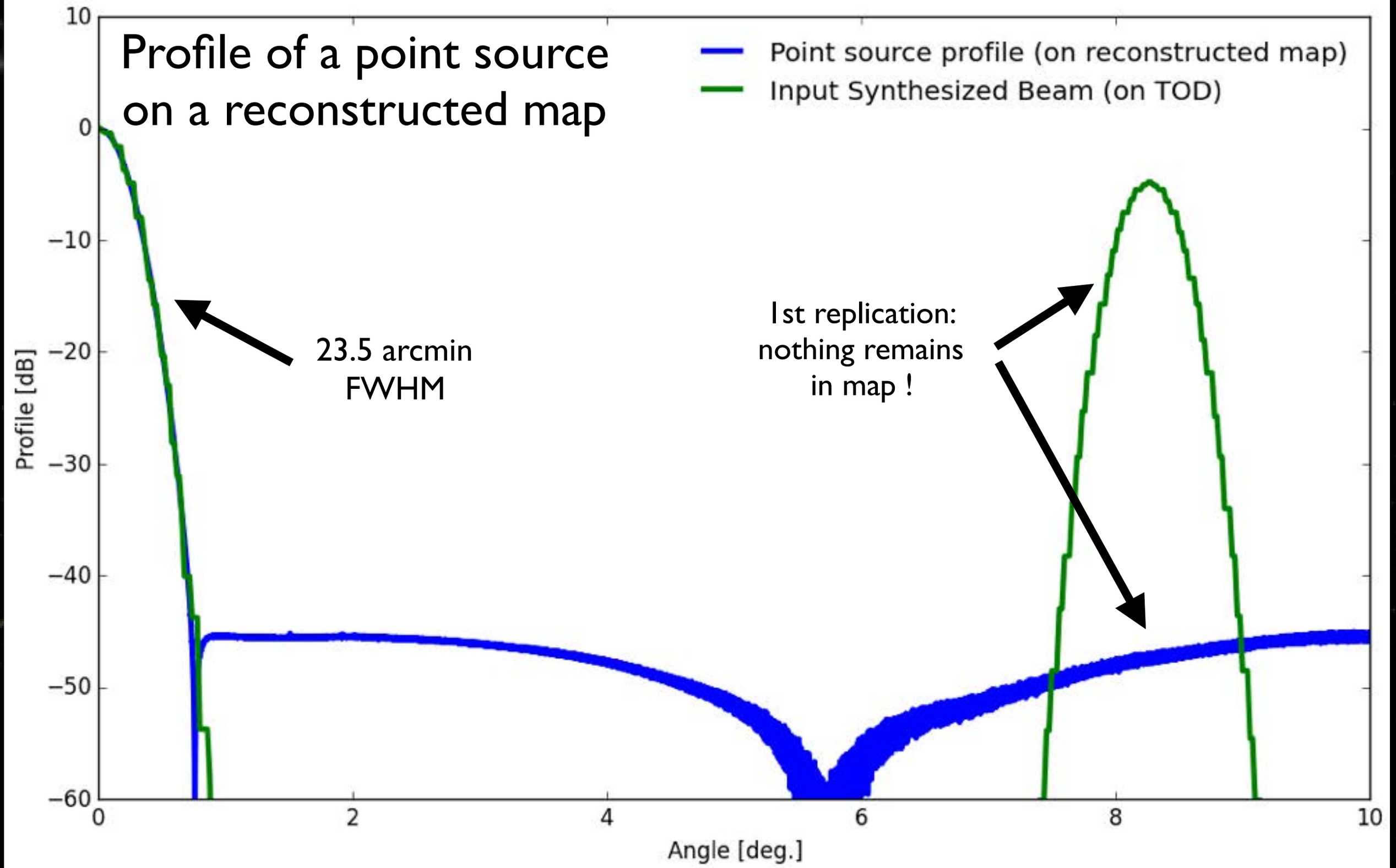
Full TOD-> Map simulation -> CI
(incorporates Planck I, Q, U maps)



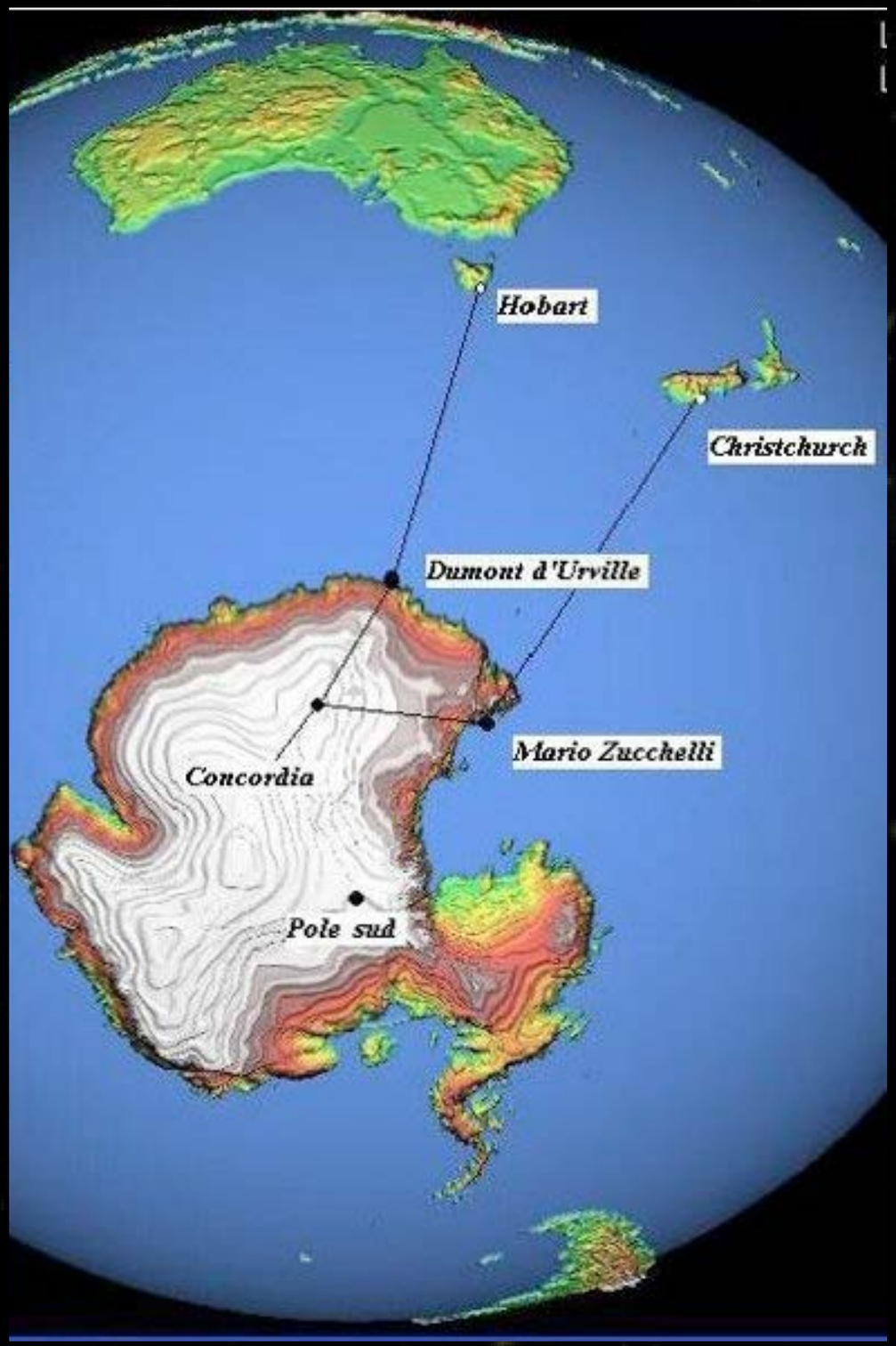




Profile of a point source on a reconstructed map



QUBIC Baseline Site: Dome C, Antarctica



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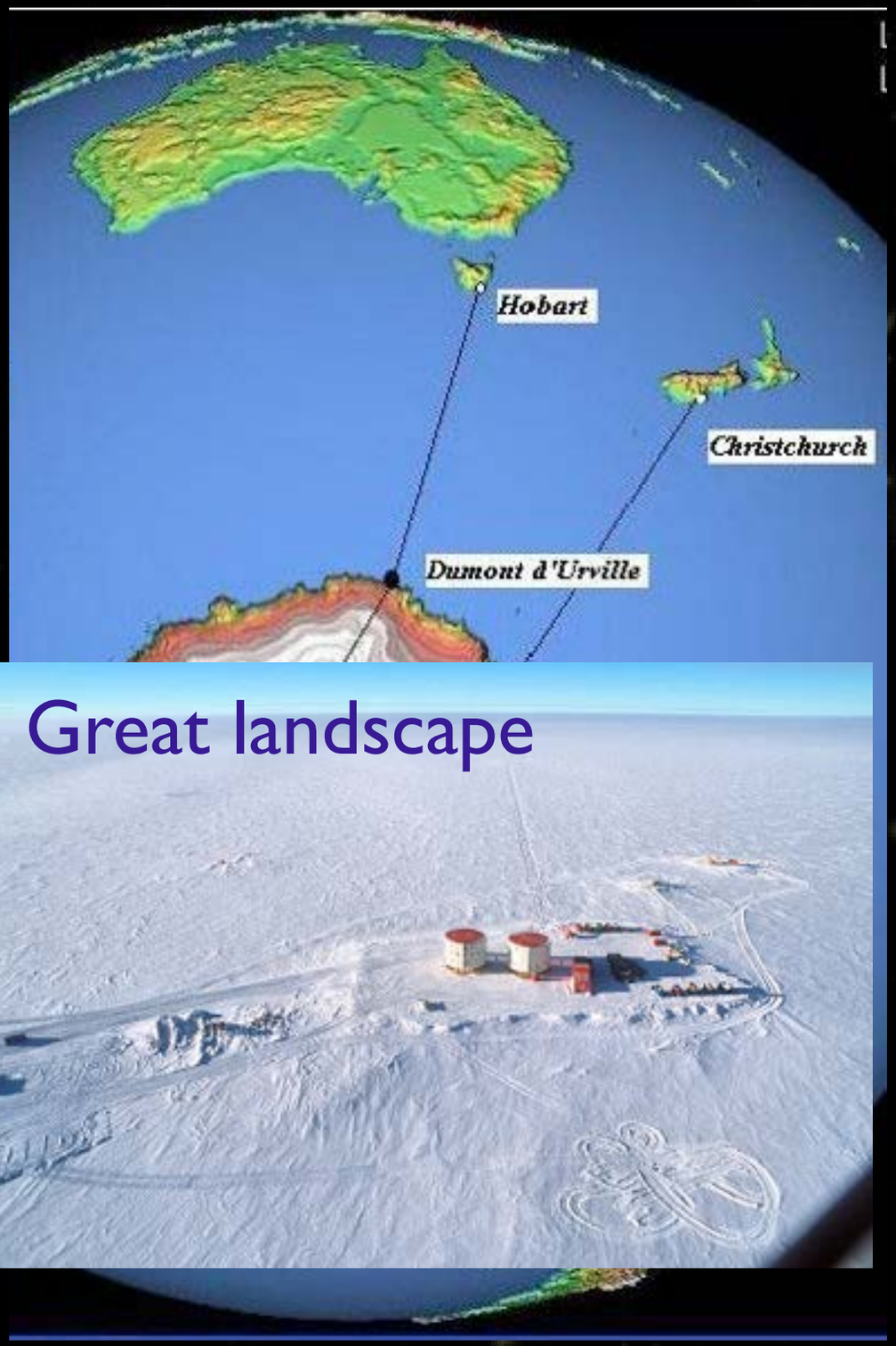

Great landscape

QUBIC Baseline Site: Dome C, Antarctica

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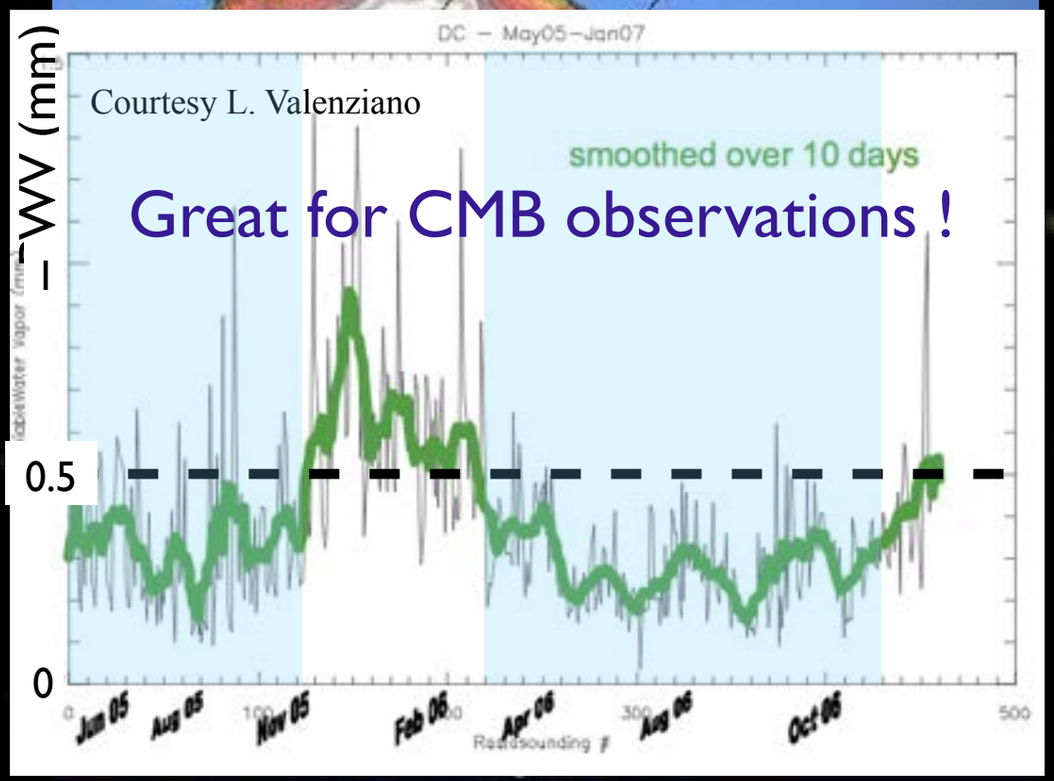

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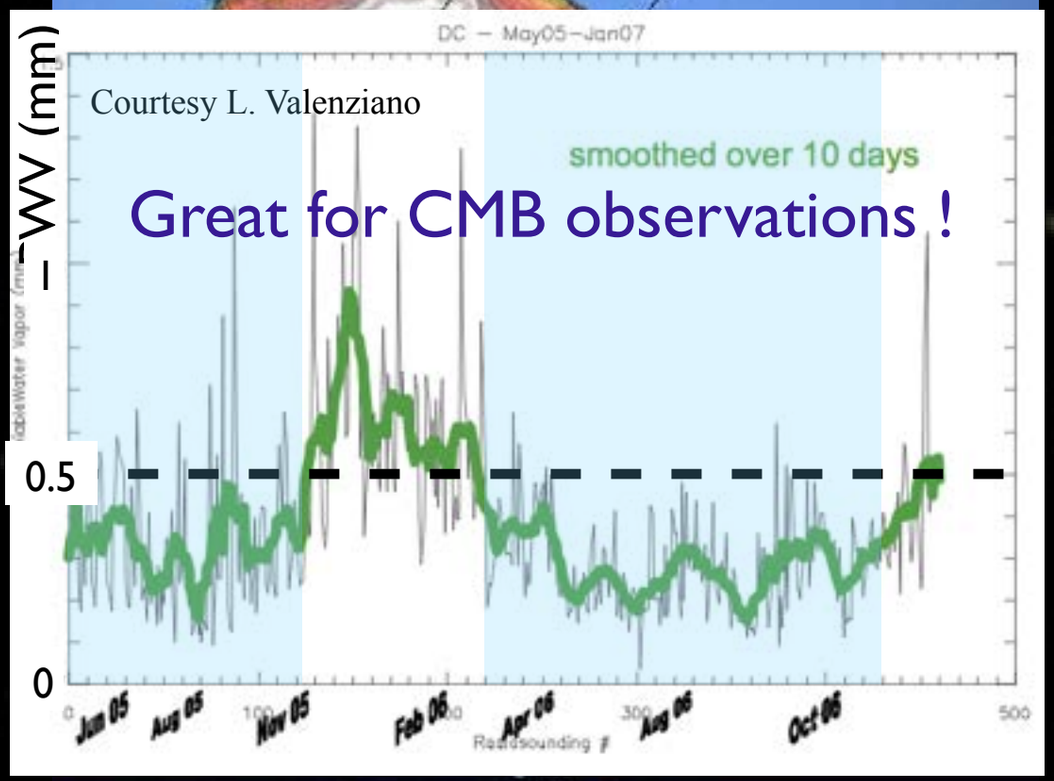

- Strengths
  - ★ Best site on Earth for CMB
  - ★ Synergy between France and Italy

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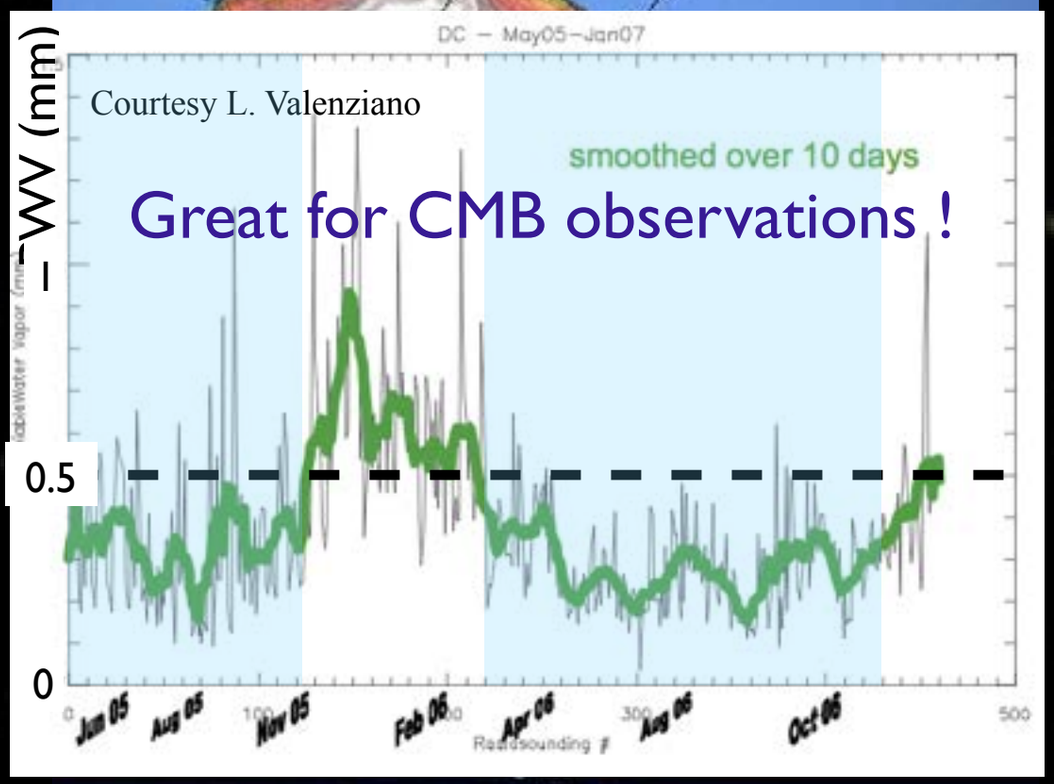
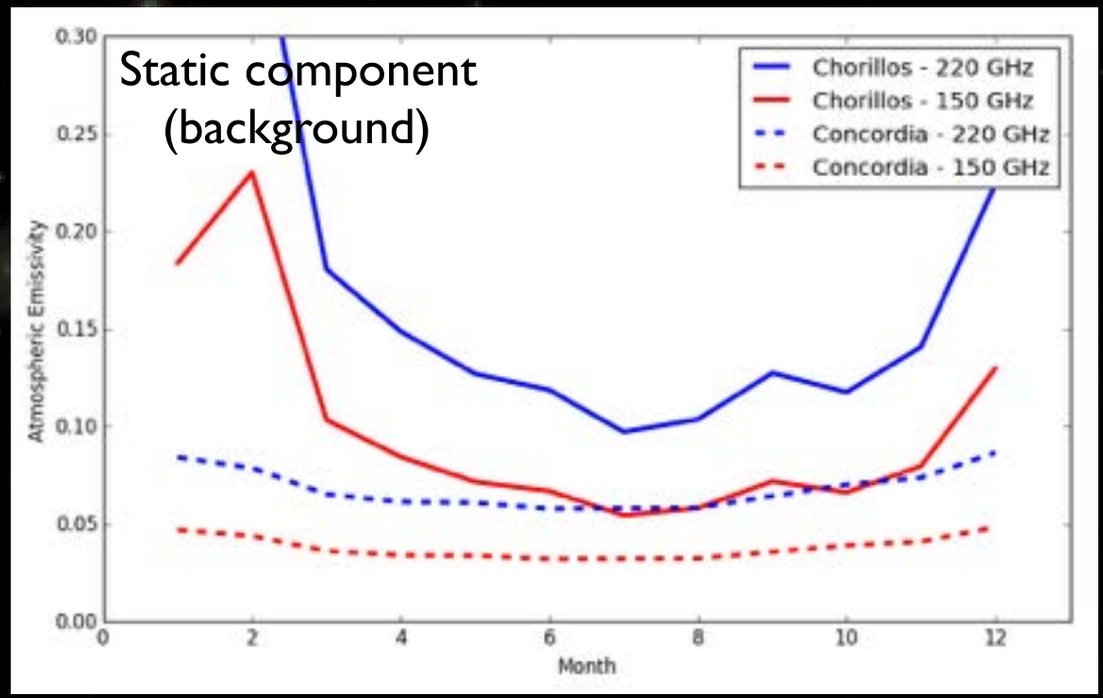


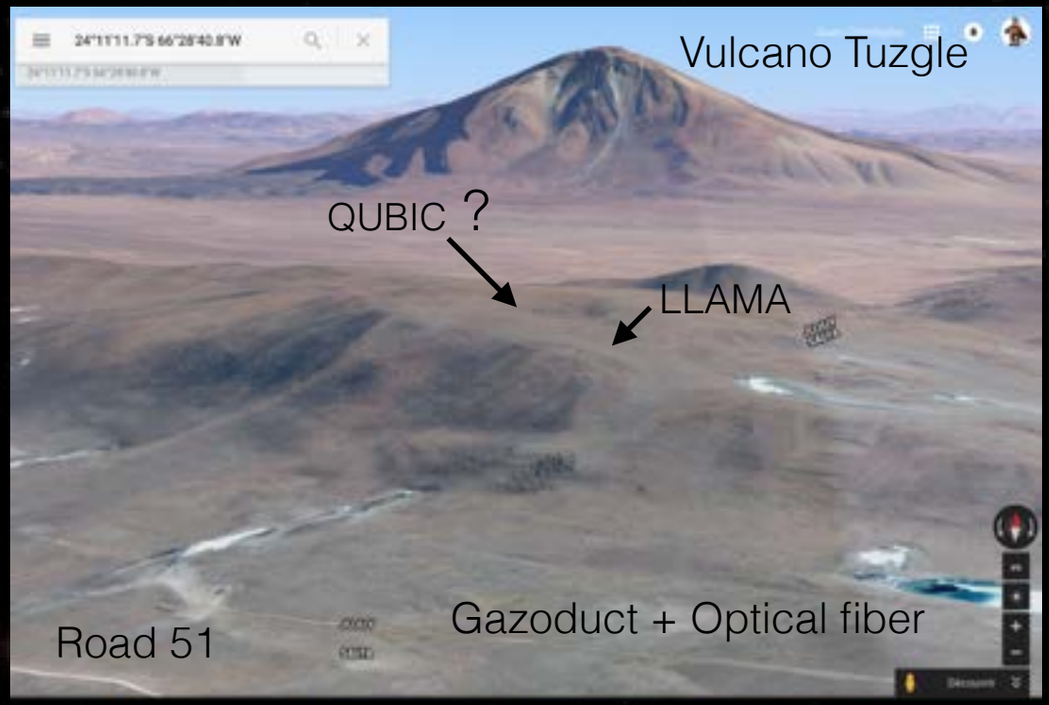
- Strengths
  - ★ Best site on Earth for CMB
  - ★ Synergy between France and Italy
- Weaknesses
  - ★ Complex logistics (add at least 1 year to schedule)
  - ★ Isolated site for 9 months / year :
    - Impossibility to repare instrument
    - Spatial-like preparation
  - ★ 1st large scale experiment deployment at Concordia

QUBIC Alternative site: Alto Chorillo, Argentina

- High quality site:
  - ★ Argentinian Puna: 5000m a.s.l.
  - ★ ~ 180km from Chajnantor (Atacama)
  - ★ factor 2-3 higher emissivity than Dome C ⇒ factor 1-3 on r sensitivity

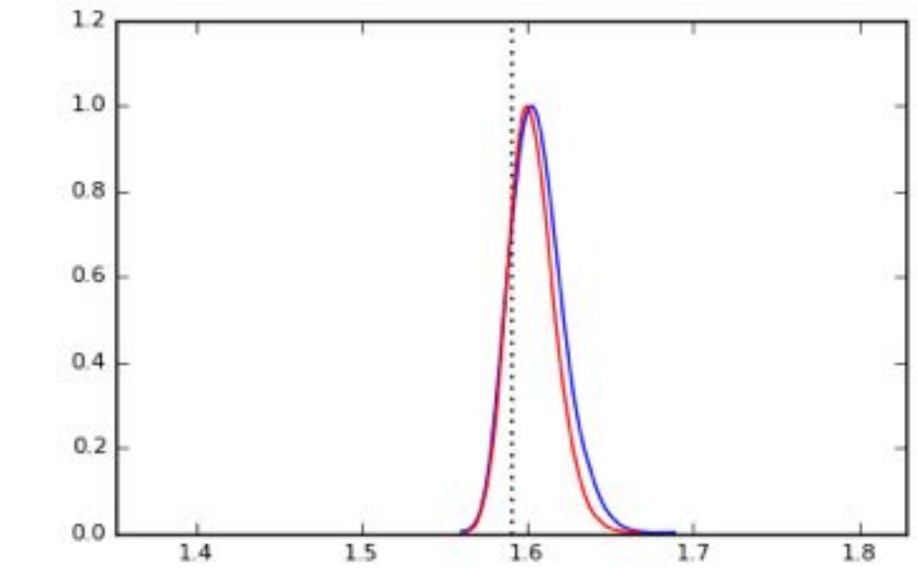


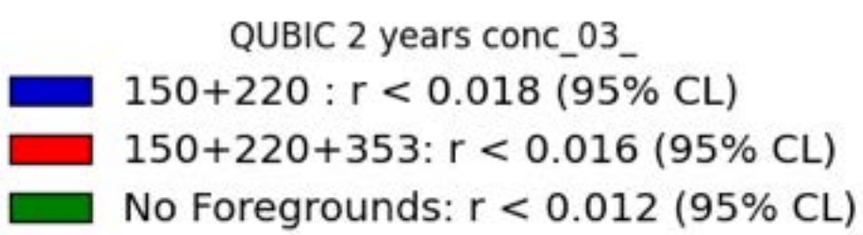
- Logistics based on that of LLAMA
  - ★ 40 min. drive from San Antonio de los Cobres
  - ★ 4h drive from Salta (airport, …)
  - ★ Large power + network available on site
  - ★ Logistics (roads, water, buildings on the mountain and downtown) being constructed
  - ★ No need to form winteroverers

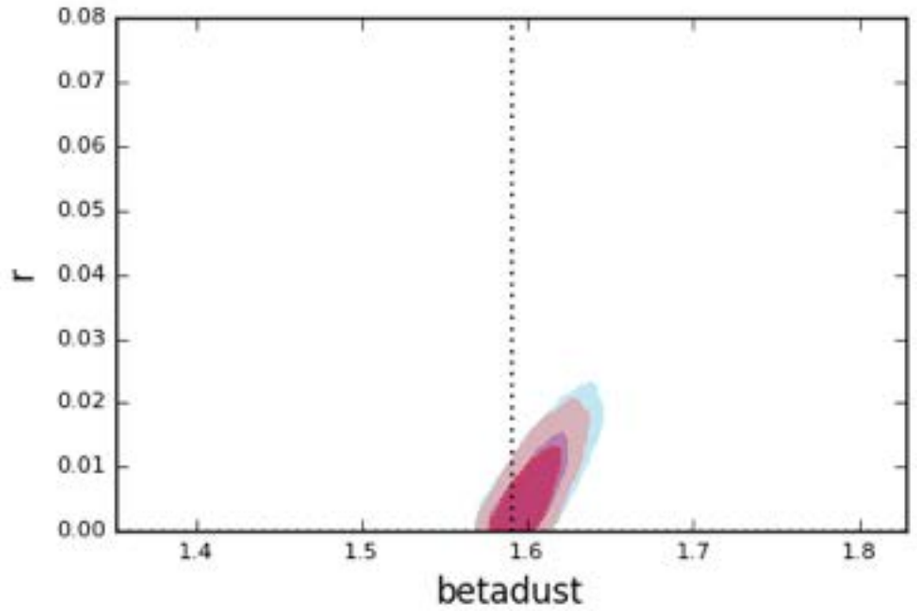


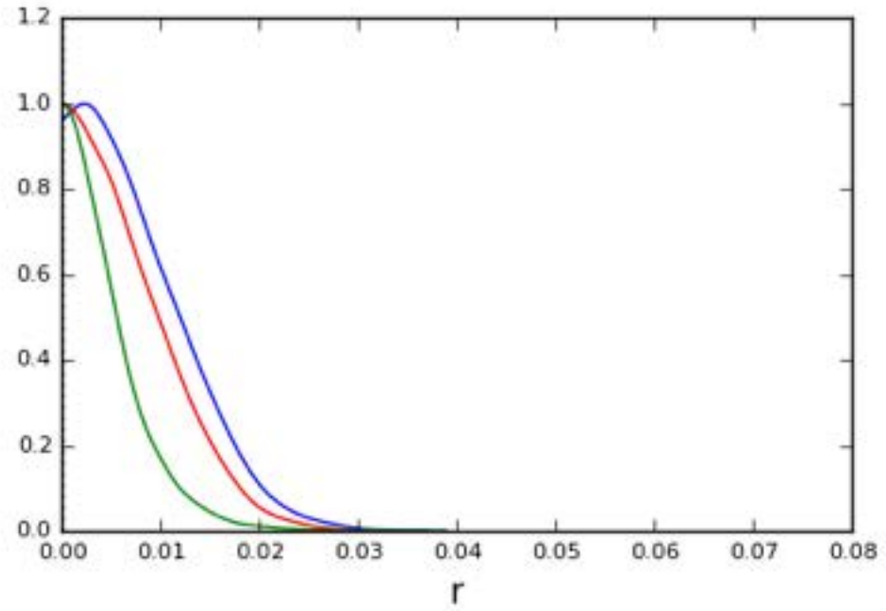
Sensitivity on r including Dust

- Likelihood using measured Planck 353 dust level in BICEP2 field





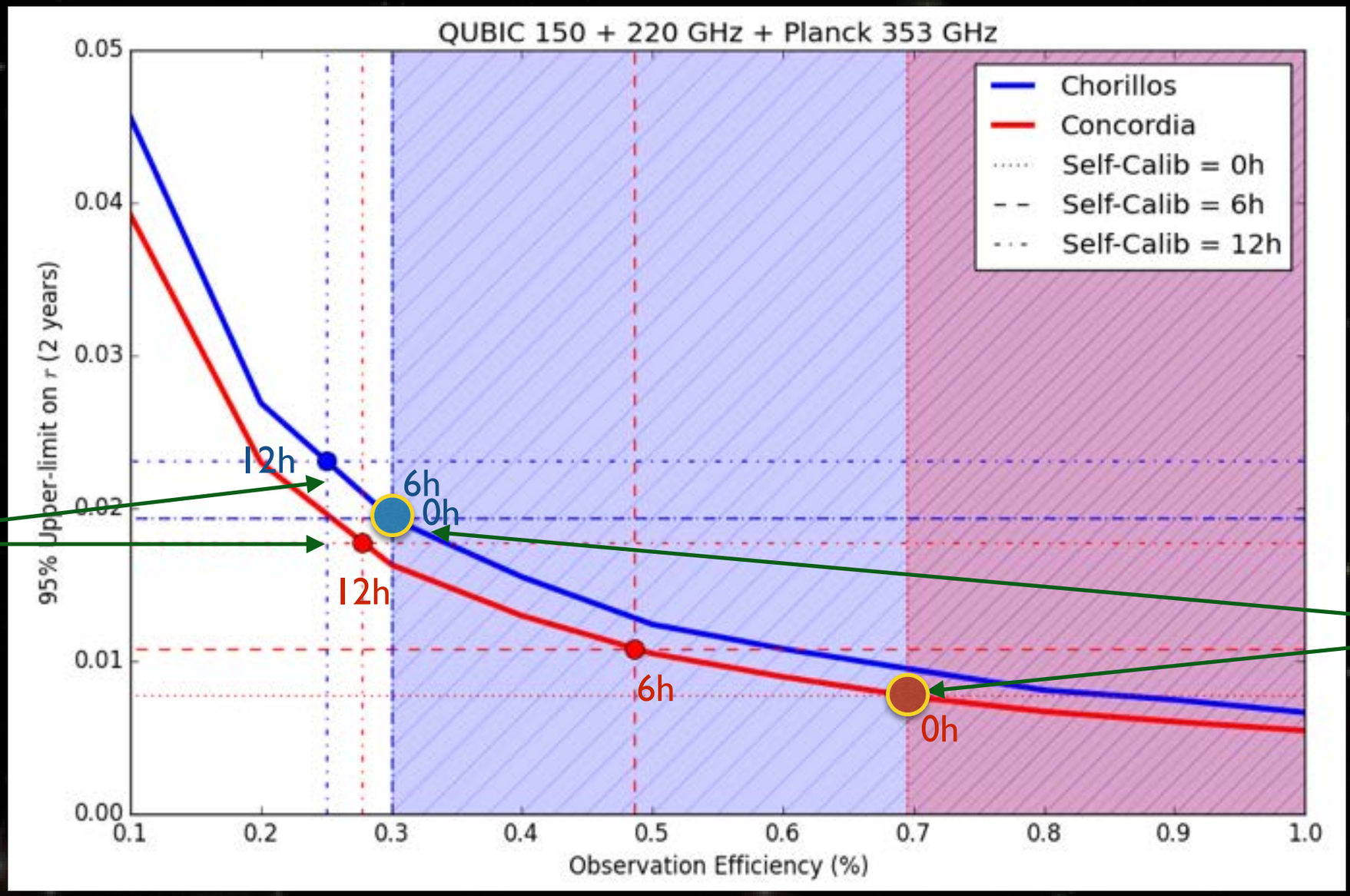




Comparing the sensitivity for both sites

Observation efficiency is different for both sites due to observability of field.
(4h fridge cycling + Summer months accounted for)

12h S.C.
Ratio ~ 1



No S.C.
Ratio ~ 2-3

Site selection will occur in the next few months

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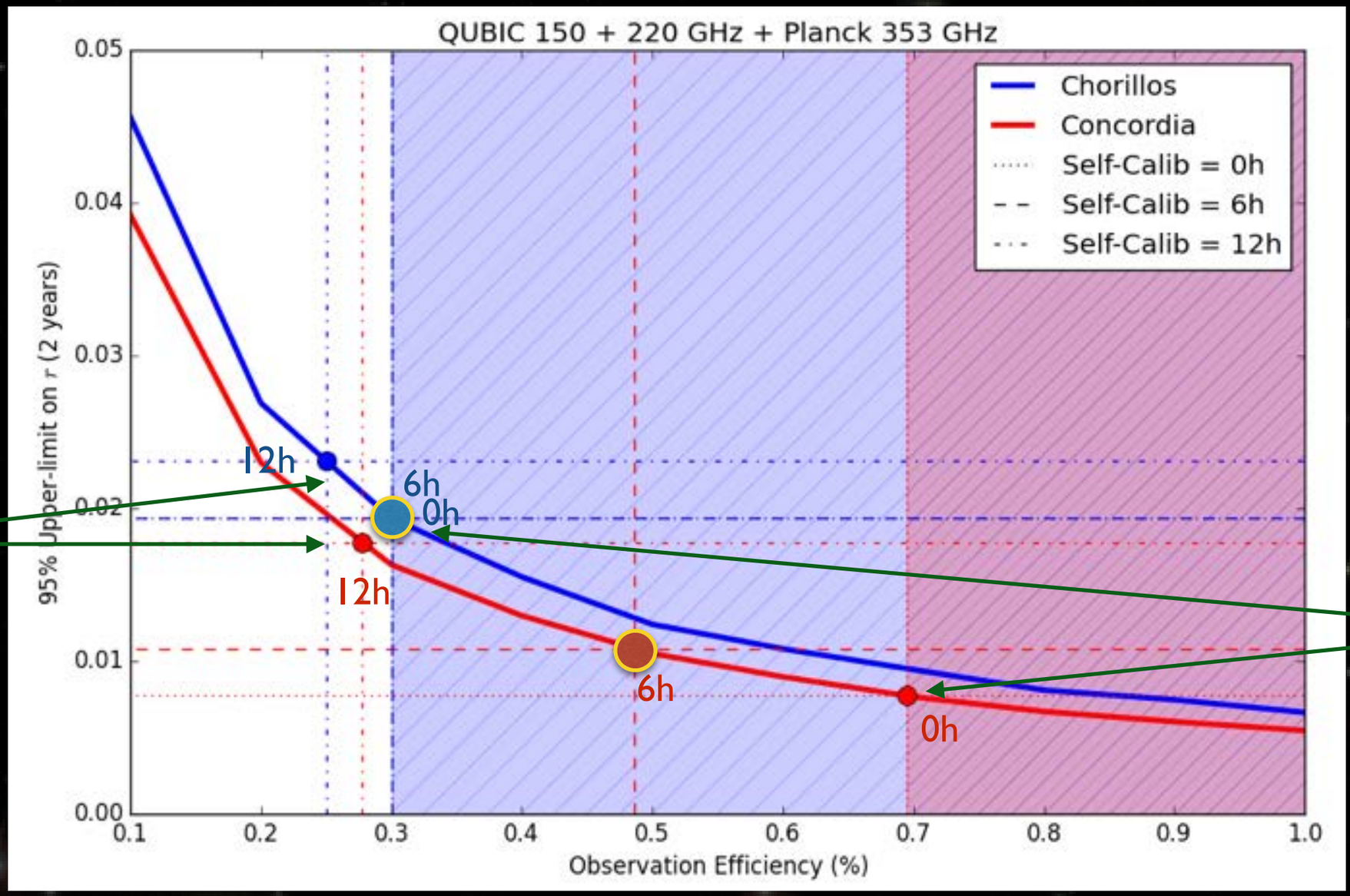

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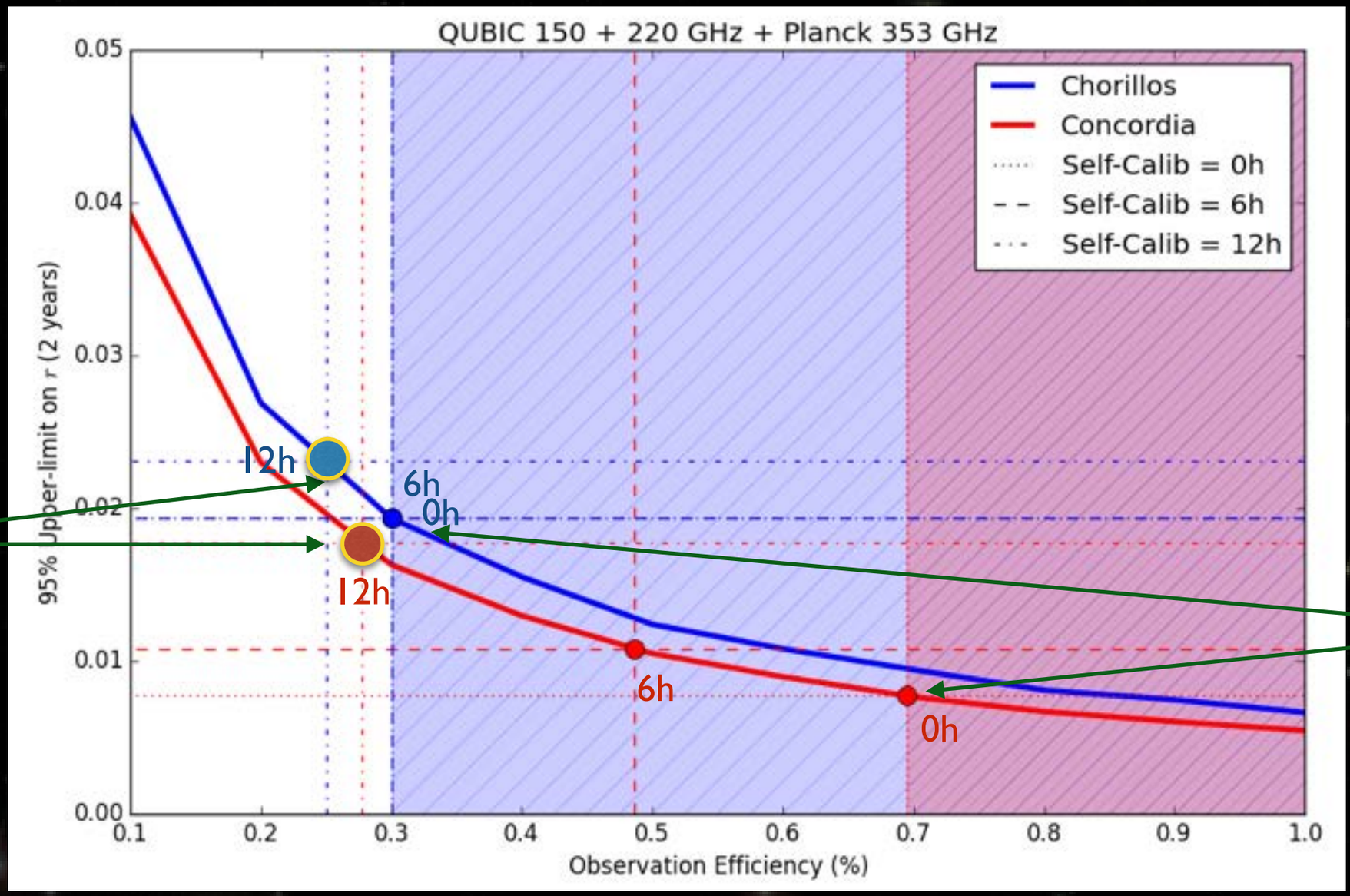

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QUBIC Plan: 3 steps

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- Focal Plane testing: 1st term 2016
  - ★ 256 TES in Lab Cryostat
  - ★ 128:1 Multiplexing

→ Validation of Detection Chain ✔

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- Technological demonstrator : End 2016
  - ★ Nominal cryostat
  - ★ 8x8 horns array
  - ★ reduced mirrors
  - ★ 256 TES / frequency
  - ★ Laboratory testing

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→ Validation of technology

- **QUBIC 1st Module: End 2017**
  - ★ 400 horns array
  - ★ nominal mirrors
  - ★ 1024 TES / frequency
  - ★ Laboratory testing
  - ★ Deployment on site and operations

→ B-mode search
r < 0.02 in 2 years

| 2016 | 2017 | 2018 | 2019

Focal Plane testing:
- 256 TES
- 128:1 Mux

Validation of Detection Chain

Technological demonstrator:
- Nominal cryostat
- reduced mirrors
- 8x8 horns
- 256 TES/Frequency

Validation of Technology

QUBIC 1st Module:
- Nominal mirrors
- 400 horns
- 1024 TES/Frequency

B-mode search
$r < 0.02$ in 2 years

Review + TDR

Review

Installation Commissioning

Operations

(**Argentina**, benefiting from LLAMA Infrastructure)

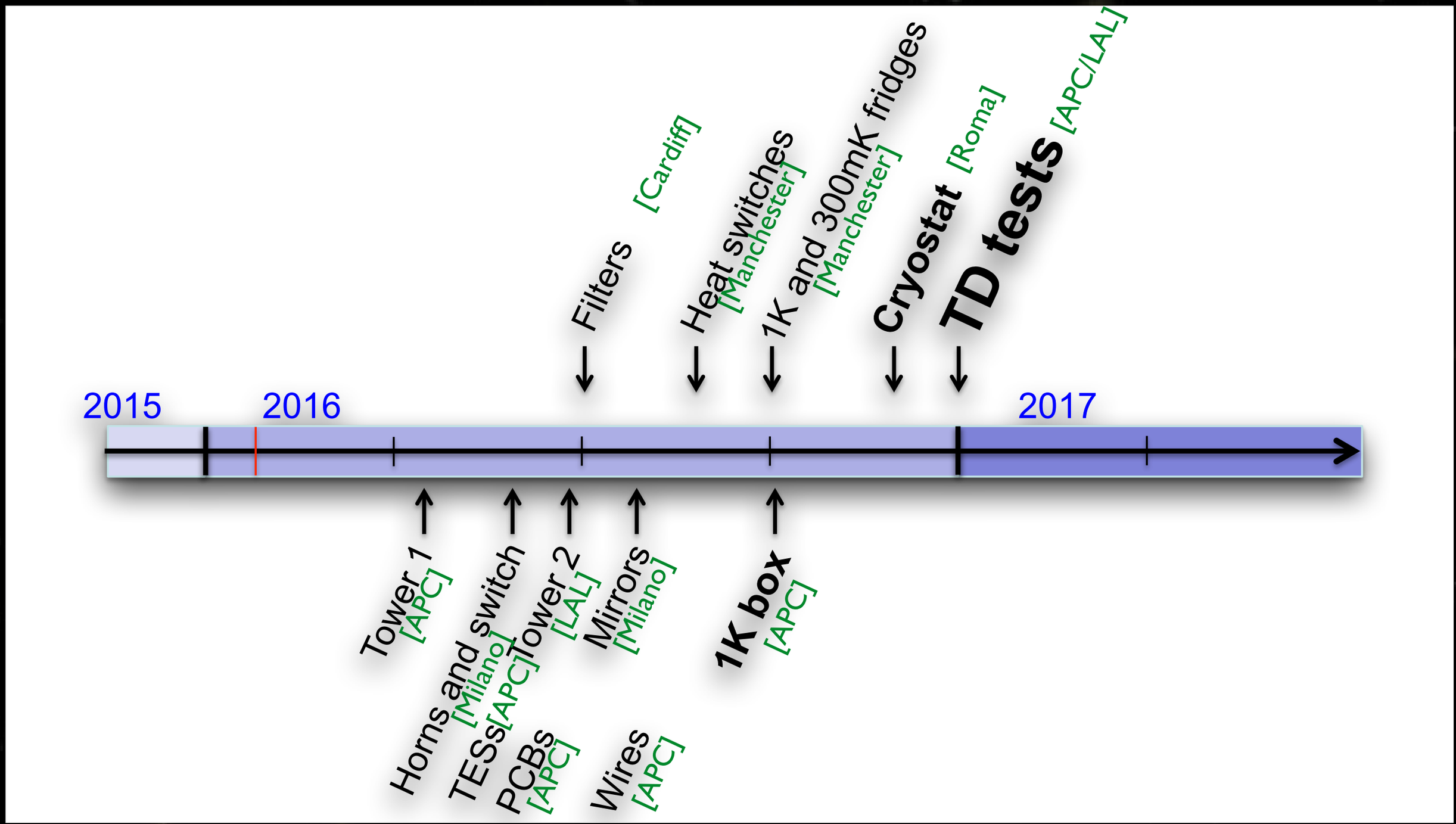
(**Antarctica**, Logistics by IPEV/PNRA)

Installation Commissioning

Operat

Two hypotheses for site

Timeline for Tech. Demonstrator



QUBIC in a worldwide perspective

Project	Lead	Location	Status	Frequencies	Ang. Res.	Science goals No foregrounds	Science goals With Foregrounds
QUBIC 1st module	France	Antarctica / Argentina ?	Late 2017	150, 220	Low	r = 0.01 (95%CL)	r=0.02 (95%CL)
BICEP/Keck	U.S.A	Antarctica	Running	95, 150, 220	Low	r = 0.01	-
ABS	U.S.A.	Chile	Running	150	Low	Technological	(HWP)
CLASS	U.S.A.	Chile	> 2016	40, 90, 150	Low	r = 0.02	-
SPTpol	U.S.A.	Antarctica	Running	95	High	Lensing (neutrinos) + r (but l > ~300)	
ACTpol	U.S.A.	Chile	Running	100, 150	High	Lensing (neutrinos) + r (but l > ~300)	
PolarBear	U.S.A.	Chile	Running	95, 150, 220	High	Lensing (neutrinos) + r (but l > ~300)	
LSPE	Italy	Arctic	> 2016	43, 90, 95, 145, 245	Low	r = 0.03	-
EBEX	U.S.A.	Antarctica	> 2017 ?	150, 250, 410	Med.	r = 0.01	+ lensing
PIPER	U.S.A.	Multiple	2016 (low channels)	200, 270, 350, 600	Med.	r = 0.01	+ lensing
SPIDER	U.S.A.	Antarctica	Early 2015	95, 150 (220 later)	Low	r = 0.01	-

2015 2020 2025

Stage III
r ~ 0.01

Many separate projects
Technological exploration
In Europe: strong interest to join Stage III
(INFN Italy, NIKHEF Netherlands)

Stage IV
r ~ 0.001

Many instruments in Synergy
Distributed over good sites
Advanced QUBIC
as a Stage IV Instrument ?

Space Mission ?
International Collaboration
ESA / NASA / JAXA ?

Summary (1/2)

- QUBIC is a novel instrumental concept
  - ★ Bolometric Interferometer optimized to handle systematics (self-calibration)
    - *Synthesized imager observing a selected range of spatial frequencies that can be accurately calibrated*
  - ★ Dedicated to CMB polarimetry and inflationary physics
  - ★ High sensitivity with ~2000 TES bolometers
  - ★ Dual Band (150 / 220 GHz): Dust contamination control
  - ★ <u>Target :</u>
    - First module (150 & 220 GHz): r < 0.02 at 95% C.L. (incl. dust)
    - Six modules (90, 150, 220 GHz) : r < 0.003 at 95% C.L. ?
    - A possible French/European contribution to CMB-S4 ?

Summary (2/2)

★ Baseline Location: Dome C, Antarctica

★ Exploring a site in Argentina as an alternative to Concordia

- *Argentina could provide Logistics + Mount with NIKHEF*
- *Strong political support from MINCYT, CONICET, French Embassy and Salta Province Governor (strong will to capitalize on clean sky).*

★ Budget is not fully secured (some parts of detection chain, mount)

- *Ongoing discussions with new partners (Netherlands, Argentina, INFN…)*

★ A lot of work to be done ! ***Both on Hardware and Data Analysis***

- *New collaborators welcome to join !*
- *Non exhaustive list of possible new / complementary contributions:*
  - *Data Analysis and Simulations*
  - *Mechanical design (Mount), Mechanical Fabrication (Mount, 1K box, mirrors)*
  - *Warm electronics (FPGA),*
  - *Microelectronics (TES Bonding & Integration, cryogenic wiring, …)*