Exploring the primordial Universe with QUBIC

the Q U Bolometric Interferometer for Cosmology

J.-Ch. Hamilton, APC, Paris, France
(CNRS, IN2P3, Université Paris-Diderot)
On behalf of the QUBIC Collaboration

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

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

Cardiff University, UK

Richmond University, USA

Brown University, USA

University of Wisconsin, USA

Argentinian Participation Group

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

QUBIC TDR on arXiv this week…

J. Aumont[7], S. Banfi[13], P. Battaglia[14], E.S. Battistelli[17], A. Baù[13], B. Bélier[8], D.Bennett[15], L. Bergé[5], J.Ph. Bernard[9], M. Bersanelli[14], M.A. Bigot-Sazy[1], N. Bleurvacq[1], G. Bordier[1], J. Brossard[1], E.F. Bunn[16], D. Buzi[17], D. Cammilleri[1], F. Cavaliere[14], P. Chanial[1], C. Chapron[1], G. Coppi[12], A. Coppolecchia[17], F. Couchot[11], G. D'Alessandro[17], P. De Bernardis[17], M. de Petris[17], T. Decourcelle[1], F. Del Torto[14], L. Dumoulin[5], C. Franceschet[13], A. Etchegoyen[10], B. Garcia[10], A. Gault[18], D. Gayer[15], M. Gervasi[13], A. Ghribi[1], M. Giard[9], Y. Giraud-Héraud[1], M. Gradziel[15], L. Grandsire[1], J.Ch. Hamilton[1], D. Harari[19], V. Haynes[12], S. Henrot-Versillé[11], N. Holtzer[5], J. Kaplan[1], A. Korotkov[2], J. Lande[5], S. Loucatos[1], A. Lowitz[18], B. Maffei[7], S. Marnieros[5], J. Martino[7], S. Masi[17], C. Medina[6], M. McCulloch[12], A. May[12], S. Melhuish[12], A. Mennella[14], L. Montier[9], A. Murphy[15], D.Néel[5], M.W. Ng[12], C. O'Sullivan[15], F.Pajot[9], A. Passerini[13], C. Perbost[1], O. Perdereau[11], F. Piacentini[17], M. Piat[1], L. Piccirillo[12], G. Pisano[4], D. Prêle[1], R. Puddu[17], D. Rambaud[9], O. Rigaut[5], G. Romero[6], M. Salatino[17], A. Schillaci[17], S. Scully[15], M. Stolpovskiy[1], A. Tartari[1], P. Timbie[18], M. Tristram[11], G. Tucker[2], D. Viganò[14], F. Voisin[1], B. Watson[12] and M. Zannoni[13]

91 Collaborators
18 Institutes
6 countries

QUBIC
QU Bolometric Interferometer for Cosmology

Towards the European Coordination of the CMB programme
Villa Finaly, Firenze, 08/09/2016

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QUBIC concept: Quasi optical correlator

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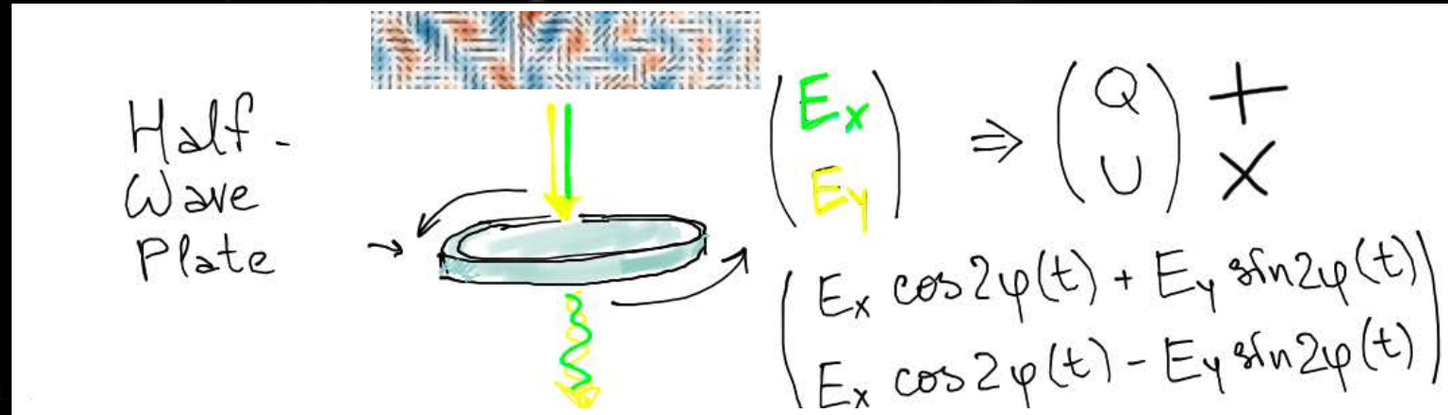
QUBIC concept: Quasi optical correlator



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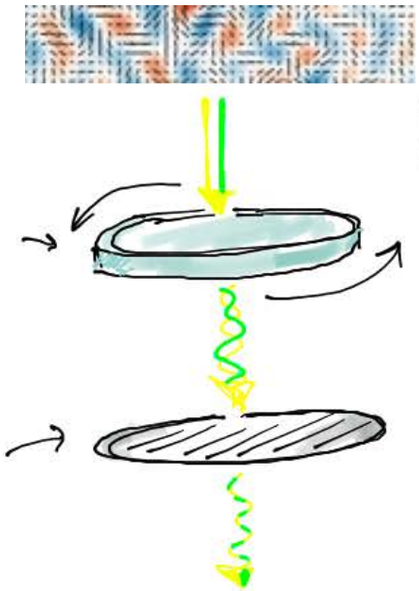

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} \Rightarrow \begin{matrix} Q \\ U \end{matrix} \begin{matrix} + \\ \times \end{matrix}$$

$$\begin{pmatrix} E_x \cos 2\varphi(t) + E_y \sin 2\varphi(t) \\ E_x \cos 2\varphi(t) - E_y \sin 2\varphi(t) \end{pmatrix}$$

$$\begin{pmatrix} E_x \cos 2\varphi(t) + E_y \sin 2\varphi(t) \\ 0 \end{pmatrix}$$

$$\Downarrow$$

$$S = I + Q \cos 4\varphi(t) + U \sin 4\varphi(t)$$

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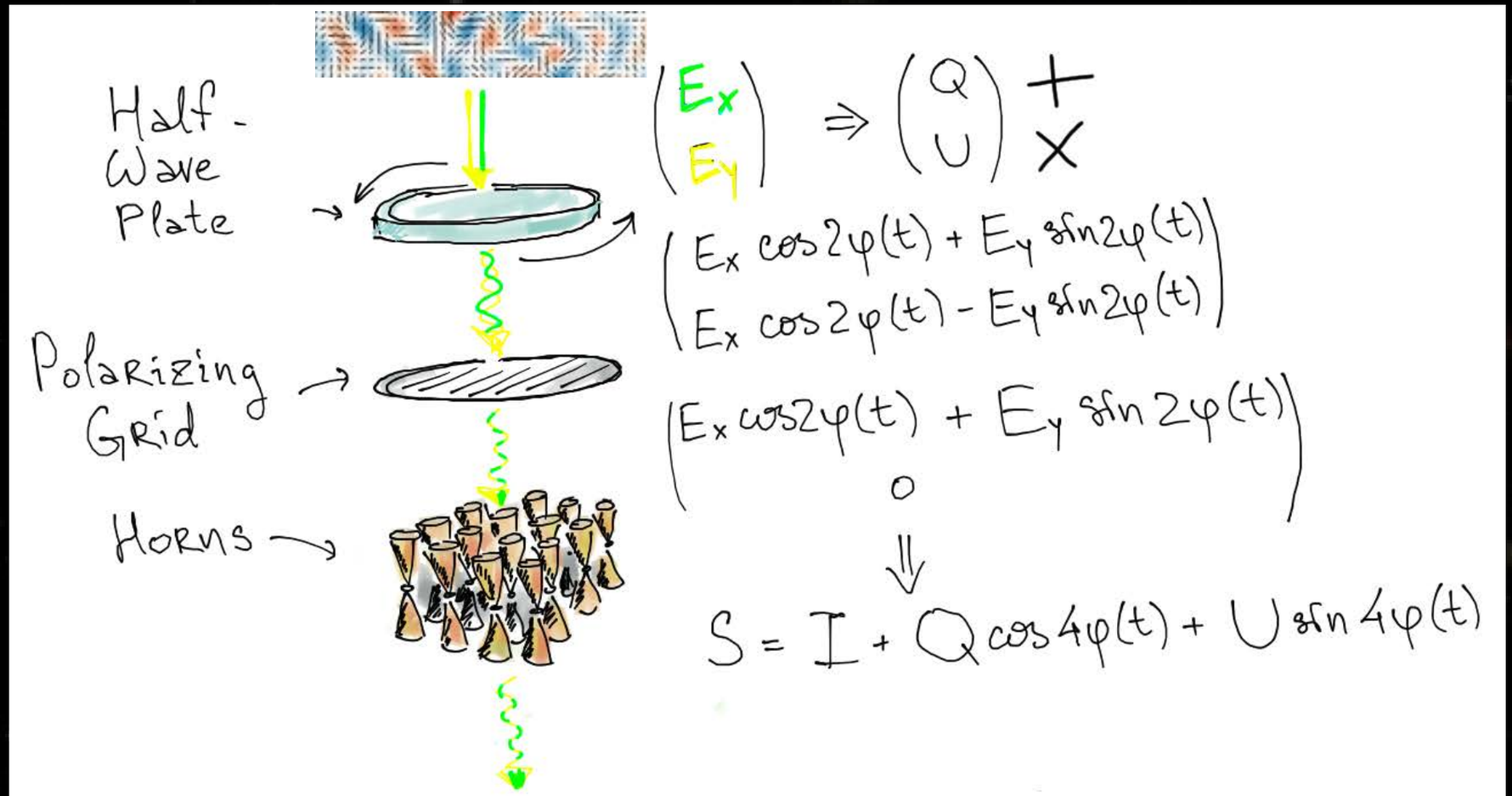

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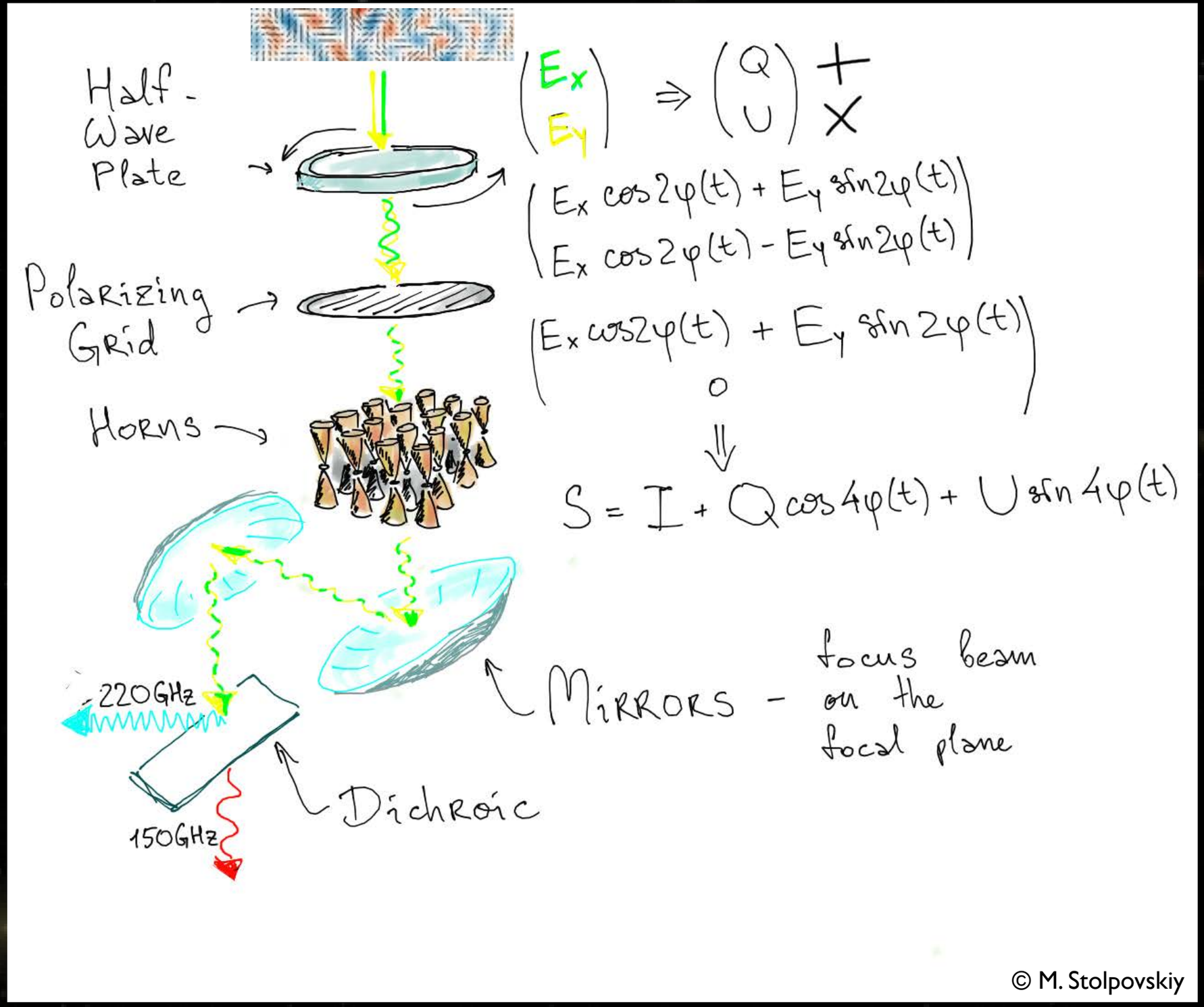

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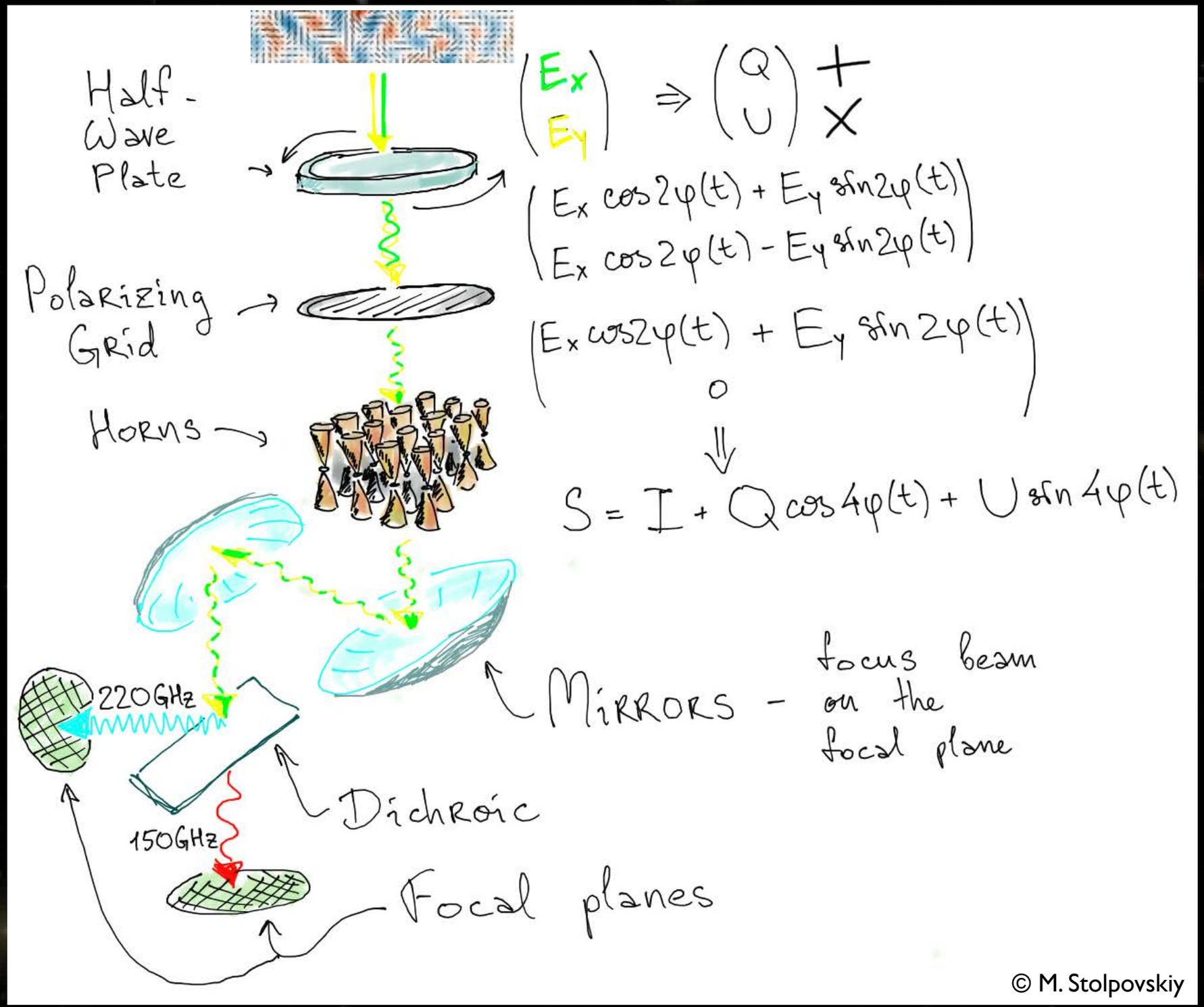

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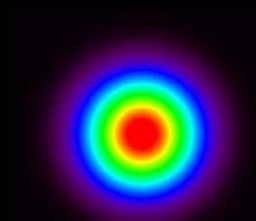
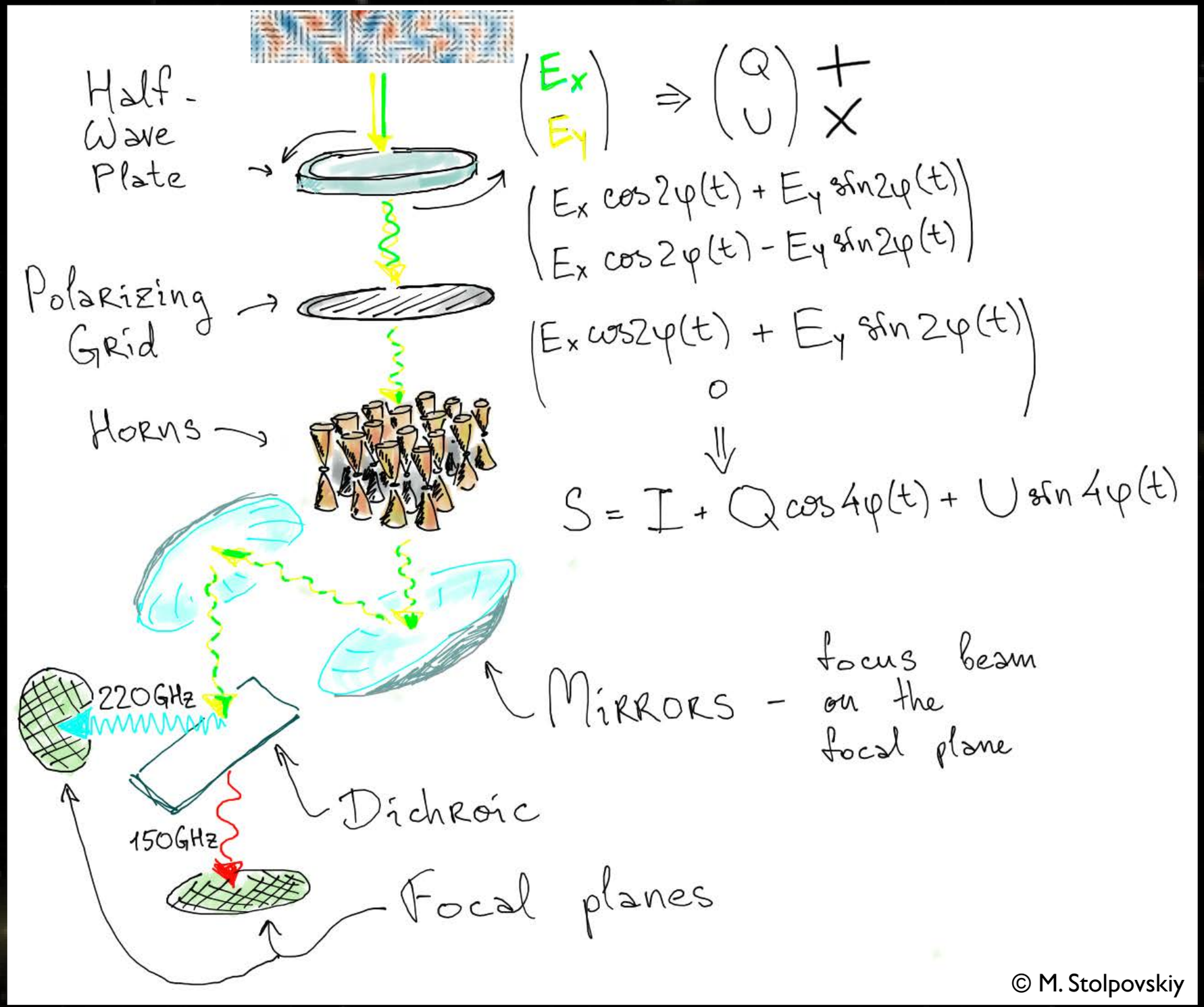


1 horn open



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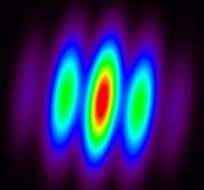
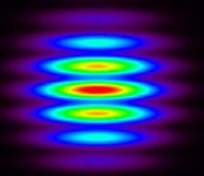
QUBIC concept: Quasi optical correlator

1 horn open

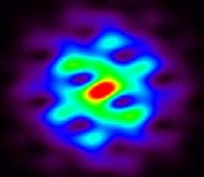
1 baseline



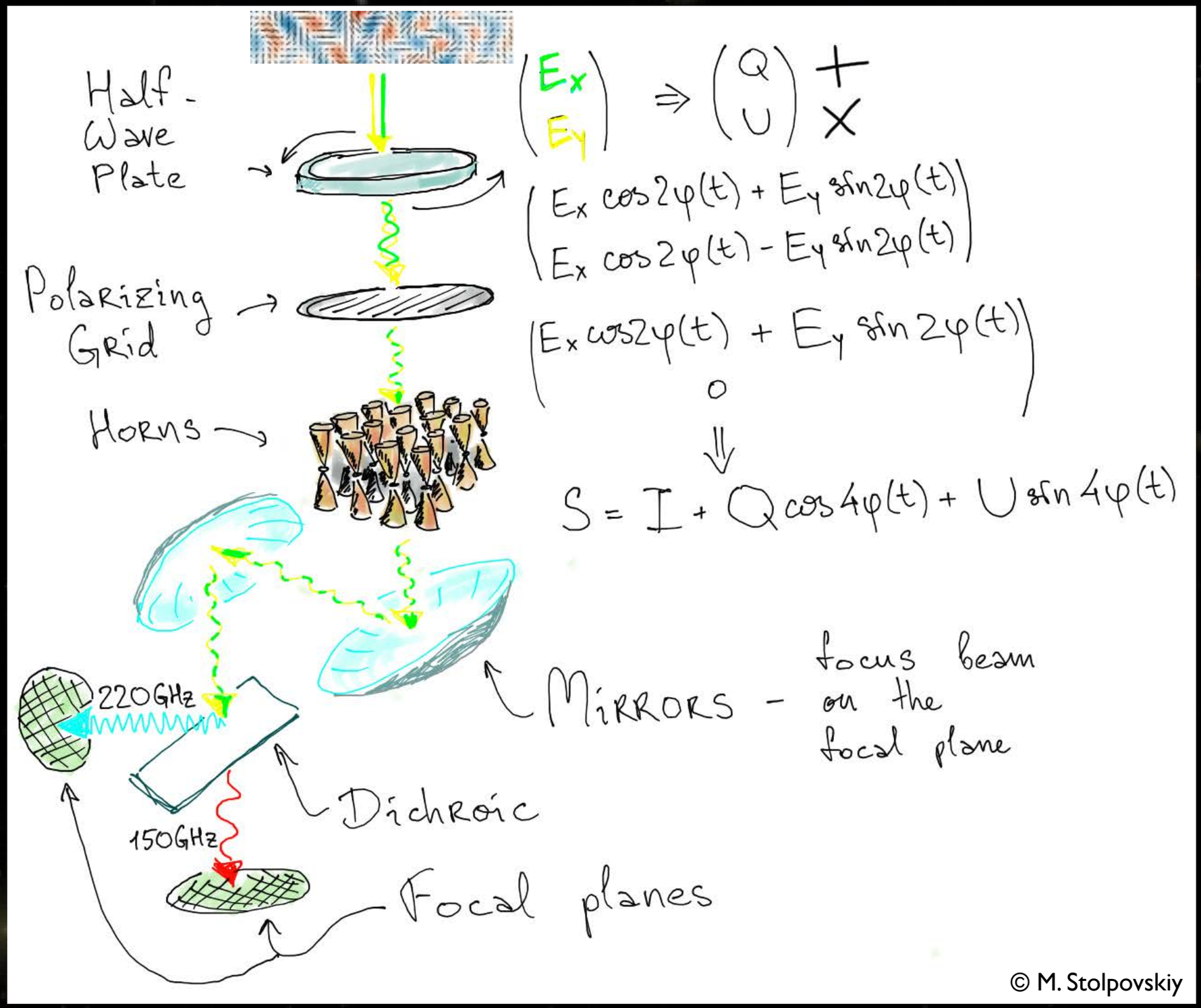
1 baseline



1 baseline



total signal
(all baselines)



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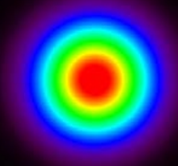
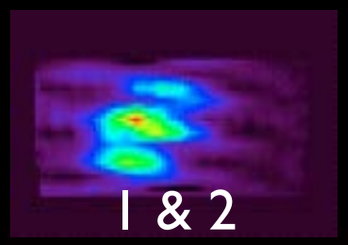
QUBIC concept: Quasi optical correlator

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

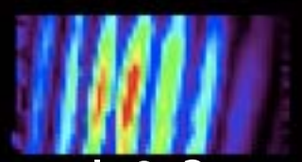


1 horn open

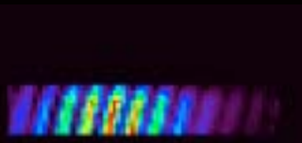
MBI-4 data
2009 campaign
(PBO- Wisc.)



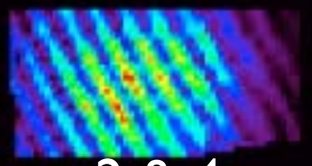
1 & 2



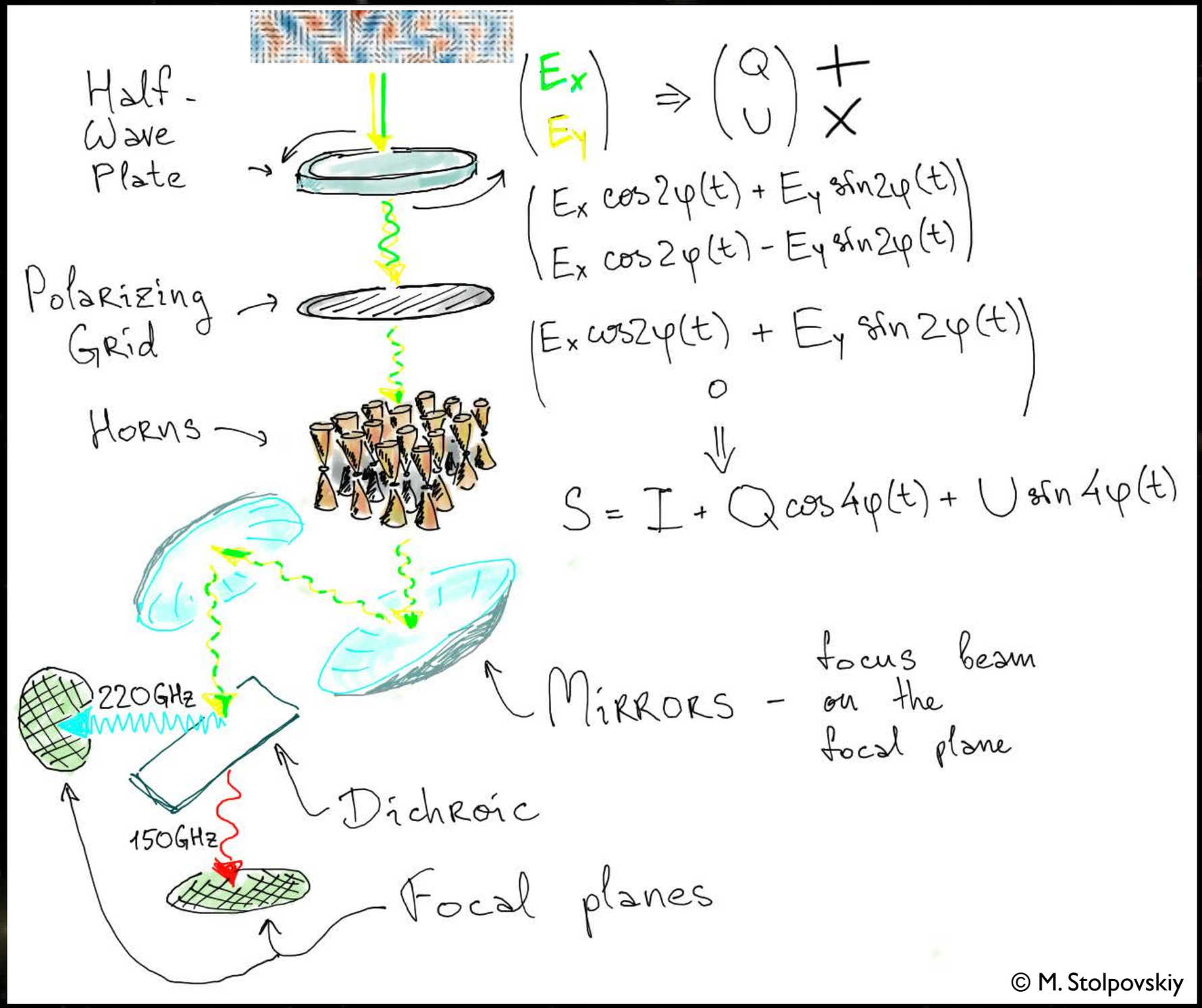
1 & 3



2 & 3



2 & 4



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

→ Unprecedented control of systematics with Self-Calibration

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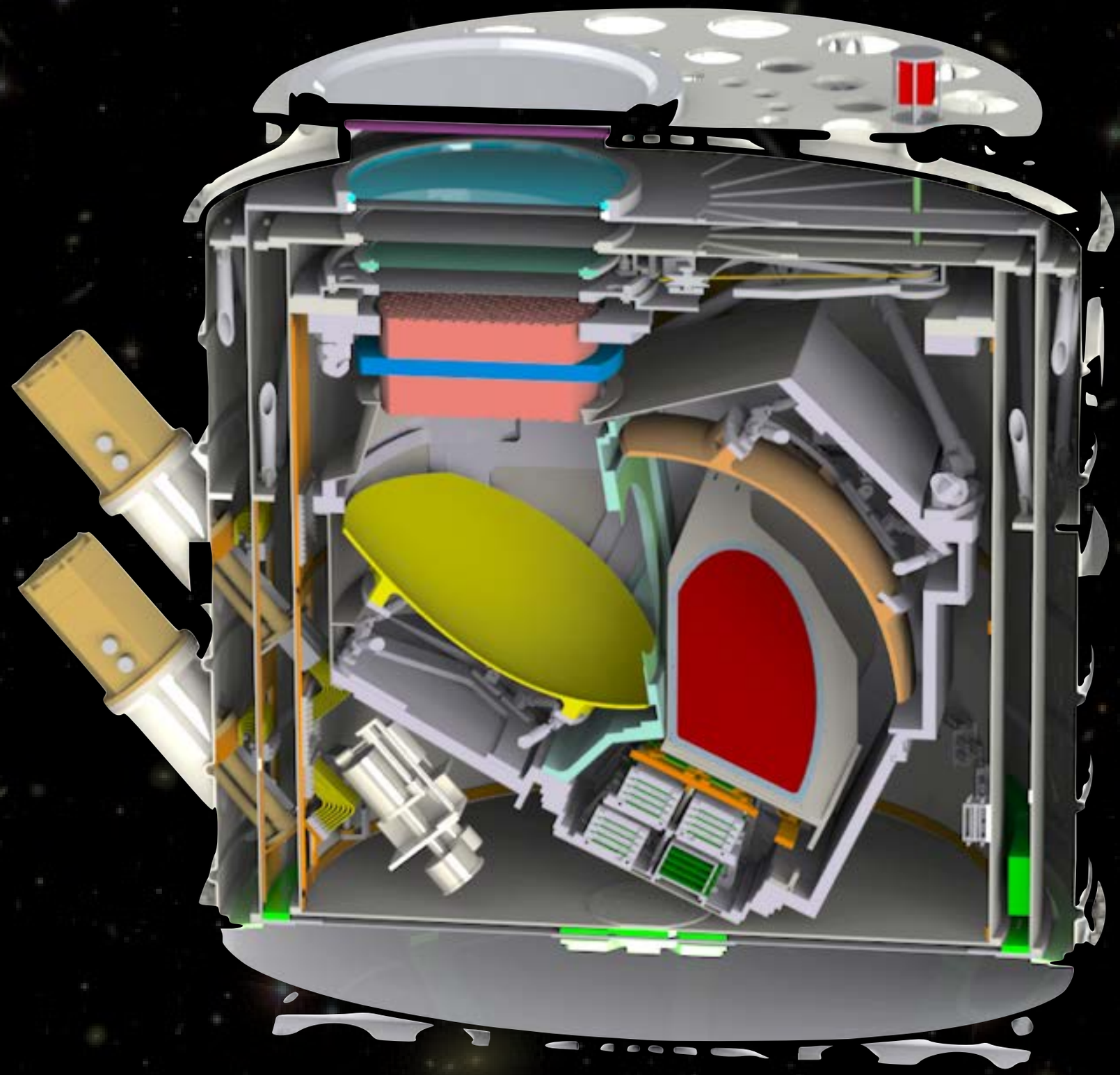

Instrument fully designed

- Outer cryostat: Roma
- HWP: Manchester / Roma
- 1K Box / detectors: APC
- Fridges: Manchester
- Optics: Roma / Maynooth / Milano
- Mount: Argentina

1.547m high
1.42m diameter
About 800kg

Parts being constructed

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QUBIC site: Alto Chorillo, Argentina

- High quality site:
  - ★ Argentinian Puna: 5000m a.s.l.
  - ★ ~ 180km from Chajnantor (Atacama)

- Logistics in synergy with 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) fully funded (MINCYT + Province of Salta) and being constructed now

- Argentinian Collaboration
  - ★ MINCYT : 500k$ (US) available
  - ★ + CONICET / CNEA / Province of Salta signing agreements

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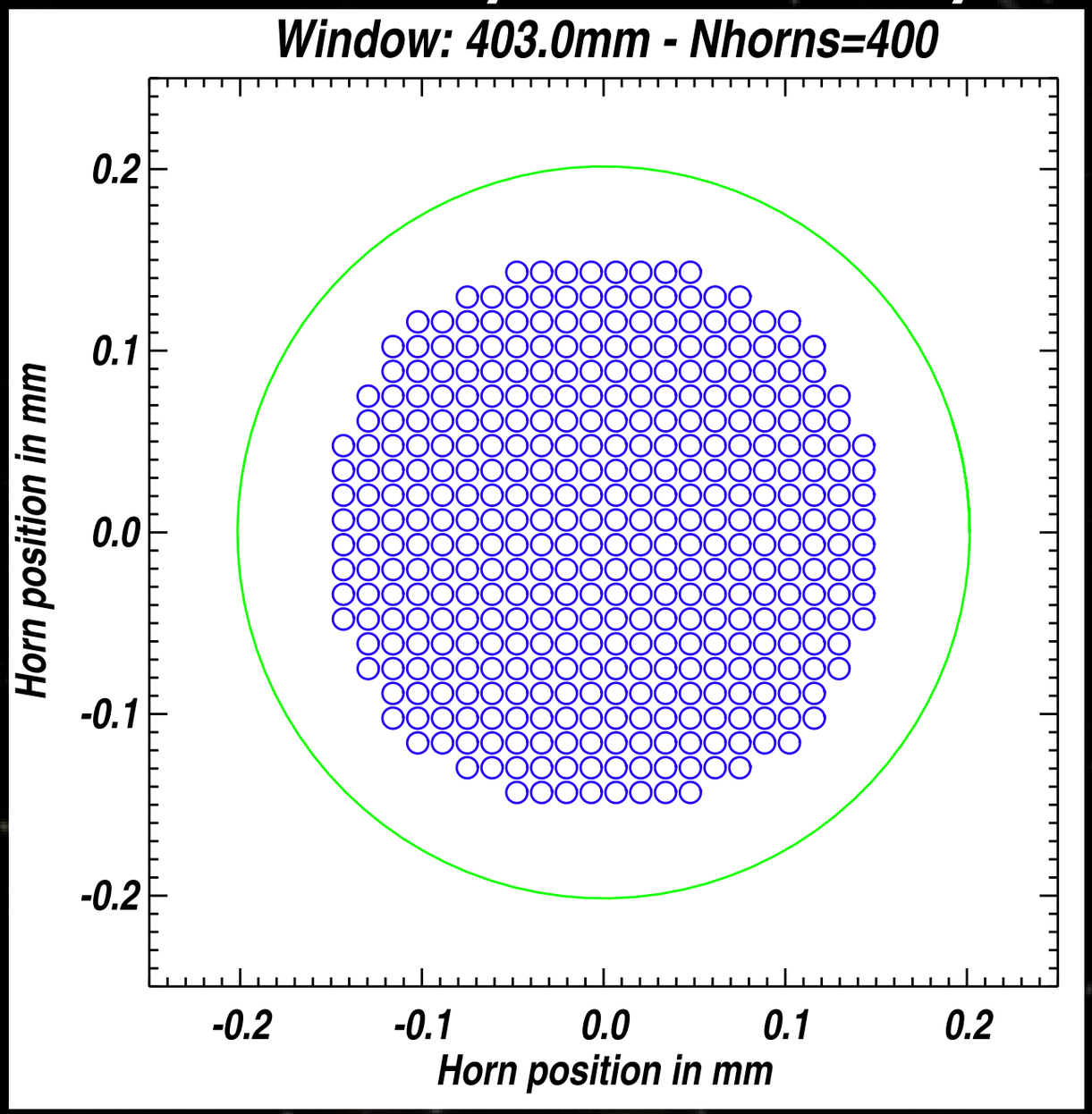
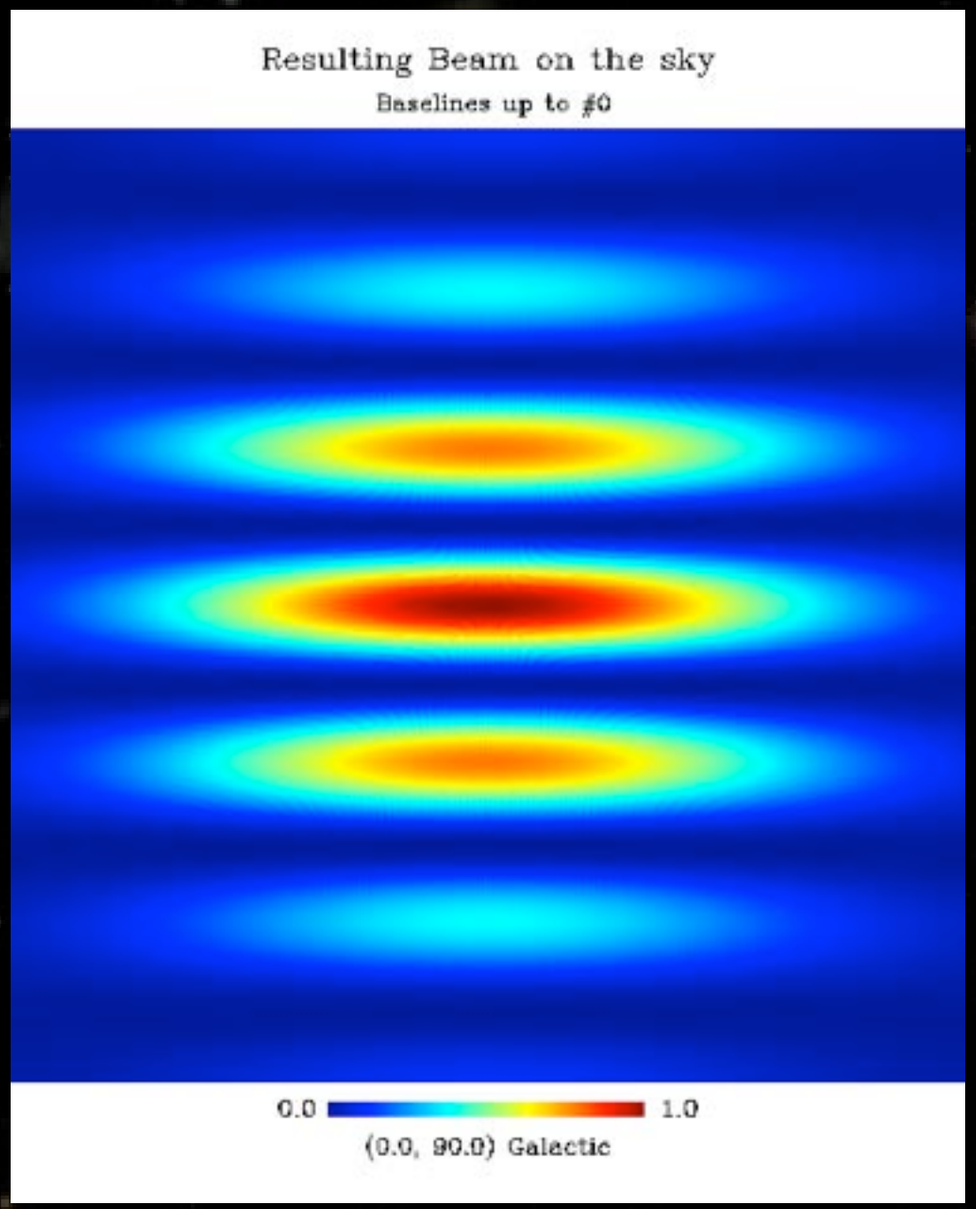
B.I. = Synthesized imager

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

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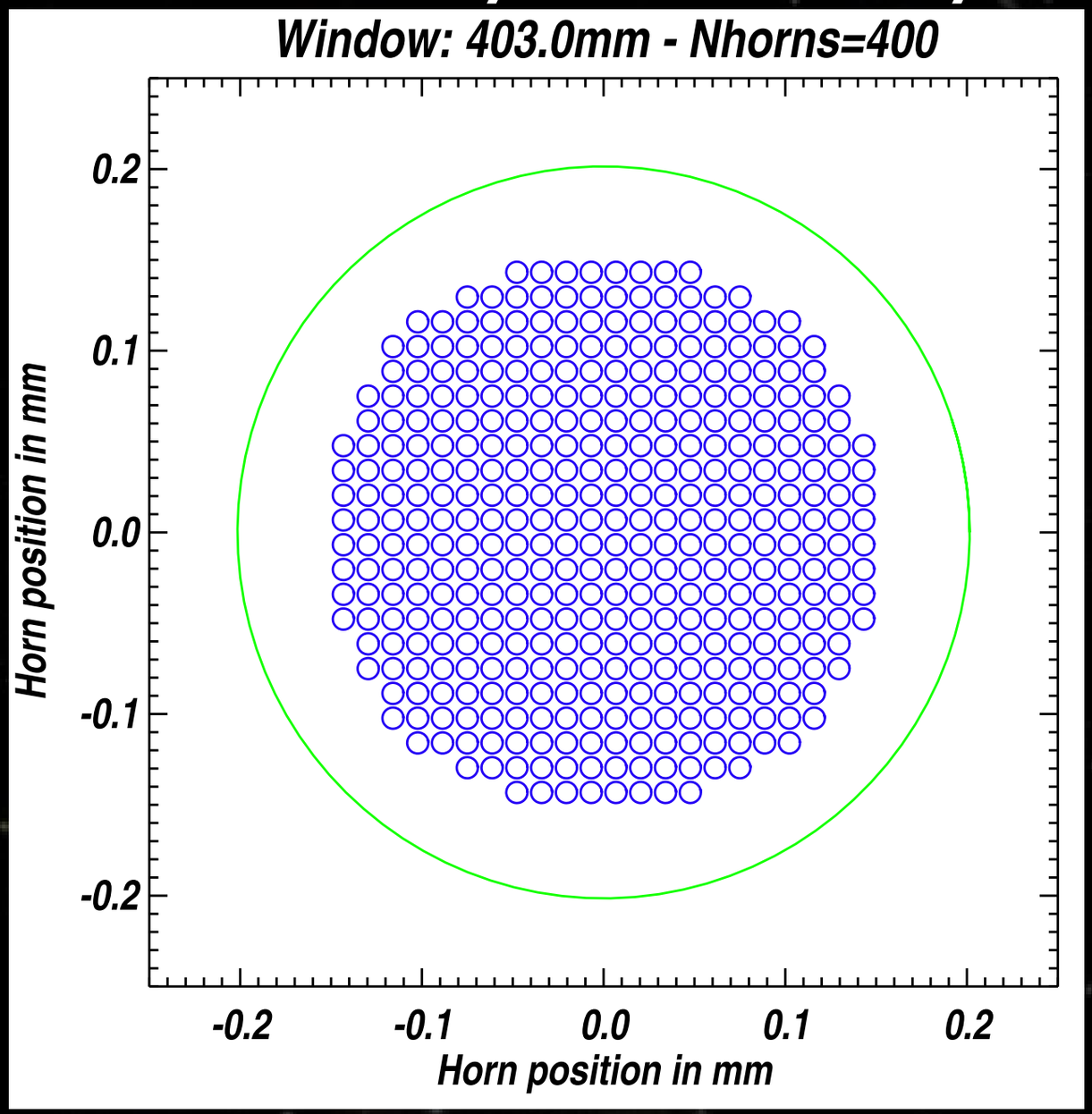
B.I. = Synthesized imager

Primary horns array



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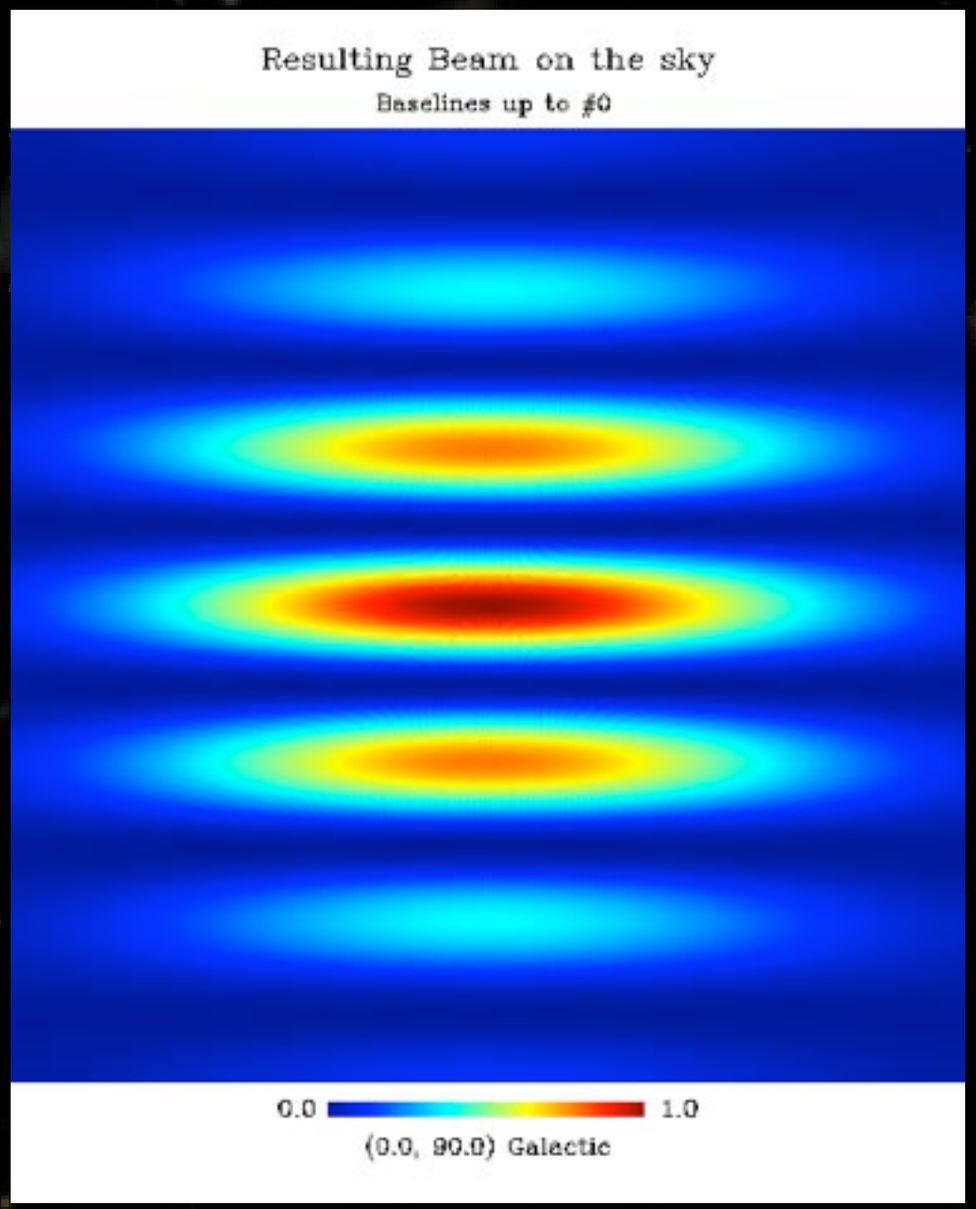

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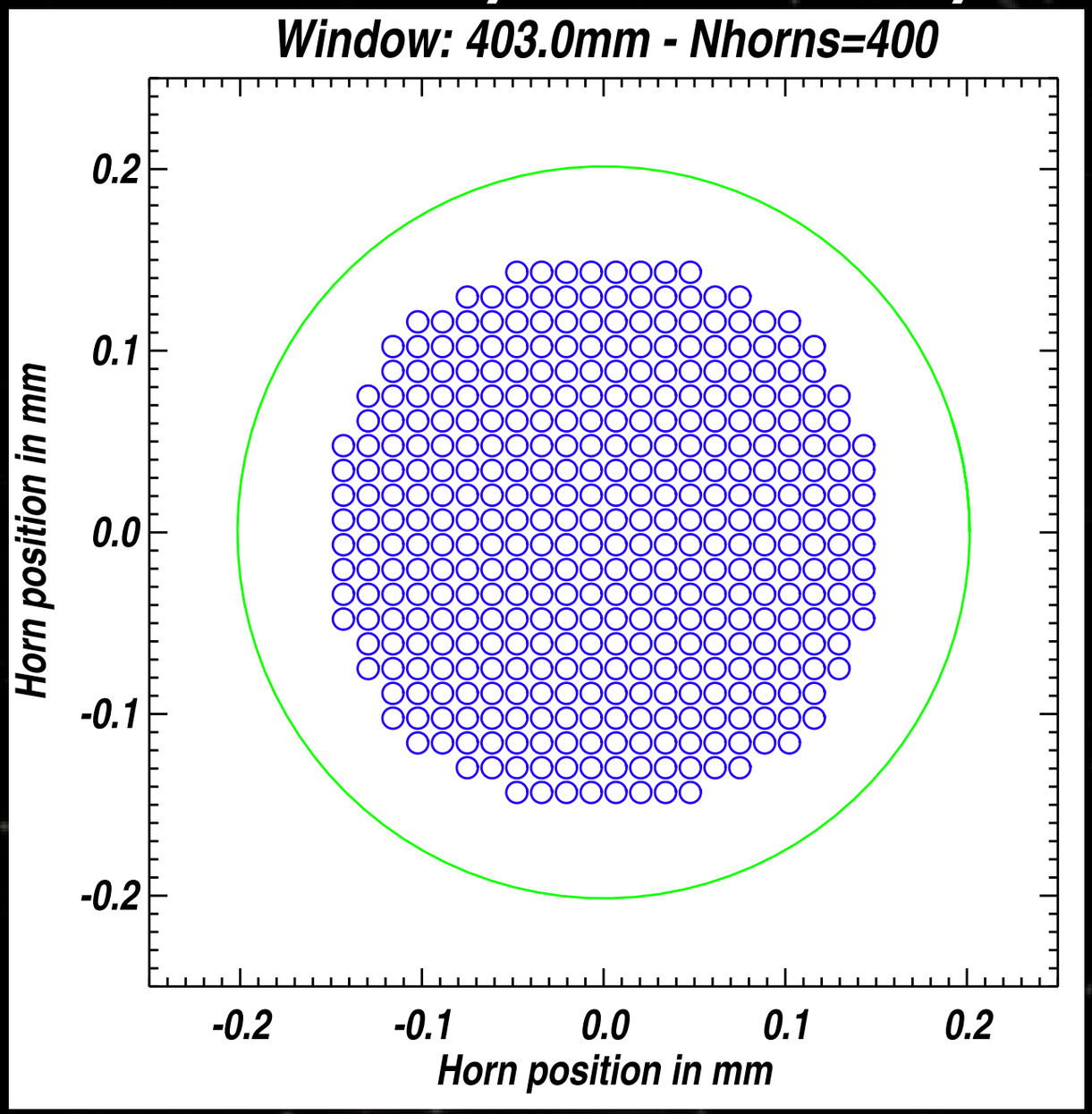

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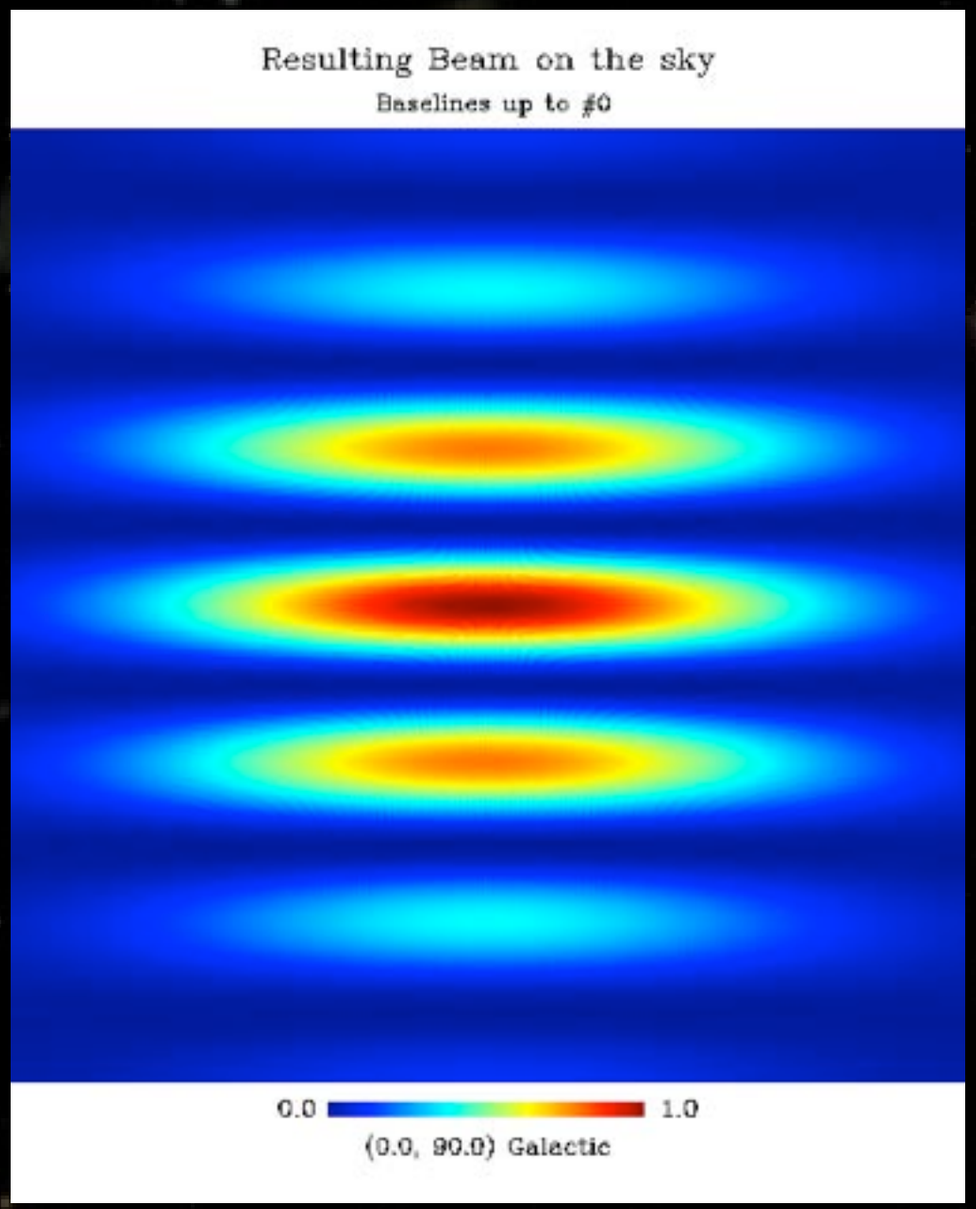

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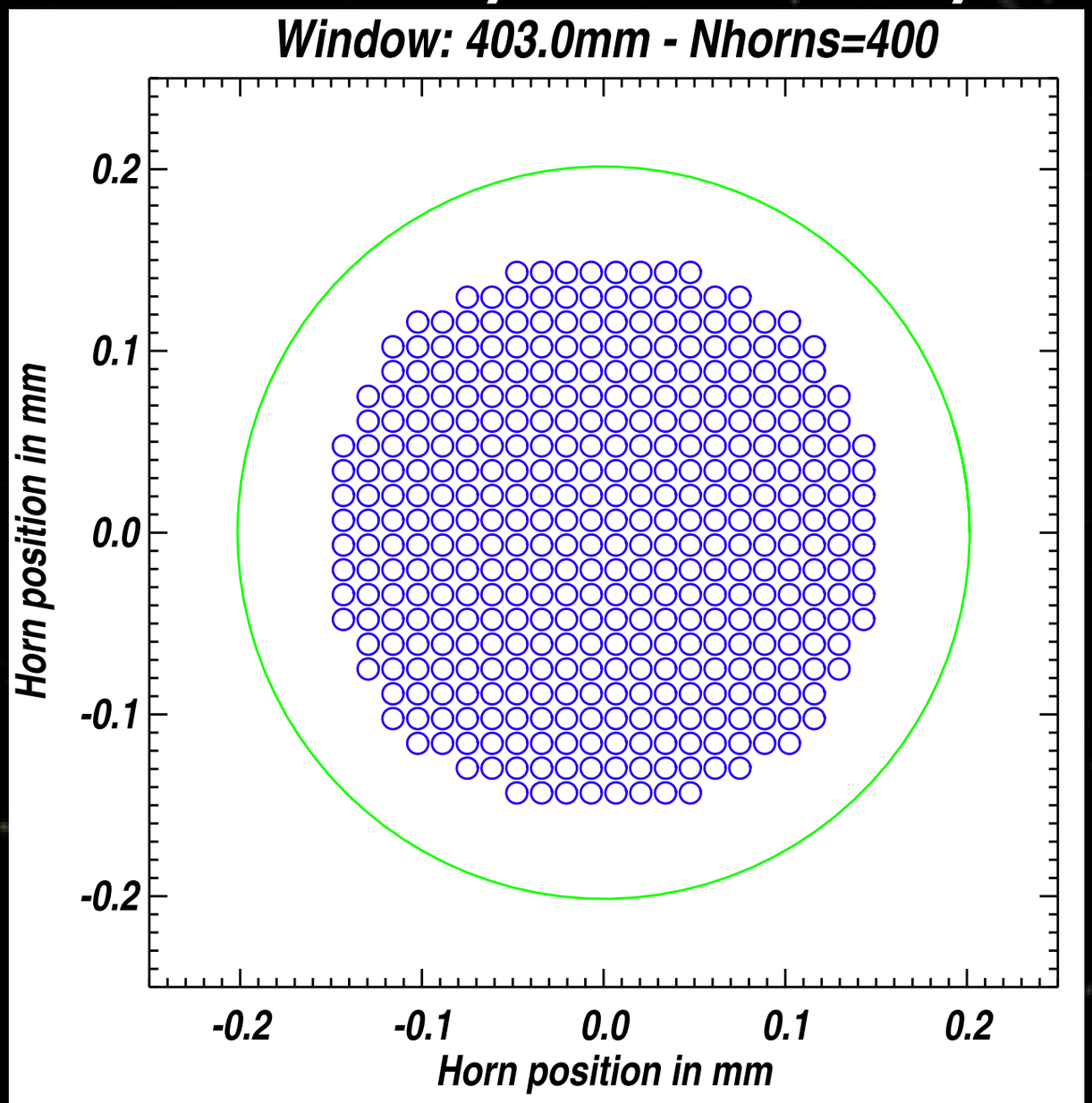

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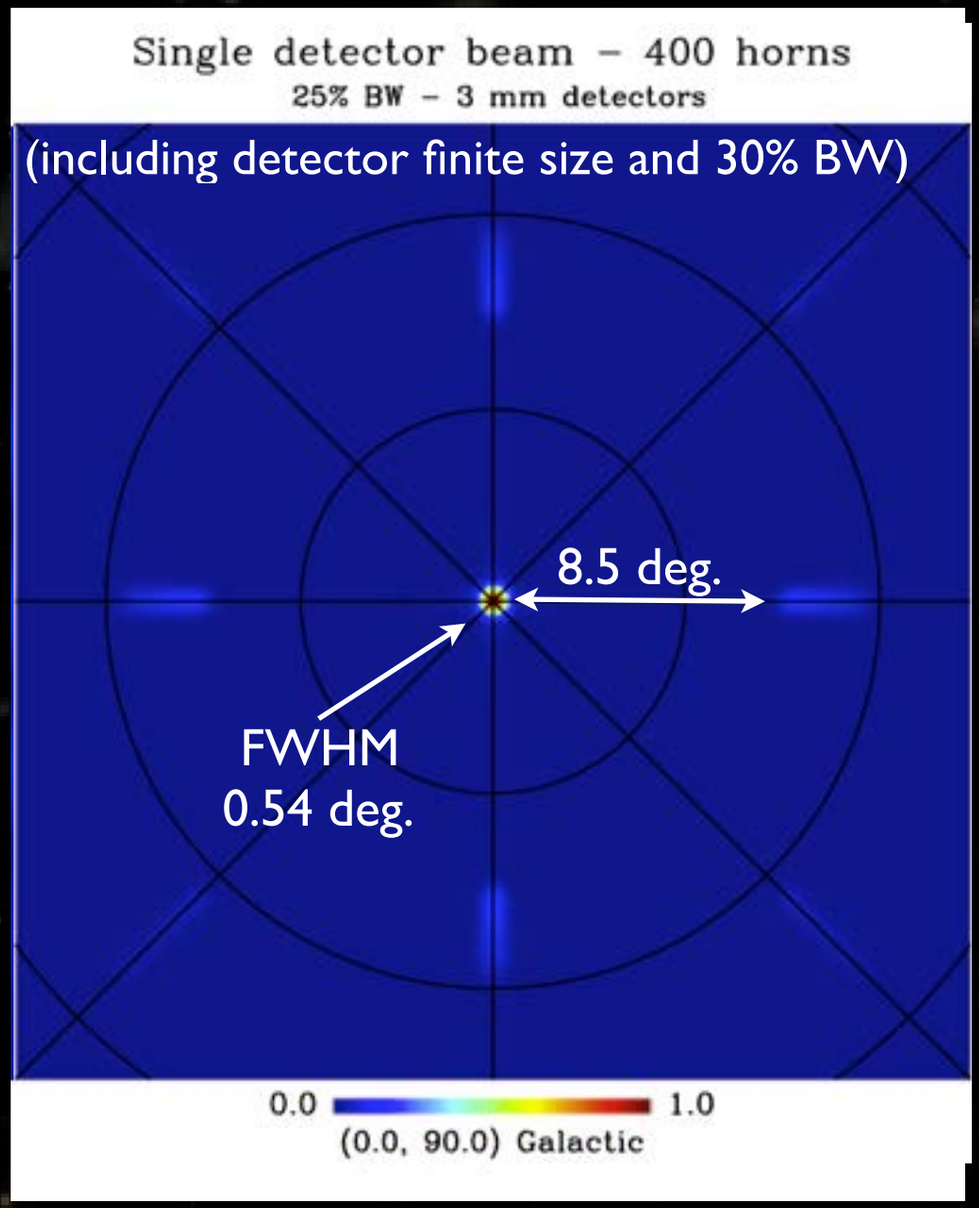

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Specificities of QUBIC w.r.t. Imagers

- Synthesized beam is:

Complex shape

Frequency dependent

Controlled by horns Geometry

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Specificities of QUBIC w.r.t. Imagers

- Synthesized beam is:

Complex shape → Map-making more complicated  just more CPU…

Frequency dependent

Controlled by horns Geometry

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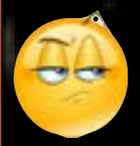

just more CPU…

Frequency dependent → QUBIC is a Spectro-Imager

Imagers can't !

Controlled by horns Geometry

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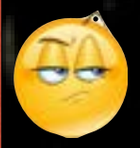
Specificities of QUBIC w.r.t. Imagers

- Synthesized beam is:

Complex shape	→	Map-making more complicated		just more CPU…
Frequency dependent	→	QUBIC is a Spectro-Imager		Imagers can't !
Controlled by horns Geometry	→	Ability to perform Self-Calibration		Imagers can't !

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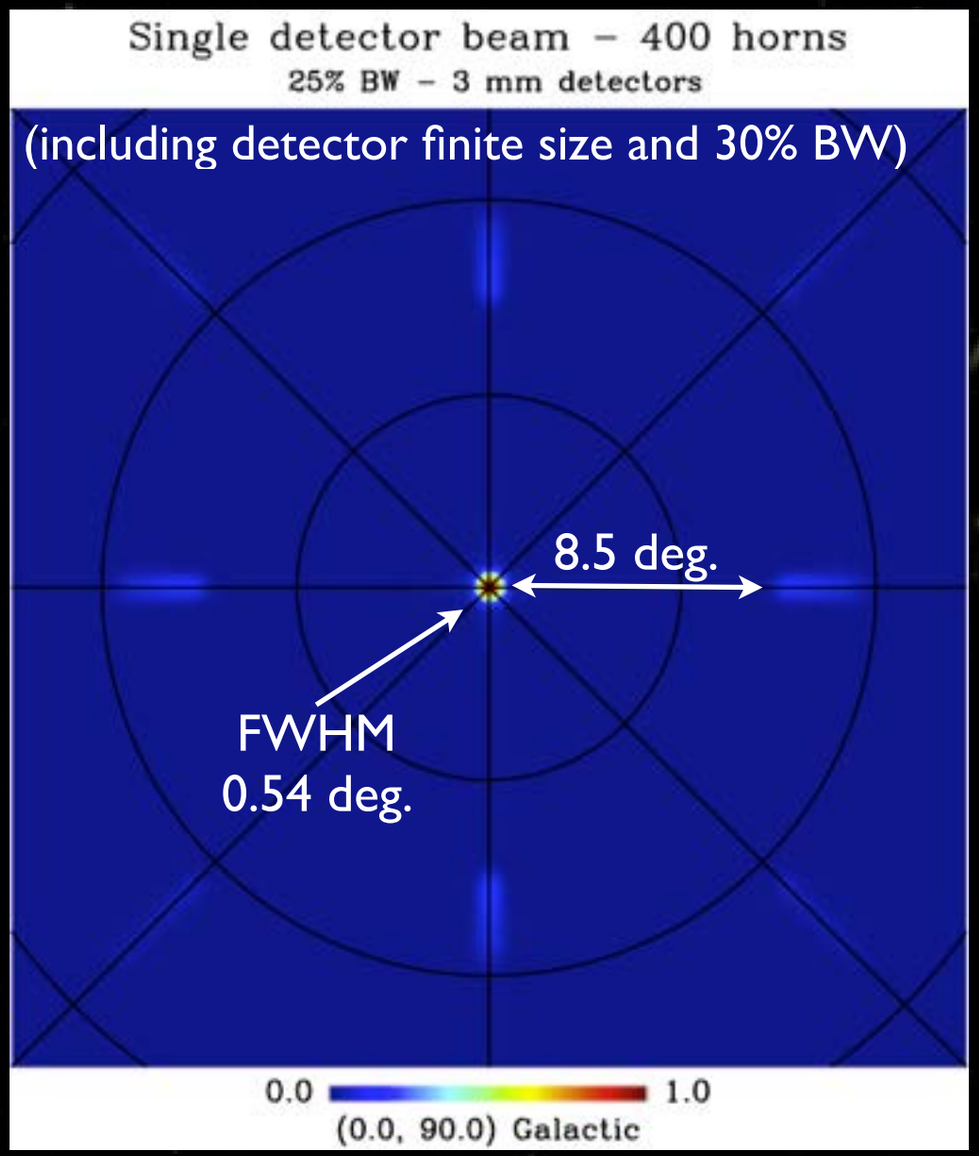
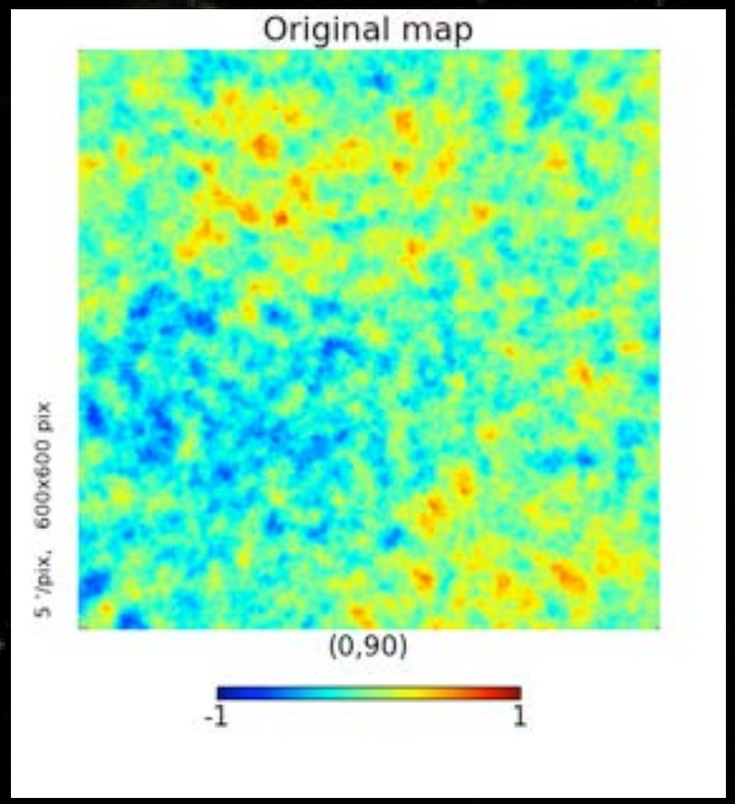
Map-making with QUBIC synthesized beam





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

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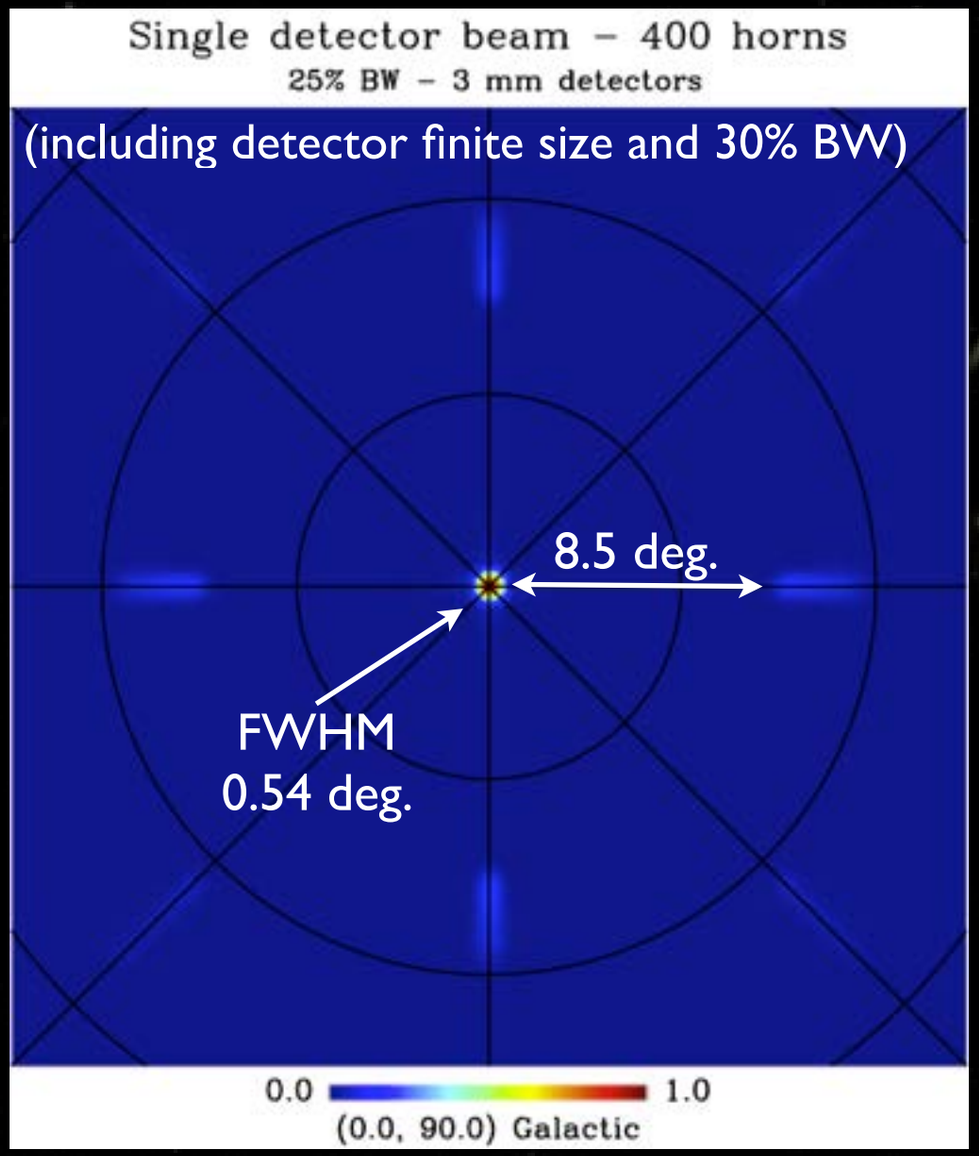
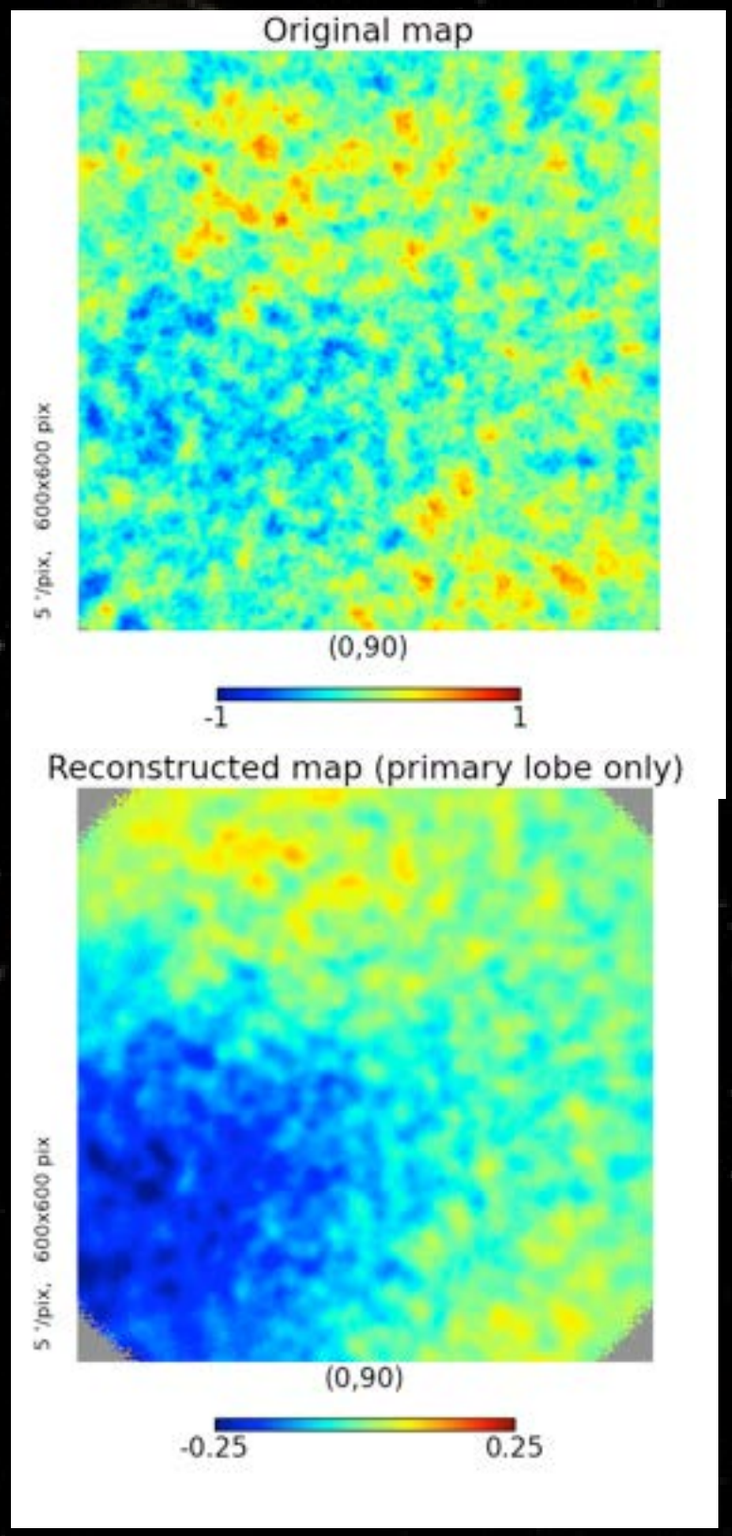
Map-making with QUBIC synthesized beam





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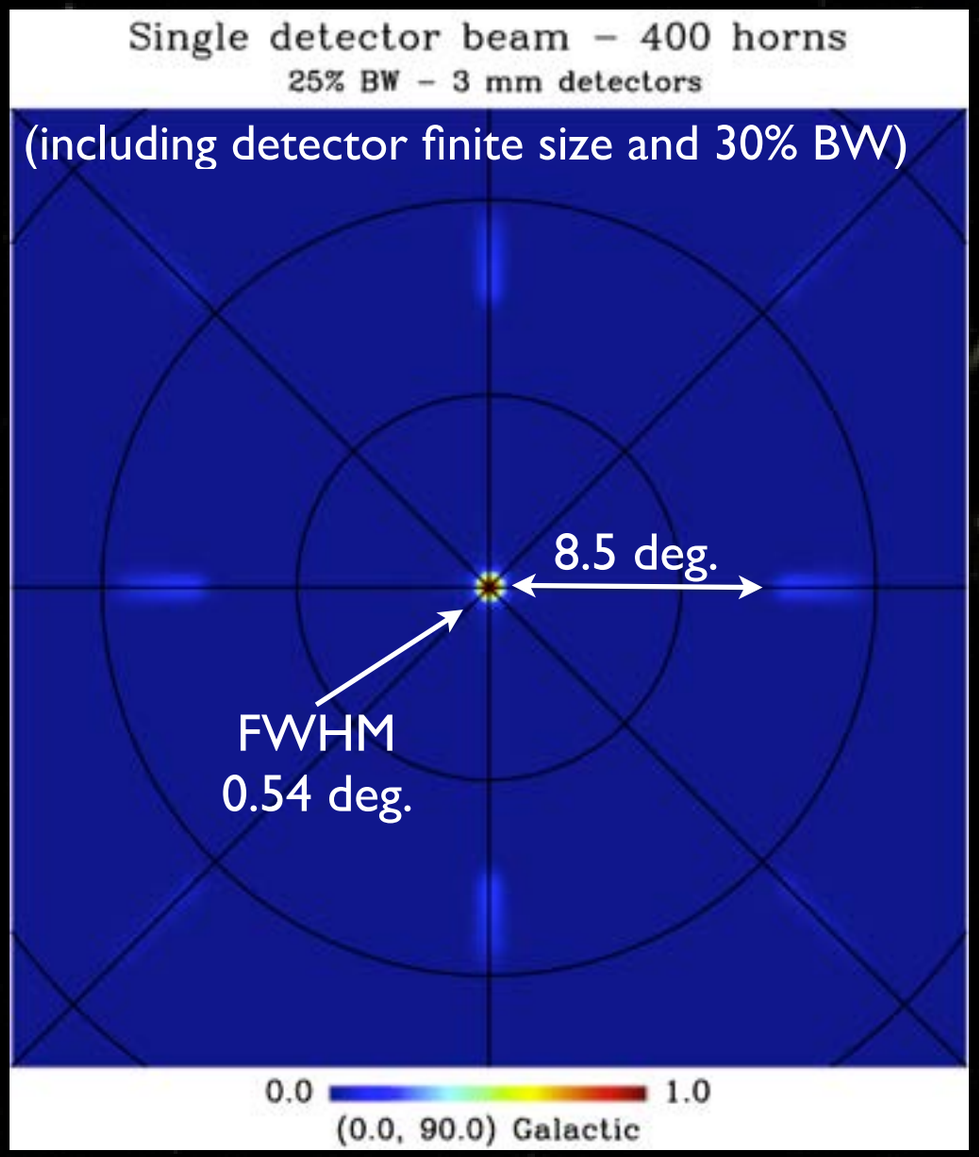

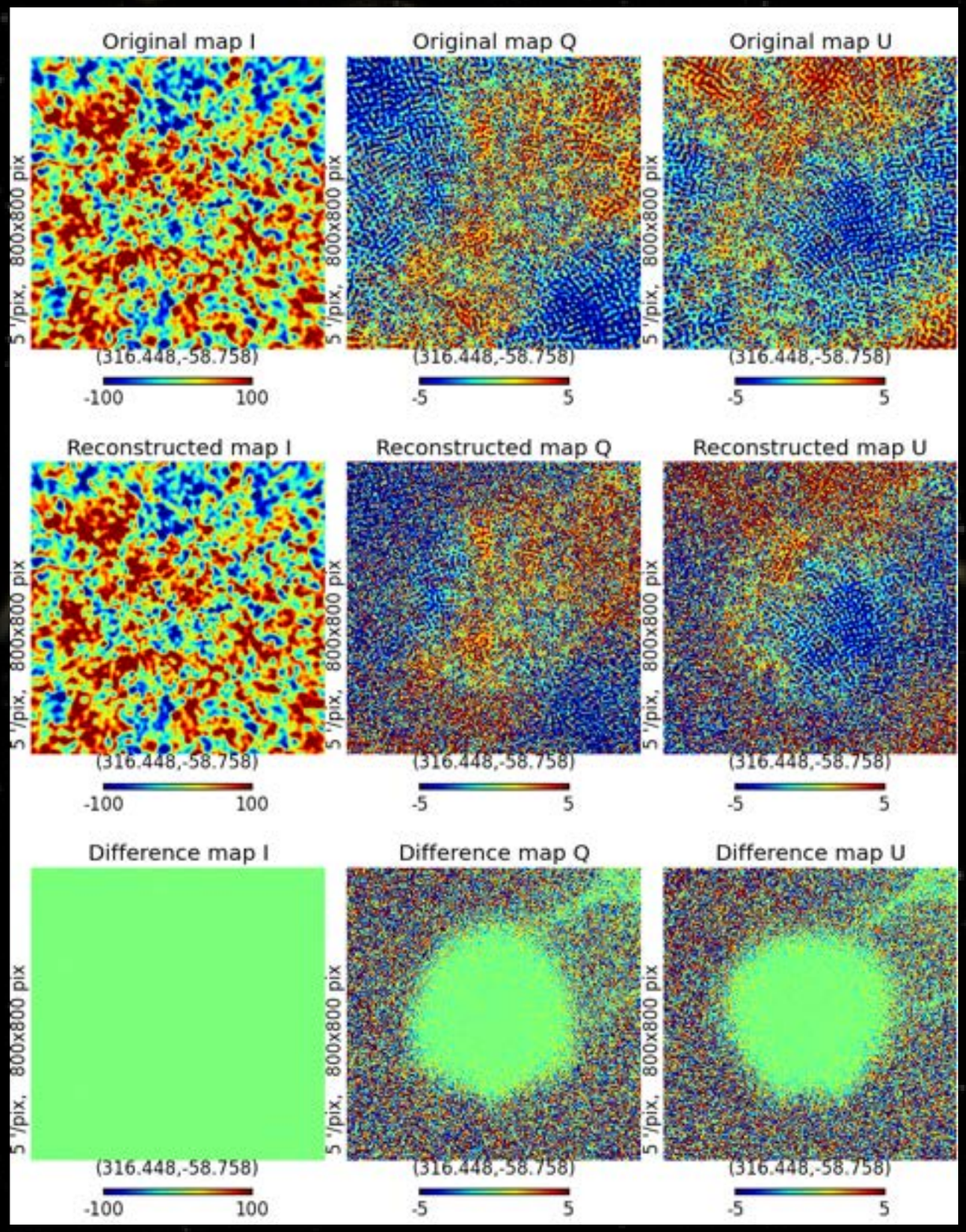

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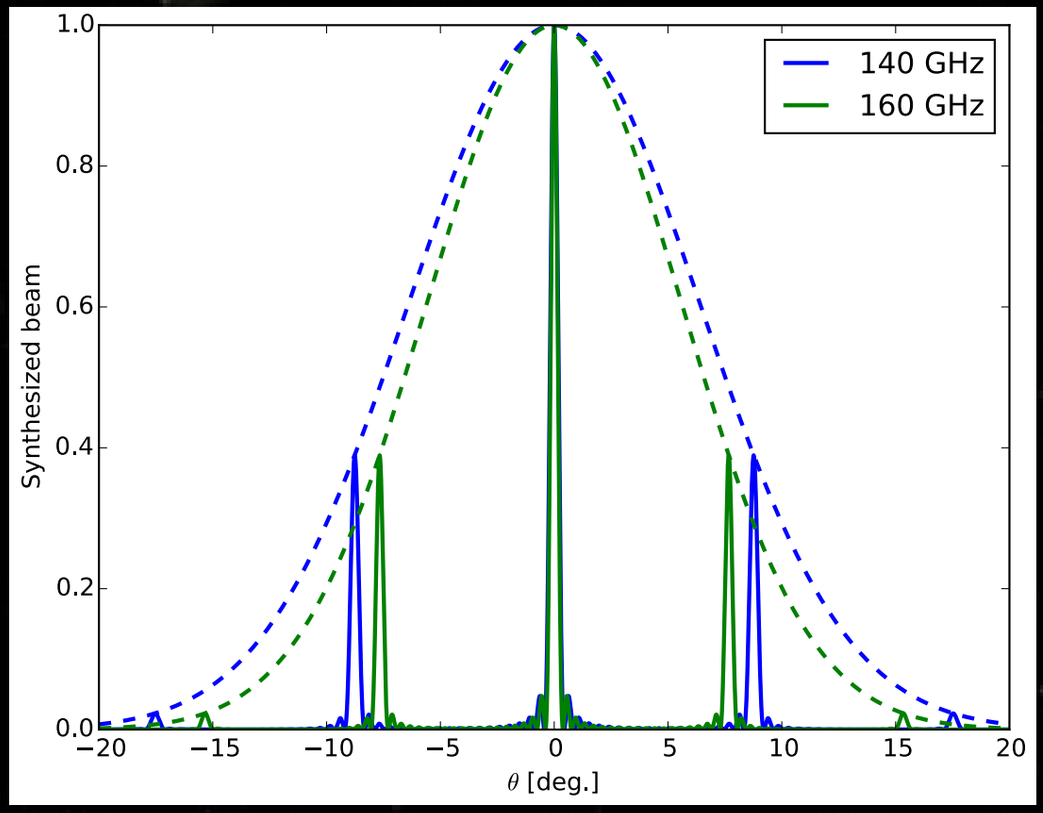
QUBIC is a Synthesized Spectro-Imager

- Synthesized beam:
  - ★ Depends on horns configuration
  - ★ AND on frequency !
    - ex: a point source emitting at 140 and 160 GHz



- There is frequency information !
- Multi-frequency map-making with the same TOD
  - ★ Spectral resolution $\Delta\nu/\nu \sim 0.05$
  - ★ proven with simulations
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QUBIC is a Synthesized Spectro-Imager

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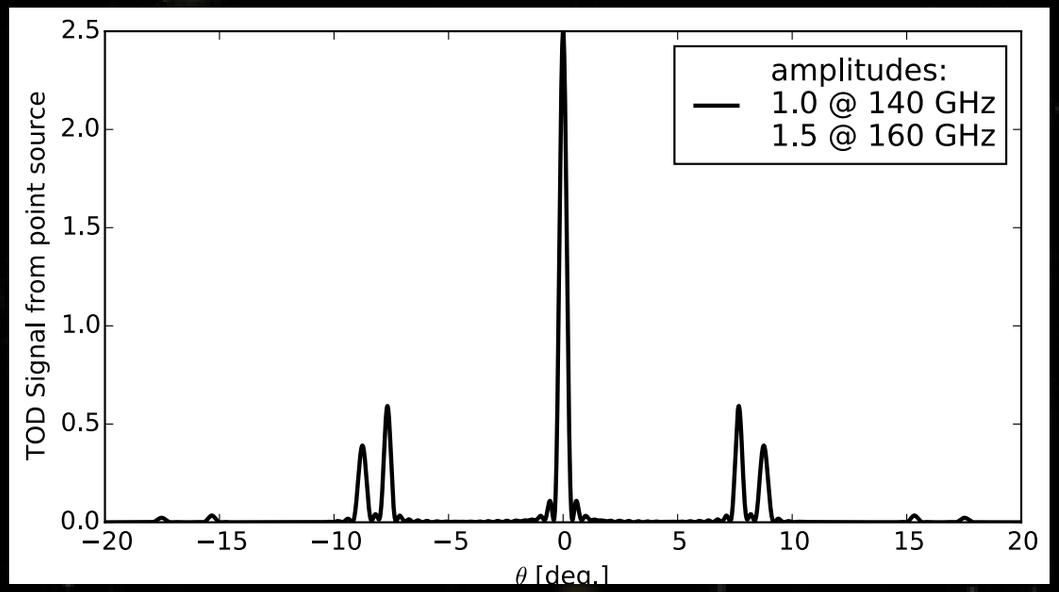

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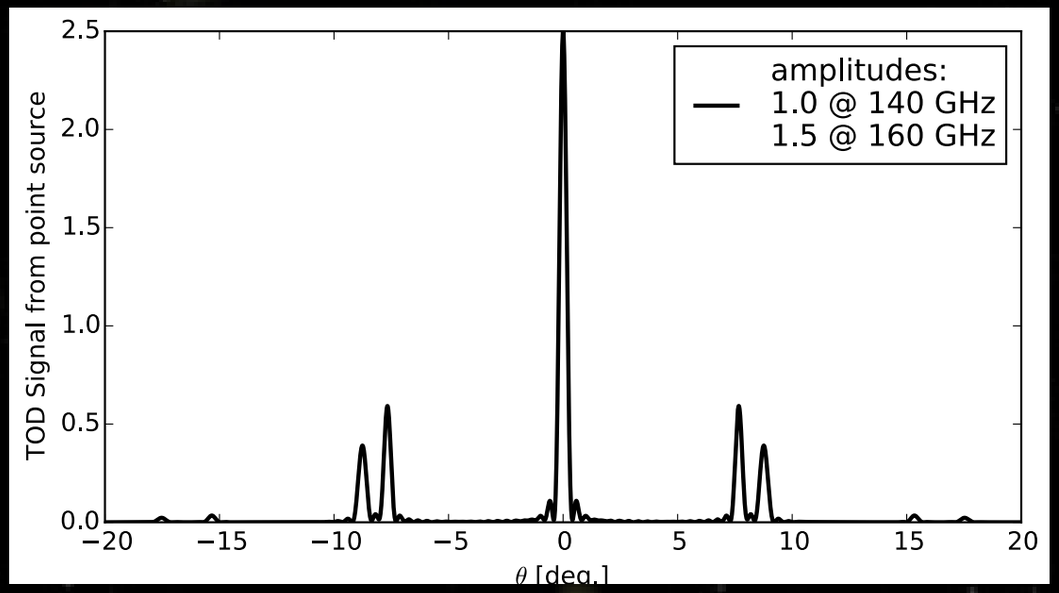

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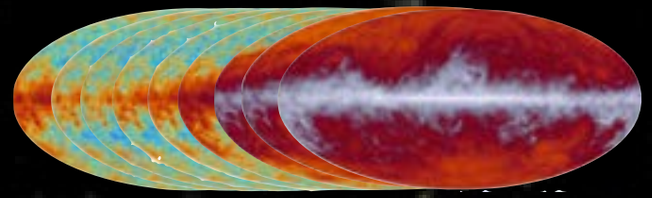

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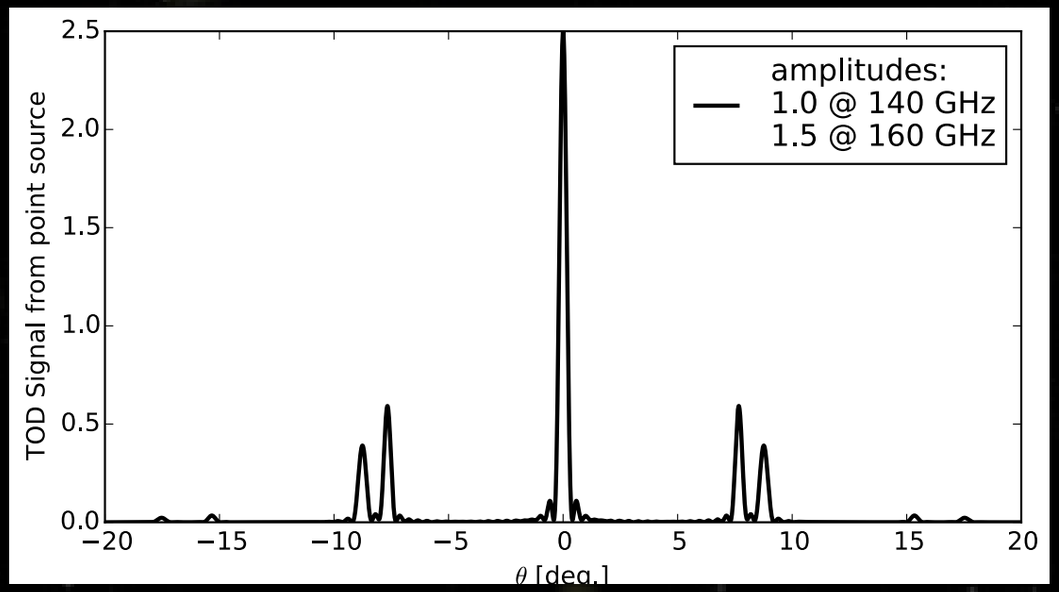

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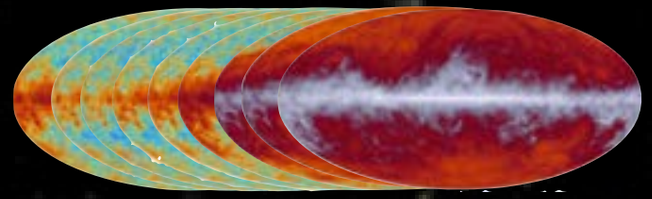

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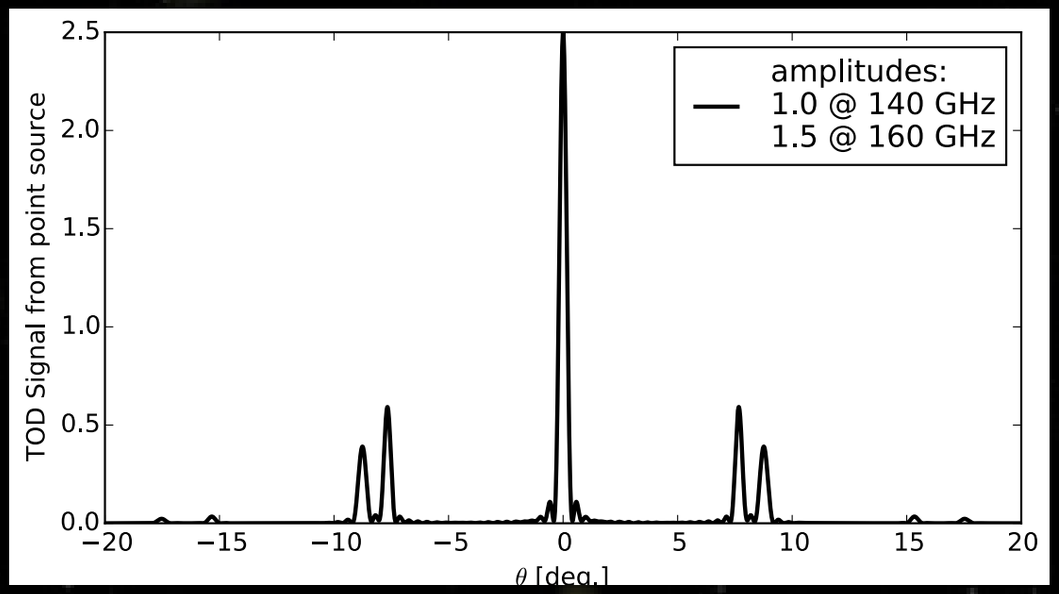

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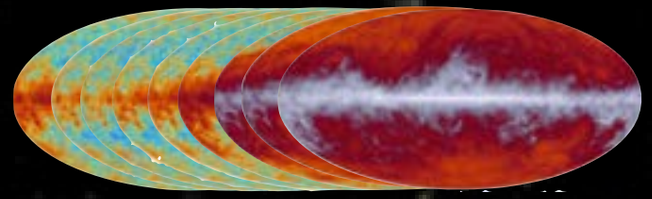

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Map Making

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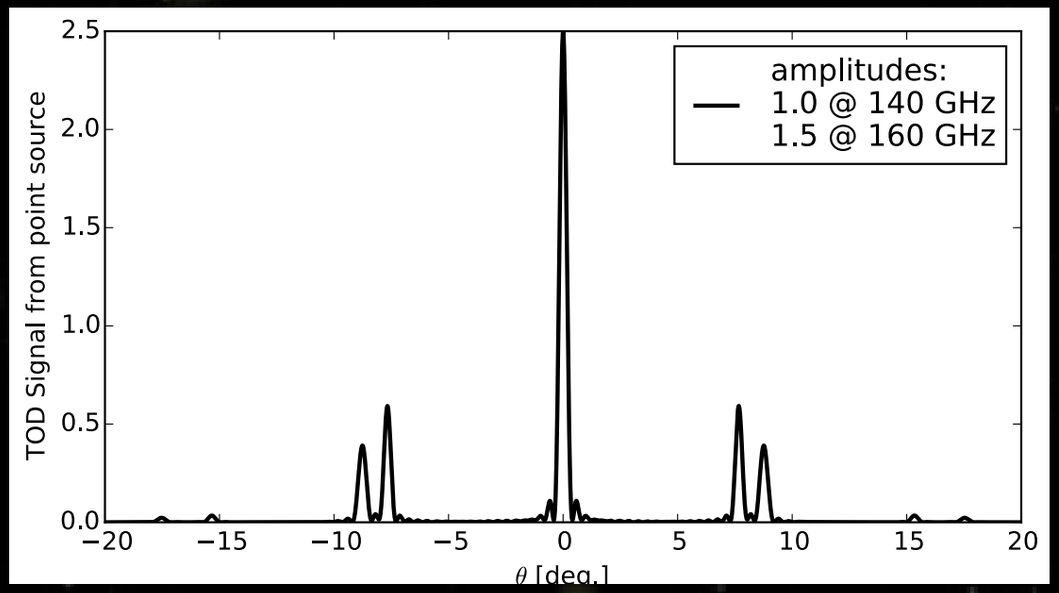

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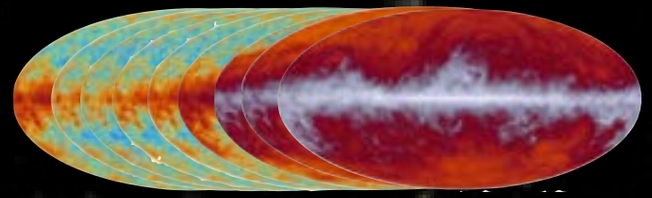

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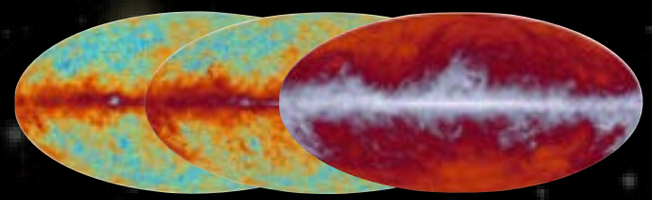
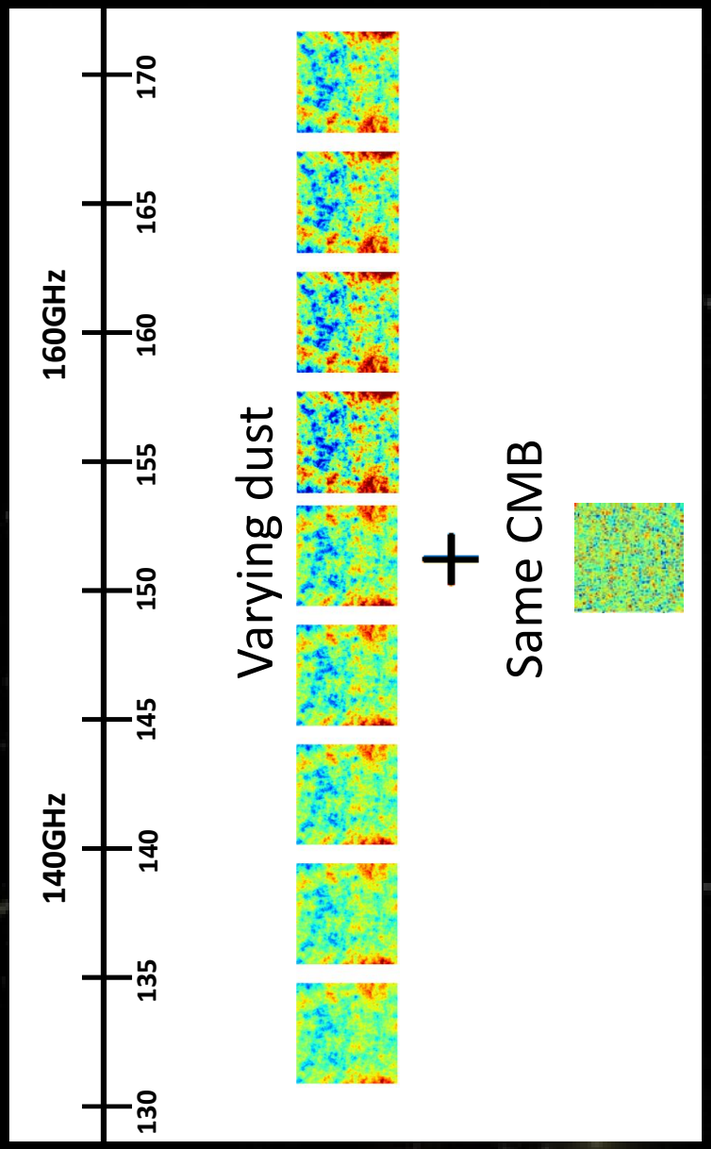
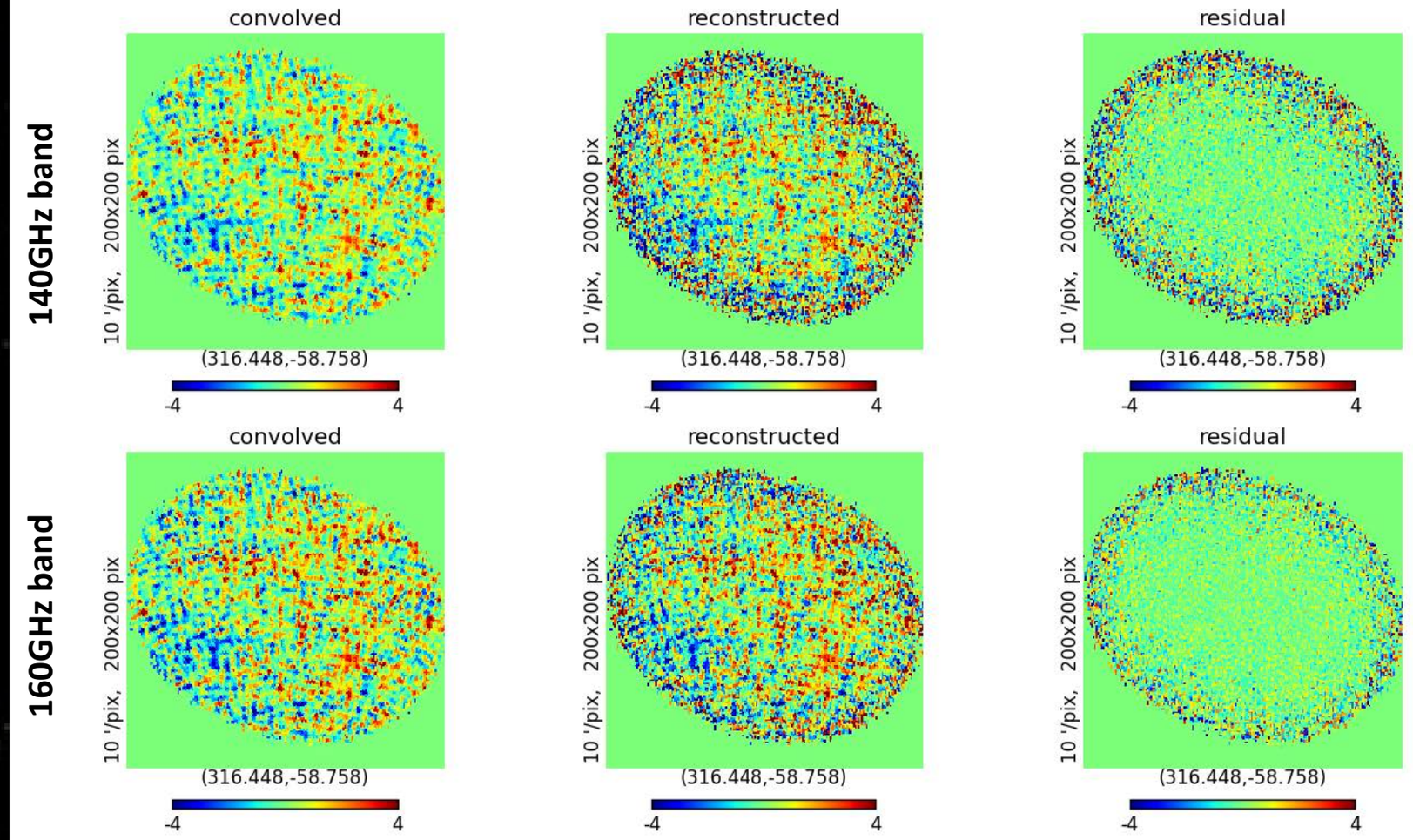


Output: N broadband frequency maps

Ex: Split one QUBIC band into two sub-bands ($\Delta\nu/\nu \sim 0.125$)



Results on Q



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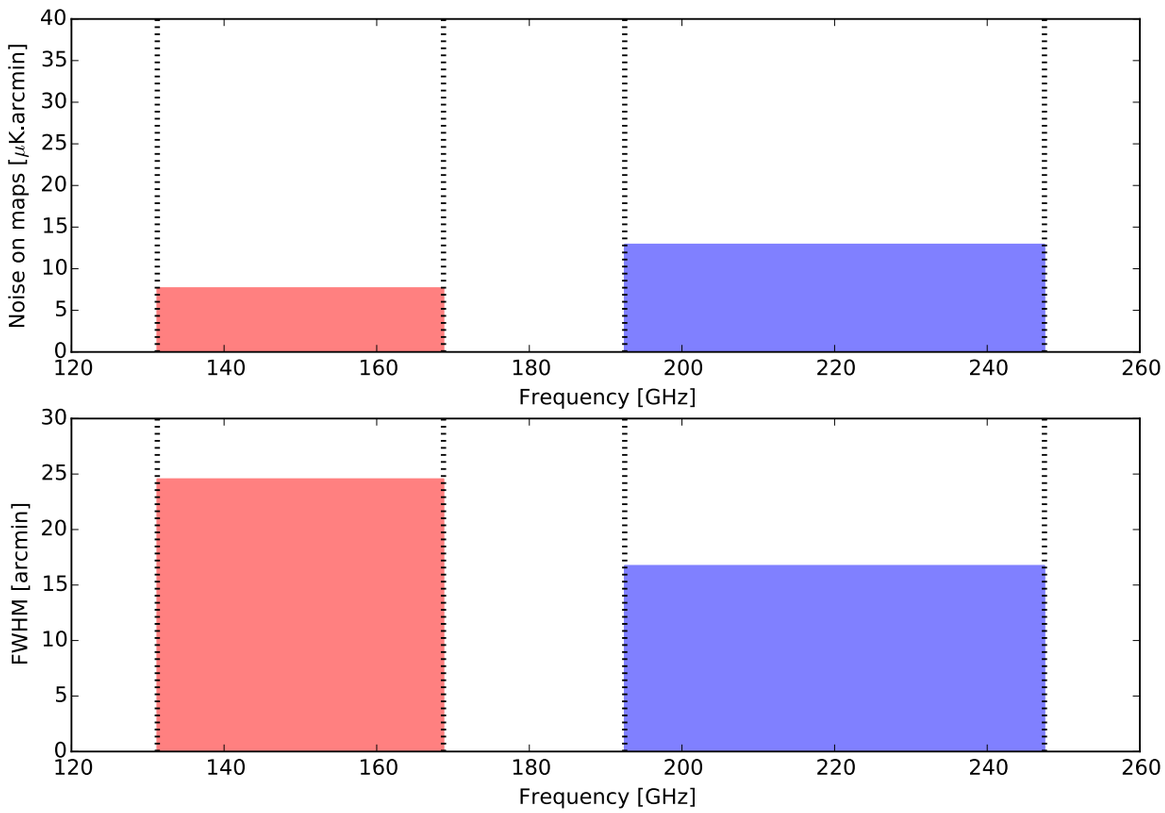
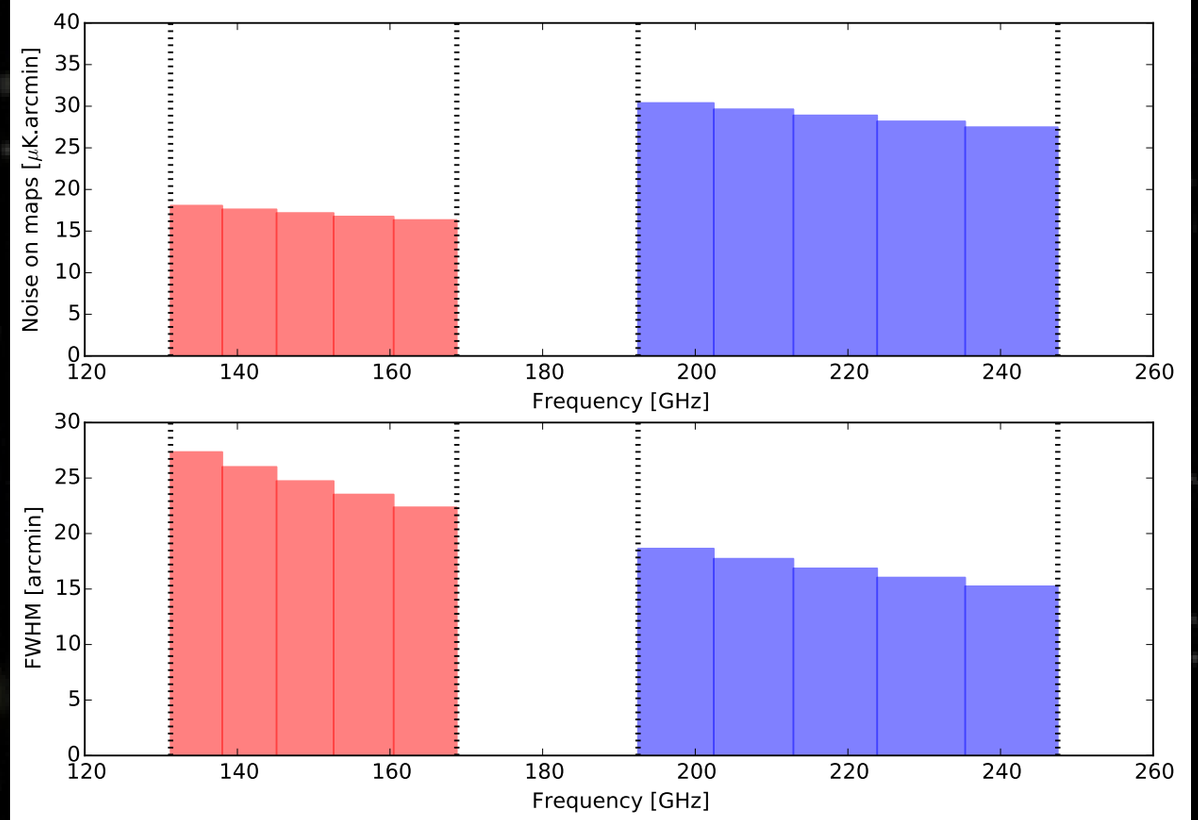
2 bands



10 smaller bands
Same overall sensitivity
Increased spectral resolution



Same Hardware… More CPUs needed but who cares ?

Might be a way to resolve complex foregrounds with non trivial frequency behavior (see F. Boulanger's talk)

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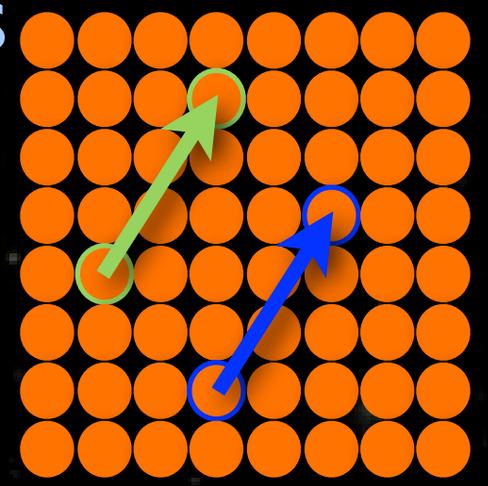
Systematics: Self-Calibration

- 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

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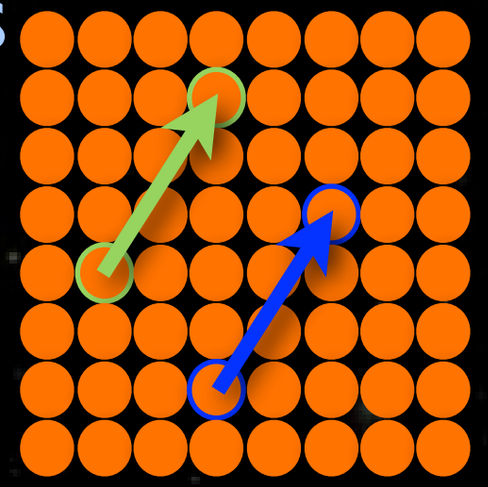

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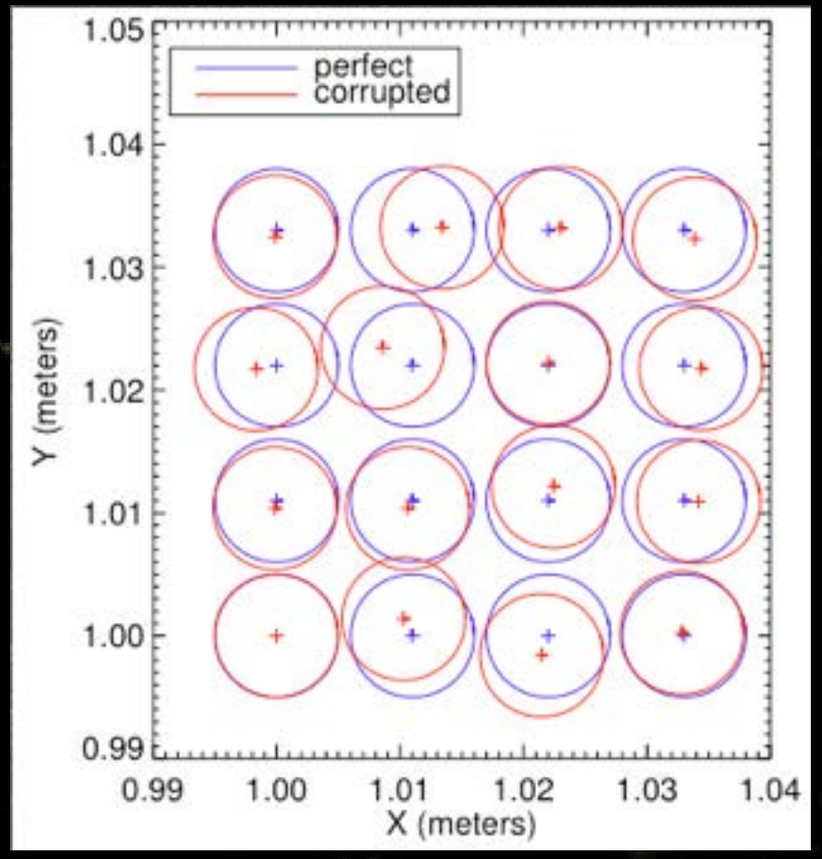

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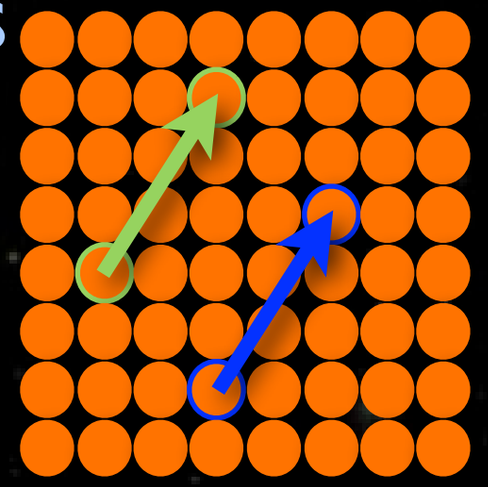

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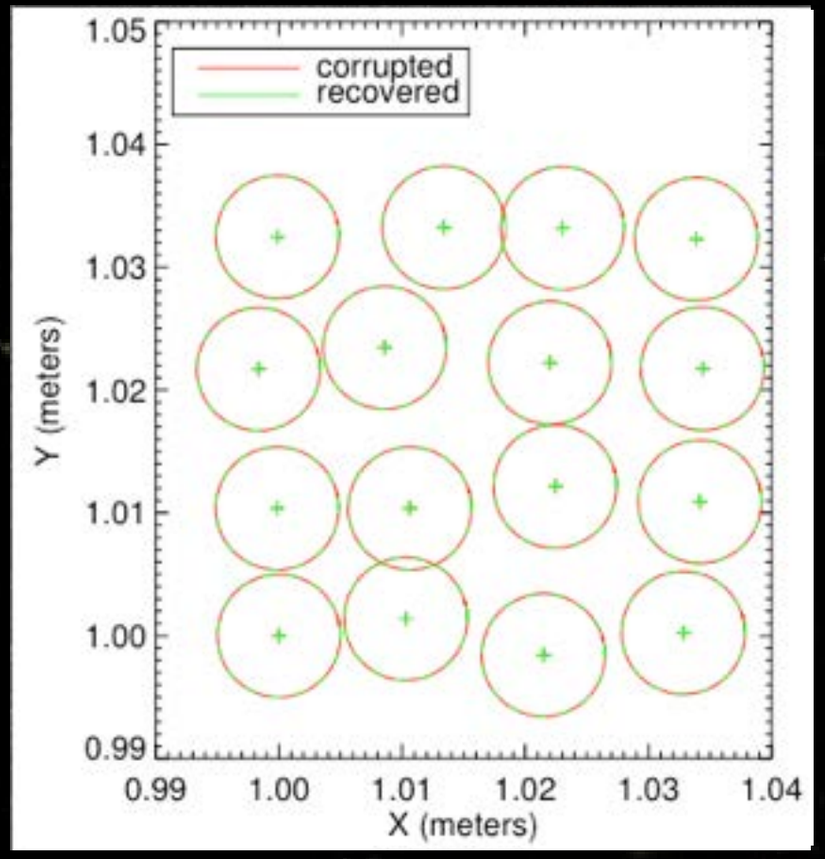

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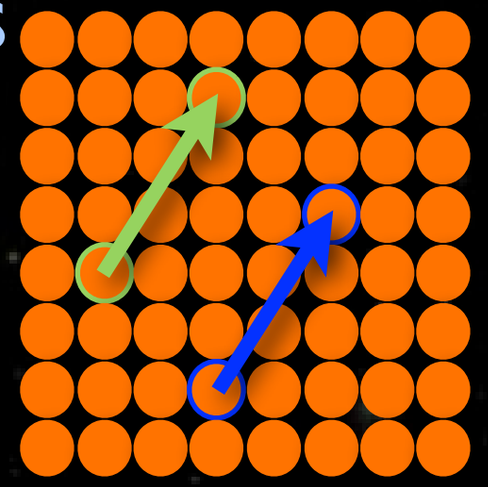

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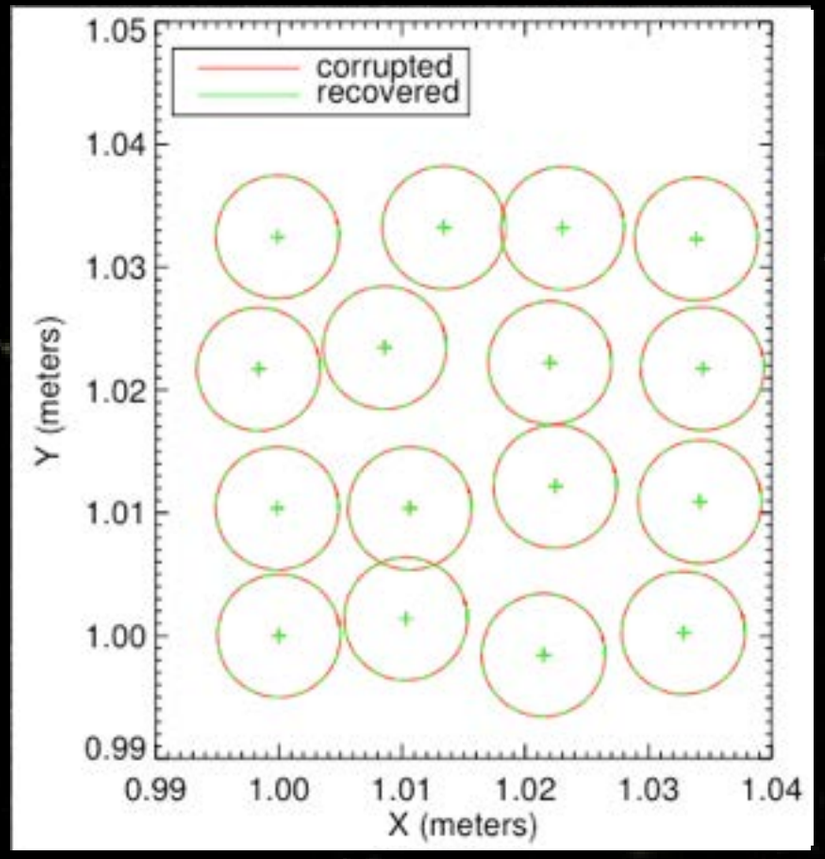

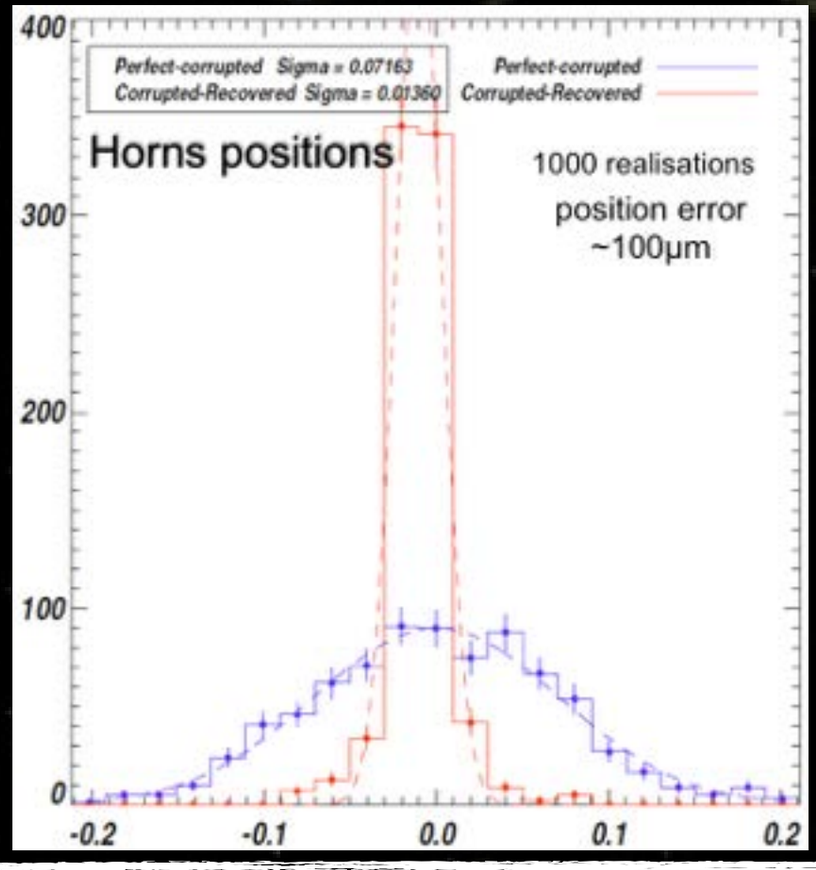

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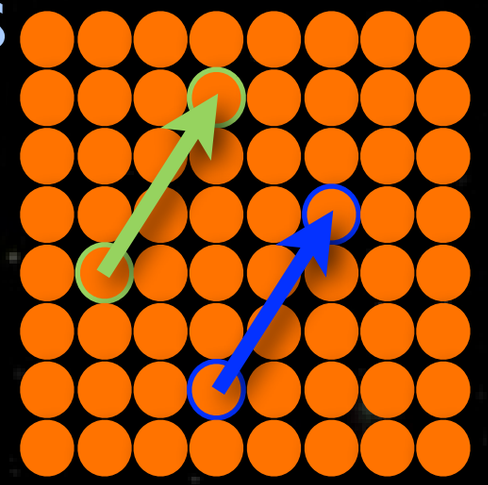

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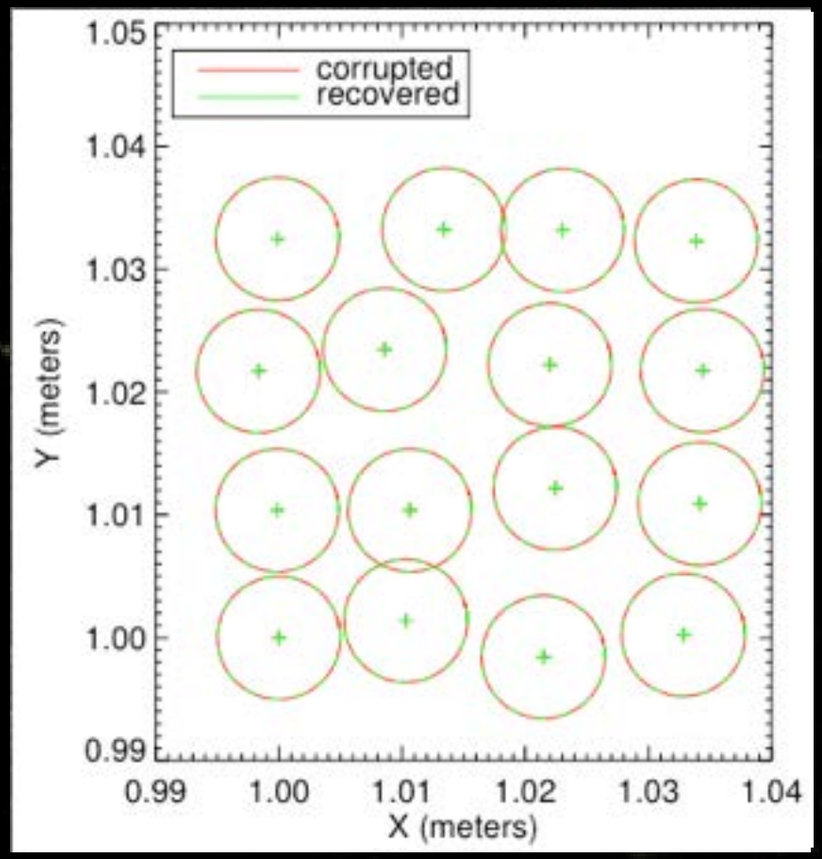

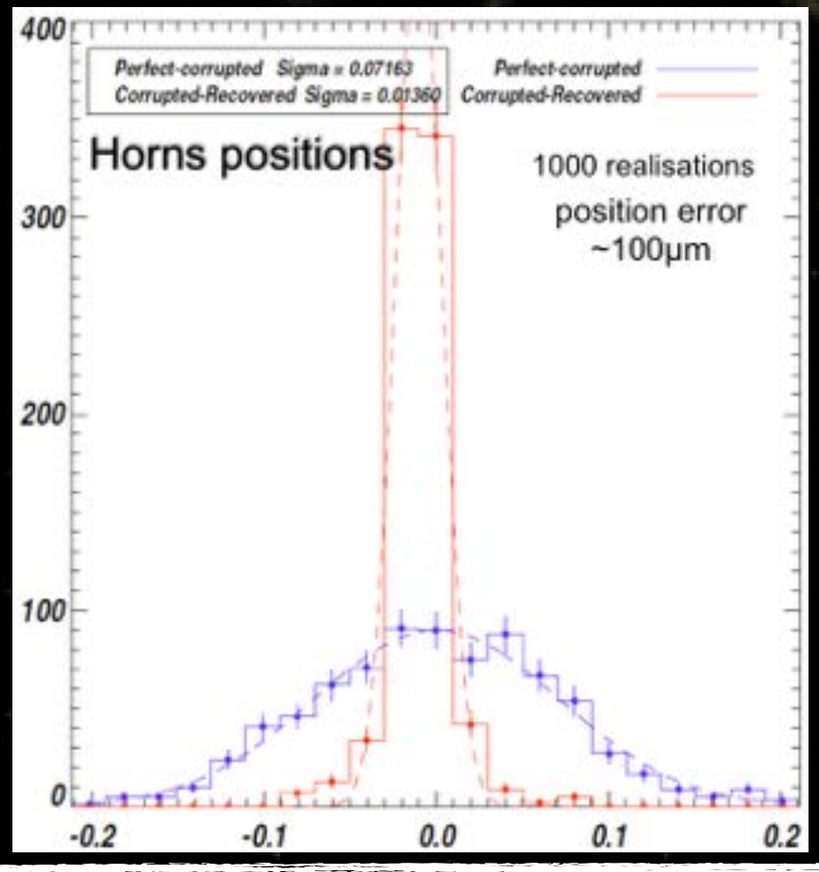

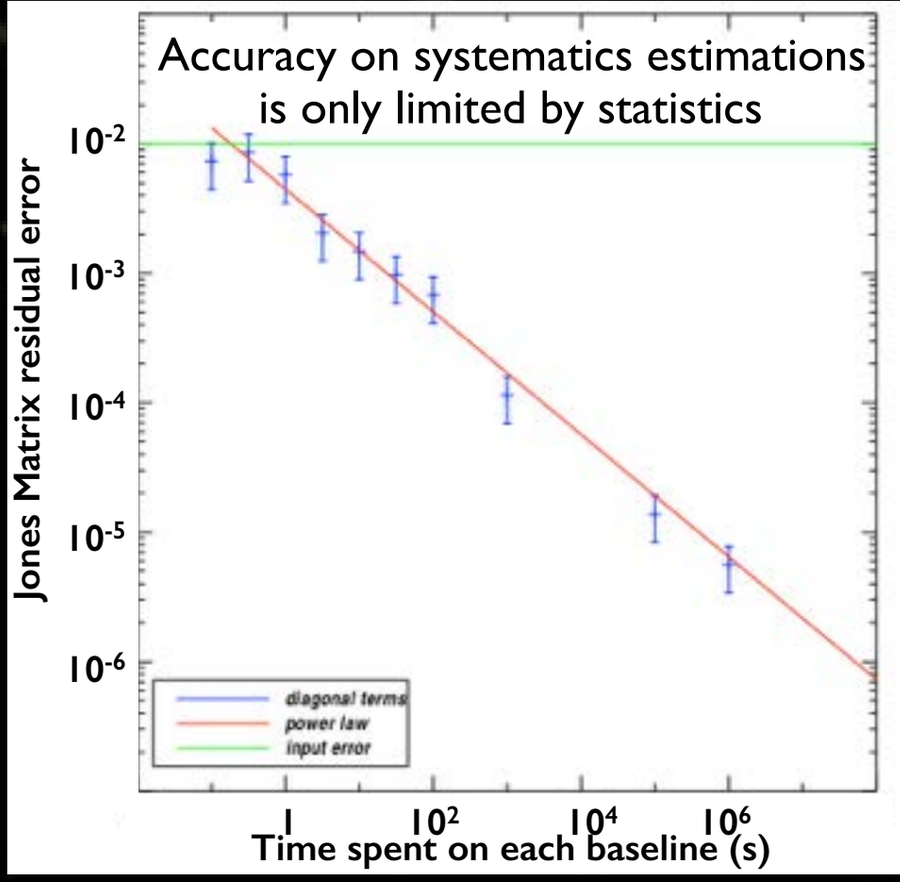

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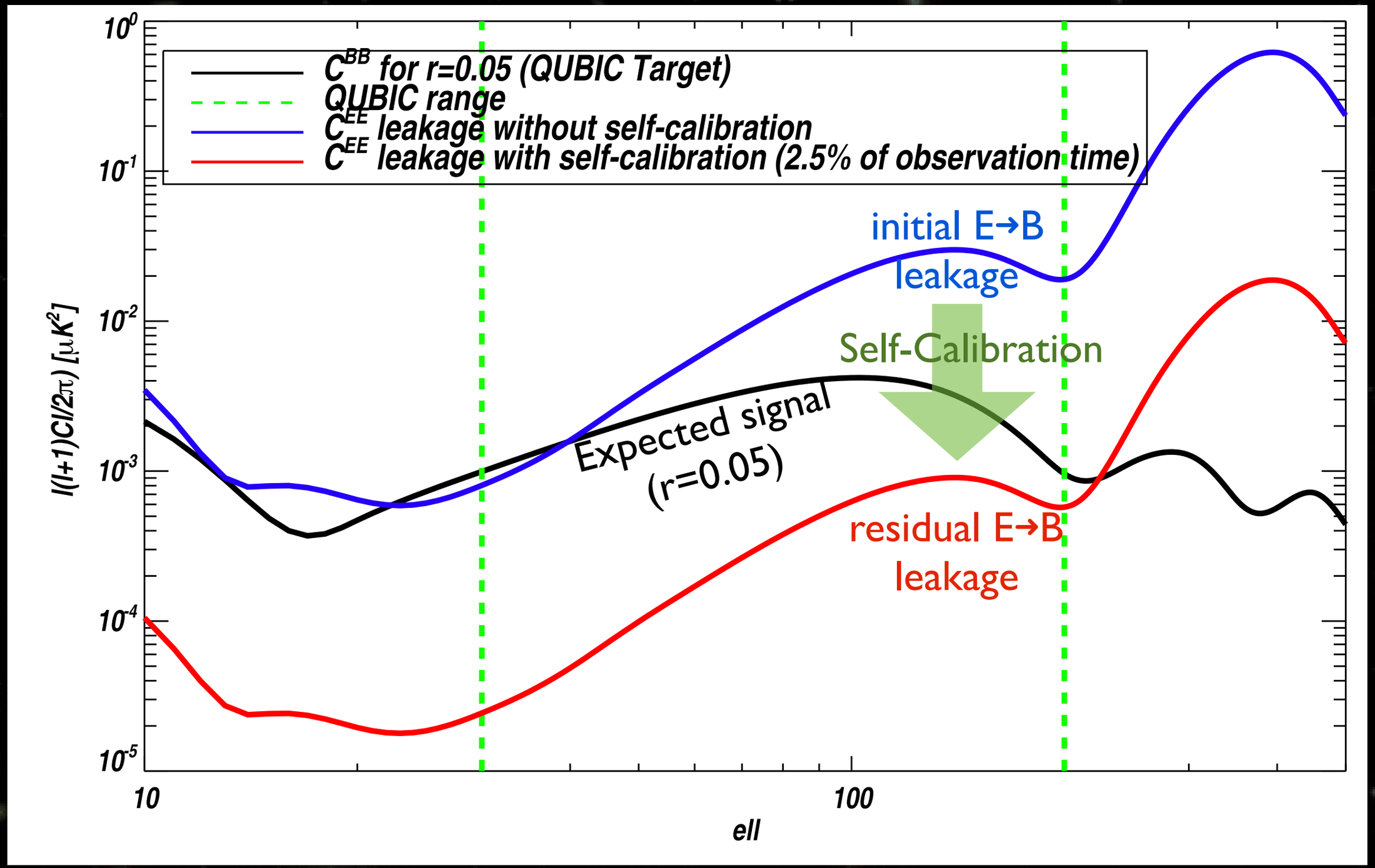
Self-Calibration results



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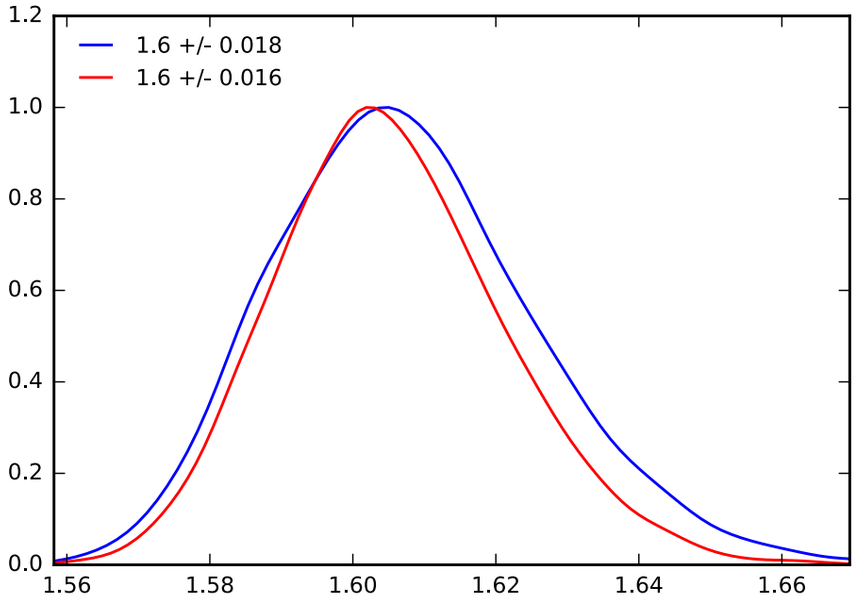
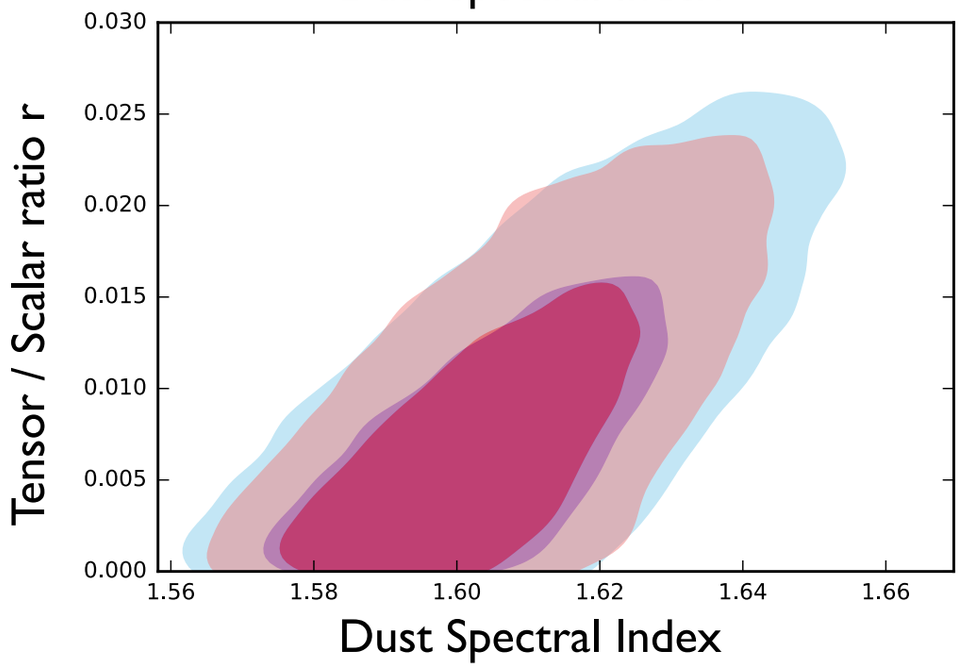
Sensitivity on r

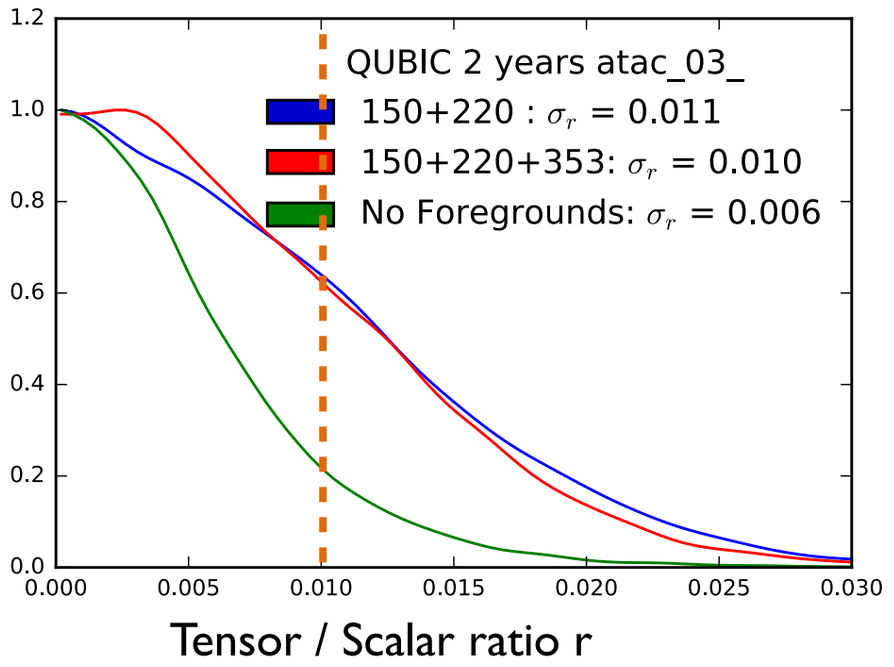
- Likelihood using measured Planck 353 dust level in BICEP2 field



Assumptions:
2 years, Argentina, 30% efficiency

$\sigma(r) \sim 0.01$





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Competitiveness

Project	Country	Location	Status	Frequencies (GHz)	ℓ range value	Ref.	$\sigma(r)$ goal no fg.	with fg.
QUBIC	Eur+Ar+US	Argentina		150,220	30-200		0.006	0.01
Bicep3/Keck	U.S.A.	Antartica	Running	95, 150, 220[1]	50-250	[22]	$2.5\ 10^{-3}$	0.013
CLASS	U.S.A.	Atacama	≥ 2016	38, 93, 148, 217	2-100	[29]	$1.4\ 10^{-3}$	0.003
SPT3G	U.S.A.	Antartica	2017	95, 148, 223	50-3000	[23]	$1.7\ 10^{-3}$	0.005
AdvACT	U.S.A.	Atacama	Starting	90, 150, 230	60-3000	[24]	$1.3\ 10^{-3}$	0.004
Simons Array	U.S.A.	Atacama	≥ 2017	90, 150, 220	30-3000	[25]	$1.6\ 10^{-3}$	0.005
LSPE	Italy	Artic	2017	43, 90, 140, 220, 245	3-150	[30]	0.03*	
EBEX10K	U.S.A.	Antartica	≥ 2017	150, 220, 280, 350	20-2000	[28]	$2.7\ 10^{-3}$	0.007
SPIDER	U.S.A.	Antartica	Running	90, 150	20-500	[26]	$3.1\ 10^{-3}$	0.012
PIPER	U.S.A.	Multiple	≥ 2016	200, 270, 350, 600	2-300	[27]	$3.8\ 10^{-3}$	0.008

From QUBIC TDR (on arXiv this week)
Numbers obtained with [Errard et al., JCAP03(2016)052] forecasting tool

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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 : Mid 2017
  - ★ Nominal cryostat
  - ★ 8x8 horns array
  - ★ reduced mirrors
  - ★ 256 TES / frequency
  - ★ Laboratory testing

→ Validation of technology

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  - ★ reduced mirrors
  - ★ 256 TES / frequency
  - ★ Laboratory testing

→ Validation of technology

- **QUBIC 1st Module: 2018**
  - ★ 400 horns array
  - ★ nominal mirrors
  - ★ 1024 TES / frequency
  - ★ Laboratory testing
  - ★ Deployment on site and operations

→ B-mode search
$\sigma(r) = 0.01$ in 2 years

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Summary

- QUBIC is a novel instrumental concept
  - ★ Bolometric Interferometer optimized to handle systematics (self-calibration)
    - *QUBIC is an synthesized spectro-imager observing a selected range of spatial frequencies that can be accurately calibrated*
  - ★ Dedicated to CMB polarimetry and inflationary physics
    - *Major topic in fundamental physics: early Universe, origin of structures, …*
  - ★ High sensitivity with ~2000 TES bolometers
    - *Sensitivity with 1st module:* $\sigma(r) = 0.01$ *(incl. dust + eff.)*
  - ★ Dual Band (150 / 220 GHz): ~ 5 sub-bands in each
    - *Enhanced control on foregrounds (better spectral resolution)*
  - ★ Location: San Antonio de los Cobres, Argentina, deployment in 2018
    - *Logistics already funded and on the way (site ready by mid-2017)*
- Possible ground for a future European Stage IV project
  - QUBIC Full (90-300 GHz) : $\sigma(r) \sim 0.001$ **(~2025)**

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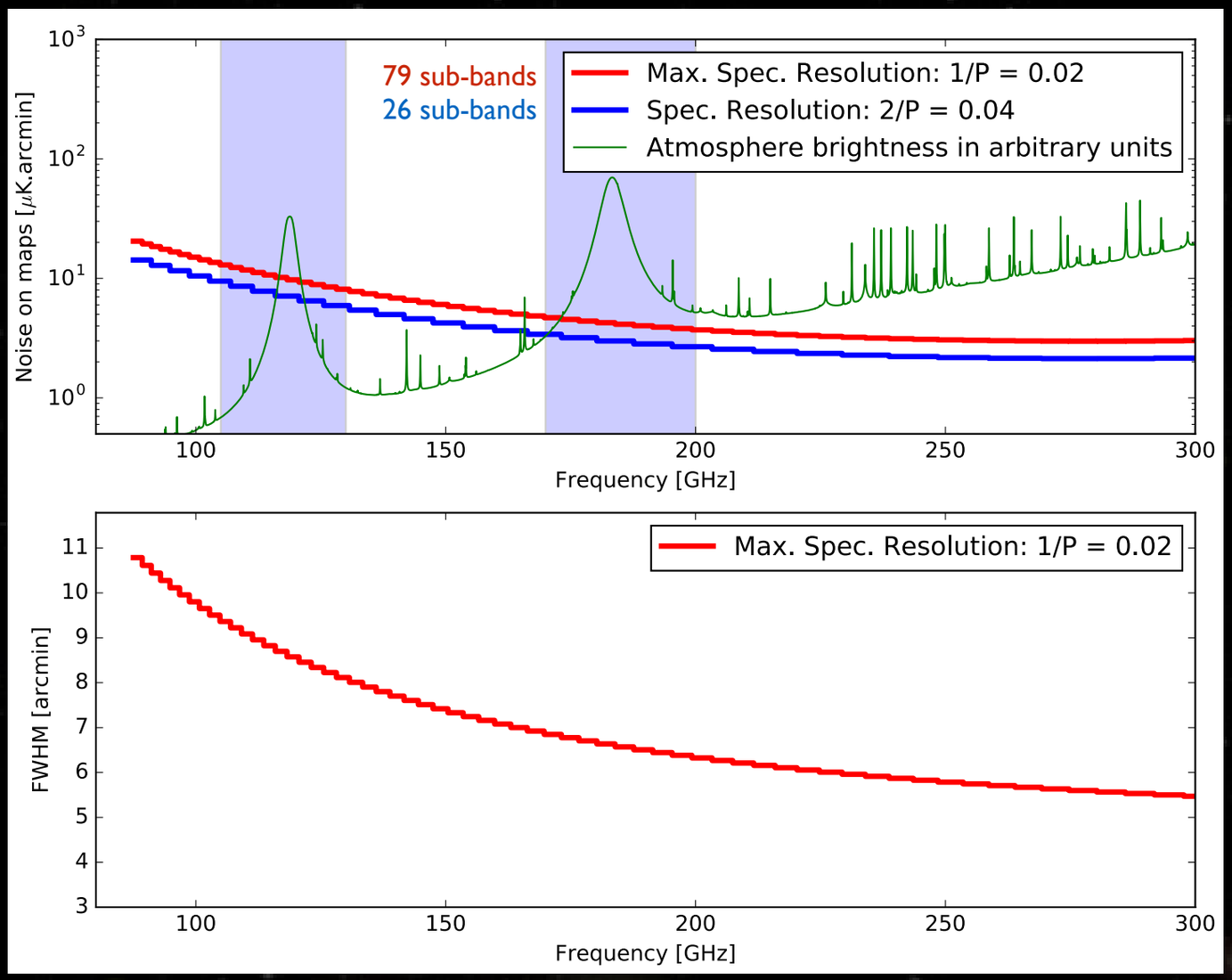
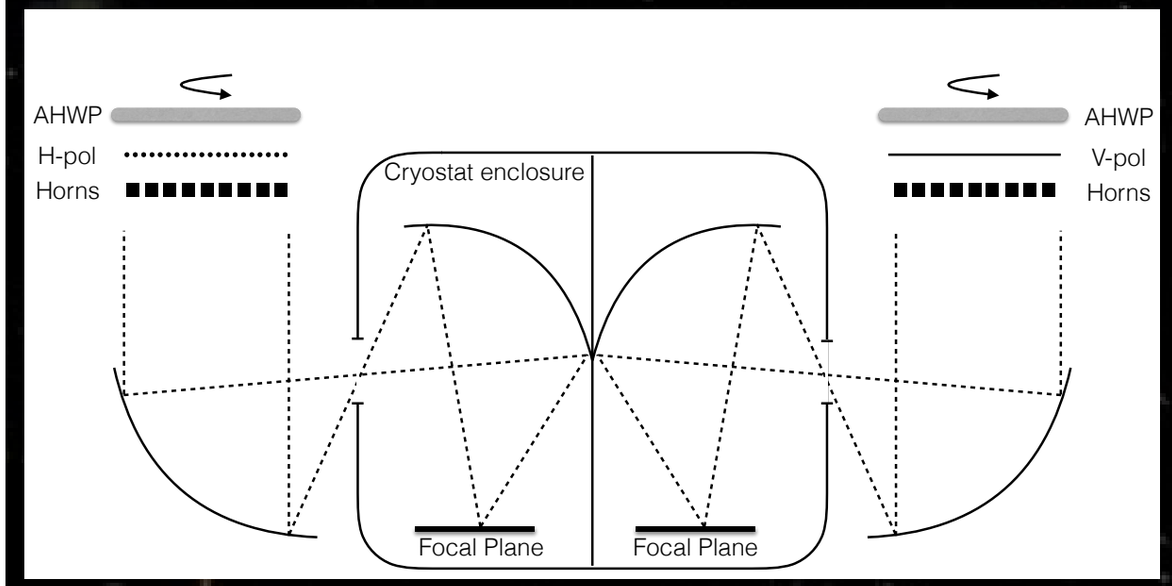
Bolometric Interferometer Stage IV ?

Wide band spectra-imaging [90-300] GHz cutting 118 (O_2) and 183 H_2O lines





Very preliminary study
(Andrea Tartari + JCH)

$\sigma(r) \sim 5 \times 10^{-4}$
using [Errard et al., JCAP03(2016)052]

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