Cosmologie Moderne
QUBIC

J.-Ch. Hamilton, APC
hamilton@apc.univ-paris7.fr

l'interférométrie en bref

★ Ligne de base : $||\vec{u}|| = \frac{D}{\lambda}$

★ Lobe (PSF): $B(\vec{x})$

★ Signal en sortie : $S(\vec{u}) = \int E_1(\vec{n}) E_2^\star(\vec{n}) B^2(\vec{n}) \mathrm{d}\vec{n}$

★ Déphasage : $\delta = 2\pi \vec{u} \cdot \vec{x}$

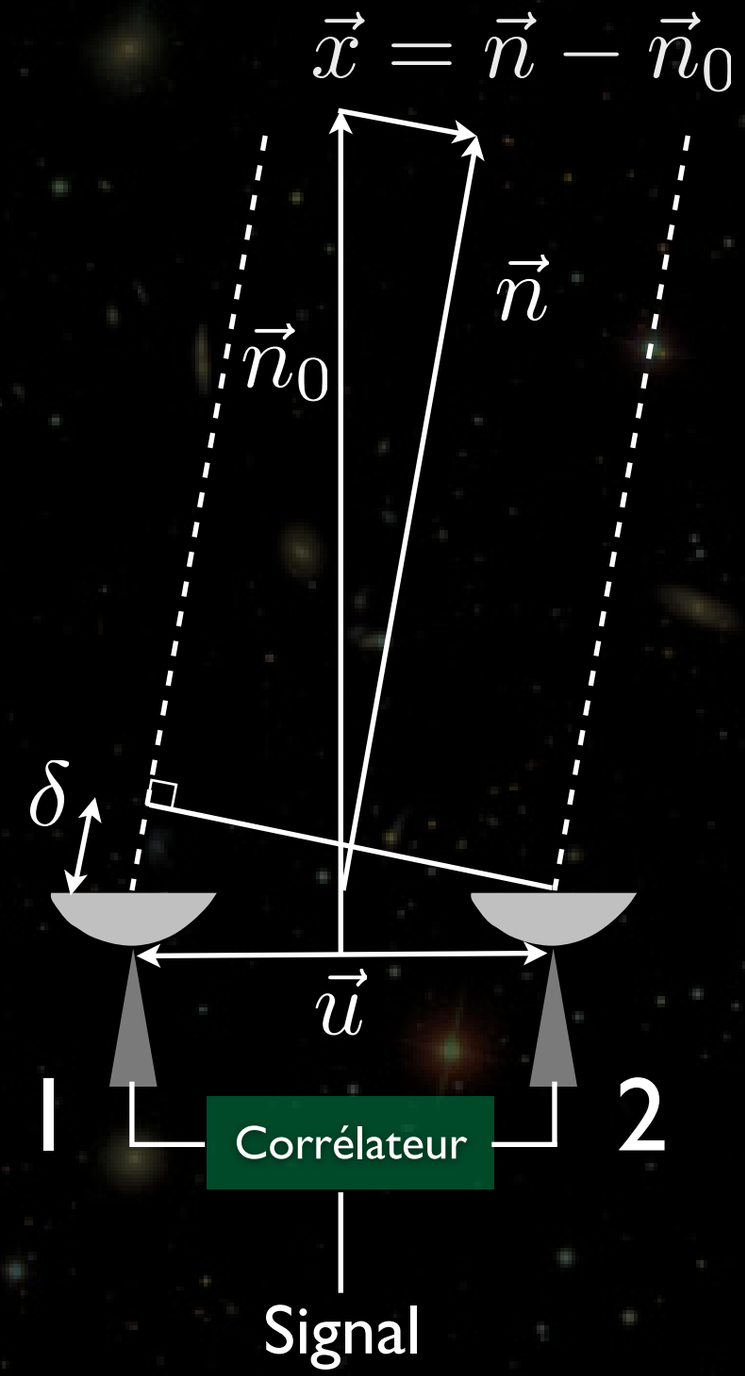
➔ $E_2^\star(\vec{n}) = E_1^\star(\vec{n}) \exp(2i\pi \vec{u} \cdot \vec{x})$

★ Visibilités :

$$S(\vec{u}) = \int |E(\vec{n})|^2 B^2(\vec{n}) \exp(2i\pi \vec{u} \cdot \vec{x}) \mathrm{d}\vec{n}$$

Un interféromètre mesure la transformée de Fourier du signal dans le champ observé

$$\ell = 2\pi ||\vec{u}||$$



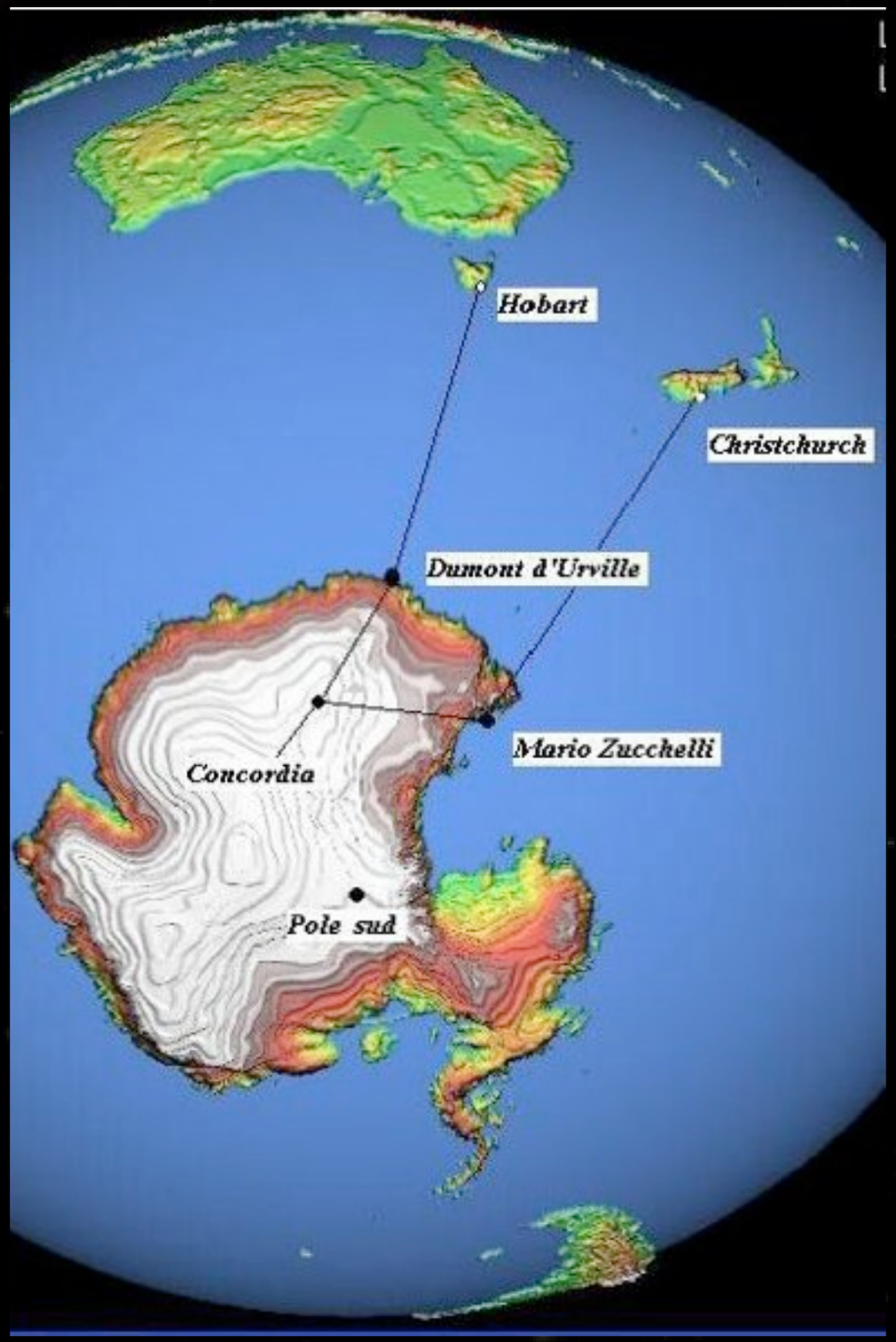
The QUBIC collaboration

APC Paris, France
IAS Orsay, France
CSNSM Orsay, France
CESR Toulouse, 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

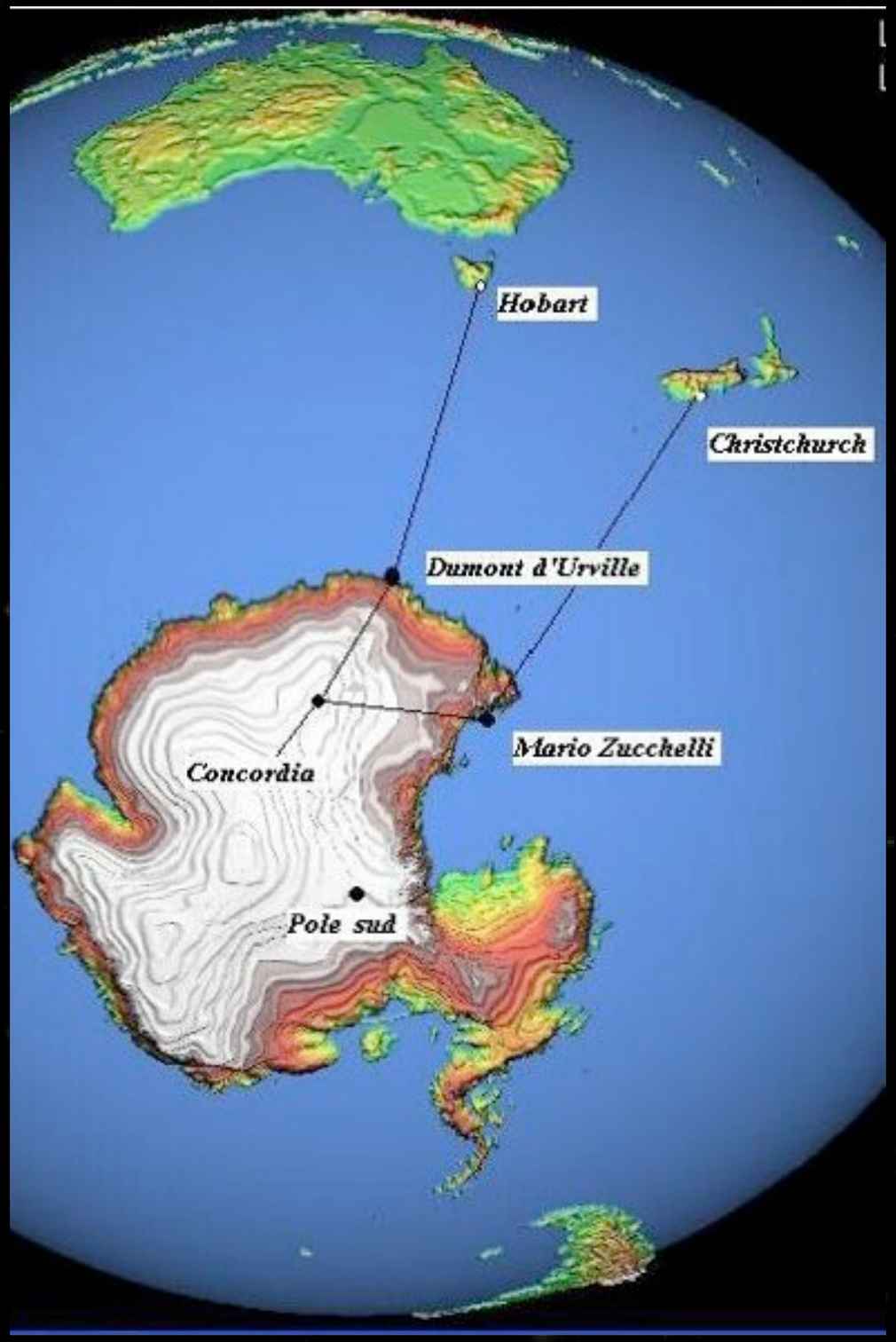
E. Battistelli [e], A. Baú [f], D. Bennett [l], L. Bergé [c], J.-Ph. Bernard [b], P. de Bernardis [e], G. Bordier [a], A. Bounab [b], É. Bréelle [a], E.F. Bunn [j], M. Calvo [e], R. Charlassier [a], S. Collin [c], A. Coppolecchia [e], A. Cruciani [e], G. Curran [l], M. de Petris [e], L. Dumoulin [c], 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

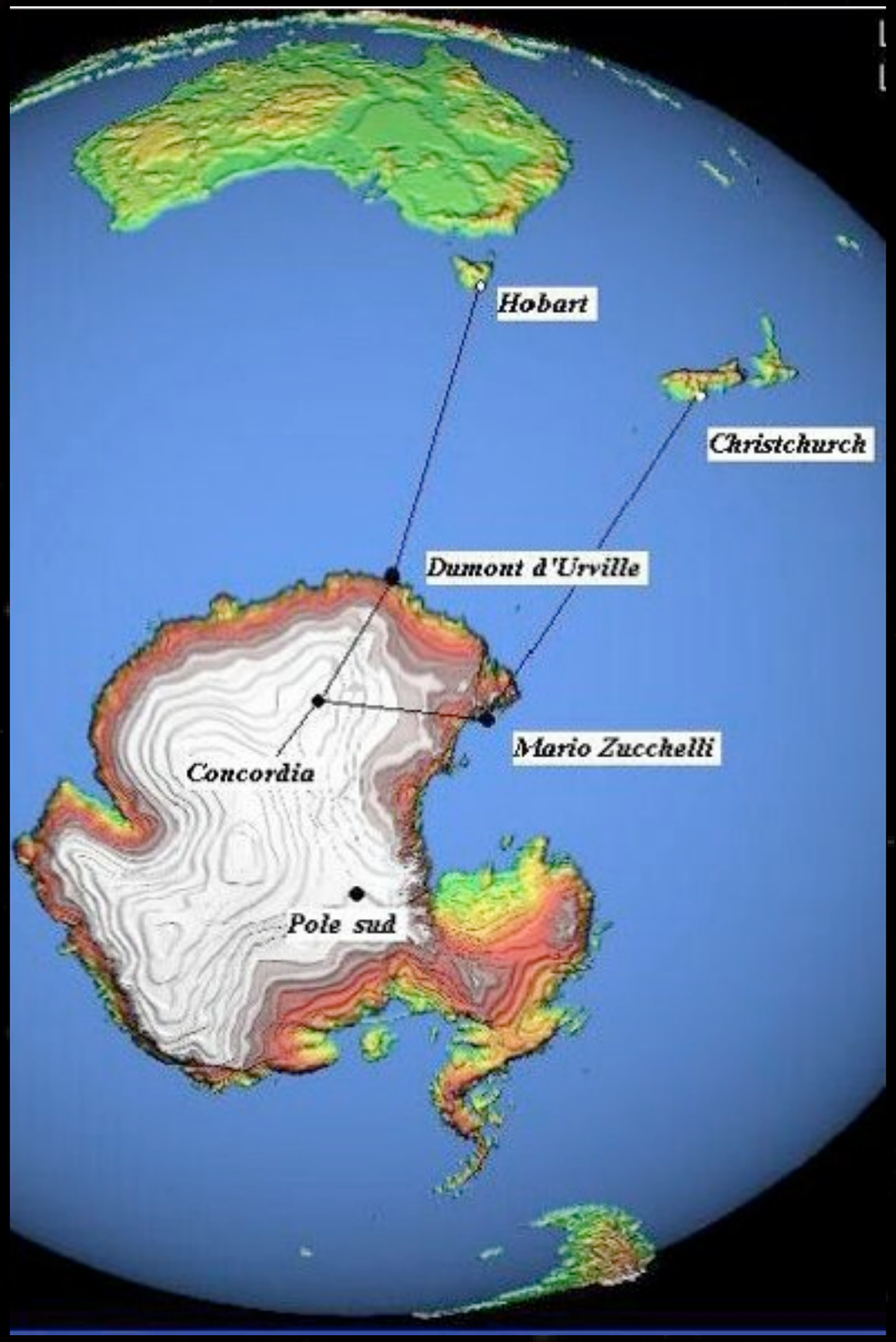


QUBIC Site: Dome C, Antarctica



Great landscape

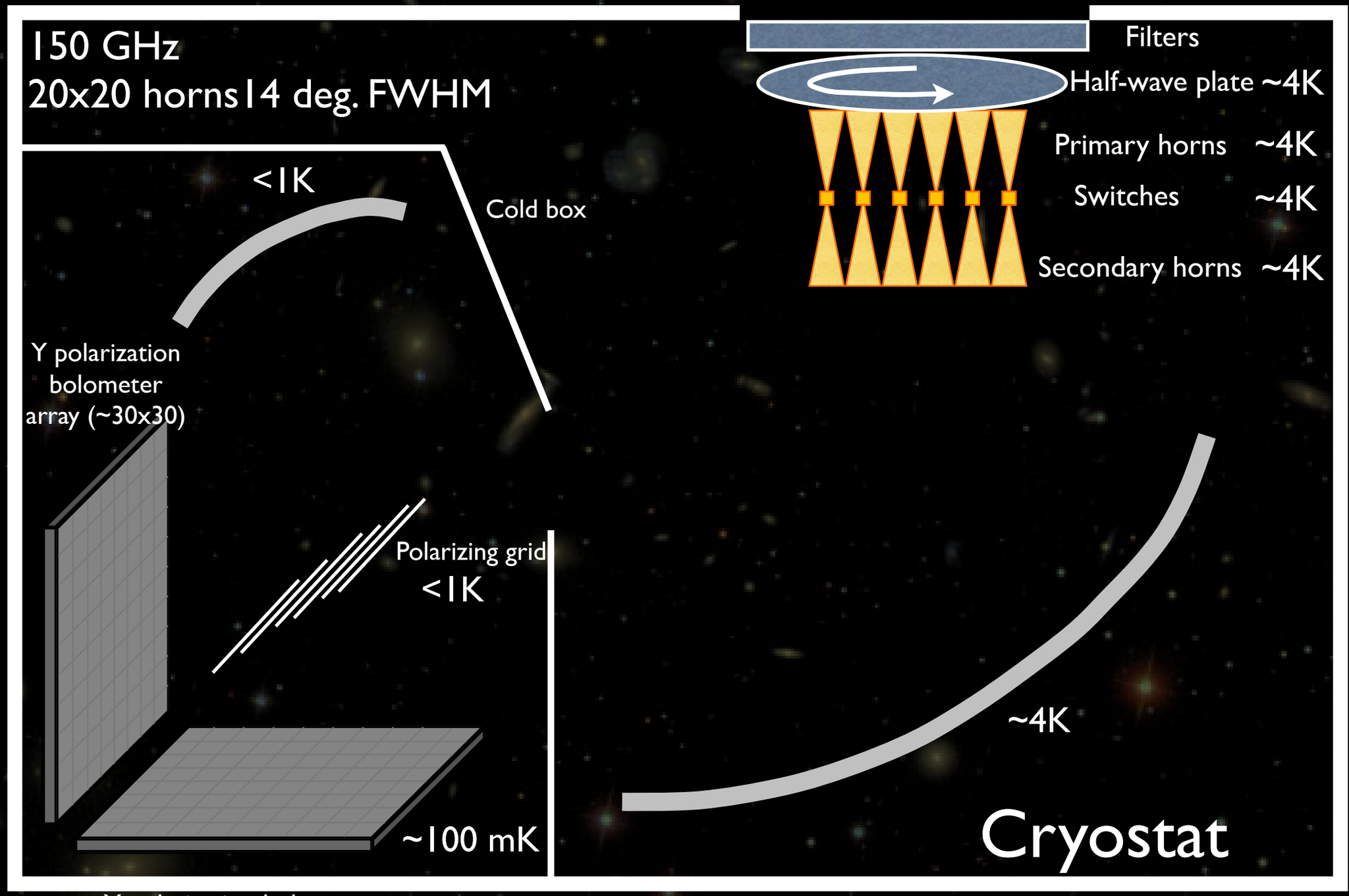
QUBIC Site: Dome C, Antarctica



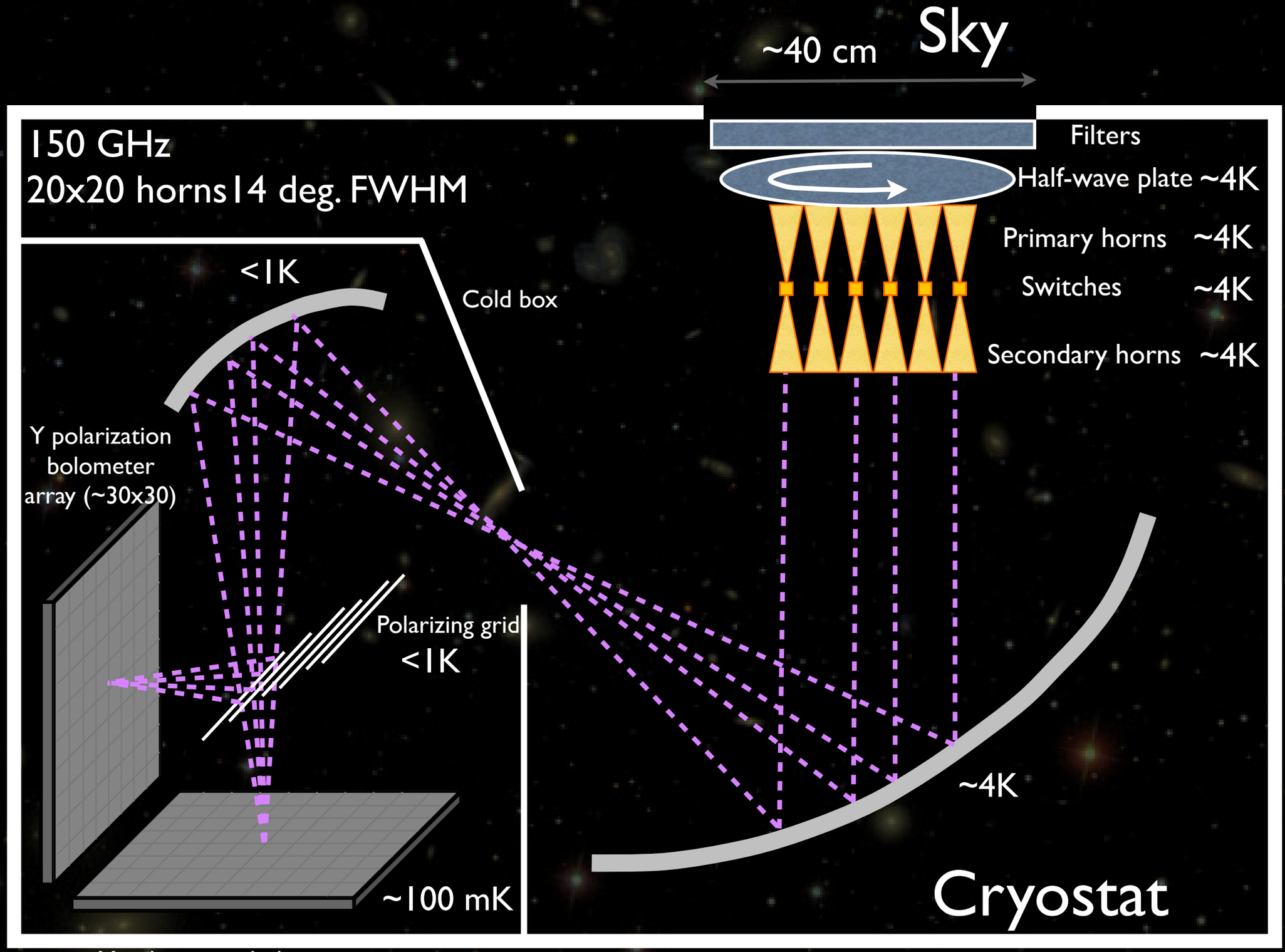
Great landscape

Healthy weather

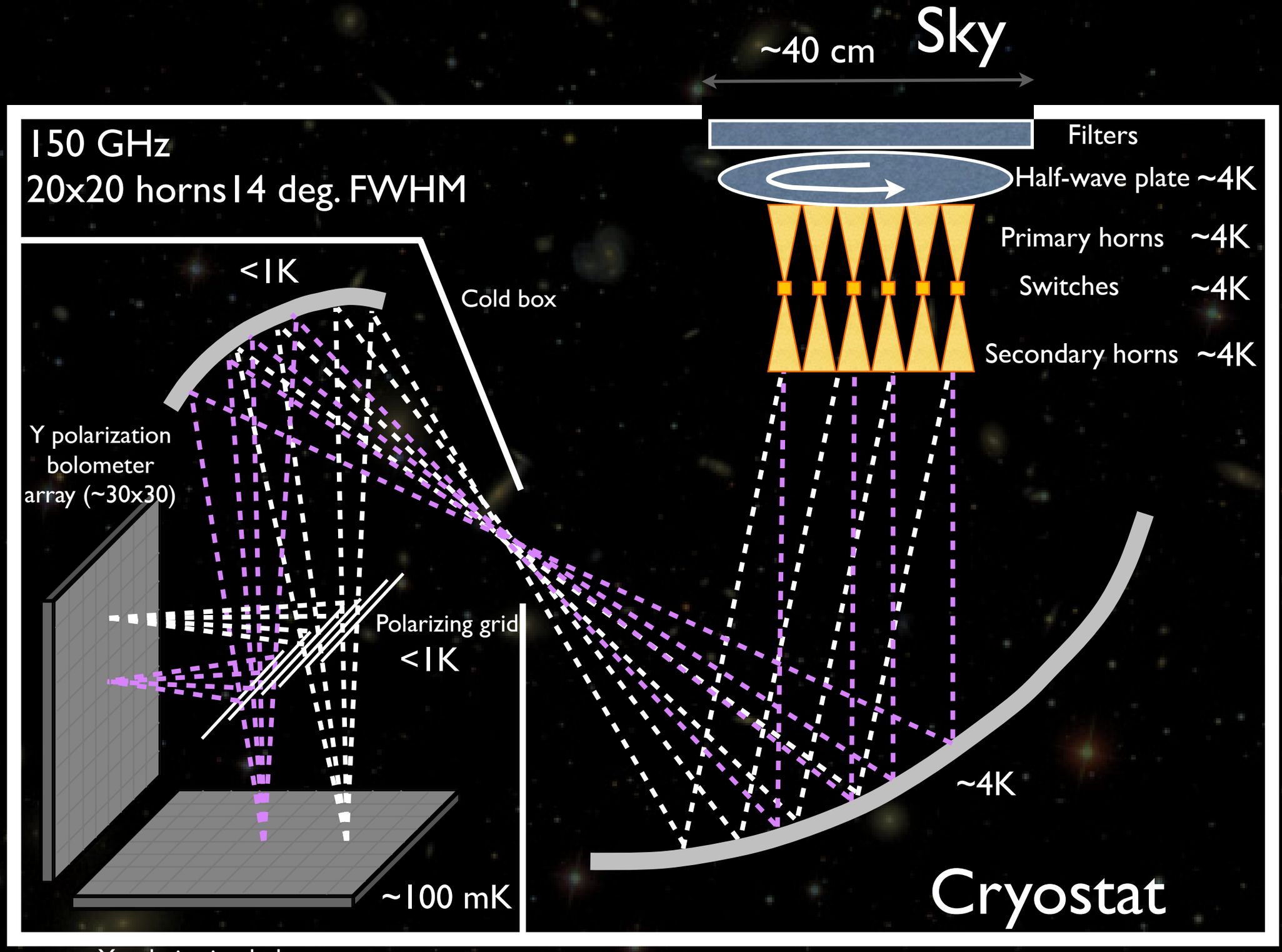
QUBIC design



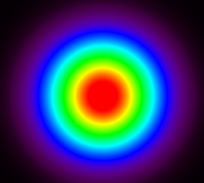
QUBIC design



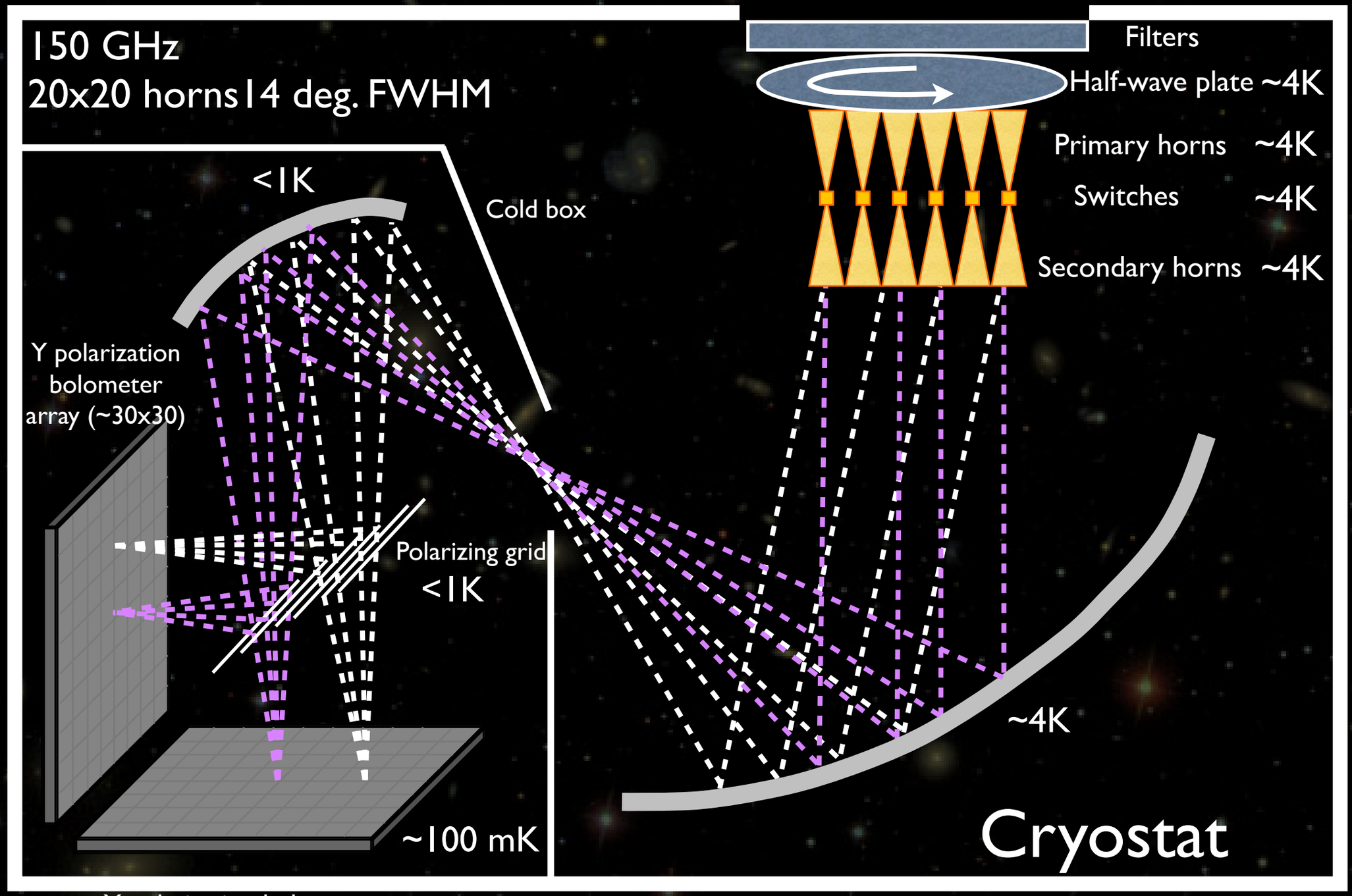
QUBIC design



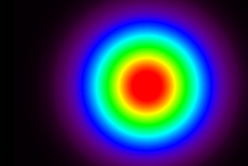
QUBIC design



1 horn open

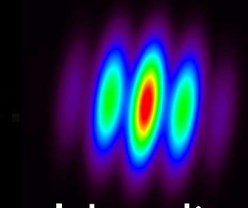


QUBIC design

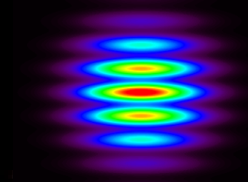


1 horn open

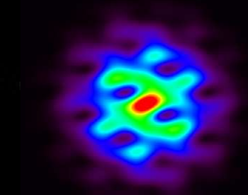
1 baseline



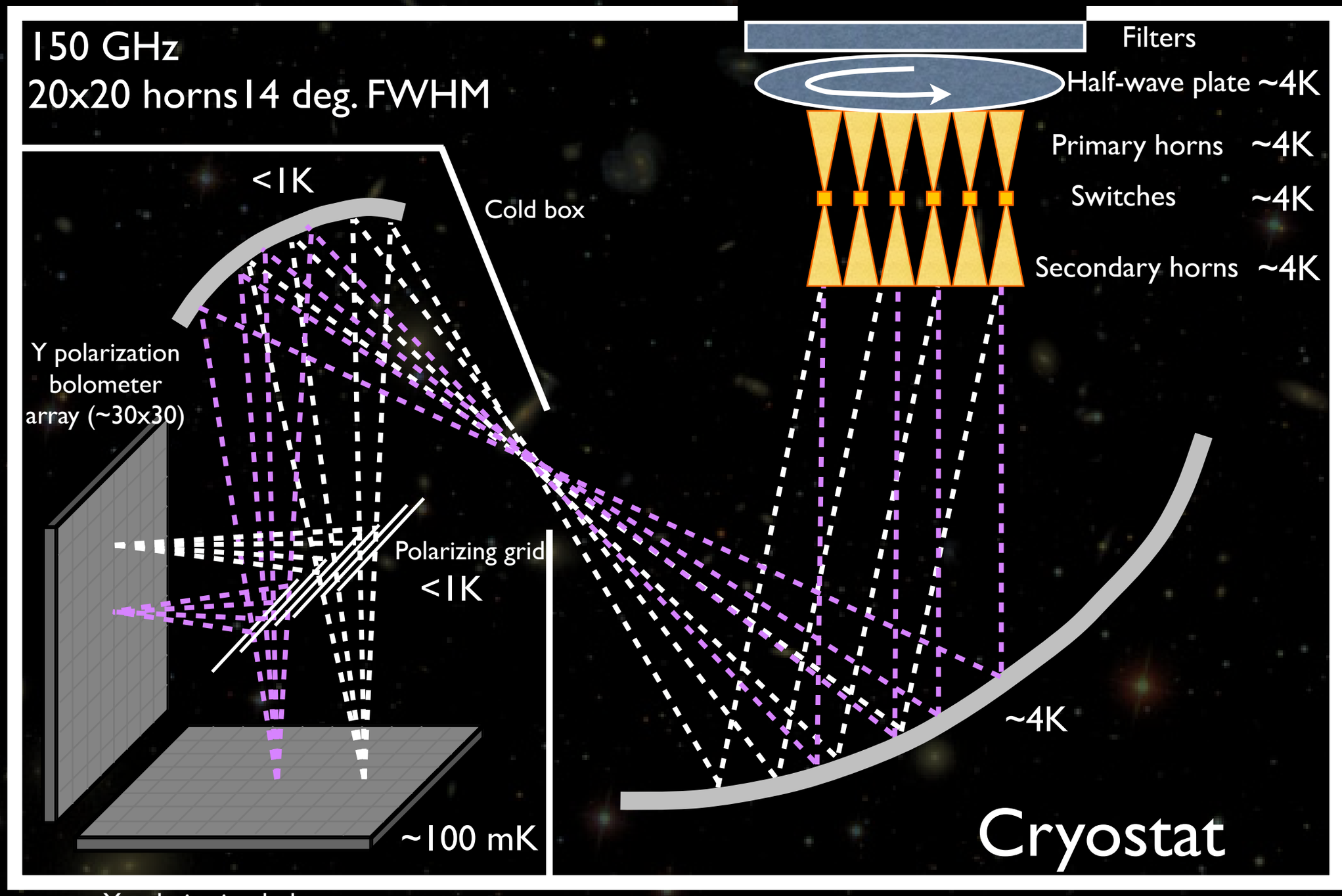
1 baseline



1 baseline



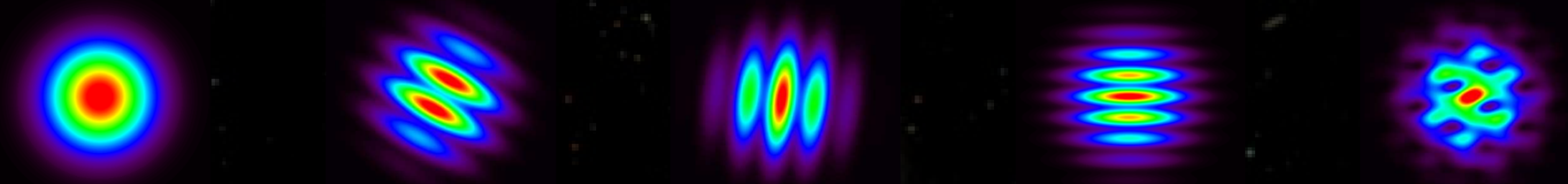
total signal
(all baselines)



Quasi Optical Combiner

- Les images de tous les cornets sont superposées sur la matrice de bolomètres

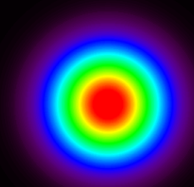
- On forme des franges d'interférence



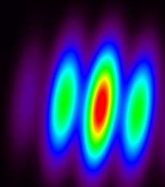
1 cornet | 1 ligne de base | 1 ligne de base | 1 ligne de base | signal final

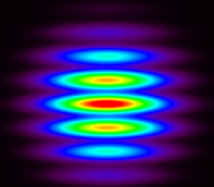
Quasi Optical Combiner

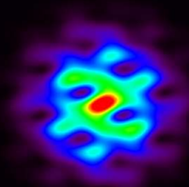
- Les images de tous les cornets sont superposées sur la matrice de bolomètres
- On forme des franges d'interférence


1 cornet

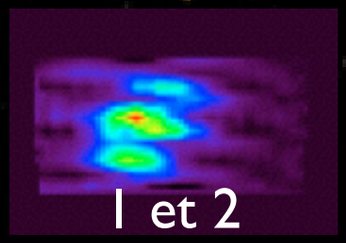

1 ligne de base

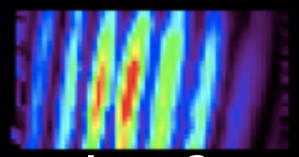

1 ligne de base

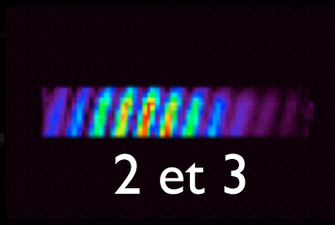

1 ligne de base

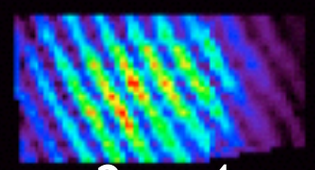

signal final

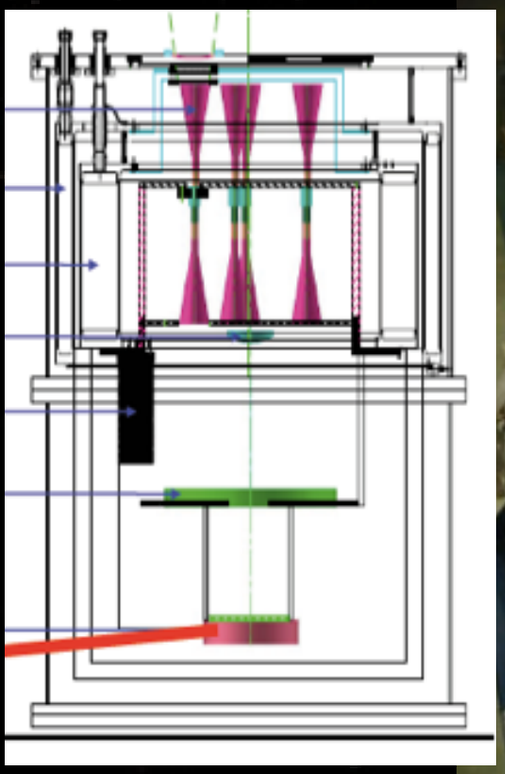
Données MBI-4 campagne 2009 (PBO- Wisc.)


1 et 2


1 et 3


2 et 3


2 et 4

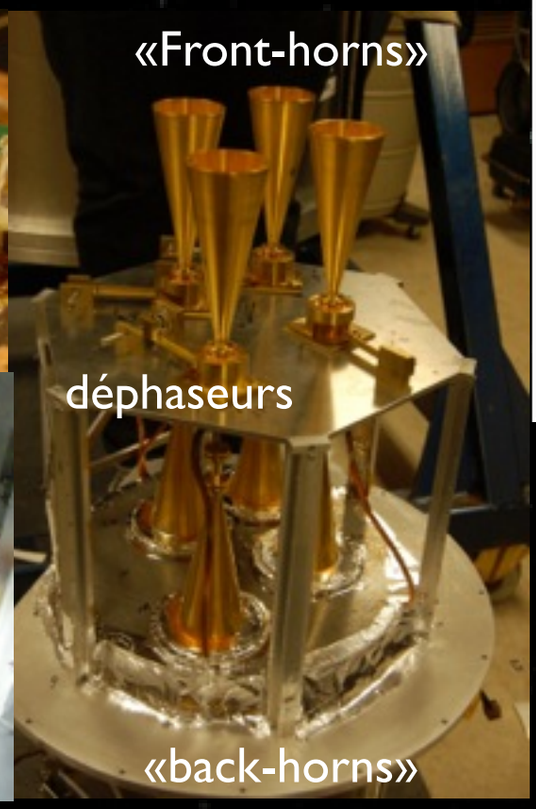



Cryostat MBI-4


Plan focal (bolomètres)

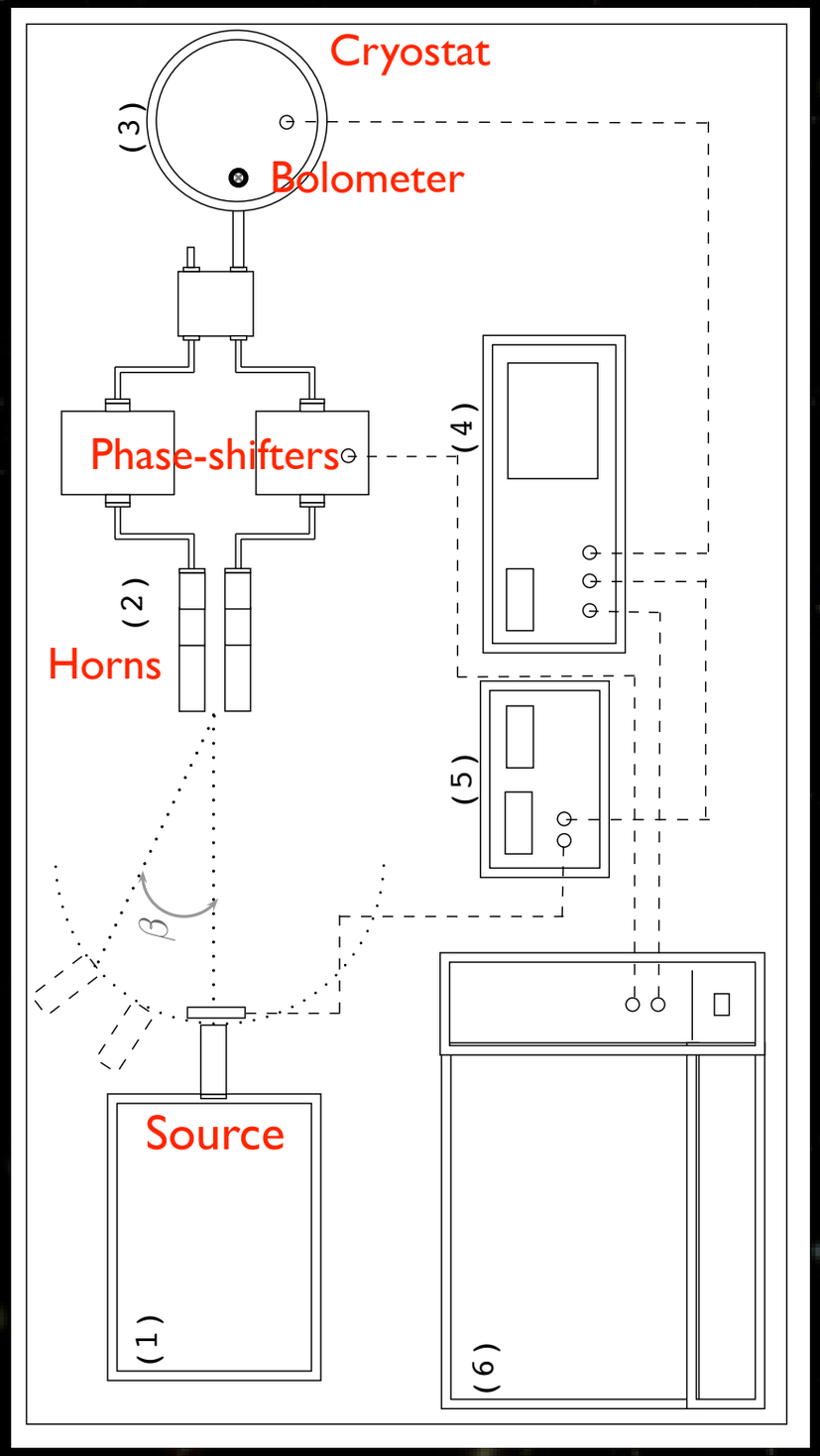

Miroir secondaire et sortie des «back-horns»

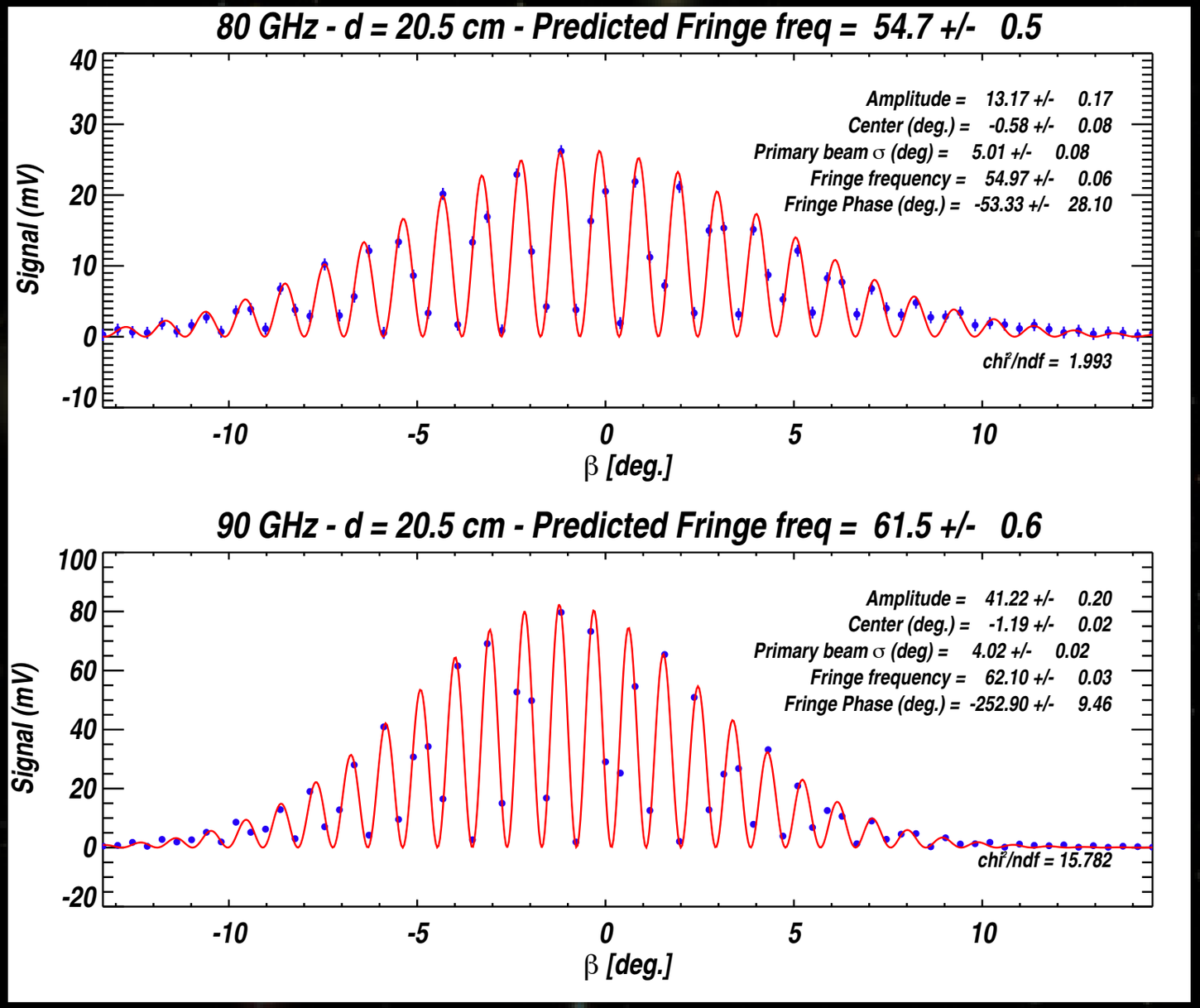
«Front-horns»


déphaseurs

«back-horns»

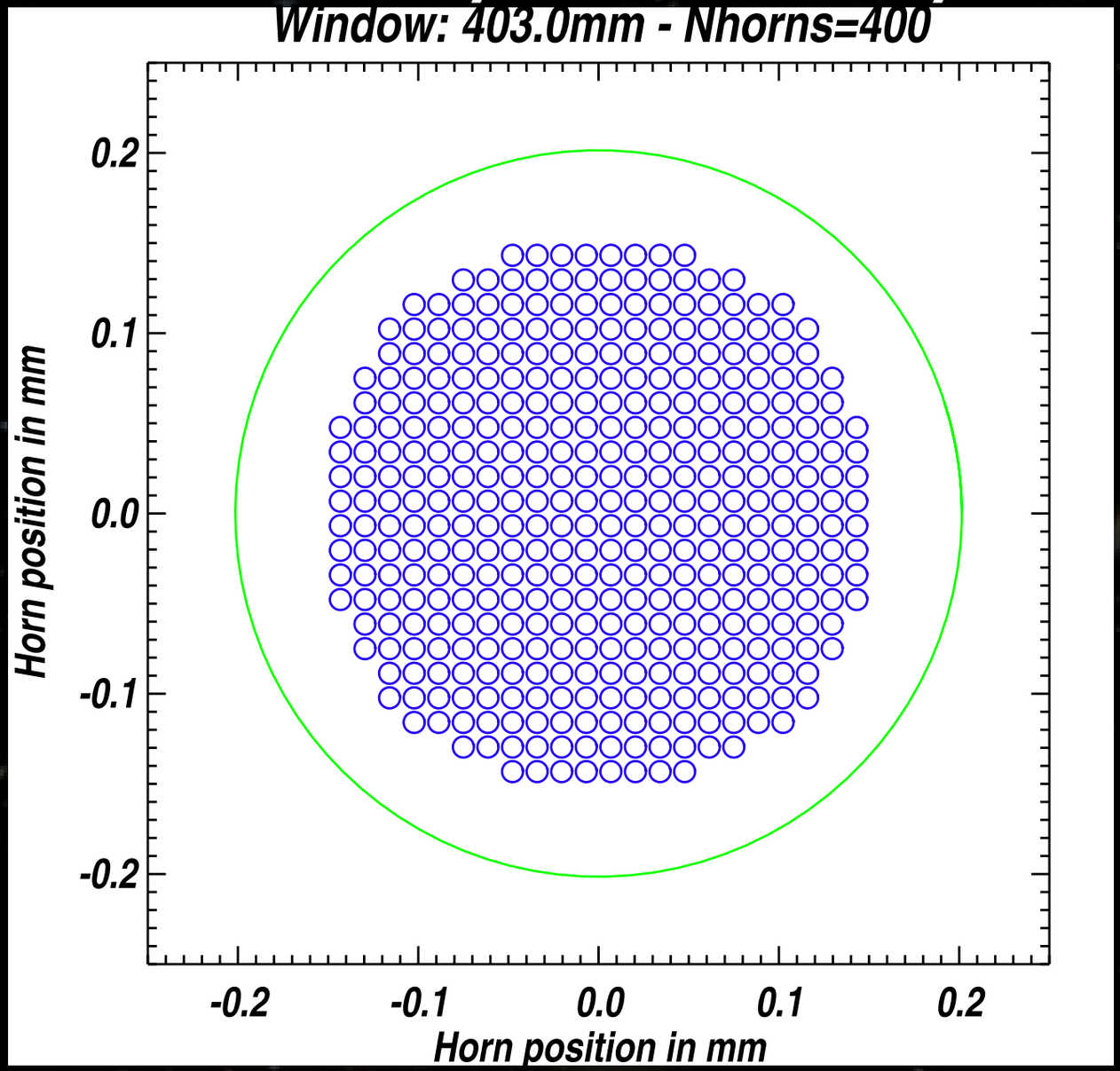
Also observed with DIBO@APC



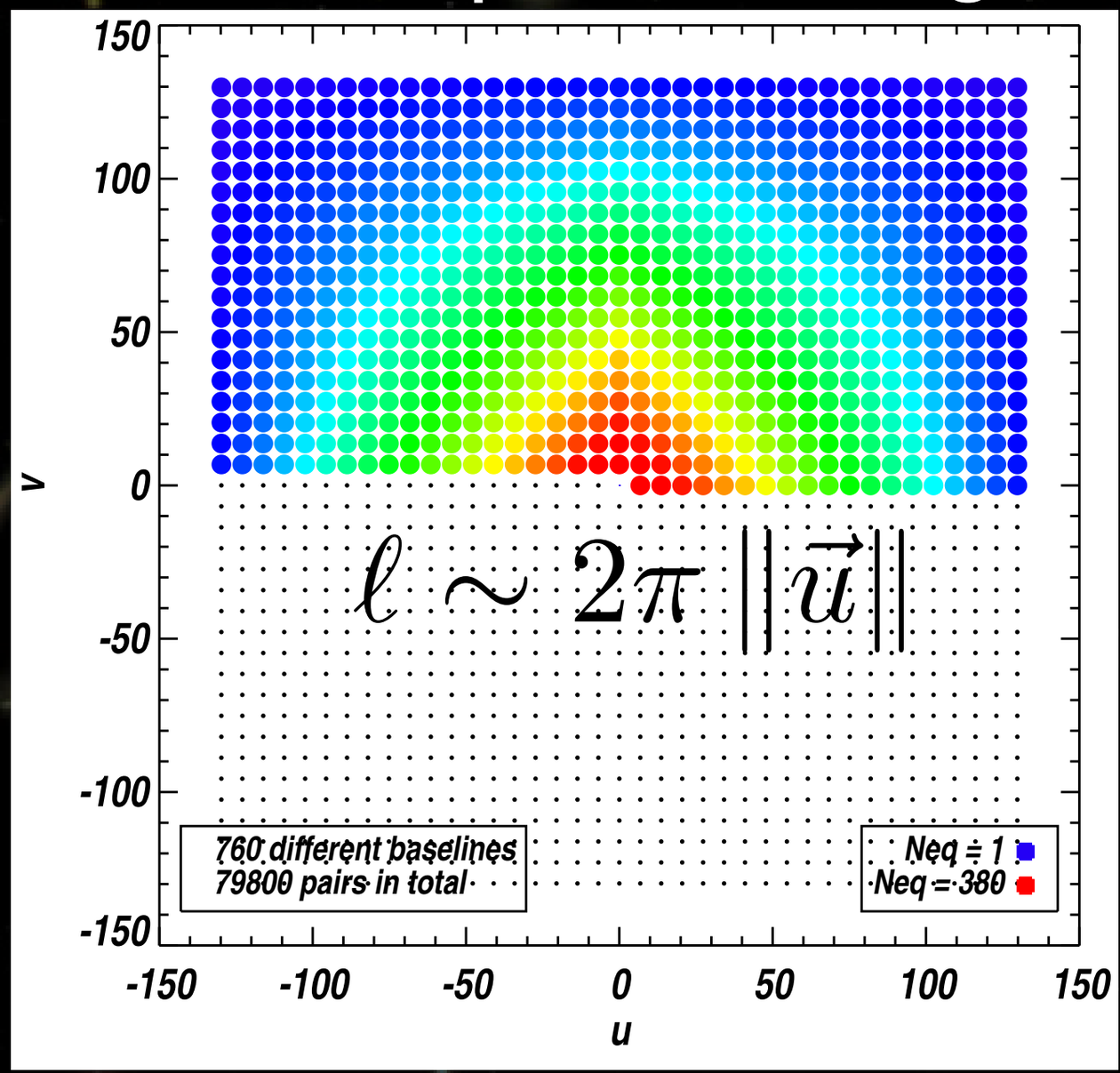


Horns and baselines

Primary horns array



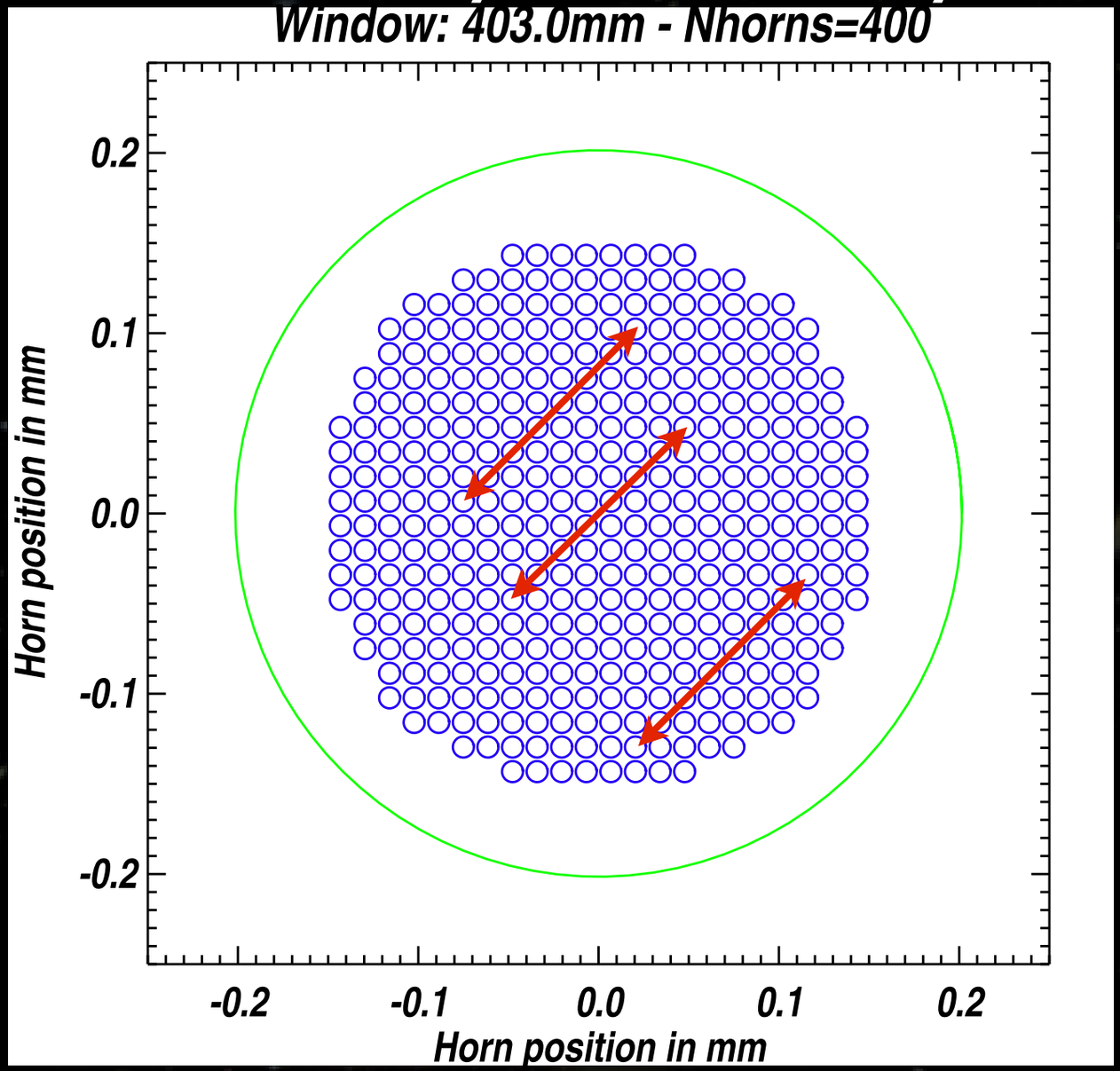
Fourier plane coverage



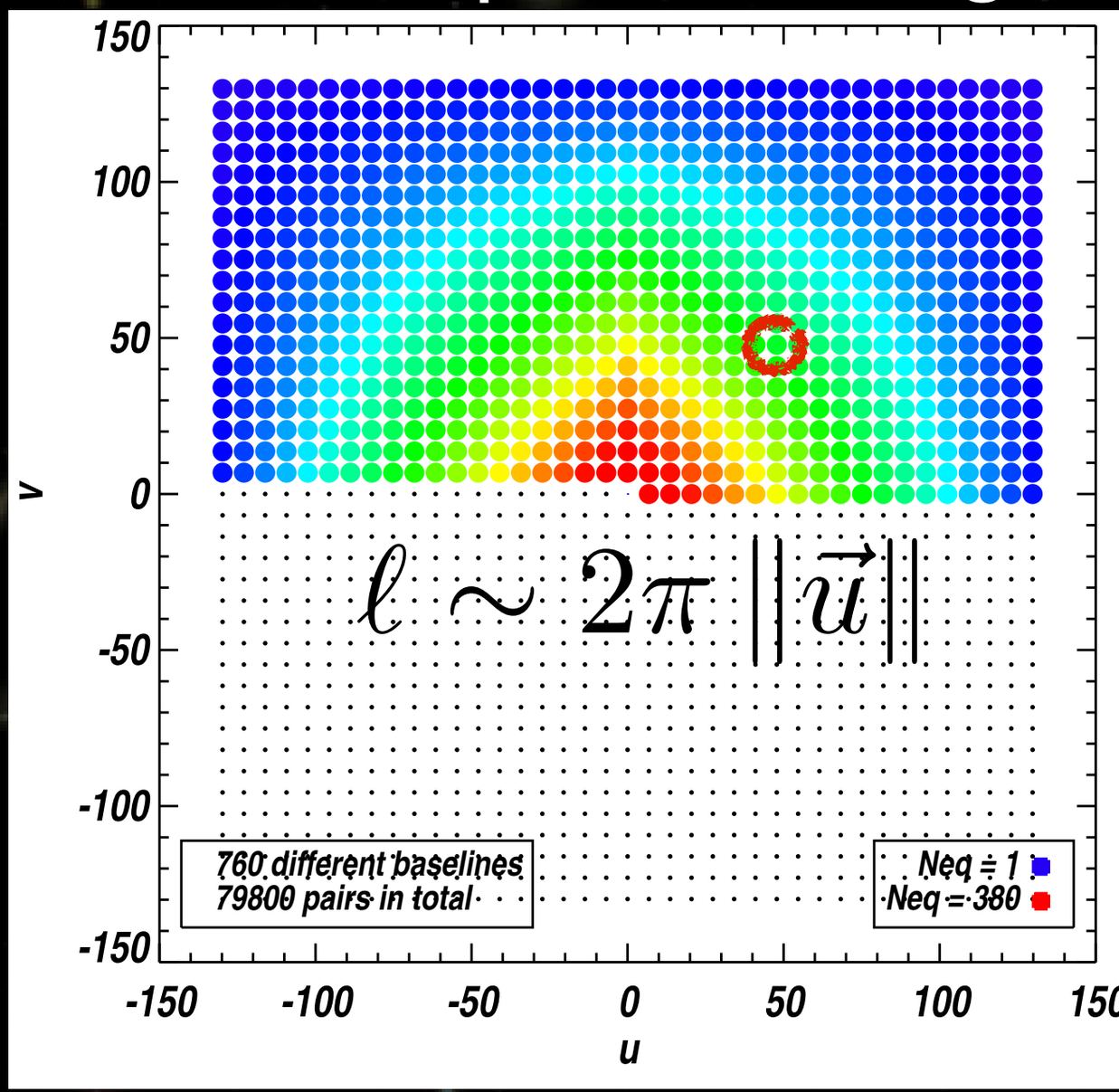
150 GHz, 20x20 horns, 14 deg. FWHM, D=1.2 cm

Horns and baselines

Primary horns array



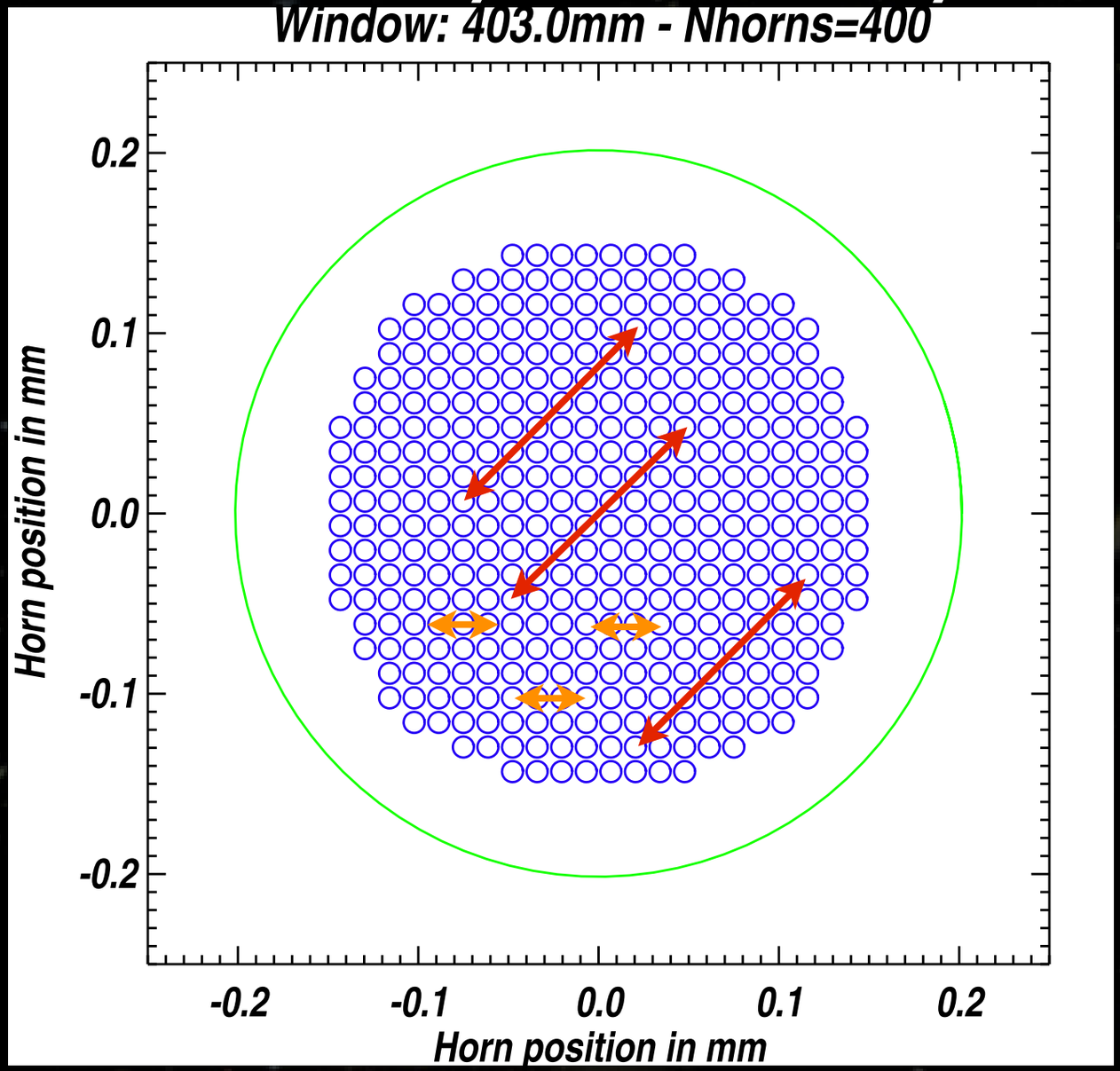
Fourier plane coverage



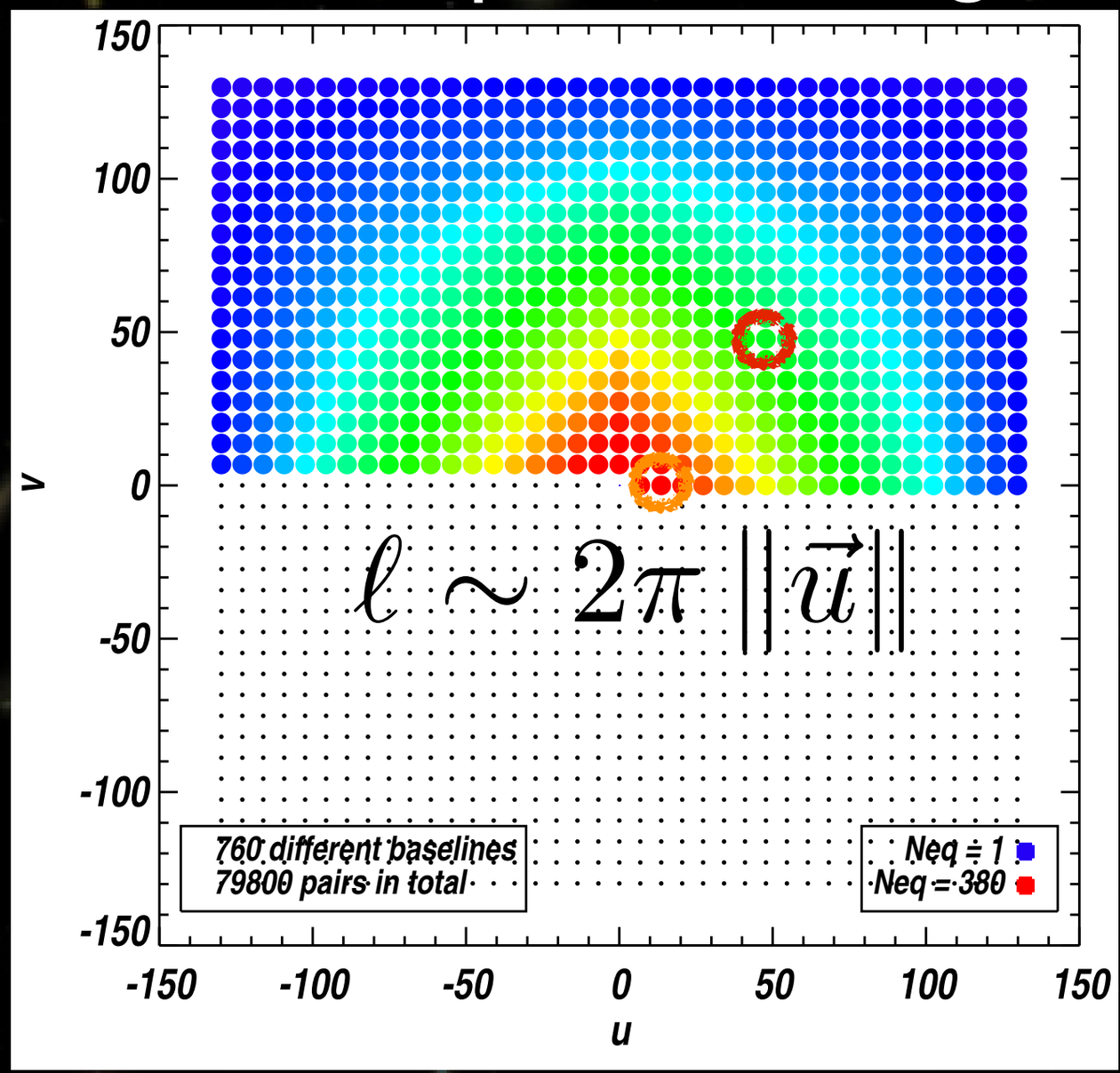
150 GHz, 20x20 horns, 14 deg. FWHM, D=1.2 cm

Horns and baselines

Primary horns array



Fourier plane coverage



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

Signal in QUBIC

- Signal on bolometer d_p (HWP modulation) :

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

- 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)

$$B_s^p(\vec{n}) = B_{\mathrm{prim}}(\vec{n}) \int\int B_{\mathrm{sec}}(\vec{d}) \times \left| \sum_i \exp\left[i2\pi \frac{\vec{x}_i}{\lambda} \cdot \left(\frac{d}{D_f} - \vec{n} \right) \right] \right|^2 J(\vec{\nu}) \Theta(\vec{d} - \vec{d}_p) \mathrm{d}\nu \mathrm{d}\vec{d}$$

Signal in QUBIC

- Signal on bolometer d_p (HWP modulation) :

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

- 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

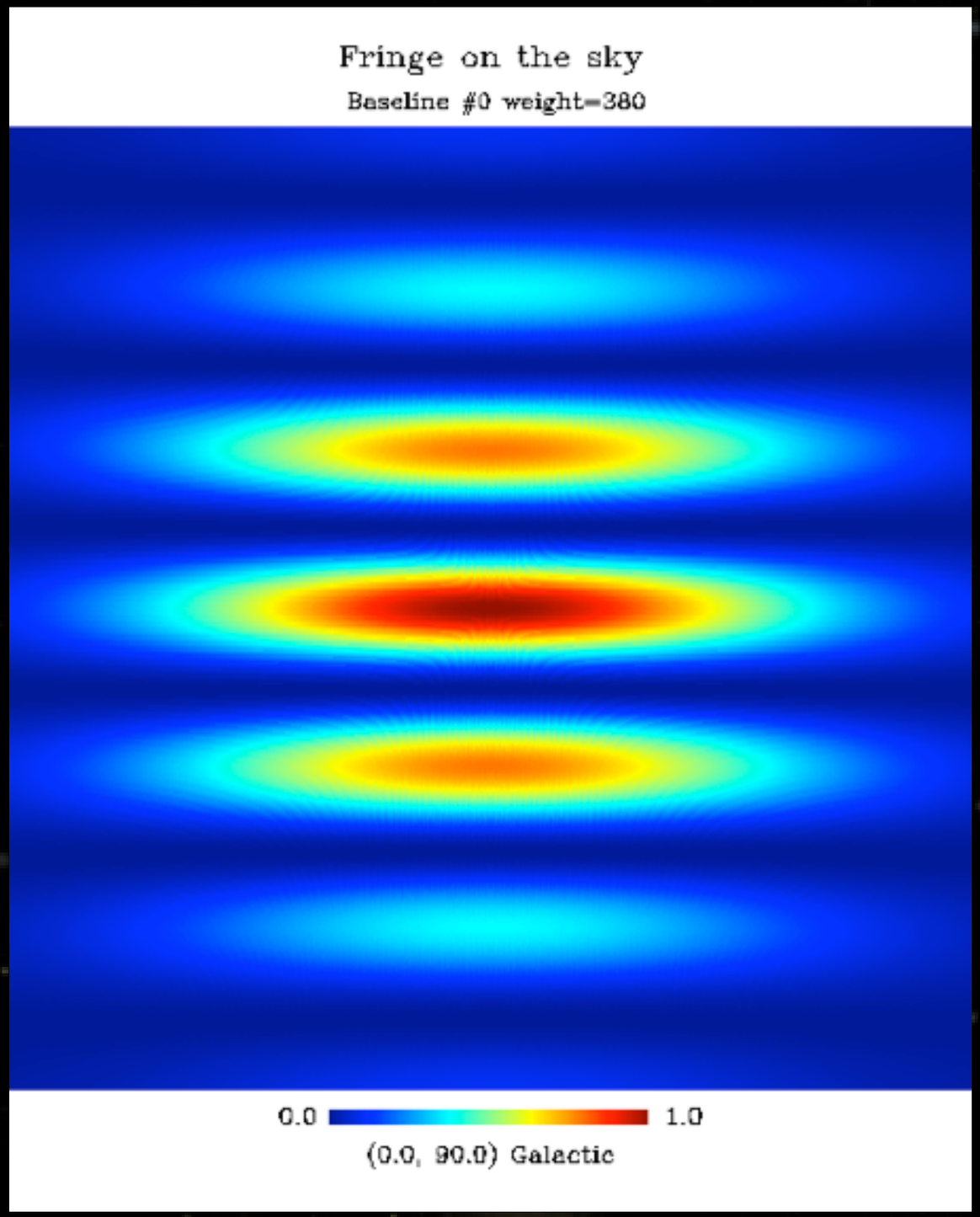
★ (x_i = locations of primary horns, D_f = focal length of the combiner)

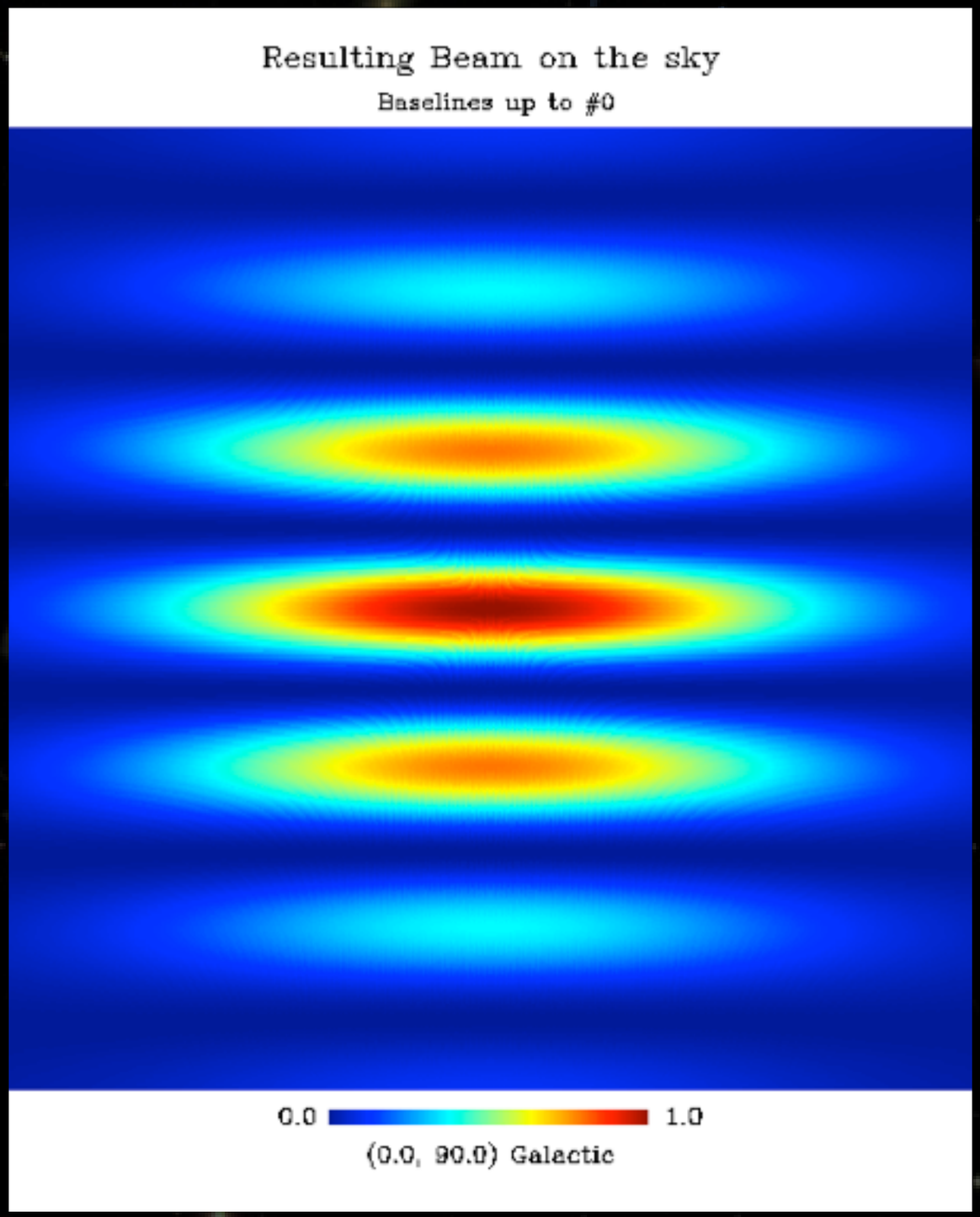
$$B_s^p(\vec{n}) = B_{\rm prim}(\vec{n}) \int\int B_{\rm sec}(\vec{d}) \times \left| \sum_i \exp\left[i2\pi \frac{\vec{x}_i}{\lambda} \cdot \left(\frac{d}{D_f} - \vec{n} \right) \right] \right|^2 J(\vec{\nu}) \Theta(\vec{d} - \vec{d}_p) \mathrm{d}\nu \mathrm{d}\vec{d}$$

QUBIC is an imager where the pupil has been filled with holes in order to filter the sky in Fourier space

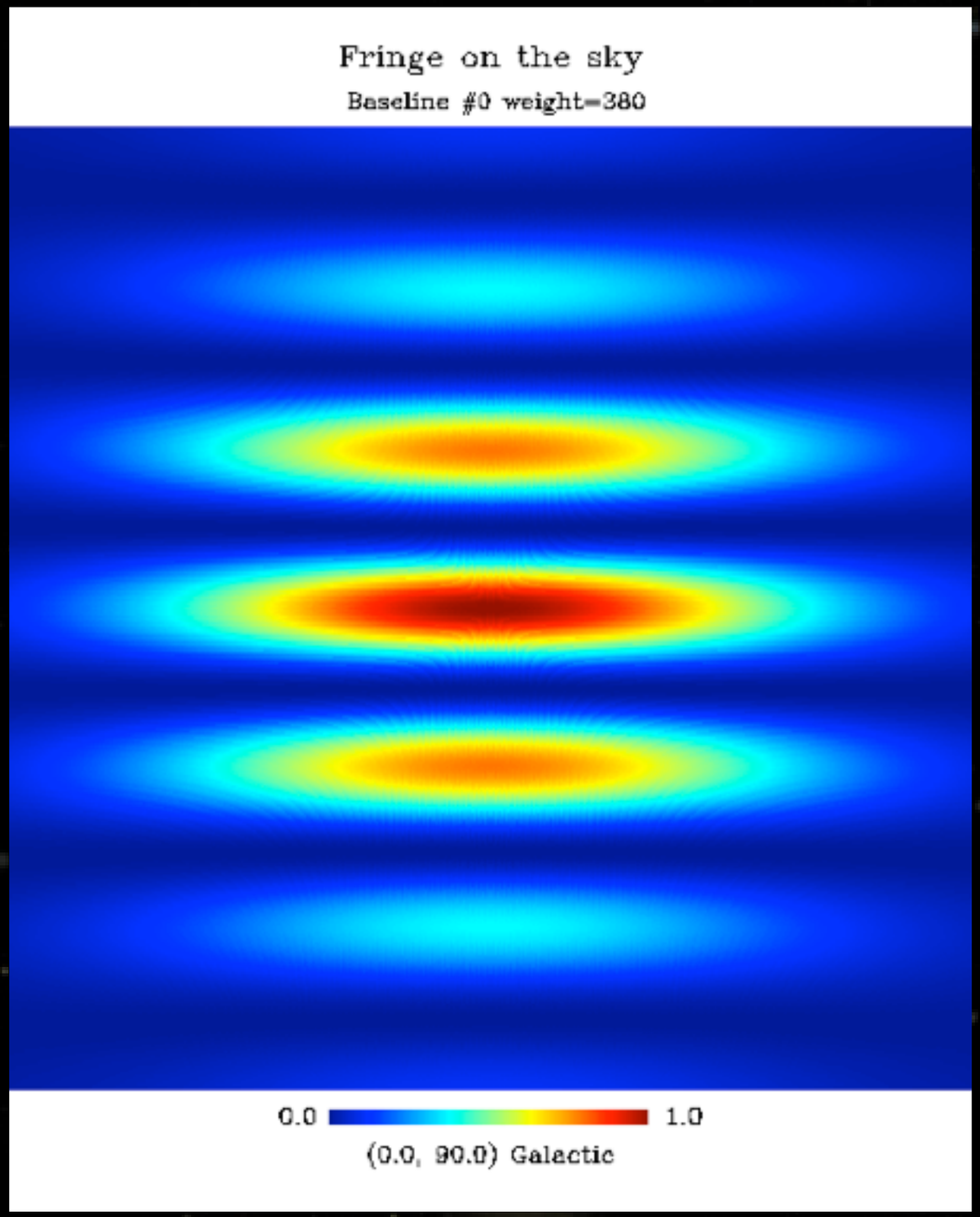
⇔ An imager with the synthesized beam

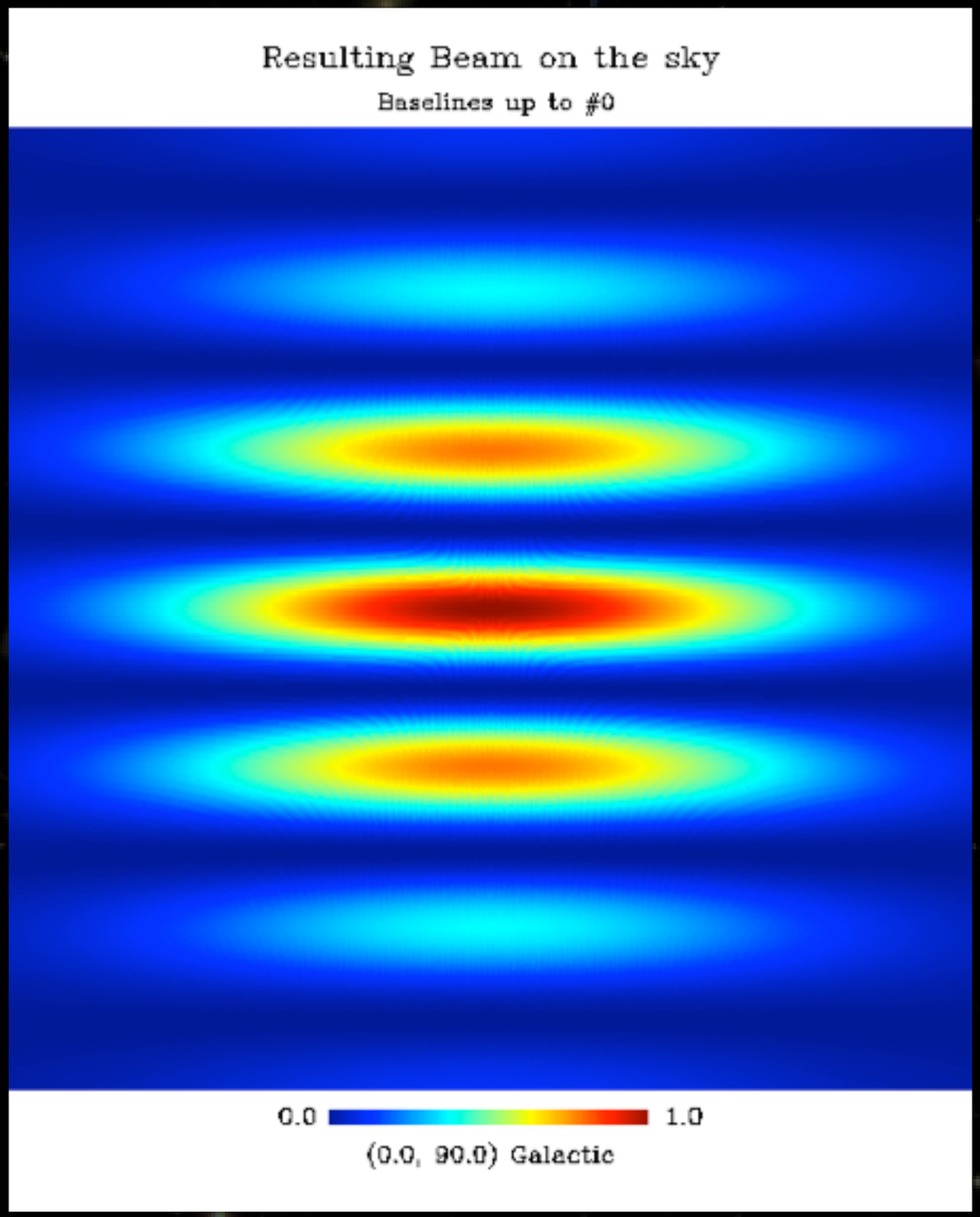
Synthesized beam on the sky



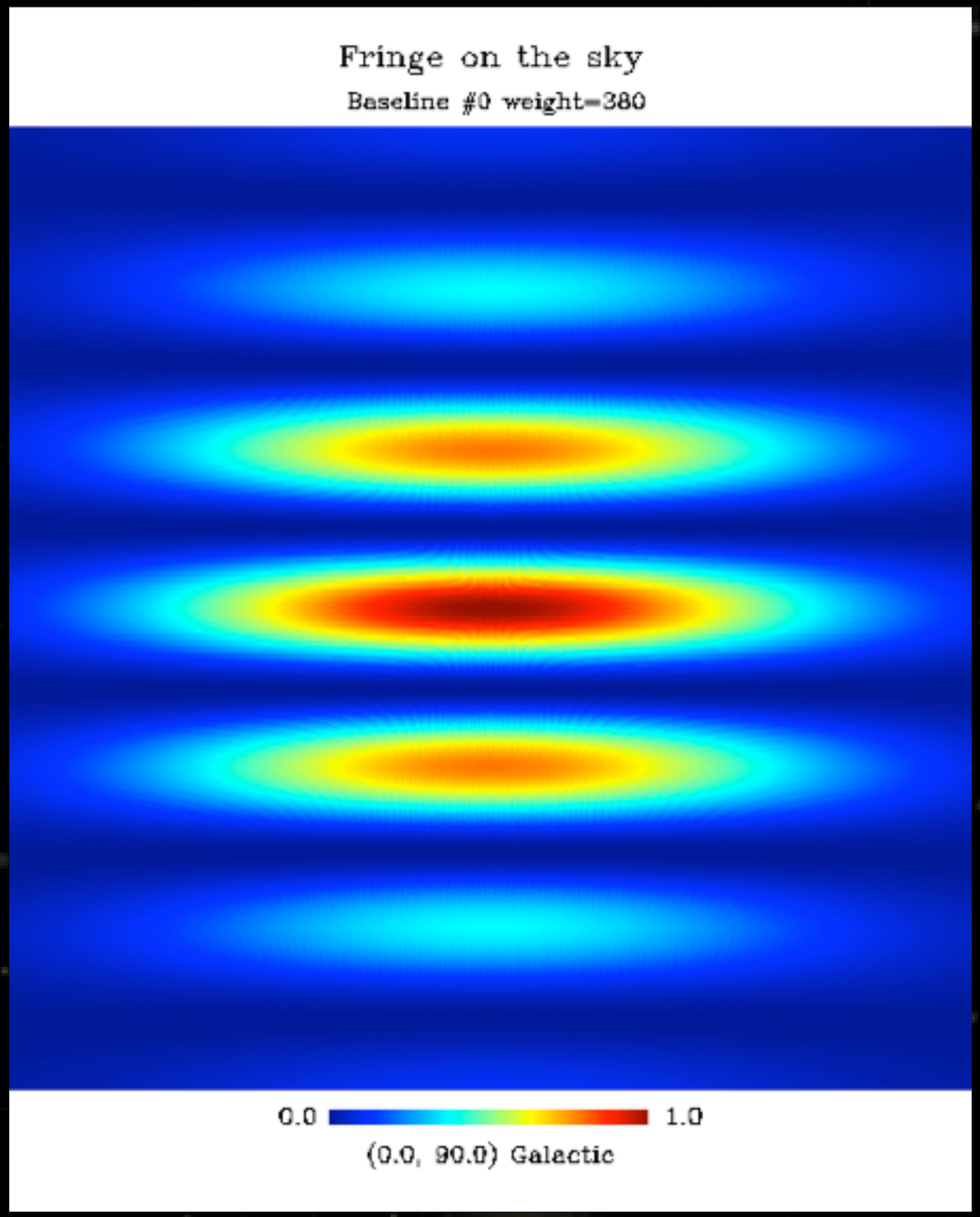


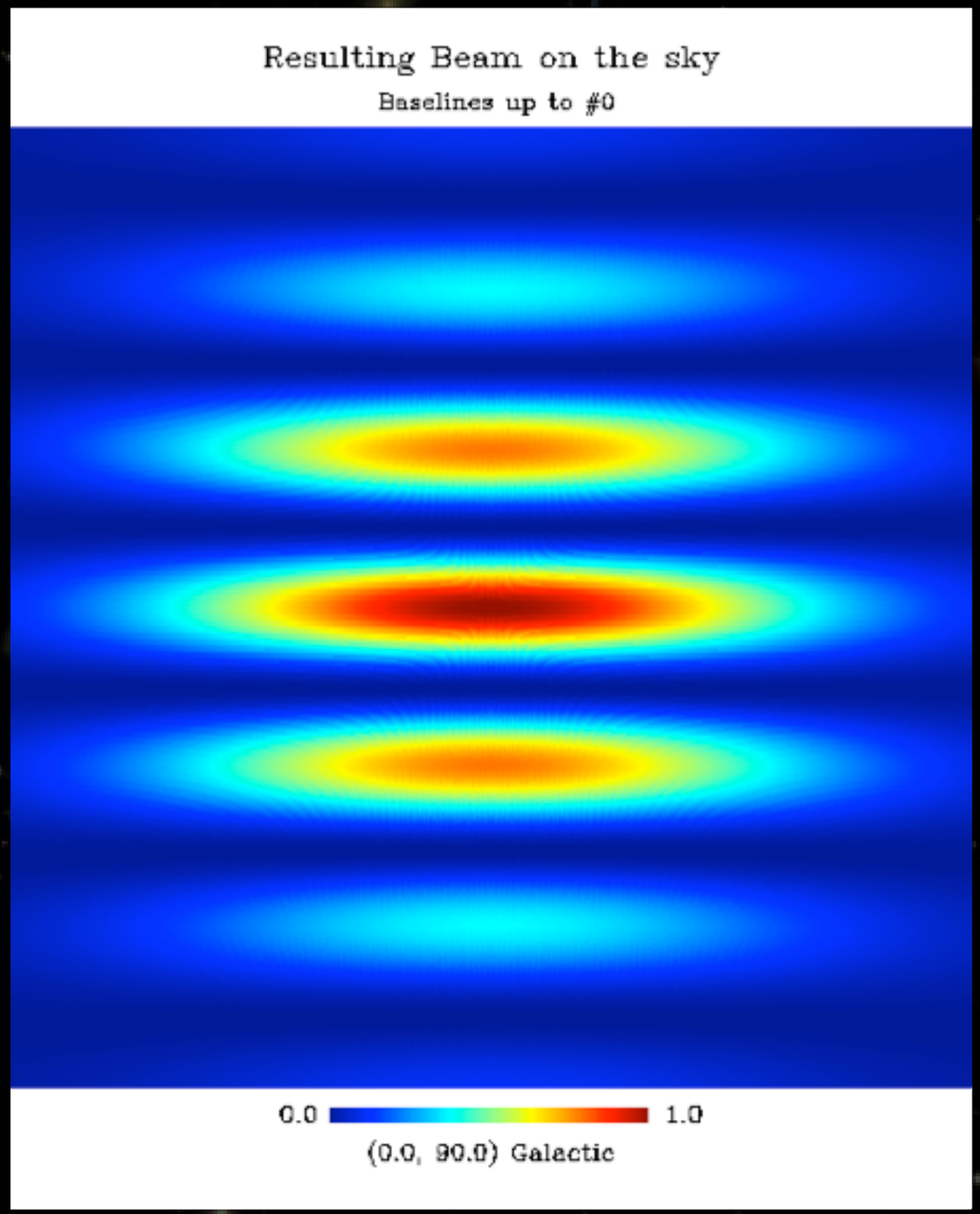
Synthesized beam on the sky



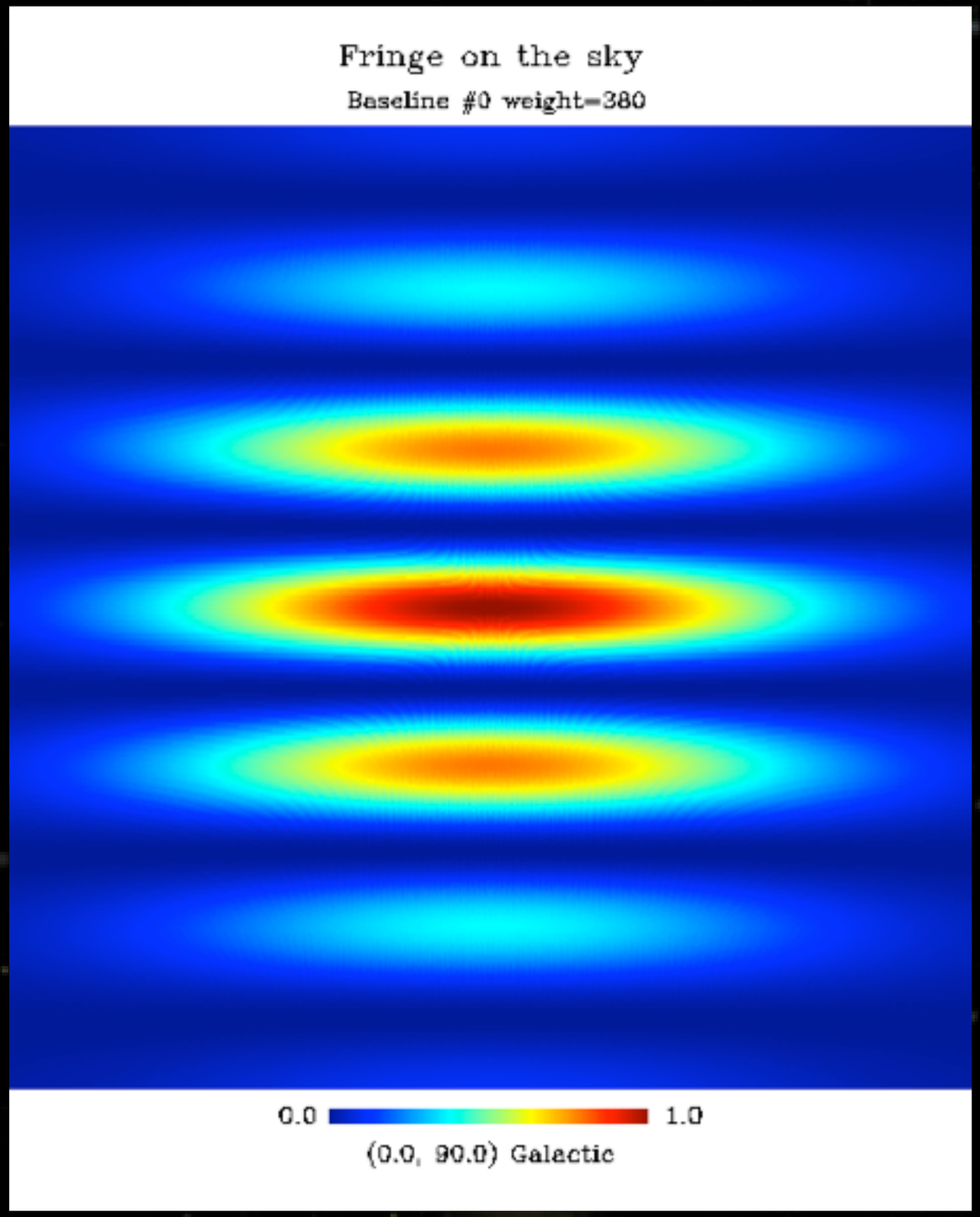


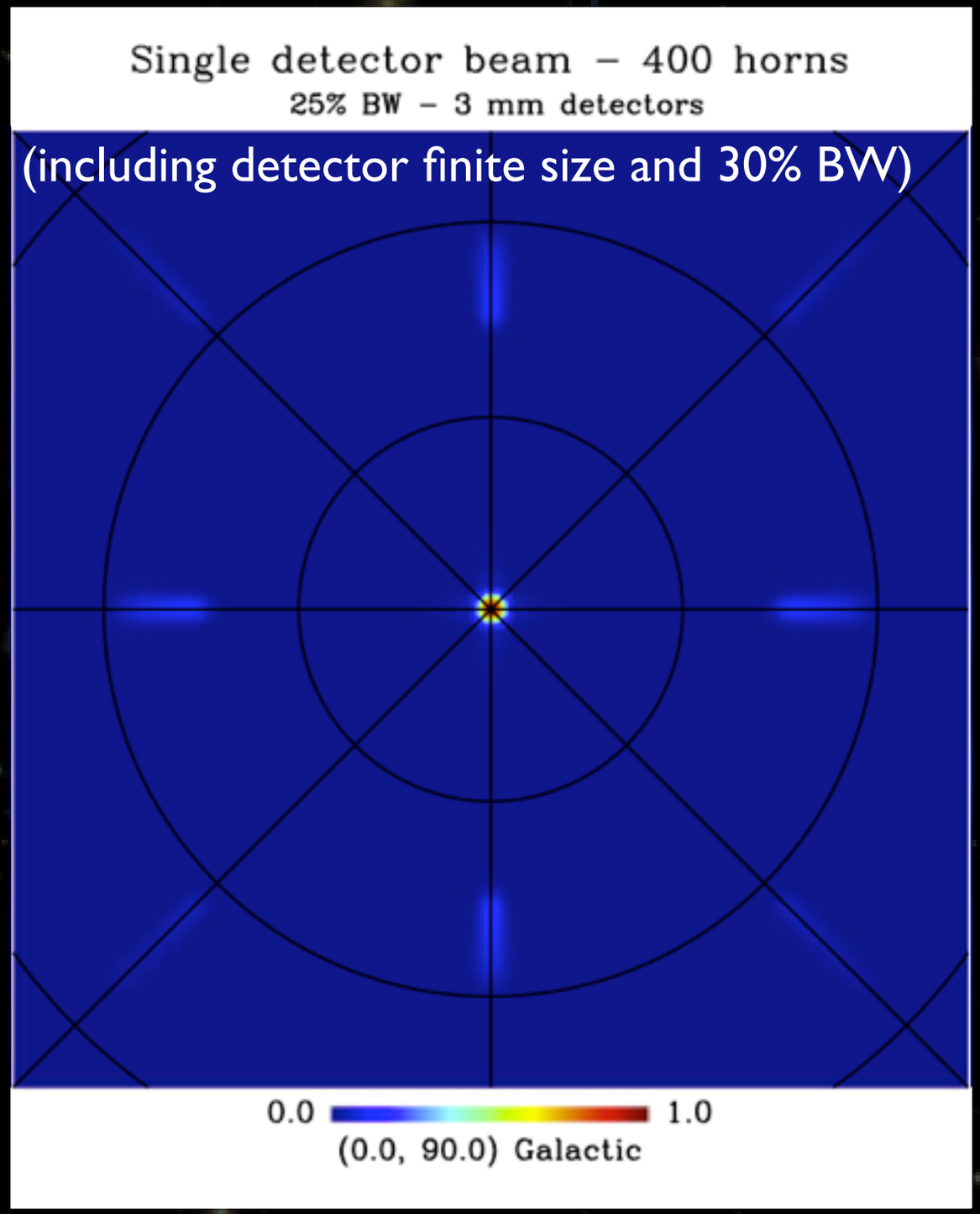
Synthesized beam on the sky



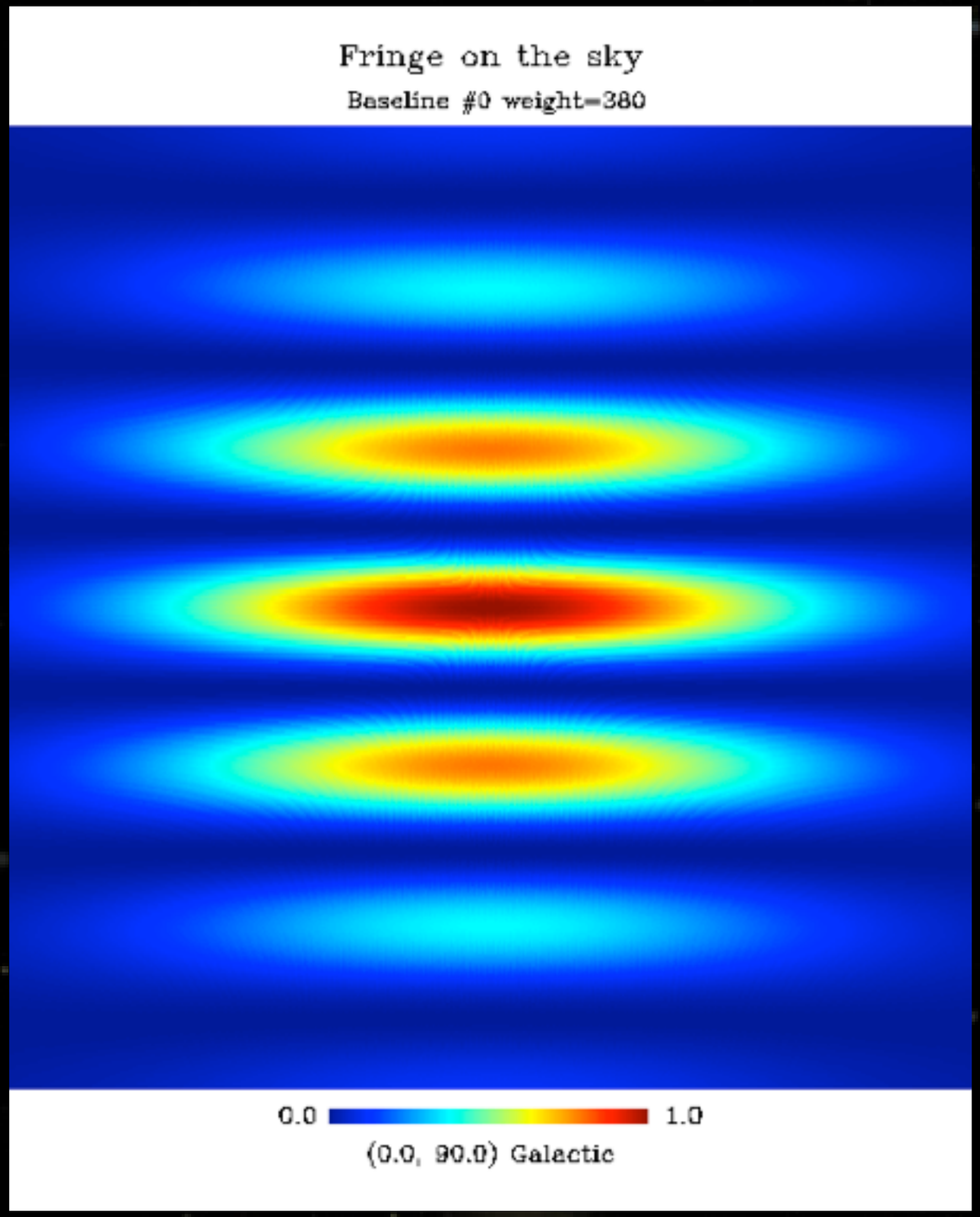


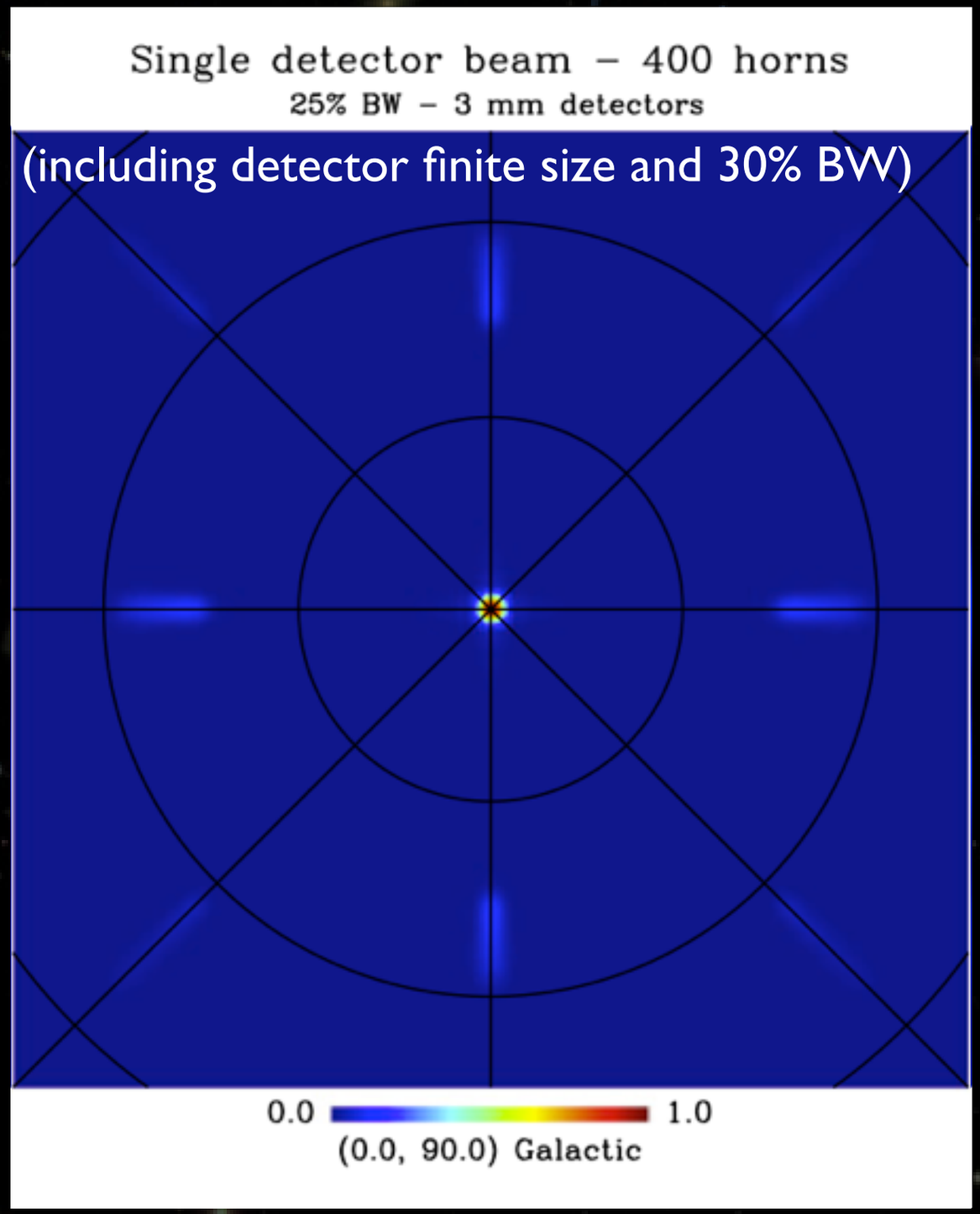
Synthesized beam on the sky



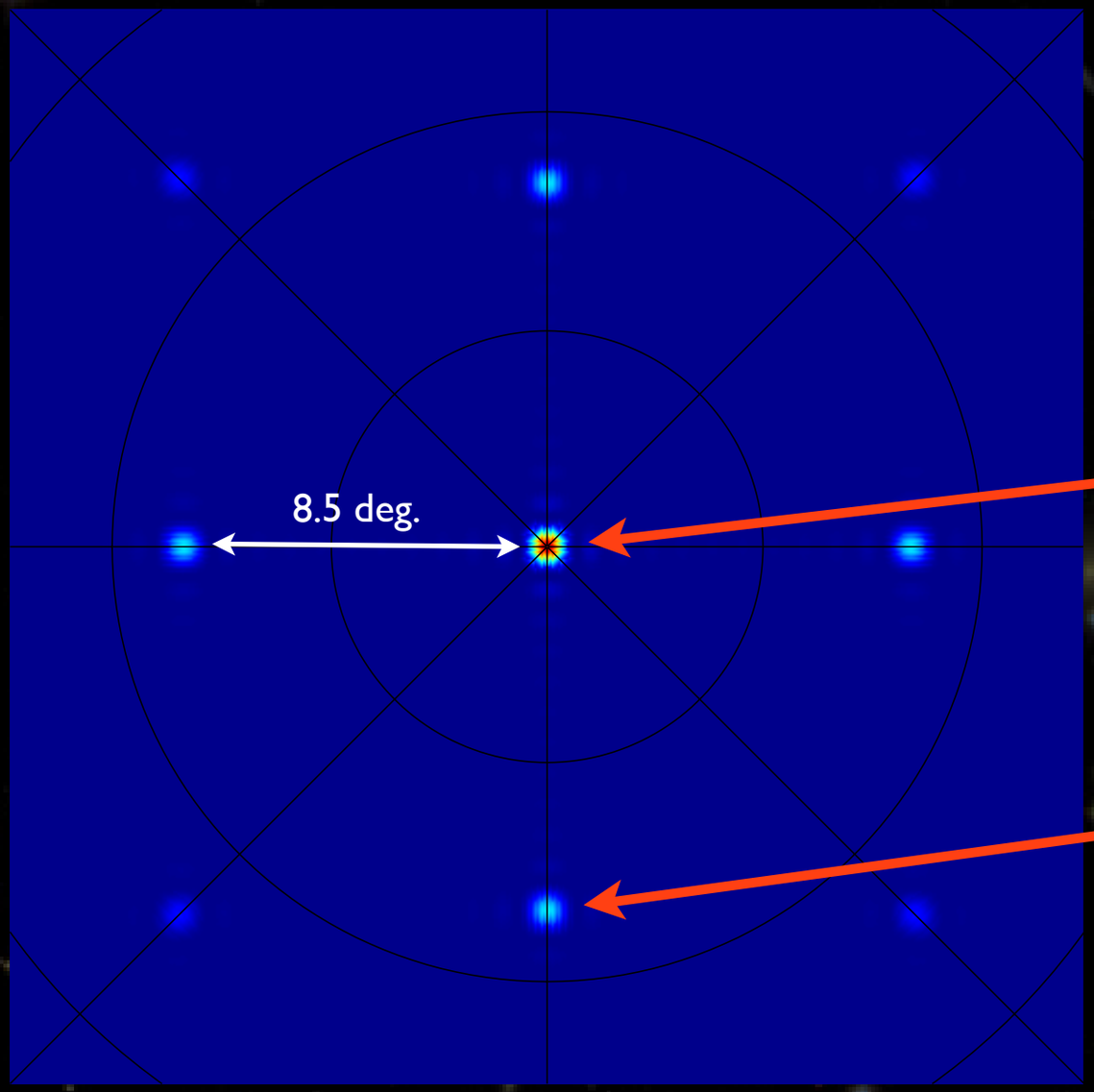


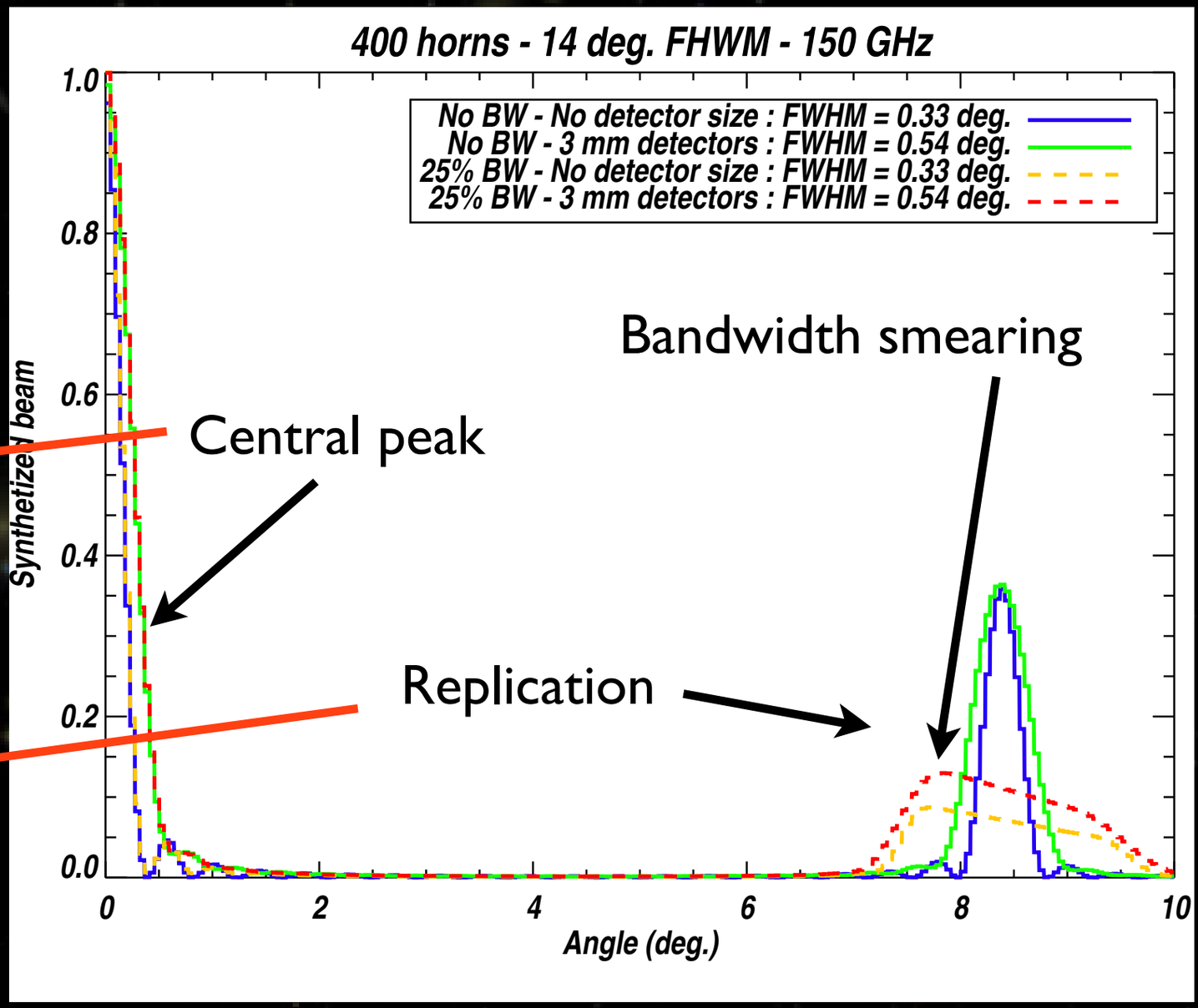
Synthesized beam on the sky





Synthesized beam



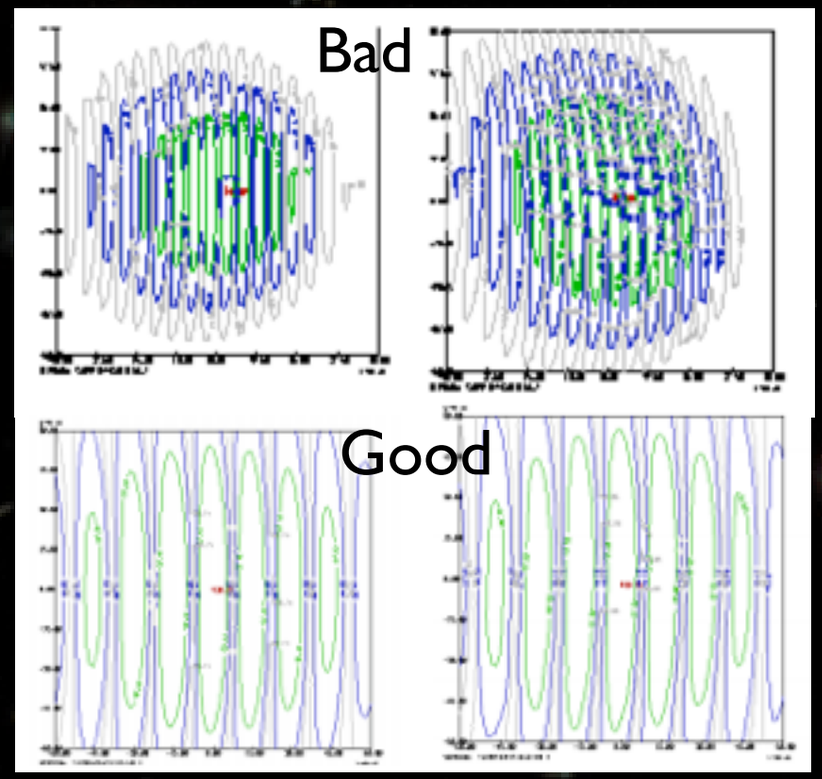


Replicated peaks **are not** (uncontrolled) sidelobes:

- 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

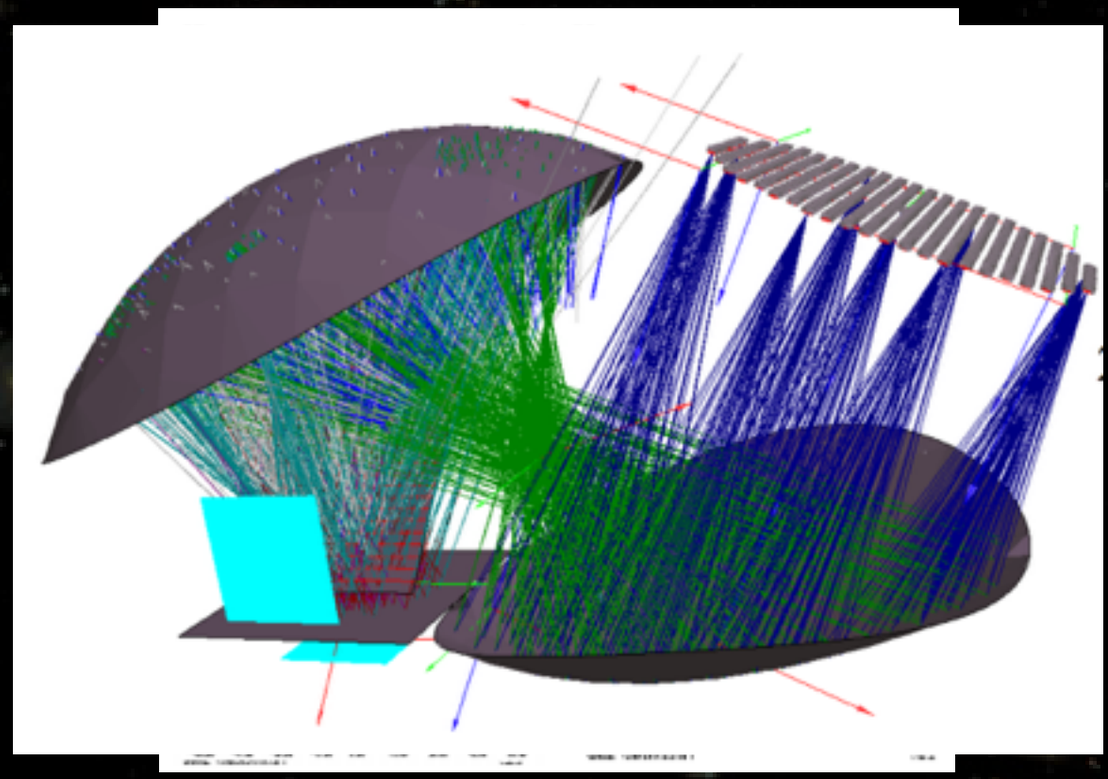
Optical aberrations ?

- Low aberrations required
  - ★ equivalent baselines need to have identical fringe patterns
- Off-Axis Gregorian
  - ★ C. O'Sullivan - Maynooth
  - ★ 300 mm equivalent focal length
  - ★ ~ 0.5 m mirrors



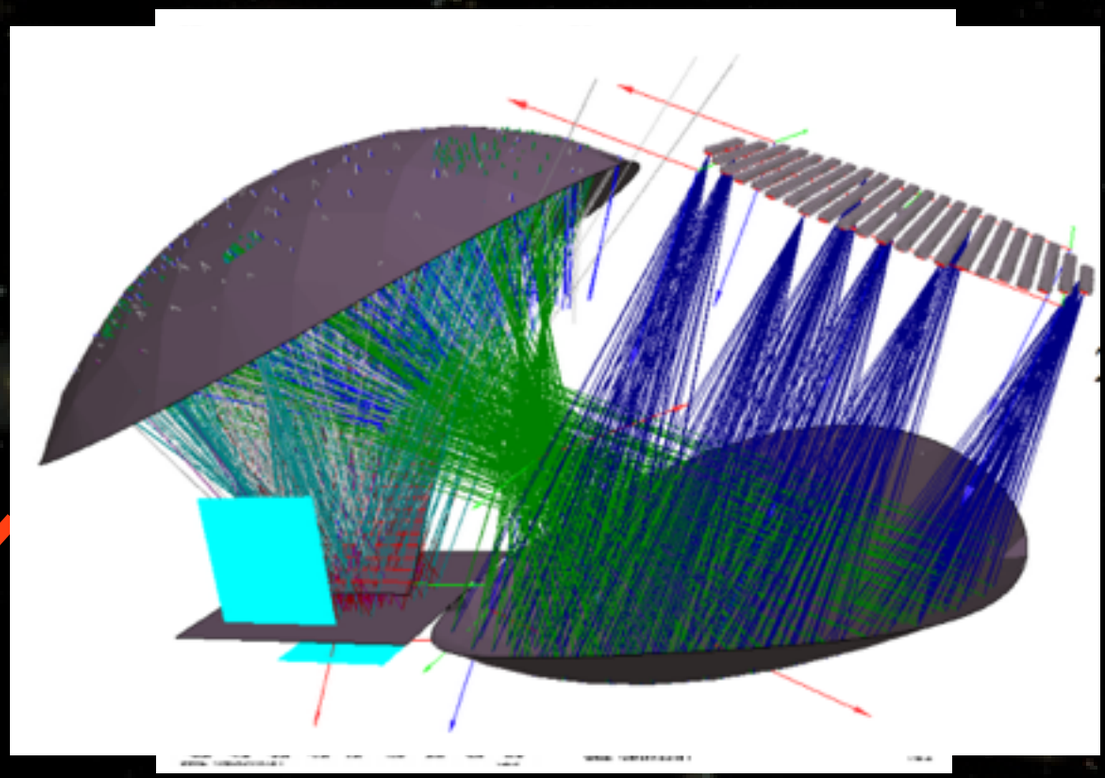
Optical aberrations ?

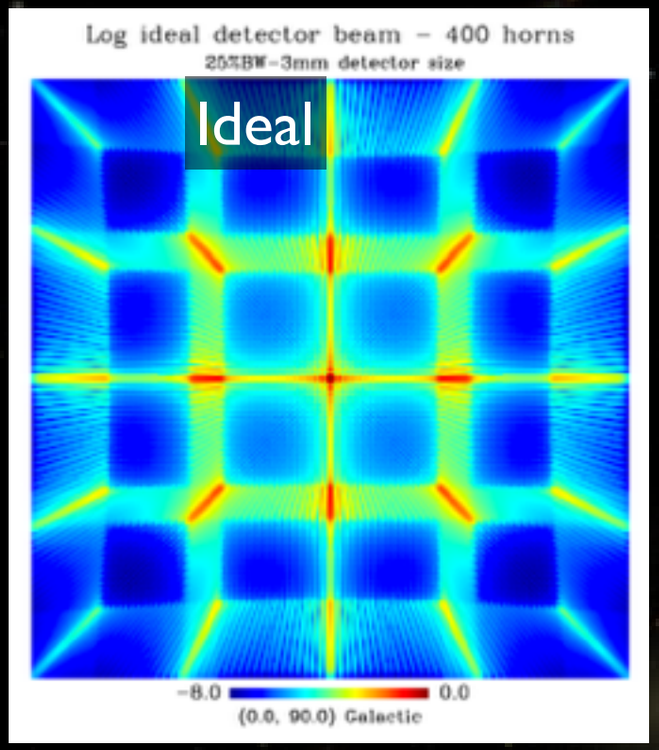
- Low aberrations required
  - ★ equivalent baselines need to have identical fringe patterns
- Off-Axis Gregorian
  - ★ C. O'Sullivan - Maynooth
  - ★ 300 mm equivalent focal length
  - ★ ~ 0.5 m mirrors

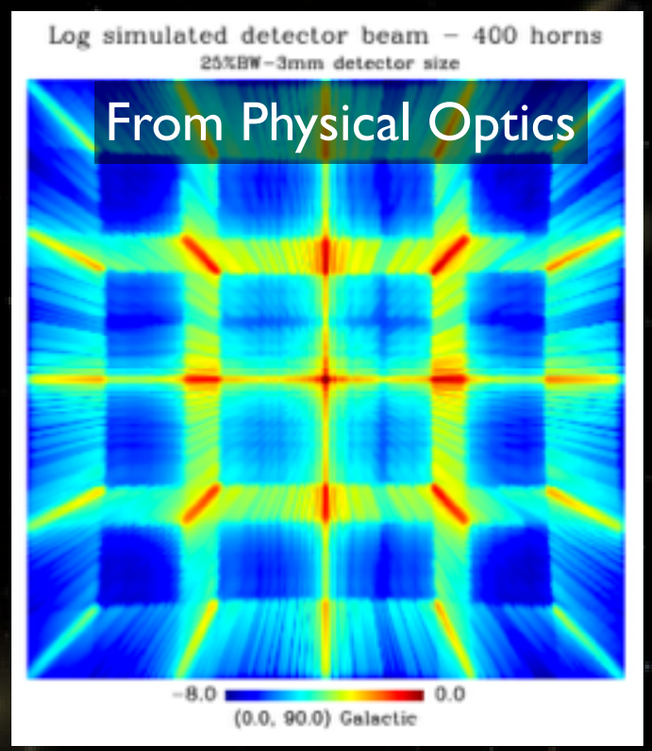


Optical aberrations ?

- Low aberrations required
  - ★ equivalent baselines need to have identical fringe patterns
- Off-Axis Gregorian
  - ★ C. O'Sullivan - Maynooth
  - ★ 300 mm equivalent focal length
  - ★ ~ 0.5 m mirrors



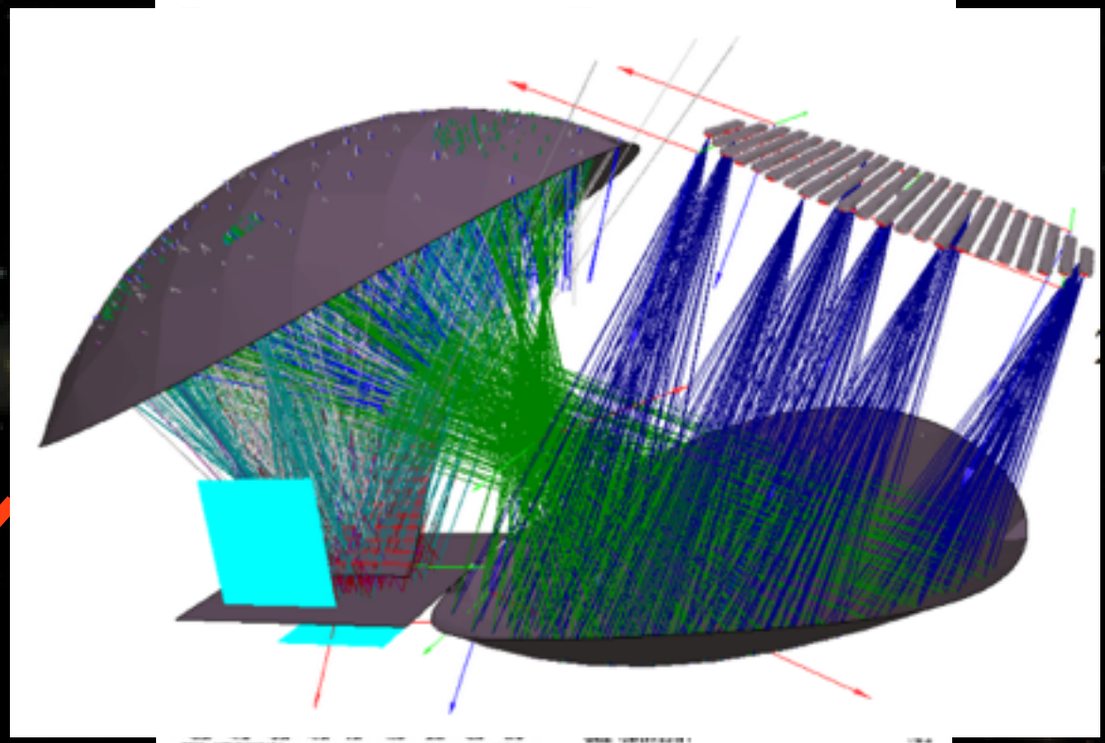


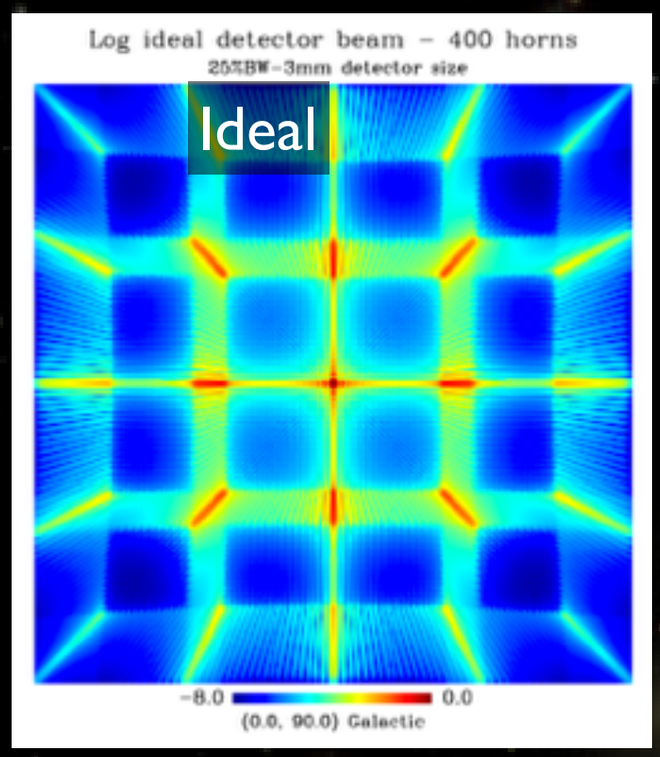


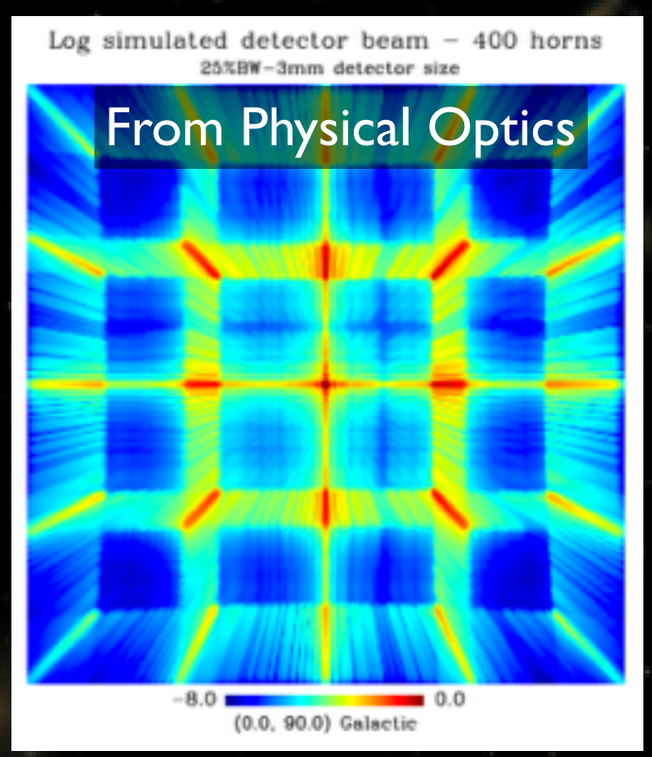
LogScale Synthesized beam

Optical aberrations ?

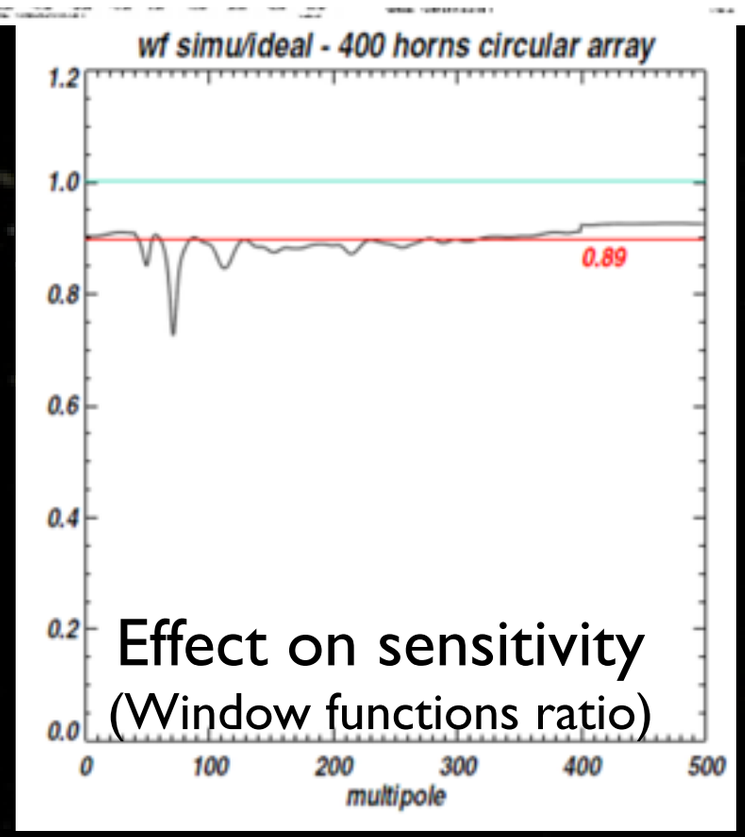
- Low aberrations required
  - ★ equivalent baselines need to have identical fringe patterns
- Off-Axis Gregorian
  - ★ C. O'Sullivan - Maynooth
  - ★ 300 mm equivalent focal length
  - ★ ~ 0.5 m mirrors





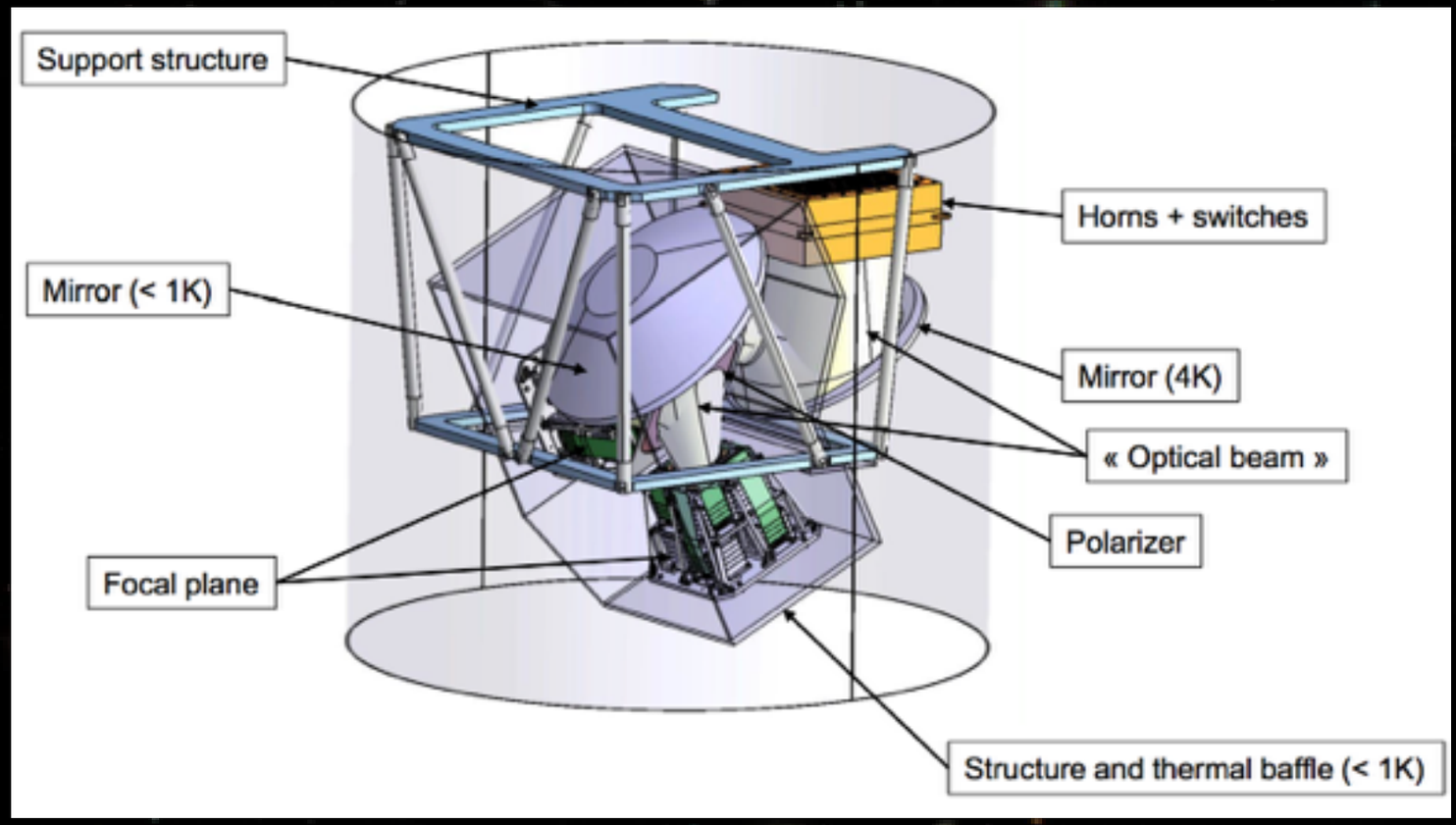


LogScale Synthesized beam



Effect on sensitivity
(Window functions ratio)

QUBIC Cryostat



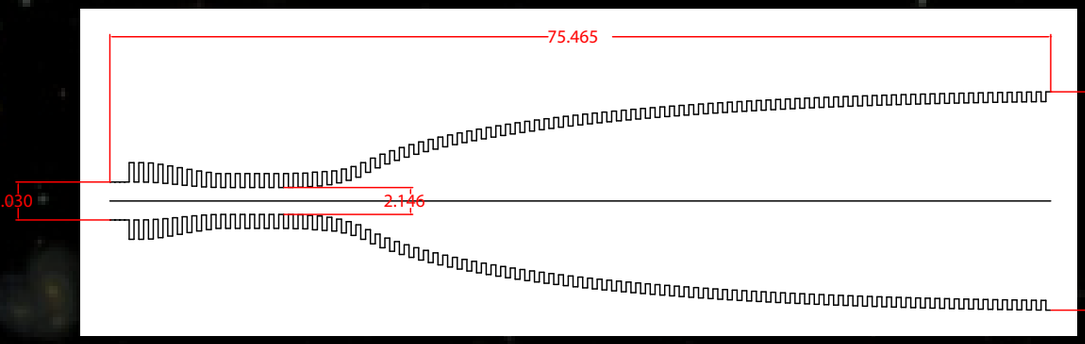
- Designed in Roma
  - ★ P. de Bernardis / S. Masi
- 40 cm window
  - ★ Stack (~20 cm) of zotefoam layers
- 1st stage: 4K: Pulse-Tube
  - ★ Filters, horns, HWP, mirrors, polarizing grid
- 2nd stage: 100mK dilution fridge from IN Grenoble
  - ★ PTC pre-cooling the mixture

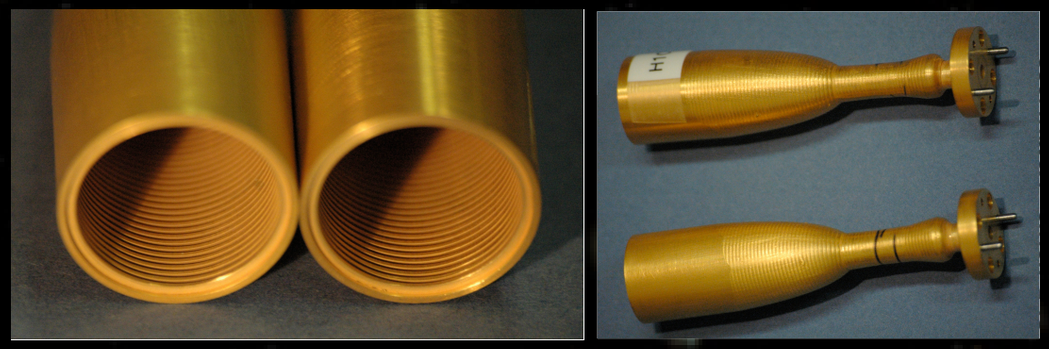
Horns

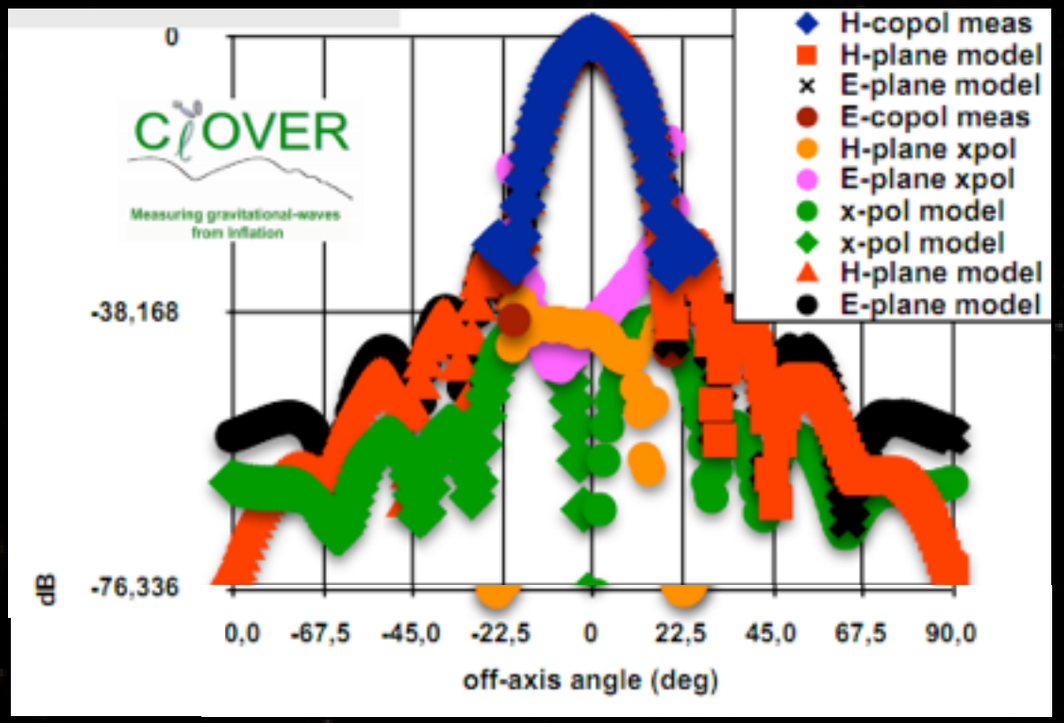
- Designed by Manchester
  - ★ B. Maffei / G. Pisano
  - ★ Clover-like profiled corrugated horns
  - ★ 150GHz, 14 deg. FWHM, 1.2 cm diam. (close to diffraction limit)
  - ★ Excellent beam/Cross Pol. perfs

  - ★ Usual fabrication:
    - Electroforming
    - Expensive (800$ / horn)

- Platelets fabrication investigated at APC (É. Bréelle)
  - ★ 271 thin copper plates
  - ★ Holes using chemical etching
  - ★ 100-200€ / horn
  - ★ 1st tests 10 days ago:
    - ➡ Good beams/cross polarization





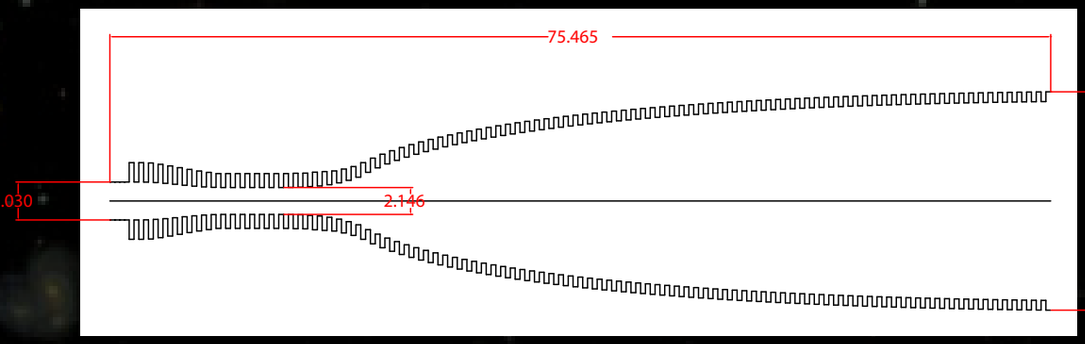


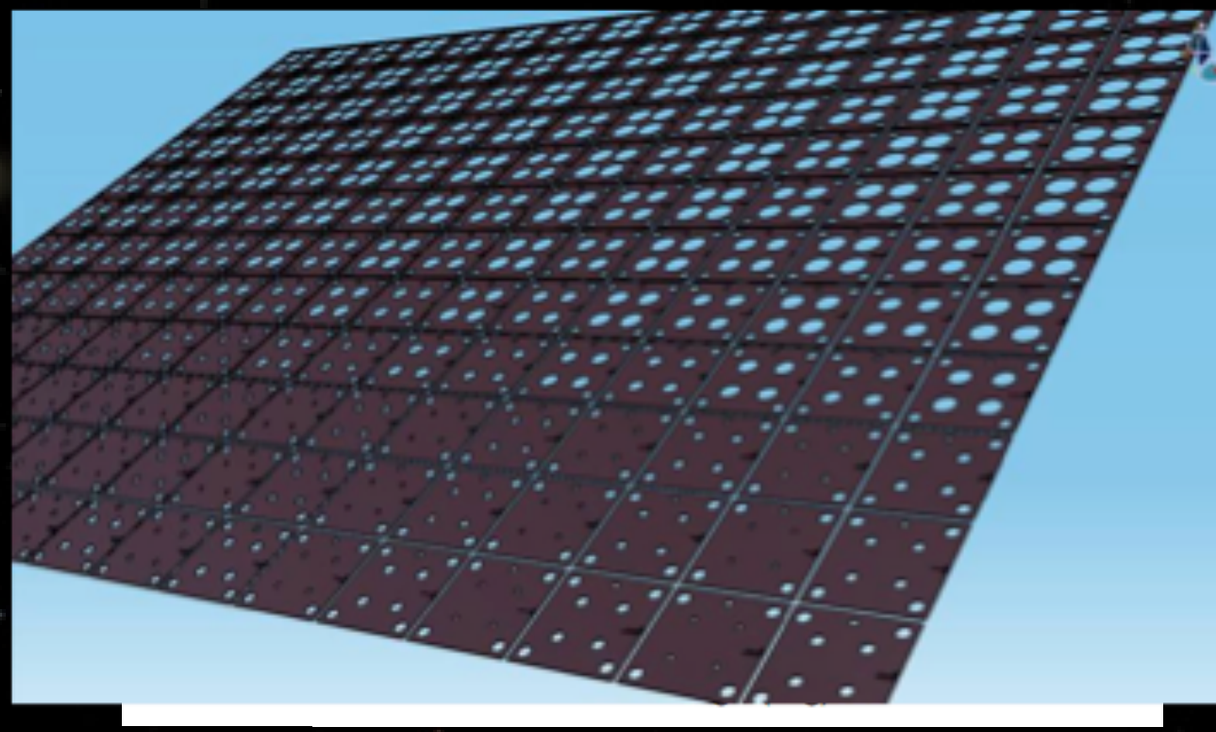
Horns

- Designed by Manchester
  - ★ B. Maffei / G. Pisano
  - ★ Clover-like profiled corrugated horns
  - ★ 150GHz, 14 deg. FWHM, 1.2 cm diam. (close to diffraction limit)
  - ★ Excellent beam/Cross Pol. perfs

  - ★ Usual fabrication:
    - Electroforming
    - Expensive (800$ / horn)

- Platelets fabrication investigated at APC (É. Bréelle)
  - ★ 271 thin copper plates
  - ★ Holes using chemical etching
  - ★ 100-200€ / horn
  - ★ 1st tests 10 days ago:
    - ➡ Good beams/cross polarization



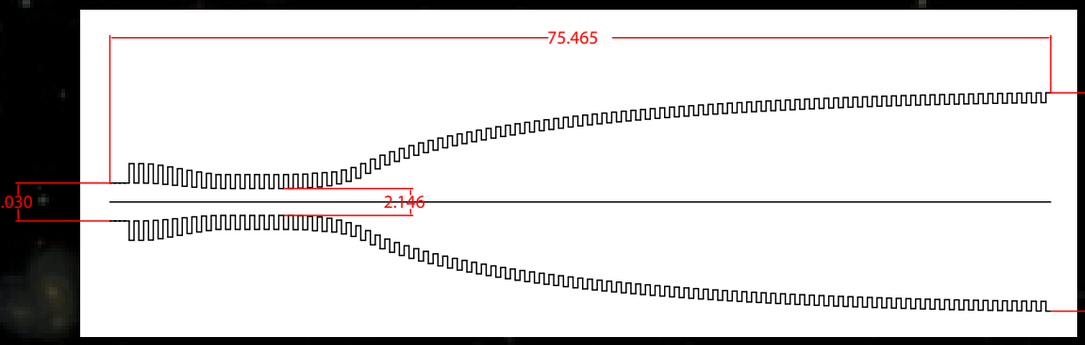


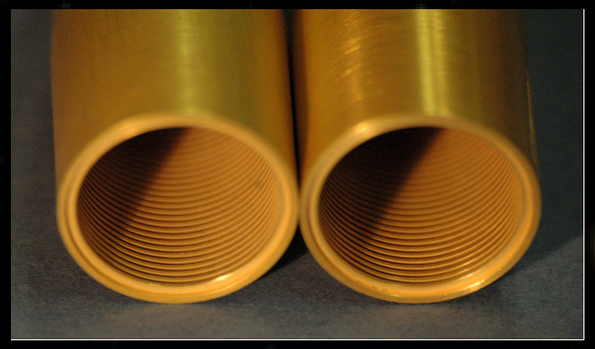
Horns

- Designed by Manchester
  - ★ B. Maffei / G. Pisano
  - ★ Clover-like profiled corrugated horns
  - ★ 150GHz, 14 deg. FWHM, 1.2 cm diam. (close to diffraction limit)
  - ★ Excellent beam/Cross Pol. perfs

  - ★ Usual fabrication:
    - Electroforming
    - Expensive (800$ / horn)

- Platelets fabrication investigated at APC (É. Bréelle)
  - ★ 271 thin copper plates
  - ★ Holes using chemical etching
  - ★ 100-200€ / horn
  - ★ 1st tests 10 days ago:
    - ➡ Good beams/cross polarization



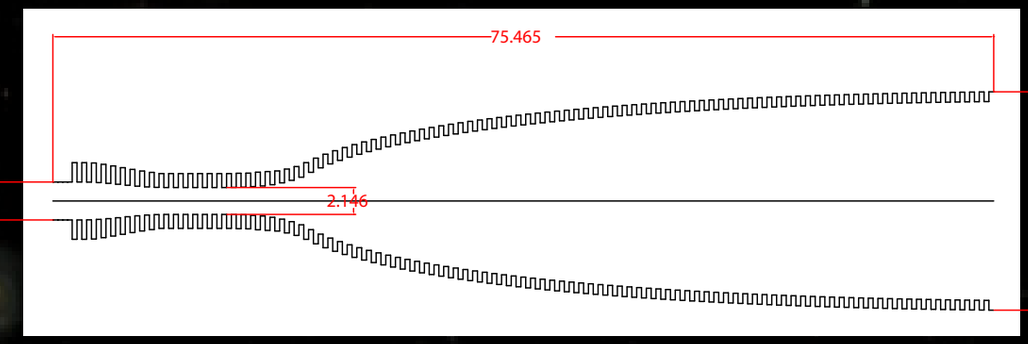


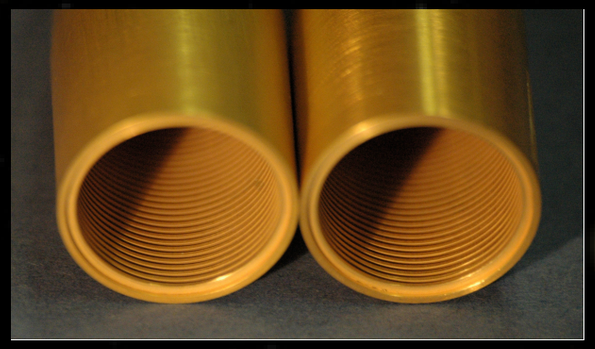
Horns

- Designed by Manchester
  - ★ B. Maffei / G. Pisano
  - ★ Clover-like profiled corrugated horns
  - ★ 150GHz, 14 deg. FWHM, 1.2 cm diam. (close to diffraction limit)
  - ★ Excellent beam/Cross Pol. perfs

  - ★ Usual fabrication:
    - Electroforming
    - Expensive (800$ / horn)

- Platelets fabrication investigated at APC (É. Bréelle)
  - ★ 271 thin copper plates
  - ★ Holes using chemical etching
  - ★ 100-200€ / horn
  - ★ 1st tests 10 days ago:
    - ➡ Good beams/cross polarization

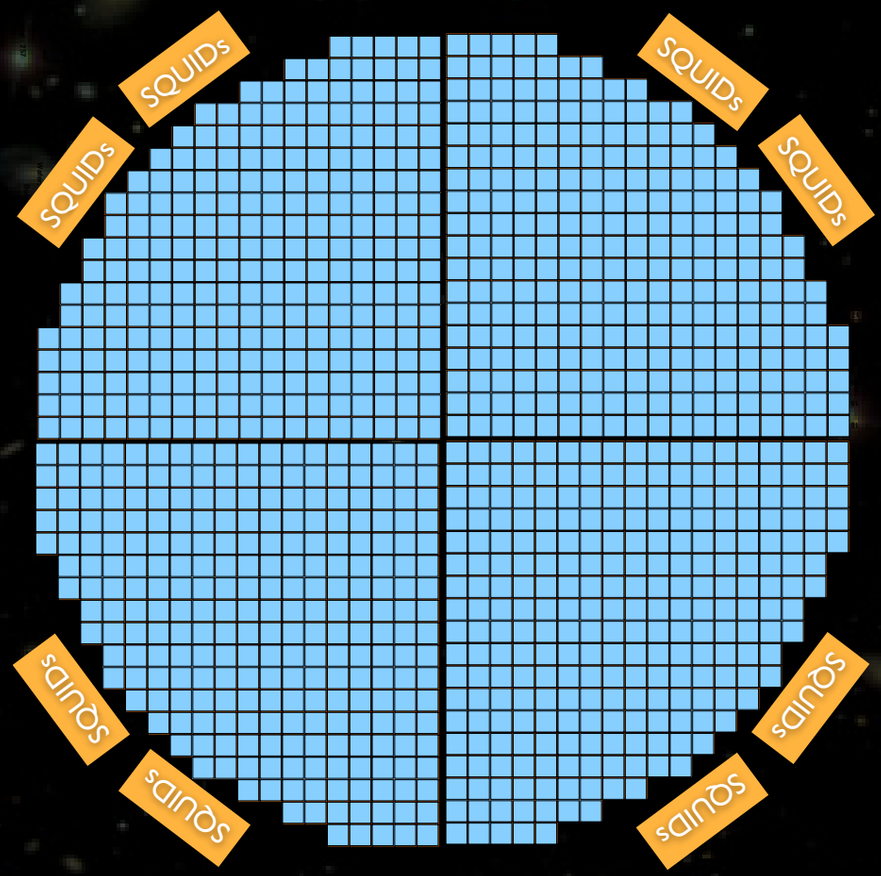




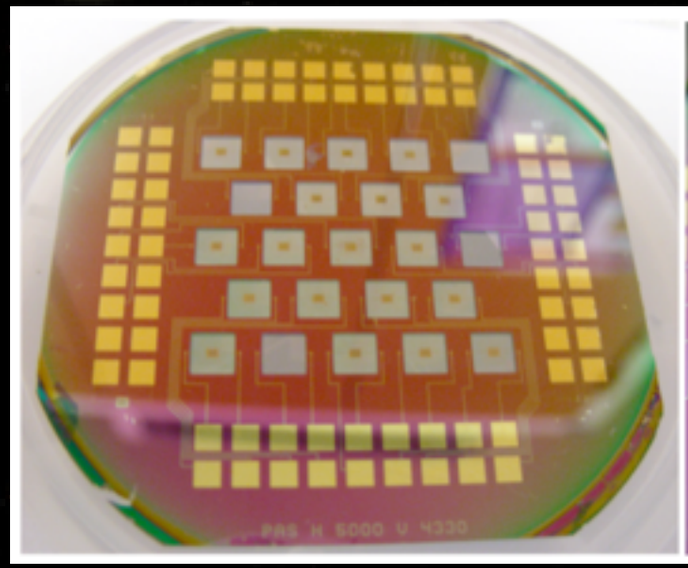
Detection Chain

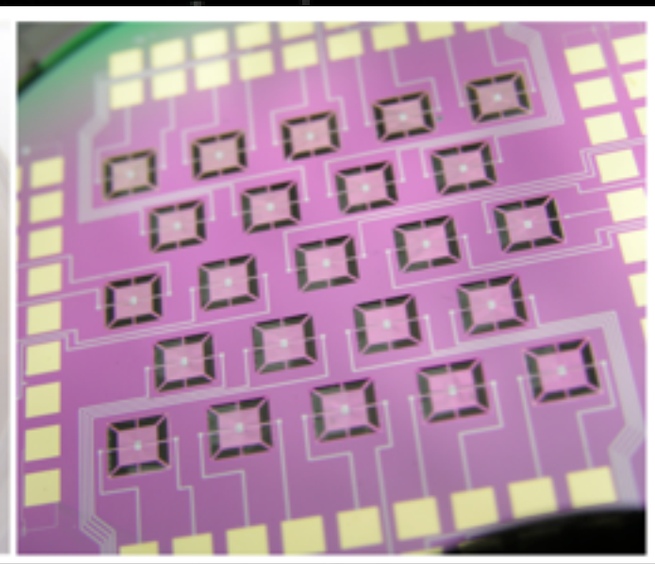
- TES + SQUIDs + 4K SiGe ASIC Mux
  - ★ APC: Michel Piat
  - ★ CSNSM: Stefanos Marnieros

- 2 arrays of 1024 NbSi TES
  - ★ Each array : 4x256 elements
  - ★ 100 mK bath (dilution)
  - ★ 3 mm size
  - ★ NEP ~ 5.10^{-18} W.Hz$^{-1/2}$
  - ★ time constant ~ 10 ms



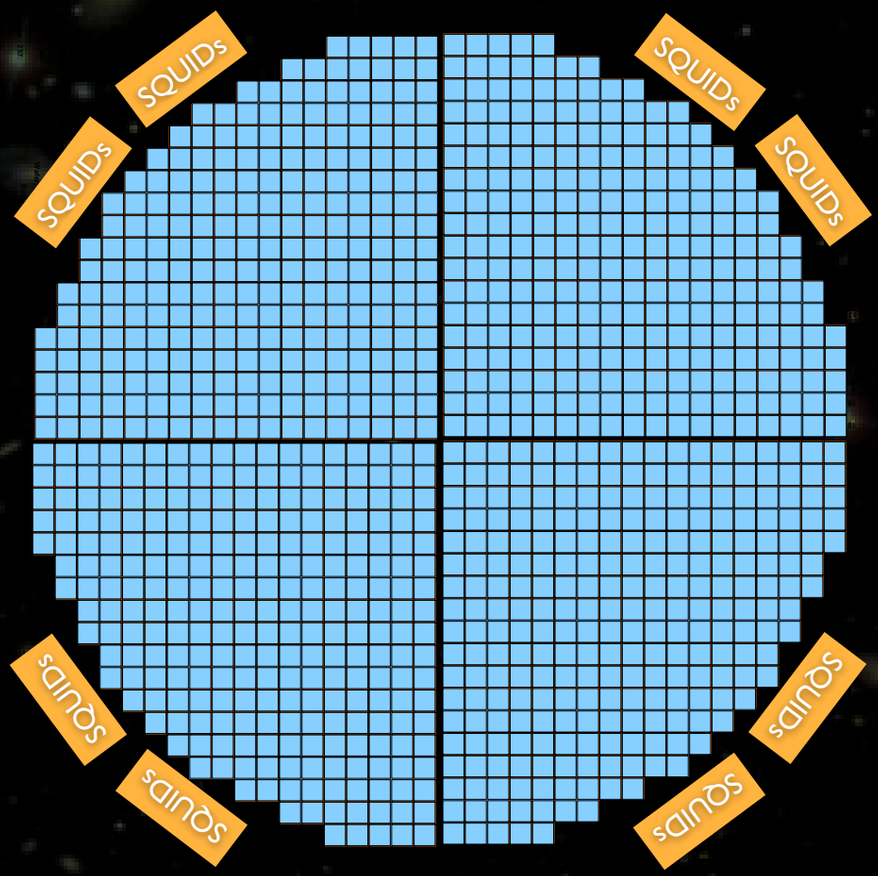
- Multiplexed Readout
  - ★ SQUIDs pre-amplifier+mux
    - 32:1 multiplexing
  - ★ 4K SiGe ASIC (amp+mux)
    - 4:1 multiplexing
  - ★ 128 channels / ASIC
  - ★ Low noise: ~200 pV.Hz$^{-1/2}$

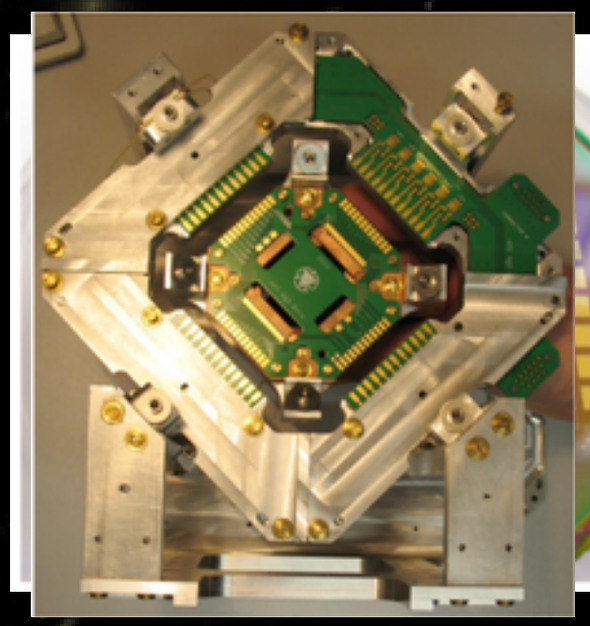


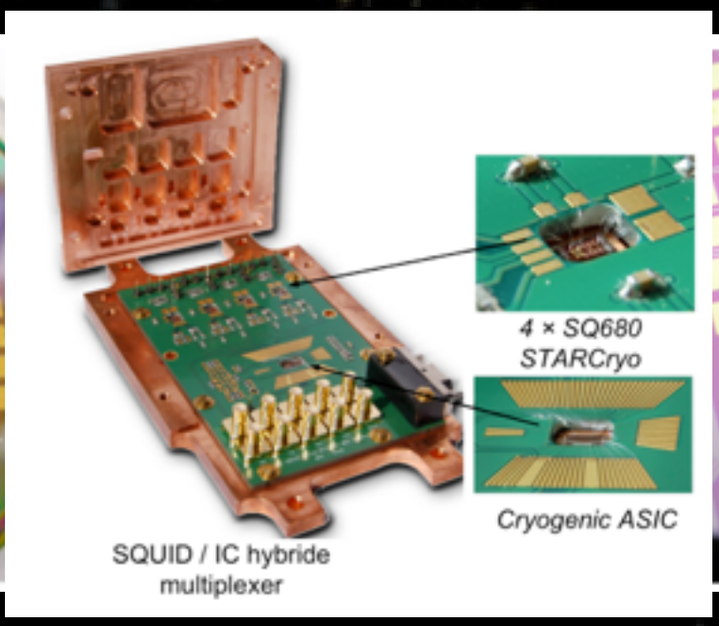


Detection Chain

- TES + SQUIDs + 4K SiGe ASIC Mux
  - ★ APC: Michel Piat
  - ★ CSNSM: Stefanos Marnieros
- 2 arrays of 1024 NbSi TES
  - ★ Each array : 4x256 elements
  - ★ 100 mK bath (dilution)
  - ★ 3 mm size
  - ★ NEP ~ 5.10^{-18} W.Hz$^{-1/2}$
  - ★ time constant ~ 10 ms
- Multiplexed Readout
  - ★ SQUIDs pre-amplifier+mux
    - 32:1 multiplexing
  - ★ 4K SiGe ASIC (amp+mux)
    - 4:1 multiplexing
  - ★ 128 channels / ASIC
  - ★ Low noise: ~200 pV.Hz$^{-1/2}$



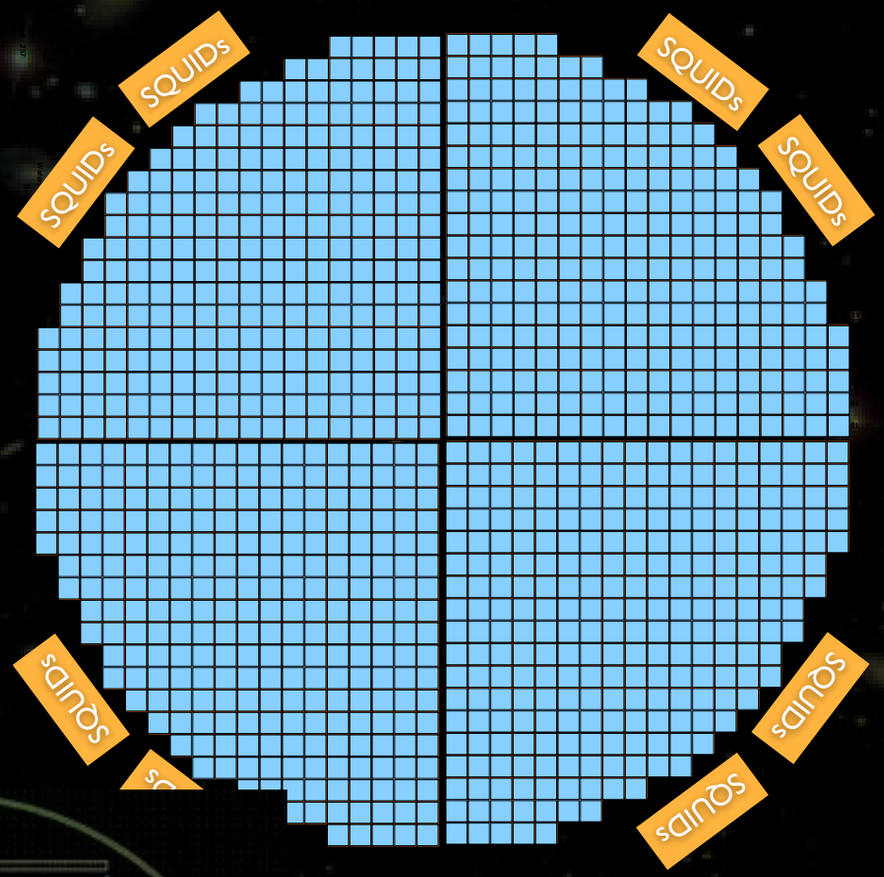




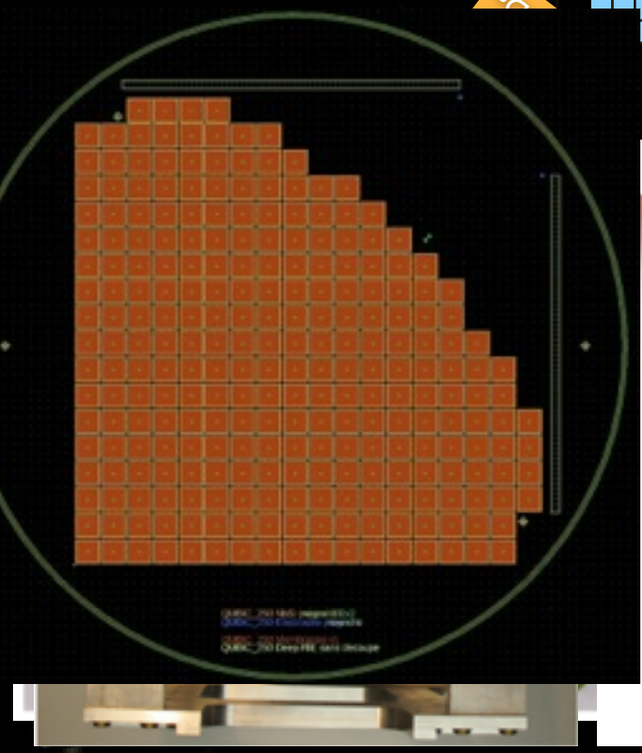
Detection Chain

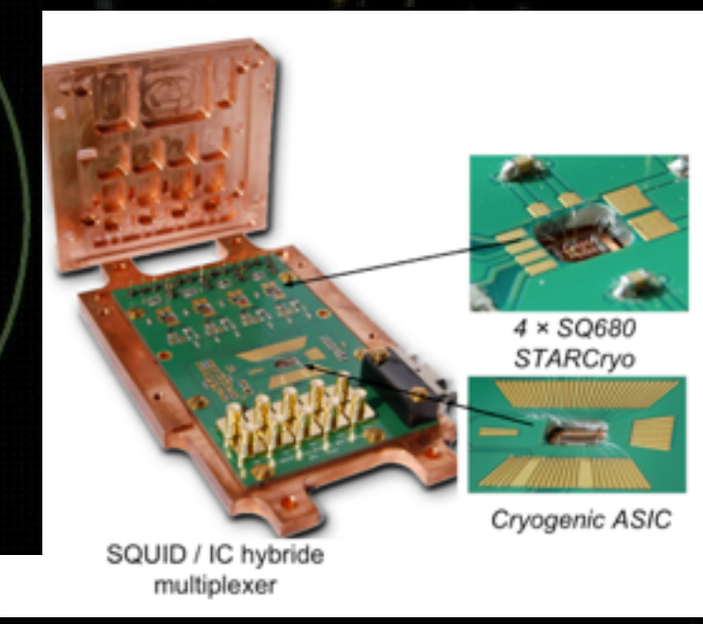
- TES + SQUIDs + 4K SiGe ASIC Mux
  - ★ APC: Michel Piat
  - ★ CSNSM: Stefanos Marnieros

- 2 arrays of 1024 NbSi TES
  - ★ Each array : 4x256 elements
  - ★ 100 mK bath (dilution)
  - ★ 3 mm size
  - ★ NEP ~ 5.10^{-18} W.Hz$^{-1/2}$
  - ★ time constant ~ 10 ms



- Multiplexed Readout
  - ★ SQUIDs pre-amplifier+mux
    - 32:1 multiplexing
  - ★ 4K SiGe ASIC (amp+mux)
    - 4:1 multiplexing
  - ★ 128 channels / ASIC
  - ★ Low noise: ~200 pV.Hz$^{-1/2}$



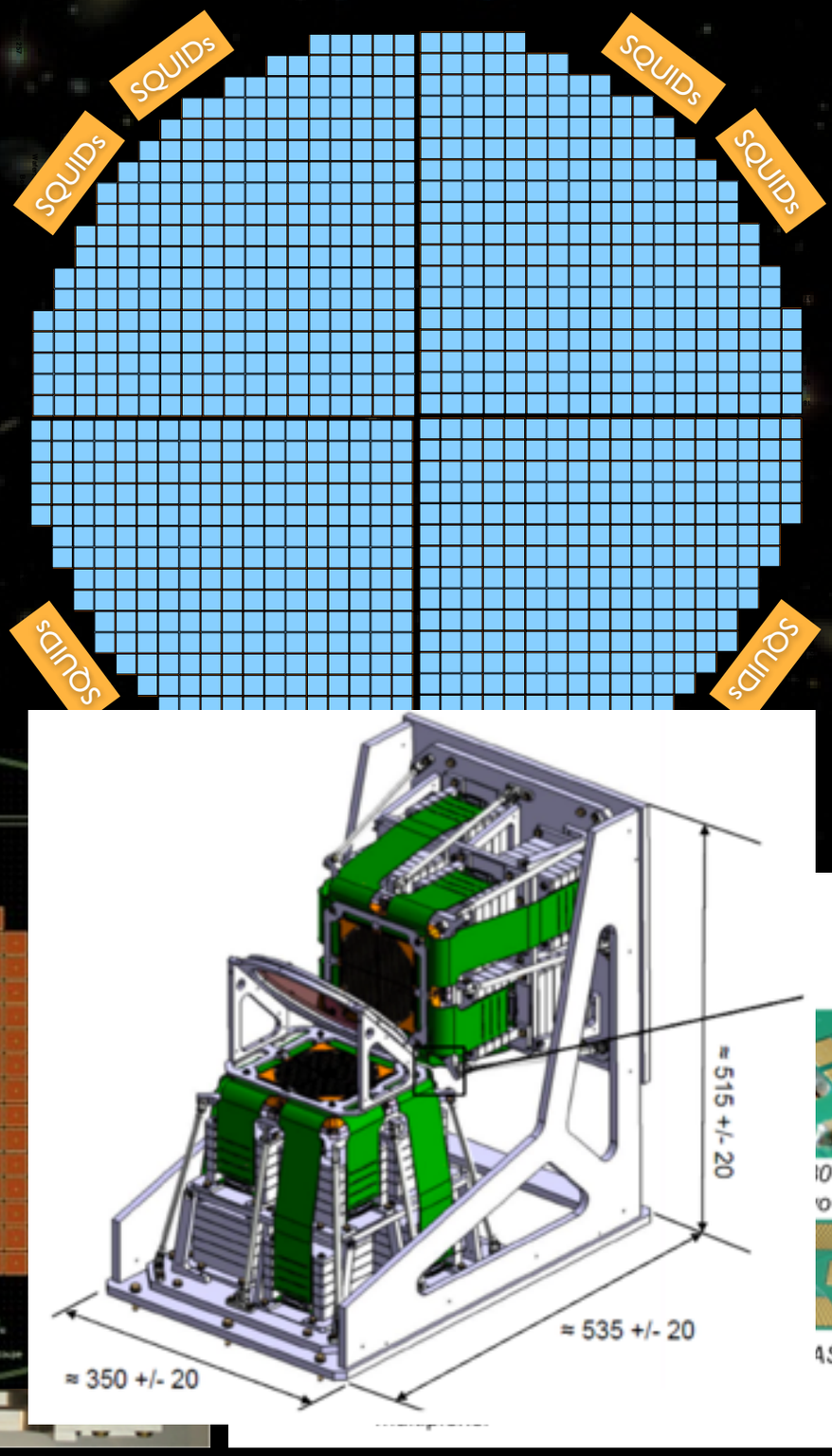


Detection Chain

- TES + SQUIDs + 4K SiGe ASIC Mux
  - ★ APC: Michel Piat
  - ★ CSNSM: Stefanos Marnieros

- 2 arrays of 1024 NbSi TES
  - ★ Each array : 4x256 elements
  - ★ 100 mK bath (dilution)
  - ★ 3 mm size
  - ★ NEP ~ 5.10^{-18} W.Hz$^{-1/2}$
  - ★ time constant ~ 10 ms

- Multiplexed Readout
  - ★ SQUIDs pre-amplifier+mux
    - 32:1 multiplexing
  - ★ 4K SiGe ASIC (amp+mux)
    - 4:1 multiplexing
  - ★ 128 channels / ASIC
  - ★ Low noise: ~200 pV.Hz$^{-1/2}$



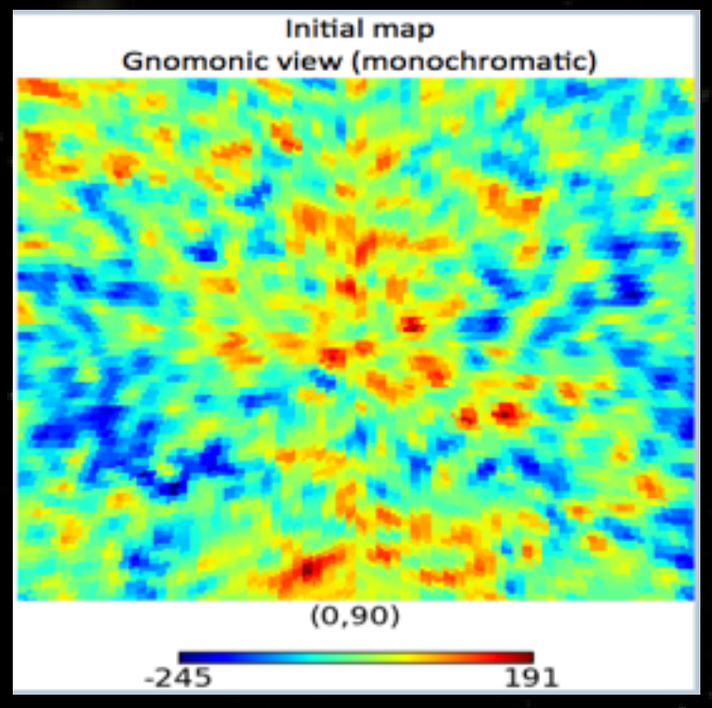
Map Making

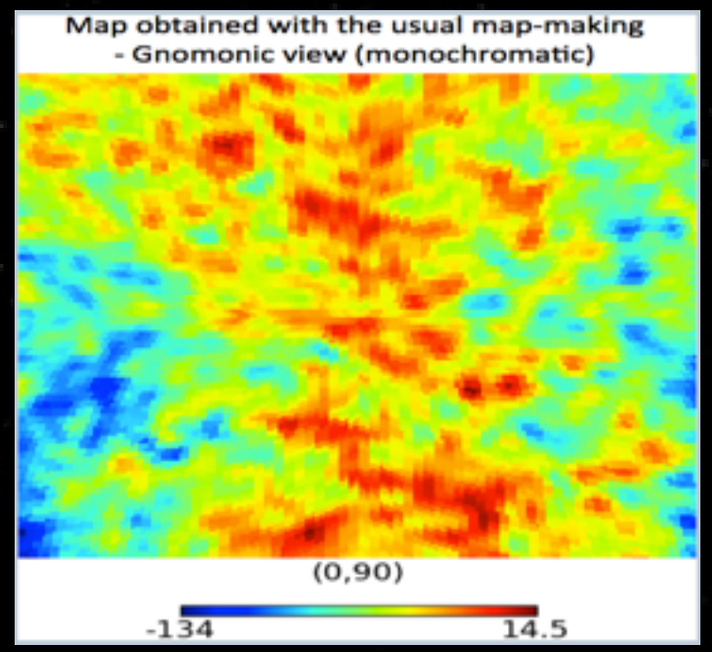
See Poster by Marie-Anne Bigot-Sazy

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

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

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





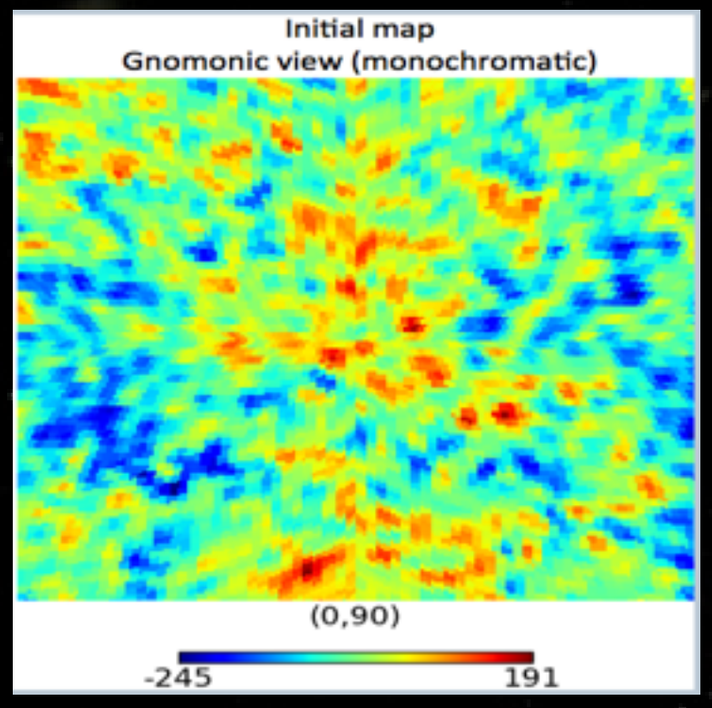
Map Making

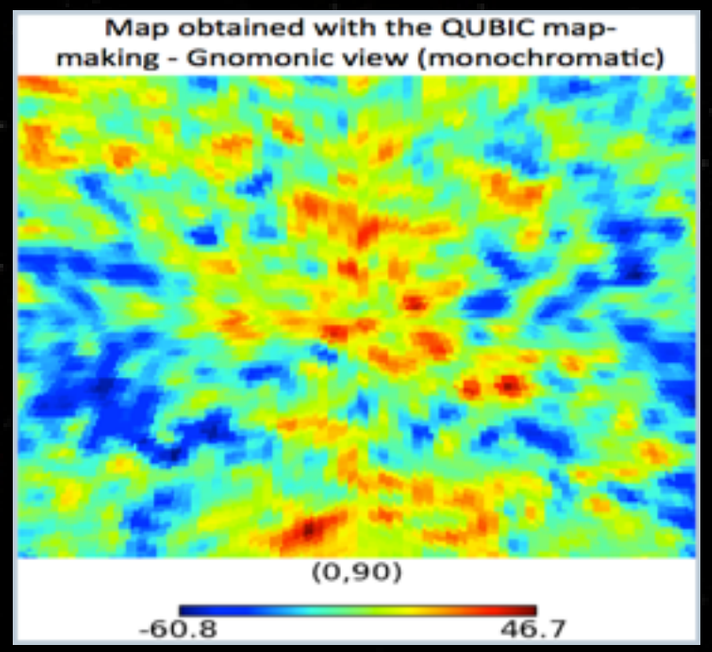
See Poster by Marie-Anne Bigot-Sazy

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

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

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

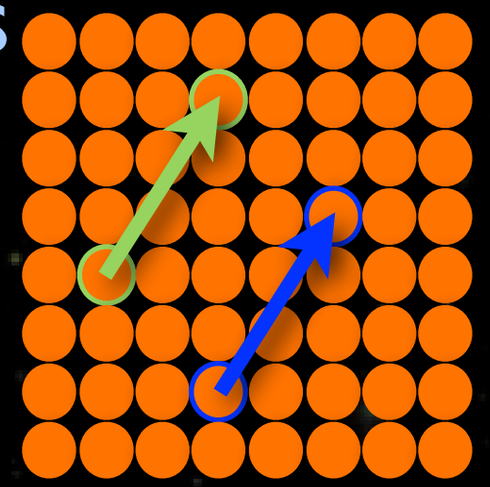




Self-Calibration

See Poster by Marie-Anne Bigot-Sazy

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

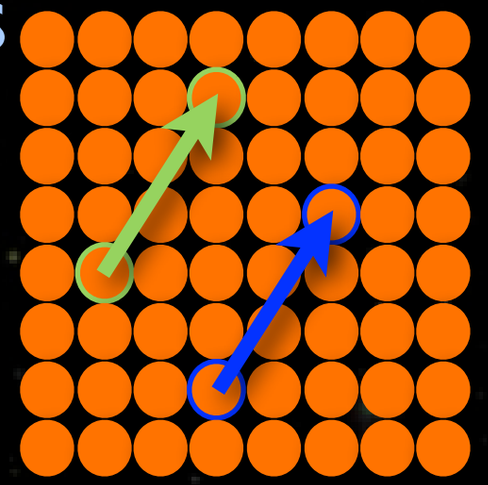


Redundant baselines : same Fourier Mode

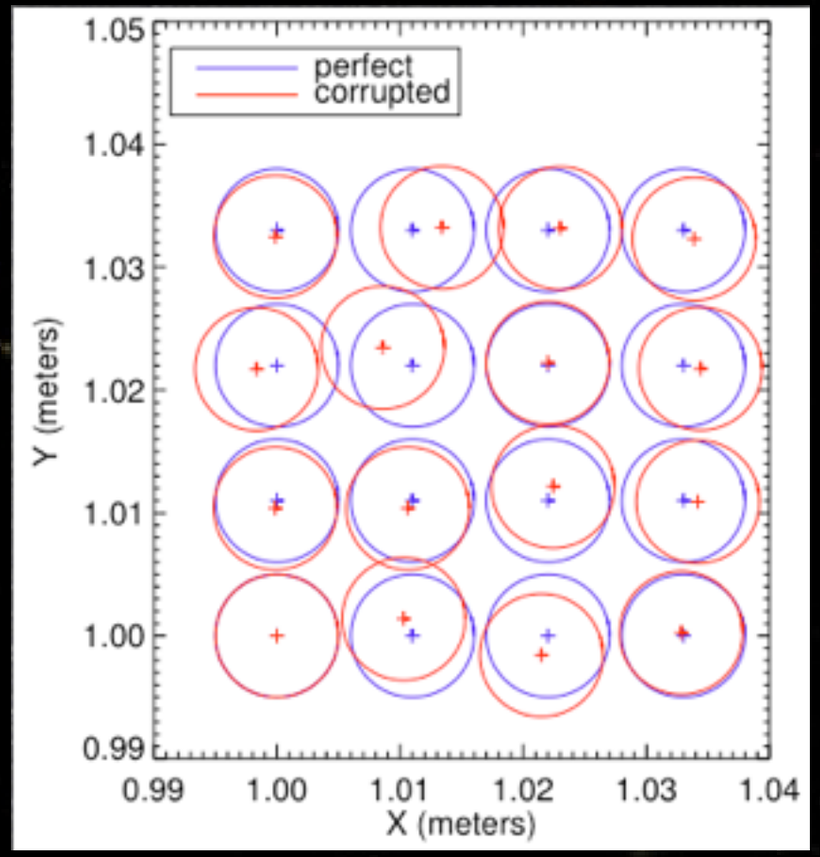
Self-Calibration

See Poster by Marie-Anne Bigot-Sazy

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



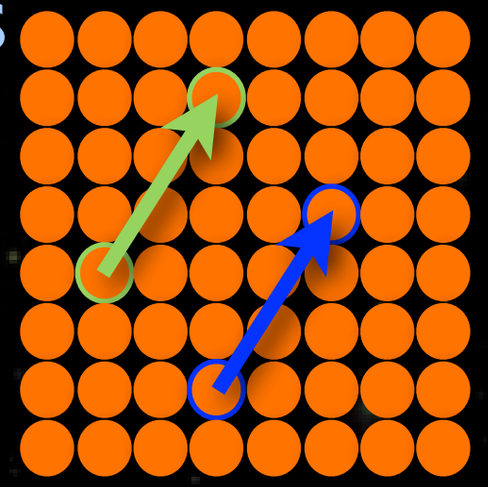
Redundant baselines : same Fourier Mode



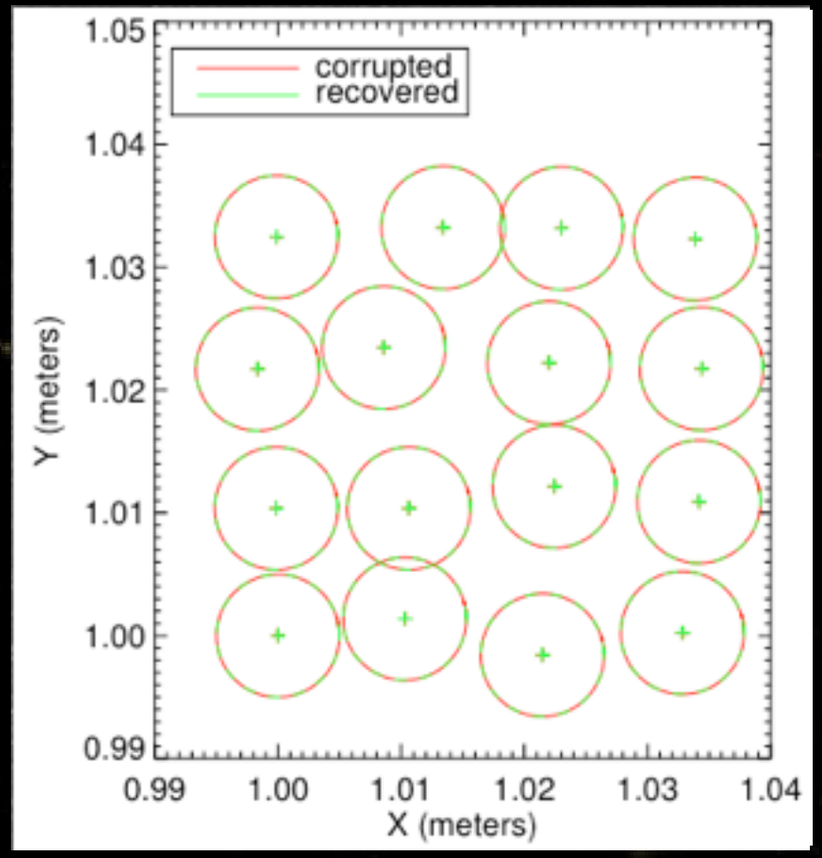
Self-Calibration

See Poster by Marie-Anne Bigot-Sazy

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



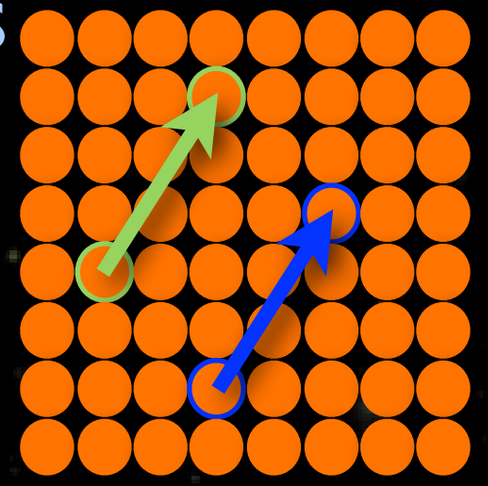
Redundant baselines : same Fourier Mode



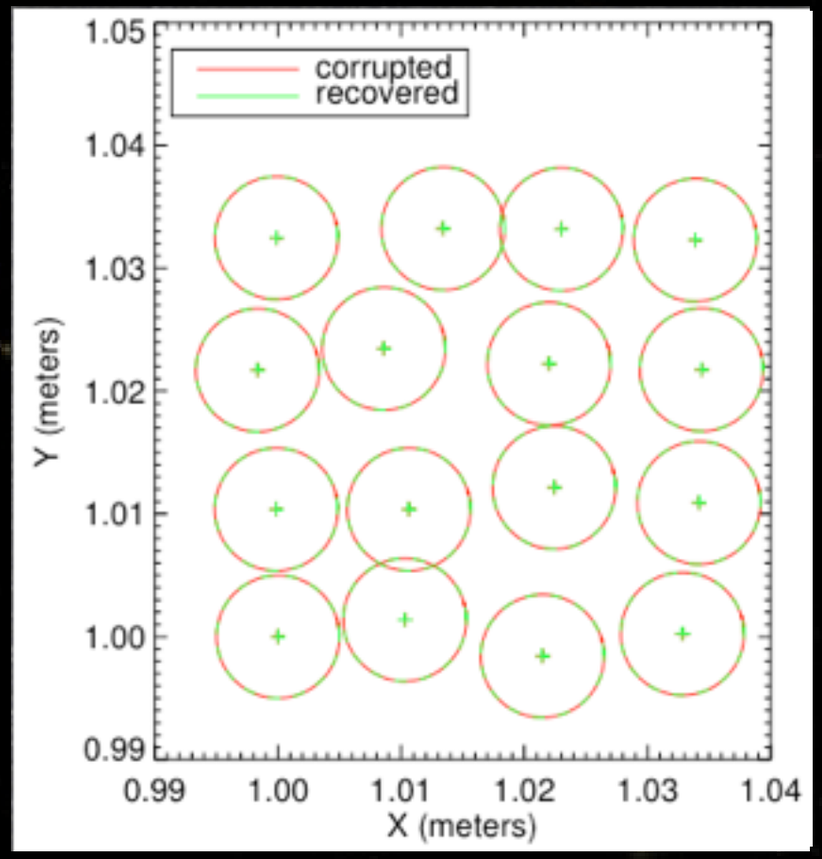
Self-Calibration

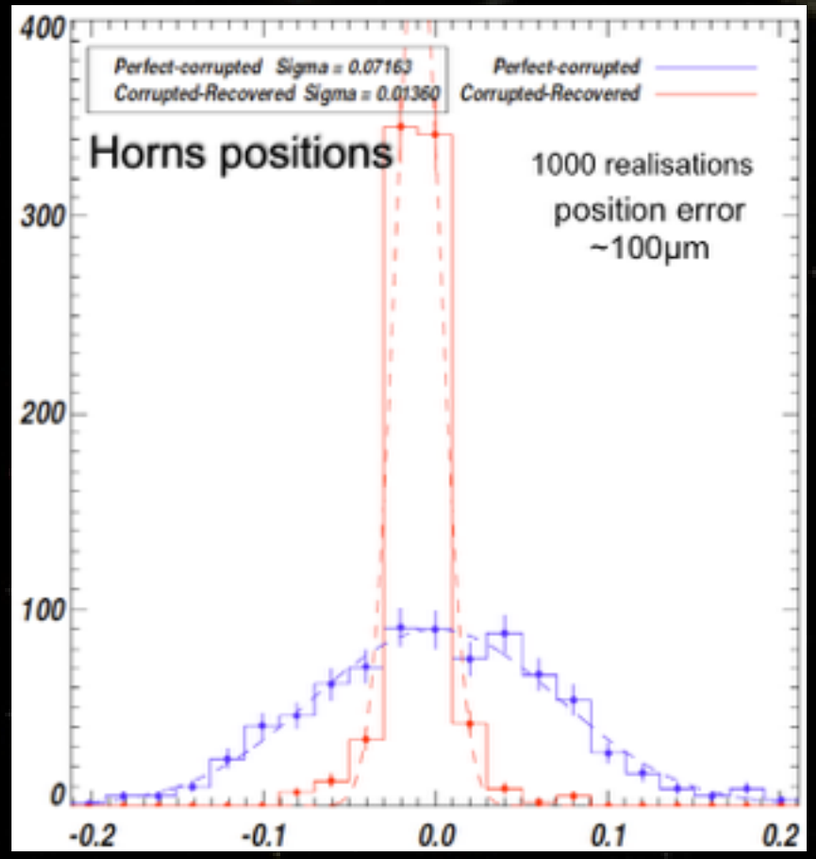
See Poster by Marie-Anne Bigot-Sazy

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



Redundant baselines : same Fourier Mode

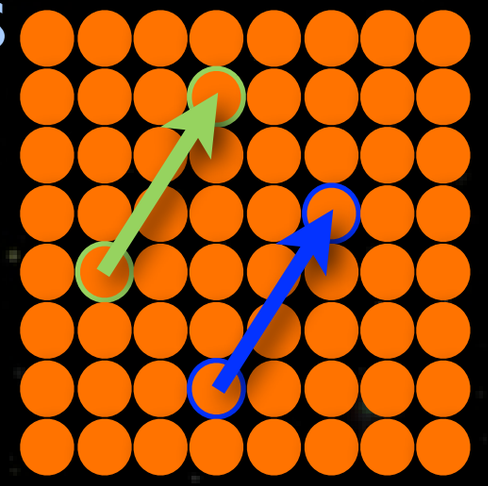




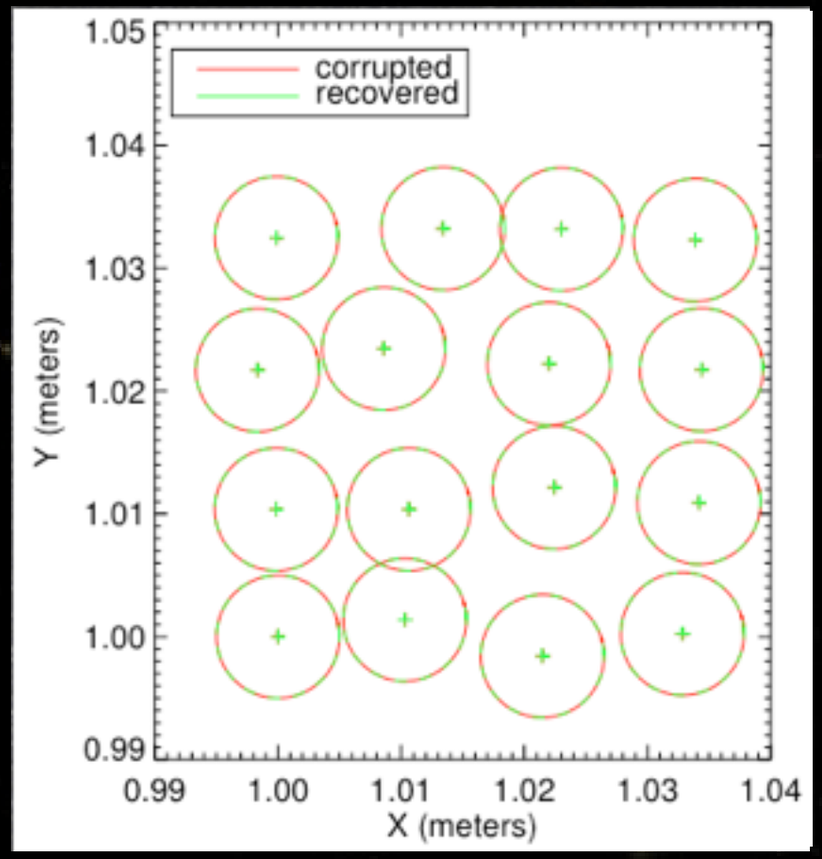
Self-Calibration

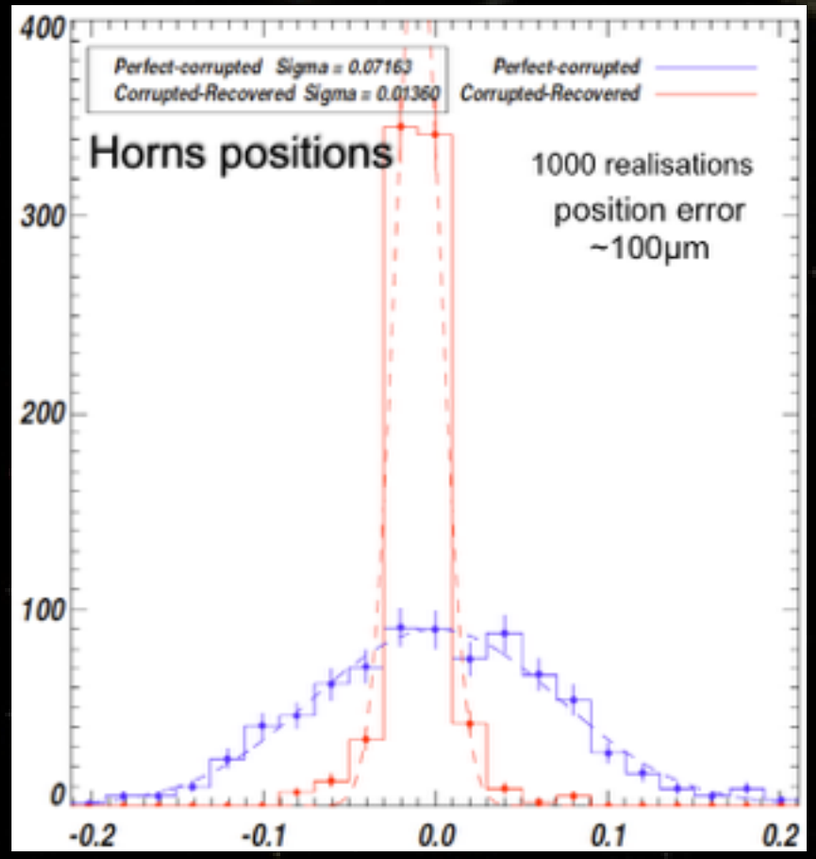
See Poster by Marie-Anne Bigot-Sazy

- 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



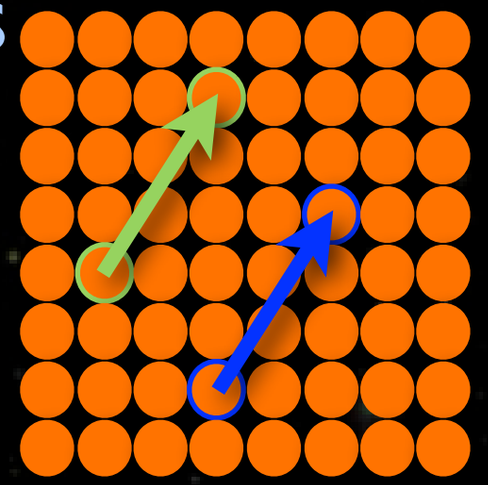


	RMS before	RMS after
Horns location	0.072	0.011
Individual beams	0.090	0.005
TES Intercalibration	0.029	0.007
pointing error, instrument effective Jones matrix	...	...

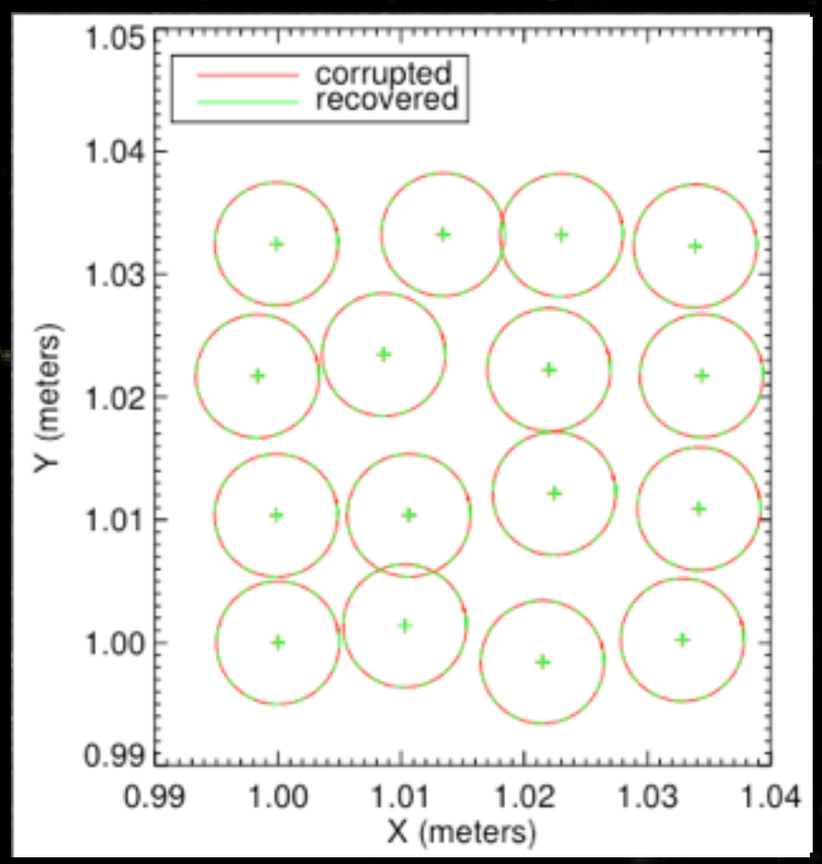
Self-Calibration

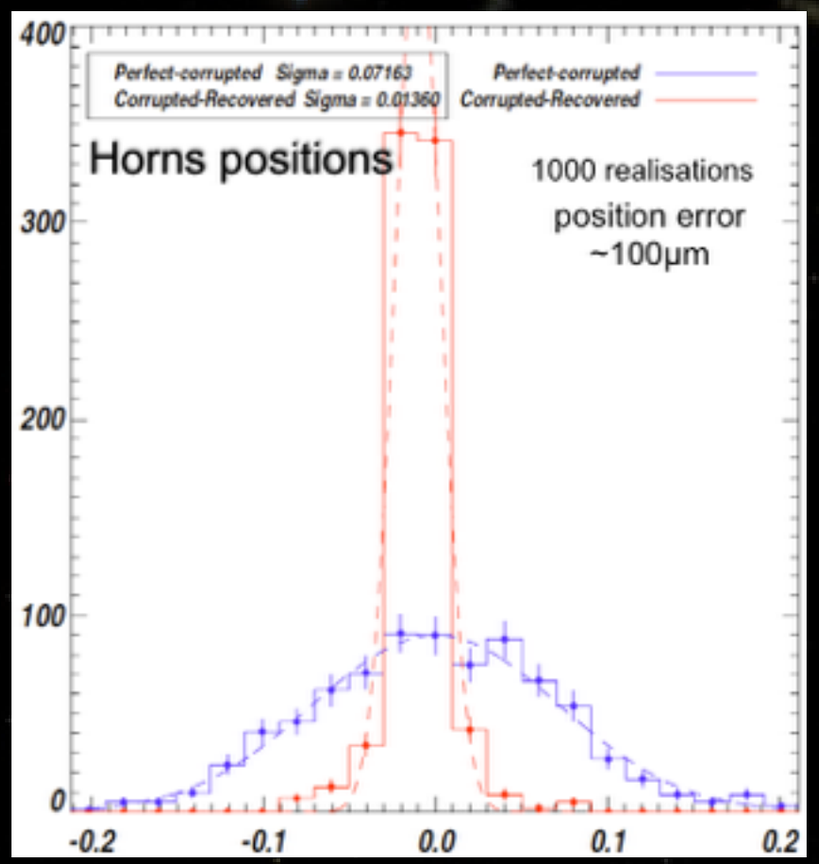
See Poster by Marie-Anne Bigot-Sazy

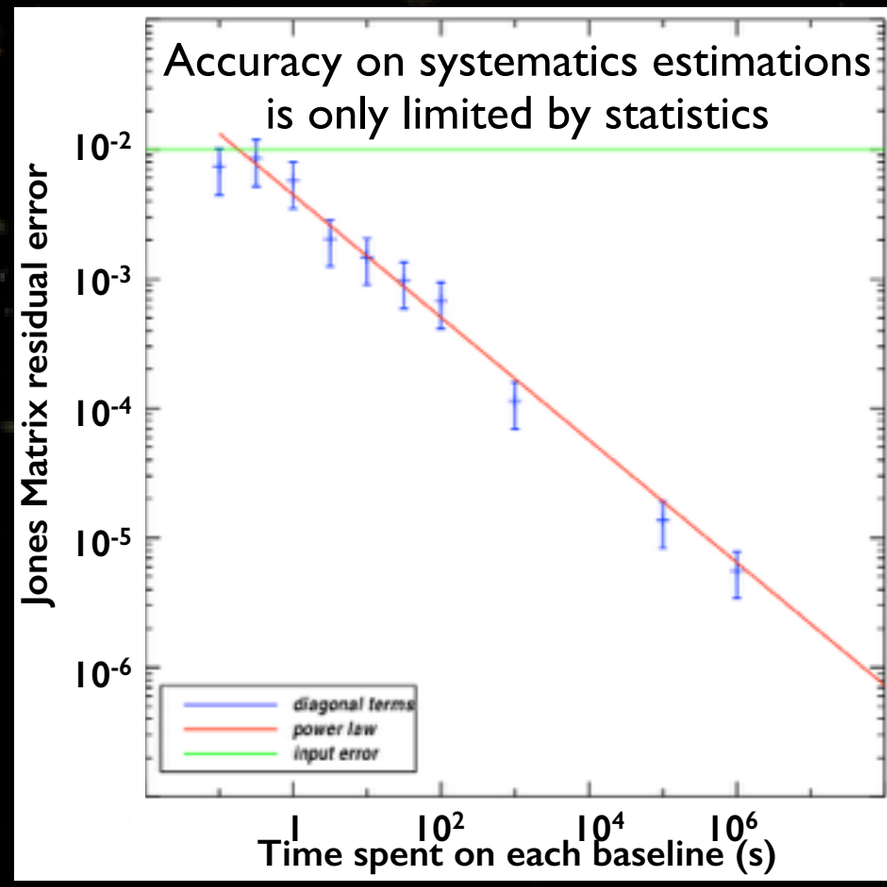
- Unique possibility to handle systematic errors
  - ★ Use horn array redundancy to calibrate systematics
    - In a perfect instrument redundant baselines should see the same signal
    - Differences due to systematics
    - Allow to fit systematics with an external source on the field
  - ★ Unique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



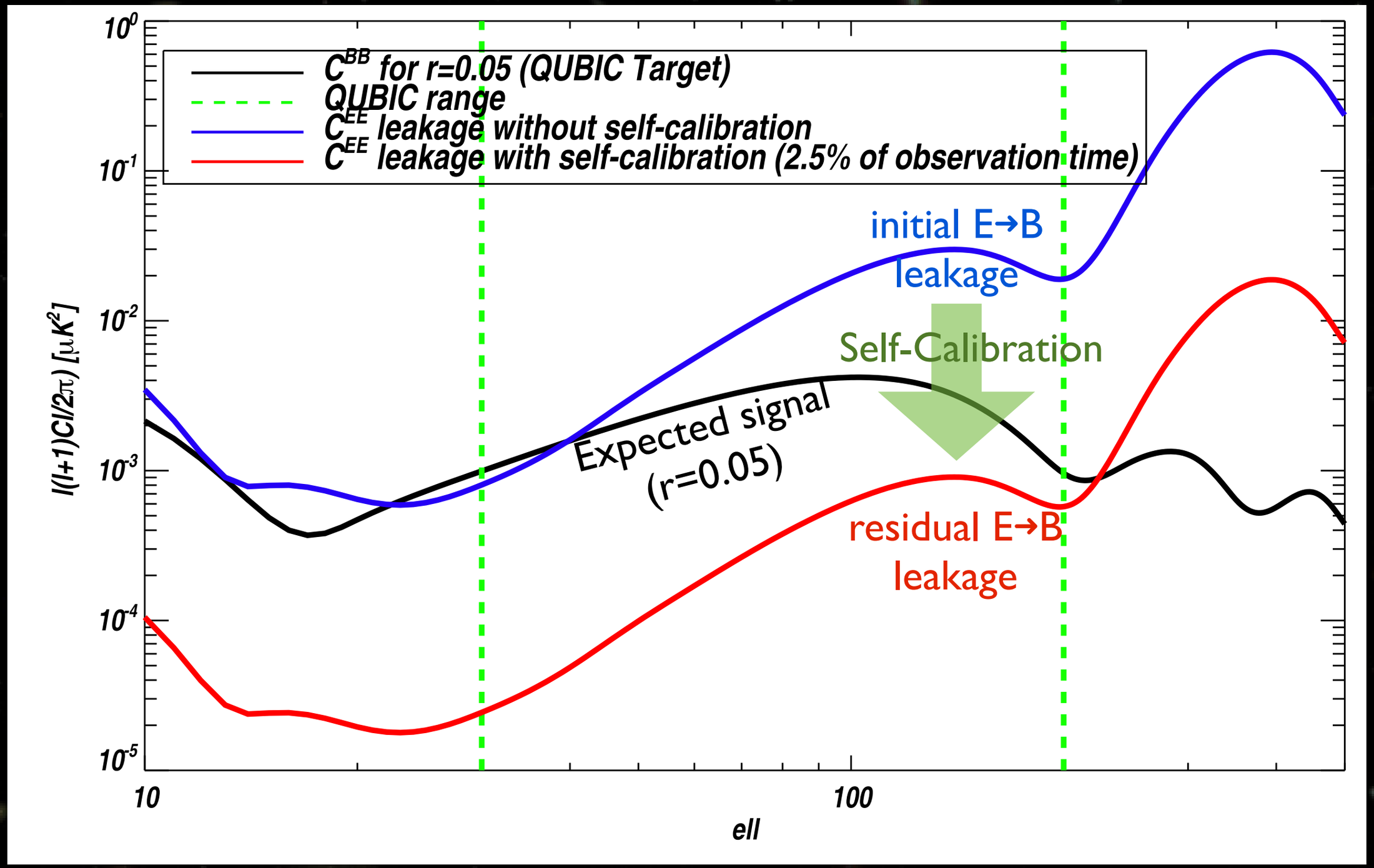
Redundant baselines : same Fourier Mode





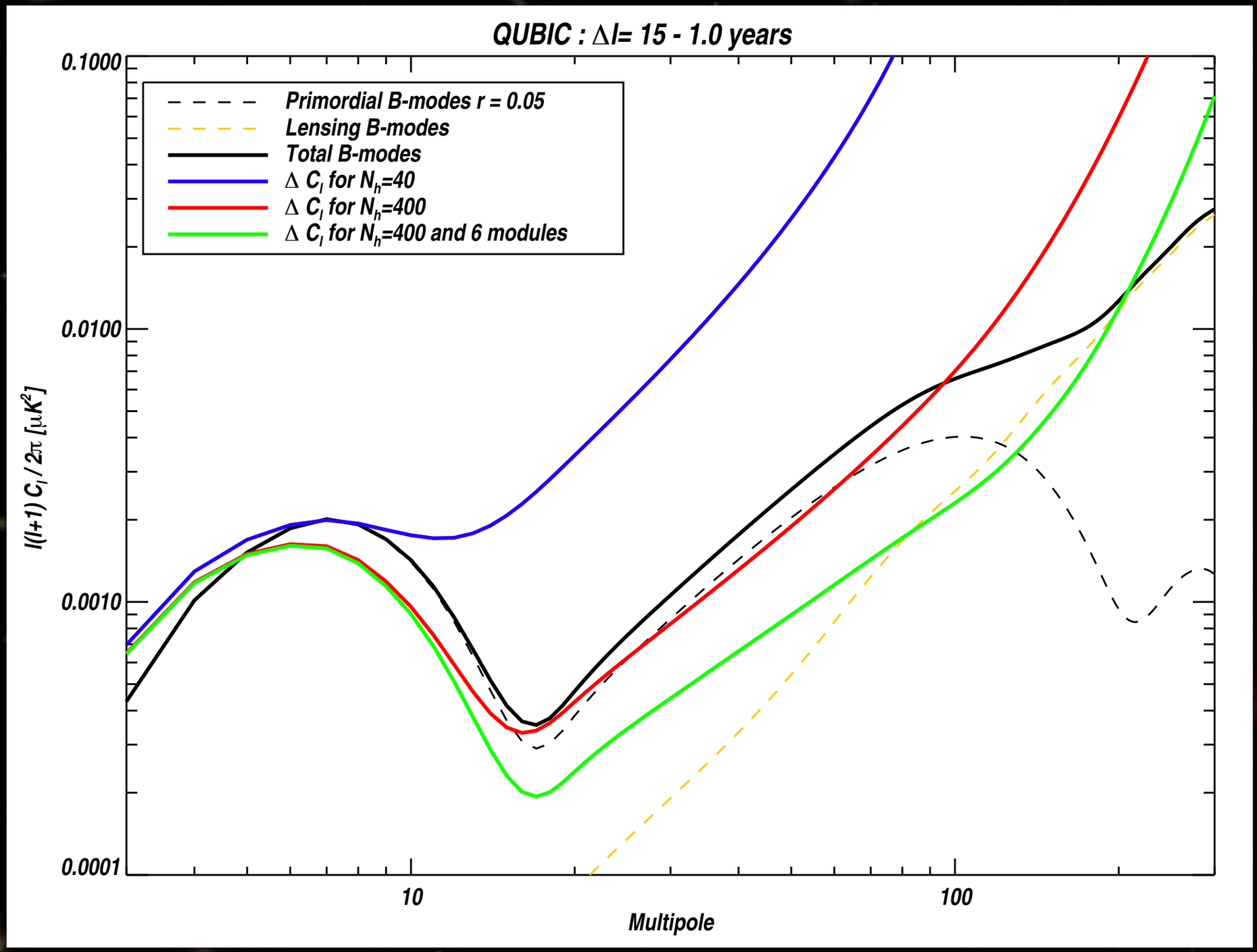


Self-Calibration results



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

B-mode sensitivity



tensor/scalar ratio sensitivity