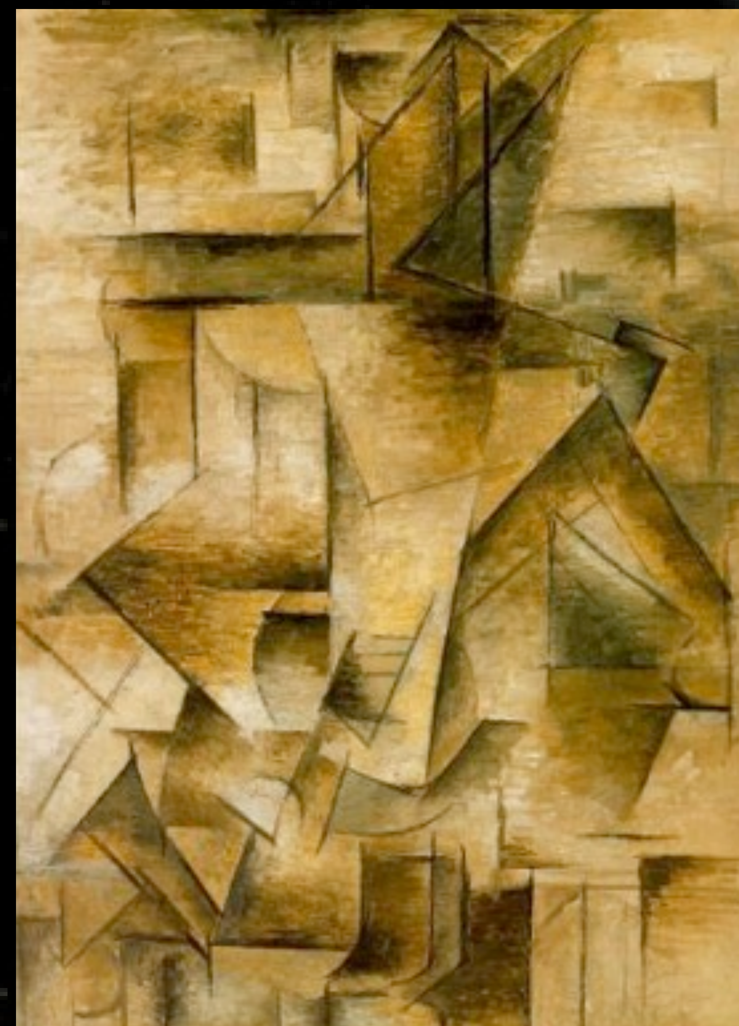
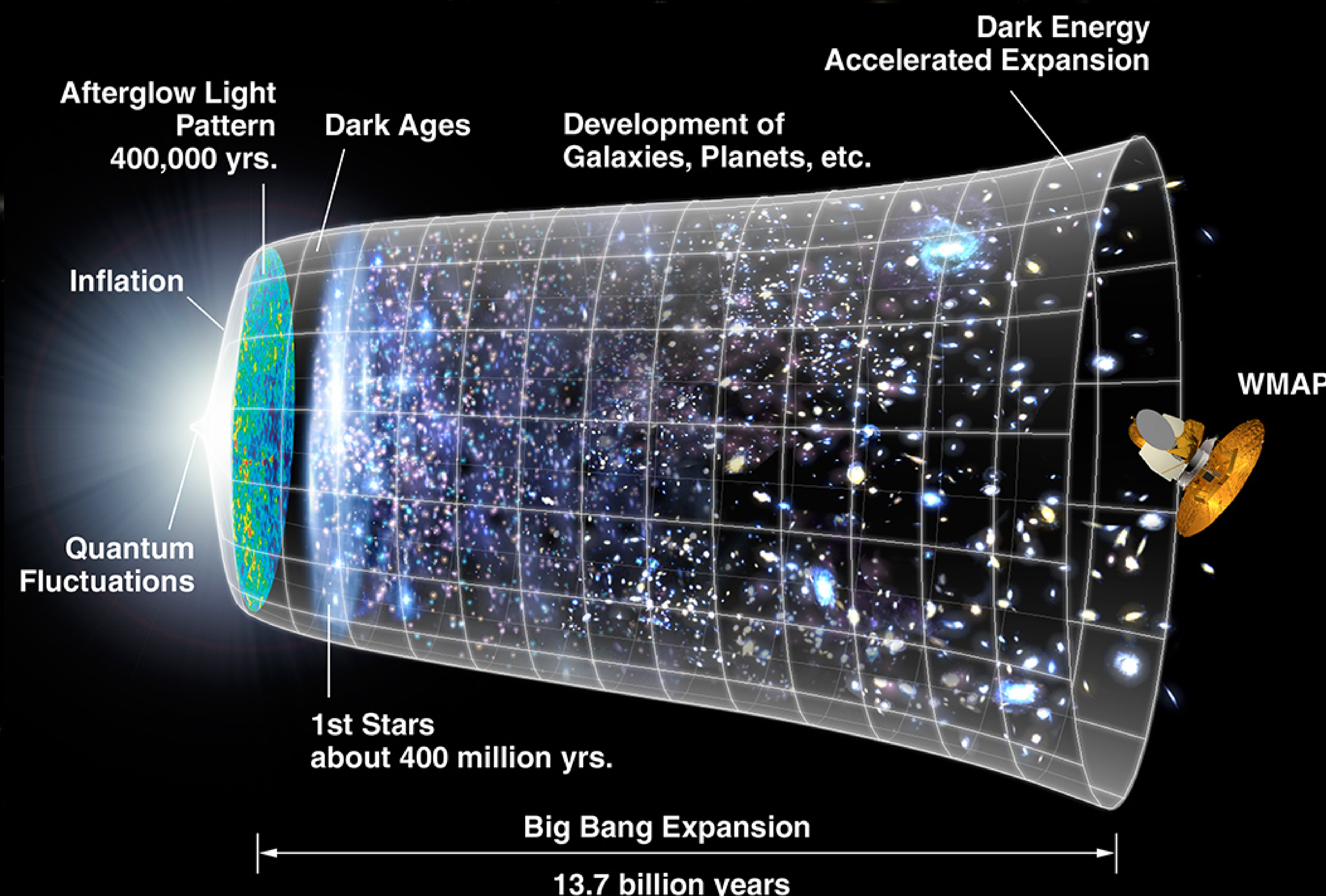
Exploring the primordial Universe with QUBIC

the Q U Bolometric Interferometer for Cosmology



J.-Ch. Hamilton
APC, Paris

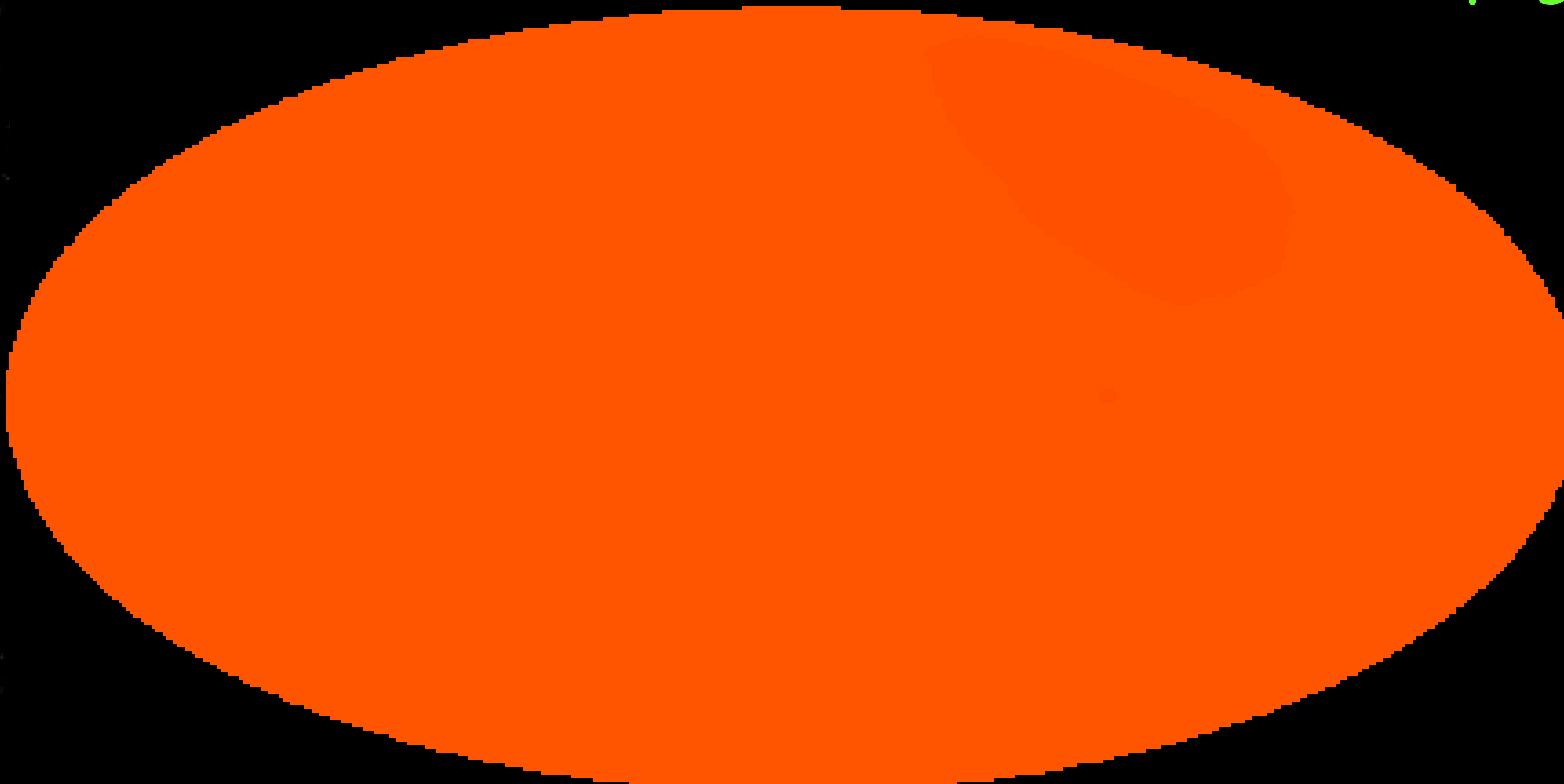
Timeline


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Cosmic Microwave Background

Cosmic Microwave Background

(COBE/DMR homepage)



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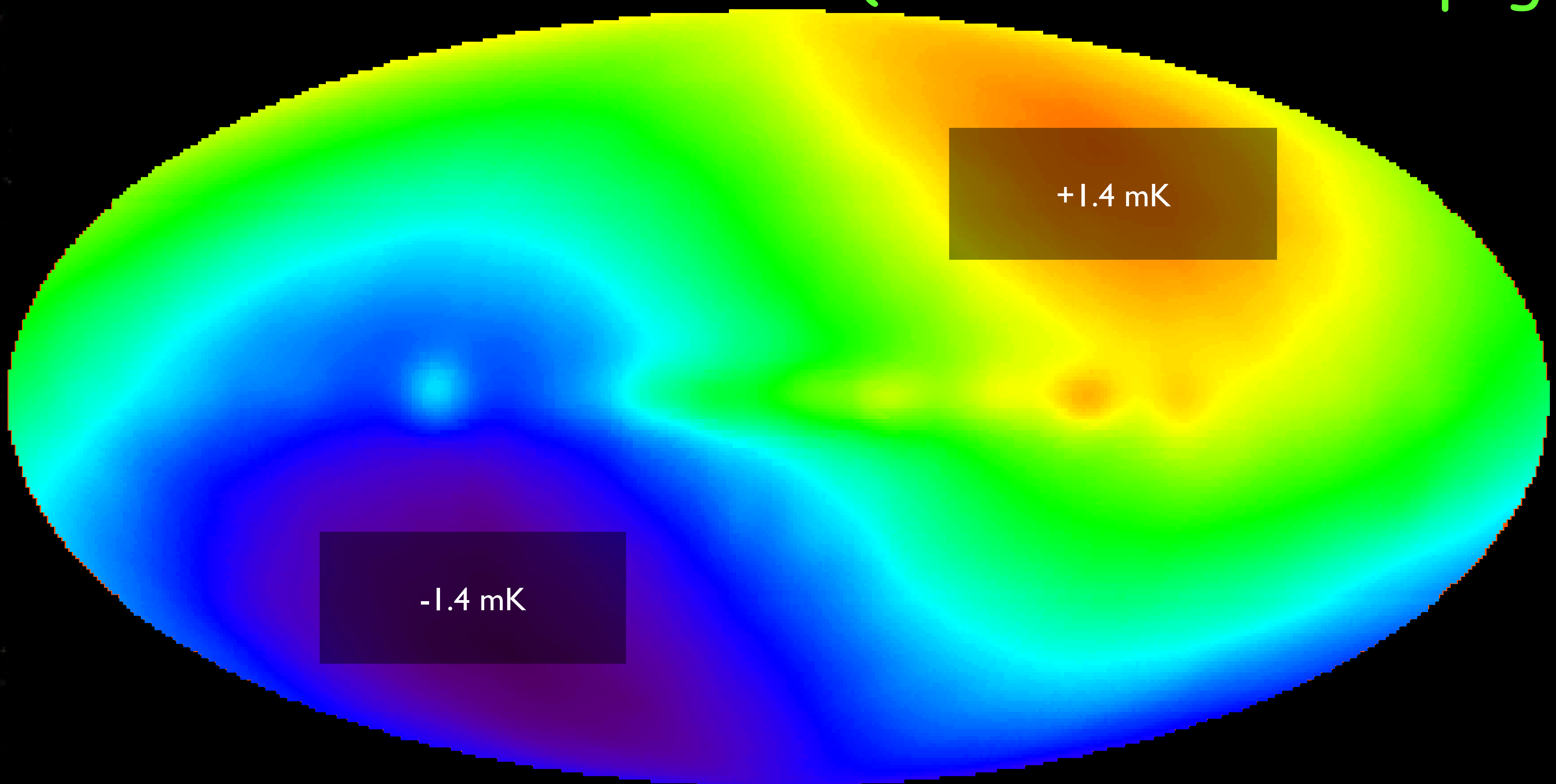

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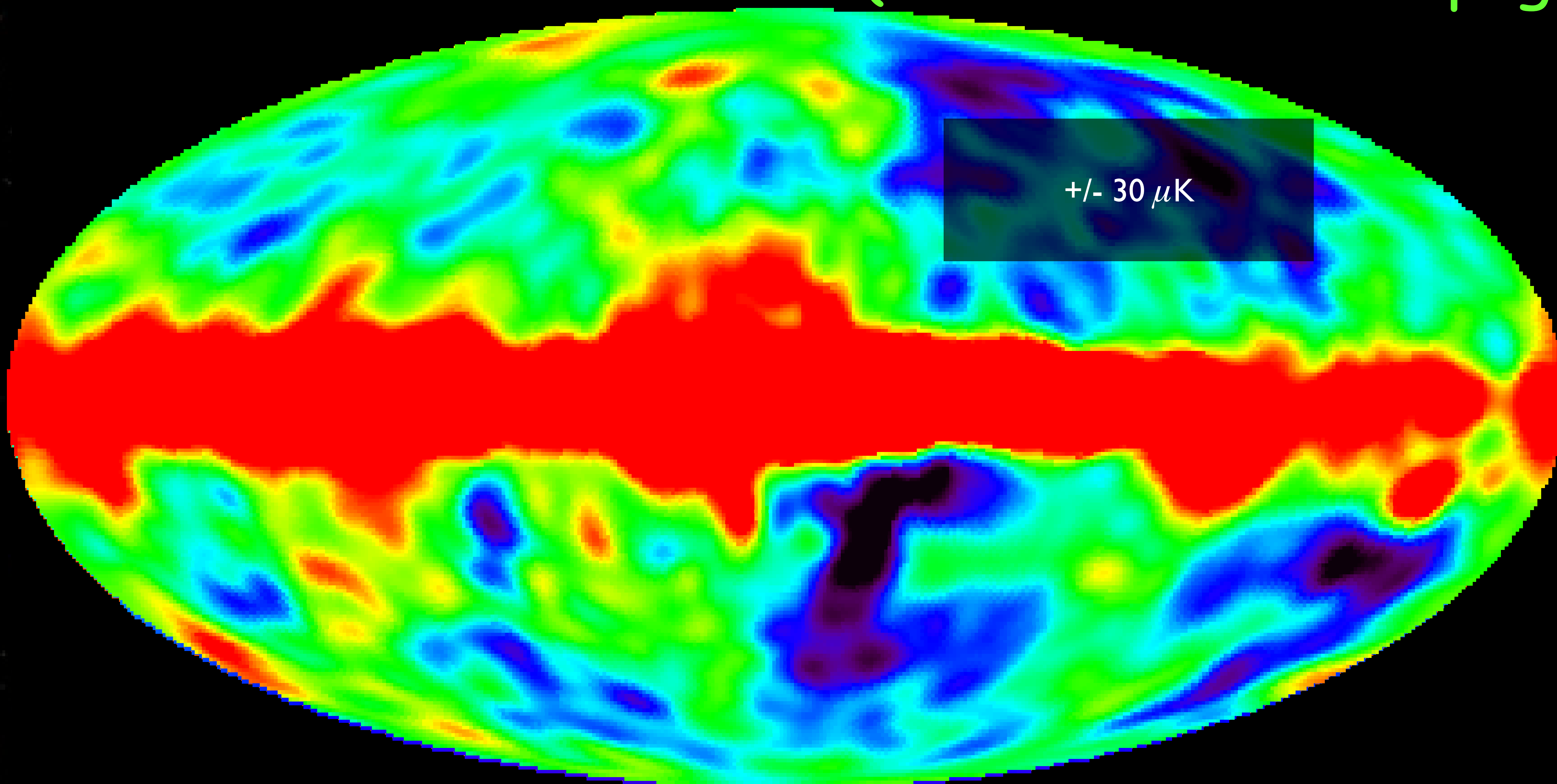

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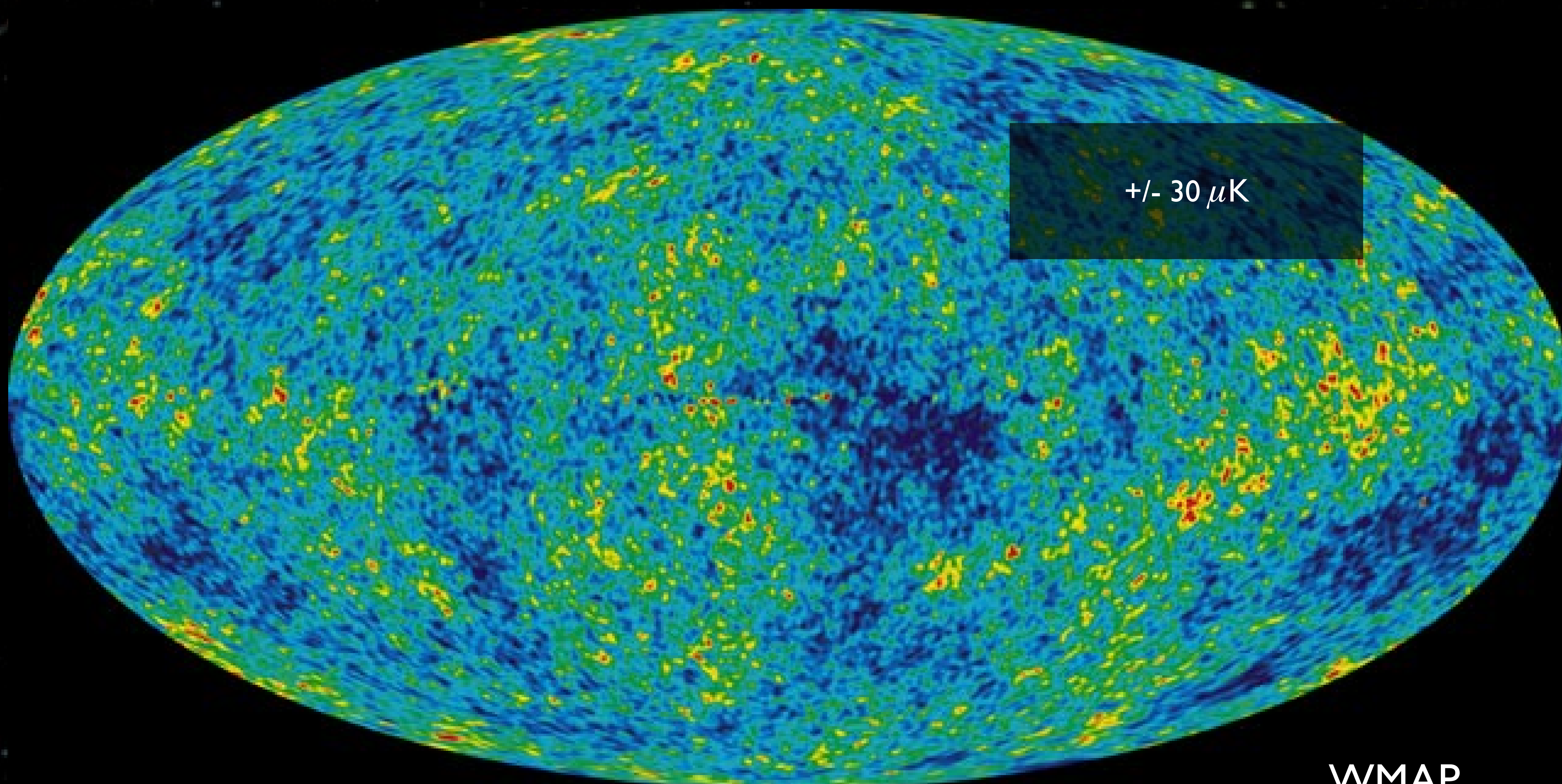
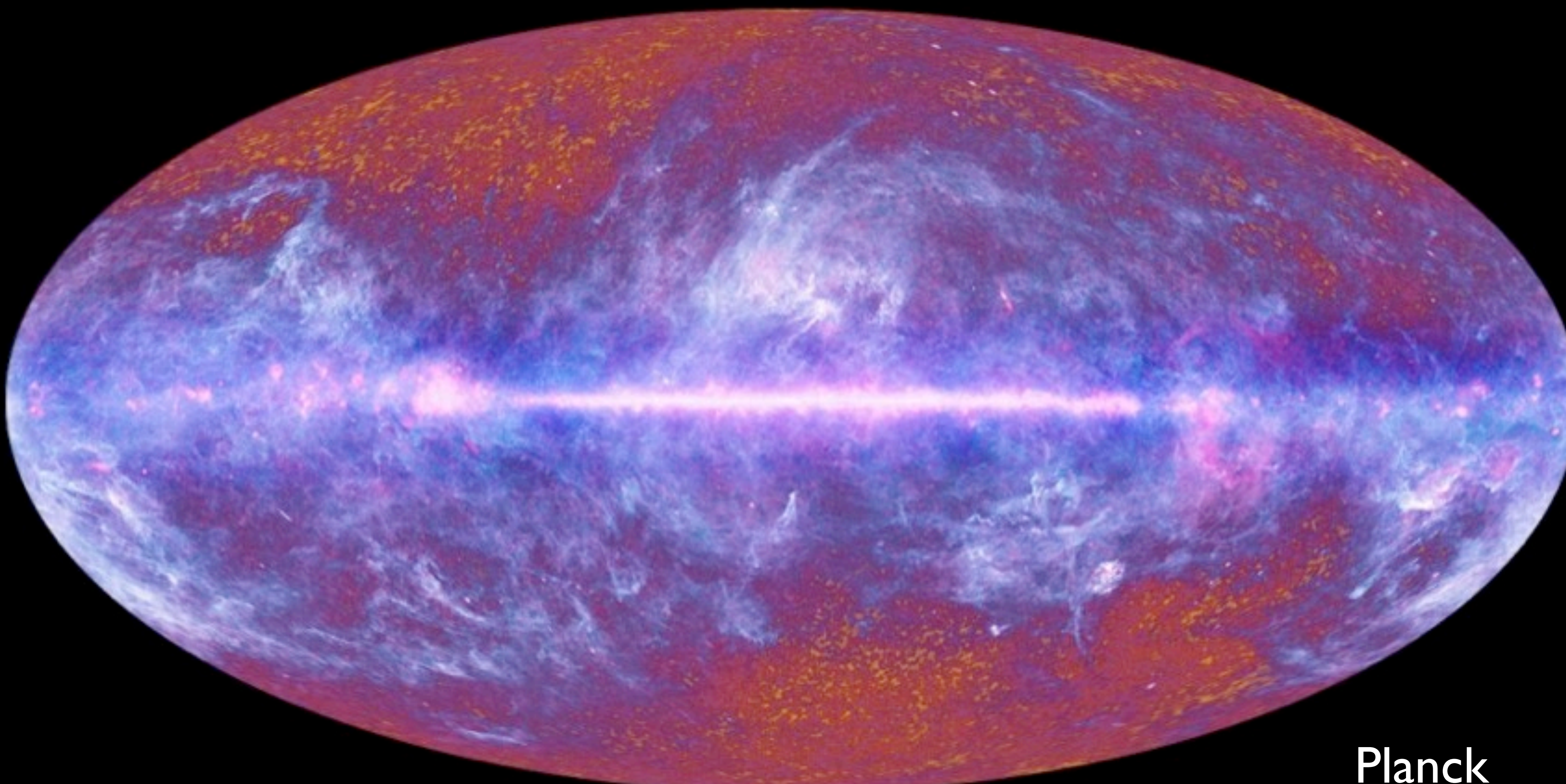


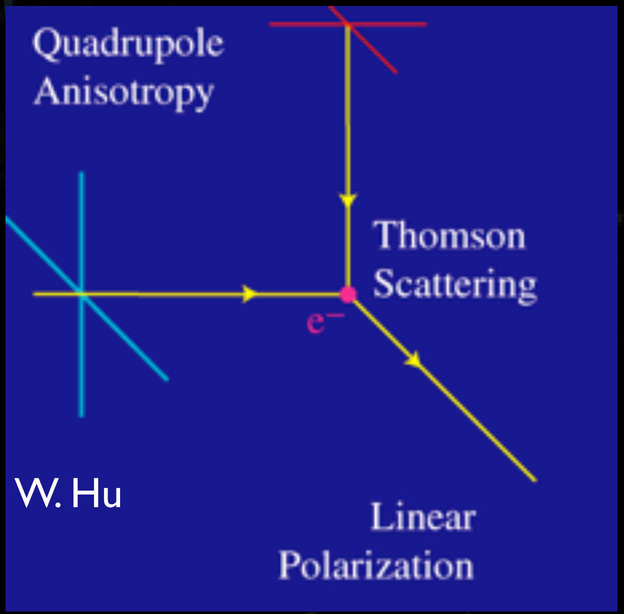
WMAP

Cosmic Microwave Background



Planck

CMB Polarization



- Generated by Thomson scattering of electrons in quadrupolar motion
- Stokes Parameters (linear pol.)

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

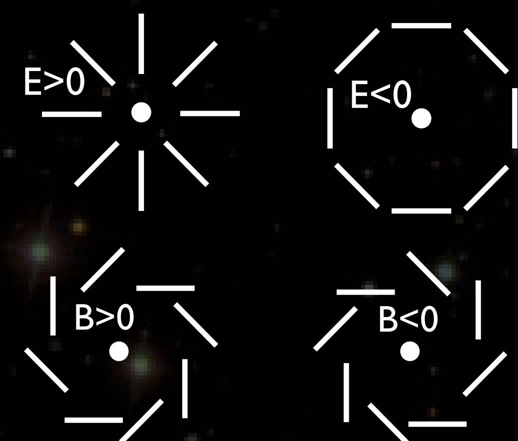
$$I = \left\langle |E_x|^2 \right\rangle + \left\langle |E_y|^2 \right\rangle$$

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

- Scalar E and B fields

$$a_{E,\ell m} = -\frac{a_{2,\ell m} + a_{-2,\ell m}}{2} \quad \text{(even)}$$

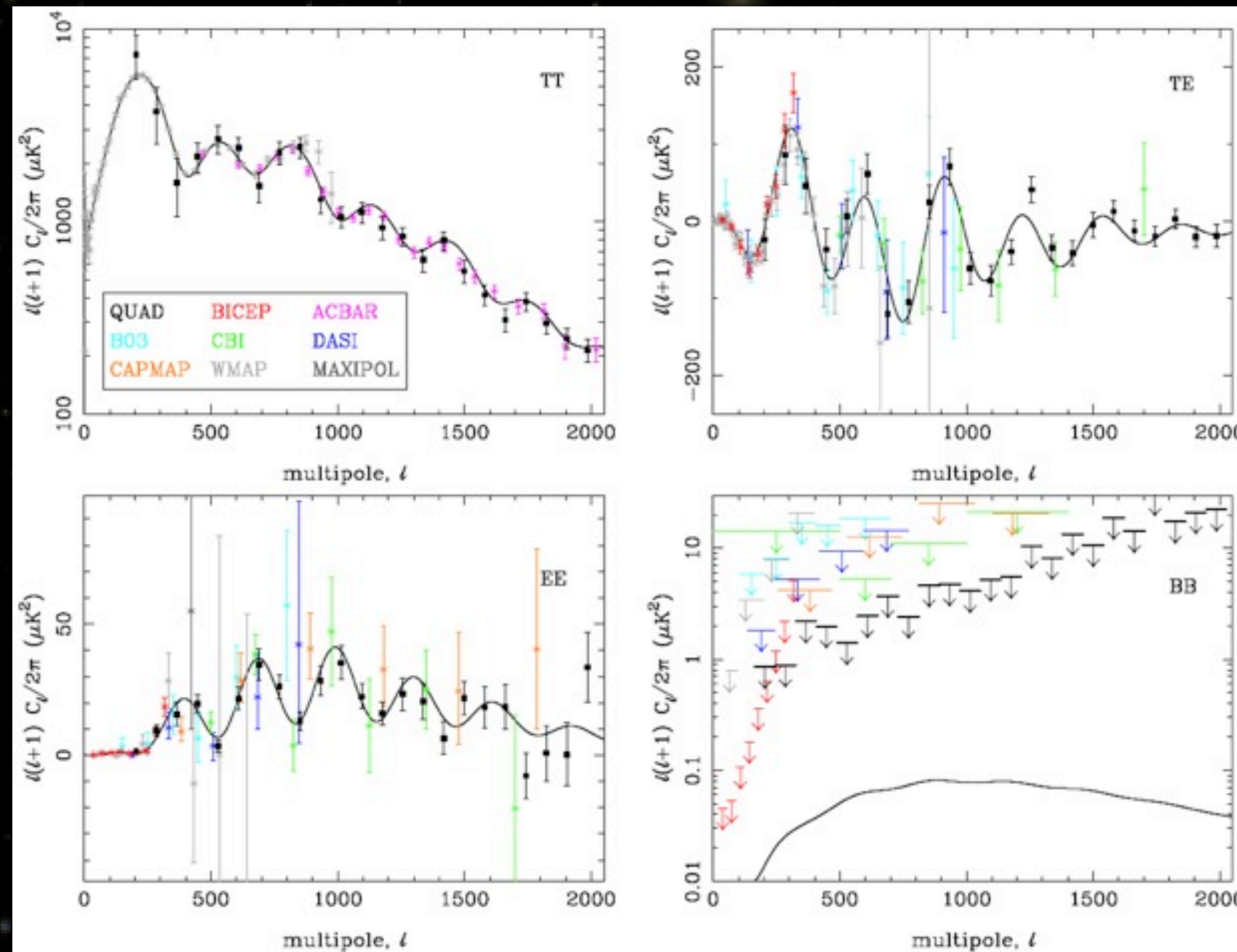
$$a_{B,\ell m} = i\frac{a_{2,\ell m} - a_{-2,\ell m}}{2} \quad \text{(odd)}$$



$$\left.\right\} \quad C_\ell^{TT} \quad C_\ell^{TE} \quad C_\ell^{EE} \quad C_\ell^{BB}$$

Recent latest CMB measurements

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



[QUAD Collaboration: Arxiv:0906.1003]

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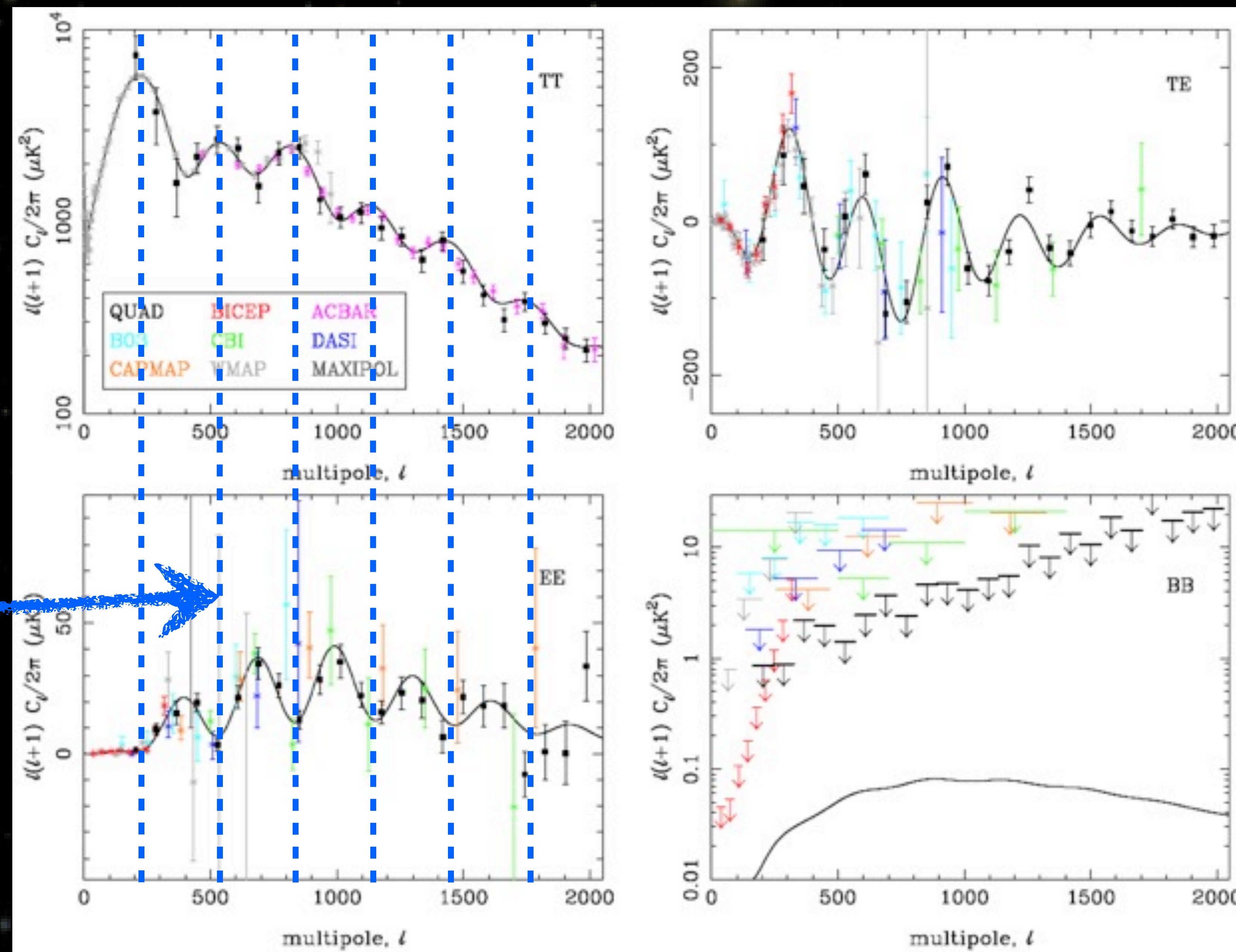

[QUAD Collaboration: Arxiv:0906.1003]

Inflation

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

Scalar and tensor modes - E & B polarization

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

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

$$\boxed{\begin{aligned}\sigma^T_{scal} &\simeq 100\mu\mathrm{K}\\ \sigma^E_{scal} &\simeq 4\mu\mathrm{K}\end{aligned}}$$

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

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

$$\boxed{\begin{aligned}\sigma^T_{tens} &\leq 30\mu\mathrm{K}\\ \sigma^E_{tens} &\leq 1\mu\mathrm{K}\\ \sigma^B_{tens} &\leq 0.3\mu\mathrm{K}\end{aligned}}$$

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

~ ratio between E and B modes

$\Rightarrow$ detect B-modes is :

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

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

Primordial fluctuations: where are we standing ?

Inflation predictions

• Flatness, Homogeneity	✔
• Nature of perturbations: ★ TT peaks at the same location as EE troughs ➡ Adiabatic perturbations	✔
• Spectral index $P(k) \propto k^{n_s - 1}$ ★ QUAD+WMAP+ACBAR+SDSS $n_s = 0.967^{+0.013}_{-0.013}$ ➡ Almost scale invariant spectrum	✔
• Gaussianity ★ No convincing evidence for non-gaussianity (despite impressive efforts)	✔
• Tensor perturbations of the metric ★ No B-mode detection (yet ...)	?

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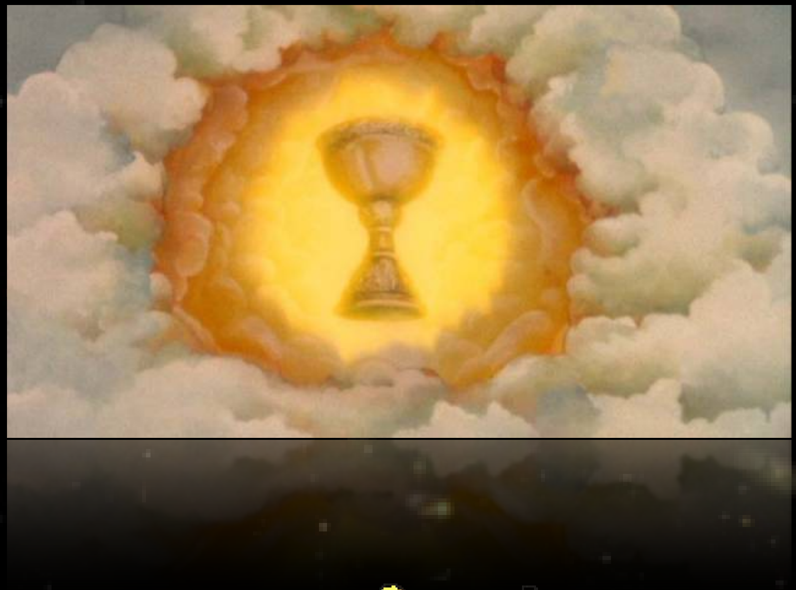
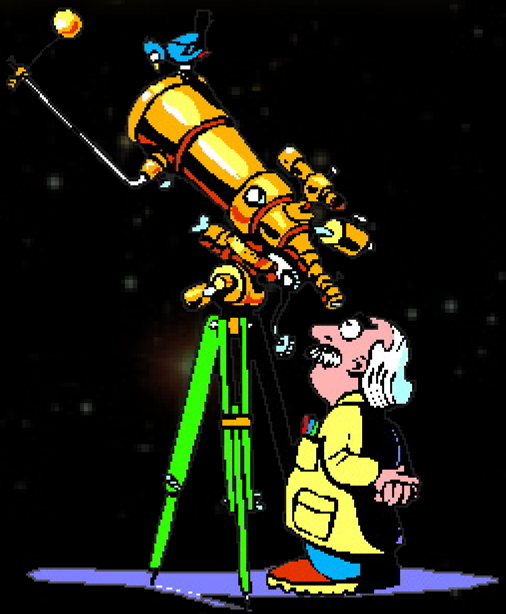
Expected difficulties in the Holy Grail Quest

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



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

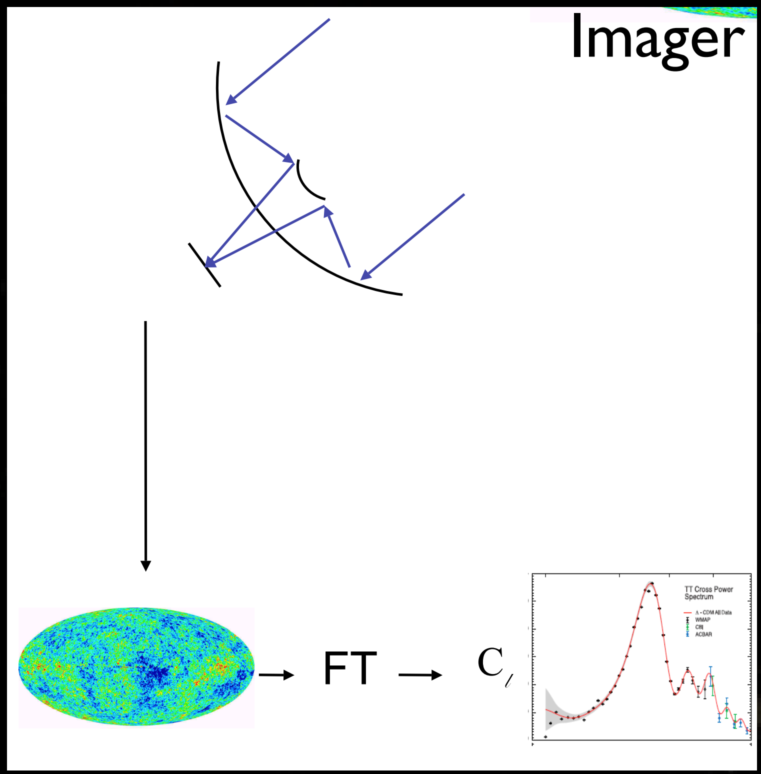


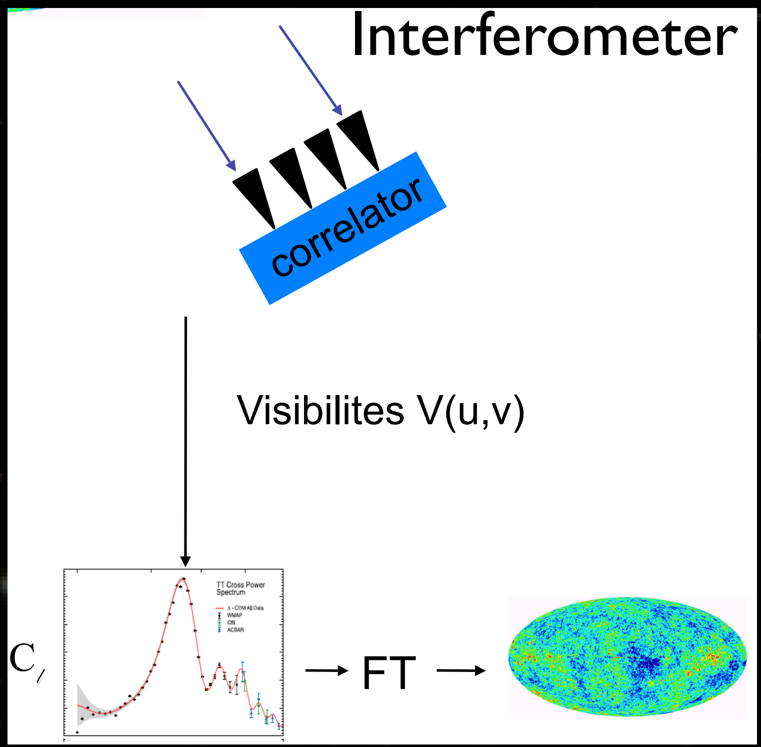
- Systematic effects :
  - ★ Instrument induces leakage of T into E and B (and T>>E>>B)
    - ➡ Cross-polarization and ground pickup are major issues
  - ★ Atmospheric polarization ...
  - ➡ Need for accurate polarization modulation

Possible instruments

- Imagers with bolometers:
  - ★ No doubt they are nice detectors for CMB:
    - wide band
    - low noise
  - ★ Especially true for a satellite (small background)
- Interferometers:
  - ★ Long history in CMB
    - CMB anisotropies in the late 90s (CAT: 1st detection of subdegrees anisotropies, VSA)
    - CMB polarization 1st detection (DASI, CBI)
  - ★ Technology used so far
    - Antennas + HEMTs : higher noise
    - Correlators : hard to scale to large #channels
  - ★ Clean systematics:
    - No telescope (lower ground-pickup & cross-polarization)
    - Angular resolution set by receivers geometry (well known)
- Can these two nice devices be combined ?
  - ➡ Bolometric Interferometry !

P. Timbie





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Good control of systematics

- Can these two nice devices be combined ?

➡ Bolometric Interferometry !

Both

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The QUBIC collaboration

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CSNSM Orsay, France
CESR Toulouse, France
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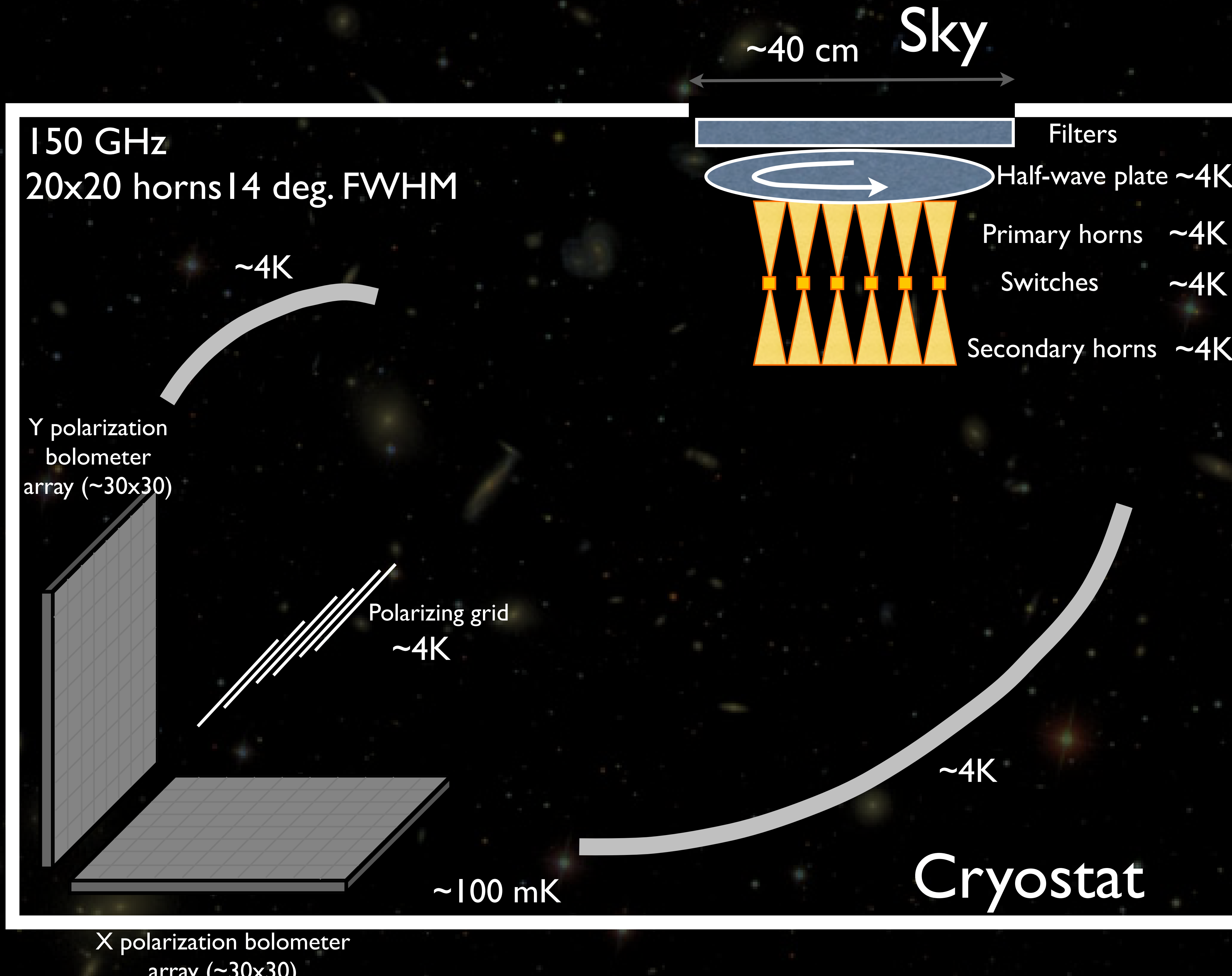
QUBIC design



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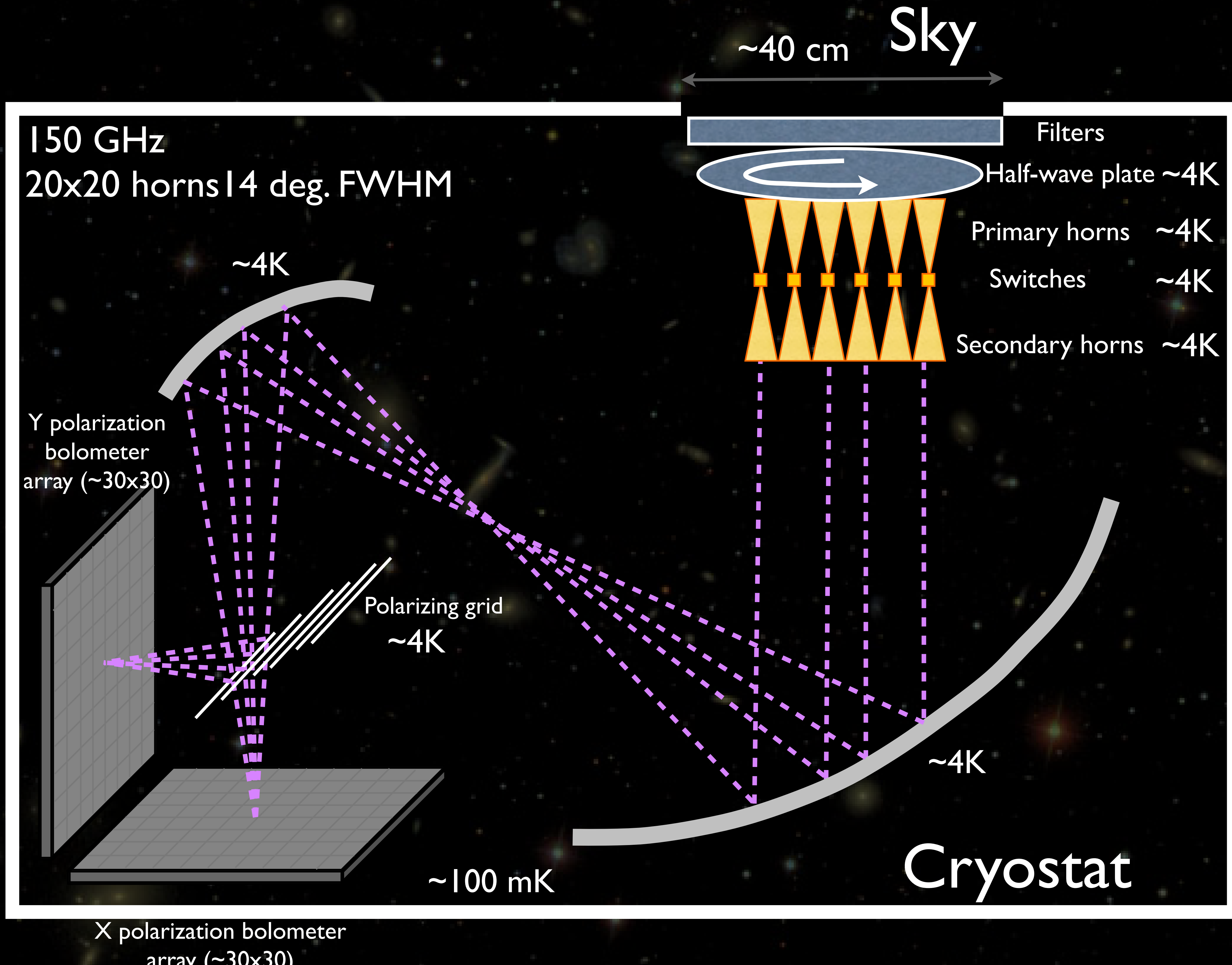

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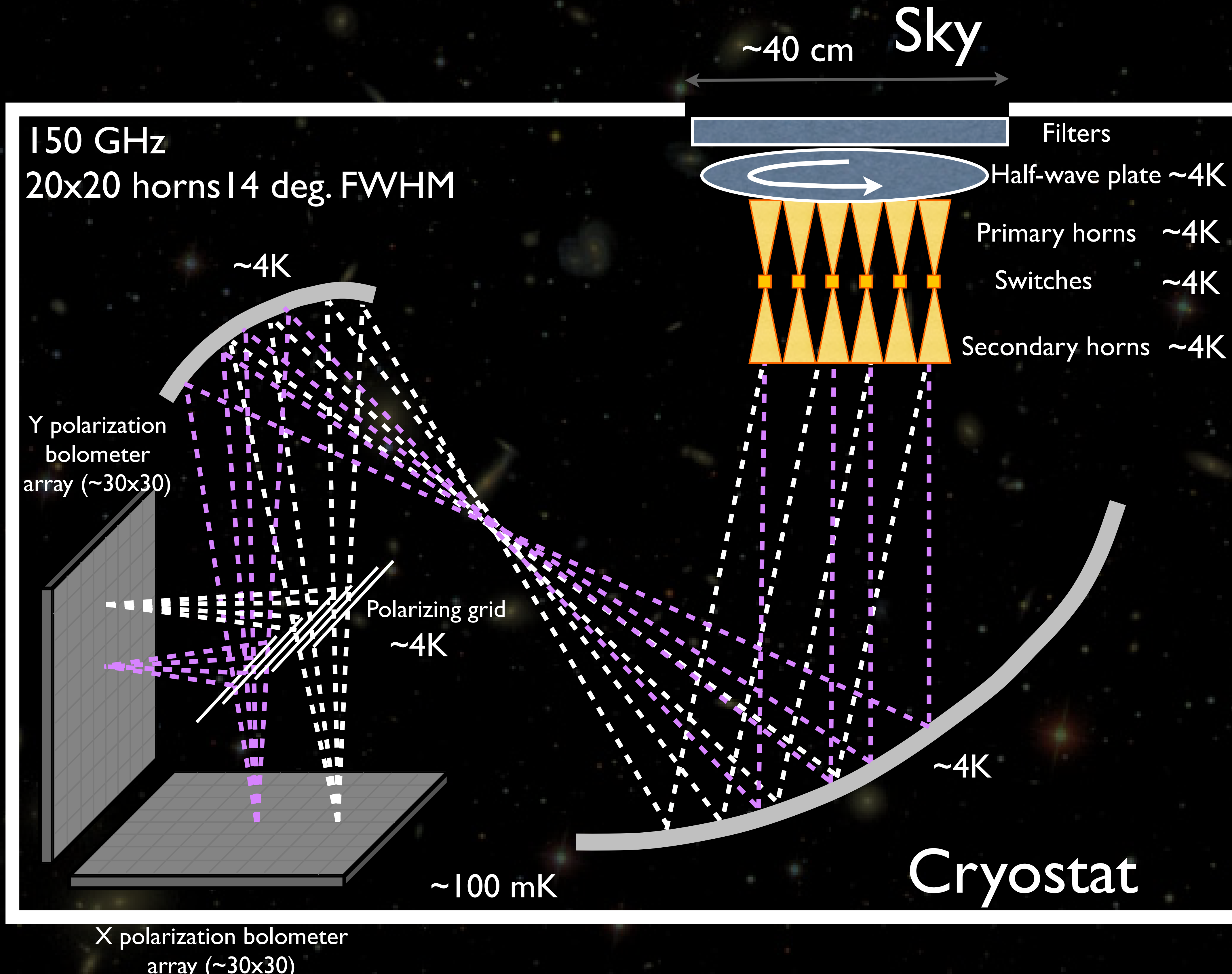

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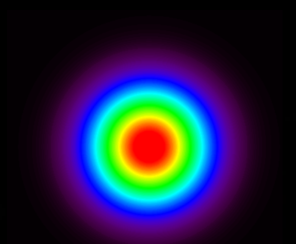

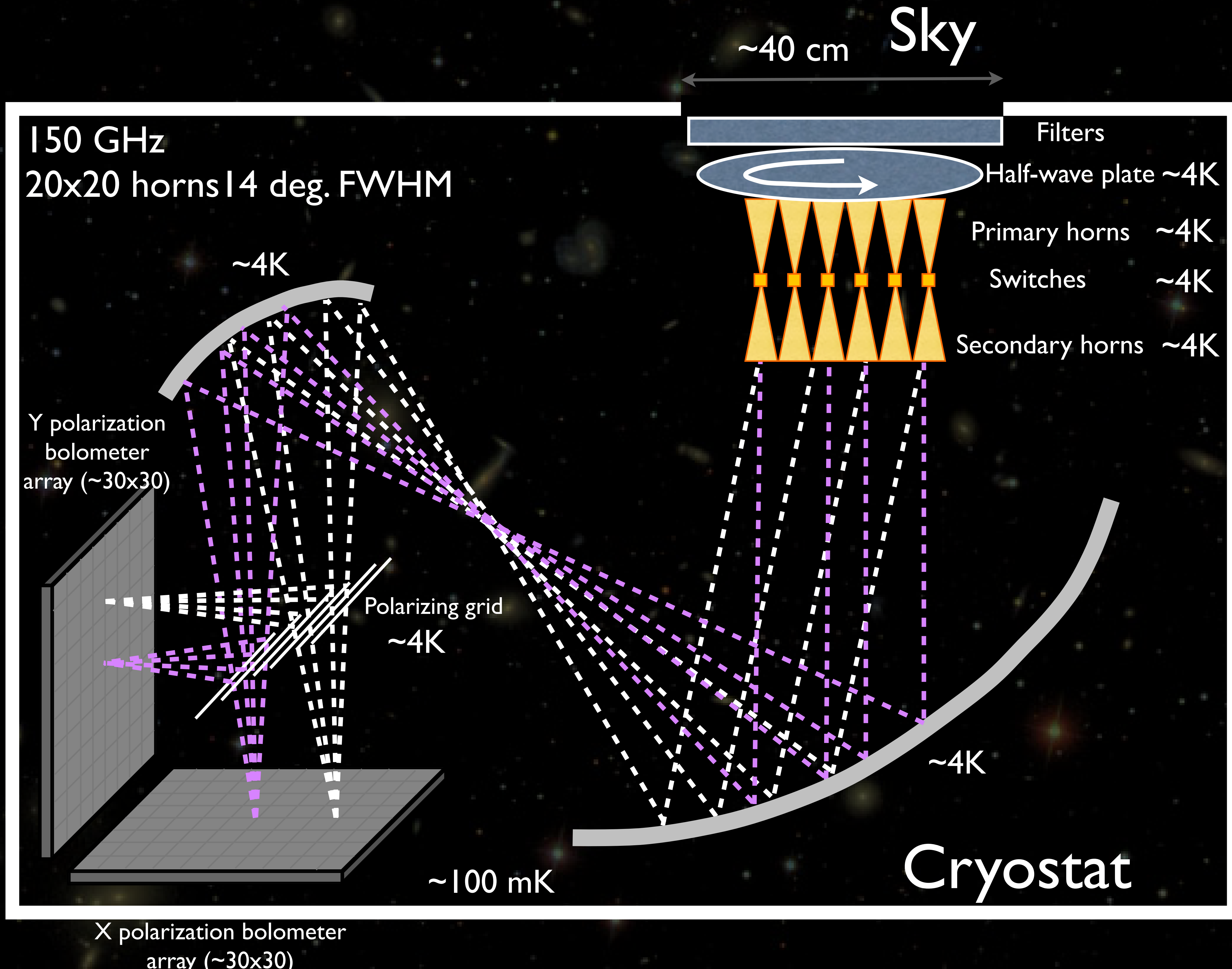

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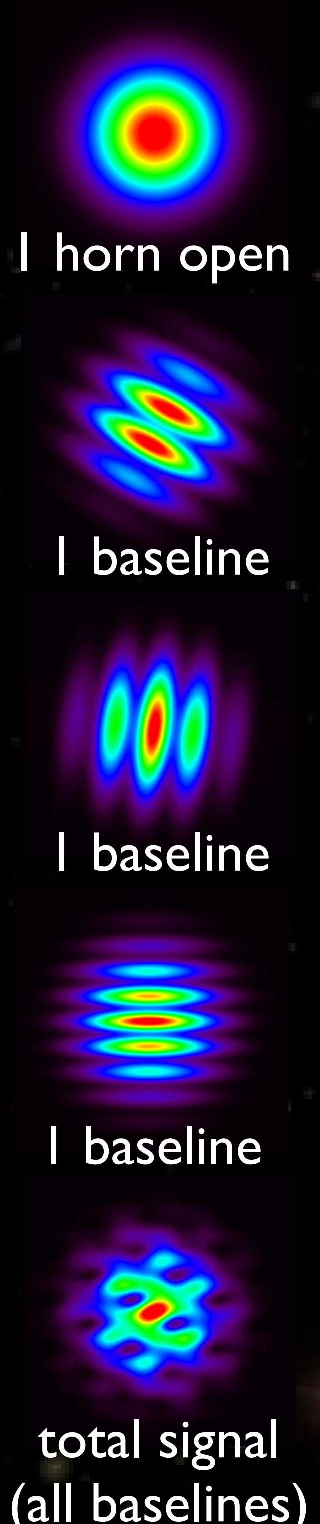
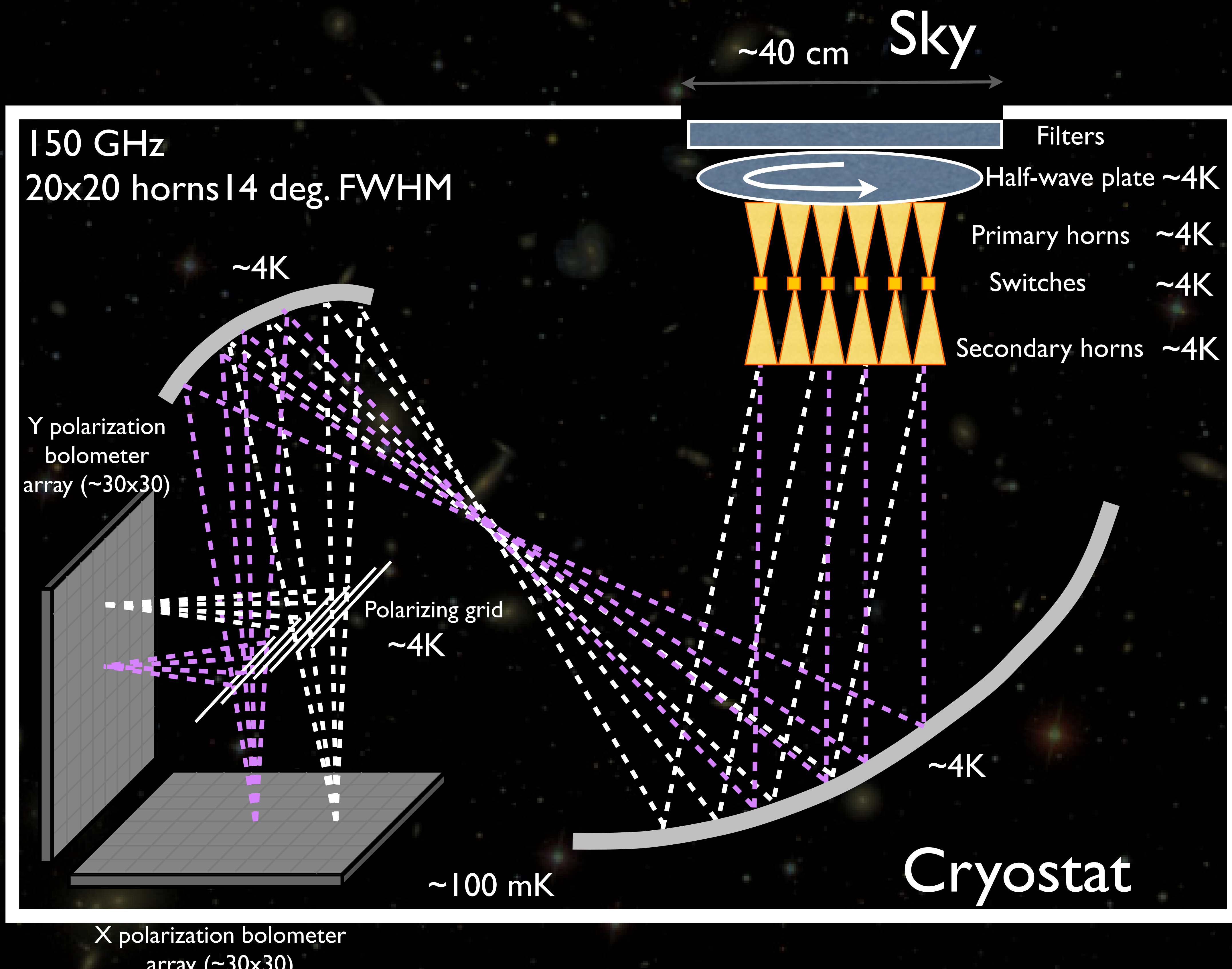
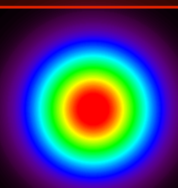




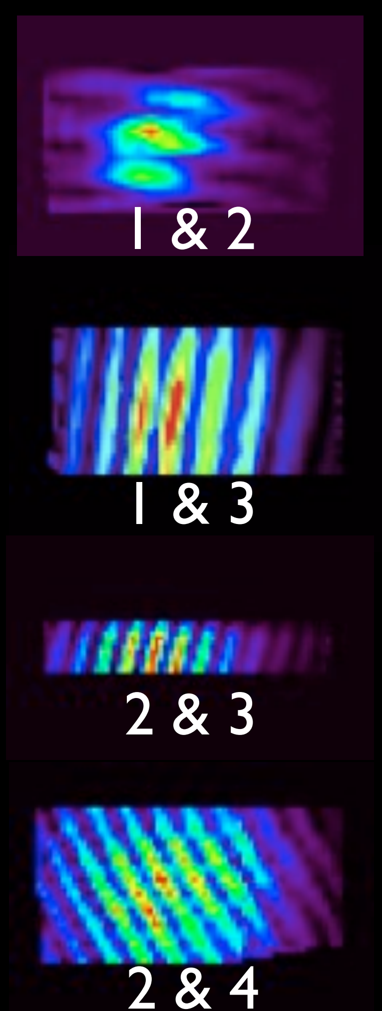
QUBIC design

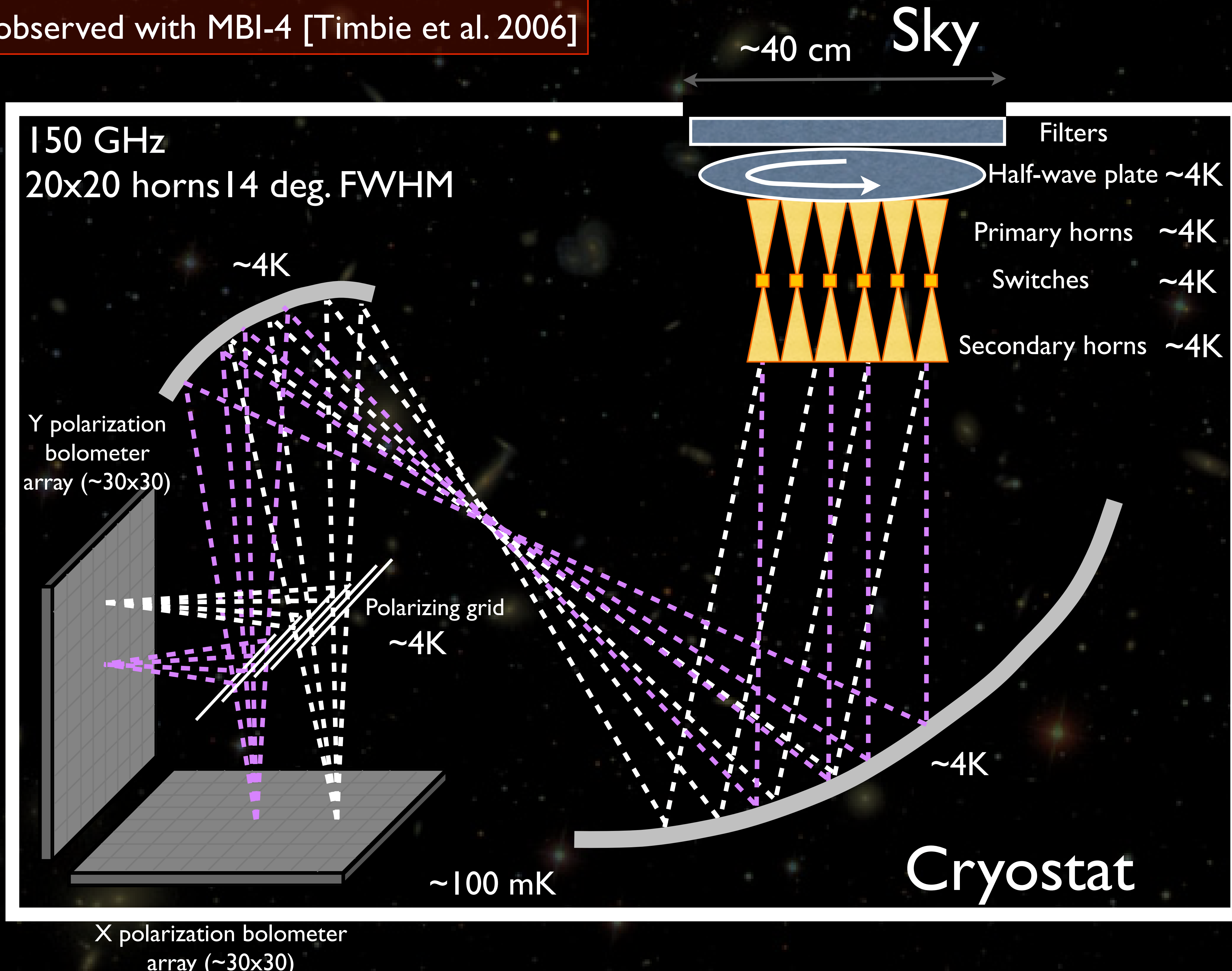
fringes successfuly observed with MBI-4 [Timbie et al. 2006]



1 horn open

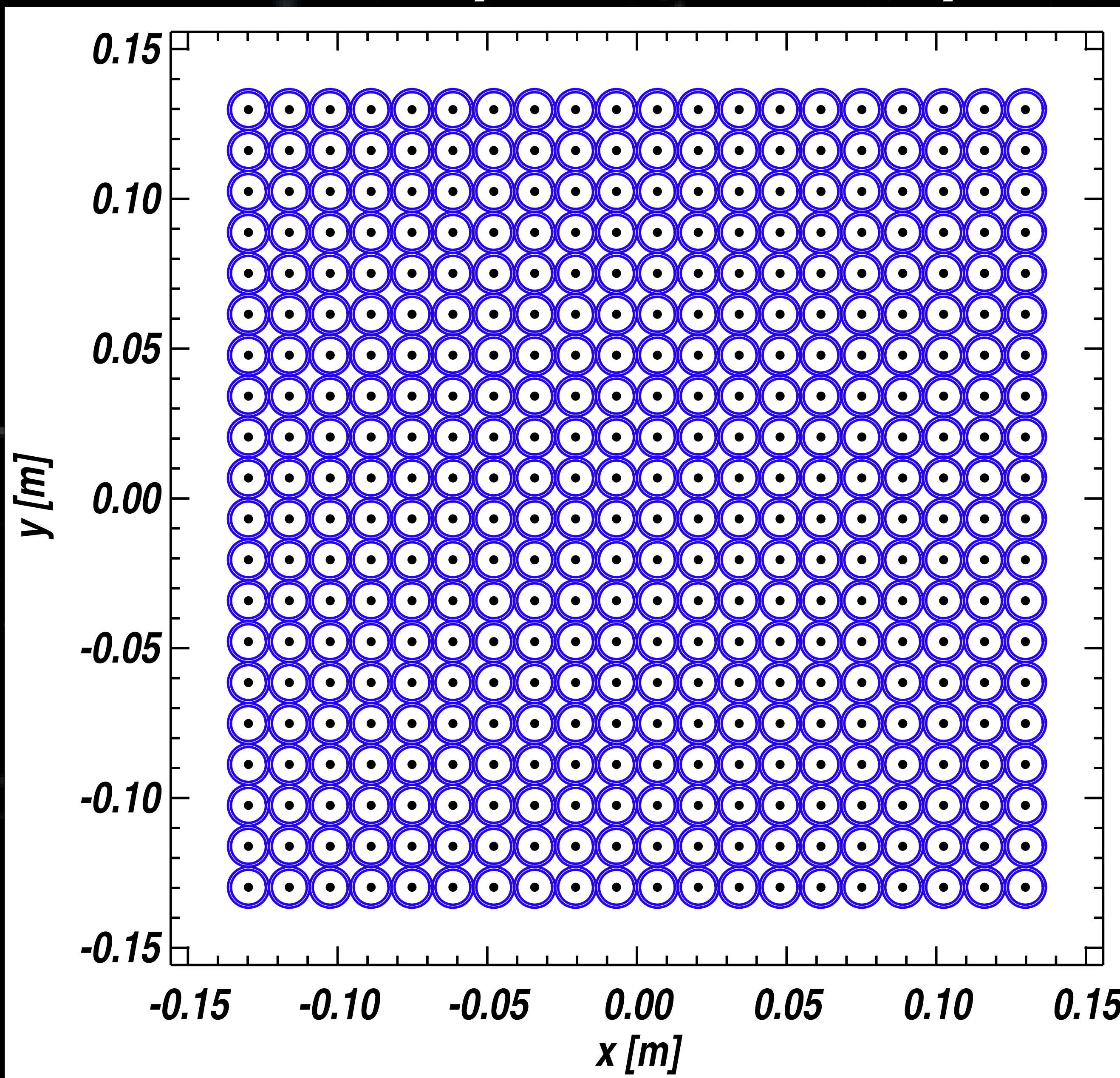
MBI-4 data
2009 campaign
(PBO- Wisc.)



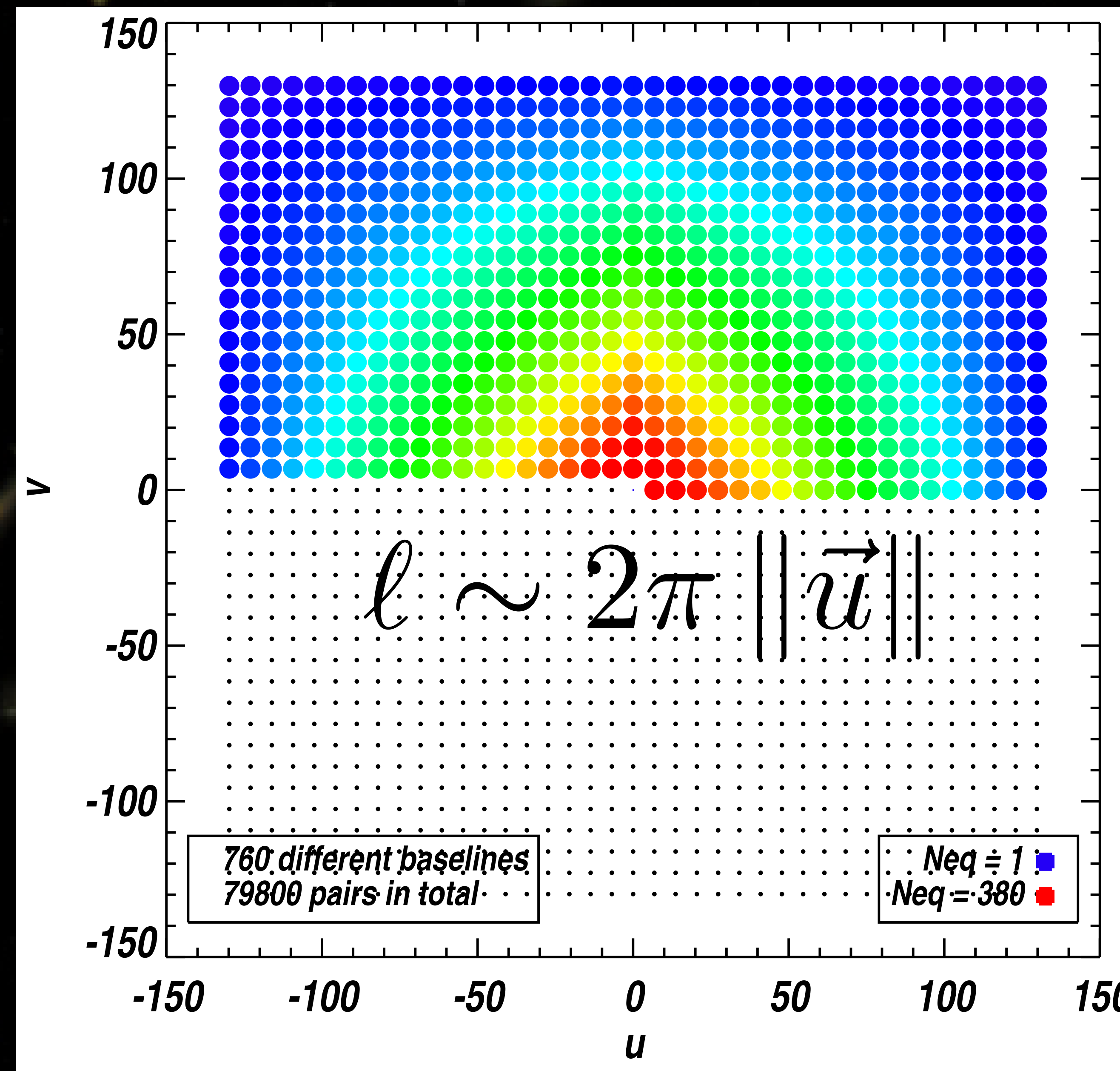


Horns and baselines

Primary horns array



Fourier plane coverage



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

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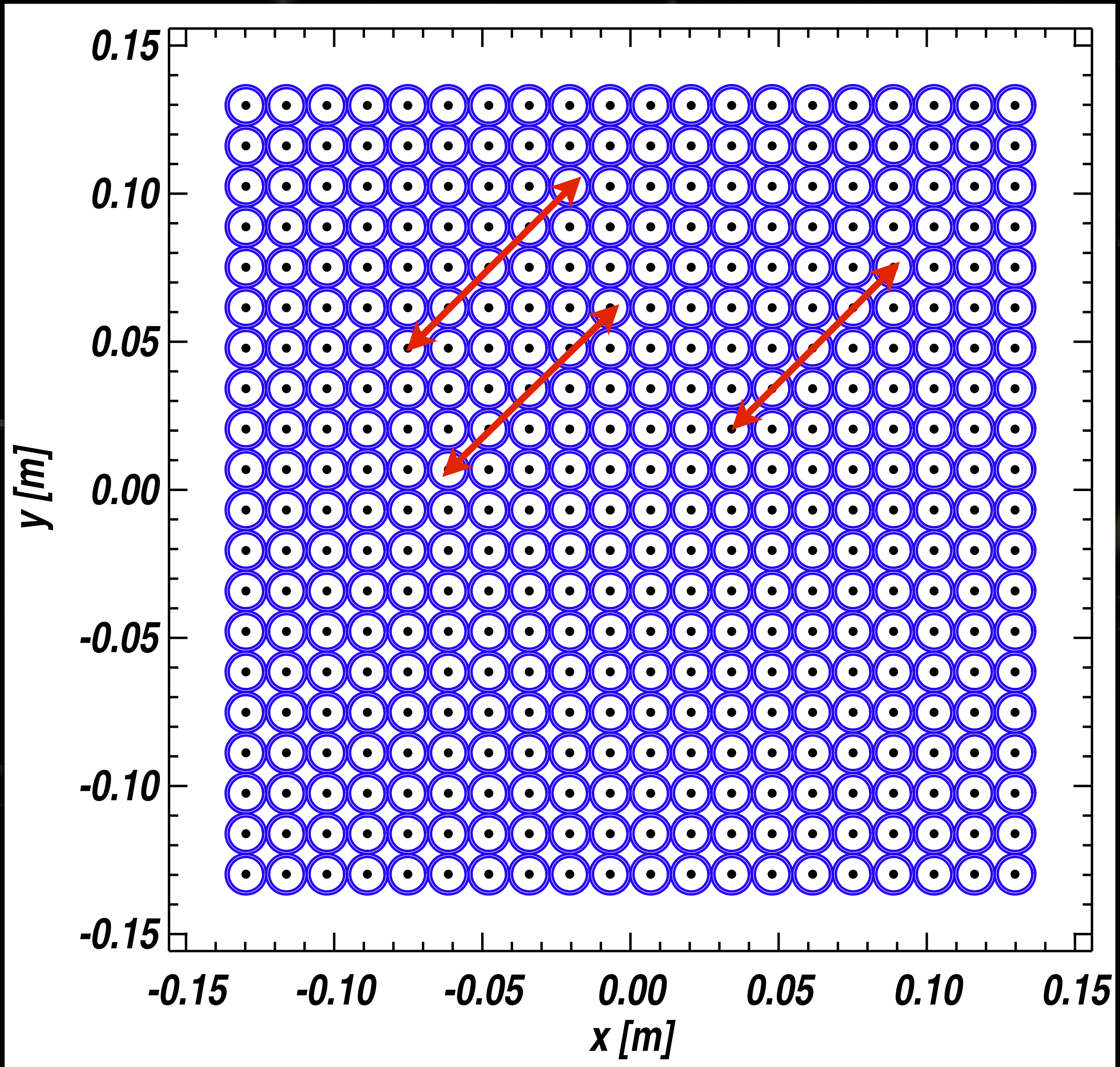

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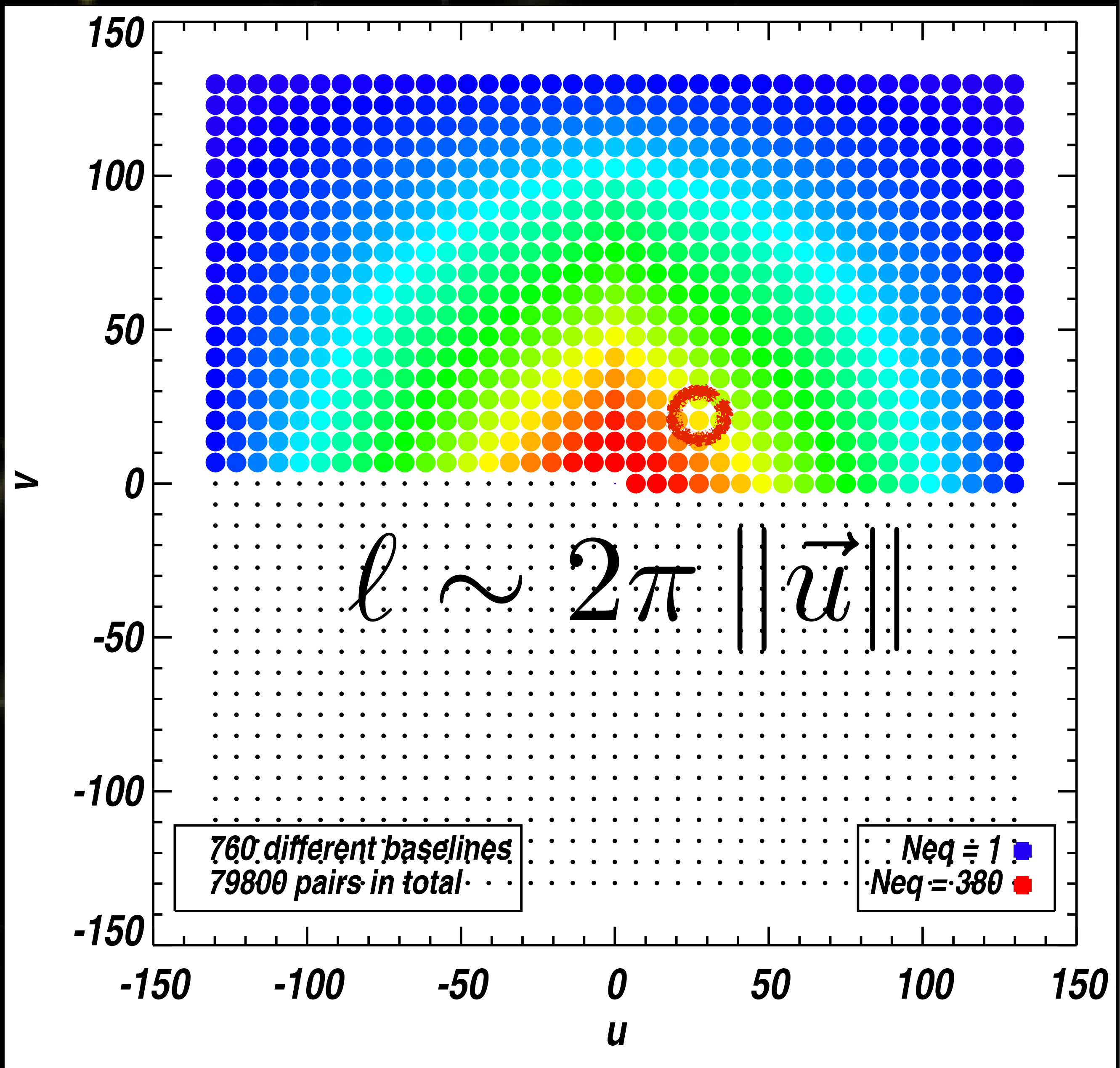

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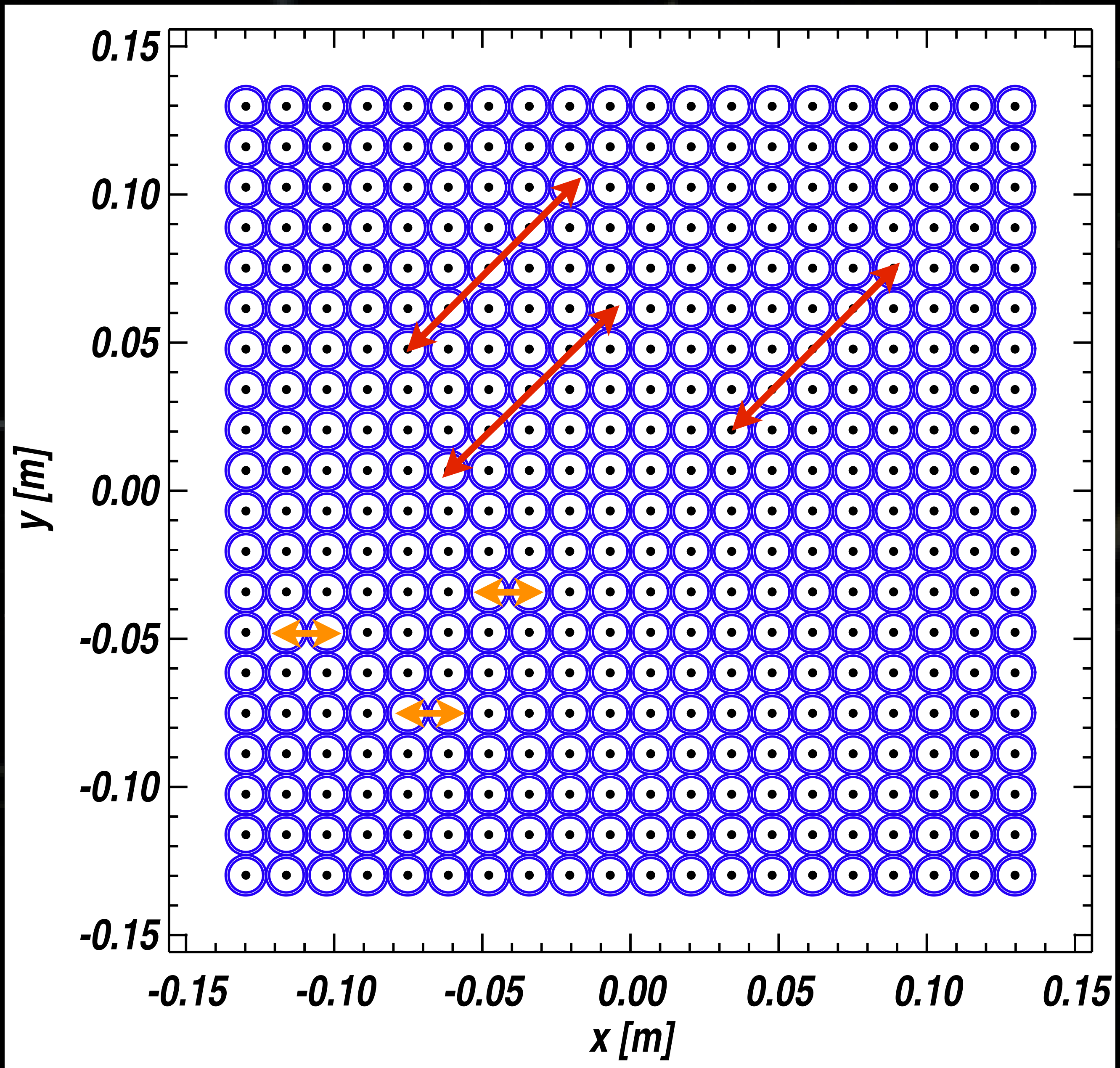

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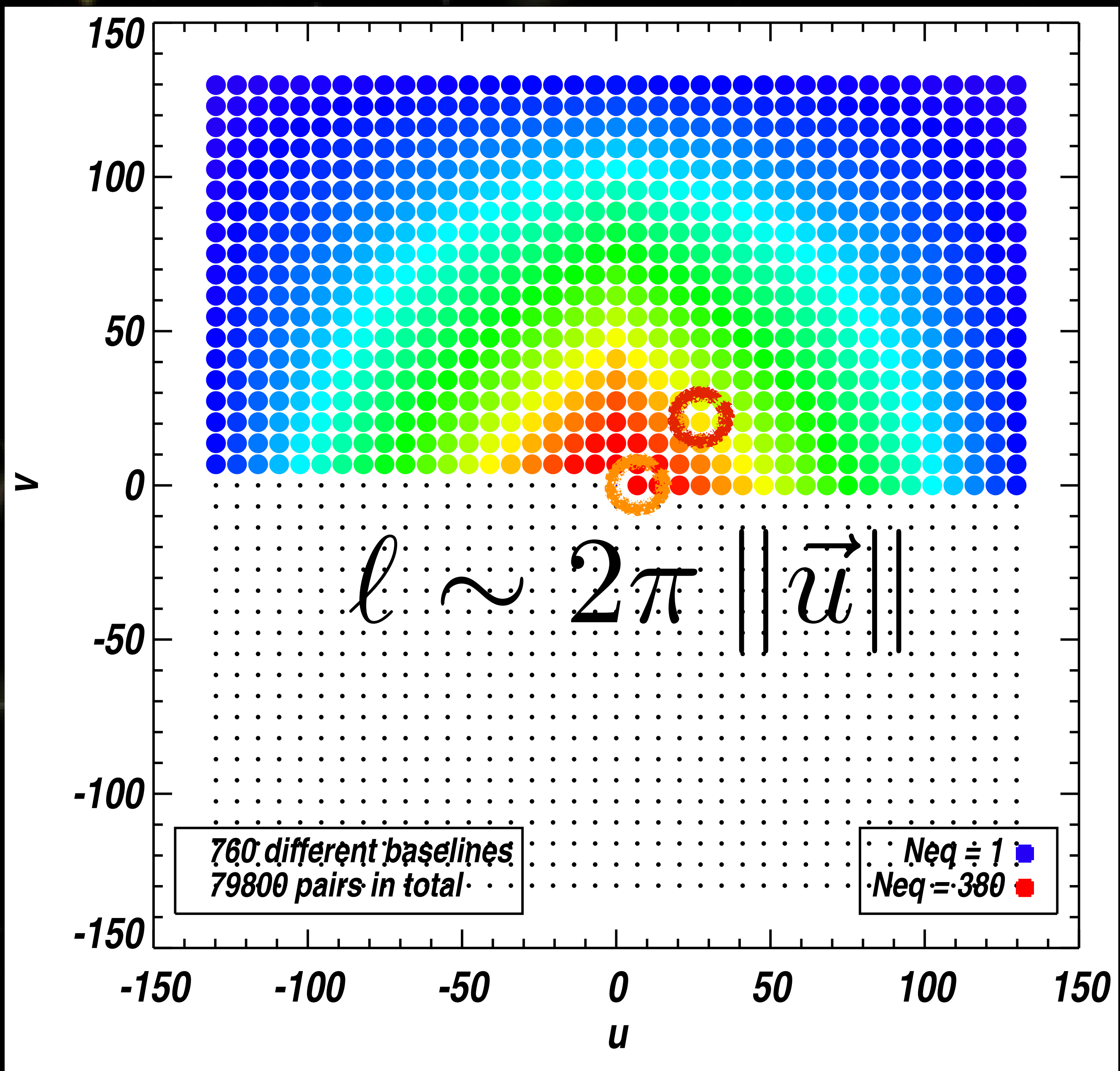

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Signal in QUBIC

- Signal on bolometer d_p (HWP modulation) :

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

+ for X focal plane
- for Y focal plane

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

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

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

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

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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

⇔ An interferometer performing direct synthesis imaging

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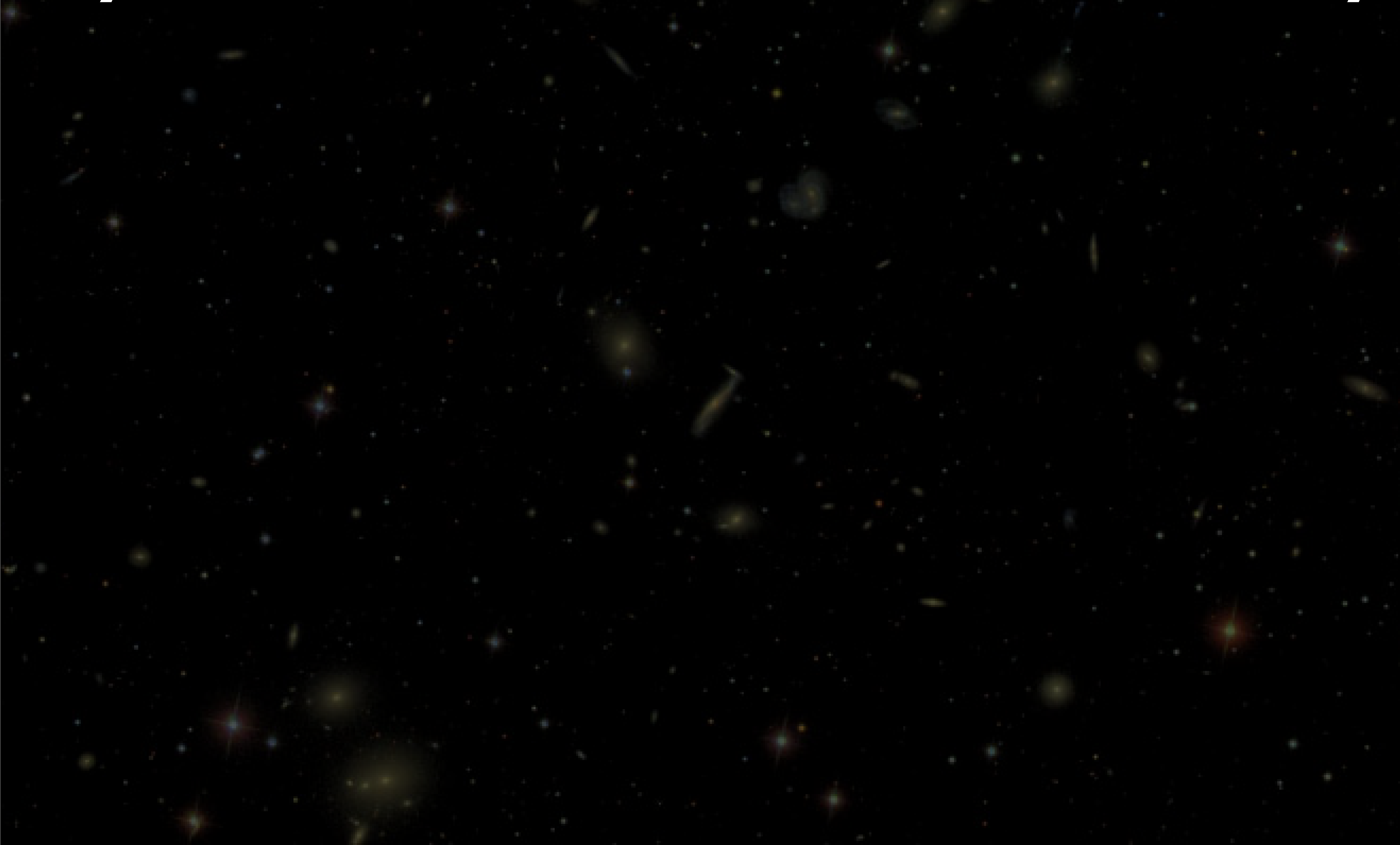
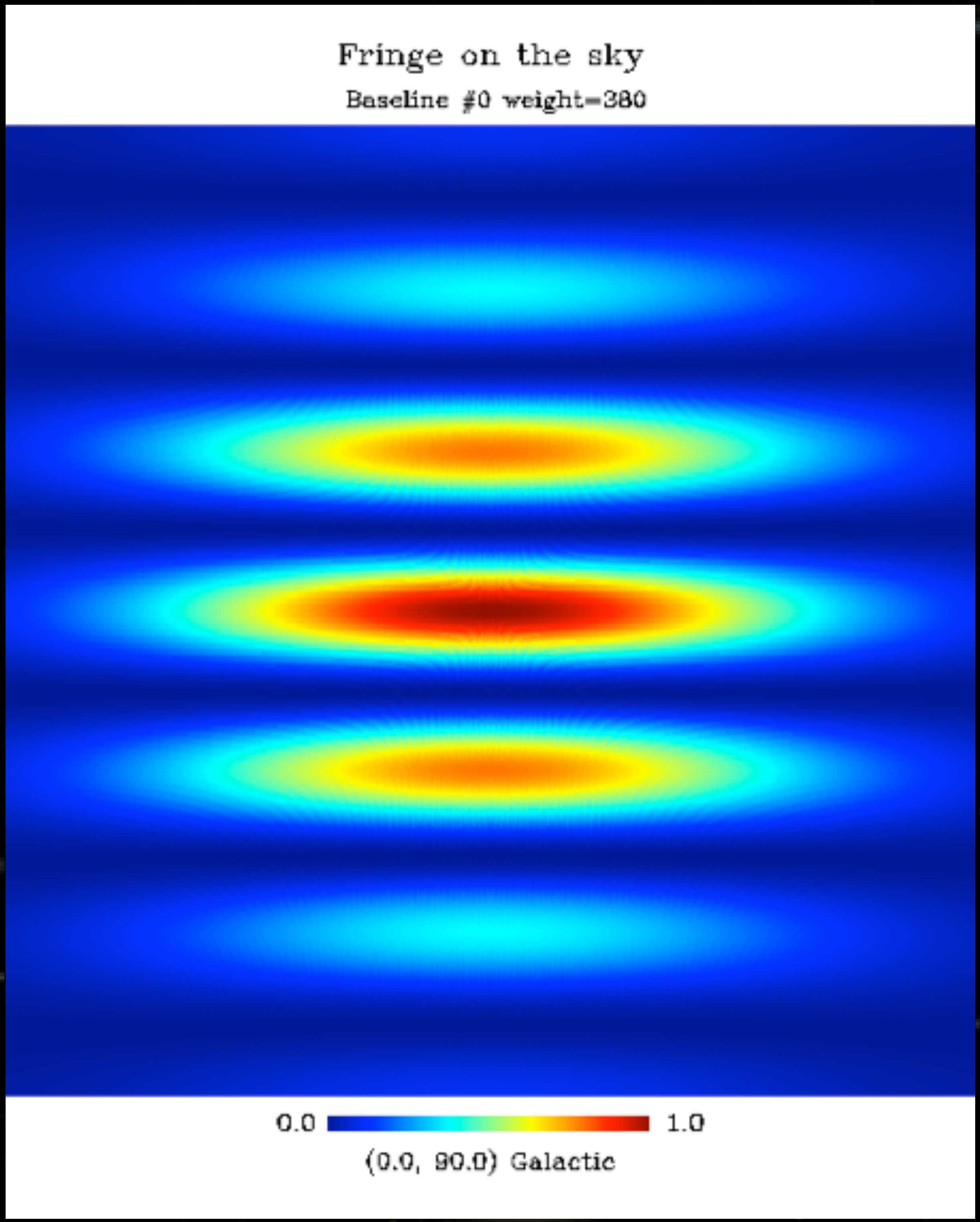
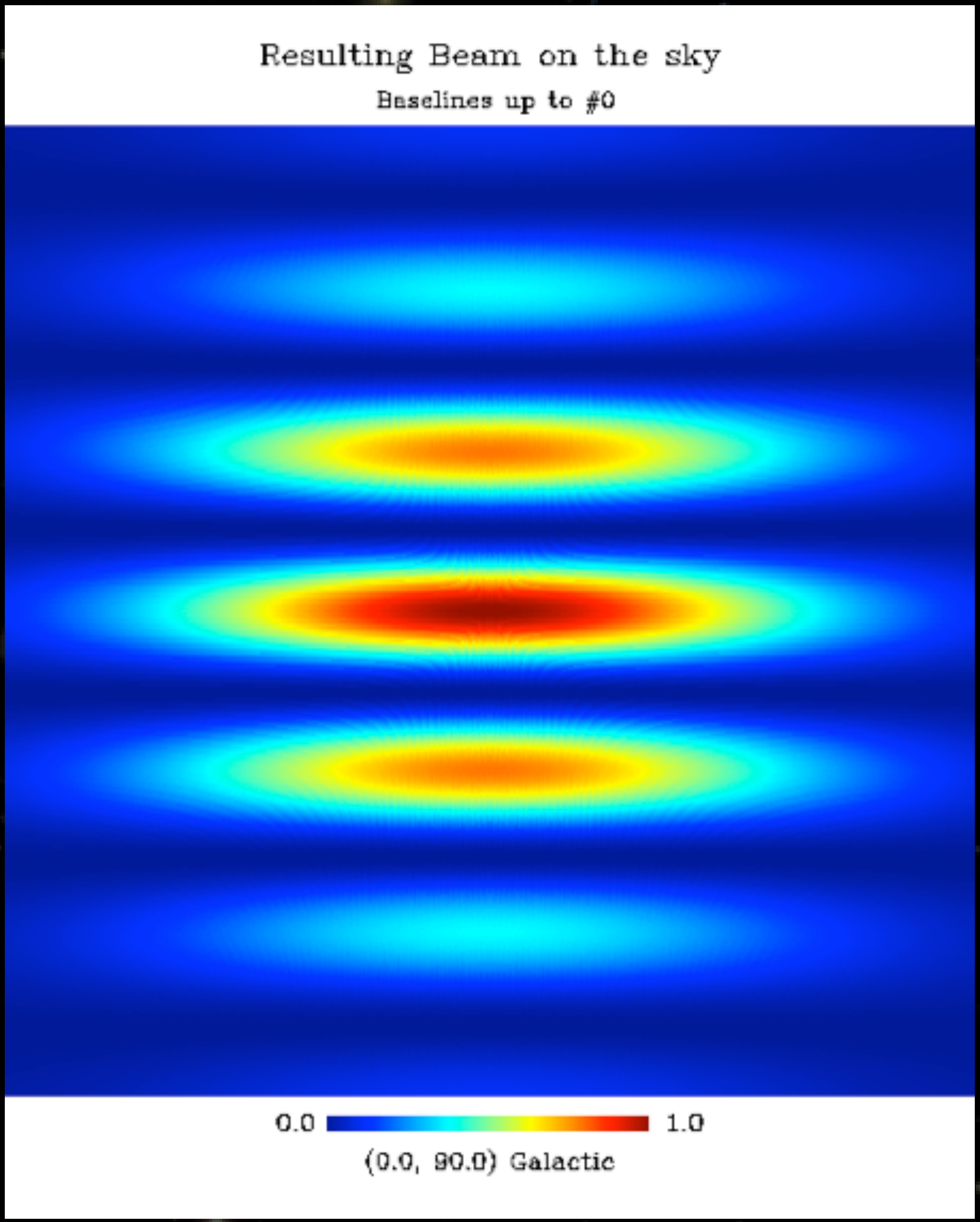
Synthesized beam on the sky



Synthesized beam on the sky





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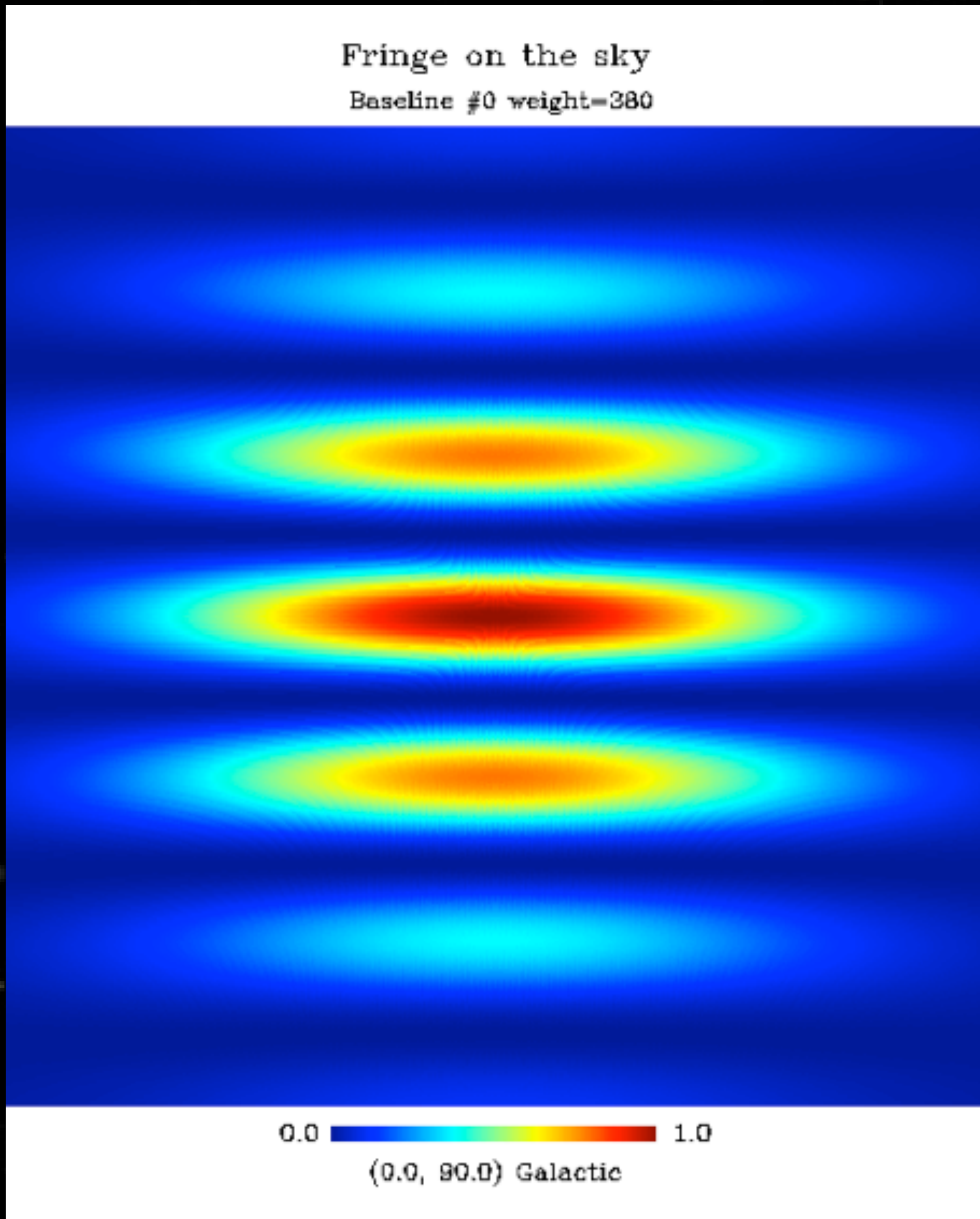

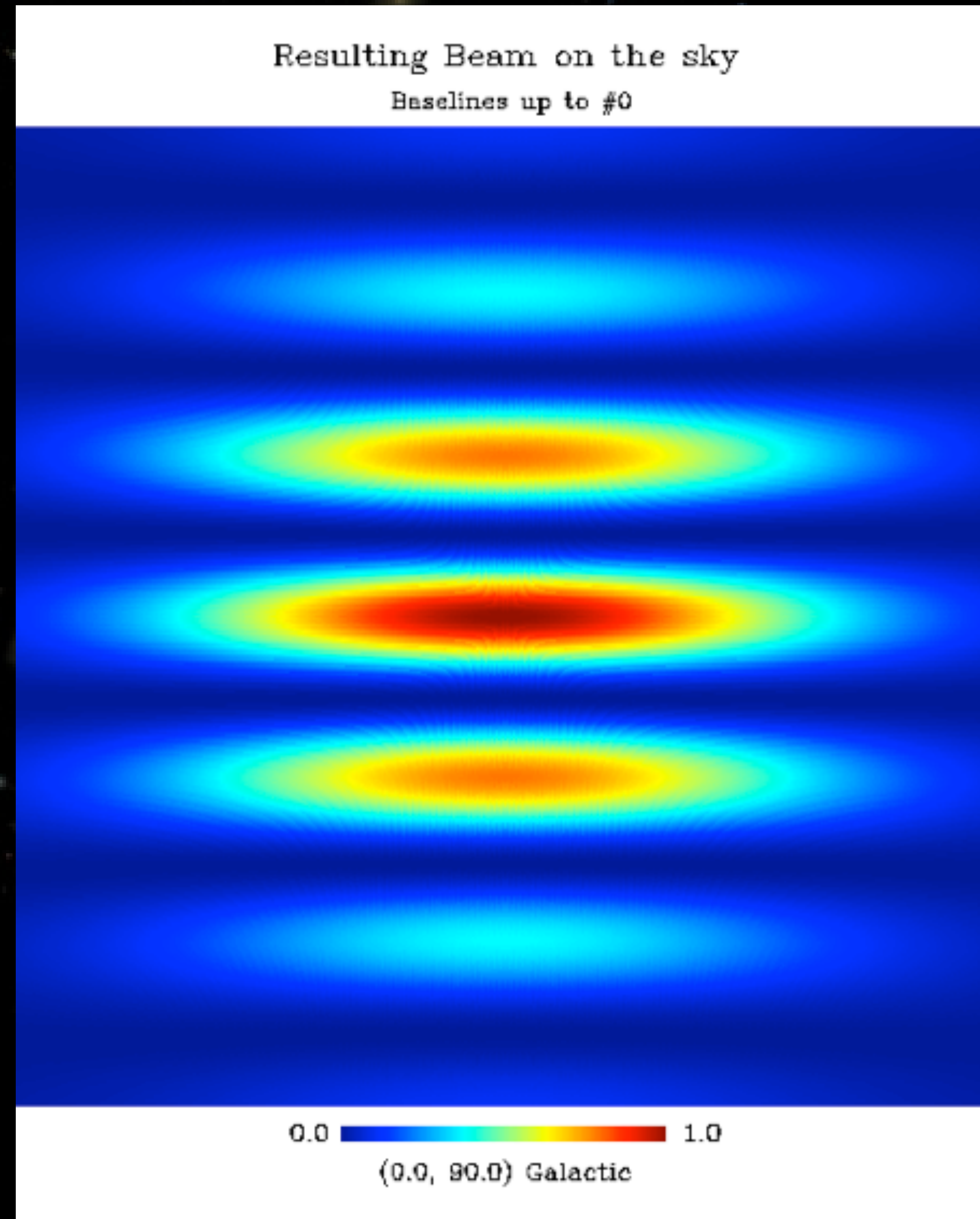

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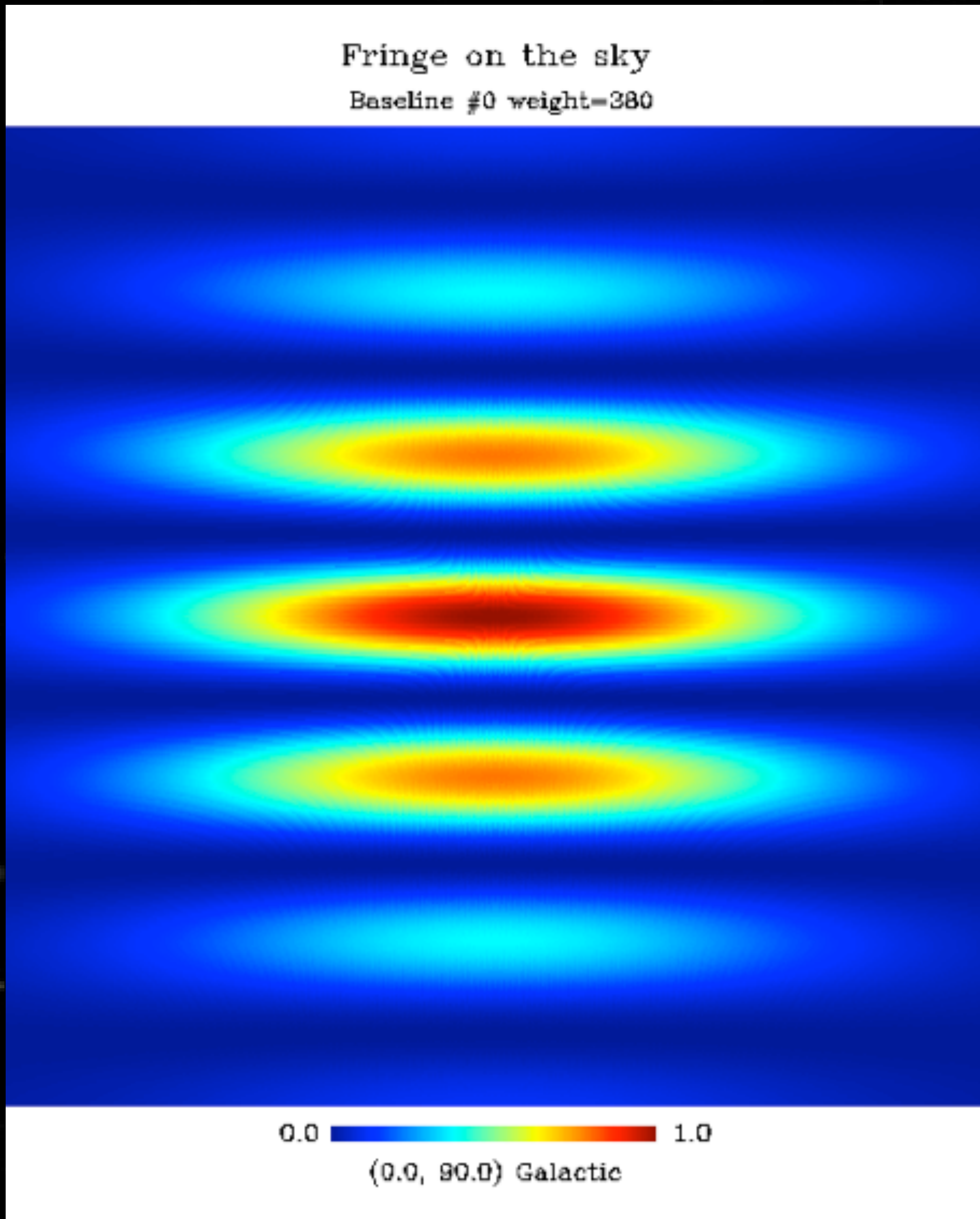
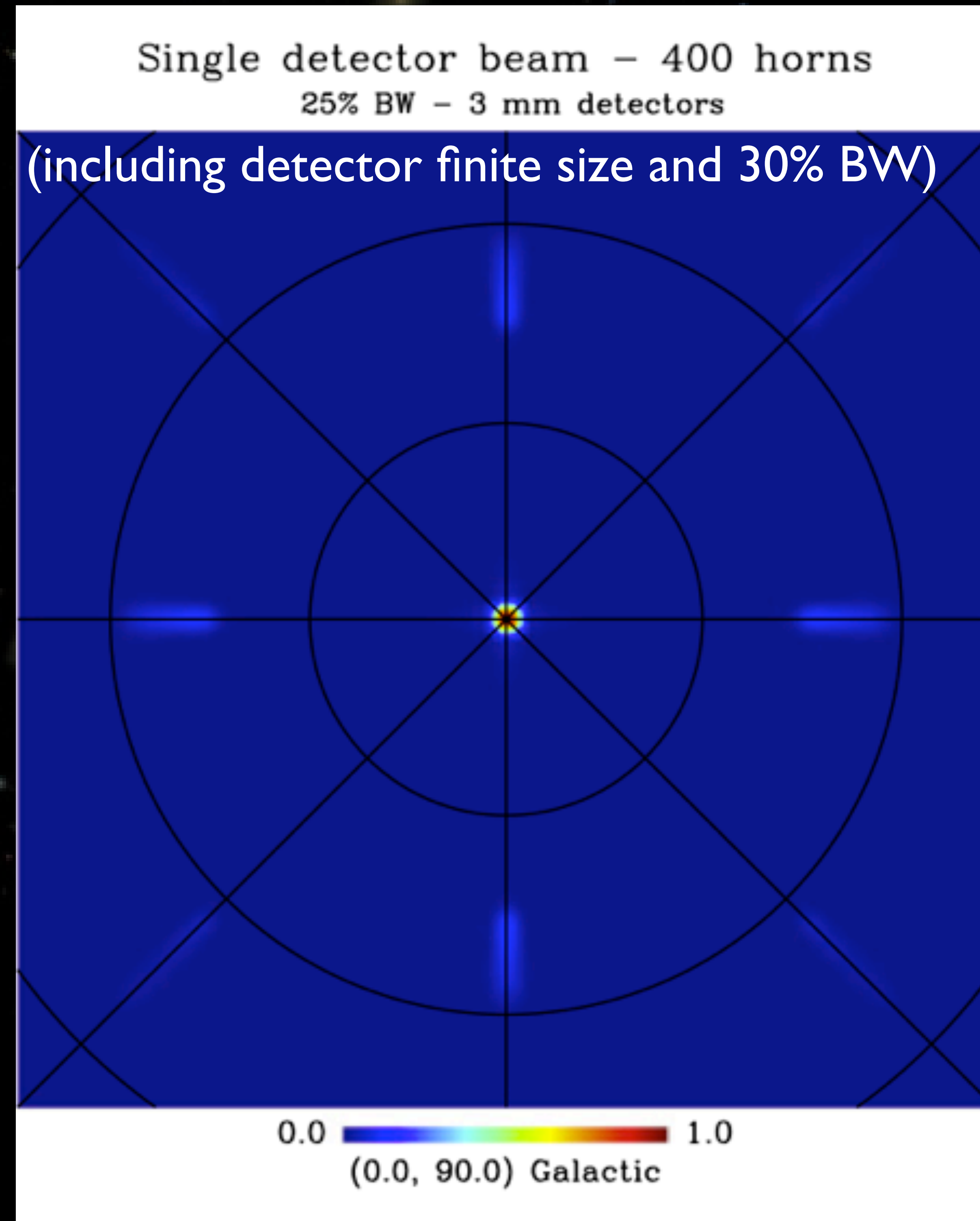
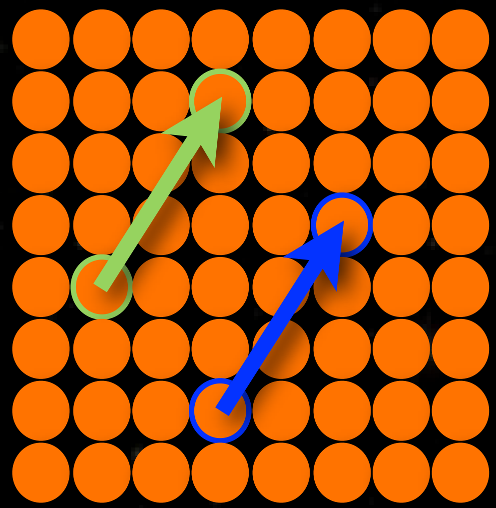




Self-Calibration

- Unique possibility to handle systematic errors
  - ★ Use horn array redundancy to calibrate systematics
    - In a perfect instrument redundant baselines should see the same signal
    - Differences due to systematics
    - Allow to fit systematics with an external source on the field
  - ★ Unique specificity of Bolometric Interferometry !
  - ★ Example: exact horns locations (figure exagerated !!)



Redundant baselines : same Fourier Mode

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 !
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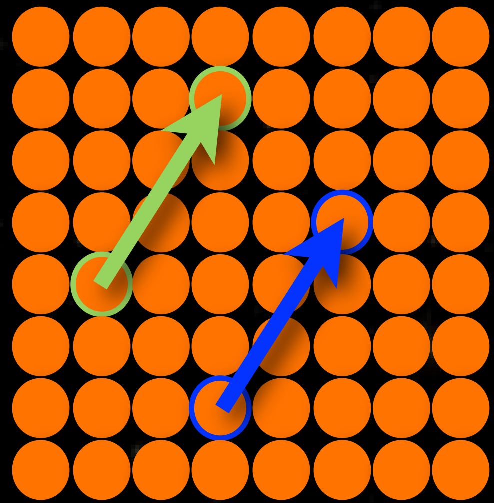

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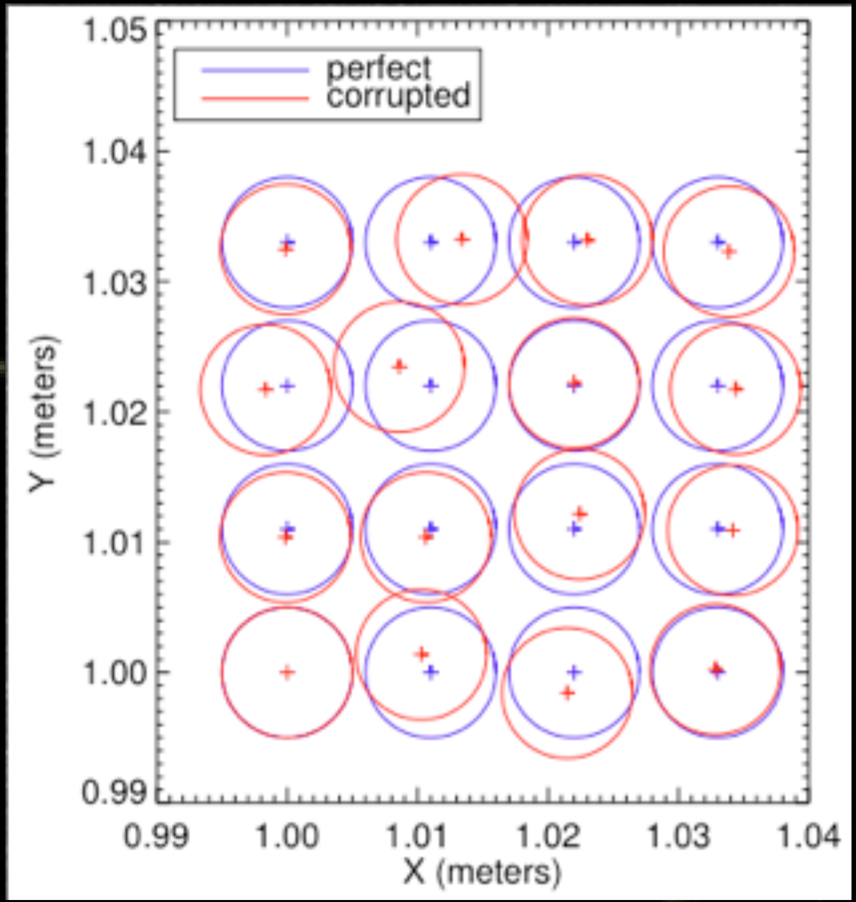

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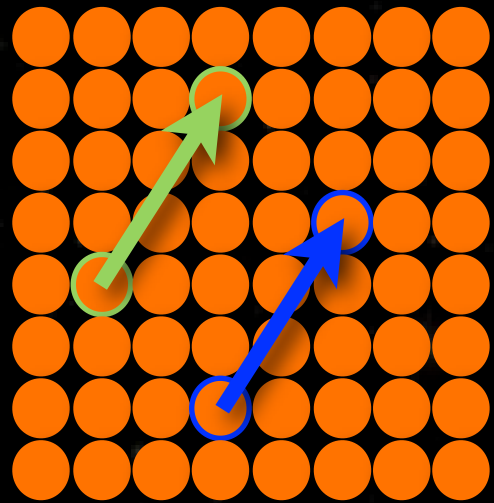

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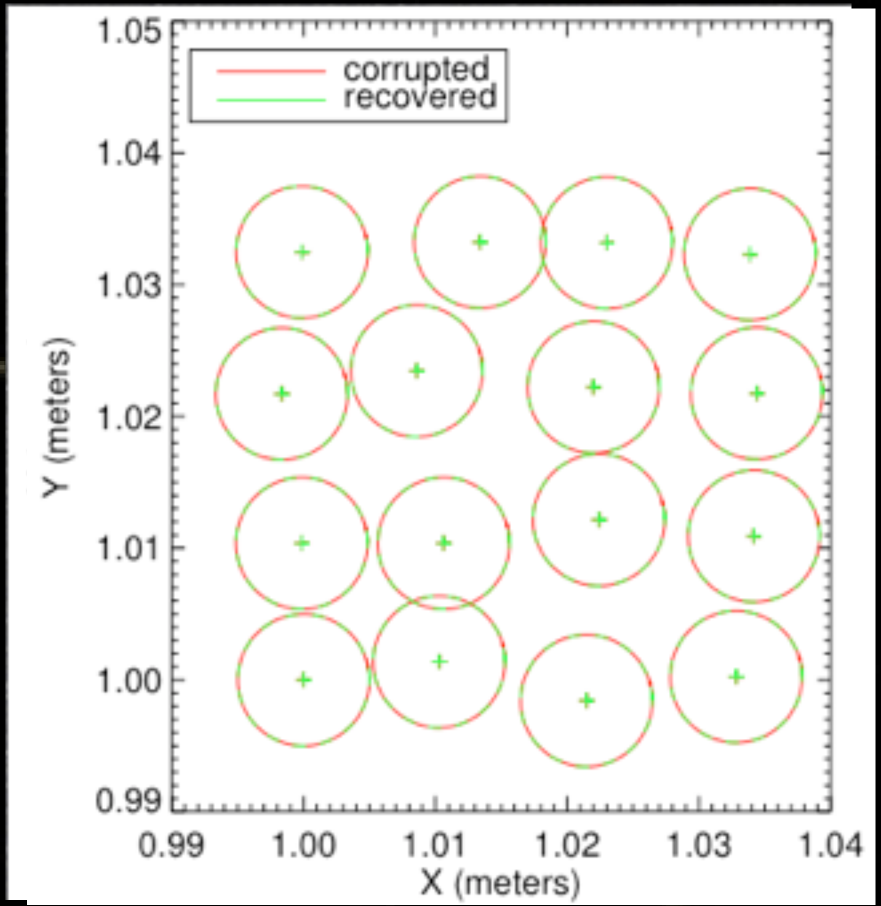

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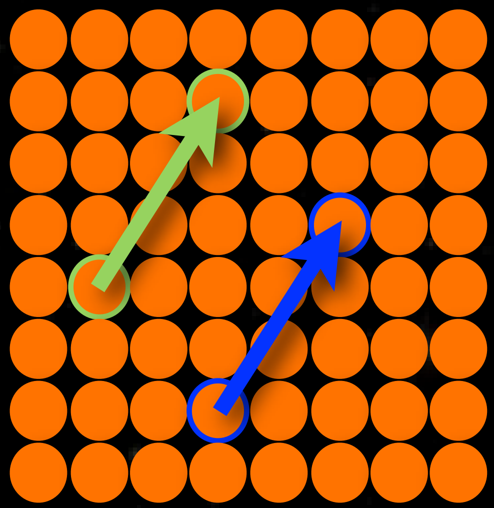

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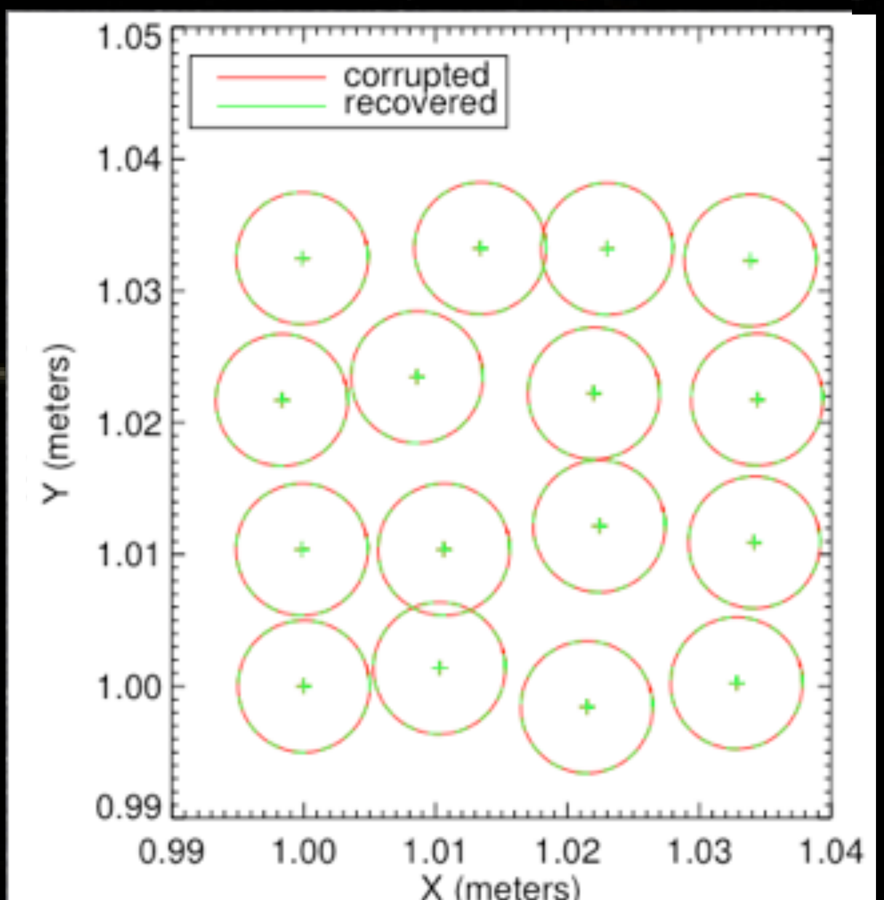

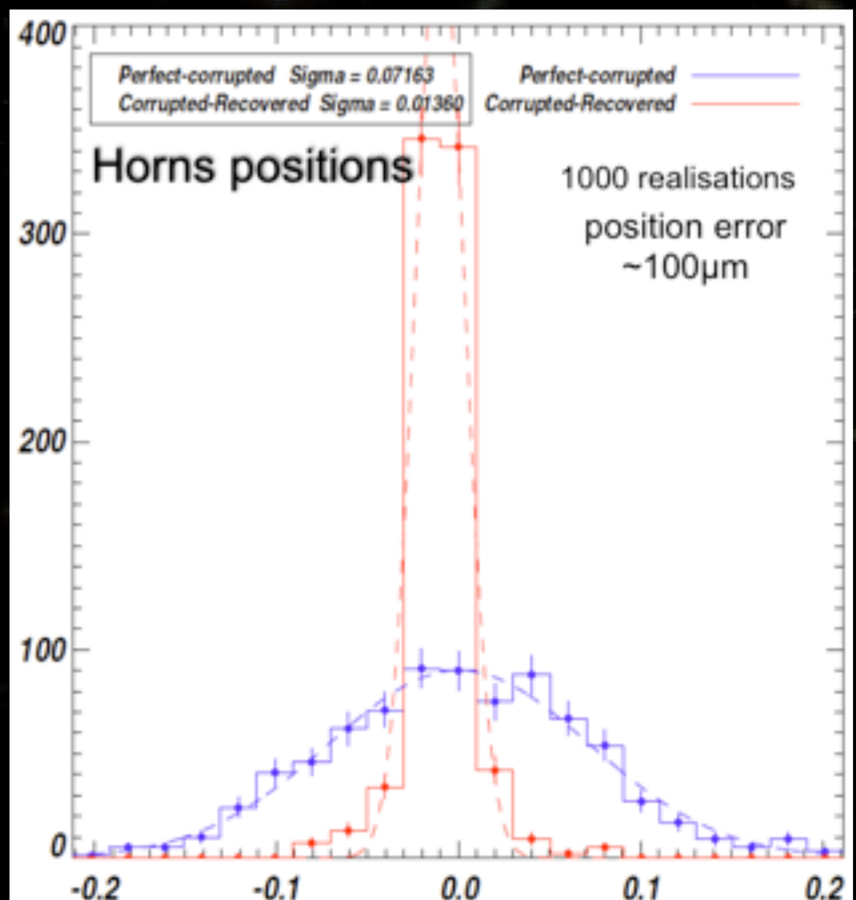

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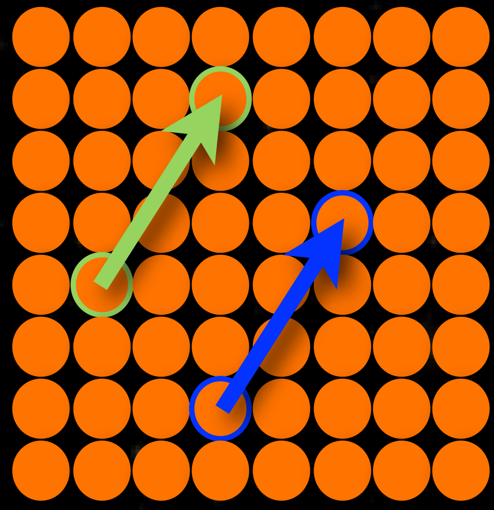

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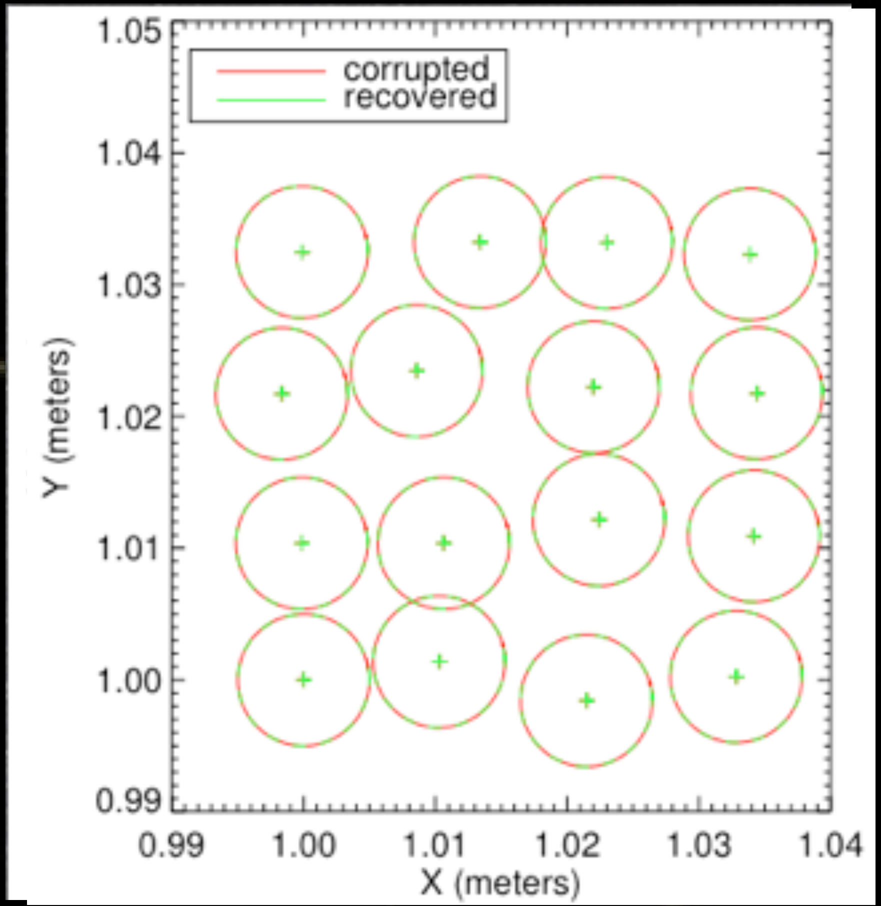

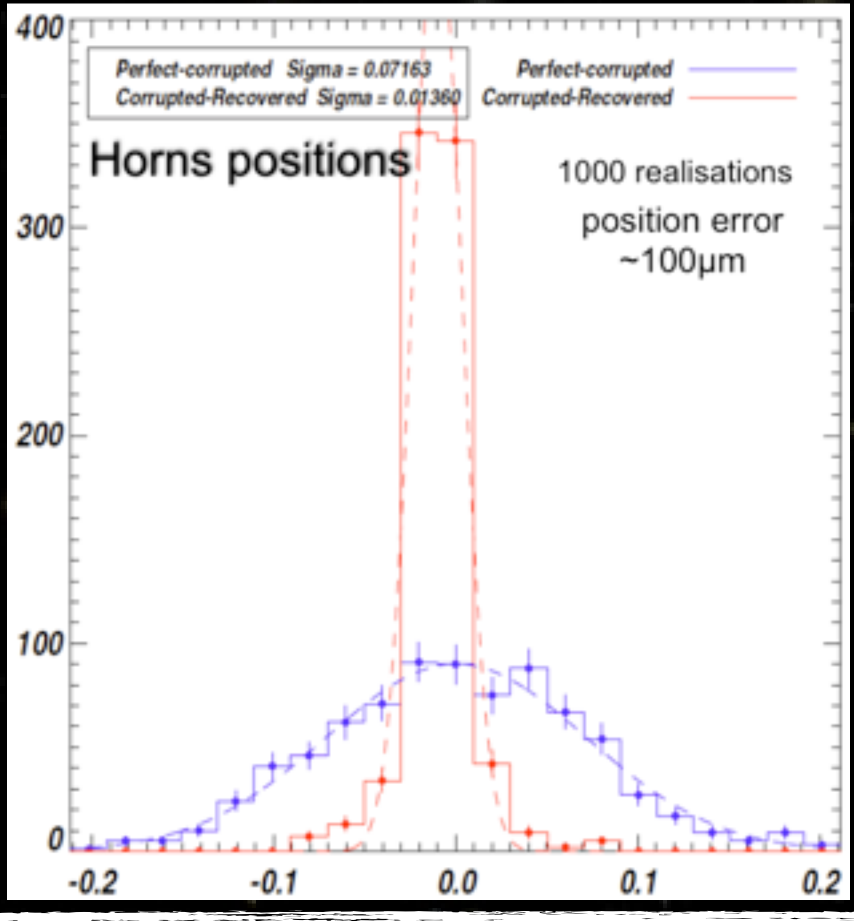

	RMS before	RMS after
Horns location	0.072	0.011
Individual beams	0.090	0.005
TES Intercalibration	0.029	0.007
...	...	...

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QUBIC timeline

- 2012: Partially funded by french ANR
  - ★ Construction starts for the 1st module
    - 400 horns - 150 GHz - 2048 TES bolometers
- 2013: Integration of the 1st module at APC
- 2014: First light at Dôme C, Antarctica
  - ★ Data taking : one to two years with one module
- 2015...: Full QUBIC construction
  - ★ 6 modules at 90, 150 and 250 GHz

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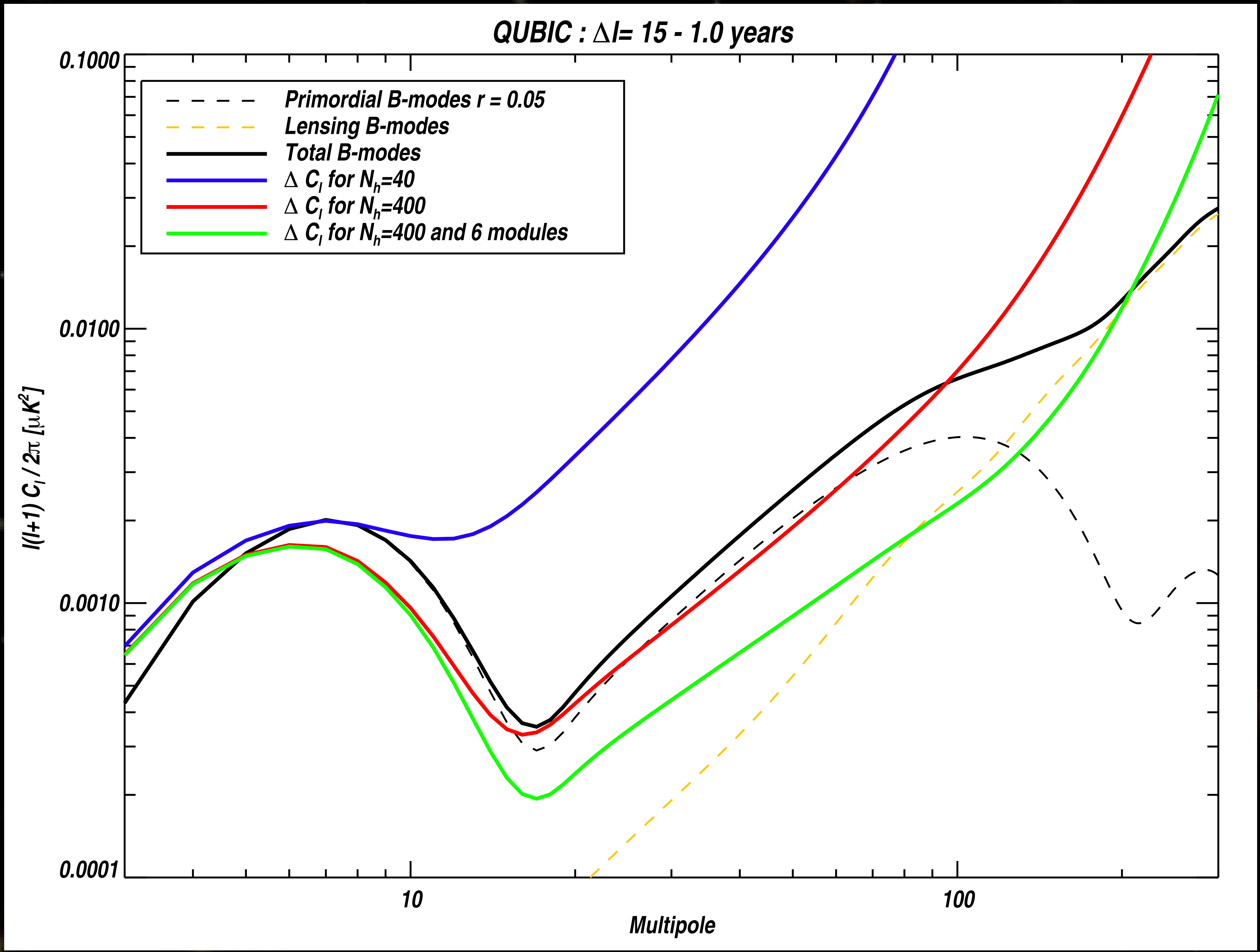
B-mode sensitivity



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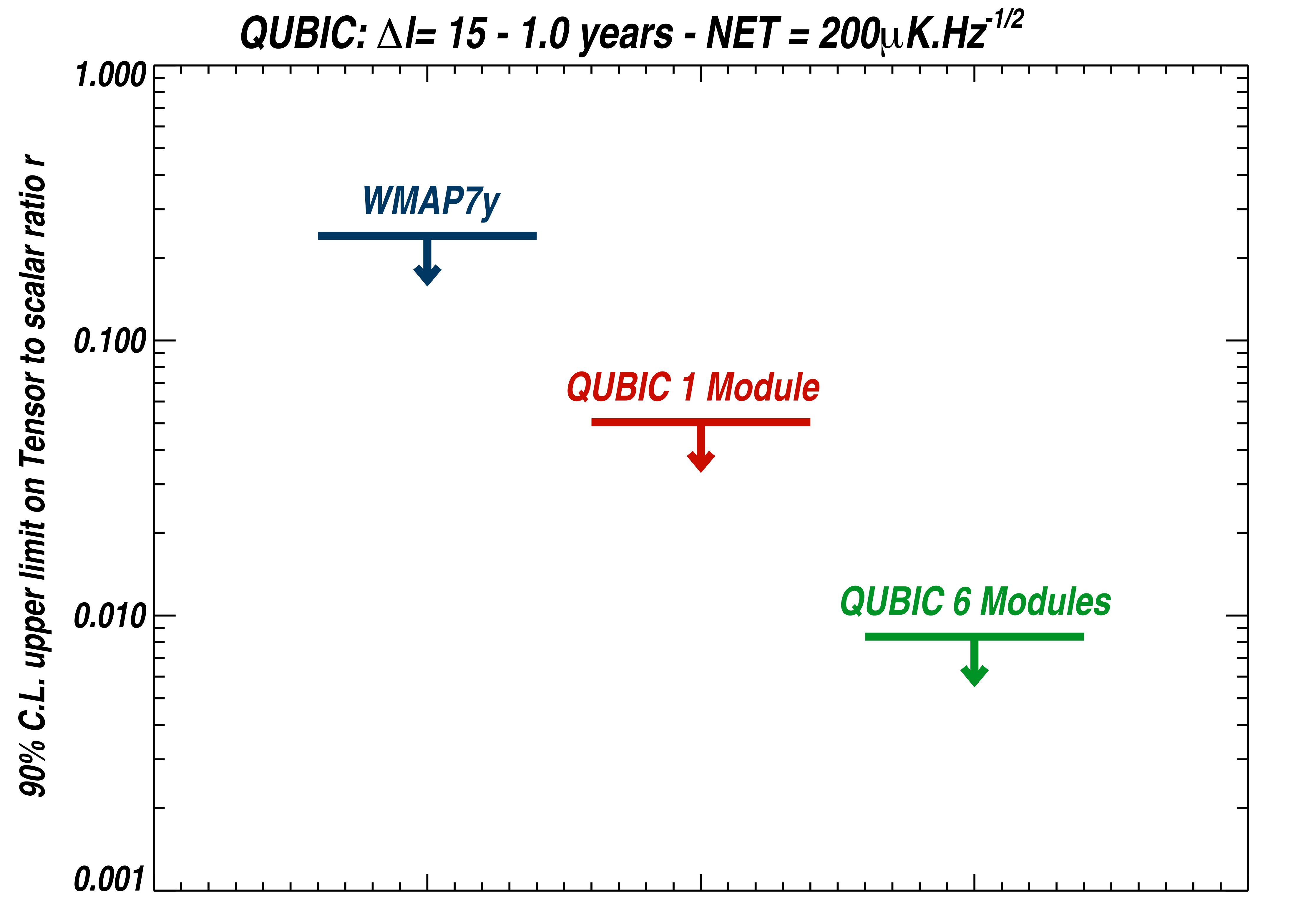
tensor/scalar ratio sensitivity



Summary

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

- New collaborators welcome !!
  - ★ Some aspects still need to be covered for the 1st module
    - Telescope Alt-Az-Phi Mount
    - In-the-Field Calibration setup (balloon or tower)
  - ★ Dome A site would as good as Dome C for future modules
  - ★ Huge need for data analysis and simulations
    - Map-making significantly different from classical imagers
    - Power spectrum extraction, E/B separation
    - Foregrounds removal

    ➡ Nice opportunity to get involved in such a hot topic

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谢谢

Thank you ...

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