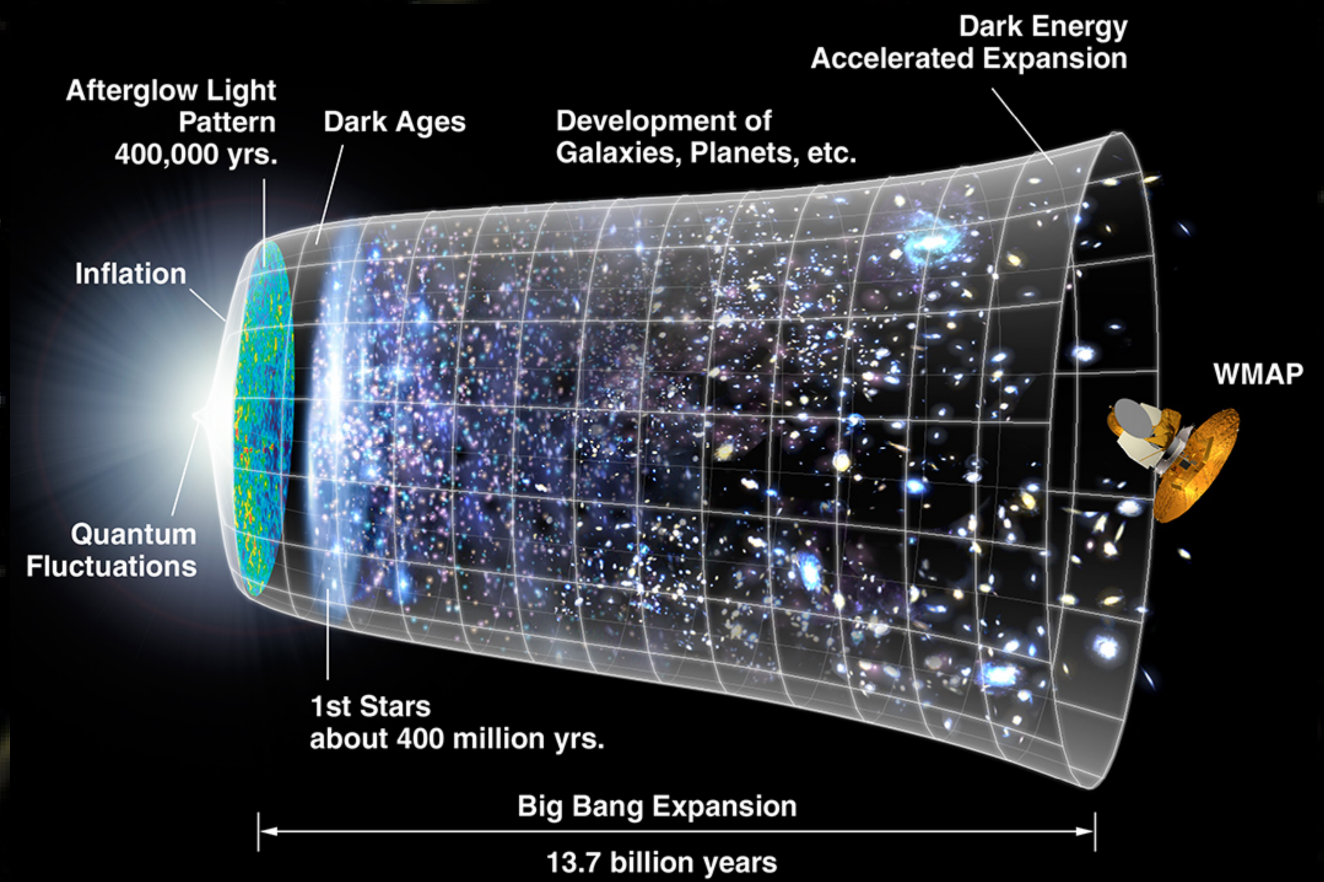
Exploring the primordial Universe with the Cosmic Microwave Background

J.-Ch. Hamilton - APC, Paris

The Cosmic Microwave Background

- Big Bang
  - Initial singularity ? Superstrings ?
- Inflation ?
  - The Universe expands exponentially
- Primordial nucleosynthesis
  - First nuclei formed H, He, Li, Be
  - Universe is still ionized
  - Matter and radiation at thermal equilibrium
- T<13.6 eV : electrons start to be captured by nuclei



Photons decouple from matter
CMB is emitted
Blackbody : T=3000 K
@ z=1000

↓

Today : Blackbody T=2.7 K

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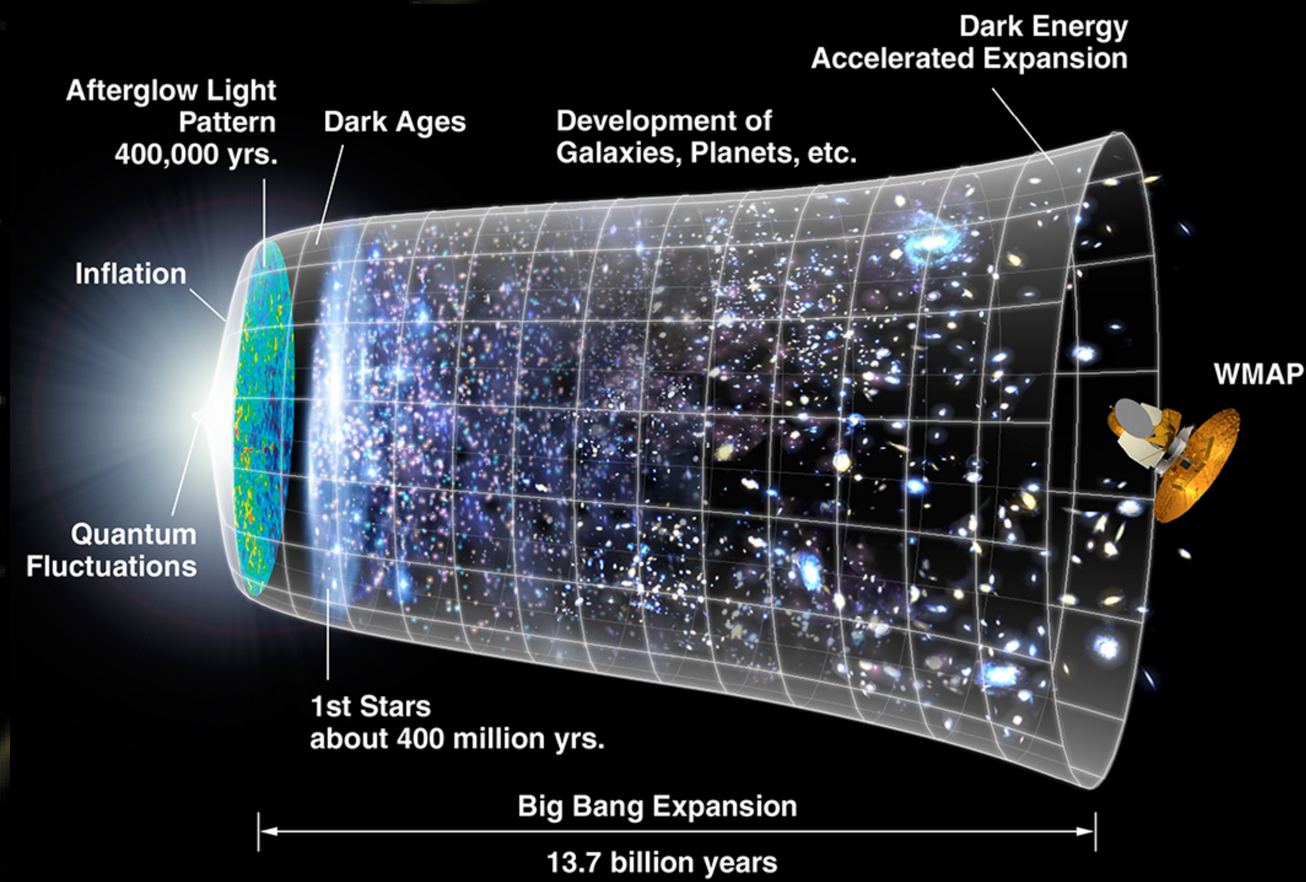

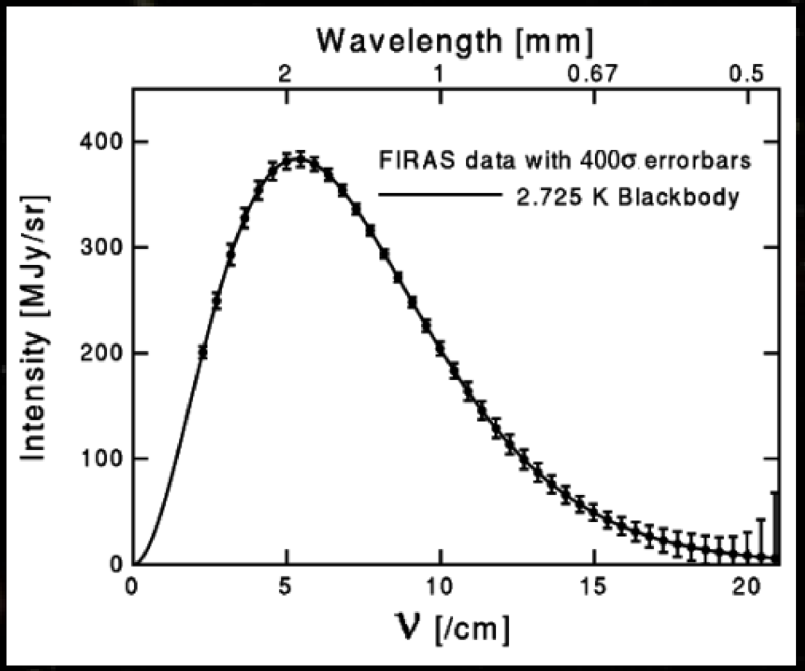

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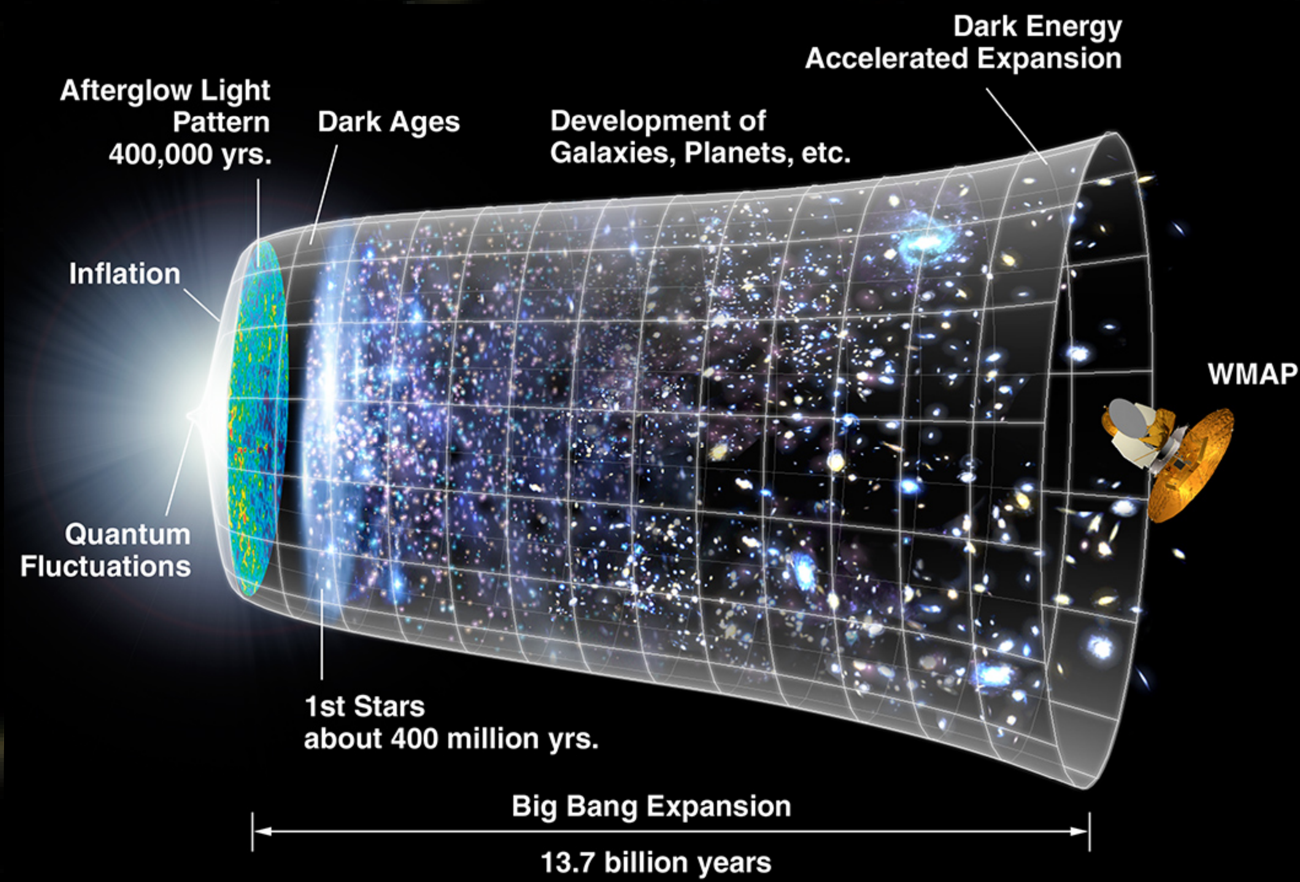
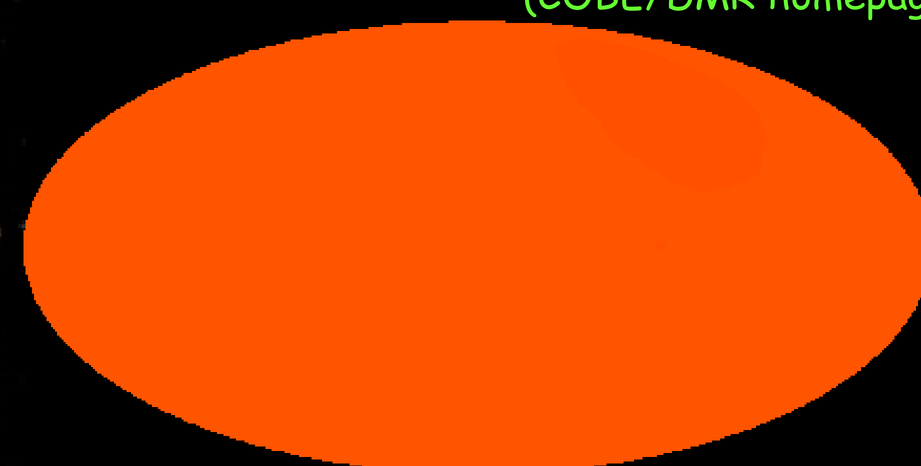


(COBE/DMR homepage)



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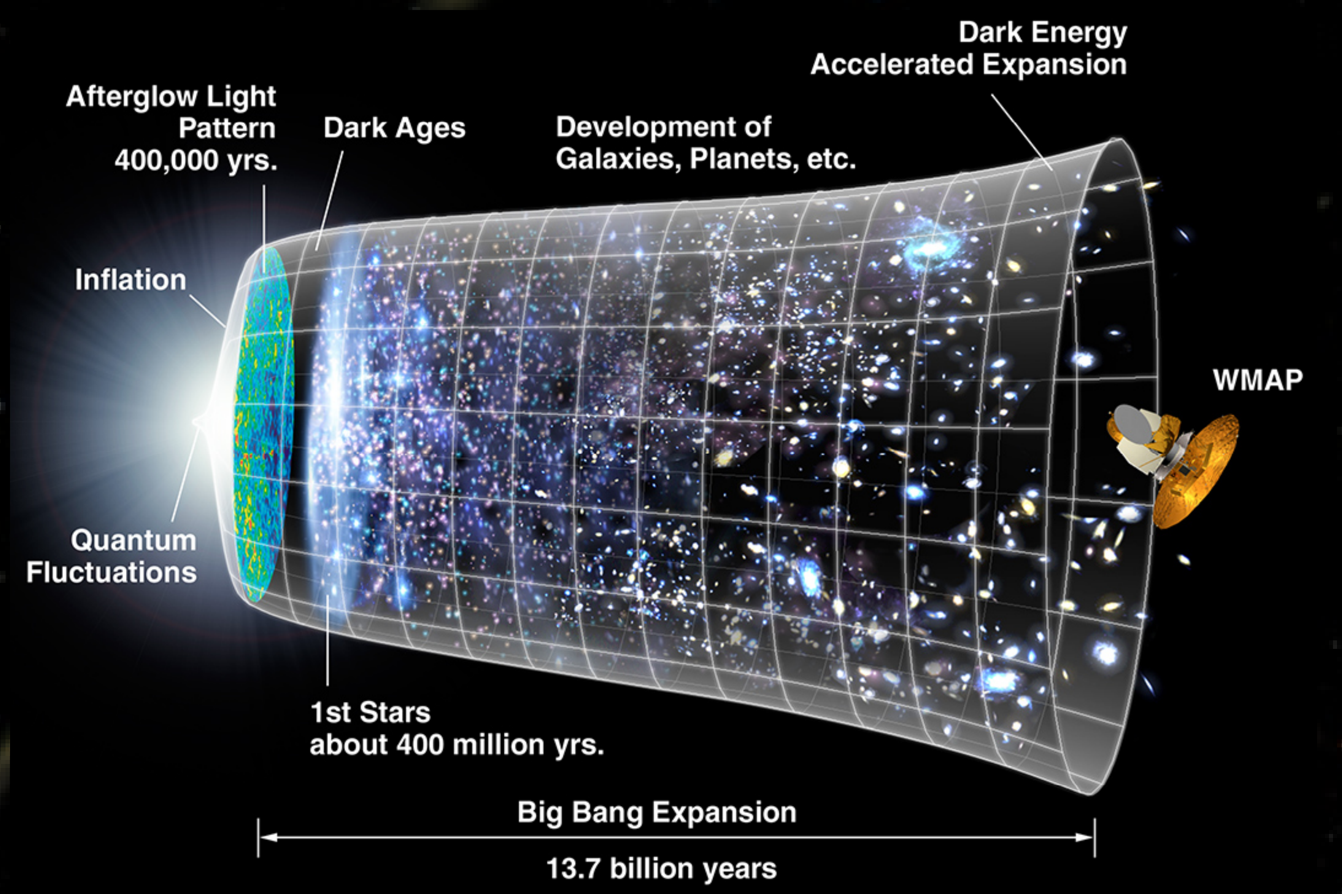

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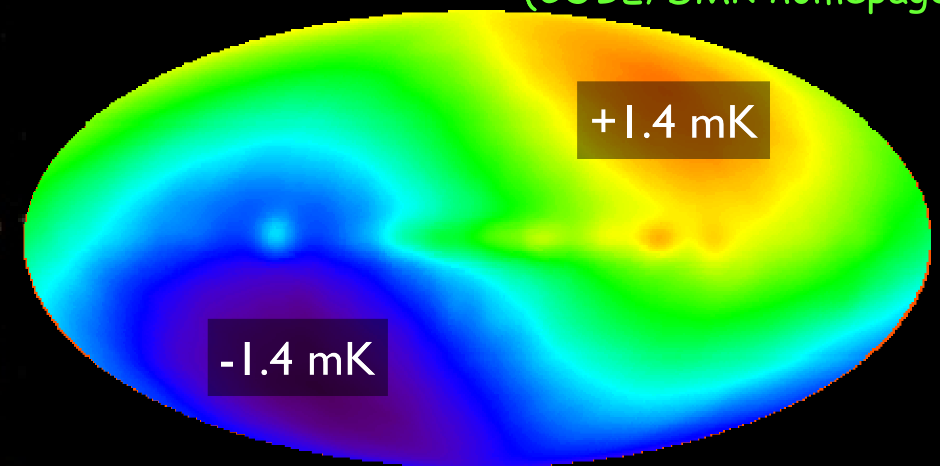

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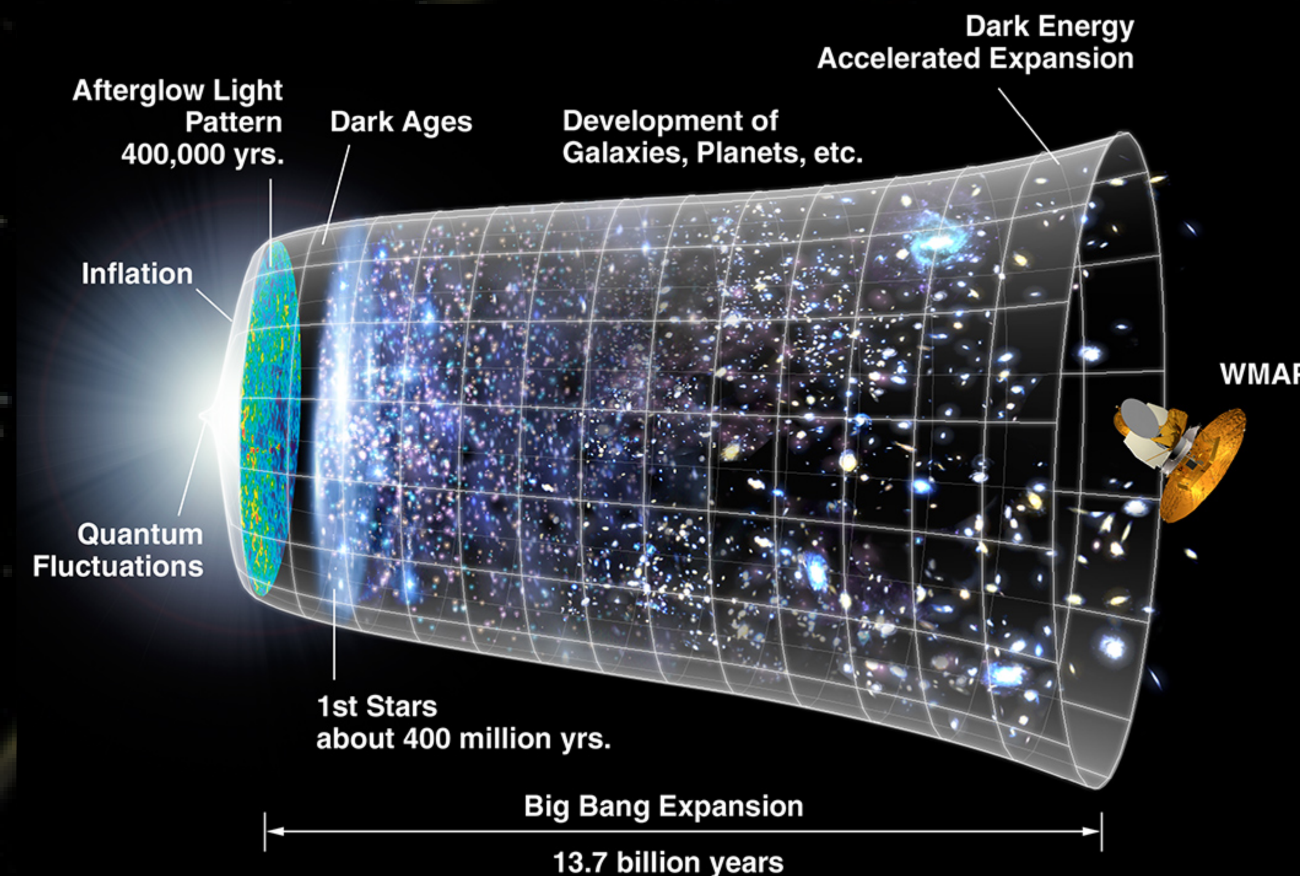

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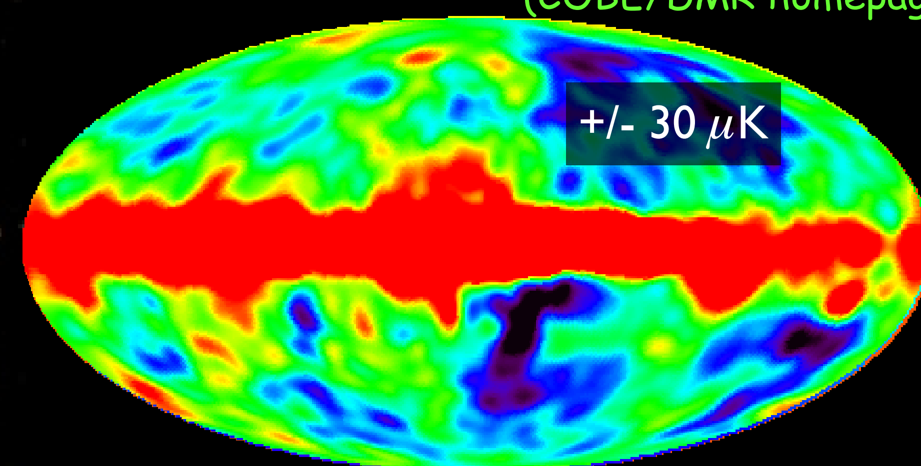

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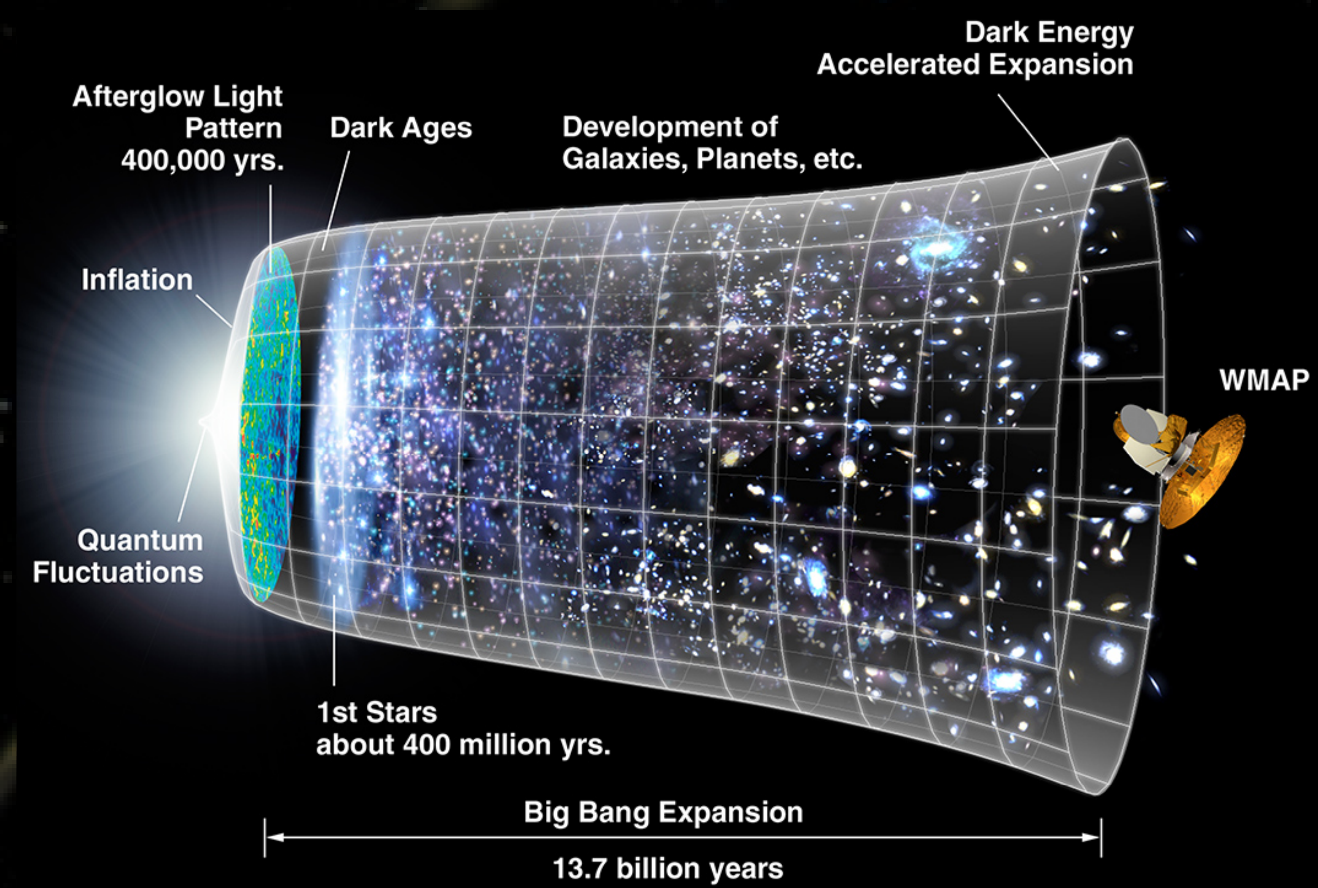

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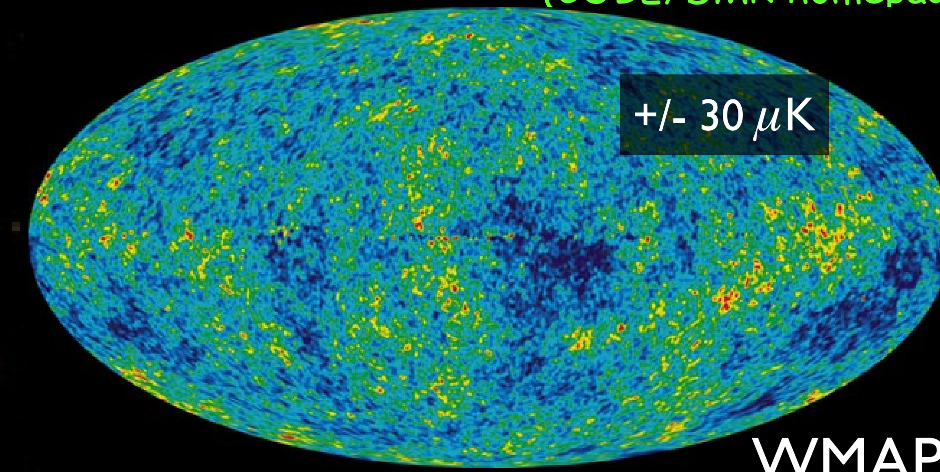
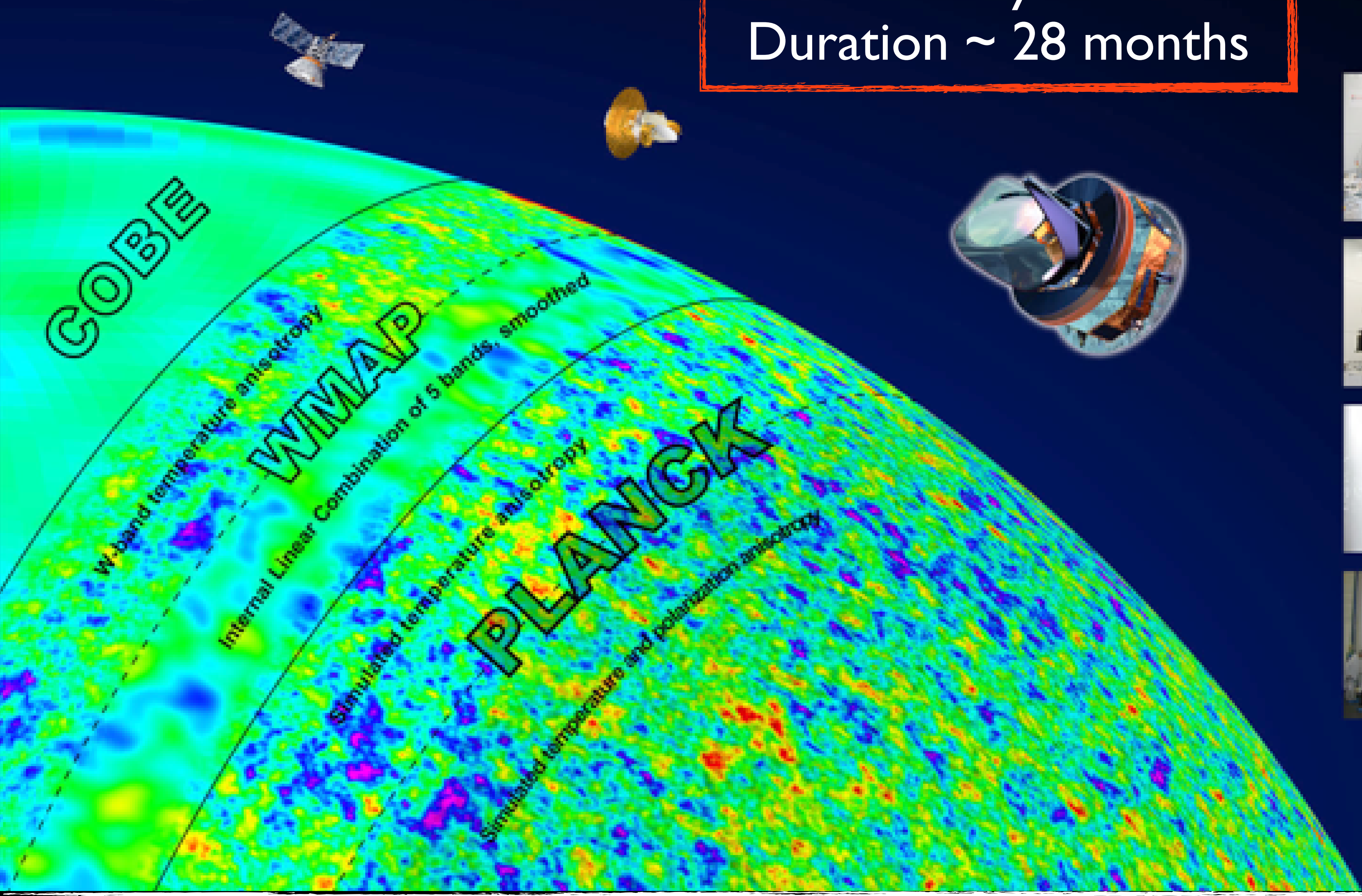
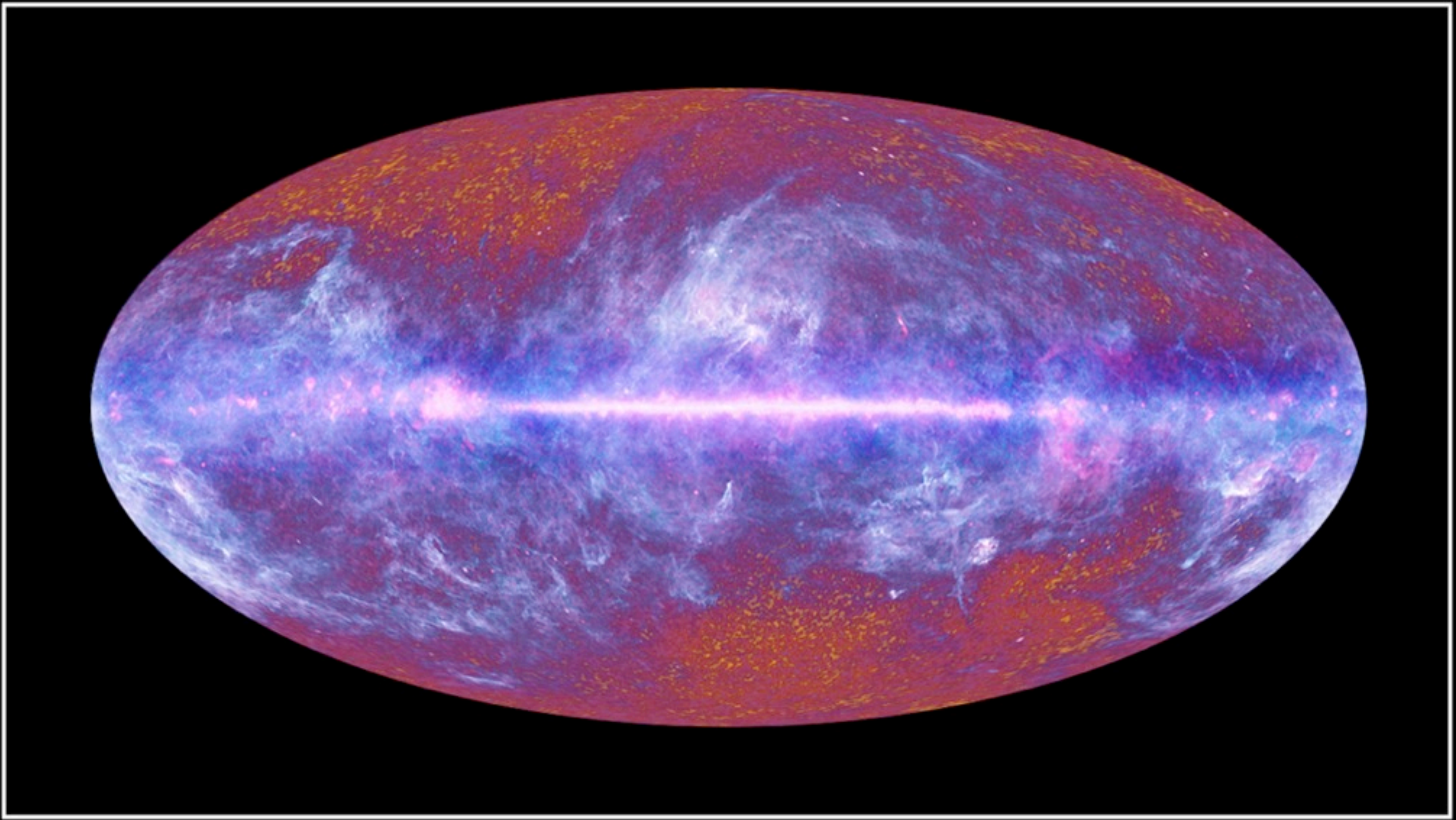


WMAP

PLANCK
SIMULATION

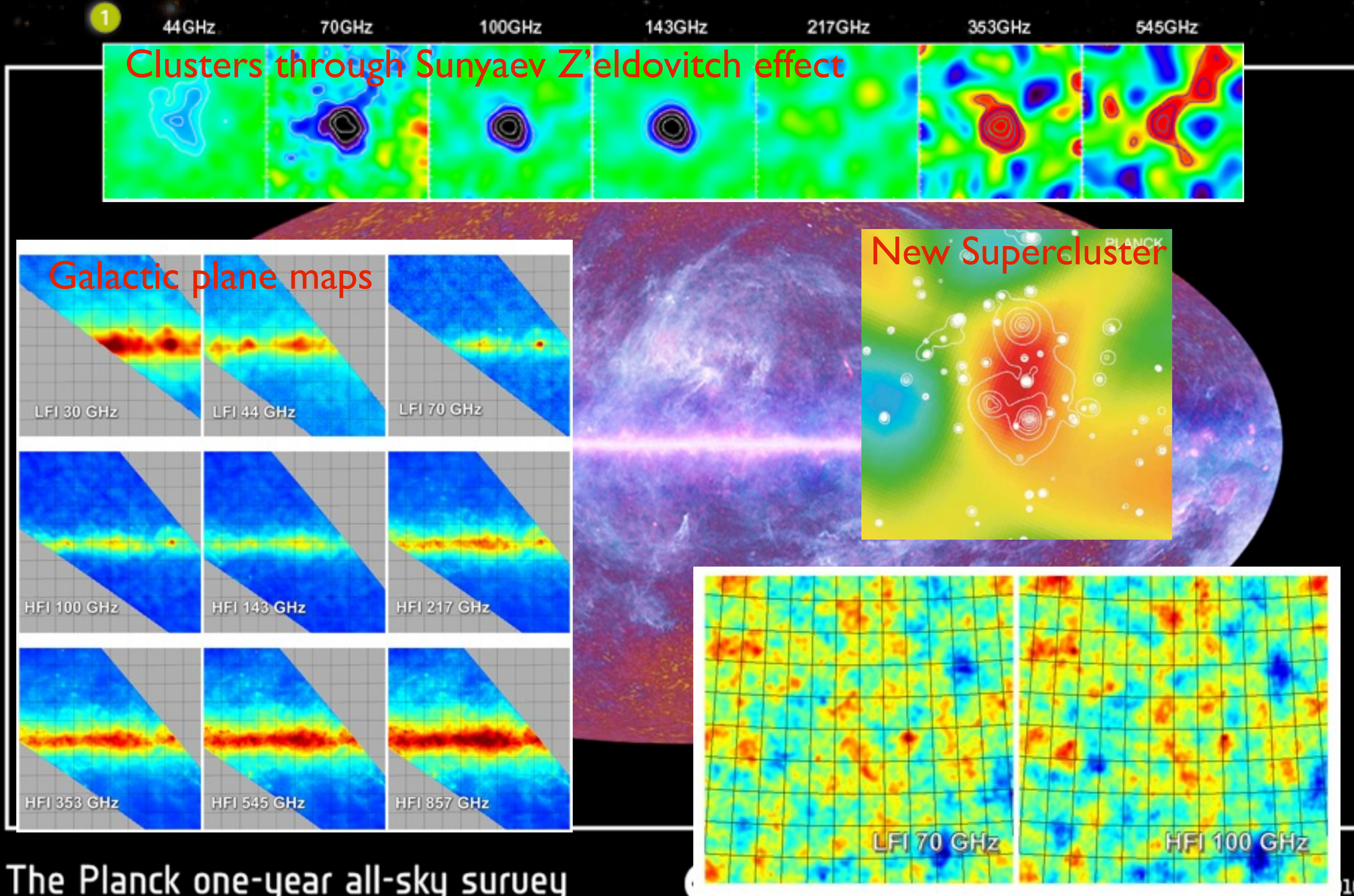
Launched may 14th 2009
Duration ~ 28 months





The Planck one-year all-sky survey

esa


44GHz
70GHz
100GHz
143GHz
217GHz
353GHz
545GHz
Clusters through Sunyaev Z'eldovitch effect
Galactic plane maps
LFI 30 GHz
LFI 44 GHz
LFI 70 GHz
HFI 100 GHz
HFI 143 GHz
HFI 217 GHz
HFI 353 GHz
HFI 545 GHz
HFI 857 GHz
New Supercluster
LFI 70 GHz
HFI 100 GHz
The Planck one-year all-sky survey

CMB maps

Gaussian perturbations : the power spectrum encodes all the information

- Spherical harmonics expansion

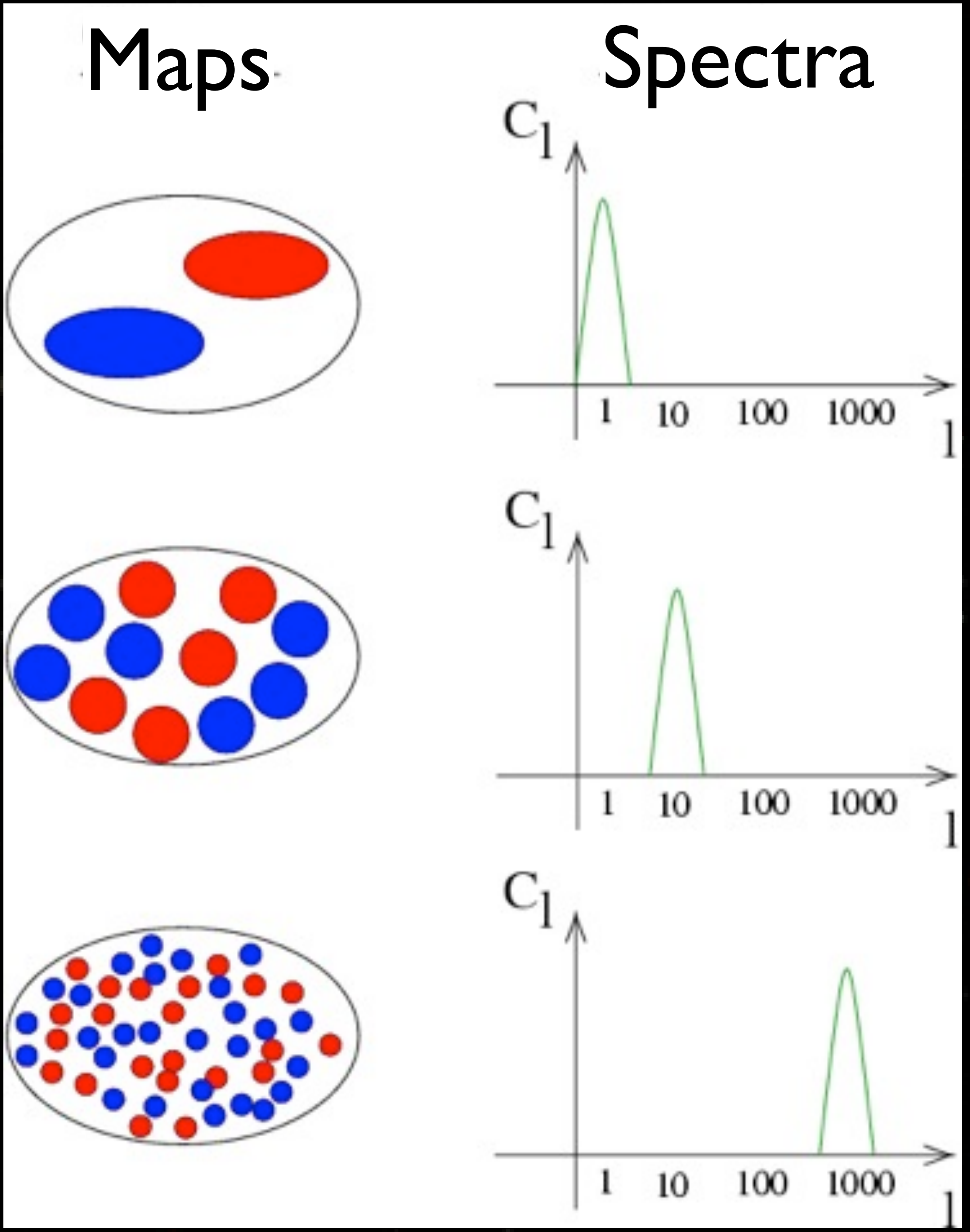
$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{\ell=0}^{\infty}\sum_{m=\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

- Angular power spectrum

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

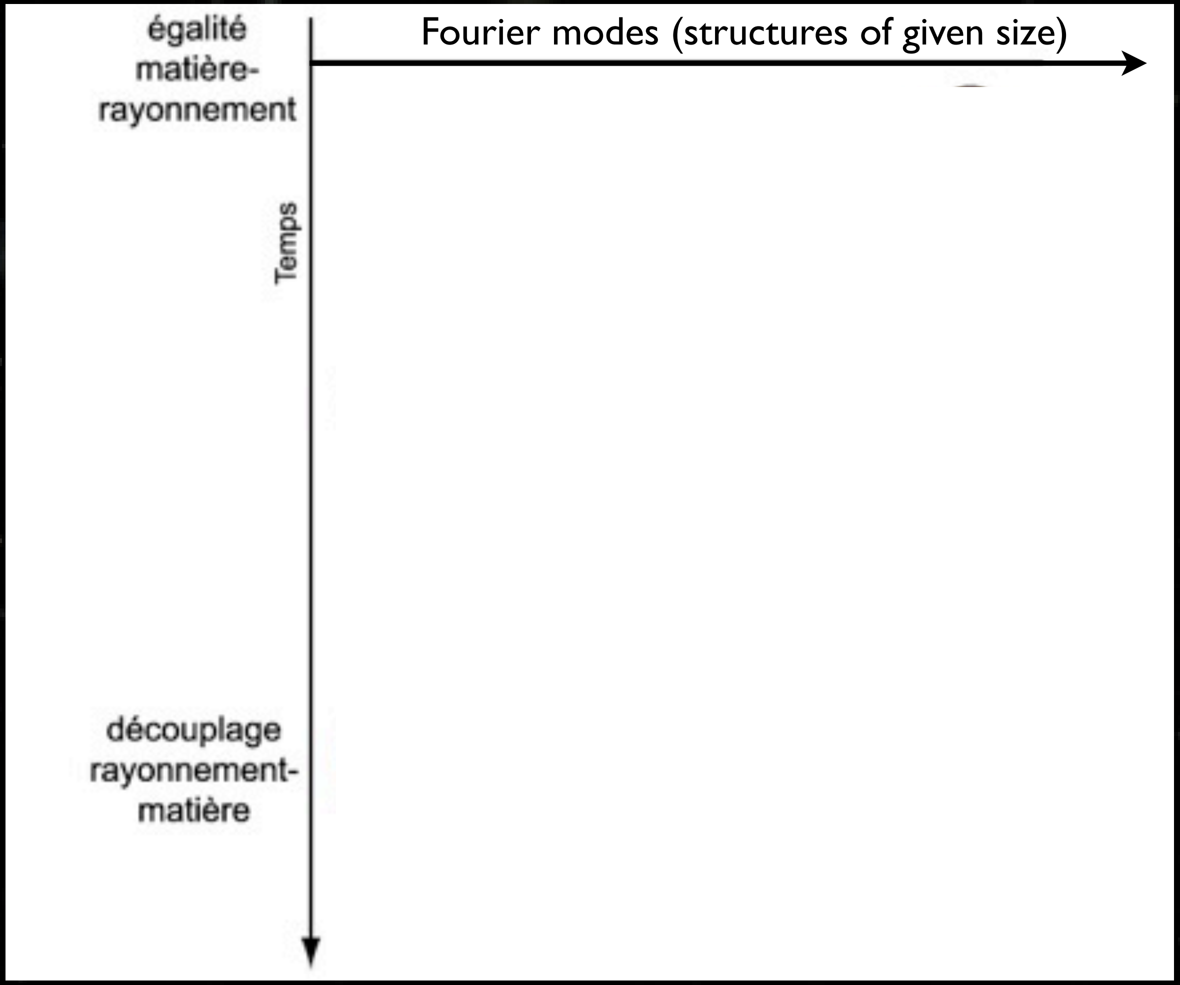
- ℓ is the inverse of an angle

$$\ell = 200 \leftrightarrow \theta = 1\mathrm{deg.}$$



Shape of the power spectrum

- ★ The primordial Universe is composed of matter-radiation coupled fluid dominated by radiation
  → Matter does not collapse
- ★ At matter-radiation equality, matter starts collapsing
- ★ Acoustic waves due to radiation pressure start to propagate at the speed of sound. Oscillations are coherent w.r.t. scale
- ★ Oscillations are frozen at matter-rdiation decoupling
- ★ 1st peak: sound horizon at decoupling



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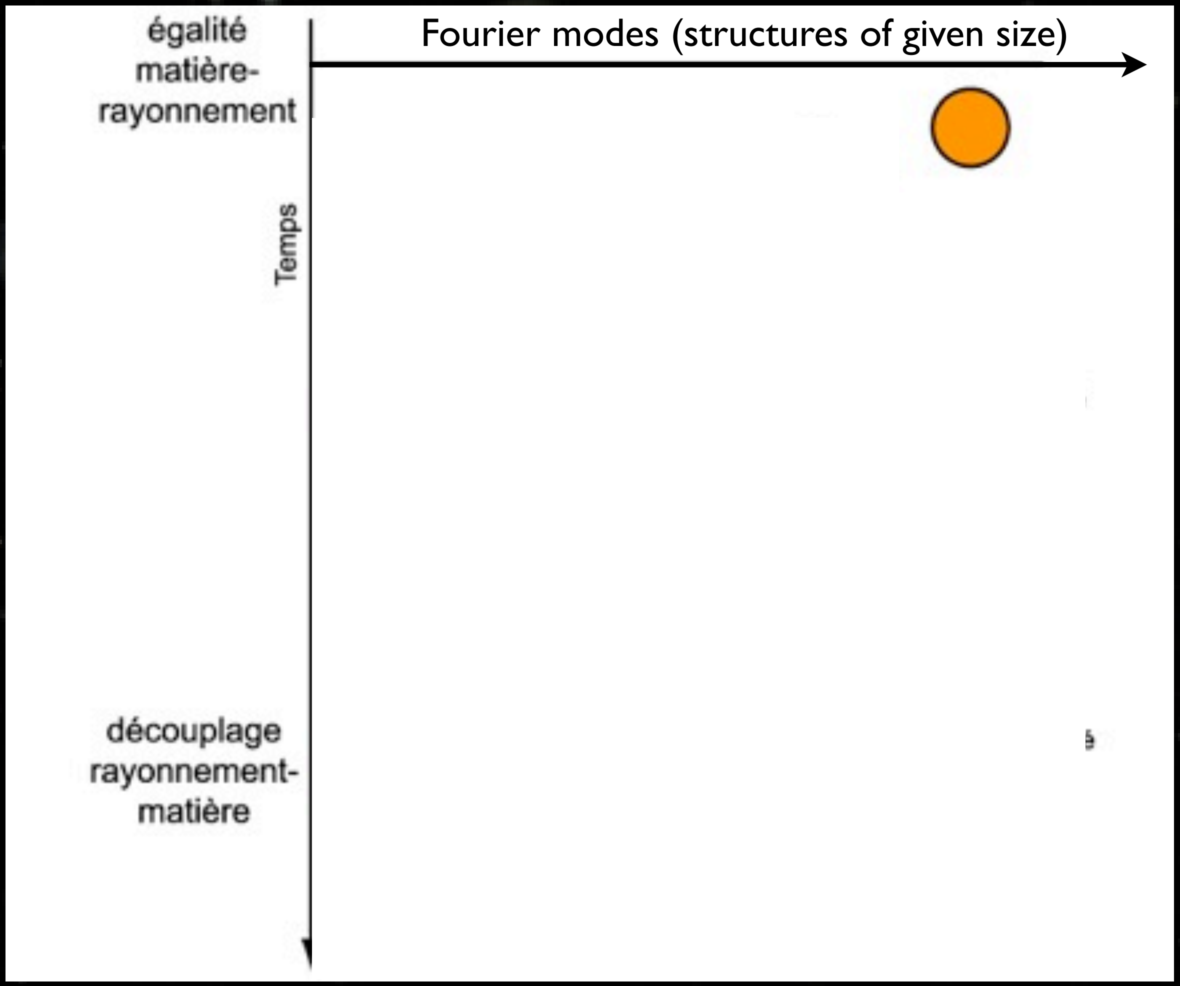

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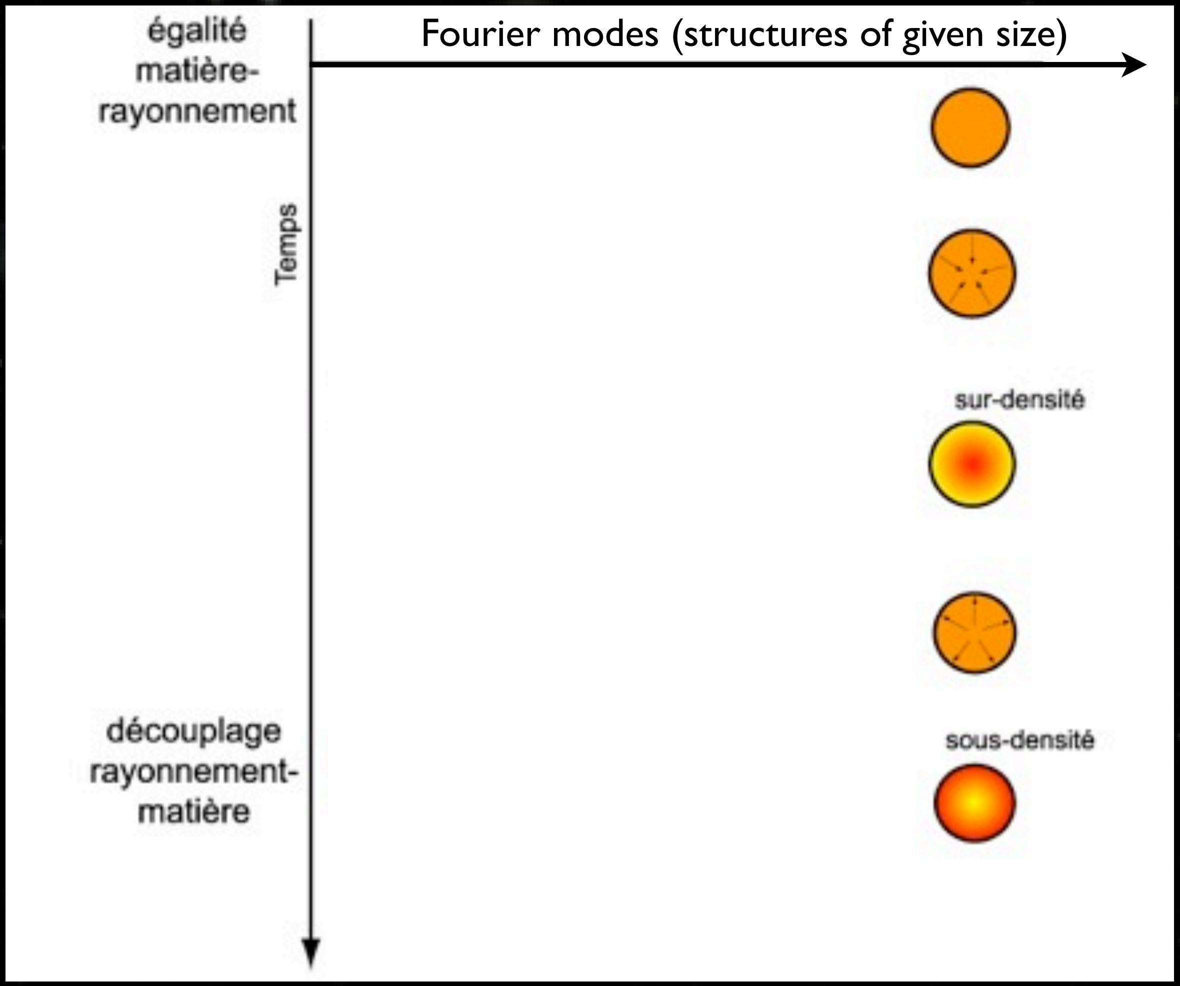

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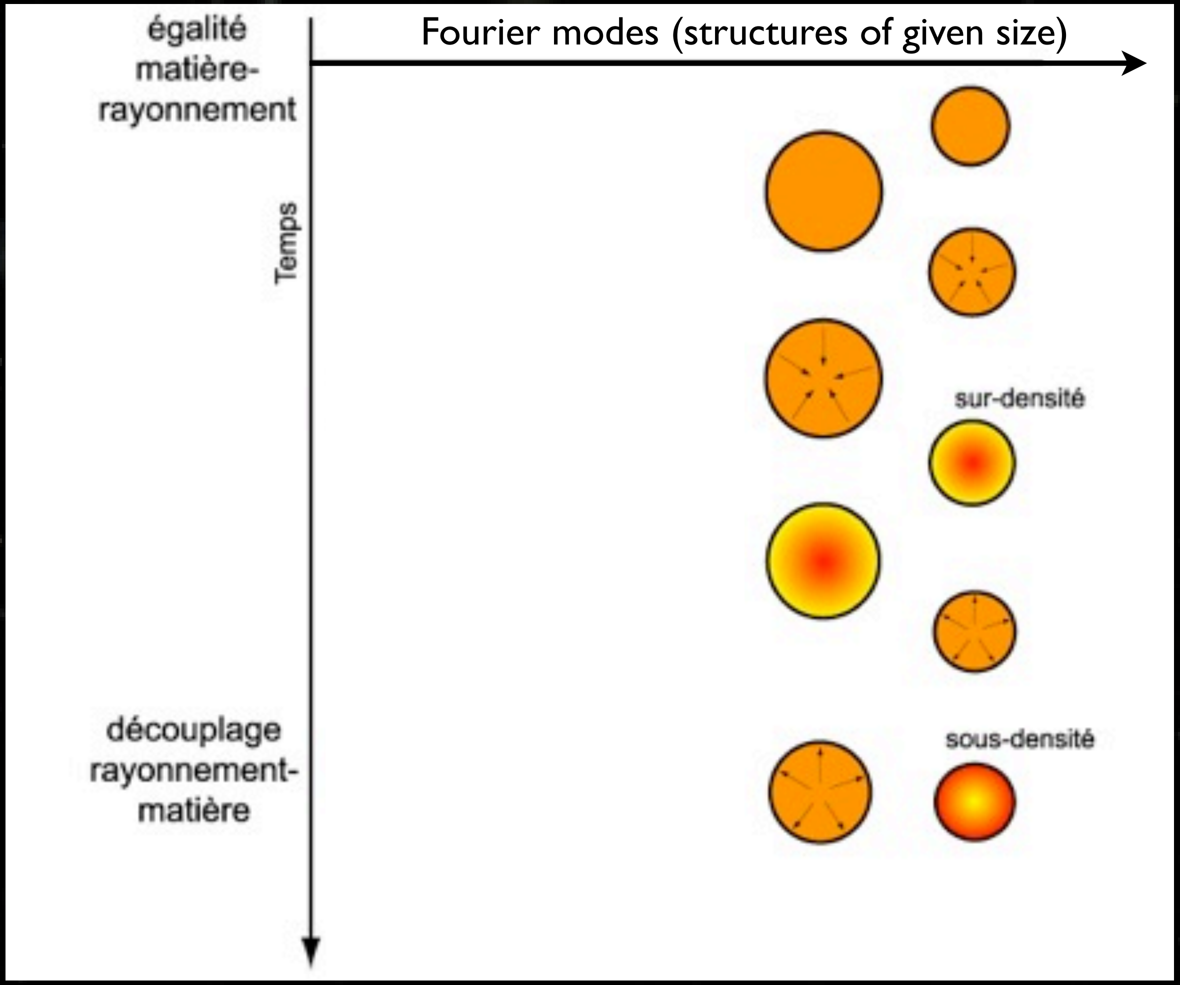

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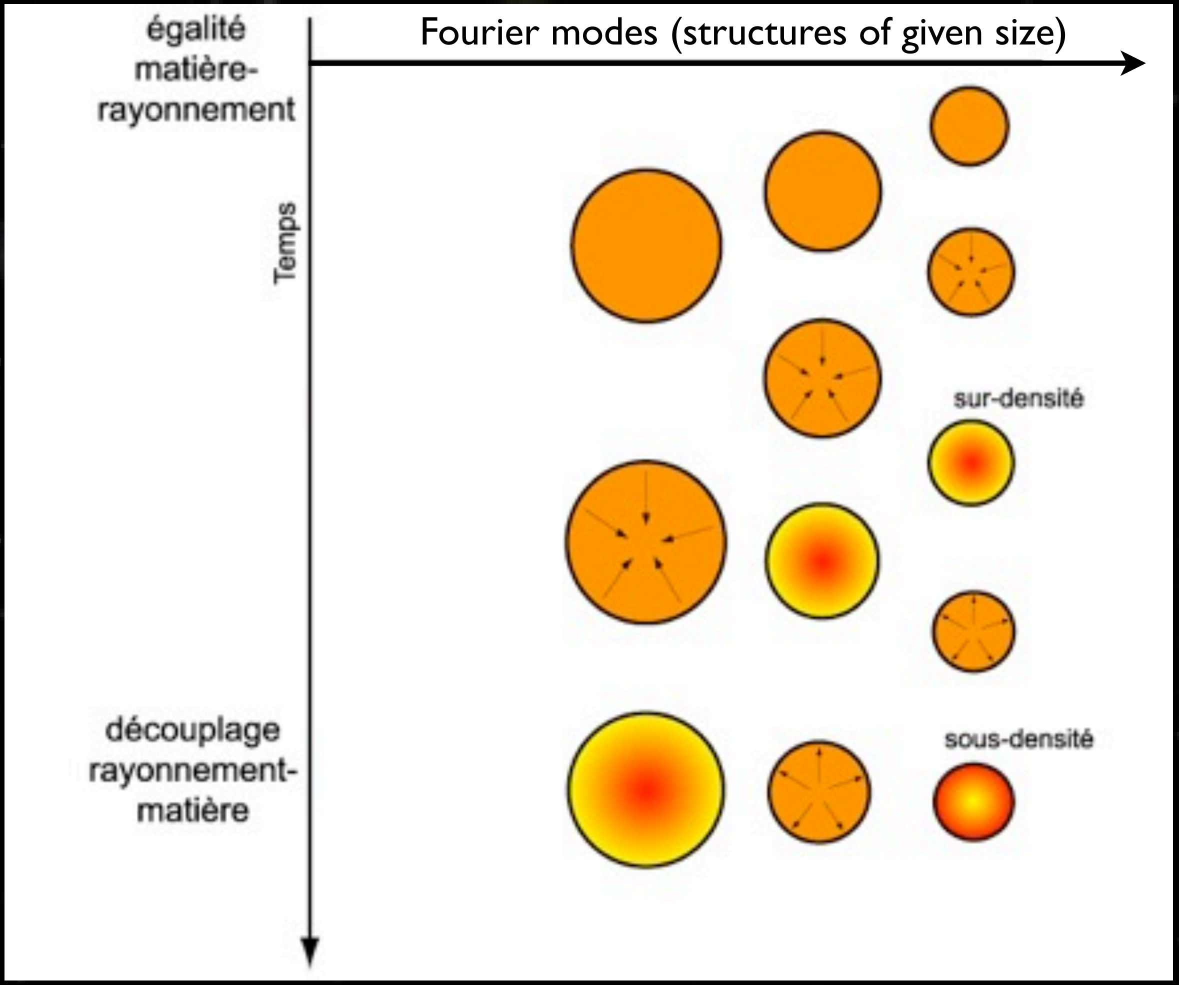

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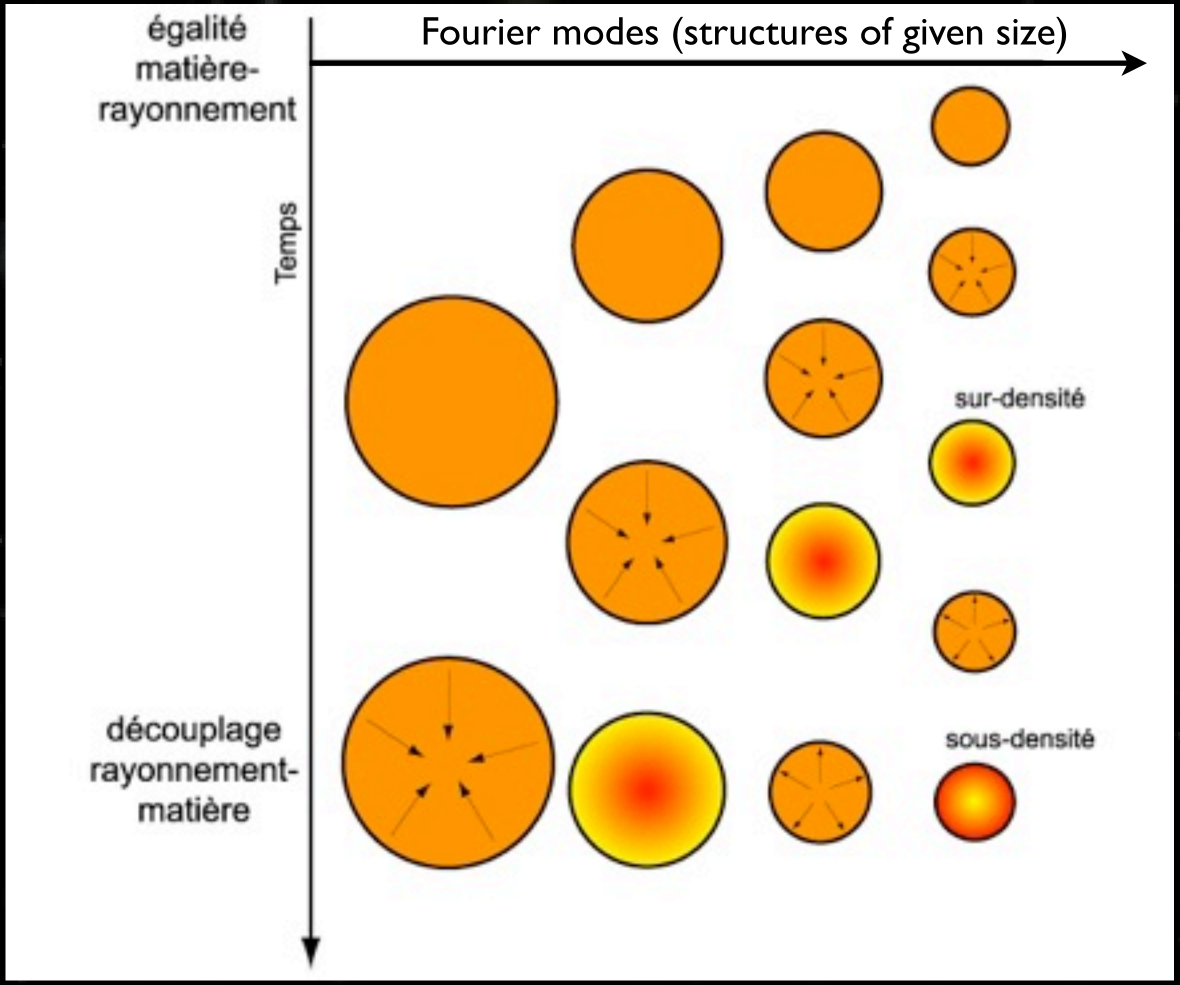

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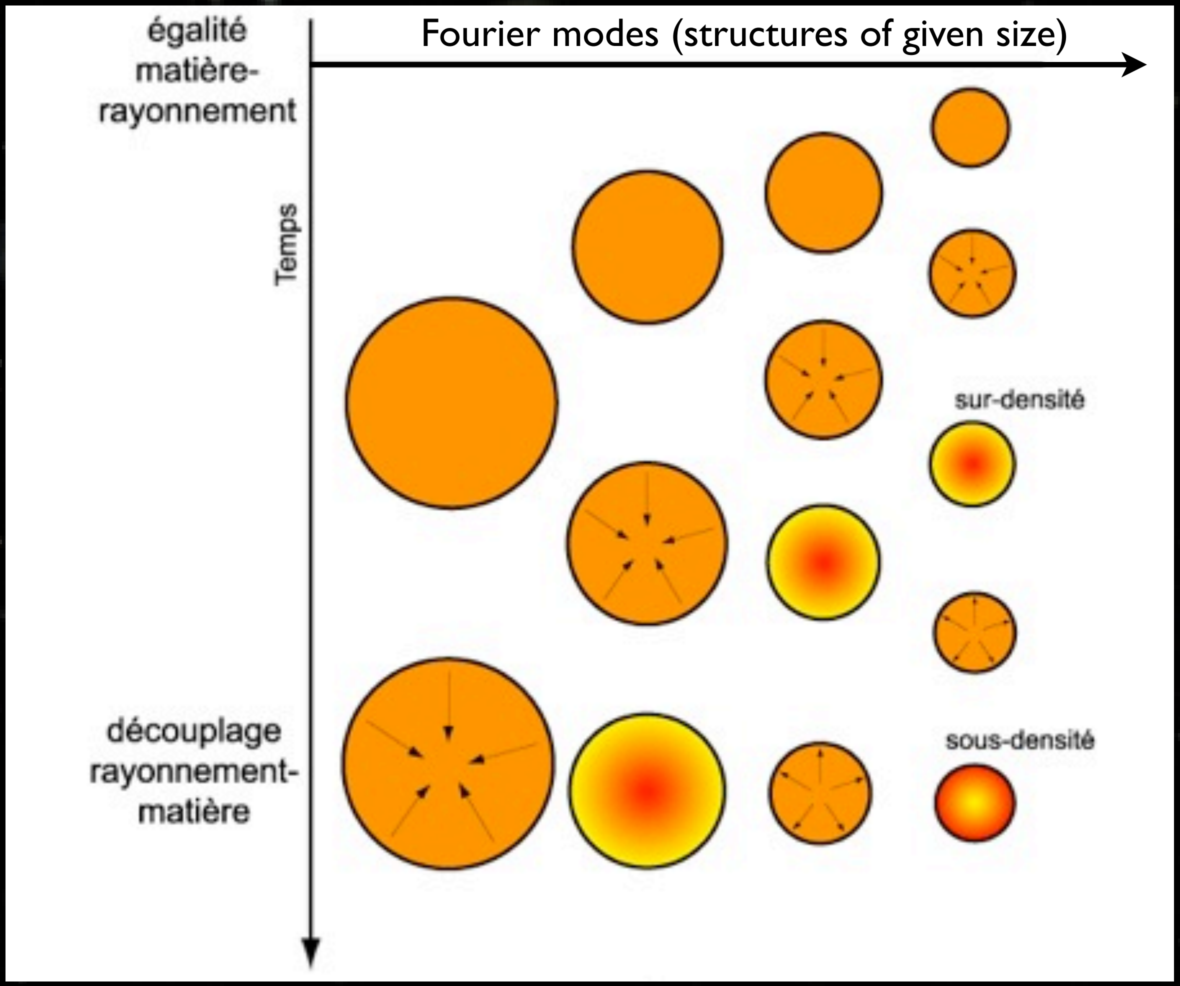
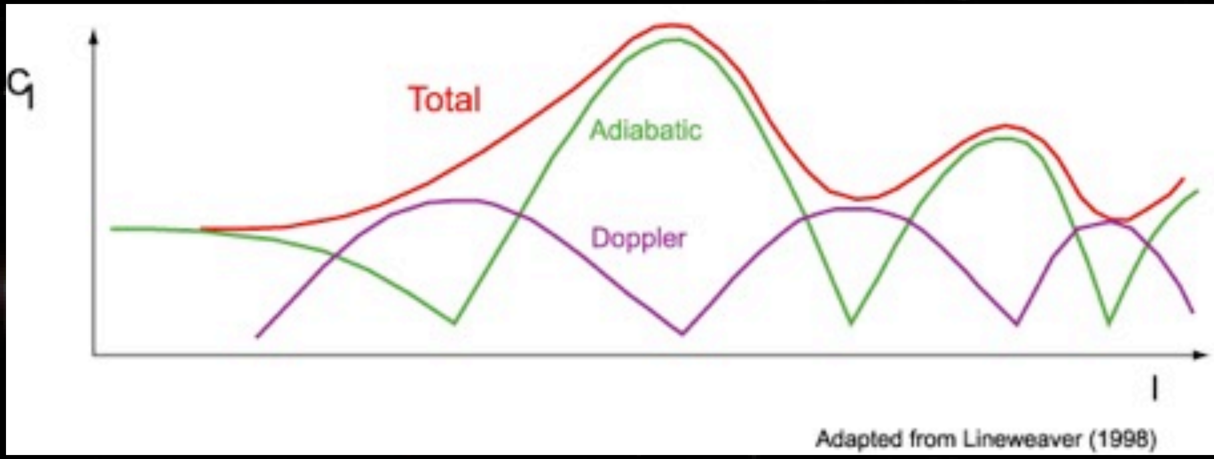
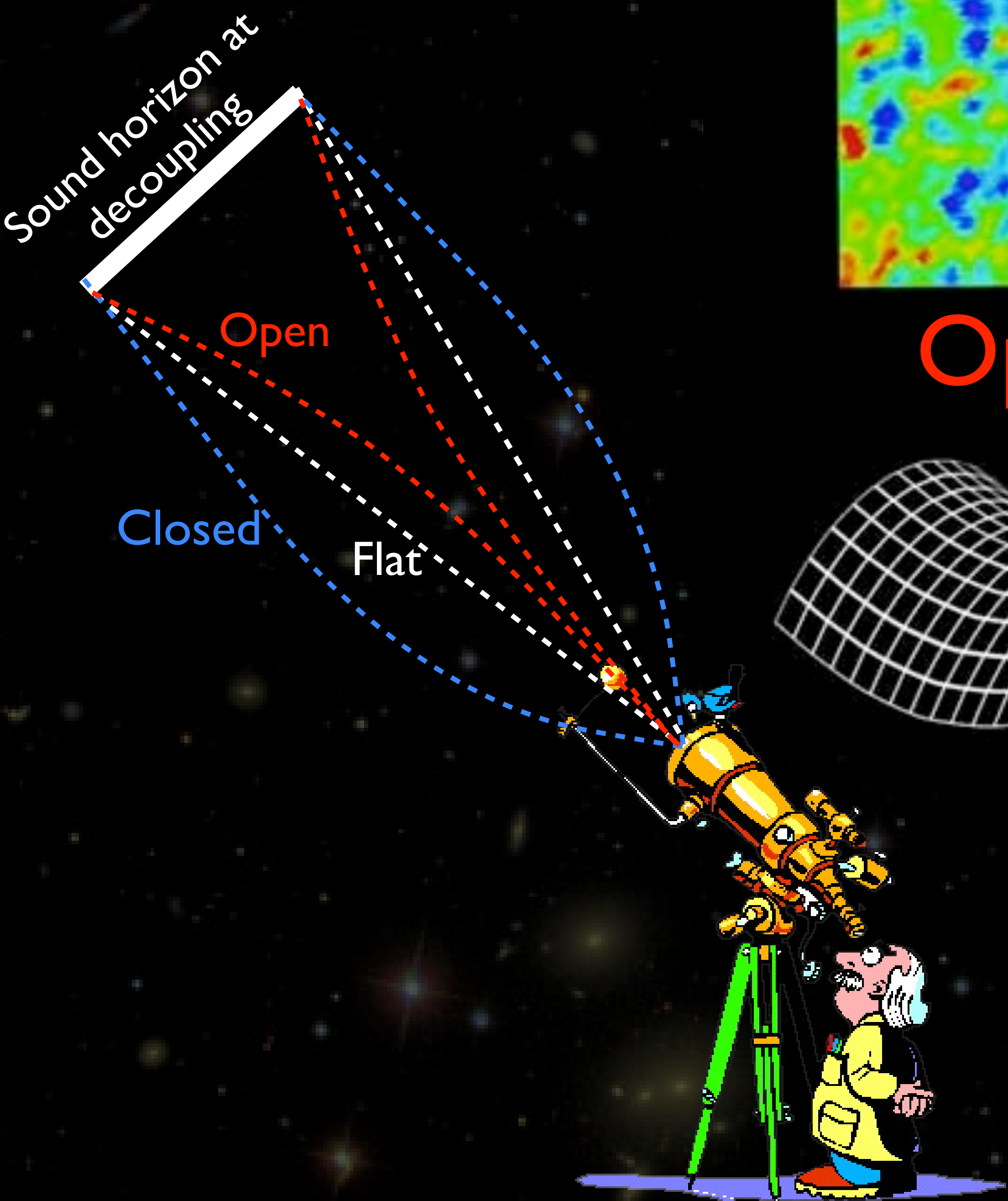
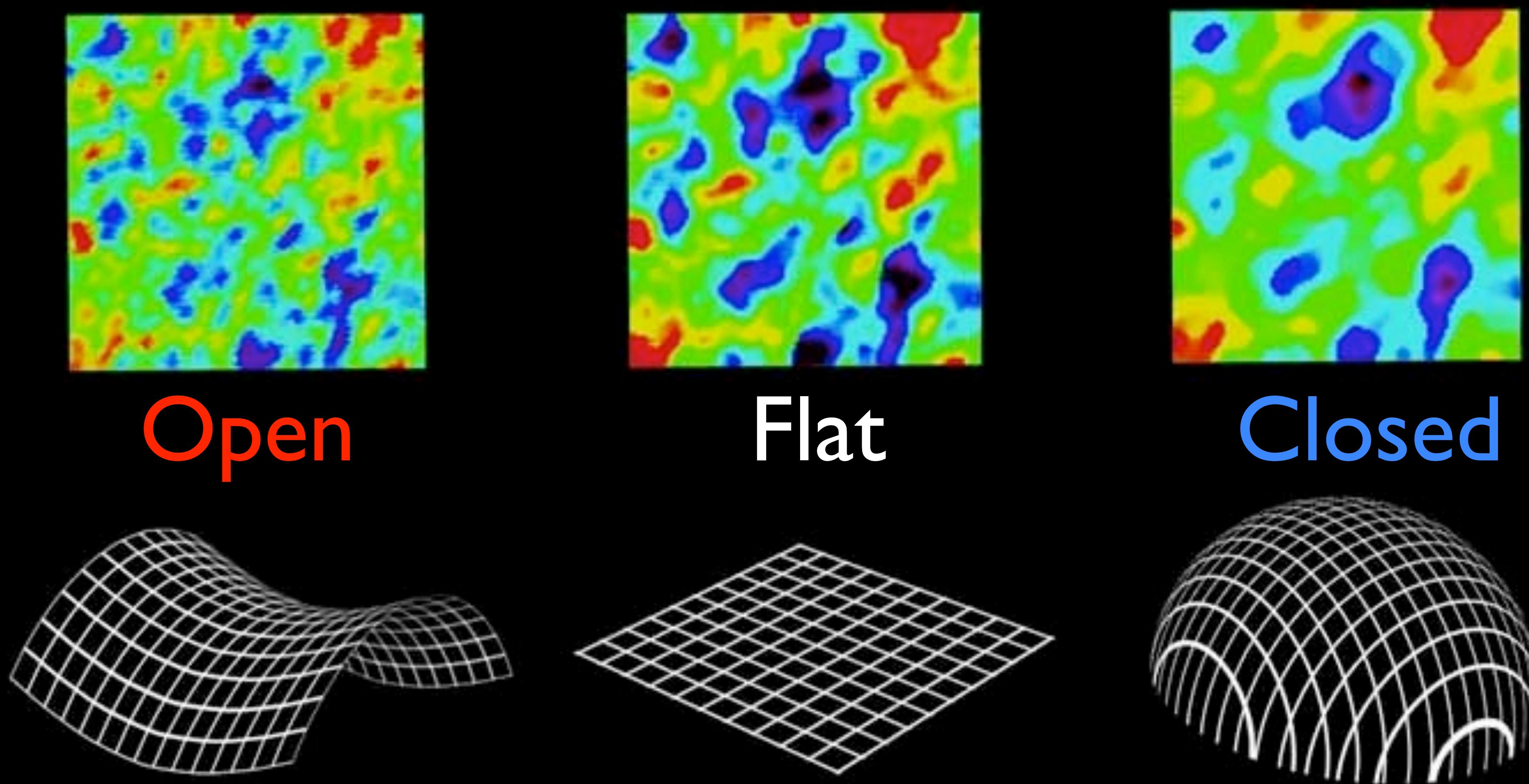




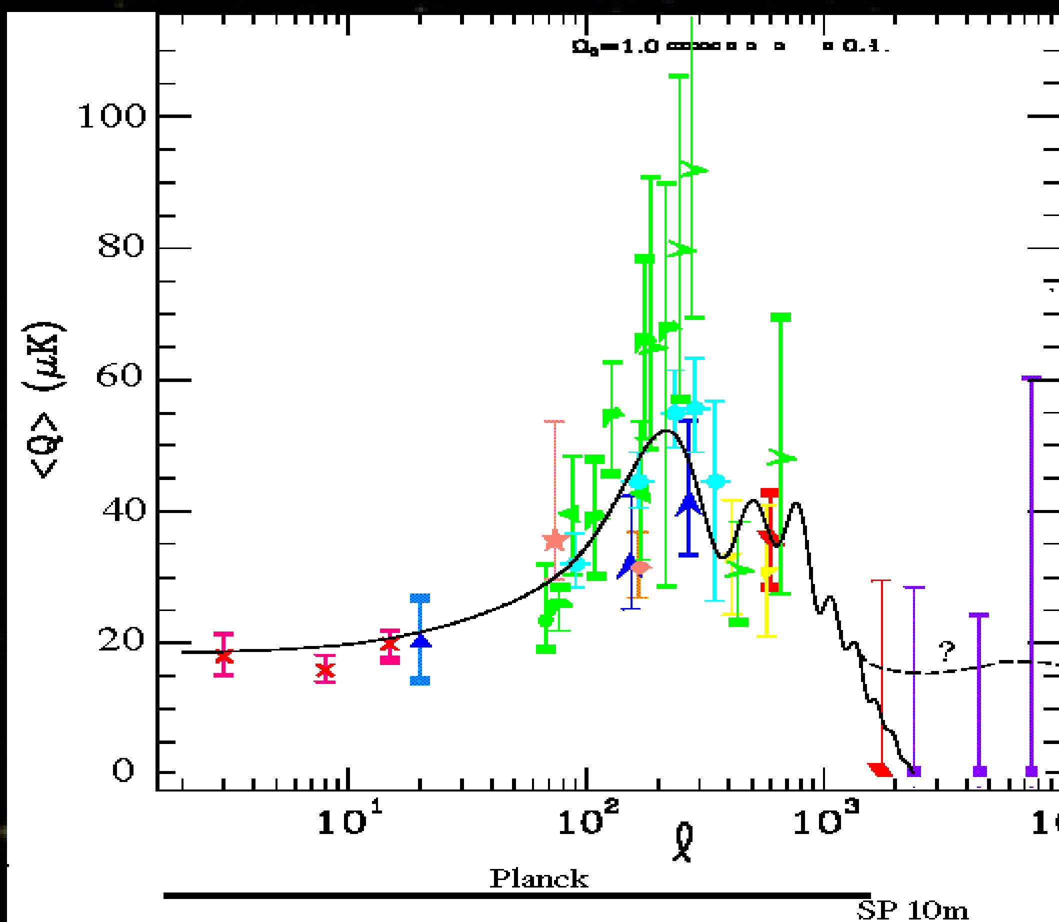
Influence of the geometry of the Universe

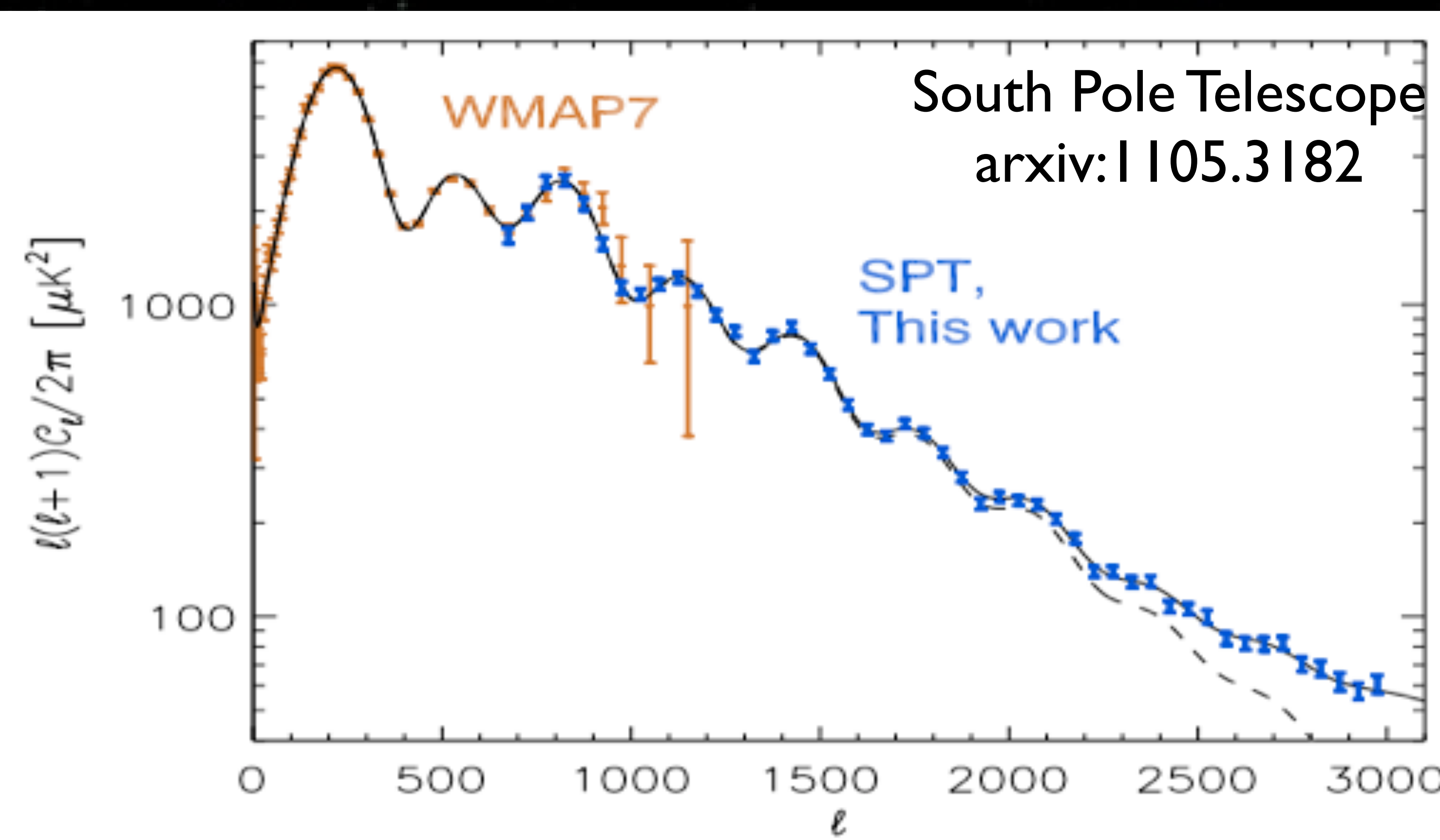




But : Actually slightly more complex due to the degeneracy with H et Λ

Tremendous progress over the last decade





1999 | 2011

Huge success : thousands of independant points fitted with less than 10 parameters and a χ^2/ndf about 1

Theoretical curve predicted in 1987 [Bond & Efstathiou] without any data ...

CMB Polarization (~10%)

★ *Stokes Parameters*

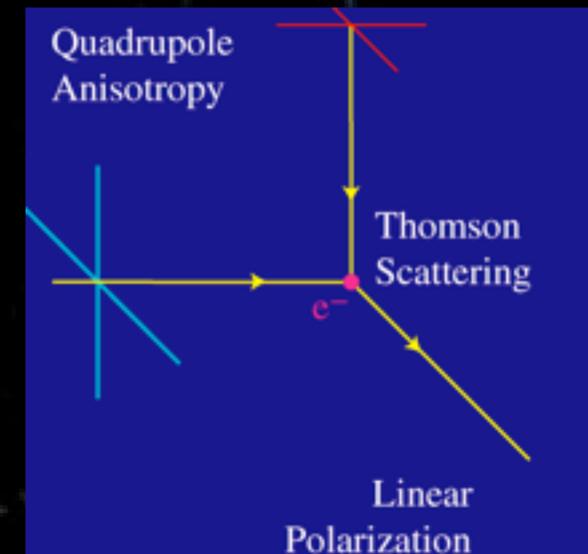
$$I(\vec{n}) = \left\langle |E_{\parallel}(\vec{n})|^2 \right\rangle + \left\langle |E_{\perp}(\vec{n})|^2 \right\rangle \quad \text{(scalar)}$$

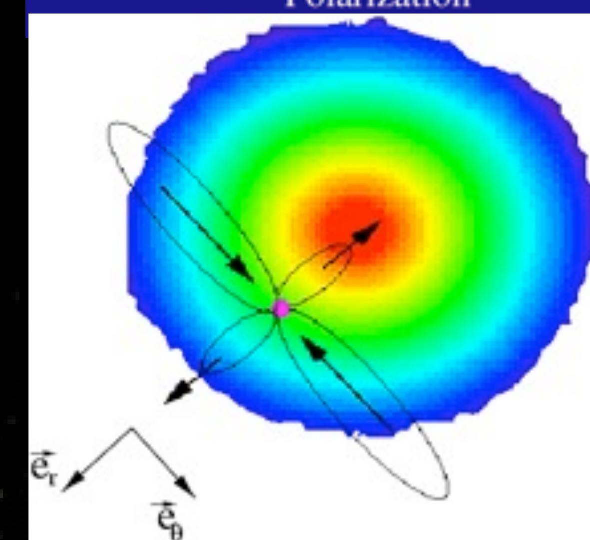
$$Q(\vec{n}) = \left\langle |E_{\parallel}(\vec{n})|^2 \right\rangle - \left\langle |E_{\perp}(\vec{n})|^2 \right\rangle \quad \text{(spin 2)}$$

$$U(\vec{n}) = \langle E_{\parallel}(\vec{n}) E_{\perp}^{\star}(\vec{n}) \rangle + \left\langle E_{\perp}(\vec{n}) E_{\parallel}^{\star}(\vec{n}) \right\rangle \quad \text{(spin 2)}$$

$$V(\vec{n}) = i \left(\langle E_{\parallel}(\vec{n}) E_{\perp}^{\star}(\vec{n}) \rangle - \left\langle E_{\perp}(\vec{n}) E_{\parallel}^{\star}(\vec{n}) \right\rangle \right) \quad \text{(spin 2)}$$

W. Hu





N. Ponthieu

★ *spin +/- 2 Spherical harmonics expansion*

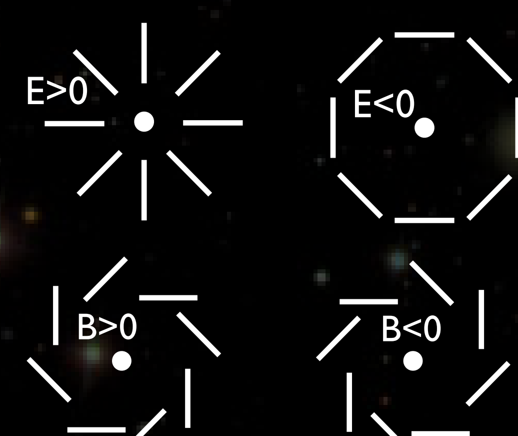
$$Q(\vec{n}) + iU(\vec{n}) = \sum_{\ell m} a_{2,\ell m} \; {}_{2}Y_{\ell m}(\vec{n})$$

$$Q(\vec{n}) - iU(\vec{n}) = \sum_{\ell m} a_{-2,\ell m} \; {}_{-2}Y_{\ell m}(\vec{n})$$

★ *Scalar E and B fields*

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

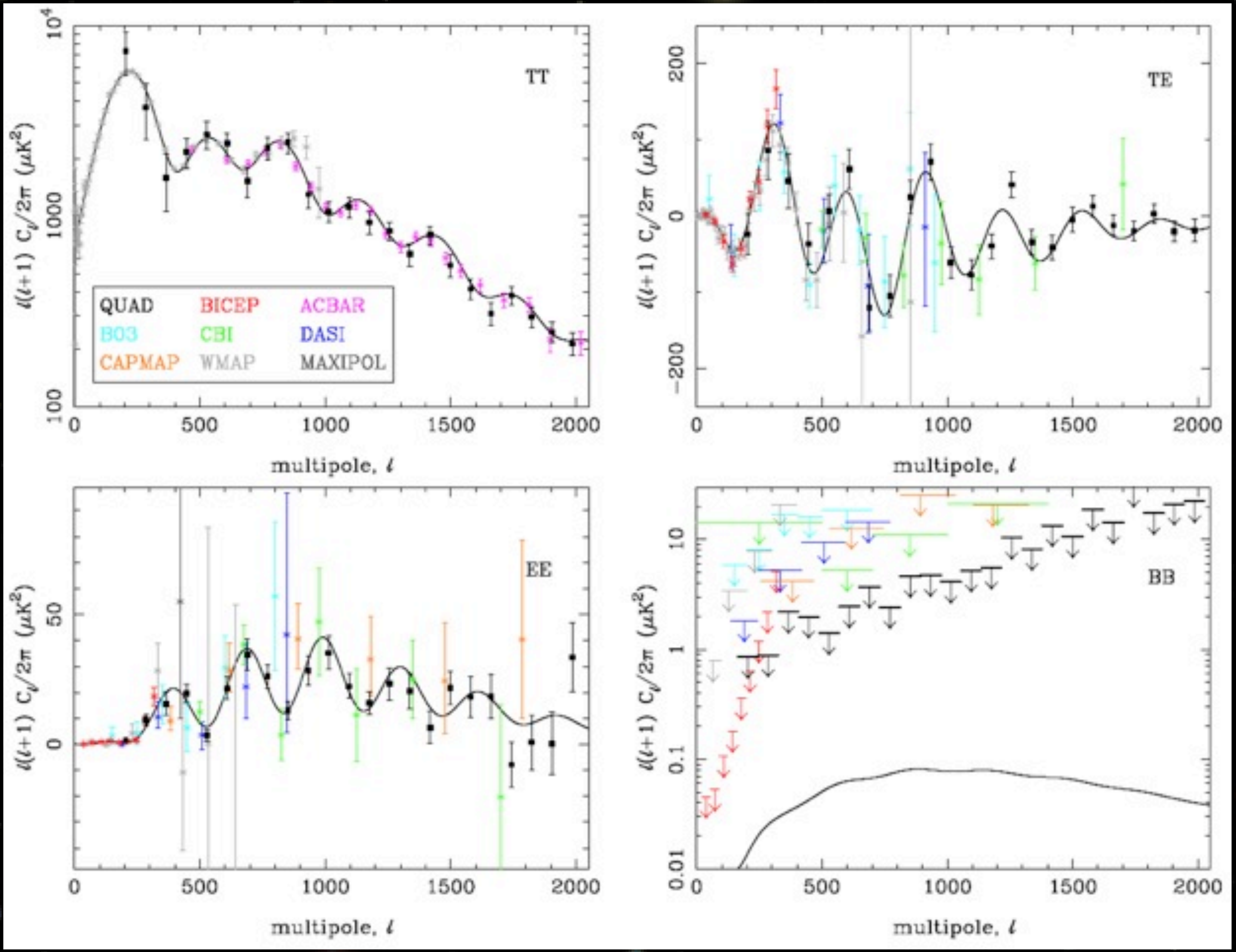
$$a_{B,\ell m} = i\frac{a_{2,\ell m} - a_{-2,\ell m}}{2} \quad \text{(odd)}$$



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

Recent CMB measurements

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



[QUAD Collaboration: Arxiv:0906.1003]

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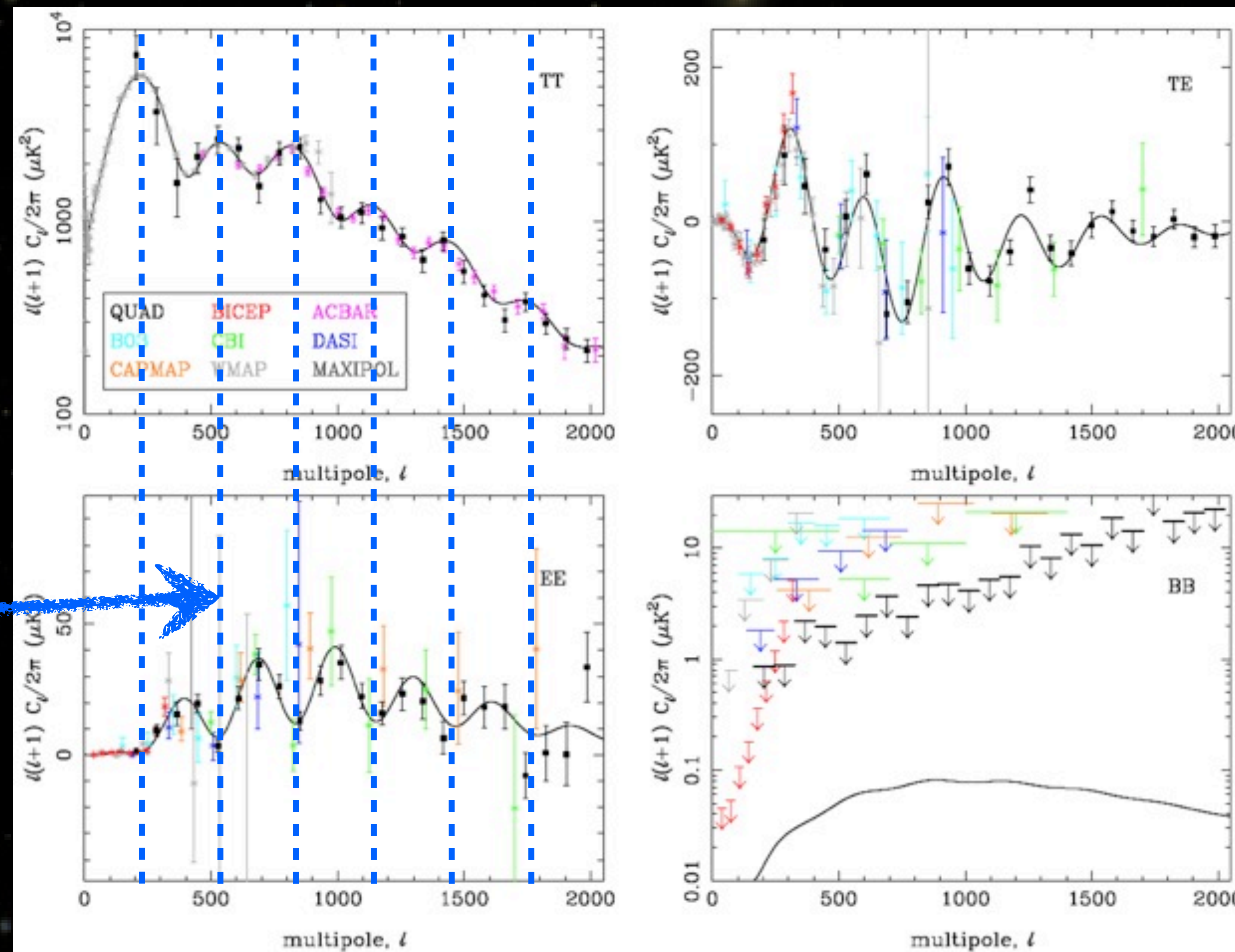

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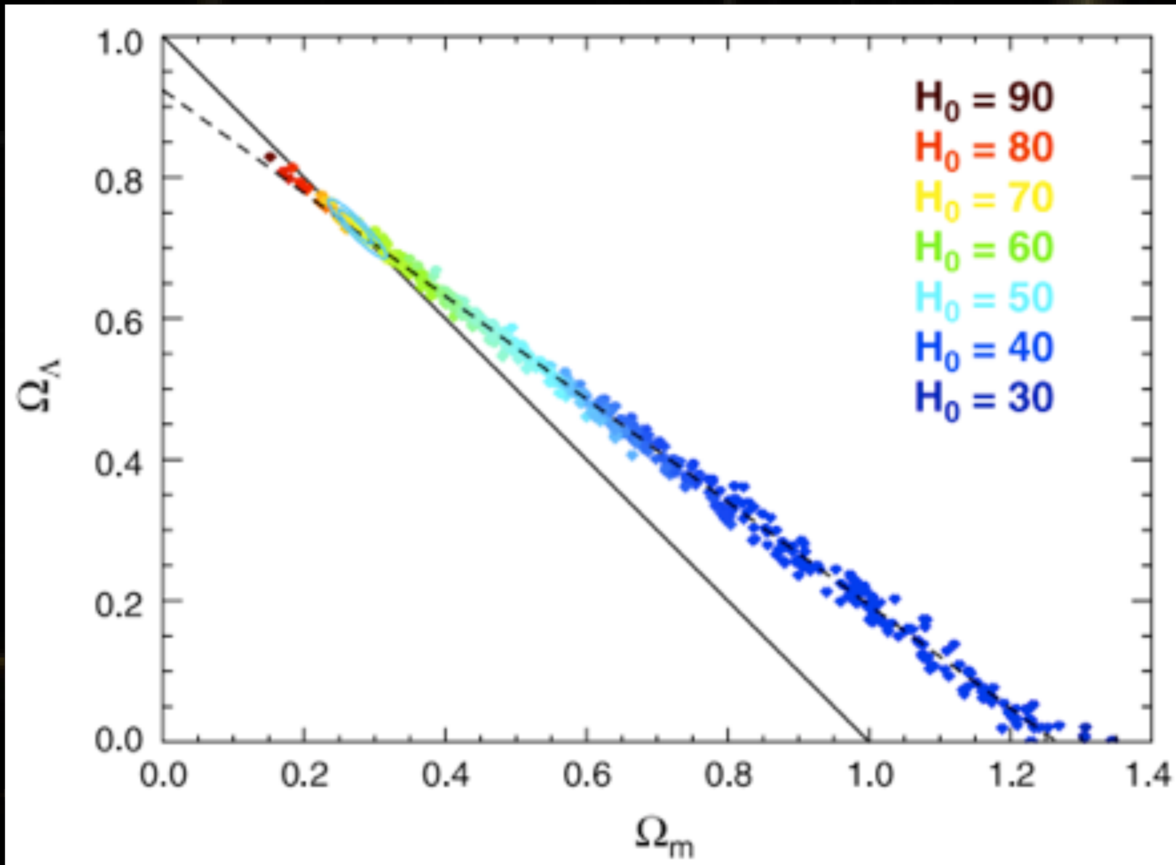
What we know today

- Standard cosmological model : ΛCDM
  - ★ The Universe is expanding
    - Hubble constant ~ 70 km.s^{-1}.Mpc^{-1}
  - ★ The Universe is ~ flat : $\Omega_{tot} \approx 1$
    - CMB + Hubble constant
  - ★ It contains ~ 22 % of Dark Matter
    - Known amount, unknown nature (SuSy ?)
    - Galaxies rotation curves, Clusters X, weak-lensing, Structure formation, CMB
  - ★ It contains ~ 74% of Dark Energy
    - Known quantity, unknown nature
    - SNIa, CMB+H, direct measurements of Ω_m



WMAP 7y

Big Question:
origin of primordial fluctuations ?

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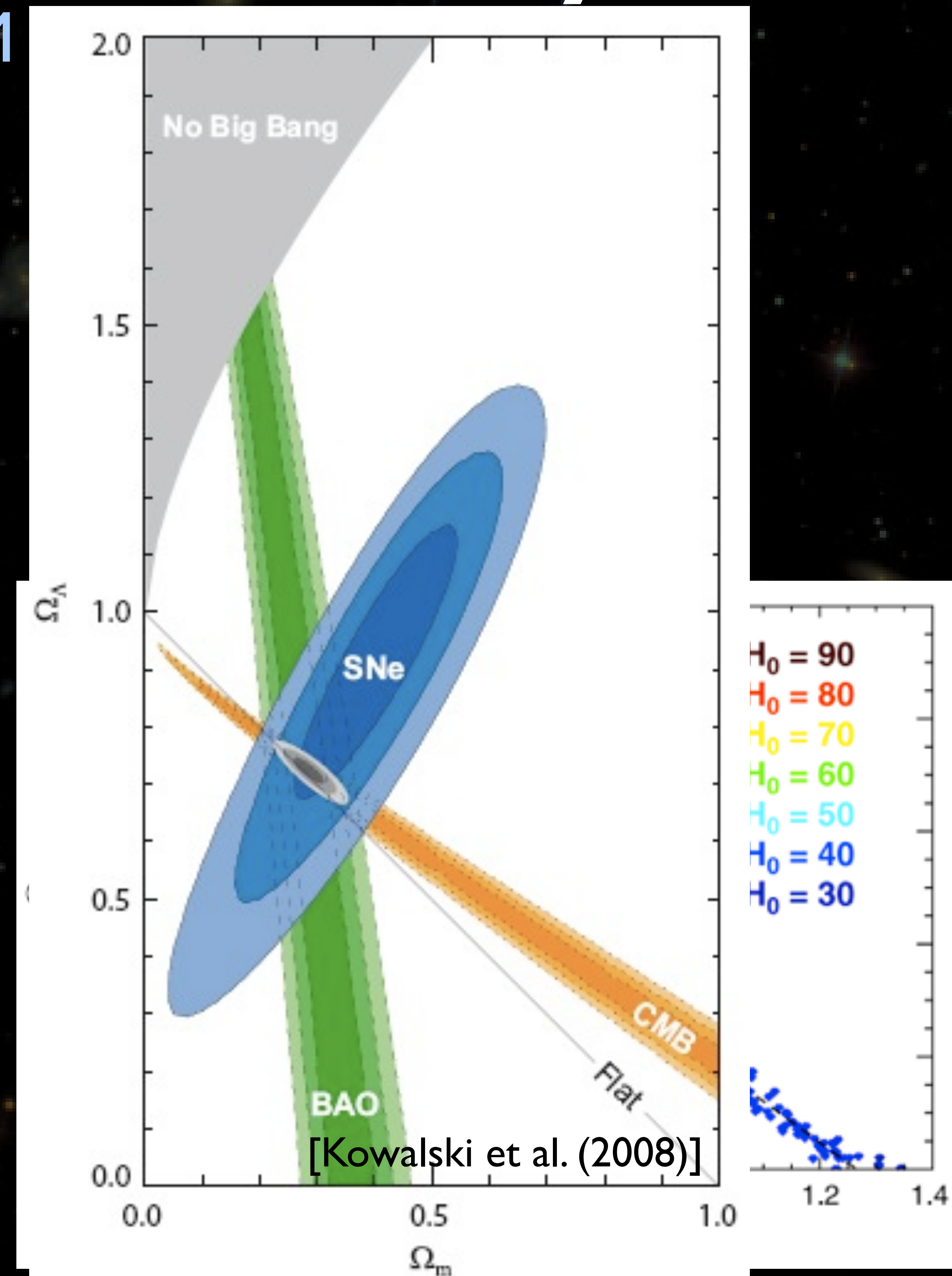

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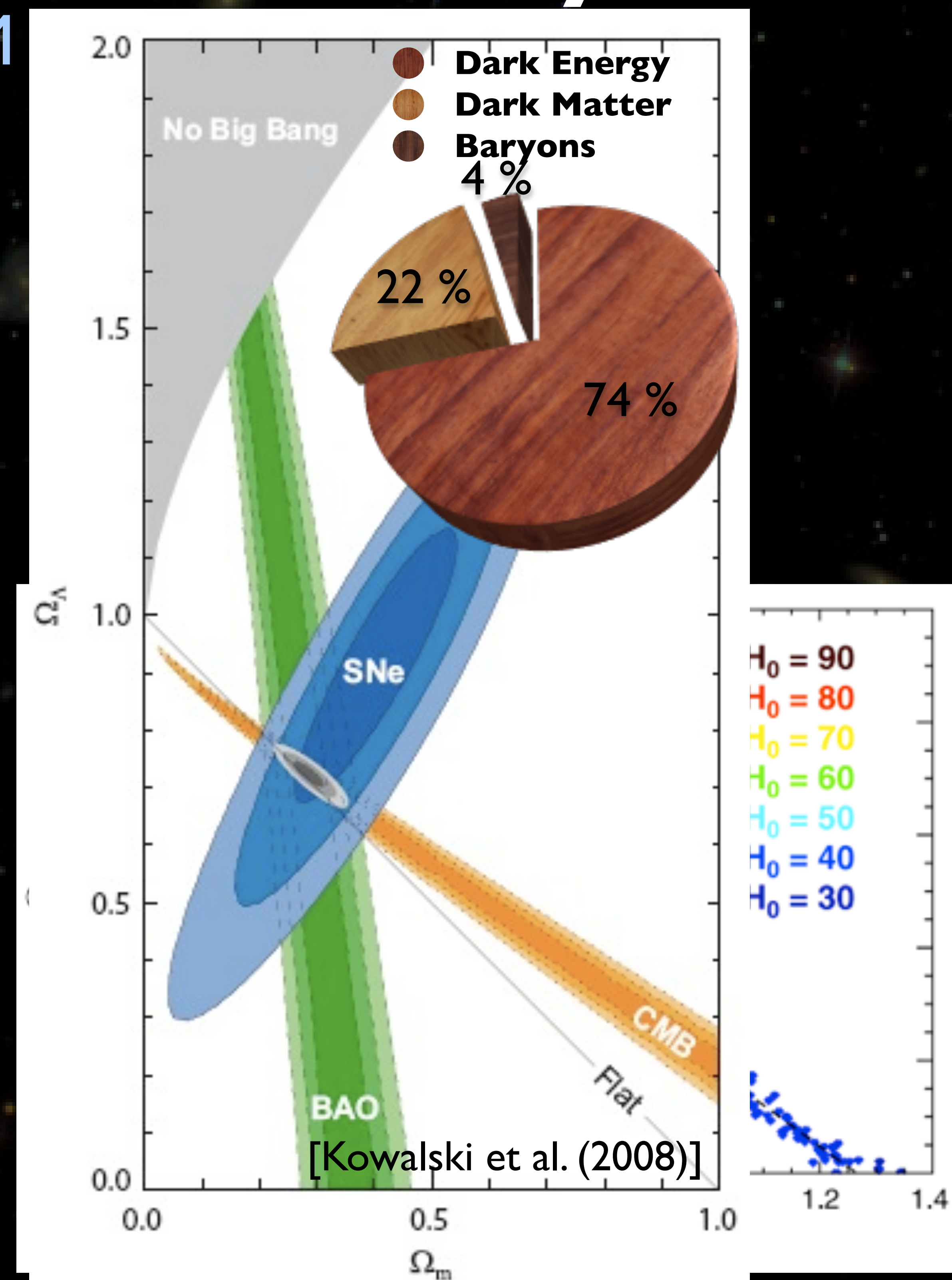

WMAP 7y

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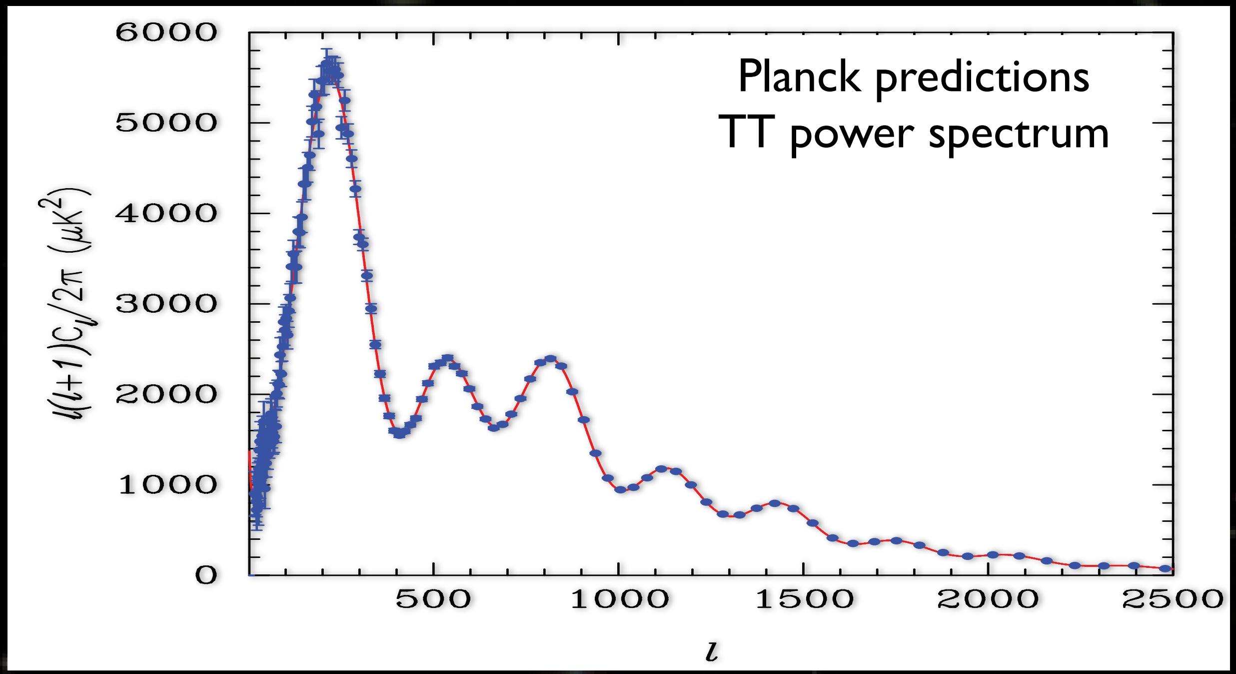
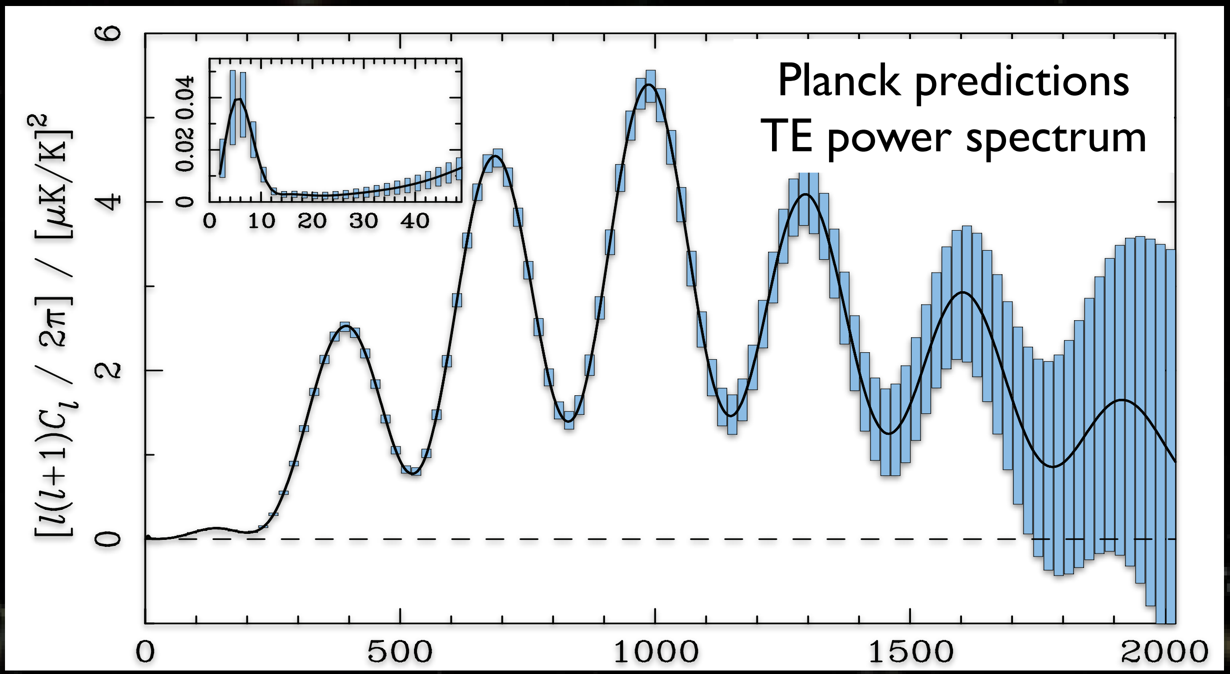
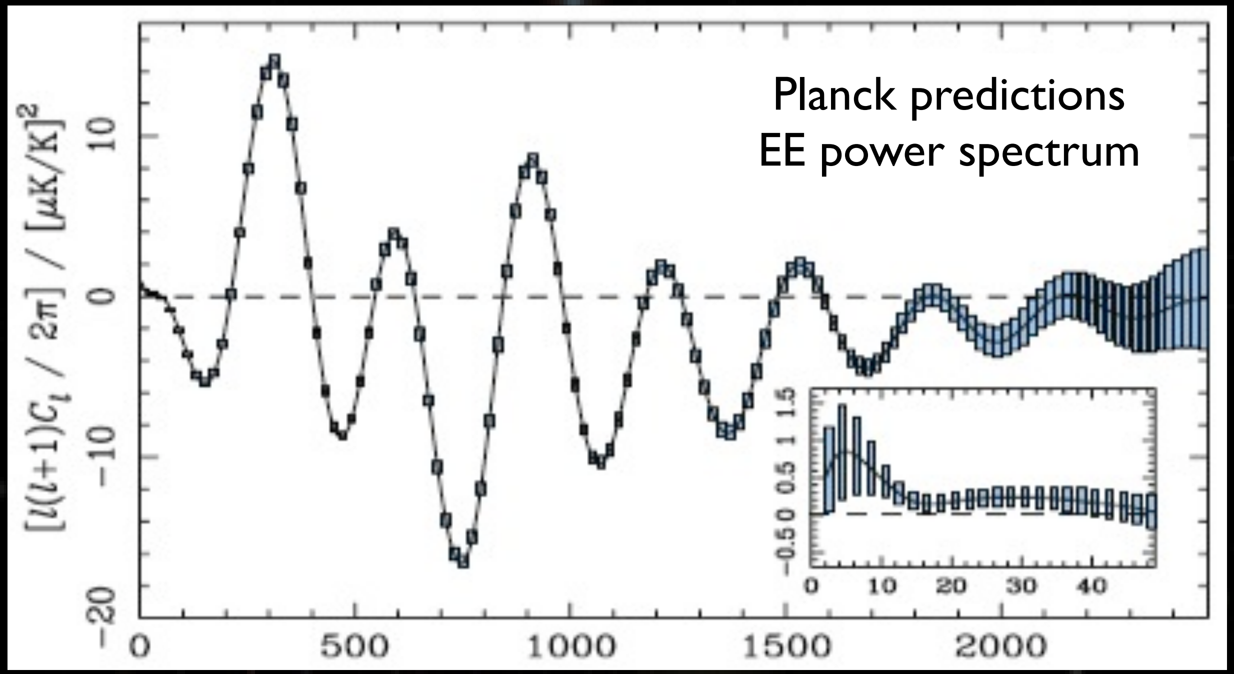
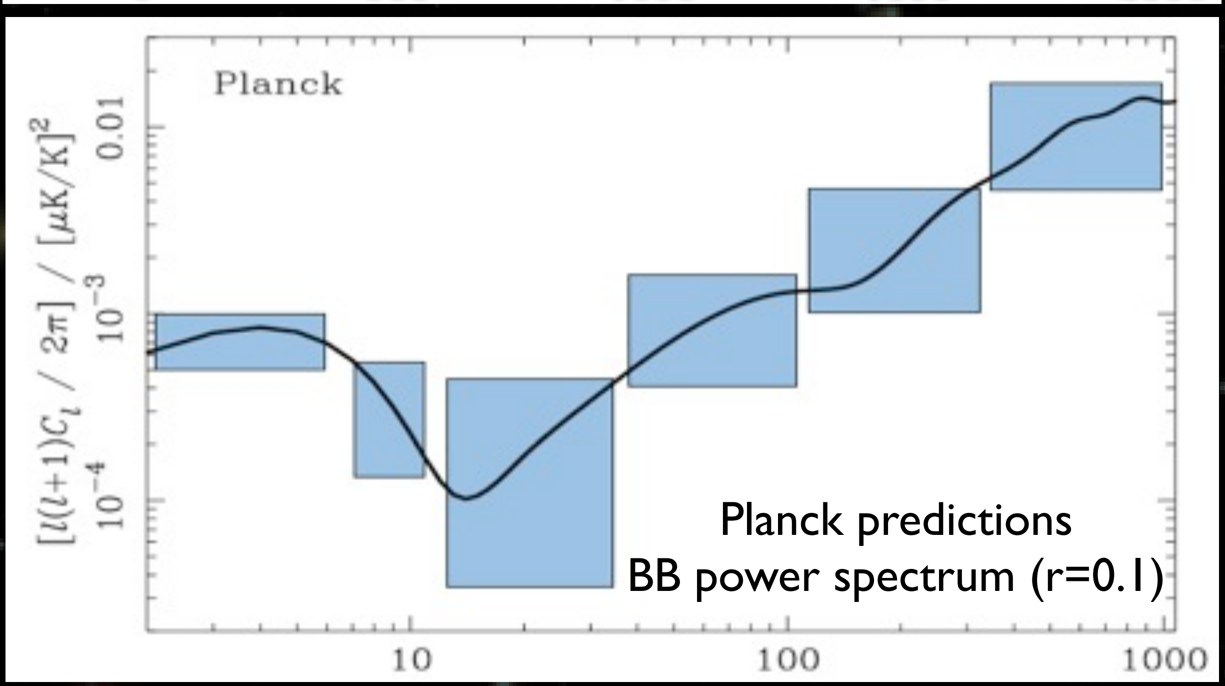
Planck expected results

[Planck Bluebook]





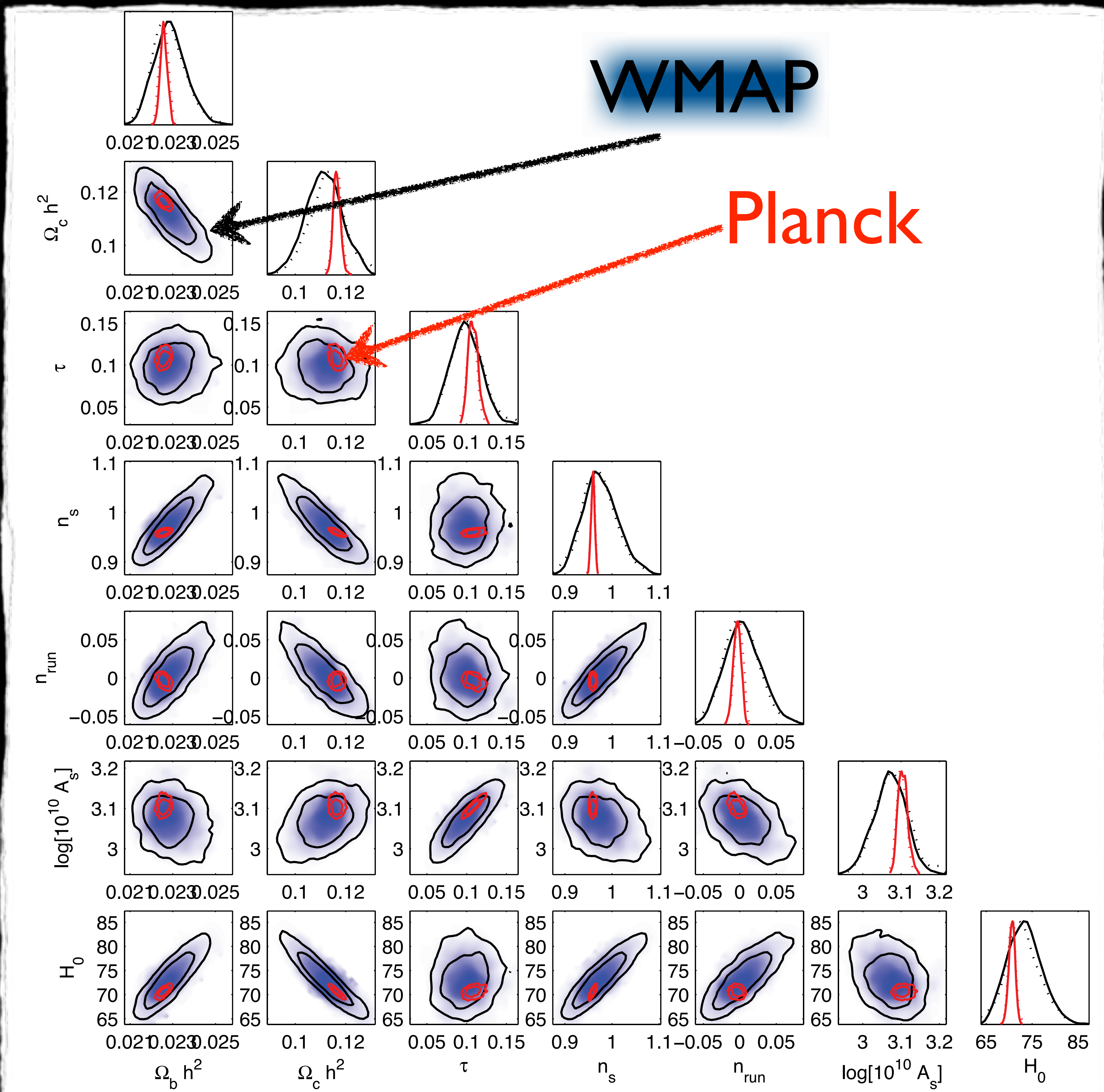




Improvements of ~ factor 3 on cosmological parameters

What we will know after Planck

(Planck Bluebook)



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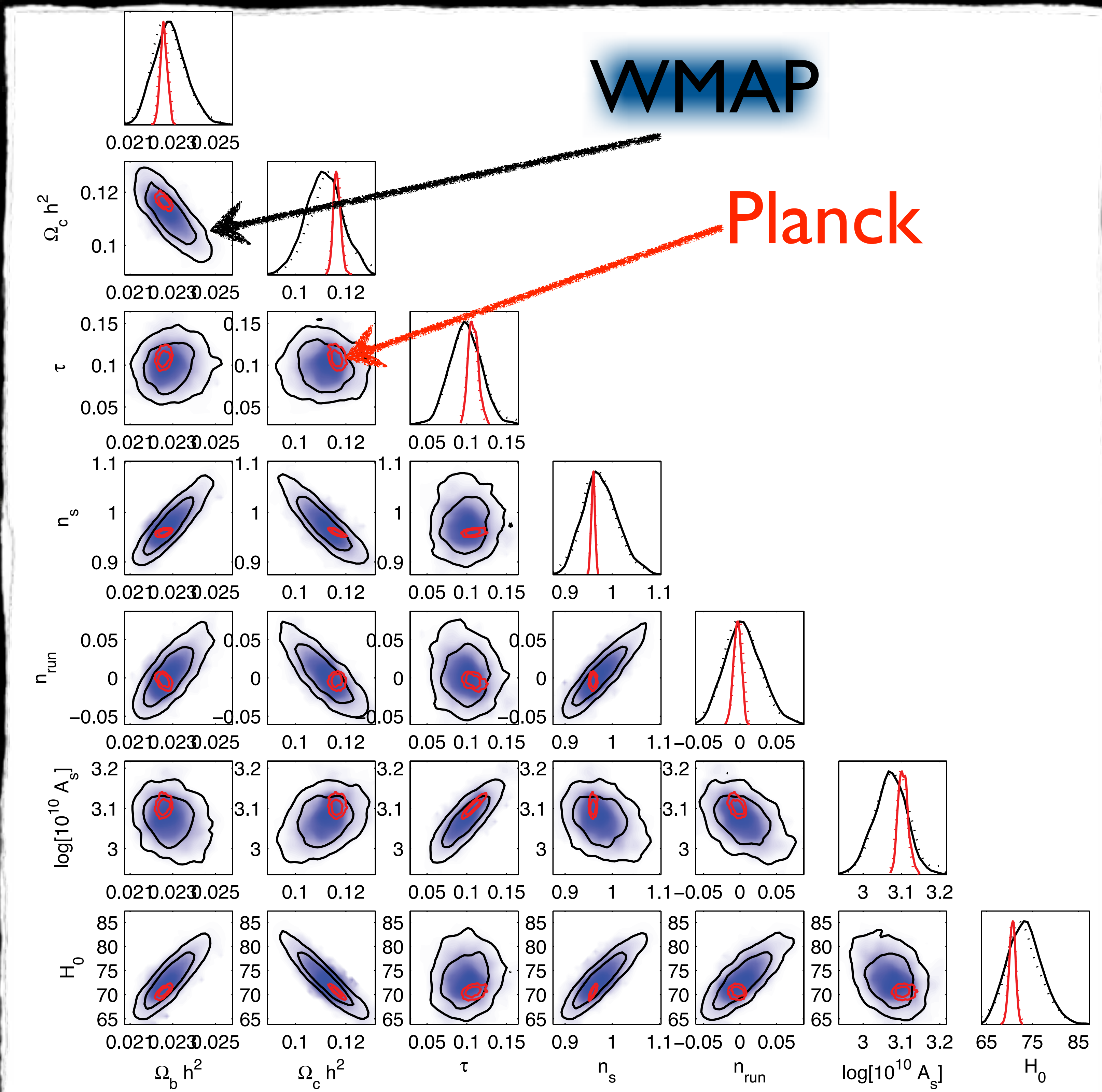


Do we need to go further ?

Where do the fitted power-spectra shapes come from ?

What is the origin of the primordial perturbations ?

Inflation ?

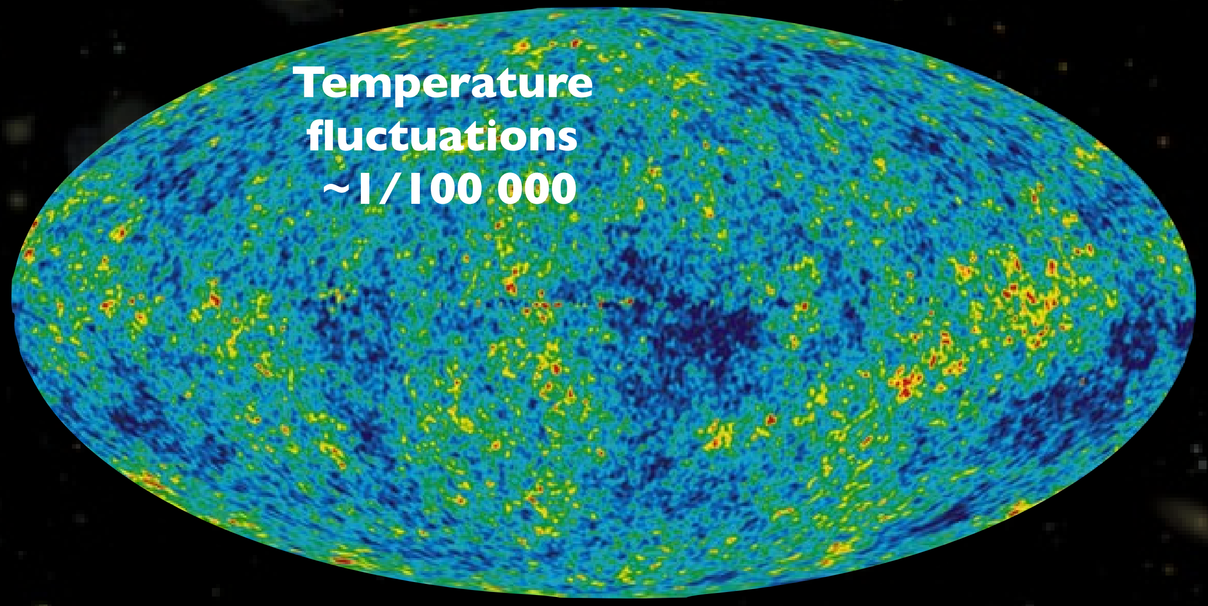
Inflation

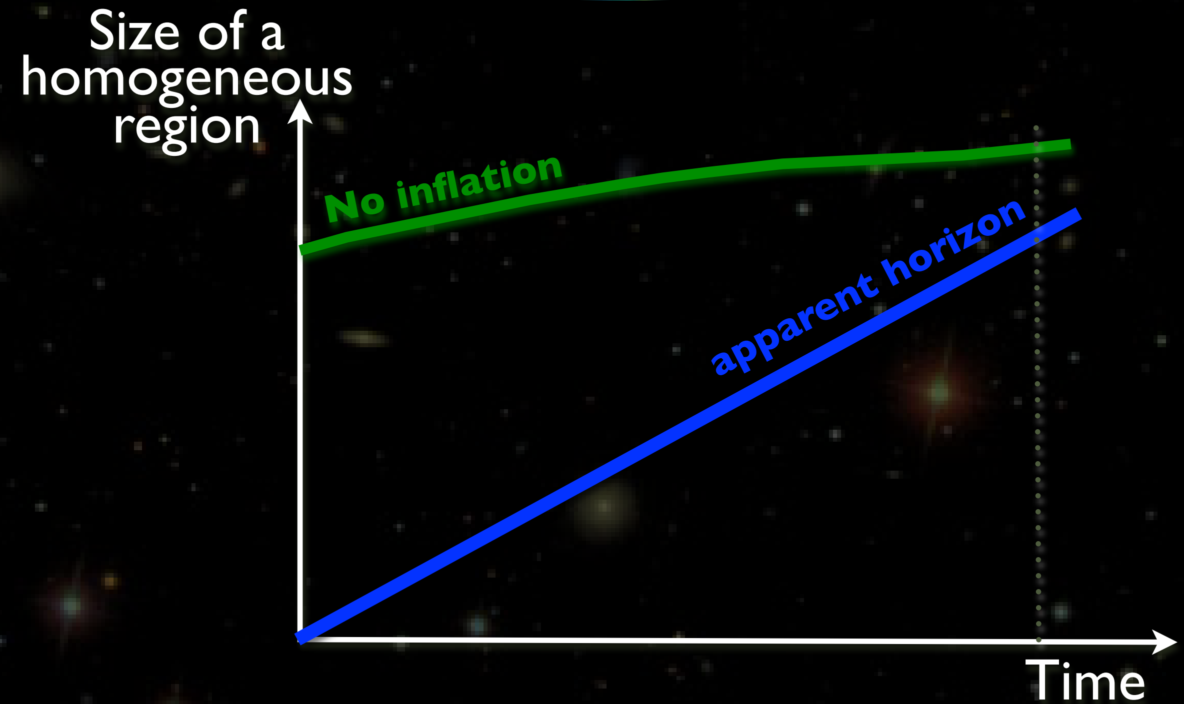
- Phase of accelerated expansion in the Early Universe
- Initially invented to solve some issues in Big-Bang theory
  - ★ Horizon
  - ★ Flatness
  - ★ Monopoles
- Predicts the shape of the primordial density perturbations
  - ★ Seeds for Structure formation
  - ★ Gaussianity
  - ★ Generation of both 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 with this detail checked ...

The horizon problem

- The Universe appears very homogeneous on the large scale
- This is the sign of some «thermalisation process» in the early Universe
- BUT at decoupling the horizon was about 1 degree
- How did causally disconnected regions manage to get thermalized ?
- **Solution : Inflation**

Temperature map of the CMB





The horizon problem

- The Universe appears very homogeneous on the large scale
- This is the sign of some «thermalisation process» in the early Universe
- BUT at decoupling the horizon was about 1 degree
- How did causally disconnected regions manage to get thermalized ?
- **Solution : Inflation**

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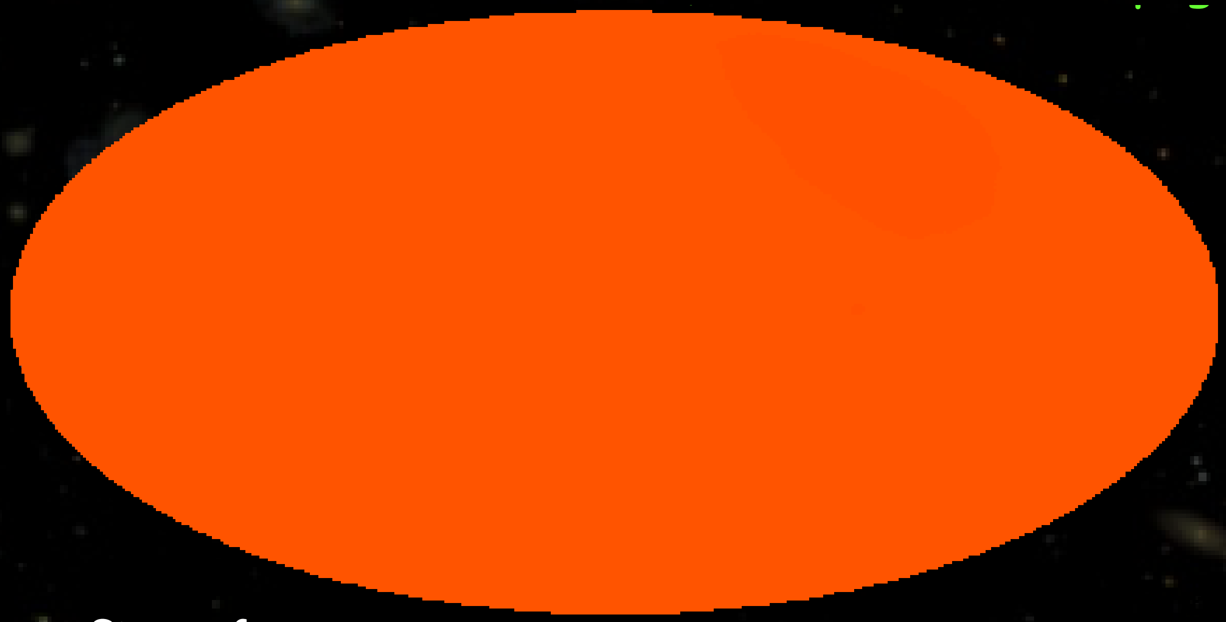

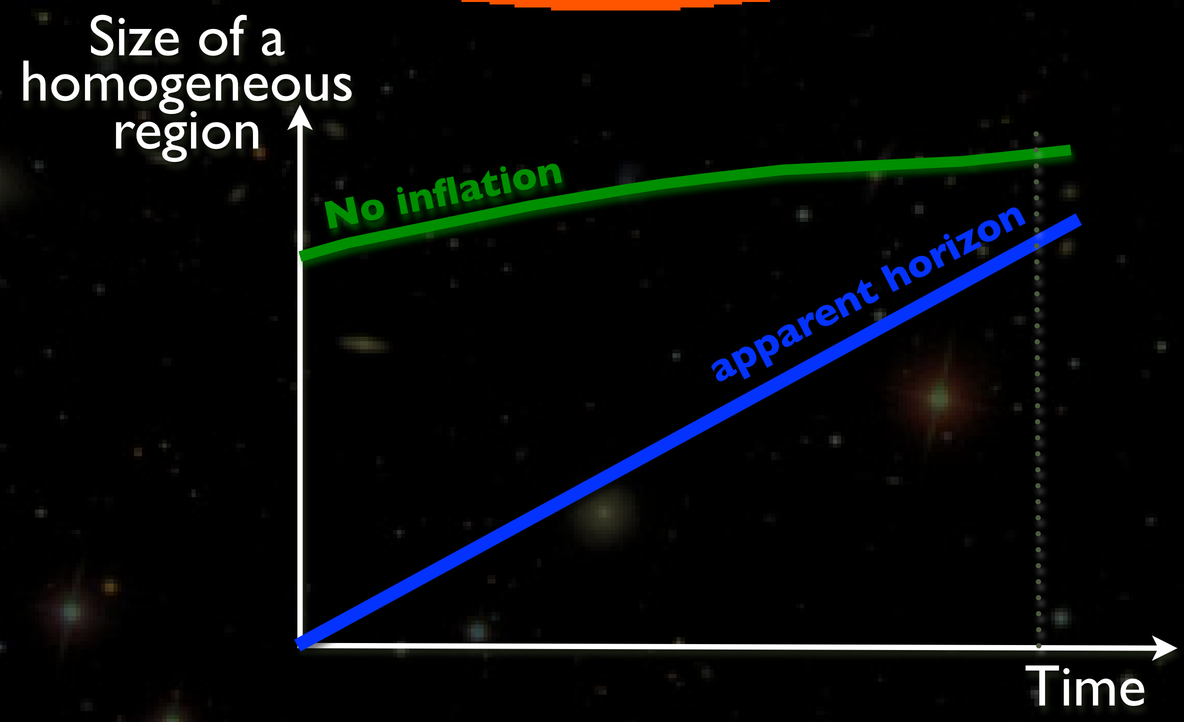

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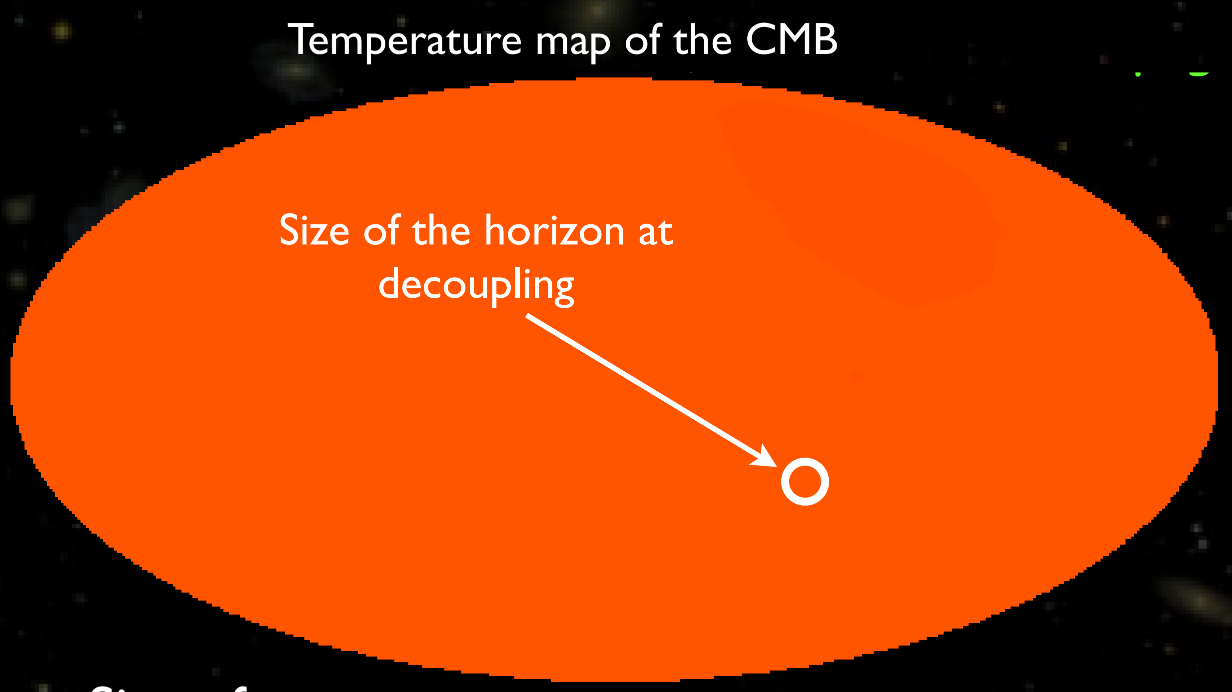

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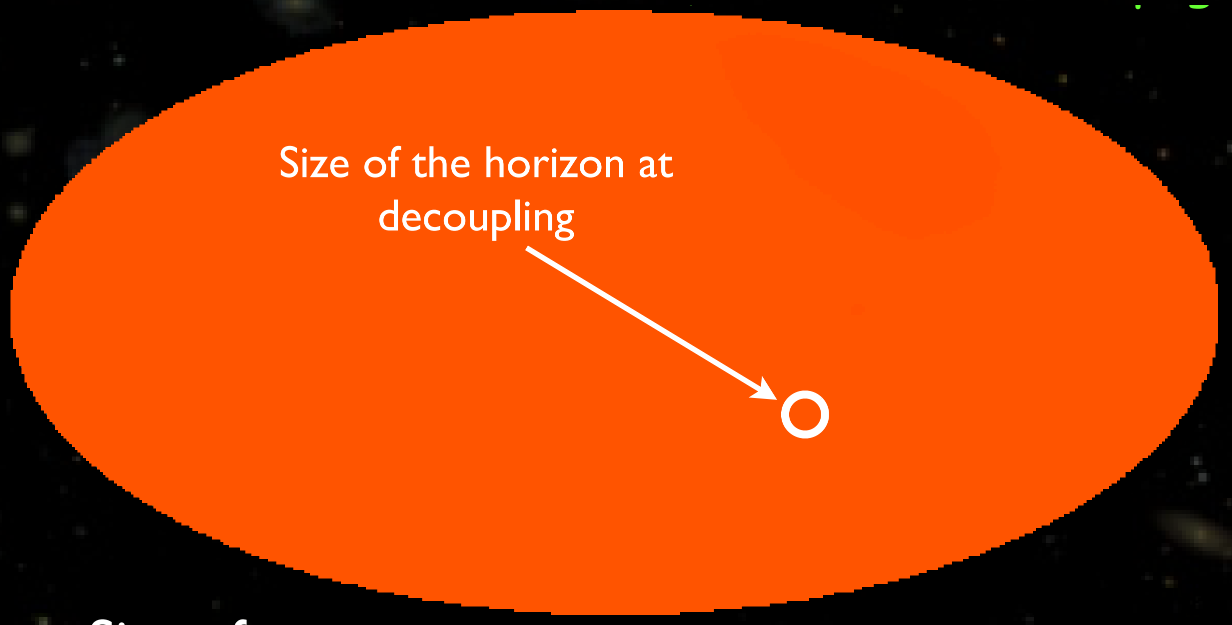

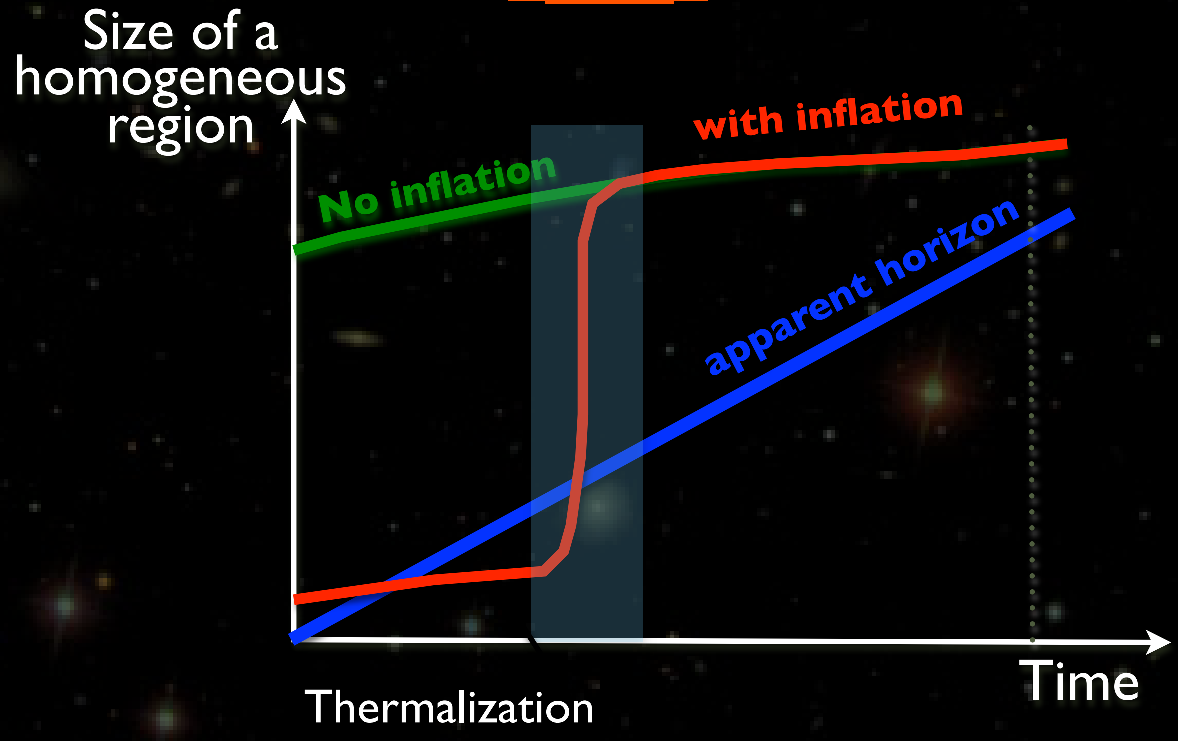

Flatness problem

- $\Omega_{tot}=1$ is «unstable»

★ any tiny excursion from exact flatness at t=0 would now be huge

★ we do measure $\Omega_{tot}=1$ with 1% accuracy !

$\Rightarrow$ at $t=10^{-43}$ sec : $|\Omega_{tot}-1|<10^{-60}$

- A «flattening» process would explain wy we observe a flat Universe, whatever its flatness at the beginning

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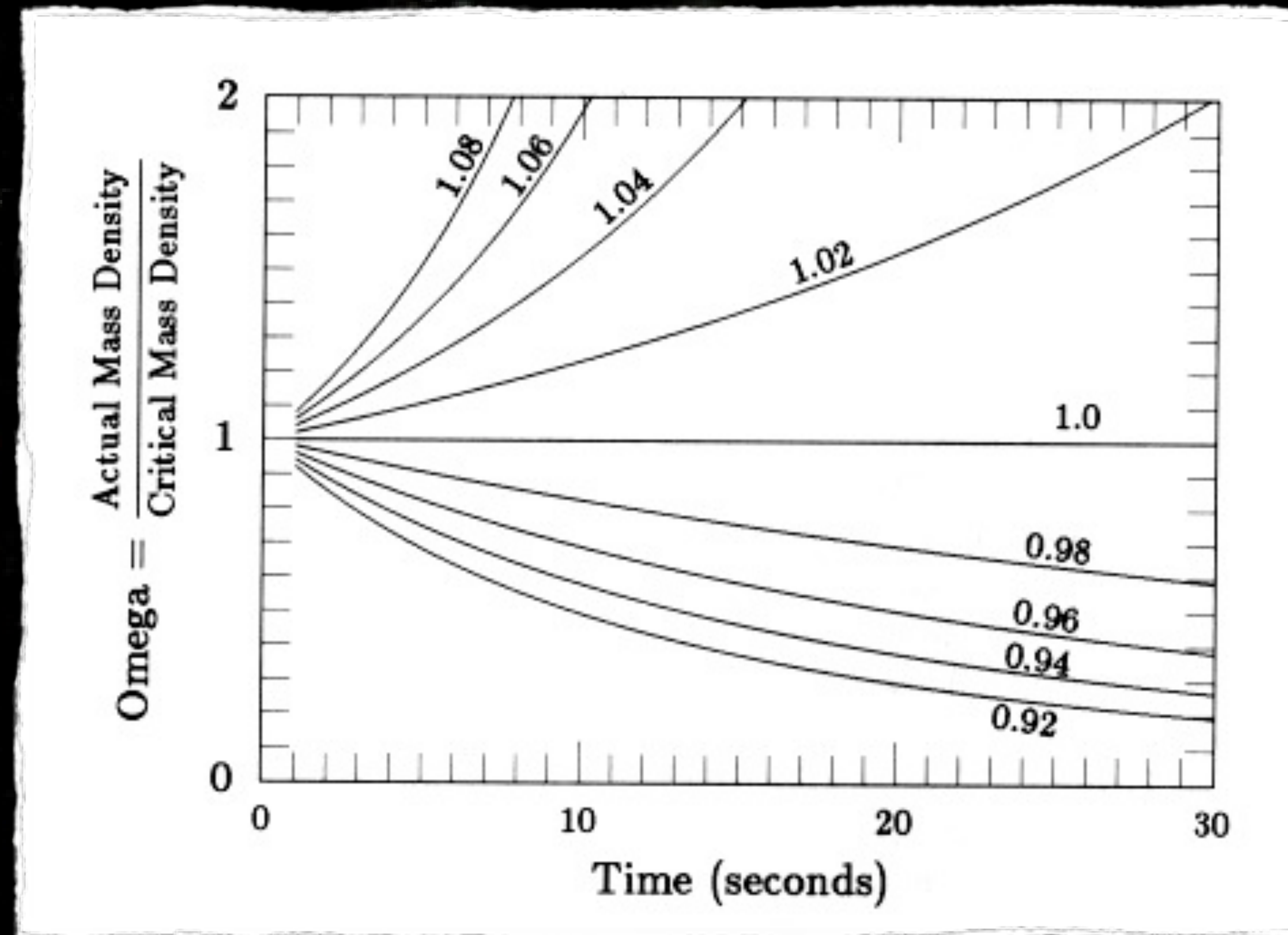

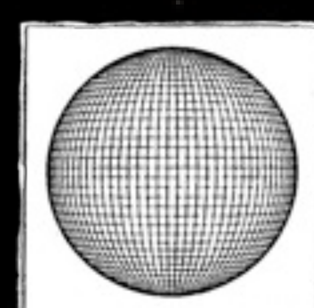
A. Guth

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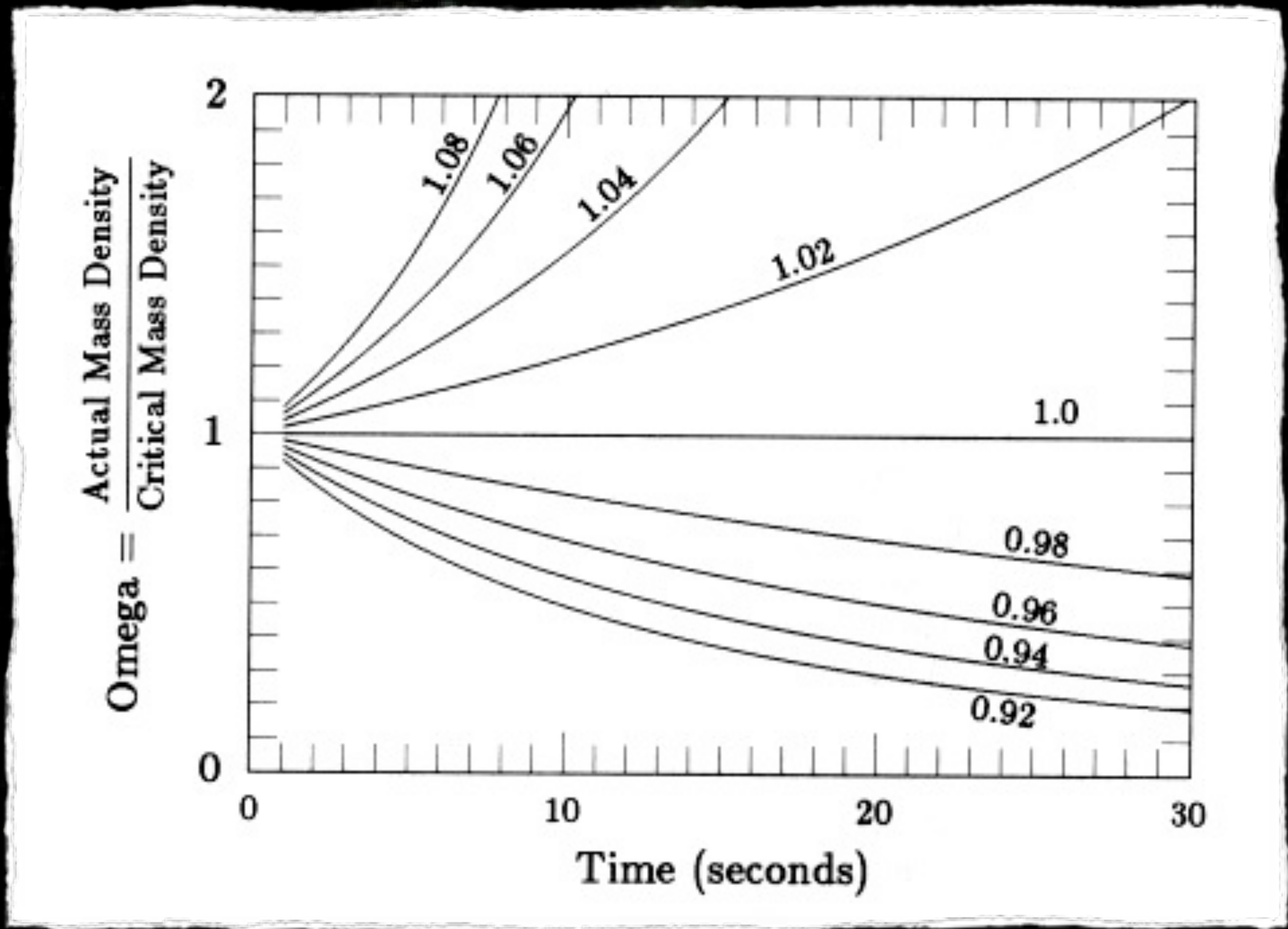
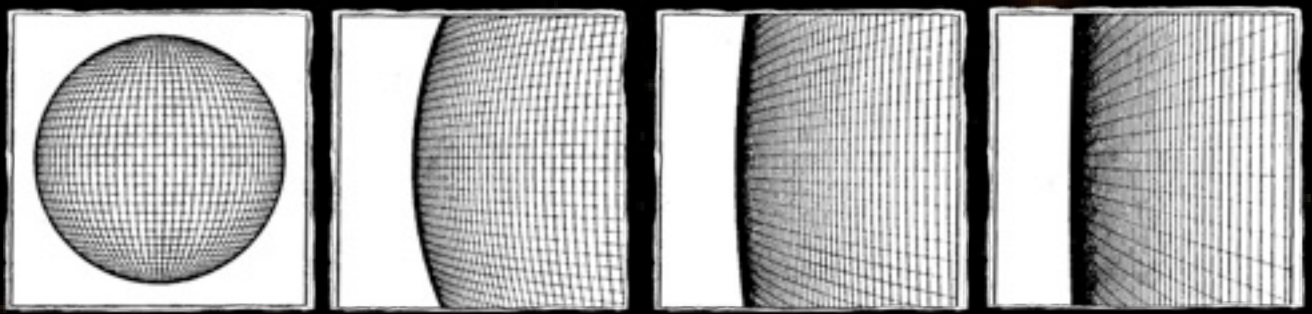


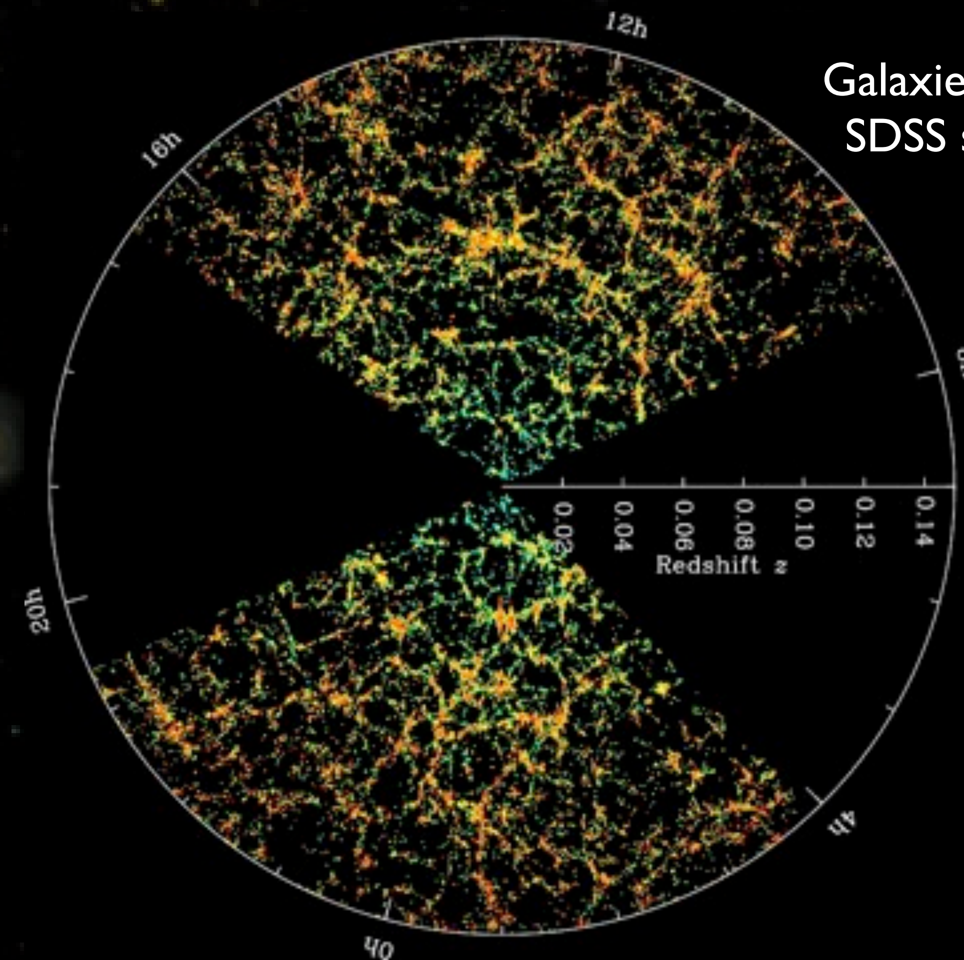


A. Guth

Where do the structures come from

- We observe many dense structures around us (galaxies, clusters, filaments)
- The «simple» Big-Bang does not explain that ... it is completelty smooth
- If you assume the correct seeds (~scale invariant power spectrum) the simulation can reproduce the observations
- Two alternatives :
  - ★ ad-hoc initial conditions
  - ★ a generic process that produces this kind of perturbations : INFLATION !

Galaxies in the SDSS survey



N-Body simulation (V. Springel - MPIA)

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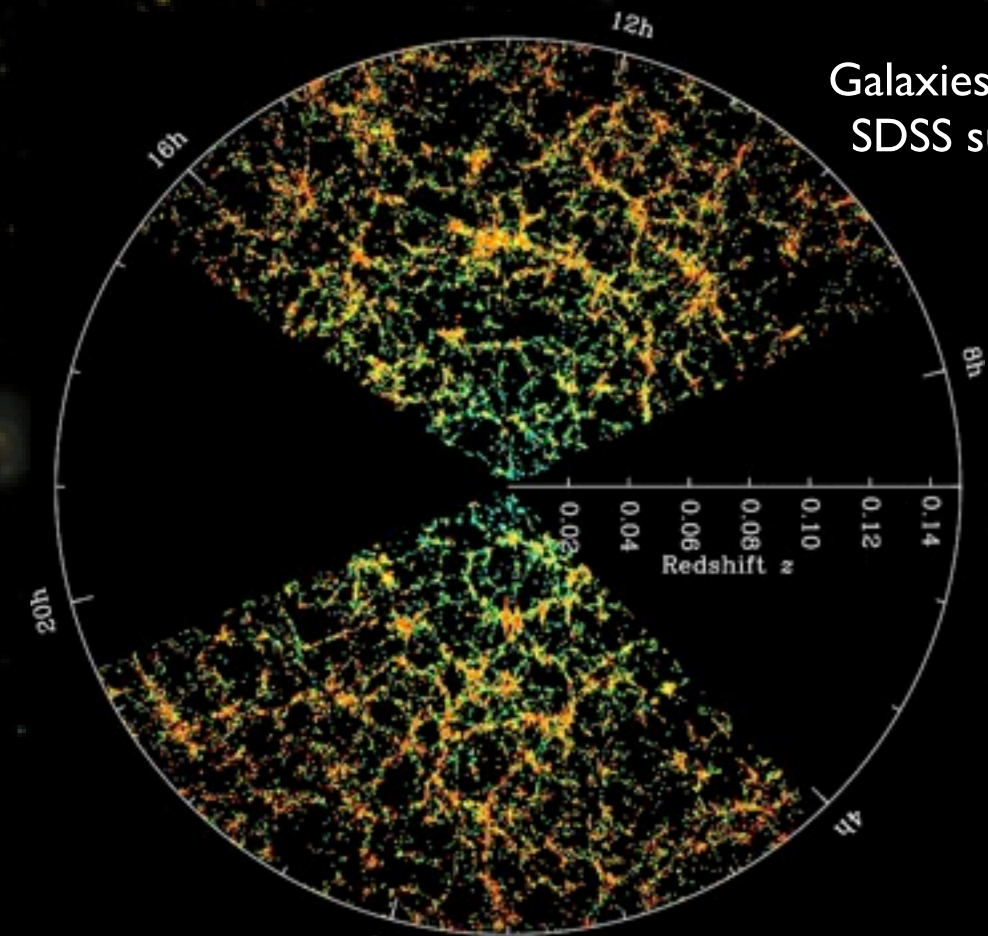
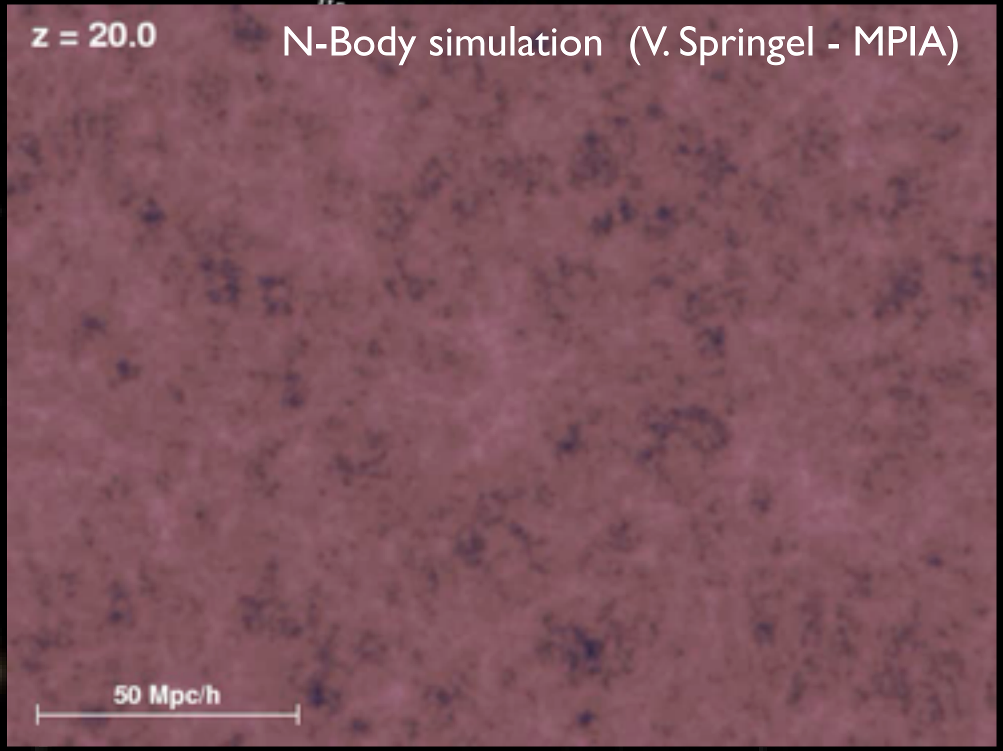




The inflation phase

- A scalar field (the inflaton) dominates the Universe
- It has a «slow-roll» shaped potential

  ⇒ accelerated expansion ⇔ inflation

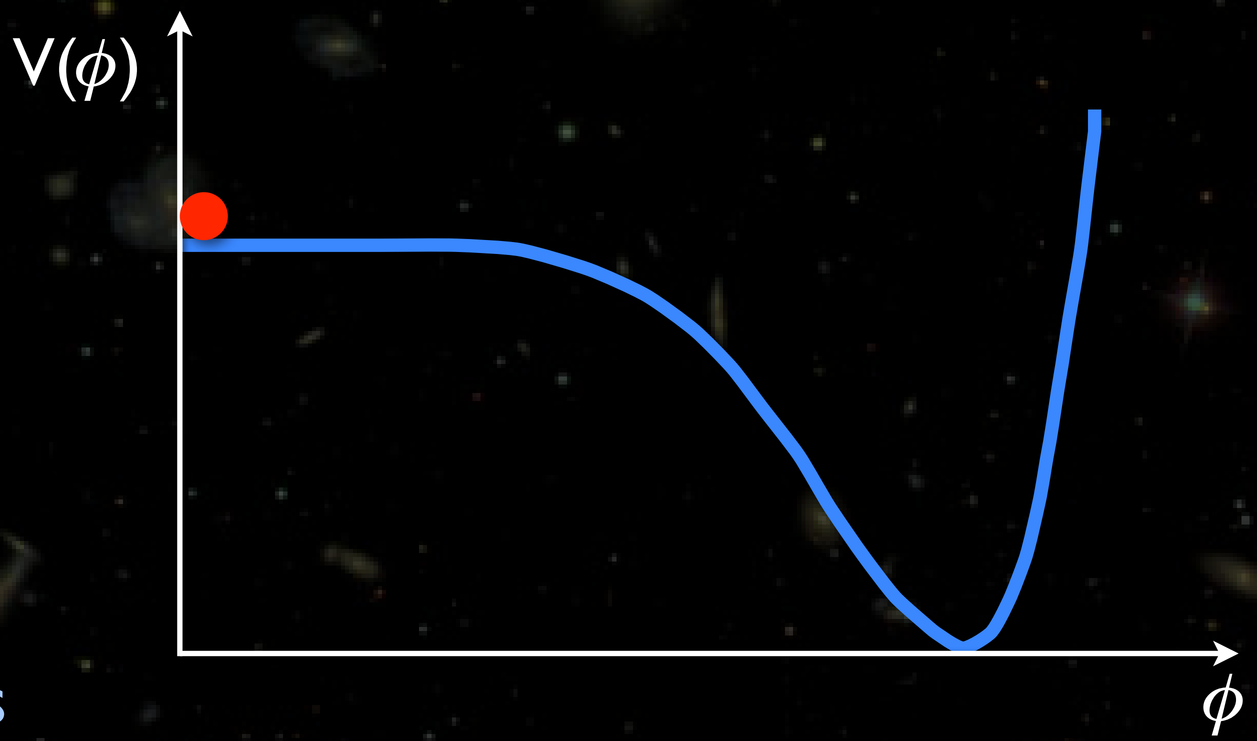
- Inflation stops when the field reaches is minimum potential

  ⇒ Reheating : the inflaton decays into

  particles

- The Universe then follows it usual evolution

Slow-Roll : small slope and small curvature



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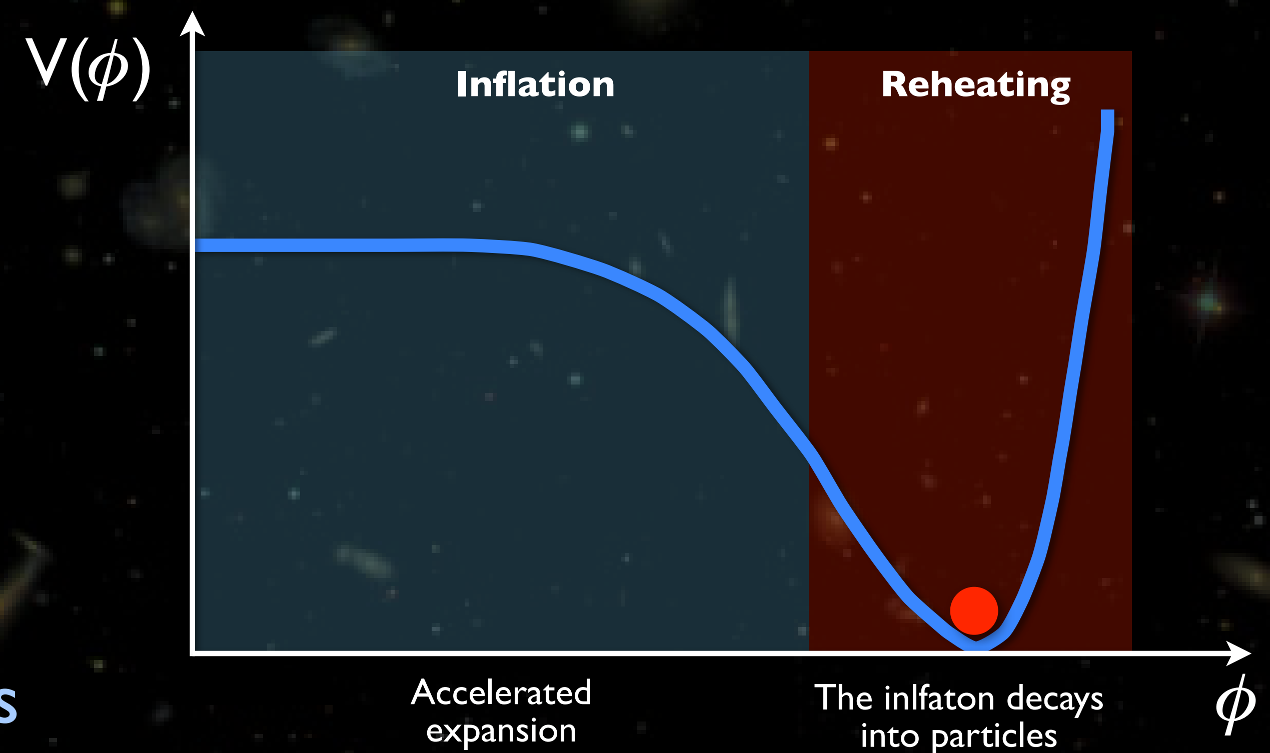

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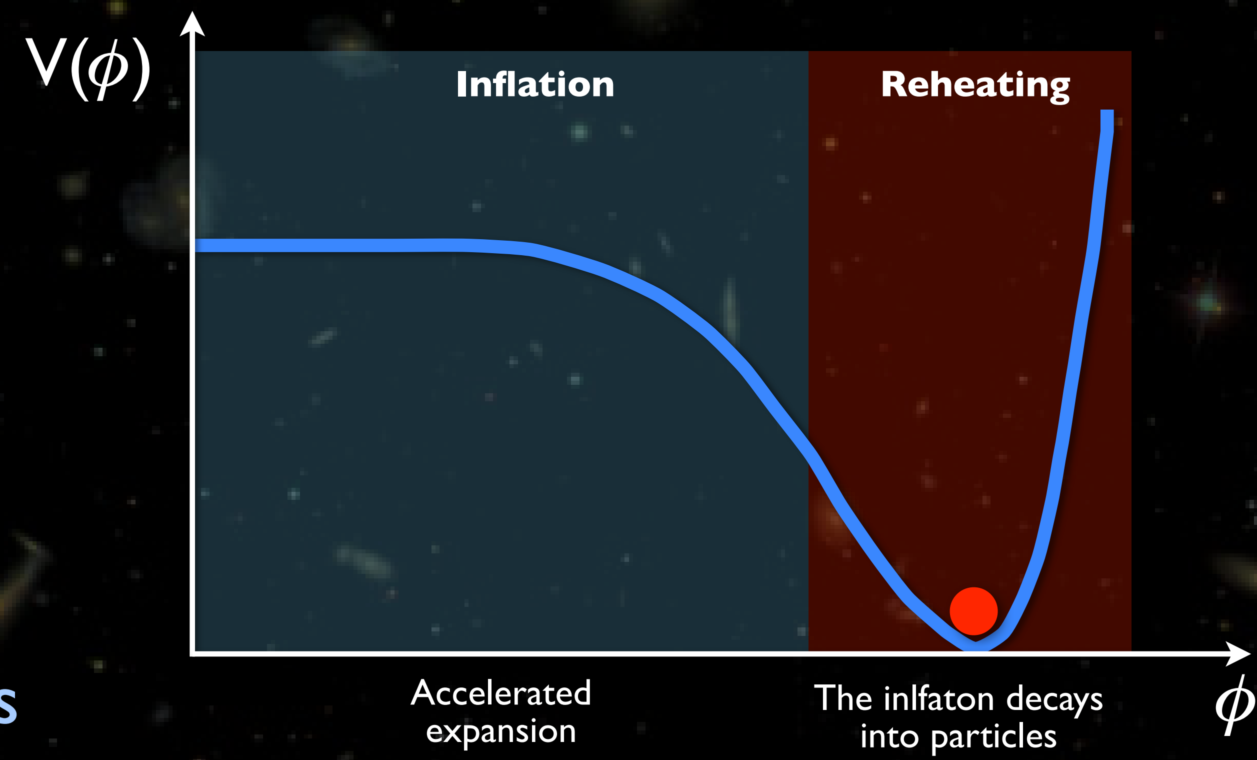


The quantum fluctuations of the potential (and of the metric) are enlarged by inflation and produce macroscopic perturbations whose power spectrum can be calculated

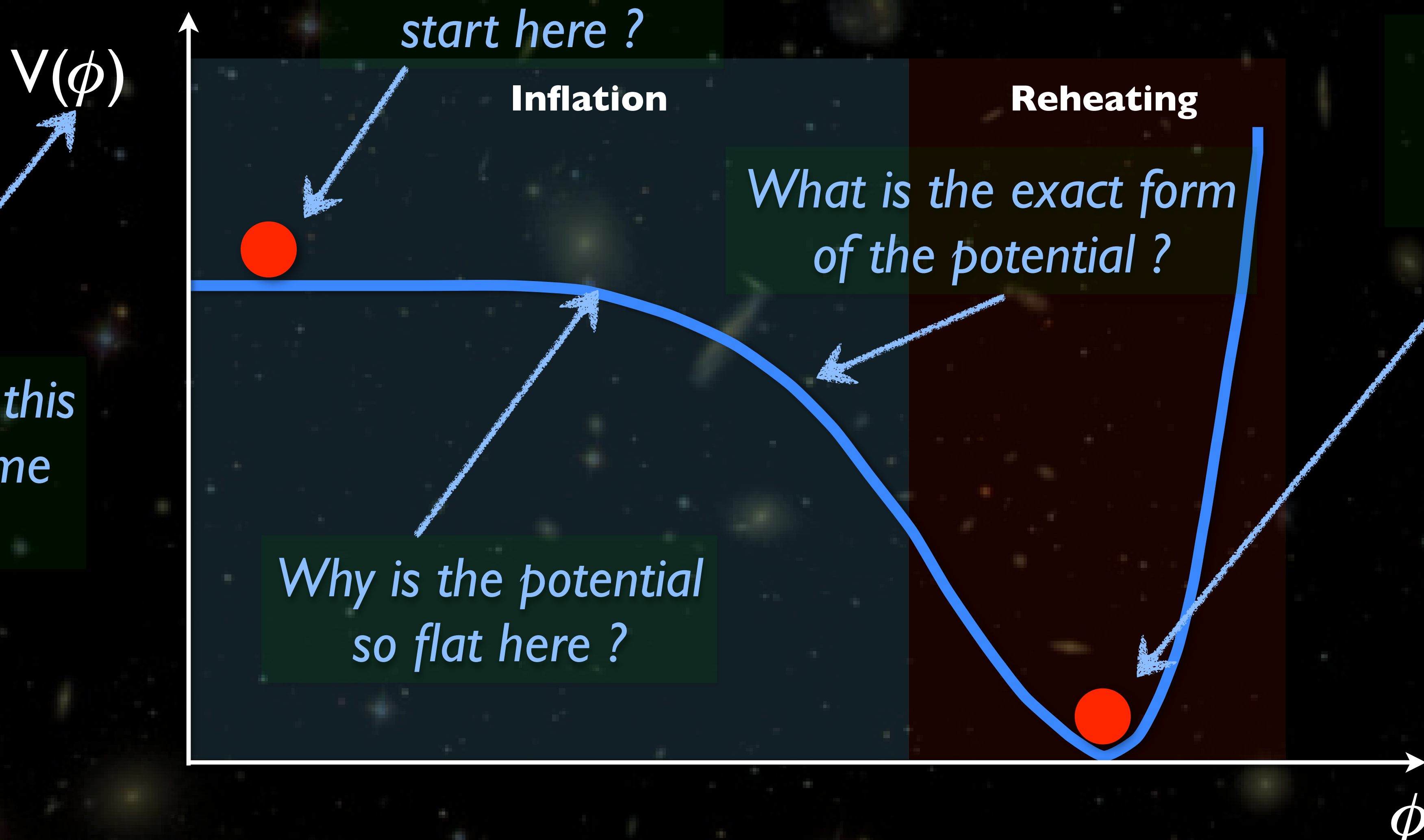
⇒ seeds for structure formation

- **Adiabatic perturbations (from reheating)**
- **Scalar and Tensor modes**
- **Almost scale invariant power spectrum (invariant if inflation was eternal)**
- **Almost gaussian perturbations**

It leaves a number of open questions

Does it make sens to add one item to the long list of unobserved scalar fields ?

Why should we start here ?



Where does this function come from ?

Why is the potential so flat here ?

What is the exact form of the potential ?

How to decay inflaton into particles ?

Is there a single field ? What is that field ?

The CMB (Temperature and Polarization) contains answers to these fundamental questions but for now, all inflation models (and there are many !) are compatible with the data.

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

$$\sigma^T_{scal} \simeq 100\mu\text{K}$$
$$\sigma^E_{scal} \simeq 4\mu\text{K}$$

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

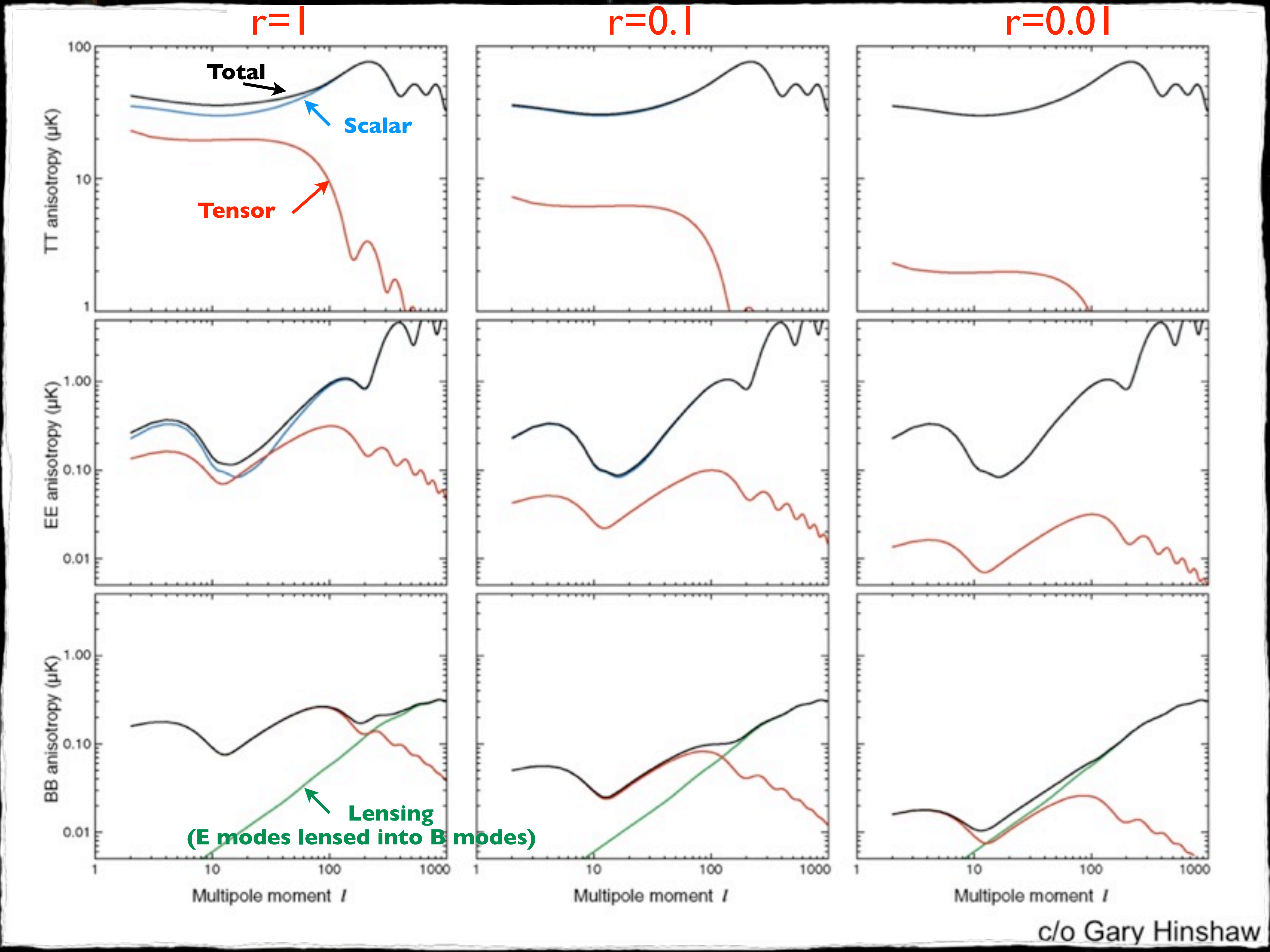
~ ratio between E and B modes

- **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

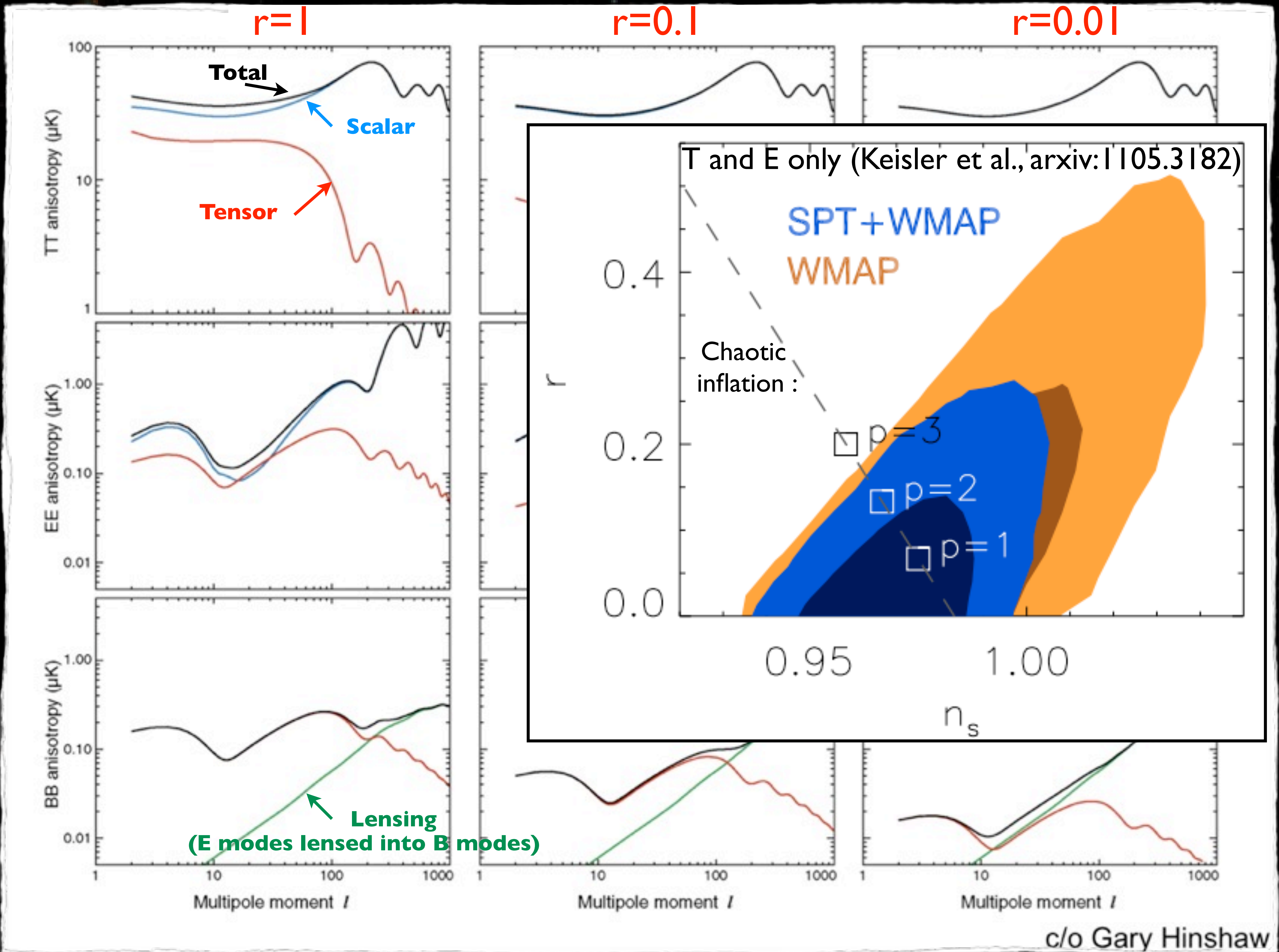
$$\sigma^T_{tens} \leq 30\mu\text{K}$$
$$\sigma^E_{tens} \leq 1\mu\text{K}$$
$$\sigma^B_{tens} \leq 0.3\mu\text{K}$$

$\Rightarrow$ **detecting B-modes is :**

- Direct detection of tensor modes
- «smoking gun» for inflation
- Measurement of its energy scale $V^{1/4} = 1.06 \times 10^{16}\text{GeV} \left(\frac{r_{\text{CMB}}}{0.01}\right)^{1/4}$



Only B modes allow to «directly observe» tensor modes



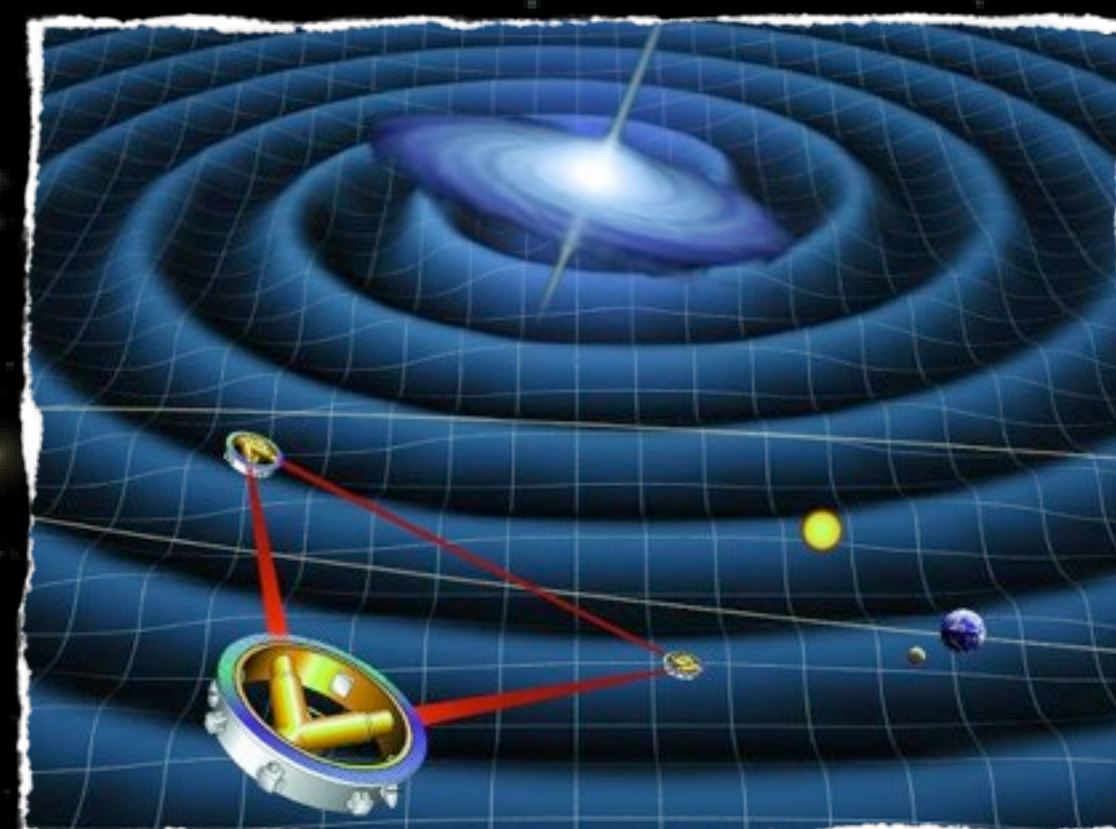
Only B modes allow to «directly observe» tensor modes

Only alternative approach

- Direct detection of gravitational waves

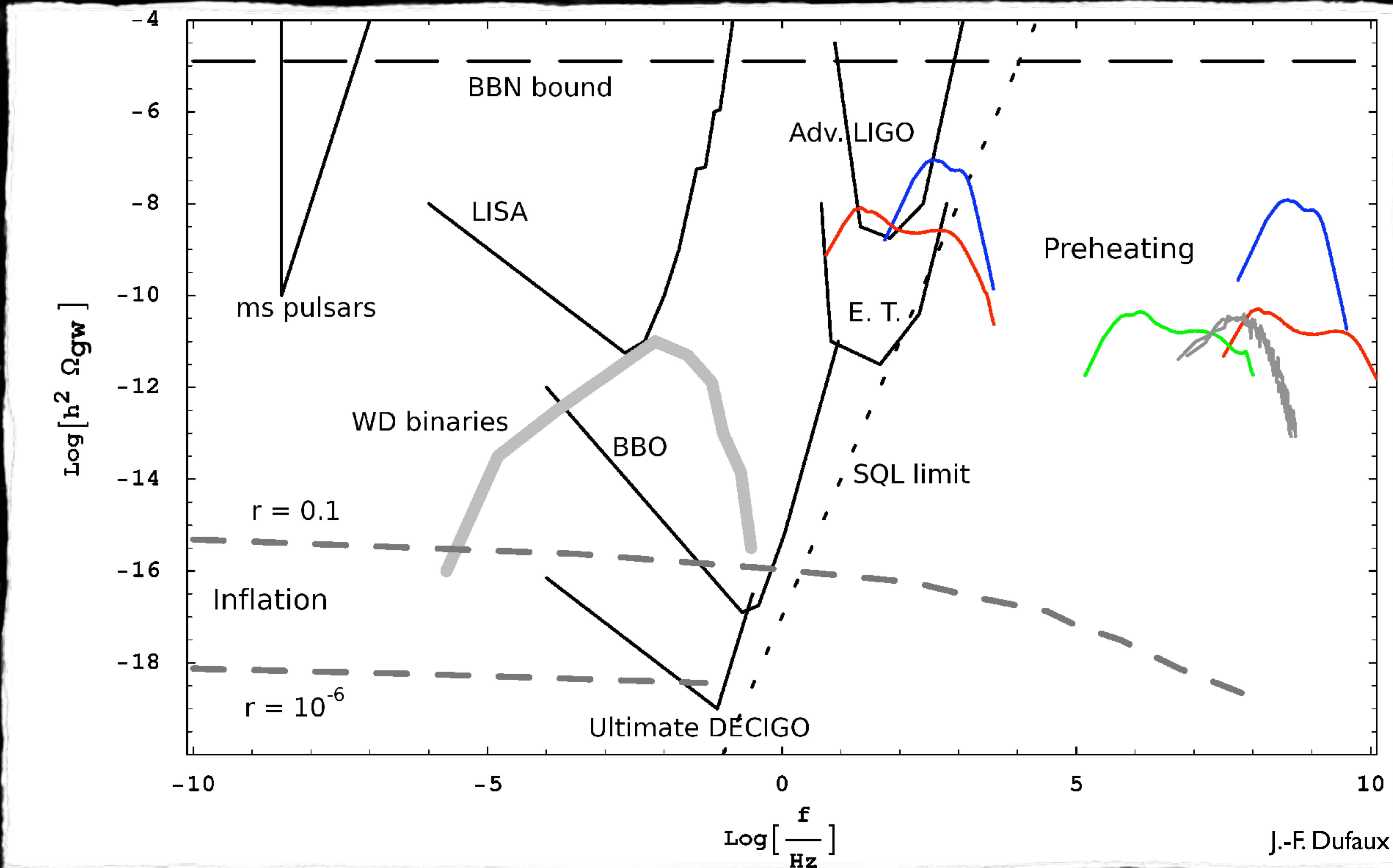
Virgo/Ligo

LISA (~2018)



- Detectors more adapted to violent events, not primordial background

PGW Direct detection perspectives ...



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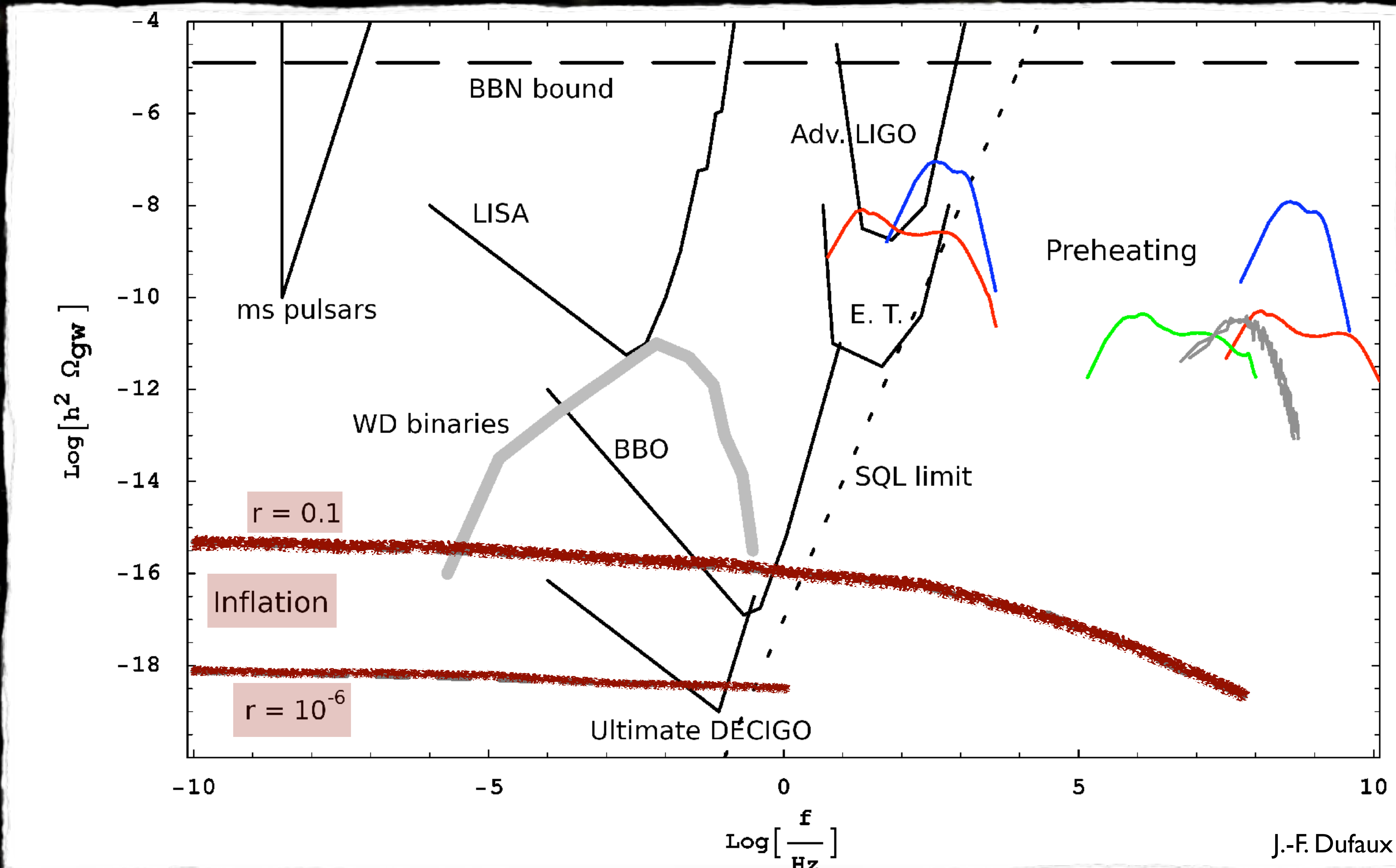

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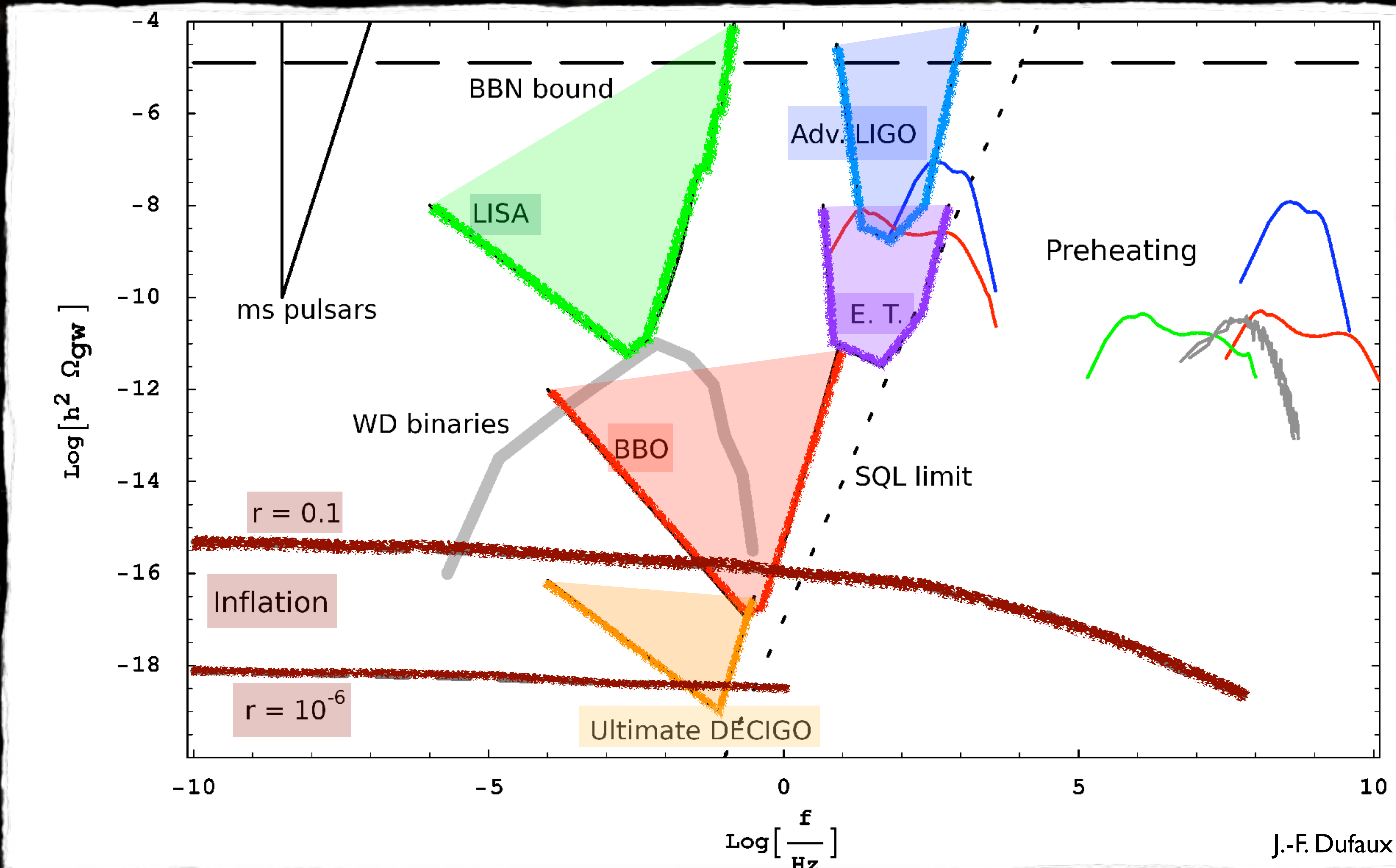


Measuring inflation with CMB B-modes

Four important quantities :

- ★ A_s : known
- ★ n_s : known
- ★ A_t or r : unknown, requires B-modes **detection**
- ★ n_t :unknown, requires B-modes **measurement**

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

- Generic prediction of inflation : $r = -8n_t$

coherence test of inflation

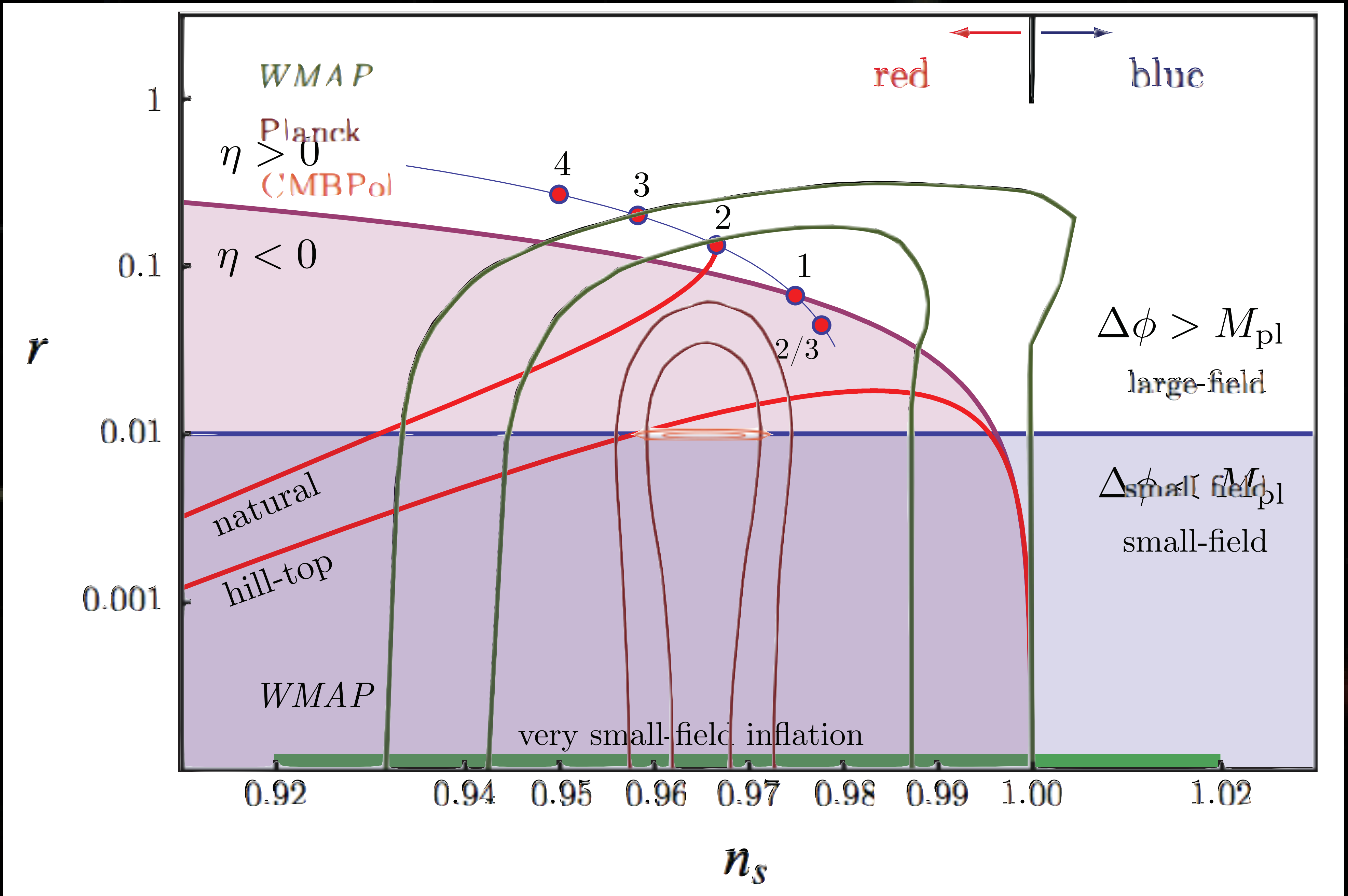
- Direct inflaton potential reconstruction (Taylor expansion):

$$V(\phi) \simeq V|_{\phi_{\mathrm{CMB}}} + V'|_{\phi_{\mathrm{CMB}}}(\phi - \phi_{\mathrm{CMB}}) + \frac{1}{2}V''|_{\phi_{\mathrm{CMB}}}(\phi - \phi_{\mathrm{CMB}})^2 + \frac{1}{3!}V'|_{\phi_{\mathrm{CMB}}}(\phi - \phi_{\mathrm{CMB}})^3$$

- ★ A_s related to V'
- ★ n_s related to V''
- ★ *running de n_s* related to V'''
- ★ A_t related to V

inflaton potential shape recovery !

ex: ns, r and (some) inflationary models



CMBpol Mission Concept Study - Inflation WG report (arXiv:0811-3119)

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 $P(k) \propto k^{n_s - 1}$ ★ SPT+WMAP [arxiv:1105.3182] $n_s = 0.9663 \pm 0.0112$ ➡ Almost scale invariant spectrum	✔
• Gaussianity ★ No convincing evidence for non-gaussianity (despite impressive efforts)	✔
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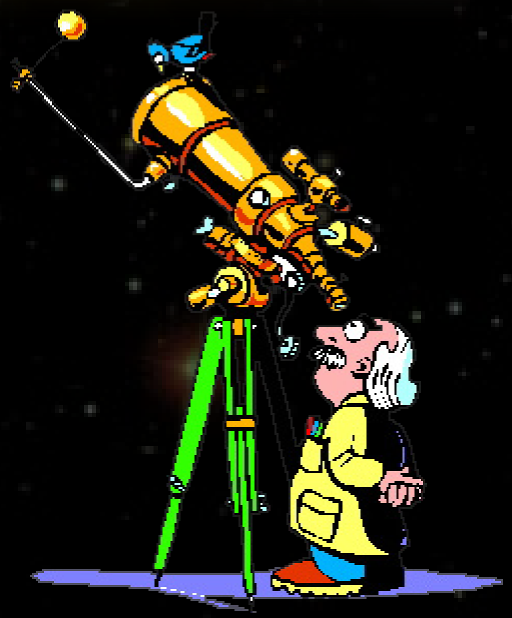
Expected difficulties in the Holy Grail Quest

- 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 (background limited)
  - ★ 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:
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- Can these two nice devices be combined ?

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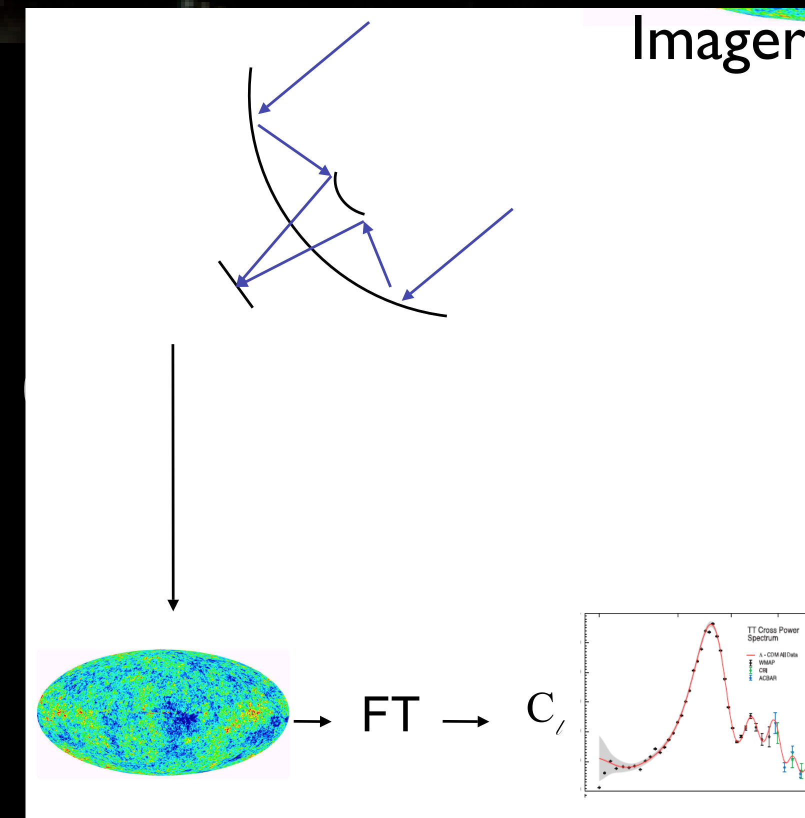

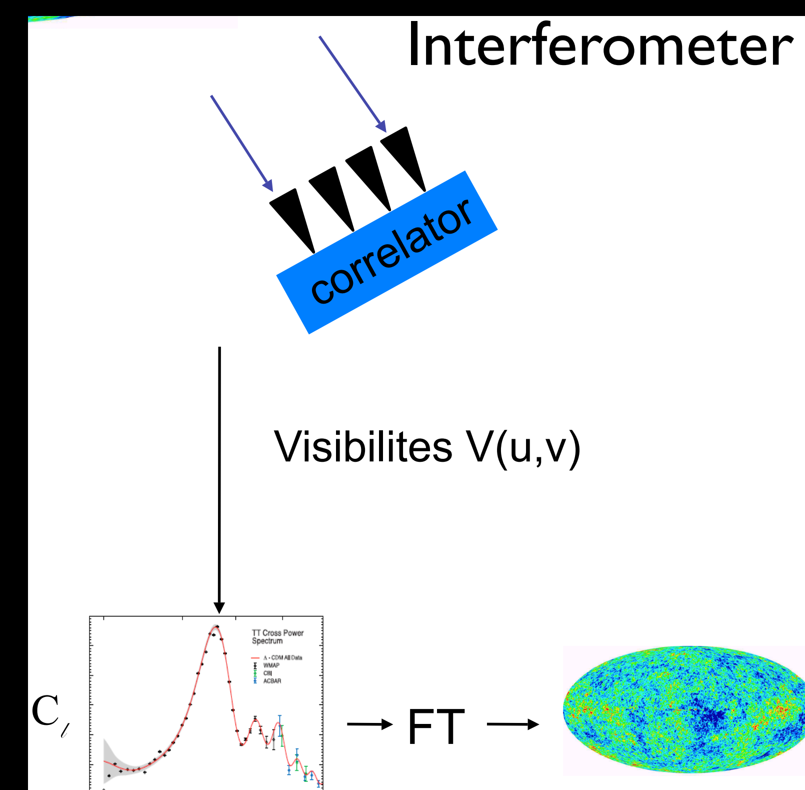

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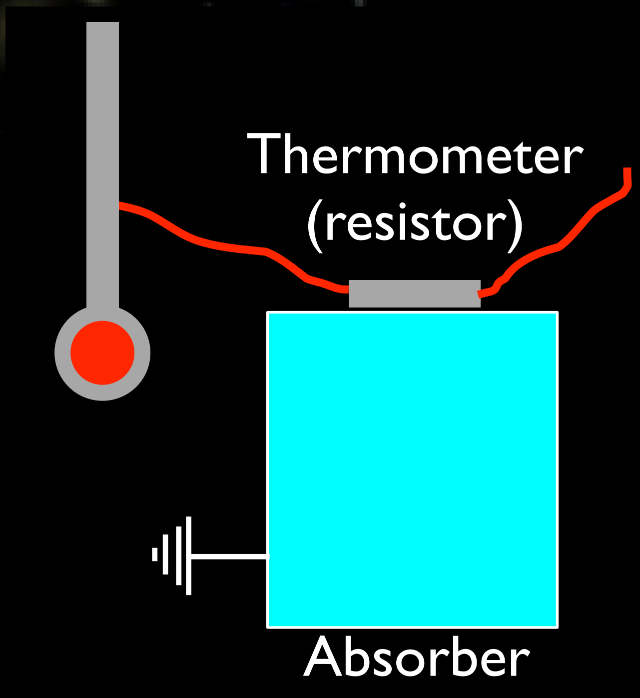

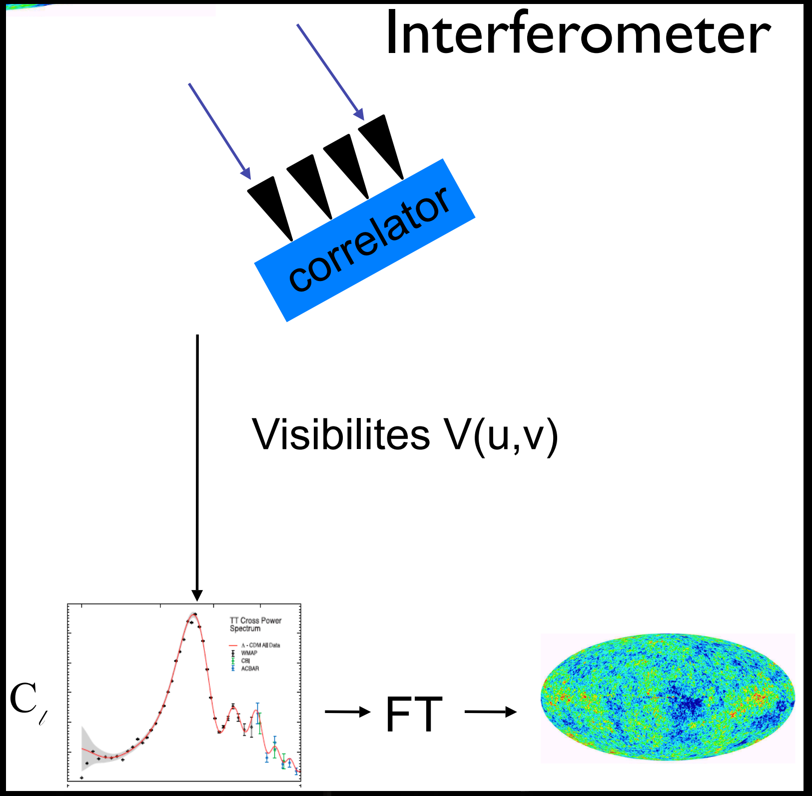

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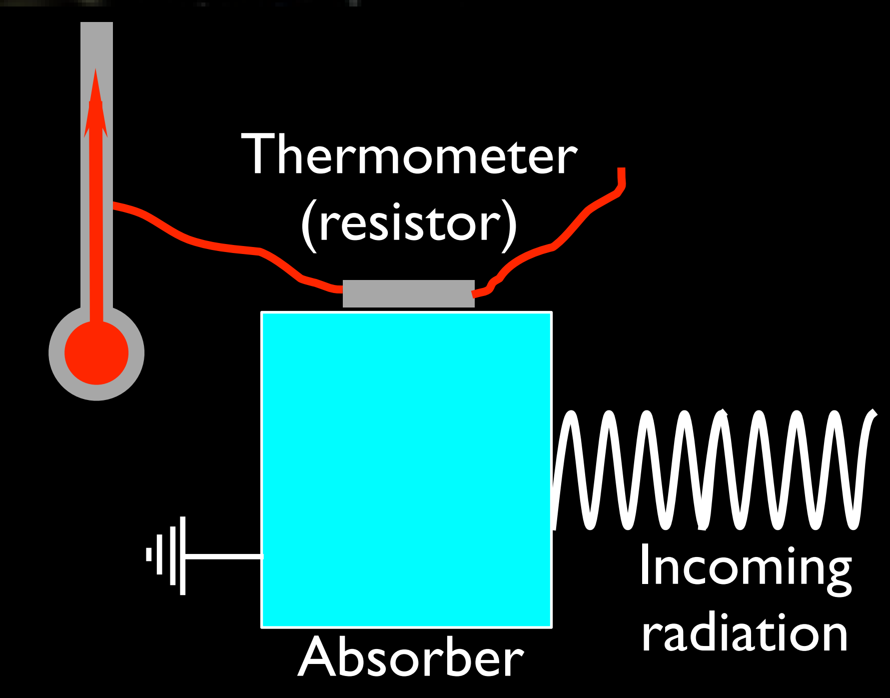

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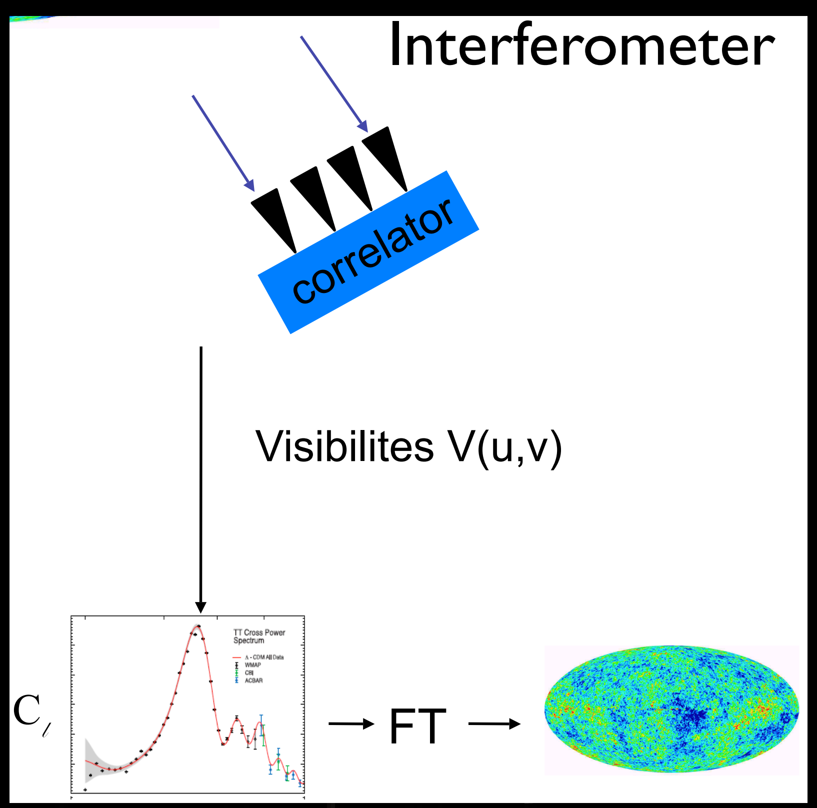

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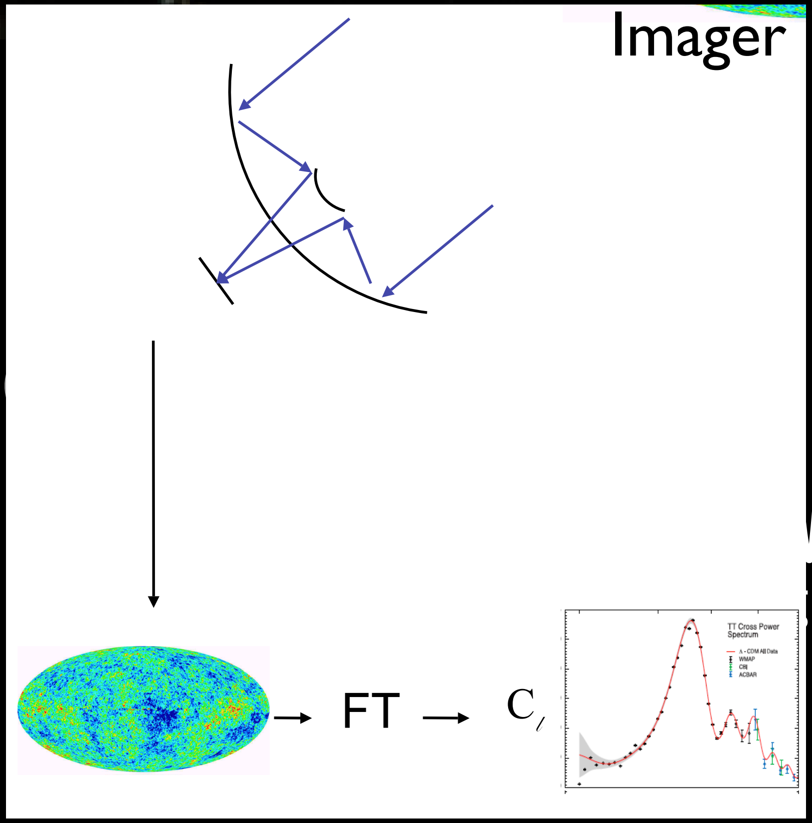

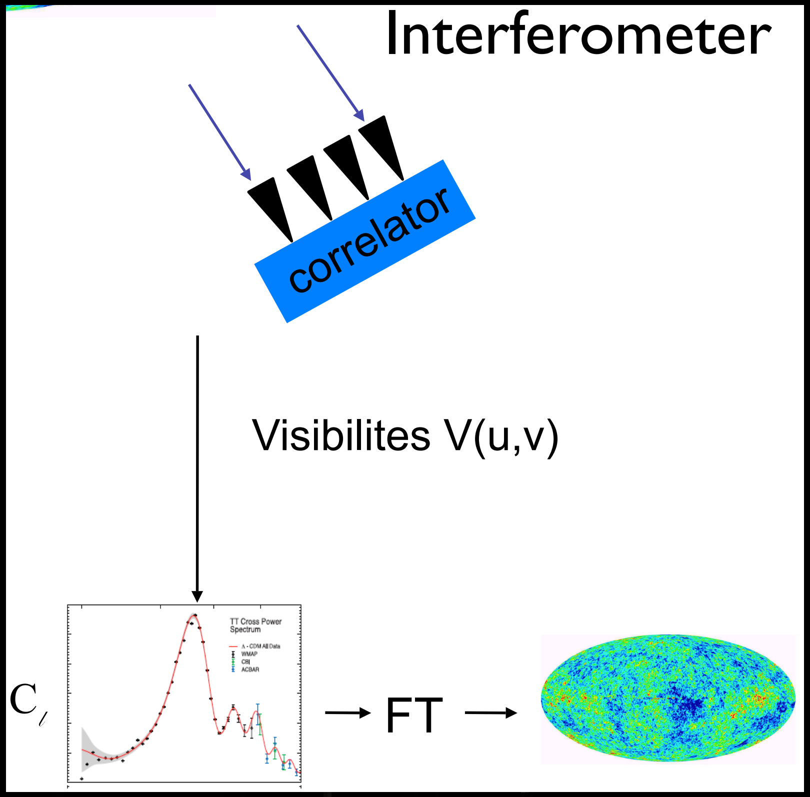

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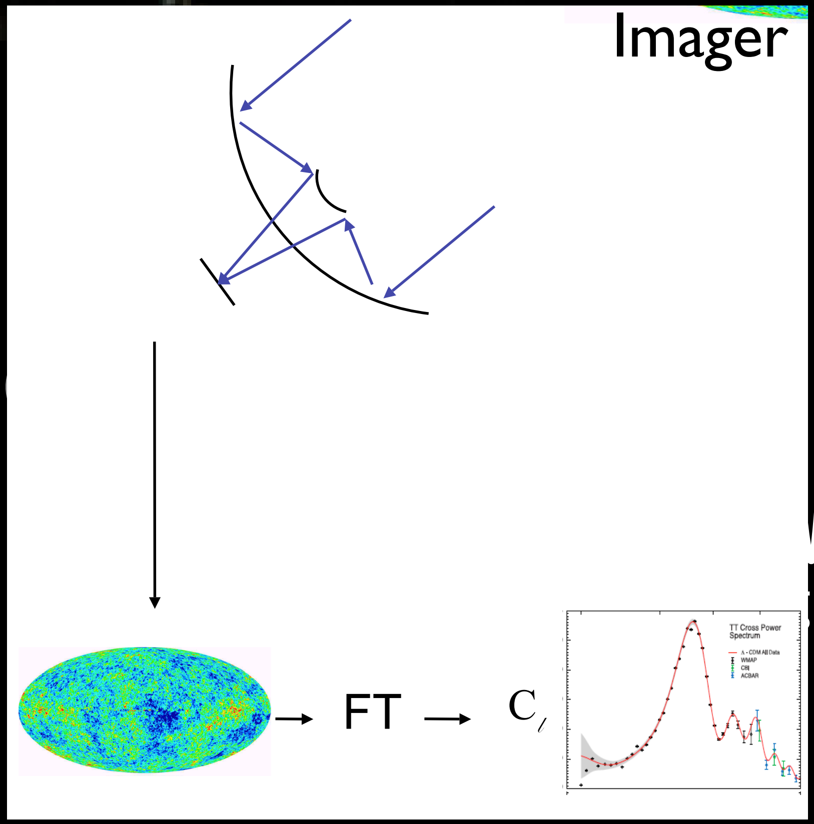

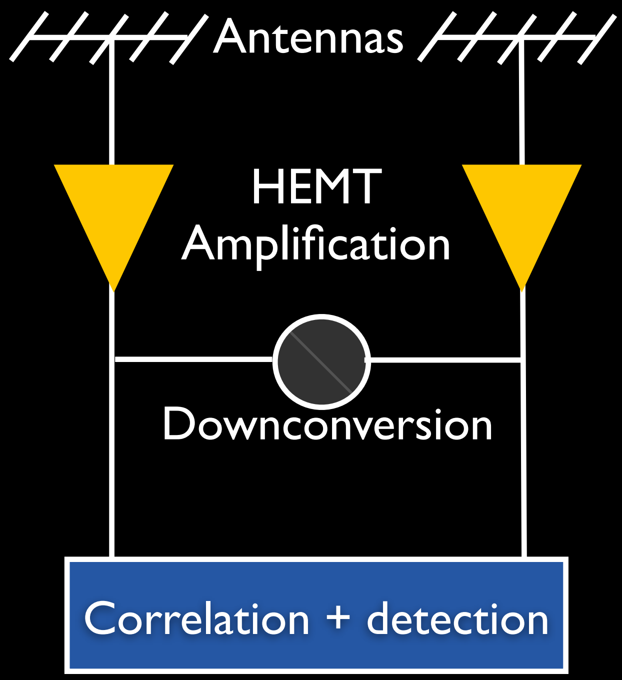

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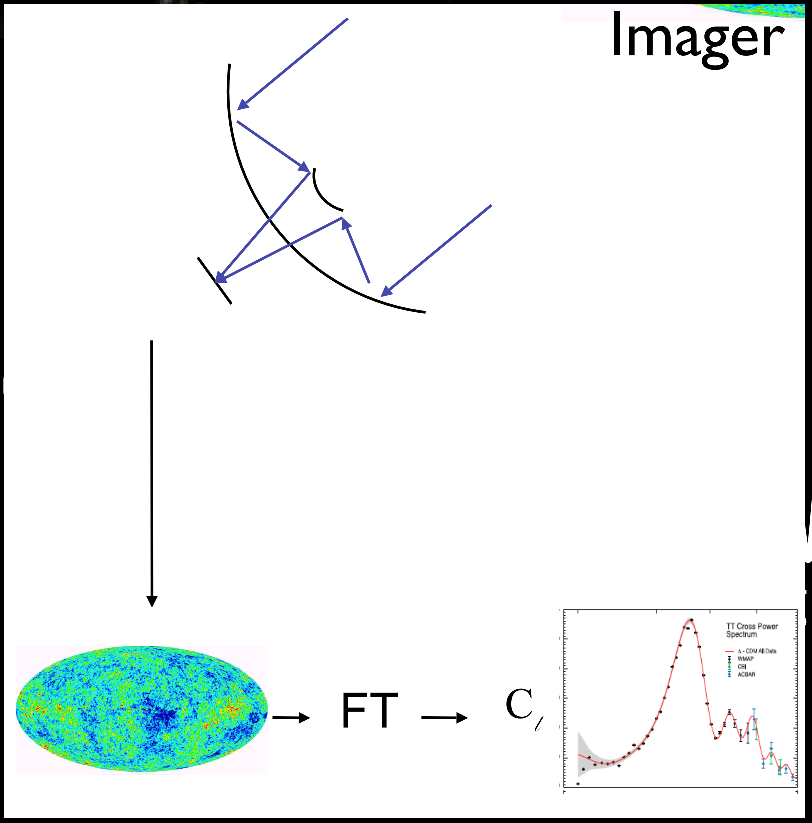

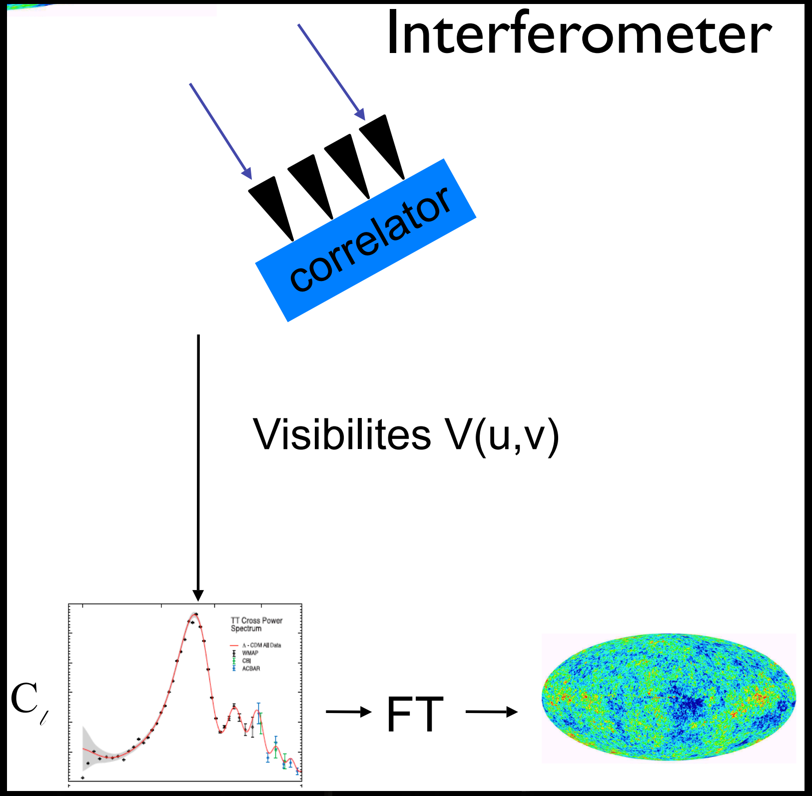

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Good sensitivity

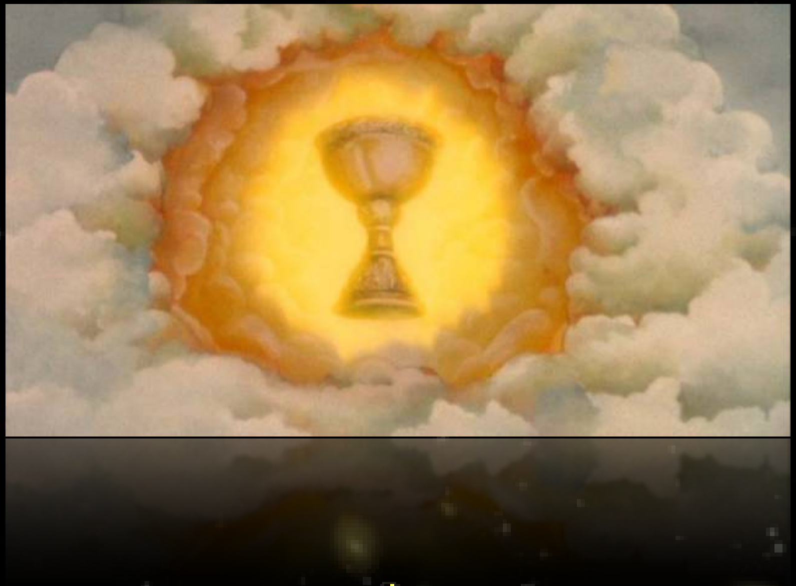
Good control of systematics

- Can these two nice devices be combined ?

➡ Bolometric Interferometry !

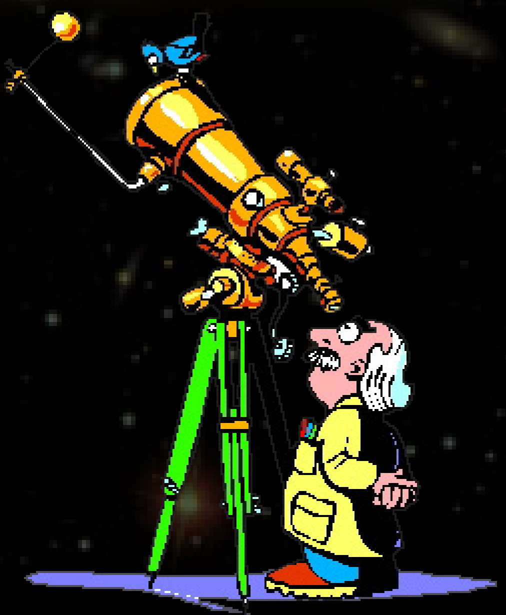
Both

Experimental projects for B mode search



- Planck !
  - ★ Possible detection of r=0.03 at 95% C.L. (28 months)
  - ★ Complete sky ⇒ reionization peak ($\ell \sim 7$)

- Suborbital
  - ➡ (USA - Europe)
  - ★ Imagers : BICEP, EBEX, SPIDER, QUIET, POLAR BEAR
  - ★ Heterodyne interferometers: CHIPS?
  - ★ Bolometric Interferometers: QUBIC



- Future satellite missions (not yet ...)
  - ★ CMBPol
  - ★ BPOL

NB: almost only imagers except QUBIC

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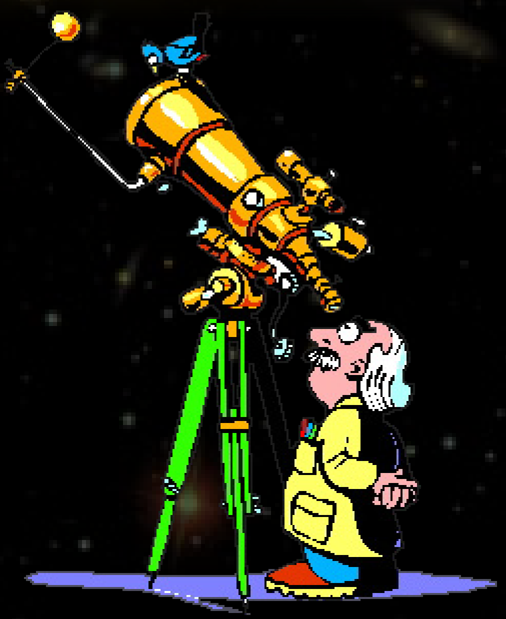

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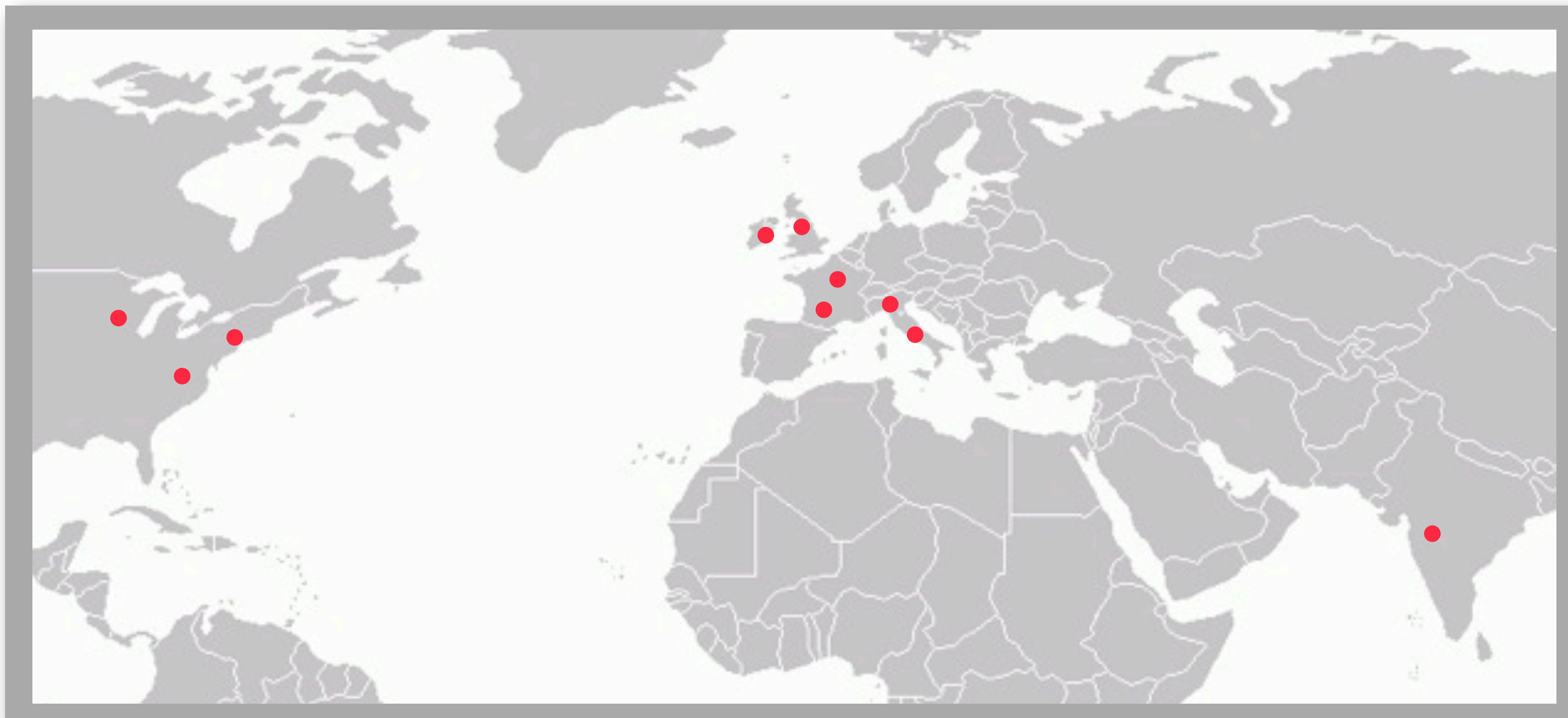
The QUBIC collaboration



APC Paris, France
IAS Orsay, France
CSNSM Orsay, France
CESR Toulouse, France
IUCAA, Pune, India
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

Interferometry in a nutshell

★ Baseline: $||\vec{u}|| = \frac{D}{\lambda}$

★ Primary beam: $B(\vec{x})$

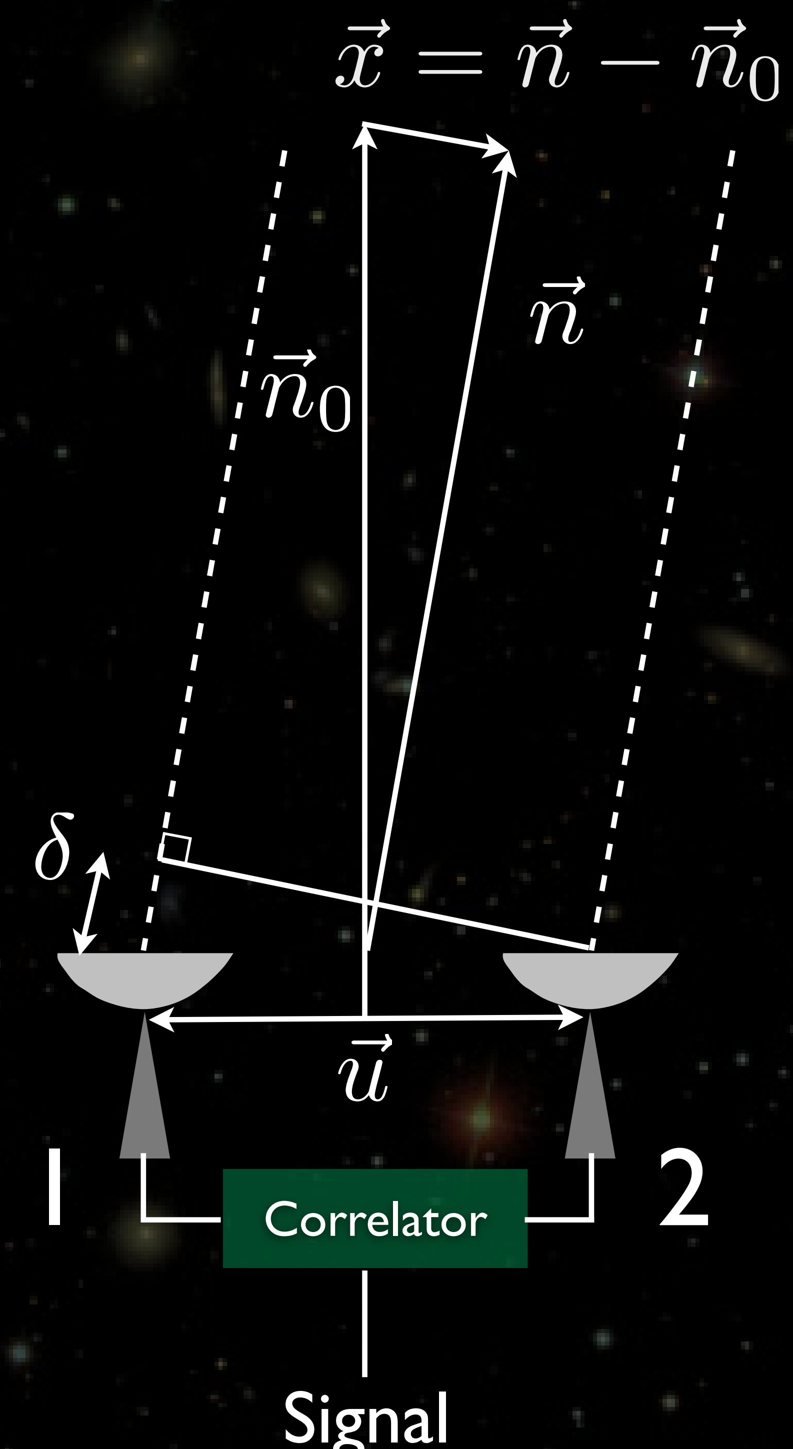
★ Correlator signal : $S(\vec{u}) = \int E_1(\vec{n}) E_2^\star(\vec{n}) B^2(\vec{n}) \mathrm{d}\vec{n}$

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

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

★ Correlator signal (visibilities) :

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



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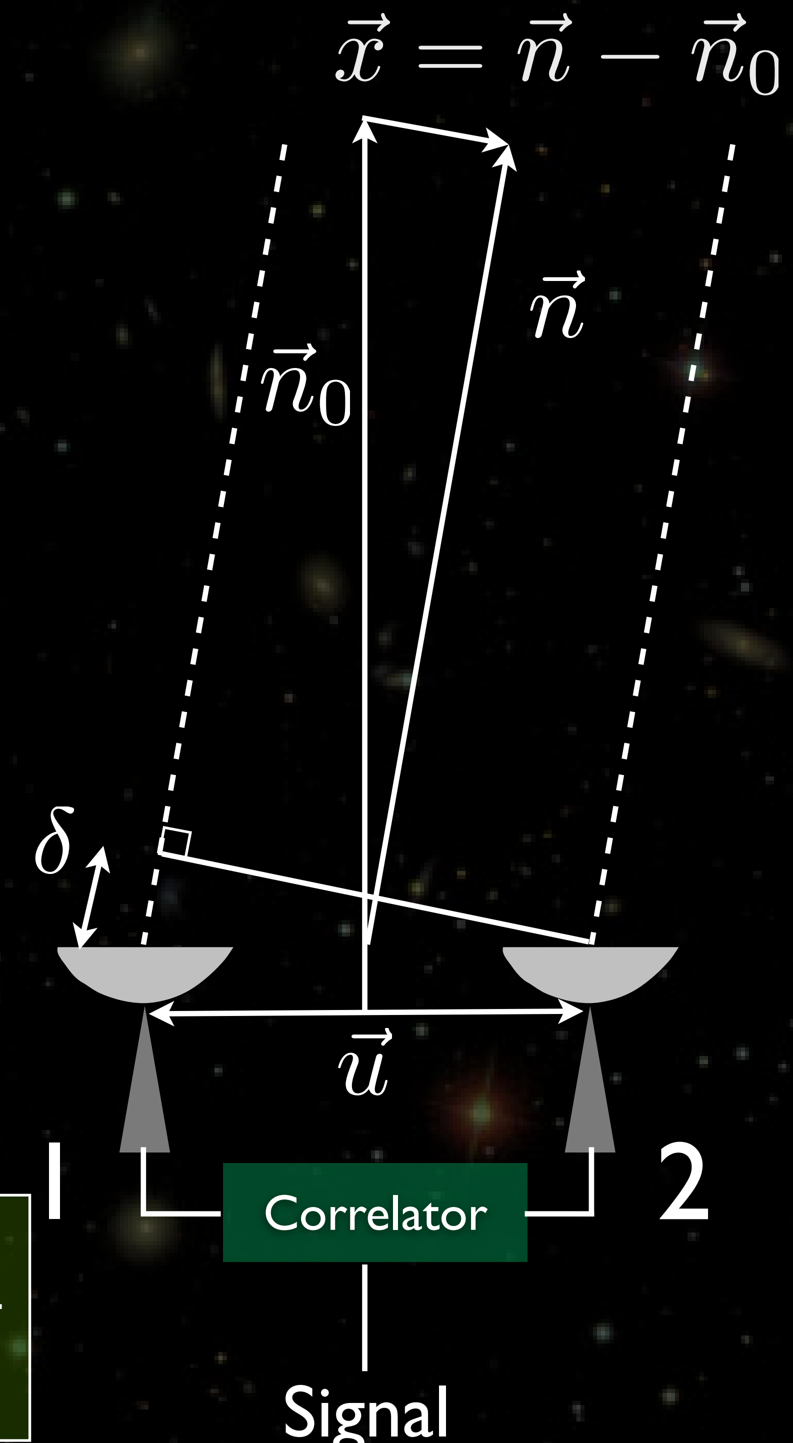
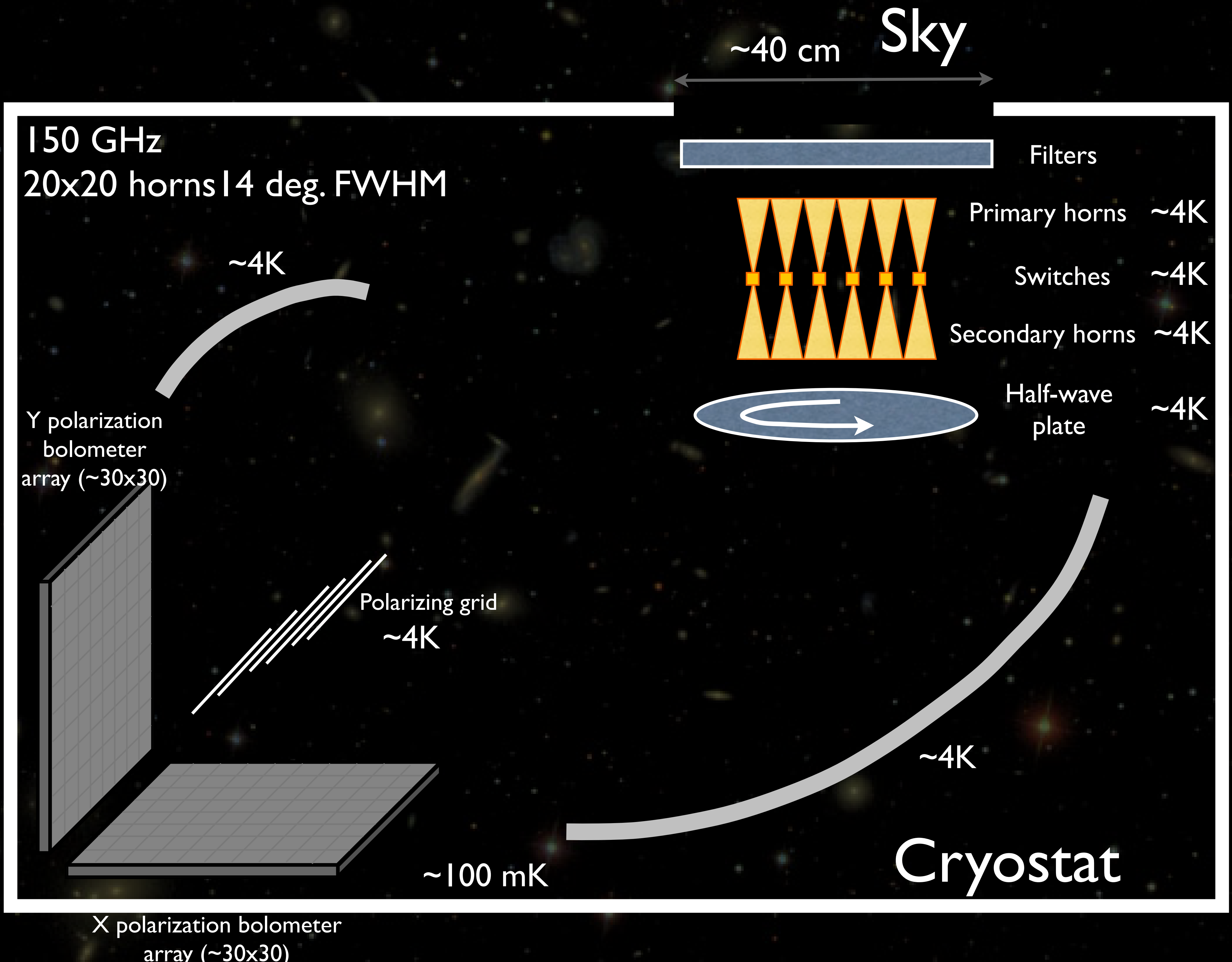


An interferometer measures the Fourier Transform of the observed sky patch at modes : $\ell = 2\pi\,||\vec{u}||$

QUBIC design



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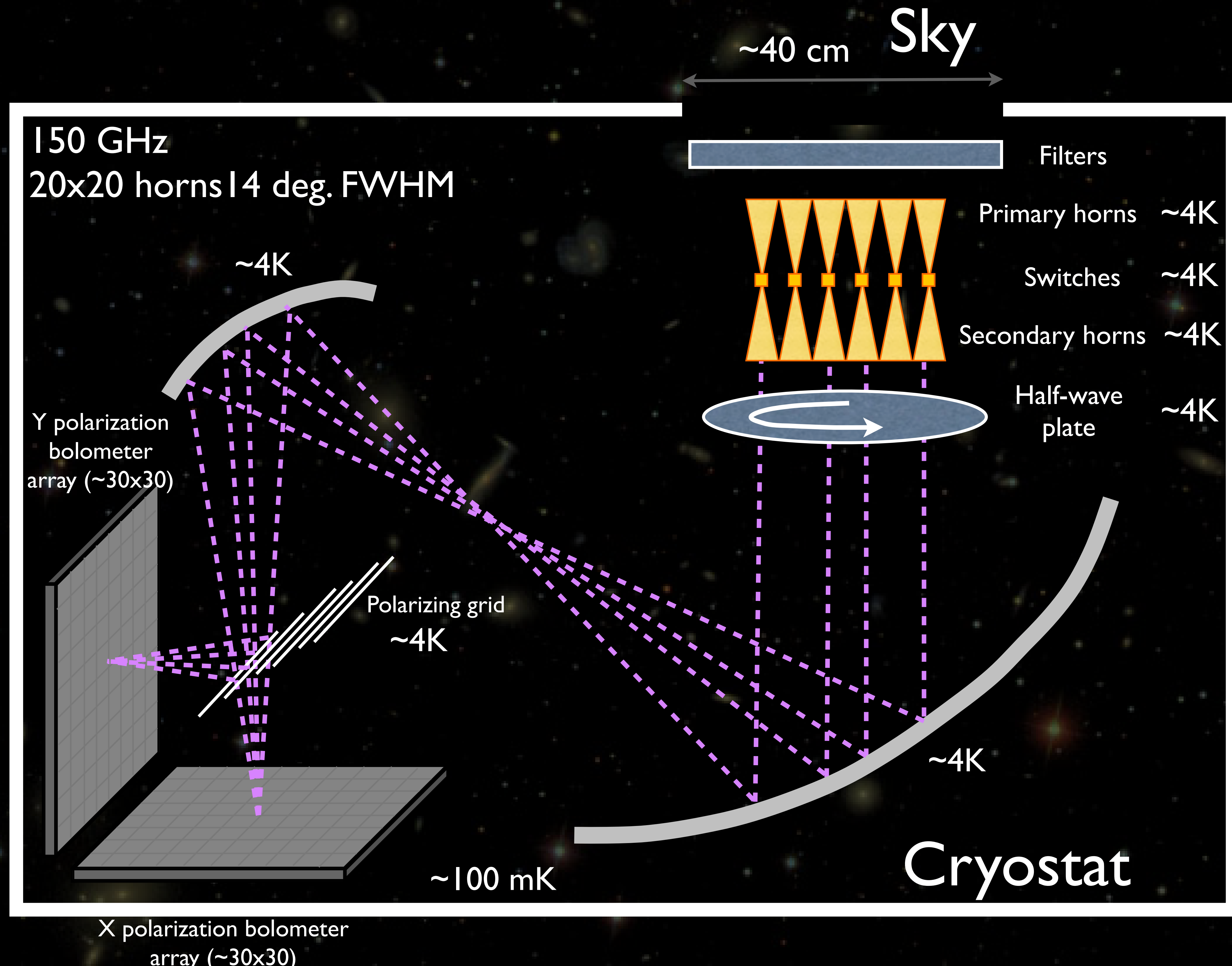

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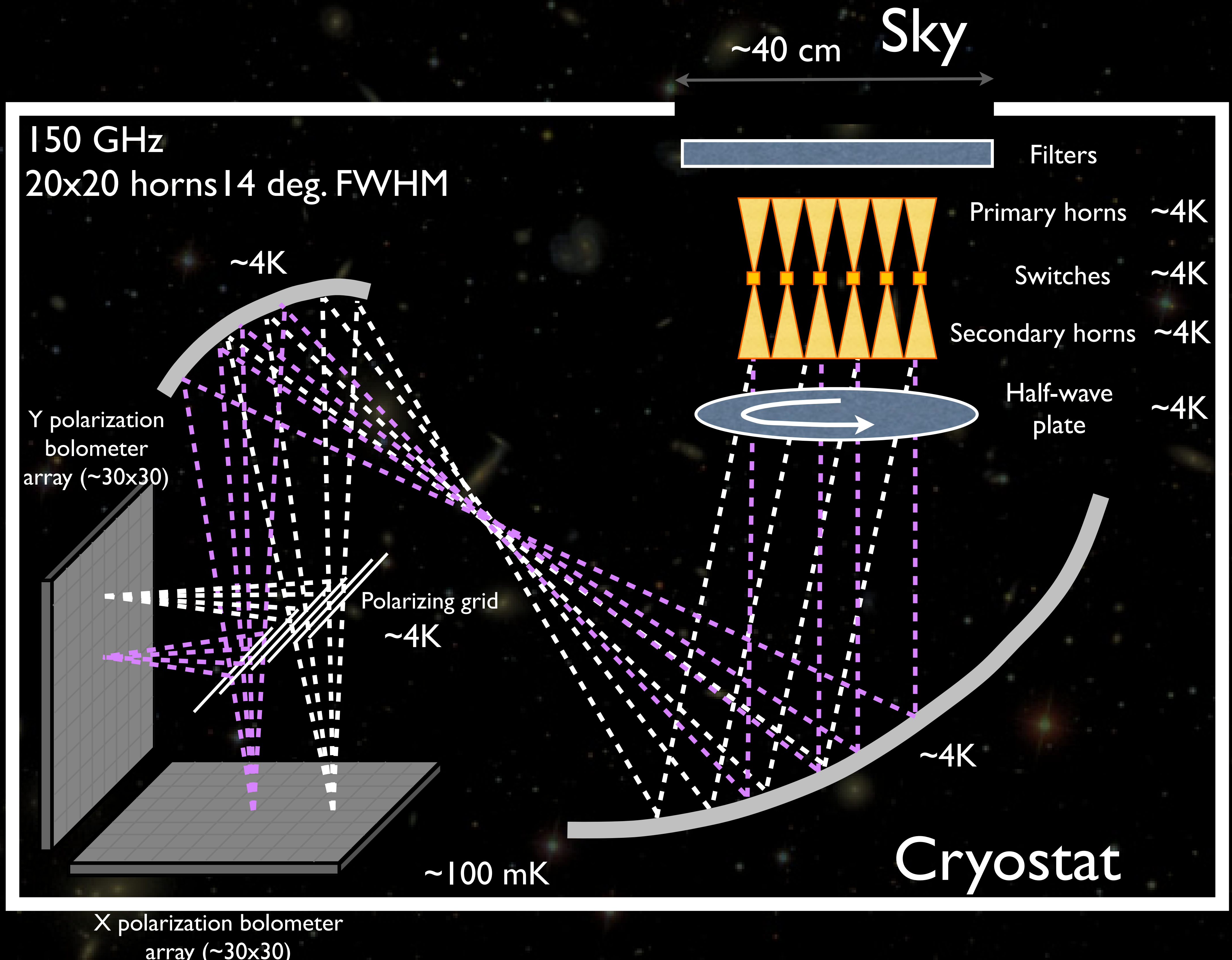

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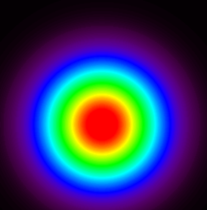
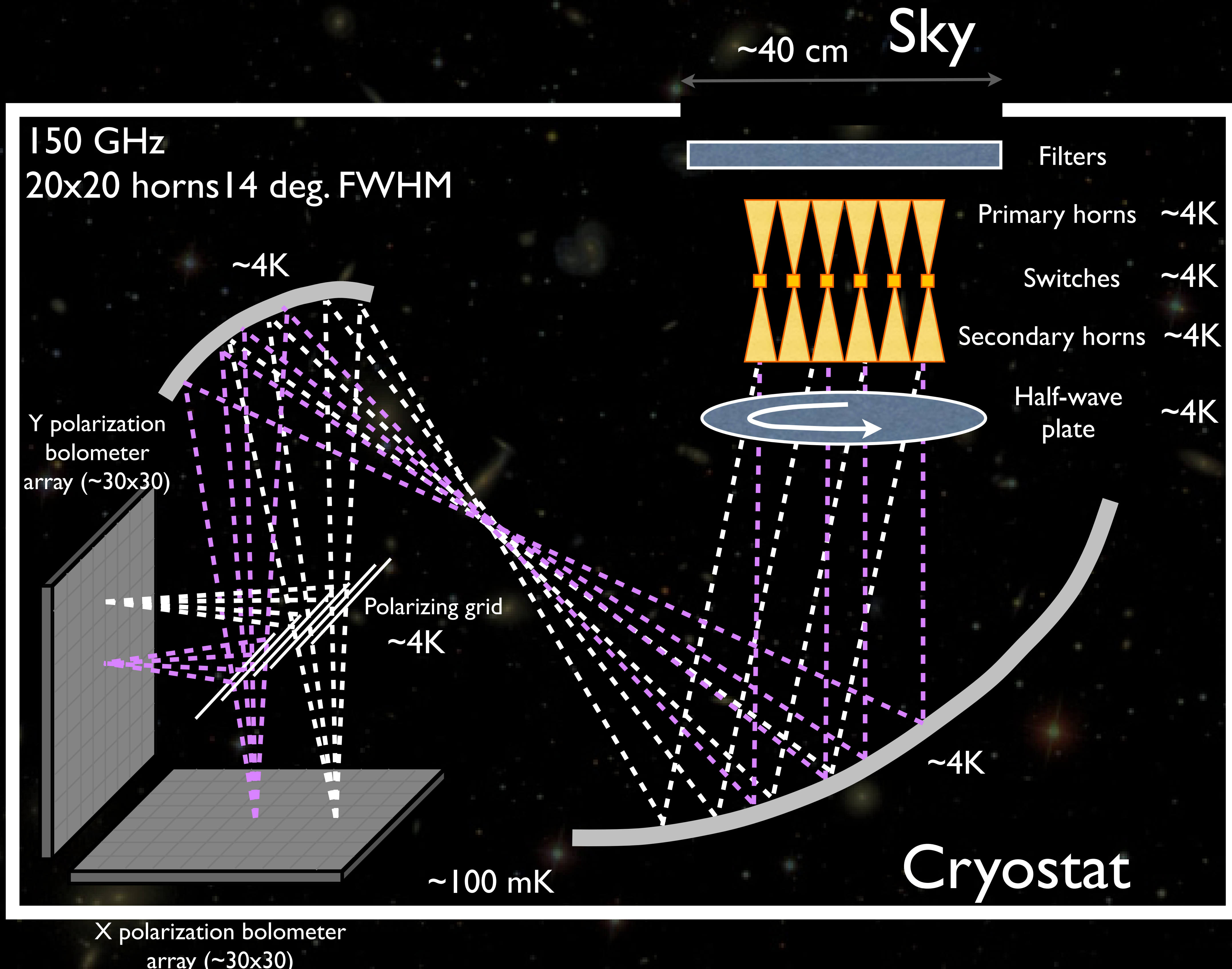
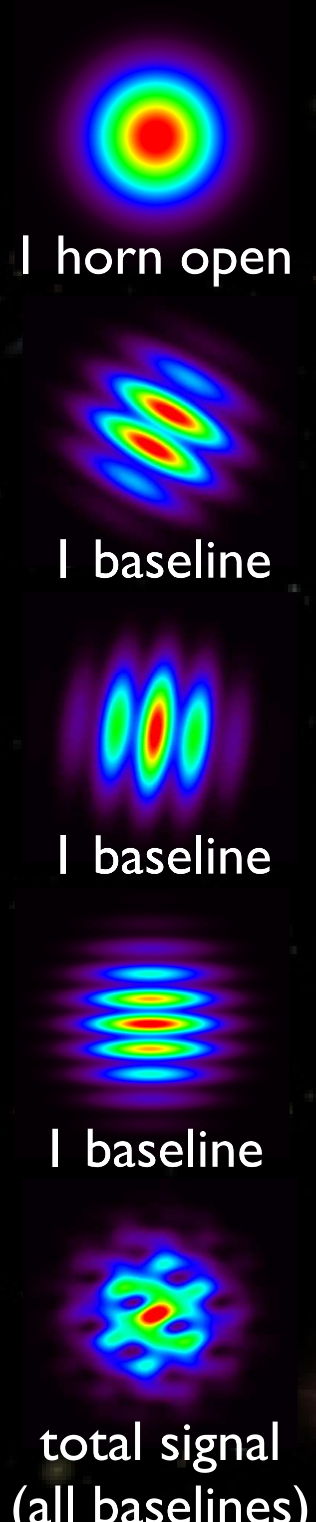
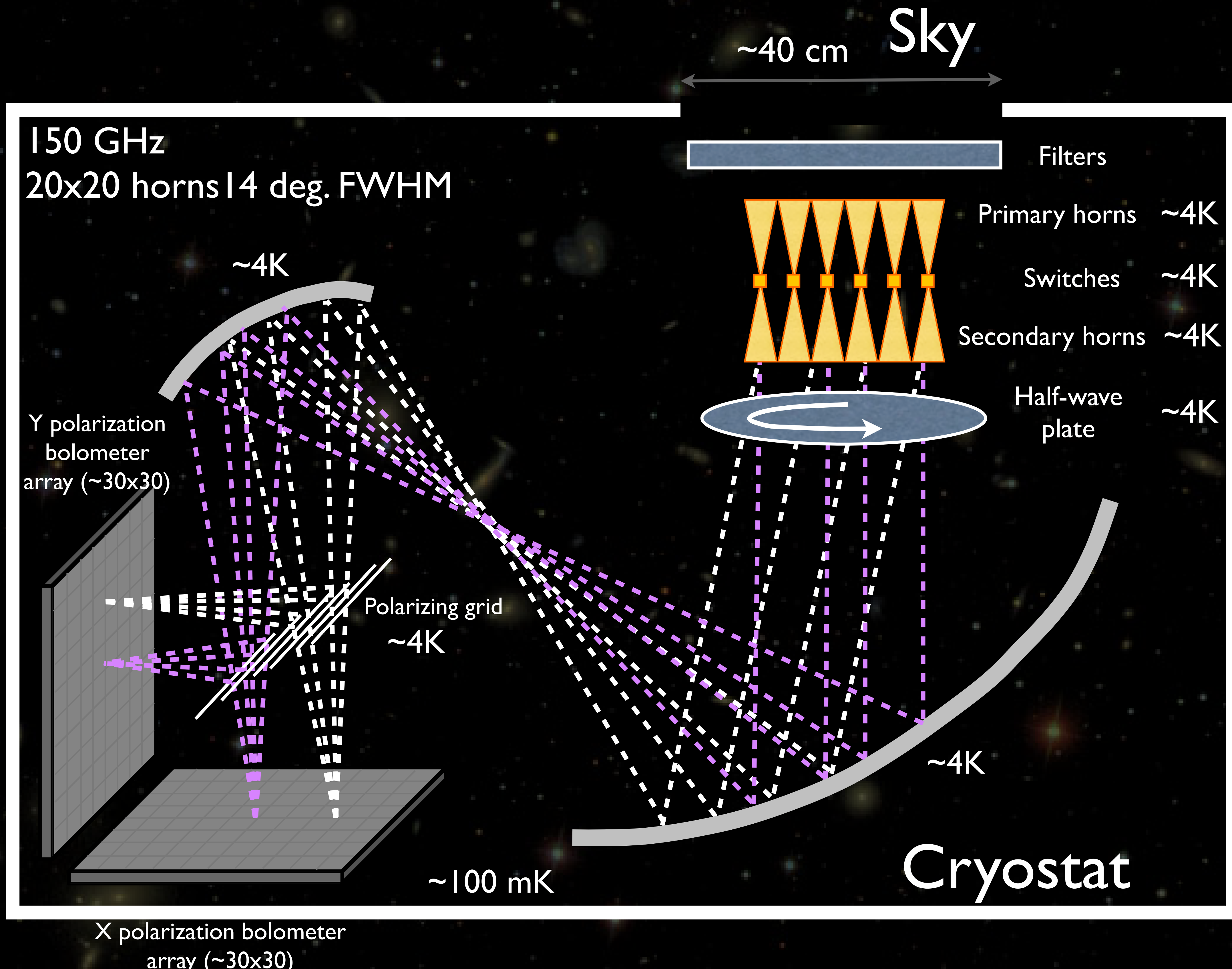

1 horn open



QUBIC design



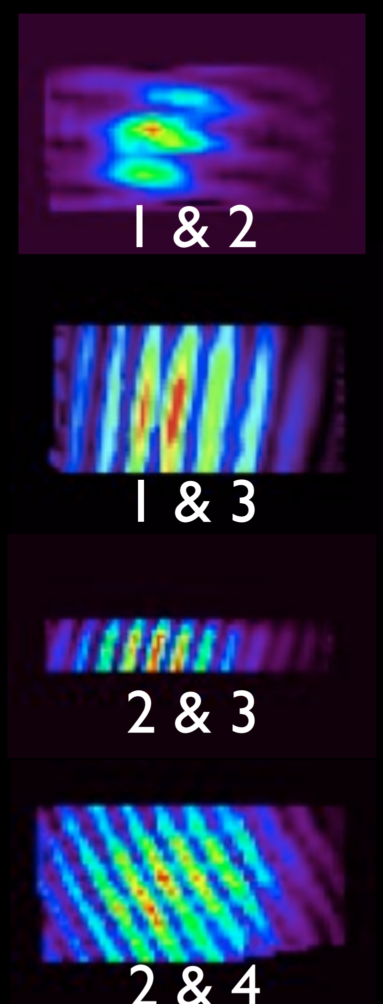


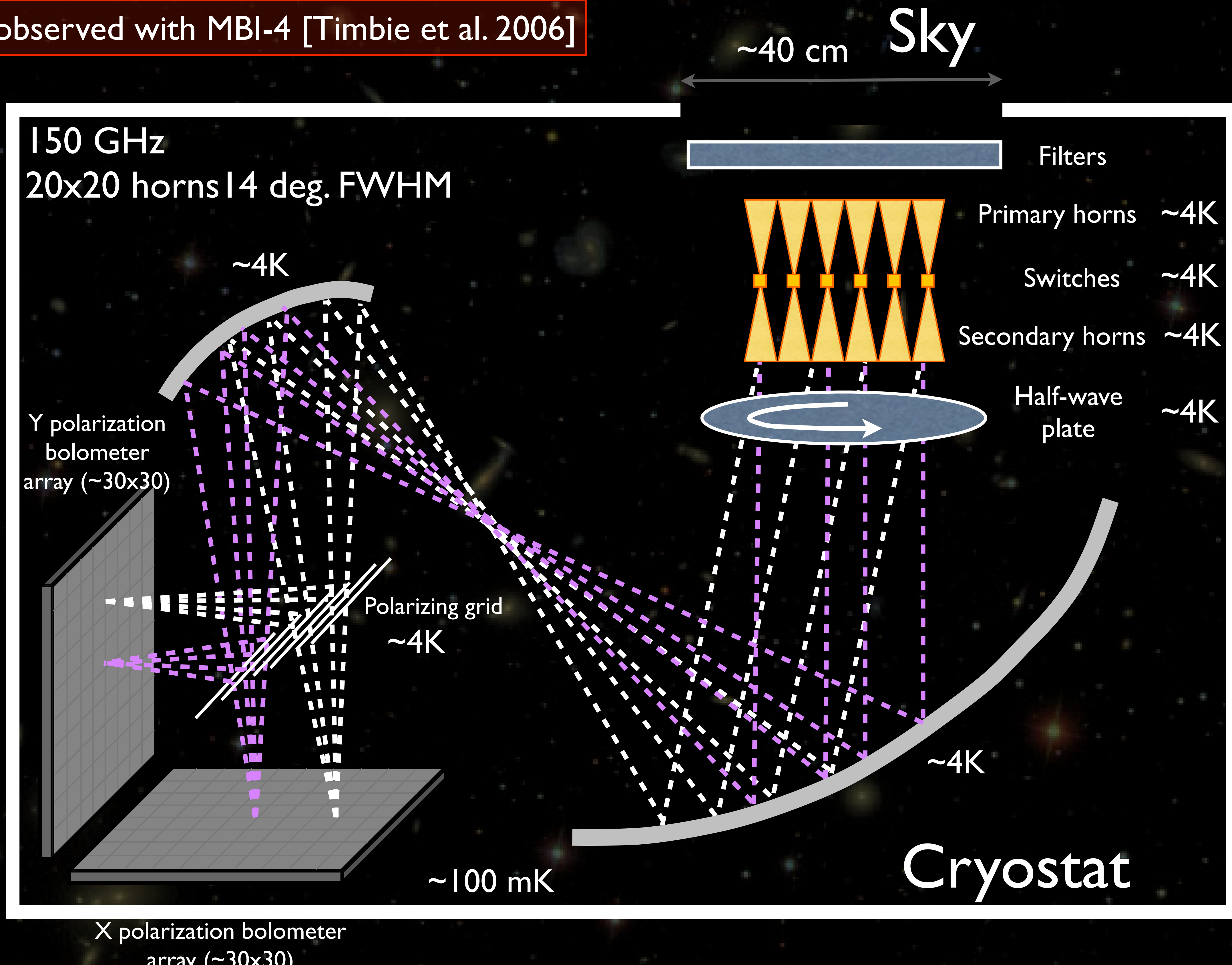
QUBIC design

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

1 horn open

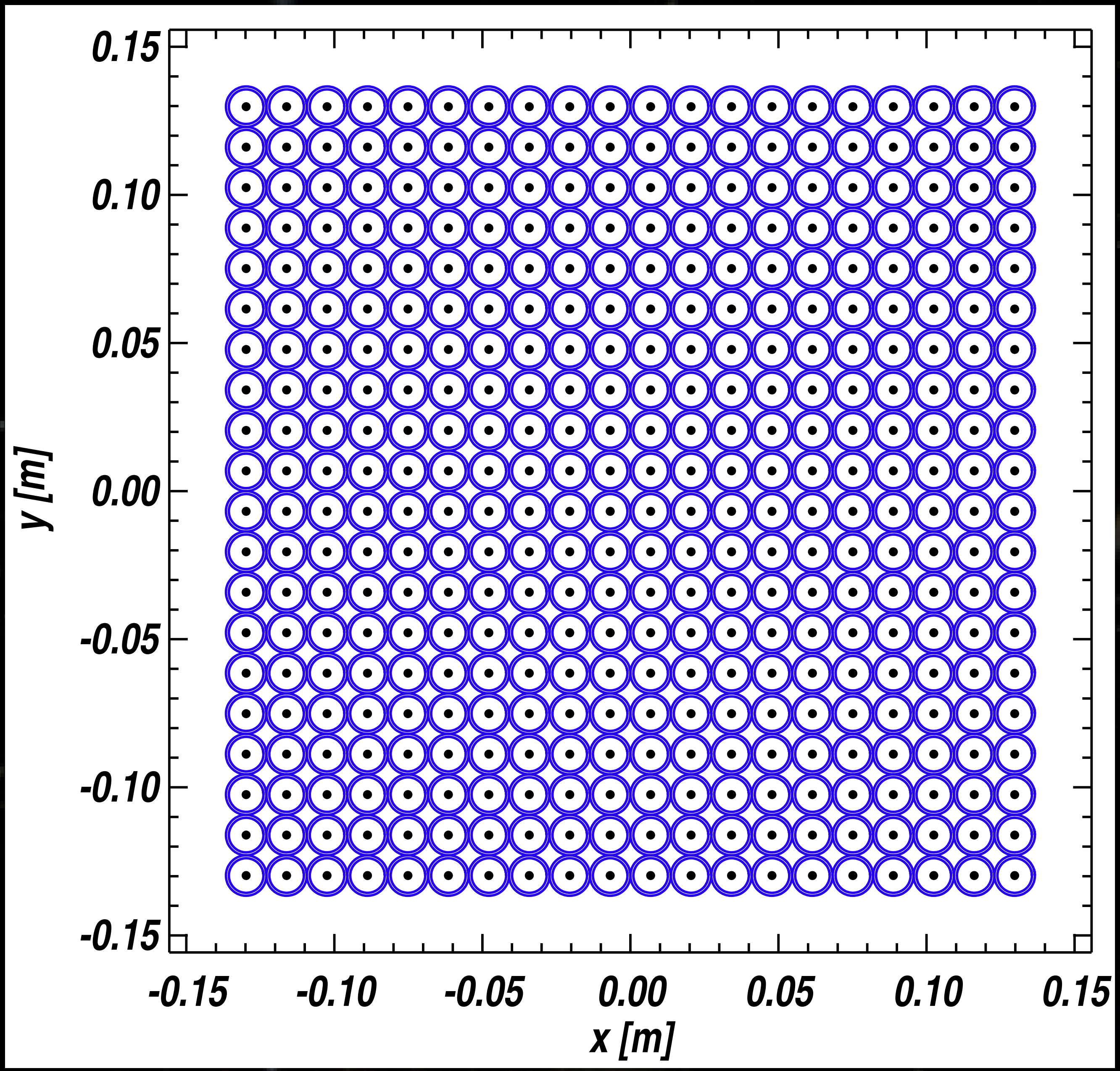
MBI-4 data
2009 campaign
(PBO- Wisc.)



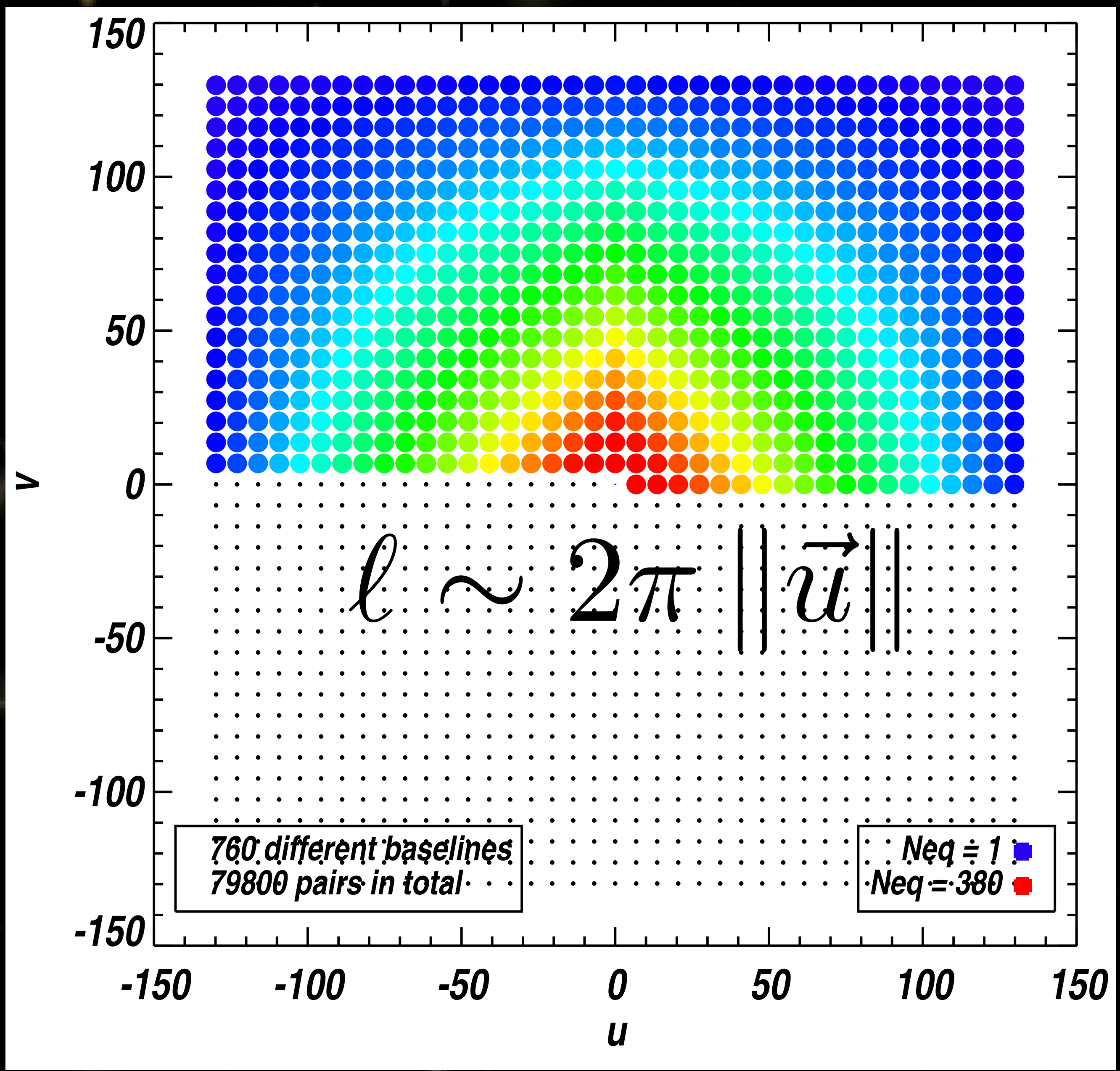


Horns and baselines

Primary horns array



Fourier plane coverage



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

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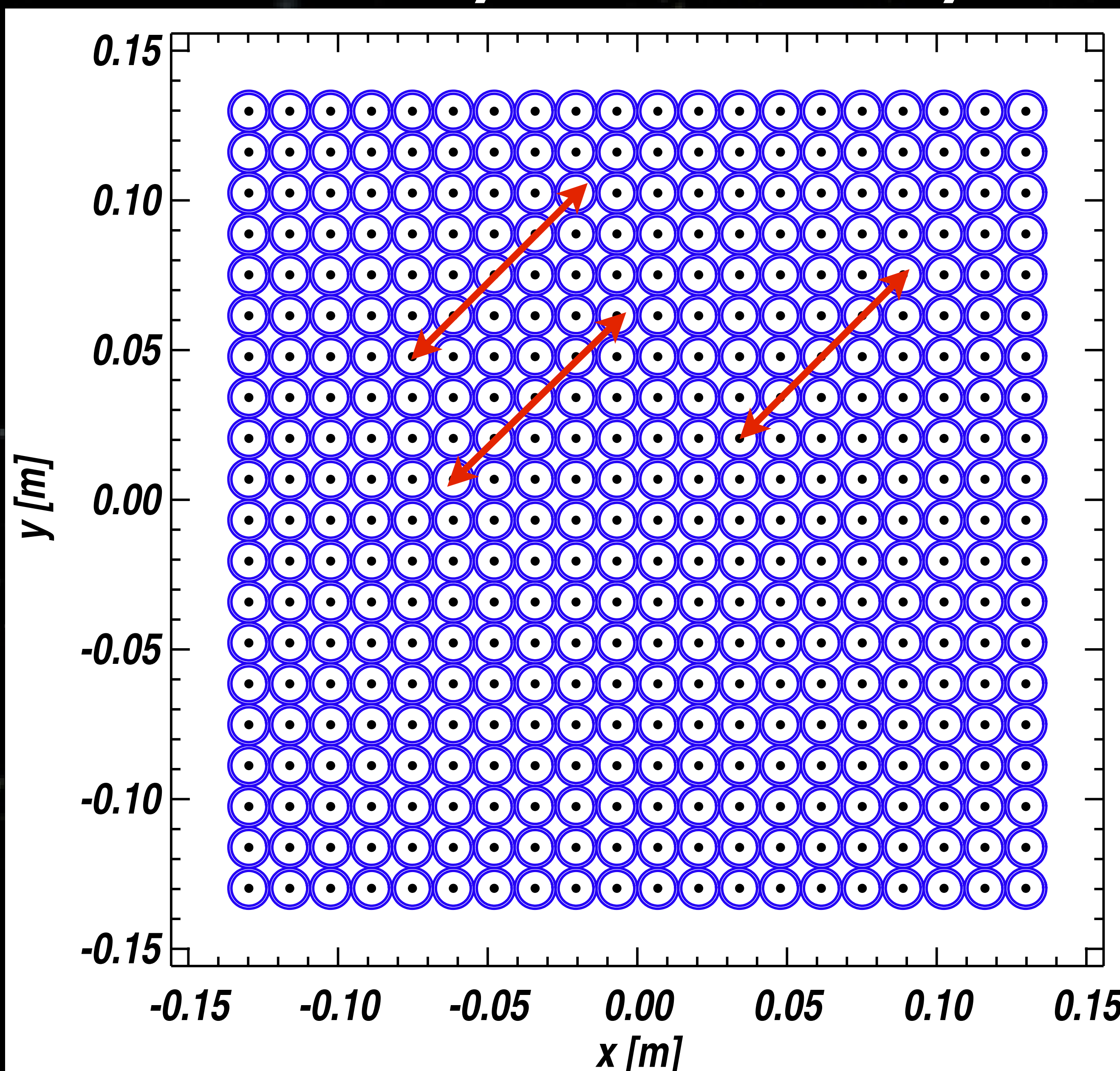

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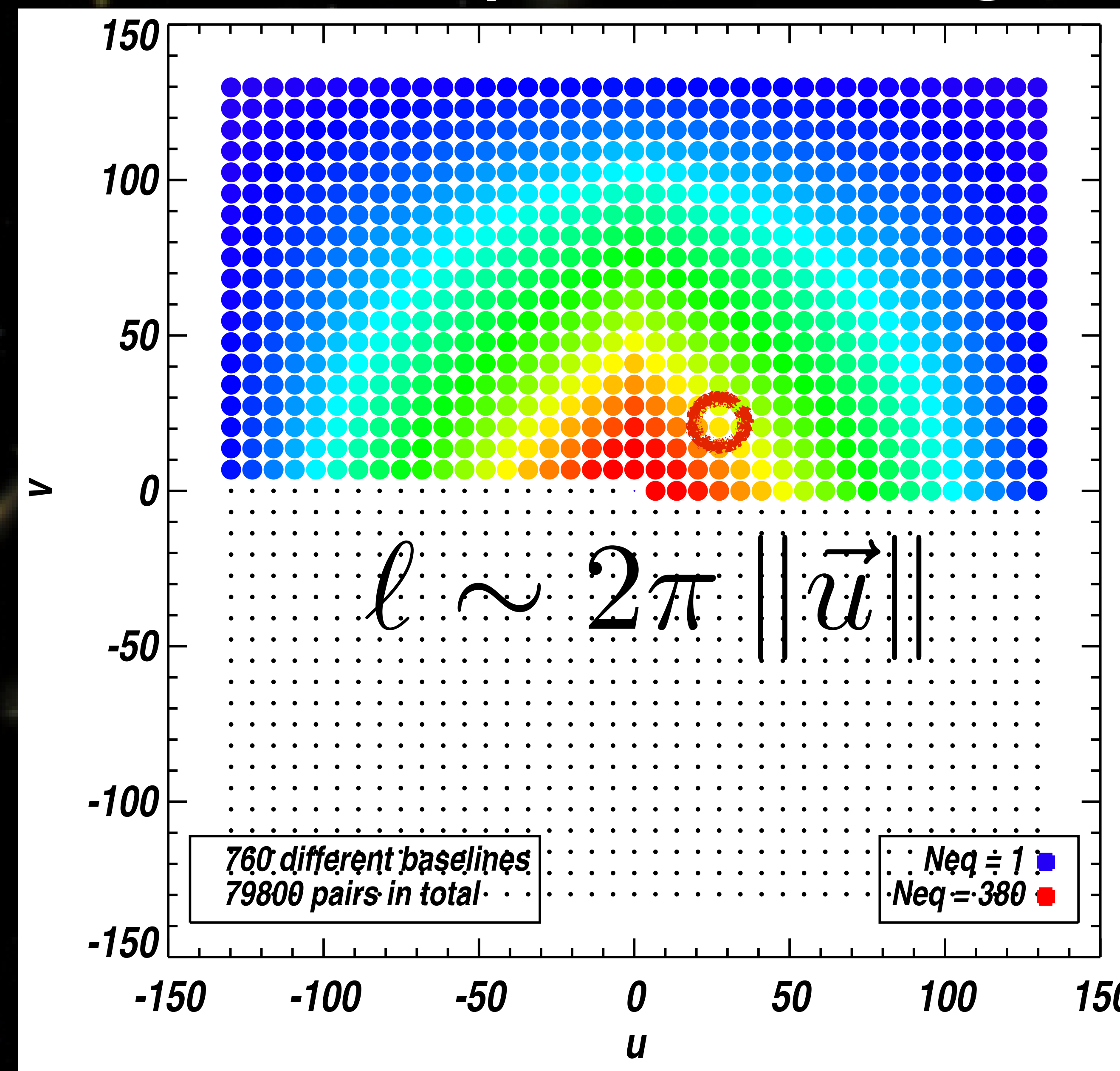

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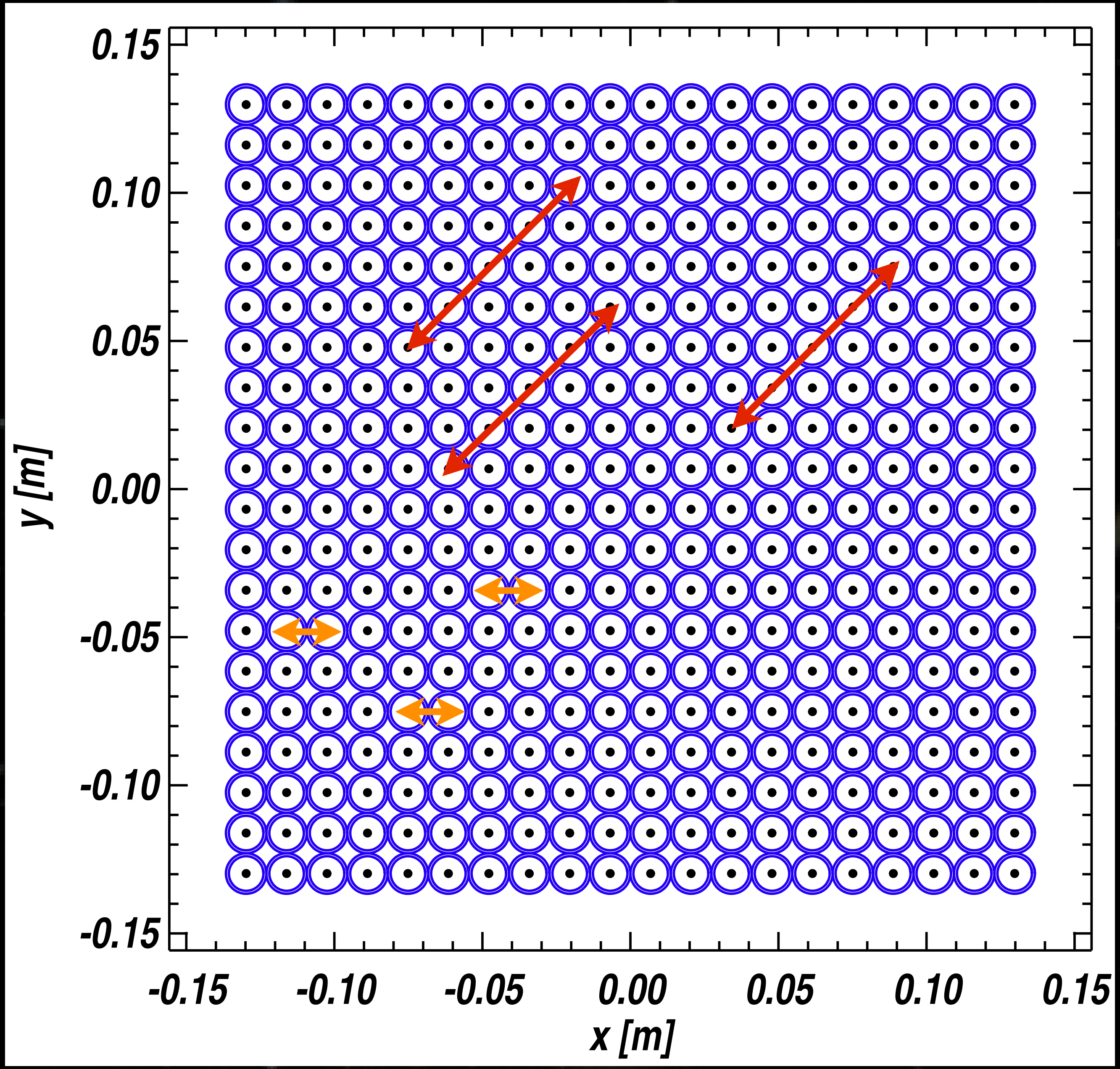

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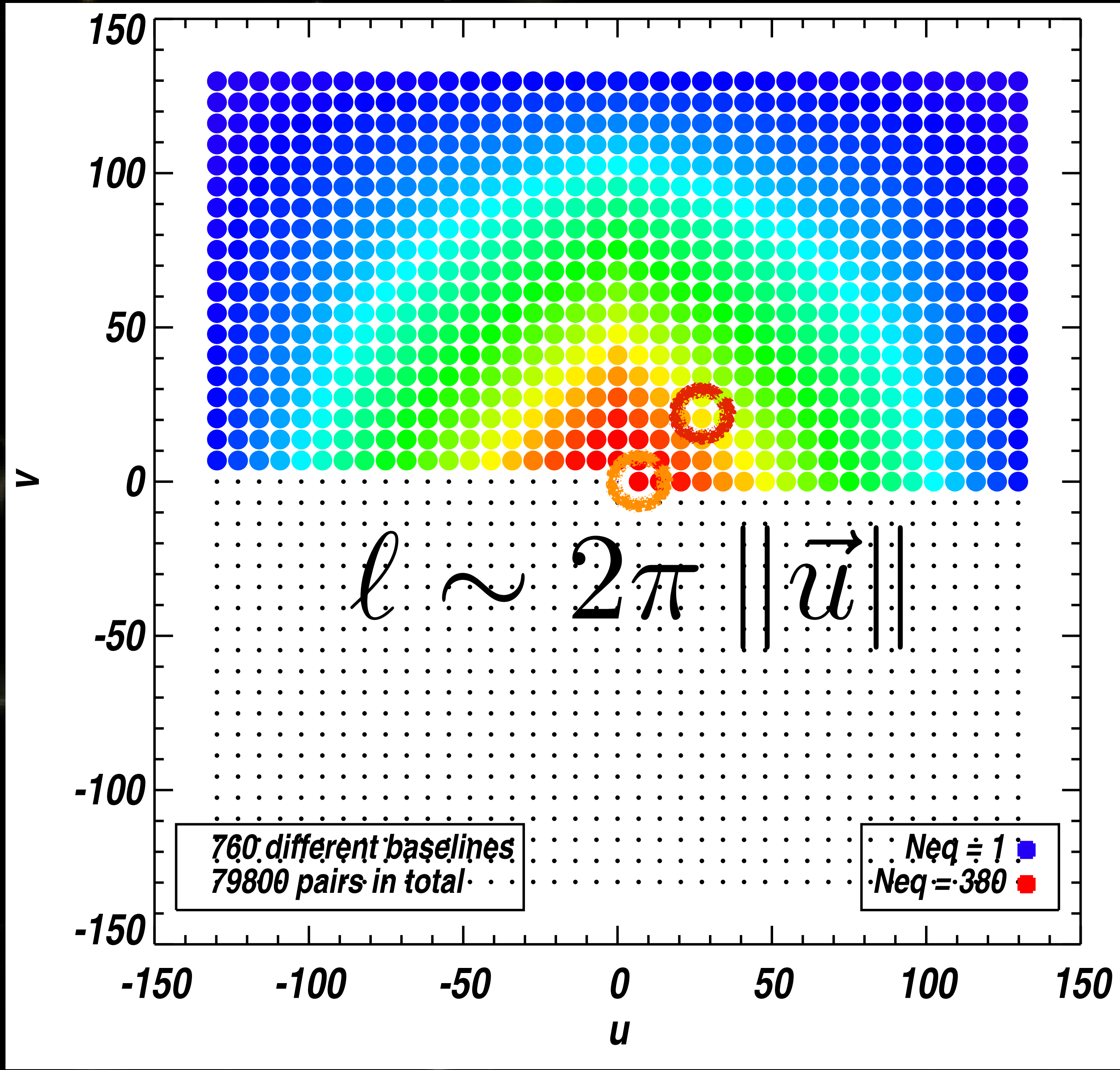

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Signal in QUBIC

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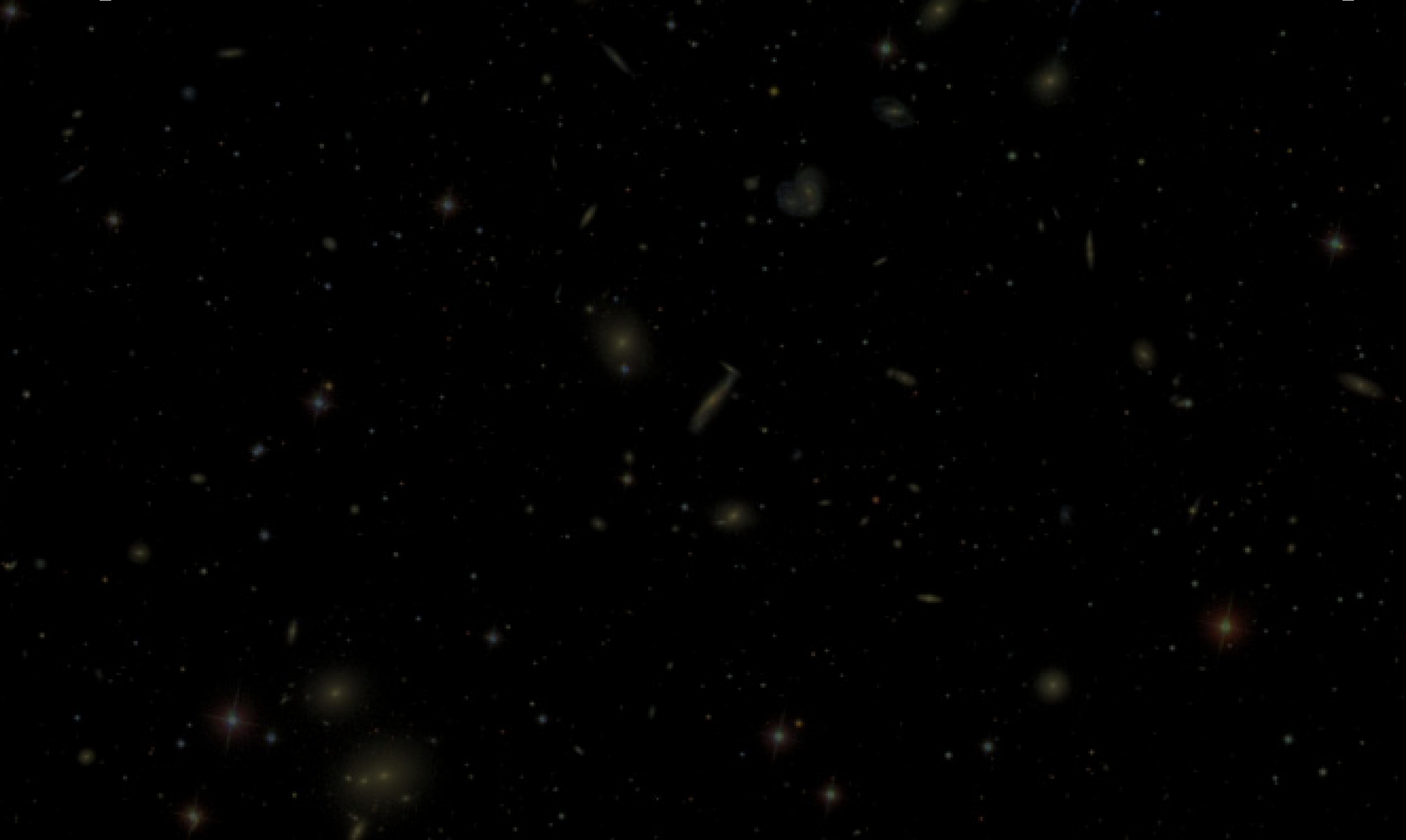
QUBIC is an imager where the pupil has been filled with holes in order to filter the sky in Fourier space

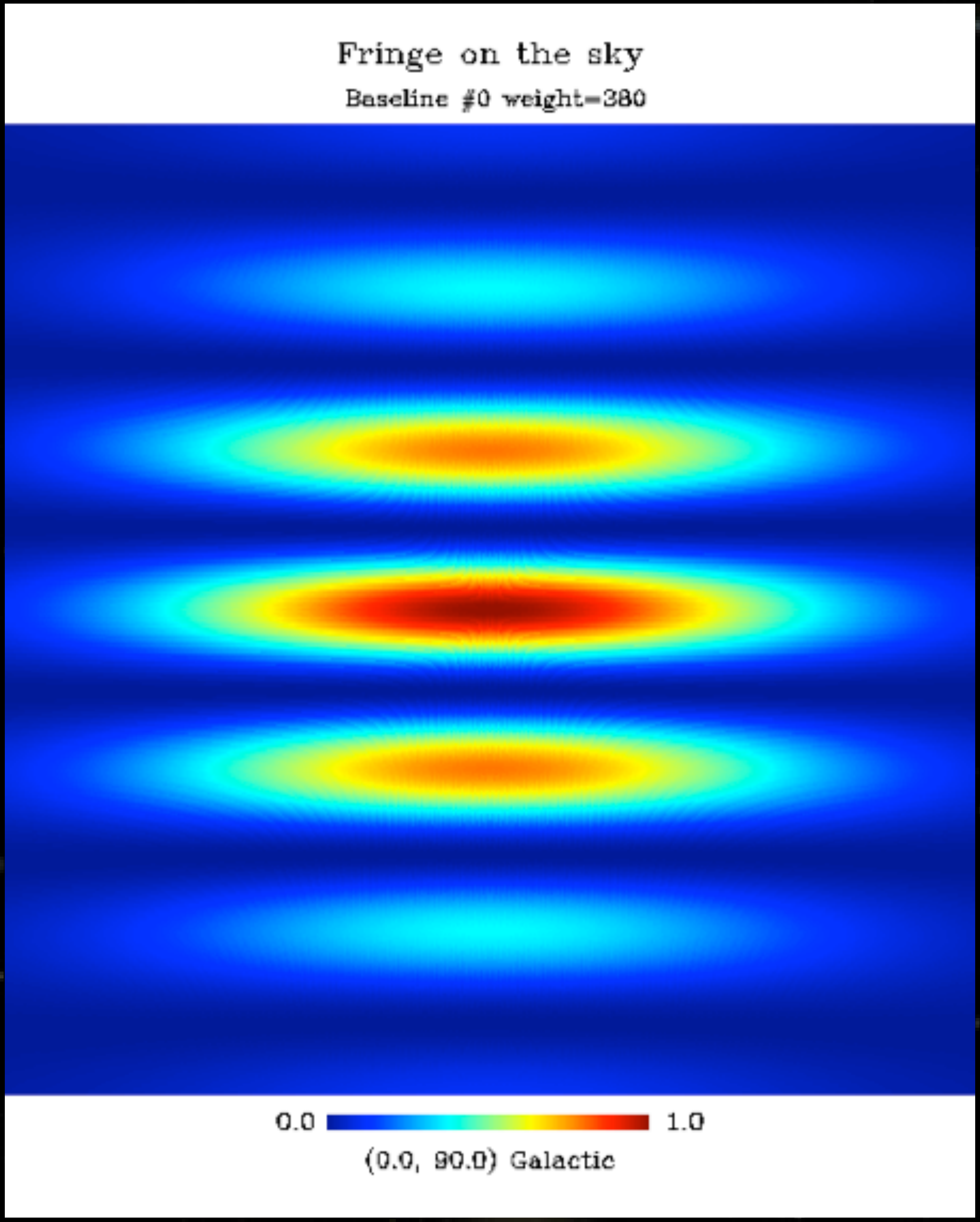
⇔ An imager with the synthesized beam

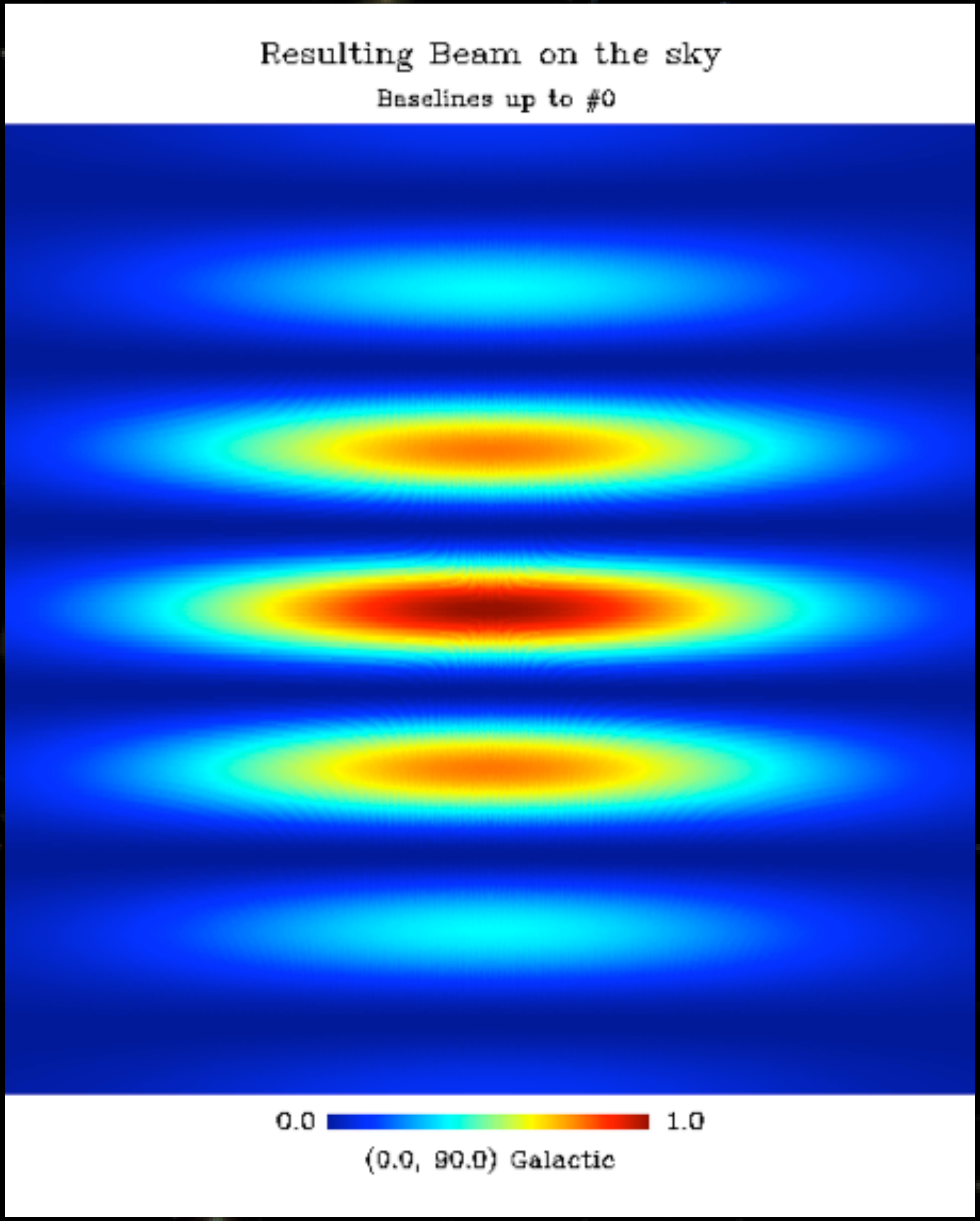
⇔ An interferometer performing direct synthesis imaging

Synthesized beam on the sky



Synthesized beam on the sky





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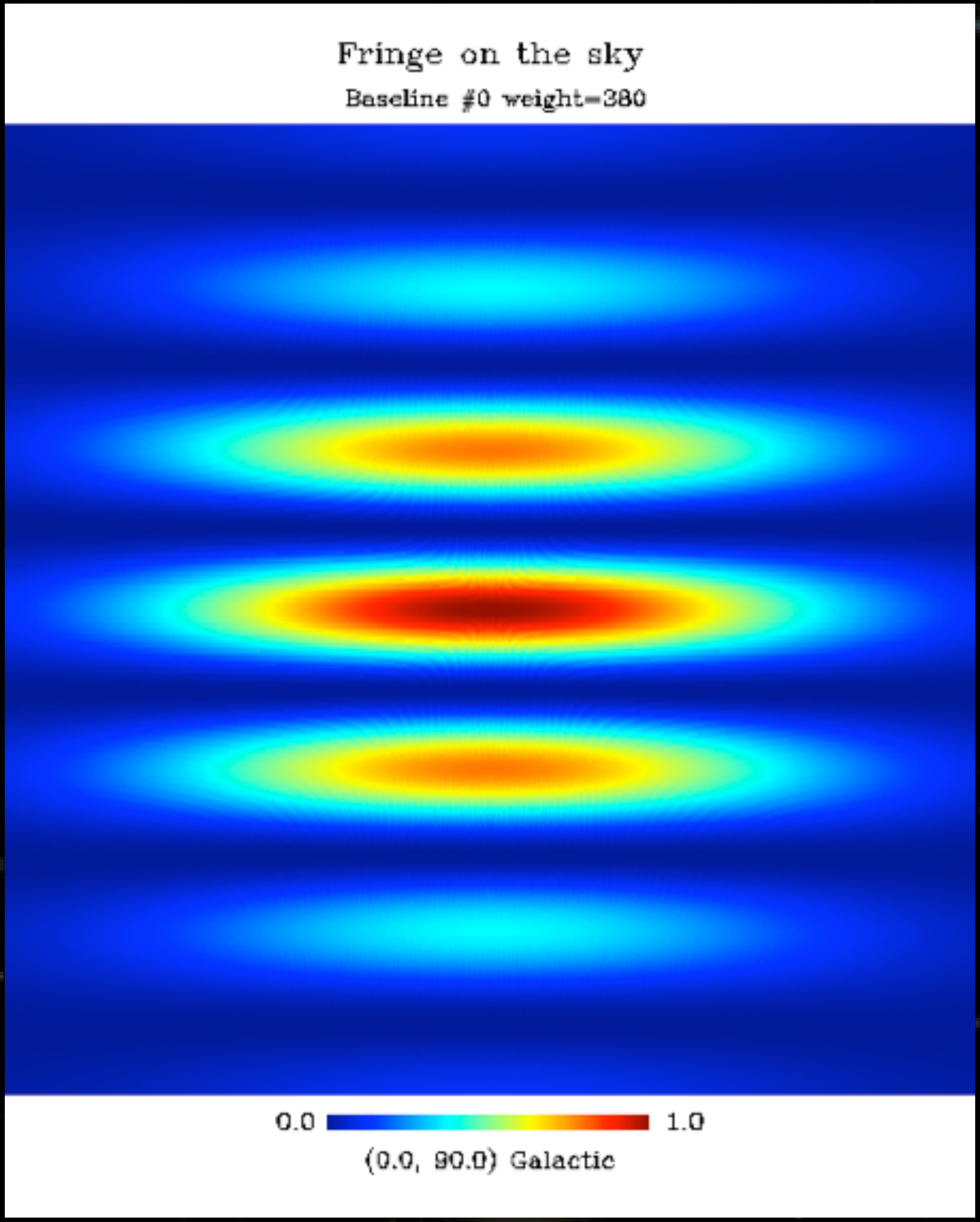

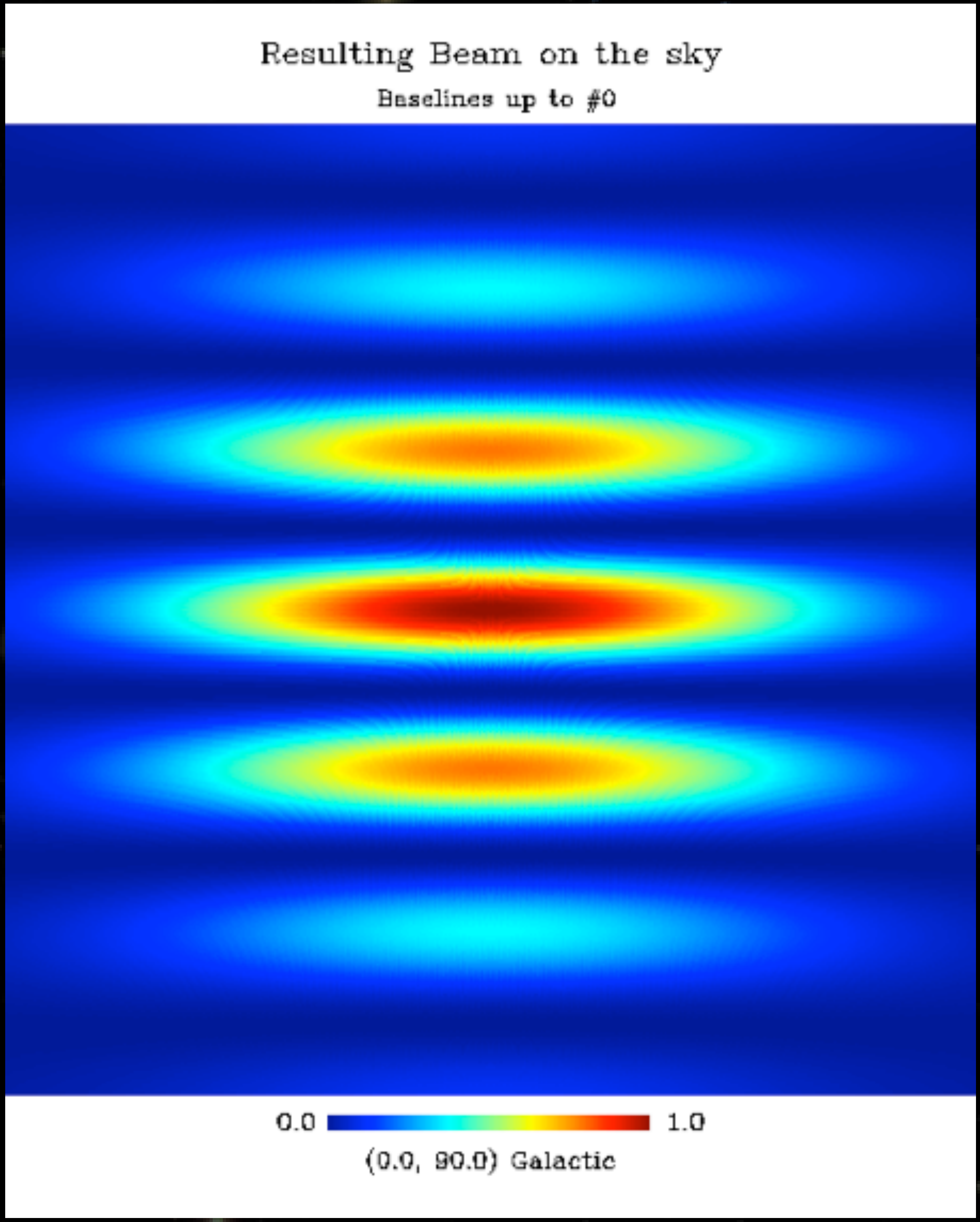

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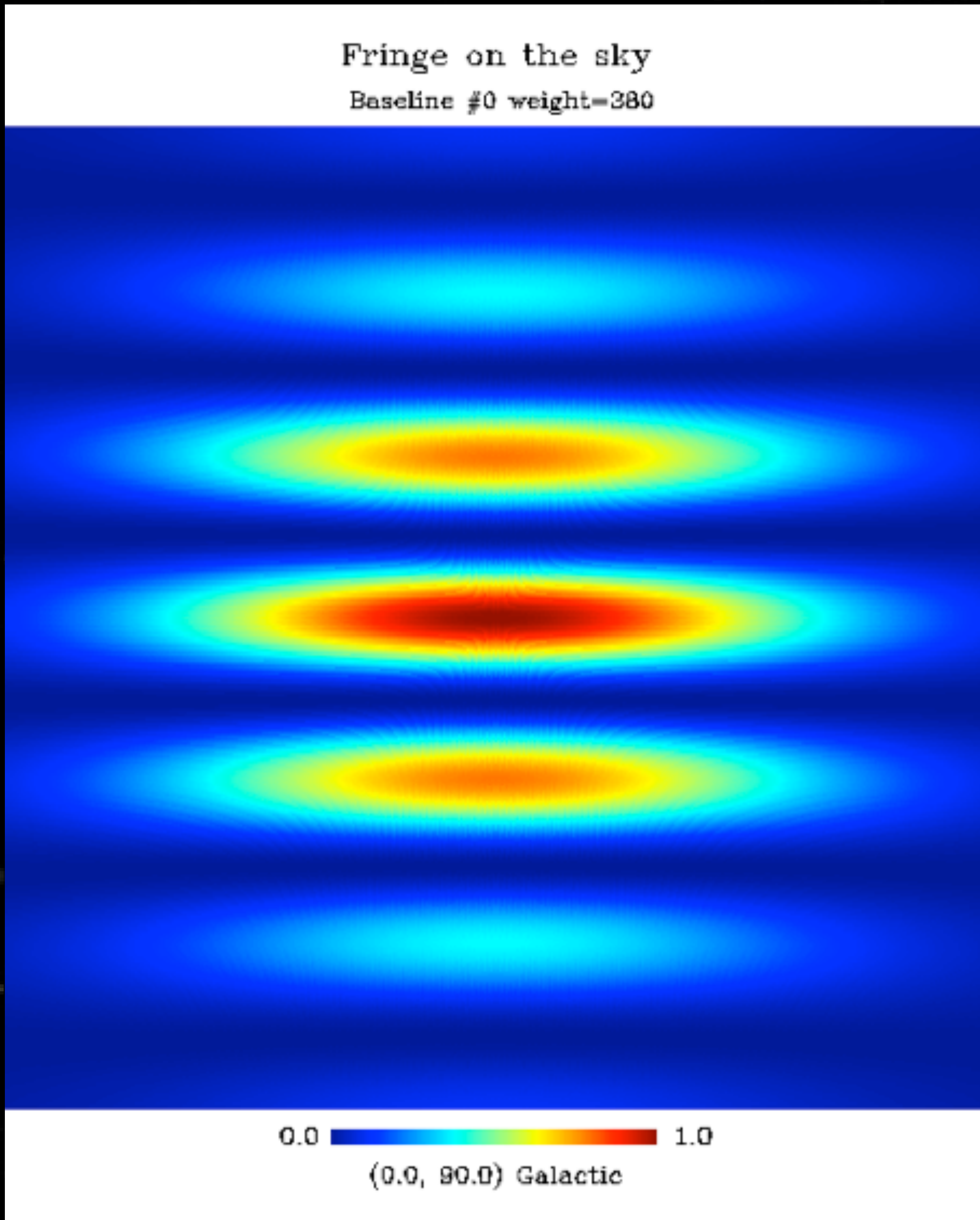

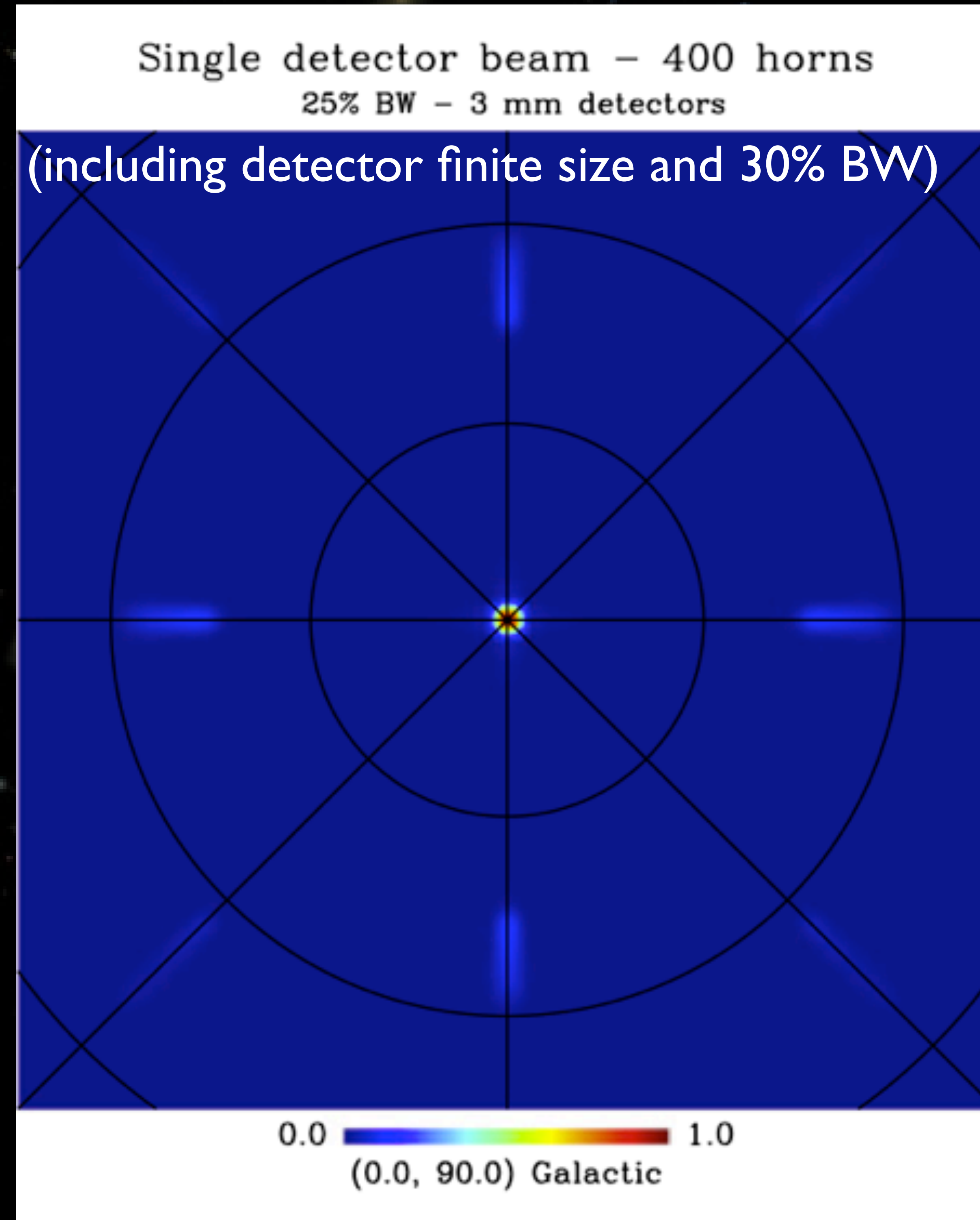

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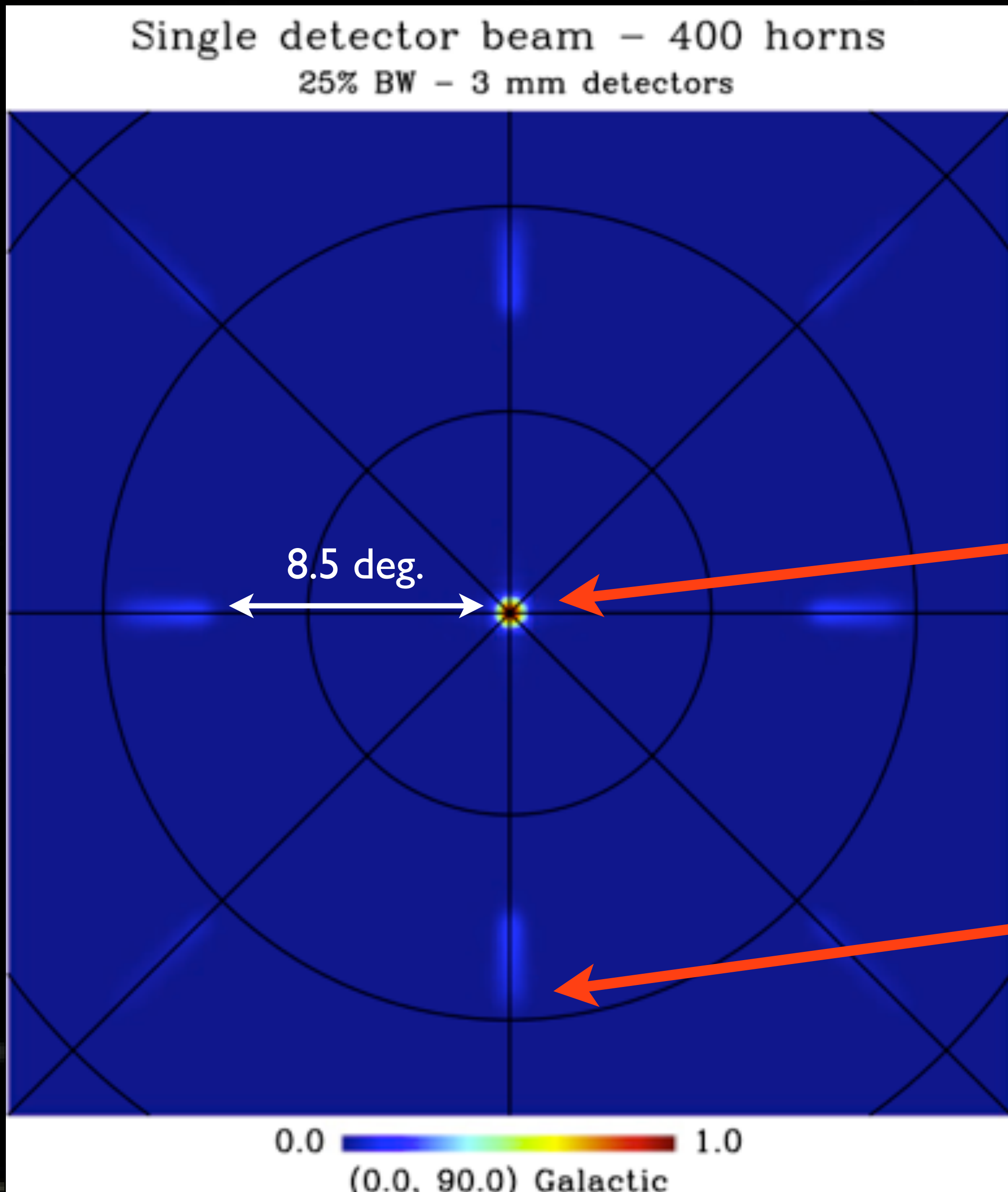
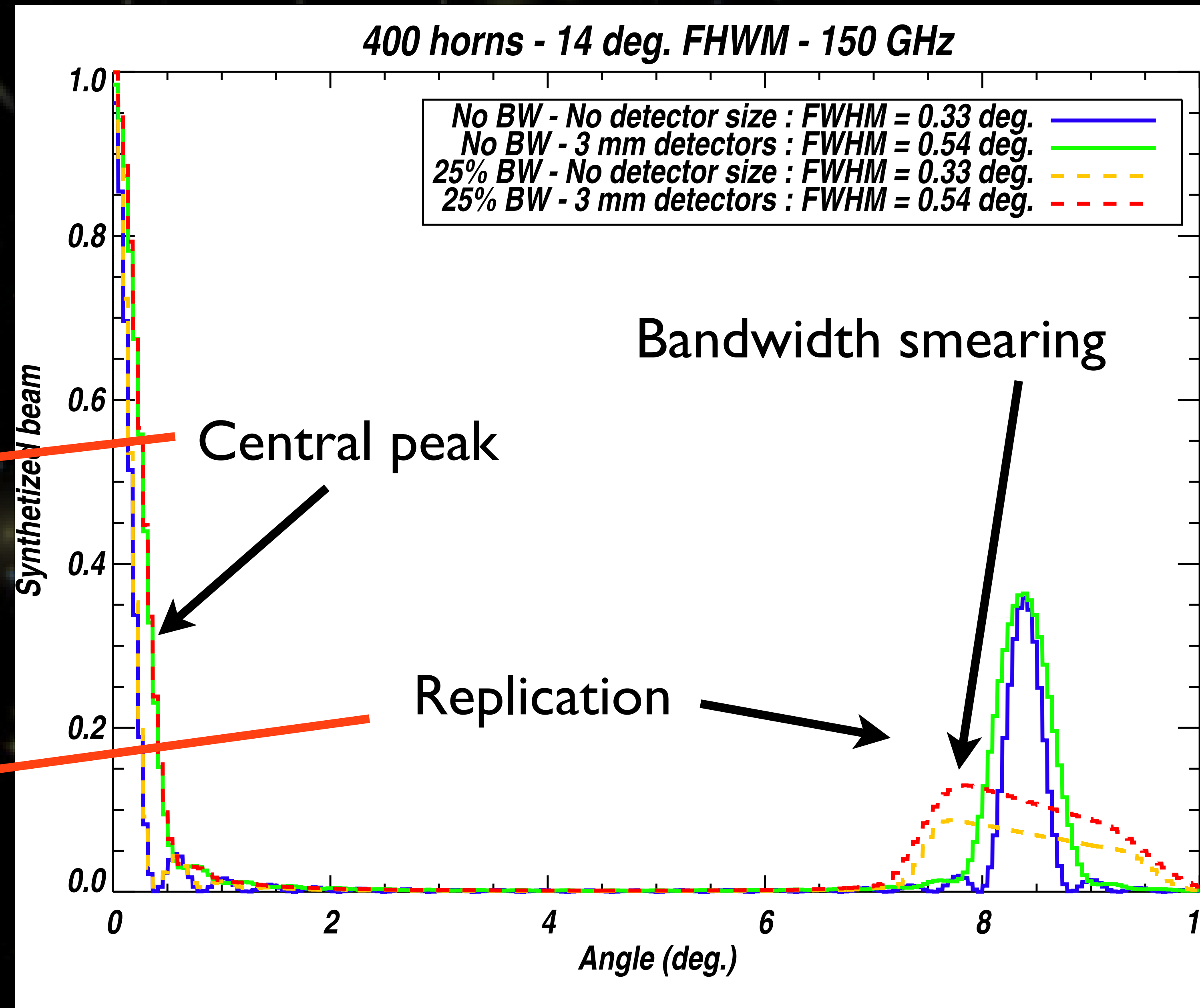


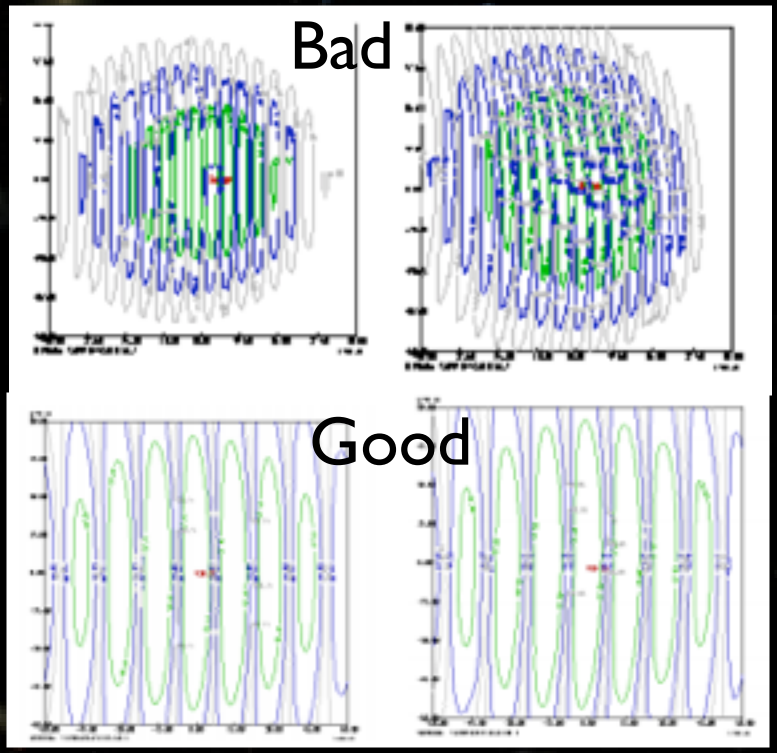


Replicated peaks **are not** (uncontrolled) sidelobes:

- 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 (very fast)
  - ★ C. O'Sullivan Team - Maynooth (Ireland)
  - ★ 300 mm equivalent focal length
  - ★ ~ 0.5 m mirrors



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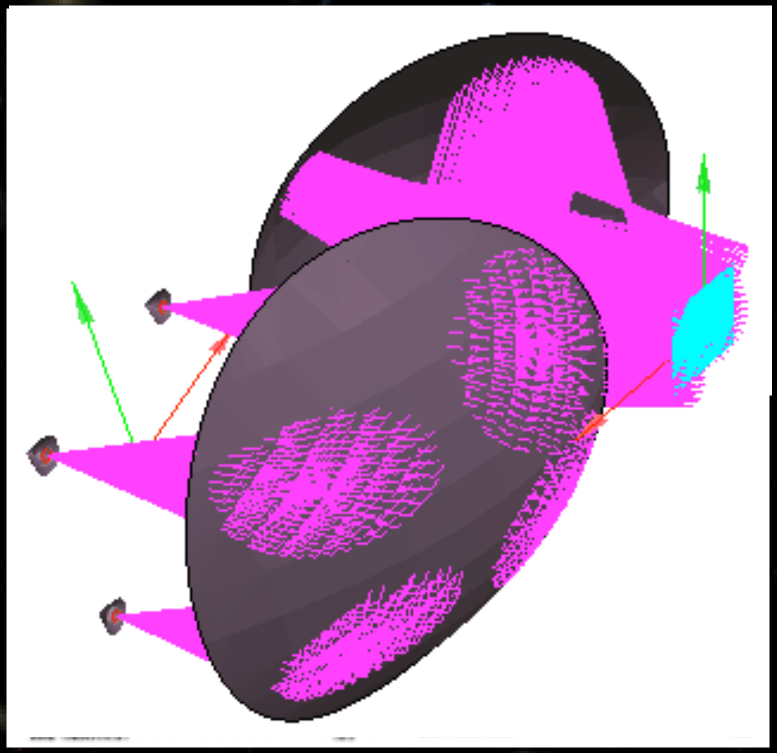

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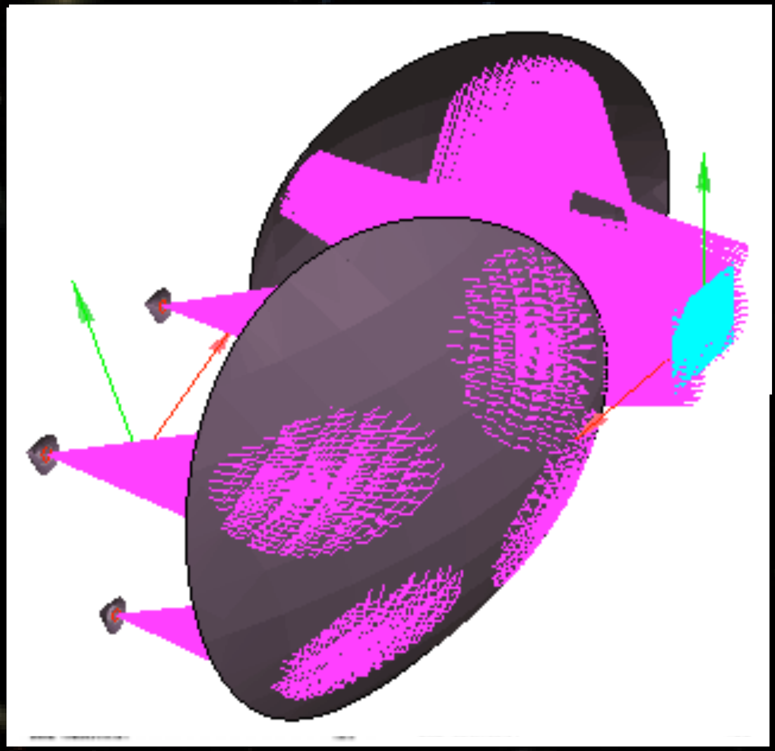

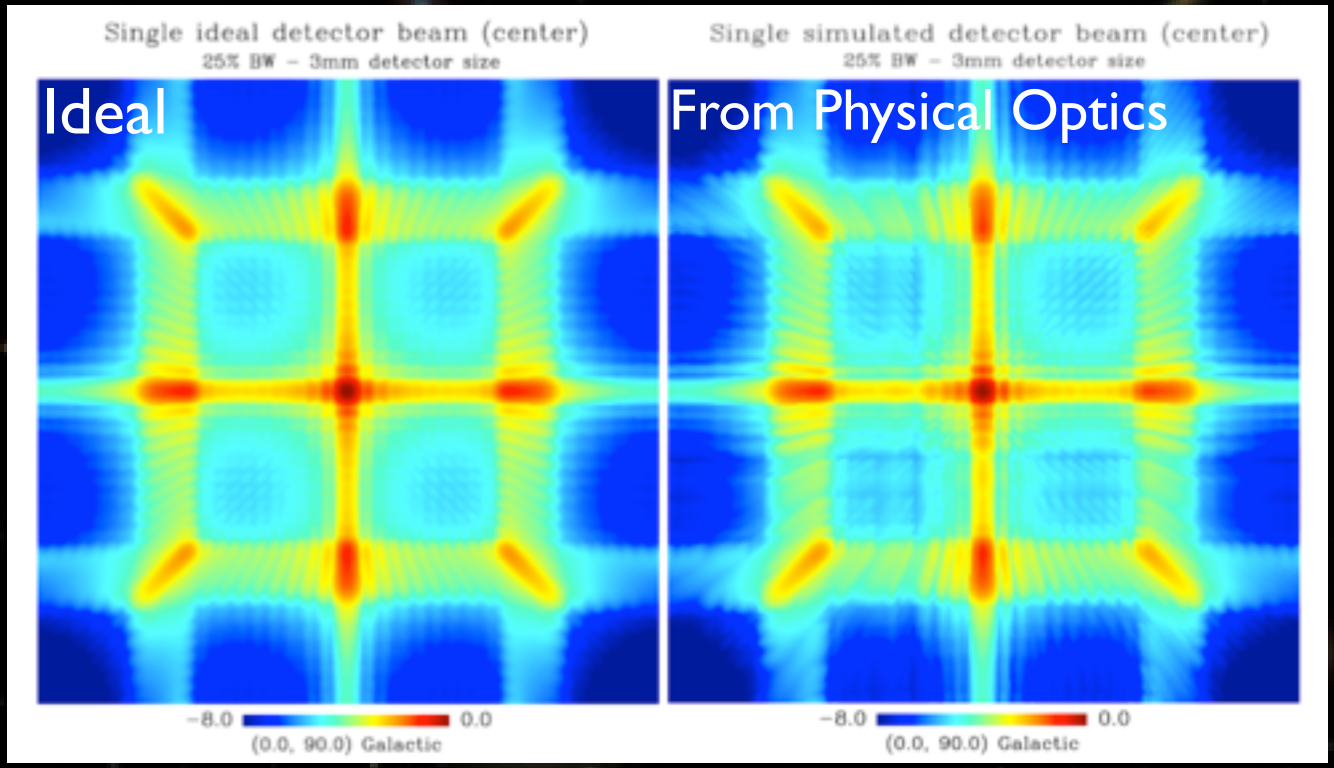

LogScale Synthesized beam

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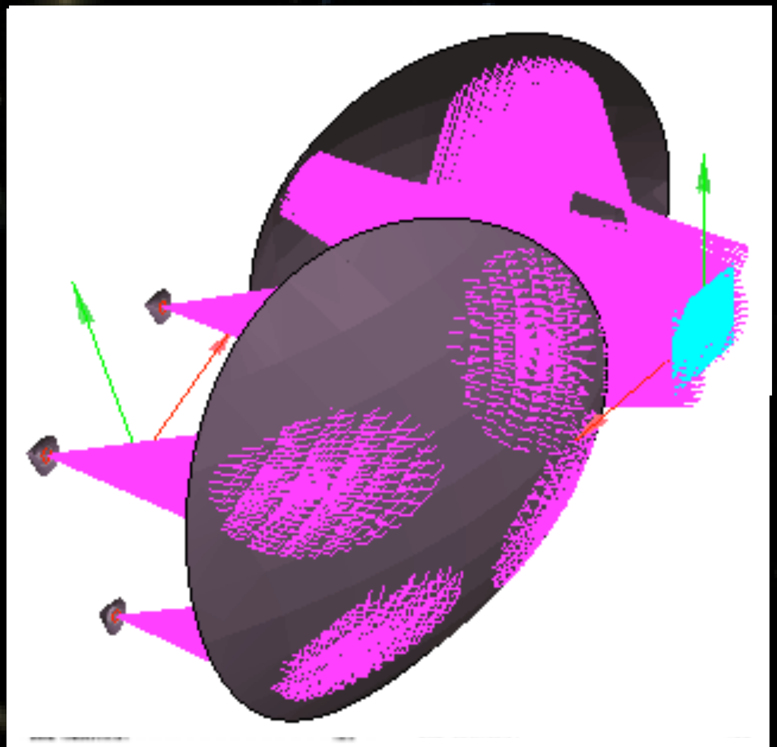

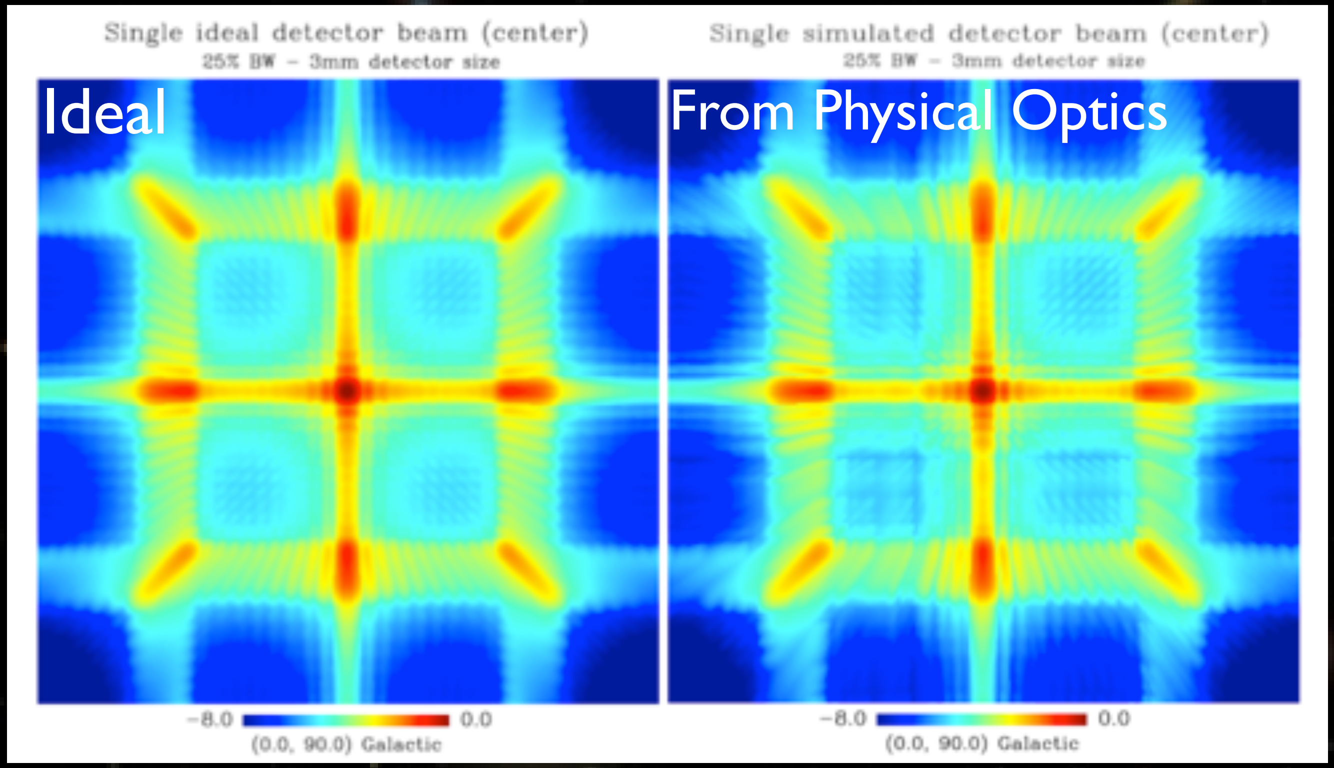

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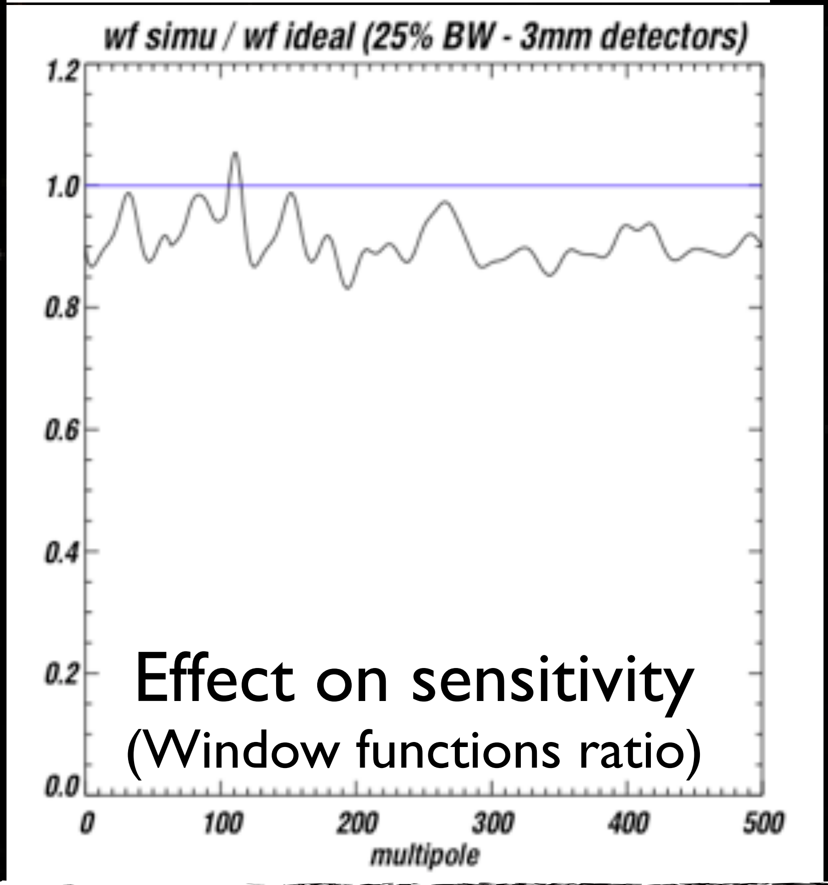


B.I. Technology

- QUBIC requires the same components as an imager
  - ★ Most of them are already available:
    - Cryostat : 4K with Pulse-Tube, 100 mK with dilution fridge
    - Large window : zotefoam: good mechanical resistance and low emissivity
    - Horns : Corrugated (Clover-like) low Xpol, low sidelobes and low return-loss
    - HWP : Metal-mesh HWP (Manchester), wide-band
    - Filters : Interference mesh filters at each cryogenic stage
    - Optical combiner : fast & compact off-axis gregorian telescope

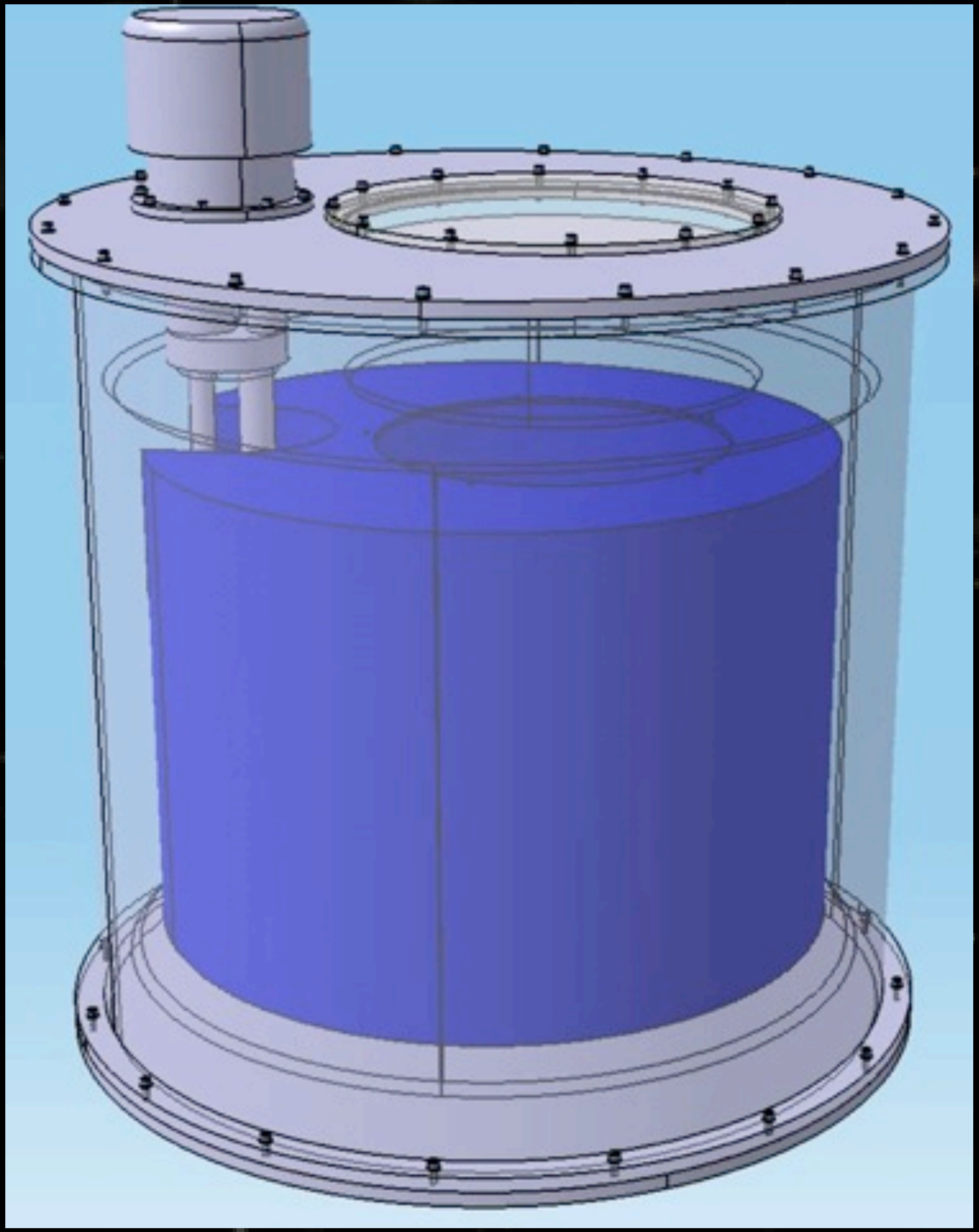
    Ready

  - ★ Some still require some reasonnable amount of R&D
    - Platelets horns: Fabrication significantly cheaper (~ 100€/horn) than usual electroforming.
      - ➡ Prototype realized, and tested: good beams [Publication in prep.]
    - Switches : basically on/off on each channel
      - ➡ shutters between the back-to-back horns activted by electromagnets
      - ➡ Tested with excellent performances [Publication in prep.]
    - Detectors : NbSi TES with $5\text{-}10 \times 10^{-18}$ W.Hz$^{-1/2}$ and $\tau < 10$ ms
      - ➡ 2x(4x256) elements array on the way [Piat et al. 2008]
    - Readout : Time domain multiplexing with SQUIDs & a 4K SiGe ASIC
      - ➡ 24:1 demonstrated succesfully [Voisin et al. 2008, Prêle et al. 2009]
      - ➡ 128:1 being finalized

    Ongoing in QUBIC

QUBIC Cryostat

- Designed/Fabricated 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
  - ★ PTC pre-cooling the mixture



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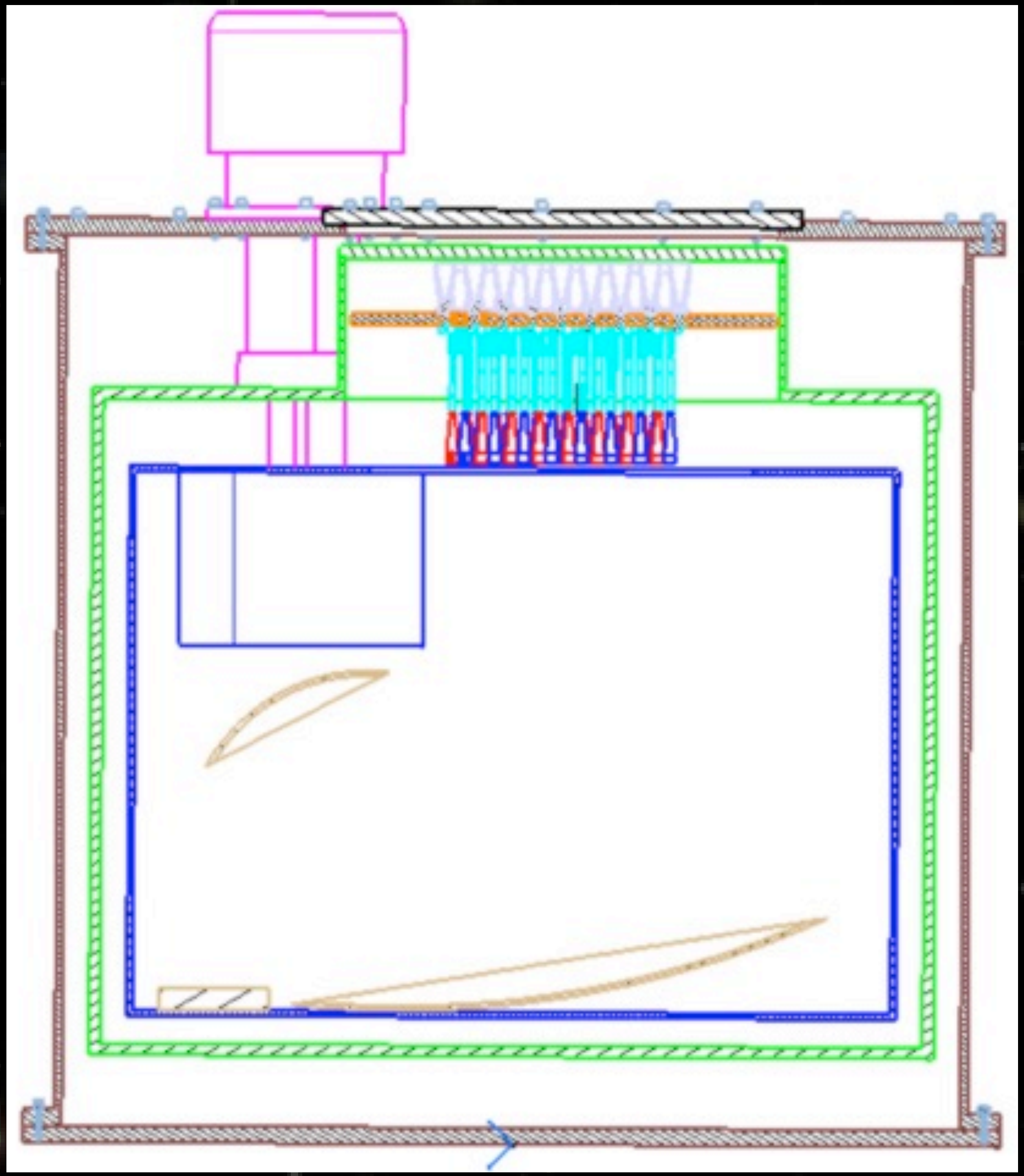
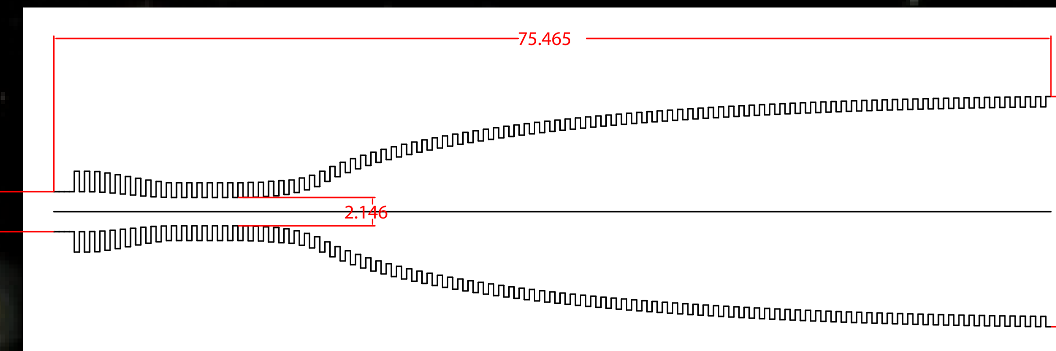
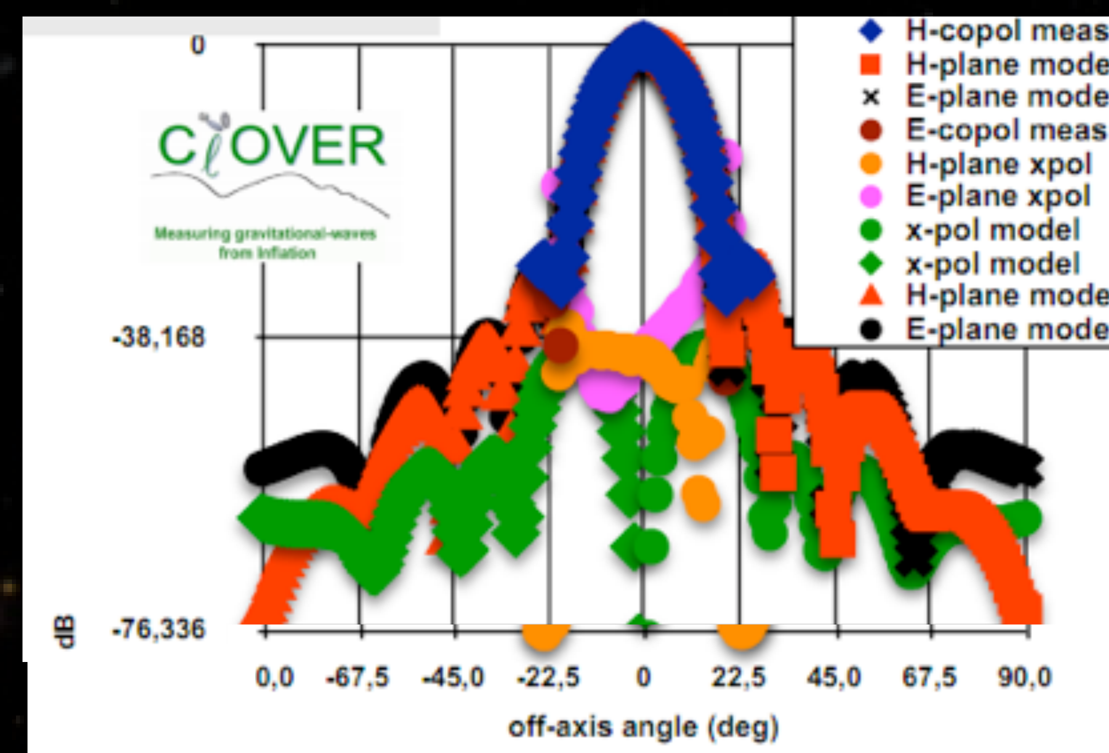


Horns

- 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





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  - ★ Excellent beam/Cross Pol. perfs
  - ★ Usual fabrication:
    - Electroforming
    - Expensive (800$ / horn)
- Platelets fabrication investigated at APC (É. Bréelle)
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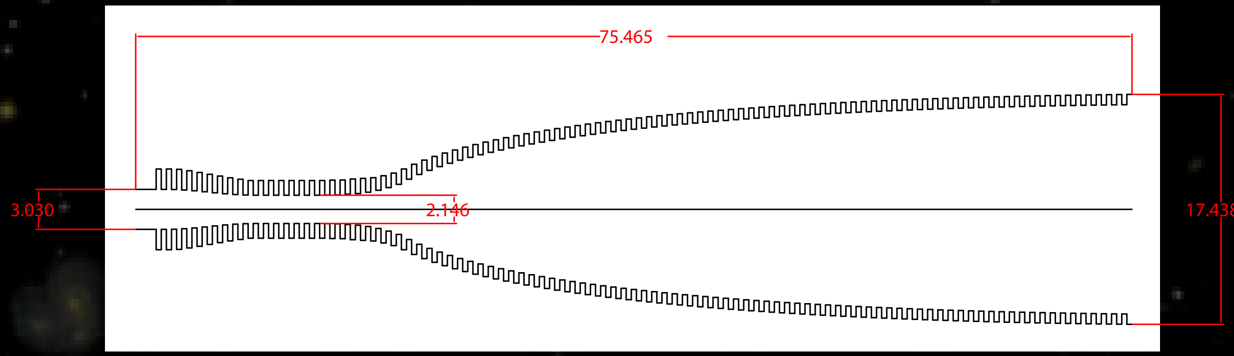

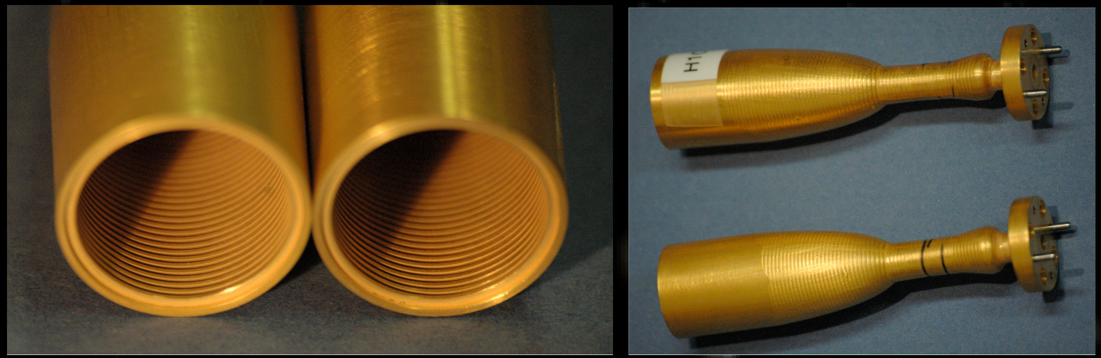

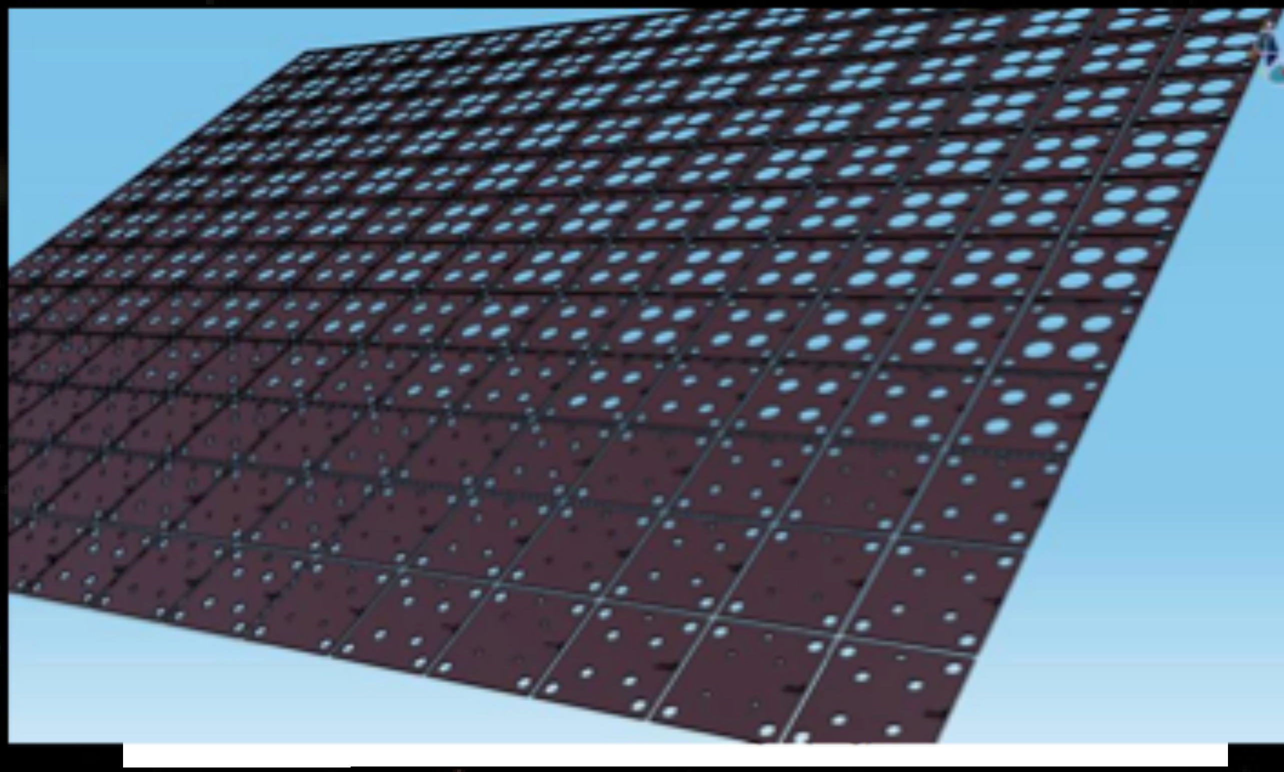

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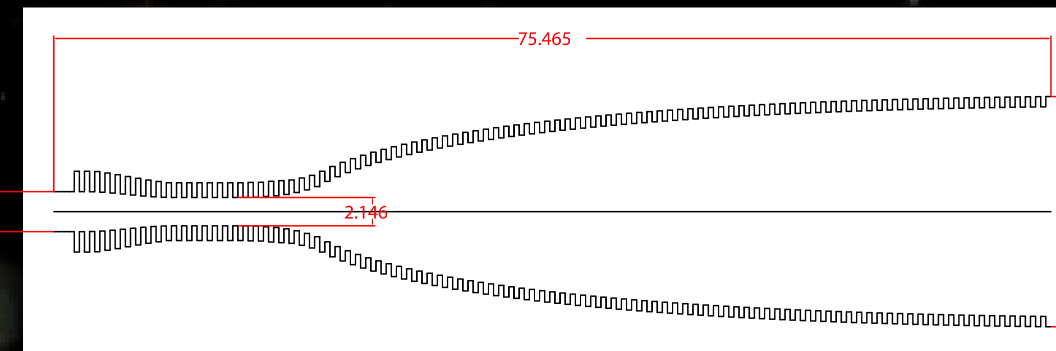

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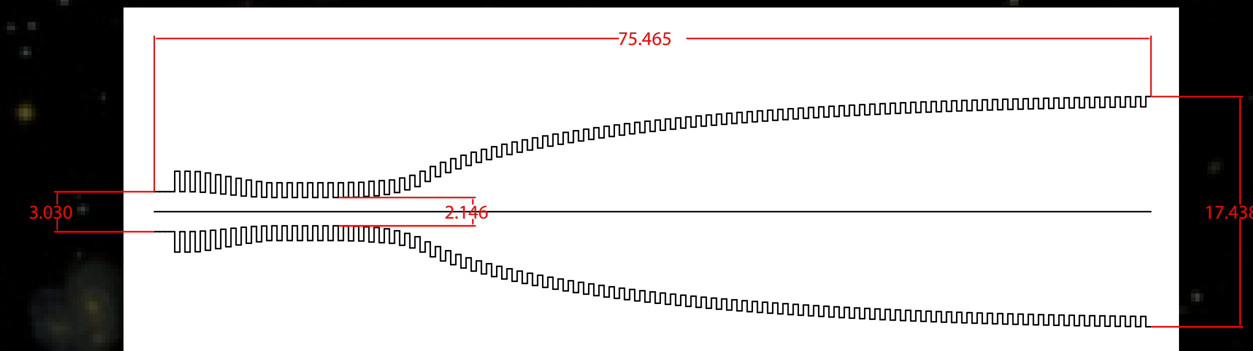
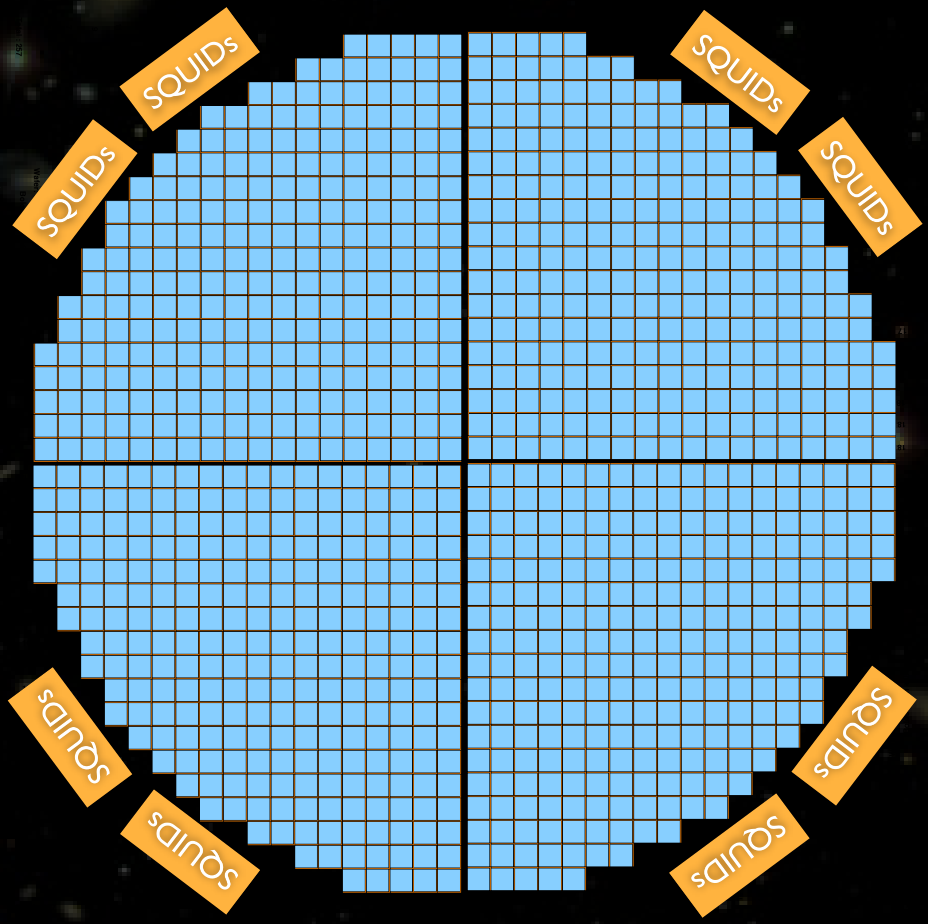
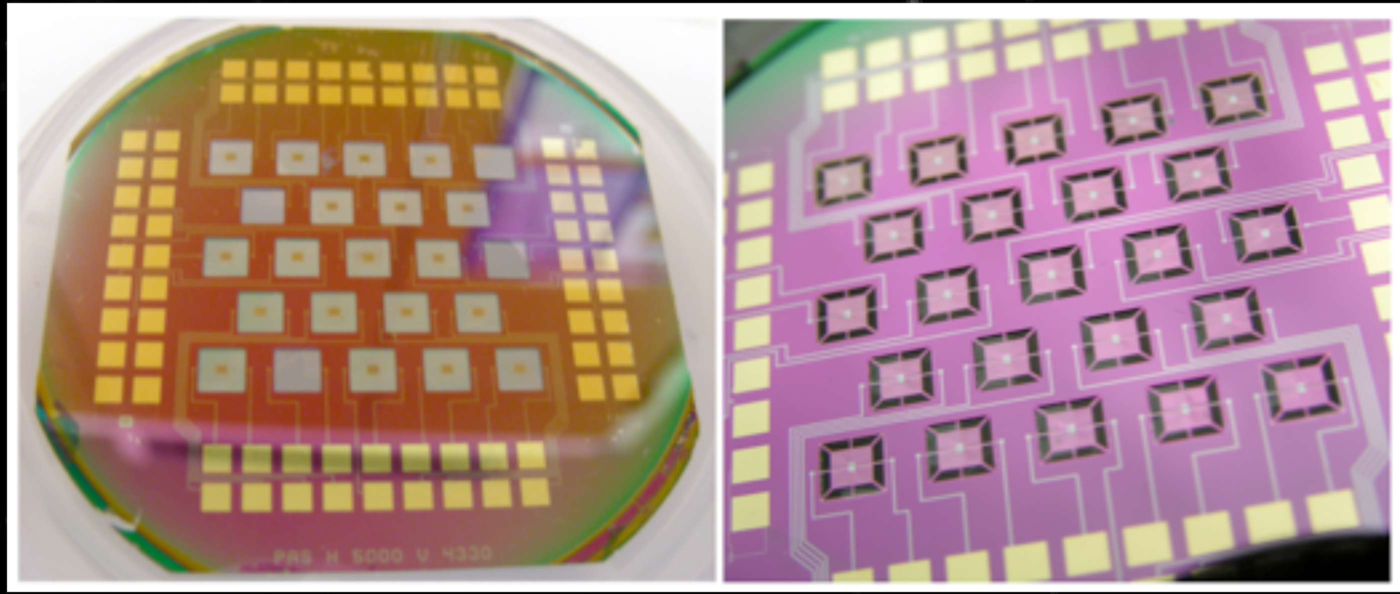


Detection Chain

- 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 $pV.Hz^{-1/2}$





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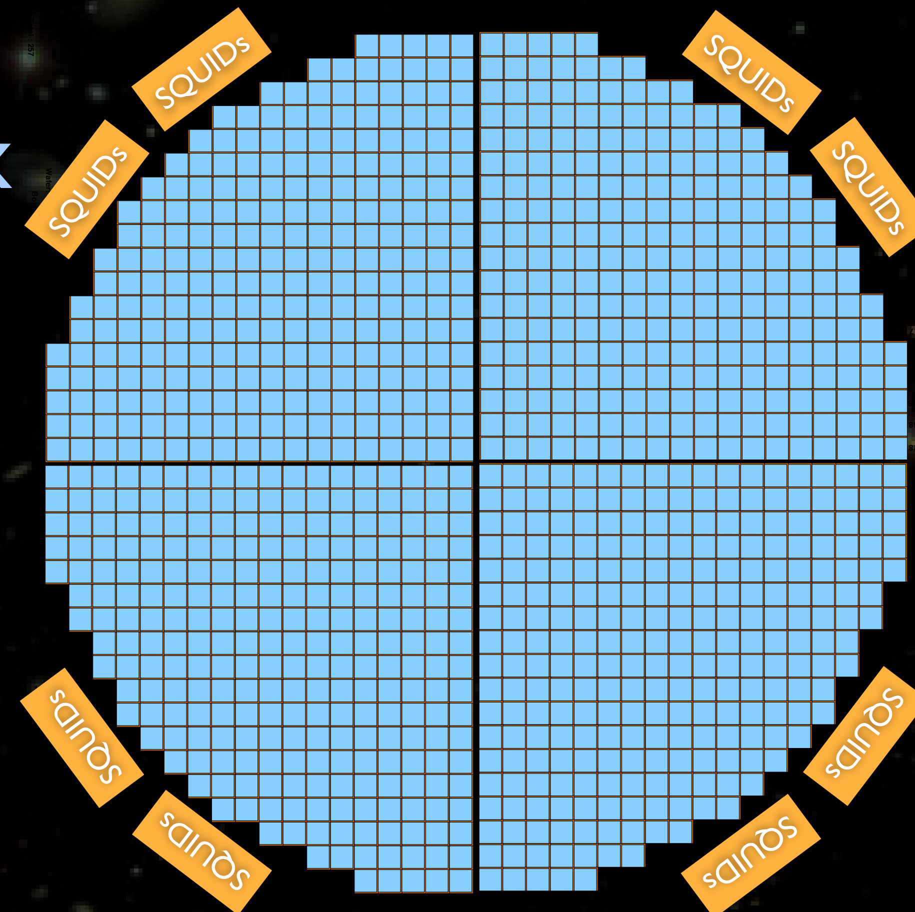
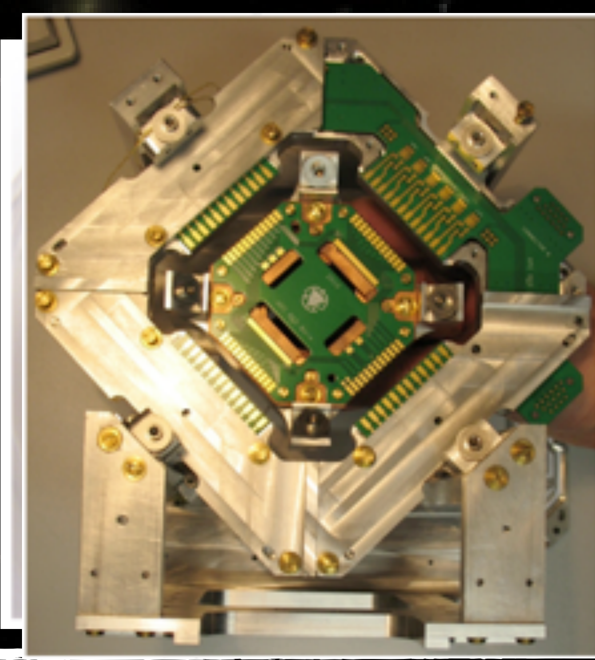
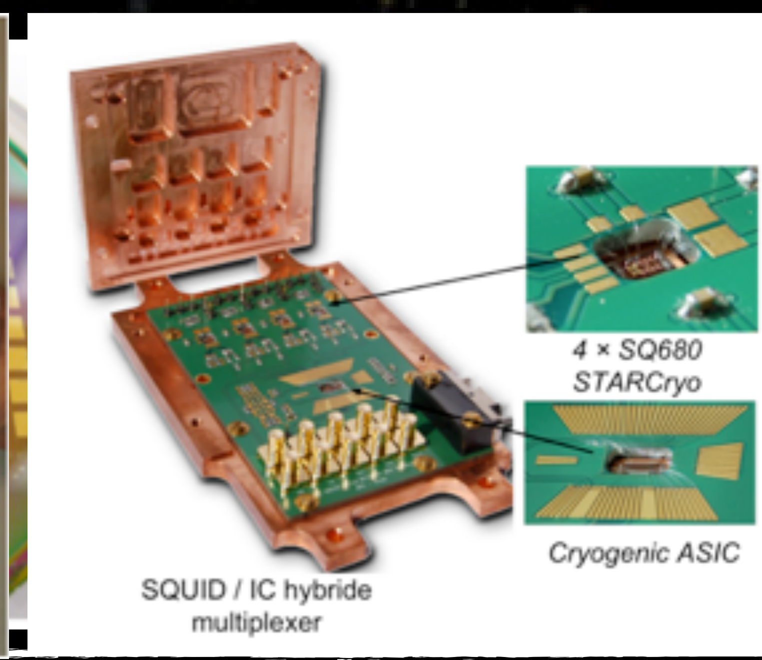
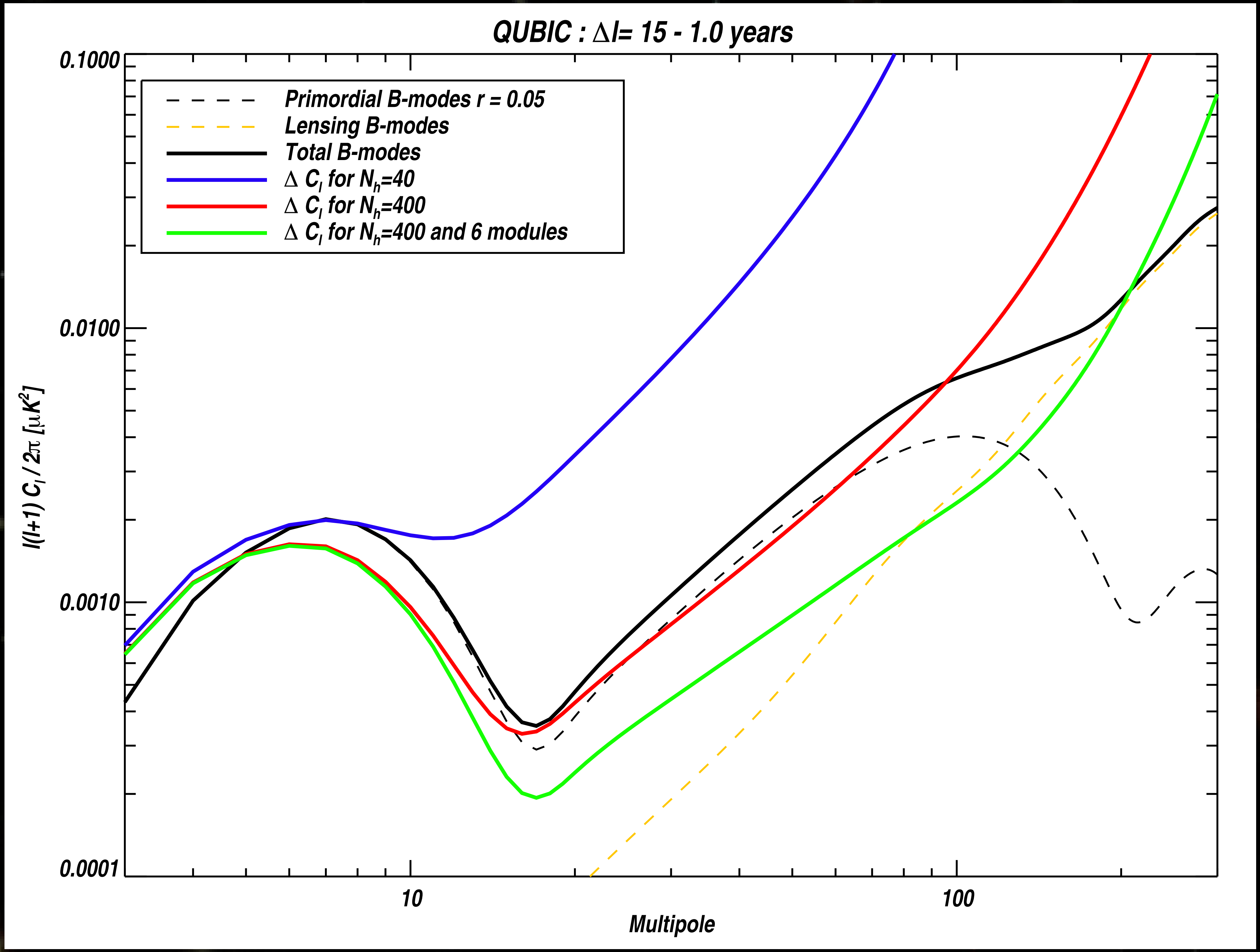


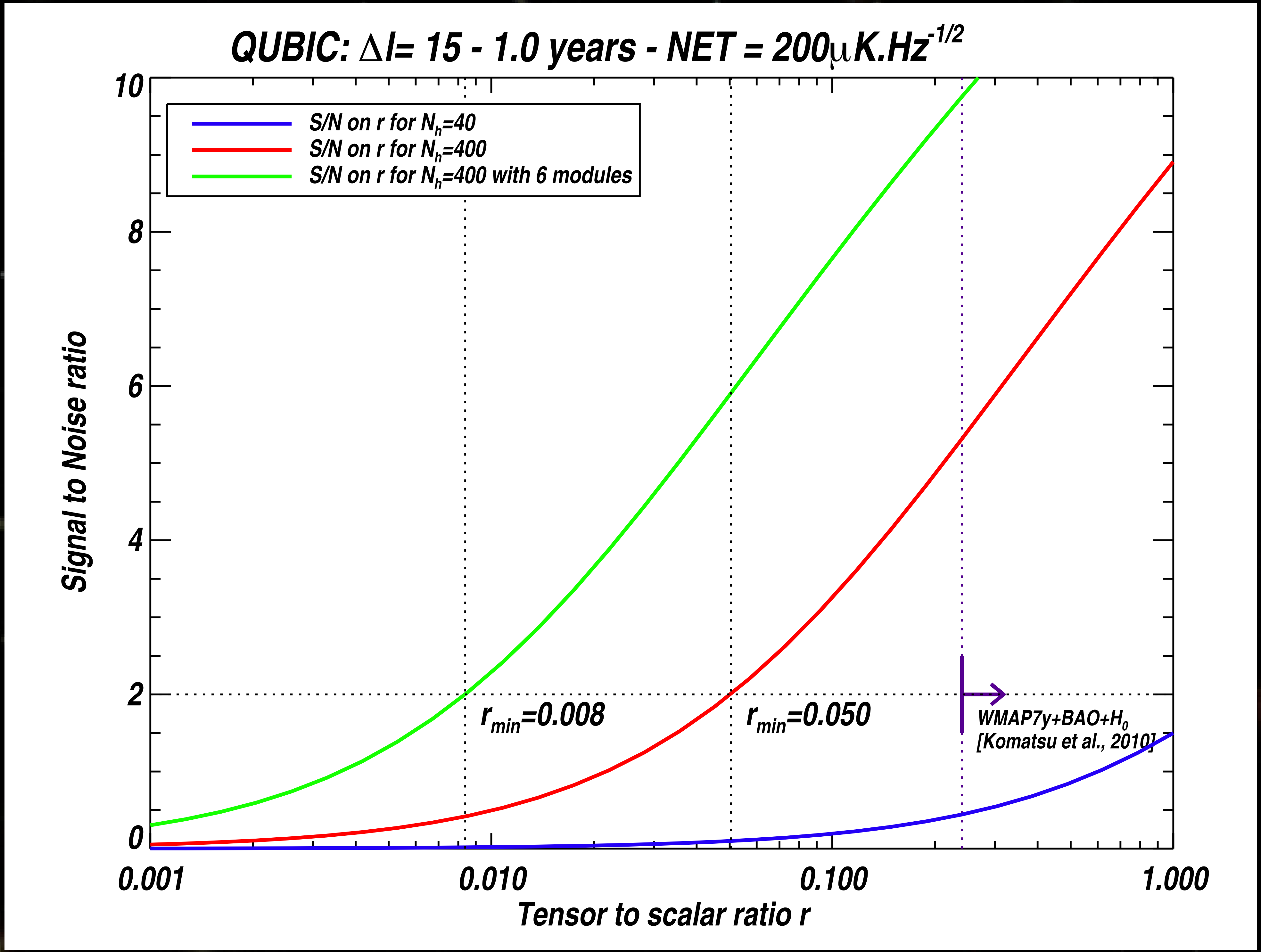




B-mode sensitivity



«r» sensitivity

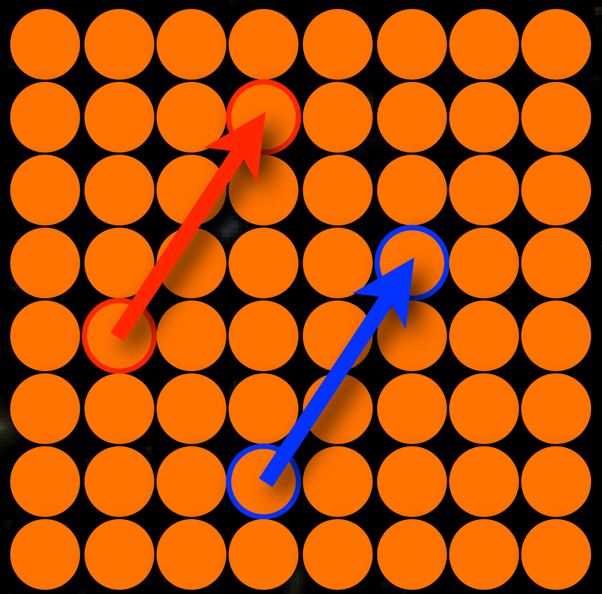


Systematics

- Different from imaging, possibly smaller ...
  - ★ cross-polarization:
    - Telescope cross-polarization in a imager is before the HWP
      - ➡ Modulated as the sky signal
    - In a B.I. the optical combiner is after the HWP
      - ➡ Telescope cross-polarization doesn't spoil Q,U
  - ★ Time constants
    - Slower scanning strategy for B.I.
      - ➡ Low impact of long time constants
  - ★ Beams
    - Lower sidelobes from naked primary horns (no telescope) :
      - ➡ lower ground pickup
    - Synthetized beam known (calculated & calibrated) with excellent accuracy
      - ➡ better controlled at high multipoles
      - ➡ low impact of primary beam differences

Autocalibration

- Autocalibration allows for systematics control
  - ★ Use array redundancy [e.g. Wieiringa, 1991 - Tegmark & Zaldarriaga, 2010]
    - Redundant baselines: same visibility if no sytematics
    - Model systematics using Jones matrices (gains and coupling / channel / pixel)
    - Open 2 horns at a time (close the rest: implies switches between back-to-back horns)
    - Construct a system of equations : overconstrained if Nhorns > 20
  - ★ recover systematics/channel/pixel with a polarized source !



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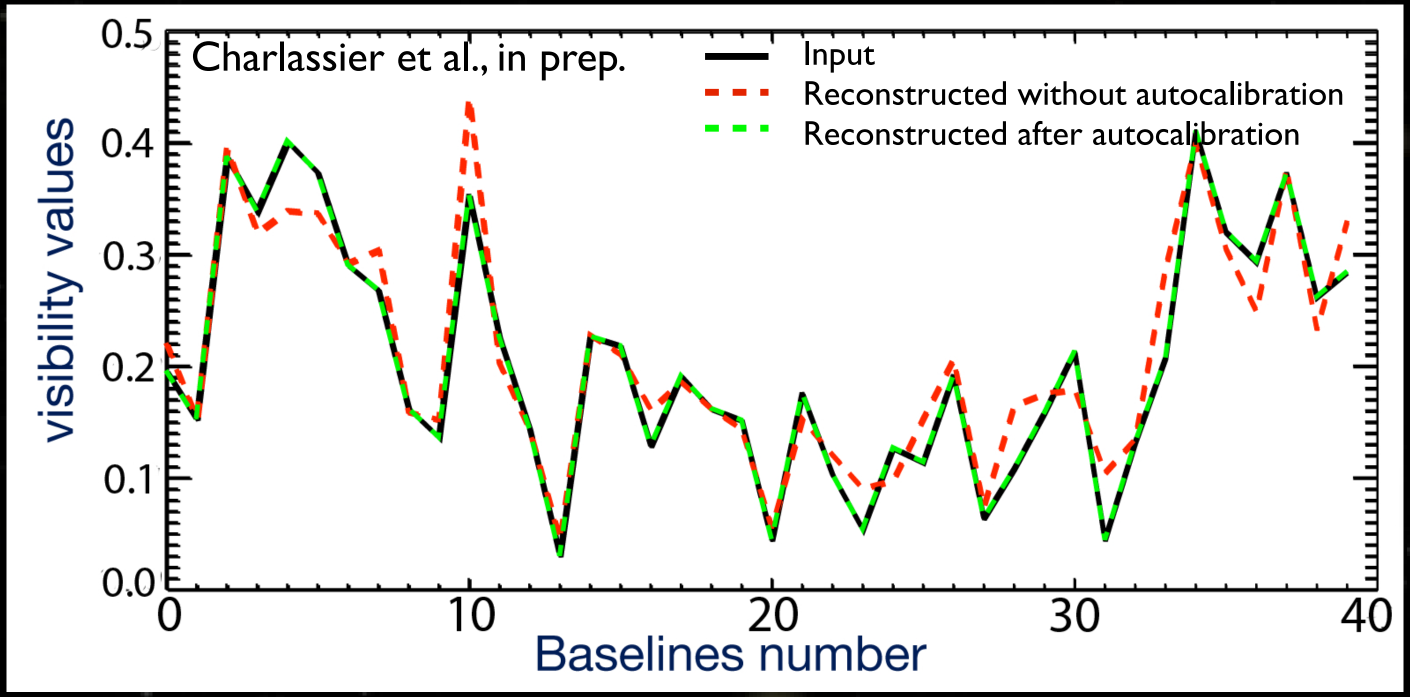

Back of the envelope : NET=300 μK.Hz$^{-1/2}$ and 100 K source : ~ 3x10^{-6} on each syst. coeff. with 1 sec/baseline

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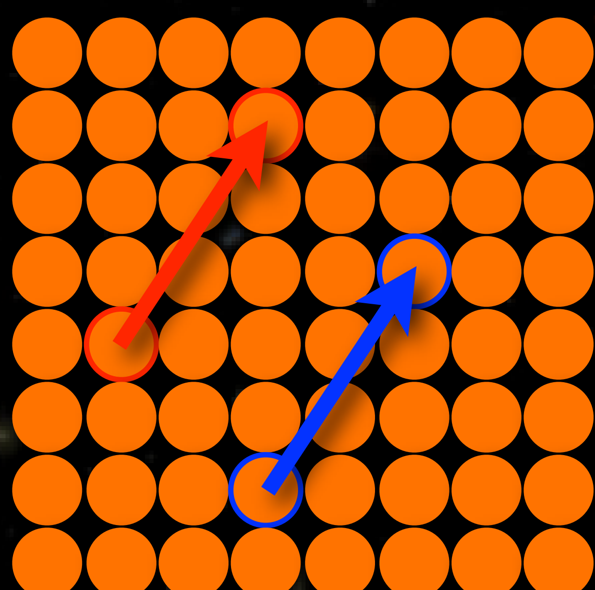

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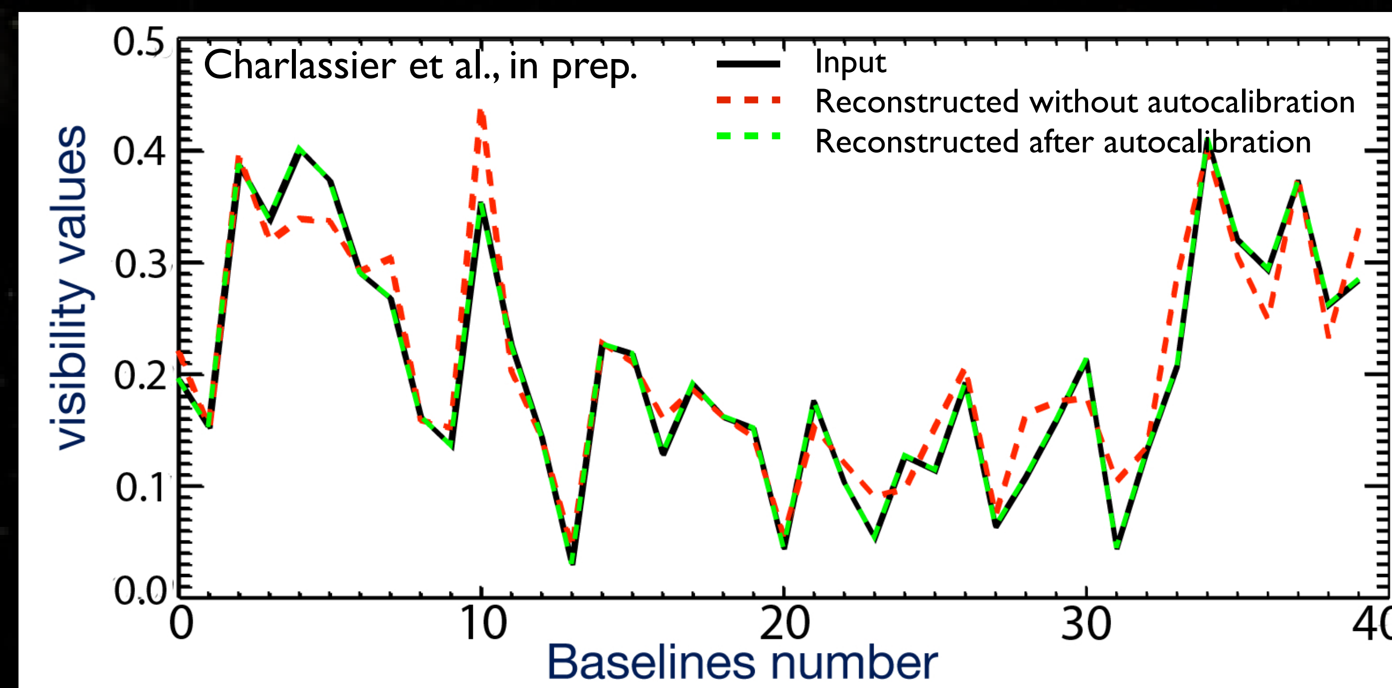

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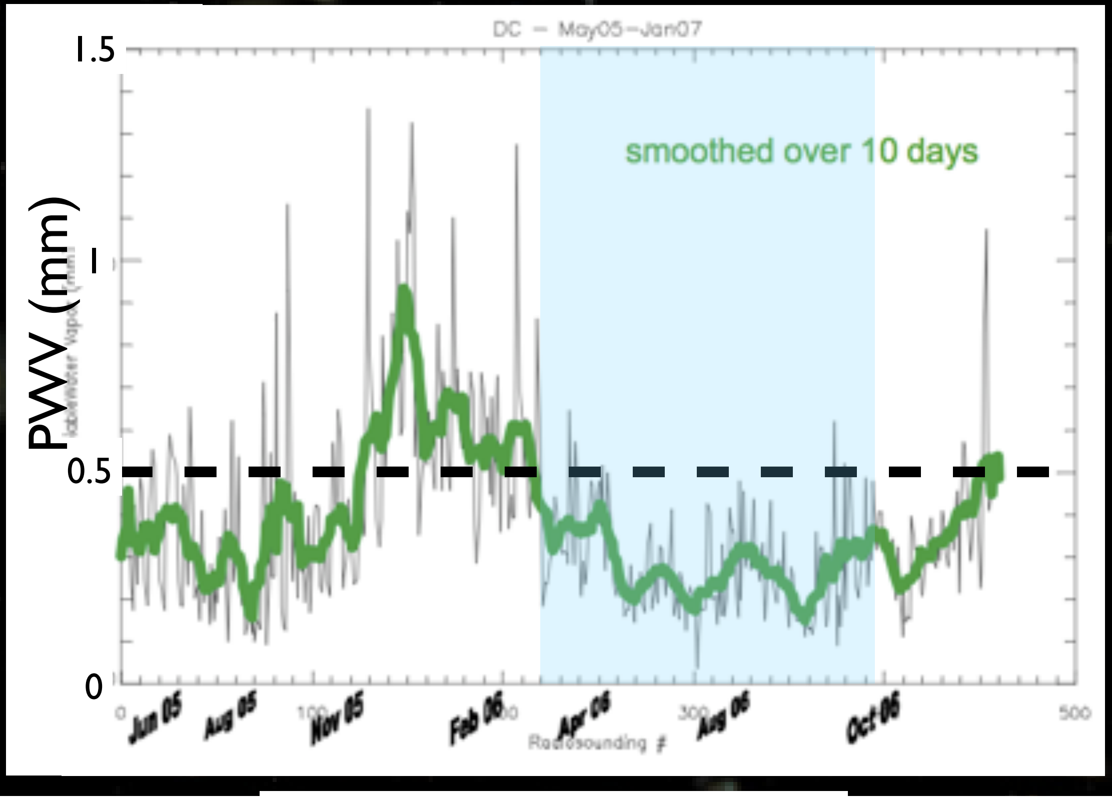
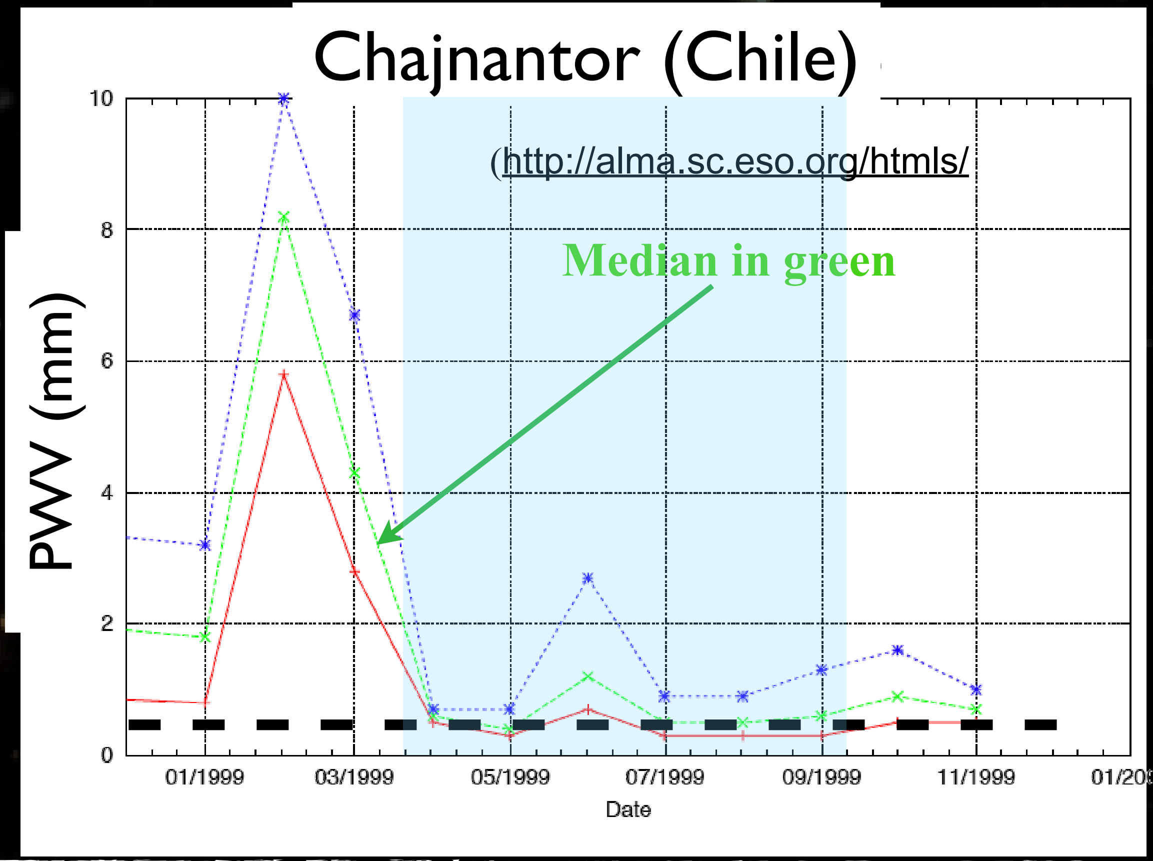
B.I. allows for internal systematic effects measurement

Dôme C, Antarctica

- French-Italian station
  - ★ 3000 m a.s.l.
- Excellent CMB site
  - ★ 24h observations at high elevation
  - ★ PWV < 0.5 mm in winter
  - ★ PWV < 1.5 mm in summer
  - ★ Equivalent atmospheric brightness
    - 14K at zenith (16.5K in Chajnantor, 21K @45deg)





reducing T_{atm} by 30%

↓

reducing integration time by 30%

+ another ~50% as PWV< 1mm most of the time

Summary and prospects

- QUBIC is a novel instrument for CMB polarimetry
  - ★ Synthetic imager: hybrid between imager and interferomter
  - ★ High sensitivity
  - ★ Low and controlable systematics
  - ★ Technology readiness: quite high finally ... almost everything on the shelf
  - ★ [only way to get an inexpensive 400 elements interferometer]

- Plans:
  - ★ First module: 2013 - 2014 (~1 M€ - not funded yet ...)
    - 400 elements, 150 GHz, 25% BW, primary beam 14 deg., 1024x2 detectors
    - Integration and first light in lab: 2013
    - Observations in 2014 from Dome C, Antarctica : r~0.05 at 90% C.L. with 1 year
  - ★ Longer term:
    - 6 modules at 90, 150 and 220 GHz
    - Observations from Dome C, Antarctica: r ~ 0.01 at 90% C.L. with 1 year