Exploring the primordial Universe with QUBIC

the Q U Bolometric Interferometer for Cosmology

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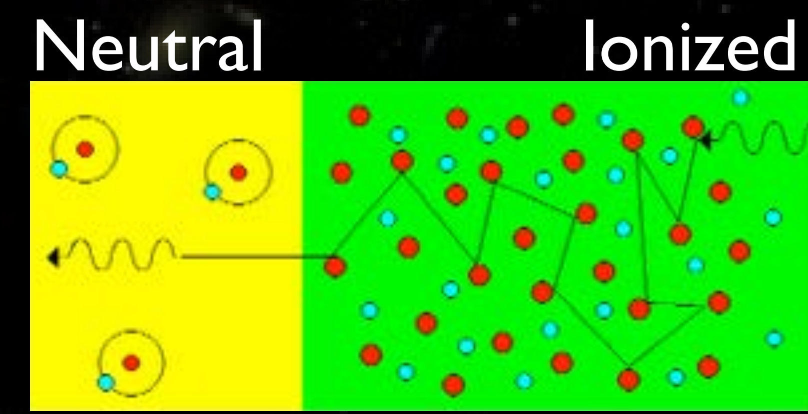
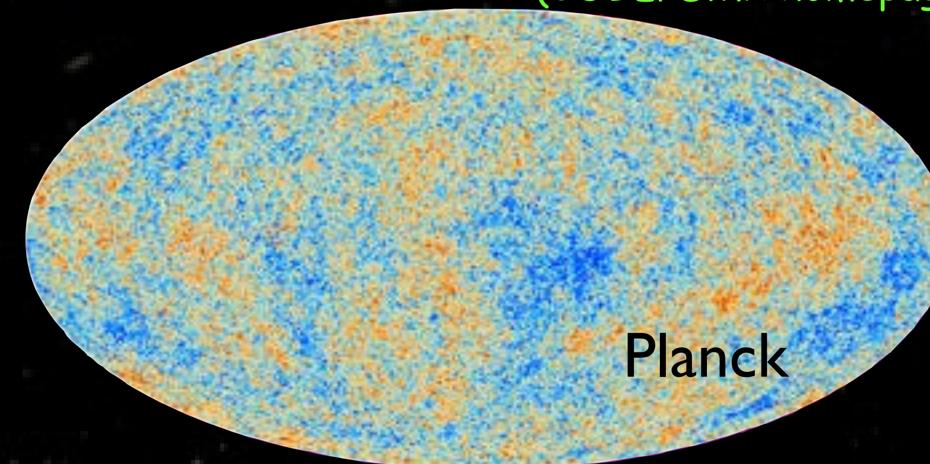
CMB Physics

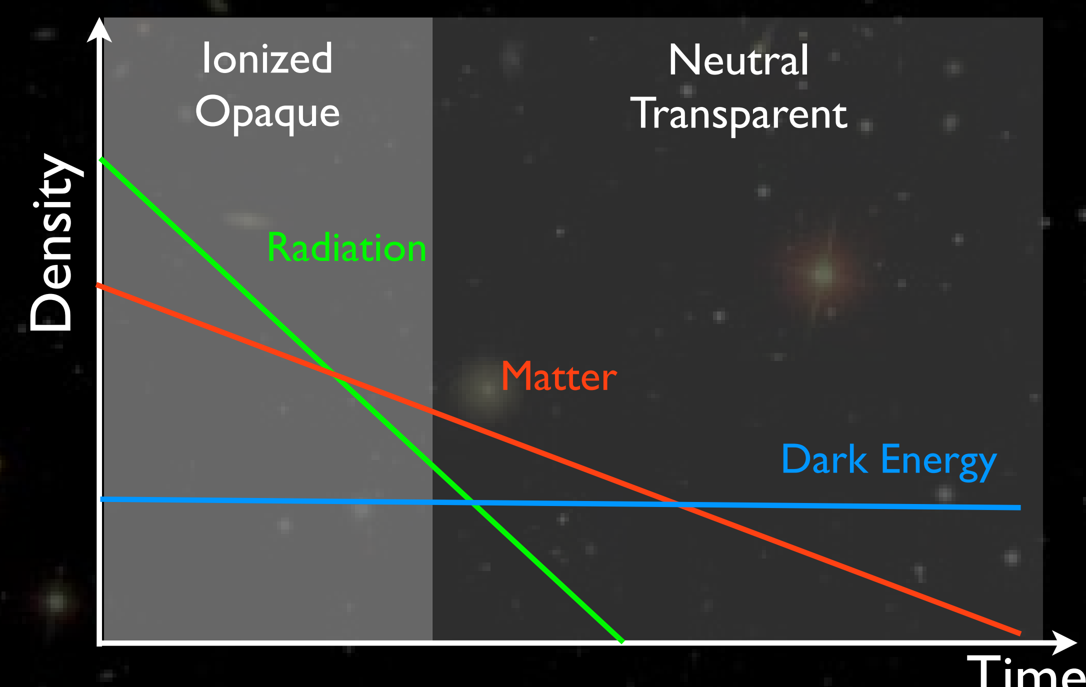
- **Origin**
  - ★ Early Universe
    - Ionized ⇒ opaque to photons
    - thermal equilibrium
  - ★ T << 13.6 eV
    - Neutral ⇒ matter/radiation decoupling
    - CMB emitted. Blackbody at 3000K (z=1000)
    - Now blackbody at 3K



(COBE/DMR homepage)



- **Shape**
  - ★ Early Universe radiation dominated
    - Matter (Dark + Baryons) cannot collapse efficiently because of radiation
  - ★ at Matter/Radiation equality
    - Baryons collapse in Dark Matter perturbations
    - Acoustic oscillations start, coherent w.r.t. scale
  - ★ At Matter/Radiation decoupling
    - Oscillations frozen
    - CMB temperature reflects density fluctuations



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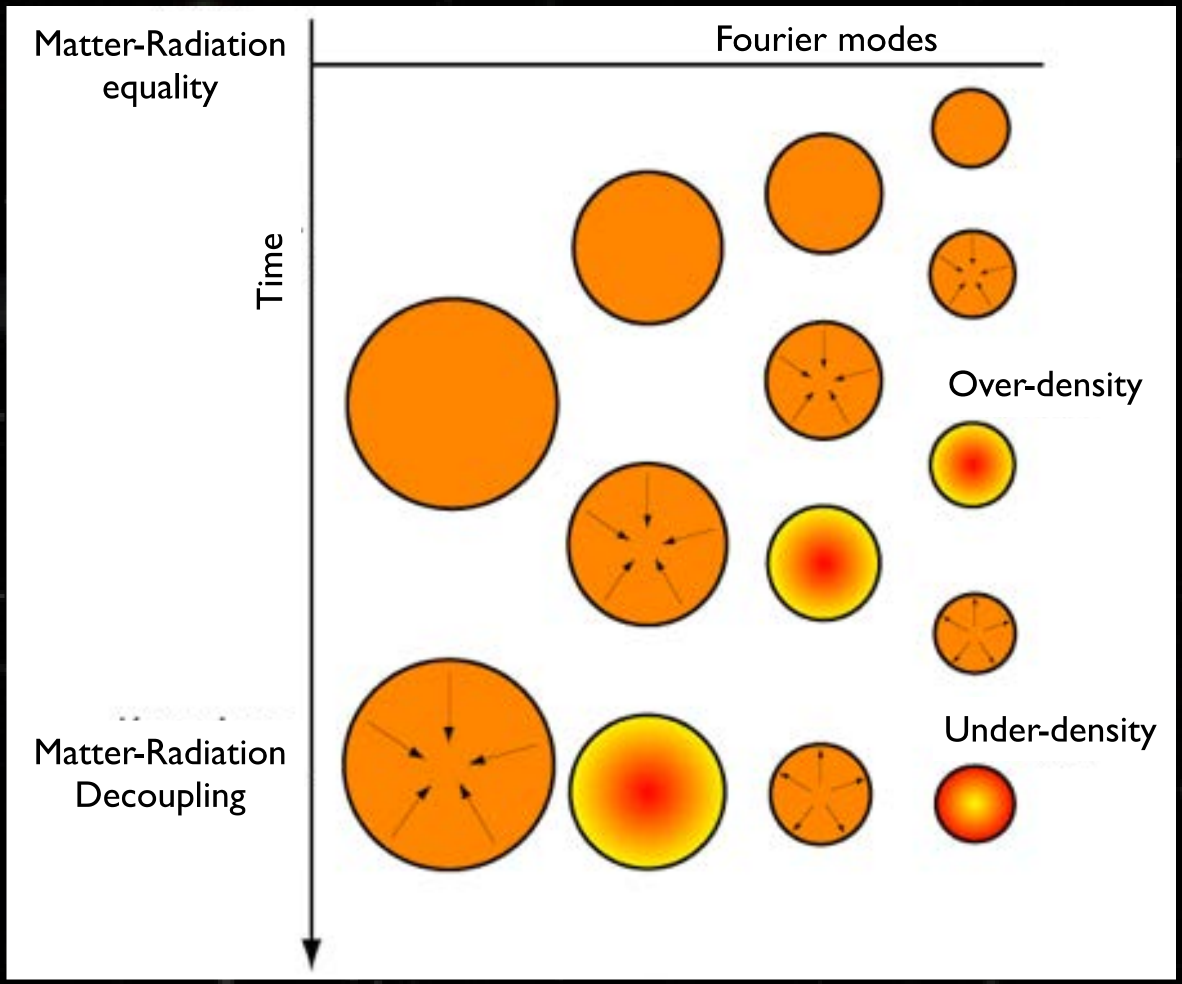
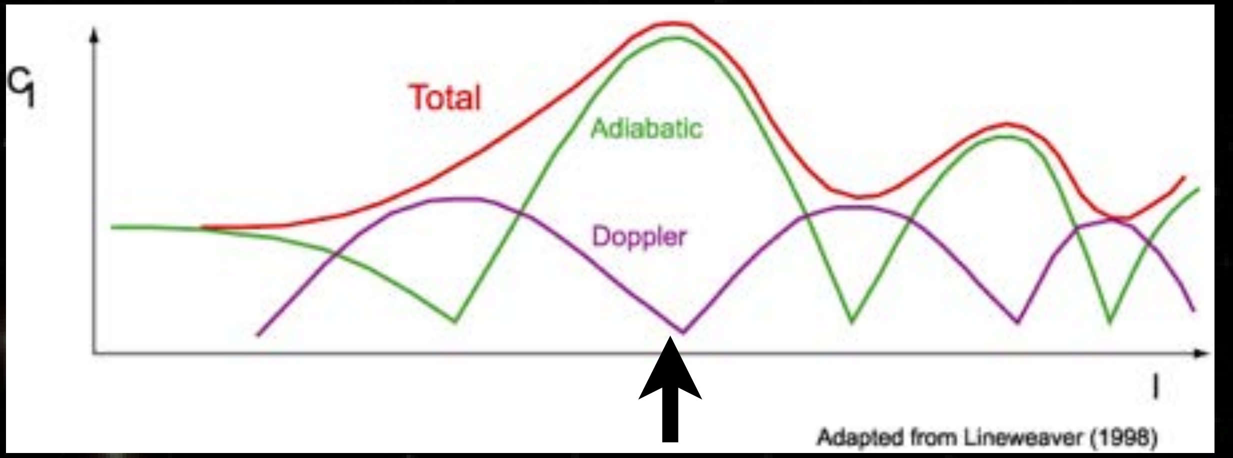
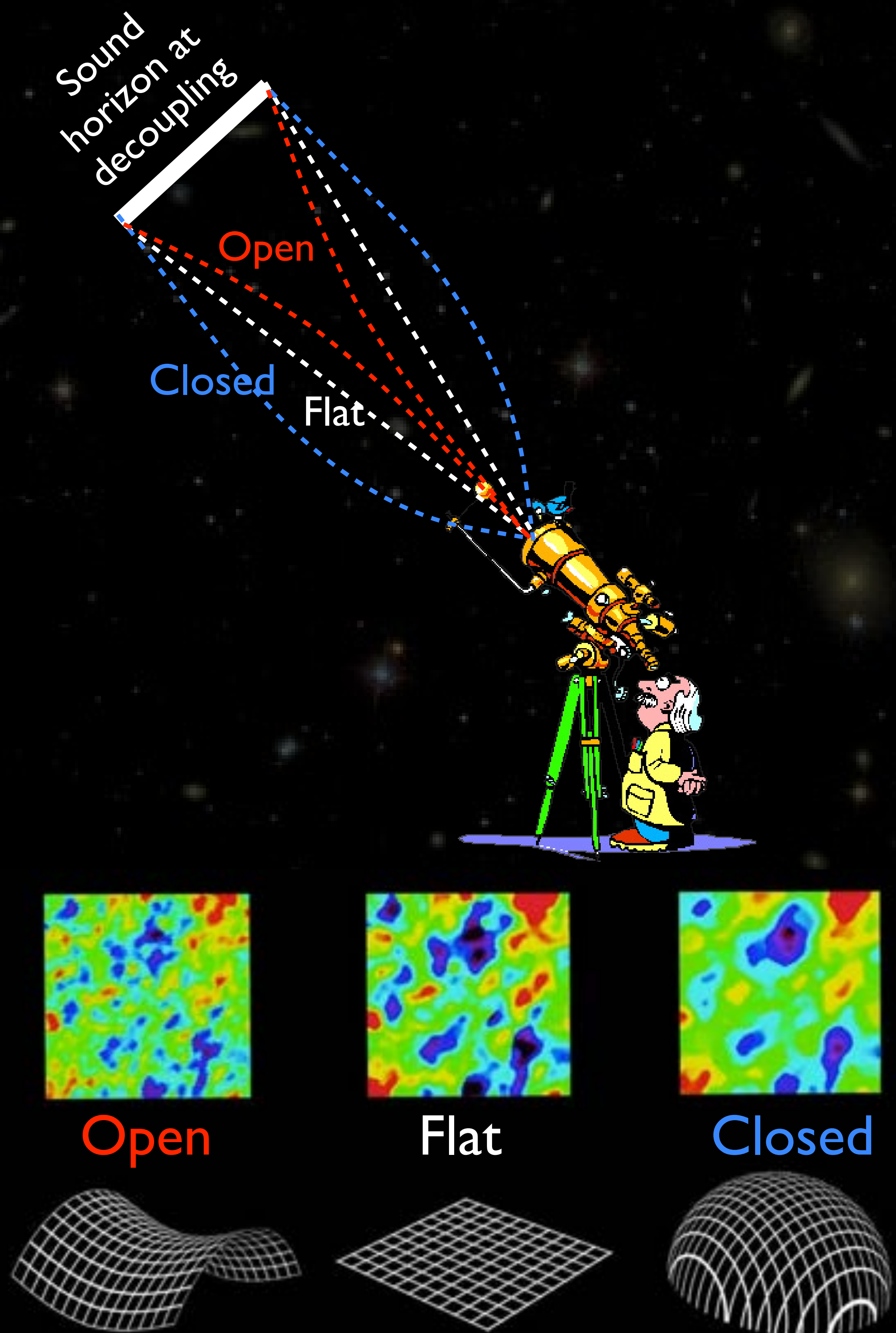
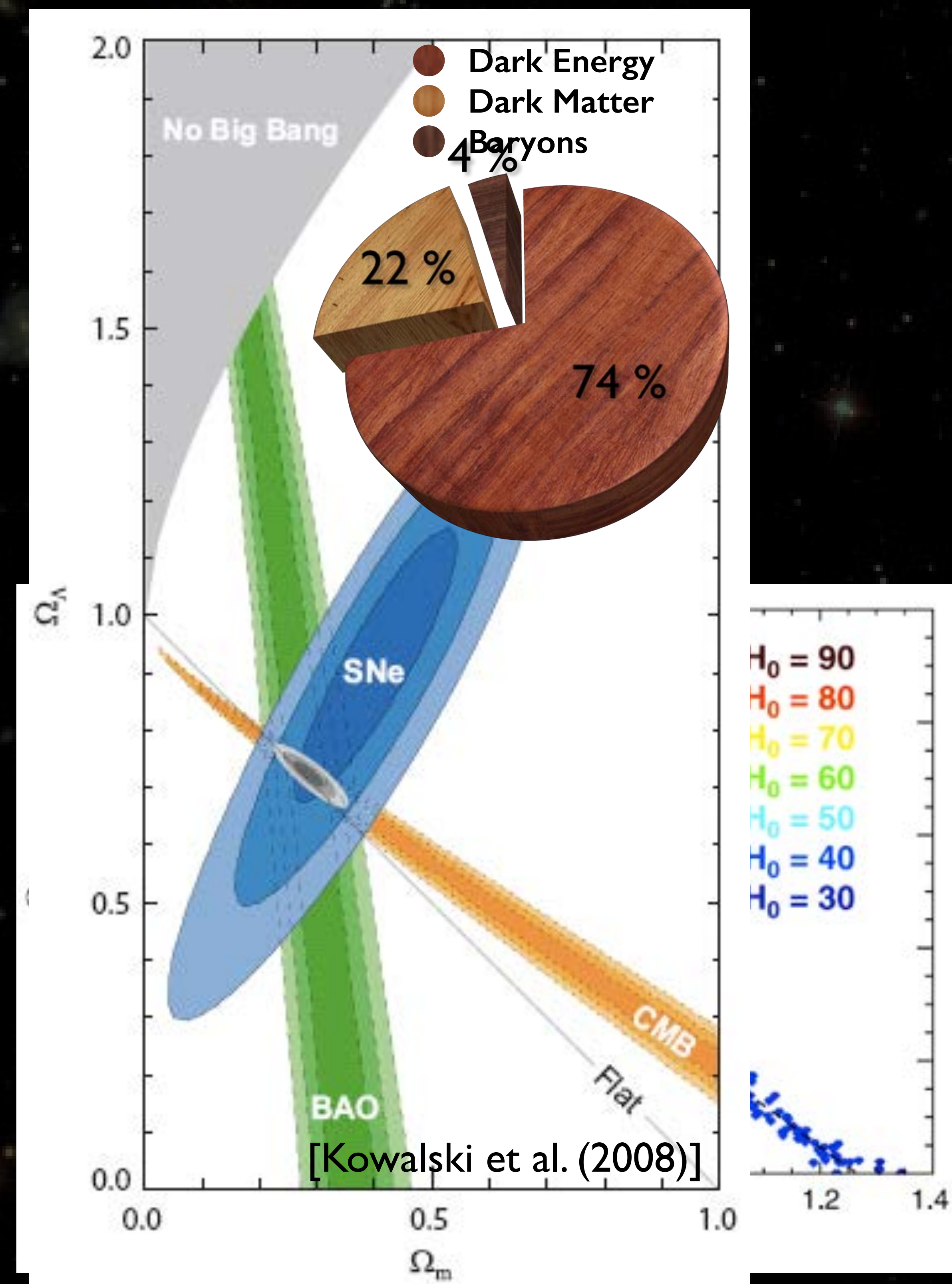




150 Mpc @ z=1000

Influence of the cosmological parameters

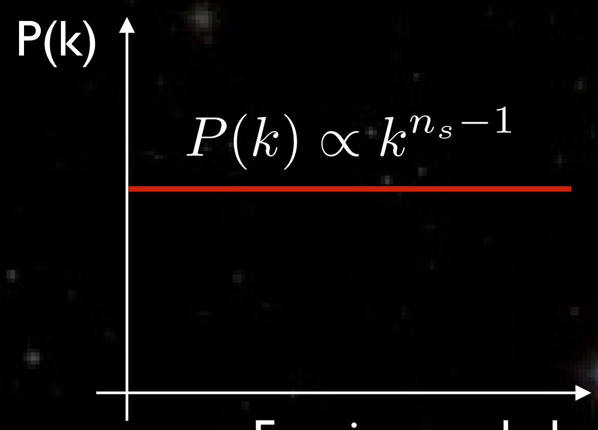


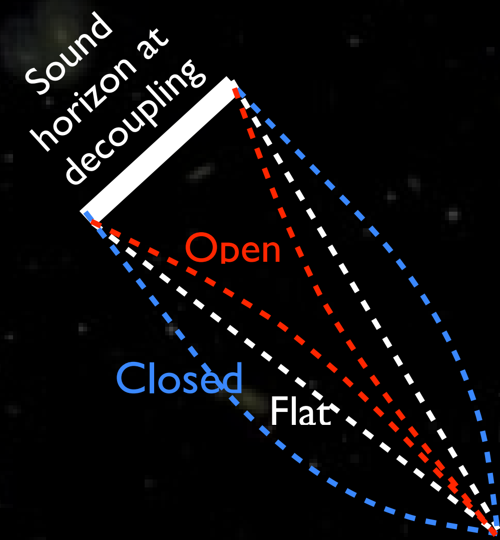


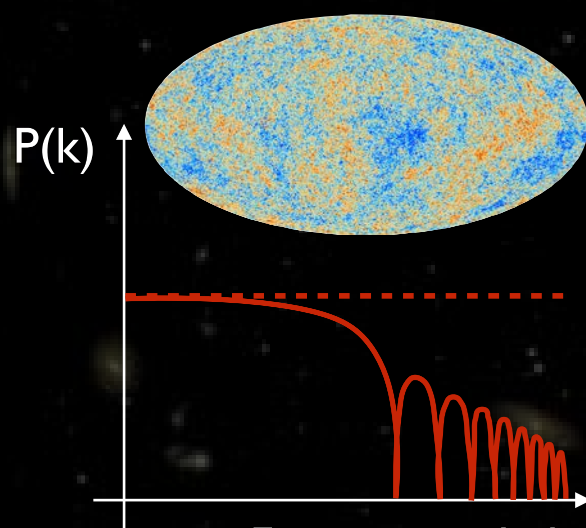
WMAP 7y

Density Field Transfer Function

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







<u>Take-home message</u>

- Density perturbations evolve from end of inflation to decoupling due to matter-radiation oscillations.
- The **<u>transfert function</u>** depends upon « simple physics » and cosmological parameters
- Allows to fit both cosmology and primordial spectra

Relating maps to cosmology

- Spherical Harmonics Expansion

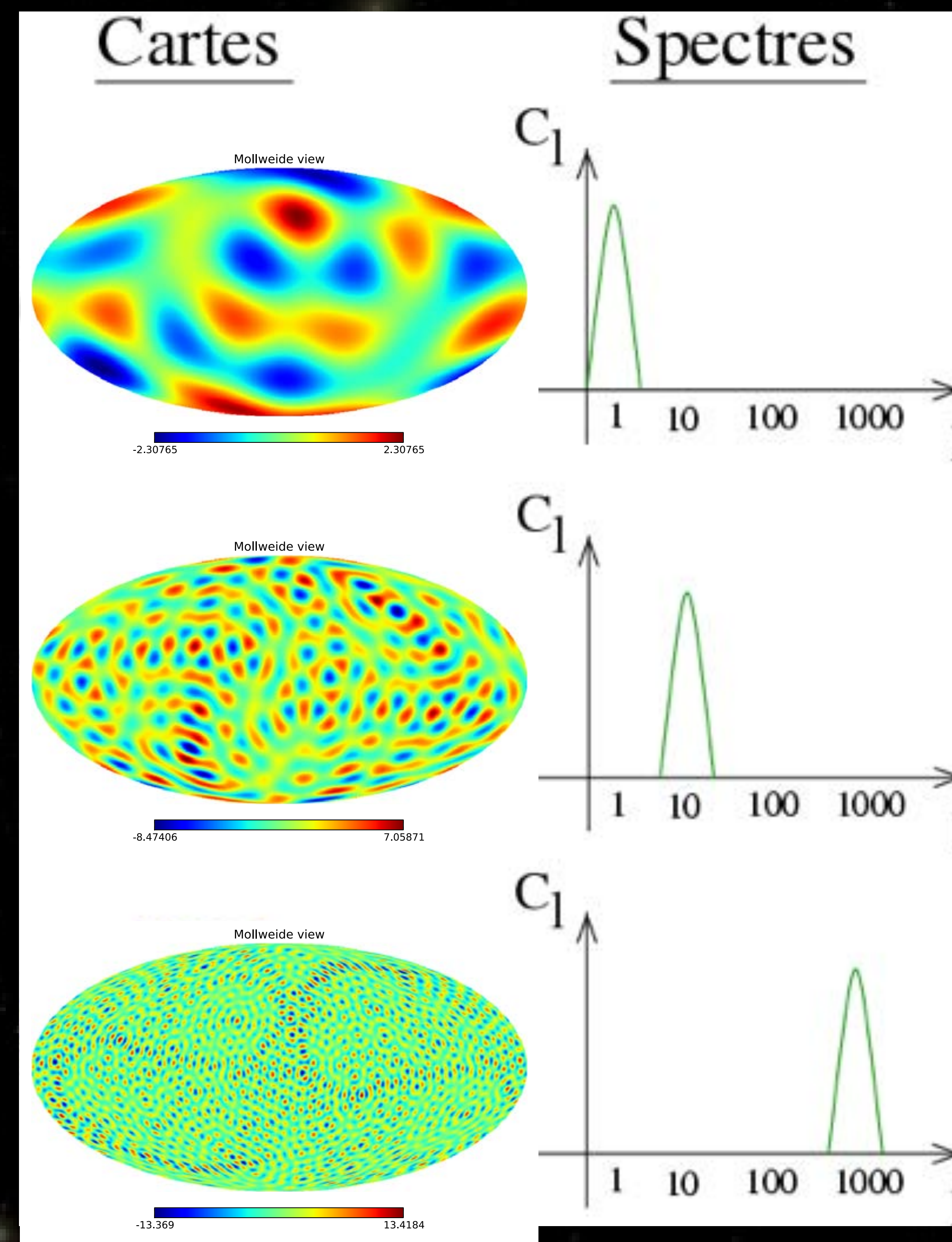
$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{\ell=0}^{\infty}\sum_{m=\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

- Angular power spectrum

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

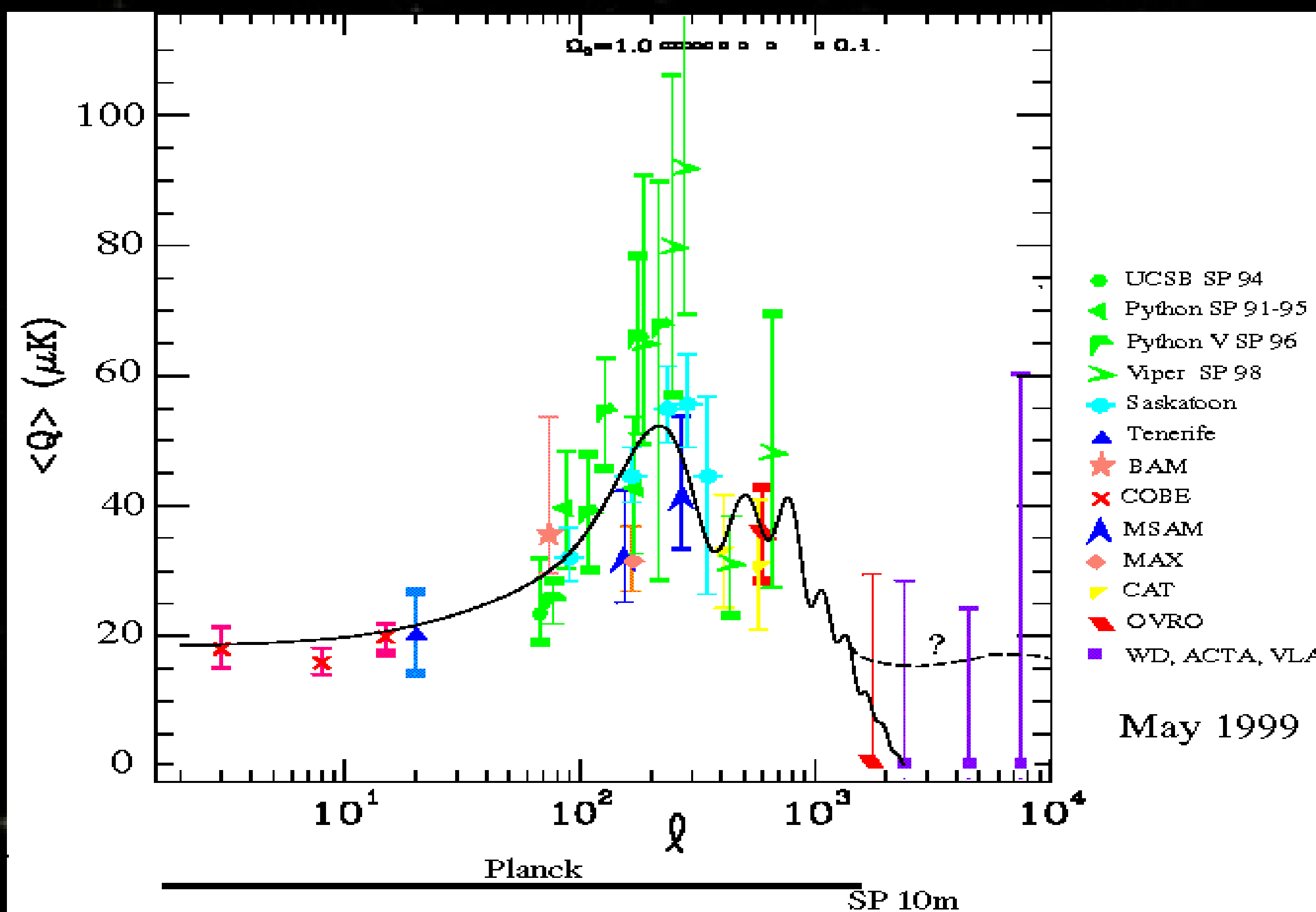
- ℓ is the inverse of an angle

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

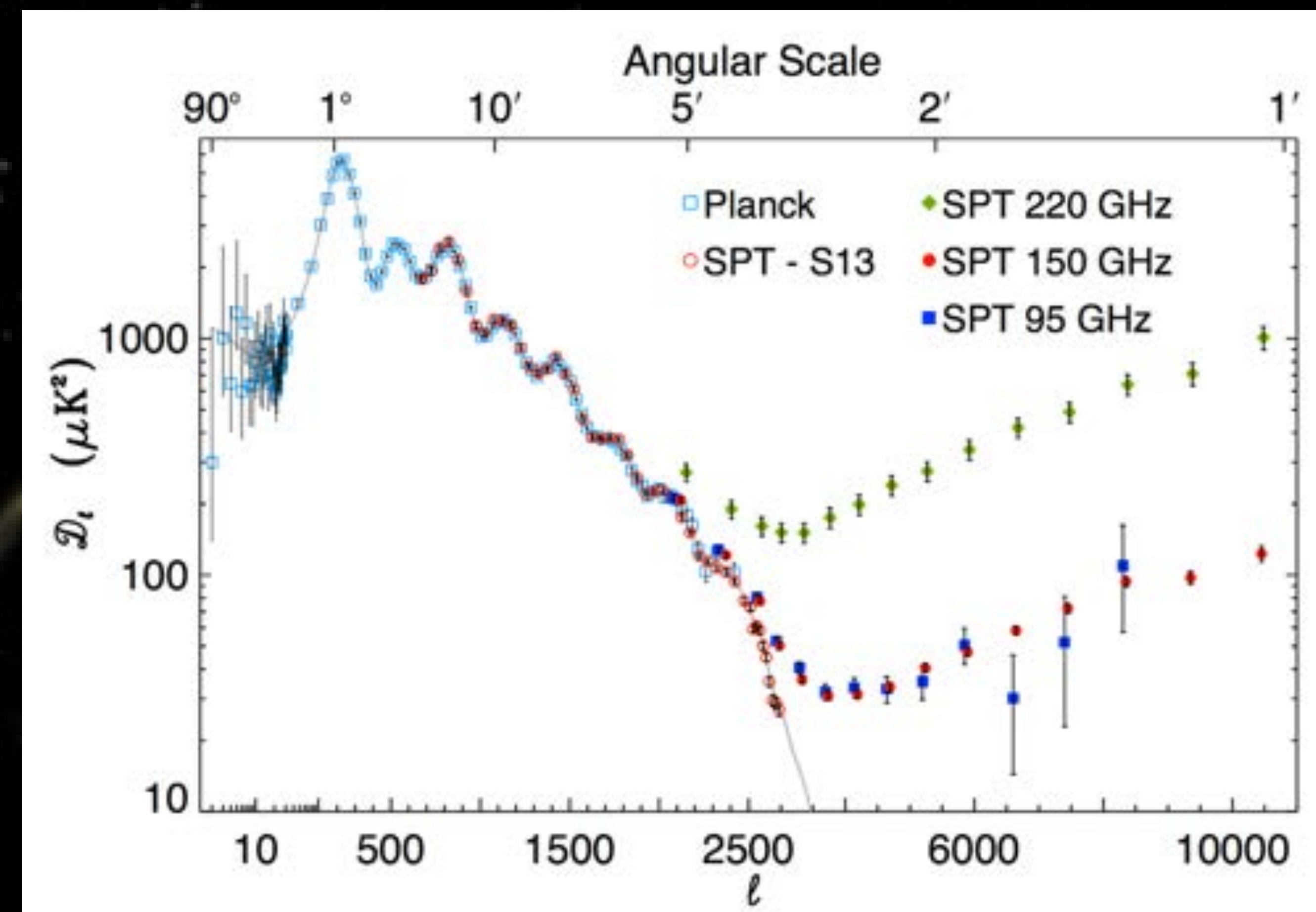


B. Revenu

CMB: Tremendous progress over

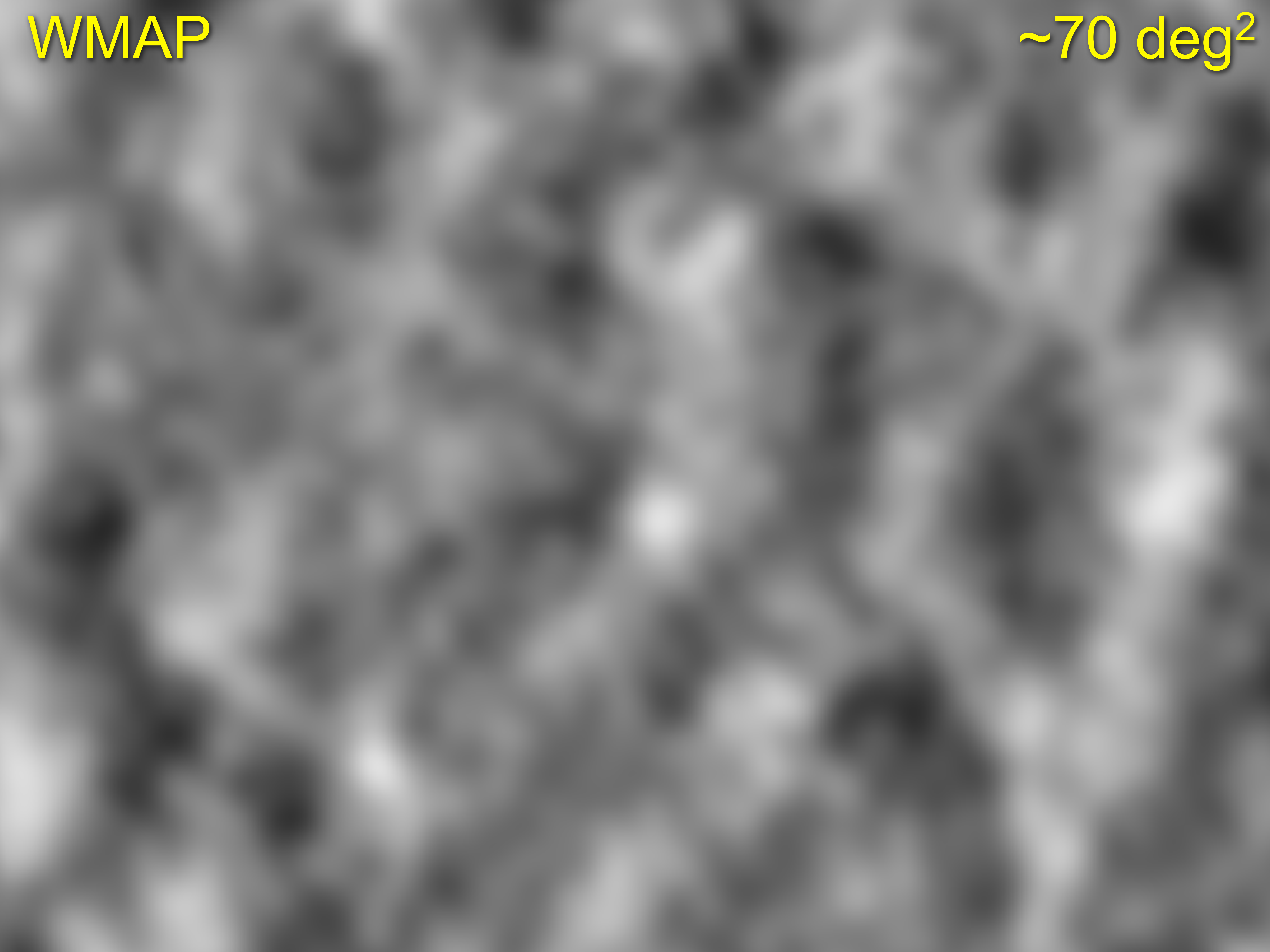


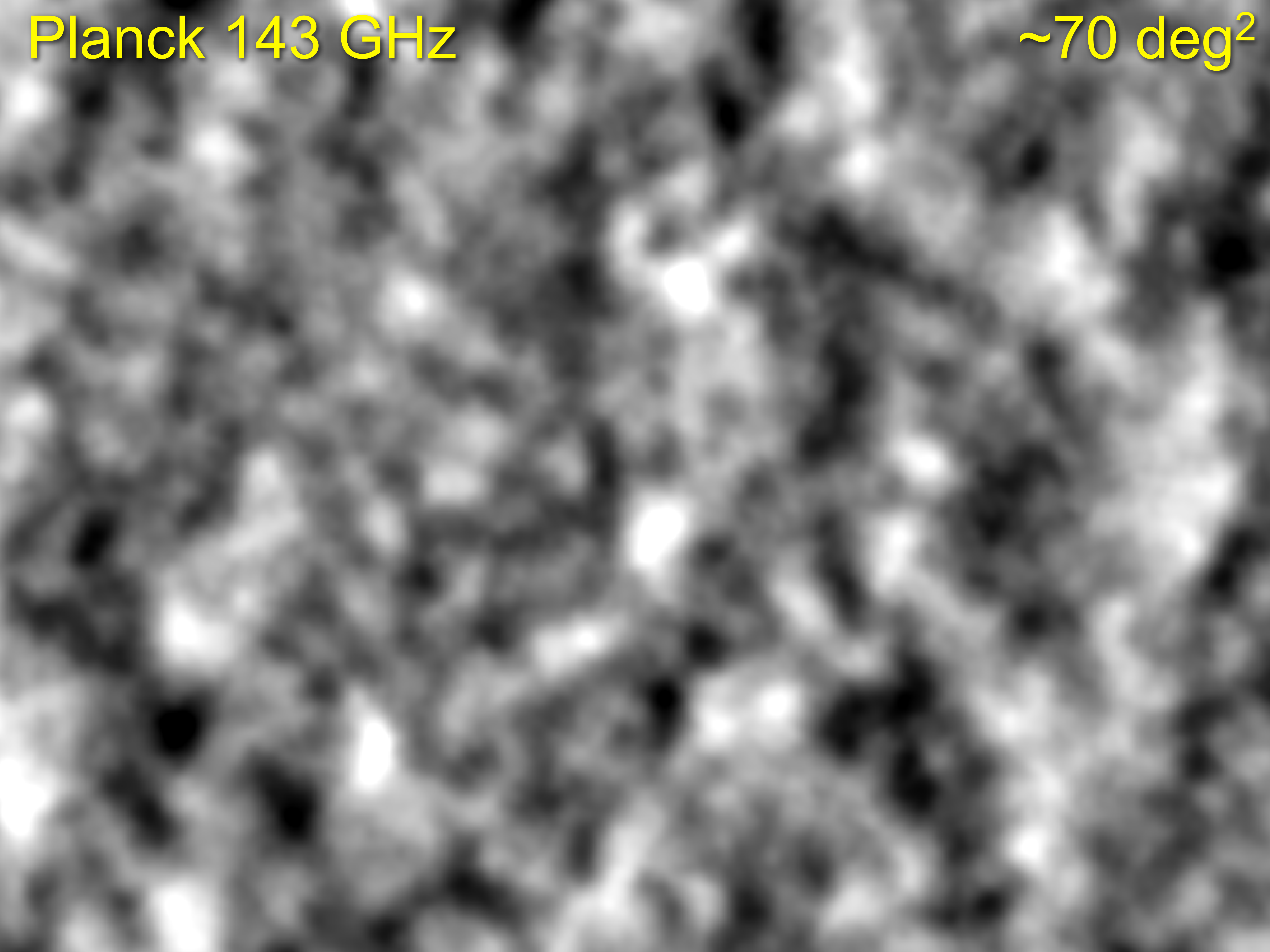
1999

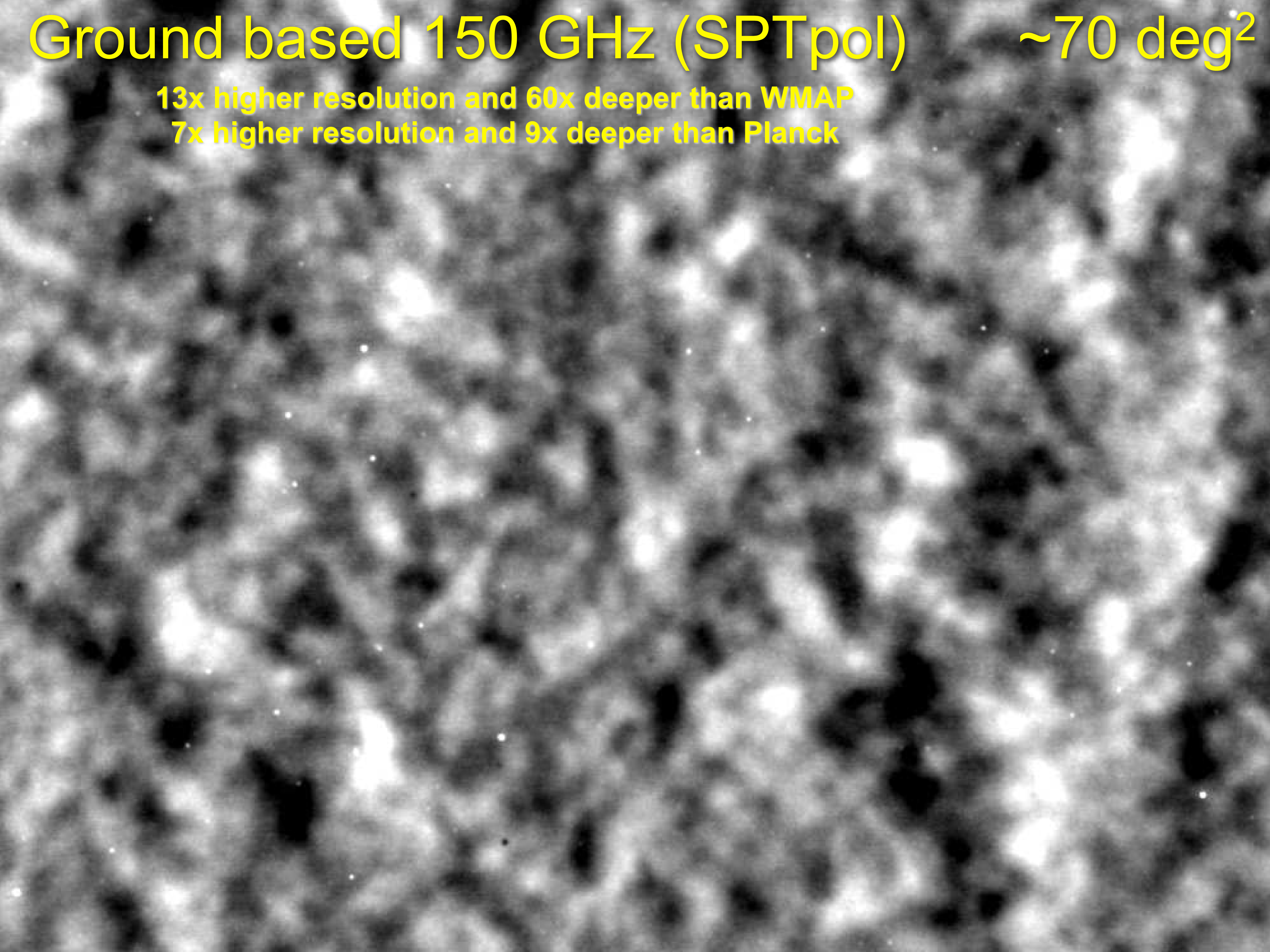


2014

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. [Also by Zeldovith, Sunyaev et al. in 1972 !!!]

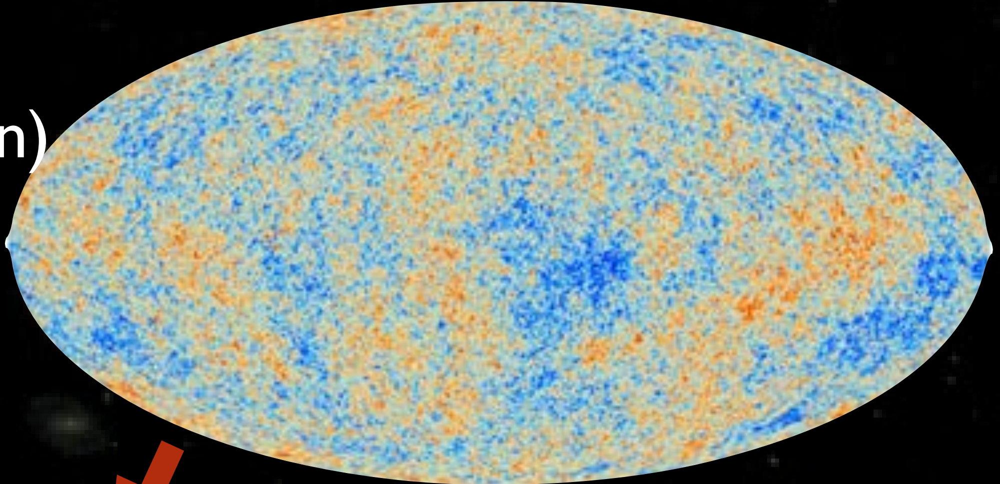

WMAP
~70 deg^2

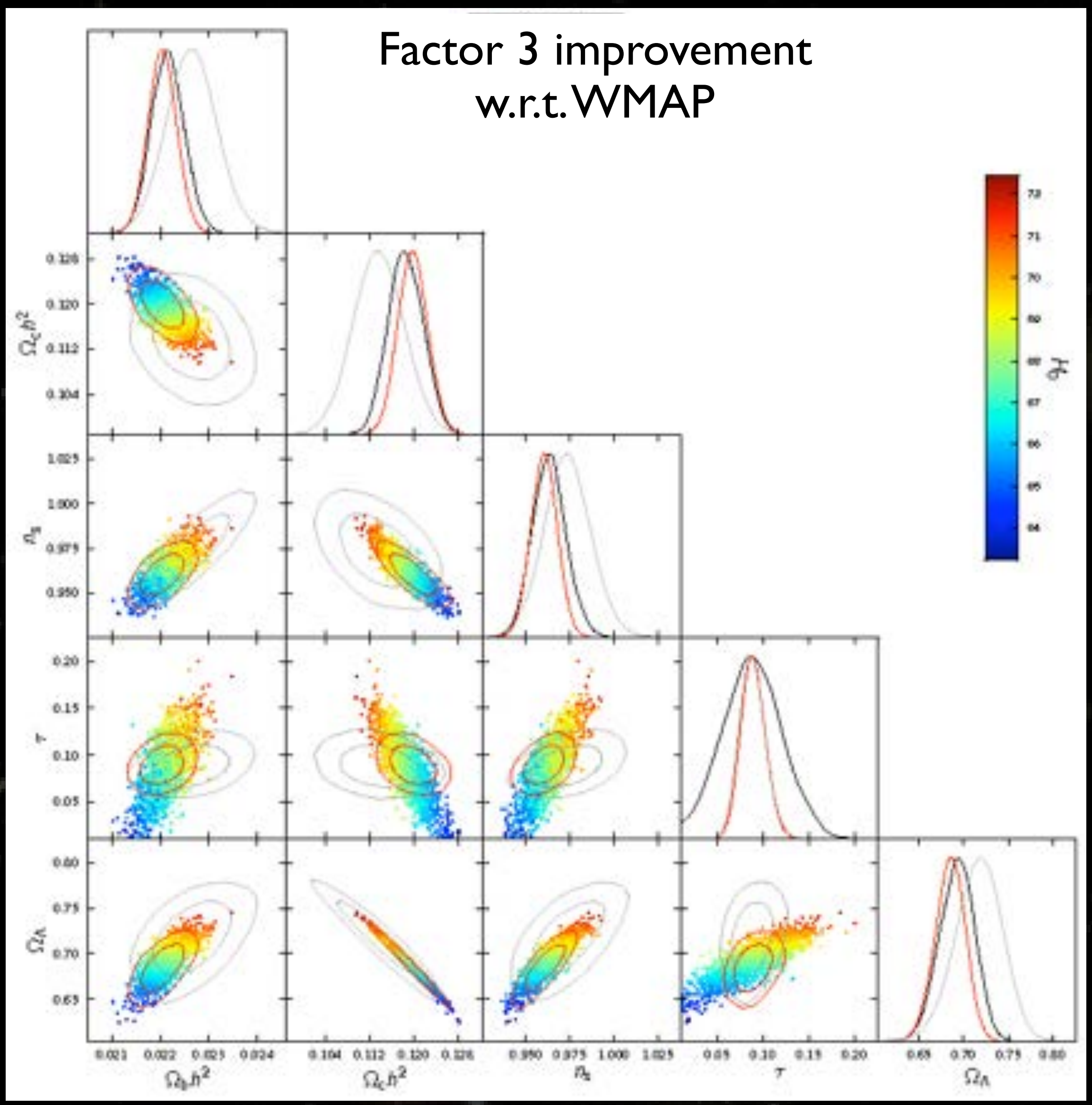

Planck 143 GHz
~70 deg^2

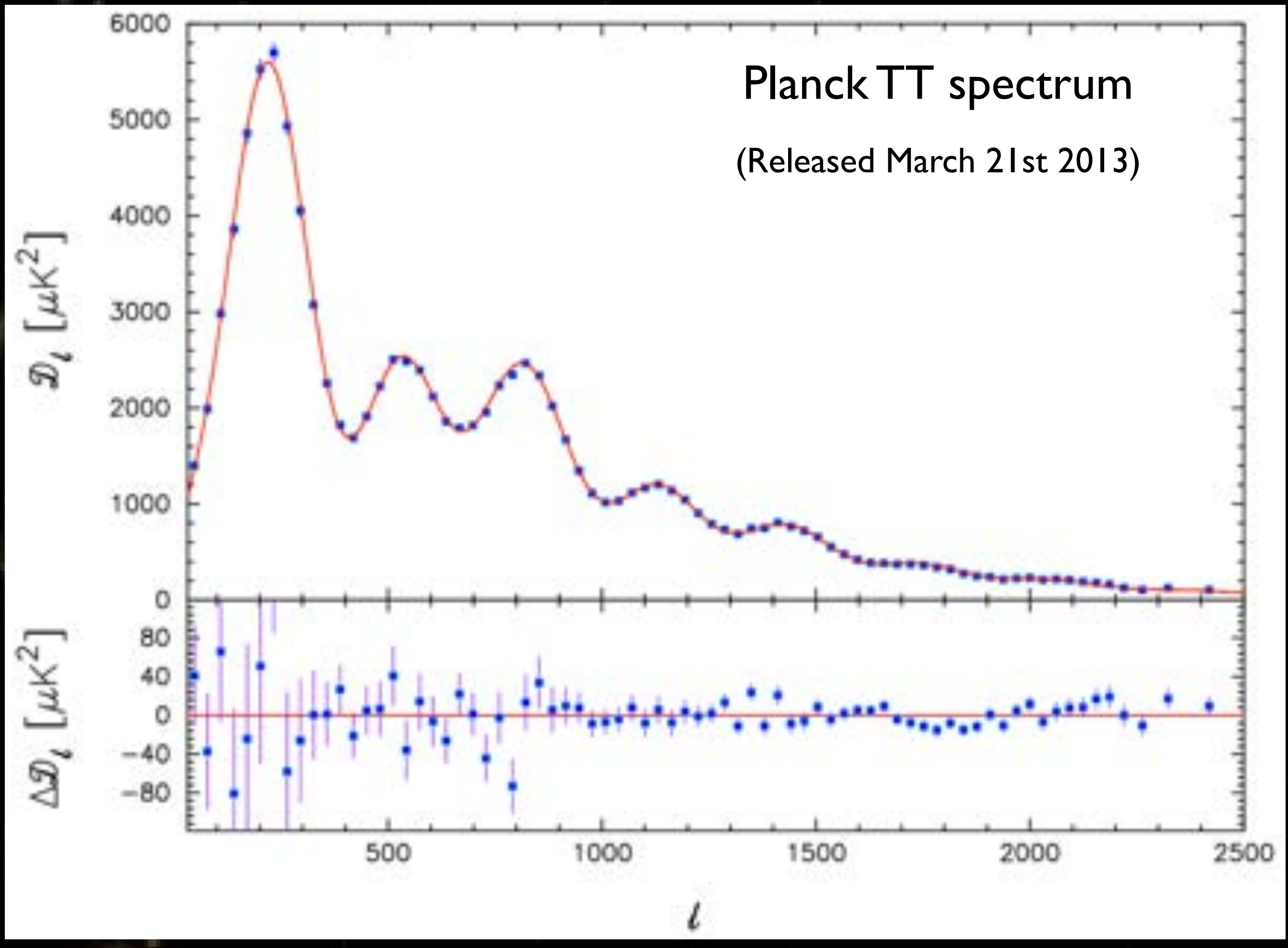

Ground based 150 GHz (SPTpol)
~70 deg^2
13x higher resolution and 60x deeper than WMAP
7x higher resolution and 9x deeper than Planck

Planck Results: ΛCDM firmly Established

Planck
(ESA Mission)



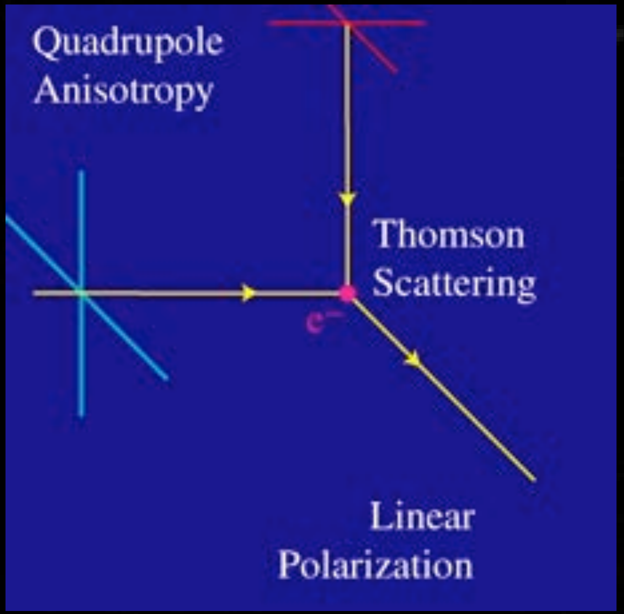




Next (current actually !) step: Inflation Physics through CMB Polarization

CMB Polarization (~10%)

- Generated by Thomson scattering
  - ★ electrons in quadrupolar motion falling into Dark Matter potential wells before decoupling



W. Hu

- Stokes Parameters (linear pol.)

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

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

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

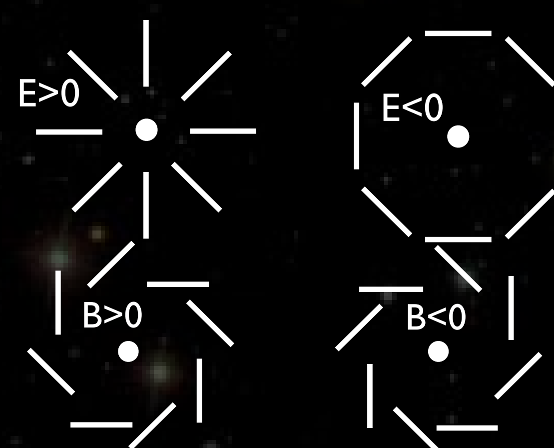
- Scalar E and B fields

$$a_{E,\ell m} = -\frac{a_{2,\ell m} + a_{-2,\ell m}}{2}$$

$$a_{B,\ell m} = i\frac{a_{2,\ell m} - a_{-2,\ell m}}{2}$$

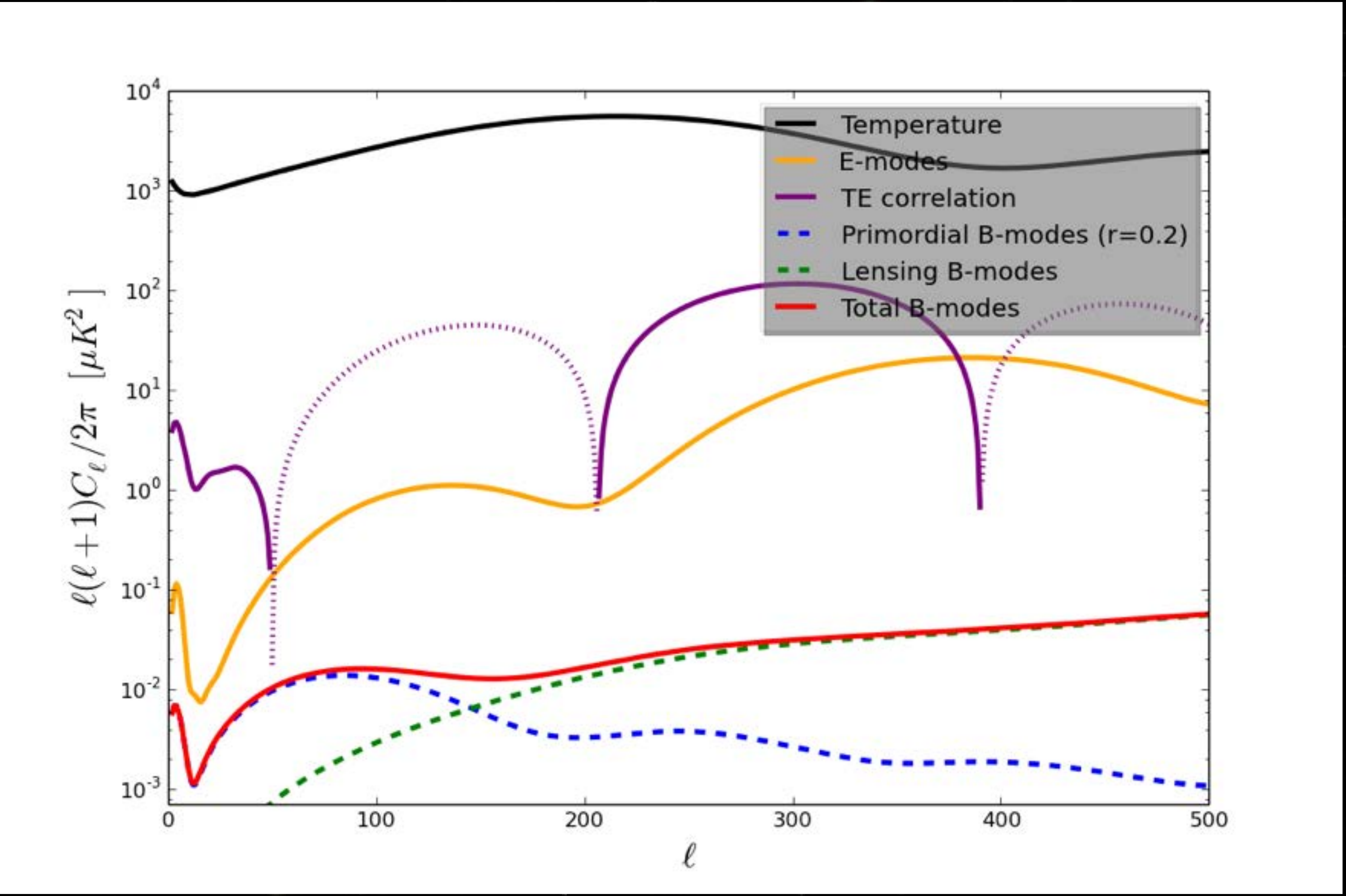
(even)

(odd)



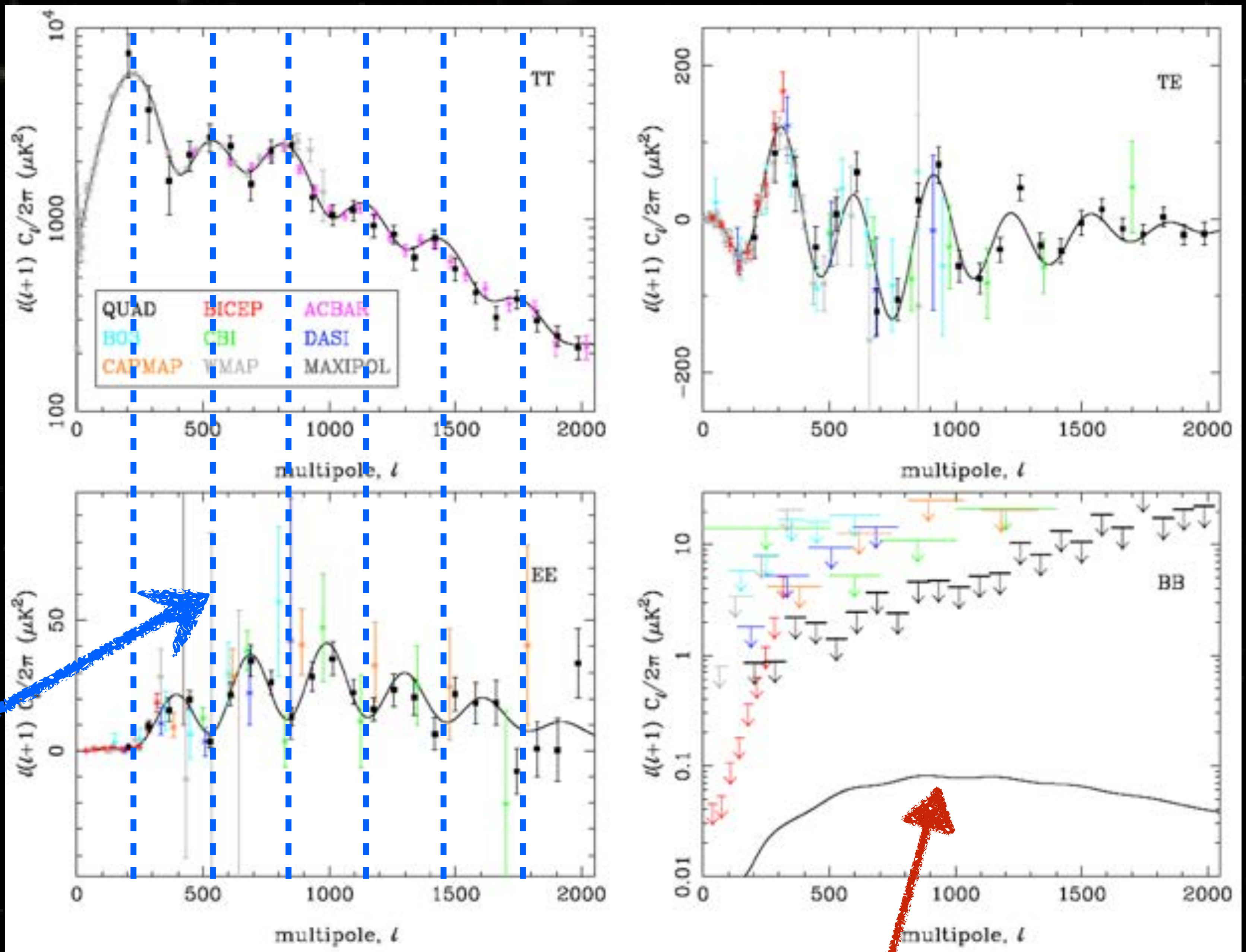
C_ℓ^{TT} C_ℓ^{TE} C_ℓ^{EE} C_ℓ^{BB}

CMB Spectra


Temperature
E-modes
TE correlation
Primordial B-modes (r=0.2)
Lensing B-modes
Total B-modes
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
ℓ
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
100
200
300
400
500

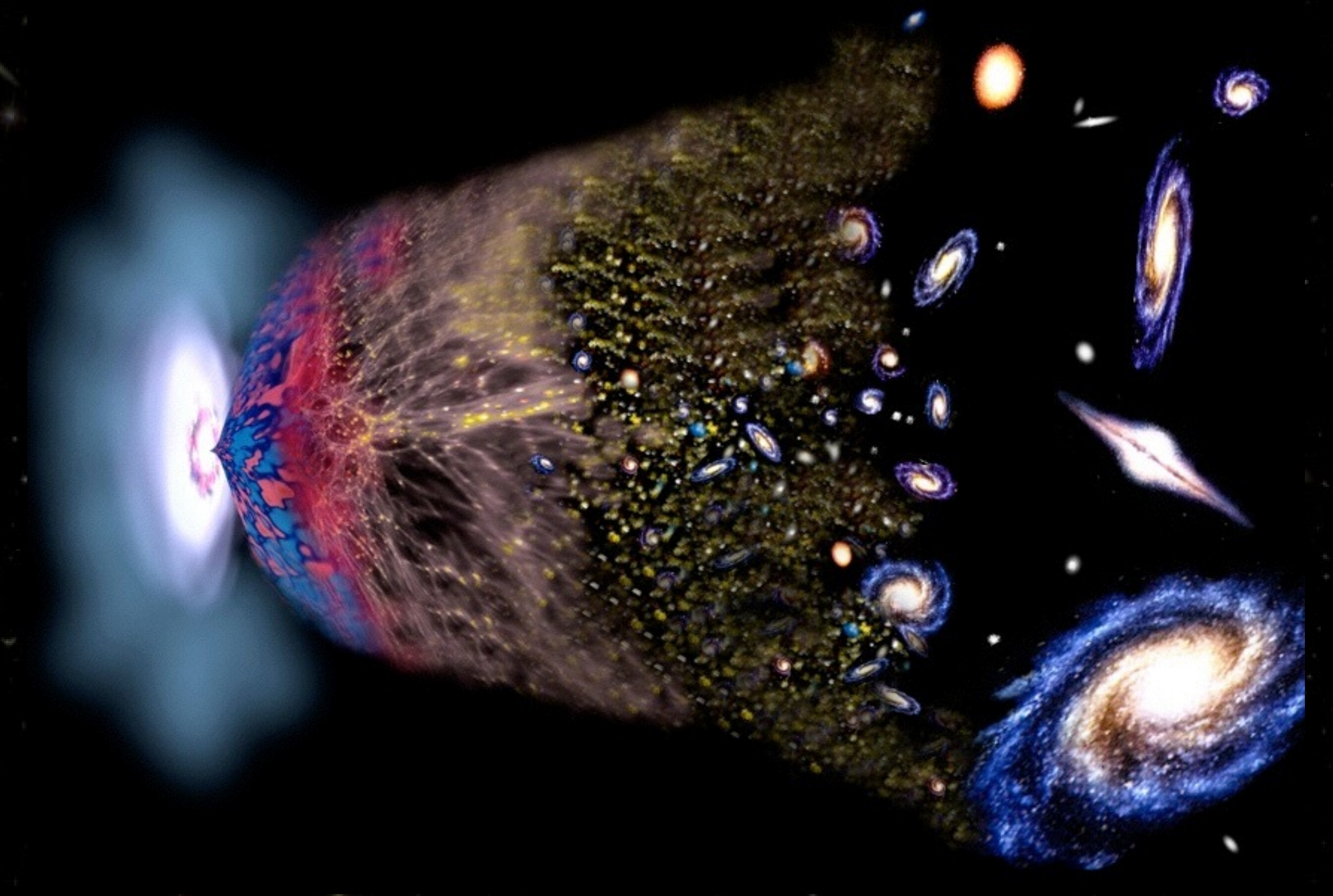
CMB Polarization

- Predicted long ago
  - ★ electrons/photons scattering before decoupling
- 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]

The smoking-gun for 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) implicitly assume inflation
  - ★ One would feel more confortable checking this detail ...

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

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

$\Rightarrow$ detect B-modes is :

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

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

What's next ? Inflation Physics

Four important quantities :

- ★ A_s : known
- ★ n_s : known
- ★ A_t or r : may have been detected at r ~ 0.2 ?
- ★ n_t :unknown, requires exquisite 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 of* n_s related to V'''
- ★ A_t related to V

inflaton potential shape recovery !
Need accuracy on r
Within reach in the next few years !

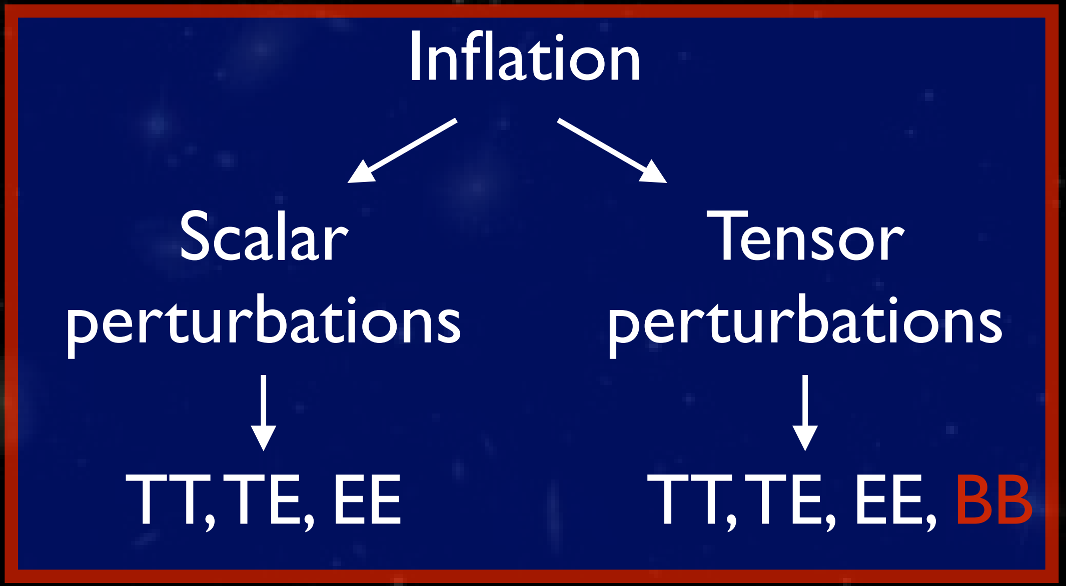
Primordial Fluctuations Origin ?

Inflation Predictions

- **Flatness, Homogeneity** ✔
- **Nature of the perturbations:** ✔
  - ★ TT peaks at same scales as EE troughs
  - ➡ Adiabatic perturbations
- **Spectral index** $P(k) \propto k^{n_s - 1}$ ✔
  - ★ Planck TT + WMAP Pol + High ℓ + BAO

    $$n_s = 0.9608 \pm 0.0054 \ (7.2\sigma \text{ from } 1)$$
  - ➡ Almost scale invariant spectrum
- **Gaussianity** ✔
  - ★ No hint for non-Gaussianity (despite impressive efforts)
- **Tensor perturbations of the metric**
  - ★ BICEP2 detection ? to be confirmed…

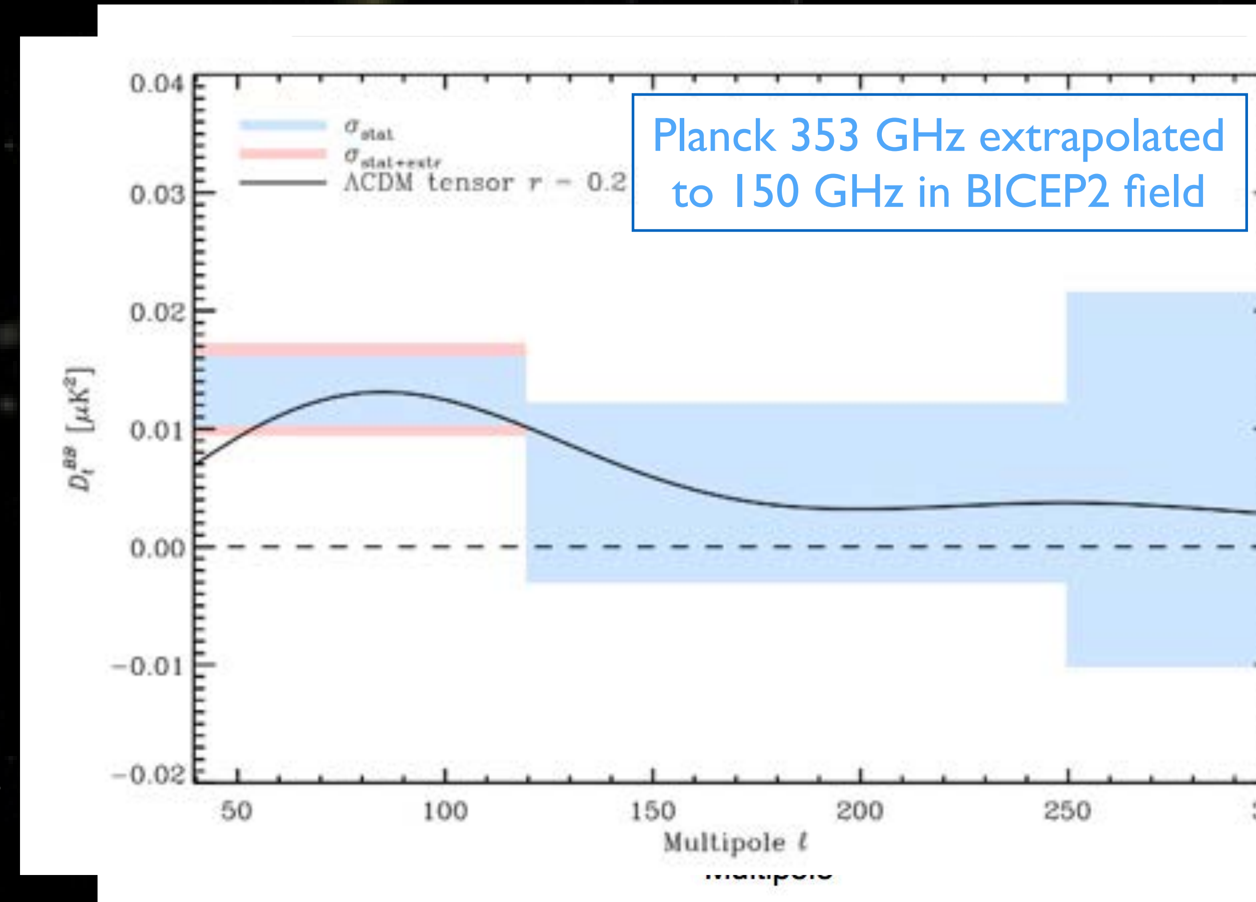
B-modes: Holy Grail for cosmology



- ## Smoking gun for inflation
  - T/S ratio:
    - < 0.11 [CMB Panck + WMAP + BAO + SNIa]
    - > 0.01 for simplest inflationary models
    - might be much lower for more complex models
- ## Cosmic strings and other defects
  - Produces distinctive B polarization
    - [Bevis et al. (2007), Phys.Rev.D76:043005]
    - [Urrestilla et al. (2008), astro-ph/0803.2059]
    - [Pogosian et Wyman (2007), astro-ph/0711.0747]
- ## Superstrings ?
  - most (all ?) string inspired inflation theories predict r << 1
  - Unique opportunity to falsify string theory ! (?)
    - [Kallosh & Linde (2007), JCAP 0704:017]
- ## CPT symetry testing
  - CPT violations may induce cosmological birefringence
  - linear polarization rotation : non vanishing TB and EB CMB spectra
    - [Feng et al. (2006), PRL 96, 221302]
    - [Xia et al., (2009), Phys. Lett. B687, 129]
    - [Gluscevic et al., (2012), arXiv:1206.5546v1]

BICEP2

- March 2014:
  - ★ « Primordial B-modes discovery »
  - ★ Strong significance
  - ★ Strong signal r~0.2 (~tension with Planck)
- BICEP2:
  - ★ Direct Imager in Antarctica
  - ★ 150 GHz, 0.5 deg. resolution
  - ★ 512 dual polarization detectors, 3 seasons

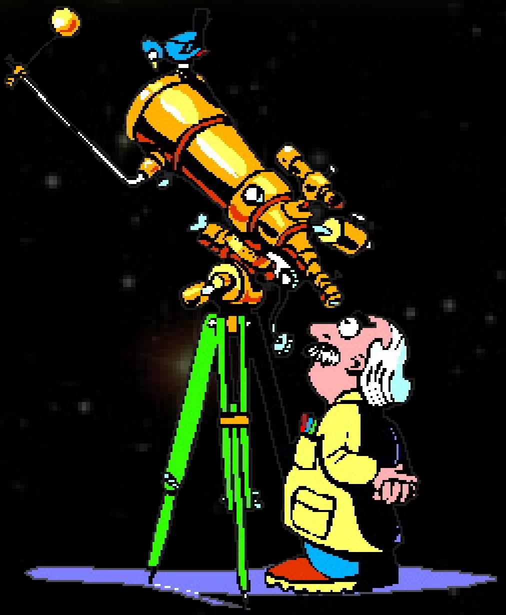


- Discovery ?
  - ★ Experienced and respectable team (DASI, QUAD)
  - ★ One single frequency… Dust contamination ?
    - Rumors floating around… Original paper replaced with much less victorious version…
    - Planck XXX article posted last week: the whole BICEP2 signal can be explained by dust…
  - ★ Little systematic control allowed by BICEP2 (but OK for r~0.2)
  - ★ Result needs to be checked by other teams: Planck, SPTPol, ACTPol, PolarBear, SPIDER, QUBIC
  - ★ QUBIC: completely different systematics (less in principle…)

Expected difficulties in the Quest for the Holy Grail

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



- 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

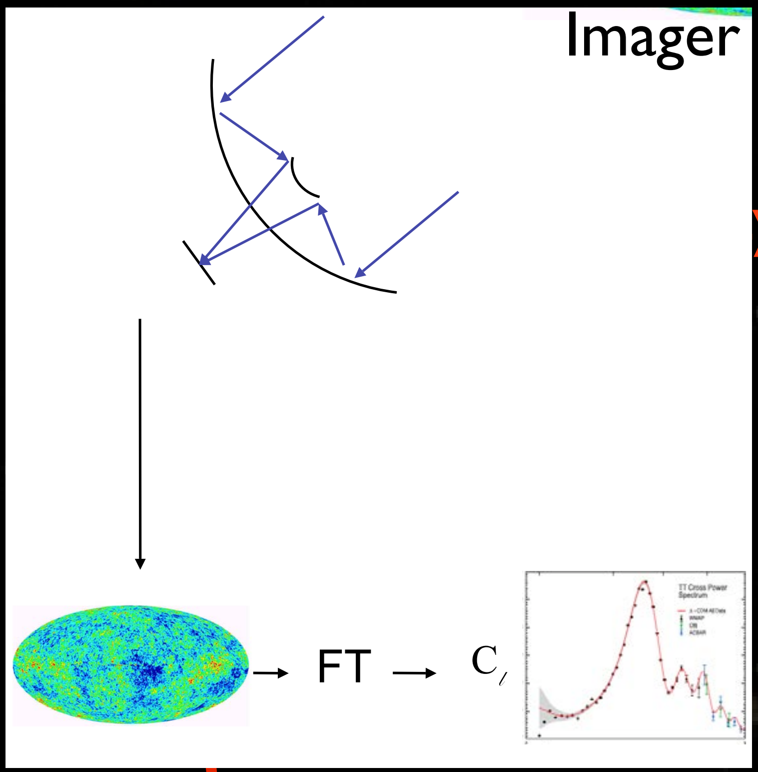
Possible instruments

- **Imagers with bolometers:**
  - ★ No doubt they are nice detectors for CMB:
    - wide band
    - low noise
  - ★ Especially true for a satellite (small background)

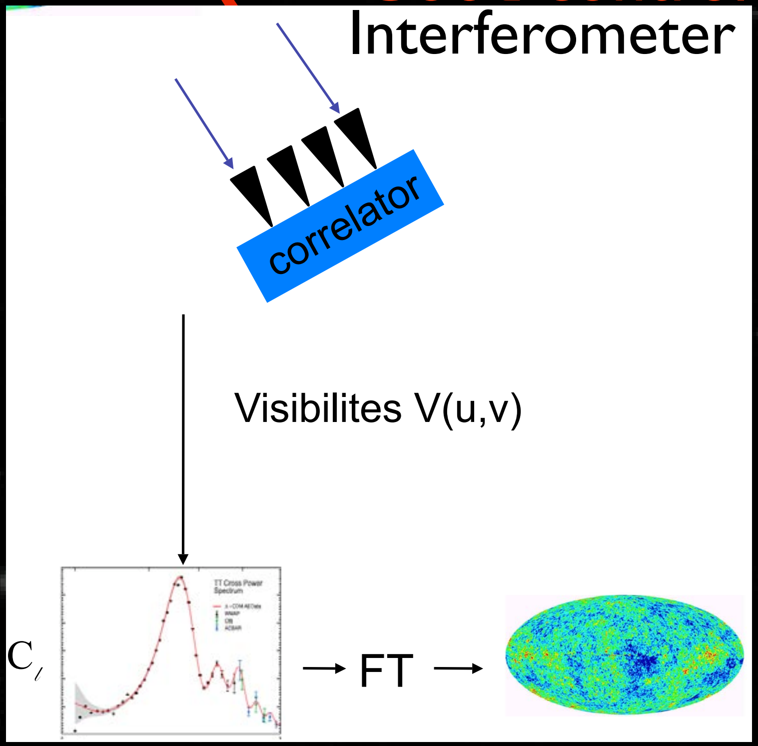
- **Interferometers:**
  - ★ Long history in CMB
    - CMB anisotropies in the late 90s (CAT: 1st detection of subdegrees anisotropies, VSA)
    - CMB polarization 1st detection (DASI, CBI)
  - ★ Technology used so far
    - Antennas + HEMTs : higher noise
    - Correlators : hard to scale to large #channels
  - ★ 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



Good control



The QUBIC Collaboration

- APC Paris, France
- IAS Orsay, France
- CSNSM Orsay, France
- IRAP Toulouse, France
- Maynooth University, Ireland
- Università di Milano-Bicocca, Italy
- Università degli studi, Milano, Italy
- Università La Sapienza, Roma, Italy
- University of Manchester, UK
- Richmond University, USA
- Brown University, USA
- University of Wisconsin, USA

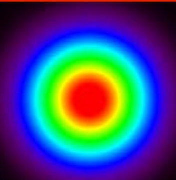
E. Battistelli [e], A. Baú [f], D. Bennett [l], L. Bergé [c], J.-Ph. Bernard [b], P. de Bernardis [e], G. Bordier [a], A. Bounab [b], É. Bréelle [a], E.F. Bunn [j], M. Calvo [e], R. Charlassier [a], S. Collin [c], A. Coppolecchia [e], A. Cruciani [e], G. Curran [l], M. de Petris [e], L. Dumoulin [c],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

NIKHEF + Leiden joining

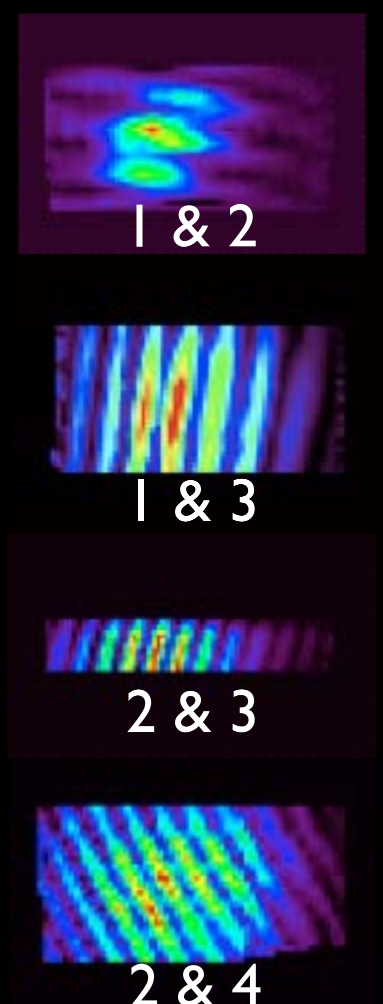
arXiv:1010.0645 ~ Astroparticle Physics 34 (2011) 705–71

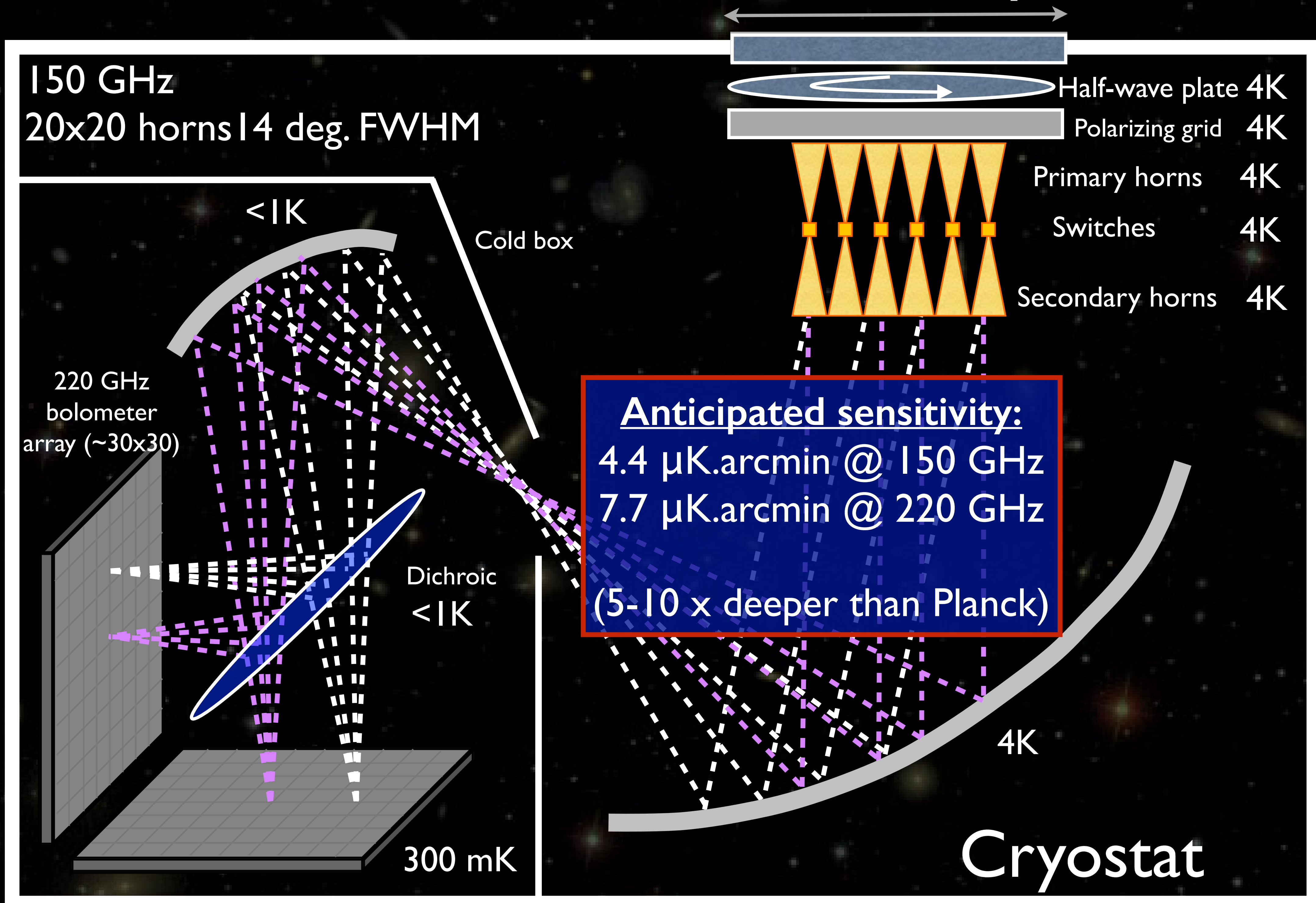
QUBIC concept: Quasi optical correlator

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



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



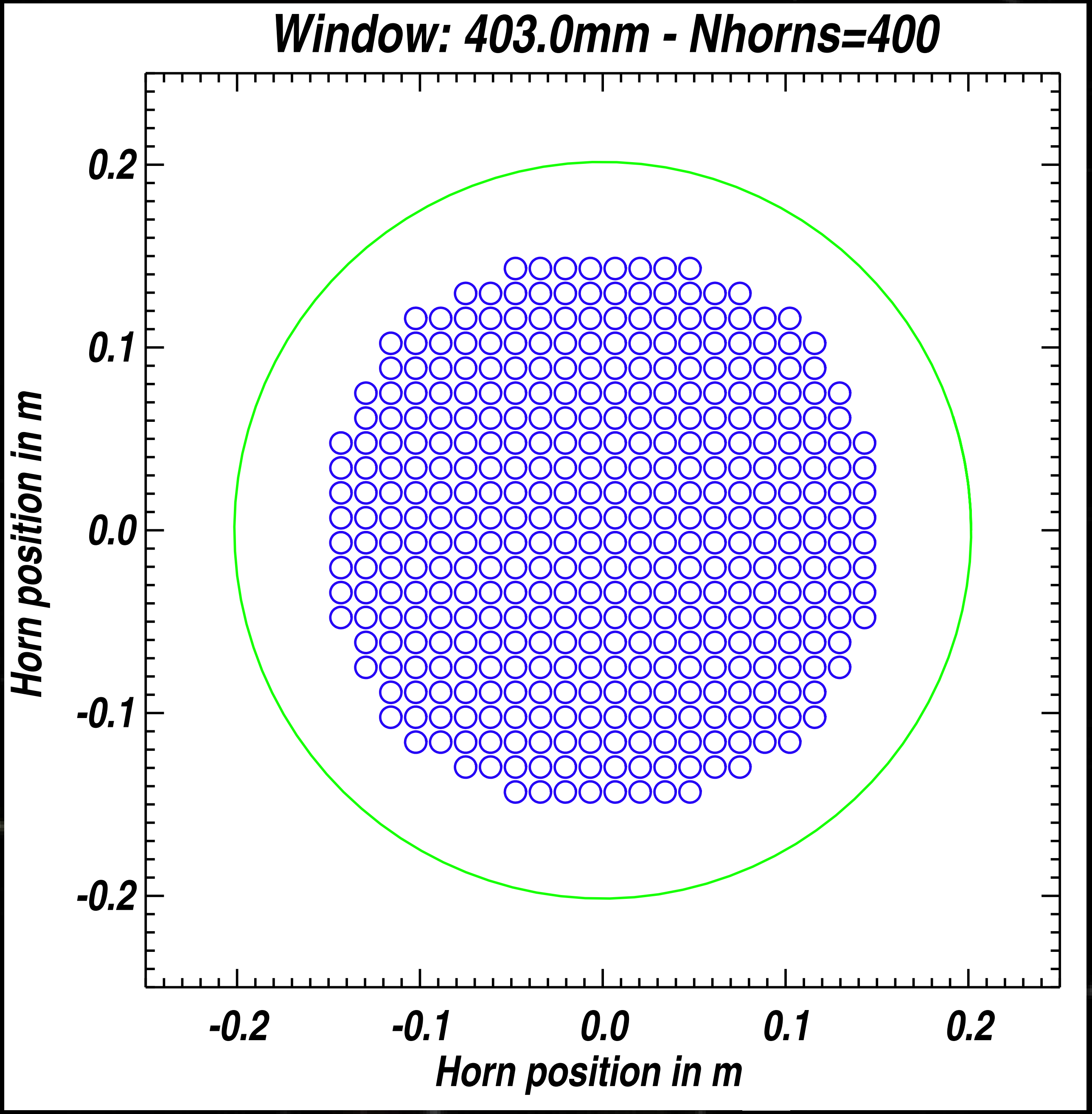


Anticipated sensitivity:
4.4 μK.arcmin @ 150 GHz
7.7 μK.arcmin @ 220 GHz

(5-10 x deeper than Planck)

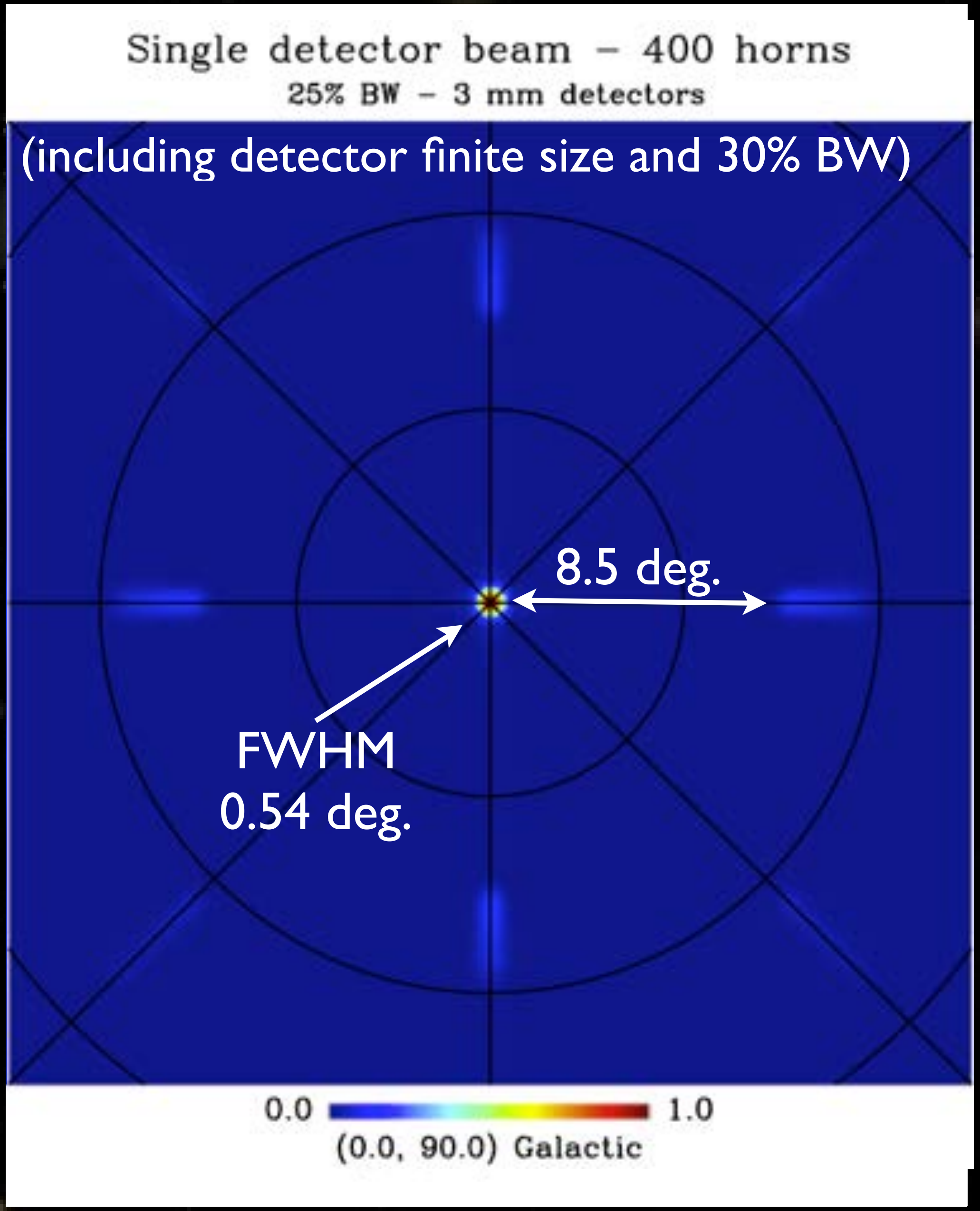
B.I. = Synthesized imager

Primary horns array



1st module: 150 GHz, 400 horns,
14 deg. FWHM, D=1.2 cm

Synthesized beam



Synthesized beam used to
scan the sky as with an imager

Signal in QUBIC

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

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

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

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

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

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

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

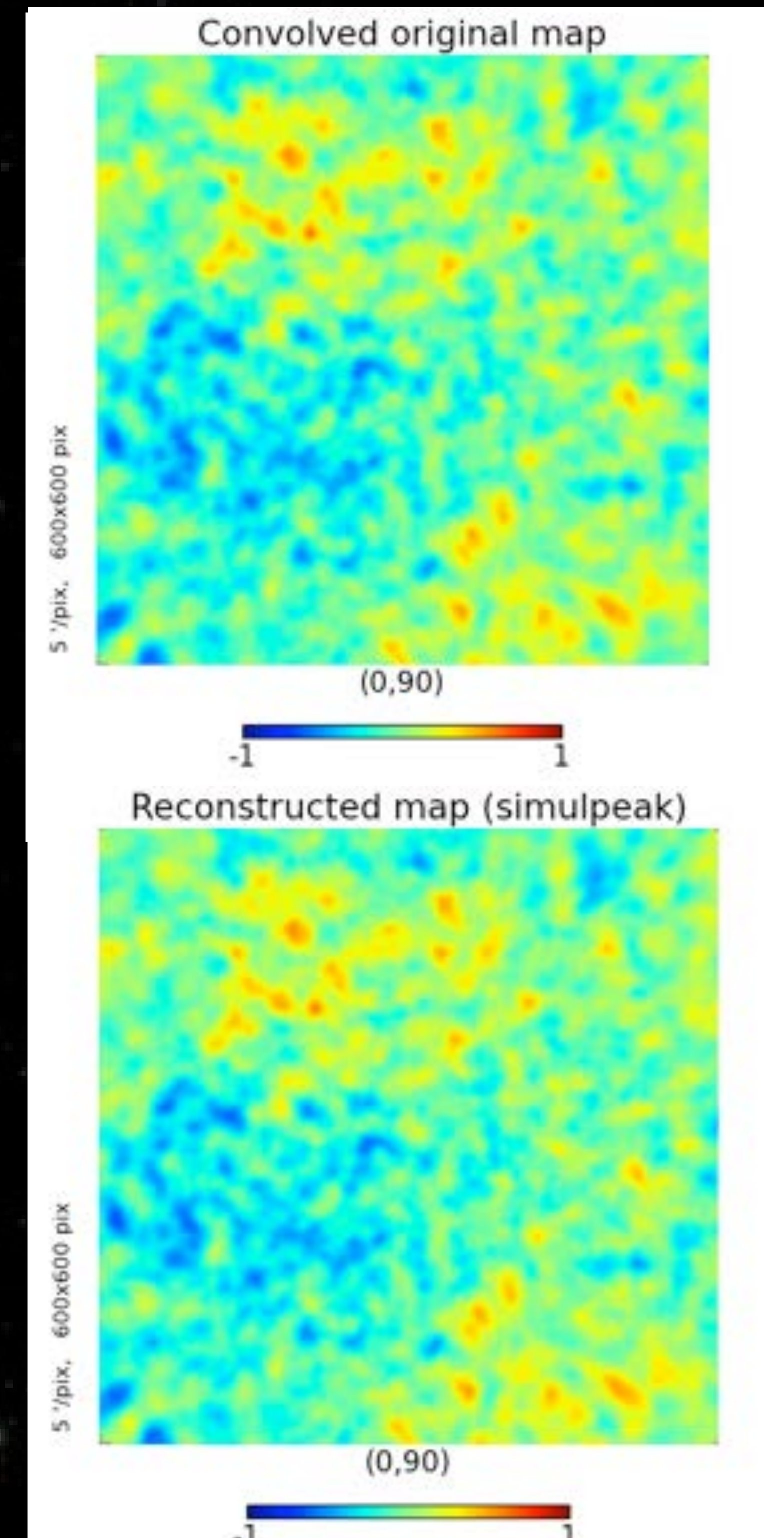
⇔ An interferometer performing direct synthesis imaging

Map Making ~ as an imager

- Scan the sky with synthesized beam
  - ★ Az. scans at constant elevation following a single field
  - ★ Phi rotation around optical axis
- 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

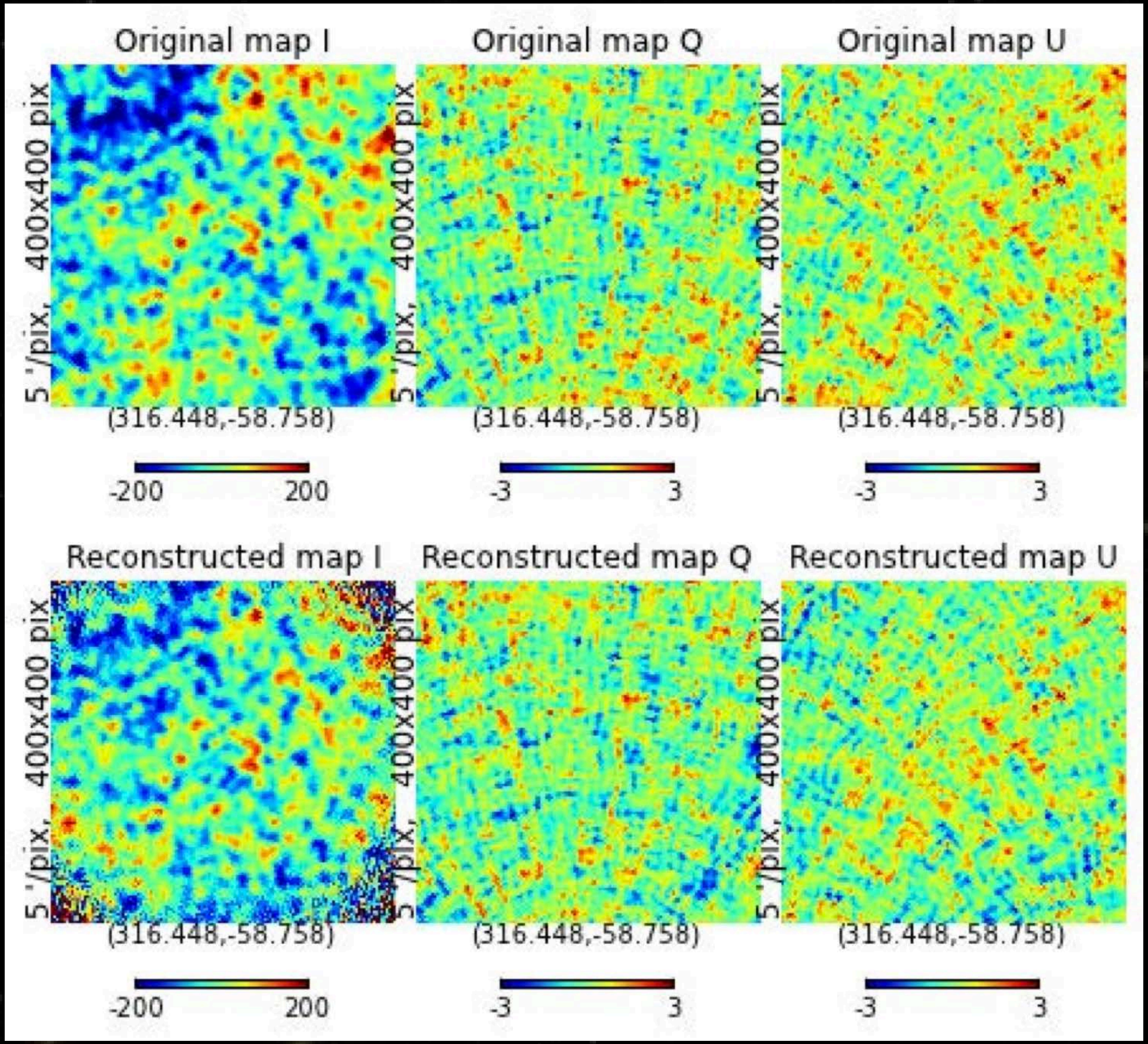


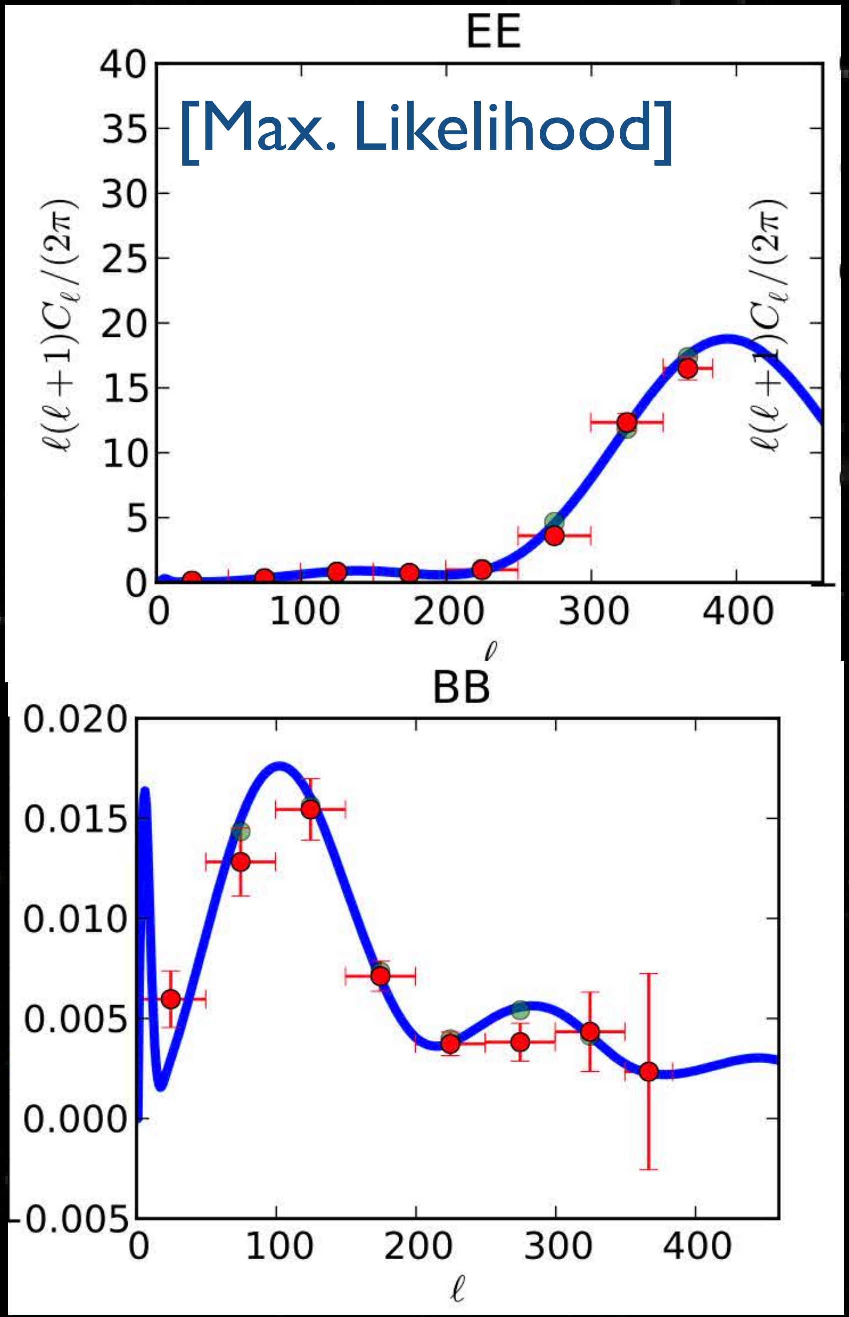
[Pierre Chanial @ APC]

« End-to-end » simulations being developed

[P. Chanial, M. Stolpovskiy, J. Kaplan, JCH]

TOD → Maps → E & B power spectra





QUBIC Site: Dome C, Antarctica

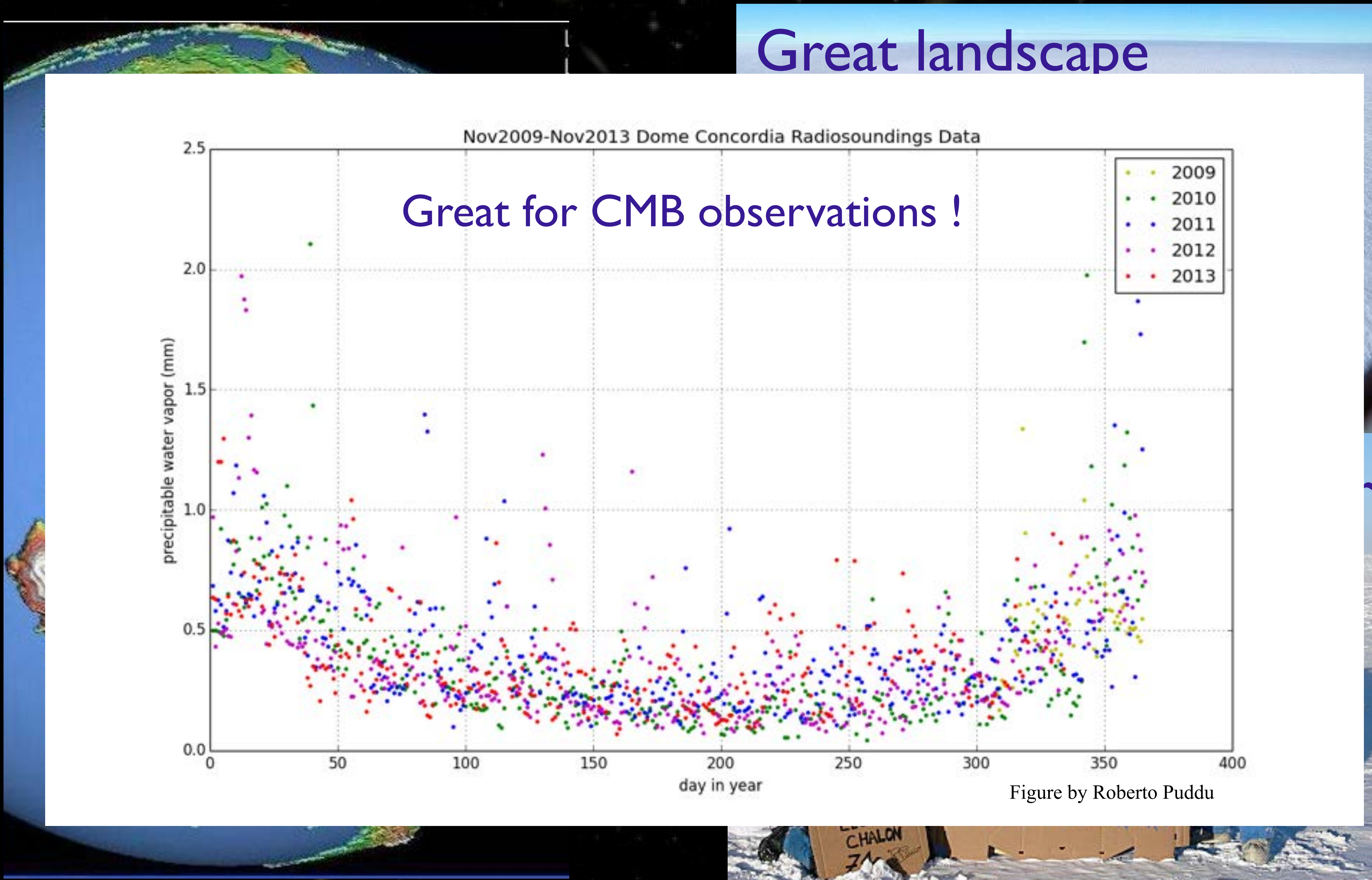
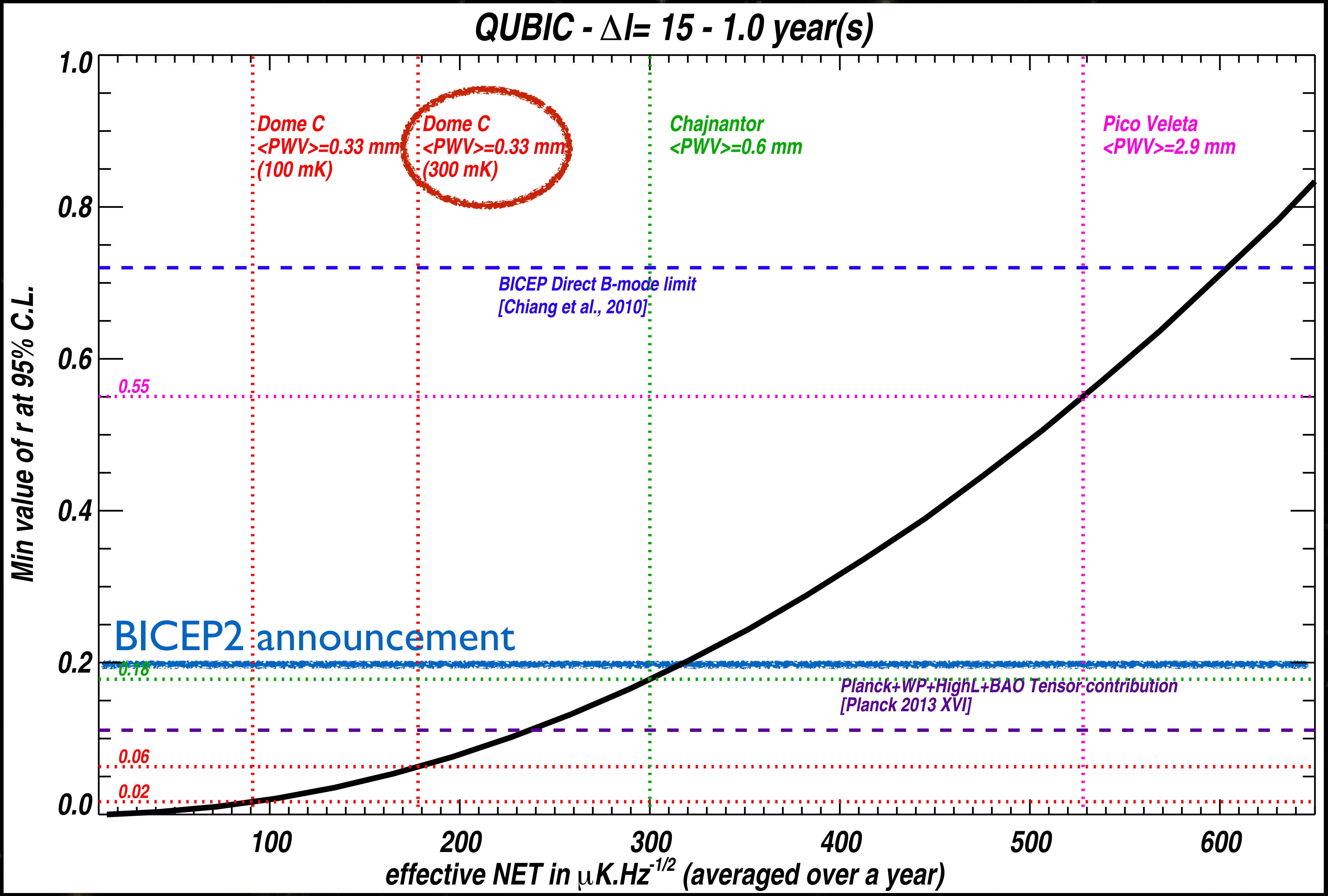


Figure by Roberto Puddu

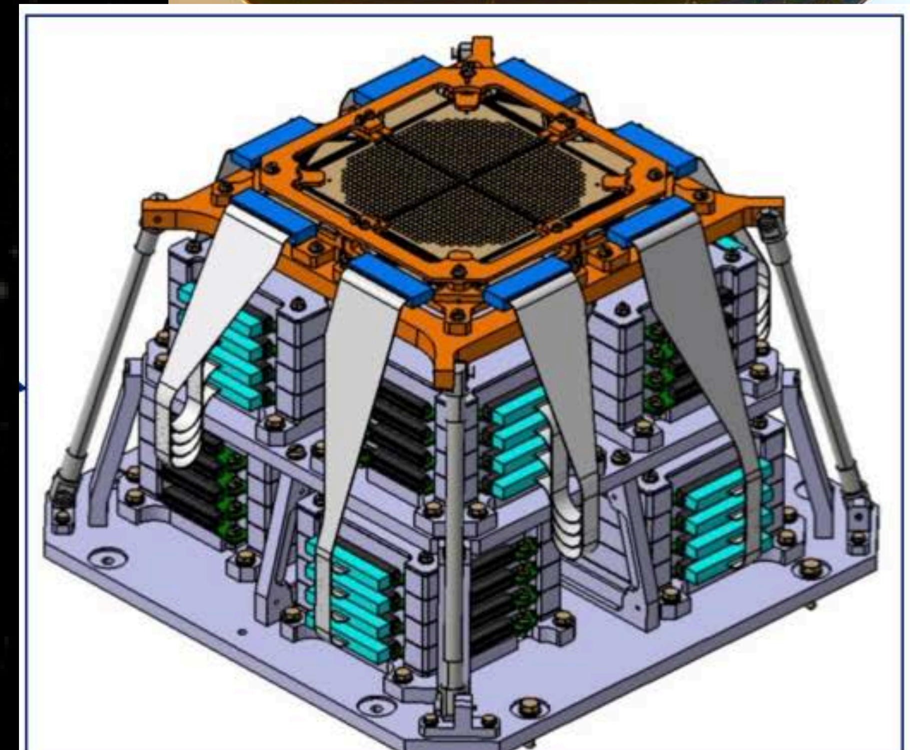
Dome C: Best site on Earth ?



Detection Chain

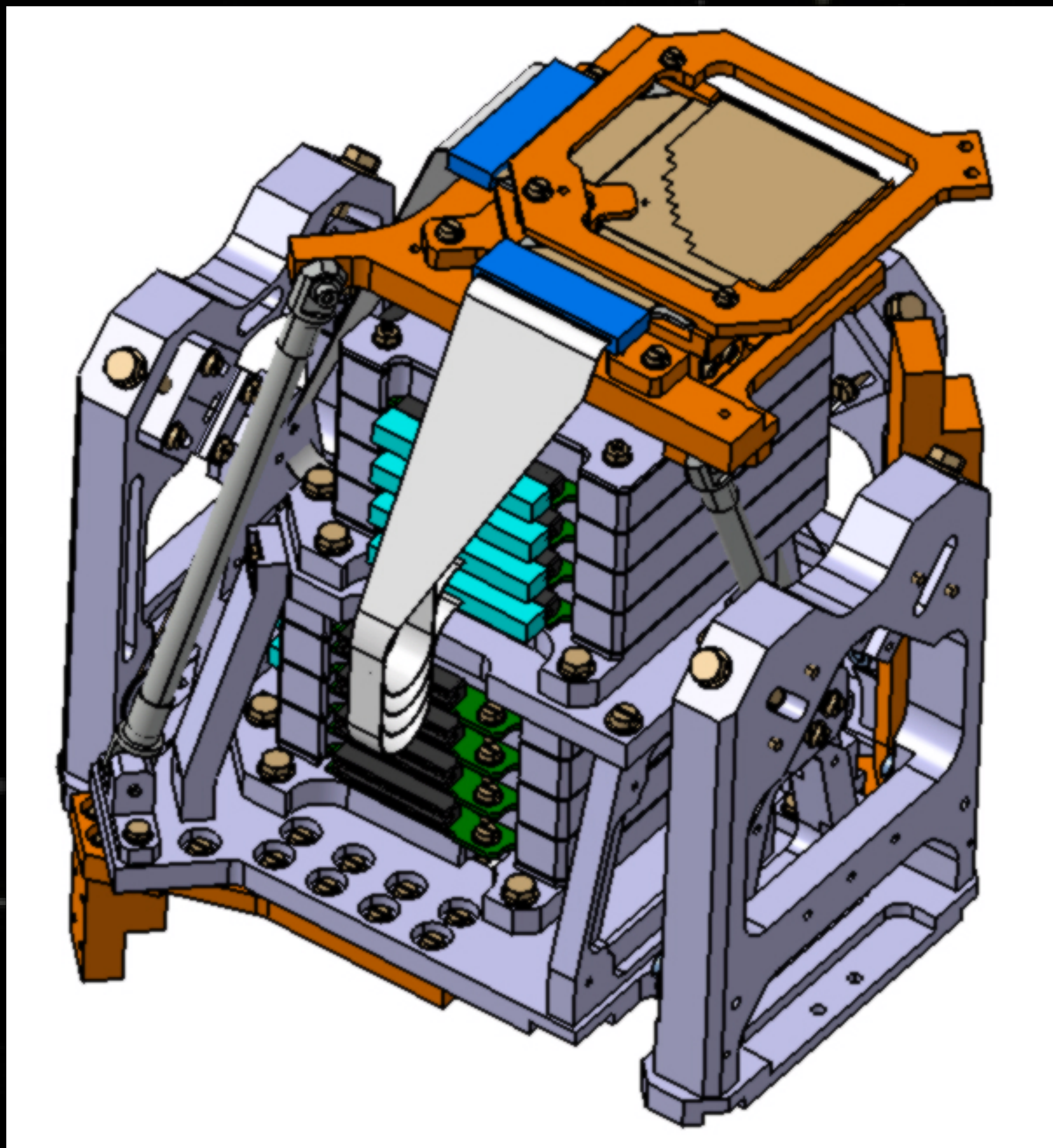
- TES + SQUIDs + 4K SiGe ASIC Mux
  - ★ CSNSM: Stefanos Marnieros
  - ★ IEF: Bruno Bélier
  - ★ APC: Michel Piat
  - ★ IRAP: Ludovic Montier
- 2 arrays of 992 NbSi TES
  - ★ CSNSM/IEF + C. Perbost, A. Cammillieri, A. Ghribi
  - ★ Each array : 4x248 elements
  - ★ 300 mK bath (^{3}He-^{4}He evaporation cooler)
  - ★ 3 mm size
  - ★ <u>Measured NEP ~ 4.10^{-17} W.Hz$^{-1/2}$</u>
  - ★ time constant ~ 10 ms
- 4K Multiplexed Readout
  - ★ F. Voisin & D. Prêle
  - ★ SQUIDs pre-amplifier+mux
    - 32:1 multiplexing
  - ★ 4K SiGe ASIC (amp+mux)
    - 4:1 multiplexing
  - ★ 128 channels / ASIC
  - ★ Low noise: ~200 pV.Hz$^{-1/2}$
  - ★ low power: ~ few mW

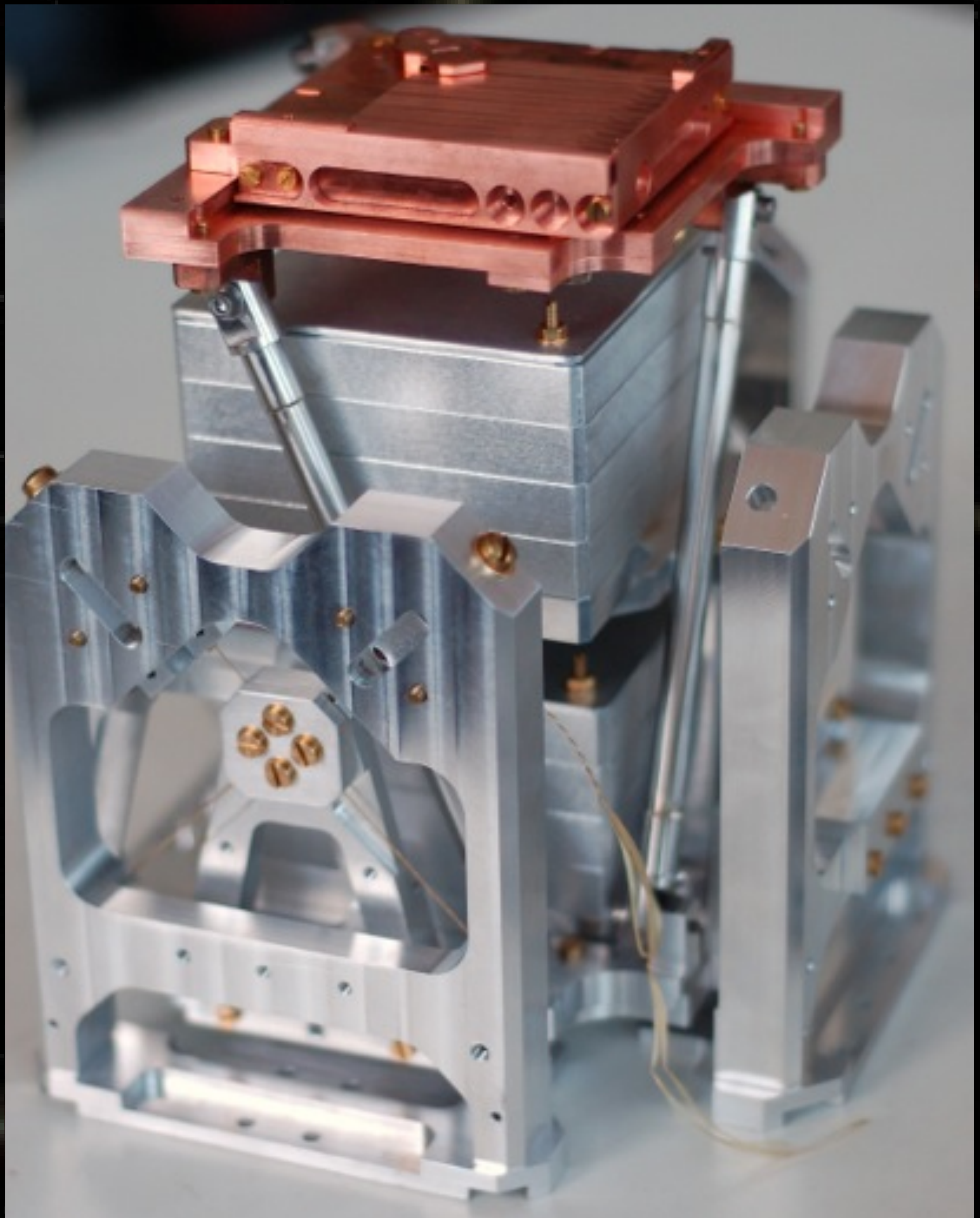
1st 248
Curre



Half focal plane

Cryo-mechanical Architecture for 1/4 focal plane [C. Chapron]



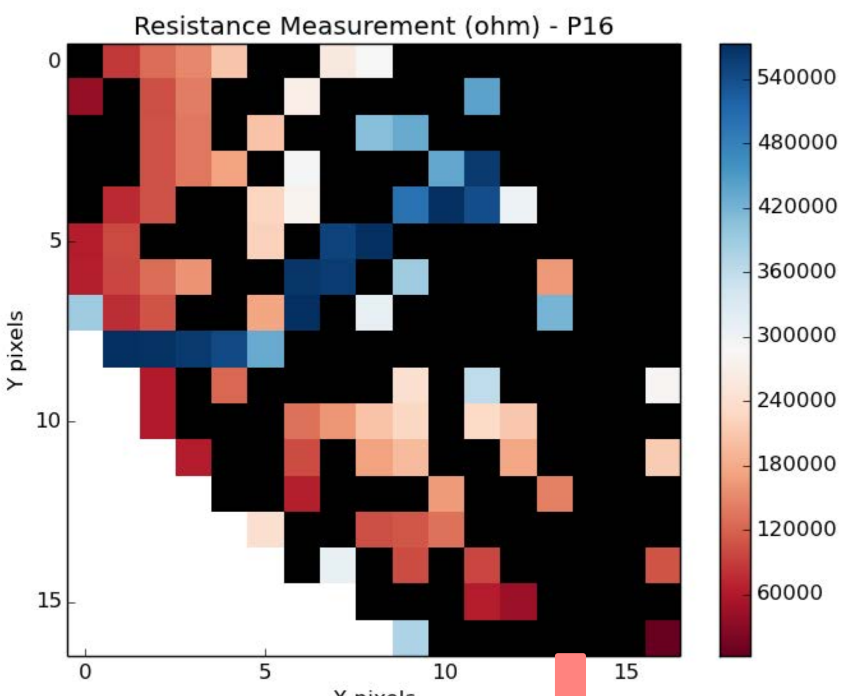


Assembled June 24th 2014

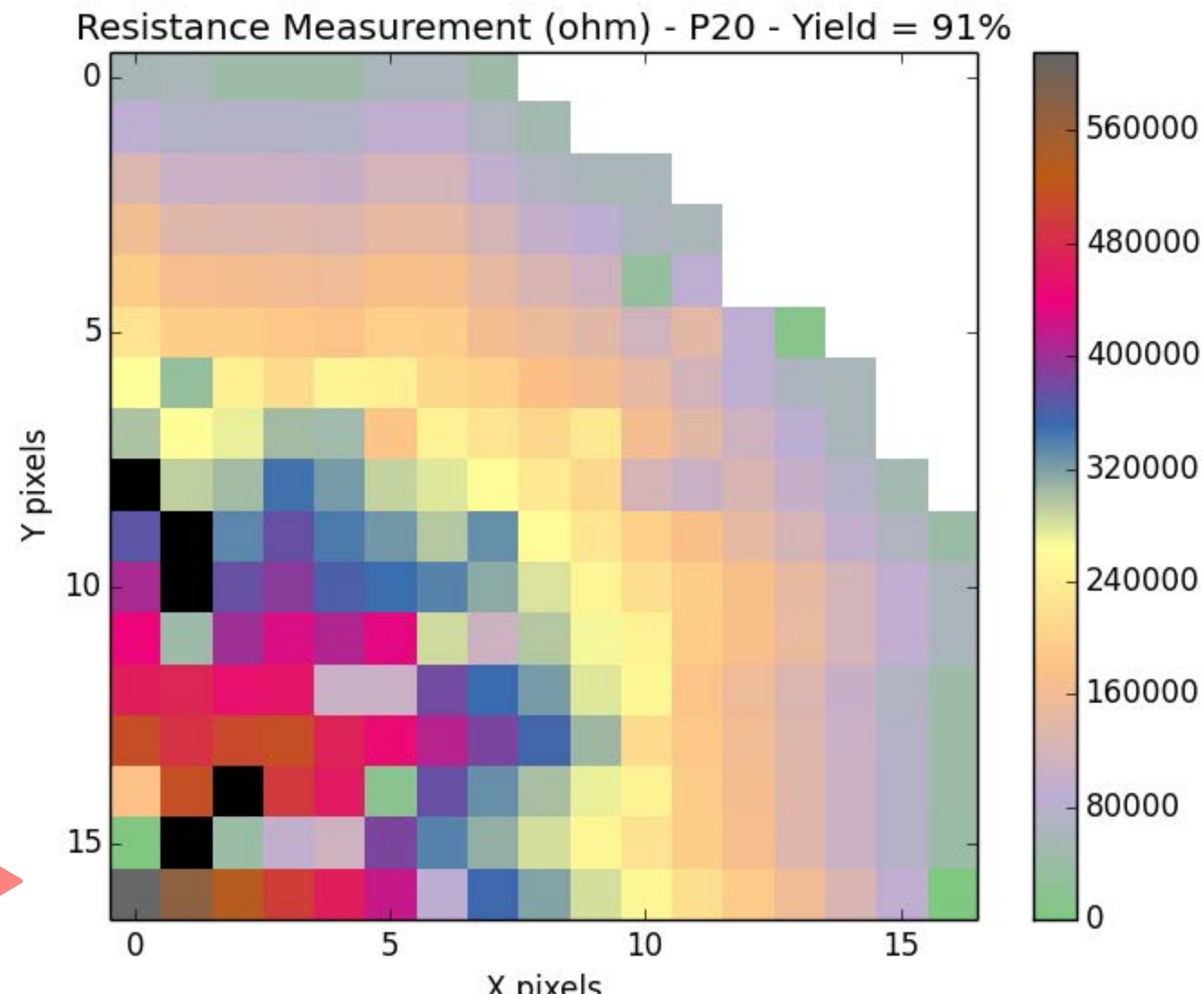
Production et tests des matrices de TES (C. Perbost, D. Cammillieri, A. Ghribi, D. Prêle)

Tests à chauds

Test électrique à température ambiante en cours de procédé : mesure de résistance des lignes pour détecter les circuits ouverts et les court-circuits



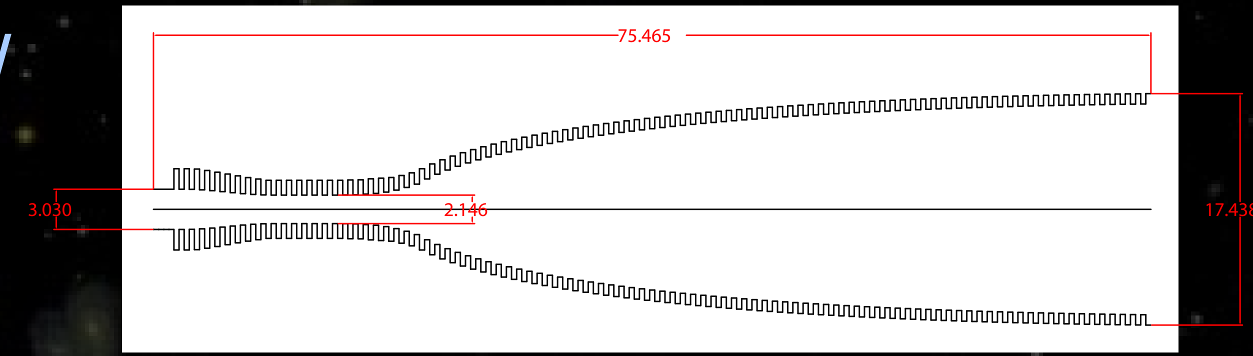
Première matrice : Beaucoup de défauts sur les lignes

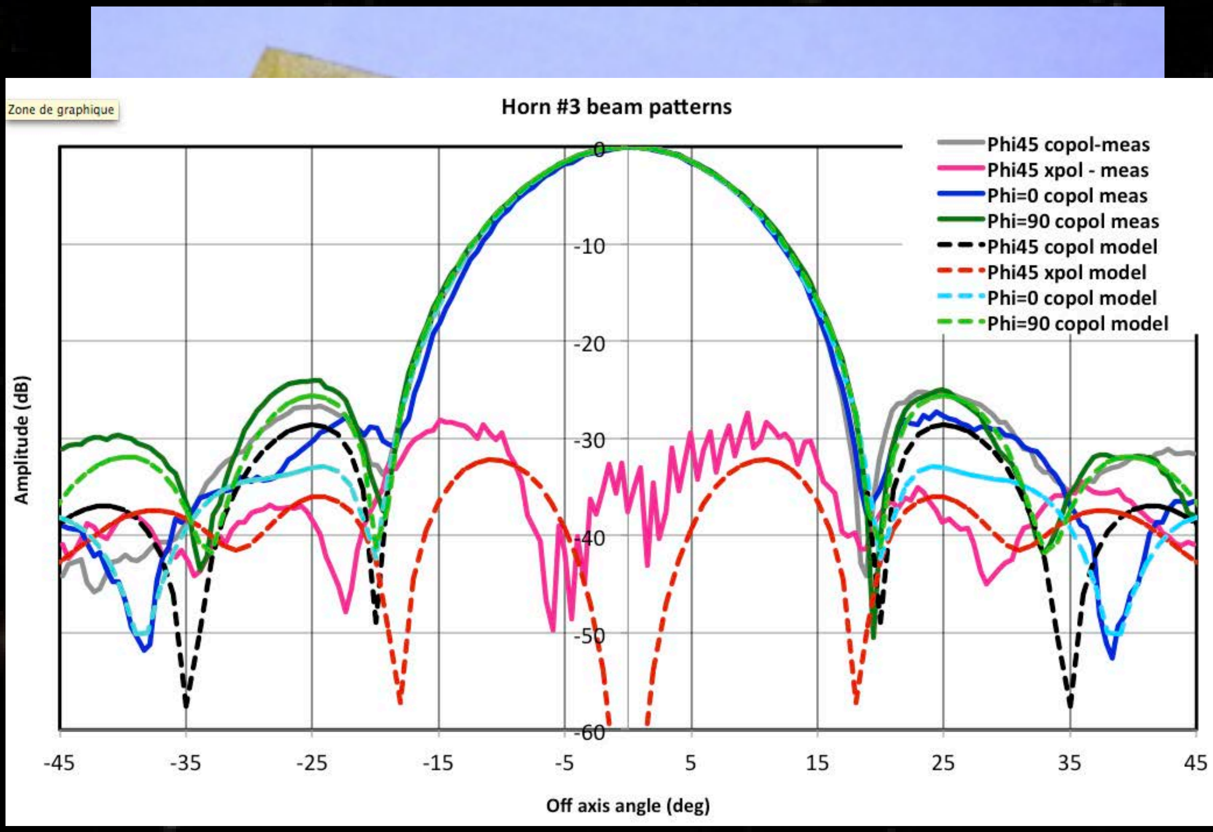


Dernière matrice :
La procédé a beaucoup progressé

Horns [animated by A. Tartari]

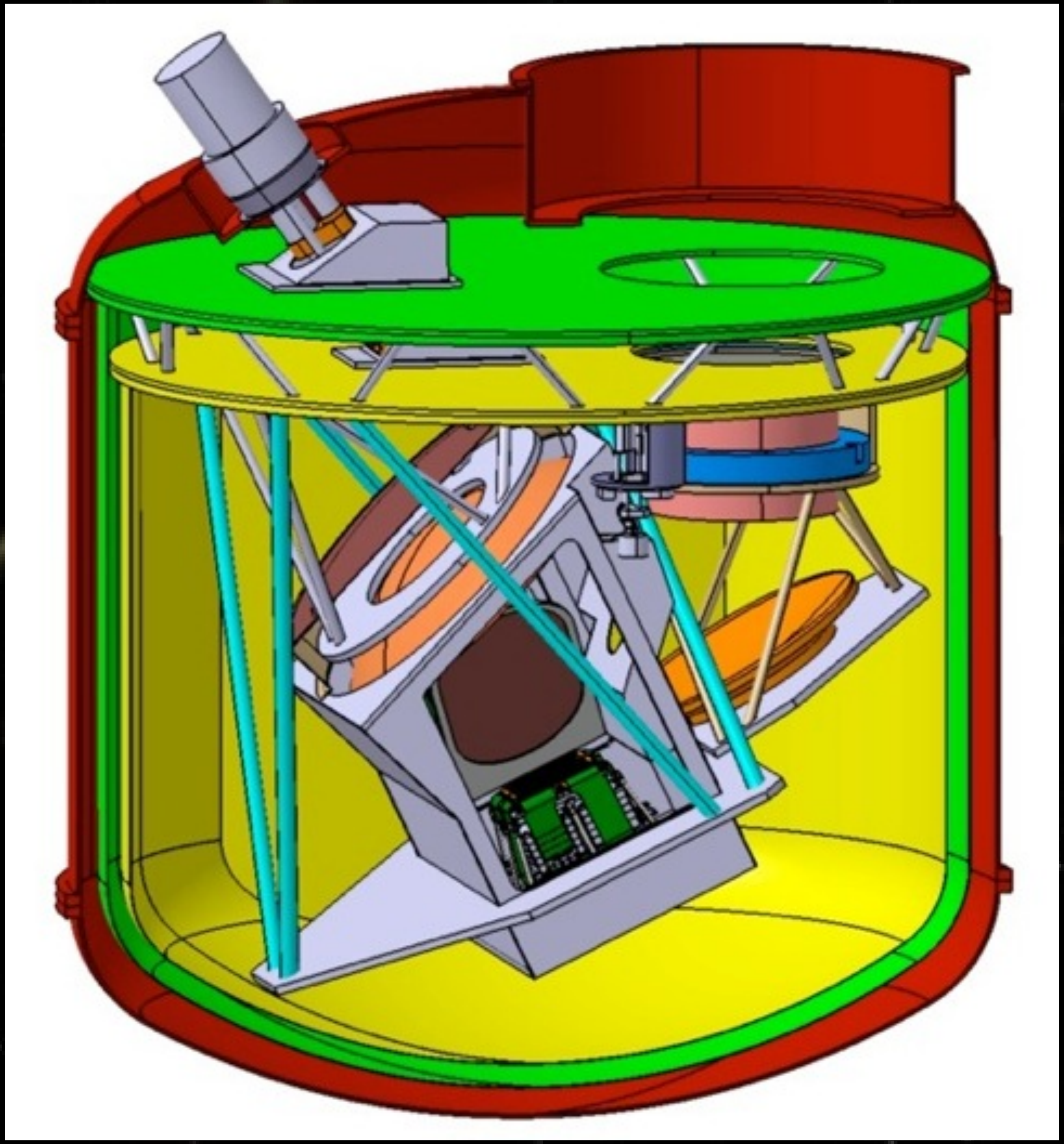
- Designed by Manchester (B. Maffei / G. Pisano)
  - ★ Clover-like profiled corrugated horns
  - ★ 150GHz, 14 deg. FWHM, 1.2 cm diam. (close to diffraction limit)
  - ★ Excellent beam/Cross Pol. perfs
  - ★ Usual fabrication:
    - Electroforming
    - Expensive (800$ / horn)
- Platelets fabrication investigated at APC and Milano (M. Bersanelli)
  - ★ 291 thin Aluminium plates
  - ★ Holes using chemical etching
  - ★ <100€ / horn
  - ★ Excellent performances !!





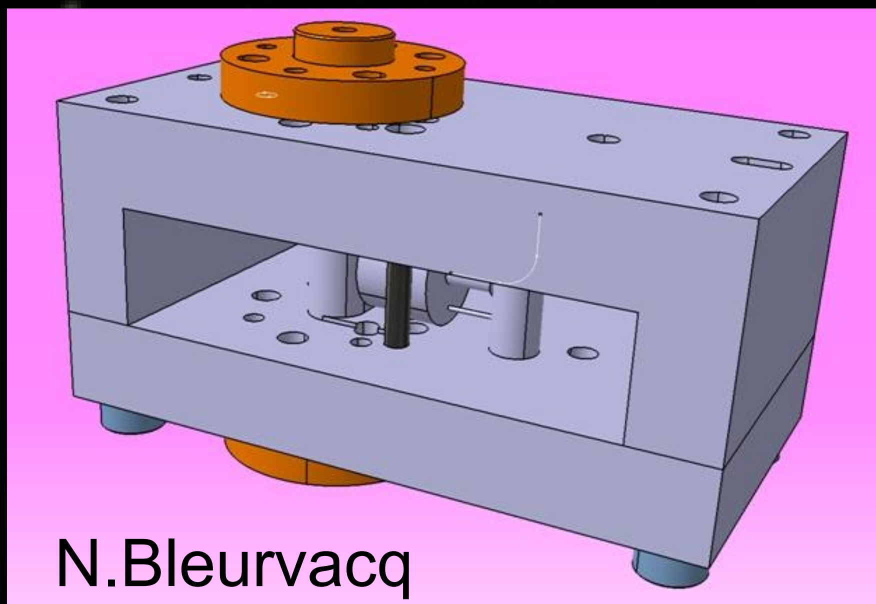
QUBIC Cryostat

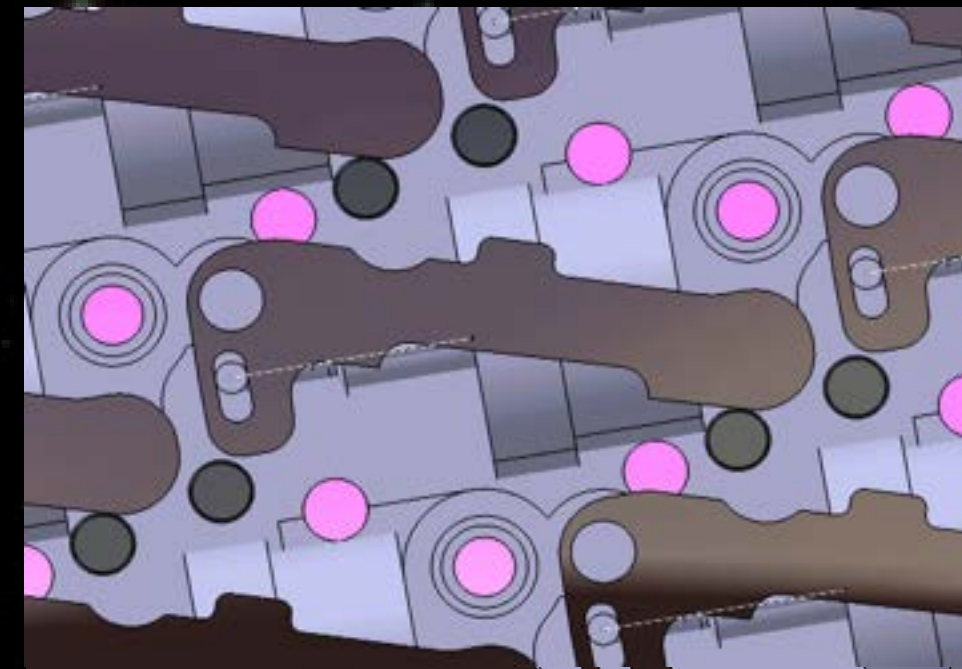
- Designed in Roma
  - ★ P. de Bernardis / S. Masi
- 45 cm window
  - ★ Stack (~20 cm) of zotefoam layers
- Large dimensions
  - ★ Weight: ~650 kg
  - ★ Height: 1.8m
  - ★ Diameter: 1.6m
- 1st stage: 4K: Pulse-Tube
  - ★ Filters, horns, switches, HWP, 1st mirror
- 2nd stage: 300 mK: ^{3}He-^{4}He evaporation cooler
  - ★ 2nd mirror, polarizing grid, detectors

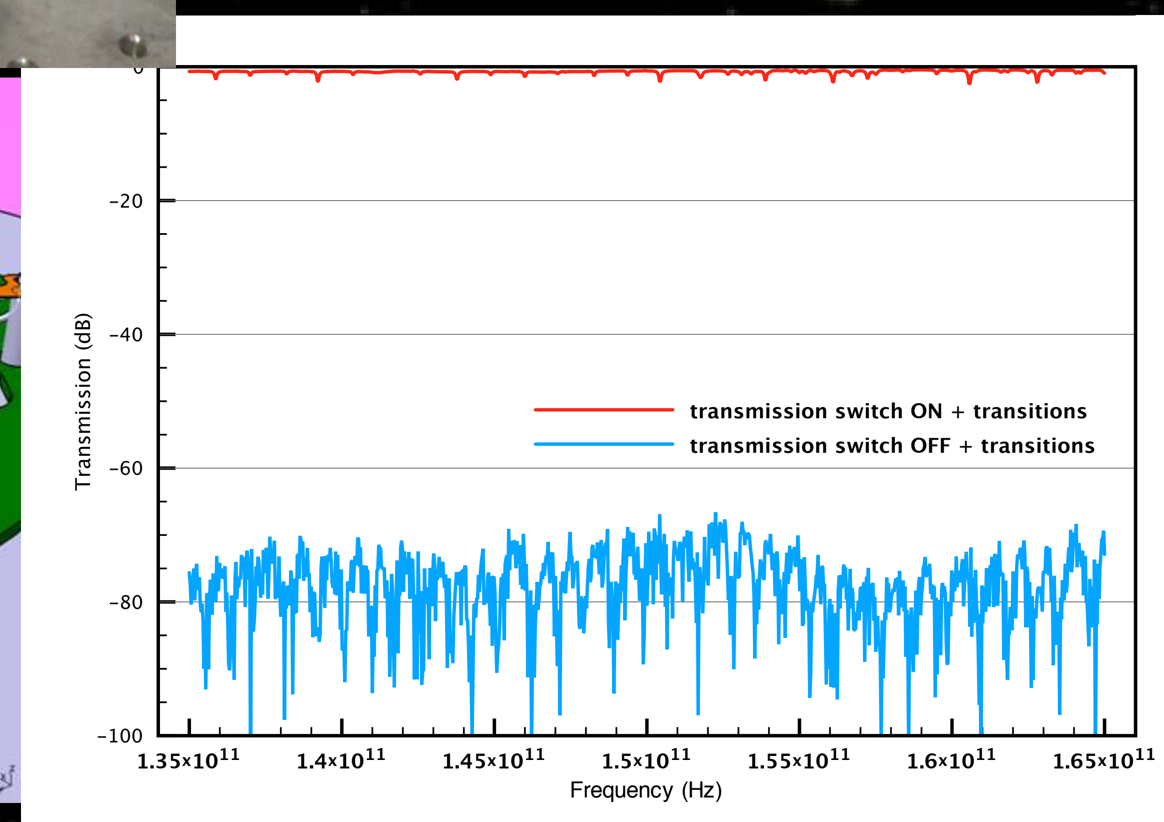


Switches

[N. Bleurvacq, G. Bordier, A. Tartari]

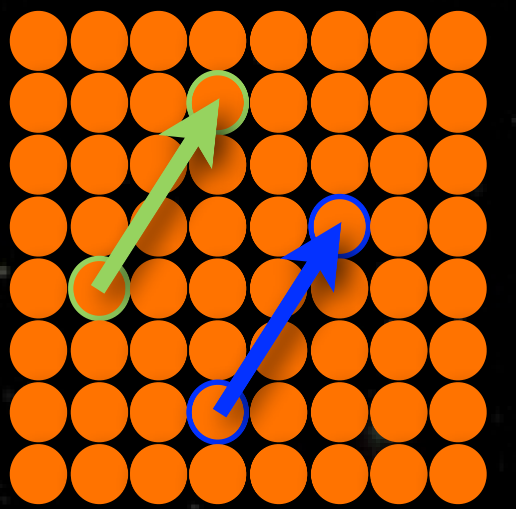




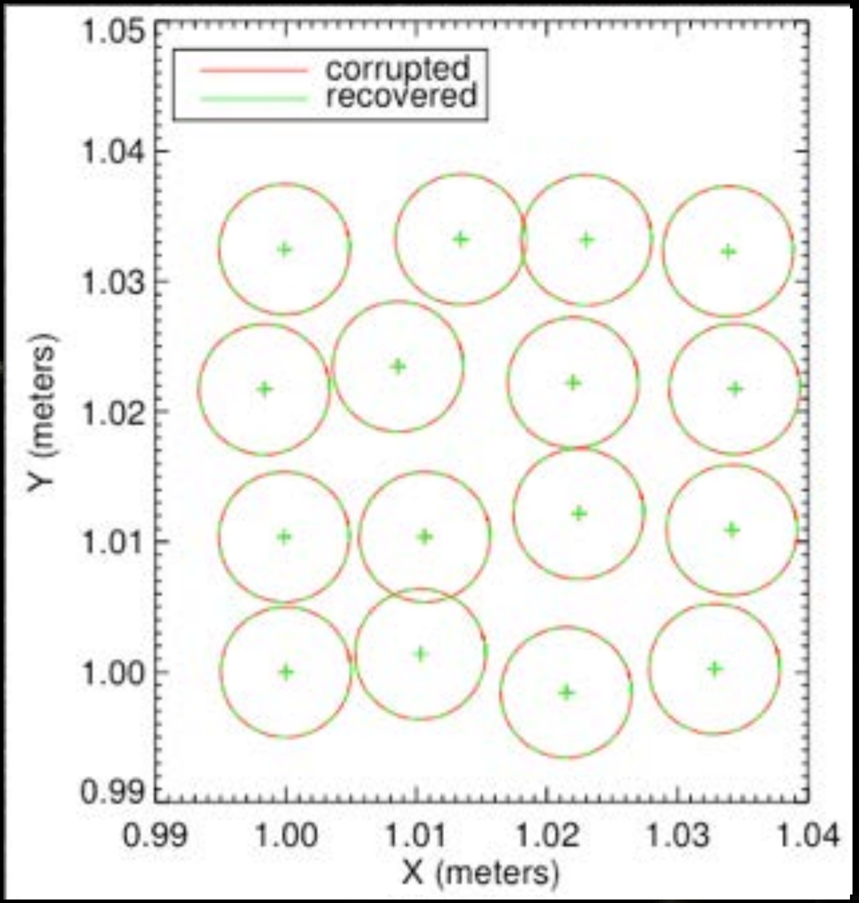


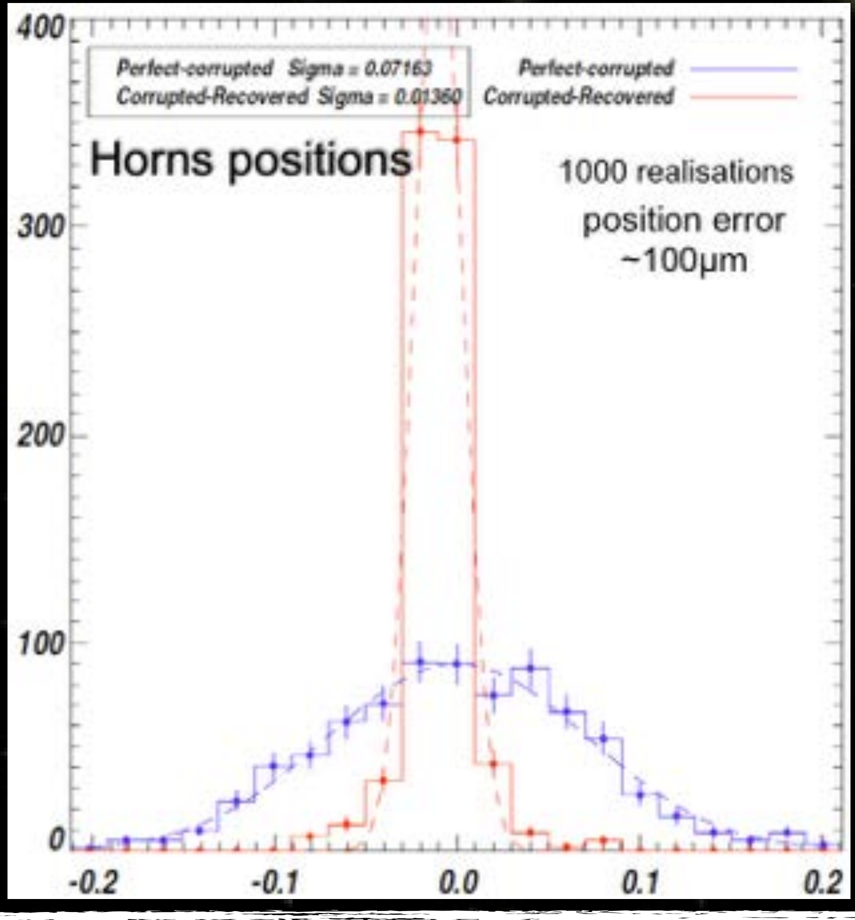
Systematics: Self-Calibration

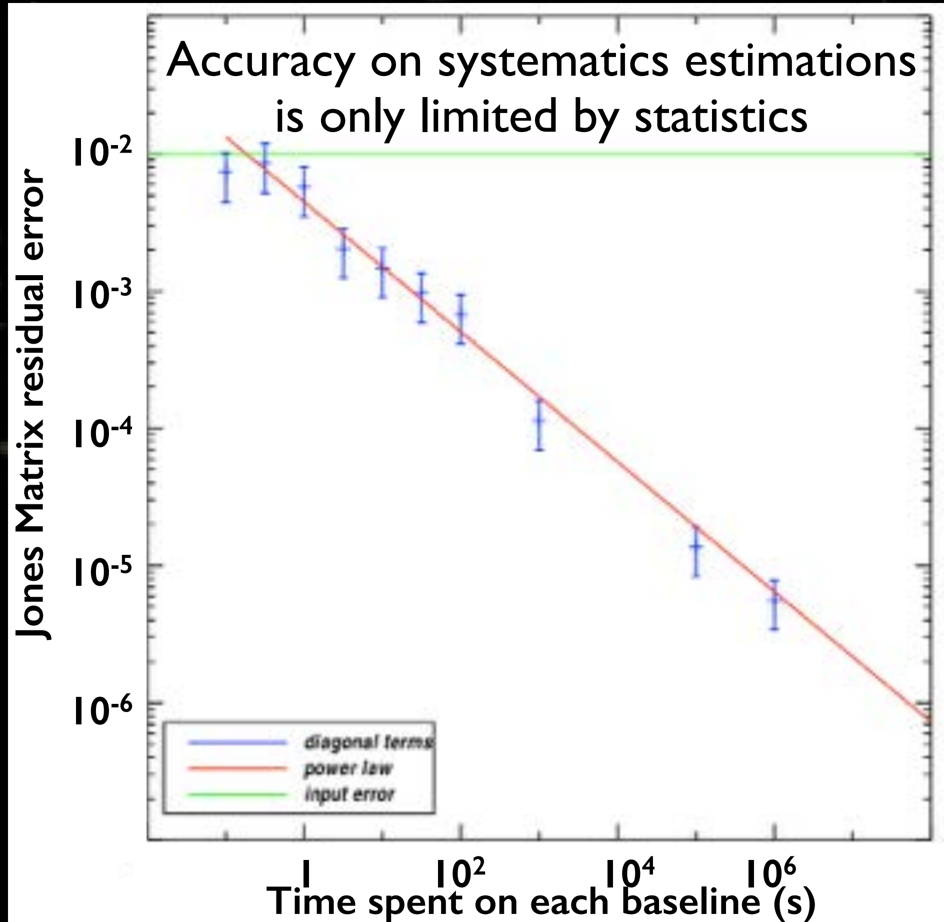
- Unique possibility to handle systematic errors
  - ★ Use horn array redundancy to calibrate systematics
    - In a perfect instrument redundant baselines should see the same signal
    - Differences due to systematics
    - Allow to fit systematics with an external source on the field
    - use switches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



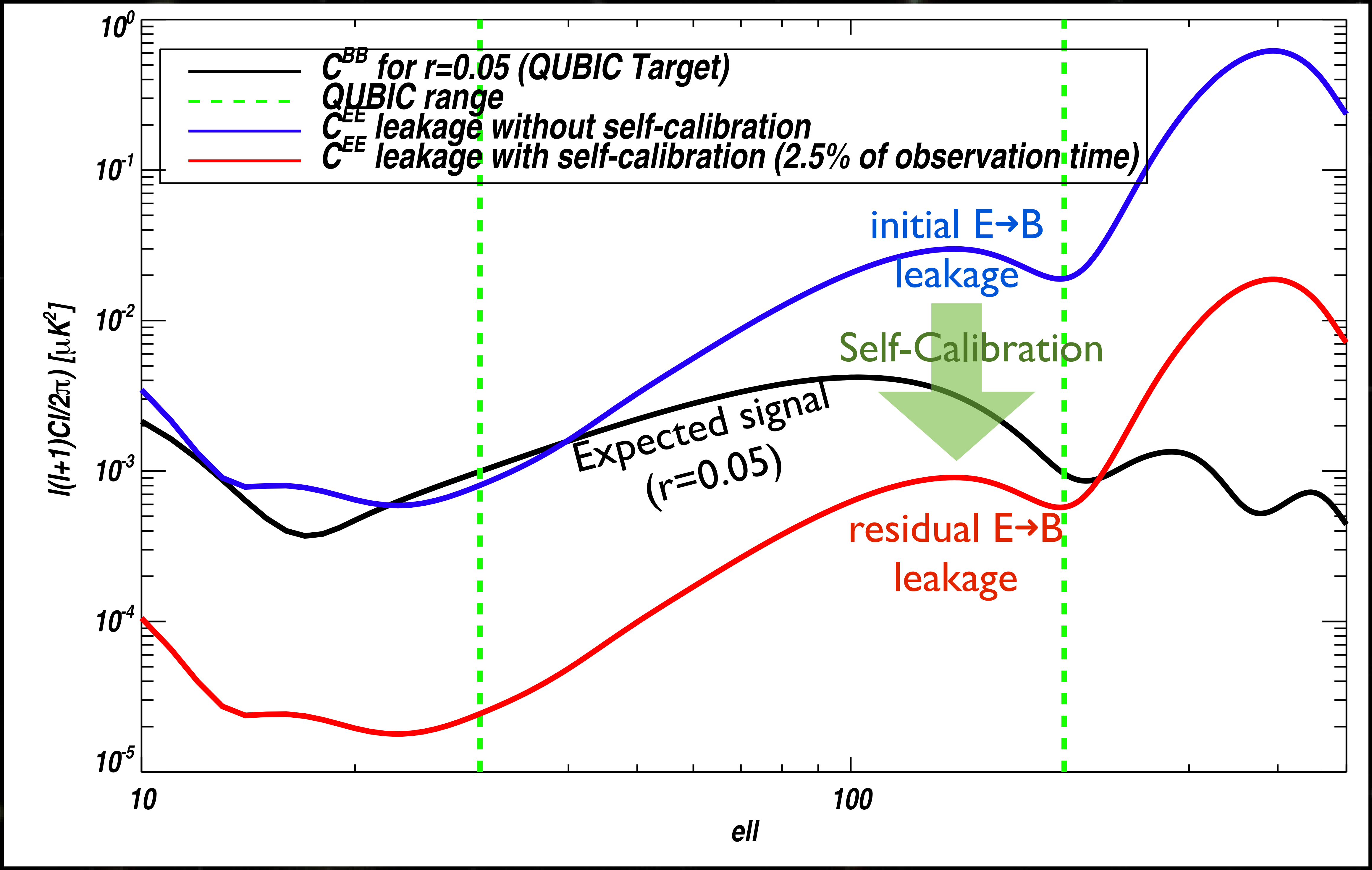
Redundant baselines : same Fourier Mode





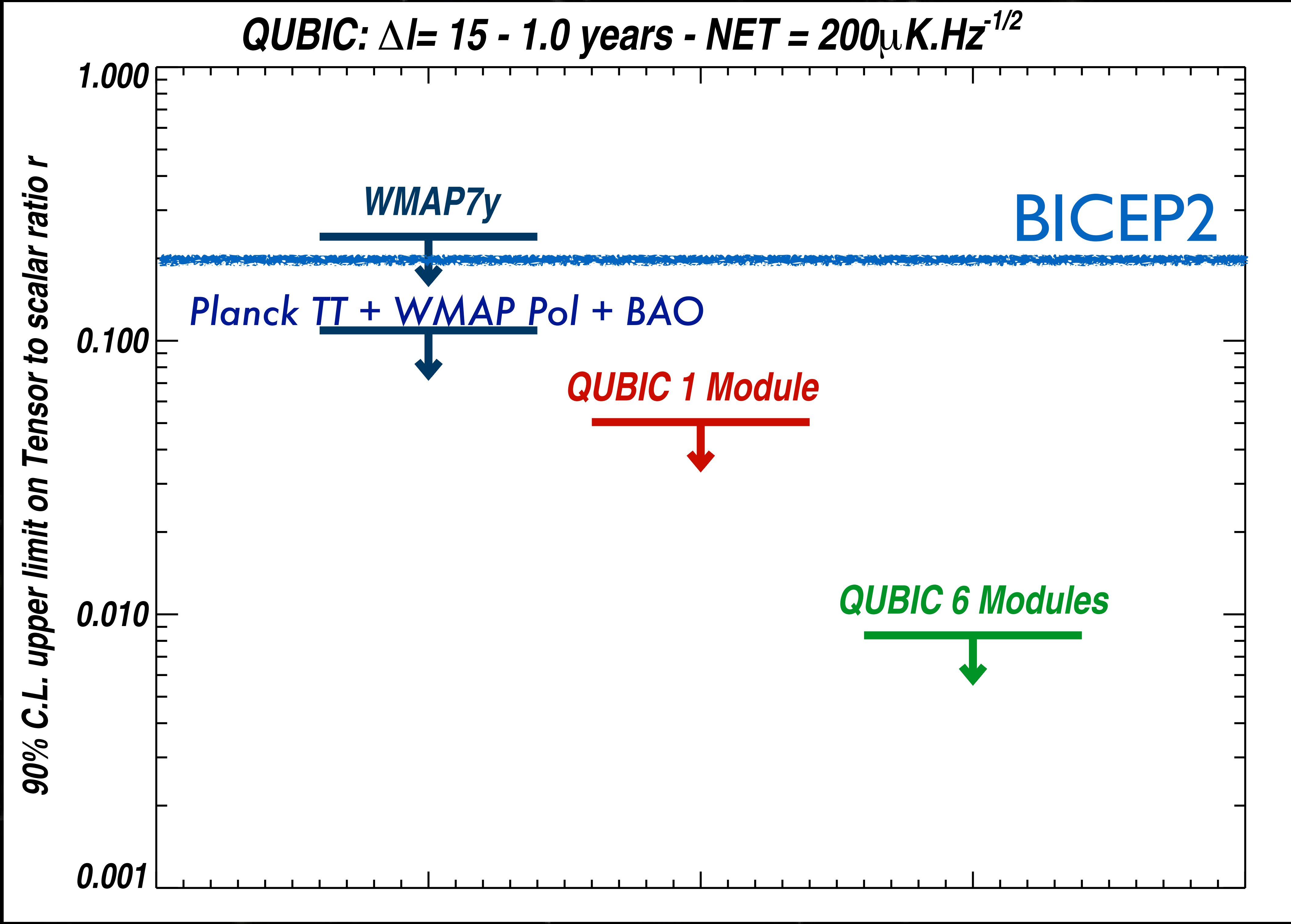


Self-Calibration results



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

Expected upper limit if r=0



QUBIC Timeline

- First Module (150 and 220 GHz)
  - ★ Elements construction phase has started
  - ★ Construction, Integration and tests at APC, Paris : 1st semester 2015
  - ★ Transportation to Dome C: mid-2016
  - ★ First light on site: End 2016
  - ★ Data Taking: 2017-2018
    - 4.4 μK.arcmin @ 150 GHz
    - 7.7 μK.arcmin @ 220 GHz
    - $r < 0.05$ @ 95% C.L. with foreground contamination control
- Future modules (100 GHz, 150 GHz, 220 GHz)
  - ★ Depend on results with first module
  - ★ Start design studies in 2016
  - ★ 3 frequencies for a clean foreground control
  - ★ Target : $r < 0.01$ @ 95% C.L.
  - ★ A great opportunity to test MKIDs technologies (think about M4 ESA mission)

Conclusions

- QUBIC is a novel instrumental concept
  - ★ High sensitivity (r < 0.05 with 1st module)
  - ★ High control of instrumental systematics
  - ★ Possibility to run at two frequencies 150 and 220 GHz
  - ★ Operations to start in late 2016 at Dome C, Antarctica

- QUBIC is in a very good position to check / challenge the BICEP2 result - and to detect (likely to be) lower B-modes
  - ★ High sensitivity
  - ★ Optimized for large scale B-modes
  - ★ 220 GHz would allow for controlling Galactic dust contamination
  - ★ No other ground-based competitors seem to have plans for the « golden » 220 GHz channel (usually target 100 and 150 GHz)