Cosmic Microwave Background Observations

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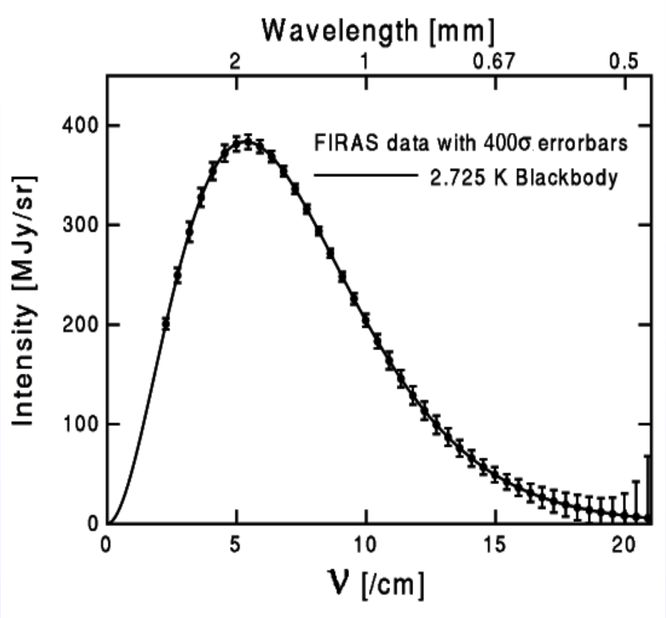
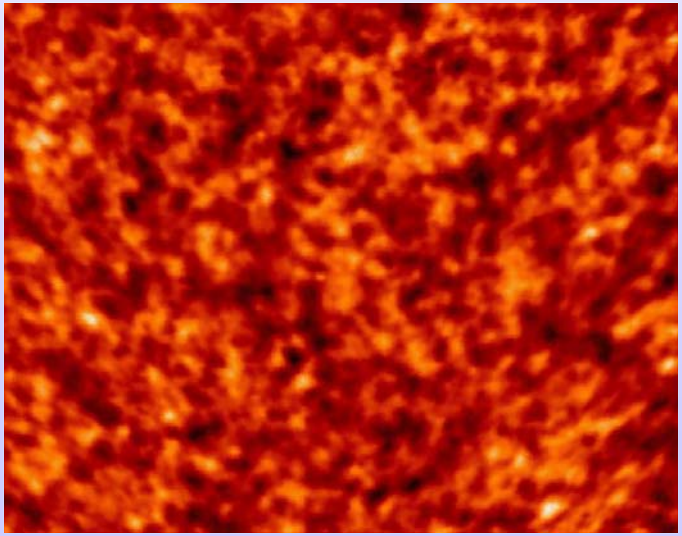
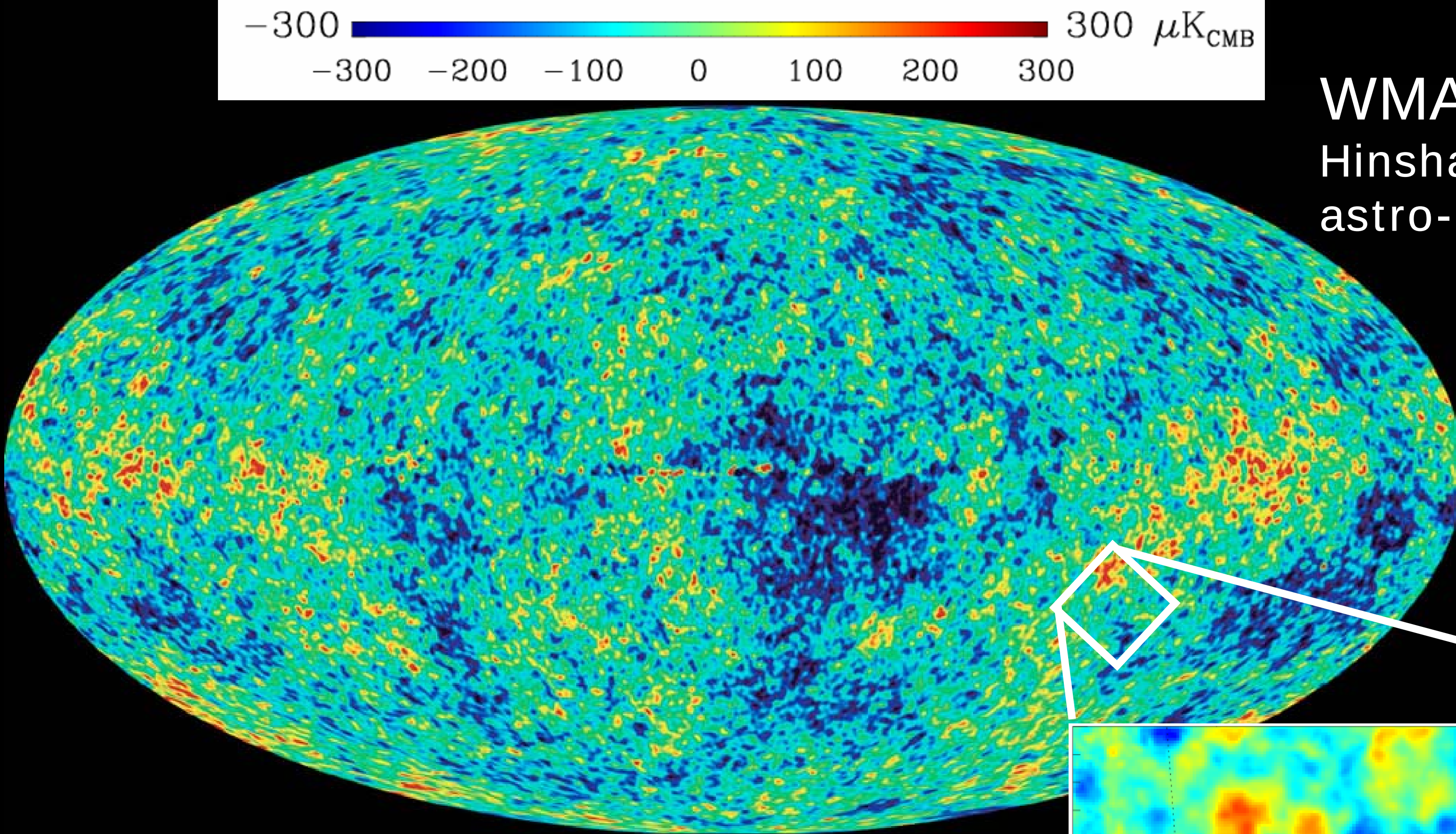
The Cosmic Microwave Background

- Is an abundant background of microwave photons filling the universe ($400\gamma/cm^3$).
- Formed a few μs after the Big Bang.
- For about 400000 yr the universe has been a fireball of photons and matter ($10^9\gamma/b$) : thermalization.
- The CMB spectrum has been measured to be planckian with outstanding accuracy (T=2.725K).
- The anisotropy ($\Delta T/T$, c_l) has been measured with good accuracy and maps inhomogeneities in the primeval fireball.

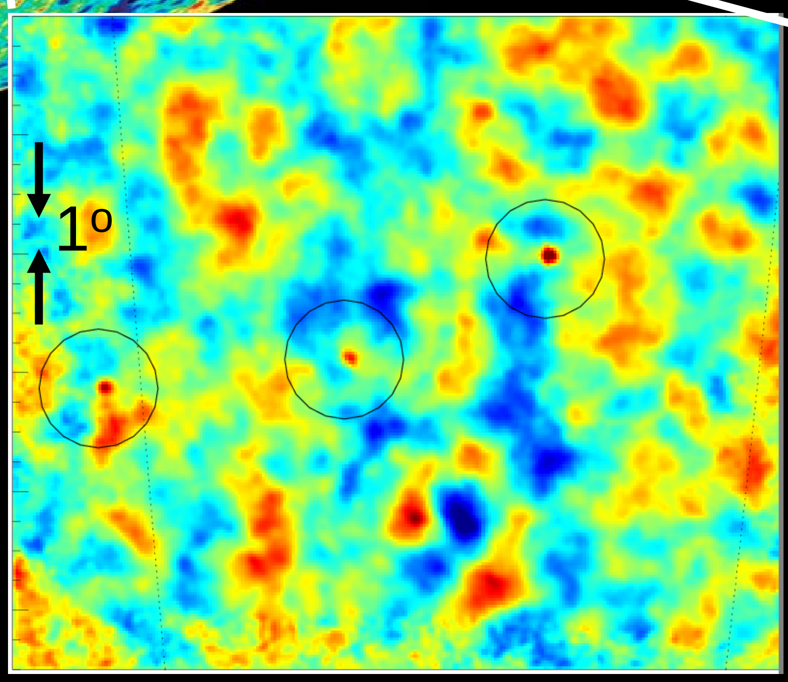




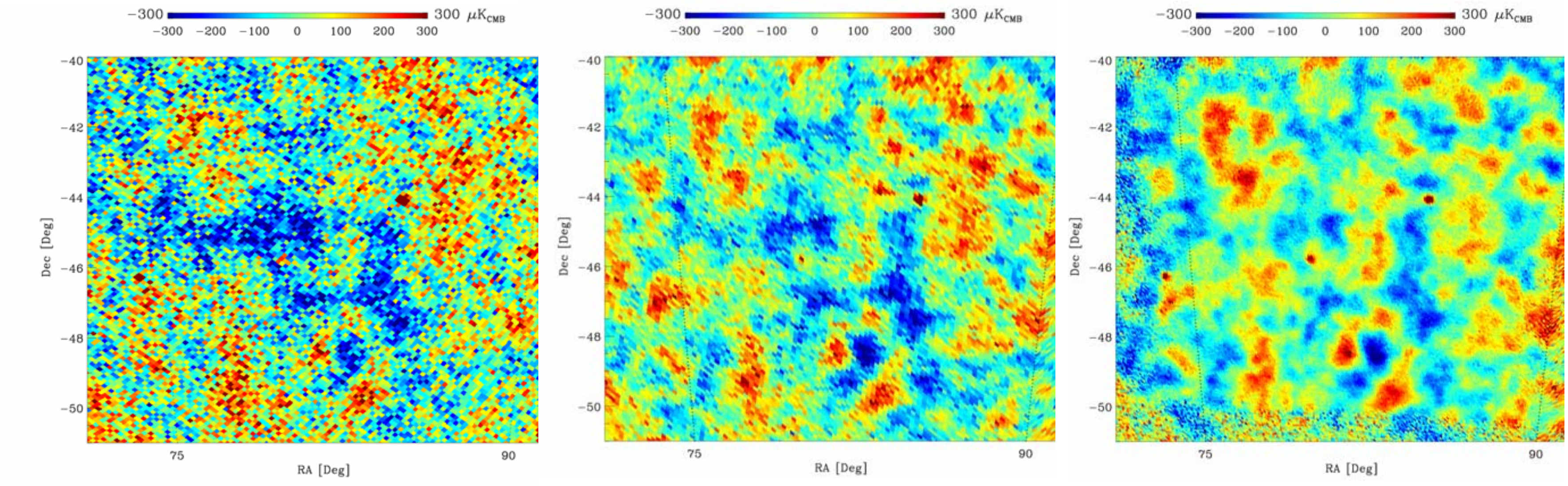


WMAP
Hinshaw et al. 2006
astro-ph/0603451

Detailed Views of the Recombination Epoch (z=1088, 13.7 Gyrs ago)



BOOMERanG
Masi et al. 2005
astro-ph/0507509



WMAP 3 years
23-94 GHz

BOOMERanG-98
145 GHz

BOOMERanG-03
145 GHz

The consistency of the maps from three *independent* experiments, working at very different frequencies and with very different mesurement methods, is the best evidence that the faint structure observed

- *is not due to instrumental artifacts*
- *has exactly the spectrum of CMB anisotropy, so it is not due to foreground emission*

The comparison also shows the *extreme sensitivity of cryogenic bolometers* operated at balloon altitude (the B03 map is the result of 5 days of observation)

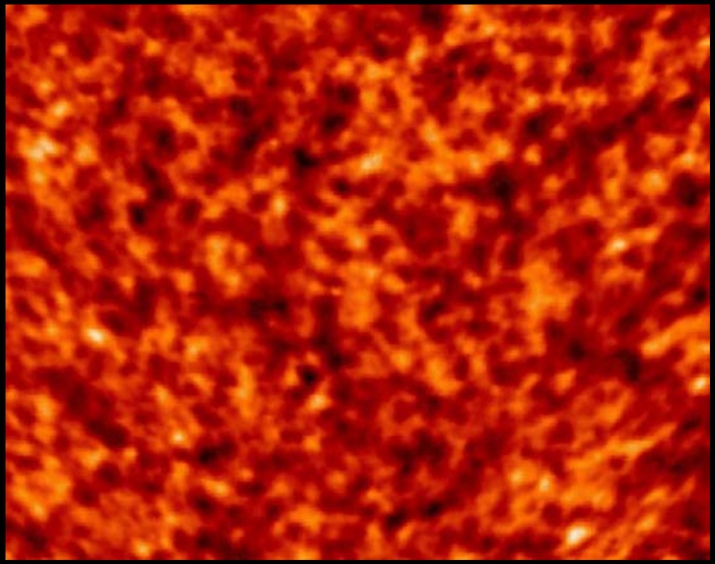
How does the image of the early universe form ?

Physics of the Primeval fireball and very early universe

Geometry of space

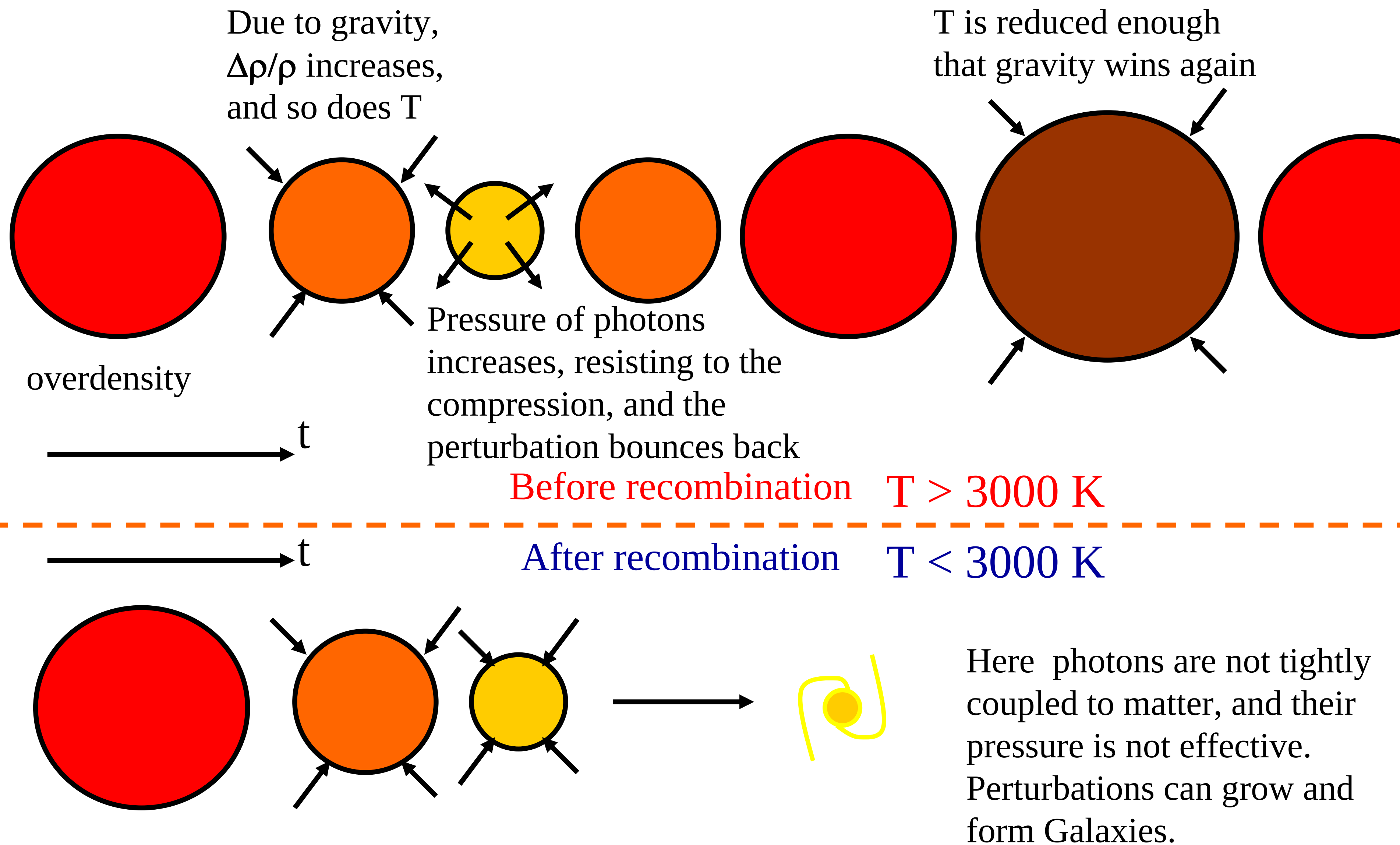
Here, now

14 billion light years



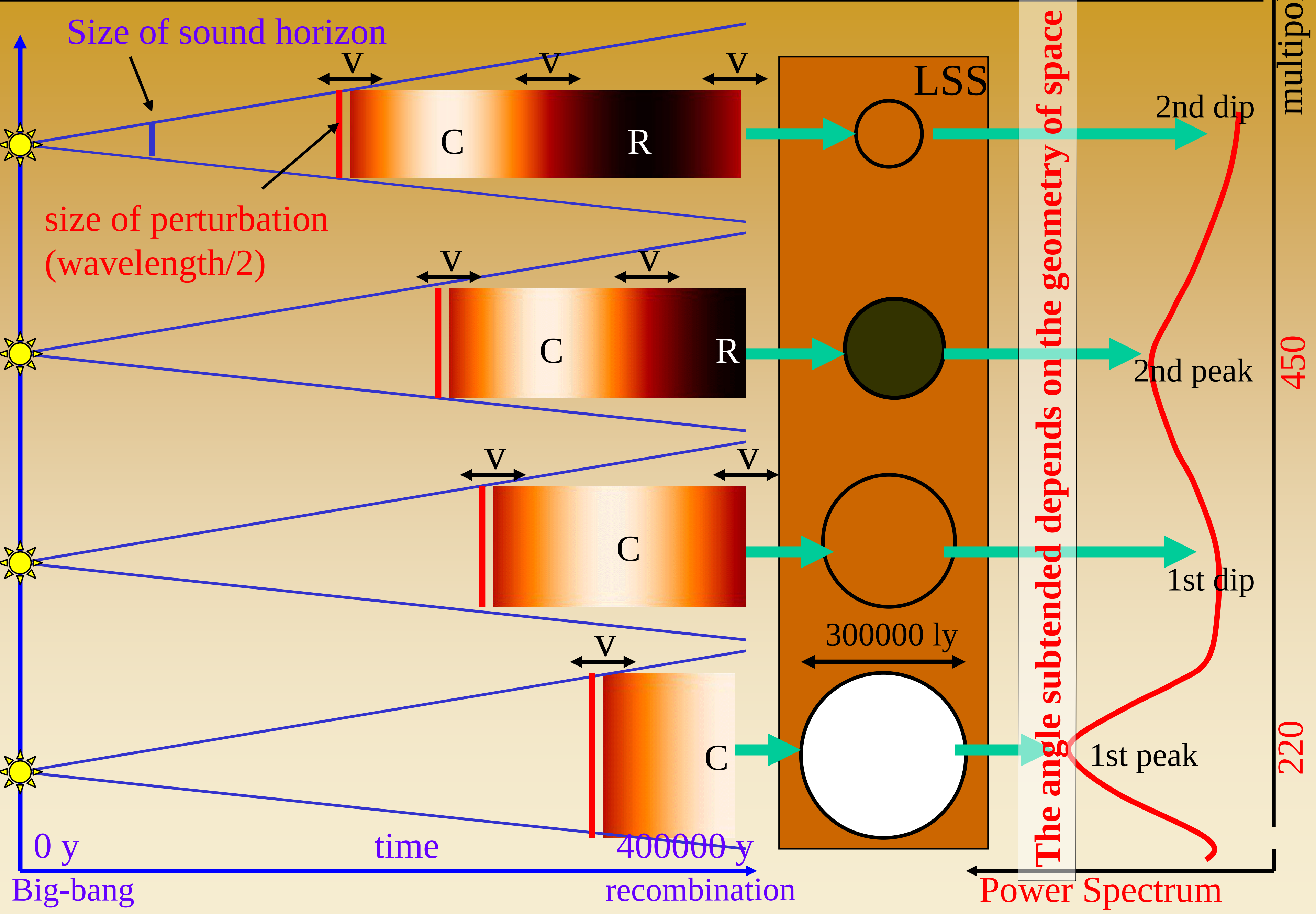
The BOOMERanG map of the last scattering surface

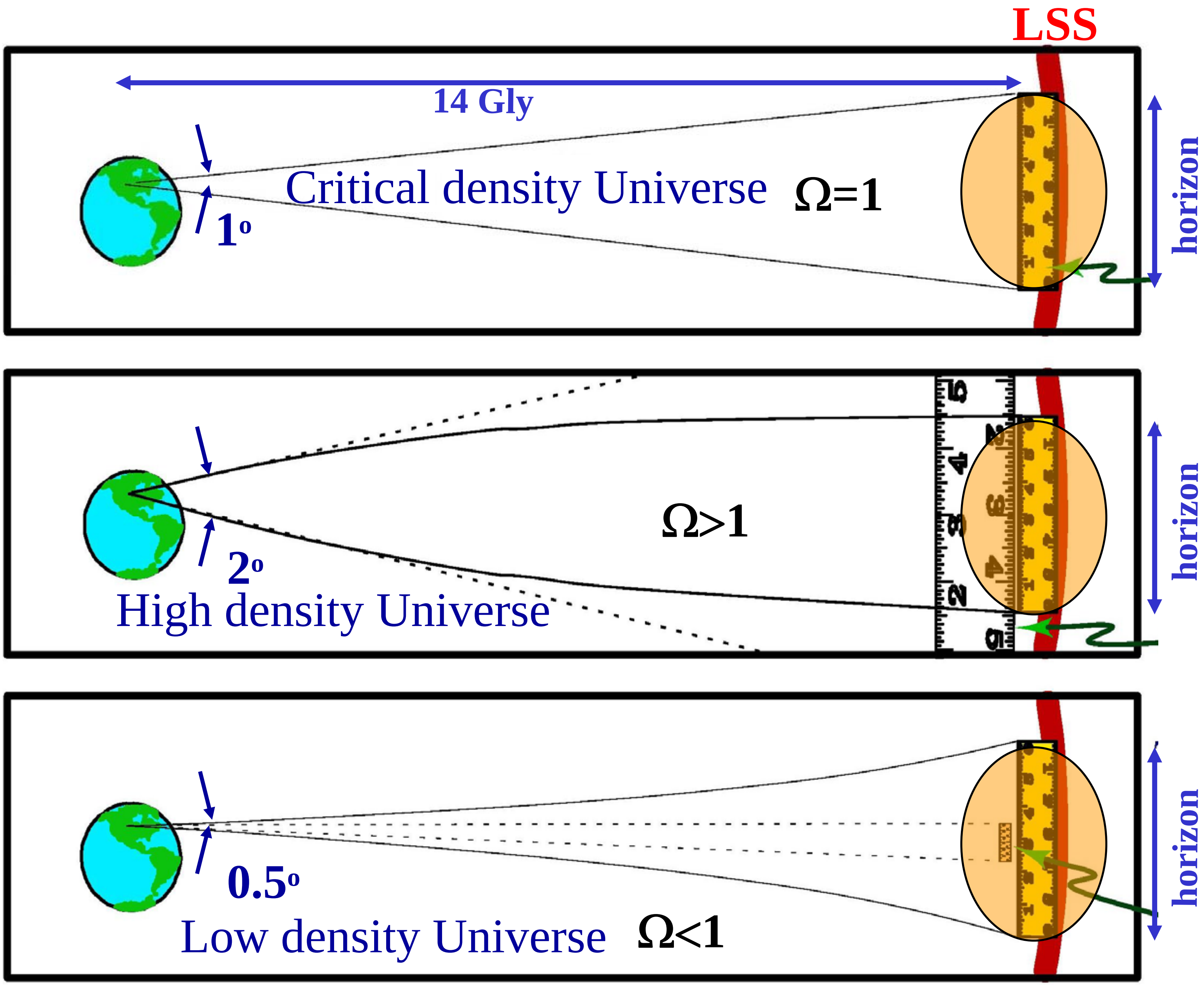
Density perturbations ($\Delta\rho/\rho$) were **oscillating** in the primeval plasma (as a result of the opposite effects of gravity and photon pressure).



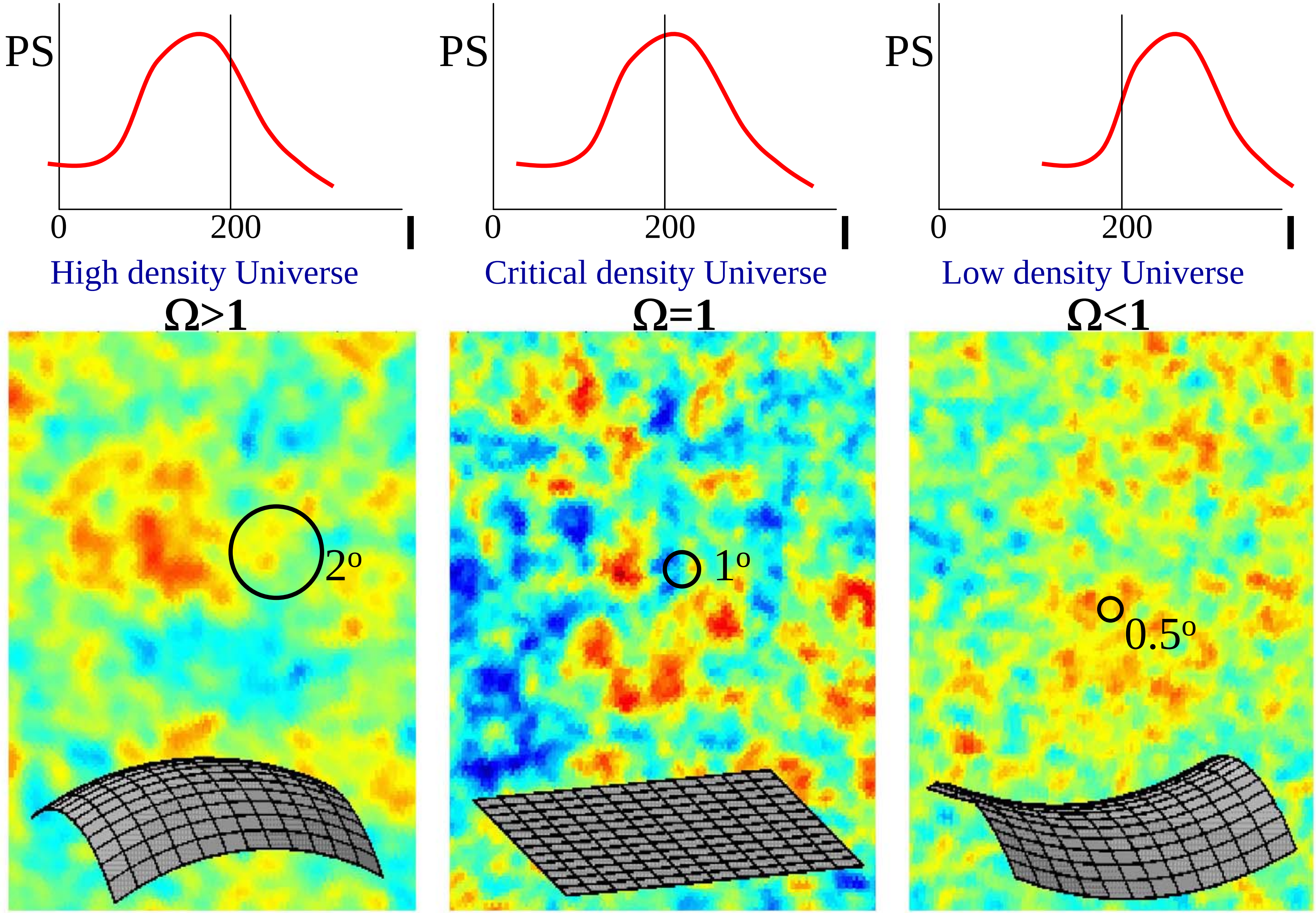
After recombination, density perturbation can **grow** and create the hierarchy of structures we see in the nearby Universe.

In the primeval plasma, photons/baryons density perturbations start to oscillate only when the sound horizon becomes larger than their linear size . Small wavelength perturbations oscillate faster than large ones.





LSS
14 Gly
Critical density Universe
Ω=1
1°
horizon
Ω>1
2°
High density Universe
horizon
0.5°
Low density Universe
Ω<1
horizon



PS
0
200
l
High density Universe
Ω>1
2º
PS
0
200
l
Critical density Universe
Ω=1
1º
PS
0
200
l
Low density Universe
Ω<1
0.5º

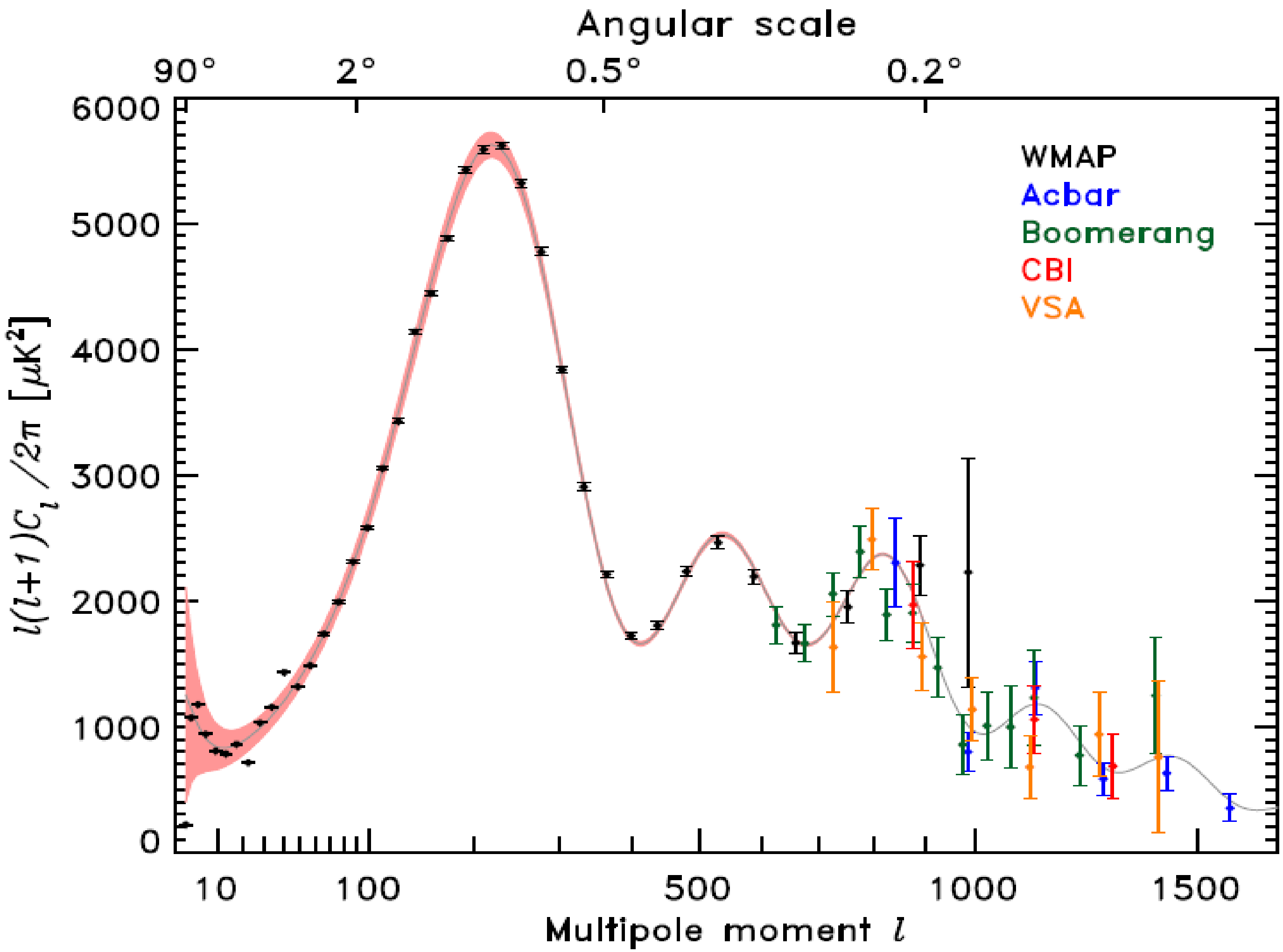
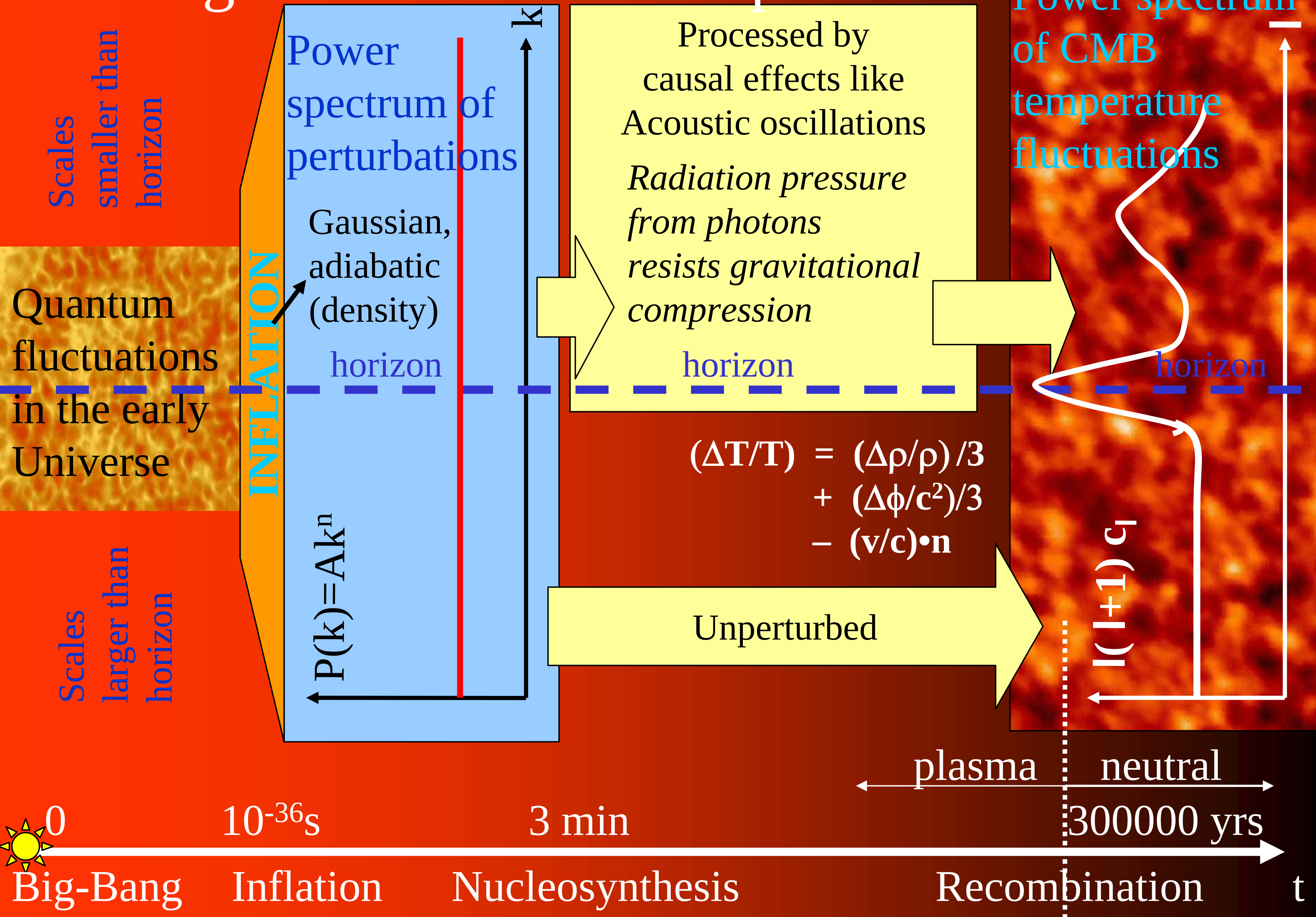


Fig. 18.— The *WMAP* three-year power spectrum (in black) compared to other recent measurements of the CMB angular power spectrum, including Boomerang (Jones et al. 2005), Acbar (Kuo et al. 2004), CBI (Readhead et al. 2004), and VSA (Dickinson et al. 2004). For clarity, the $l < 600$ data from Boomerang and VSA are omitted; as the measurements are consistent with *WMAP*, but with lower weight. These
vely confirm the turnover in the 3rd acoustic peak and probe the onset of Silk damping.
l sensitivity on sub-degree scales, the *WMAP* data are becoming an increasingly important
rce for high-resolution experiments.

2006

Hinshaw et al. 2006

Paradigm of CMB anisotropies



Cosmological Parameters

Assume an adiabatic inflationary model, and compare with same weak prior on $0.5<h<0.9$

WMAP

(100% of the sky, <1% gain calibration, <1% beam, multipole coverage 2-700)

Bennett et al. 2003

- $\Omega_o = 1.02 \pm 0.02$
- $n_s = 0.99 \pm 0.04$ *
- $\Omega_b h^2 = 0.022 \pm 0.001$
- $\Omega_m h^2 = 0.14 \pm 0.02$
- $T = 13.7 \pm 0.2$ Gyr
- $\tau_{rec} = 0.166 \pm 0.076$

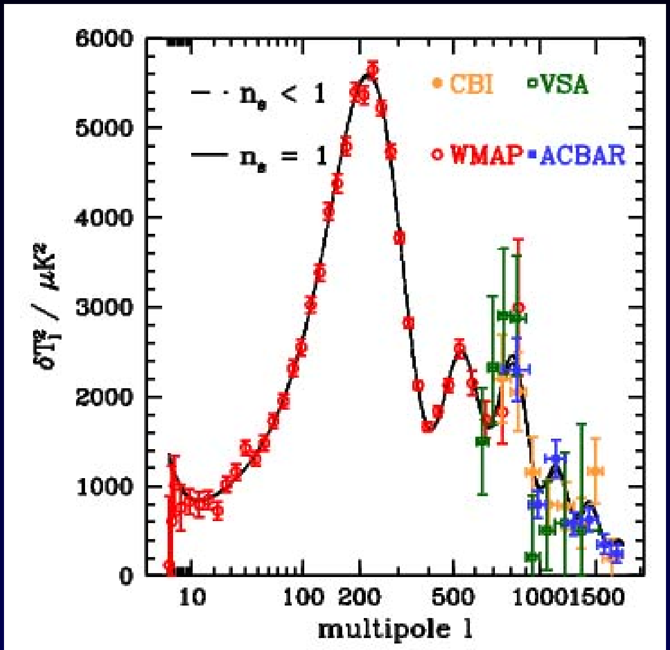
BOOMERanG

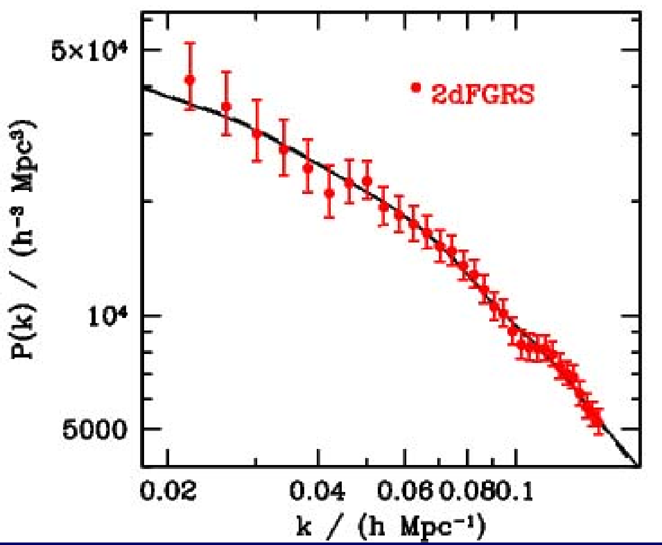
(4% of the sky, 10% gain calibration, 10% beam, multipole coverage 50-1000)

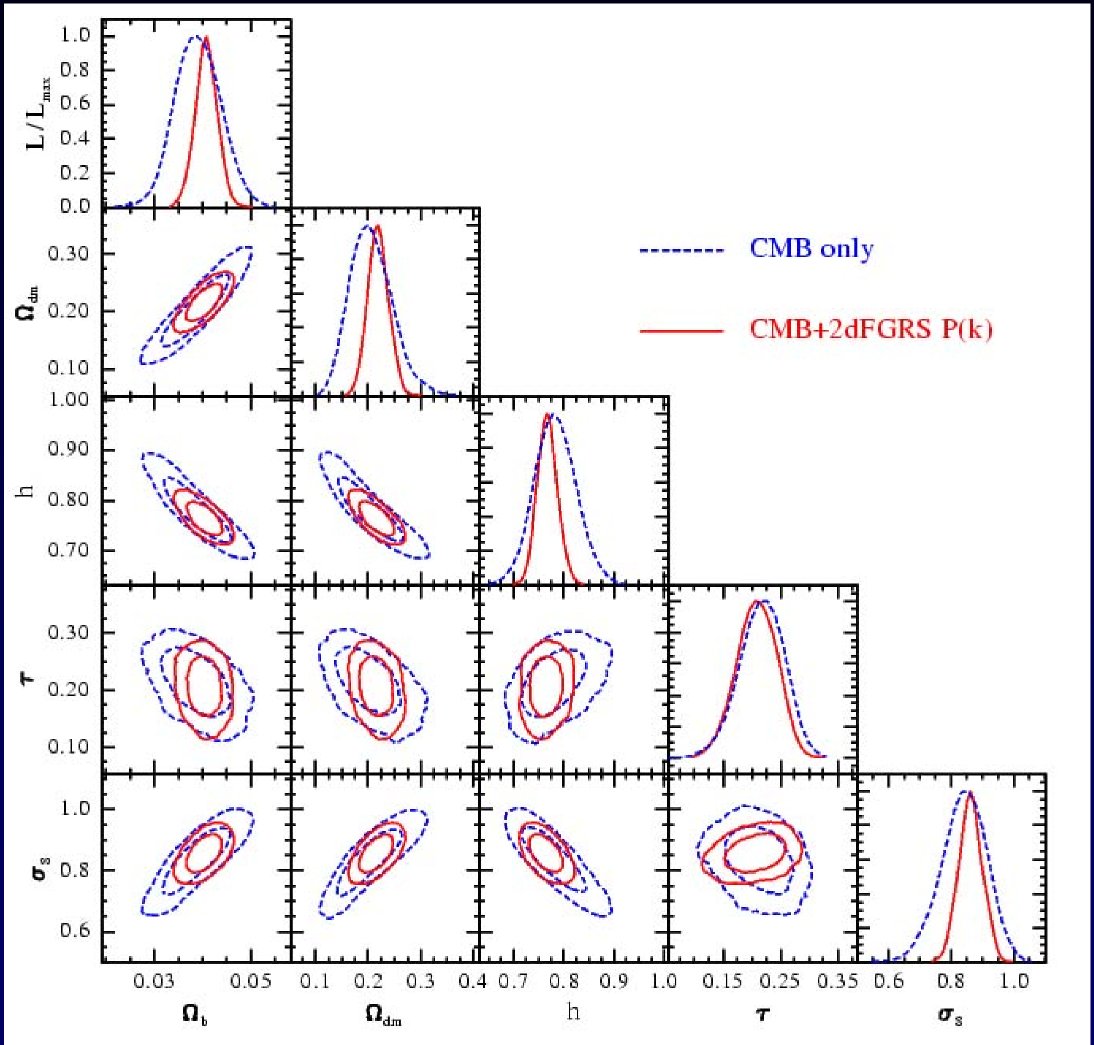
Ruhl et al. astro-ph/0212229

- $\Omega_o = 1.03 \pm 0.05$
- $n_s = 1.02 \pm 0.07$
- $\Omega_b h^2 = 0.023 \pm 0.003$
- $\Omega_m h^2 = 0.14 \pm 0.04$
- $T = 14.5 \pm 1.5$ Gyr
- $\tau_{rec} = ?$

Constraining Cosmological Parameters







From Sanchez et al. astro-ph/0507583

See also Tegmark et al. PRD 69 103501

- There is a minimalist model with only 6 free parameters (H_o, Ω_o, Ω_b, Ω_Λ, n, A) describing very well the angular power spectrum of the CMB, but also other measurements:
  - The spectrum of the CMB
  - The primordial abundances of light elements
  - The expansion of the Universe
  - The fluxes of high redshift SN1a "candles"
  - The large-scale distribution of galaxies and Ly-α clouds
  - The polarization of the CMB …. etc …
- So one could naively ask:

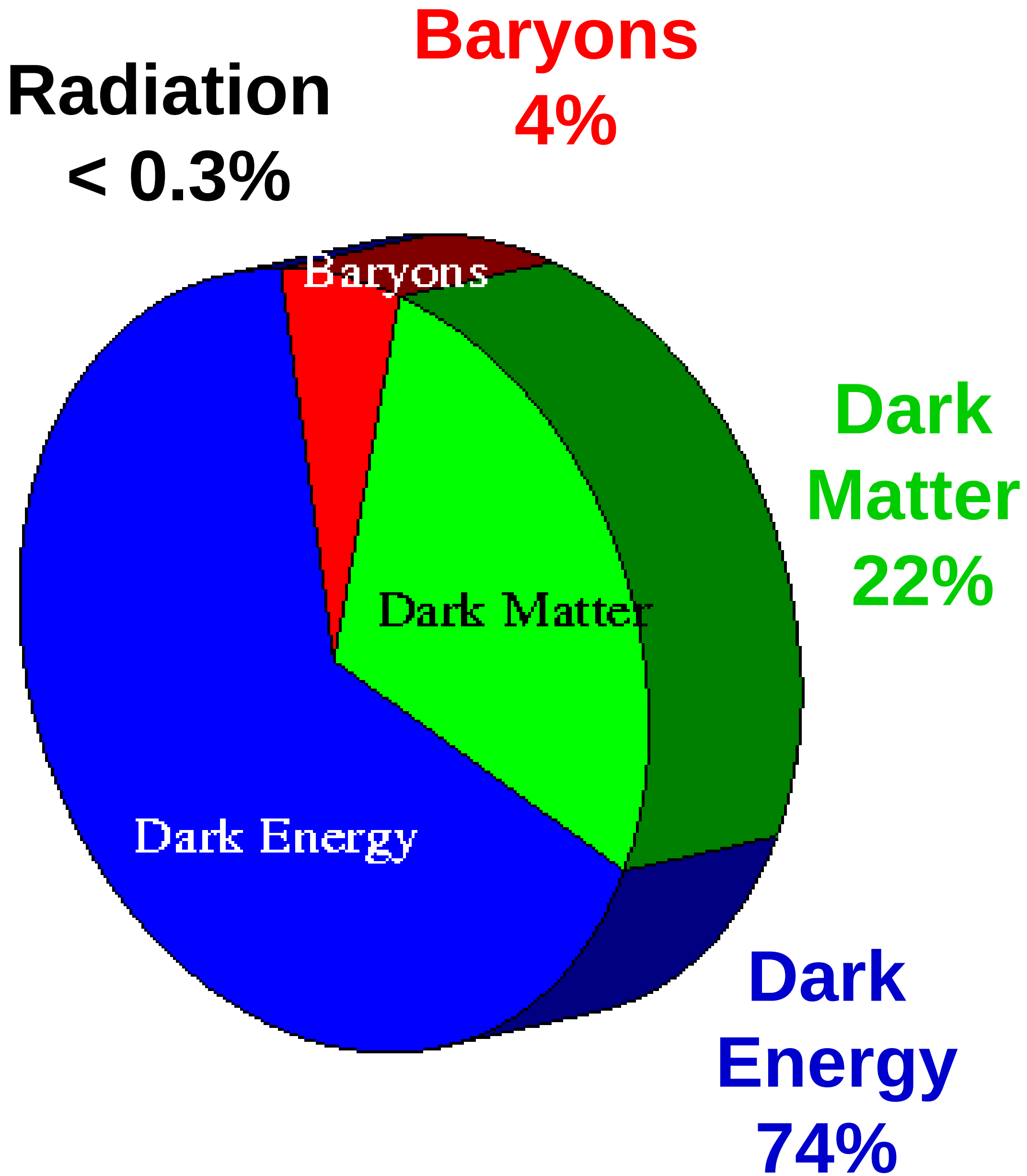
" *are we done with cosmology ?...* "

- So one could naively ask: “ *are we done with cosmology ?...”*

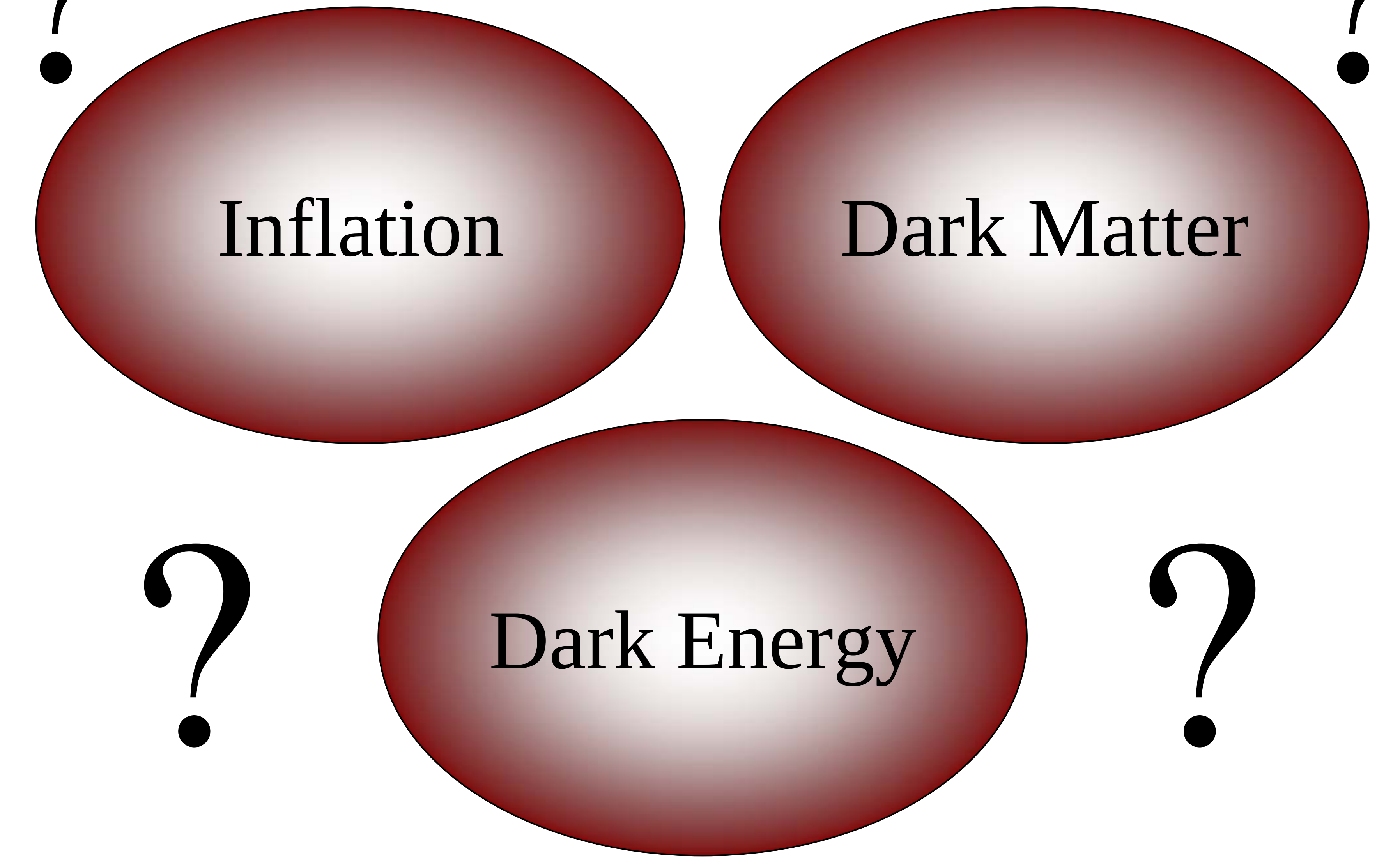
- *Not at all*. The “model” is still not satisfactory, since it requires “dark matter”, “dark energy”…

- … and also an “inflation phase” in the very early universe.

- There is no evidence yet, from physics, for these features.



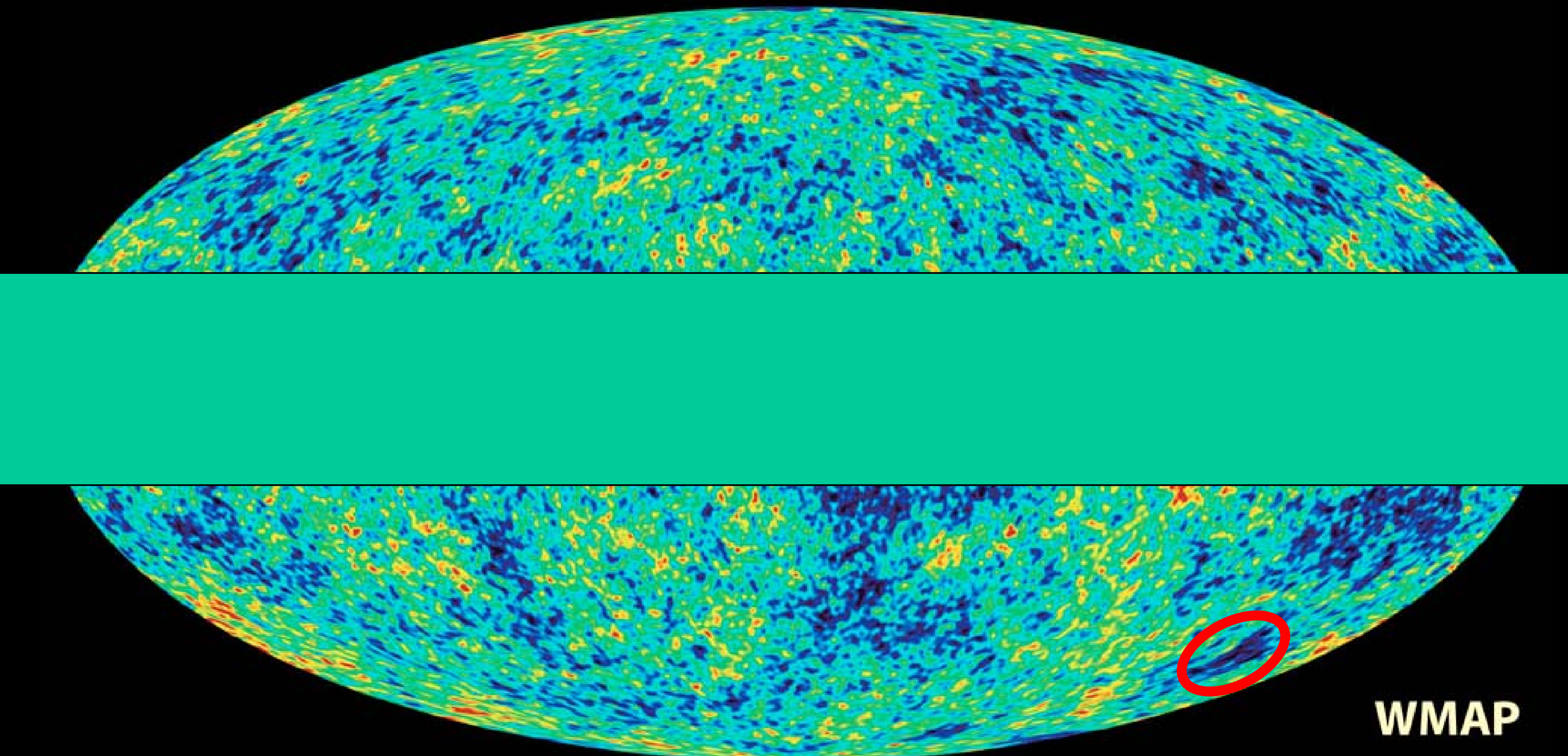
Enigmas in Cosmology



- As a CMB experimentalist, I would rather try to answer two different questions:
  - **are there open issues in CMB anisotropy measurements ?**
  - **are there critical CMB observations still to be done, aimed at solving the three enigmas ?**

Open issues related to CMB anisotropy (1)

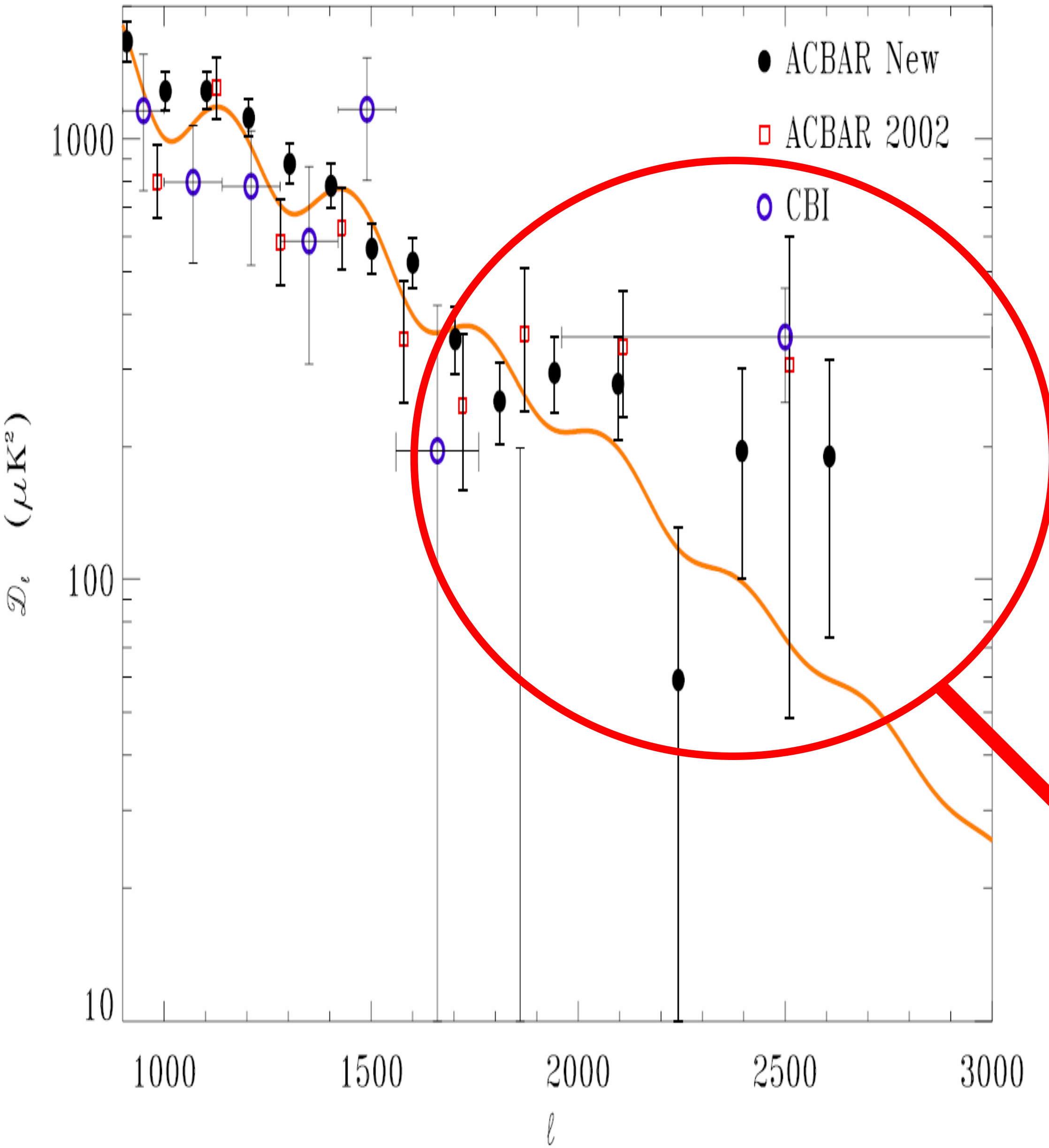
- Large angular scales :
  - The quadrupole component is somewhat low (confirmed in WMAP 3-yrs data)
  - There is some degree of alignment of the lowest multipoles
  - There is an evident galactic north-south anomaly in the CMB map of WMAP: the distribution is smoother in the north than in the south (see e.g. Eriksen 2004, Hansen 2004, Hansen 2006 …)
  - There is evidence for localized non gaussian spots in the maps (see e.g. Vielva 2004, Cruz 2006 ...)
  - There is evidence for threshold-independent ellipticity of the cold and hot spots in WMAP and BOOMERanG data (see Gurzadyan et al. 2003,2004,2005)
- We should not forget that the full-sky CMB map from WMAP is the result of a components separation process
- All this seems enough to call for an independent measurement of CMB anisotropy at large angular scales, with wider frequency coverage to better monitor the foregrounds, and with the highest possible sensitivity to make it easier to detect instrumental systematics.
- The **Planck** mission will assess all these issues.

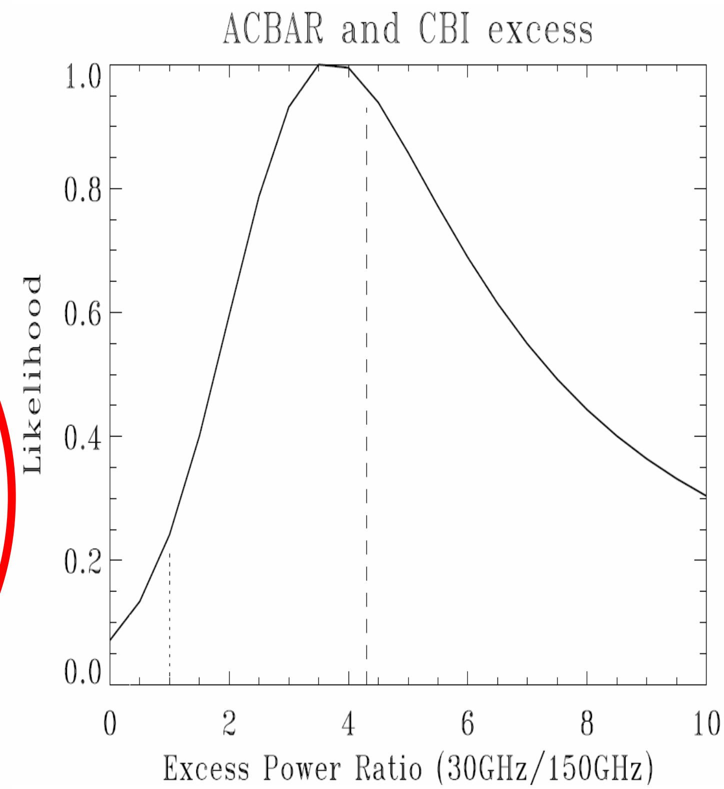


WMAP

Open issues related to CMB anisotropy (2)

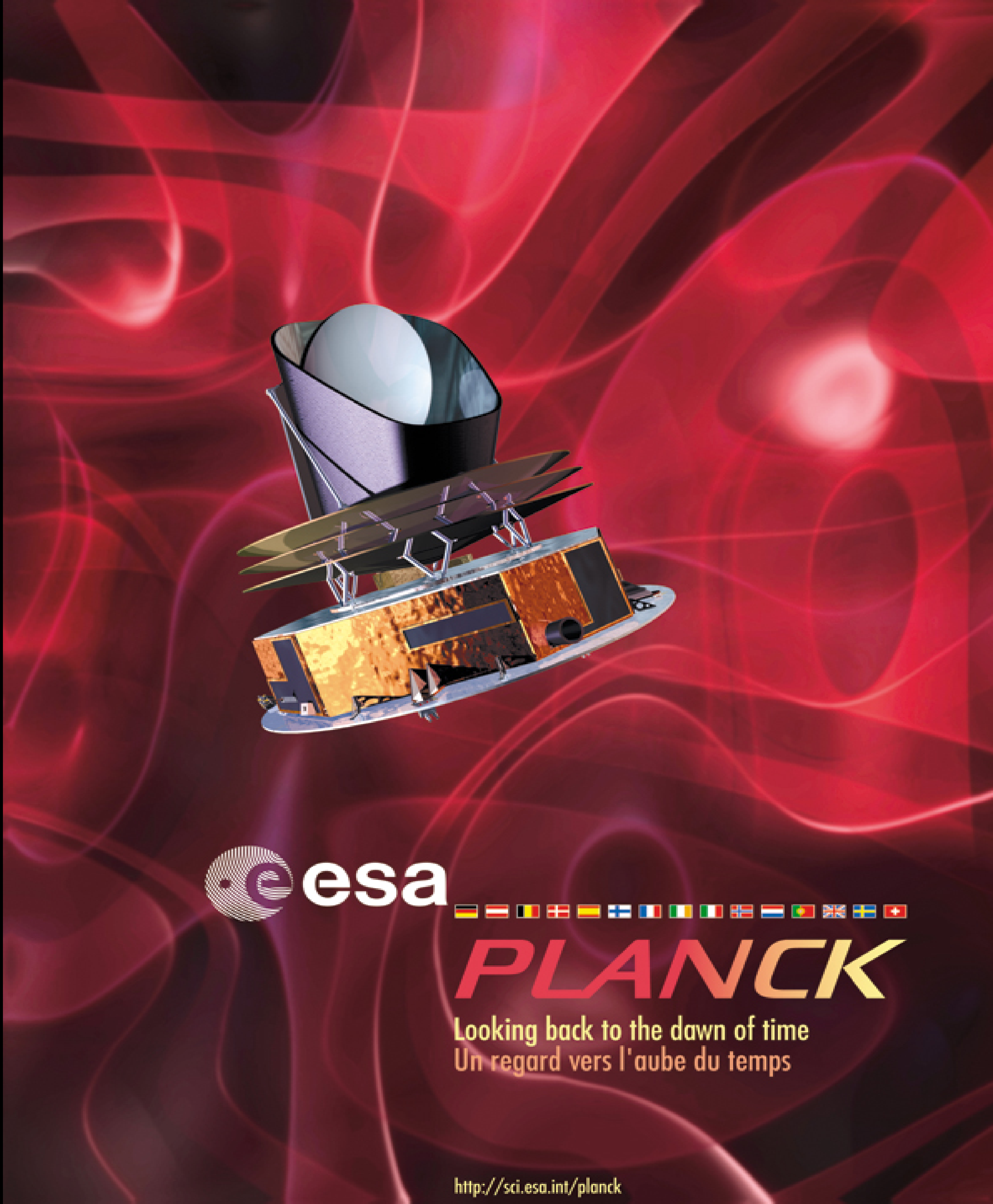
- Small angular scales :
  - The third peak and the damping tail of the angular power spectrum of the CMB are not measured as well as multipoles <500.
  - There is some evidence for excess anisotropy at multipoles >2000 (CBI, ACBAR)
  - Surveys of Sunyaev-Zeldovich effect in a large number of clusters of galaxies can provide fundamental cosmological information
- Planck will assess the first and second issues very well
- For the third issue
  - Planck will contribute with a shallow survey of clusters
  - Very powerful machines based on larger telescopes and larger arrays of bolometric detectors will provide huge datasets





ACBAR & CBI excess power at multipoles 2000-3000. Inconsistent with CMB anisotropy. Consistent with SZ.

Kuo et al. 2006


esa
PLANCK
Looking back to the dawn of time
Un regard vers l'aube du temps
http://sci.esa.int/planck

PLANCK

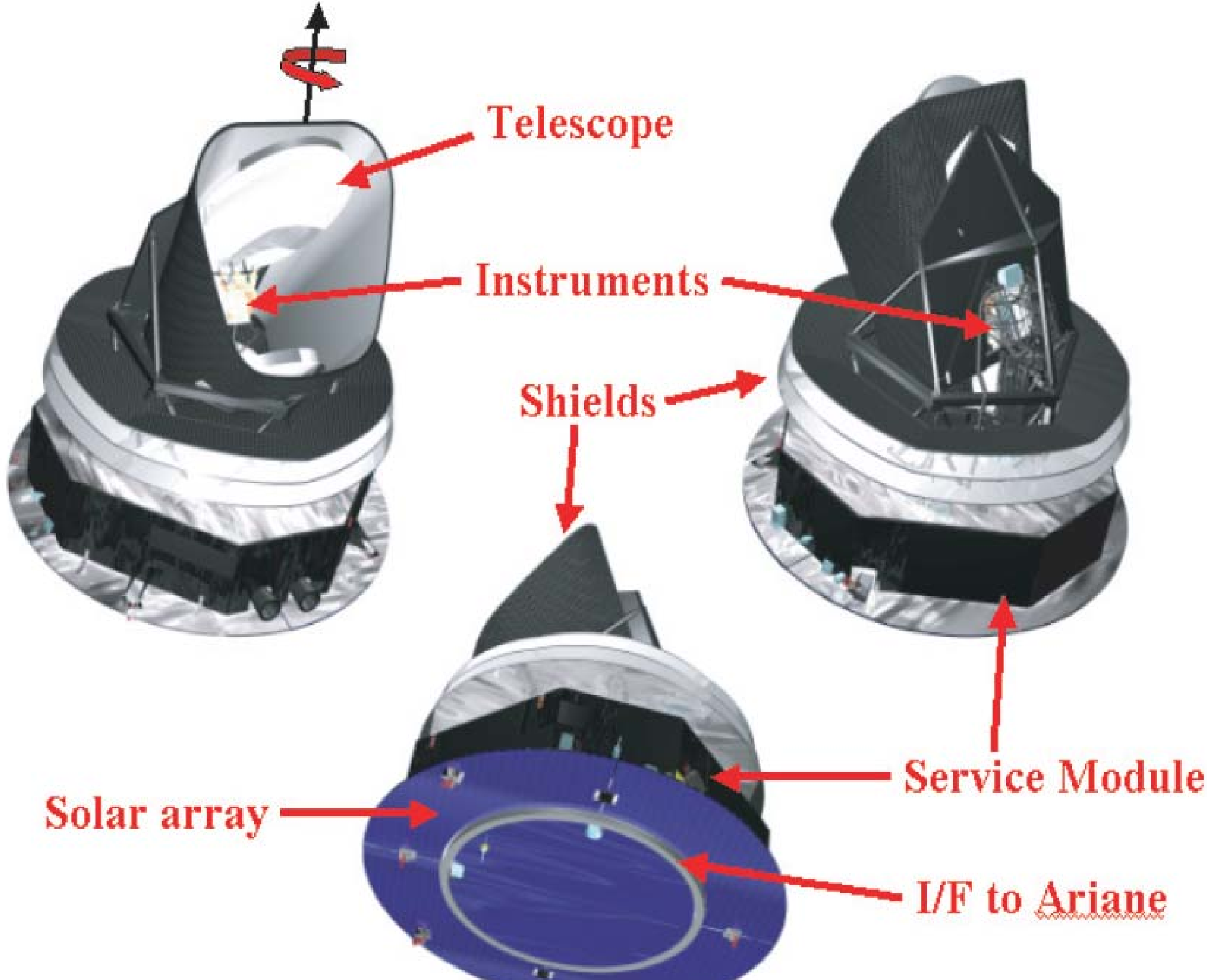
ESA mission to map the Cosmic Microwave Background

Image of the whole sky at wavelengths near the intensity peak of the CMB radiation, with

- high instrument sensitivity ($\Delta T/T \sim 10^{-6}$)
- high resolution (≈5 arcmin)
- wide frequency coverage (25 GHz-950 GHz)
- high control of systematics

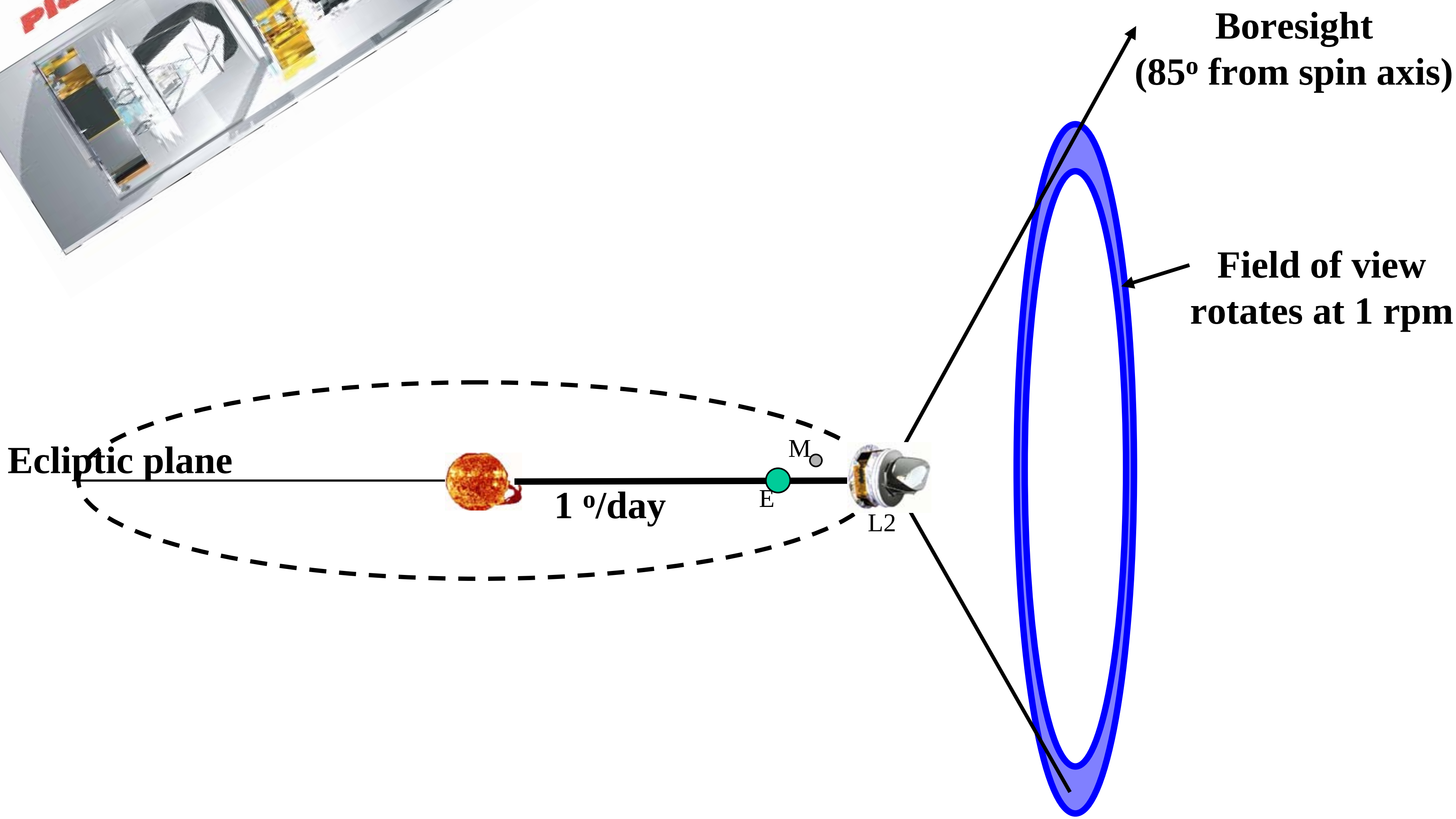
Launch: 2008; payload module: 2 instruments and telescope

- Low Frequency Instrument (LFI, HEMTs)
- High Frequency Instrument (HFI, bolometers)
- Telescope: primary (1.50x1.89 m ellipsoid)


Telescope
Instruments
Shields
Service Module
Solar array
I/F to Ariane

Observing strategy

The payload will work from L2, to avoid the emission of the Earth, of the Moon, of the Sun



Instrument Performance Goals

Telescope	**1.5 m (proj. aperture) aplanatic; shared focal plane; system emissivity 1%**								
	Viewing direction offset 85^o from spin axis; Field of View 8^o								
Instrument	**LFI**			**HFI**					
Center Freq. (GHz)	**30**	**44**	**70**	**100**	**143**	**217**	**353**	**545**	**857**
Detector Technology	**HEMT LNA arrays**			**Bolometer arrays**					
Detector Temperature	**~20 K**			**0.1 K**					
Cooling Requirements	**H_2 sorption cooler**			**H_2 sorption + 4 K J-T stage + Dilution cooler**					
Number of Unpol. Detectors	**0**	**0**	**0**	**0**	**4**	**4**	**4**	**4**	**4**
Number of Linearly Polarised Detectors	**4**	**6**	**12**	**8**	**8**	**8**	**8**	**0**	**0**
Angular Resolution (FWHM, arcmin)	**33**	**24**	**14**	**9.5**	**7.1**	**5**	**5**	**5**	**5**
Bandwidth (GHz)	**6**	**8.8**	**14**	**33**	**47**	**72**	**116**	**180**	**283**
Average $\Delta T/T_I$* per pixel#	**2.0**	**2.7**	**4.7**	**2.5**	**2.2**	**4.8**	**14.7**	**147**	**6700**
Average $\Delta T/T_{U,Q}$* per pixel#	**2.8**	**3.9**	**6.7**	**4.0**	**4.2**	**9.8**	**29.8**		

* **Sensitivity (1σ) to intensity (Stokes I) fluctuations observed on the sky, in thermodynamic temperature ($x10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).**

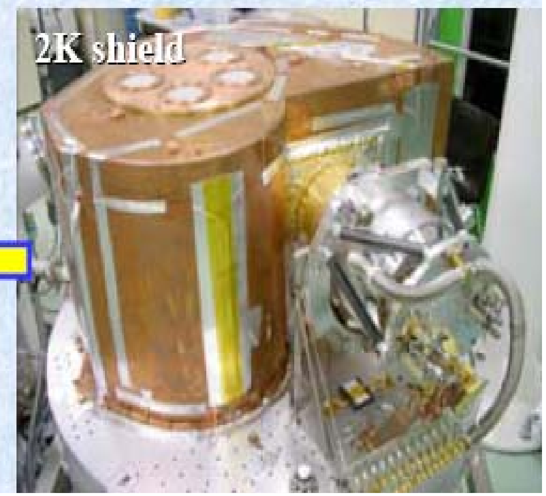
\# **A pixel is a square whose side is the FWHM extent of the beam.**

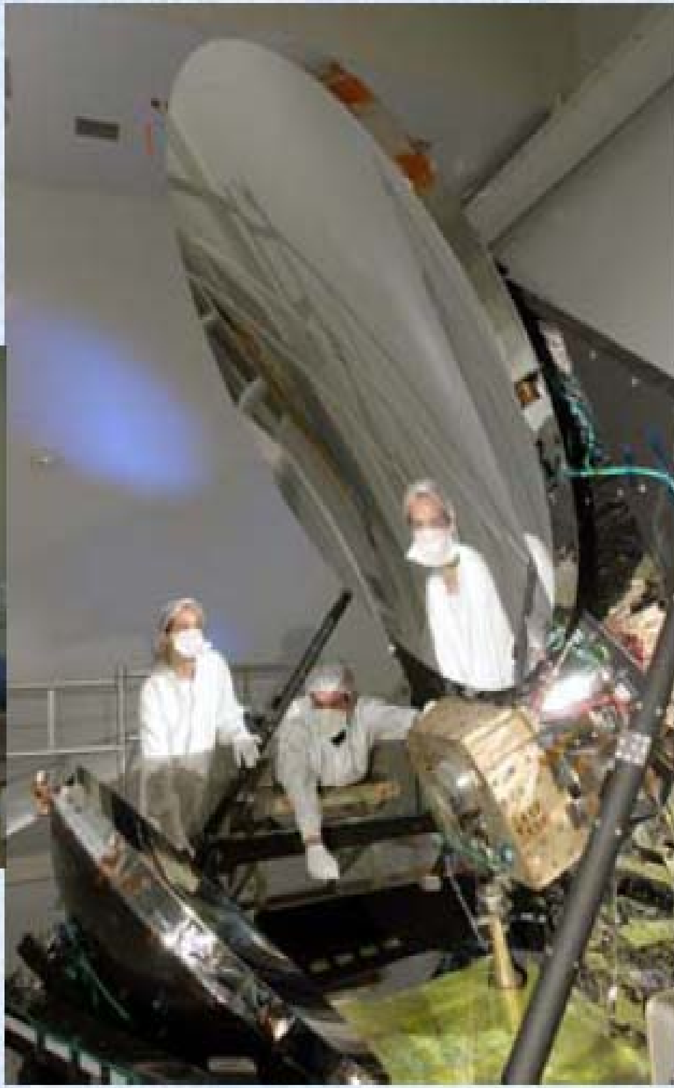
* **Sensitivity (1σ) to polarised intensity (Stokes U and Q) fluctuations observed on the sky, in thermodynamic temperature ($x10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).**

A very ambitious instrument (expecially HFI) based on the technology developed and tested with BOOMERanG and ARCHEOPS

CQM integration & calibration @ IAS

(CQM = Cryogenic Qualification Model)

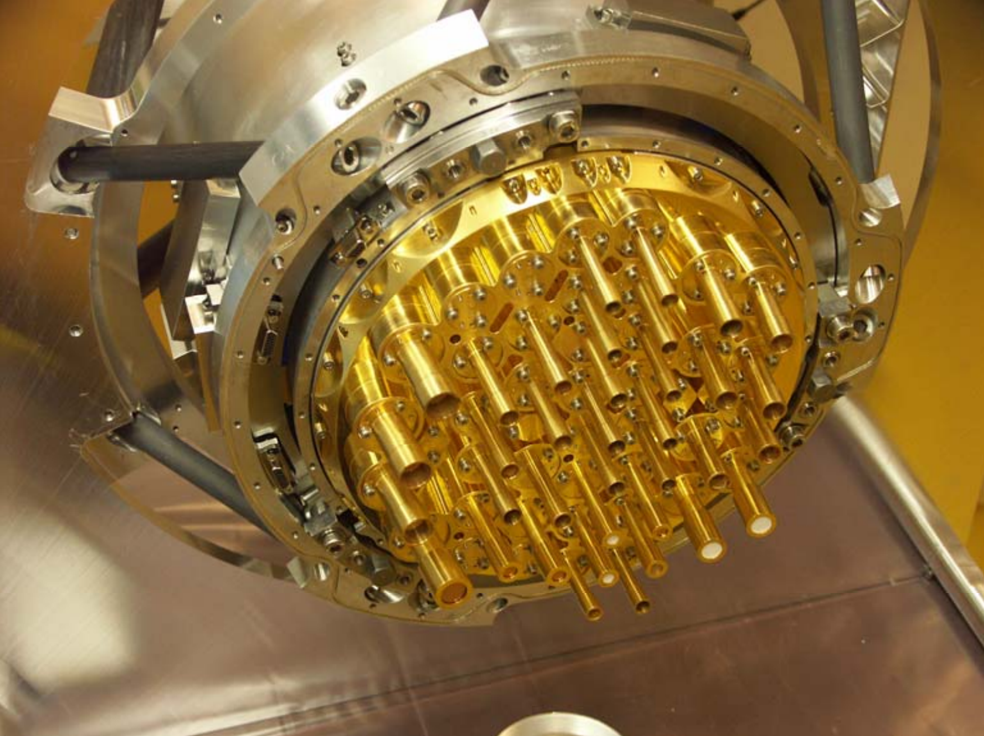


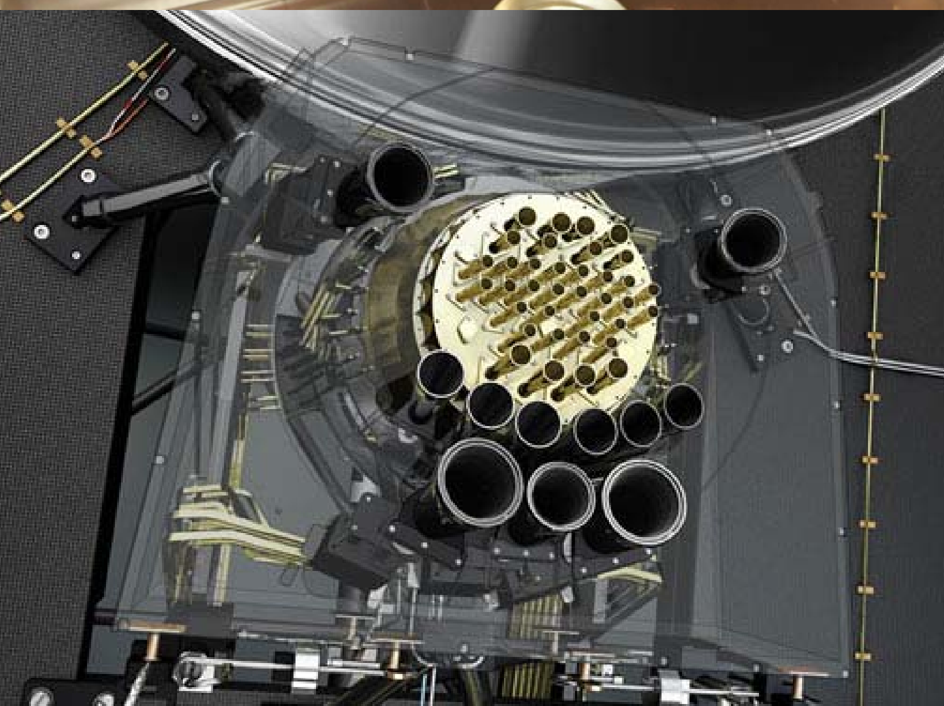


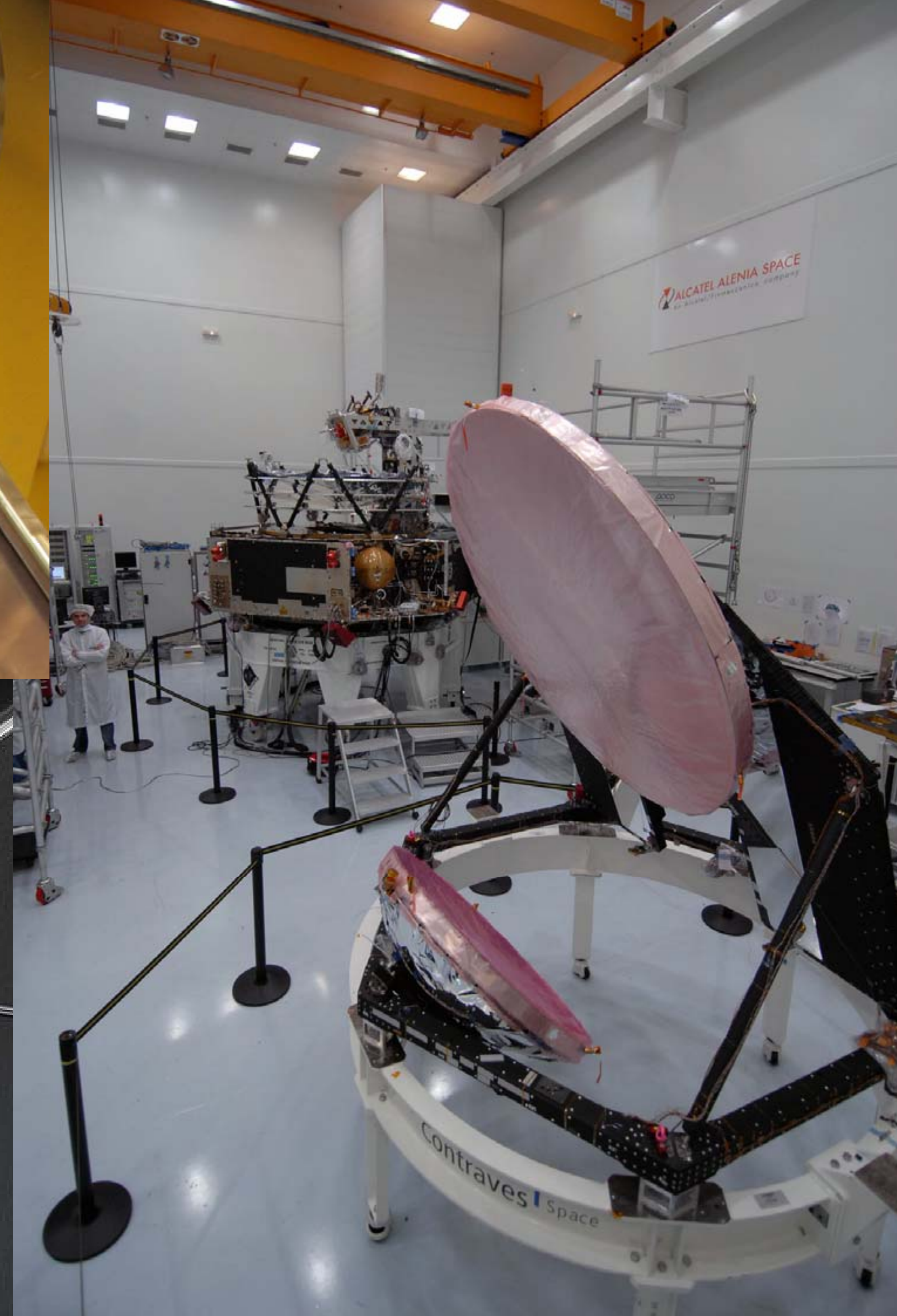
- And the full cryogenic qualification model has been vibration and thermal tested.

FM Calibrated; Payload Integrated

- The HFI flight model has been recently calibrated in Orsay, the LFI has been calibrated in Milan.
- The goal performance has been achieved for both.
- The HFI has been integrated with LFI and with the telescope and bus in Alcatel-Alenia (Cannes).

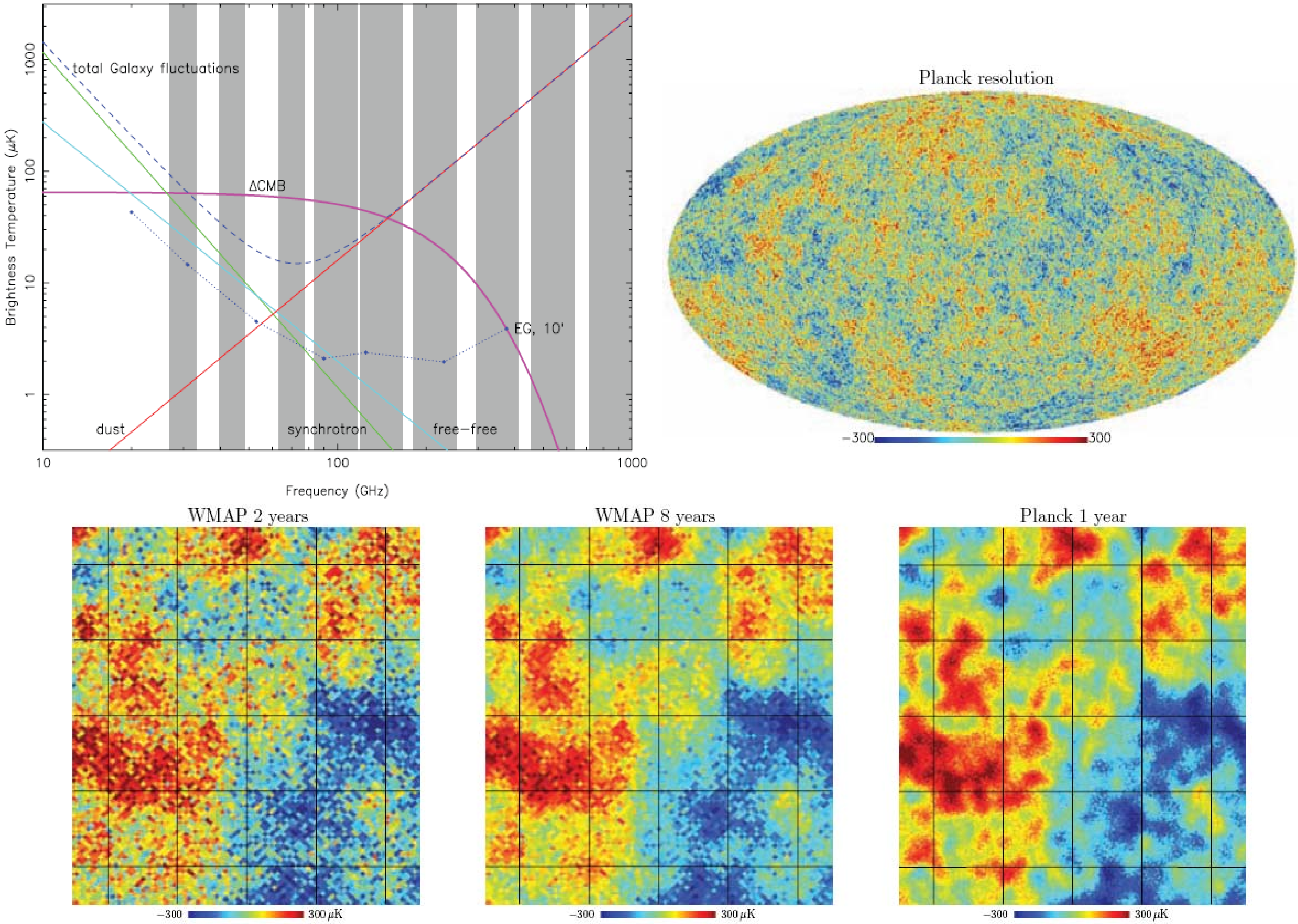





ALCATEL ALENIA SPACE
Contraves Space

FM Calibrated; Payload Integrated

- We can expect, in two years from now :
  - A precisely calibrated instrument operating in the best possible space environment
  - Maps covering the full wavelength range and angular resolution of primary CMB anisotropy and of relevant foregrounds
  - Maps of mm sky polarization



total Galaxy fluctuations
ΔCMB
EG, 10'
dust
synchrotron
free−free
Brightness Temperature (μK)
Frequency (GHz)
1000
100
10
1
10
100
1000
Planck resolution
−300
300
WMAP 2 years
WMAP 8 years
Planck 1 year
−300
300 μK
−300
300 μK
−300
300 μK

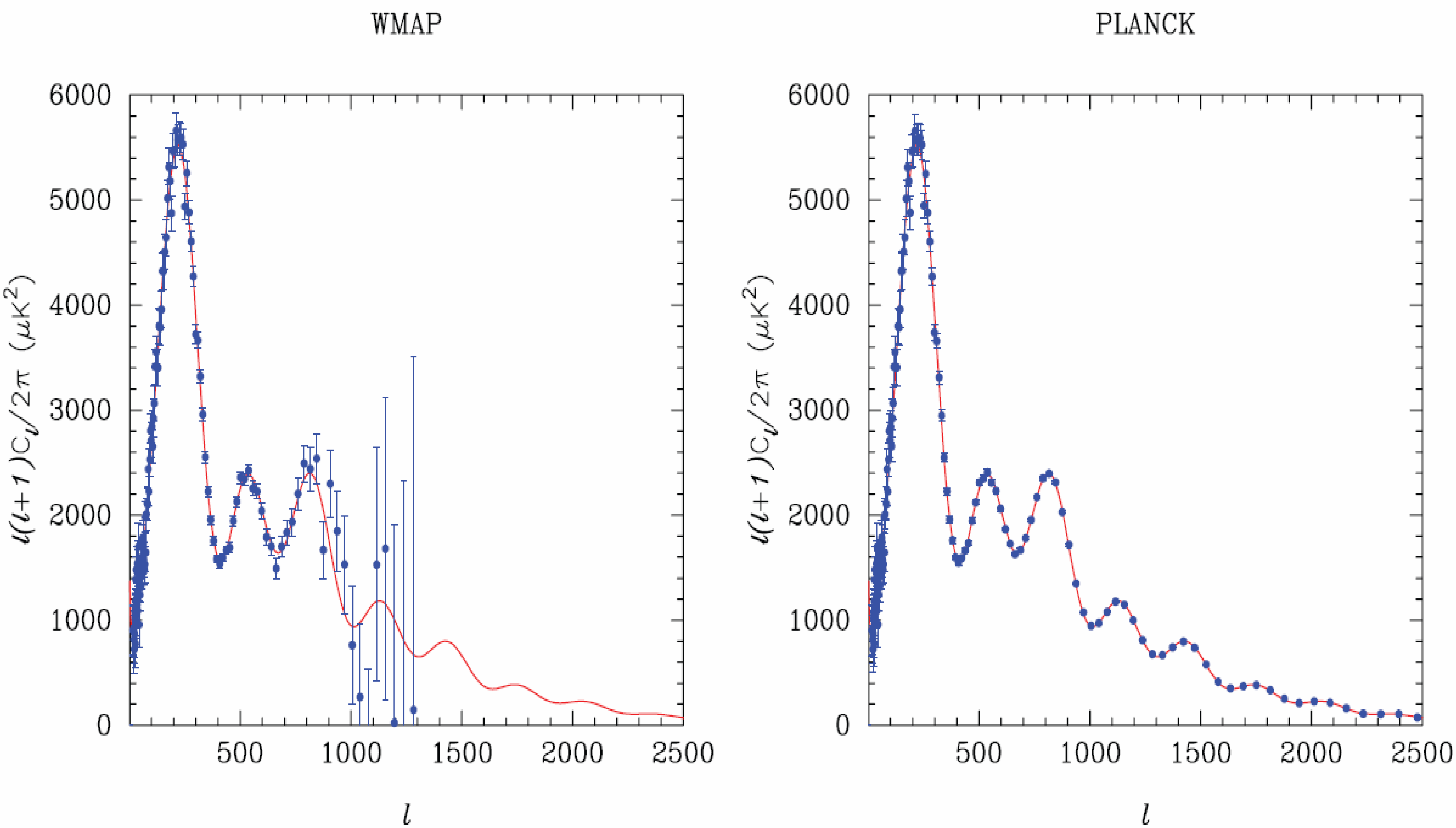


FIG 2.8.—The left panel shows a realisation of the CMB power spectrum of the concordance ΛCDM model (red line) after 4 years of *WMAP* observations. The right panel shows the same realisation observed with the sensitivity and angular resolution of *Planck*.

Inflation

- Measuring n_s and its running dn_s/dk with high accuracy is extremely important to *confirm* the inflationary hypothesis, and to obtain *physical insight* on the inflation potential

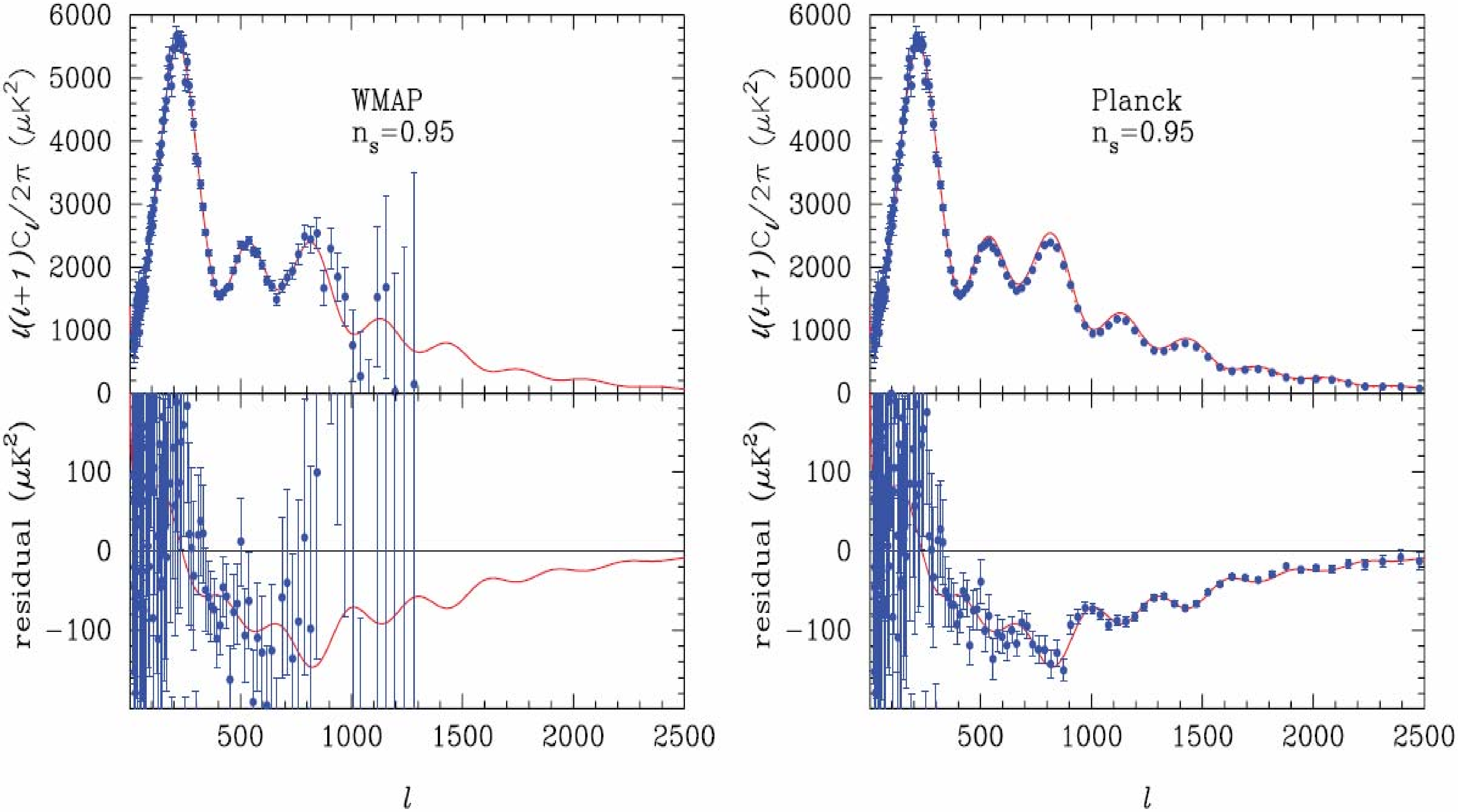


FIG 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance ΛCDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower panels show the residuals between the points and the $n_S = 1$ model, and the solid lines show the theoretical expectation for these residuals. The left and right plots show simulations for *WMAP* and *Planck*, respectively.

Enigmas in Cosmology

?

?

Inflation

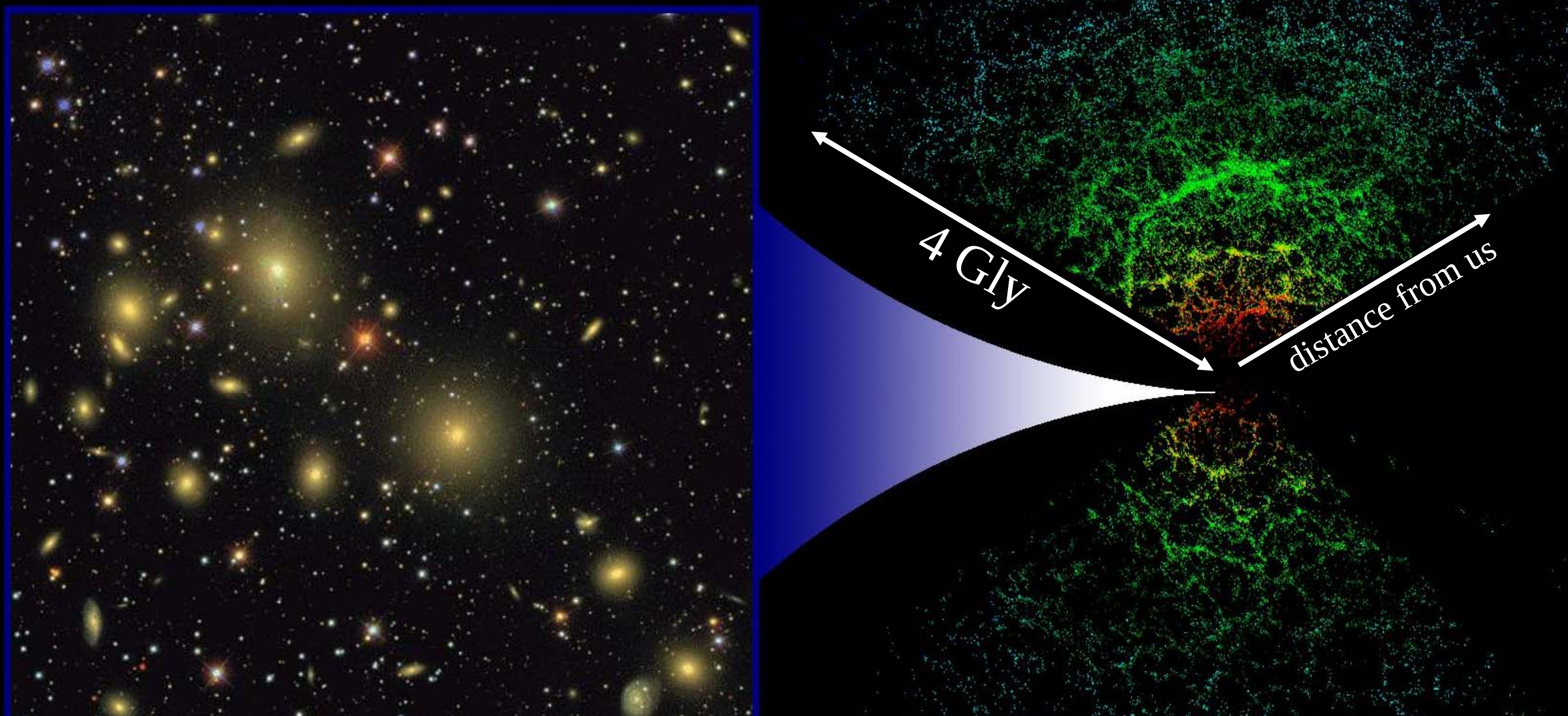
Dark Matter

Dark Energy

?

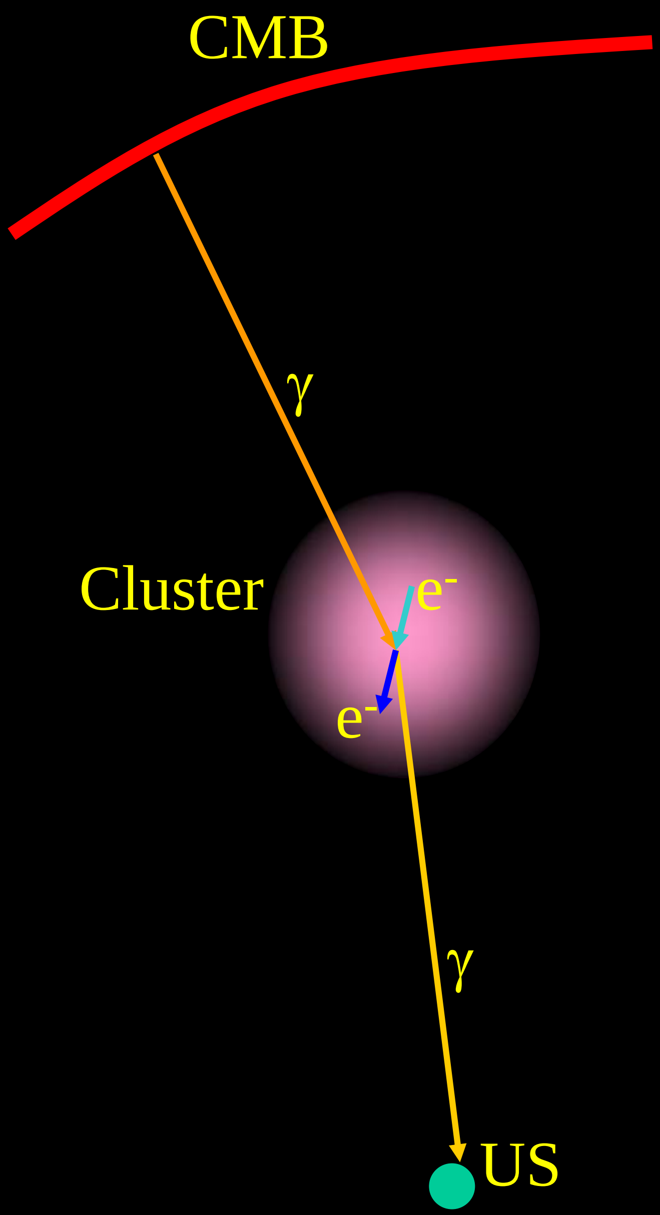
?

Spectroscopic surveys (SDSS, 2dF) have now mapped the 3D large scale structure of the Universe at distances up to 1000 Mpc



Clusters of Galaxies are evident features of this distribution. When did they form ? How did gravity coagulate them from the unstructured early universe ? Was the process affected by Dark Energy ? **Can we see early clusters at large distances, and use them to constrain cosmology ? SZ !**

Sunyaev-Zeldovich effect



Inverse Compton scattering of CMB photons against hot electrons in the intergalactic medium of rich clusters of galaxies

About 1% of the photons acquire about 1% boost in energy, thus slightly shifting the spectrum of CMB to higher frequencies.

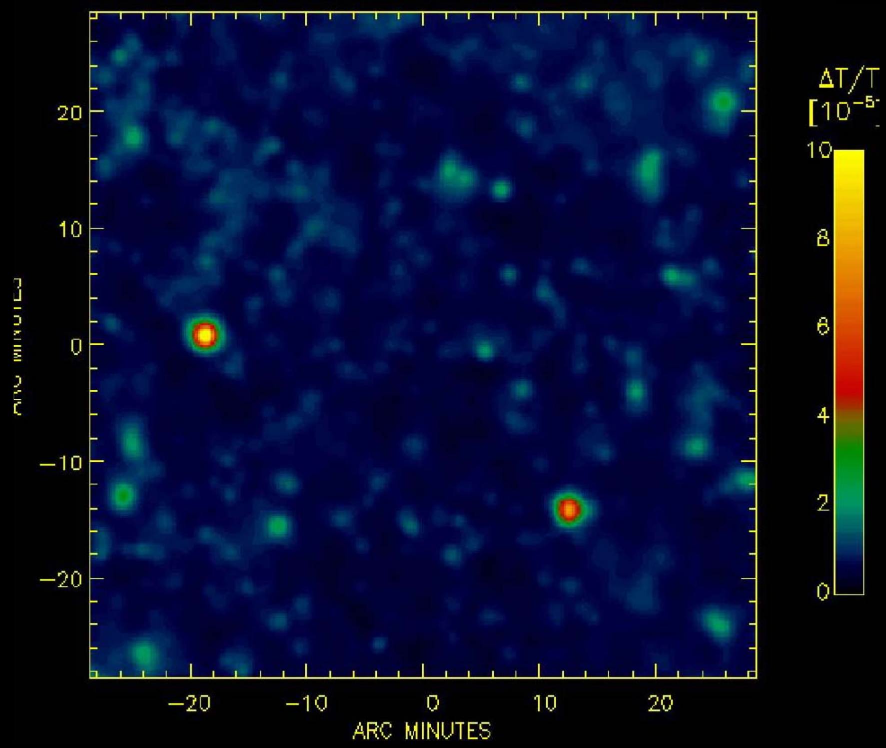
$$\Delta T/T \sim 10^{-4}$$

The result is a decrease of CMB brightness in the line of sight crossing the cluster at ν<217 GHz, and an increase at ν>217 GHz

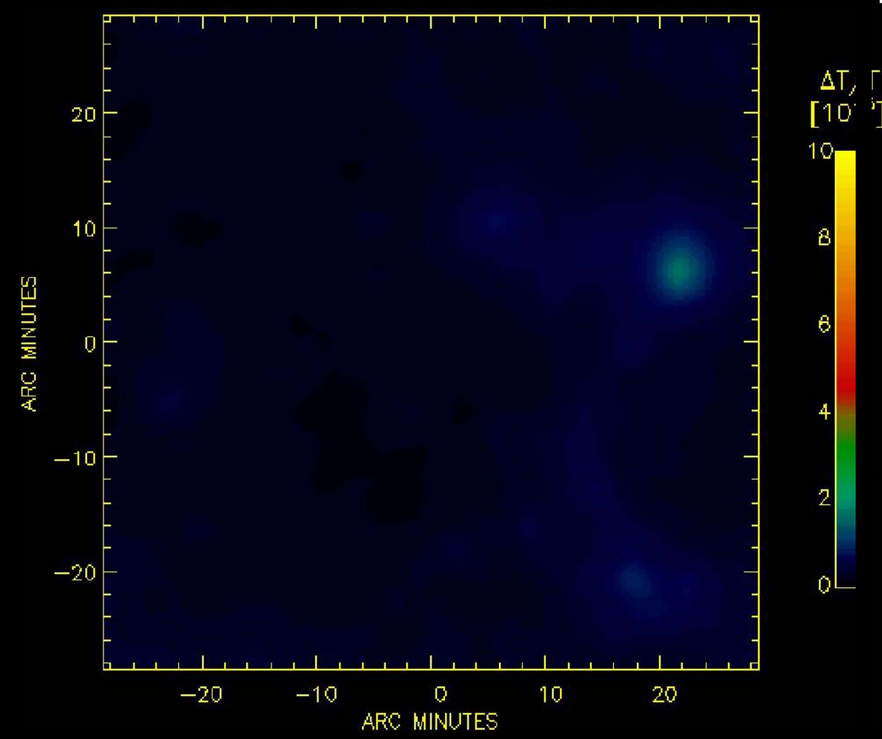
Independent of redshift !

Dark Energy

Simulations show that the background from distant SZ clusters is very sensitive to Λ (see e.g. Da Silva et al. astro-ph/0011187)



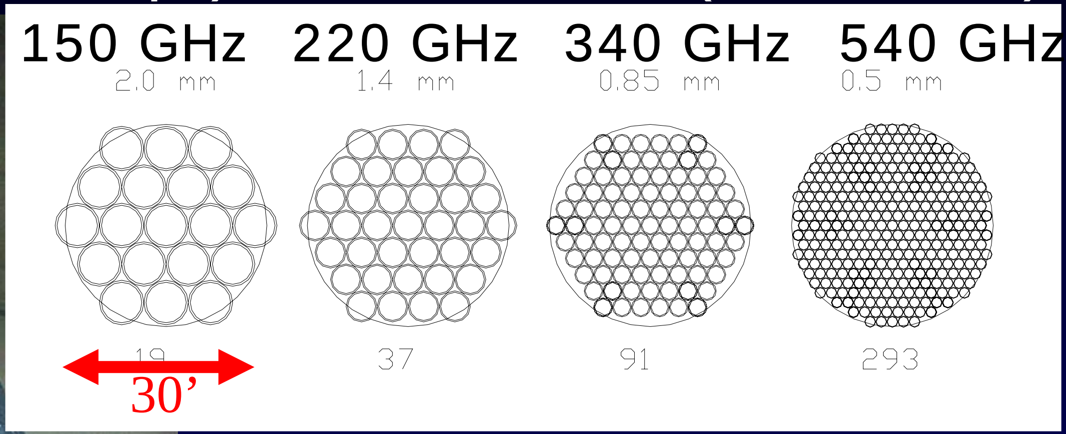
Λ=0. 7

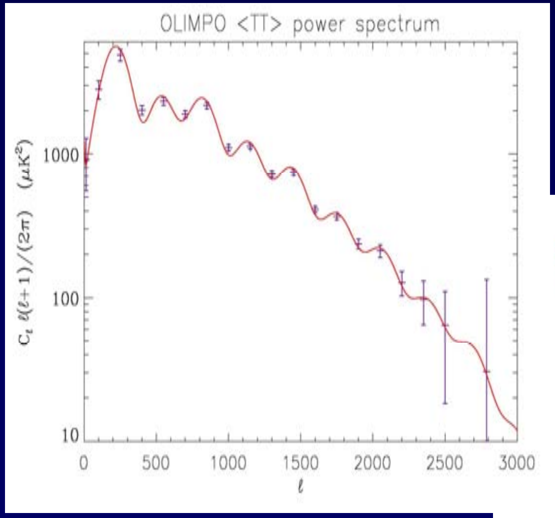


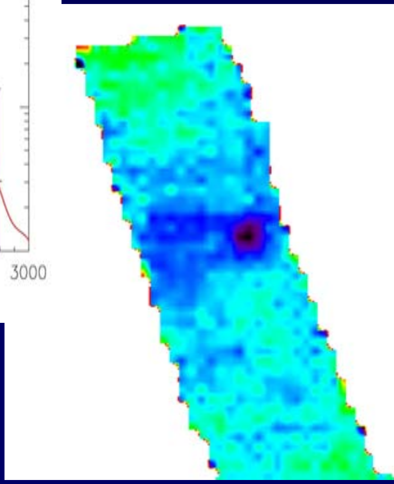
Λ=0.0

OLIMPO (PI Silvia Masi, Roma)

- Focal plane can host >400 bolometers
- from Cardiff (P. Mauskopf) and Genoble (P. Camus)

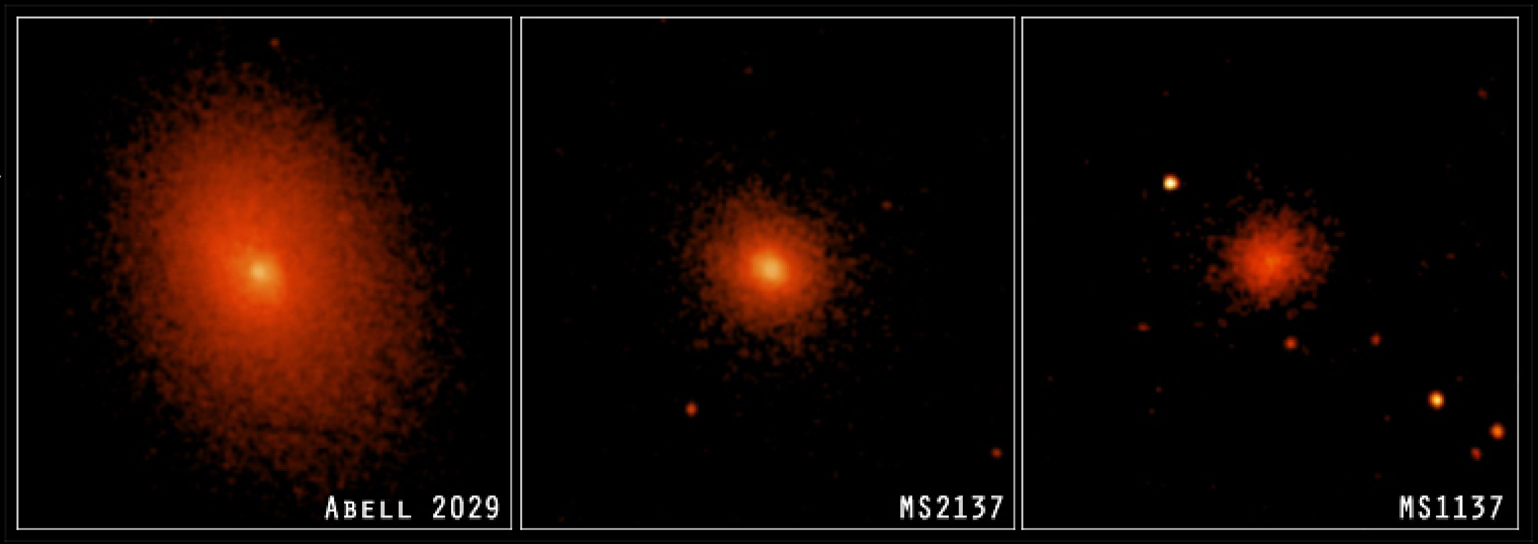






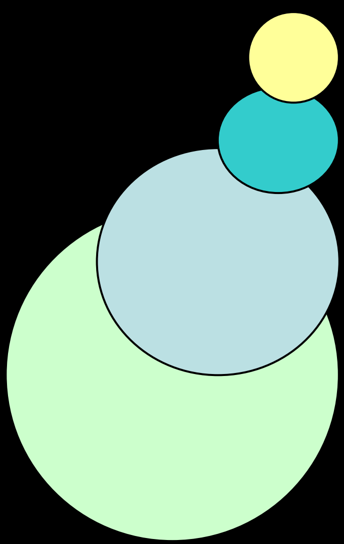
Dynamically Relaxed Clusters

X-ray
Images
(Chandra)



D = 1 GLy | 3.5 GLy | 6.7 GLy

OLIMPO



0.9’ FWHM beam (λ = 0.54 mm D = 2600 mm)

1.1’ FWHM beam (λ = 0.73 mm D = 2600 mm)

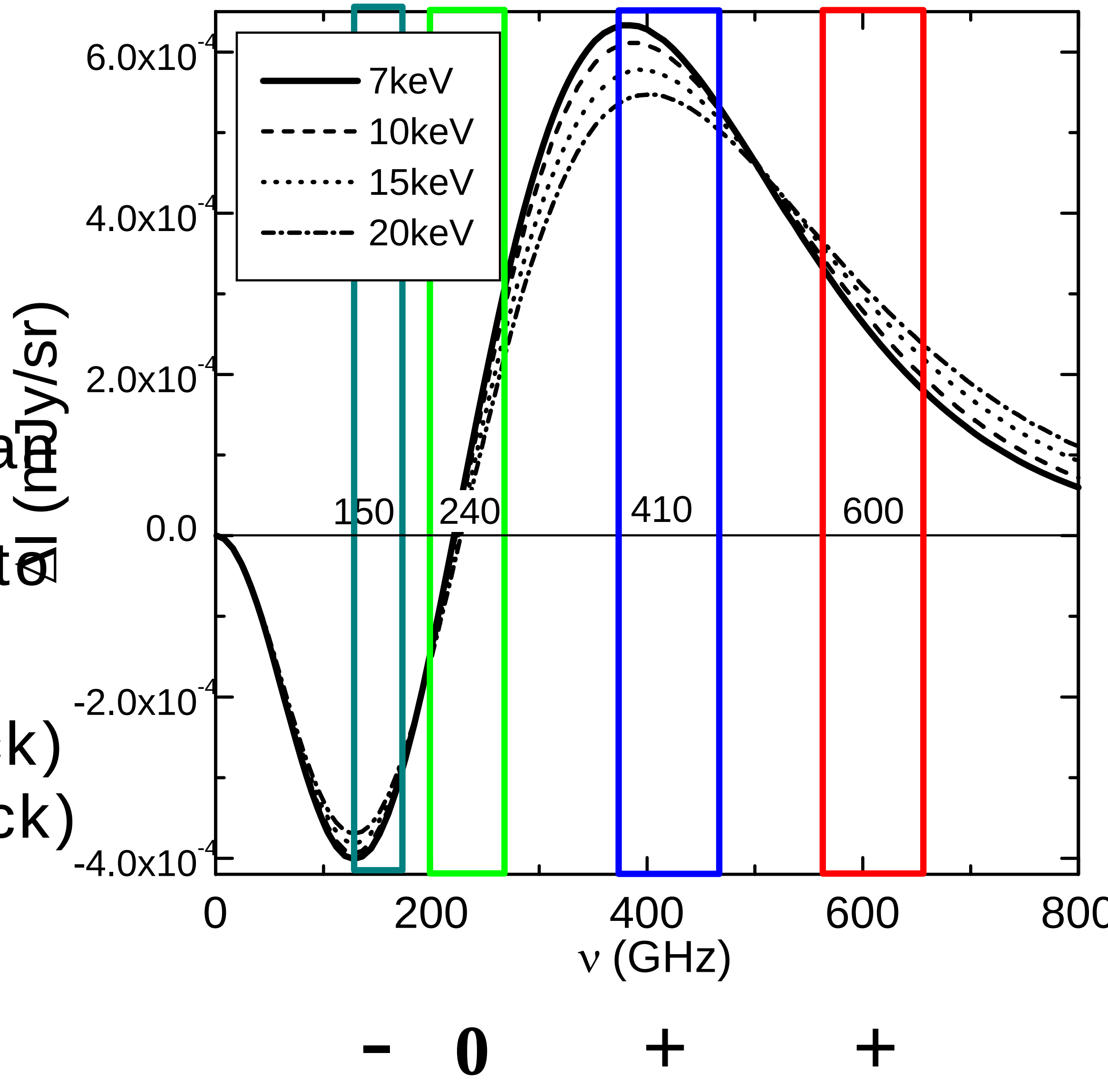
2.2’ FWHM beam (λ = 1.4 mm D = 2600 mm)

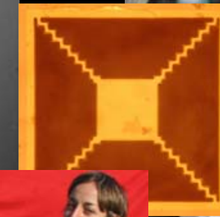
3.1’ FWHM beam (λ = 2.0 mm D = 2600 mm)

Uniqueness of OLIMPO

- 4 frequency bands simultaneously.
- Optimally sample the spectrum of the SZ effect.
- Opposite signals at 410 GHz and at 150 GHz provide a clear signature of the SZ detection.
- 4 bands allow to clean the signal from dust and CMB, and even to measure T_e

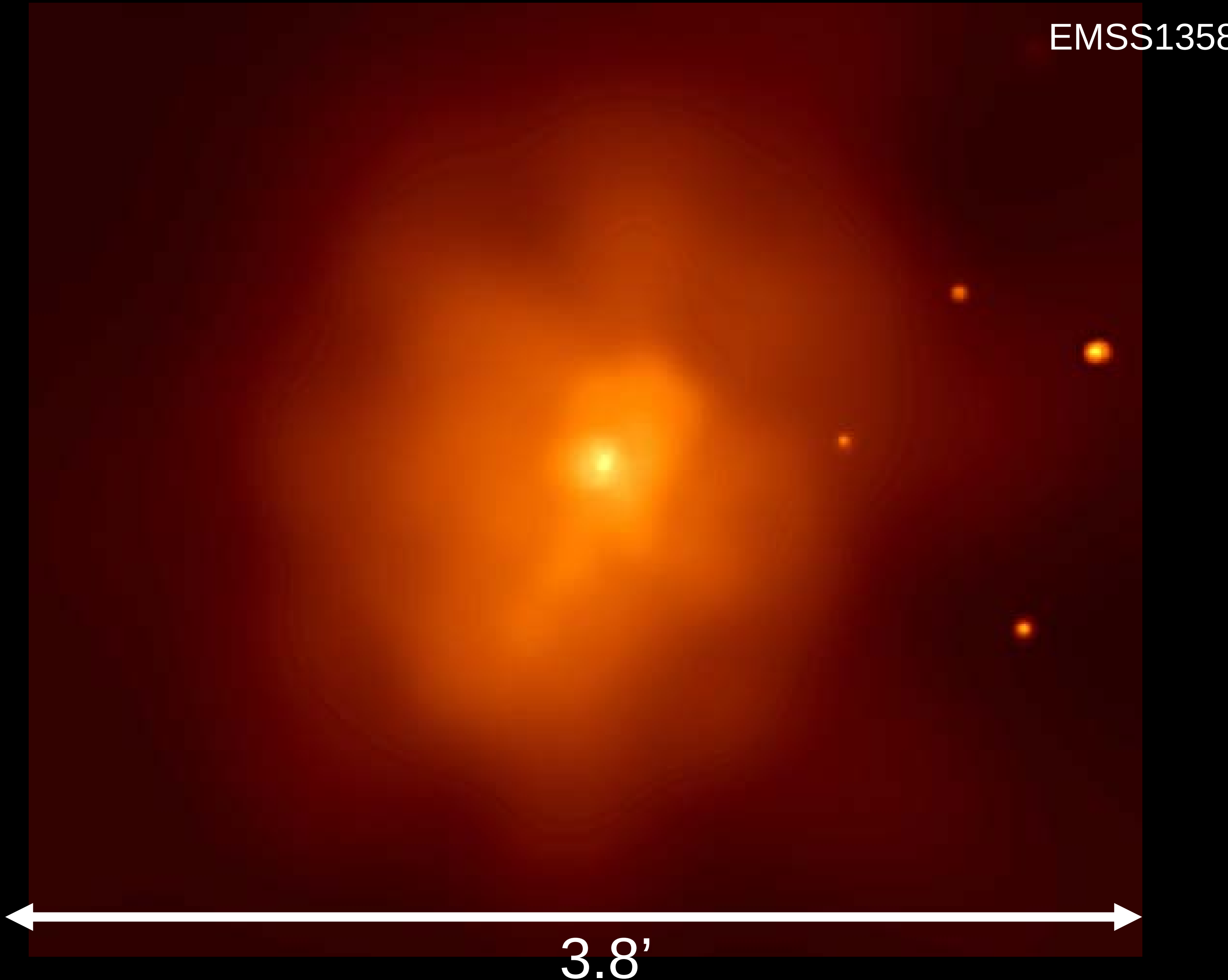
- Resolution: 2x(Planck)
- Detectors: 10x(Planck)
- Integration time per cluster: 10x(Planck) (40 clusters/flight + blind survey)

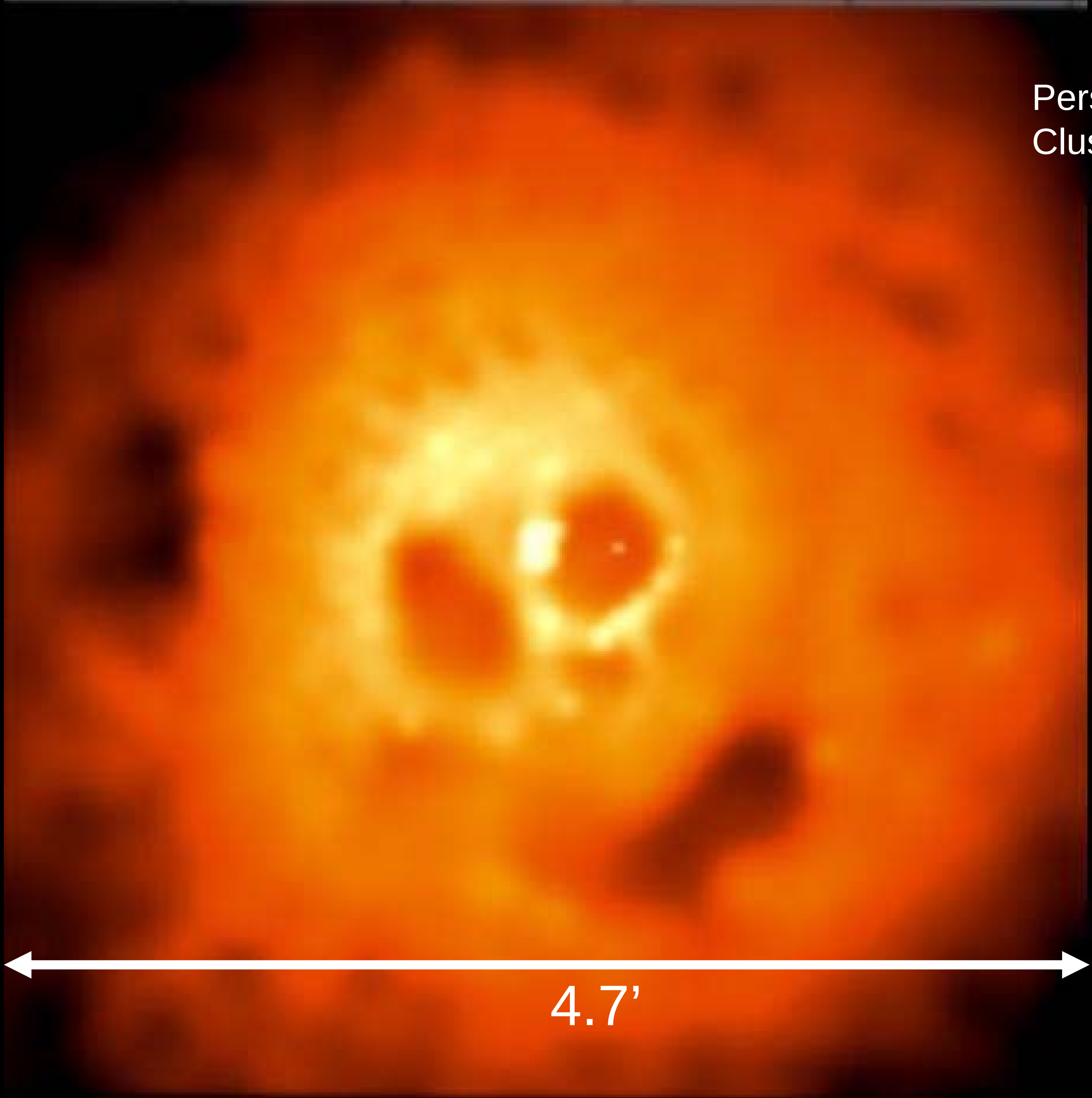


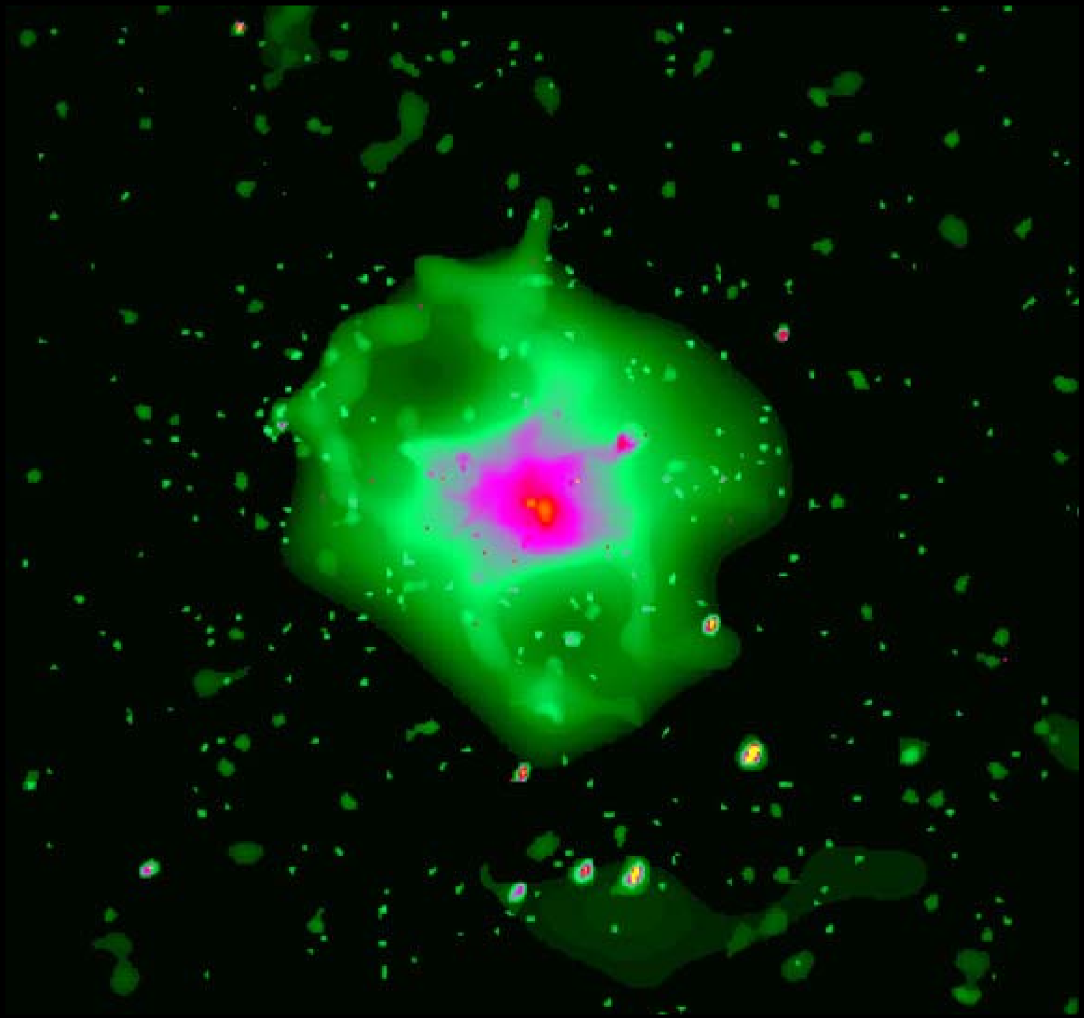



Flights:
2008 & 2009

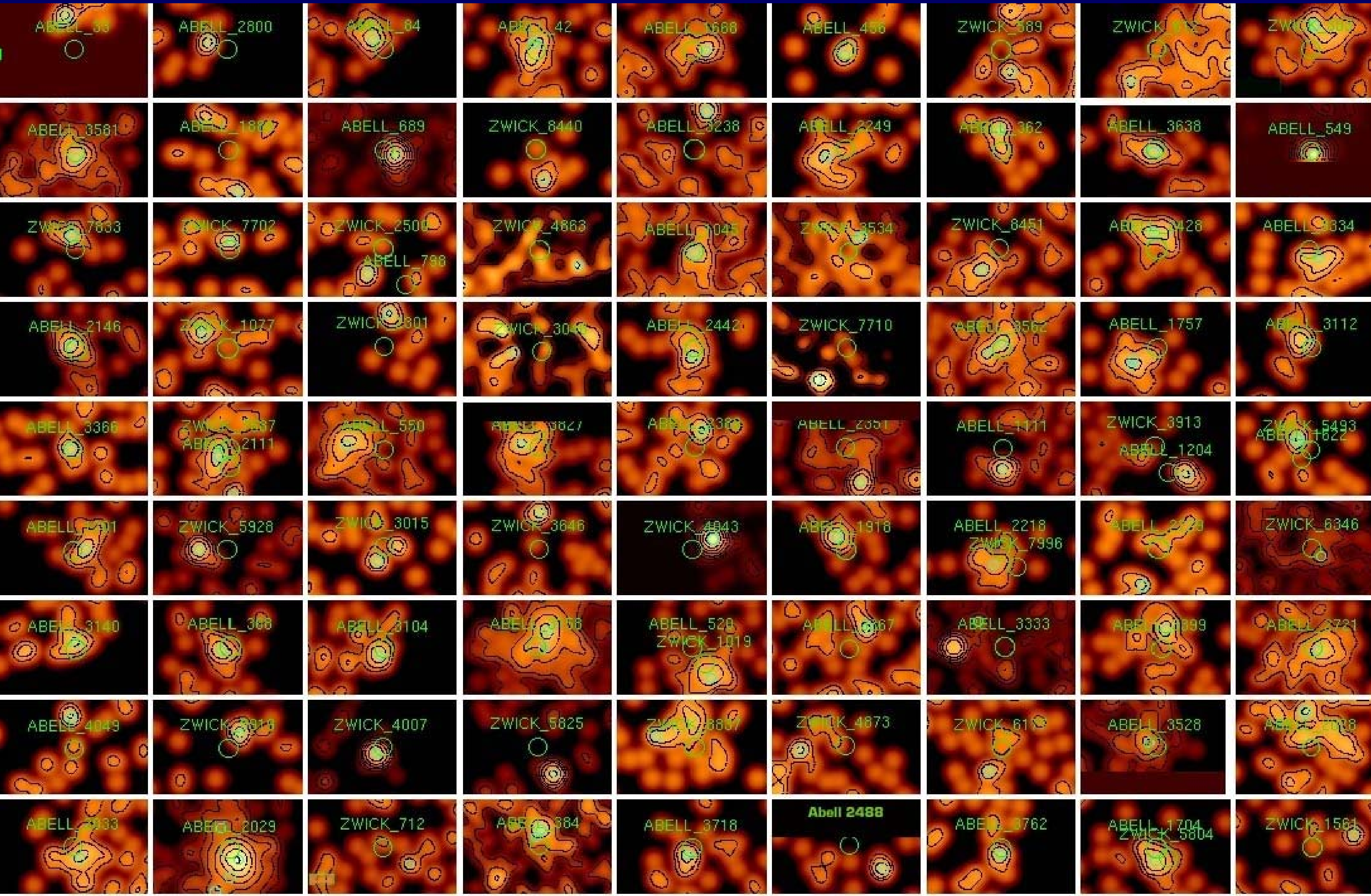


EMSS1358
3.8’


Perseus
Cluster
4.7’

HGC62

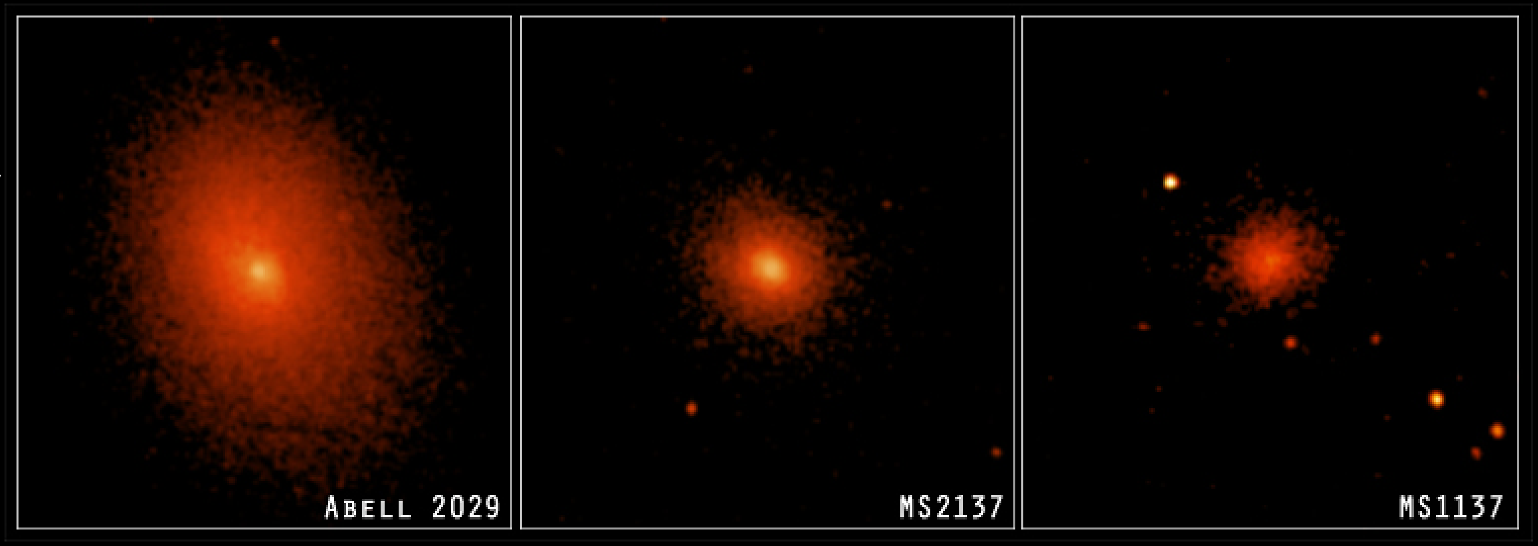


4’


ABELL_2800
ABELL_689
ZWICK_8440
ABELL_3638
ABELL_549
ZWICK_8451
ZWICK_7710
ABELL_1757
ZWICK_3913
ABELL_1204
ZWICK_5928
ABELL_2218
ZWICK_6346
ABELL_520
ZWICK_1019
ABELL_3333
ABELL_3104
ZWICK_4007
ZWICK_5825
ABELL_3528
ZWICK_712
ABELL_3718
Abell 2488

Dynamically Relaxed Clusters

X-ray Images (Chandra)



D = 1 GLy   3.5 GLy   6.7 GLy

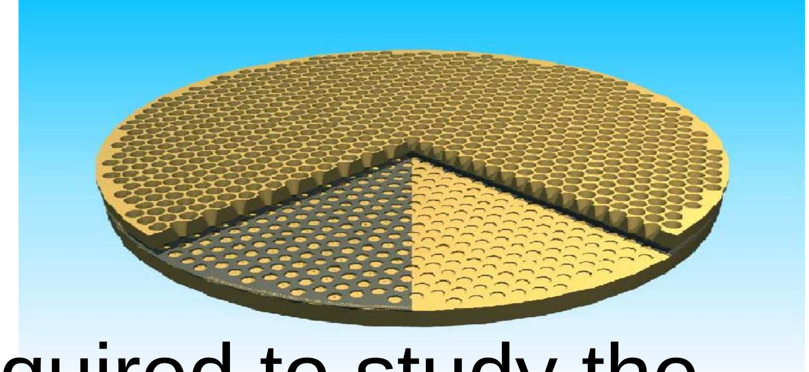
SPT

0.55’ FWHM beam (λ = 1.1 mm D = 8000 mm) ?

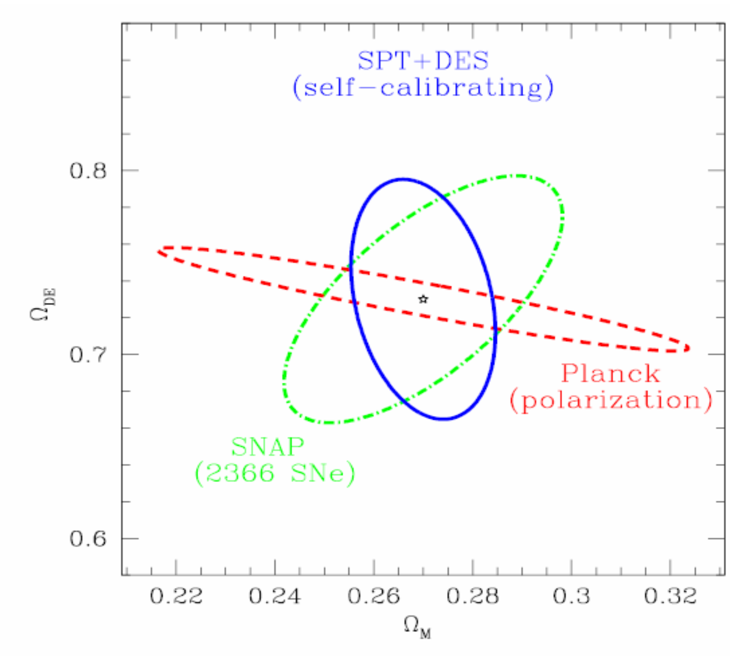
0.7’ FWHM beam (λ = 1.4 mm D = 8000 mm)

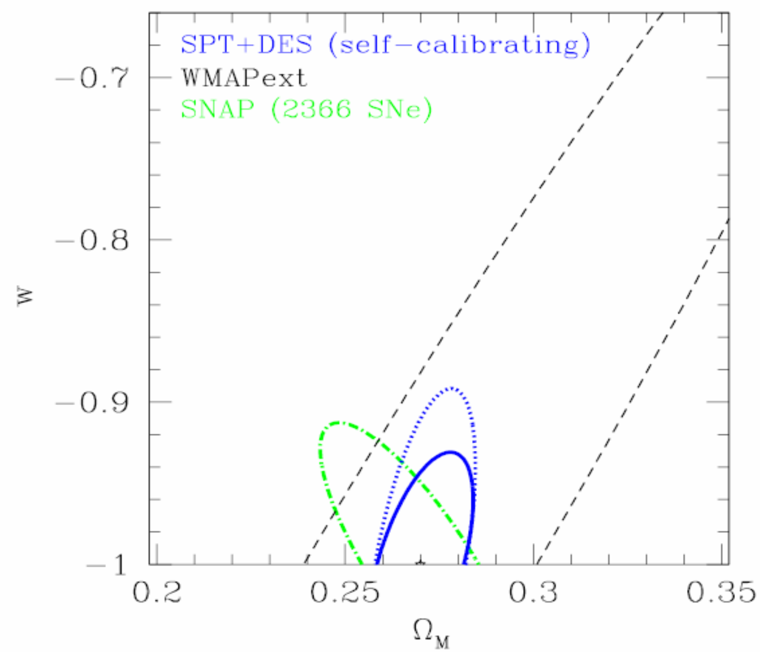
1.0’ FWHM beam (λ = 2.0 mm D = 8000 mm)

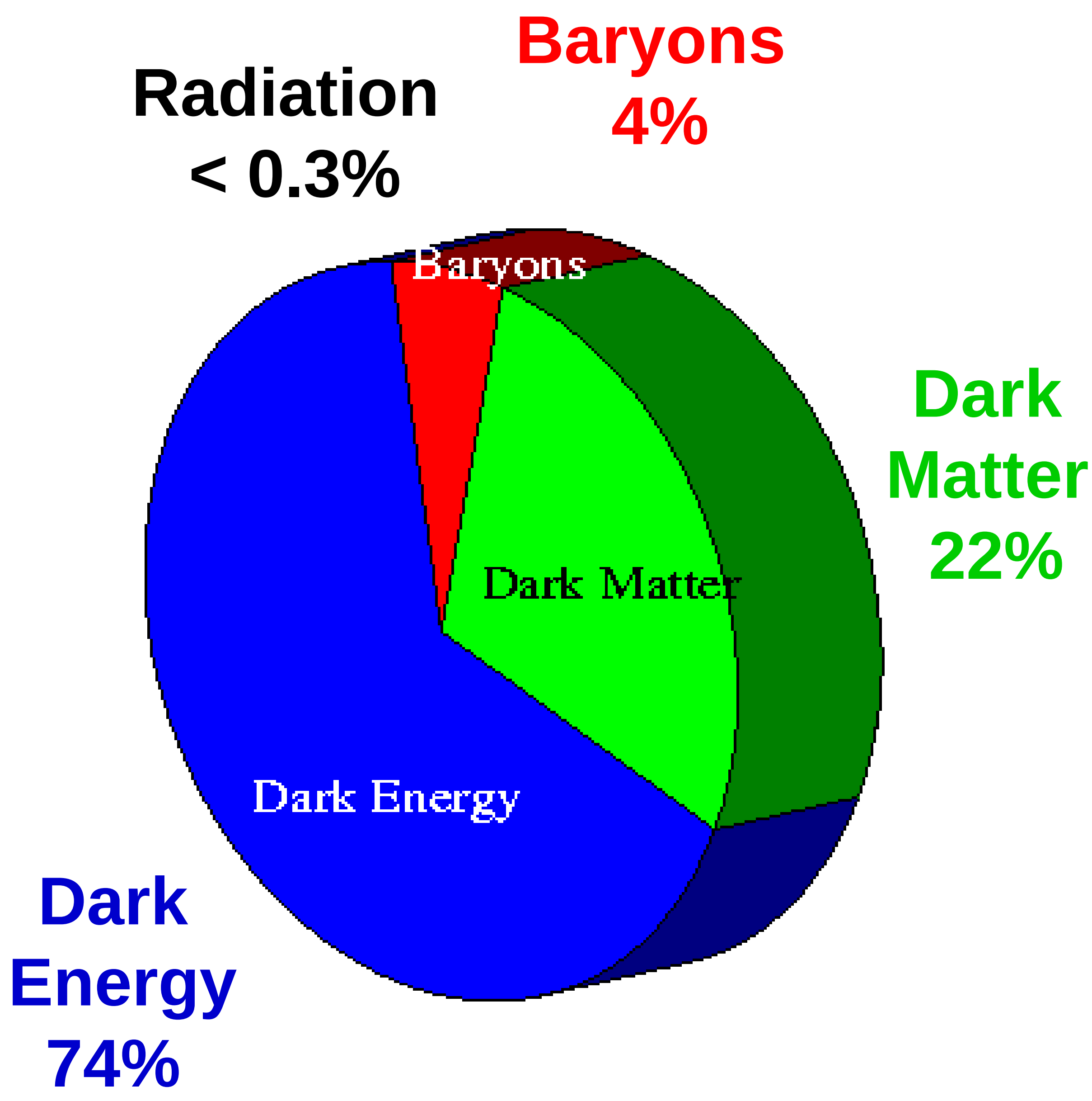
Large SZ telescopes



- Large telescopes are required to study the physics of the cluster and check for deviations from simple SZ.
- South Pole telescope: SPT → Dark Energy






Radiation
< 0.3%
Baryons
4%
Dark
Matter
22%
Dark
Energy
74%
Baryons
Dark Matter
Dark Energy

What is Dark Matter ?

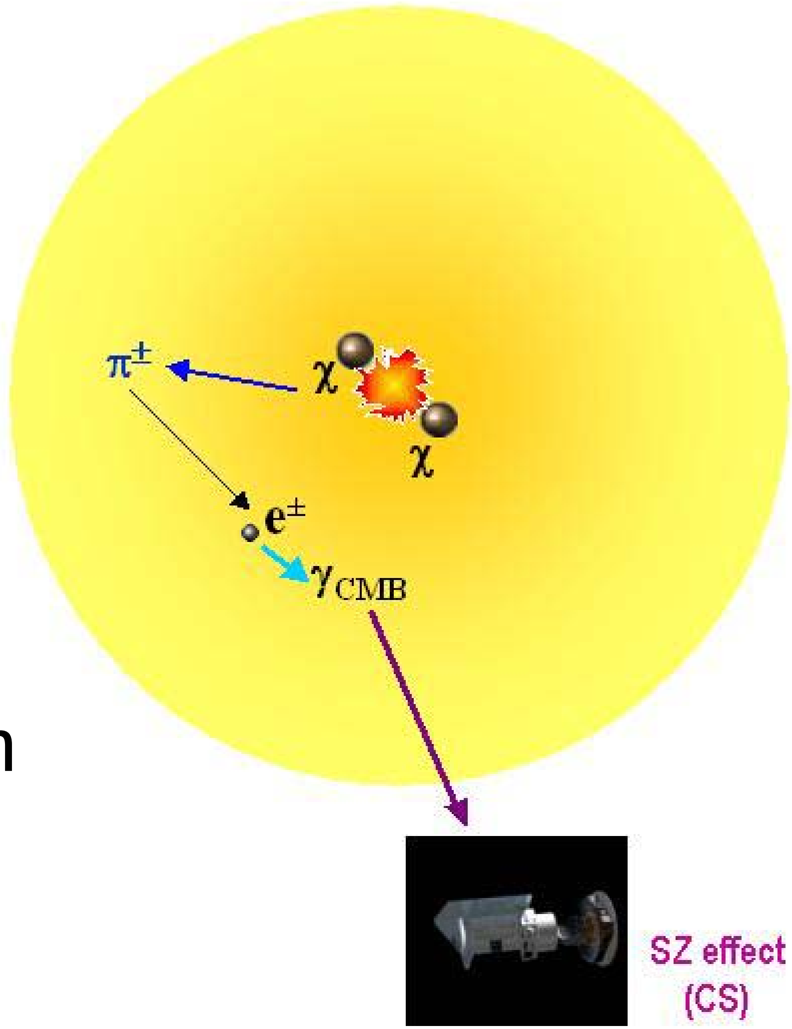
- **Hp**: Weakly Interacting Supersymmetric Particles (WIMPs)
- Lightest one predicted by SUSY :

  Neutralino χ

- Could be measured by LHC
- χs tend to cluster in the center of astrophysical structures, including clusters of galaxies (M/L)

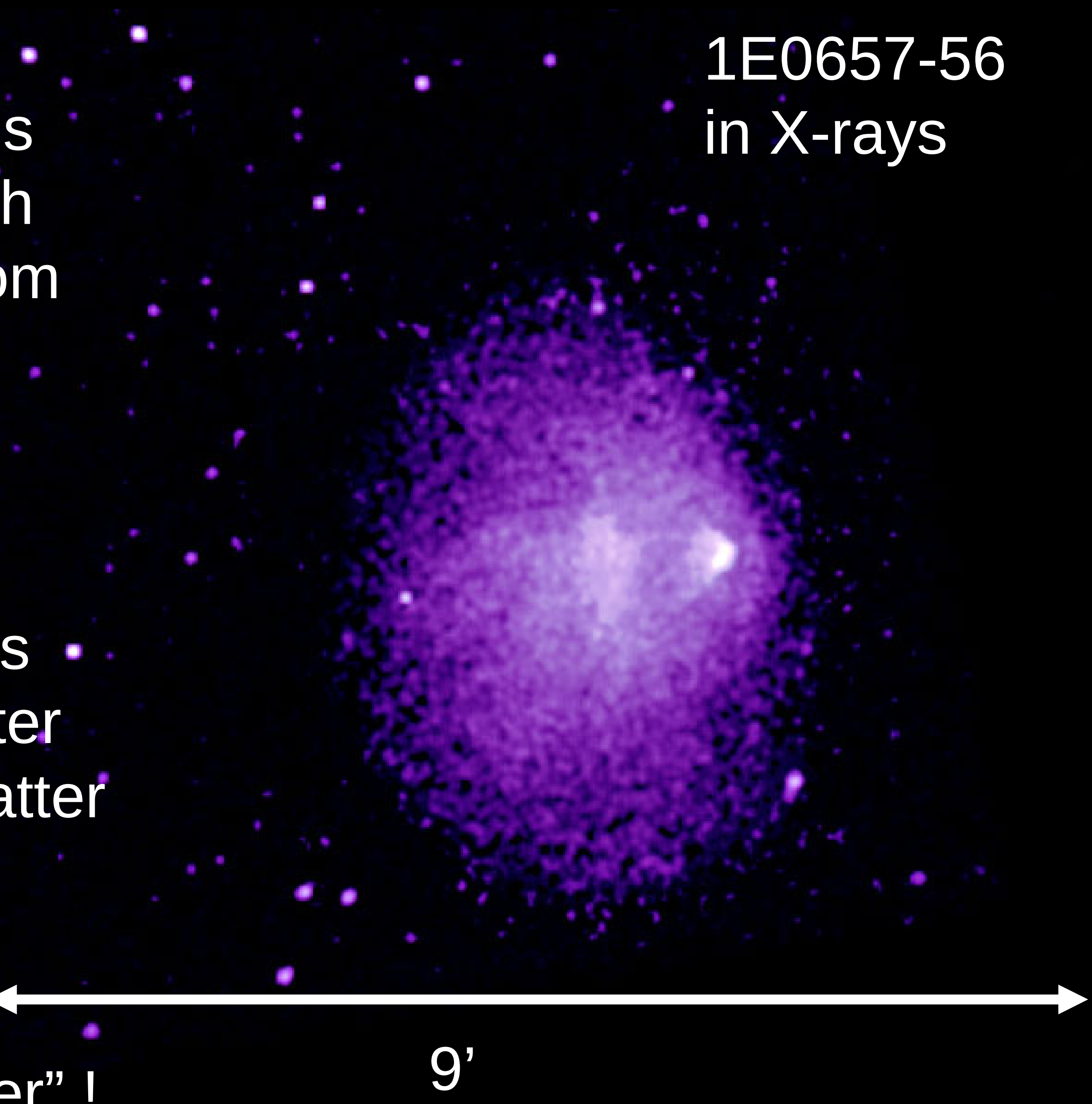
SZ effect from χχ annihilation

- Annihilation of Neutralinos would produce fluxes of
  - Neutral and charged pions
  - Secondary electrons protons
  - Neutrinos
  - etc.
- They produce various effects
- One of them is the SZ from the charged component (see Colafrancesco, 2004)



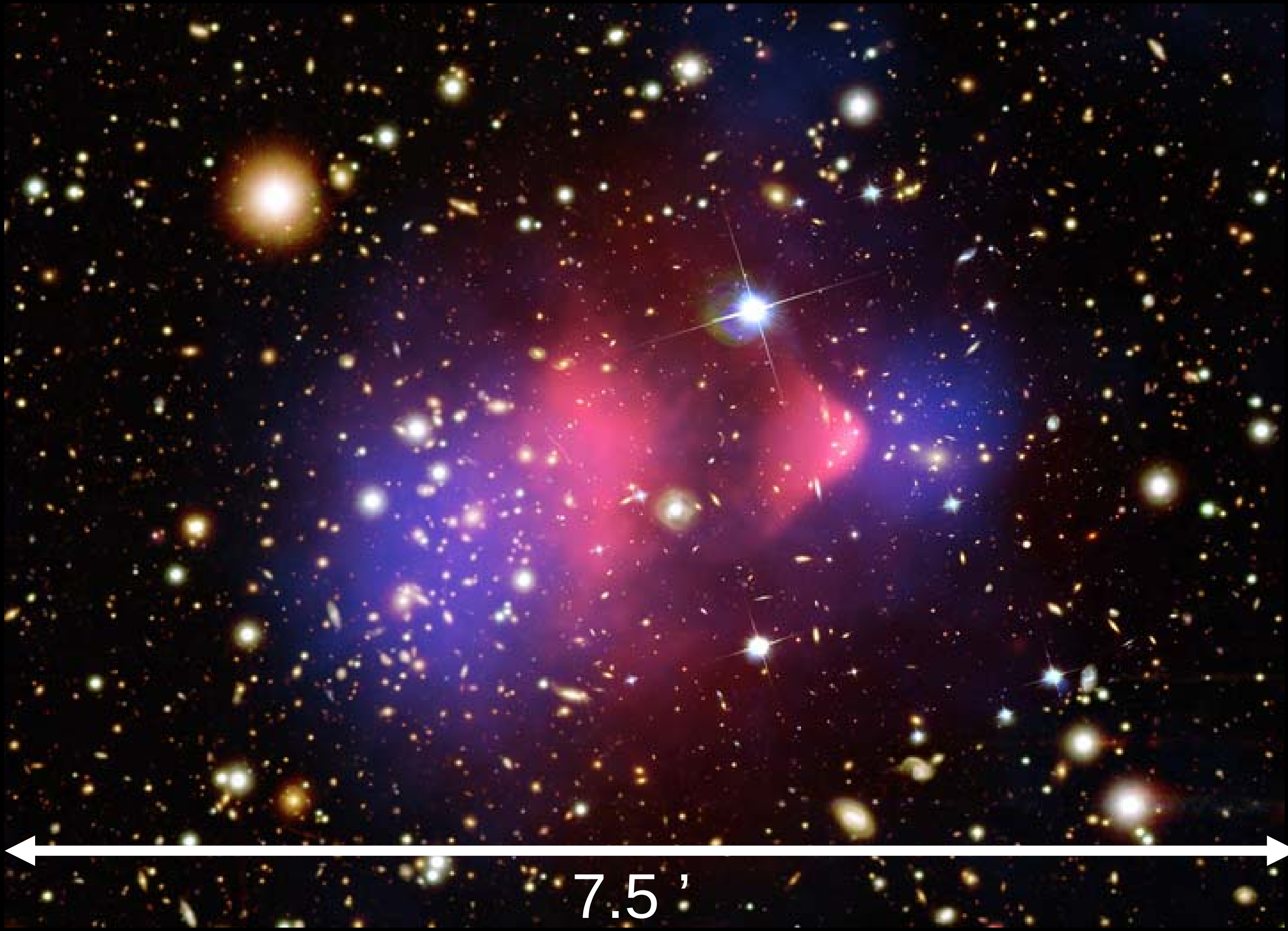
The SZ from the decay products is subdominant with respect to SZ from the hot gas (see Colafrancesco, 2004)

We need clusters where Dark Matter and Baryonic Matter are separated.



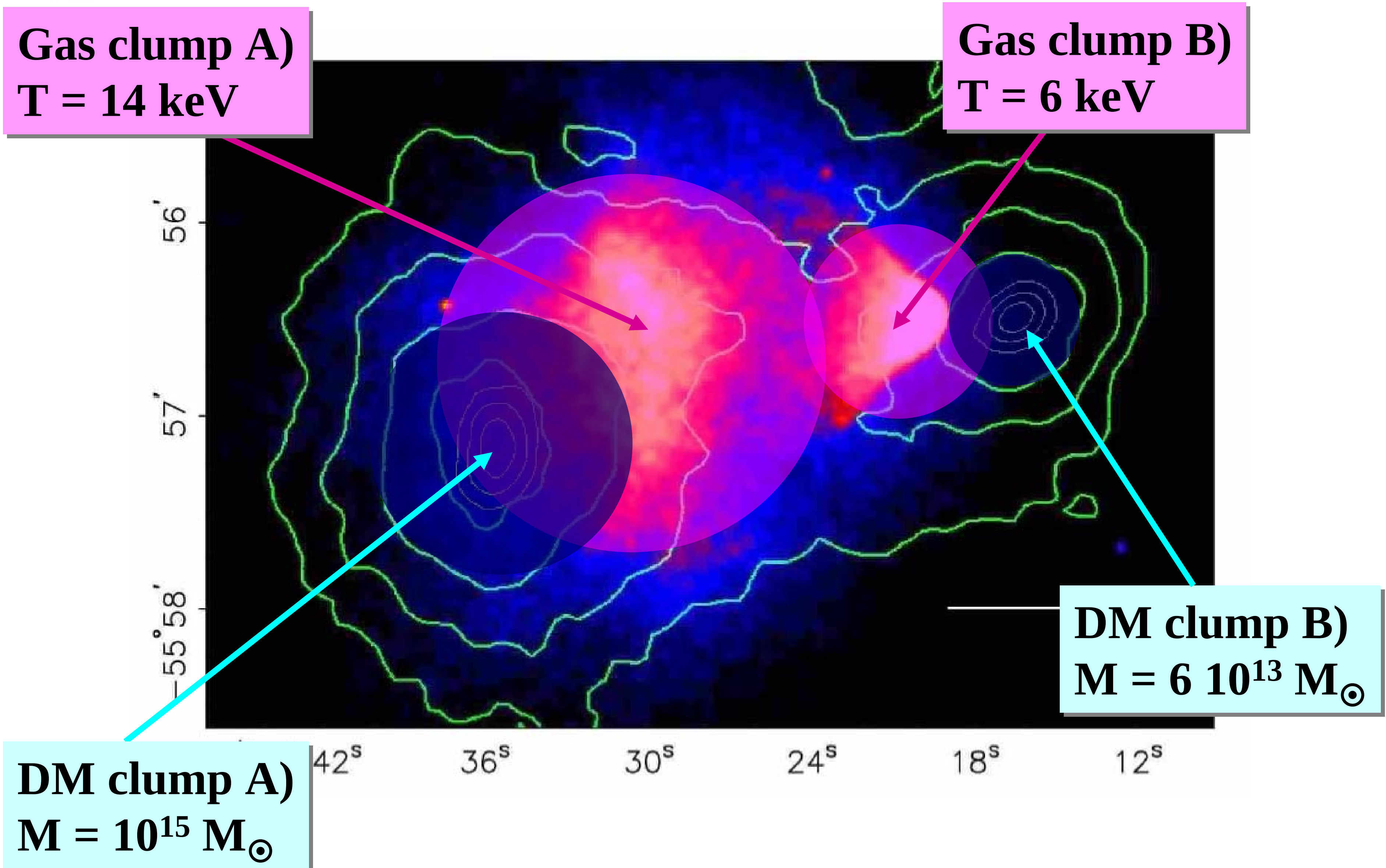
The “bullet cluster” !

In blue: mass (dark matter) from lensing measurements
In red: baryonic matter (X rays)



1E0657-56

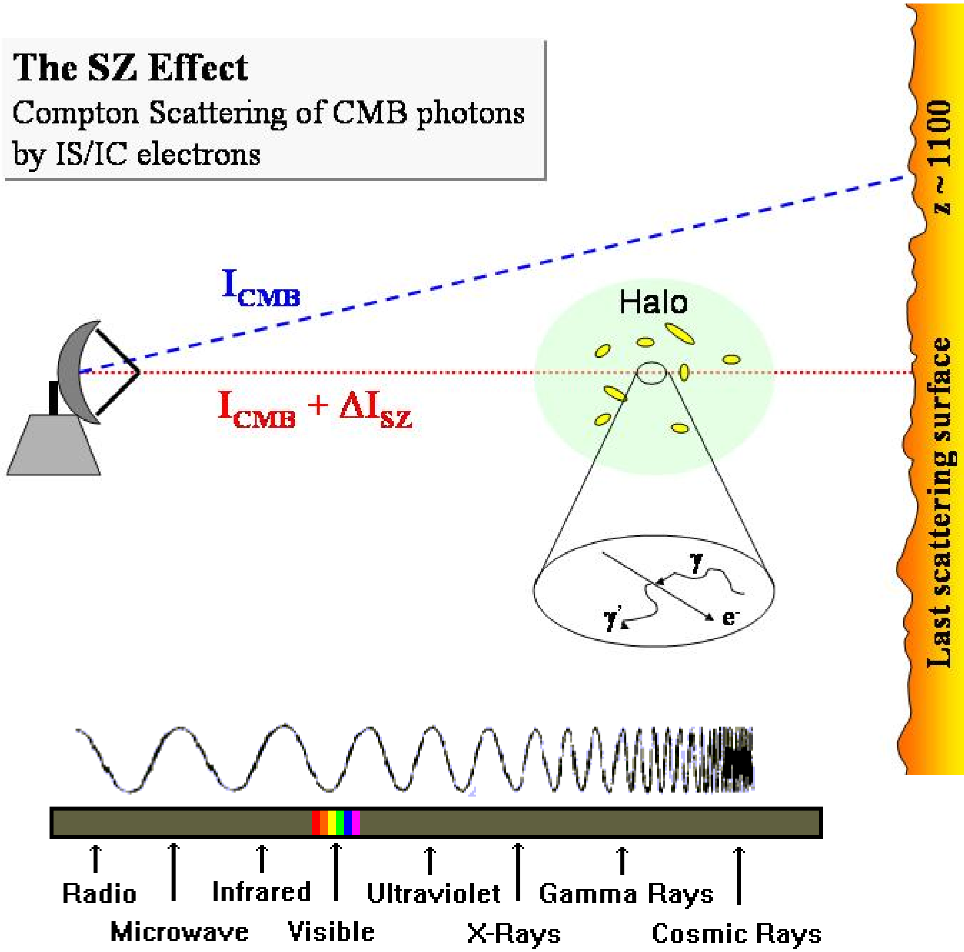
1ES0657-556: DM + thermal gas



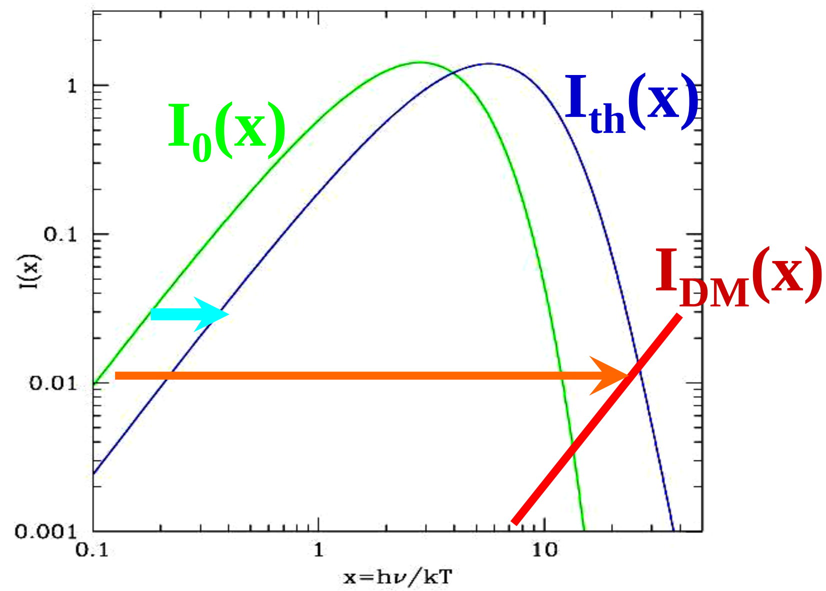
[Clowe et al. 2006, and refs. therein]

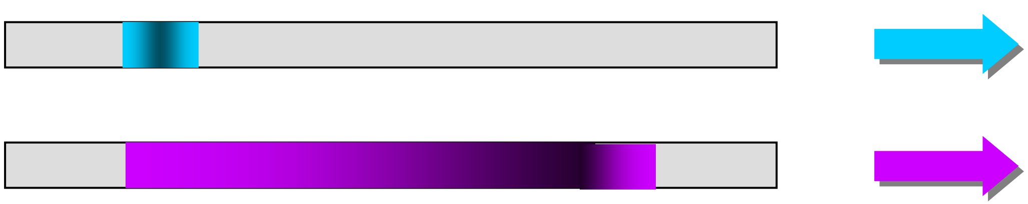
SZ effect from DM

[Colafrancesco 2004 , A&A, 422, L23]



$$\Delta I(x) = I(x) - I_0(x)$$

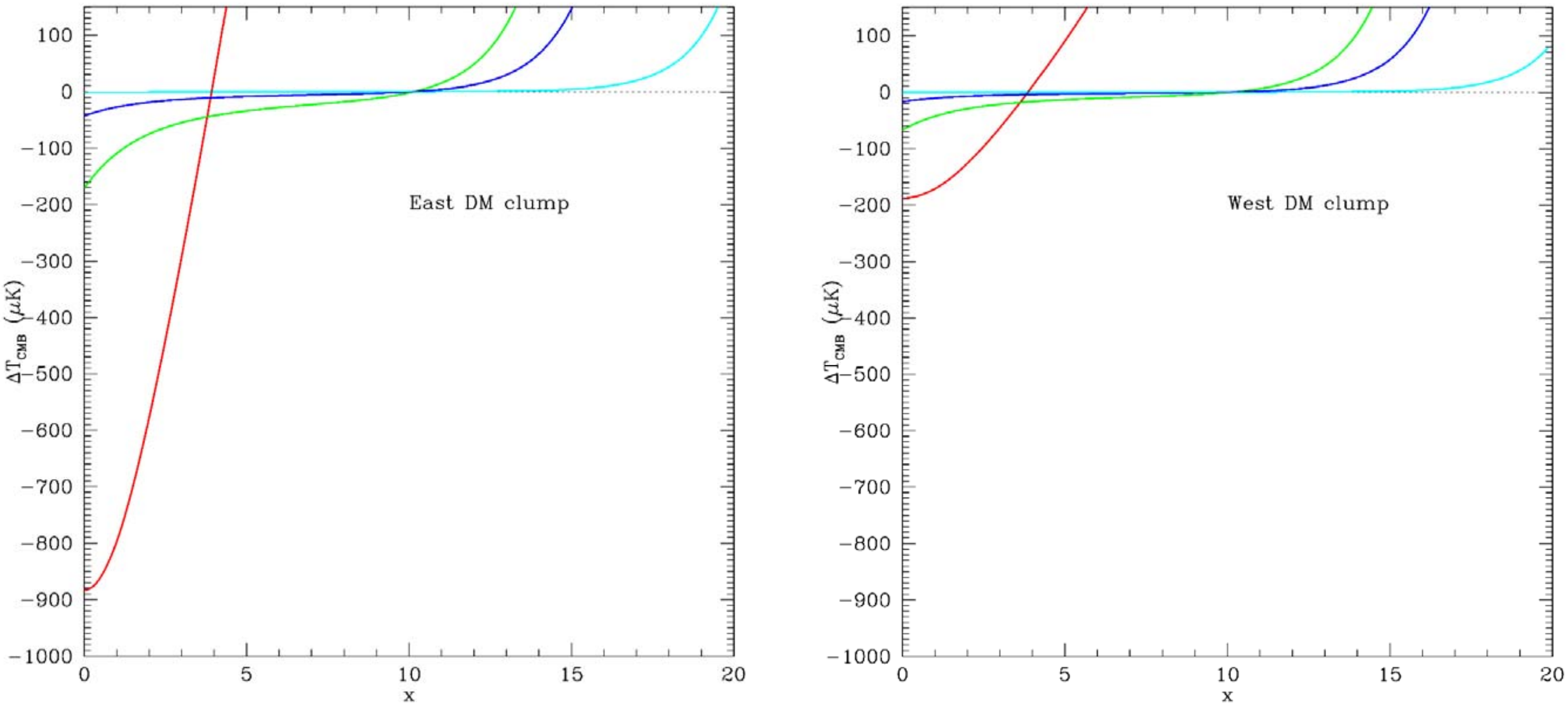




thermal e^- $\quad \dfrac{\nu'}{\nu} = \dfrac{4}{3}$

relativistic e^- $\quad \dfrac{\nu'}{\nu} = \dfrac{4}{3}\gamma^2 - 1$

SZ effect at clump centres



[Colafrancesco, de Bernardis, Masi, Polenta & Ullio 2007]

150 GHz 223 GHz 350 GHz

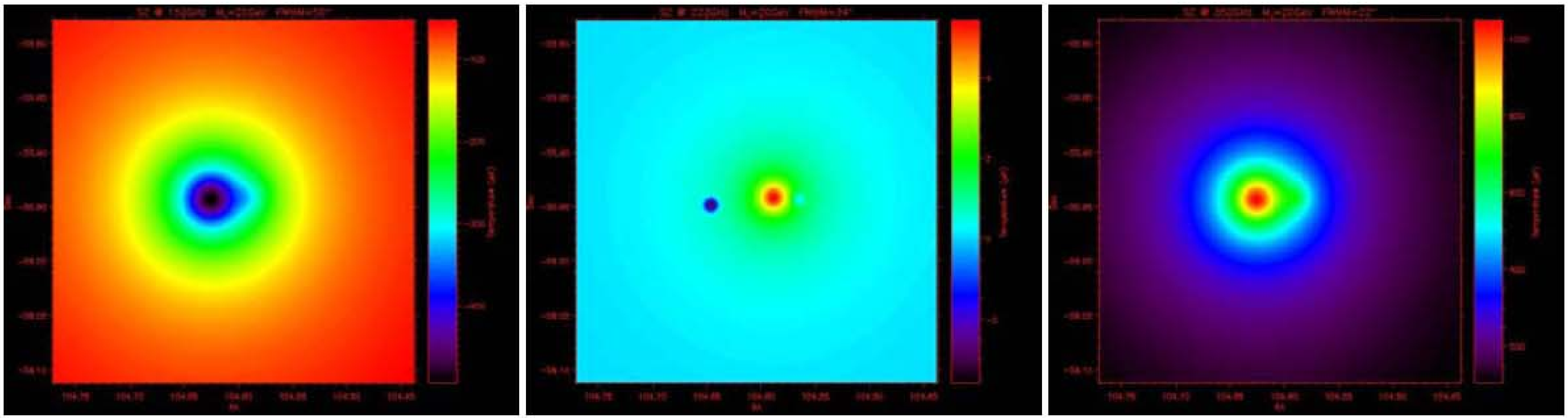
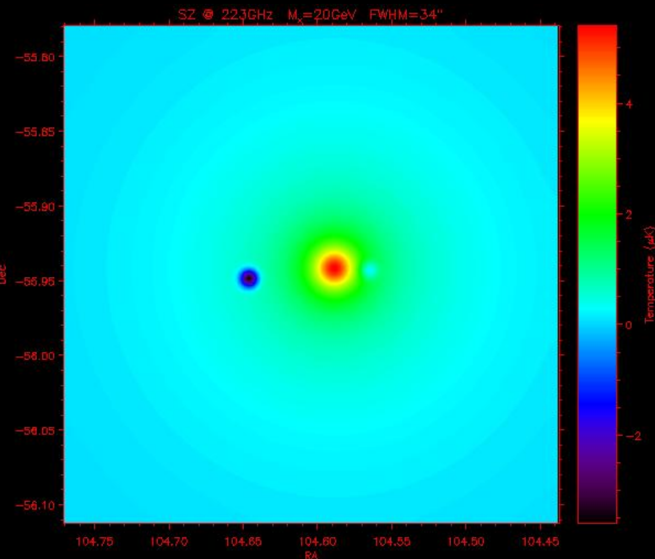


Fig. 2. The simulated SZ maps of the cluster 1ES0657-556 as observable with the SPT telescope at three frequencies: $\nu = 150$ GHz (left panel), $\nu = 223$ GHz (mid panel), $\nu = 350$ GHz (right panel). A neutralino mass of $M_\chi = 20$ GeV has been adopted here. Note that choosing the frequency of 223 GHz where the thermal SZE from the E baryonic clump vanishes maximizes the detectability of the SZ_{DM} effect from the two DM clumps.

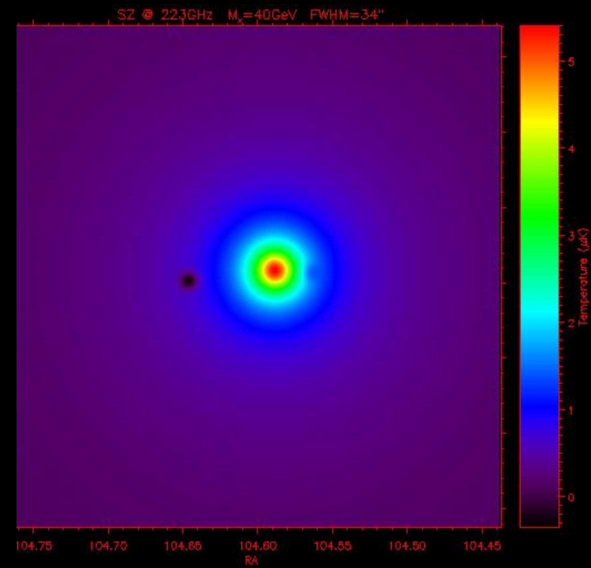
[Colafrancesco, de Bernardis, Masi, Polenta & Ullio 2007]

Isolating SZ_{DM} (at 223 GHz)

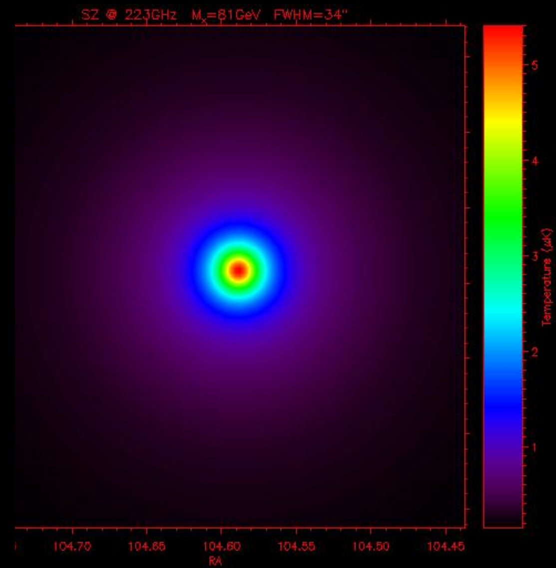
M_χ = 20 GeV



M_χ = 40 GeV



M_χ = 80 GeV



The SZE from the hot gas disappears at $x_{0,th}$ (~ 220-223 GHz) while the SZ_{DM} expected at the locations of the two DM clumps remains negative and with an amplitude and spectrum which depend on M_χ (-20 uK for 20 GeV).

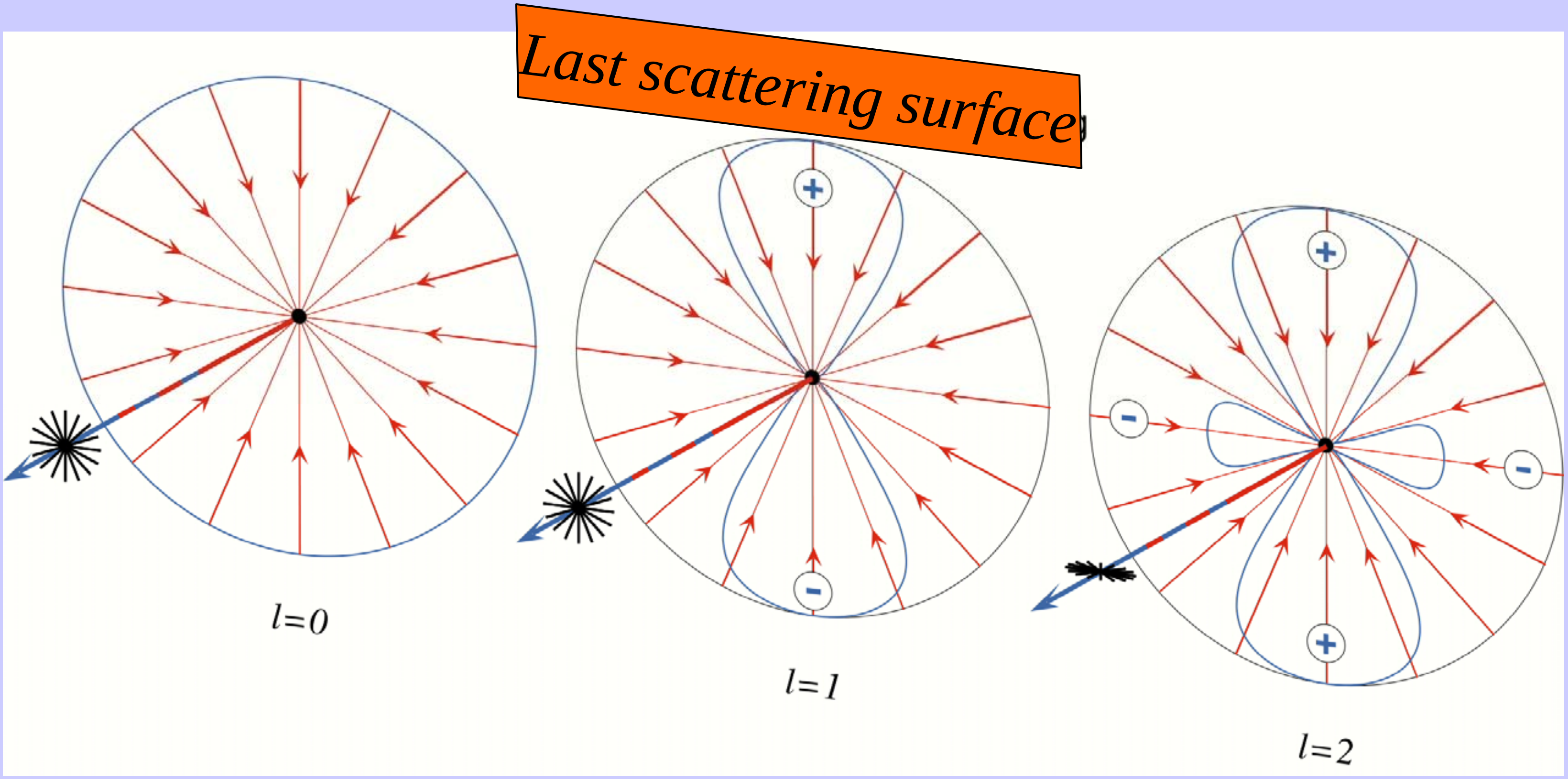
[Colafrancesco, de Bernardis, Masi, Polenta & Ullio 2007]

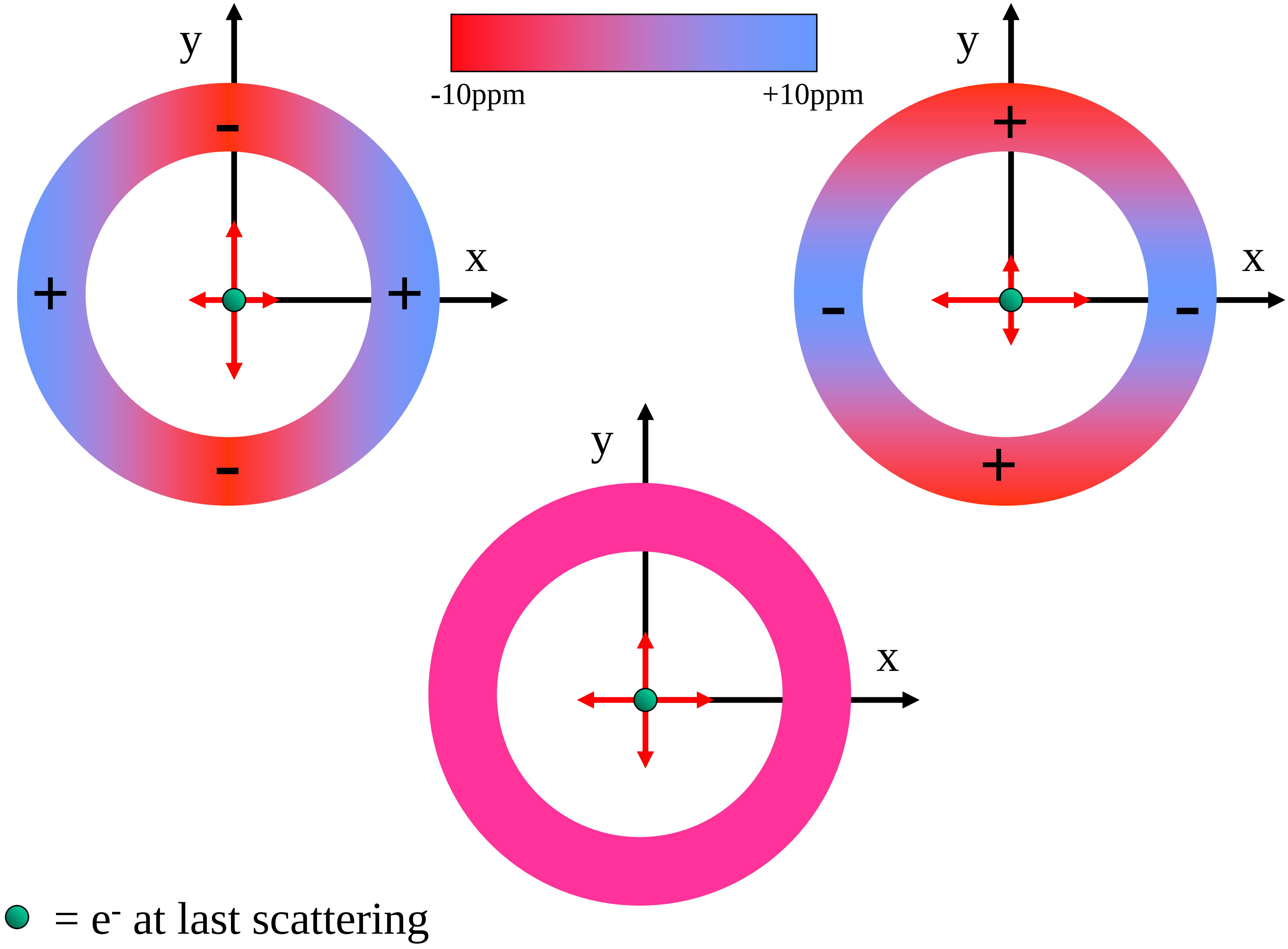
Did Inflation really happen ?

- **We do not know**. Inflation has not been proven yet. It is, however, a mechanism able to produce primordial fluctuations with the right characteristics.
- Four of the basic predictions of inflation have been proven:
  - existence of super-horizon fluctuations
  - gaussianity of the fluctuations
  - flatness of the universe
  - scale invariance of the density perturbations
- One more remains to be proved: the stochastic background of gravitational waves produced during the inflation phase.
- **CMB can help** in this – see below.

CMB polarization

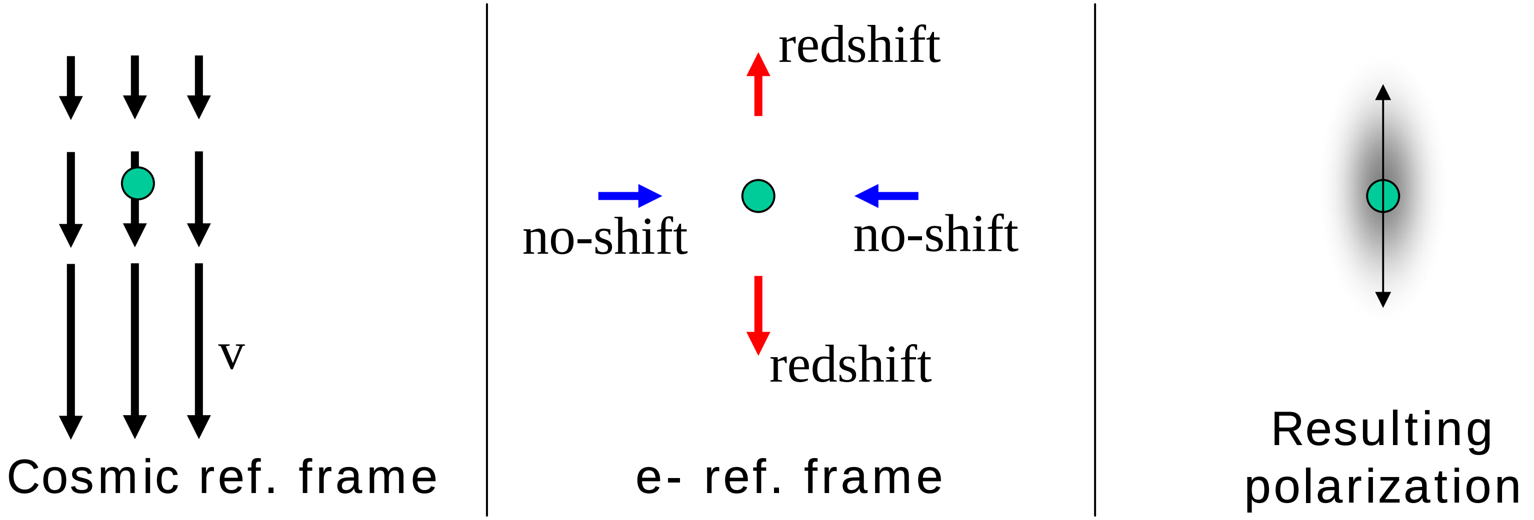
- CMB radiation is Thomson scattered at recombination.
- If the local distribution of incoming radiation in the rest frame of the electron has a *quadrupole moment*, the scattered radiation acquires some degree of linear polarization.



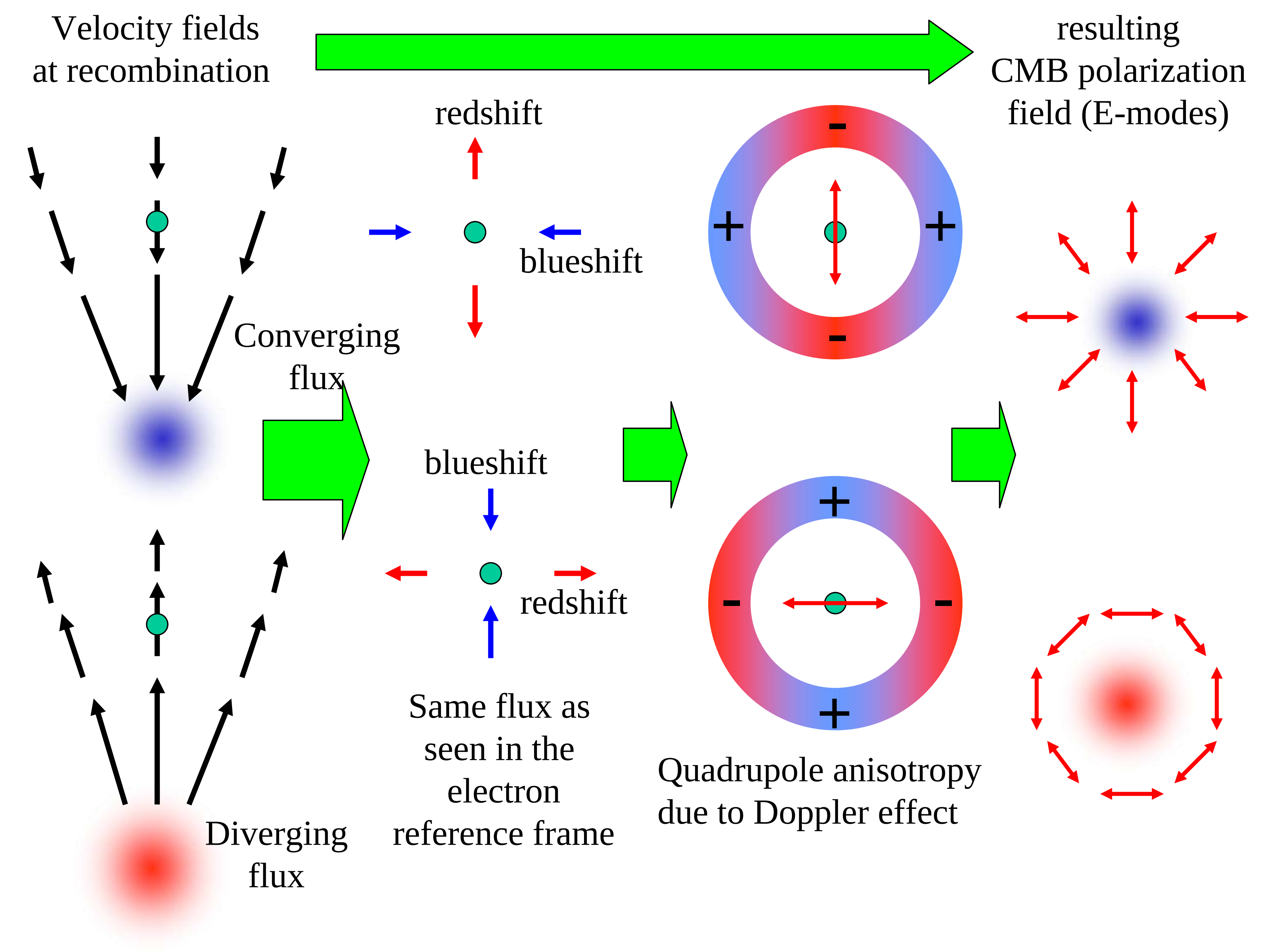


-10ppm
+10ppm
y
x
= e- at last scattering

- There are two sources of quadrupole anisotropy at the last scattering:
- **1-Velocity gradients** in the cosmic fluid at recombination produce a **quadrupole** in the rest-frame of the scattering electron.



- This component of the CMB polarization field is called **E** component, or **gradient component**.
- We expect correlations between the CMB anisotropy (T) and the E-modes of the polarization field.


Velocity fields
at recombination
resulting
CMB polarization
field (E-modes)
redshift
blueshift
Converging
flux
blueshift
redshift
Same flux as
seen in the
electron
reference frame
Quadrupole anisotropy
due to Doppler effect
Diverging
flux

- E-modes are irrotational

- E modes are related to velocities, while T is related mainly to density

- We expect a power spectrum of the E-modes, <EE>, with maxima and mimina in quadrature with the anisotropy power spectrum <TT>.

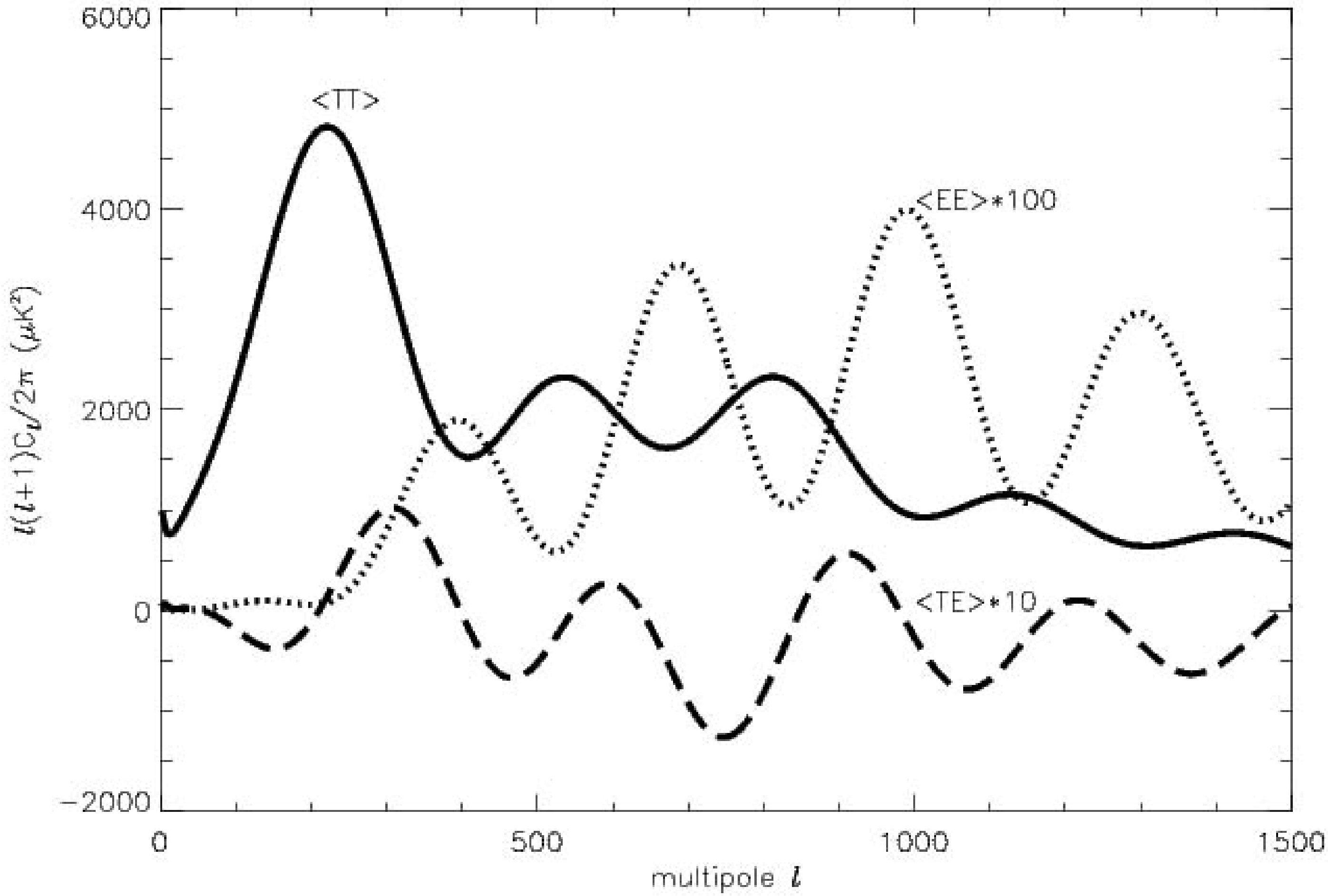


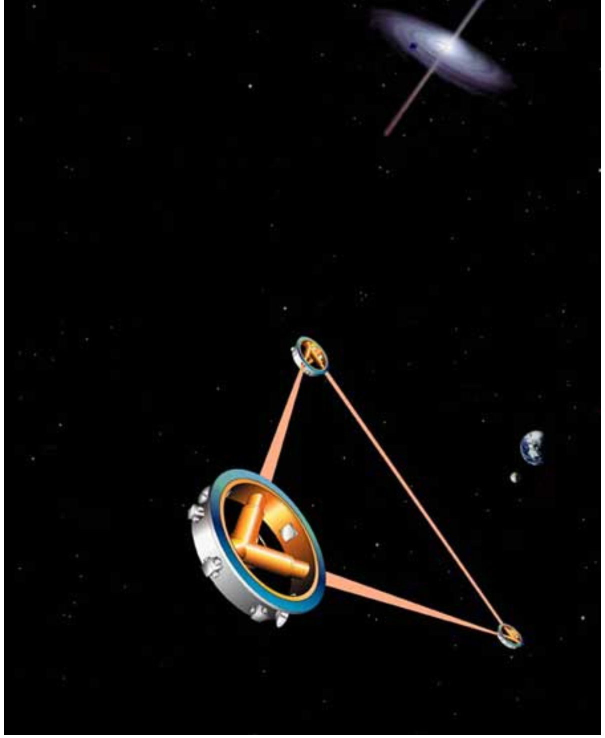
Figure 1.7: Estimated power spectra for the cosmological parameters: $\Omega_b = 0.05$, $\Omega_{cdm} = 0.3$, $\Omega_\Lambda = 0.65$, $\Omega_\nu = 0$, $H_0 = 65$ km/s/Mpc, $\tau = 0.17$. The temperature power spectrum, $\langle TT \rangle = C_\ell^T$, the E-modes power spectrum $\langle EE \rangle = C_\ell^E$ multiplied by a factor 100 to make it visible and the cross power spectrum between temperature and polarization, $\langle TE \rangle = C_\ell^{TE}$ multiplied by a factor 10. The spectra are computed using the publicly available code CMBFAST (http://www.cmbfast.org),

If inflation really happened...

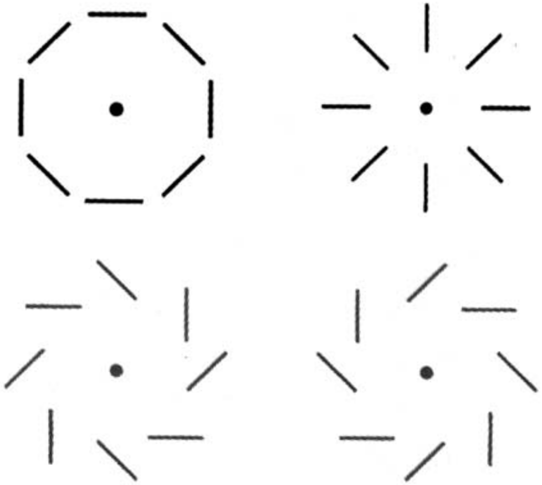
- It stretched the geometry of space to nearly Euclidean — OK
- It produced a nearly scale invariant spectrum of density fluctuations — OK
- It produced a stochastic background of gravitational waves. — ?

Quadrupole from P.G.W.

- If inflation really happened:
  - ✓ It stretched the geometry of space to nearly Euclidean
  - ✓ It produced a nearly scale invariant spectrum of gaussian density fluctuations
  - ✓ It produced a stochastic background of gravitational waves: Primordial G.W. The background is so faint that even LISA will not be able to measure it.
- Tensor perturbations also produce quadrupole anisotropy. They generate irrotational (E-modes) **and rotational (B-modes) components** in the CMB polarization field.
- Since B-modes are not produced by scalar fluctuations, they represent a signature of inflation.



E-modes



B-modes

B-modes from P.G.W.

- The amplitude of this effect is very small, but depends on the Energy scale of inflation. In fact the amplitude of tensor modes normalized to the scalar ones is:

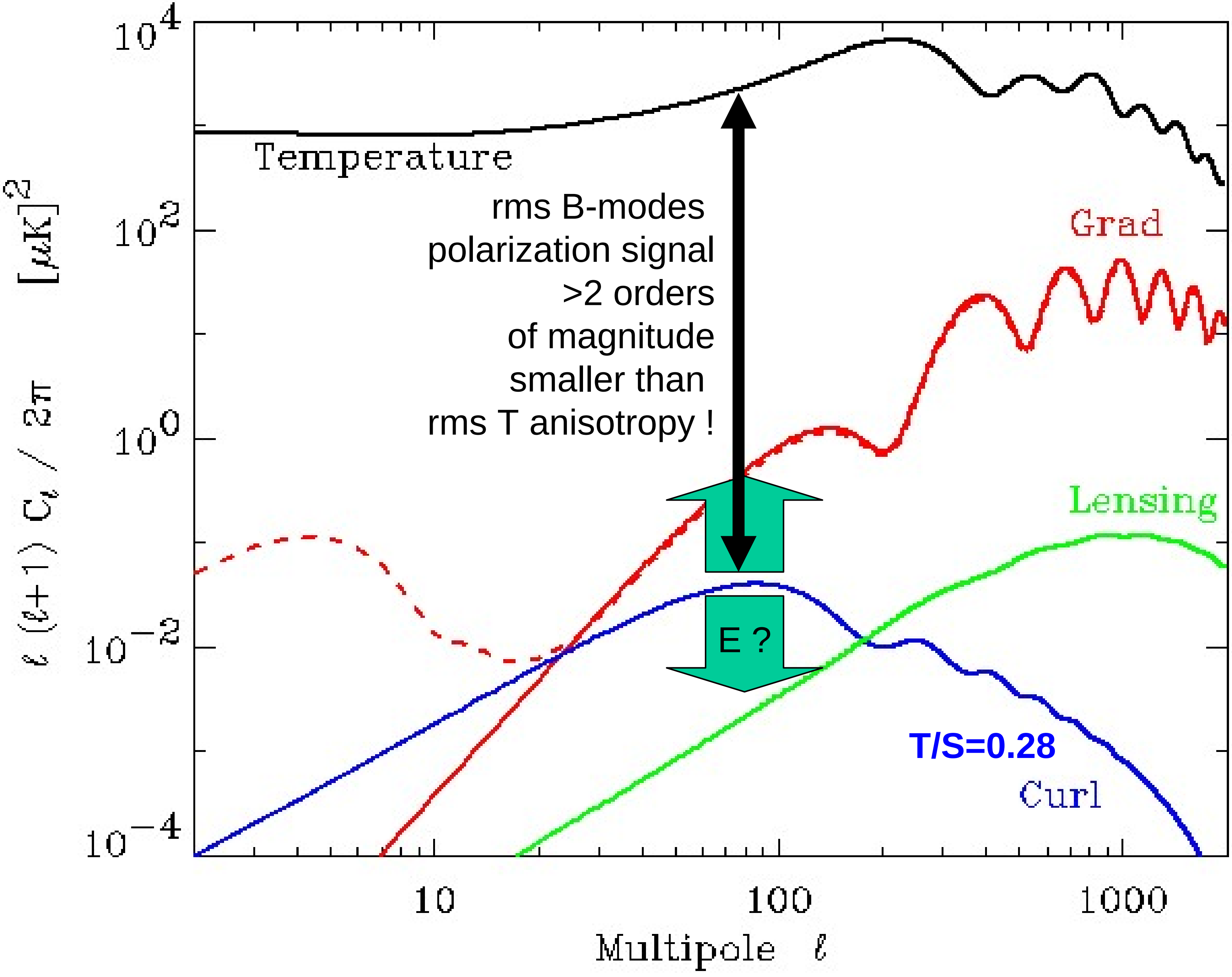
$$\left(\frac{T}{S}\right)^{1/4} \equiv \left(\frac{C_2^{GW}}{C_2^{Scalar}}\right)^{1/4} \cong \frac{V^{1/4}}{3.7\times 10^{16}\,\mathrm{GeV}}$$

Inflation potential

- and

$$\sqrt{\frac{\ell(\ell+1)}{2\pi}c^{B}_{\ell\,\mathrm{max}}} \cong 0.1\mu K\left[\frac{V^{1/4}}{2\times 10^{16}\,\mathrm{GeV}}\right]$$

- There are theoretical arguments to expect that the energy scale of inflation is close to the scale of GUT i.e. around 10^{16} GeV.
- The current upper limit on anisotropy at large scales gives T/S<0.5 (at 2σ)
- A competing effect is lensing of E-modes, which is important at large multipoles.

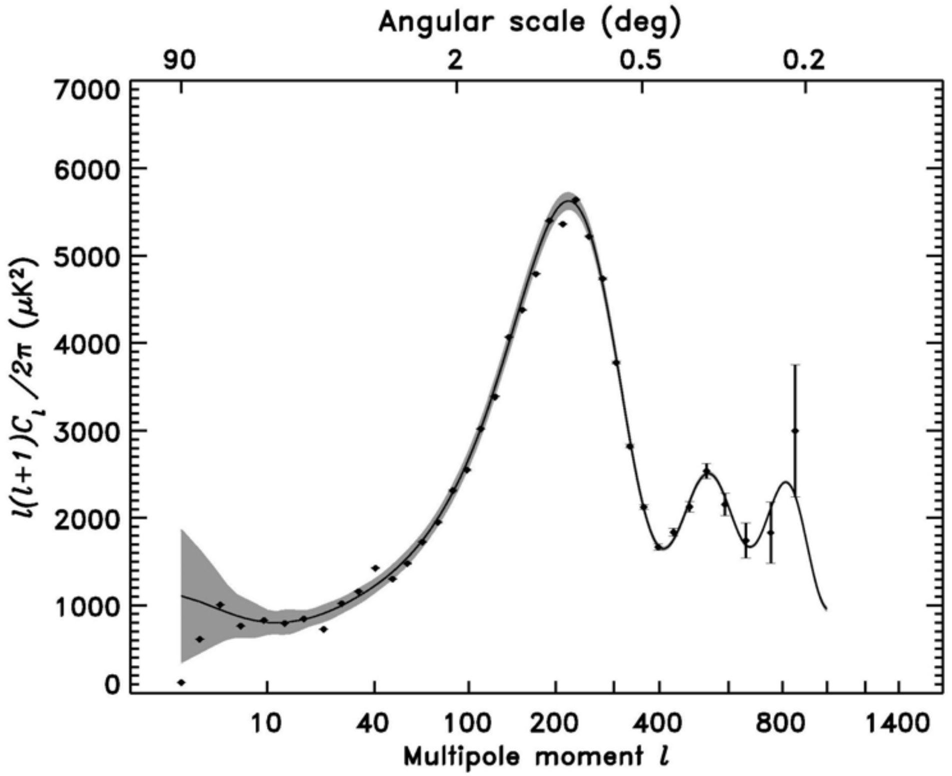


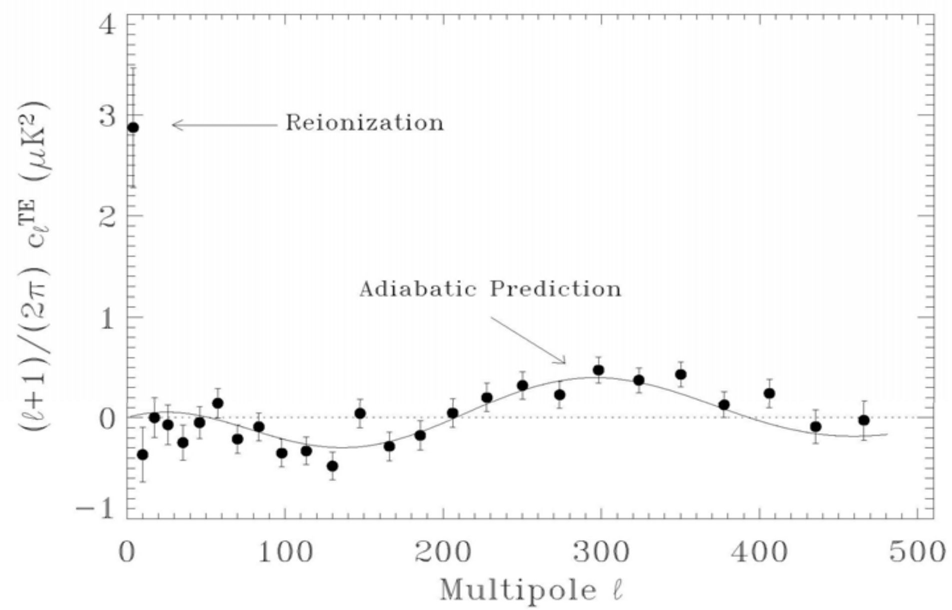
Temperature
rms B-modes
polarization signal
>2 orders
of magnitude
smaller than
rms T anisotropy !
Grad
Lensing
E ?
T/S=0.28
Curl
10^4
10^2
10^0
10^{-2}
10^{-4}
$[\mu K]^2$
$\ell(\ell+1)\ C_\ell\ /\ 2\pi$
10
100
1000
Multipole ℓ

The signal is extremely weak

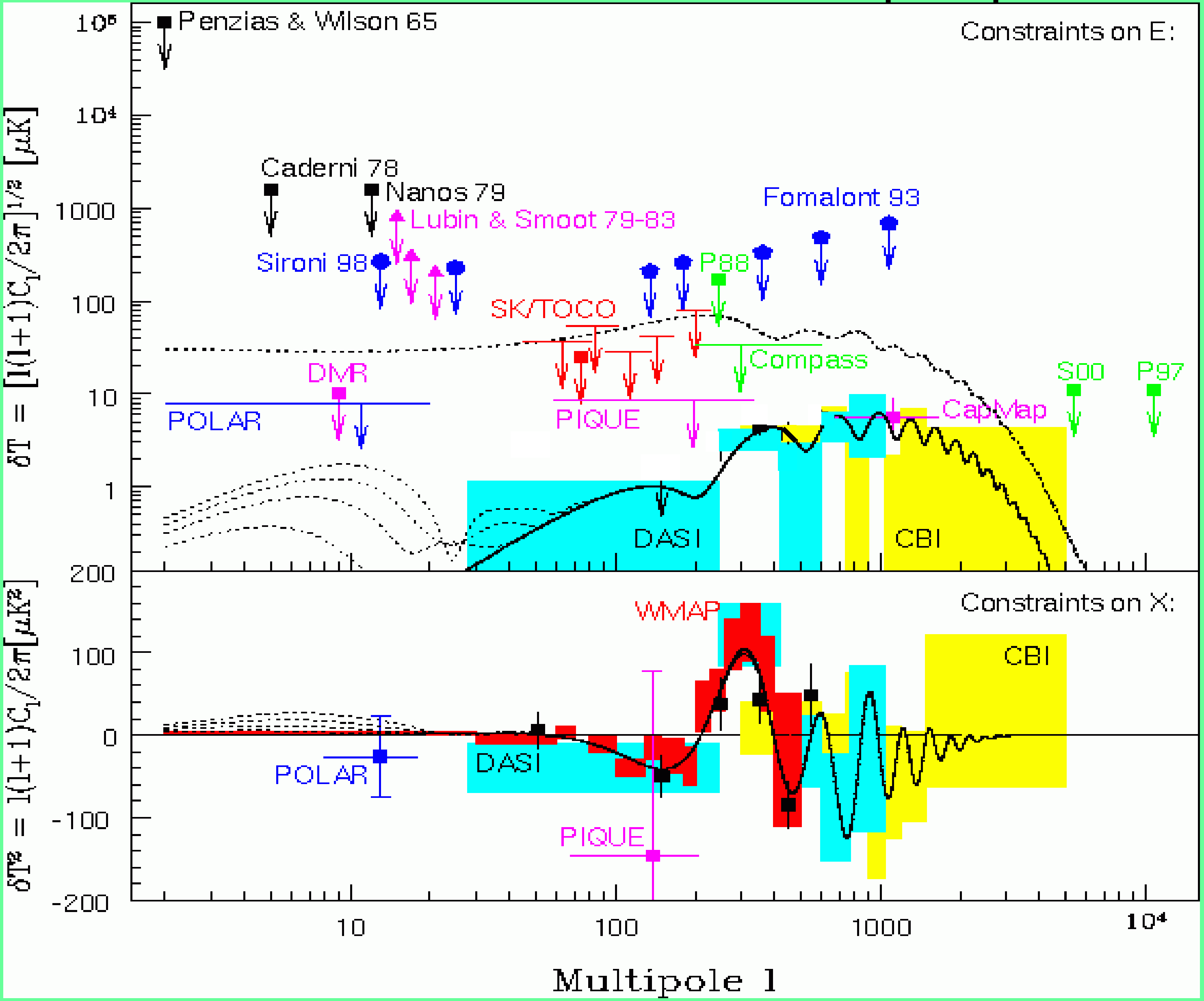
- Nobody really knows how to detect this.
  - Pathfinder experiments are needed
- Whatever smart, ambitious experiment we design to detect the B-modes:
  - It needs to be extremely sensitive
  - It needs an extremely careful control of systematic effects
  - It needs careful control of foregrounds
  - It will need independent experiments with orthogonal systematics.
- There is still a long way to go: ...

- 2003: First results from WMAP, the CMB anisotropy mission of NASA, working from L2.
- The TT power spectrum, limited by cosmic variance up to l=350
- The power spectrum of TE (correlation between anisotropy and polarization) in agreement with the acoustic oscillations scenario, and featuring an excess at low l.





CMB polarization has been detected recently by DASI, WMAP*, CBI and CapMap.



- The second LDB flight of BOOMERanG was devoted to CMB polarization measurements
- Was motivated by the desire to measure polarization :
  - at 145 GHz (higher ν wrt WMAP, DASI, CBI etc.)
  - with bolometers (vs. coherent amplifiers of WMAP, DASI, CBI etc.)
  - controlling the dominant foreground (dust) by means of simultaneous observations at higher frequencies (245, 345 GHz)
  - in one of the best sky regions (foreground-wise)
  - in a multipoles range where the polarization signal can be higher than the foreground signal.

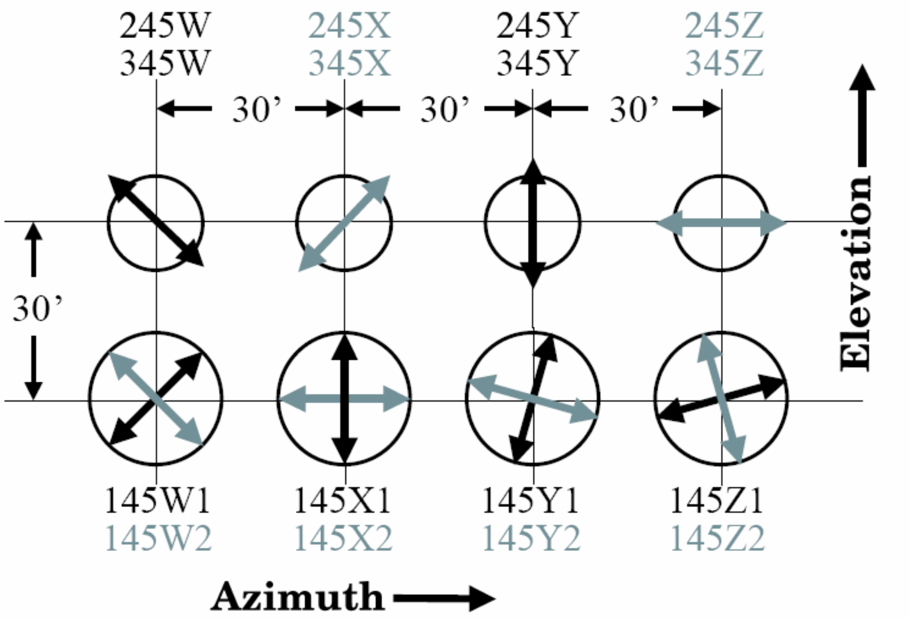
Universita' di Roma, La Sapienza:
P. de Bernardis, G. De Troia, A. Iacoangeli, **S. Masi**, A. Melchiorri, L. Nati, F. Nati, F. Piacentini, G. Polenta, S. Ricciardi, P. Santini, M. Veneziani
Case Western Reserve University:
J. Ruhl, T. Kisner, E. Torbet, T. Montroy
Caltech/JPL:
A. Lange, J. Bock, W. Jones, V. Hristov
University of Toronto:
B. Netterfield, C. MacTavish, E. Pascale

Cardiff University: P. Ade, **P. Mauskopf**
IFAC-CNR: A. Boscaleri
INGV: G. Romeo, G. di Stefano
IPAC: B. Crill, E. Hivon
CITA: D. Bond, S. Prunet, D. Pogosyan
LBNL, UC Berkeley: J. Borrill
Imperial College: A. Jaffe, C. Contaldi
U. Penn.: M. Tegmark, A. de Oliveira-Costa
Universita' di Roma, Tor Vergata: N. Vittorio, G. de Gasperis, P. Natoli, P. Cabella

The Polarization-sensitive BOOMERanG: B03

- Distribution of the PSBs in the focal plane :

Freq	Bandwidth	#detectors	Beam FWHM	NET_{CMB}
145 GHz	45 GHz	8	$9.95'$	$170\ \mu K\sqrt{s}$
245 GHz	80 GHz	4	$6.22'$	$320\ \mu K\sqrt{s}$
345 GHz	100 GHz	4	$6.90'$	$450\ \mu K\sqrt{s}$

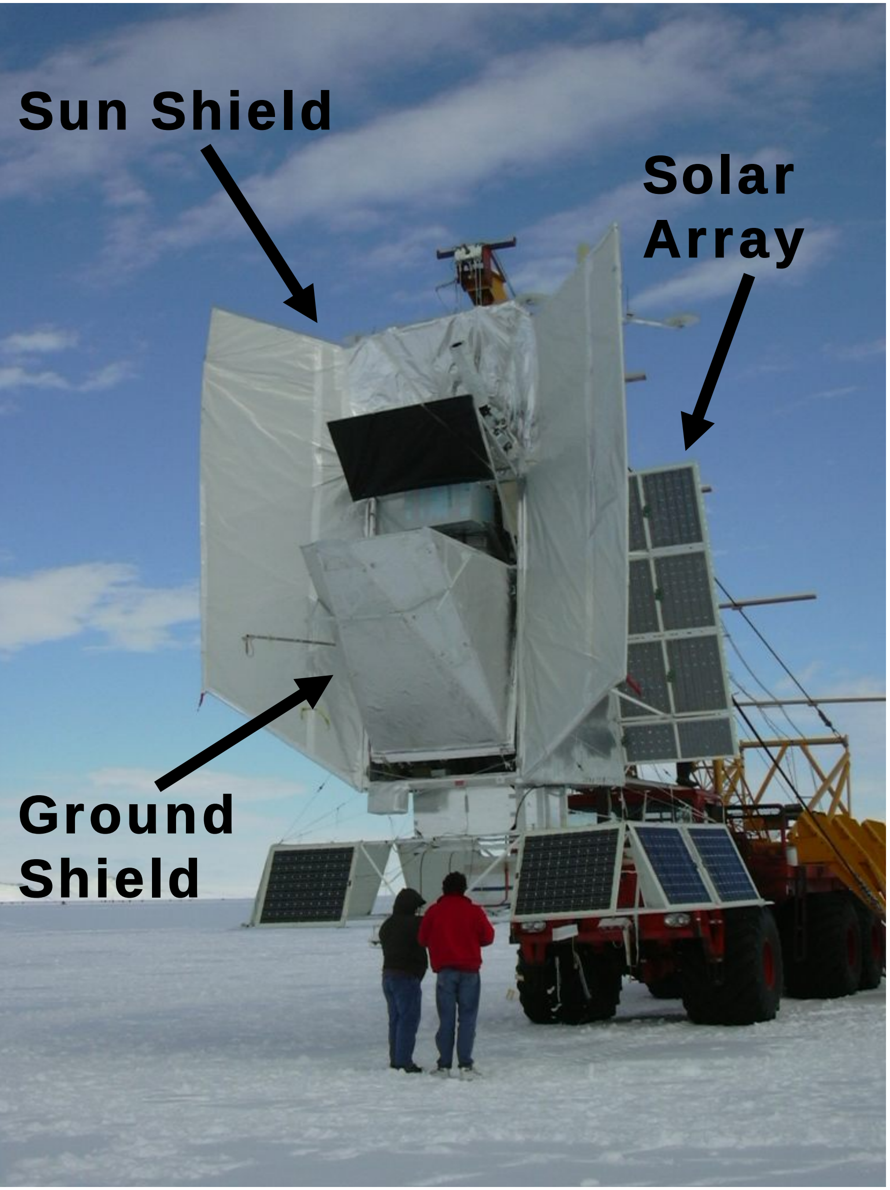


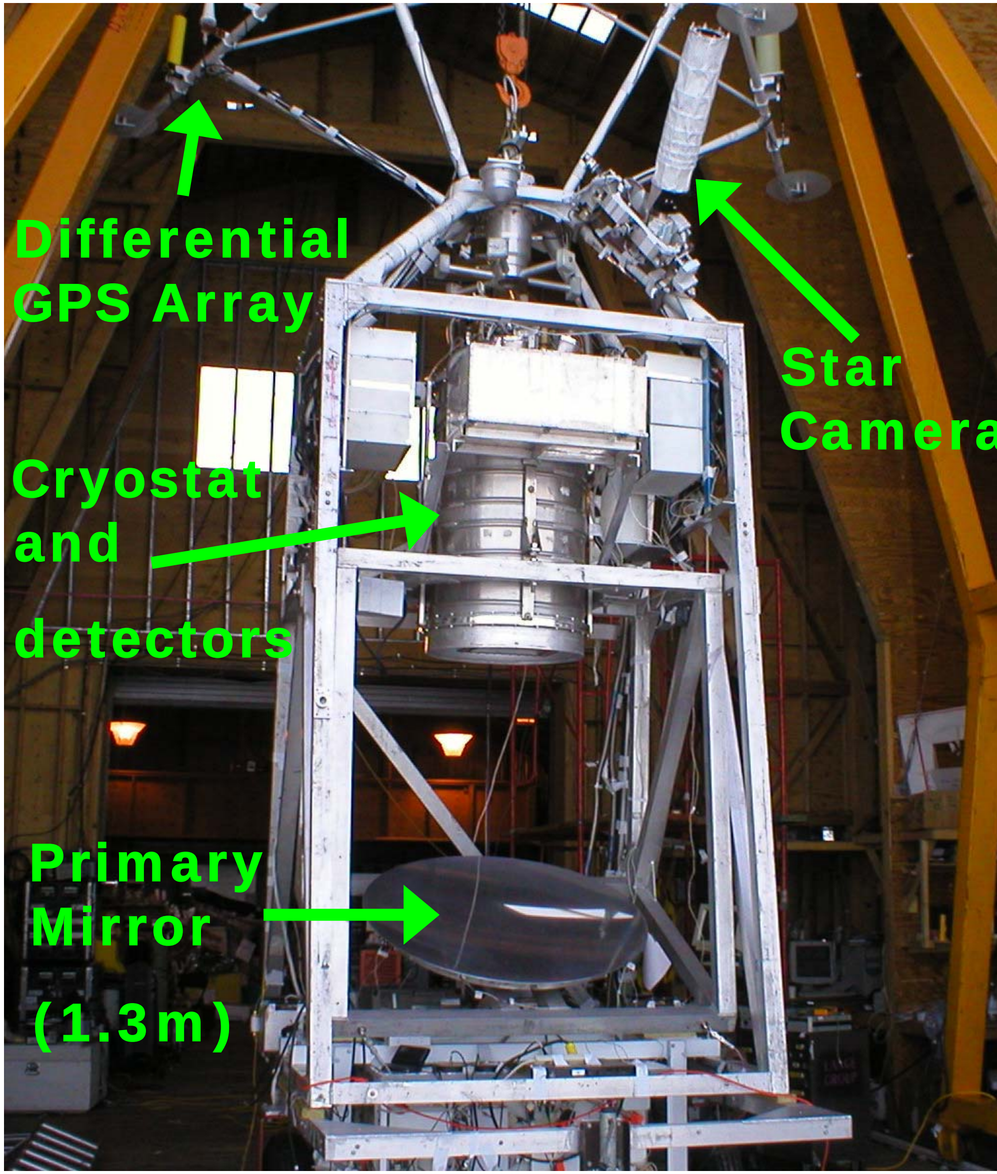
- 8 pixels in the focal plane, separated by 30’.
- Masi et al. 2005 astro-ph/0507509

- The focal plane : all you see is cooled at 270 mK

10 cm

the BOOMERanG balloon-borne telescope





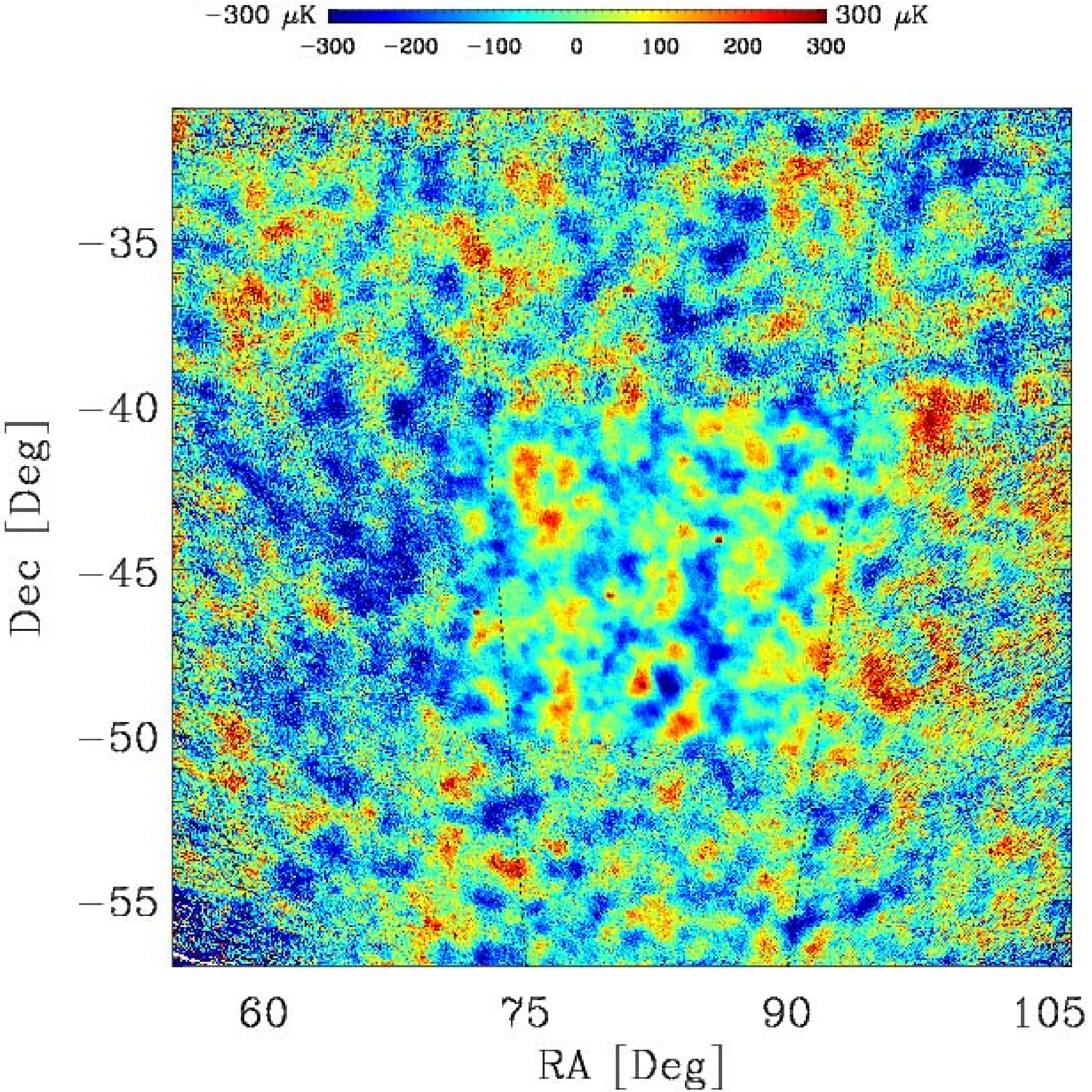
B03 Sensitive at 145, 245, 345 GHz

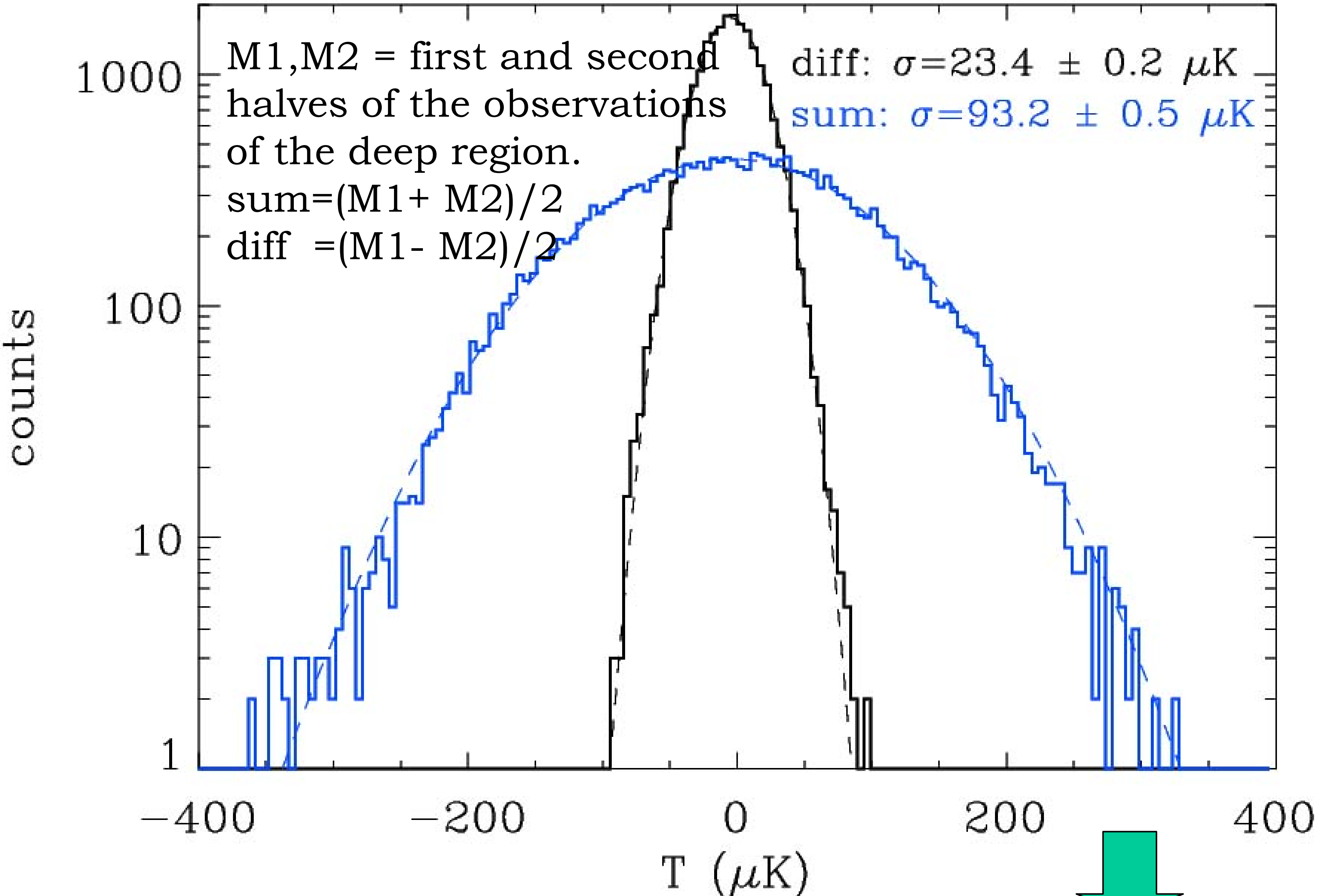

06/01/2003

145 GHz
T map

(Masi et al., 2005)

the deepest CMB map ever



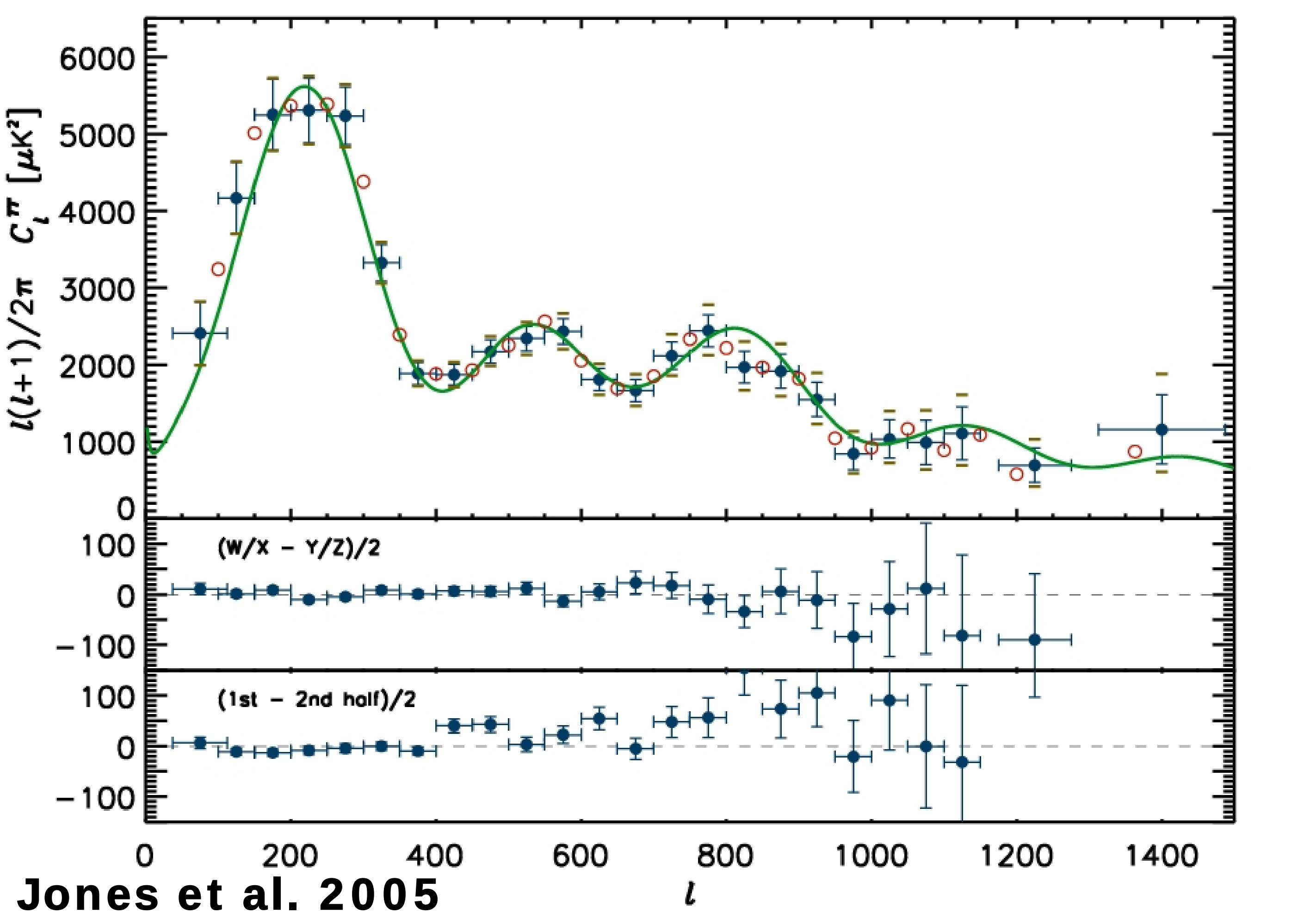


$\Delta T_{rms} = (90.2 \pm 2.3)\ \mu K$

- In the deep survey the S/N is high.
- The fluctuations are gaussian.

B03 TT Power Spectrum

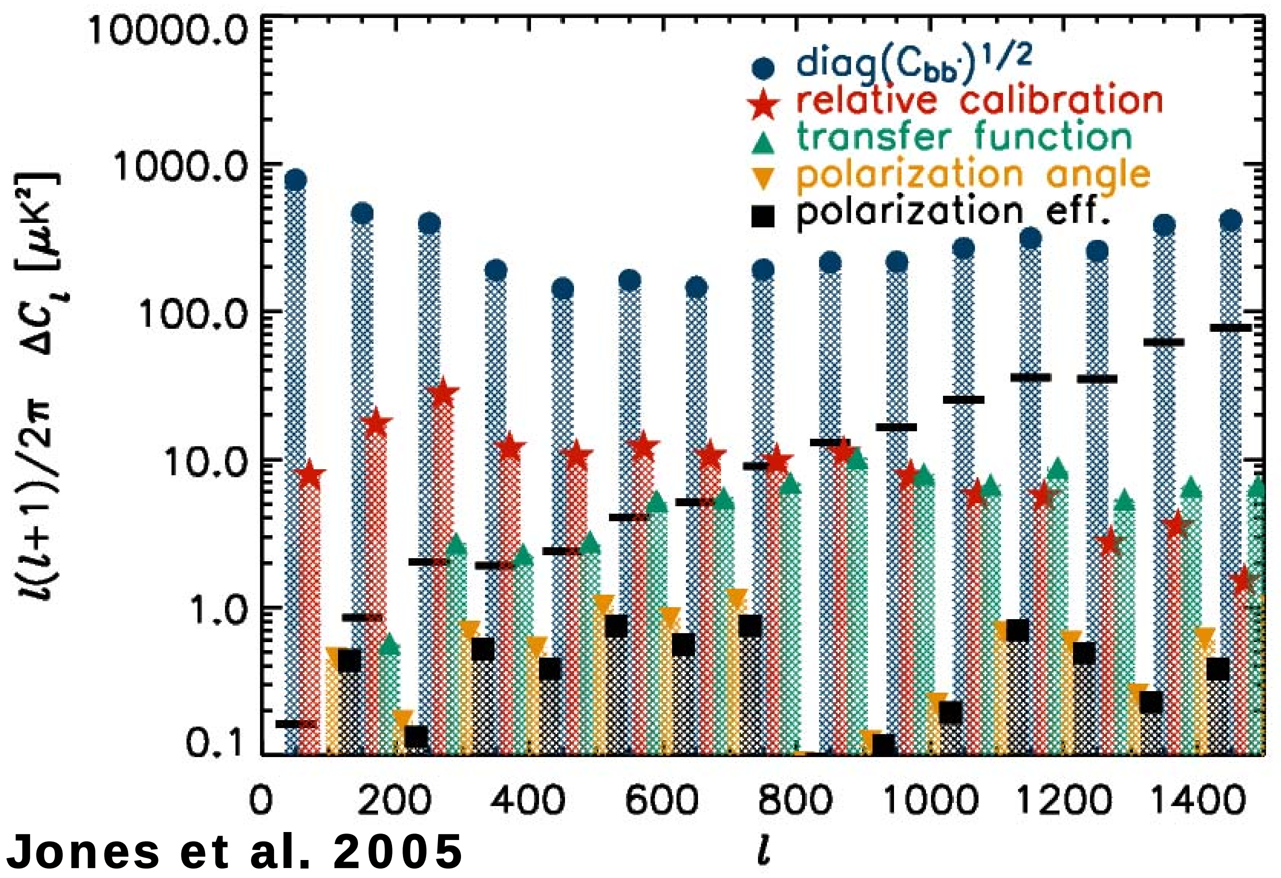
- Detection of anisotropy signals all the way up to **l**=1500
- Time and detector jacknife tests OK
- Systematic effects negligible wrt noise & cosmic variance



Jones et al. 2005

B03 TT Power Spectrum

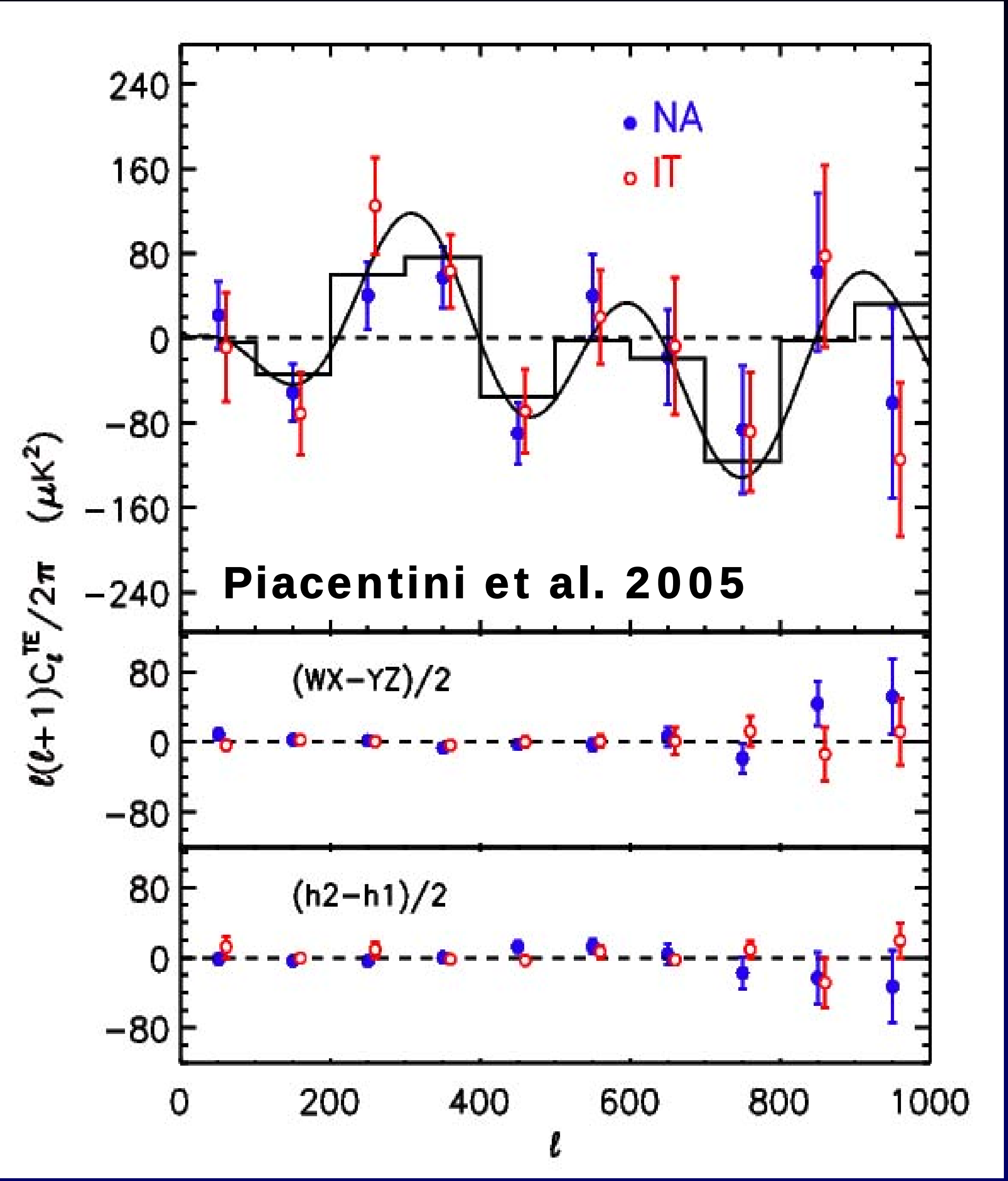
- The use of fast estimators (FASTER, Hivon et al; XFASTER Contaldi et al.) allow us to carry out a very detailed analysis of how possible systematic effects propagate to the spectrum.
- The short summary is that all systematics we have considered are negligible wrt the effect of noise.



Jones et al. 2005

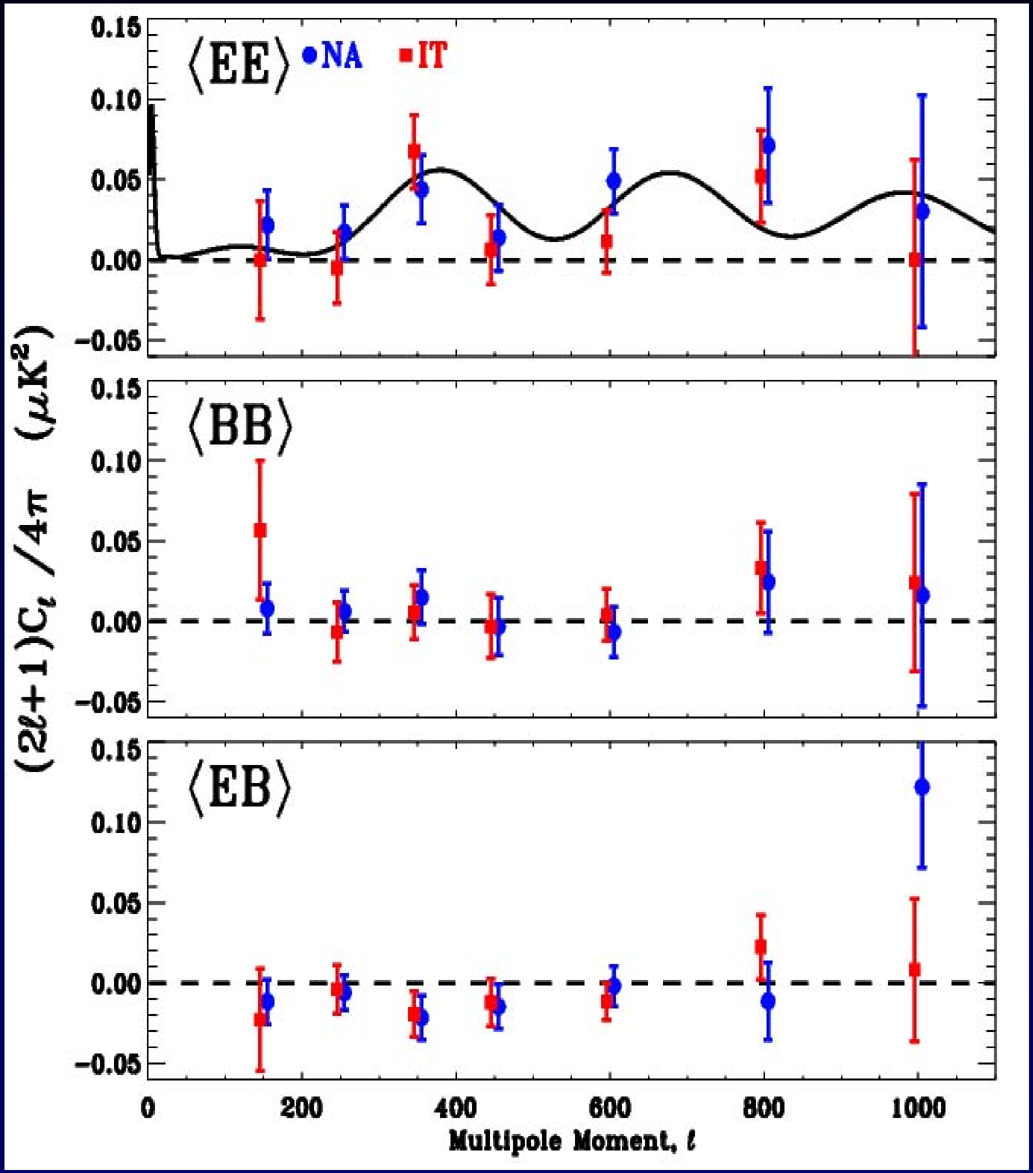
TE Power Spectrum

- Smaller signal, but detection evident (3.5σ)
- NA and IT results consistent
- Error bars dominated by cosmic variance
- Time and detectors jacknife OK, i.e. systematics negligible
- Data consistent with TT best fit model



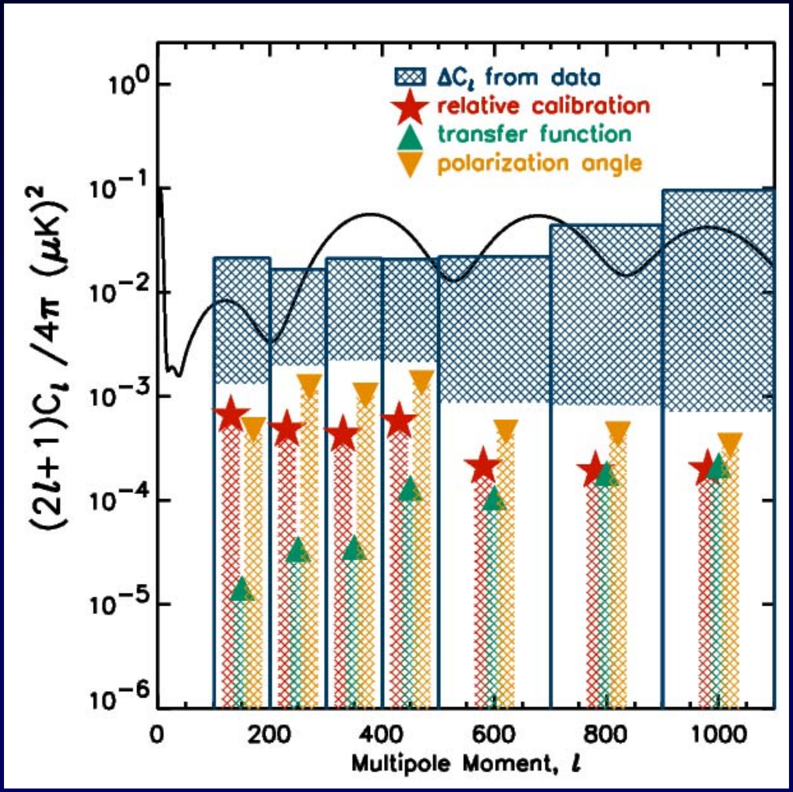
EE Power Spectrum

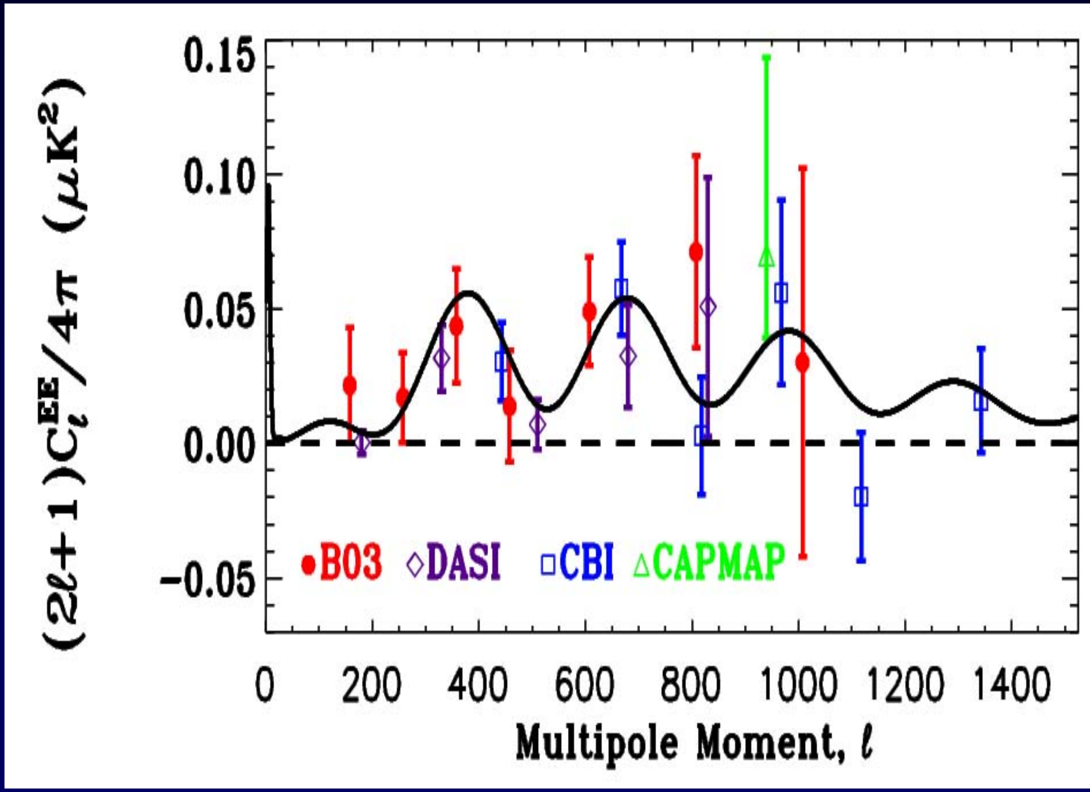
- Signal extremely small, but detection evident for EE (non zero at 4.8σ).
- No detection for BB nor for EB
- Time and detectors jacknife OK, i.e. systematics negligible
- Data consistent with TT best fit model
- Error bars dominated by detector noise.



EE Power Spectrum

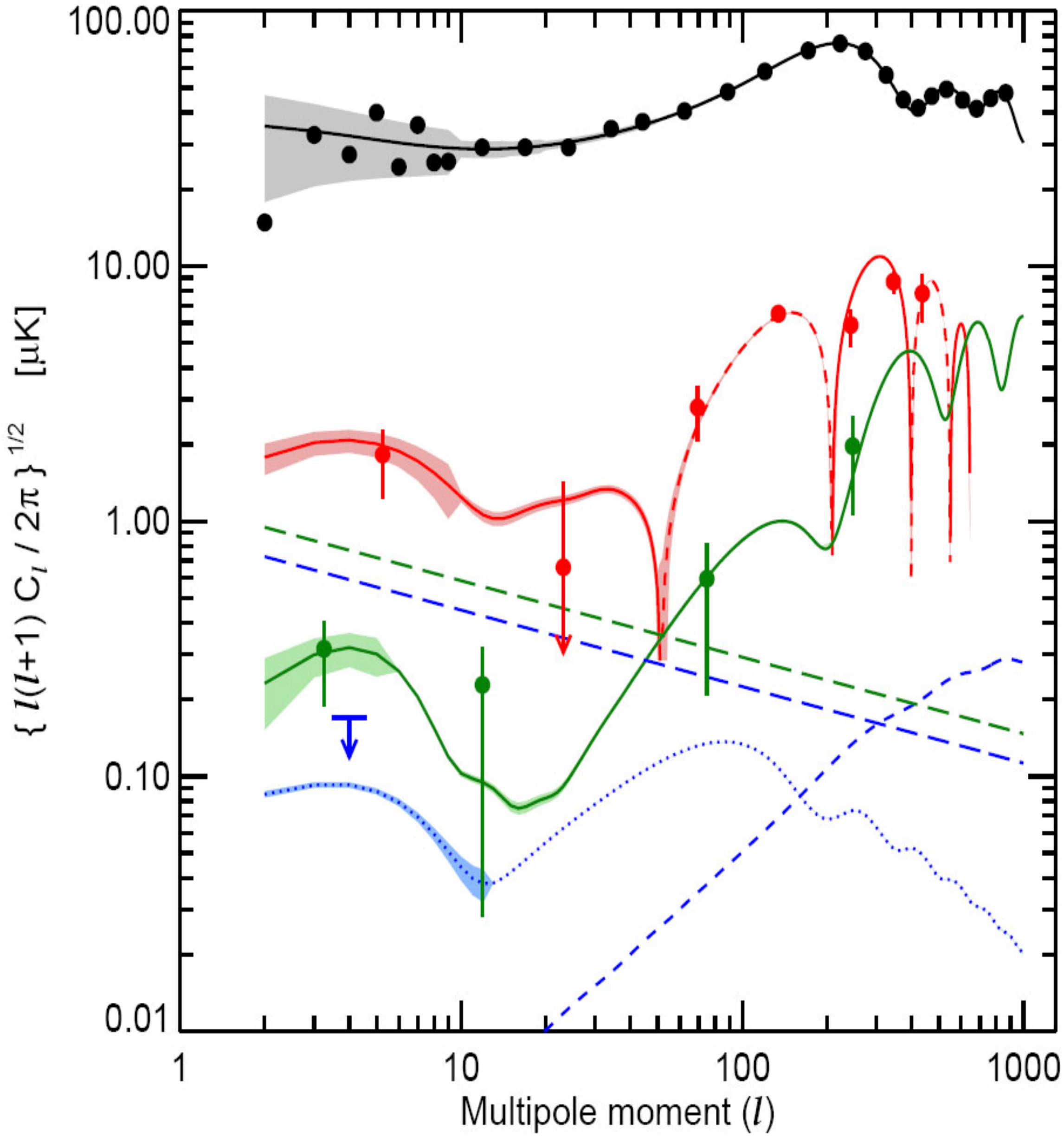
- Time and detectors jacknife OK, i.e. systematics negligible
- Data consistent with TT best fit model
- and with other experiments:





- In 2006 the WMAP team has published the results of 3 years of data.

- Polarization is detected at intermediate and large scales, after removal of a model for the polarized foreground from the Galaxy.



BOOMERanG wrt WMAP polarization measurement

- Work in different frequency and multipoles ranges and on different sky cuts.
- The ratio between polarized CMB and polarized foregrounds is completely different.

	B03 **145 GHz**	*WMAP* **65 GHz**	*WMAP* **65 GHz**	*WMAP* **65 GHz**
l-range	100 - 1200	4-6	50-200	200-800
rms CMB polarization (μK)	4	0.3	0.7	2
rms foreground polarization (μK)	< 0.4	~0.6	~0.4	~0.2

From Page et al. 2006

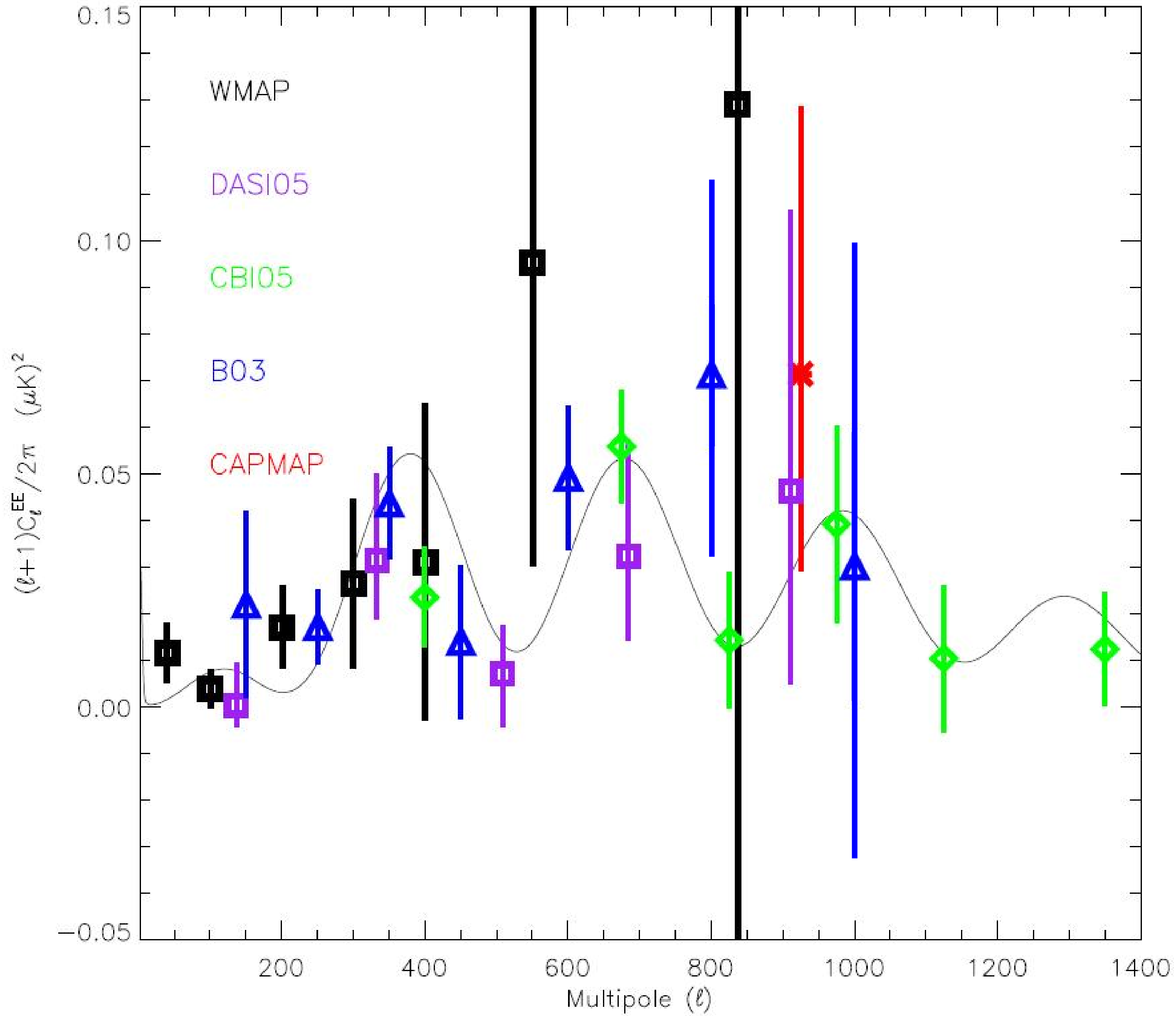
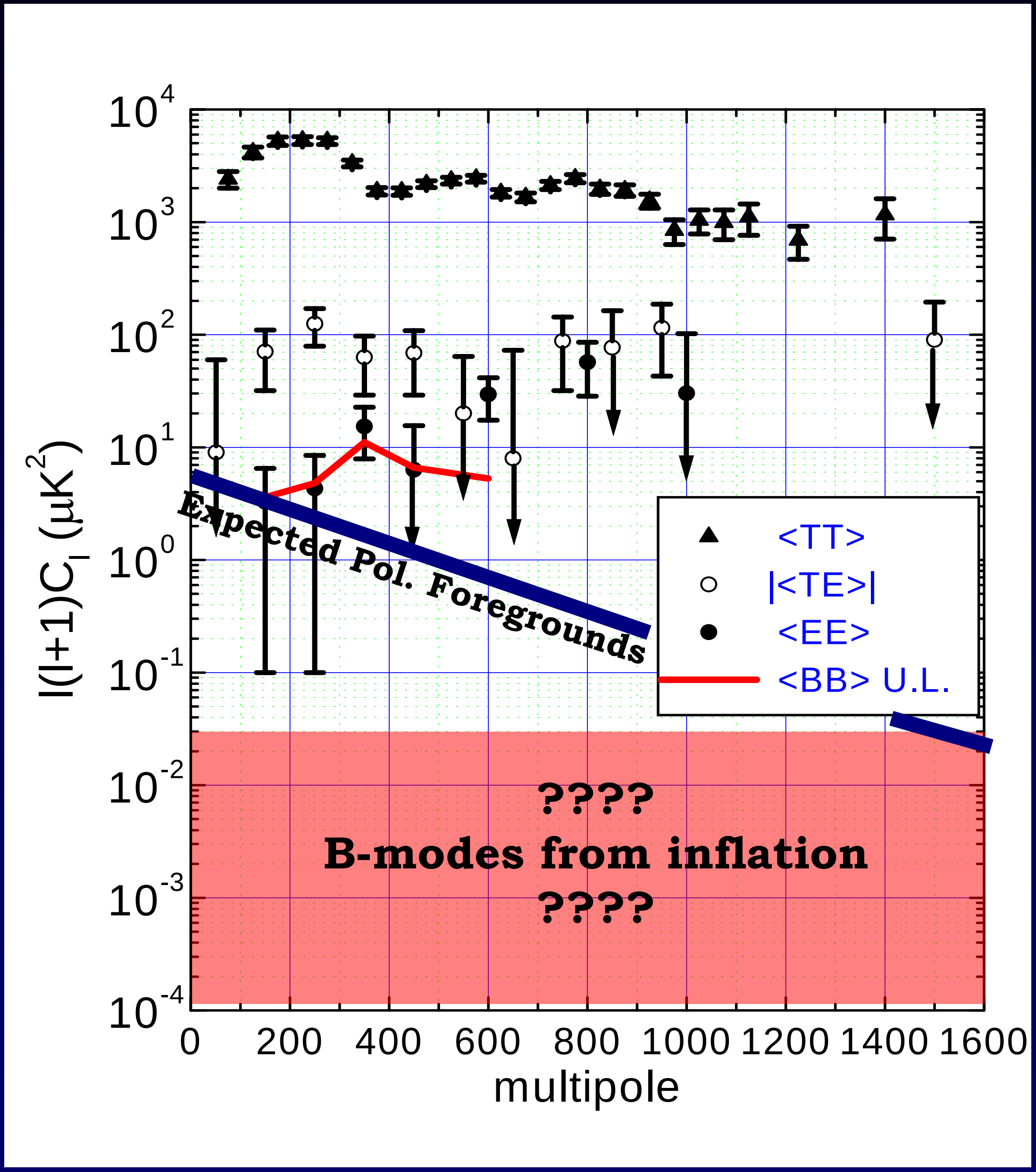


FIG. 22.— The EE spectrum at $\ell > 40$ for all measurements of the CMB polarization. The curve is the best fit EE spectrum. Note that the y axis has only one power of ℓ. The black boxes are the *WMAP* data; the triangles are the BOOMERanG data; the squares are the DASI data; the diamonds are the CBI data; and the asterisk is the CAPMAP data. The *WMAP* data are the QVW combination. For the first point, the cleaned value is used. For other values, the raw values are used. The data are given in Table 8

Summary of TT, |TE|, EE, BB Spectra from B03



- We have detected VERY SMALL polarization signals, 2-3 orders of magnitude lower than anisotropy
- We are safe from the point of view of systematcs and foregrounds
- We are VERY FAR from detecting inflationary B-modes

Where do we go from here

- Polarization measurements do not constrain parameters better than anisotropy measurements, yet.
- Most of the weight in the results above is in Temperature power spectra.
- If we want to constrain better the cosmological model, and finally detect B-modes, and we need to improve in three ways:

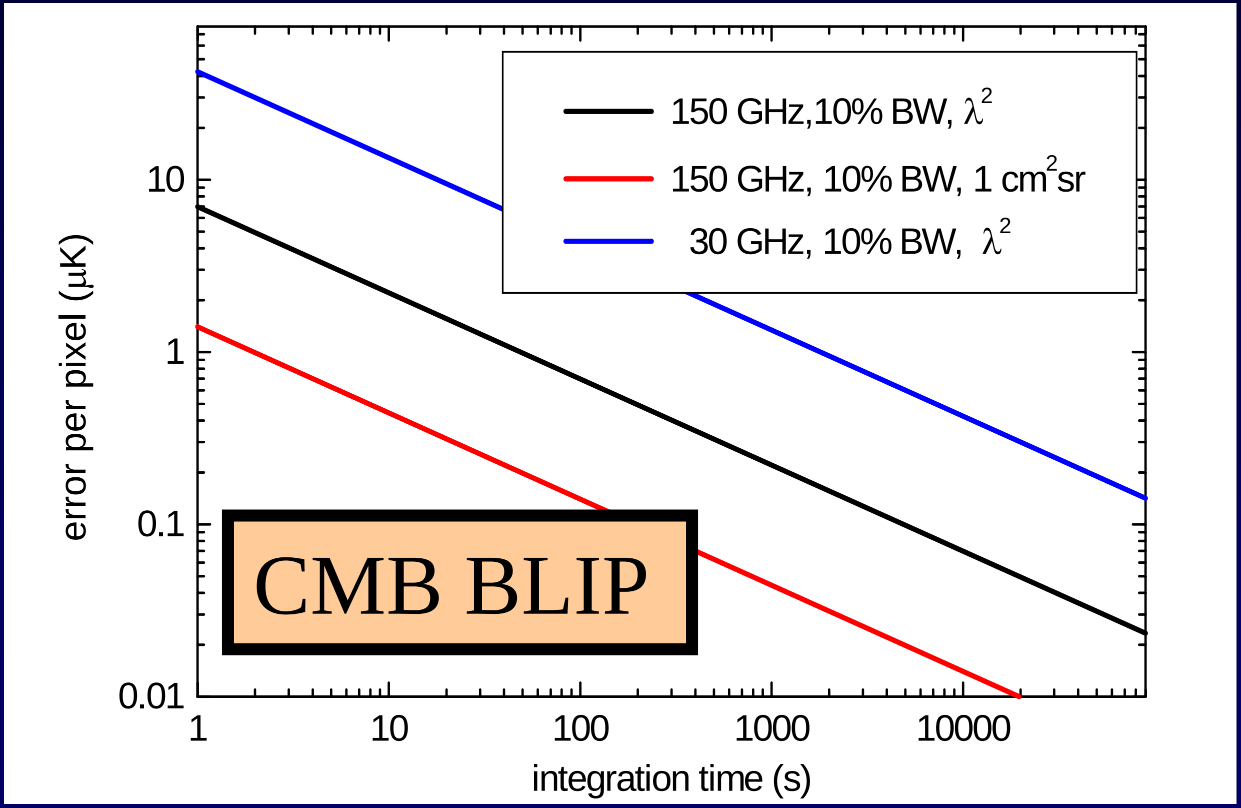
1. Sensitivity
2. Control of systematics
3. Knowledge of foregrounds

Sensitivity

- B03 has shown that Polarization Sensitive Bolometers work well for CMB polarization measurements.
- Their sensitivity is close to be photon-noise-limited. In Planck-HFI the same bolometers will be cooled a factor 3 more and will be limited only by quantum fluctuations of the CMB itself. It is useless to improve the detector noise below the photon noise limit.

A post-Planck mission

- Planck will or will not detect Inflationary B-Modes (depending on amplitude, foregrounds, systematics… and if they are really there).
- In a diffraction limited 150 GHz survey, CMB BLIP gives 1 μK in 1 min of integration. But we need to observe 10^5 pixels !



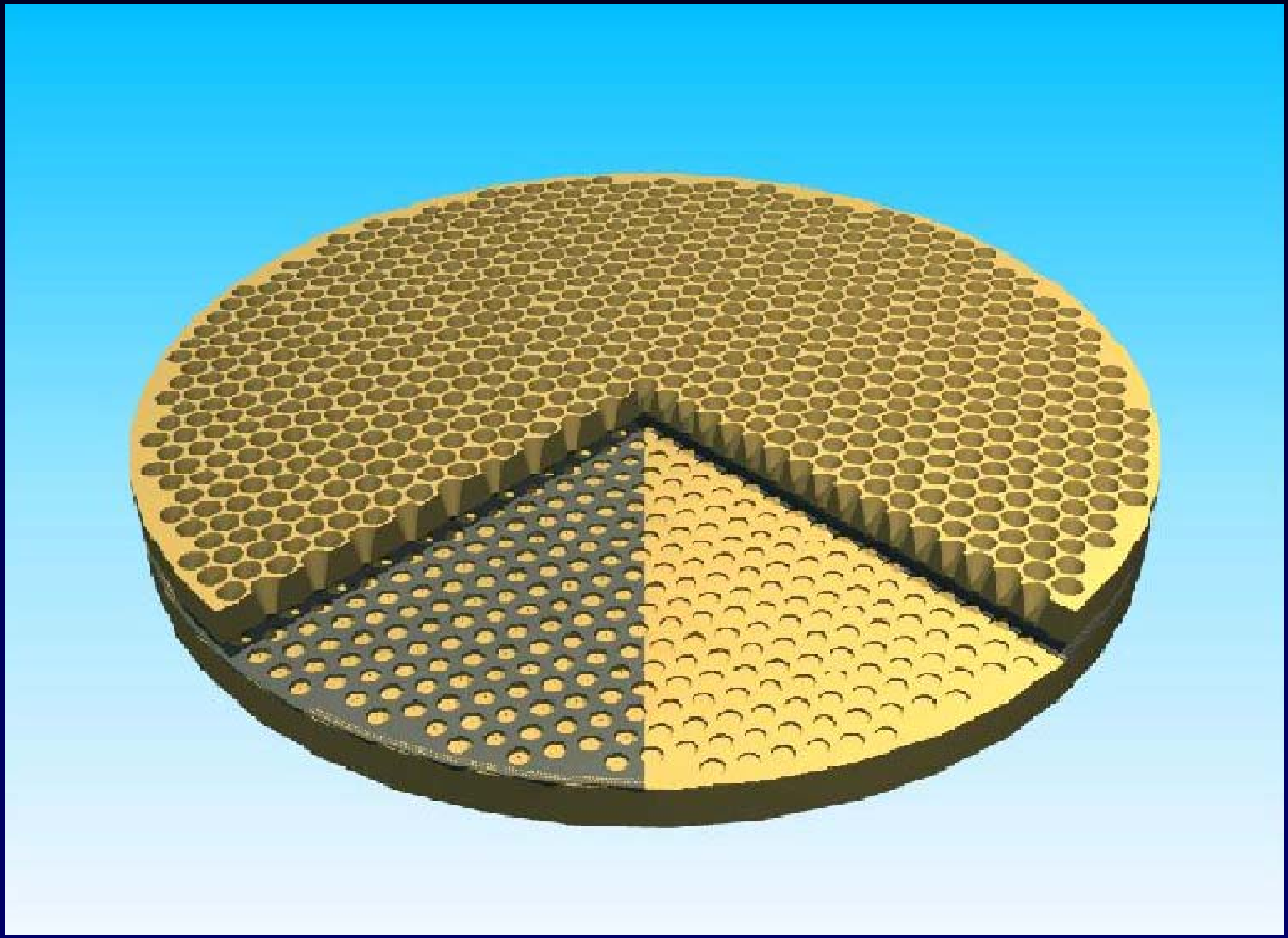
- We need to increase the mapping speed using more detectors than in the Planck focal plane.

Sensitivity

- At variance with interferometers, Bolometer technology is easily scalable, and the throughput can be larger than λ^2.
- Focal planes hosting thousands of bolometers are being developed already.

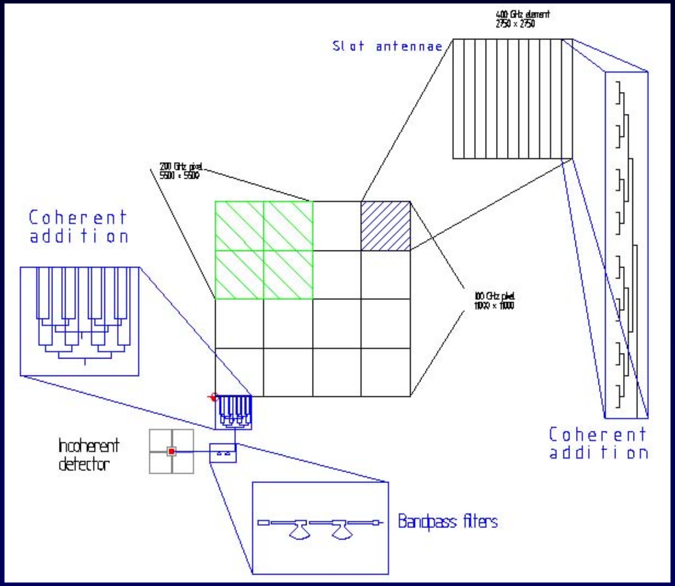
Large Bolometer Arrays

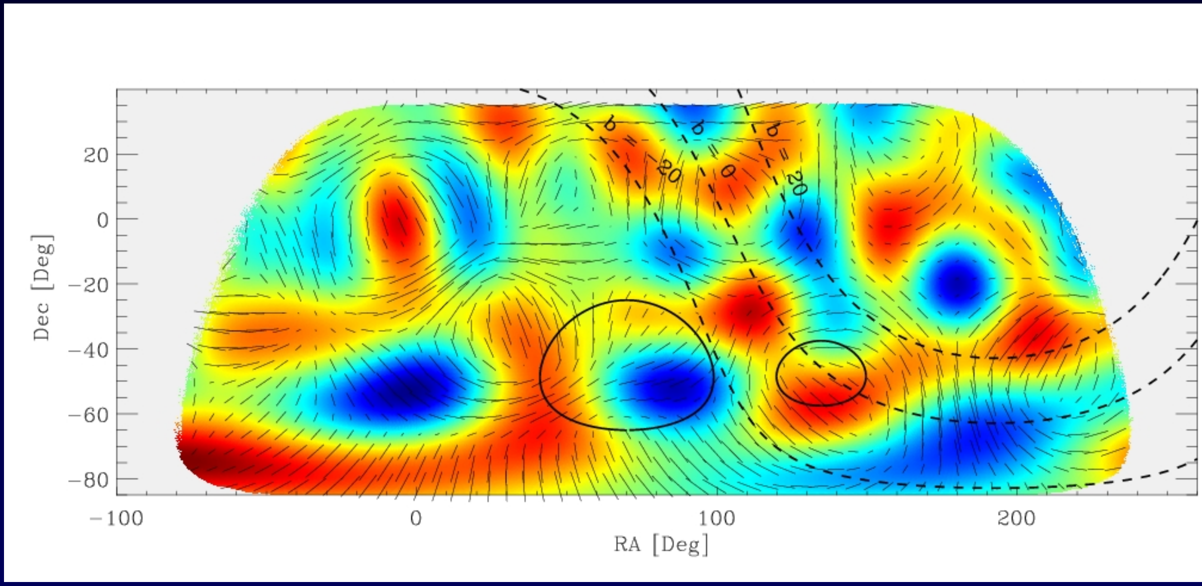
- > 1000 TES bolometers for the South Pole Telescope devoted to SZ (Adrian Lee, Berkeley)

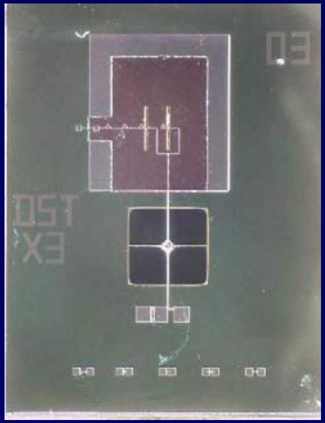


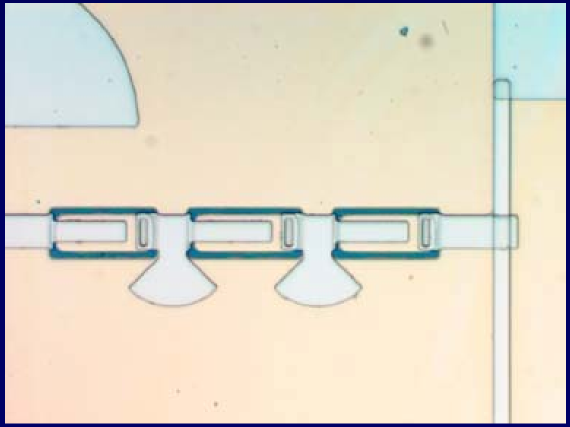
Large Bolometer Arrays

- > 1000 TES bolometers for SPIDER a proposed spinning polarimeter on a LDB (Andrew Lange, Caltech) devoted to large scale CMB polarization







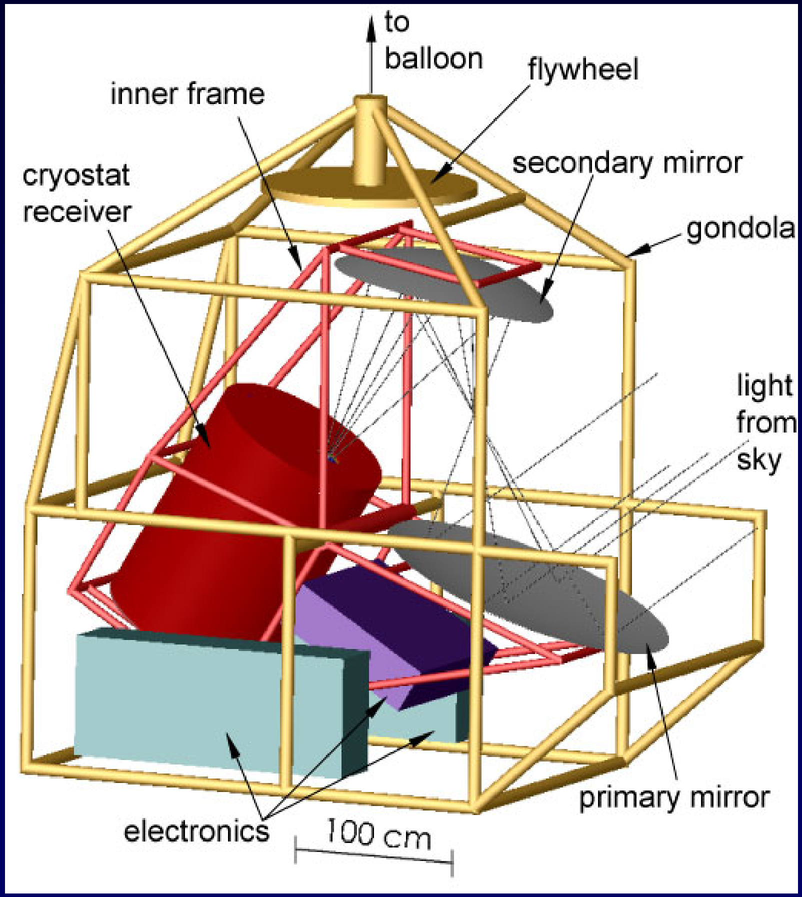


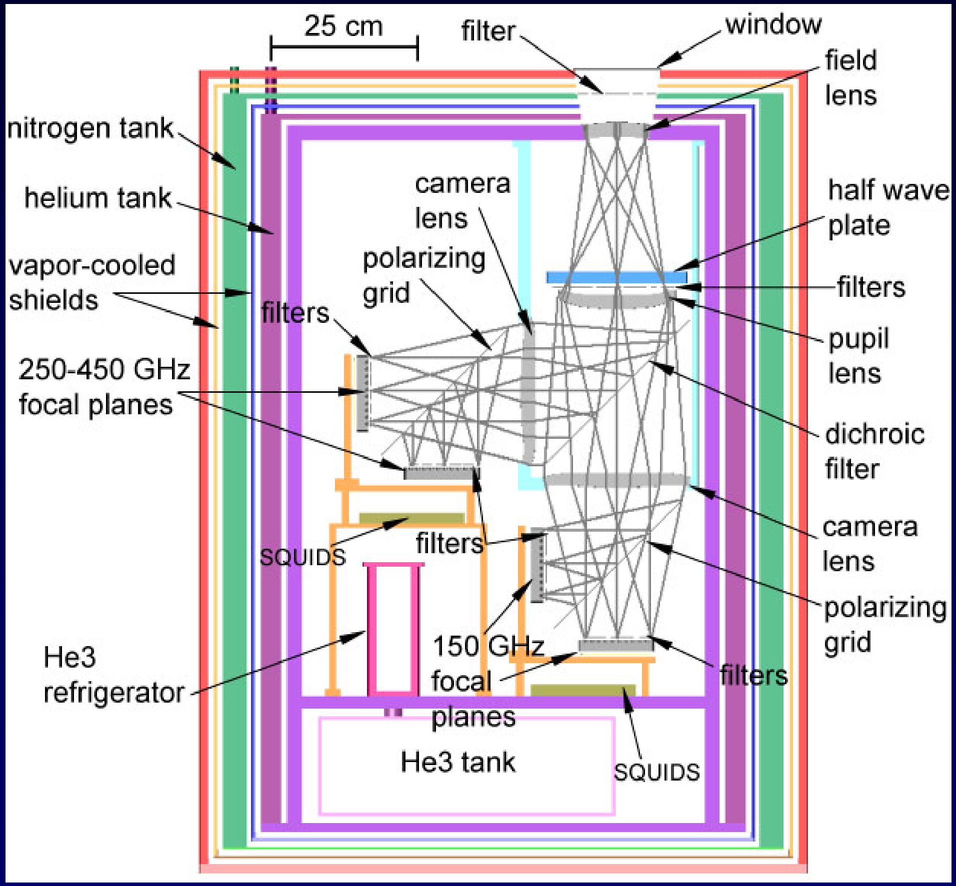
Spider Instrument Summary

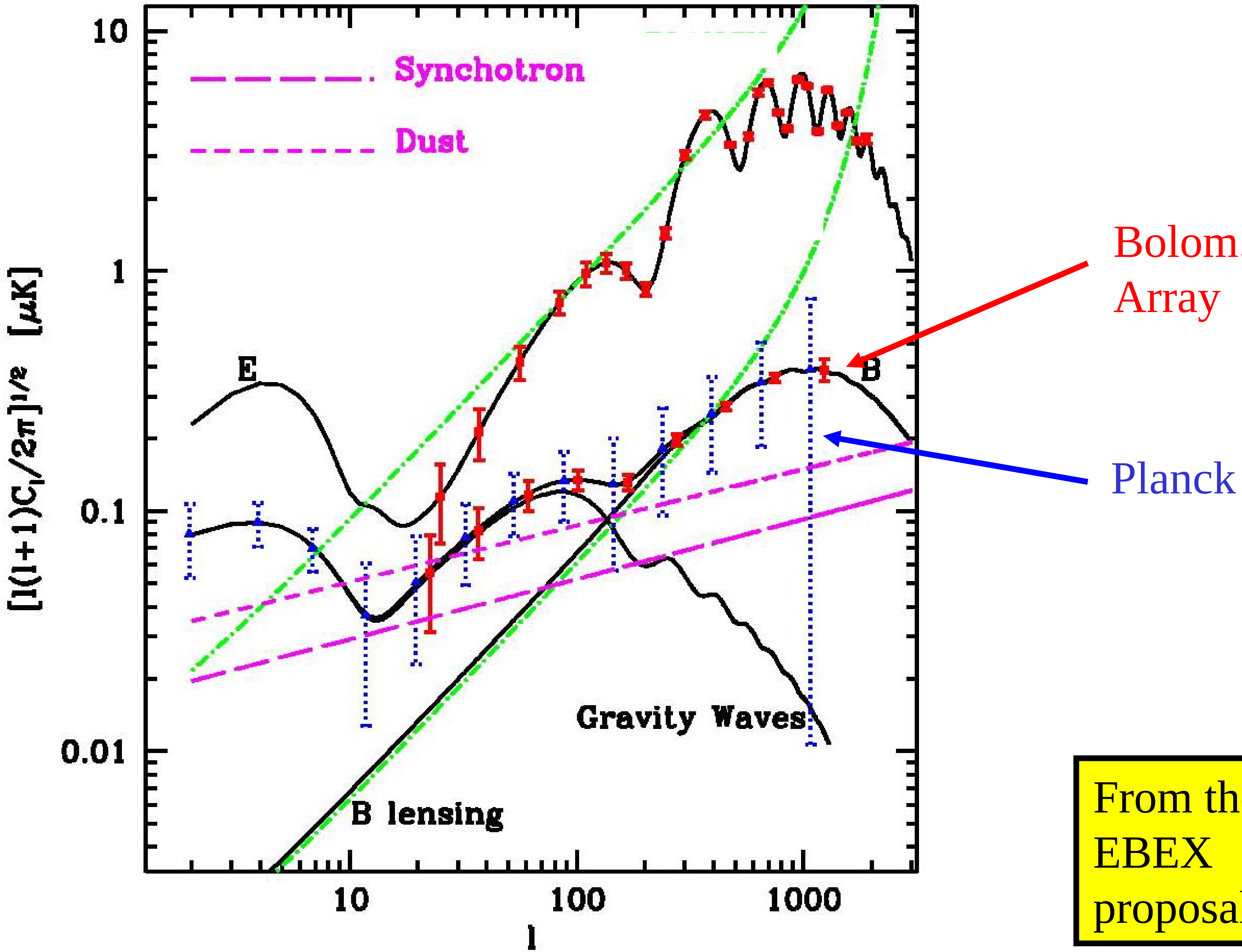
	40 GHz	90 GHz	145 GHz	220 GHz
Bandwidth [GHz]	10	33	32	40
# Detectors	64	768	512	512
Beam FWHM [arcmin]	145	60	40	26
NET_cmb [uKrt(s)]	16.3	3.8	3.5	6.6

Large Bolometer Arrays

- >1000 TES bolometers for the EBEX CMB polarization balloon telescope (Shaul Hanany, Minneapolis)







From the EBEX proposal

Control of Systematic Effects

- B03 has shown that systematic effects can be controlled by a combination of
  - Multifrequency capabilities
  - Scan variation
  - Polariziation angle redundancy
  - Variations of observing conditions
  - Accurate pre-flight and in-flight calibration
- This was OK at the level of sensitivity of B03 (i.e. 3σ detection of E-modes, 4 μK rms).
- Nobody knows how to control systematics for a B-modes experiment (<0.1 μK rms).
- The only way is to experiment !
- Calibration sources must be found and characterized.
- Balloon and Antarctica experiments are necessary to test the technique/methodology before to start the design of a B-modes space mission.

EXPERIMENTS

NAME	ν [GHz]	N[a]	RESOLUTION [arcminutes]	COMMENT
ACBAR	150	8	4.8	
	219	4	3.9	
	274	4	3.9	
BICEP	100	50	60	
	150	48	42	
CAPMAP	40	8	6	
	90	24	4	
CBI	31	13	5	Interferometer
CℓOVER.............	97	320	8	
	150	512	8	
	225	512	8	
COFE	10	10	80	Balloon
	15	20	60	
	20	30	40	
EBEX	150	796	8	Balloon
	250	398	8	
	420	282	8	
KuPID	15	6	13.8	
MBI..................	90	16	60	Interferometer
PAPPA	100	240	30	Balloon
	200	240	30	
	300	240	30	
PolarBEAR	90	400	7	
	150	400	5	
	220	400	3	
QUAD................	100	24	6	
	150	38	4	
QUIET	40	136	29	
	44	136	26	
	86	1588	14	
	95	1588	12	
	40	44	10	
	44	44	9	
	86	596	5	
	95	596	4	
Spider	45	64	145	Balloon
	75	256	69.1	
	85	256	60.4	
	108	256	52.4	
	144	512	36.0	
	162	512	32.0	
VSA	34	14	8	Interferometer
ACT	145	1024	1.7	SZ
	225	1024	1.1	
	265	1024	0.9	
APEX-SZ	150	324	1.0	SZ
SPT..................	90	320	1.7	SZ
	150	320	1.0	
	220	320	0.7	
SZA	30	8	0.5	SZ Interferometer
	90	8	0.5	

[a] N is number of detectors or number of interferometer elements.

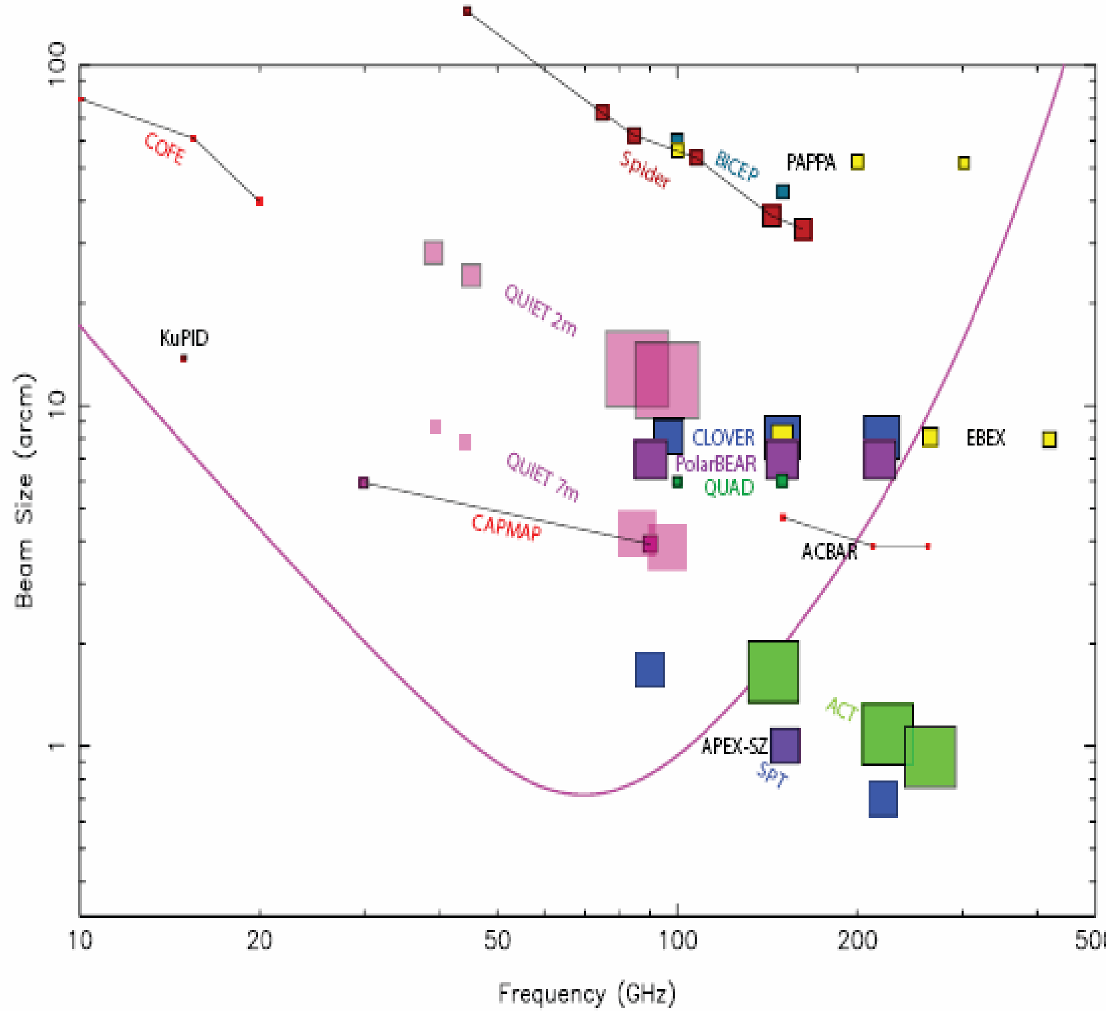
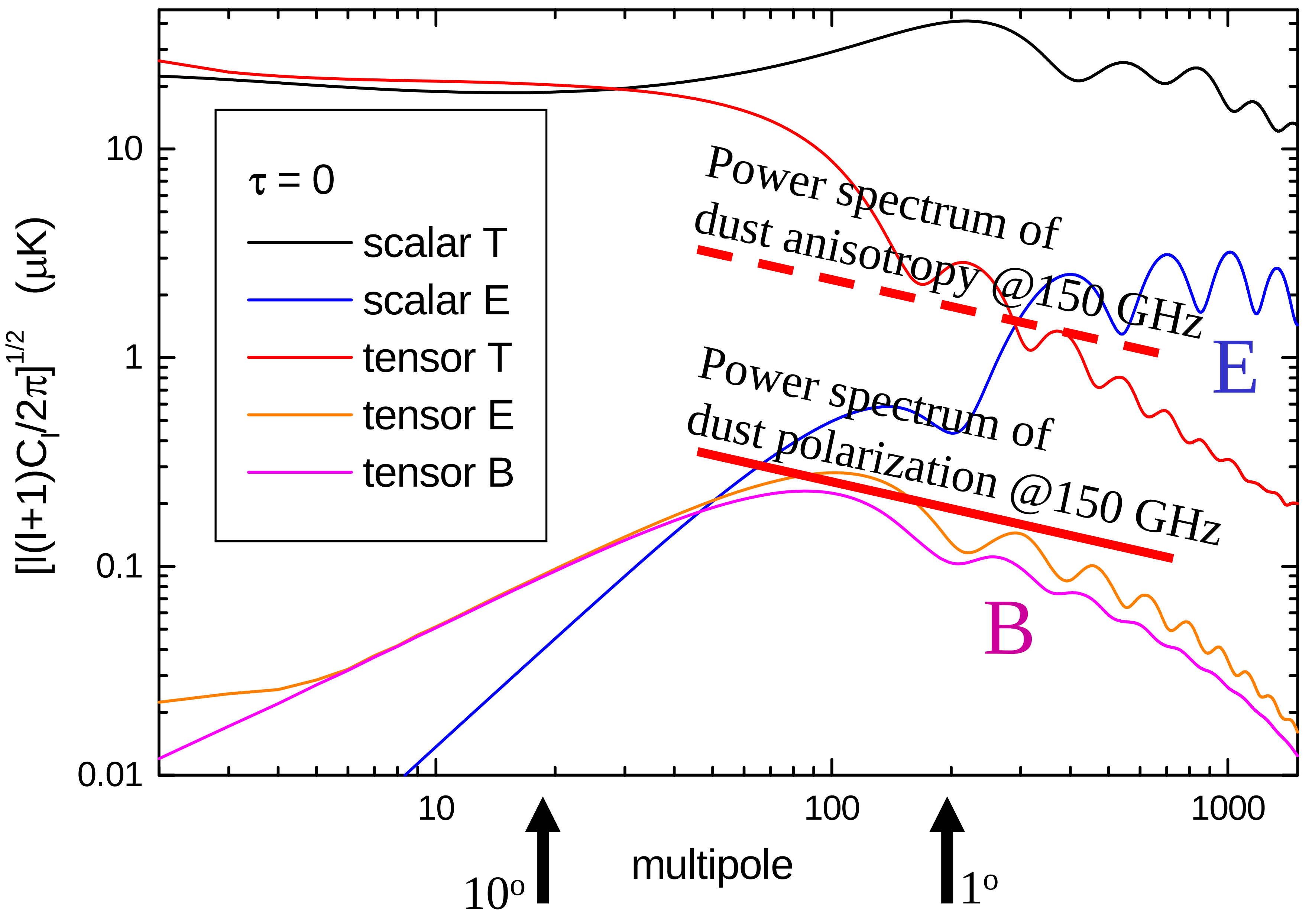


Figure 3: A sampling of suborbital experiments underway or planned. The area of the square is proportional to the number of detectors × integration time, where time = 1 year for ground experiments, and 20 days × 5 for balloon experiments. The factor of 5 for balloon experiments accounts roughly for the sensitivity advantage of bolometers above the atmosphere. No additional adjustments for sensitivity have been attempted, nor has any account been taken of planned sky coverage, etc. All frequency bands of the same experiment

From
C. Lawrence, PoS (CMB2006) 012

Control of Foregrounds

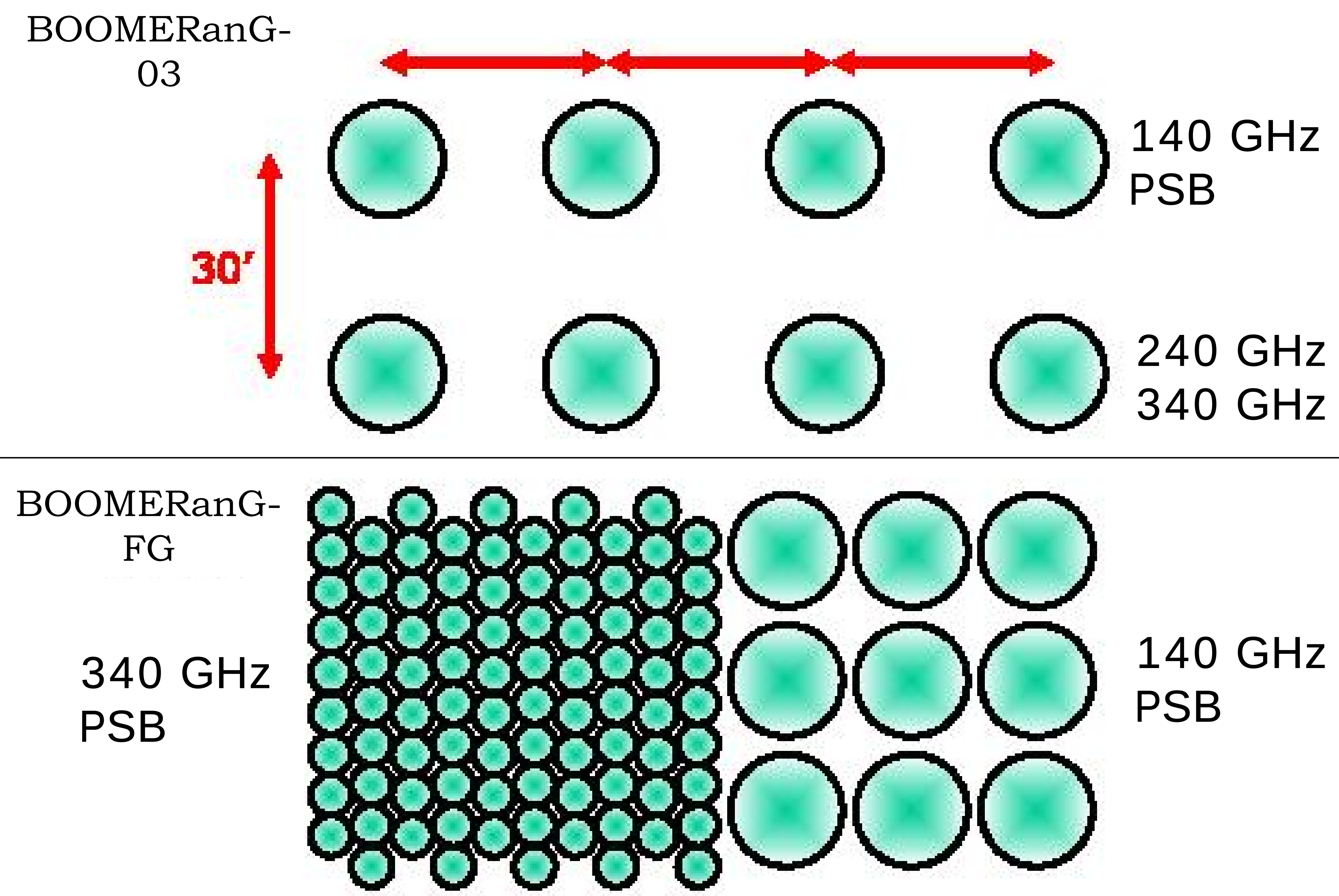
- Diffuse Dust emission is polarized at 10% in the plane of the Galaxy. See **astro-ph/0306222** "First Detection of Polarization of the Submillimetre Diffuse Galactic Dust Emission by Archeops".
- Its polarization will have both E-modes and B-modes.
- We know that **at 150 GHz** at high latitudes the PS of dust emission is about 1% of the PS of CMB anisotropy (Masi et al. **Ap.J. 553,** L93-L96, 2001)
- So **we naively expect B-modes from dust polarization PS at a level of 10^{-4} of the anisotropy**.
- This is an important foreground for B-modes of CMB, whose level is also about 10^{-4} of anisotropy !
- These are only rough estimates. We know very little about the configuration and distribution of the magnetic fields aligning the dust grains.



τ = 0
scalar T
scalar E
tensor T
tensor E
tensor B
Power spectrum of dust anisotropy @150 GHz
Power spectrum of dust polarization @150 GHz
E
B
[l(l+1)C_l/2π]^{1/2} (μK)
10
1
0.1
0.01
10
100
1000
multipole
10°
1°

BOOMERanG-FG

- We plan to re-fly B03 with an upgraded forcal plane, to go after foreground cirrus dust polarization.
- This information is **essential** for all the planned B-modes experiments (e.g. BICEP, Dome-C etc.) and is very difficult to measure from ground.
- The BOOMERanG optics can host an array of >100 PSB at >350 GHz.



Frequency range complementary to PILOT
(higher f. J.F. Bernard, Toulouse)

A post-Planck mission

- A post-Planck mission, with a large array of sensitive polarized detectors, is needed to detect B-modes **and** constrain inflationary parameters (energy scale, r, n_T, $V(\phi)$ ...)
  - NASA – Beyond Einstein : Inflation Probe
  - ESA - Cosmic Vision : Full Sky Polarization Mapper
  - ASI : B-POL
  - CNES : SAMPAN

ESA COSMIC VISION CALL ISSUED YESTERDAY

- Meanwhile, laboratory, ground-based, and balloon-borne experiments are necessary develop the needed technology

We have an image of the early universe,
new intriguing questions,
and key observations to carry out