BOOMERANG
and CMB polarization

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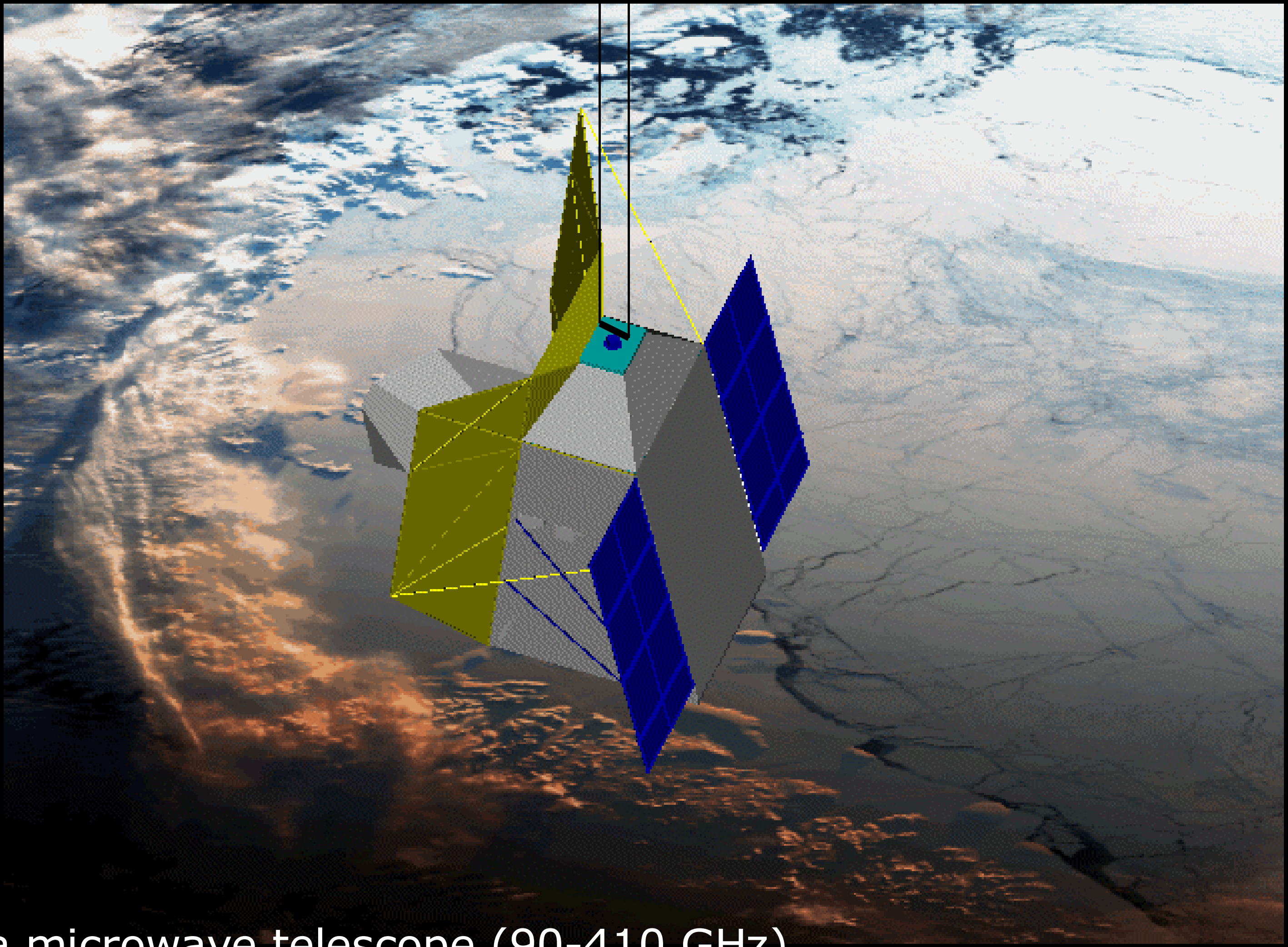
BOOMERanG-03

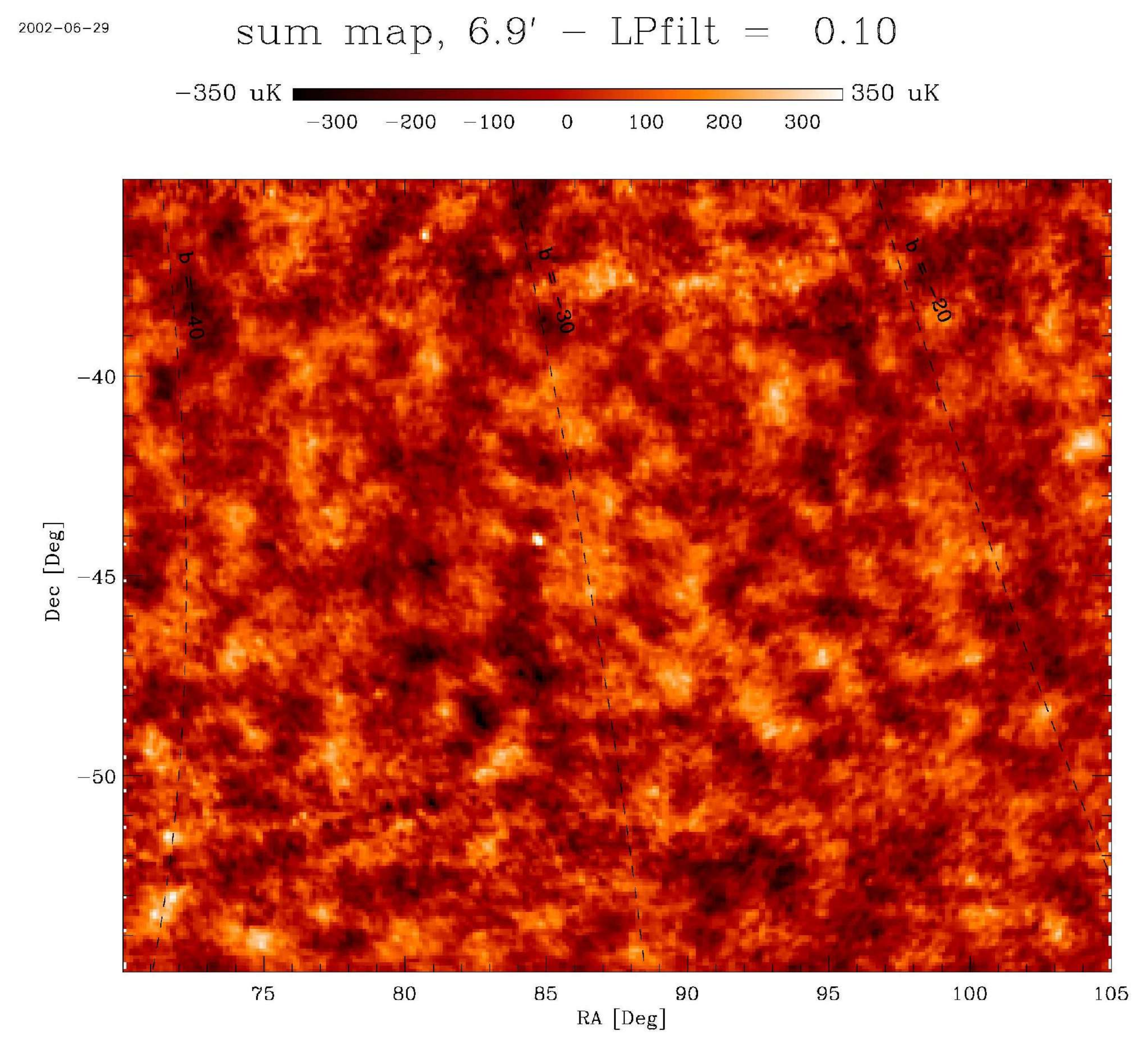
BOOMERanG



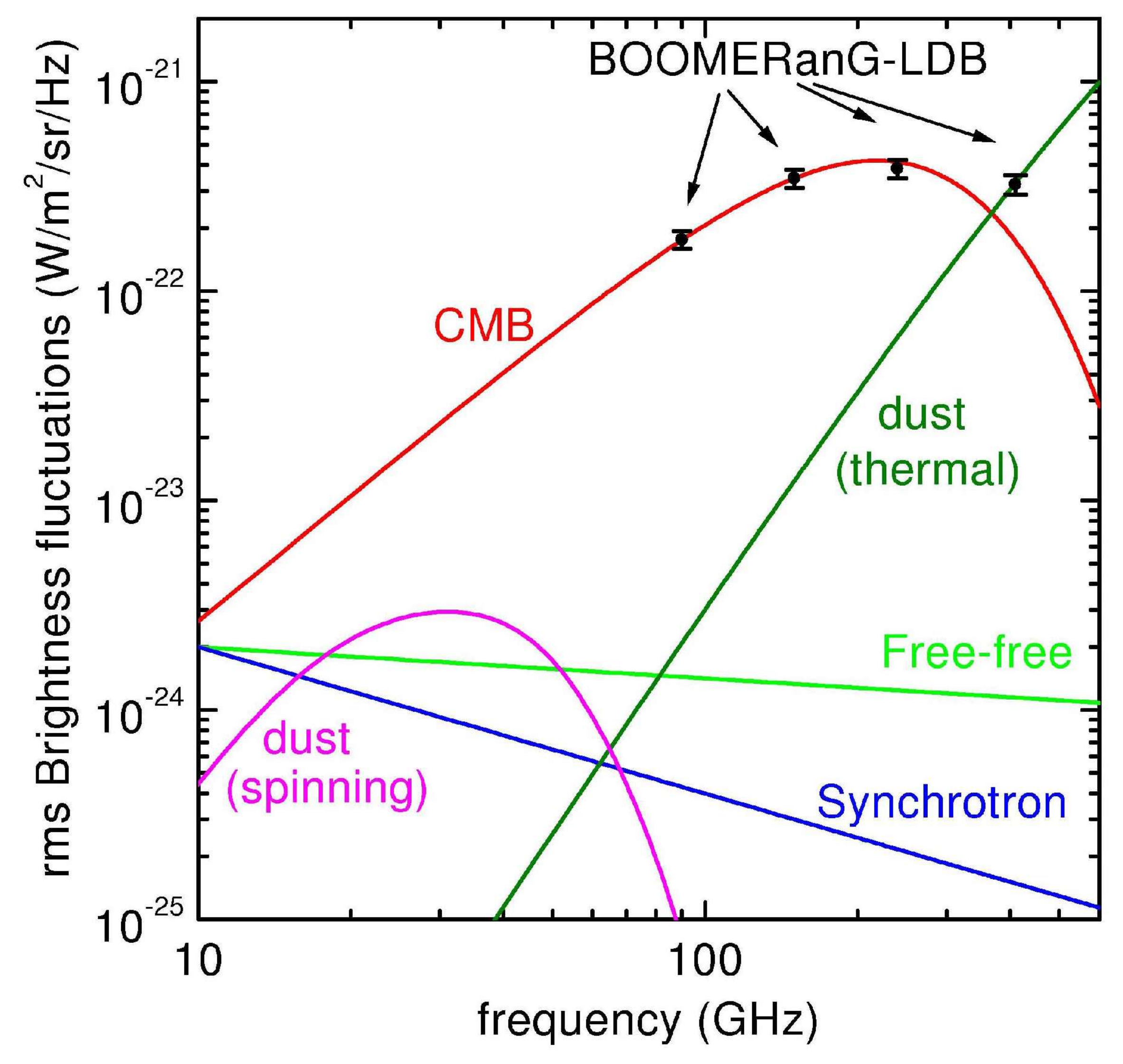
- Is a microwave telescope (90-410 GHz)
- with sensitive bolometric receivers (10′ resolution)
- scanning the sky from the Antarctic stratosphere.

BOOMERanG

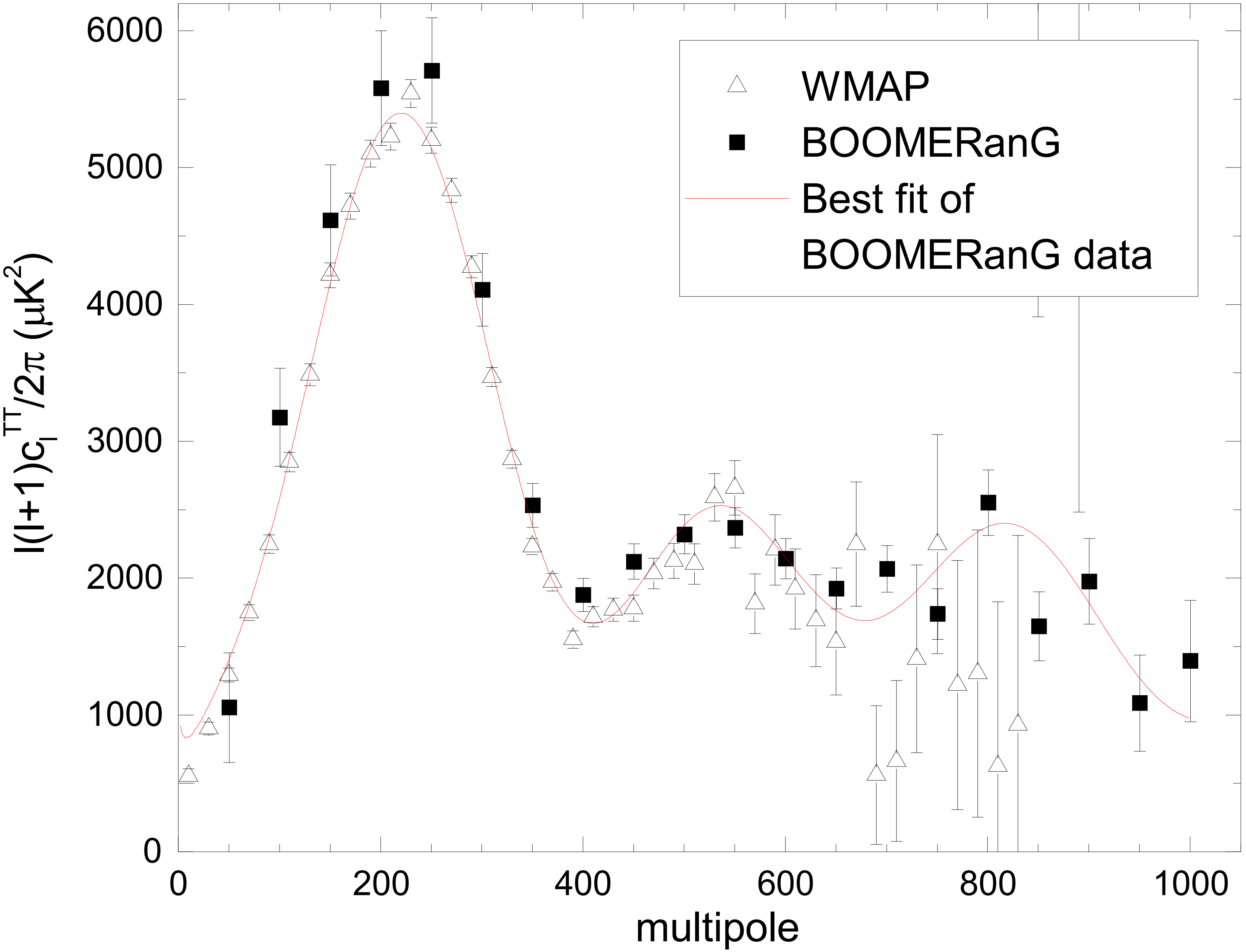
- Measures the temperature of the primordial (380 000 years) universe
- First flight (B98): BOOMERanG mapped the temperature fluctuations of the CMB at 150 GHz at sub-horizon scales (<1°).



- The rms signal has the CMB derivative spectrum and does not fit any spectrum of foreground emission.
- Foreground Contamination is less than 1% of the CMB PS at 145 GHz.



Statistical information: angular power spectrum



Cosmological Parameters

Compare with same weak prior on 0.5<h<0.9

BOOMERanG 98

Ruhl et al. astro-ph/0212229

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

WMAP 1

Bennett et al. astro-ph/0302208

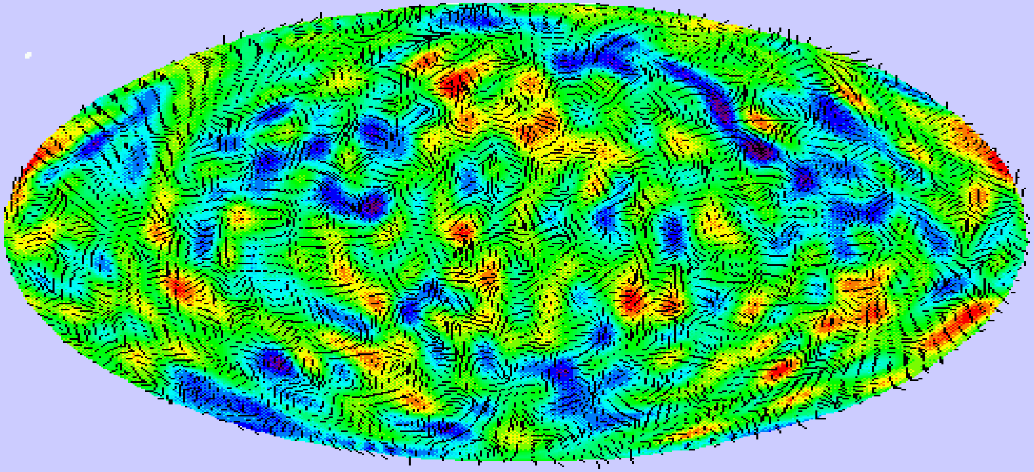
- $\Omega = 1.02 \pm 0.02$
- $n_s = 0.99 \pm 0.04$ *
- $\Omega_b h^2 = 0.022 \pm 0.001$
- $\Omega_m h^2 = 0.14 \pm 0.02$
- $T = 13.7 \pm 0.2$ Gyr
- $\tau_{rec} = 0.166 \pm 0.076$

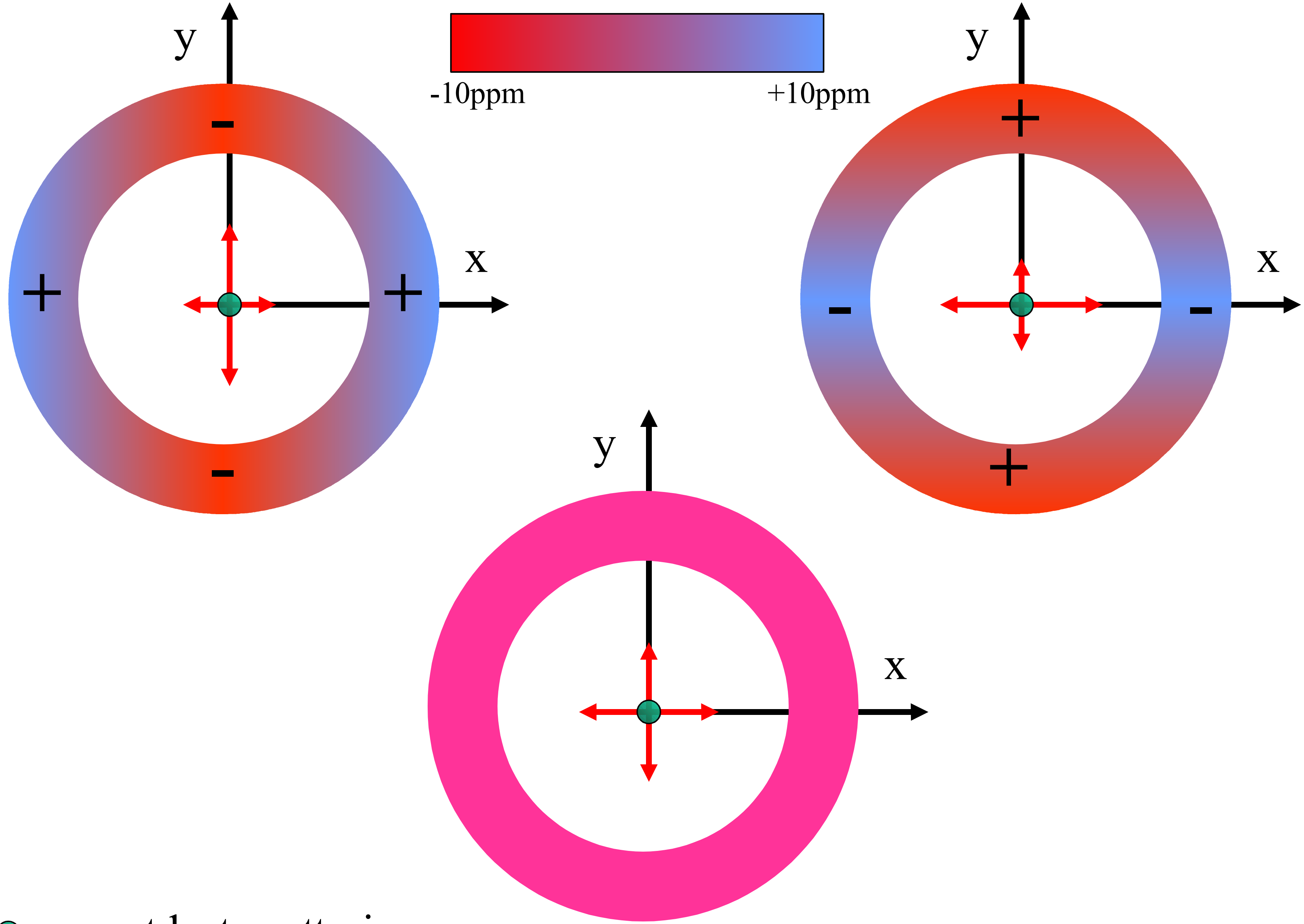
Remarkable consistency among completely independent experiments.

The parameters fit the inflationary model.

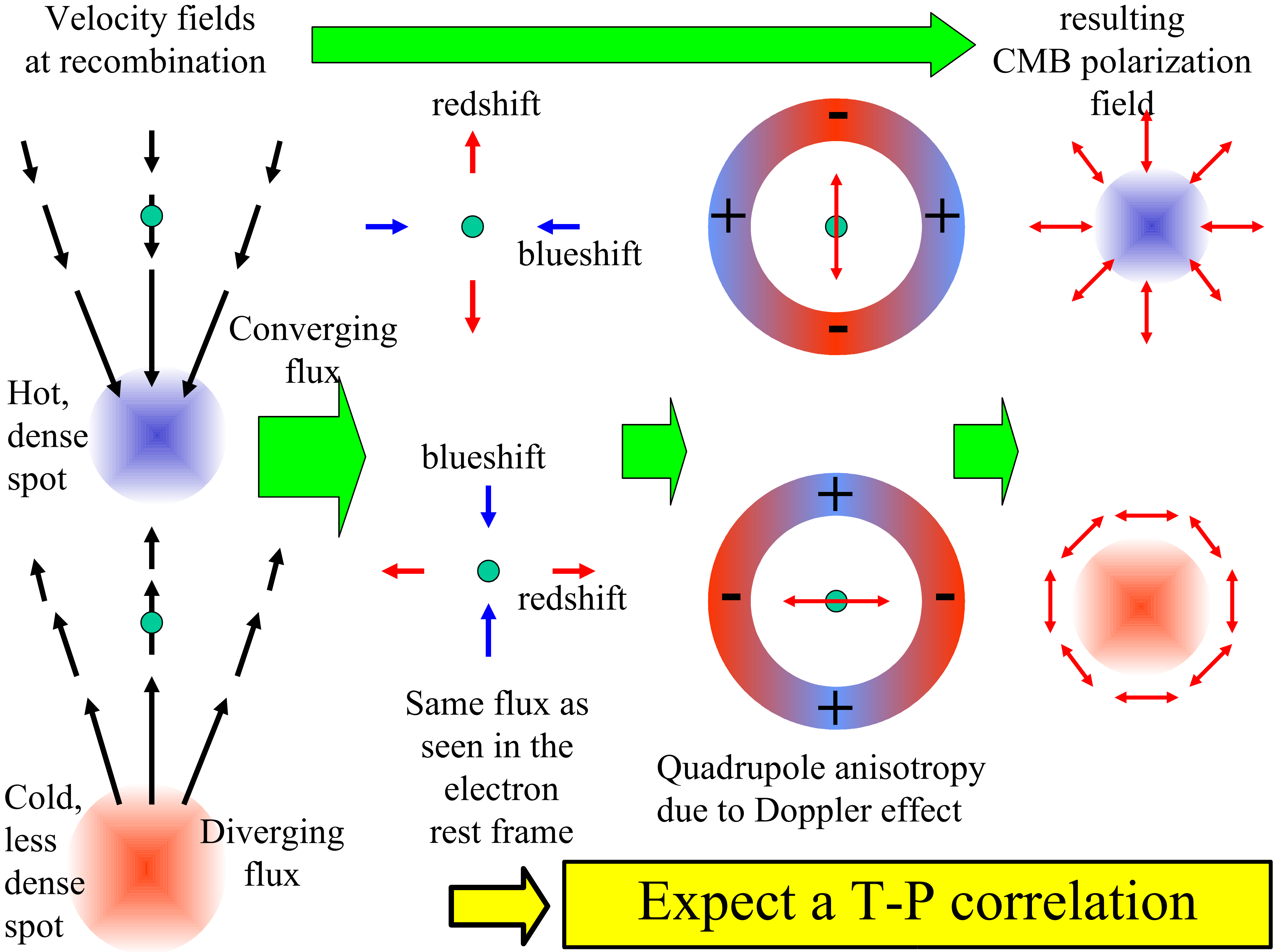
CMB polarization

- We do expect CMB polarization since CMB photons are 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
- Polarization is described by the Stokes Parameters (I,Q,U,V)
- Linear polarization is described by rods in the sky (I,Q,U)





● = e^- at last scattering



Velocity fields at recombination

resulting CMB polarization field

Hot, dense spot

Converging flux

redshift

blueshift

Cold, less dense spot

Diverging flux

blueshift

redshift

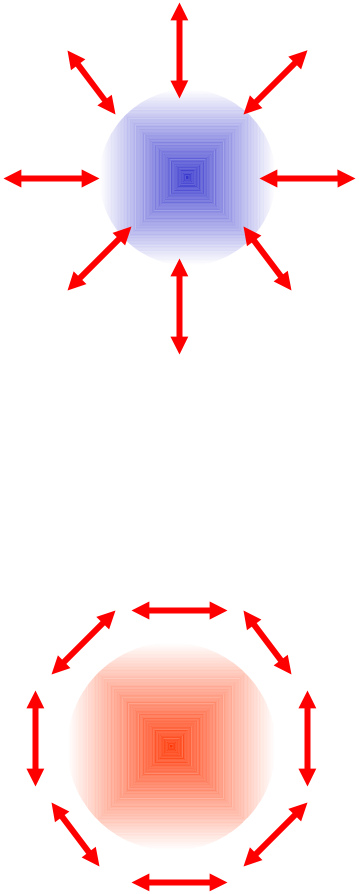
Same flux as seen in the electron rest frame

Quadrupole anisotropy due to Doppler effect

Expect a T-P correlation

- Velocity and density fields can only generate polarization patterns symmetric under coordinate inversion (positive parity): E-modes

- From the cosmological parameters is possible to predict the angular power spectrum of the E-modes



Interest of detecting E-modes:

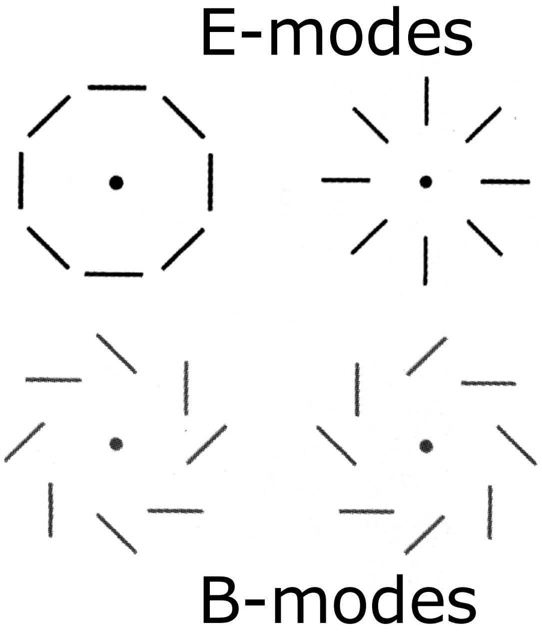
- In all the cosmological parameters analysis an ***adiabatic* type of fluctuations** is assumed (because simple and predicted by the simplest inflation models)
- If **other types of fluctuations** are considered (for example iso-curvature ones) the determination of cosmological parameters becomes much less precise.
- Precision can be recovered by studying independent observables, like the **polarization** of the CMB.

Interest of detecting E-modes:

- The universe gets reionized when the first stars form.
- The **polarization** of the CMB at **large angular scales** is heavily affected by reionization.
- It is a way to measure the redshift of reionization, between z=5 and 20, complementary to work based on the Gunn-Peterson effect (see e.g. Becker et al. (2001) and Djorgovski et al. (2001).)

B-modes polarization

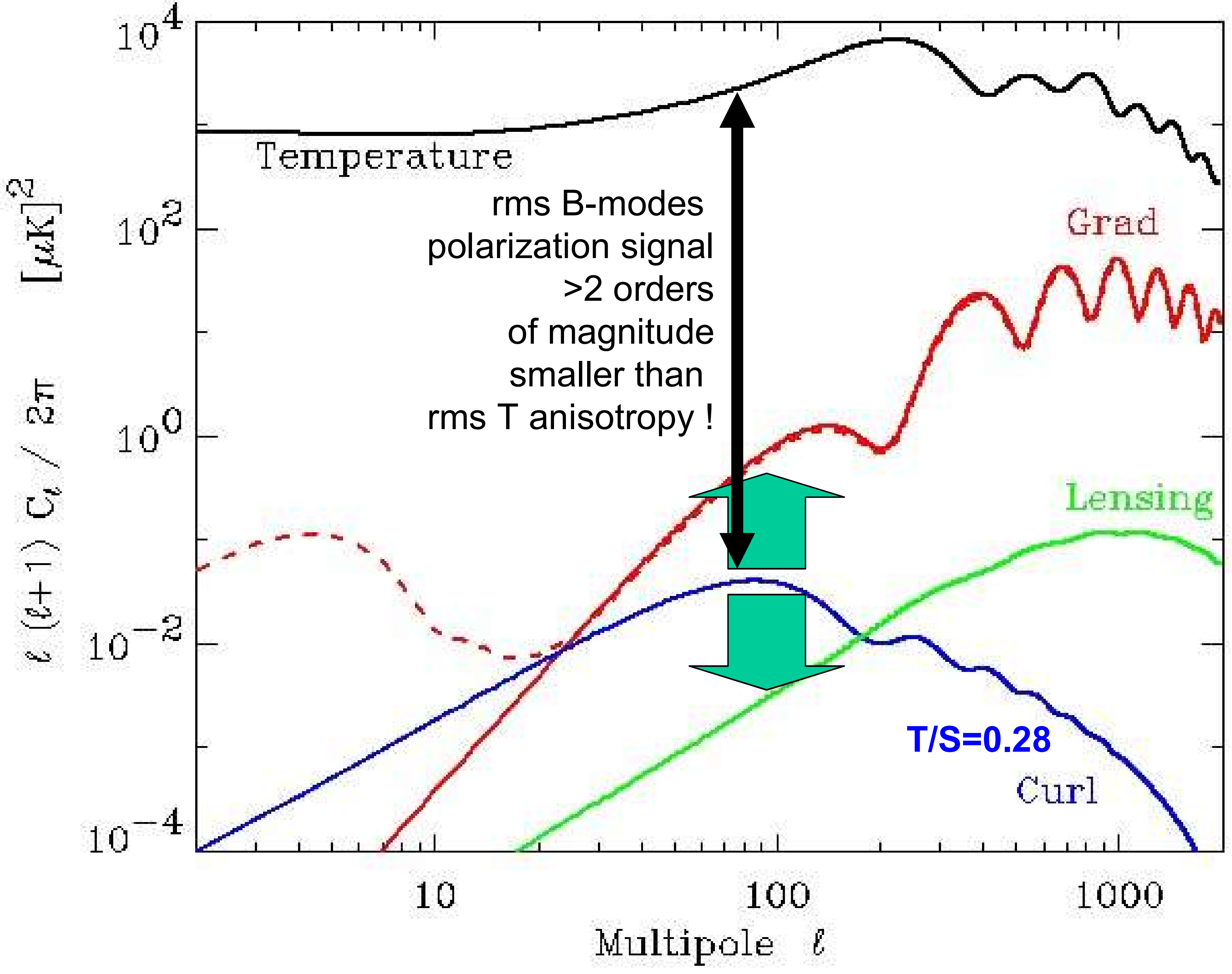
- If inflation really happened:
  - ✓ It stretched geometry of space to nearly Euclidean
  - ✓ It produced a nearly scale invariant spectrum of Gaussian density fluctuations
  - ✓ It produced a stochastic background of gravitational waves: Primordial G.W. The background is so faint that even LISA will not be able to measure it.
- G-W also produce quadrupole anisotropy in the plasma. They generate E-modes **and negative parity components (B-modes)** in the CMB polarization field.



Only gravitational waves can generate B-modes

CMB pol. becomes a detector of primordial gravitational waves

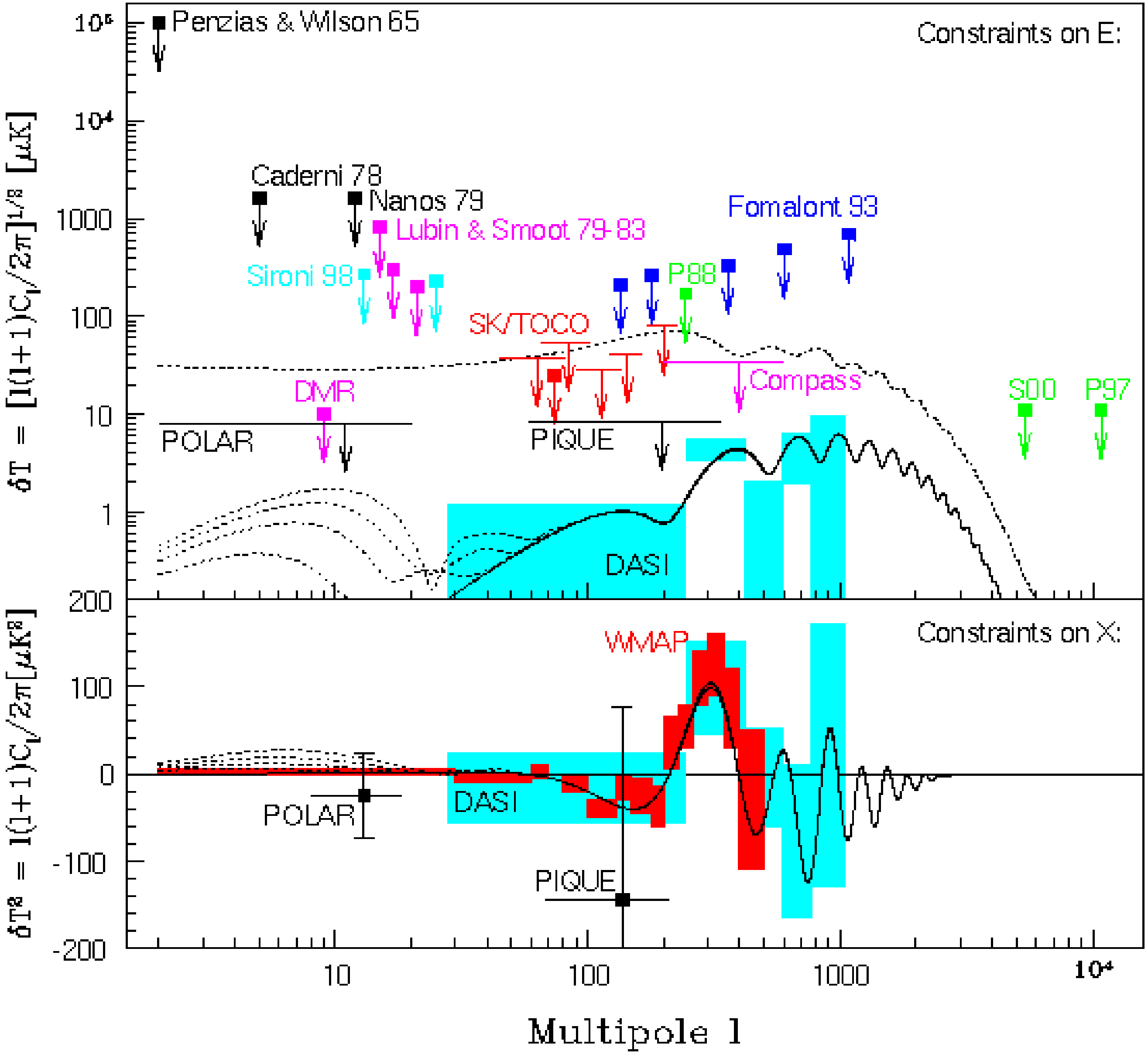
CMB pol. becomes a detector of inflationary energy



rms B-modes
polarization signal
>2 orders
of magnitude
smaller than
rms T anisotropy !

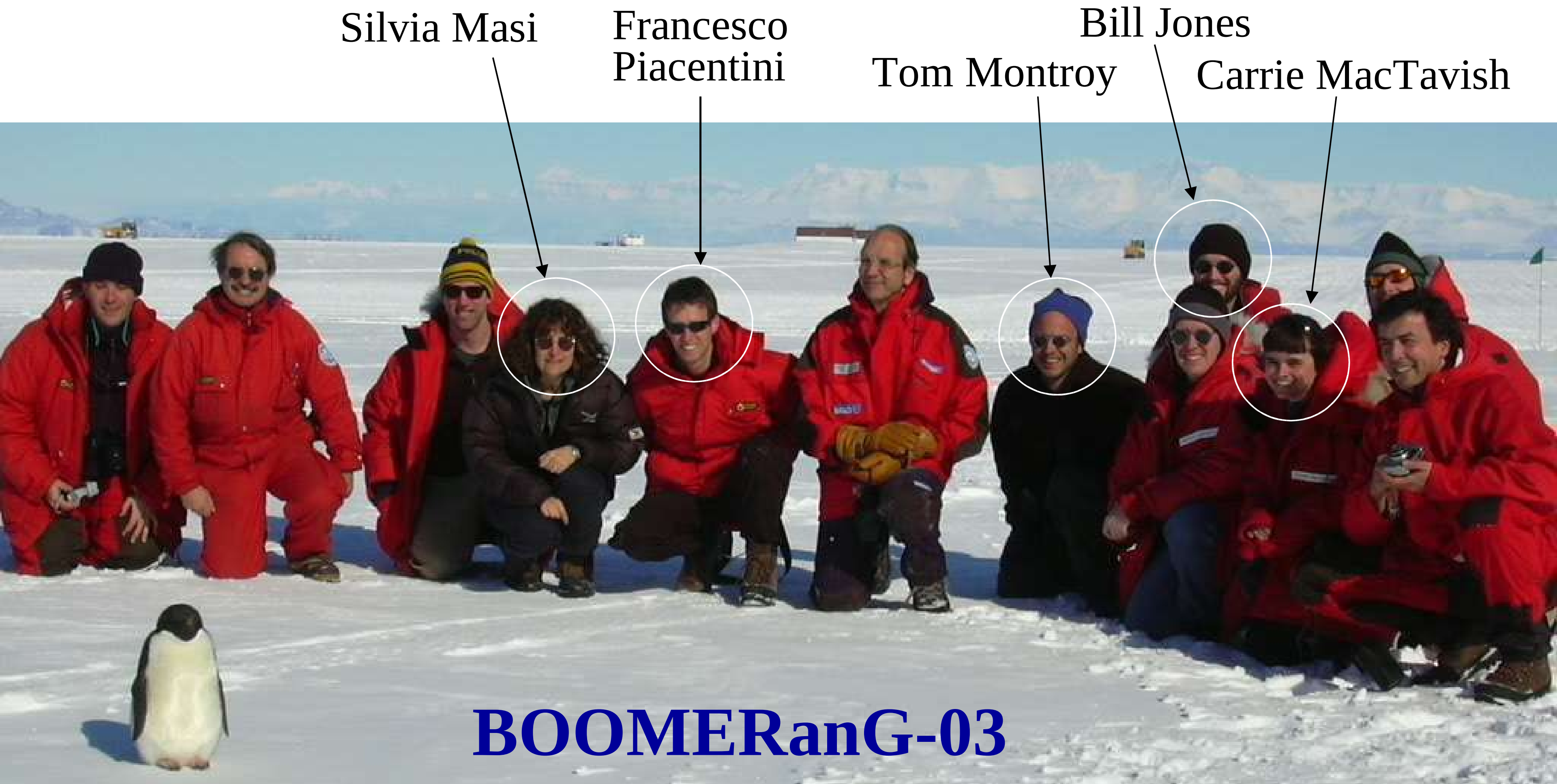
T/S=0.28

Polarization data at June 2005



First release of data: July 2005 Five papers:

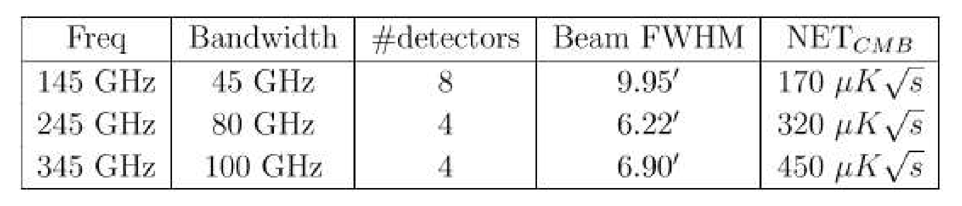
- Masi et al. astro-ph/0507509 : instrument & maps
- Jones et al. astro-ph/0507494 : <TT>
- Piacentini et al. astro-ph/0507507 : <TE>
- Montroy et al. astro-ph/0507514 : <EE>
- MacTavish et al. astro-ph/0507503 : cosmological parameters



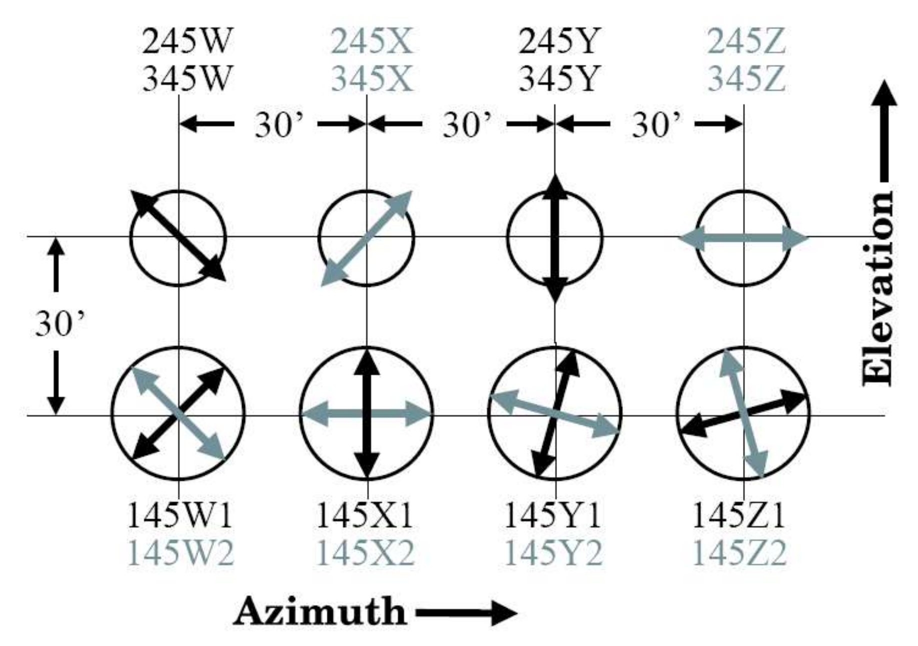
BOOMERanG-03

The Polarization-sensitive BOOMERanG: B03

- We have modified the focal plane of BOOMERanG after the anisotropy flight of 1998, to accomodate Bolometers sensitive to the Polarization.

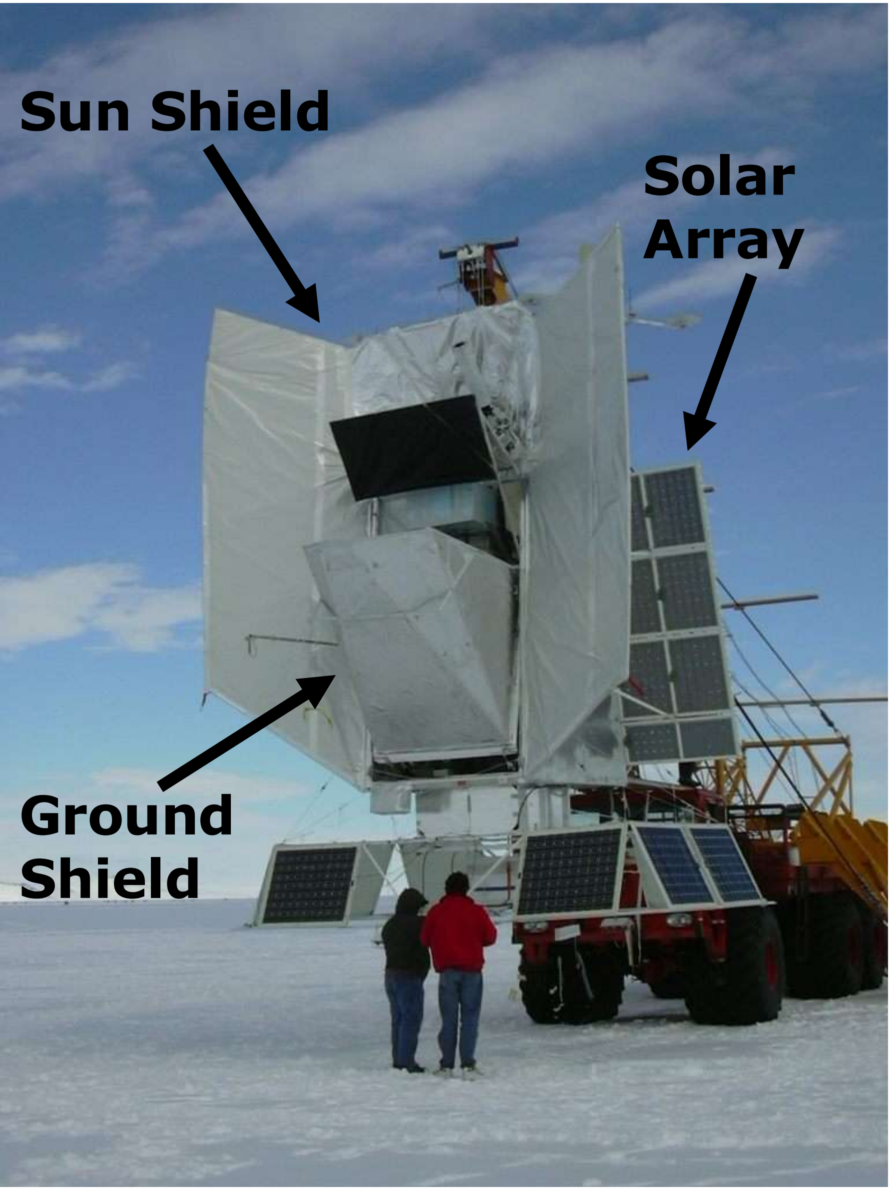


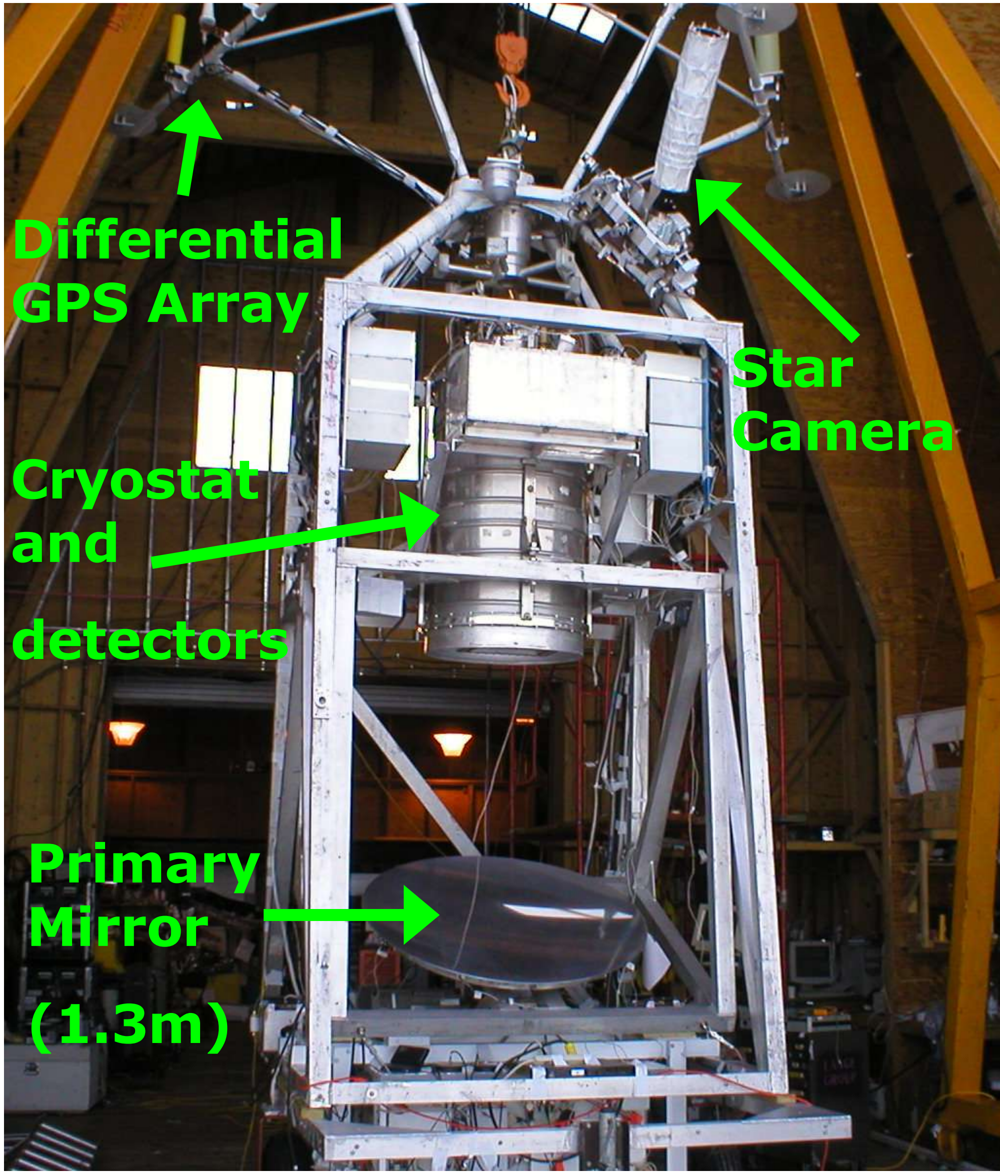
Freq	Bandwidth	#detectors	Beam FWHM	NET$_{CMB}$
145 GHz	45 GHz	8	$9.95'$	$170\ \mu K\sqrt{s}$
245 GHz	80 GHz	4	$6.22'$	$320\ \mu K\sqrt{s}$
345 GHz	100 GHz	4	$6.90'$	$450\ \mu K\sqrt{s}$



- 16 detectors
- 8 pixels in the focal plane, separated by 30'.
- 145, 245, 345 GHz bands

the BOOMERANG balloon-borne telescope

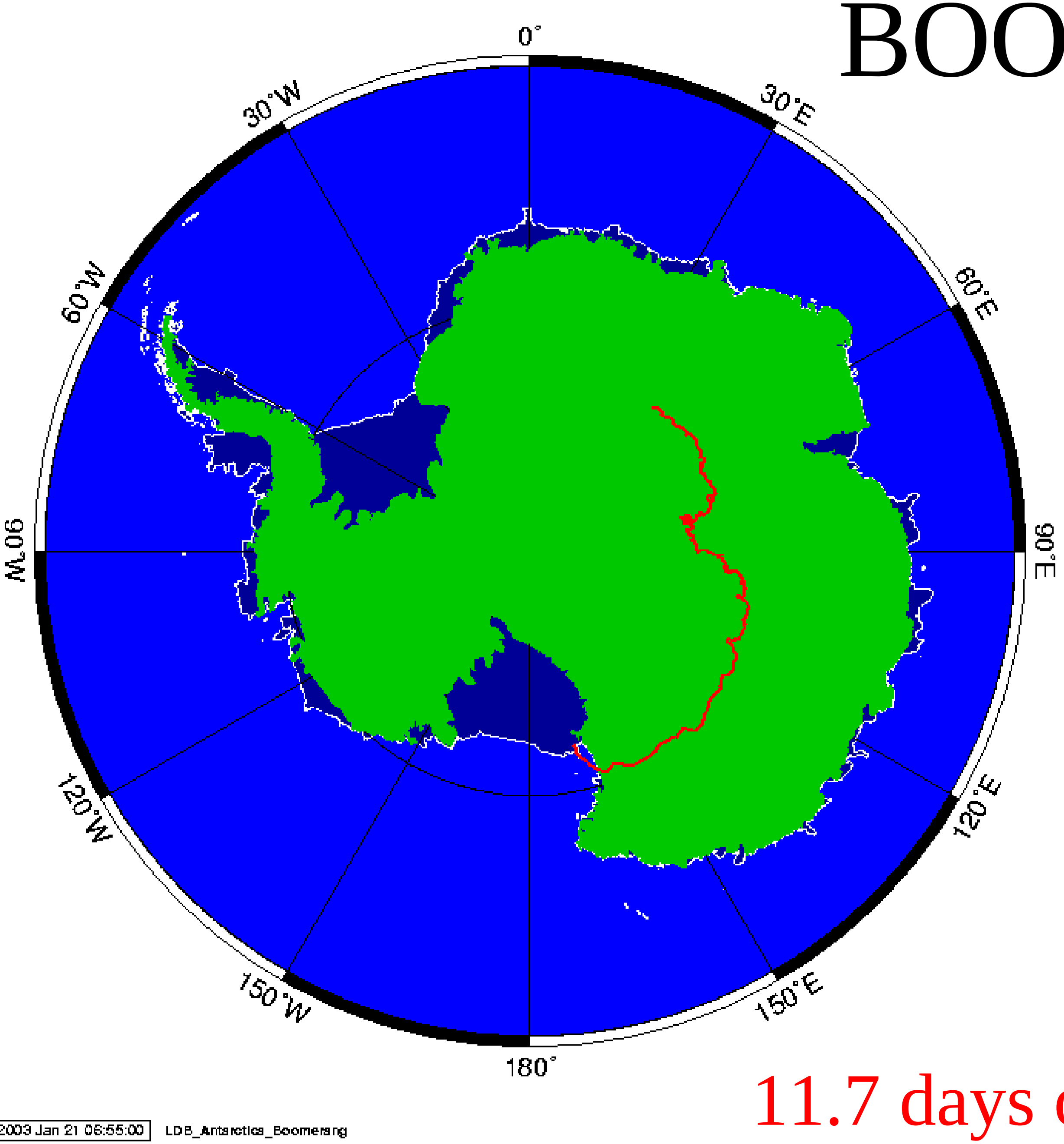




B03 Sensitive at 145, 245, 345 GHz

06/01/2003

BOOM03 Flight



Launched:

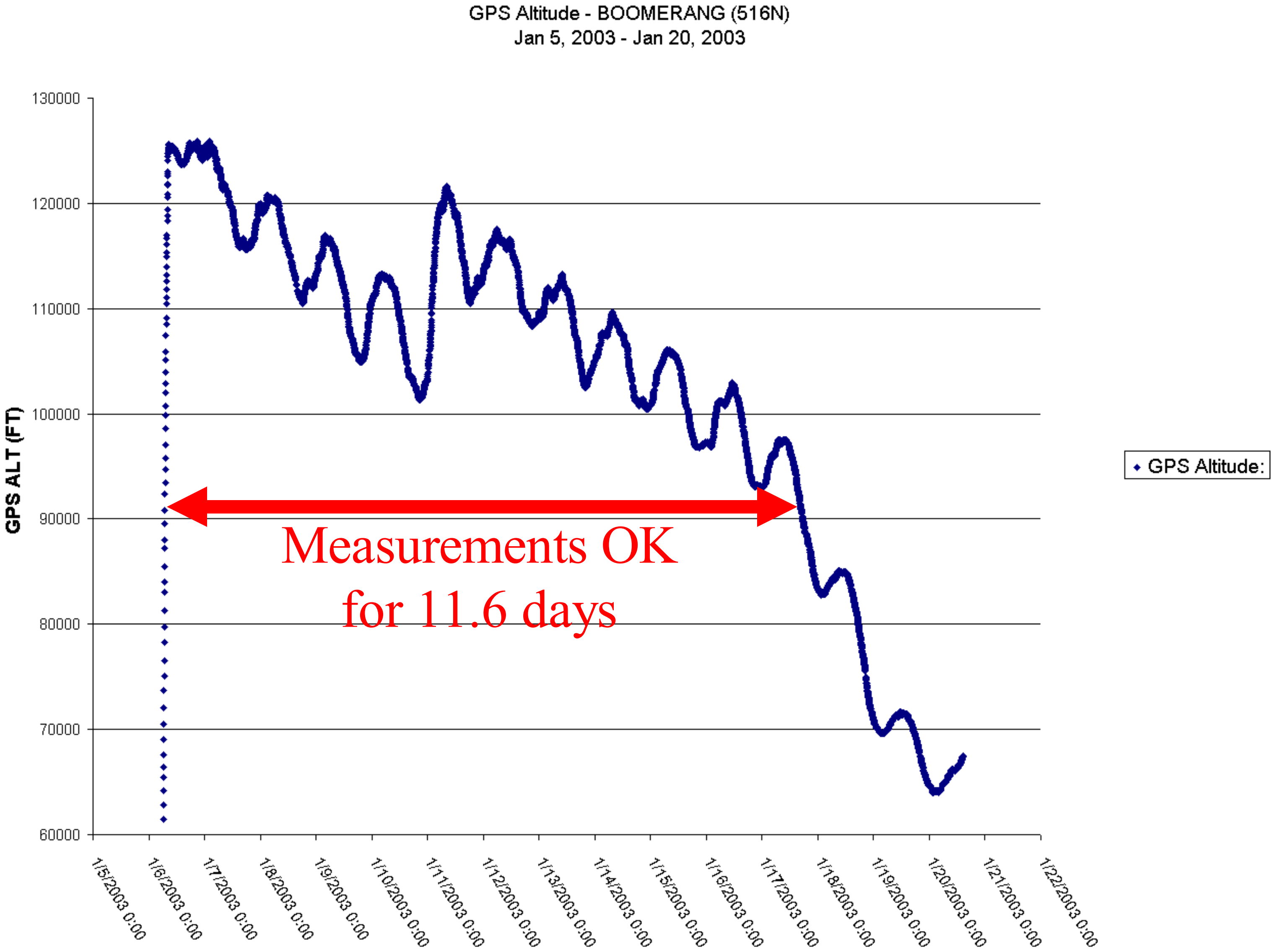
January 6, 2003

From:

McMurdo Station,

Antarctica

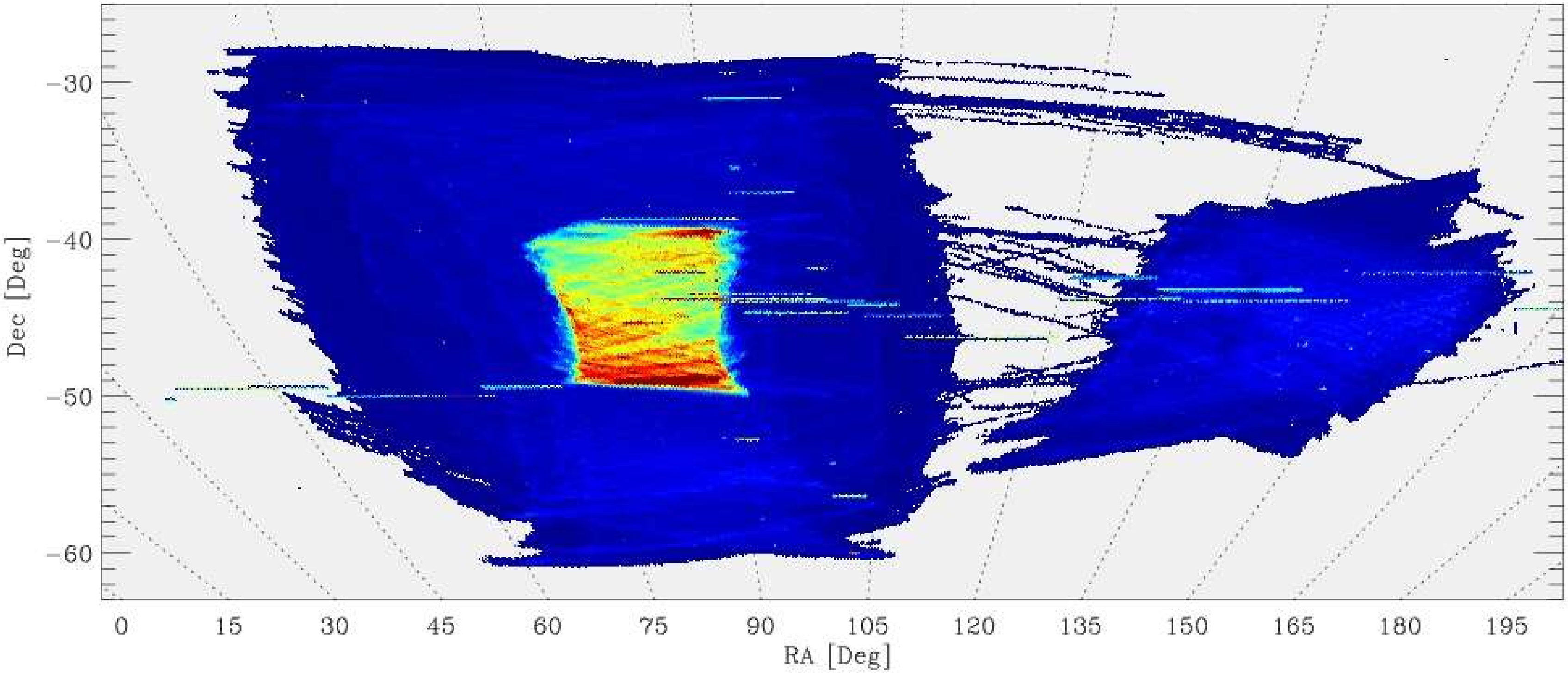
11.7 days of good data



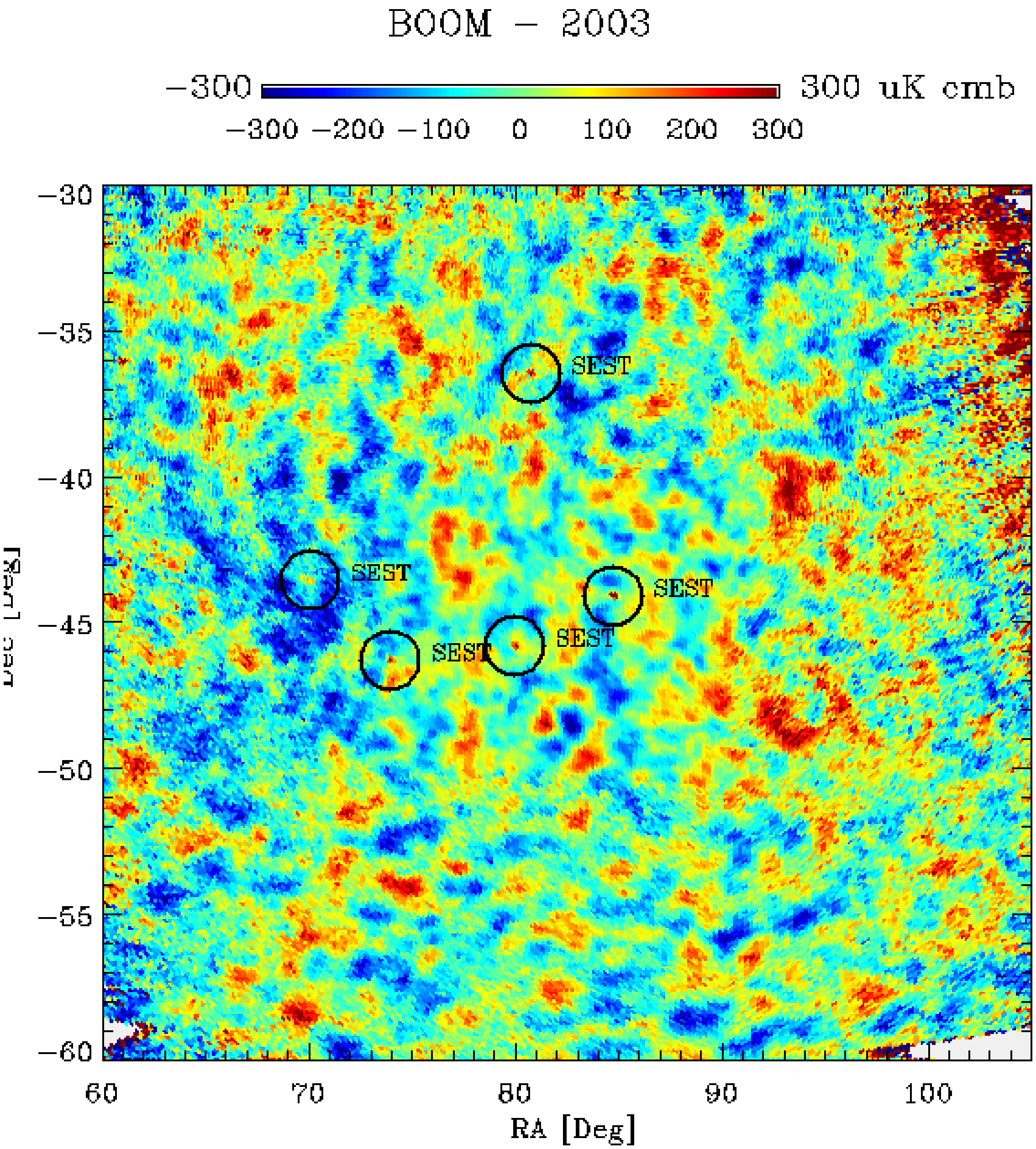
GPS Altitude - BOOMERANG (516N)
Jan 5, 2003 - Jan 20, 2003

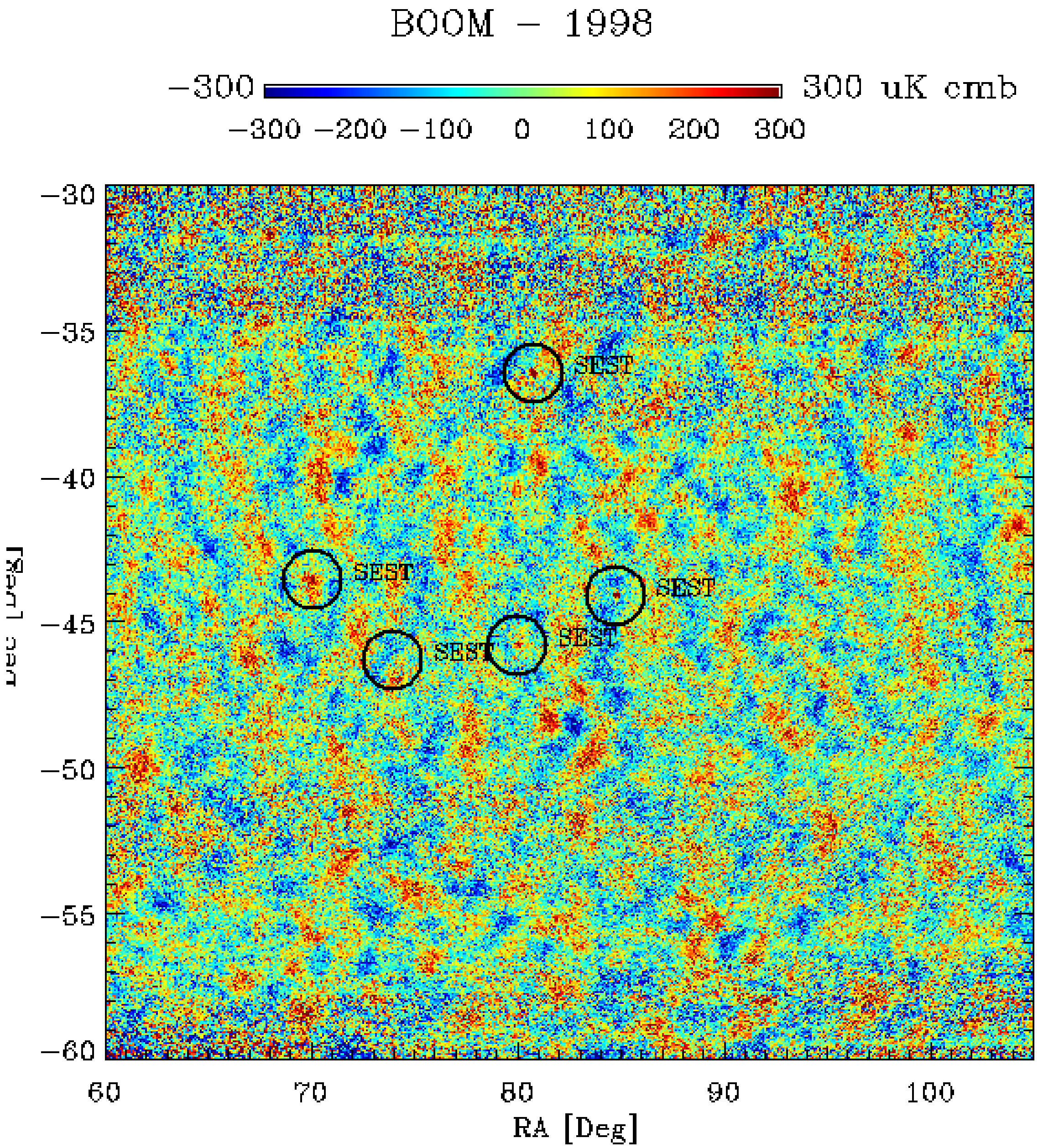
Measurements OK
for 11.6 days

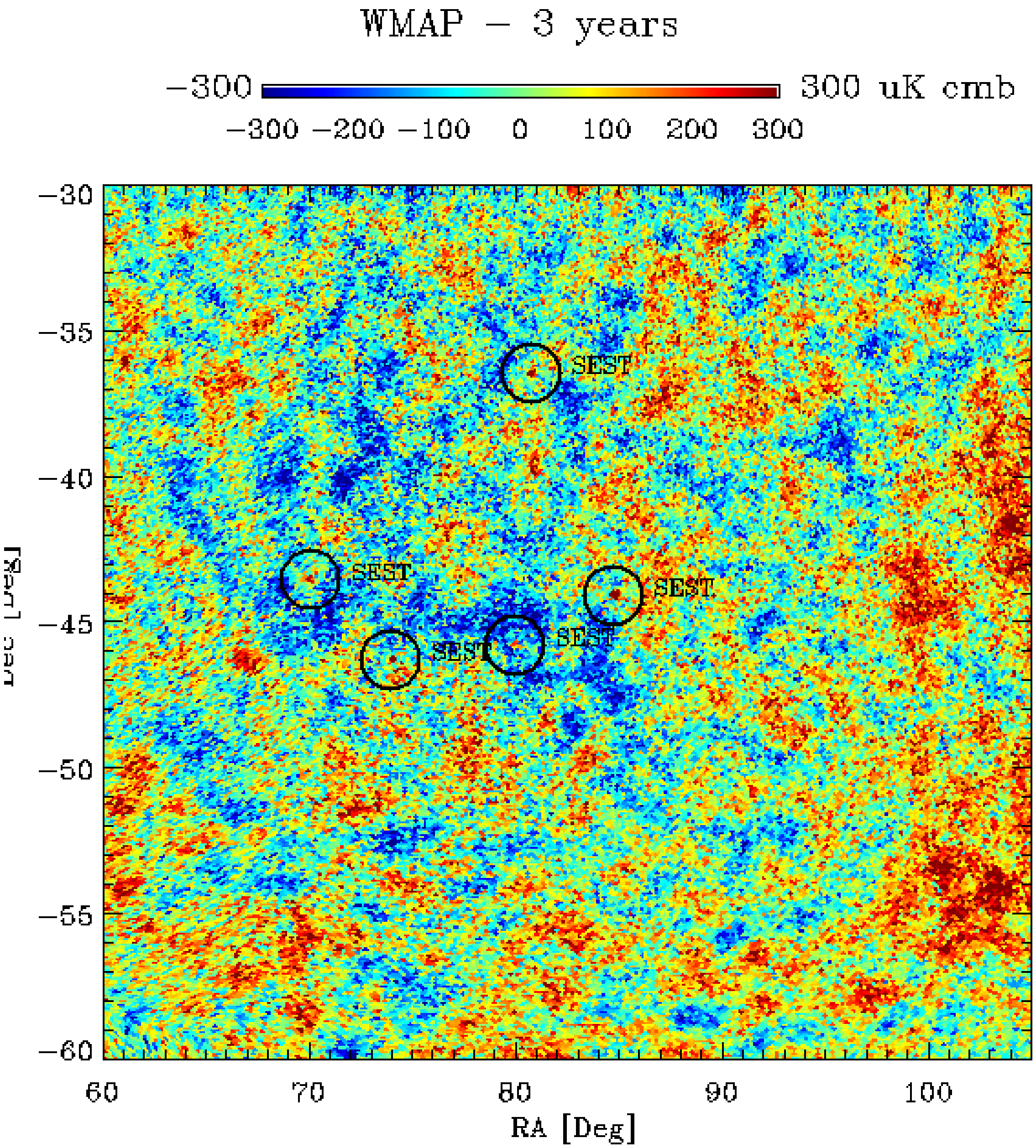
Survey Strategy



Region	Size (sq deg)	Goal	Time per 7’ pixel (for each detector)
Deep CMB	115	<EE>	60 sec
Shallow CMB	1130	<TE> and <TT>	3.3 sec
Galactic Plane	390	Polarized Foregrounds	4.7 sec


BOOM – 2003
−300
300 uK cmb
−300 −200 −100 0 100 200 300
−30
−35
−40
−45
−50
−55
−60
Dec [Deg]
60
70
80
90
100
RA [Deg]
SEST
SEST
SEST
SEST
SEST


BOOM – 1998
−300
300 uK cmb
−300 −200 −100 0 100 200 300
−30
−35
−40
−45
−50
−55
−60
Dec [Deg]
SEST
SEST
SEST
SEST
SEST
60
70
80
90
100
RA [Deg]

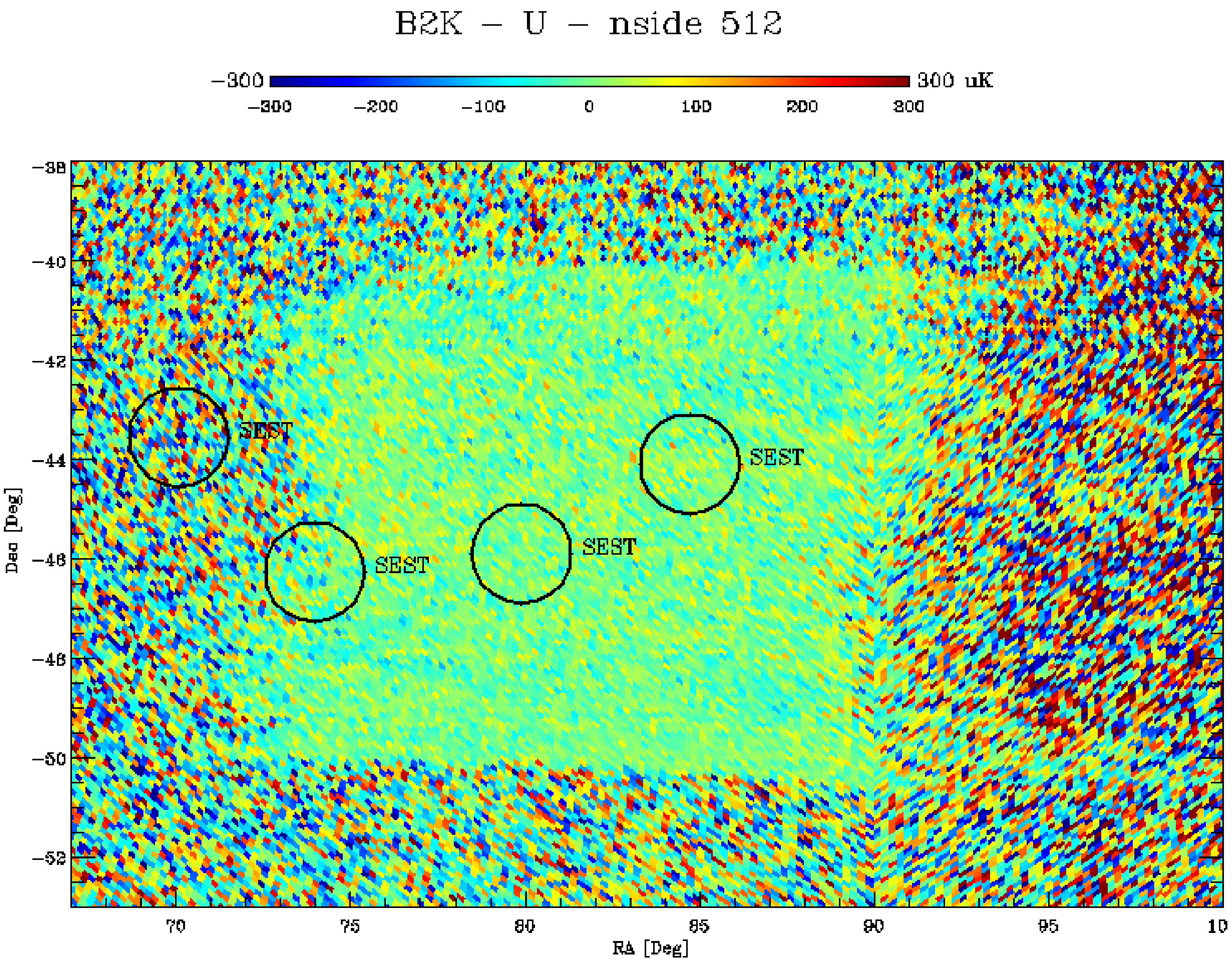
WMAP – 3 years
–300
300 uK cmb
–300 –200 –100 0 100 200 300
SEST
SEST
SEST
SEST
SEST
–30
–35
–40
–45
–50
–55
–60
Dec [Deg]
60
70
80
90
100
RA [Deg]

Remarkable agreement of 3 independent experiments.

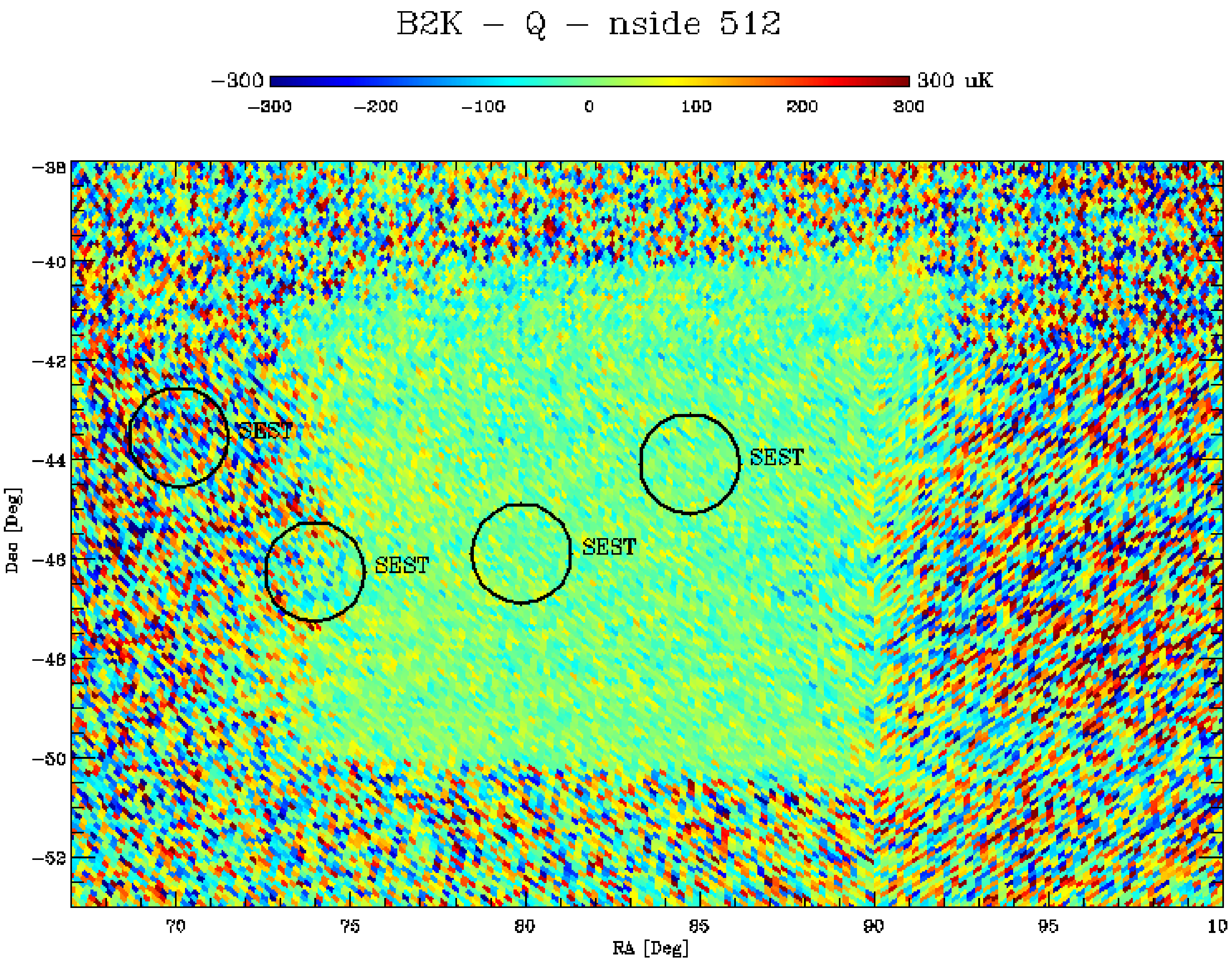
In the deep survey, B03 has improved the pixel sensitivity by a factor about 10, wrt WMAP at the same pixellization

Is this enough to see CMB polarization ? **No**

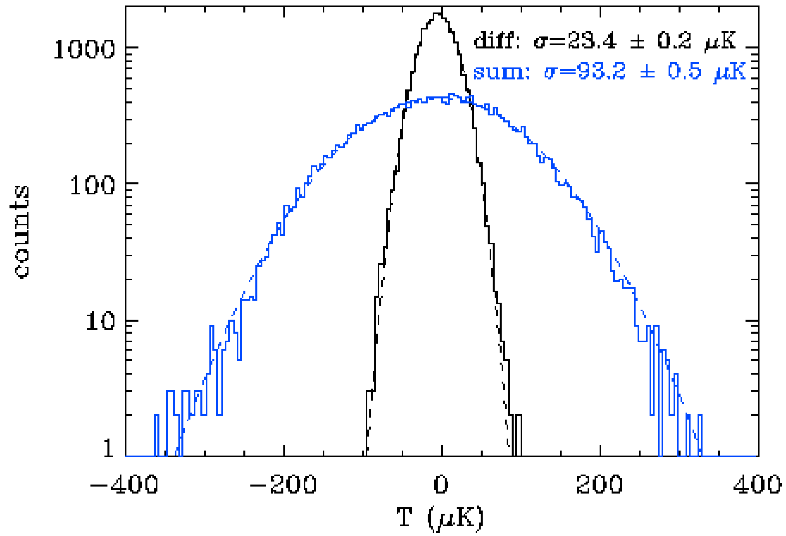
Is this enough to measure CMB polarization ? **Yes**



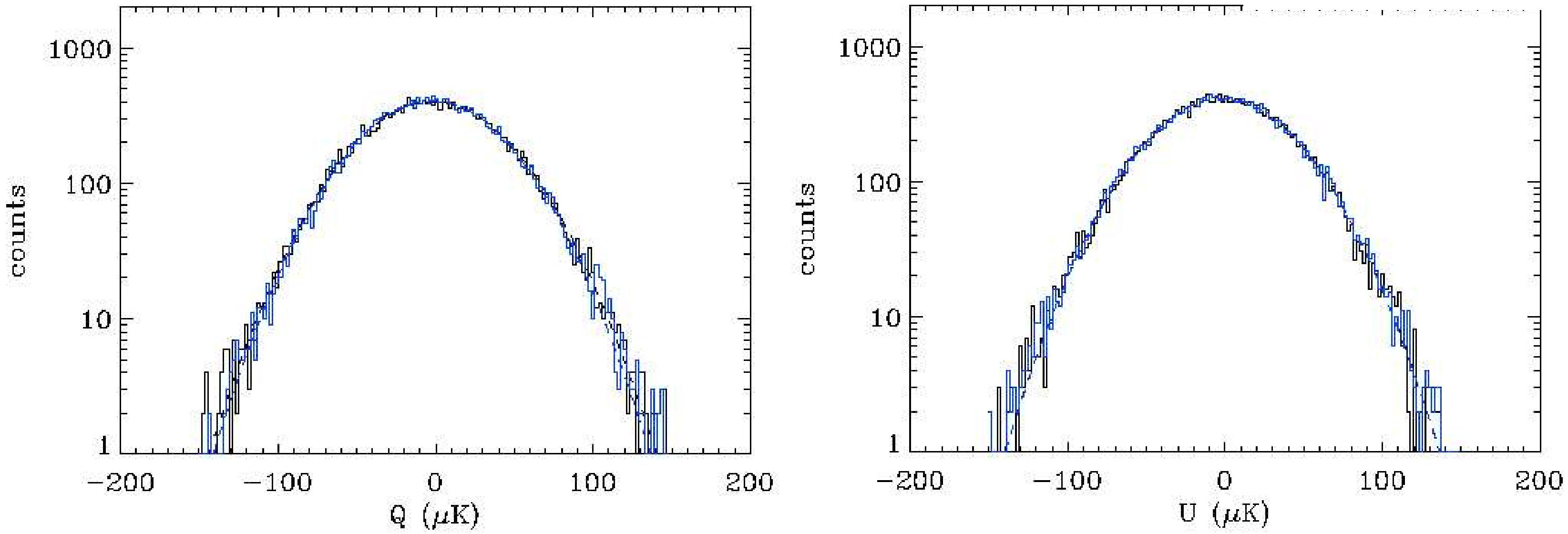
Optimal maps obtained with IGLS, the Rome pipeline (Natoli et al. 2001)



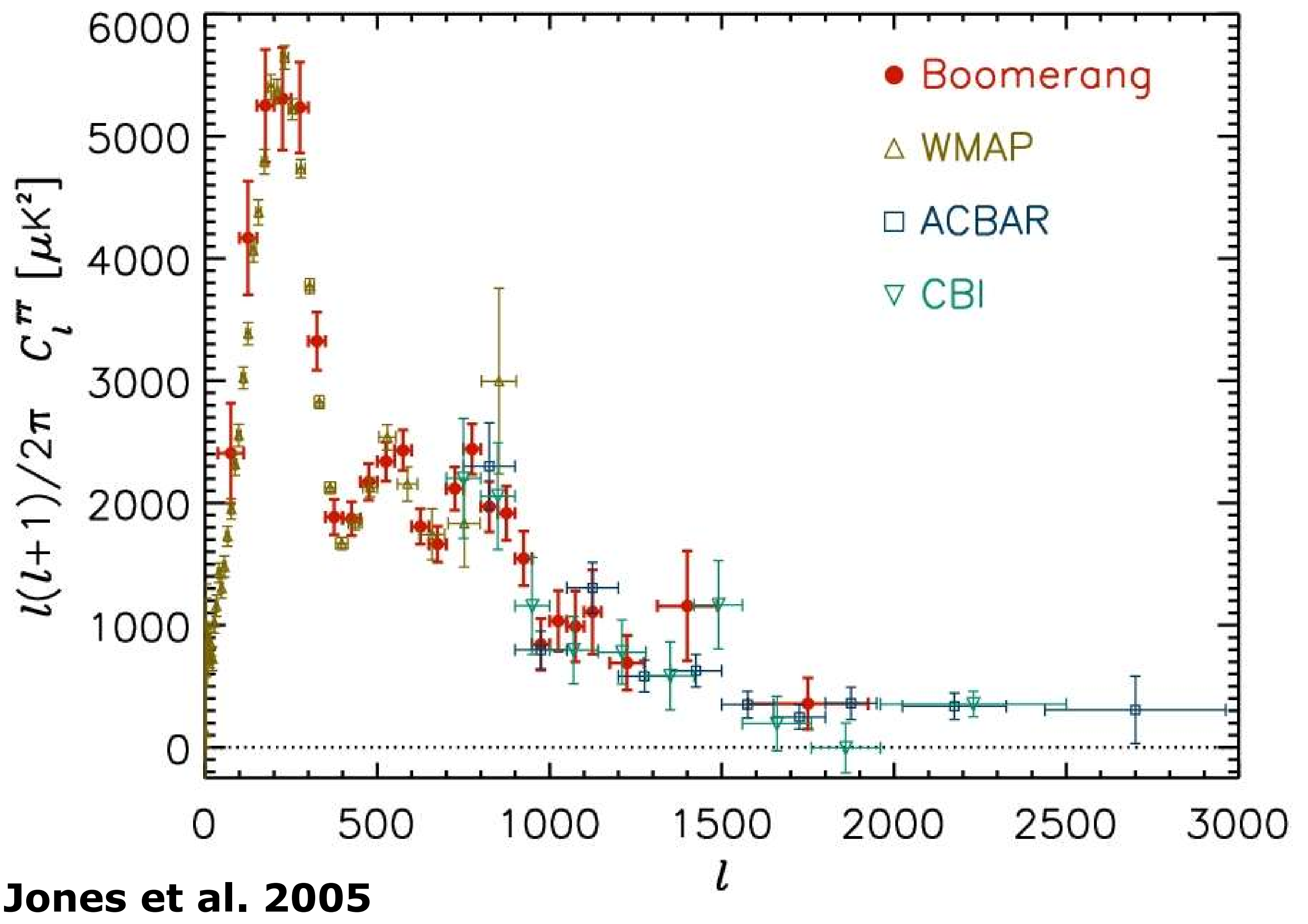
Optimal maps obtained with IGLS, the Rome pipeline (Natoli et al. 2001)



Masi et al. 2005, astro-ph/0507509



B03 T Power Spectrum vs other current exp.s

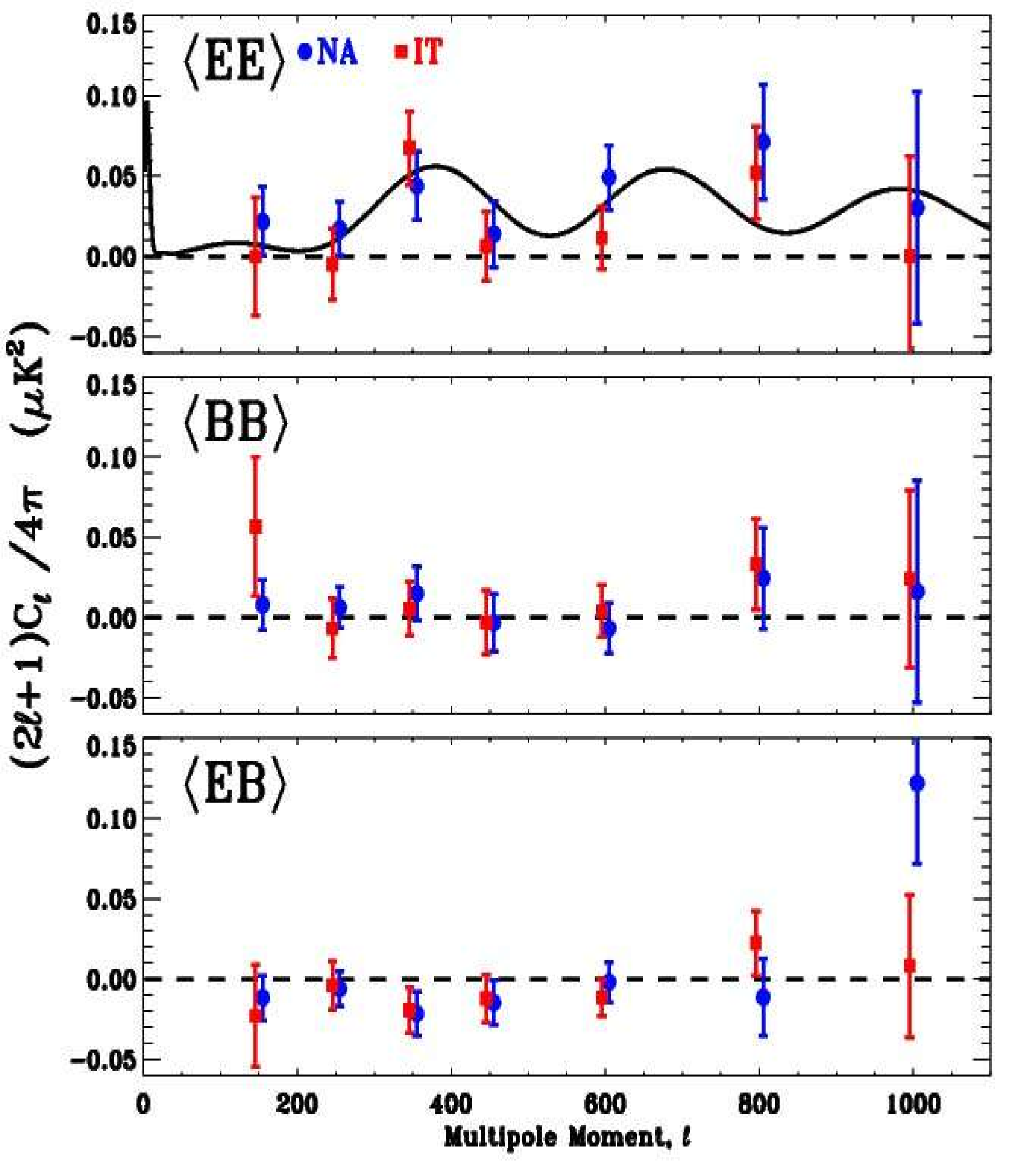


Jones et al. 2005

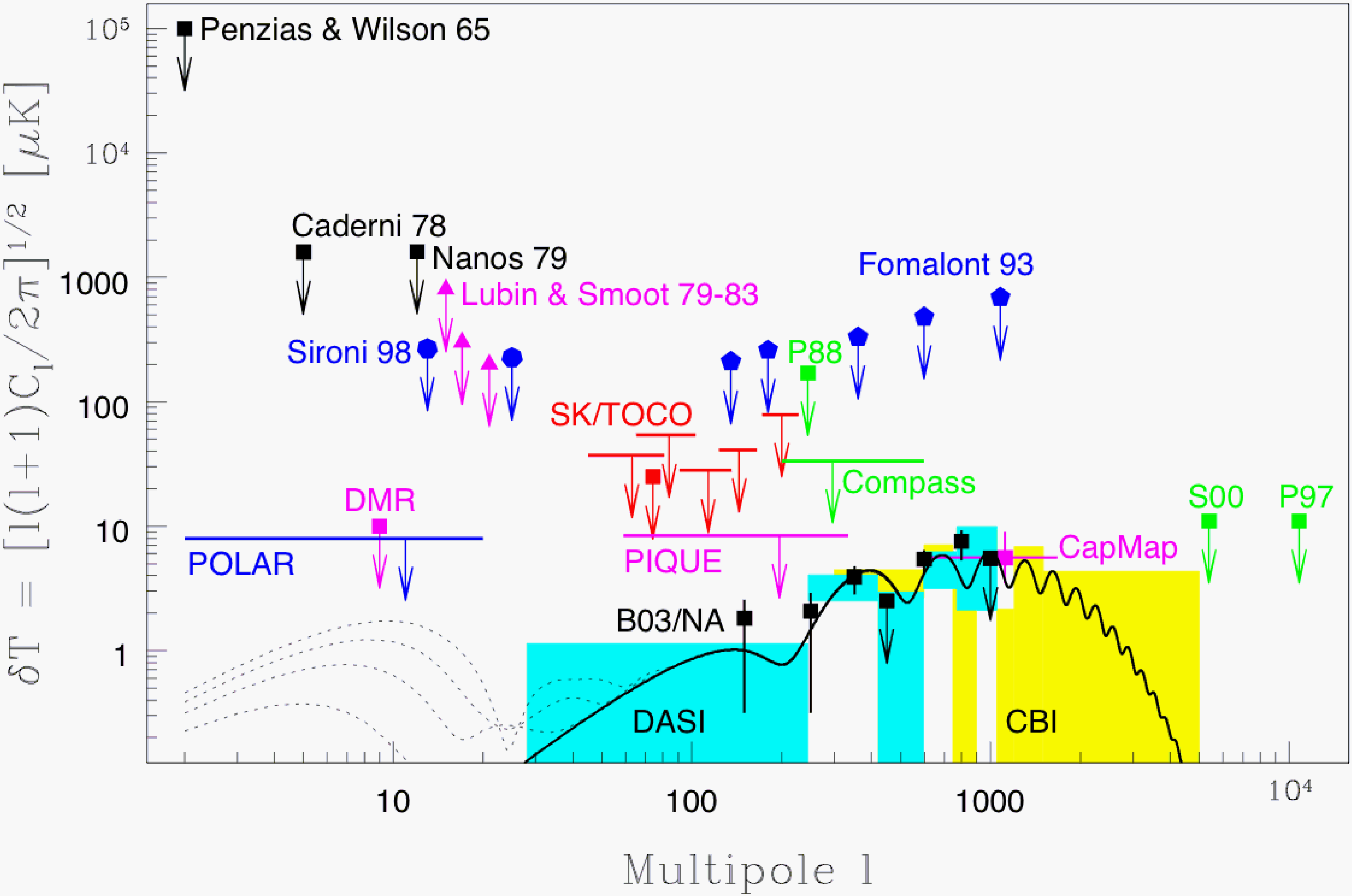
[Jones et al. 2005]

E-modes polarization angular 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.

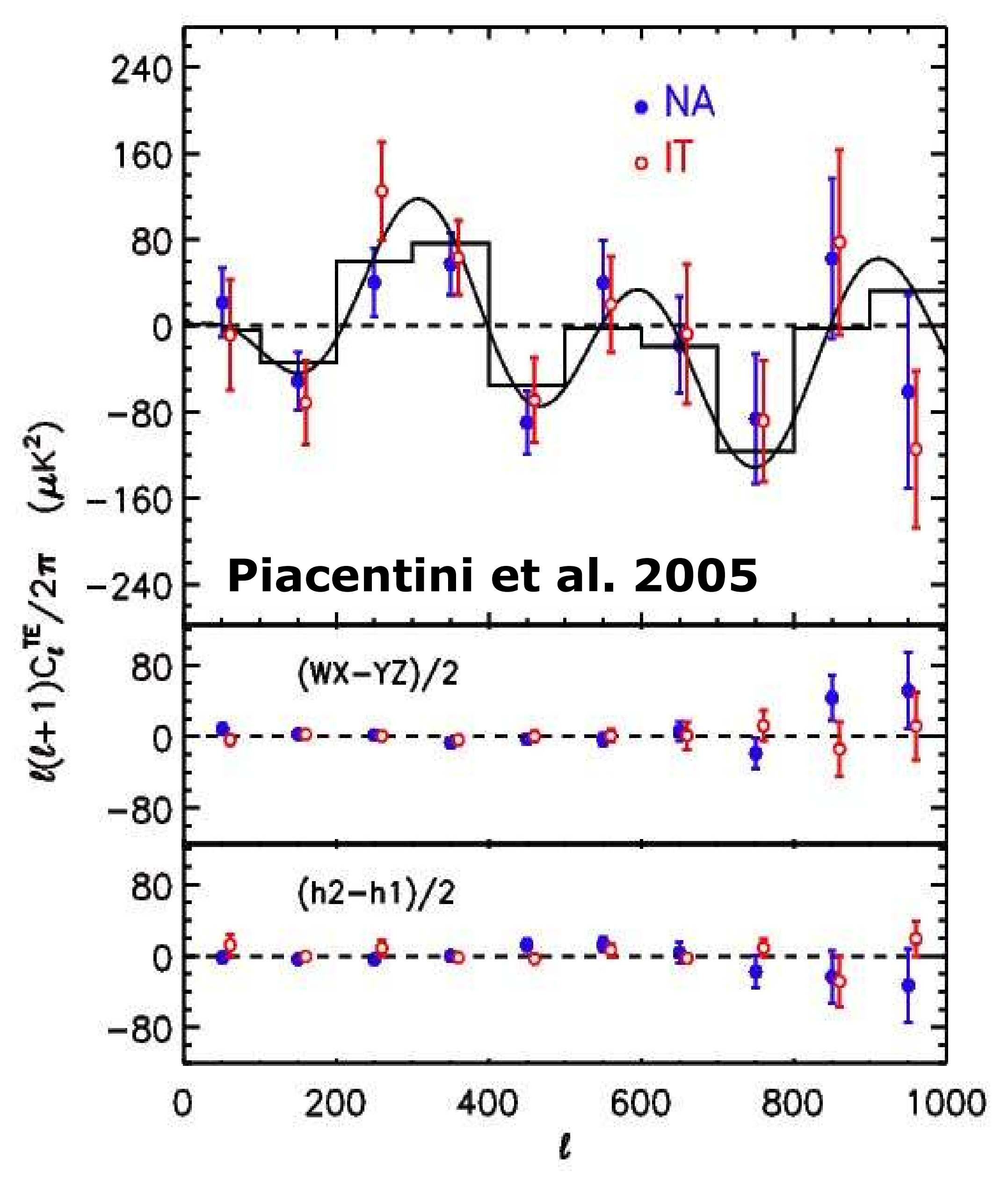


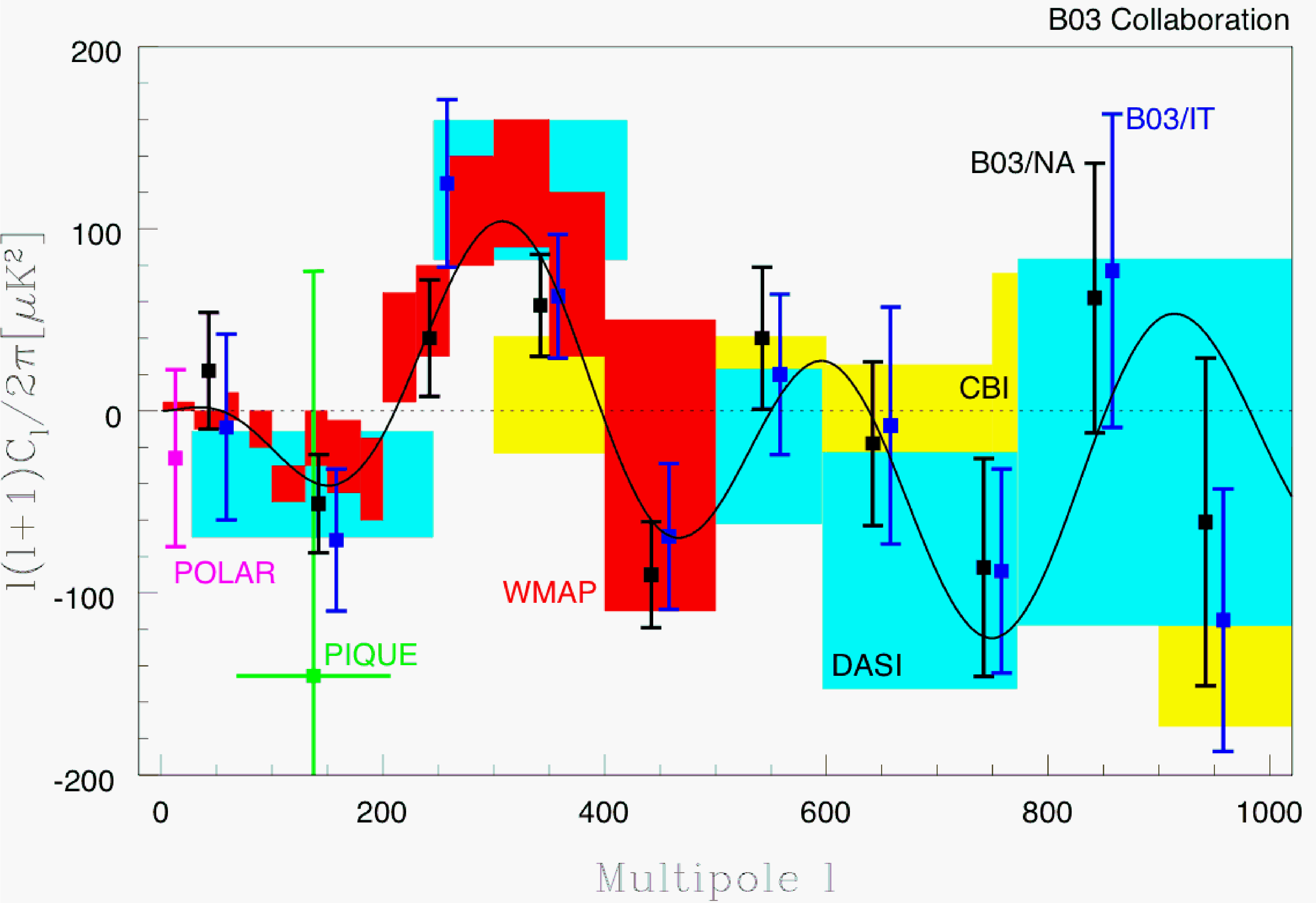
B03 Collaboration



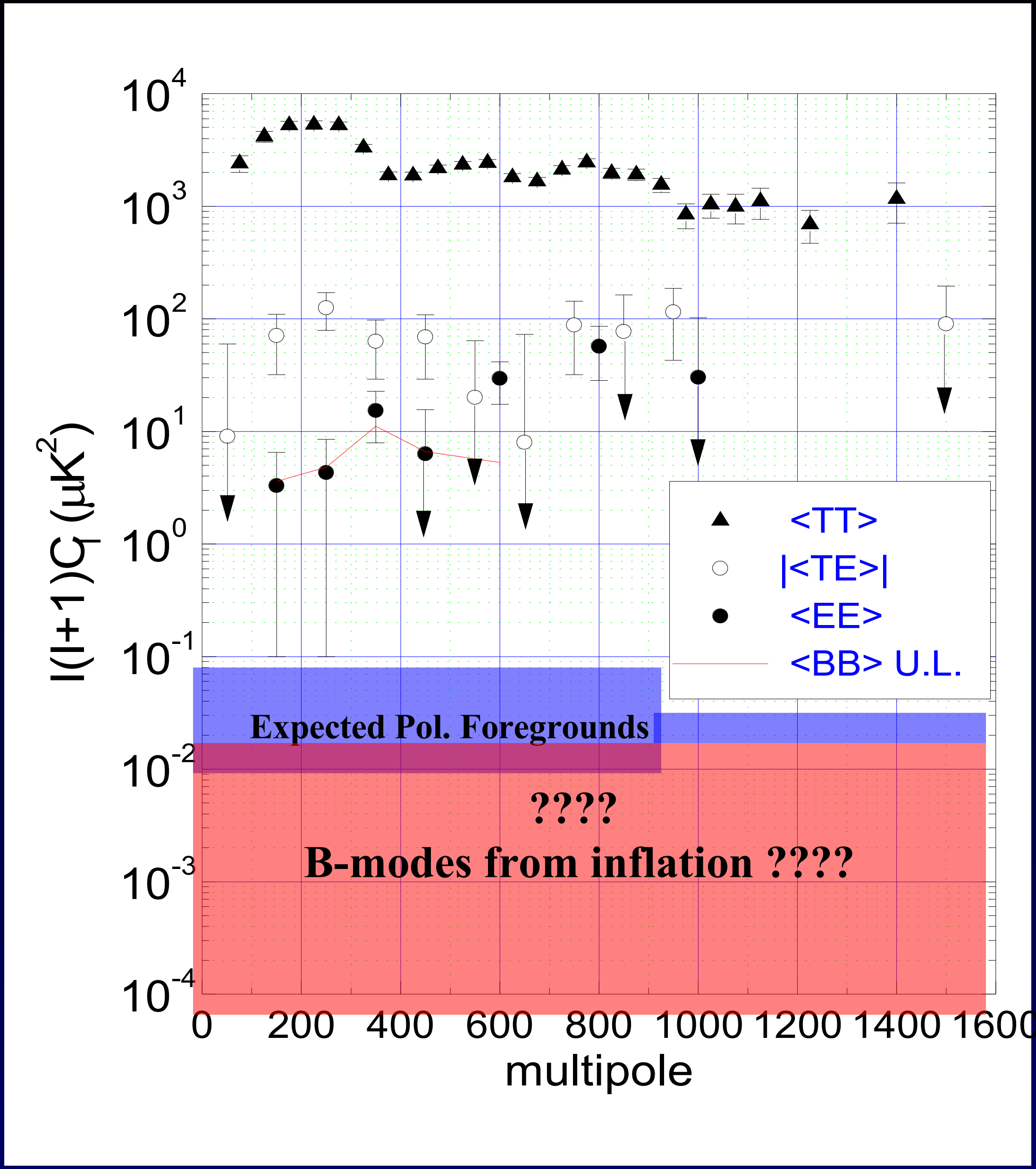
T-E correlation angular Power Spectrum

- Detection evident (3.5σ)
- Time and detectors jacknife OK, i.e. systematics negligible
- Data consistent with TT best fit model




B03 Collaboration
B03/IT
B03/NA
CBI
DASI
WMAP
POLAR
PIQUE
$l(l+1)C_l/2\pi\,[\mu K^2]$
Multipole l
200
100
0
-100
-200
0
200
400
600
800
1000

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



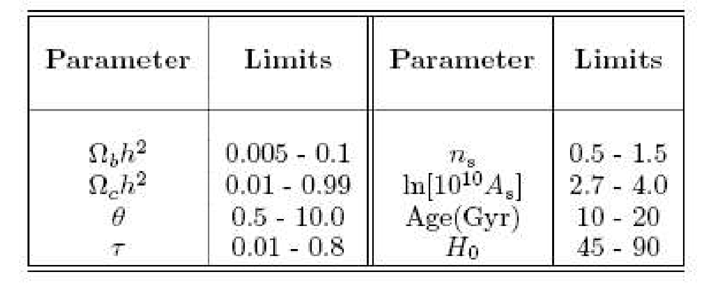
- We have detected VERY SMALL polarization signals, 2-3 orders of magnitude lower than anisotropy
- We are safe from the point of view of systematics and foregrounds
- We are VERY FAR from detecting inflationary B-modes

Constraining Cosmological Parameters

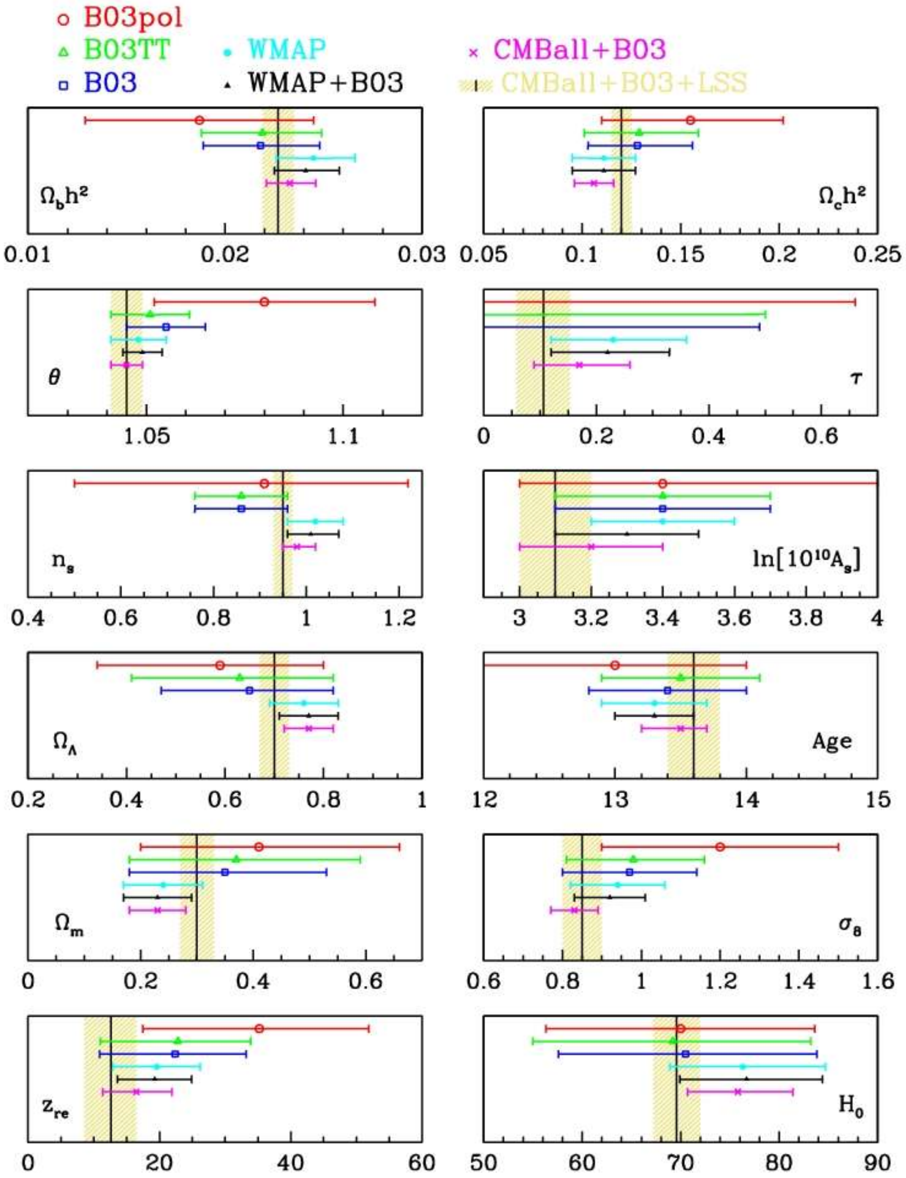
- We have now several high quality data sets to probe cosmological parameters:
  - CMB spectrum
  - CMB temperature anisotropy and polarization angular power spectra
  - 3-D distribution of galaxies (2dFGRS , SDSS)
  - SN1a
  - Lensing
  - Ly-α forest
- CMB spectra have well known degeneracies: cannot be used alone to constrain all cosmological parameters
- Non-CMB data sets have lower accuracy than CMB anisotropy ones.
- A very simple minimalist model with 5 parameters works extremely well and is consistent with all the observations above.
- It is a flat universe with baryons, dark matter, dark energy in the form of a cosmological constant, and with Gaussian, adiabatic, scale invariant primordial density fluctuations.
- Is described by the parameters ω_b(=$\Omega_b h^2$), ω_{dm} (=$\Omega_{dm} h^2$), Ω_Λ, τ, $\mathbf{A_s}$. Here n_s=1, Ω_k=0, w_{de}=-1, r=0.

Combining B03 anis. and pol. measurements :

- Pol only constraints consistent with concordance model
- Parameter constraints dominated by small errors on the TT spectrum
- ‘CMBall’ == ACBAR, CBI, DASI, MAXIMA, VSA, WMAP (TT + TE)
- Corrected likelihoods at low ℓ (Slosar & Seljak 2004)
- 2dF and SDSS LSS data included with marginalization over linear bias parameter b_g = 1.0 +/- 0.1
- SN1a ‘gold’ compilation from Reiss et al.
- Weak uniform priors:



Parameter	Limits	Parameter	Limits
$\Omega_b h^2$	0.005 - 0.1	n_s	0.5 - 1.5
$\Omega_c h^2$	0.01 - 0.99	$\ln[10^{10} A_s]$	2.7 - 4.0
θ	0.5 - 10.0	Age(Gyr)	10 - 20
τ	0.01 - 0.8	H_0	45 - 90

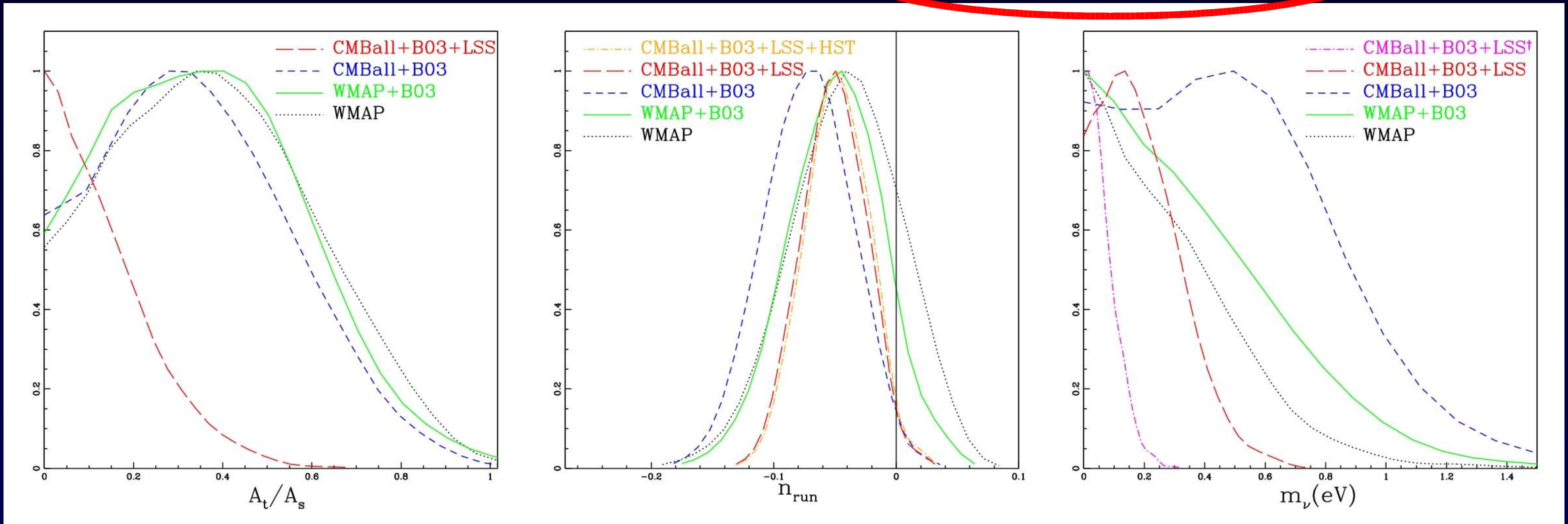


MacTavish et al. 2005

Extensions of Minimalist Model

- Curvature
- Running of the spectral index
- Tensor modes
- Massive neutrinos

$$
\begin{aligned}
\Omega_k &= -0.022 \pm 0.015 \\
n_{\rm run} &= -0.051^{+0.027}_{-0.026} \\
A_t/A_s &< 0.36 \\
f_\nu &< 0.093 \\
m_\nu &< 0.40\,\mathrm{eV}
\end{aligned}
$$



The presence of massive neutrinos slows the growth of small scale structures
To match the growth of structures with CMB data, mass of neutrinos have to be lower than a certain level

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 detect B-modes, we need to improve in three ways::

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

Sensitivity

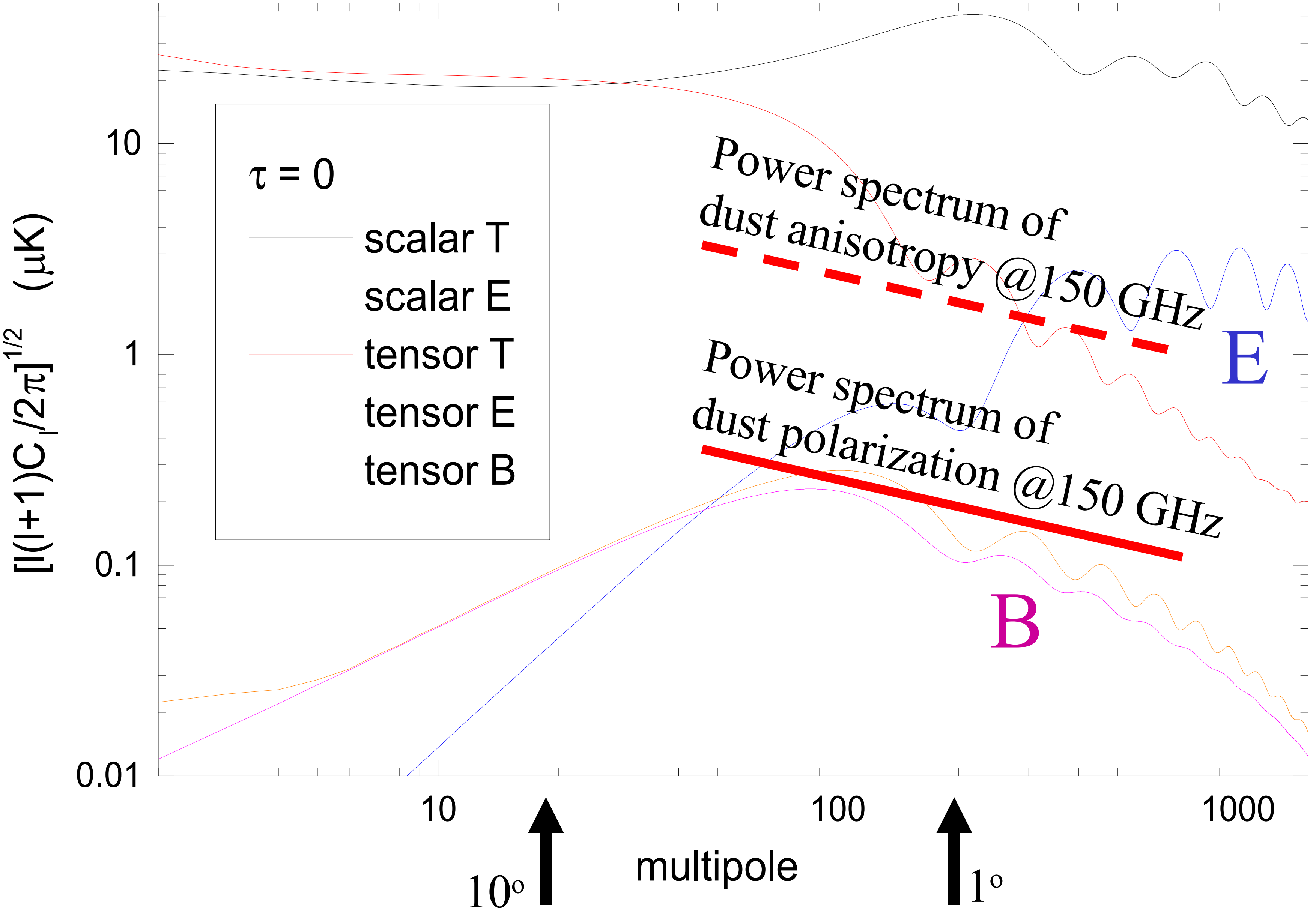
- B03 has shown that Polarization Sensitive Bolometers work well for CMB polarization measurements.
- Their sensitivity is close to be photon-noise-limited. In Planck-HFI the same bolometers will be cooled a factor 3 more and will be limited only by quantum fluctuations of the CMB itself. It is useless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

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).
- Experiments are necessary to test the technique/methodology before to start the design of a B-modes space mission.

Control of Foregrounds

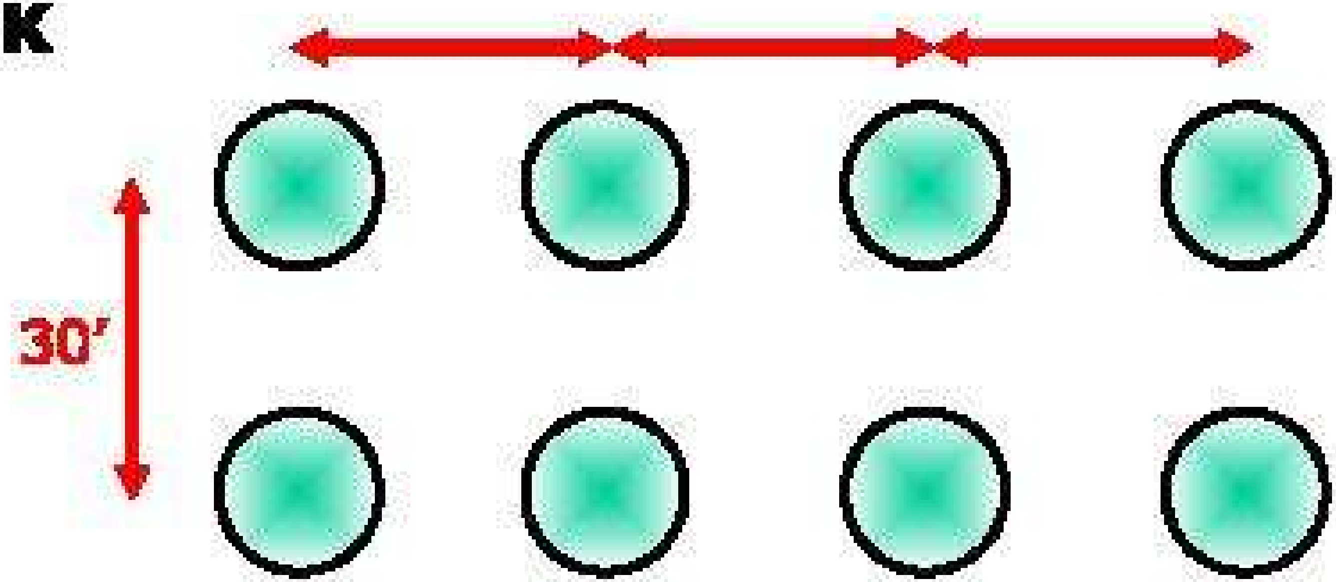
- Diffuse Dust emission is polarized at 10% in the plane of the Galaxy. See **astro-ph/0306222** "First Detection of Polarization of the Submillimetre Diffuse Galactic Dust Emission by Archeops".
- Its polarization will have both E-modes and B-modes.
- We know that **at 150 GHz** at high latitudes the 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.


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

B2K5

- We plan to re-fly B2K with an upgraded focal 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.

B2K

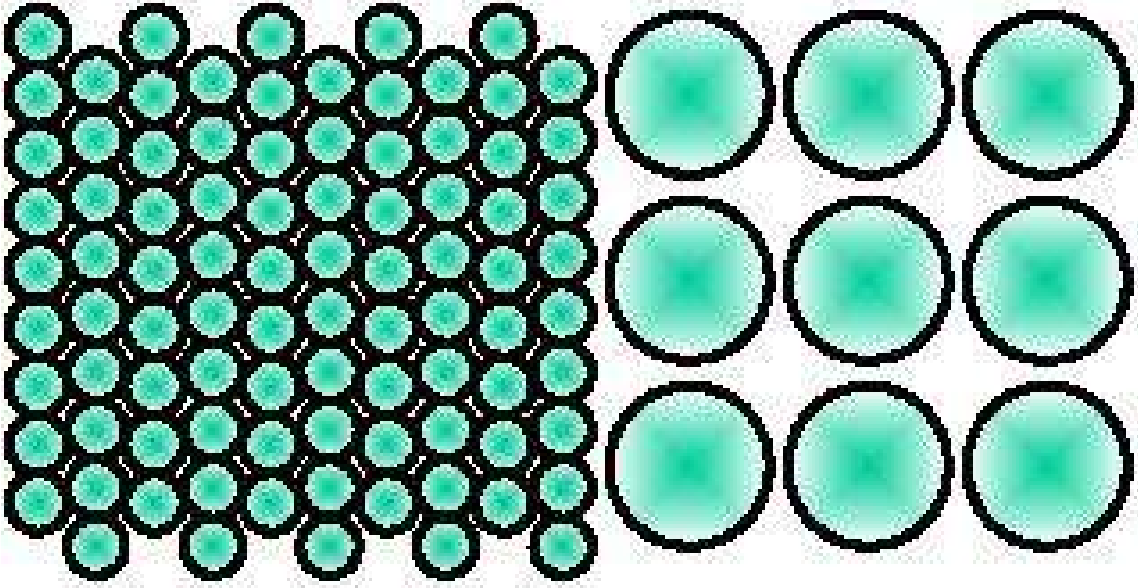


140 GHz
PSB

240 GHz
340 GHz

B2K5

340 GHz
PSB



140 GHz
PSB

A post-Planck mission

- A post-Planck dedicated 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 - Origins : Inflation Probe
  - ESA - Cosmic Vision : Full Sky Polarization Mapper
  - ASI - COFIS : B-POL
  - … ? …
- Meanwhile, laboratory, balloon-borne and ground-based experiments will develop the needed technology
- **10 years timescale ????**