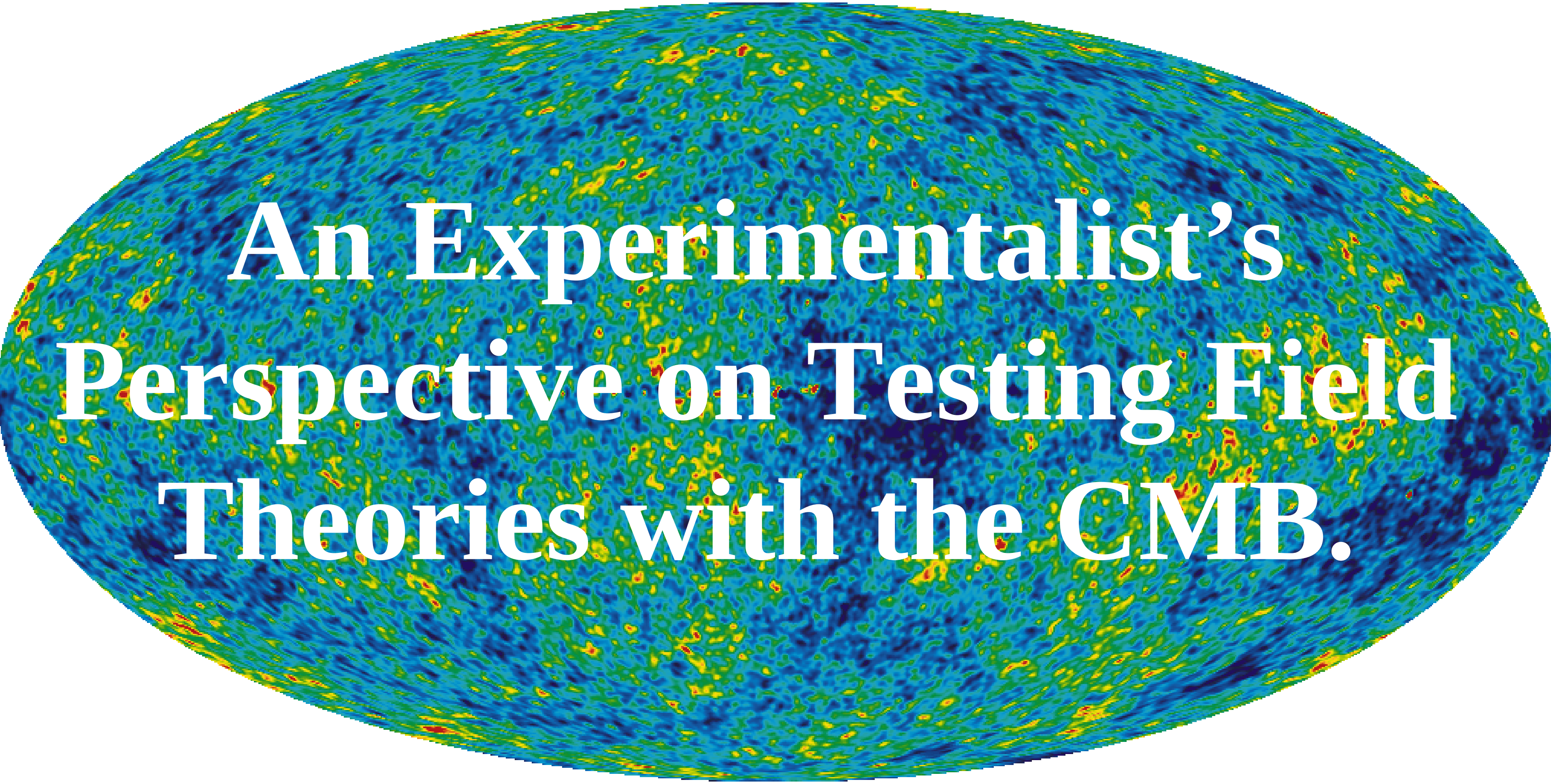
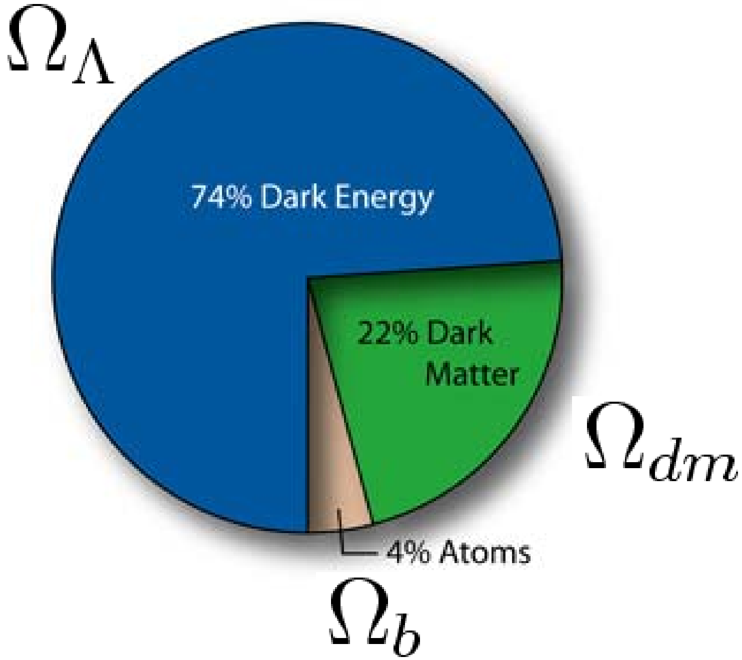


An Experimentalist's Perspective on Testing Field Theories with the CMB.

L. Page, AlbaNova, June 2007



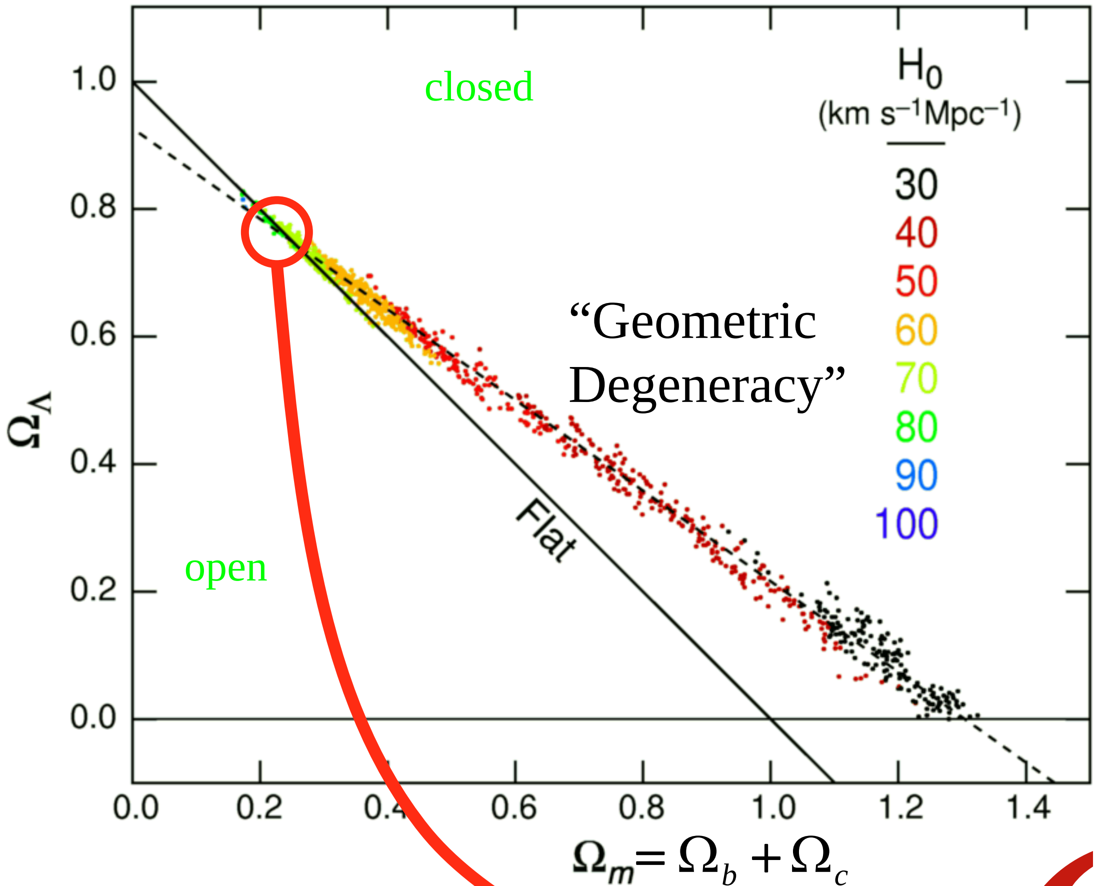
The current cosmological model agrees with virtually all cosmological measurements regardless of redshift or method.

The model assumes a flat geometry (a couple %), a new form of matter (>15σ), something that mimics a cosmological constant (many σ), and a deviation from scale invariance ($\mathrm{P}(\mathrm{k}) \propto k^{n_s=1}$, ~3σ).

WMAP3 only	**WMAP3 + all**
$\Omega_b h^2 = 0.02233 \pm 0.0008$	$\Omega_b h^2 = 0.02186 \pm 0.0007$
$\Omega_m h^2 = 0.126 \pm 0.009$	$\Omega_m h^2 = 0.132 \pm 0.004$
$h = 0.735 \pm 0.032$	$h = 0.704 \pm 0.015$
$\sigma_8 = 0.76 \pm 0.05$	$\sigma_8 = 0.776 \pm 0.031$
$\tau = 0.088 \pm 0.03$	$\tau = 0.073 \pm 0.03$
$n_s = 0.961 \pm 0.017$	$n_s = 0.947 \pm 0.015$

No SZ marg.

Models based on some kind of field theory of the early universe predict n_s.



CMB alone tells us we are on the "geometric degeneracy" line

WMAP3 only best fit LCDM

Assume flatness

$$
\begin{aligned}
\Omega_b h^2 &= 0.02233 \pm 0.0008 \\
\Omega_m h^2 &= 0.126 \pm 0.009 \\
h &= 0.735 \pm 0.032 \\
\sigma_8 &= 0.76 \pm 0.05 \\
\tau &= 0.088 \pm 0.03 \\
n_s &= 0.961 \pm 0.017
\end{aligned}
$$

Reduced $\chi^2 = 1.037$

Testing Specific Field Theories

Experimental handles

(1) Spectrum of Fluctuations n_s **&** $\alpha = dn_s/d\ln k$

(2) Anisotropies from Gravitational Waves.

(3) Non-Gaussanity

Types of Cosmological Perturbations

Scalars: $\frac{\delta\rho}{\rho}$, $\mathrm{P(k)} \propto k^{n_s}$

- Temperature
- E polarization

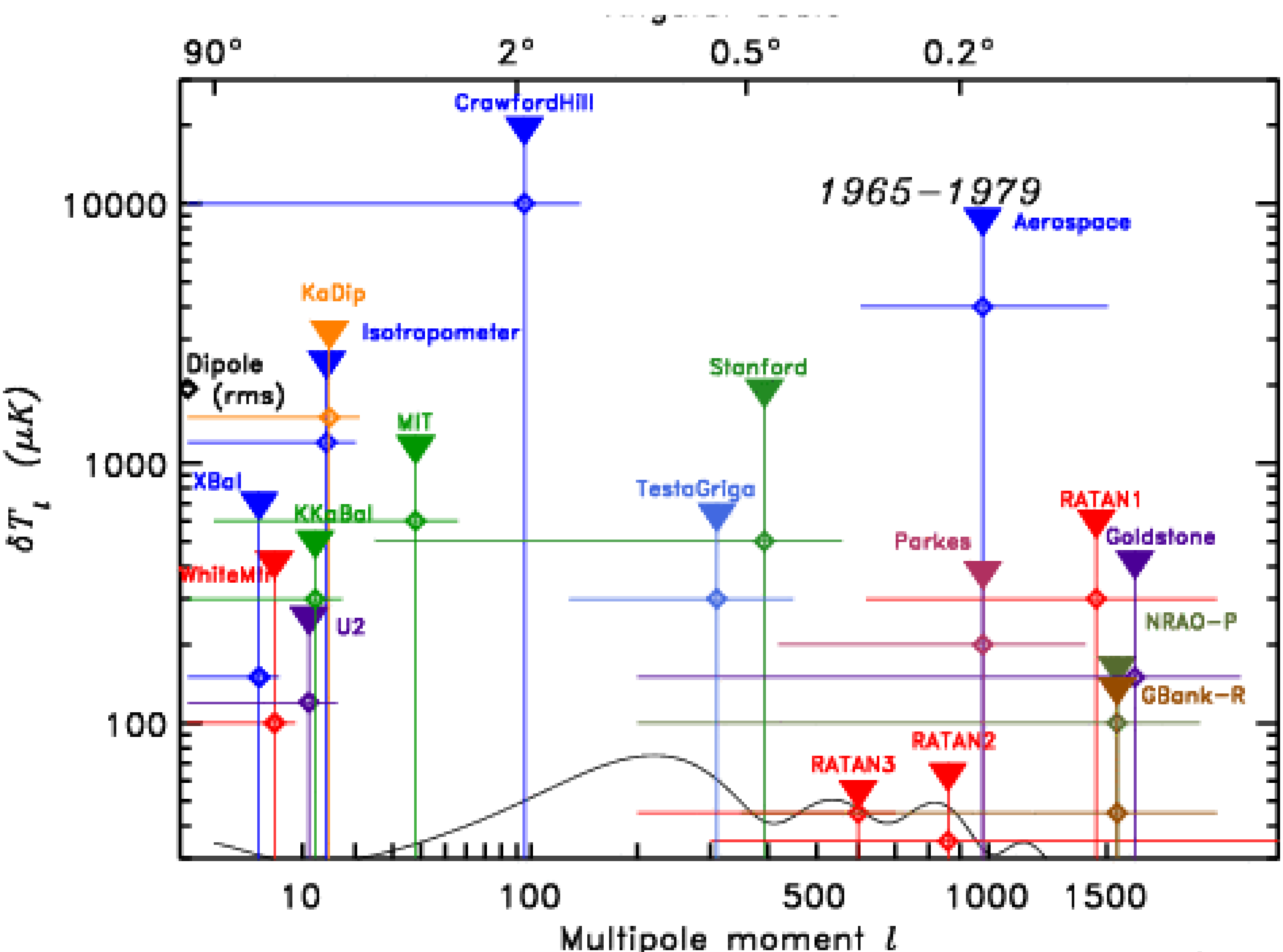
Tensors: h (GW strain)

- Temperature
- E polarization
- B polarization

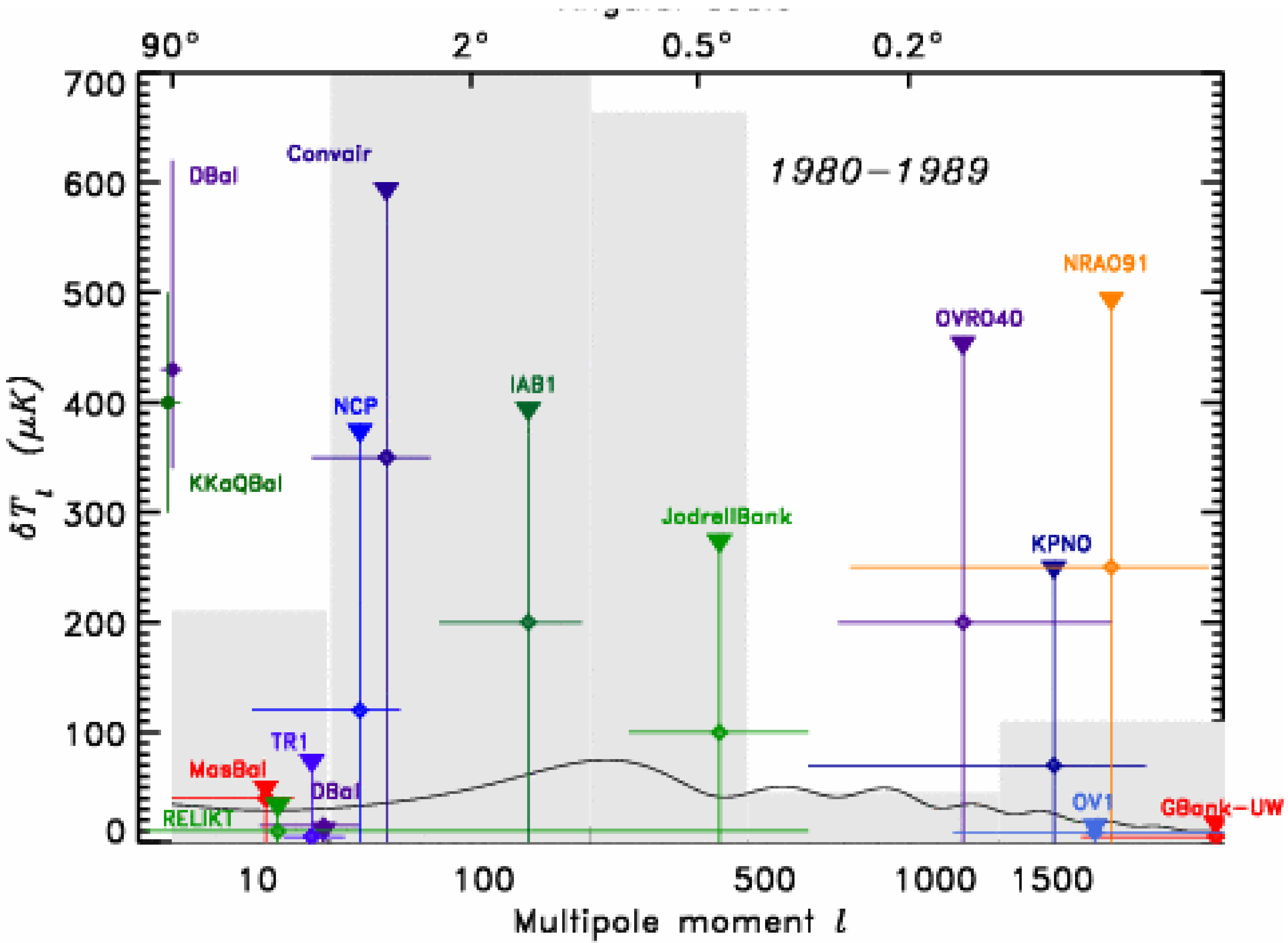
$$r = \frac{\mathrm{Var(Tensors)}}{\mathrm{Var(Scalars)}} \sim 0.3$$

Or less!

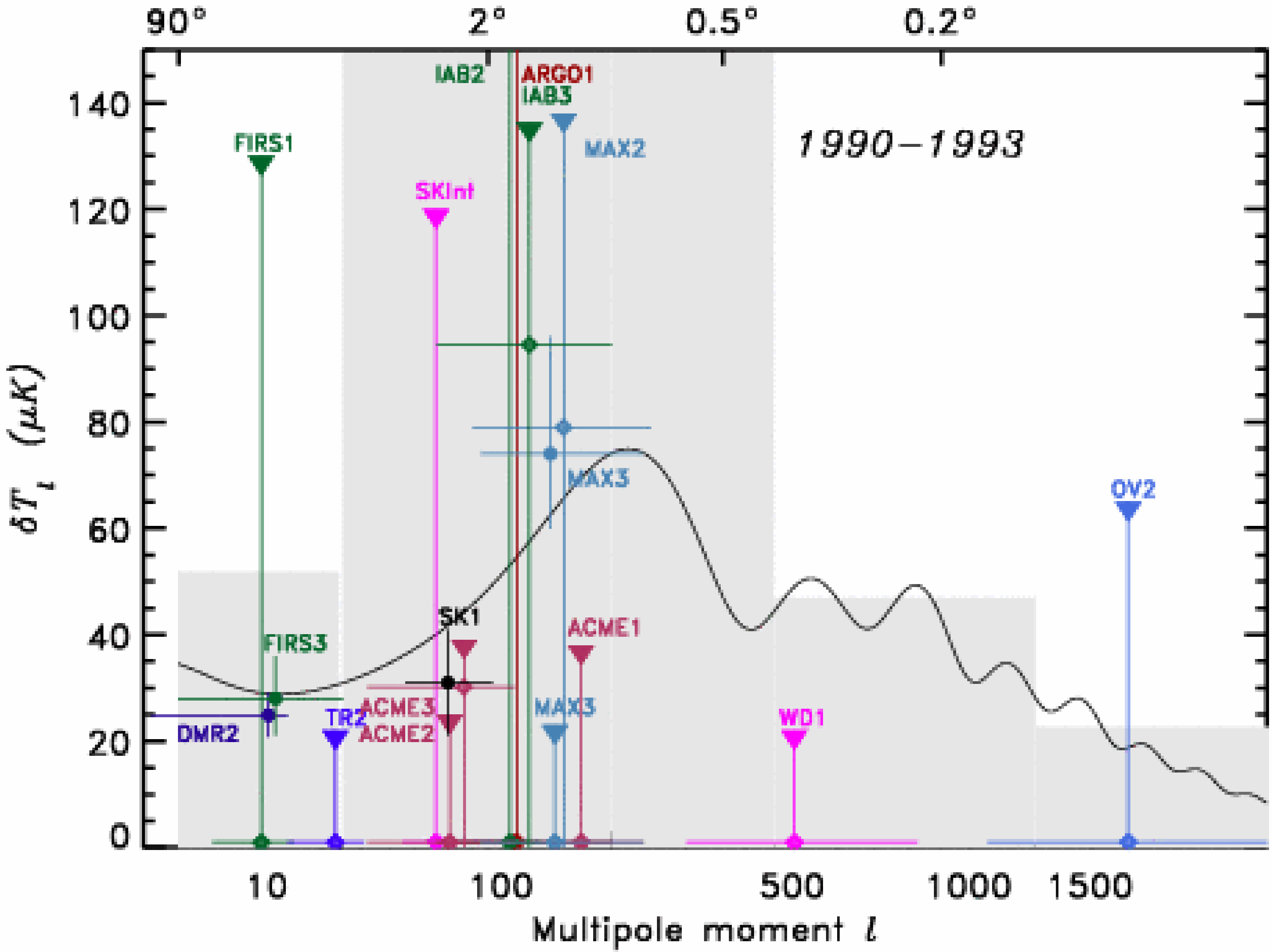
n and r are predicted by models of the early universe



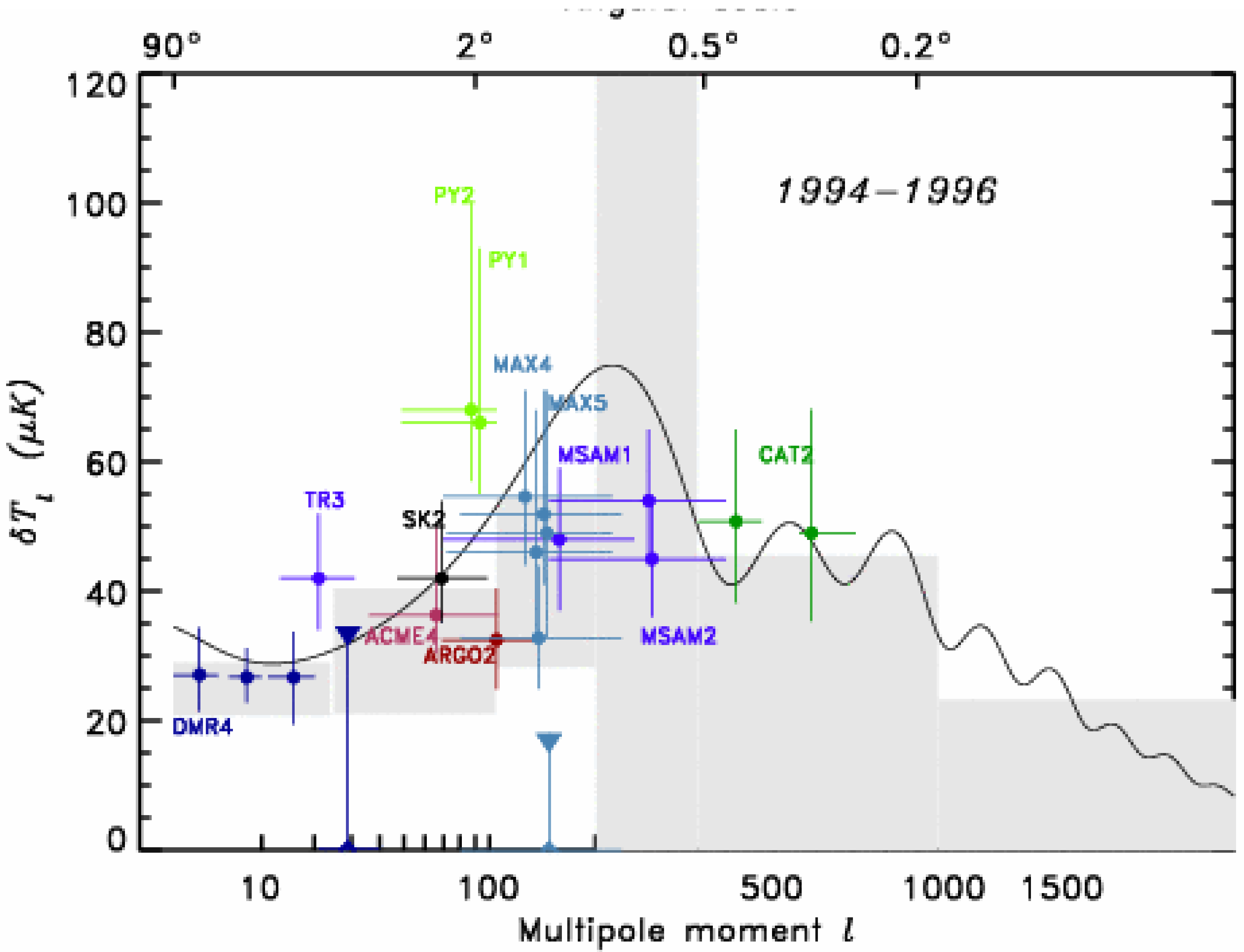
PRELIMINARY!



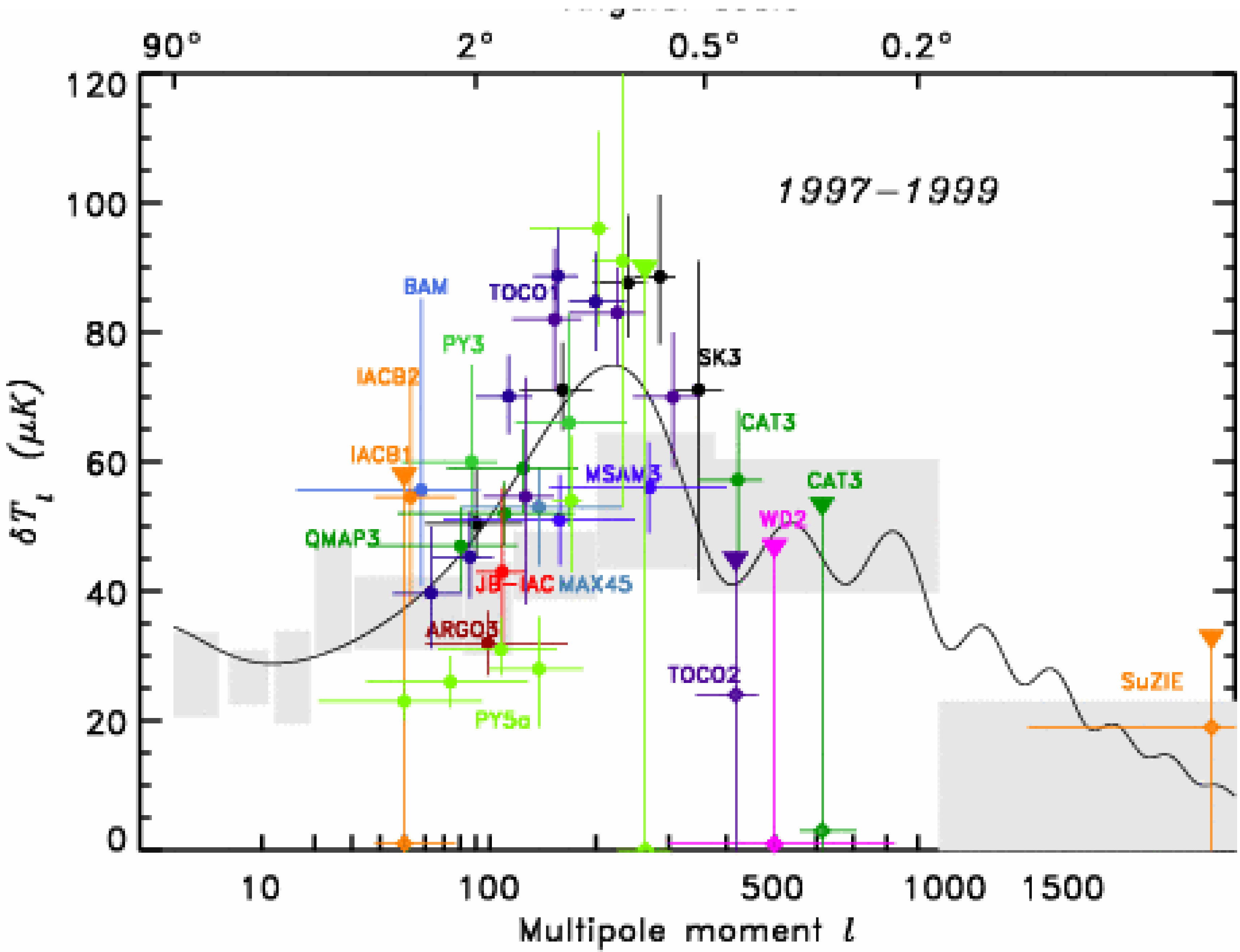
90°
2°
0.5°
0.2°
700
600
500
400
300
200
100
0
1980−1989
DBal
Convair
NRAO91
OVRO40
IAB1
NCP
KKaQBal
JodrellBank
KPNO
TR1
MaxBal
DBal
RELIKT
OV1
GBank−UW
δT_l (μK)
10
100
500
1000
1500
Multipole moment l

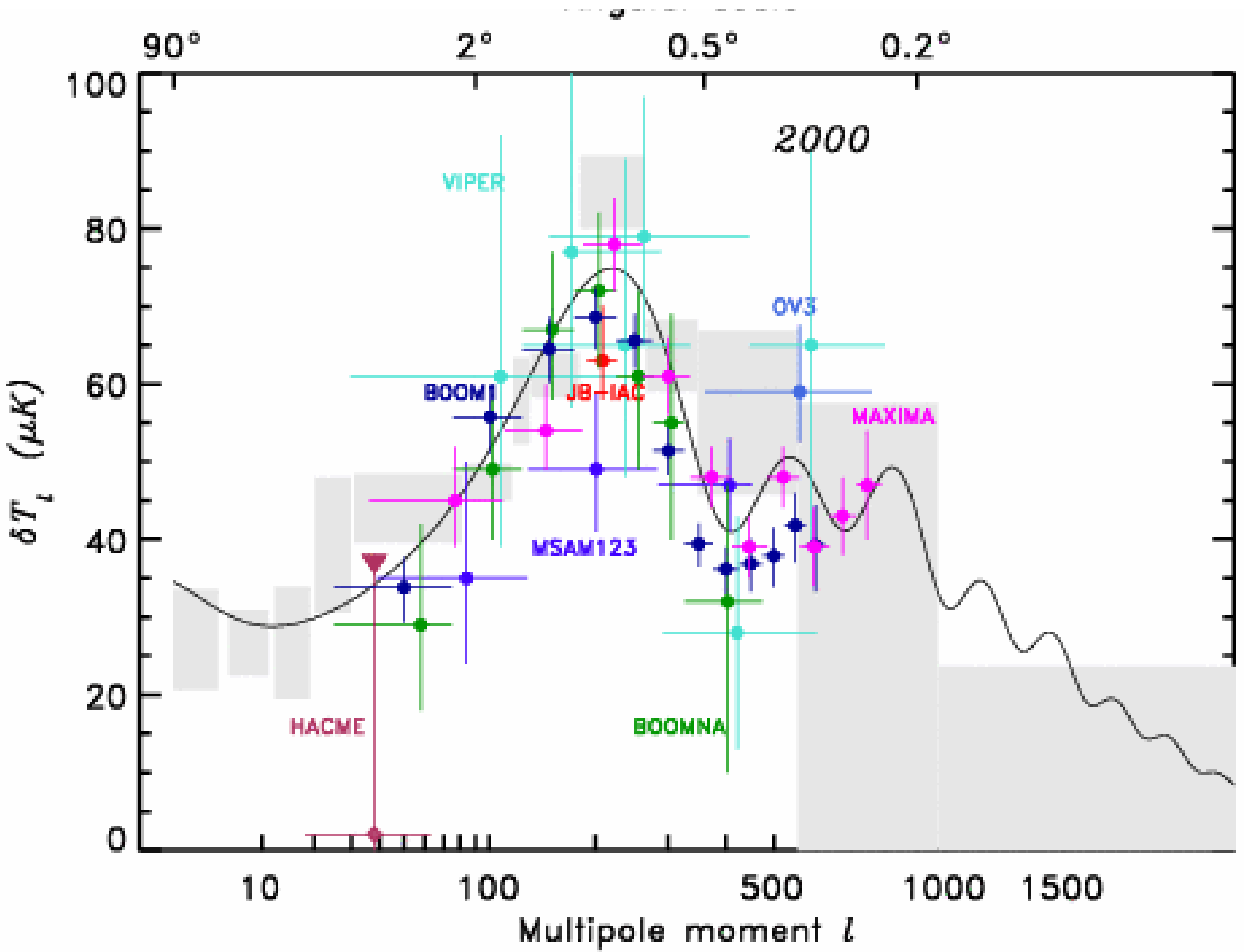


90°
2°
0.5°
0.2°
1990−1993
140
120
100
80
60
40
20
0
δT_l (μK)
FIRS1
IAB2
ARGO1
IAB3
MAX2
SKInt
MAX3
OV2
SK1
ACME1
FIRS3
ACME3
ACME2
TR2
DMR2
MAX3
WD1
10
100
500
1000
1500
Multipole moment l

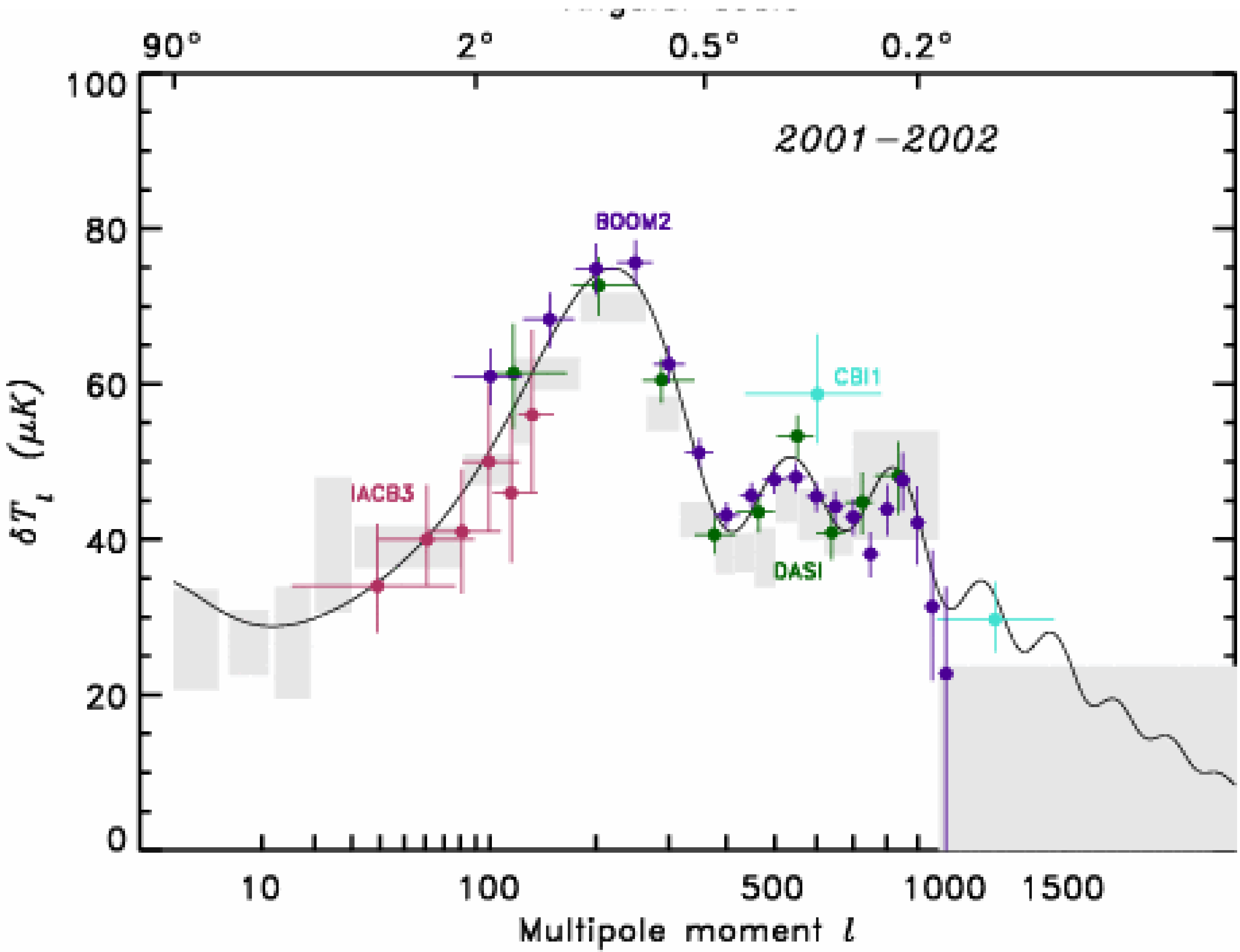


90°
2°
0.5°
0.2°
120
100
80
60
40
20
0
δT_l (μK)
1994–1996
PY2
PY1
MAX4
MAX5
MSAM1
CAT2
TR3
SK2
ACME4
ARGO2
MSAM2
DMR4
10
100
500
1000
1500
Multipole moment l

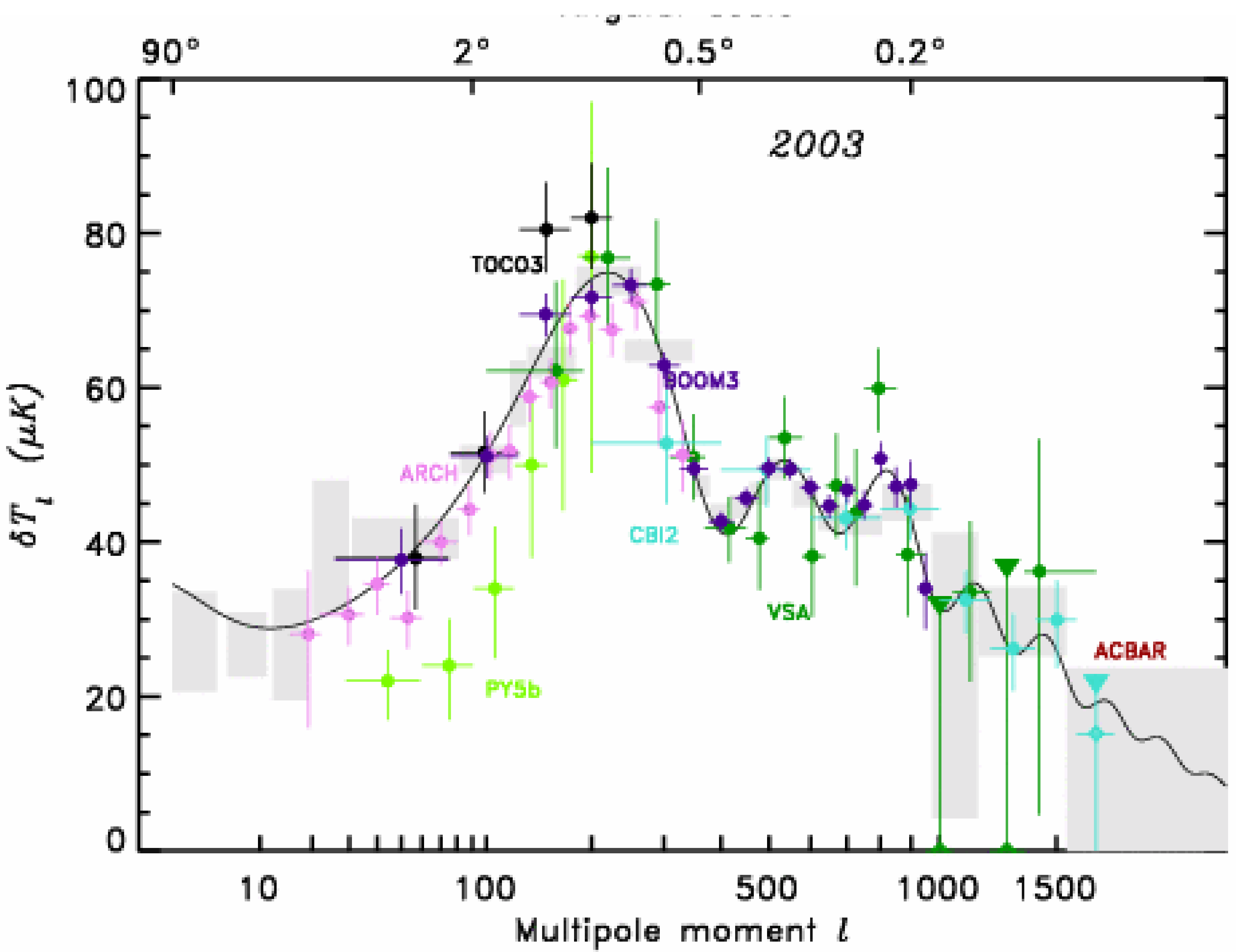

90°
2°
0.5°
0.2°
120
100
80
60
40
20
0
1997–1999
BAM
TOCO1
PY3
IACB2
SK3
CAT3
IACB1
MSAM3
CAT3
WD2
QMAP3
JB–IAC
MAX45
ARGO3
TOCO2
SuZIE
PY5a
10
100
500
1000
1500
Multipole moment l
δT_l (μK)



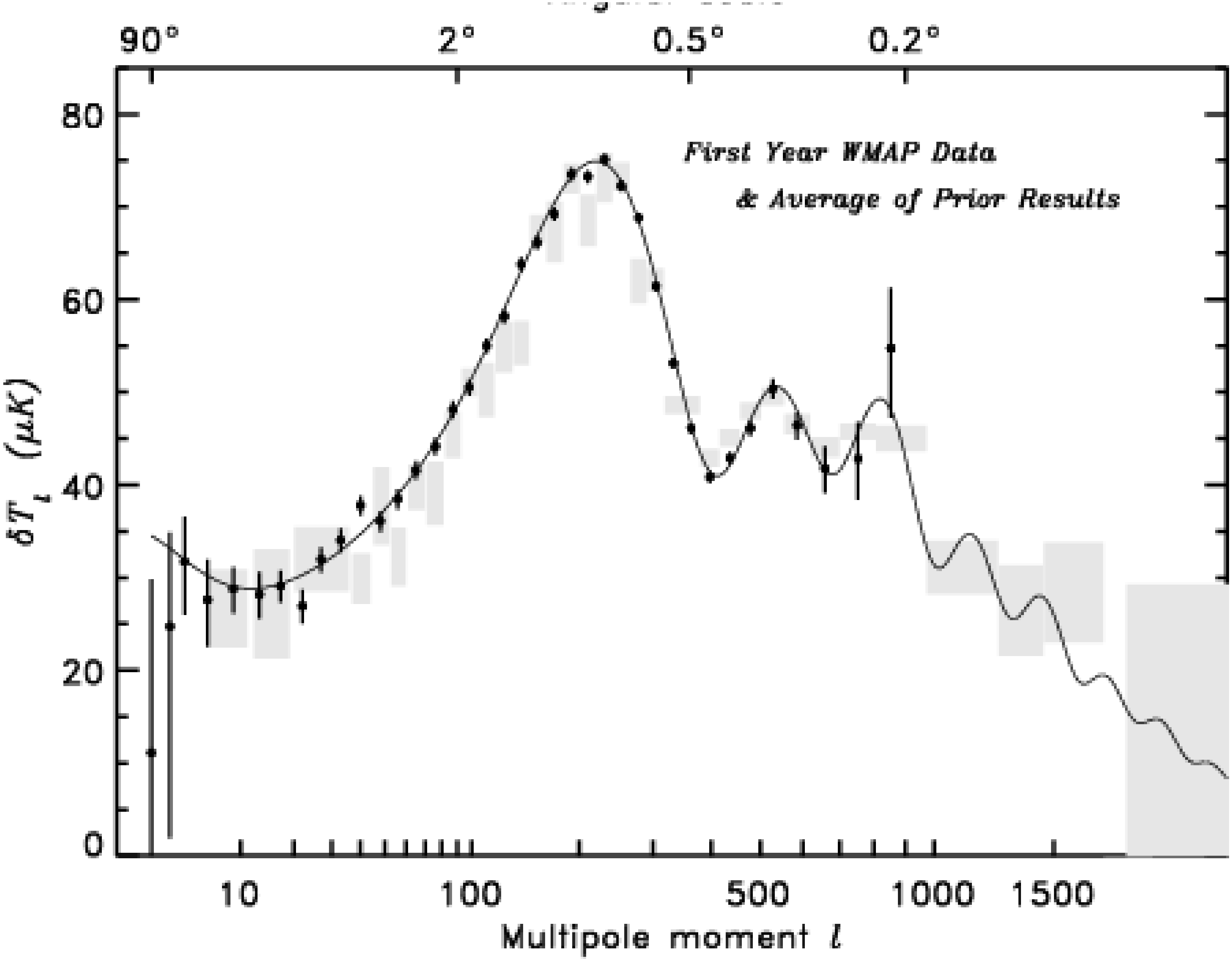
90°
2°
0.5°
0.2°
2000
VIPER
OV3
BOOM1
JB-IAC
MAXIMA
MSAM123
HACME
BOOMNA
δT_l (μK)
100
80
60
40
20
0
10
100
500
1000
1500
Multipole moment l



90°
2°
0.5°
0.2°
2001−2002
BOOM2
CBI1
IACB3
DASI
δT_l (μK)
100
80
60
40
20
0
10
100
500
1000
1500
Multipole moment l



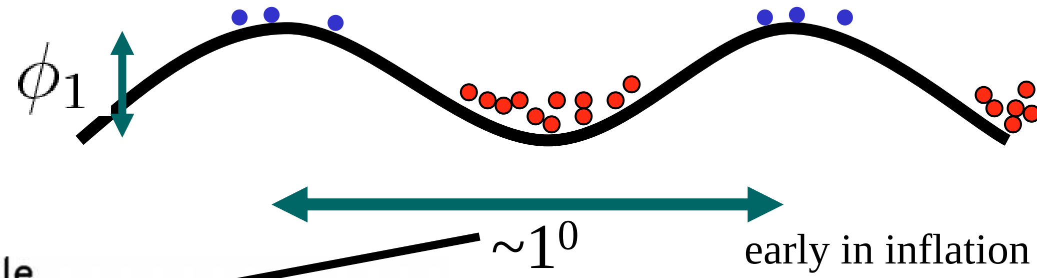
90°
2°
0.5°
0.2°
100
80
60
40
20
0
2003
TOCO3
BOOM3
ARCH
CBI2
VSA
PY5b
ACBAR
δT_l (μK)
10
100
500
1000
1500
Multipole moment l

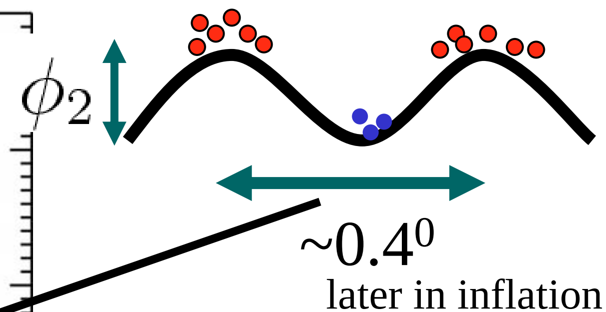


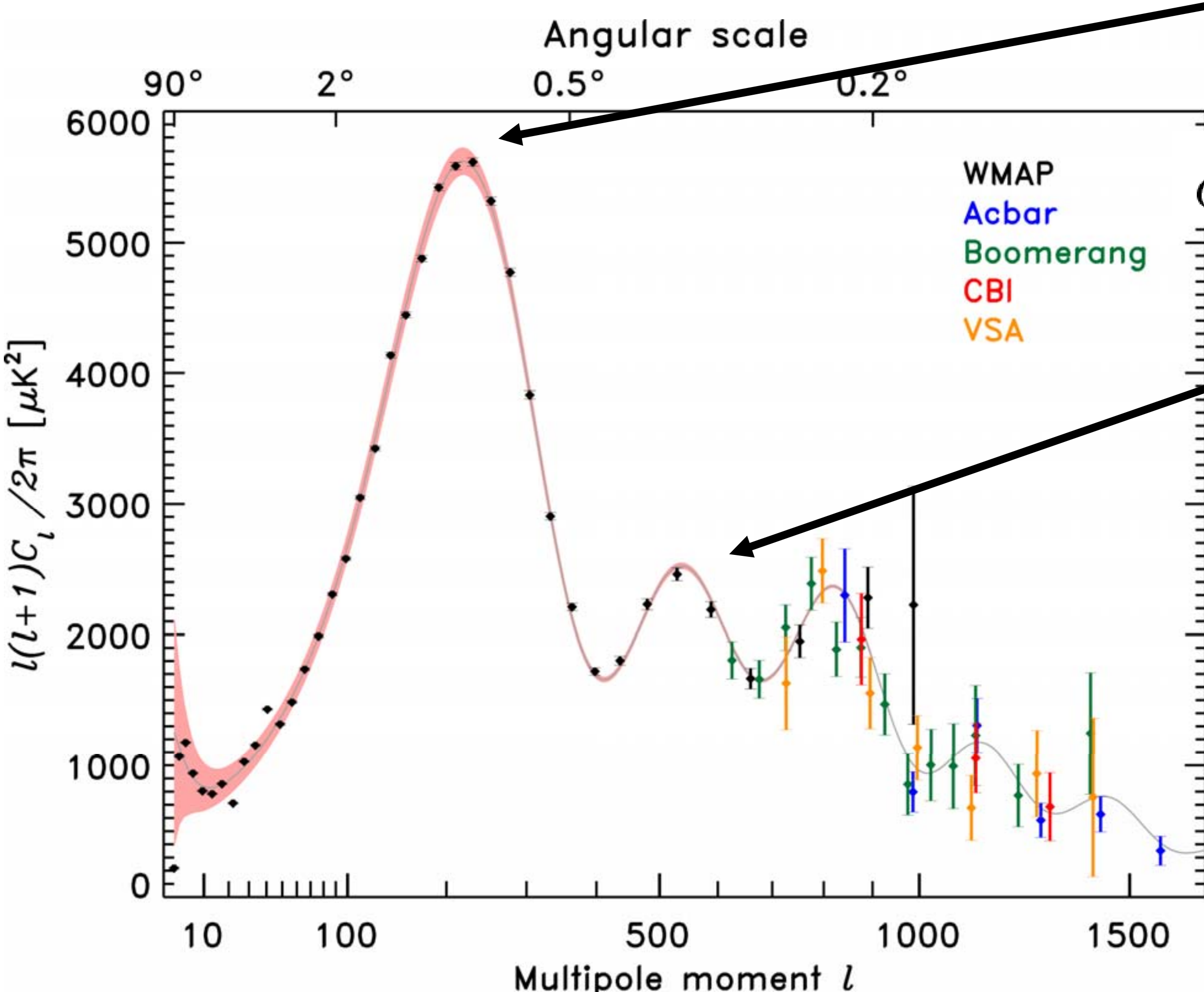
90°
2°
0.5°
0.2°
First Year WMAP Data
& Average of Prior Results
80
60
40
20
0
δT_l (μK)
10
100
500
1000
1500
Multipole moment l

Angular Power Spectrum.

Physical size = plasma speed X age of universe at decoupling

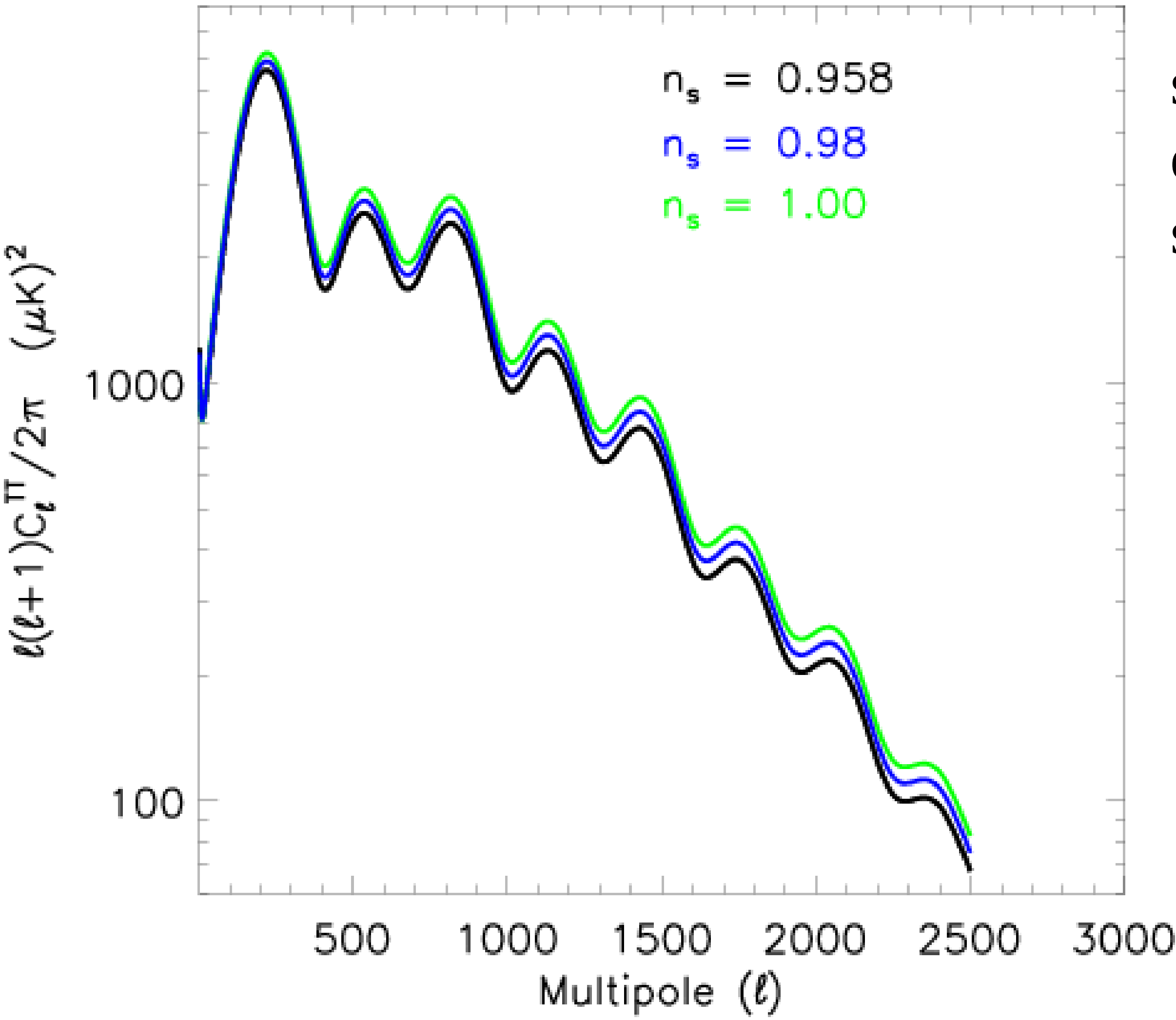






The overall tilt of this spectrum--- encoded in the "scalar spectral index" n_s--- is the new handle on the early universe.

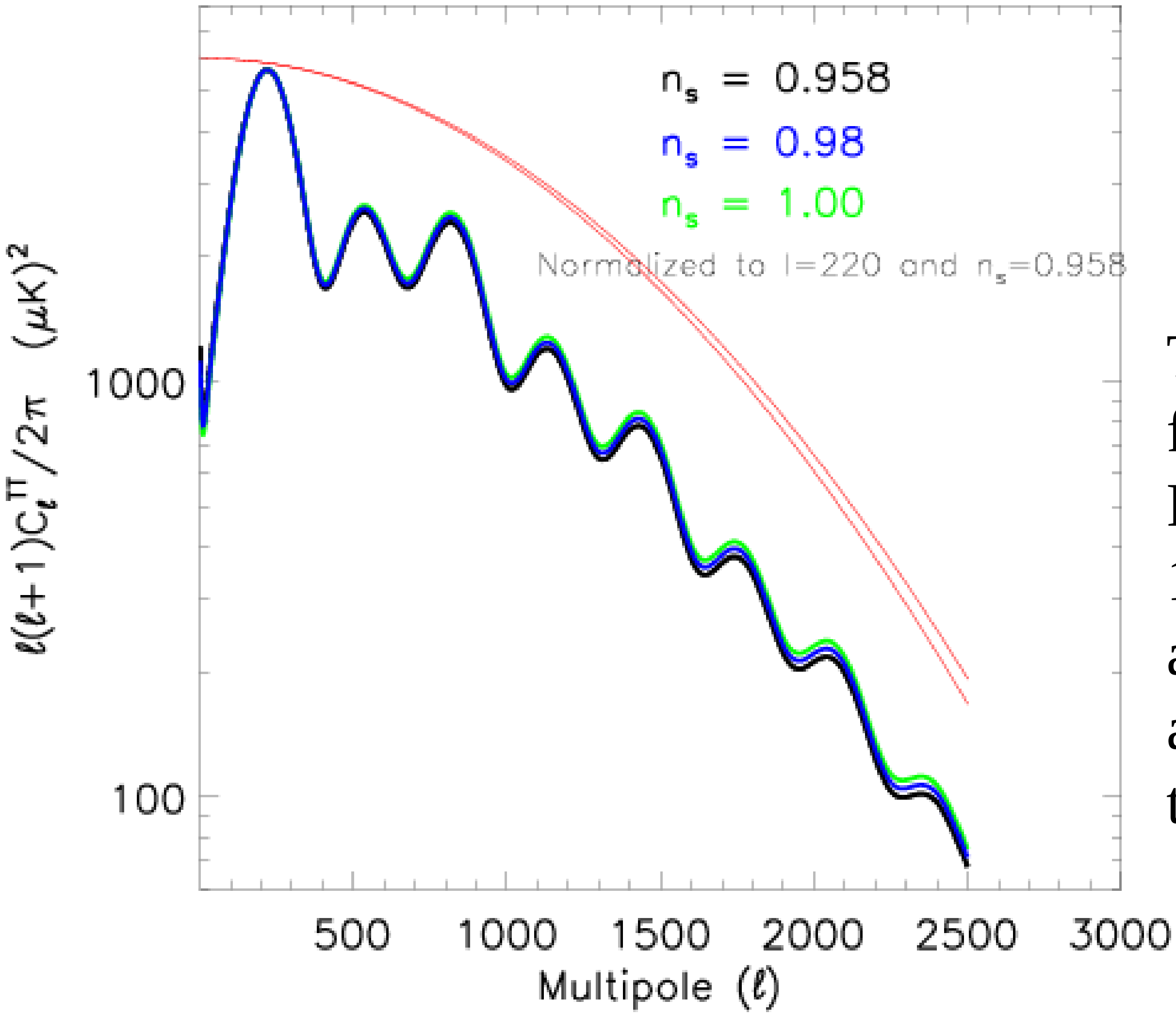
Spectral Index, Experimental Challenges



Three different spectra that differ only in spectral index.

The black line is the best WMAP model.

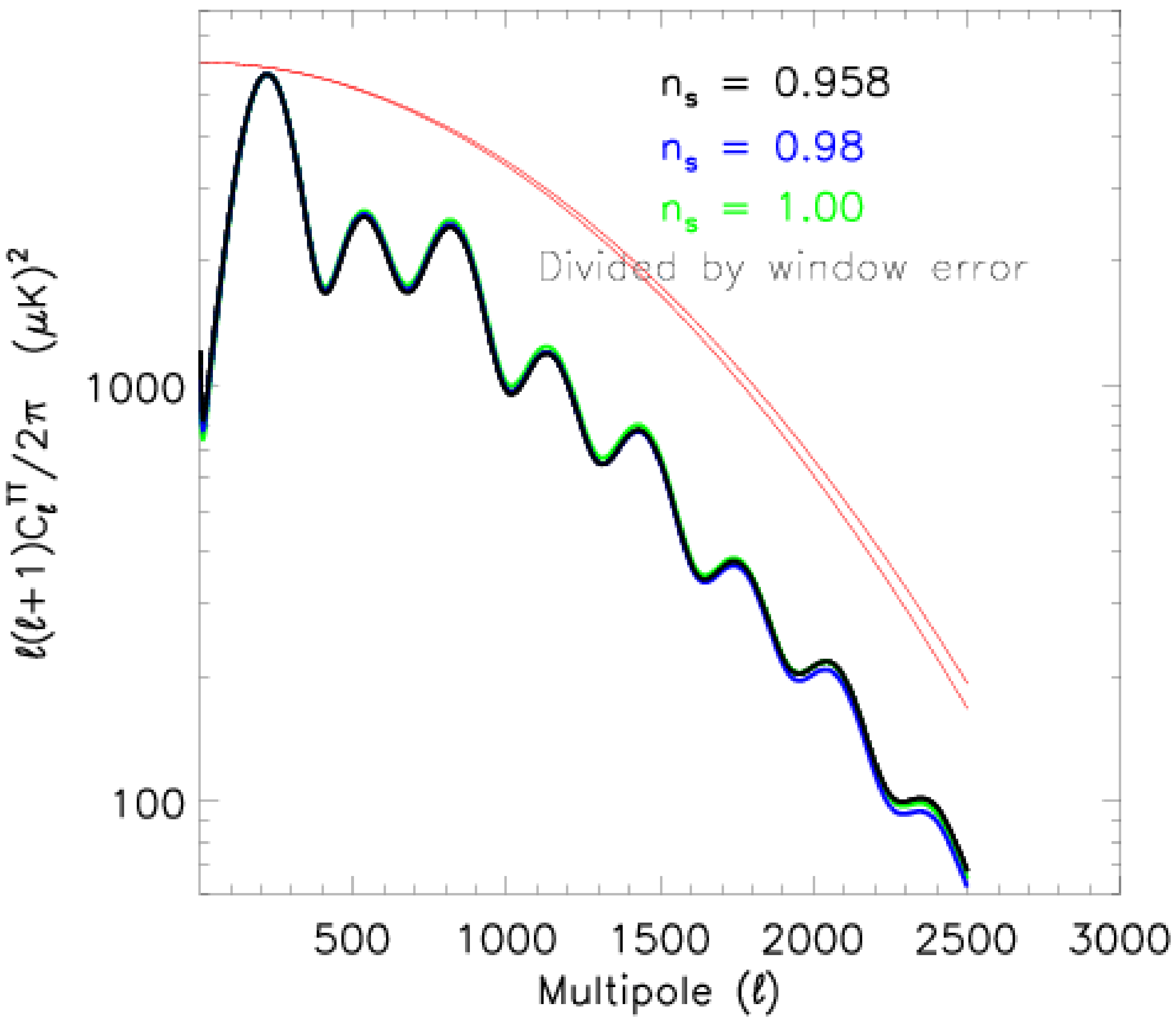
Spectral Index



Normalize the spectra to l=220 (mimics n_s-amplitude degeneracy)

The two window functions are for 0.1 deg FWHM beams with a 1% difference in solid angle. Only WMAP has achieved anything like this accuracy.

Spectral Index



Divide by fractional window function.

Conclusion: To probe the index the beams need to be understood to the 1% level.

In addition, there are astrophysical challenges.

Spectral Index: Astrophysical Challenges

The formation of the first stars produces free electrons that:

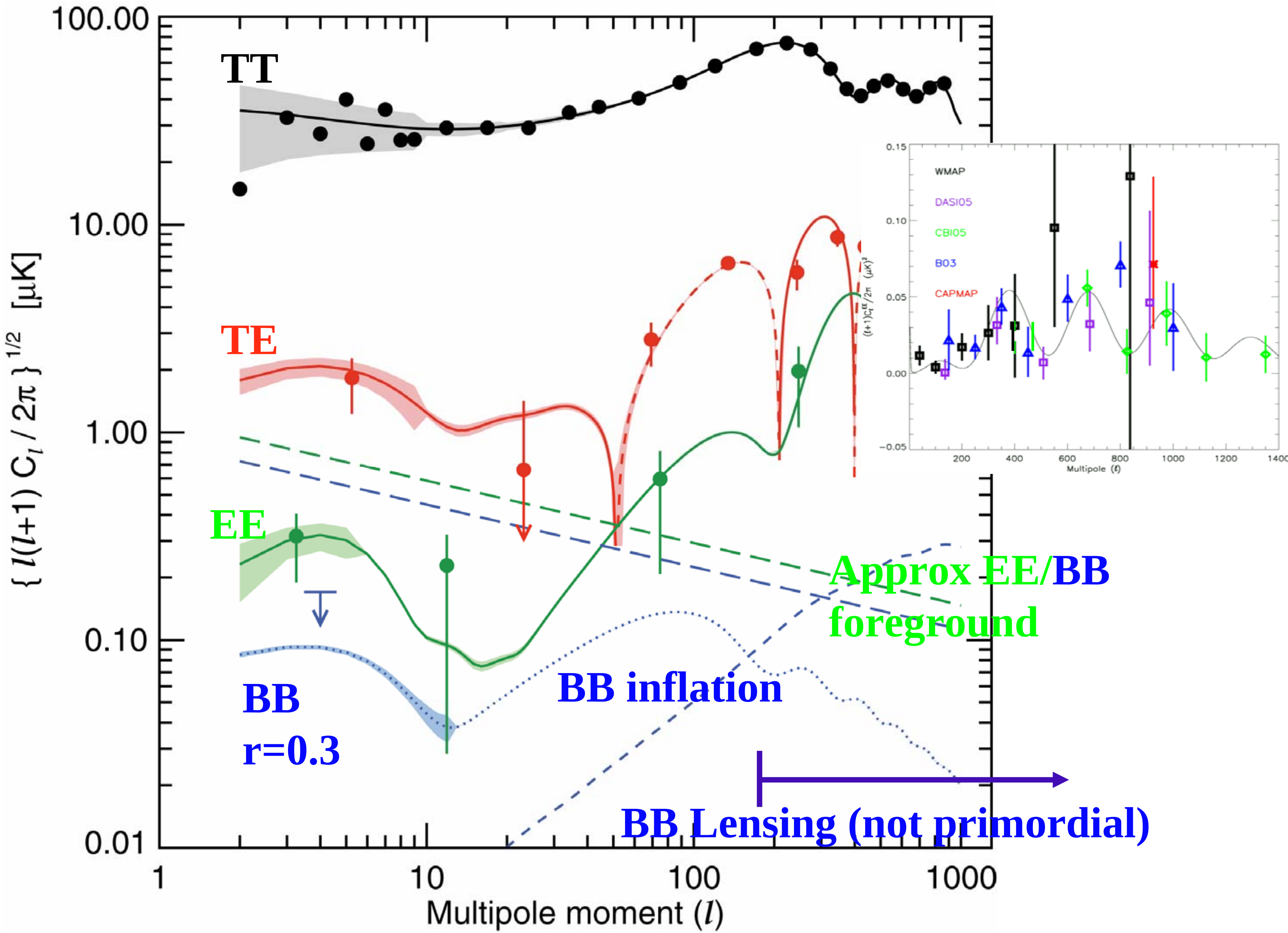
(1) rescatter CMB photons thereby reducing the anisotropy and

(2) polarize the CMB at large angular scales.

These effects mimic a change in n_s:

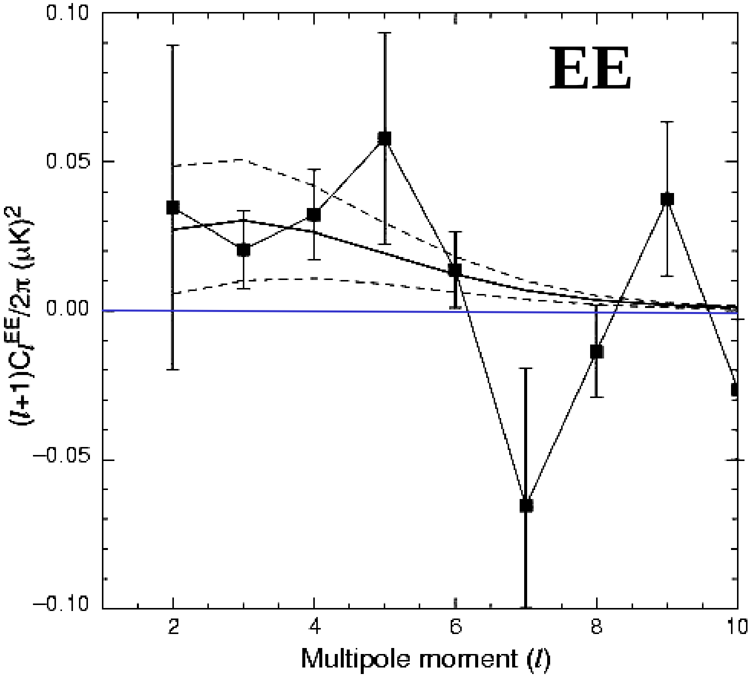
"the n_s - tau" degeneracy

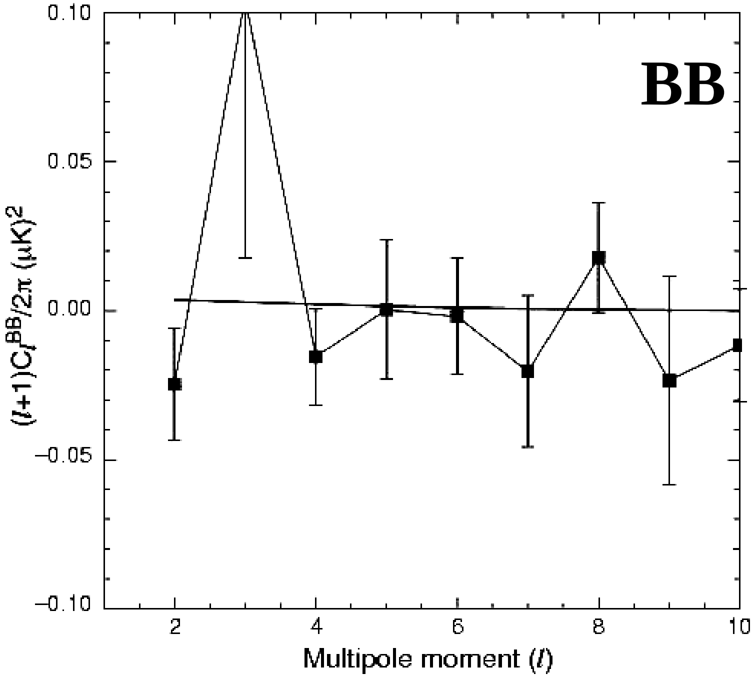
WMAP measures (2) to break the degeneracy



TT
TE
EE
BB
r=0.3
BB inflation
Approx EE/BB
foreground
BB Lensing (not primordial)
100.00
10.00
1.00
0.10
0.01
1
10
100
1000
Multipole moment (l)
{ l(l+1) C_l / 2π }^1/2 [μK]
WMAP
DASI05
CBI05
B03
CAPMAP
Multipole (ℓ)

Low-l EE/BB





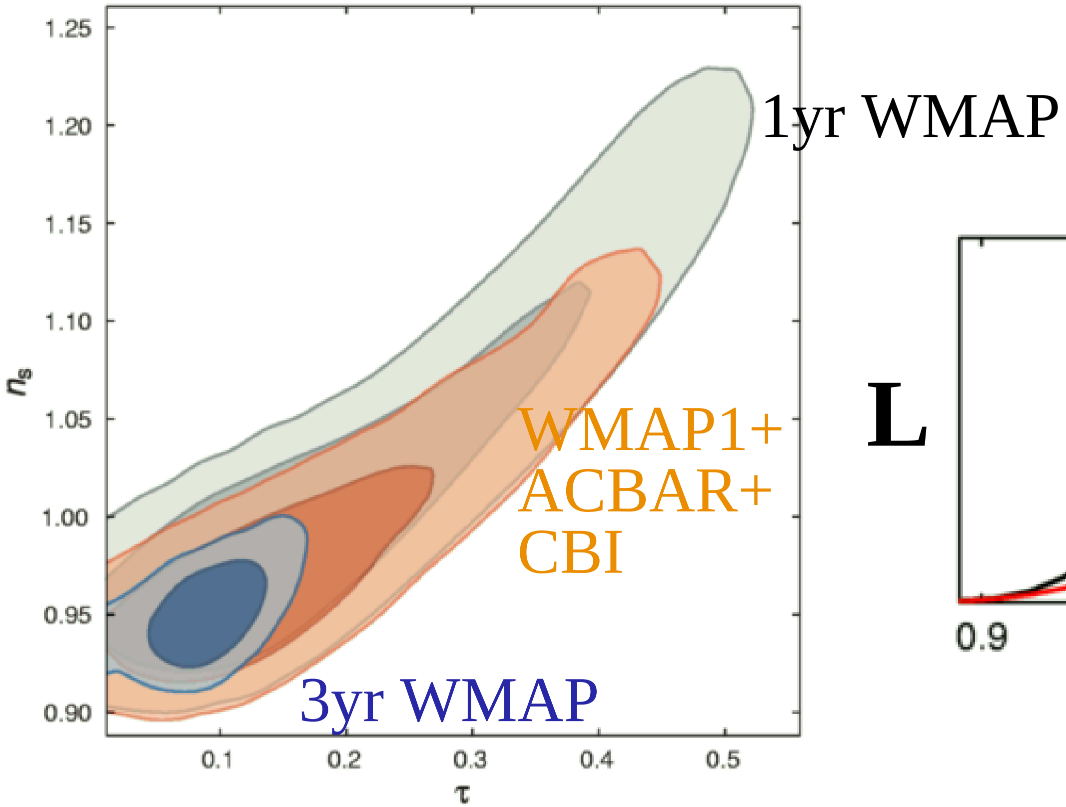
EE Polarization: from reionization by the first stars

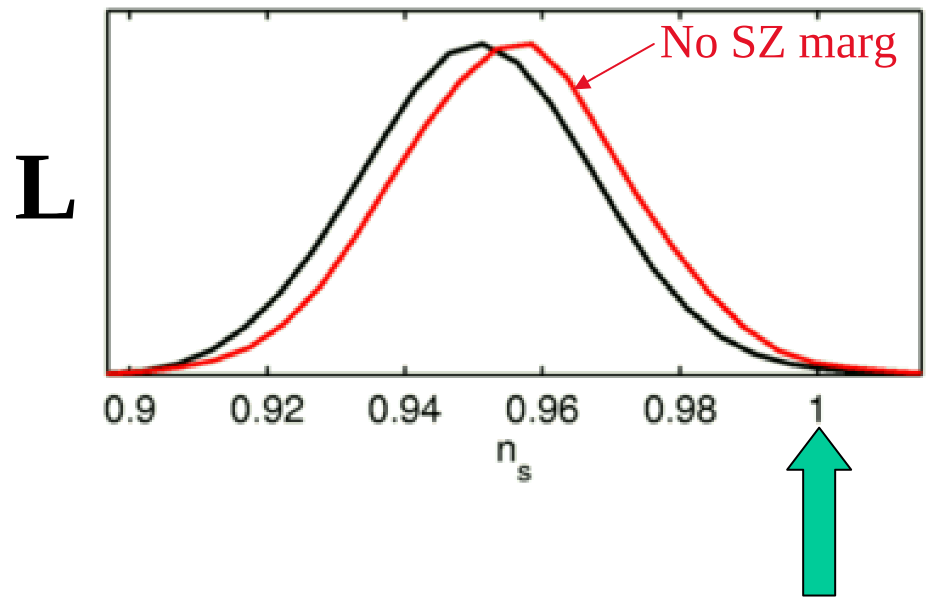
BB Polarization: null check and limit on gravitational waves.

Just Q and V bands.

r<2.2 (95% CL) from just EE/BB

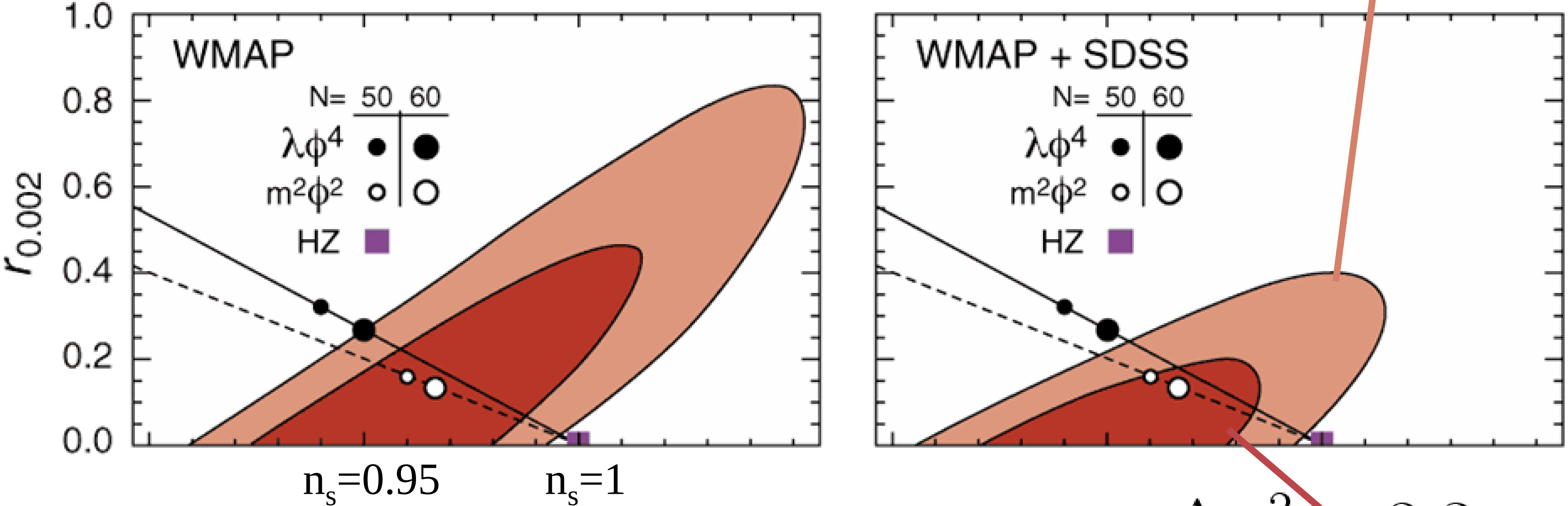
$n_s - \tau$ Degeneracy





Knowledge of optical depth breaks the $n_s - \tau$ degeneracy

Index and Tensors



(2σ in 2d)

$$\Delta\chi^2 = 6.17$$

$$\Delta\chi^2 = 2.3$$

(1σ in 2d)

What Does the Model Need to Describe the Data?

changing one of the 6 parameters at a time….

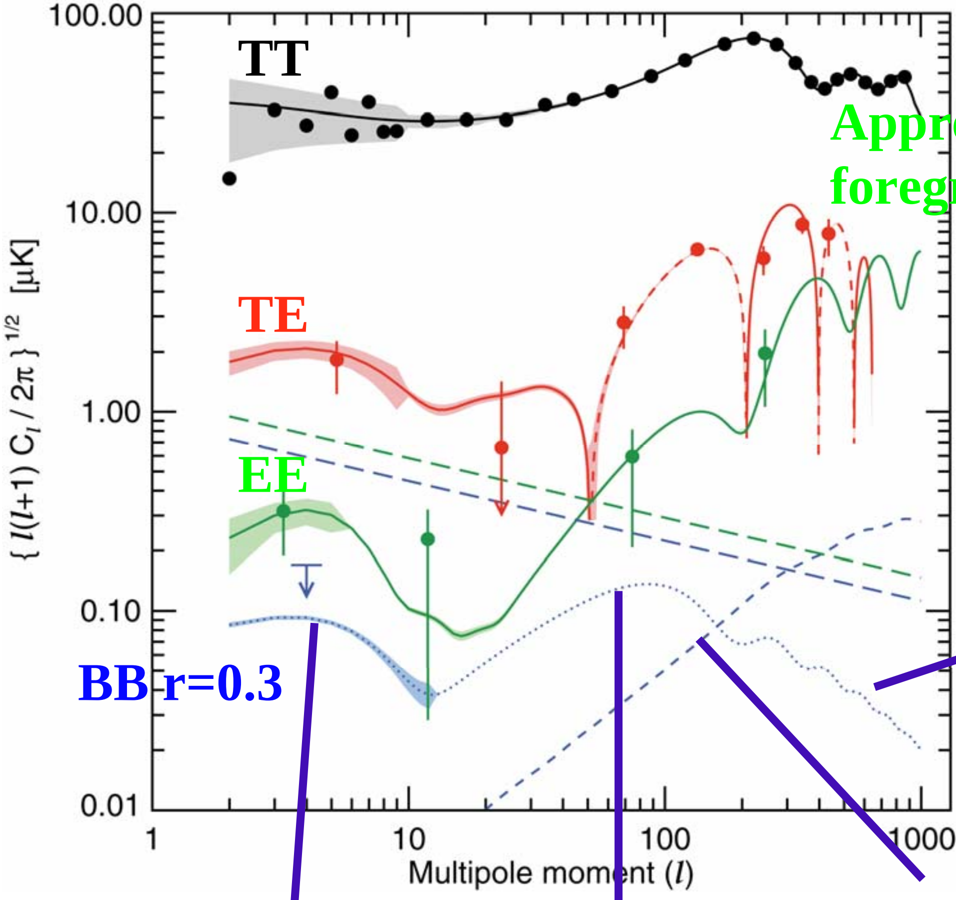
- Model needs $\tau, \Delta\chi^2 = 8$ ("2.8 sigma")
- Model needs n_s not unity, $\Delta\chi^2 = 6$
- Model needs dark matter, $\Delta\chi^2 = 248$ ("15 sigma")

….but Eriksen & Huffenberger

- Model does not need: "running," r, or massive neutrinos, $\Delta\chi^2 < 3$.

The data are, of course, less restrictive when there are more parameters.

Gravitational Waves



B modes from tensors only.

$$\delta T_l^B \propto r^{1/2} \propto E_{infla}^2$$

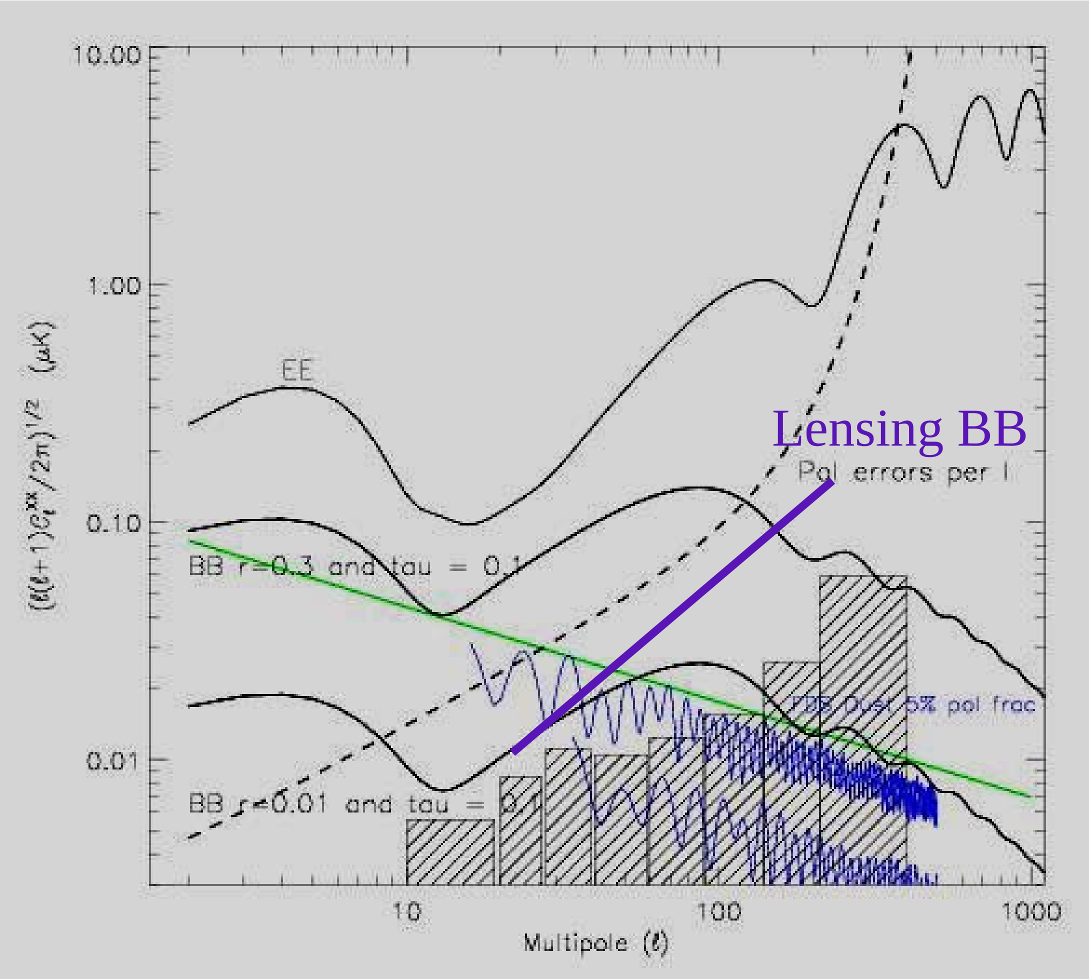
G-waves decay once inside the horizon.

B modes from lensing of E modes (not primordial).

Reionization peak (z_r=10)

Horizon size at decoupling (z_{dec}=1089)

Expectations at l=100



From Jo Dunkley

Dust at 150 GHz from FDS

1000 close packed dets for 1 year at 350 uK-sec^{1/2} raw or 700 uK-sec^{1/2} on sky.

Boxes inst sensitivity not sky rms sens.

Lensing B modes

Non-Gaussanity

- The quadrapole is not anomalously low. For the full sky, the 2-pt correlation function is not anomalous.
- All “detections” of non-Gaussanity are based on *a posteriori* statistics. That is, one seeks any oddity in the maps and quantifies it.
- The North-South asymmetry was visible in the COBE data.

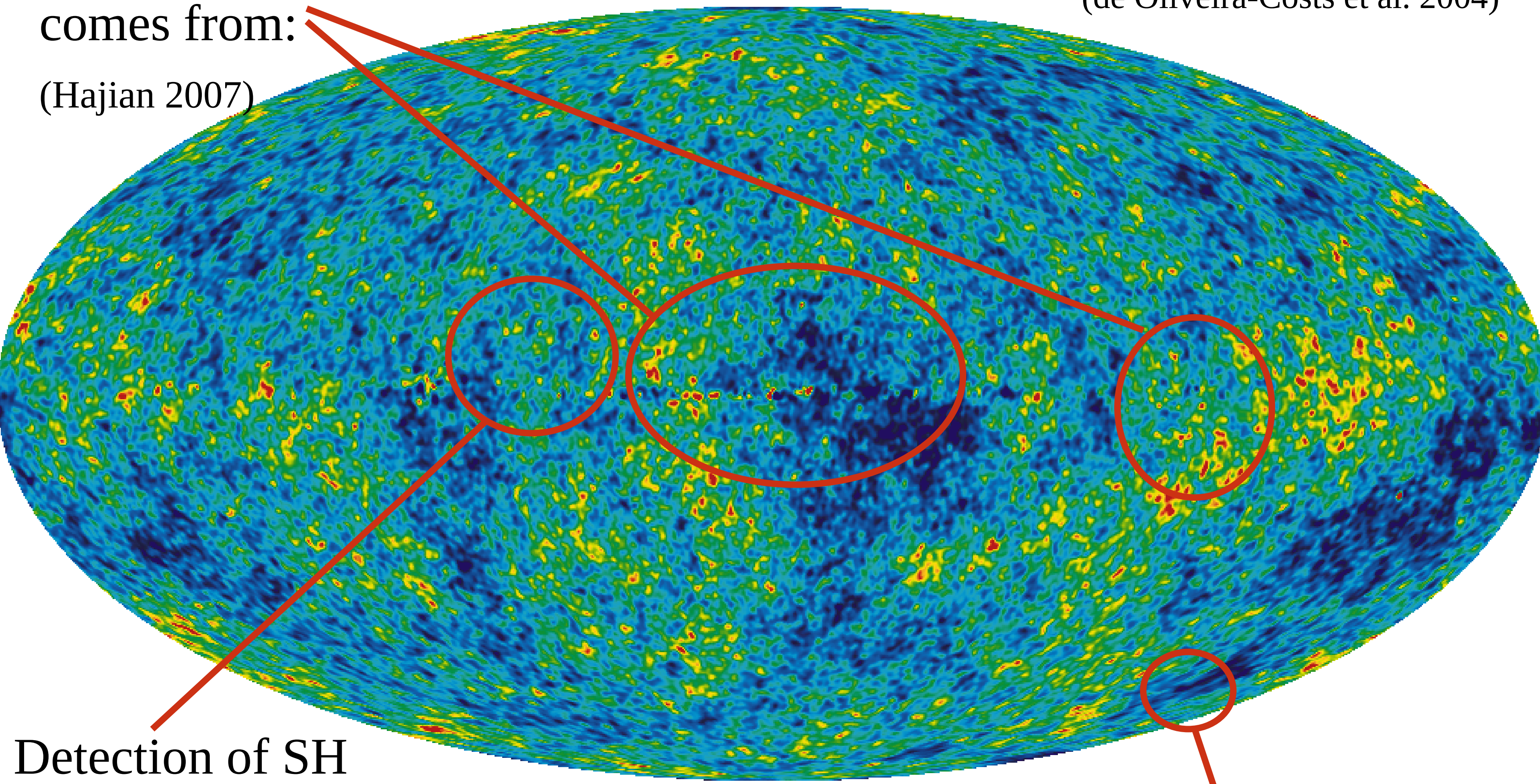
It would be fantastic to find a clear signature of cosmic non-Gaussanity. The WMAP team has not found one.

A significant fraction of the full-sky quadrupole comes from:

(Hajian 2007)

Alignment? See Max!

(de Oliveira-Costs et al. 2004)

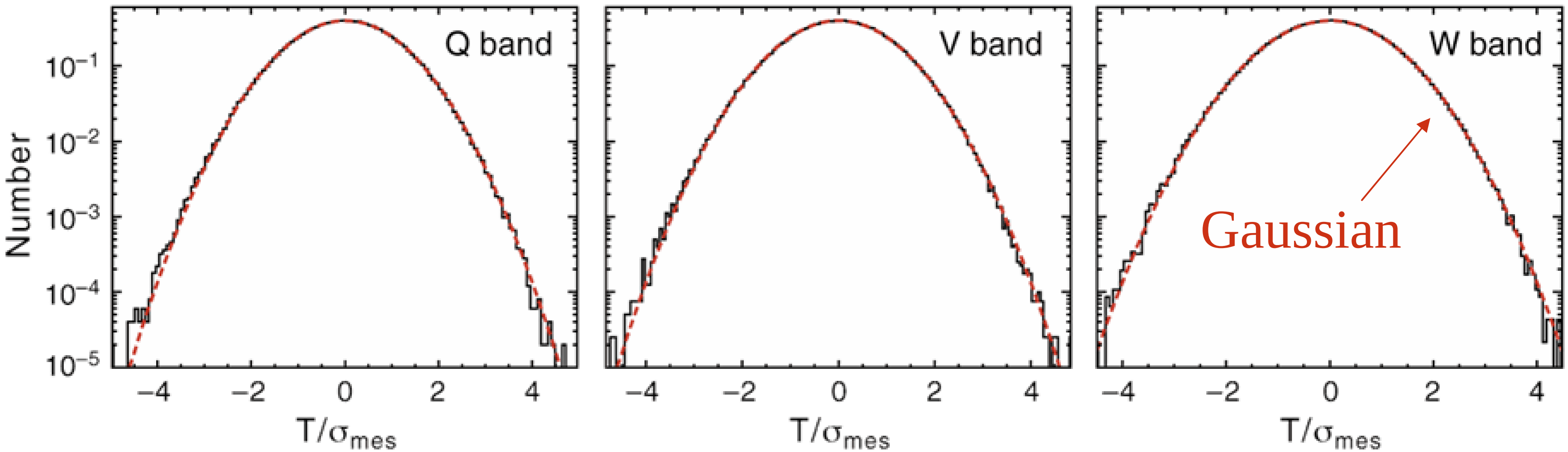


Detection of SH persists!

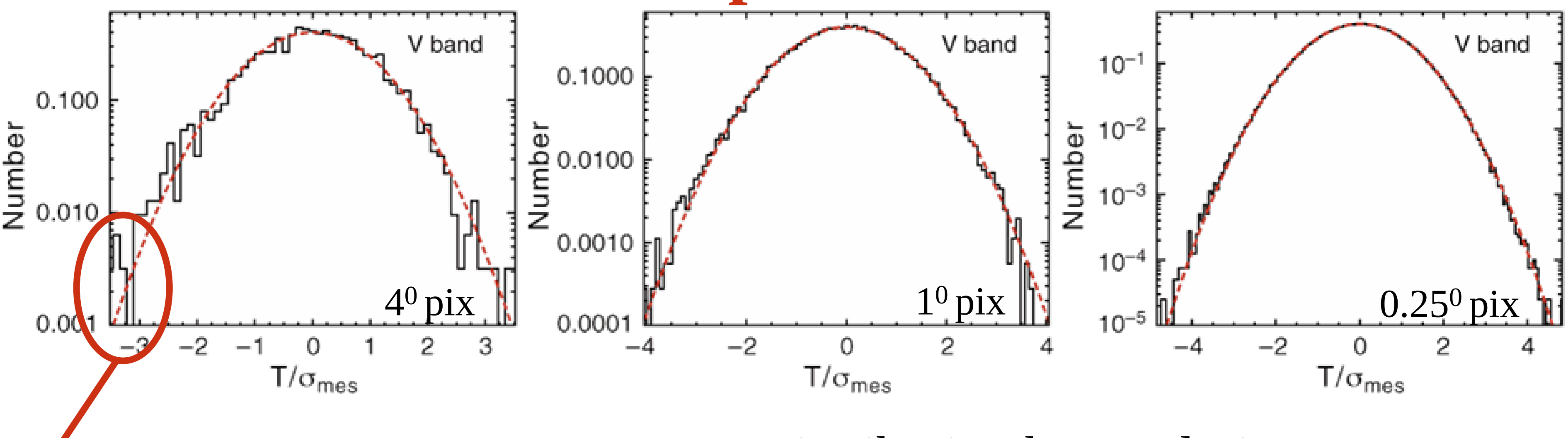
Extra cold spot:

(Vielva et al. 2004, Cruz et al. gave 1.8% prob. 2005)

Distribution by map temp. by frequency (accounting for uneven weighting)



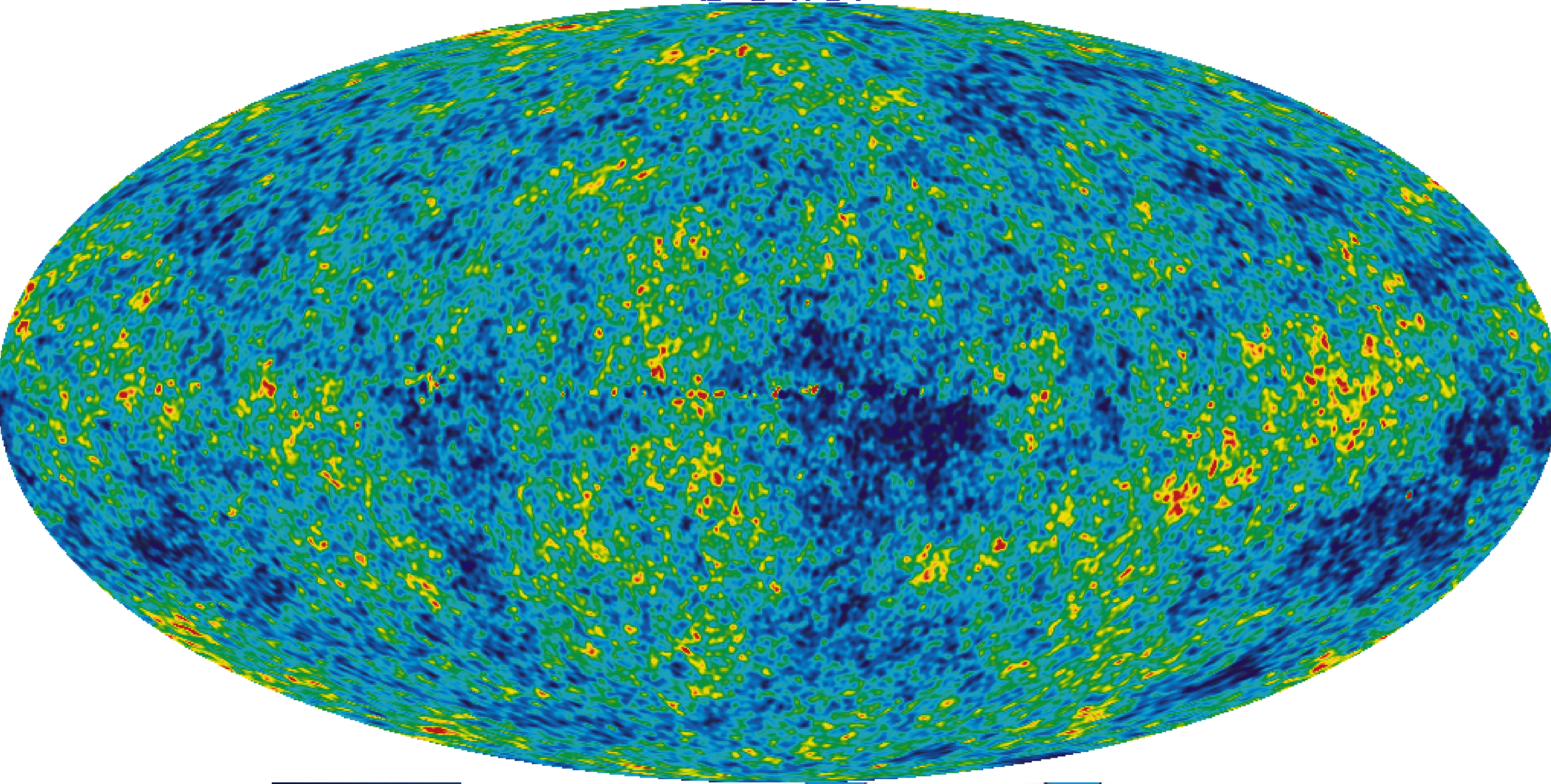
Data are an excellent representation of a Gaussian!



Cold spot

Distribution by resolution.

What's Next?



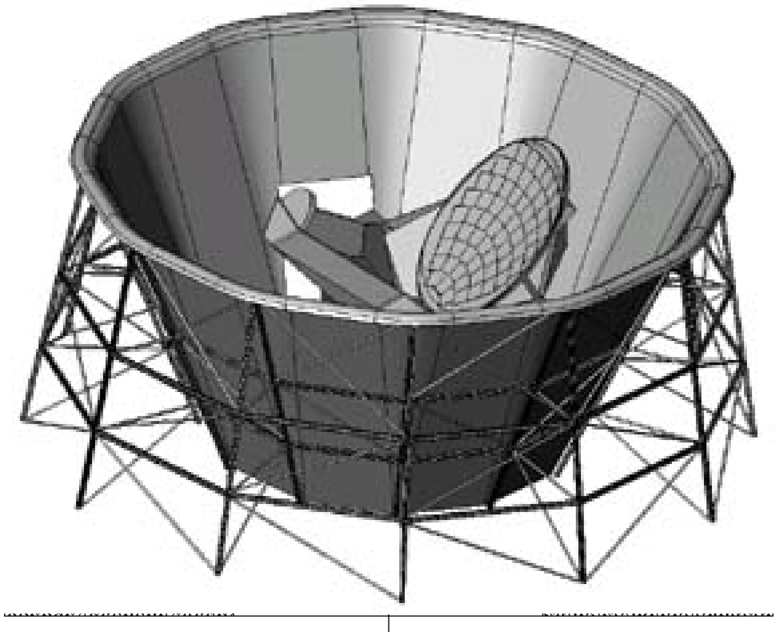
POLARBEAR

(50 bolometers)
L2, data 2012

ACT

Science:
- ★Growth of structure
- ★Eqn. of state
- ★Neutrino mass
- ★Ionization history
- ★Inflation
- ★Power spectrum

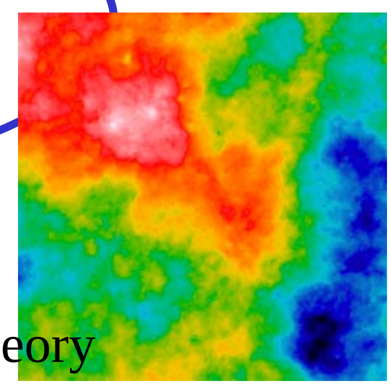
Observations:
- ★CMB: l>1000
- ★ Cluster (SZ, KSZ X-rays, & optical)
- ★ Diffuse SZ
- ★ OV/KSZ
- ★ Lensing



X-ray

Optical

Theory



Collaboration:

Cardiff | Columbia | CUNY | Haverford | INAOE | NASA/GSFC | NIST | Princeton

Rutgers | UBC | U. Catolica | U. KwaZulu-Natal | UMass | UPenn | U. Pittsburgh | U. Toronto

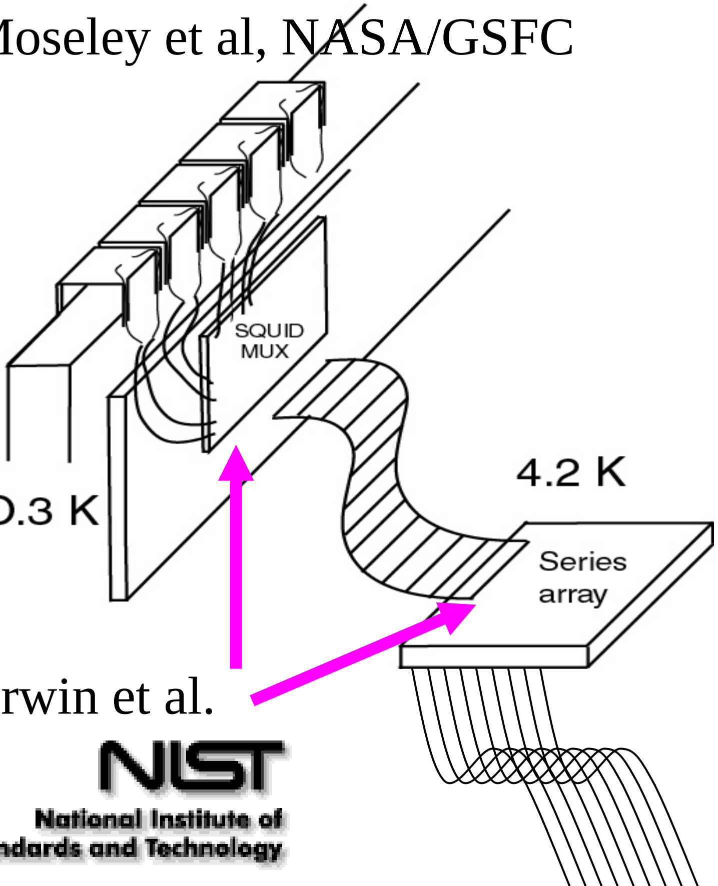
New Type of Telescope

M. Devlin is lead

Telescope at AMEC in Vancouver. Ship to Chile in 2006.

Arrays of bolometers (S. Staggs is lead)

Moseley et al, NASA/GSFC

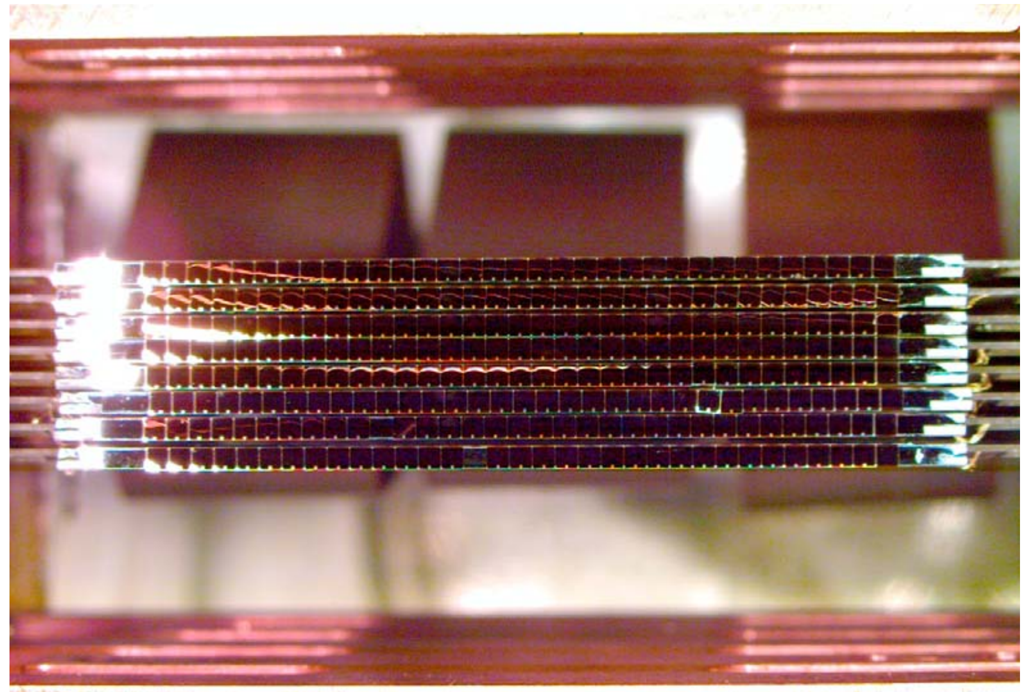


Irwin et al.

National Institute of Standards and Technology

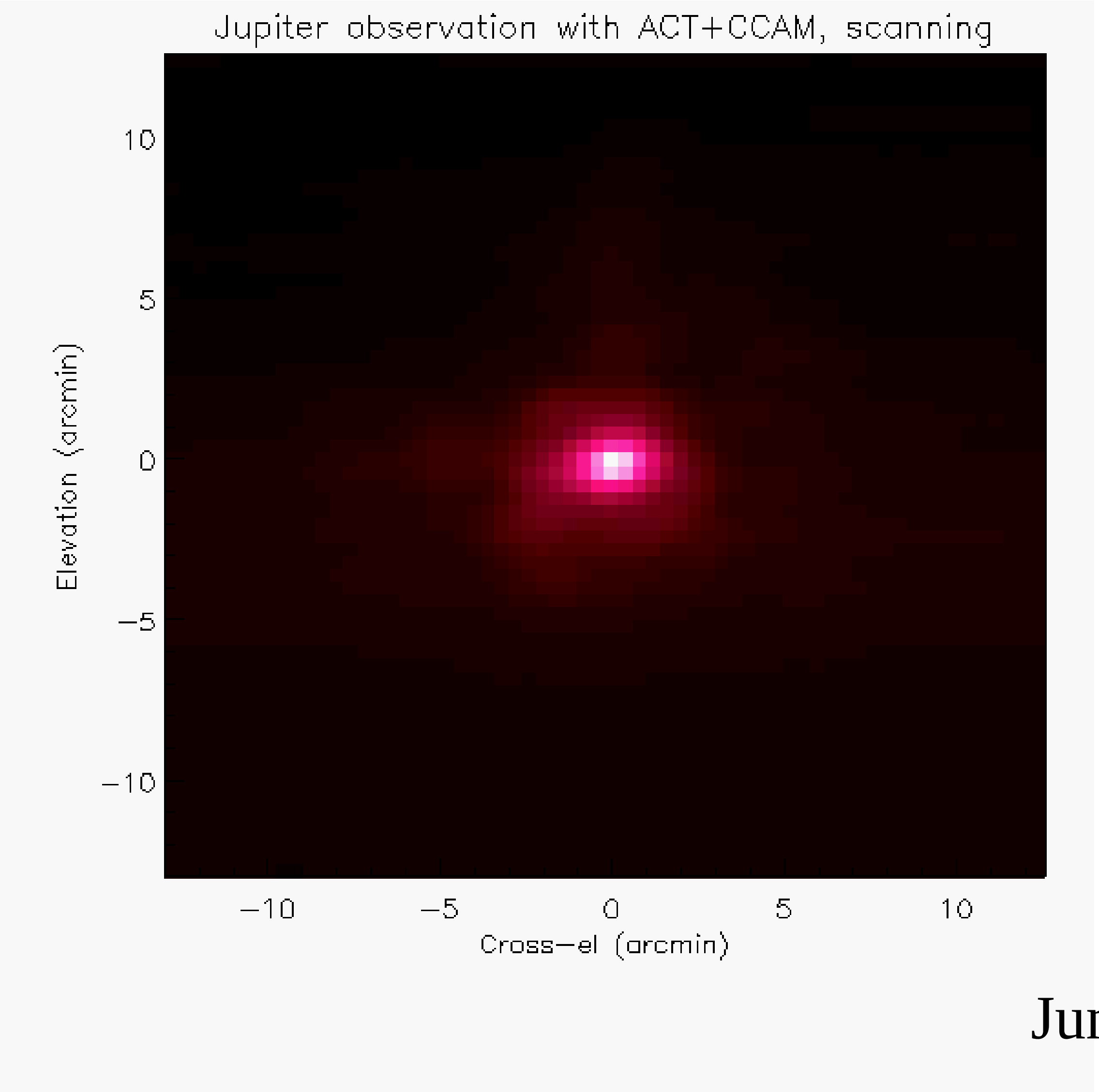
Warm electronics based on SCUBA2

Halpern et al. **UBC**



8x32 Array of 1mm x 1mm detectors. Now in Chile on the telescope.

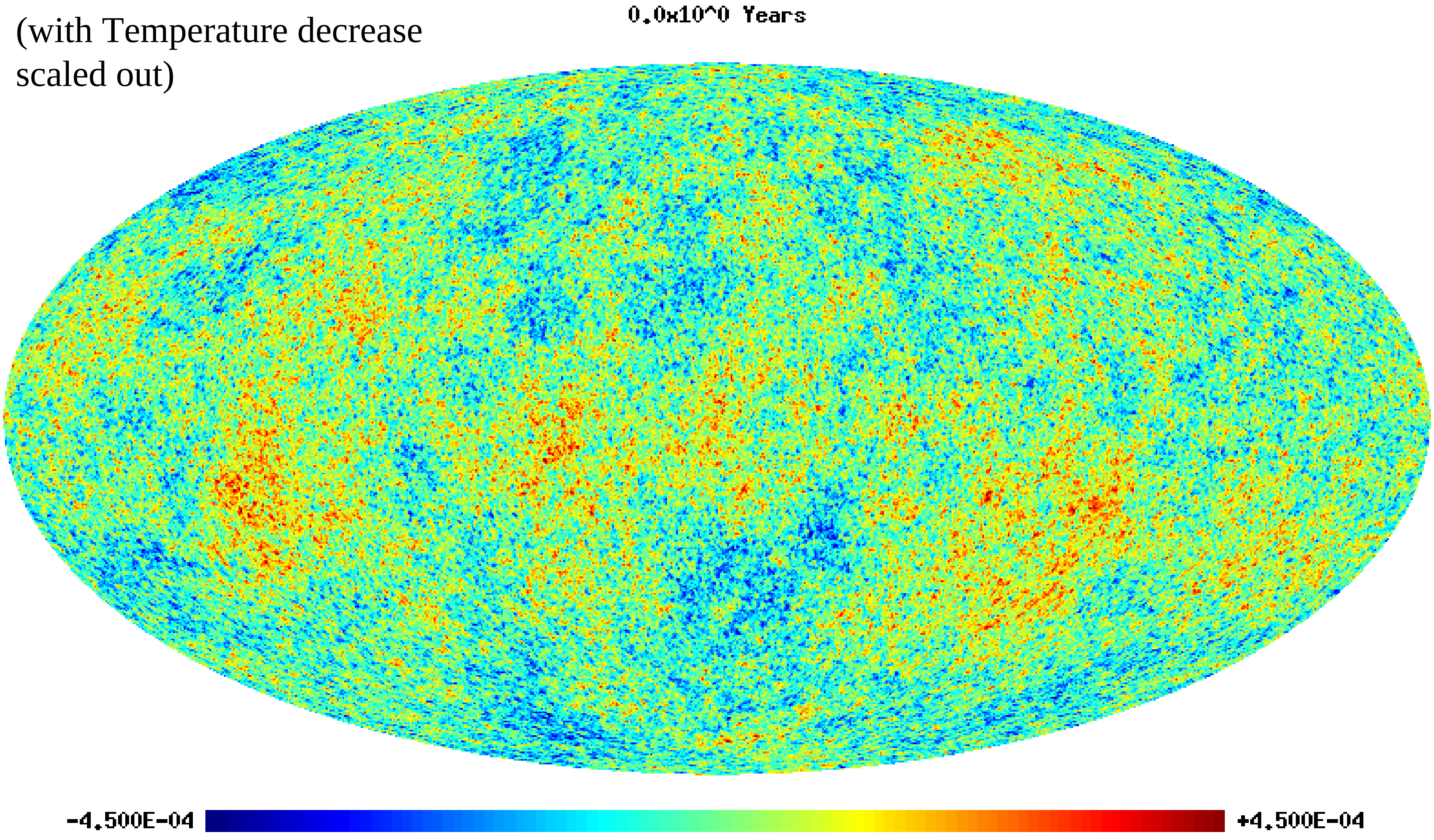
First Light from ACT



June 8, 2007

Expanding CMB Photosphere

(with Temperature decrease scaled out)

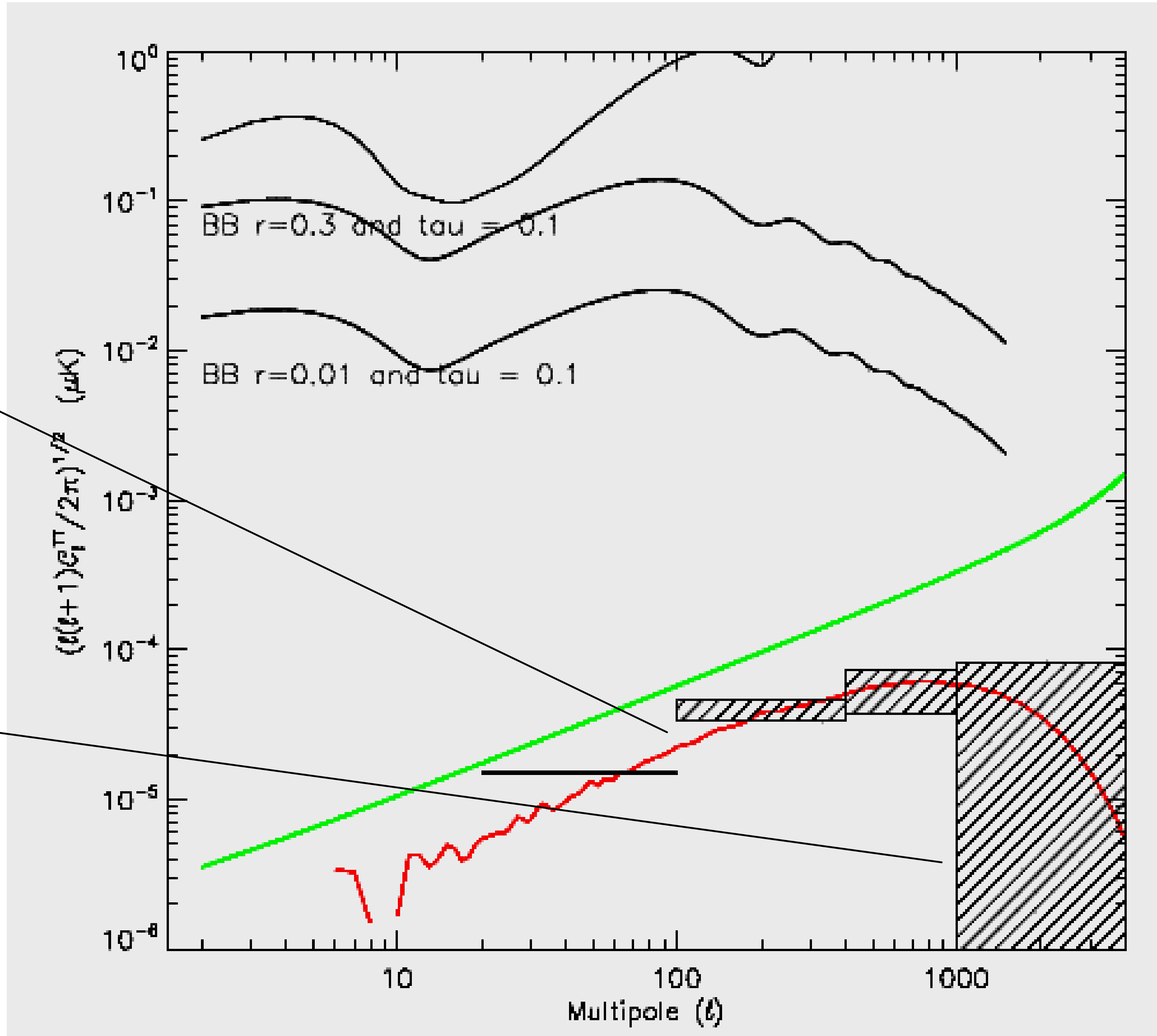


Stuart Lange, Senior Thesis, 2007

An Experiment for the Century

Power spectrum of difference between two maps made 100 years apart.

Error bars with a 3000x3000 array of detectors.



Thank You!