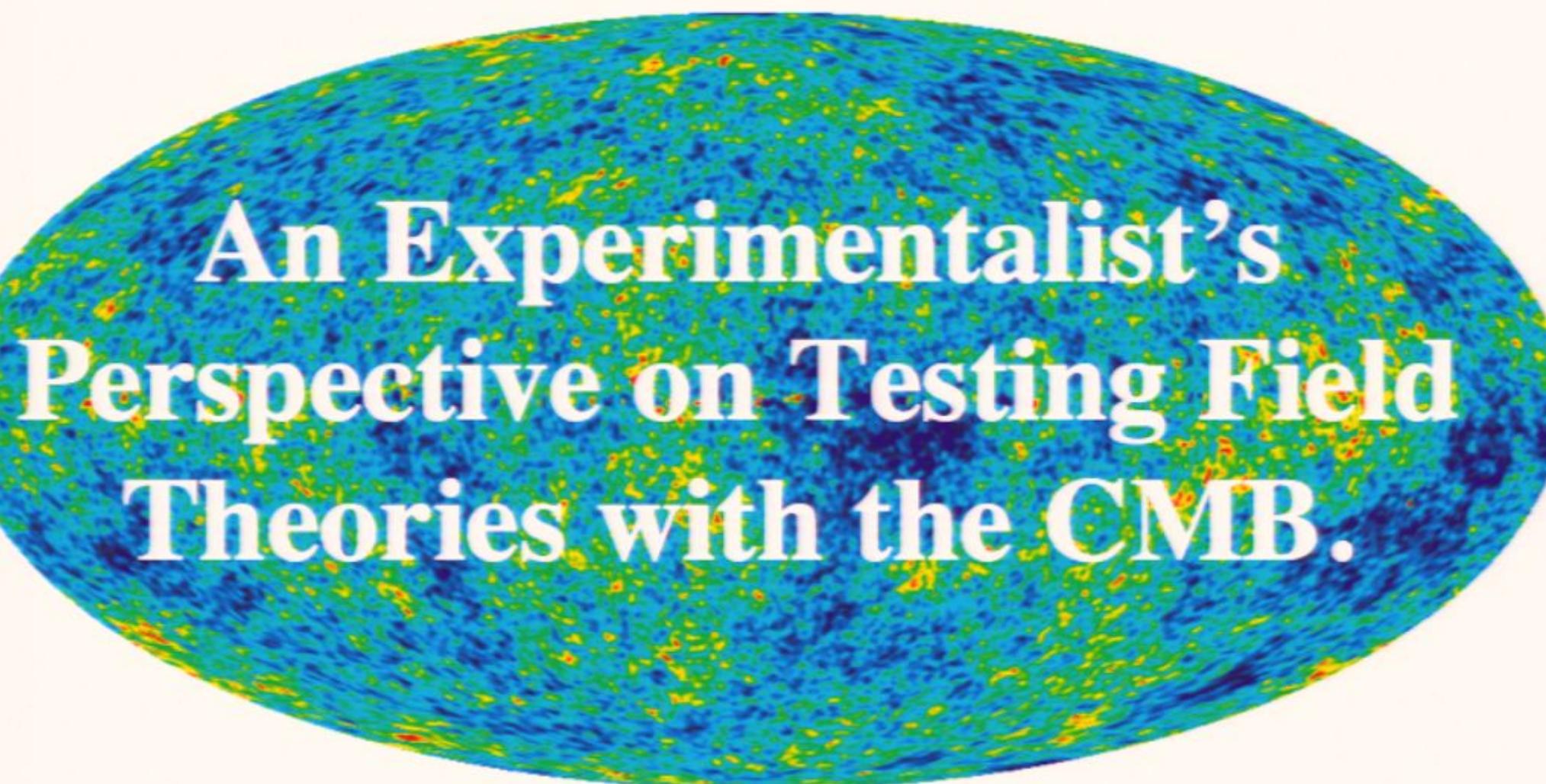


Title: An Experimentalist's Perspective on Testing Field Theories with the CMB

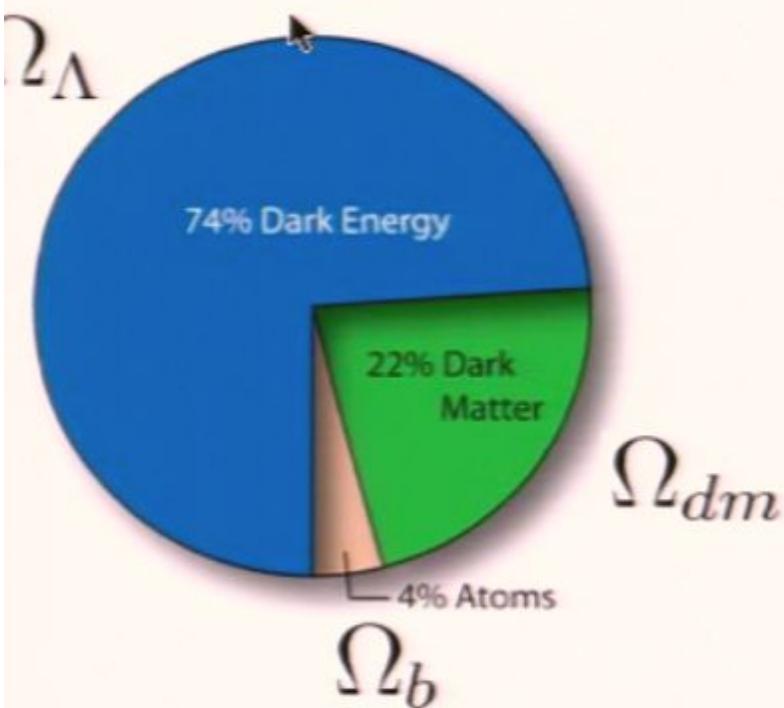
Date: Sep 10, 2007 08:30 AM

URL: <http://pirsa.org/07090032>

Abstract:



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



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 ($>15\sigma$), something that mimics a cosmological constant (many σ), and a deviation from scale invariance ($P(k) \propto k^{n_s=1}$, $\sim 3\sigma$).



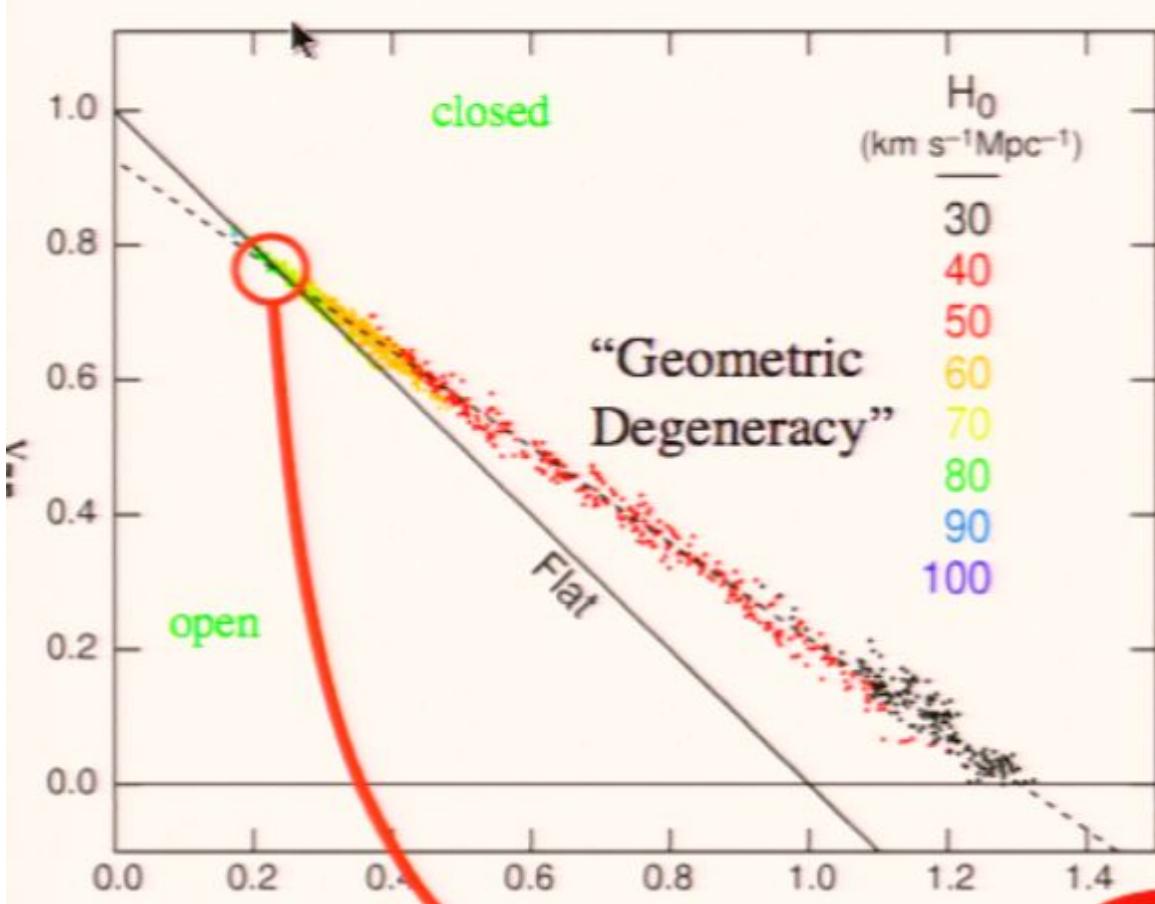
WMAP3 only

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

WMAP3 + all

$$\begin{aligned}\Omega_b h^2 &= 0.02186 \pm 0.0007 \\ \Omega_m h^2 &= 0.132 \pm 0.004 \\ h &= 0.704 \pm 0.015 \\ \sigma_8 &= 0.776 \pm 0.031 \\ \tau &= 0.073 \pm 0.03 \\ n_s &= 0.947 \pm 0.015\end{aligned}$$

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



Reduced $\chi^2 = 1.037$

Assume flatness

$$\Omega_m = \Omega_b + \Omega_c$$

CMB alone tells us we are on the “geometric degeneracy” line

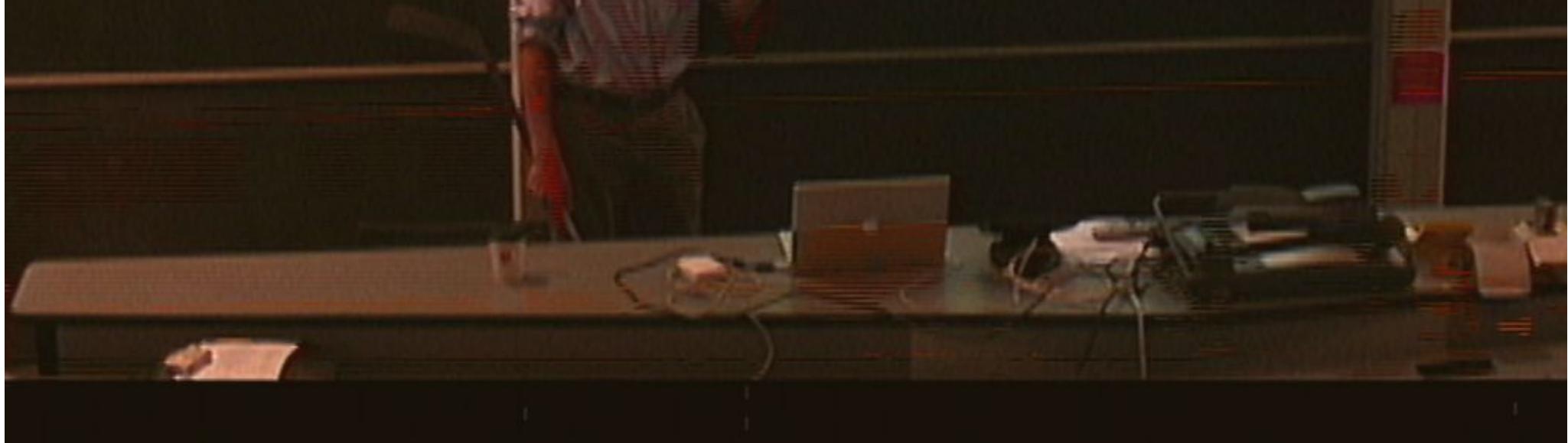
WMAP3 only best fit LCDM

$\Omega_b h^2$	$= 0.02233 \pm 0.0008$
$\Omega_m h^2$	$= 0.126 \pm 0.009$
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σ_8	$= 0.76 \pm 0.05$
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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-Gaussianity



Testing Specific Field Theories

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- (3) Non-Gaussianity**

Types of Cosmological Perturbations

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

Temperature

E polarization

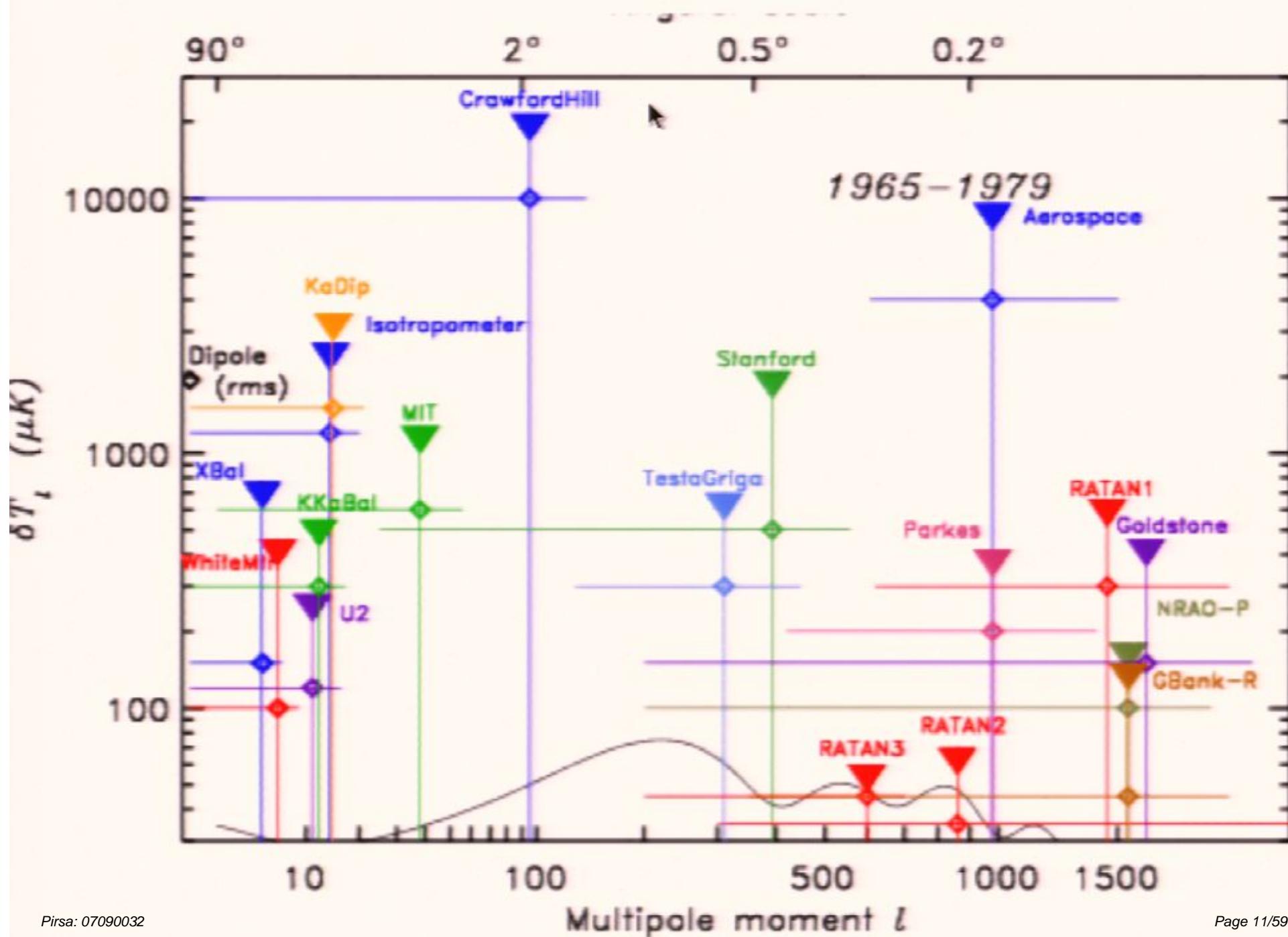
Tensors: h (GW strain)

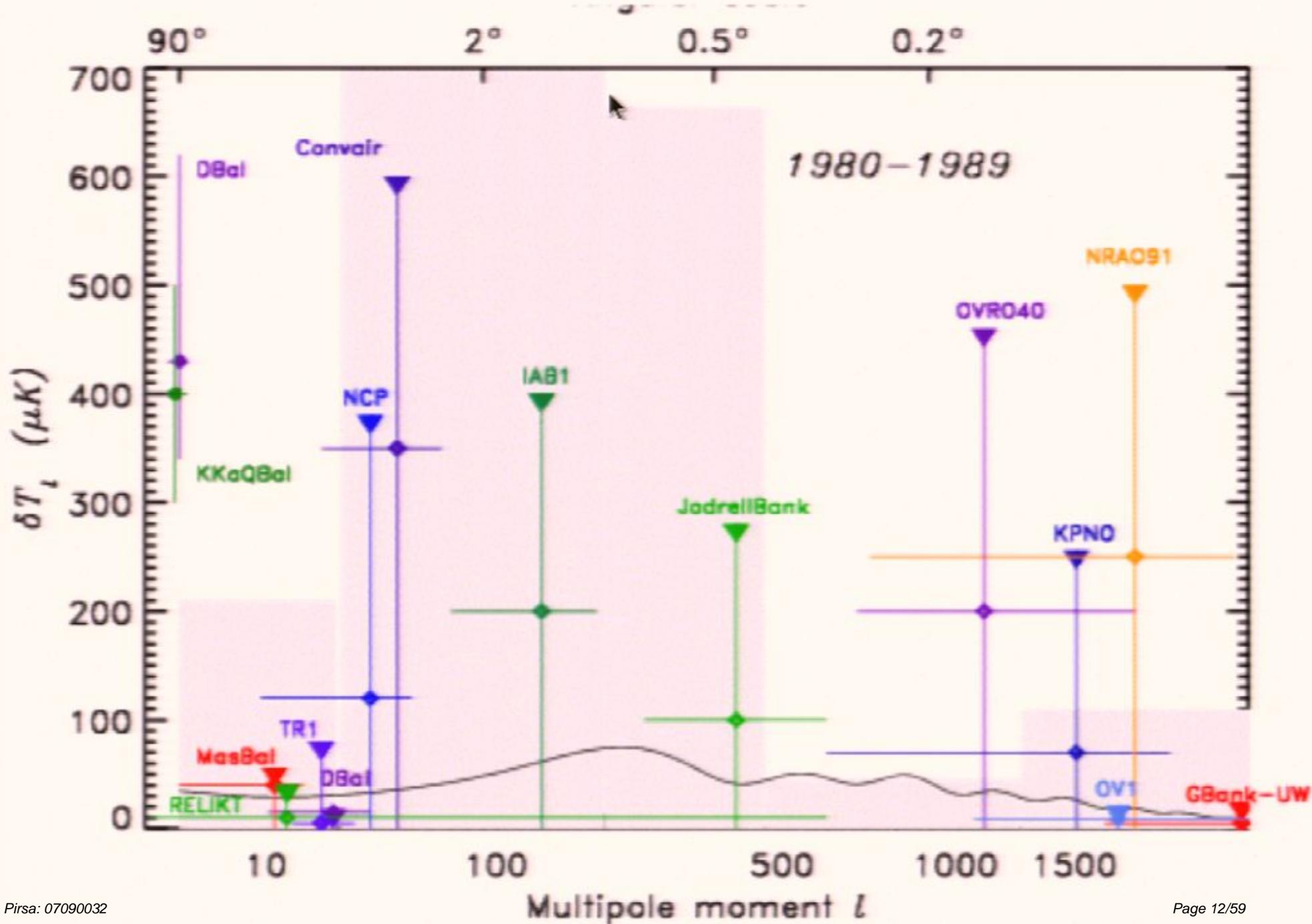
Temperature

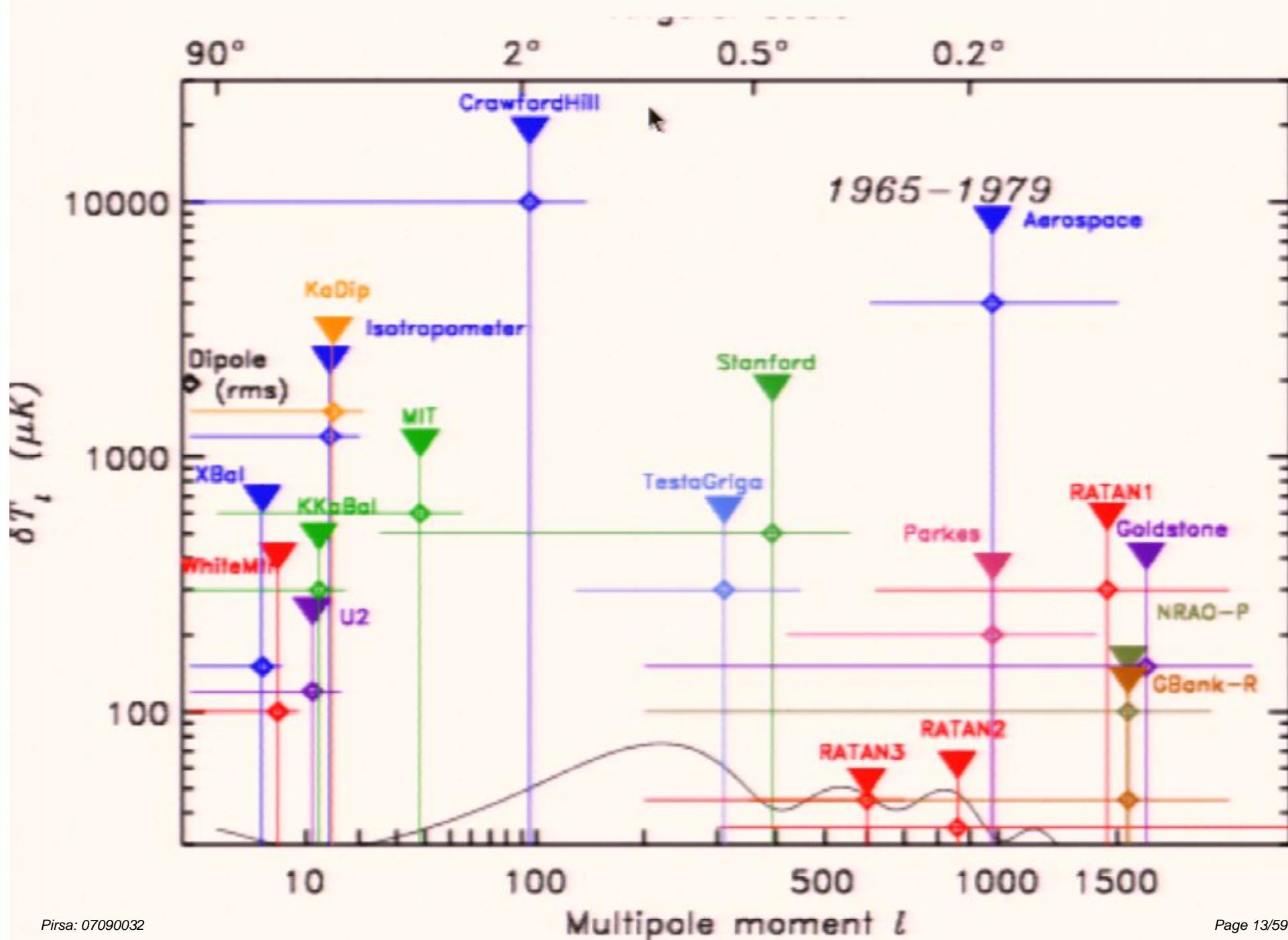
E polarization

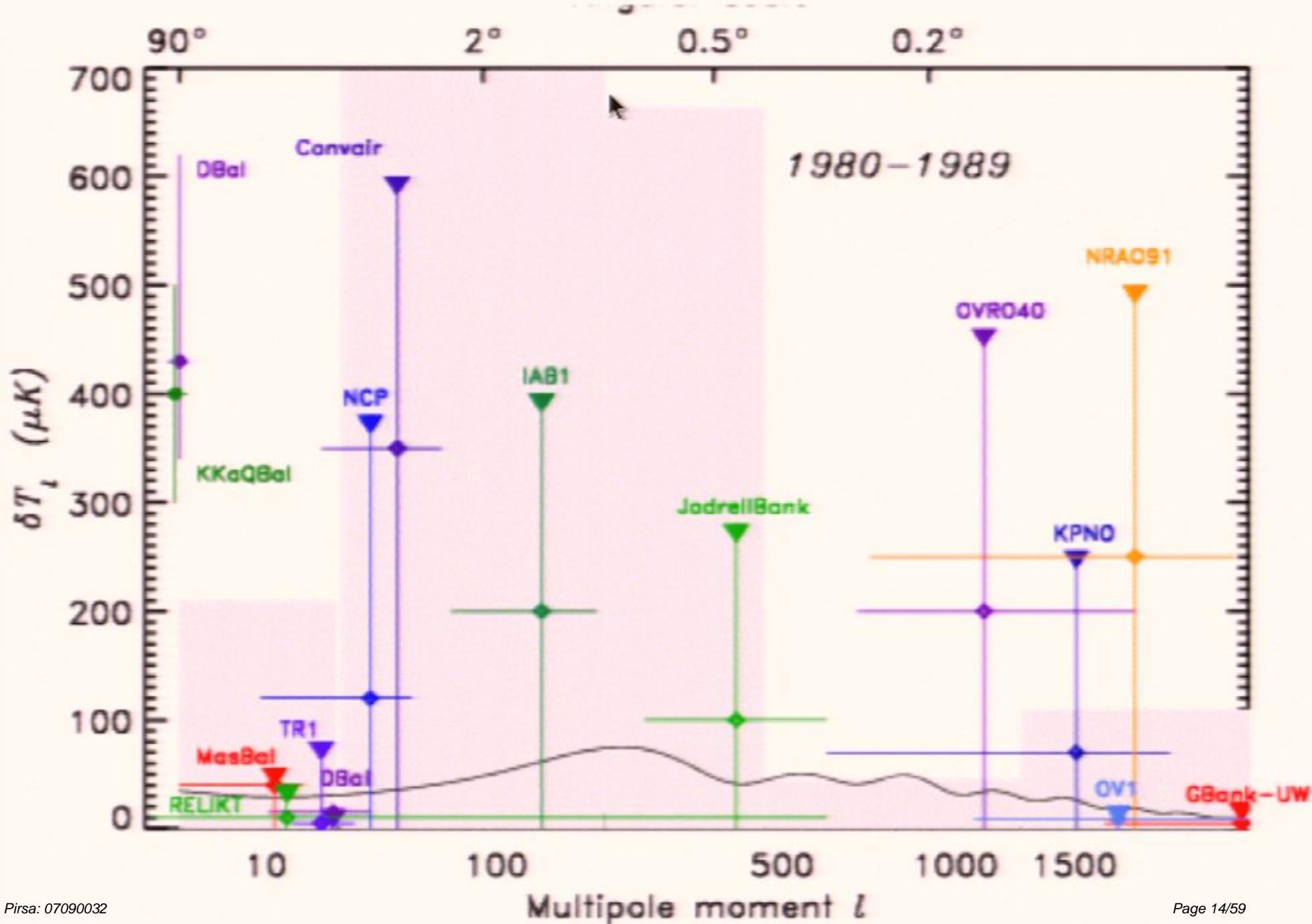
B polarization

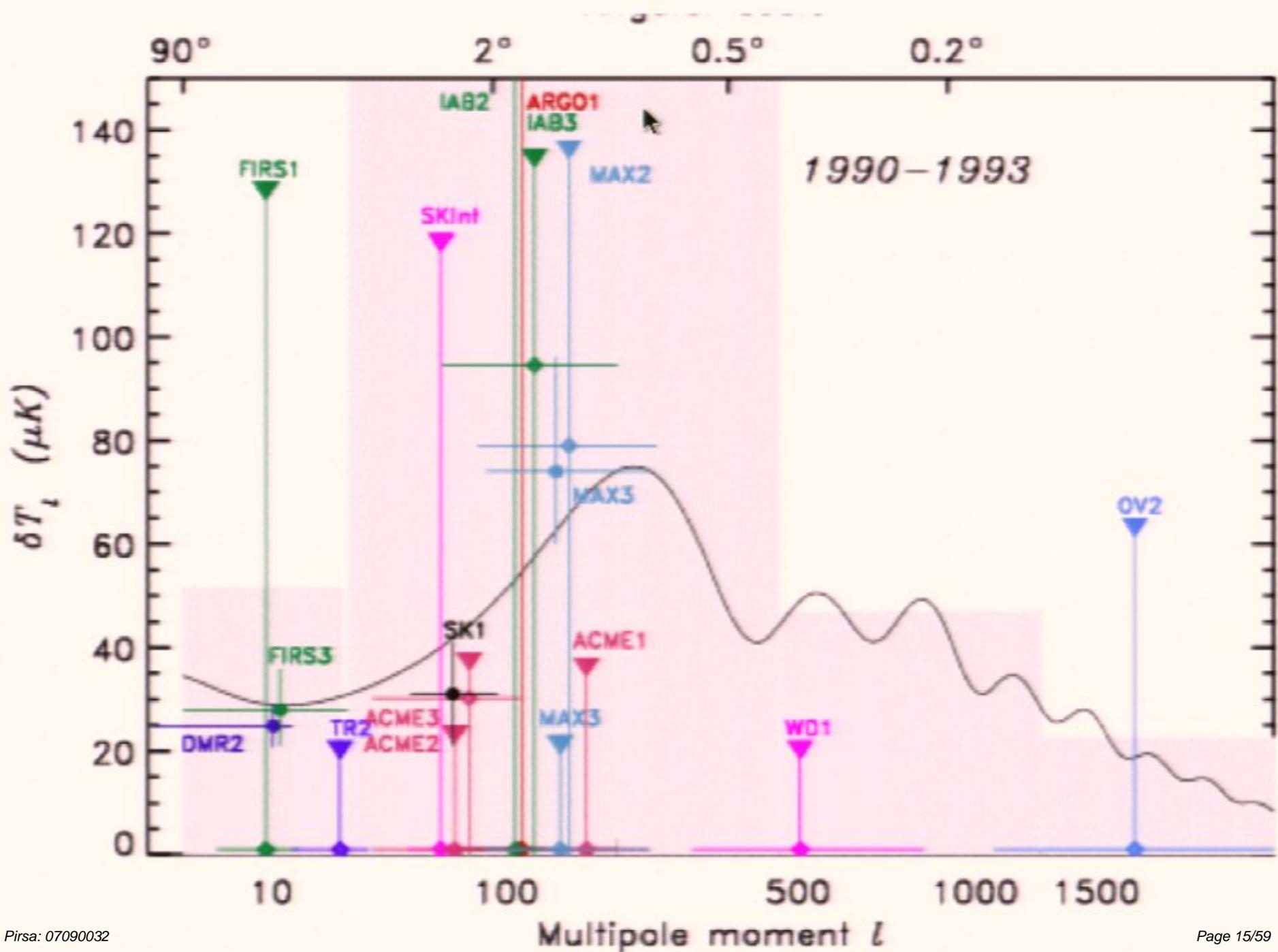
$$r = \frac{\text{Var(Tensors)}}{\text{Var(Scalars)}} \sim 0.3 \quad \text{Or less!}$$

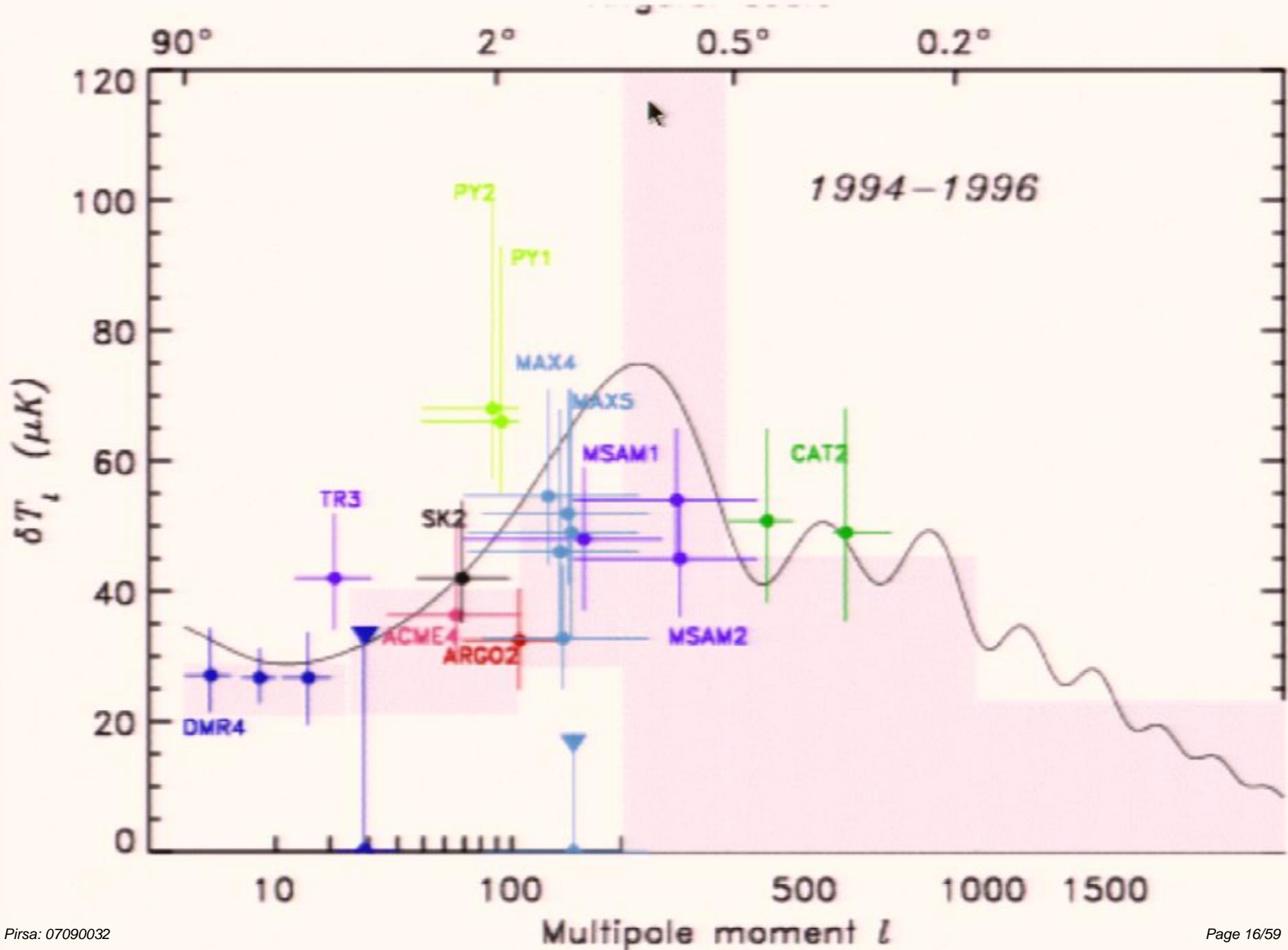


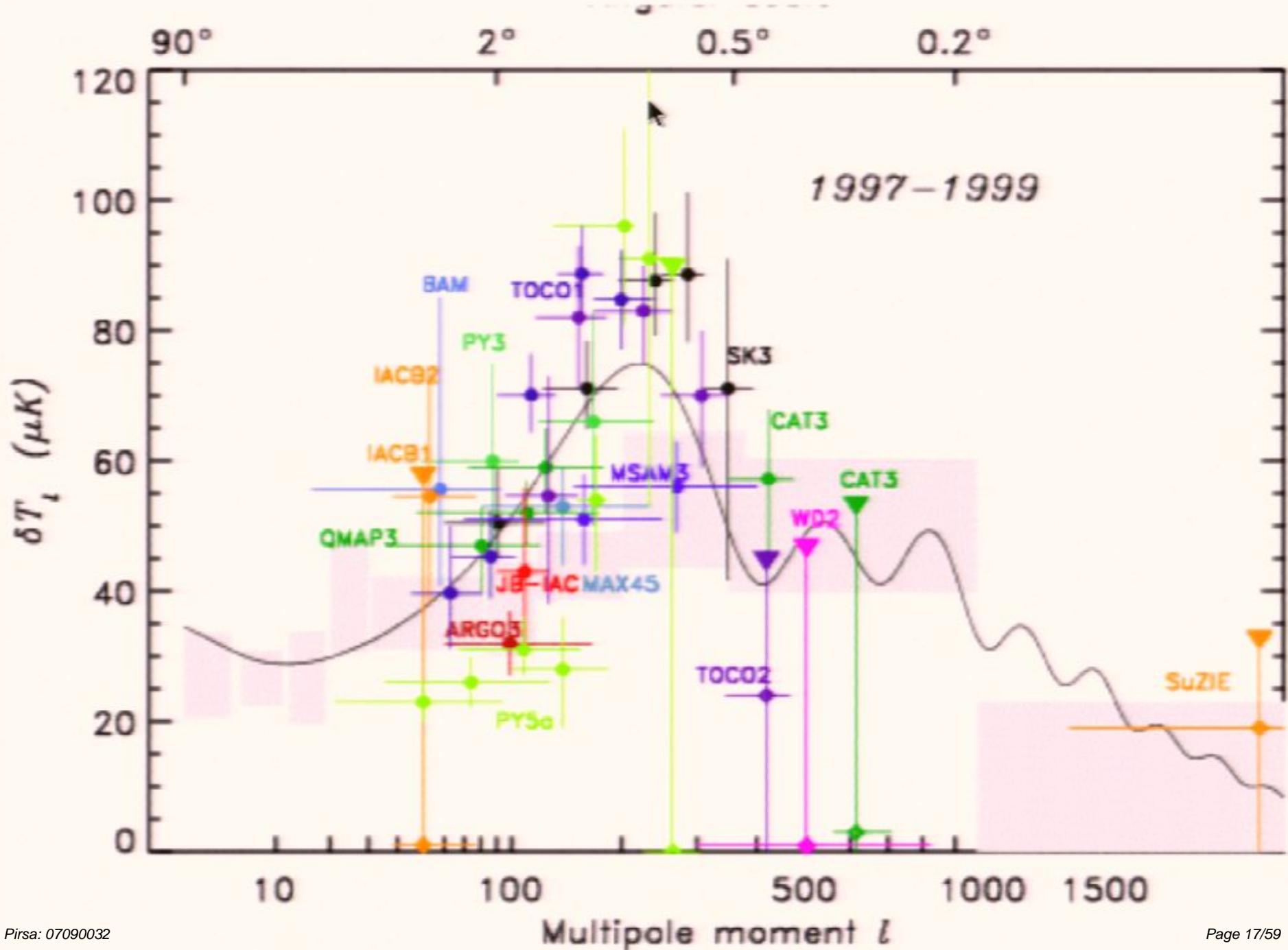


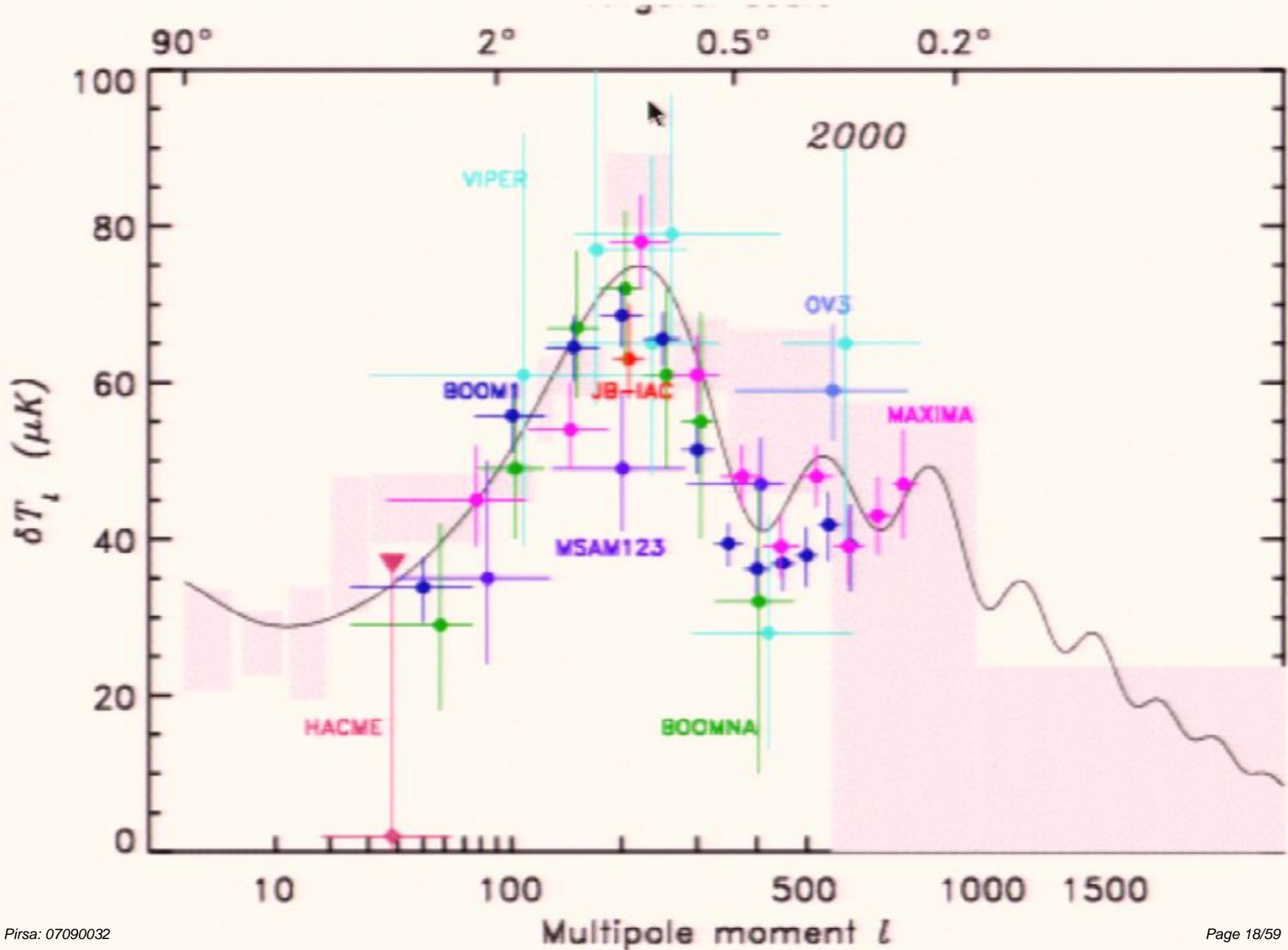


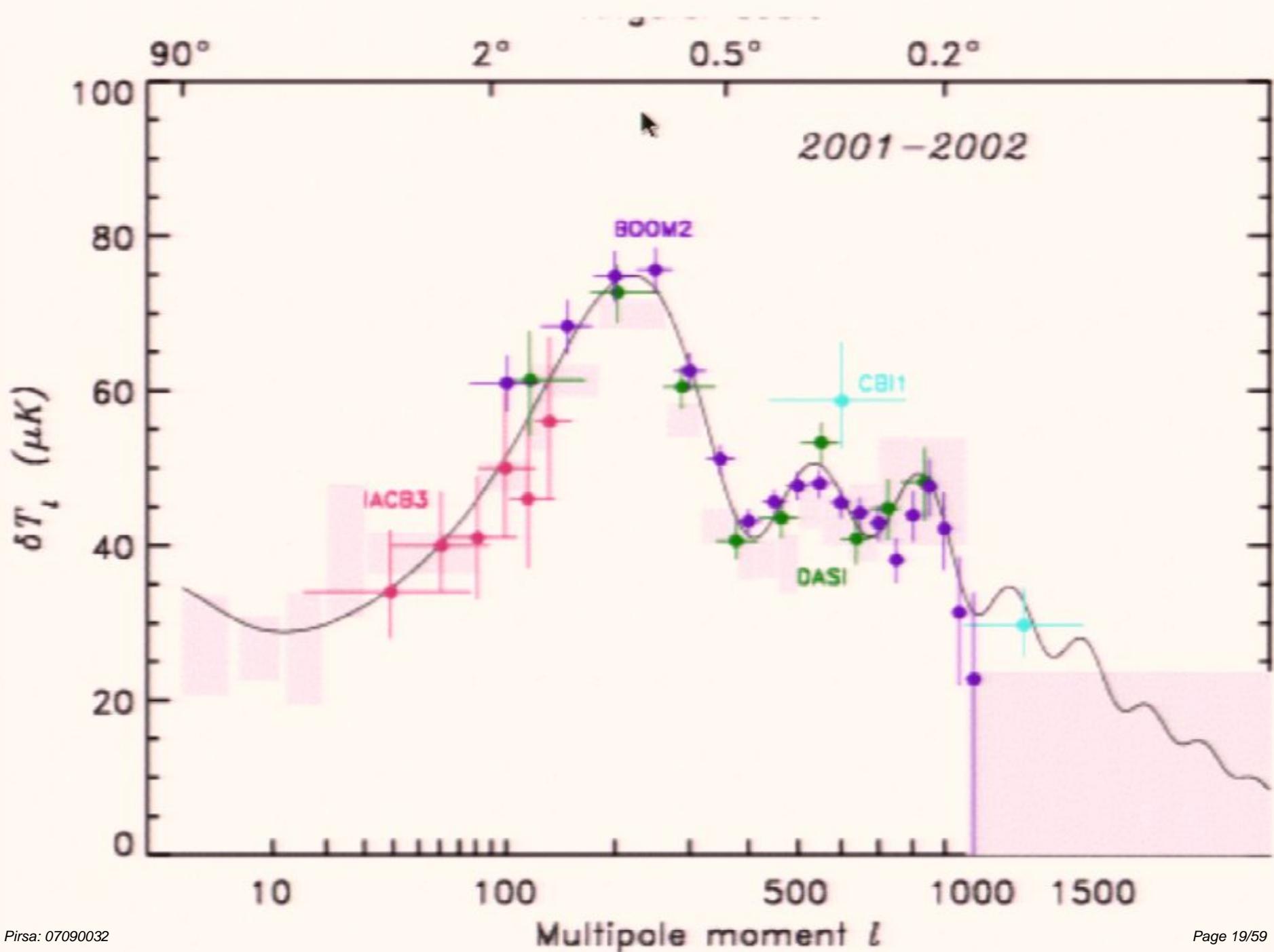


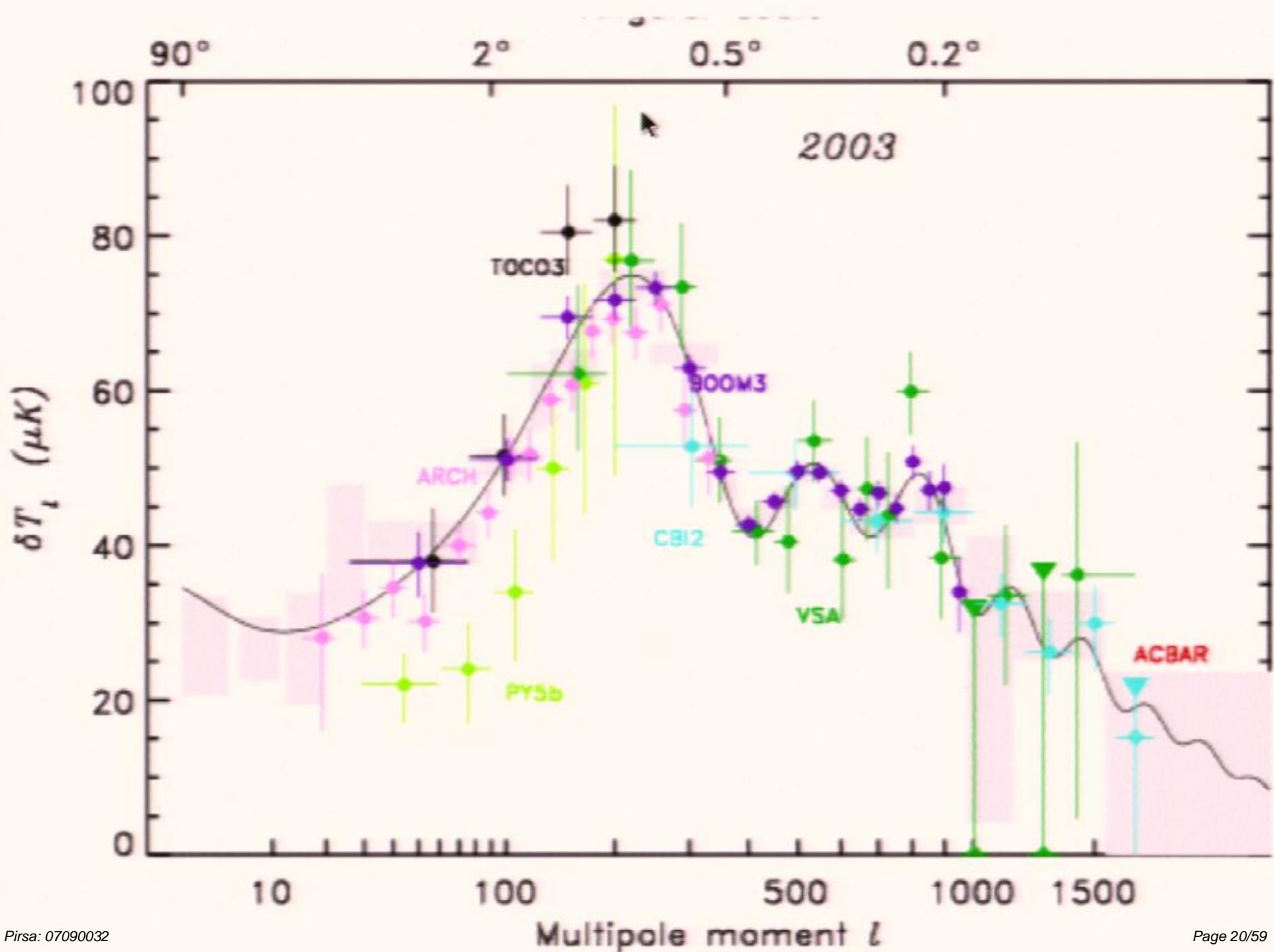


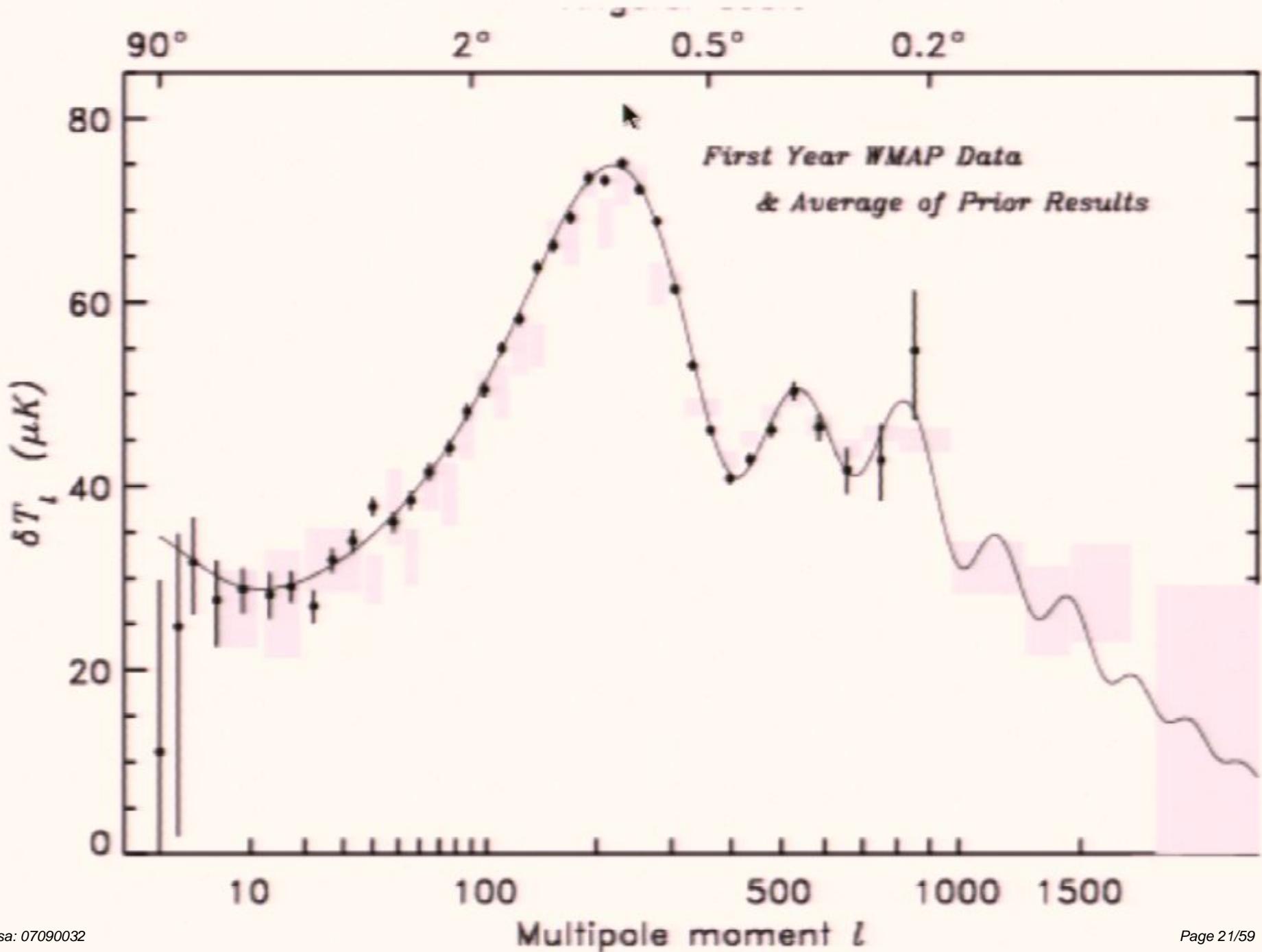




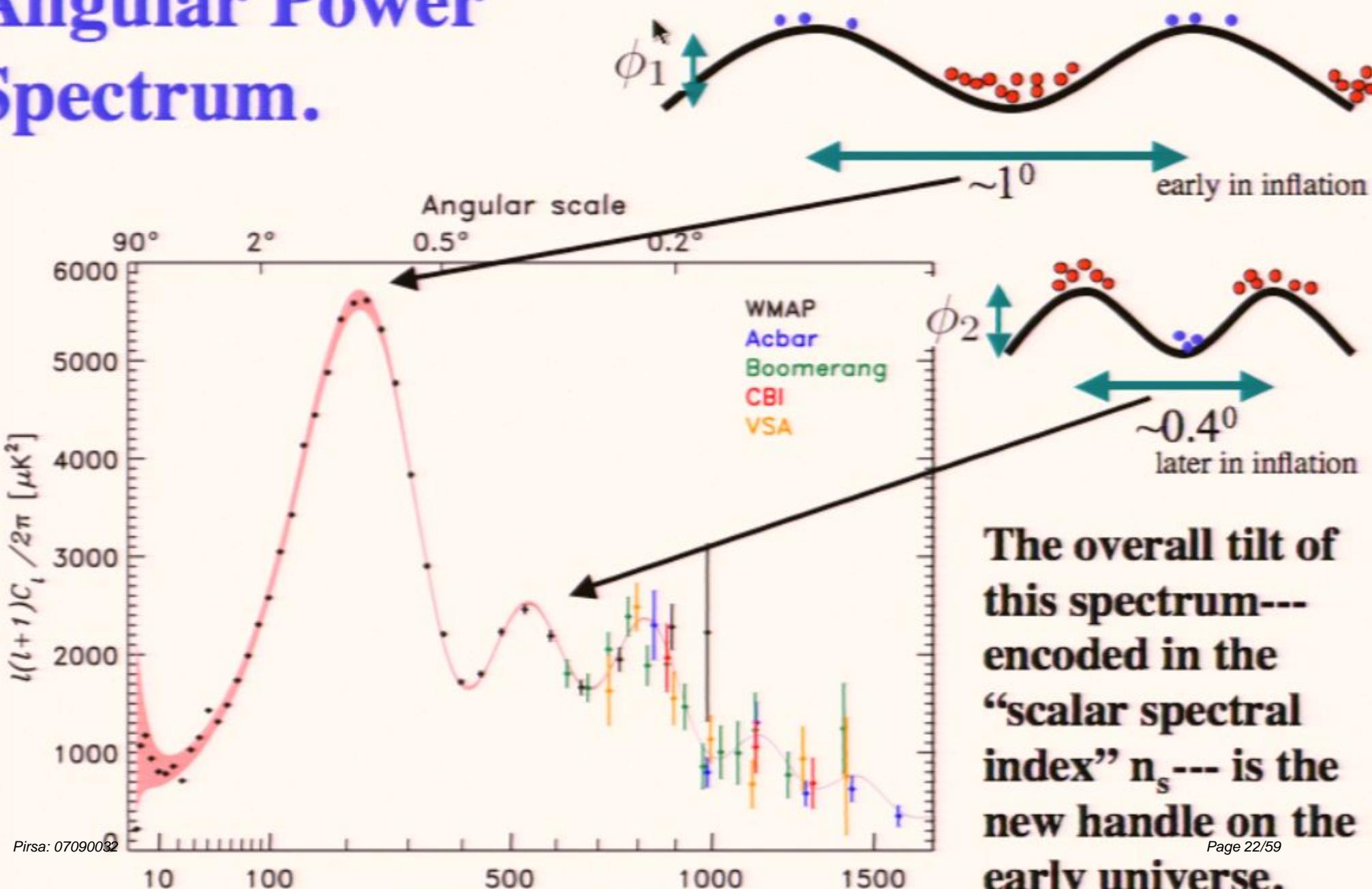




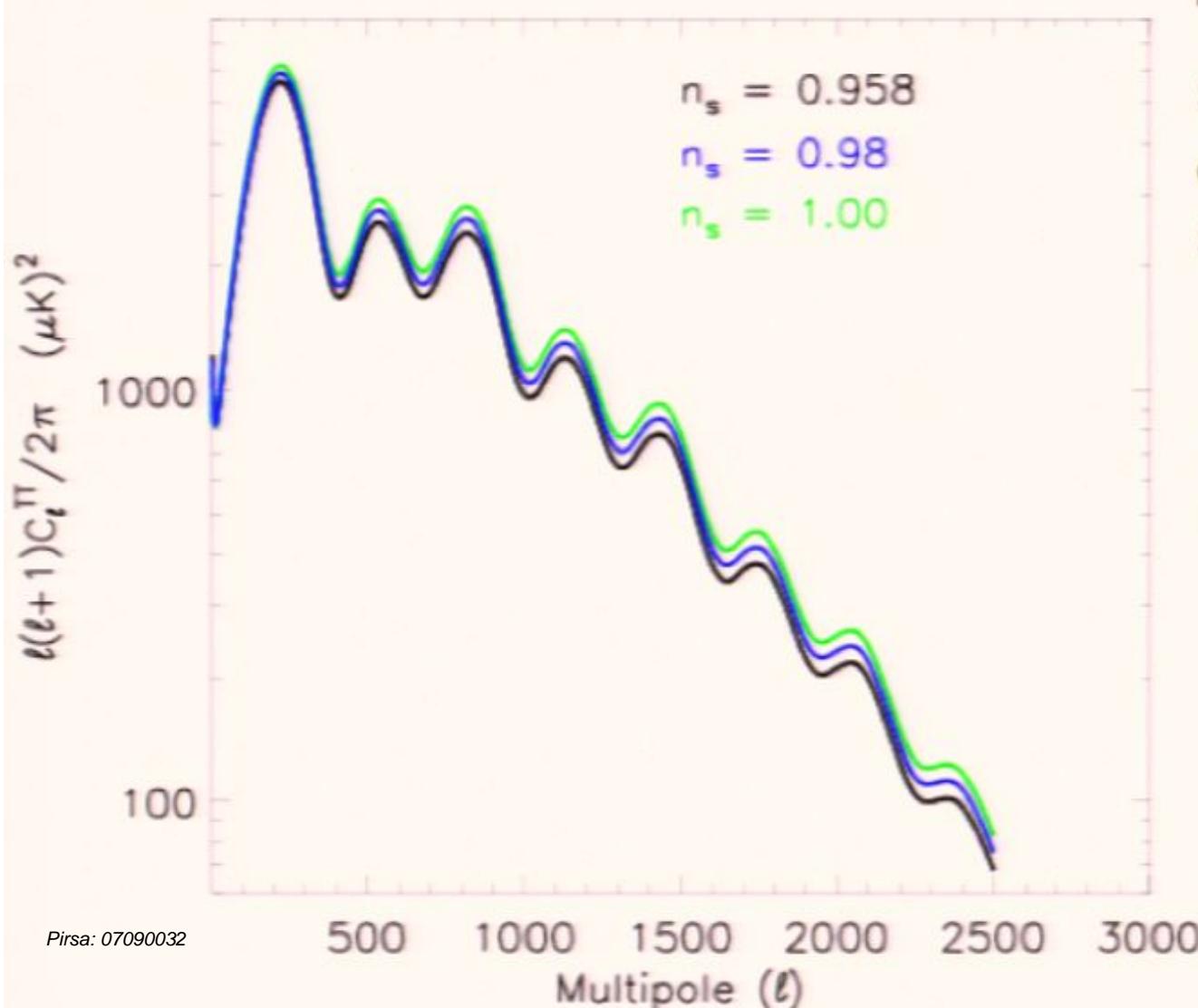




Angular Power Spectrum.



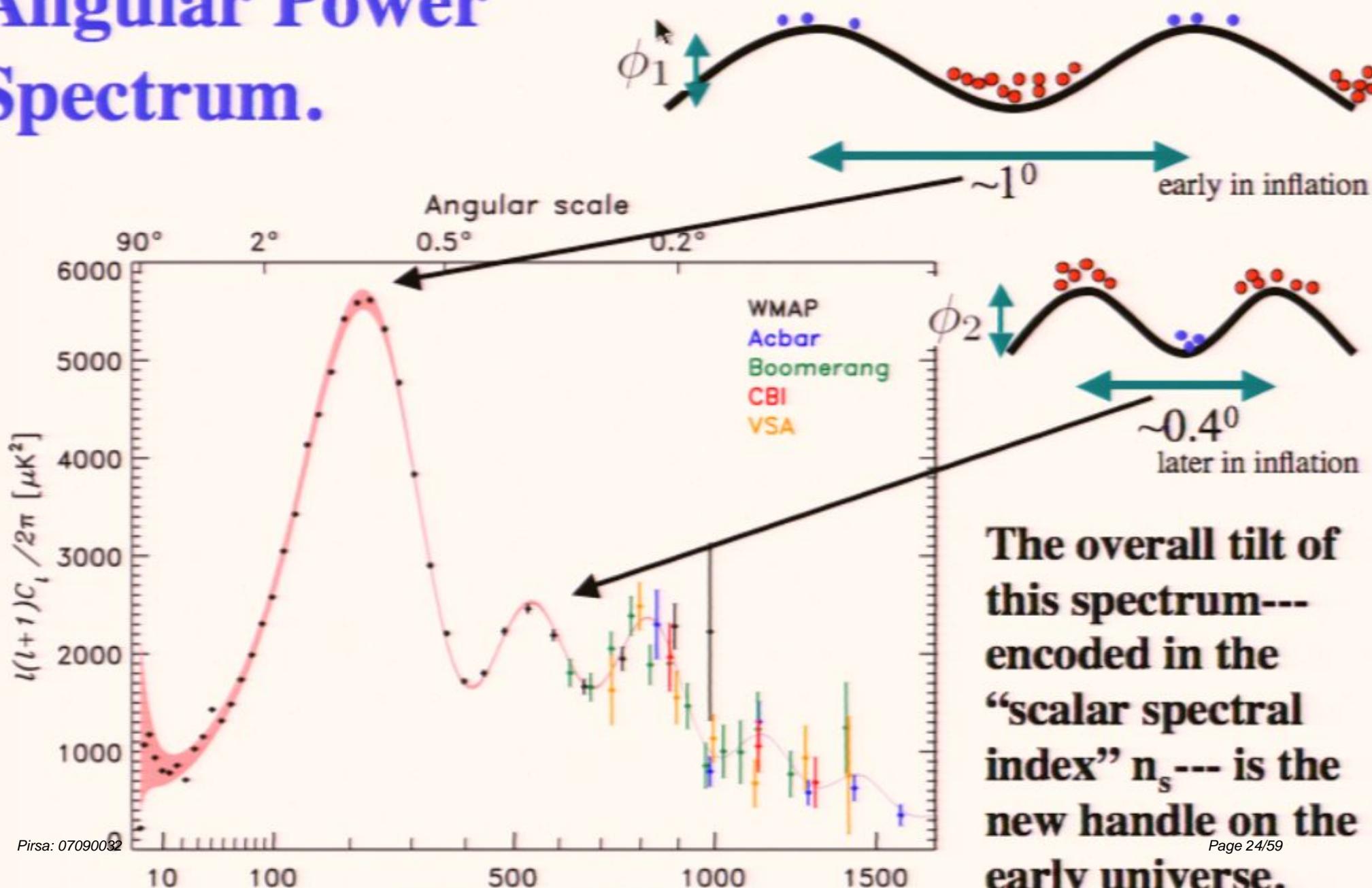
Spectral Index, Experimental Challenges



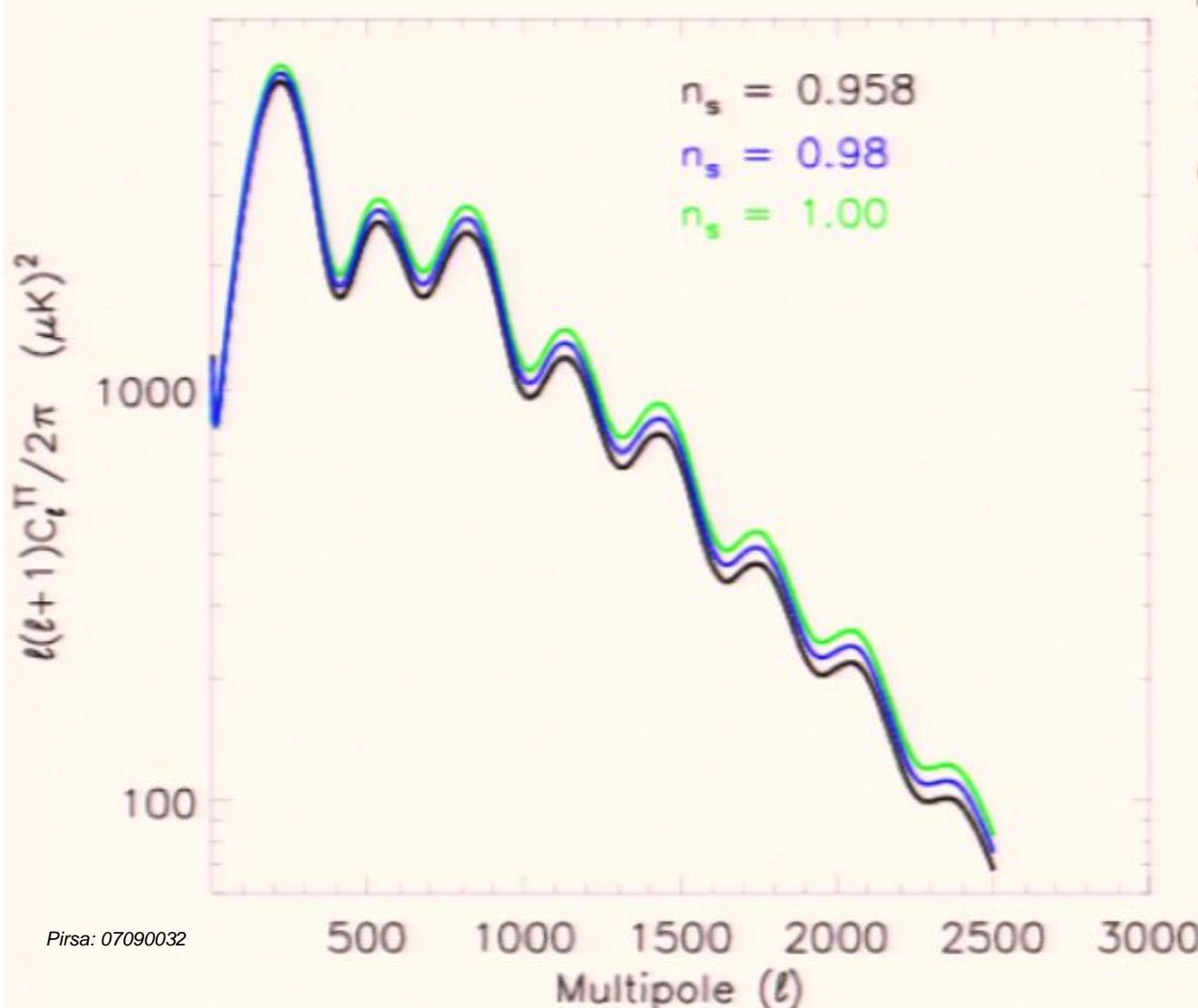
Three different spectra that differ only in spectral index.

The black line is the best WMAP model.

Angular Power Spectrum.



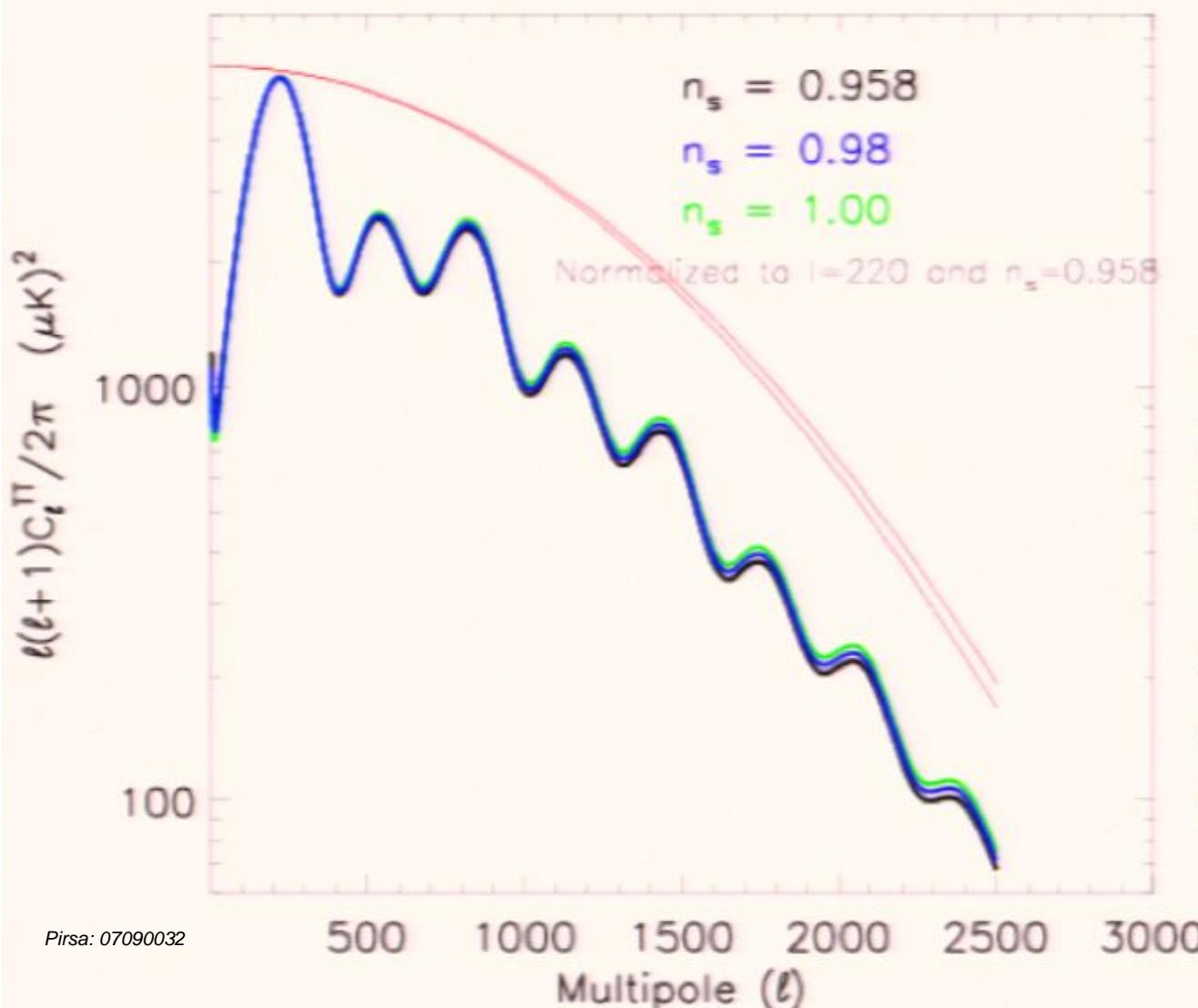
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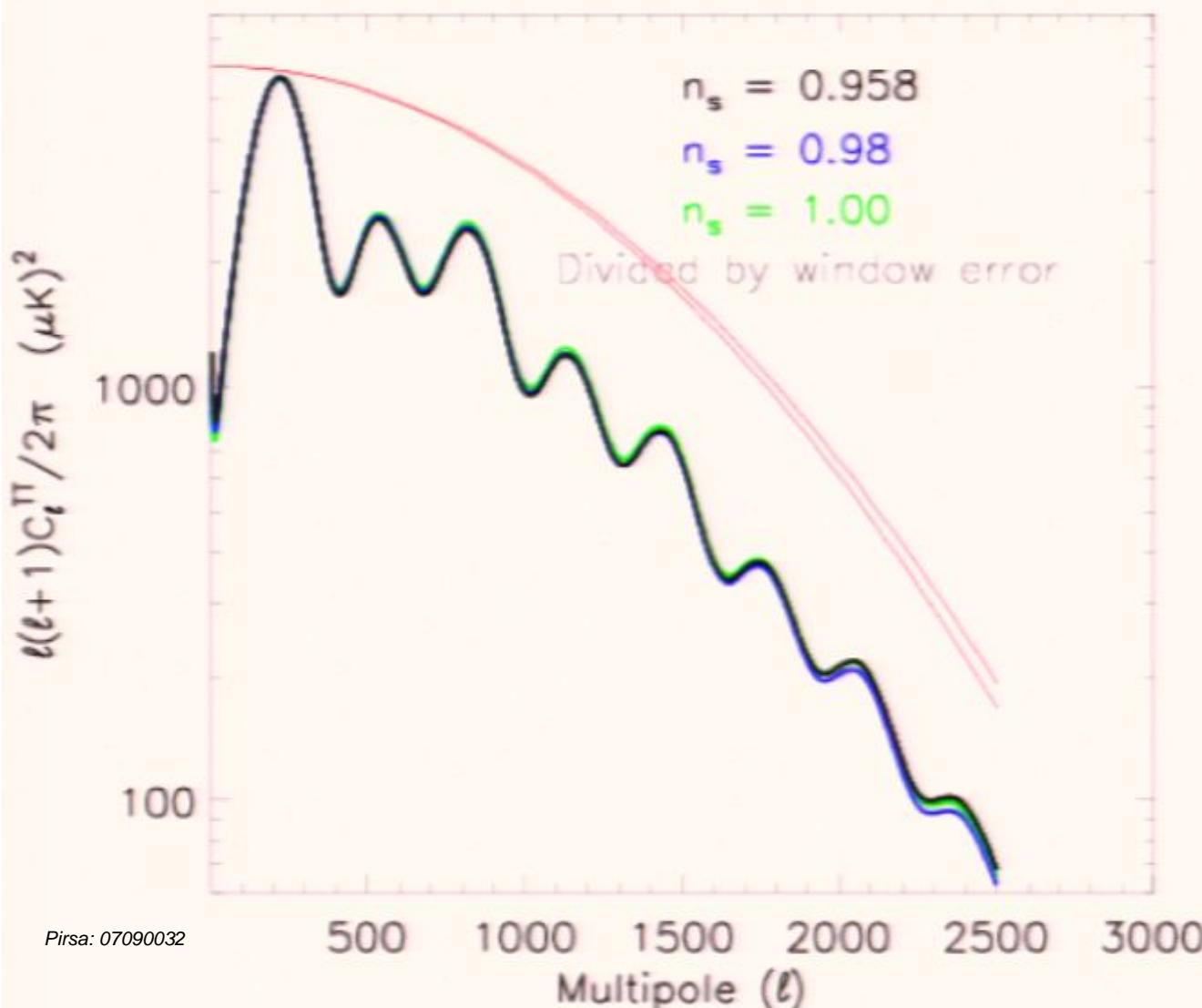
Spectral Index



Normalize the spectra to $\ell=220$ (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

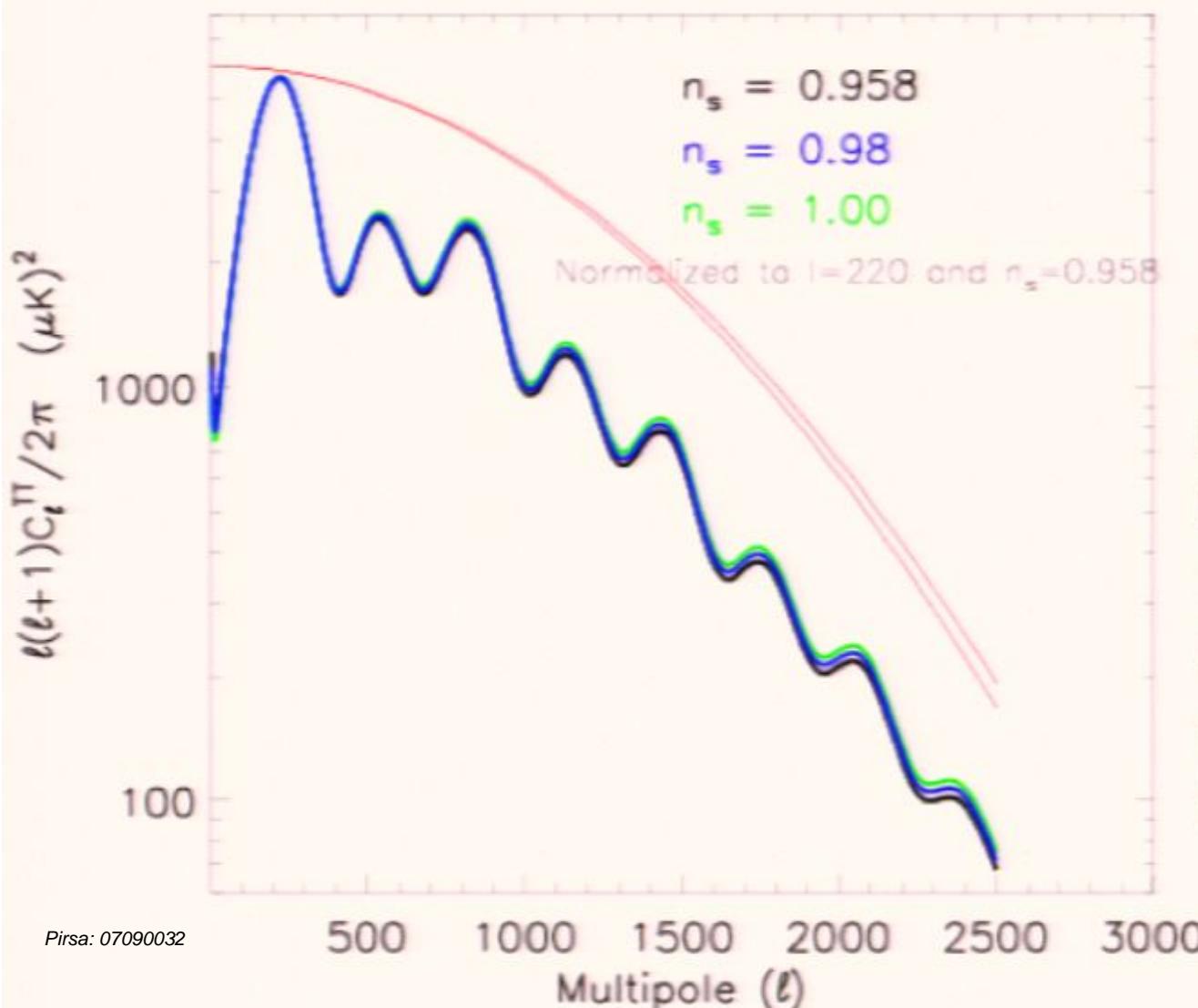


Divide by fractional window function.

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

In addition, there are astrophysical challenges.

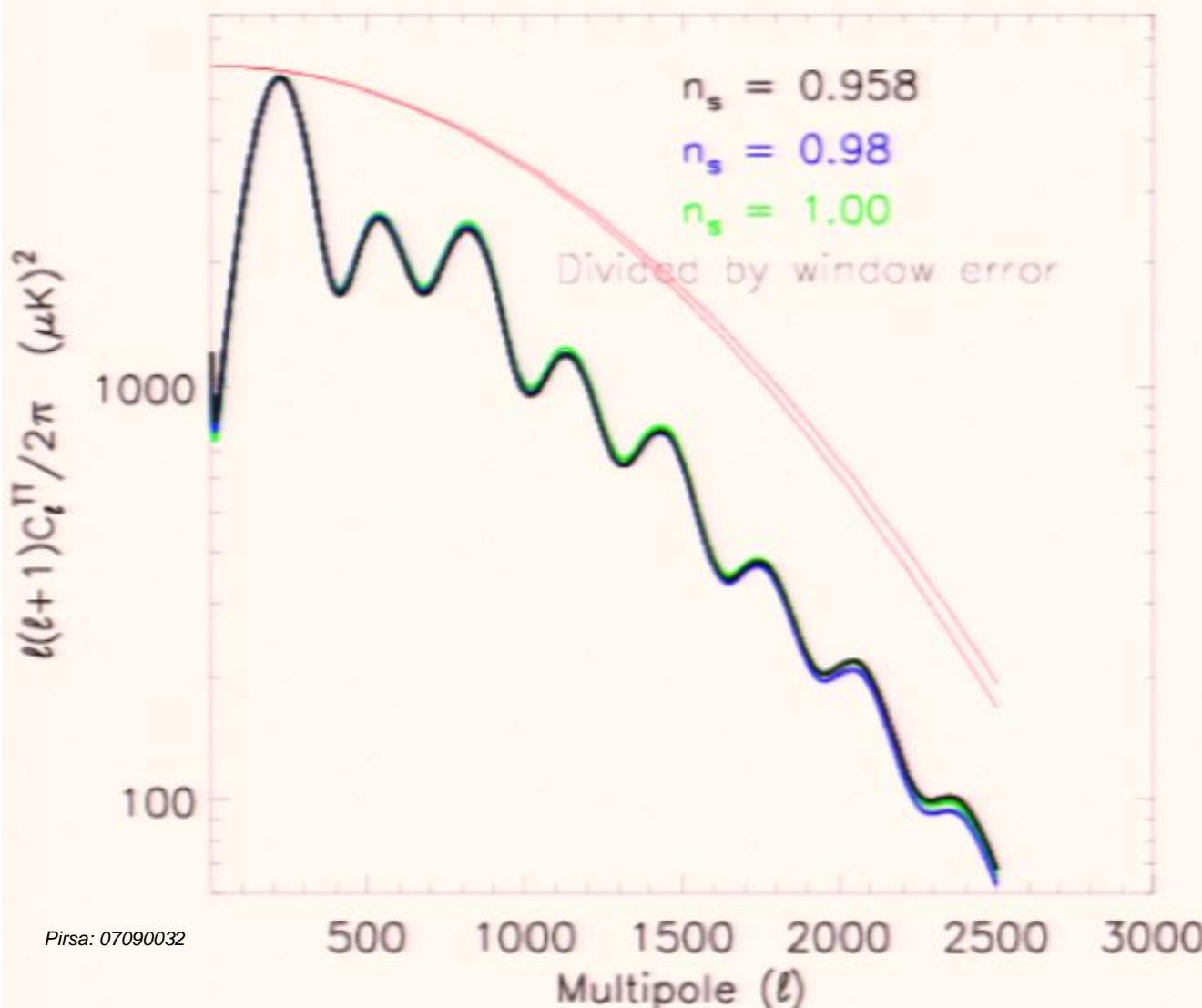
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Spectral Index: Astrophysical Challenges

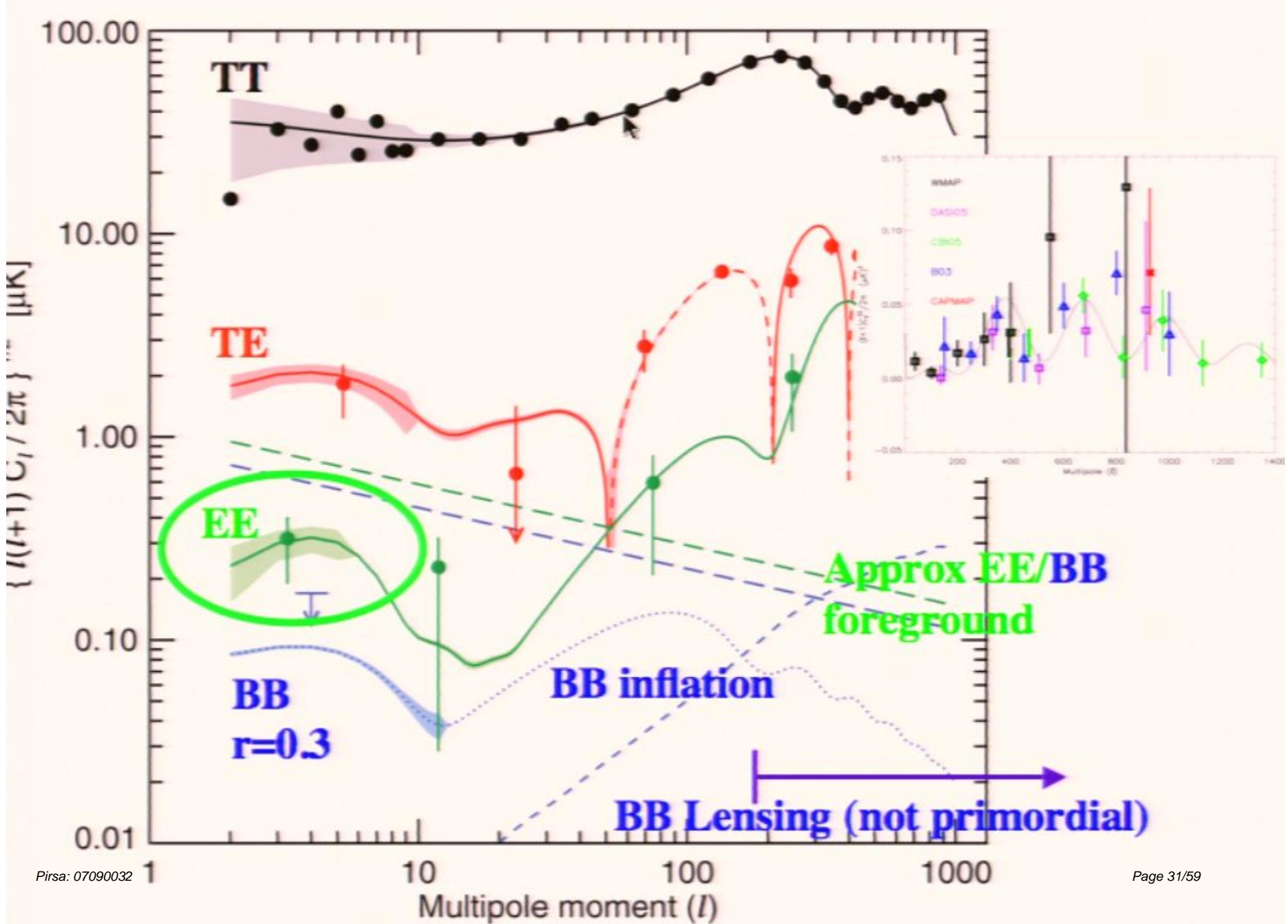
The formation of the first stars produces free electrons that:

- (1) rescatter CMB photons thereby reducing the anisotropy and
- (2) polarize the CMB at large angular scales.

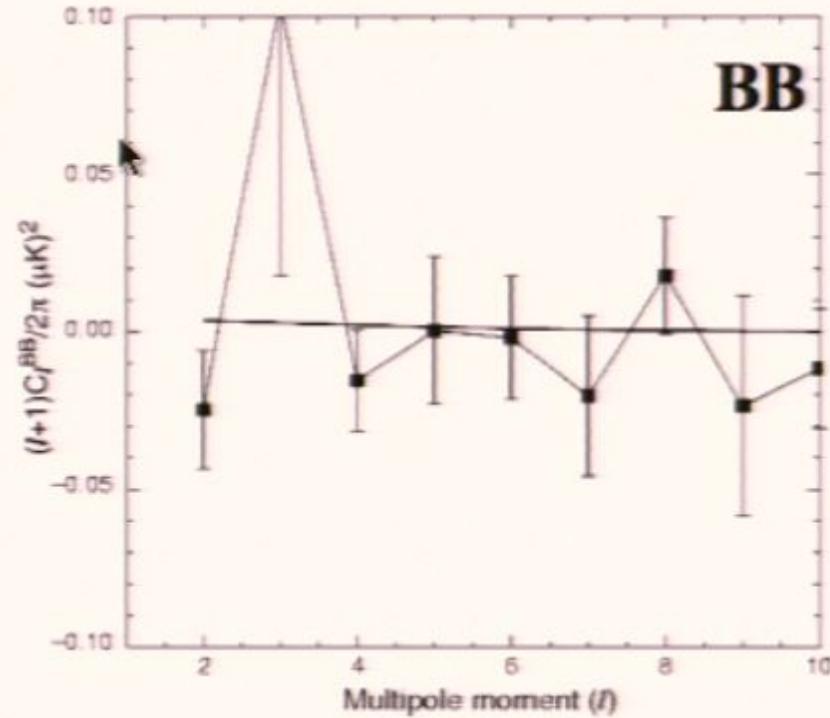
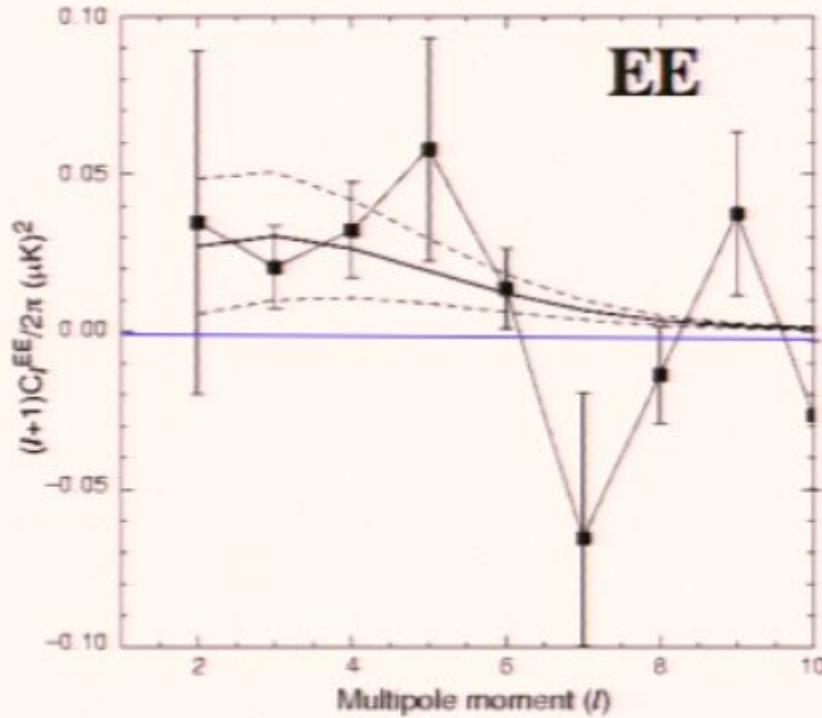
These effects mimic a change in n_s :

“the n_s - tau” degeneracy

WMAP measures (2) to break the degeneracy



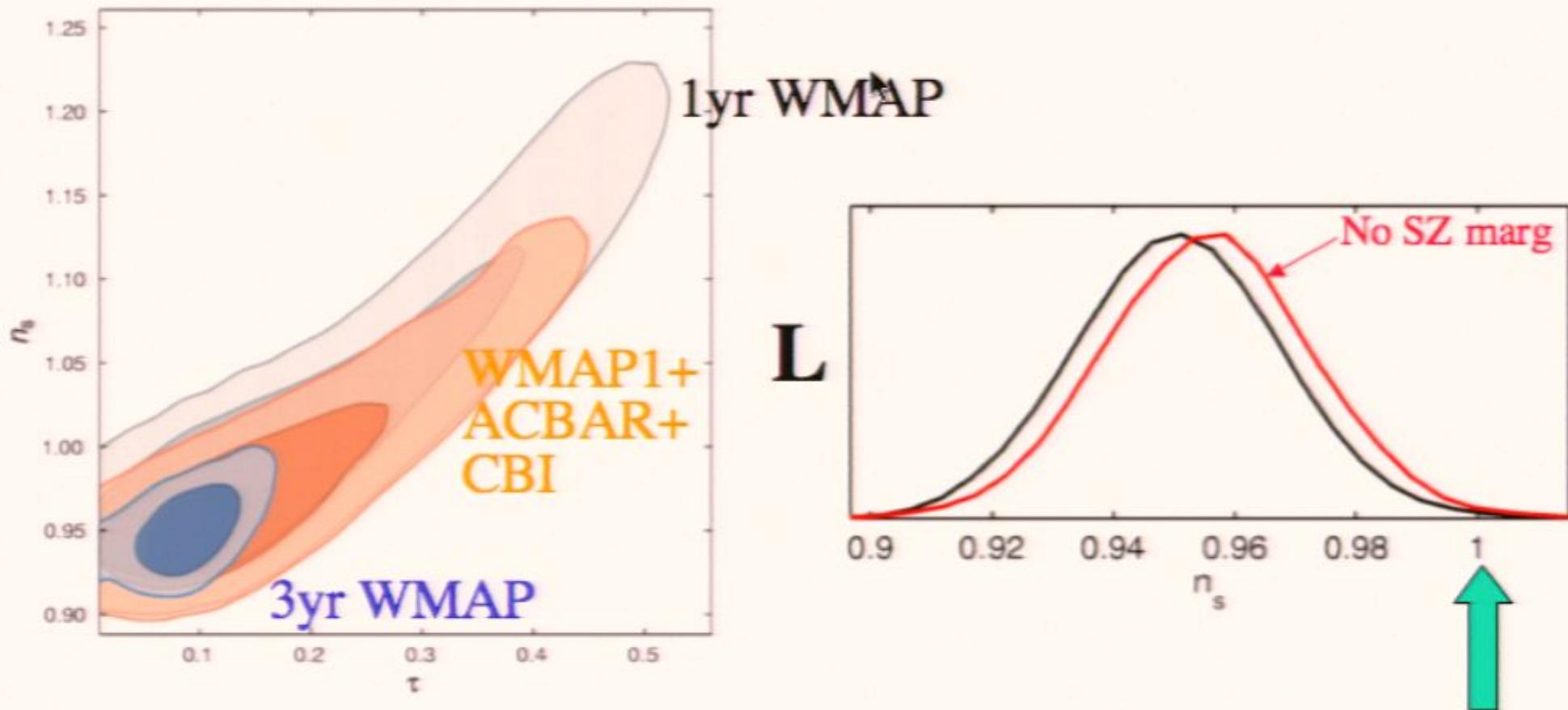
Low-l EE/BB



EE Polarization: from
reionization by the
first stars

BB Polarization: null
check and limit on
gravitational waves.

$n_s - \tau$ Degeneracy

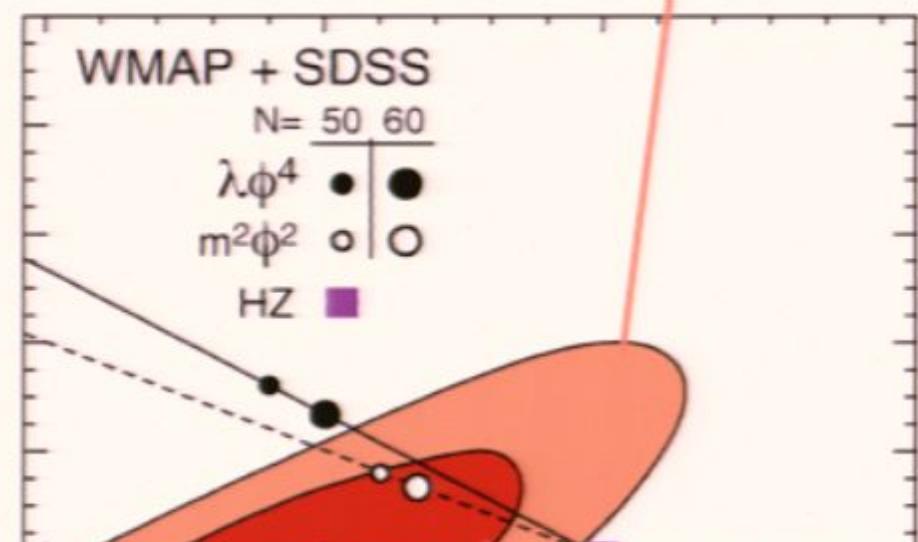
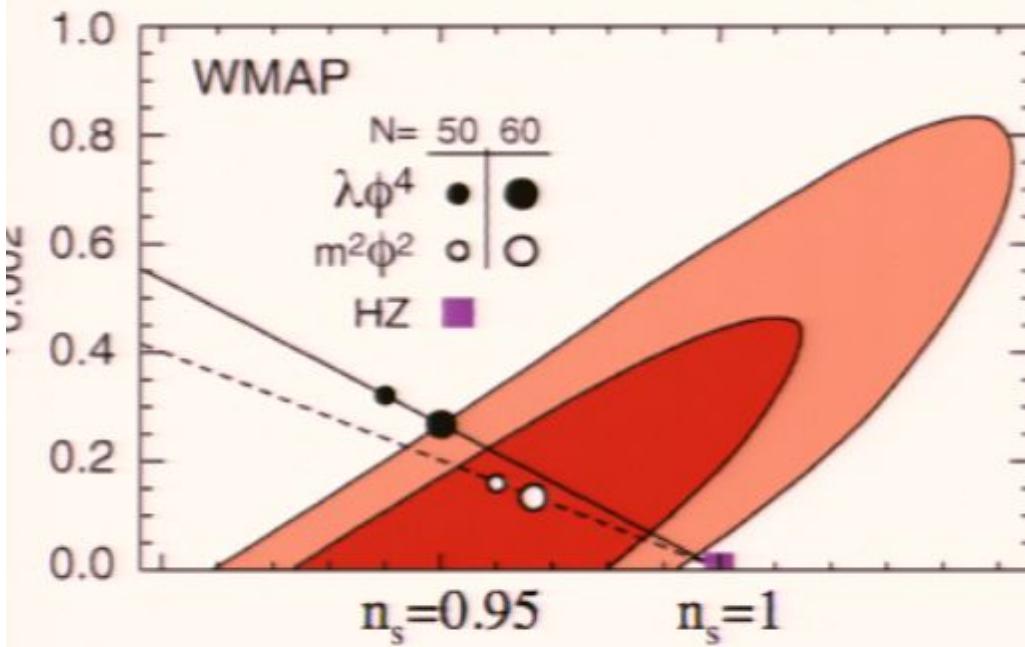


Knowledge of optical depth breaks the $n_s - \tau$ degeneracy

Index and Tensors

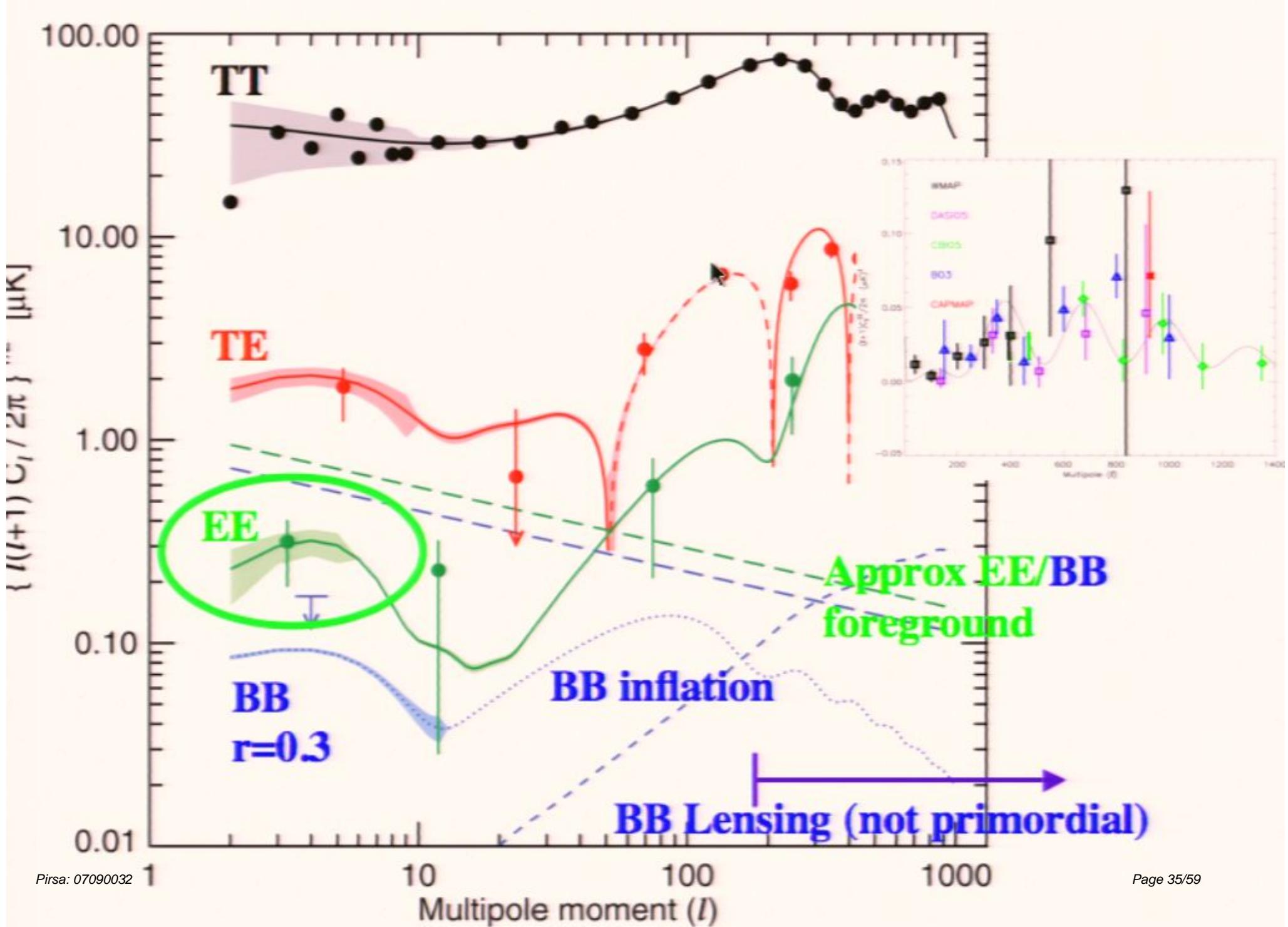
(2σ in 2d)

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

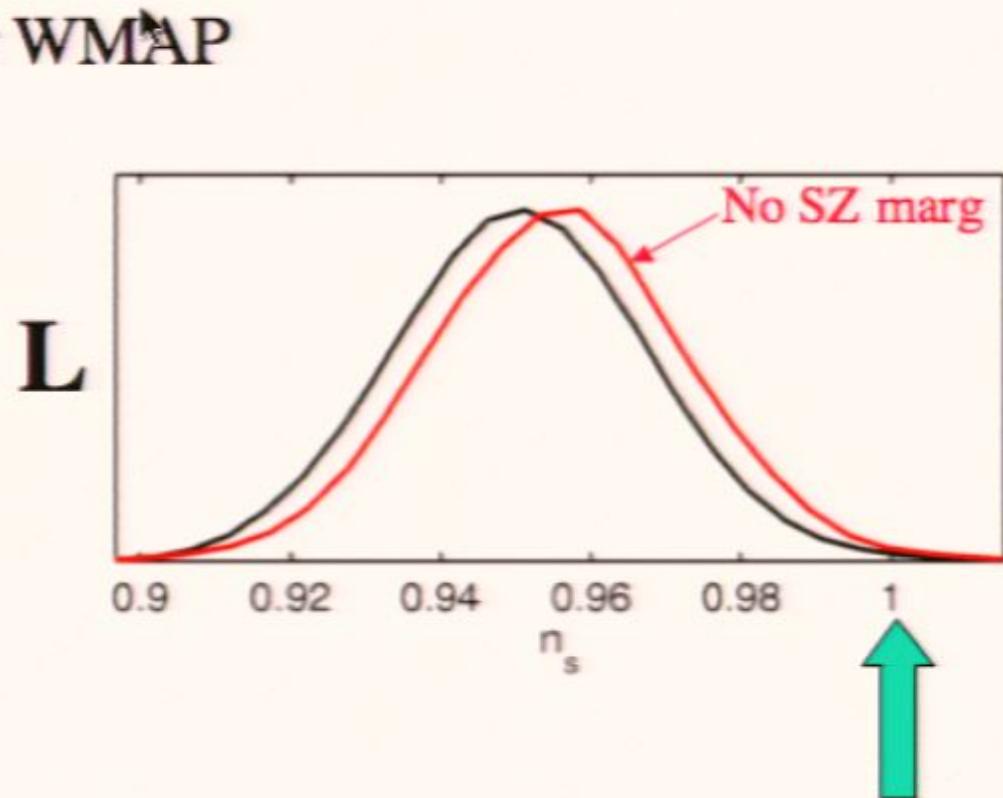
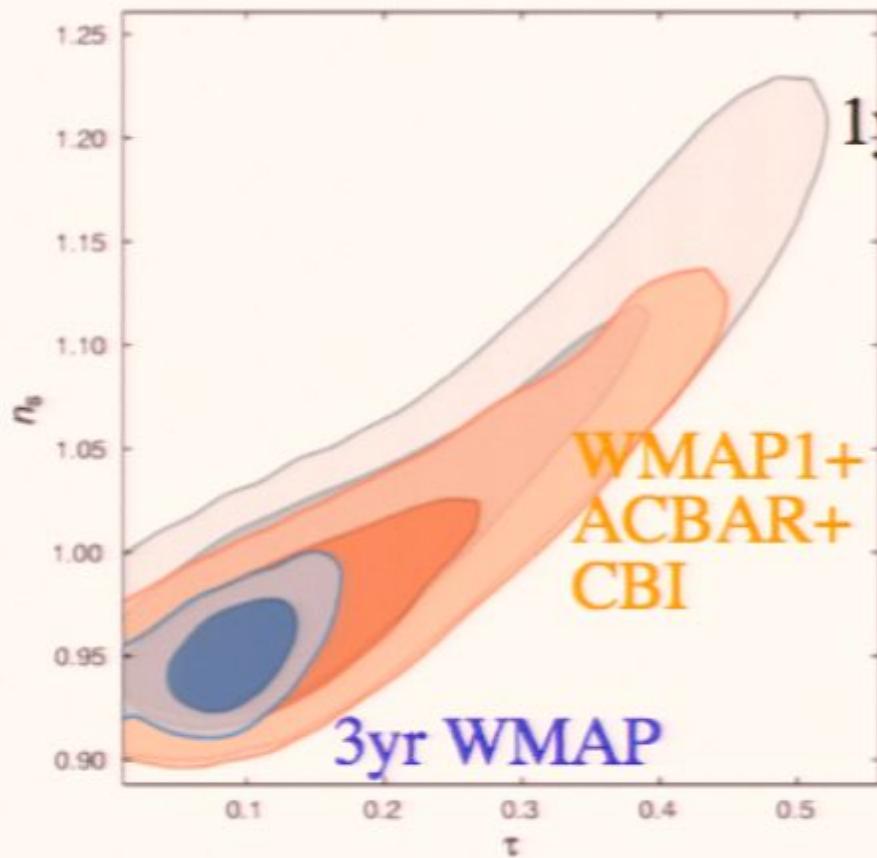


$$\Delta\chi^2 = 2.3$$

(1σ in 2d)



$n_s - \tau$ Degeneracy

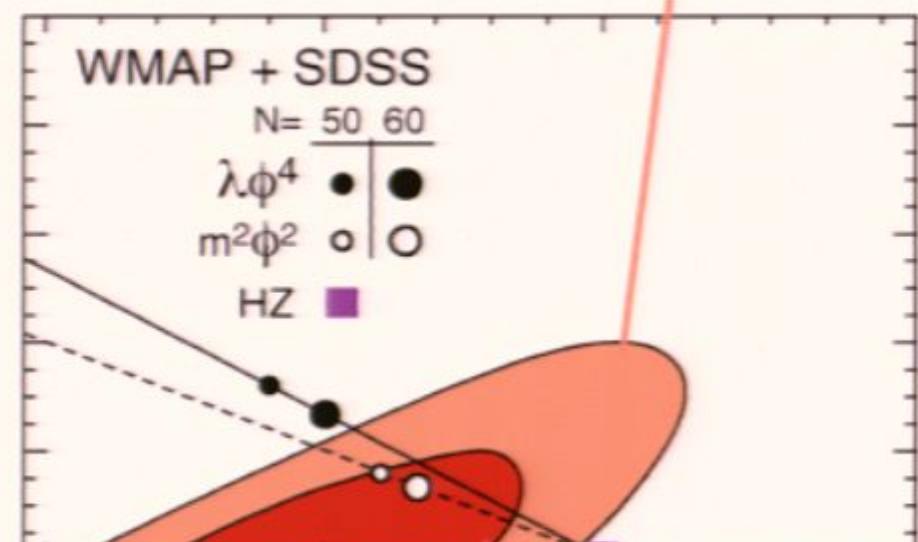
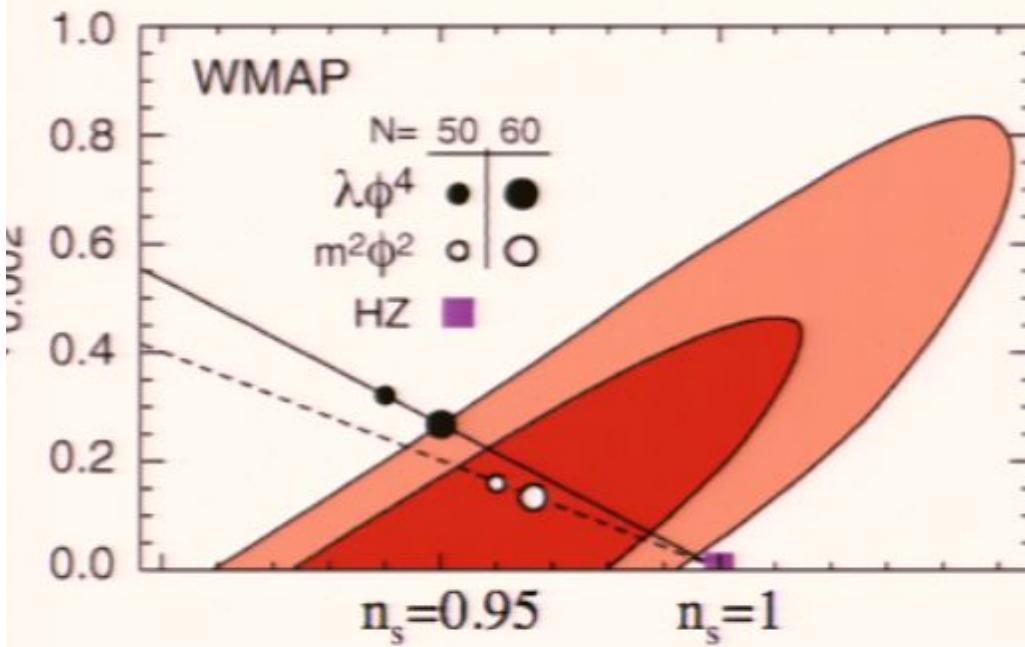


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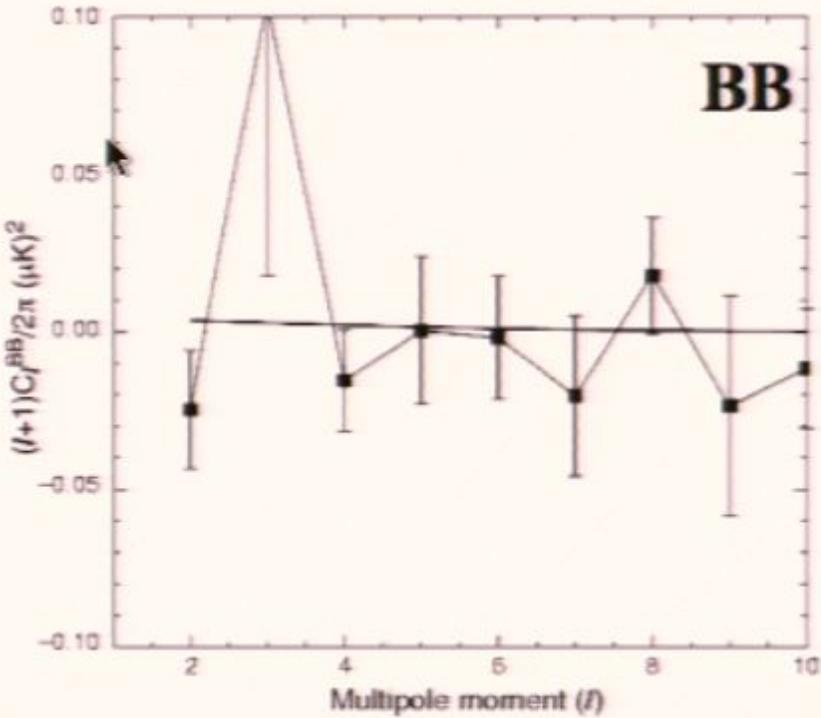
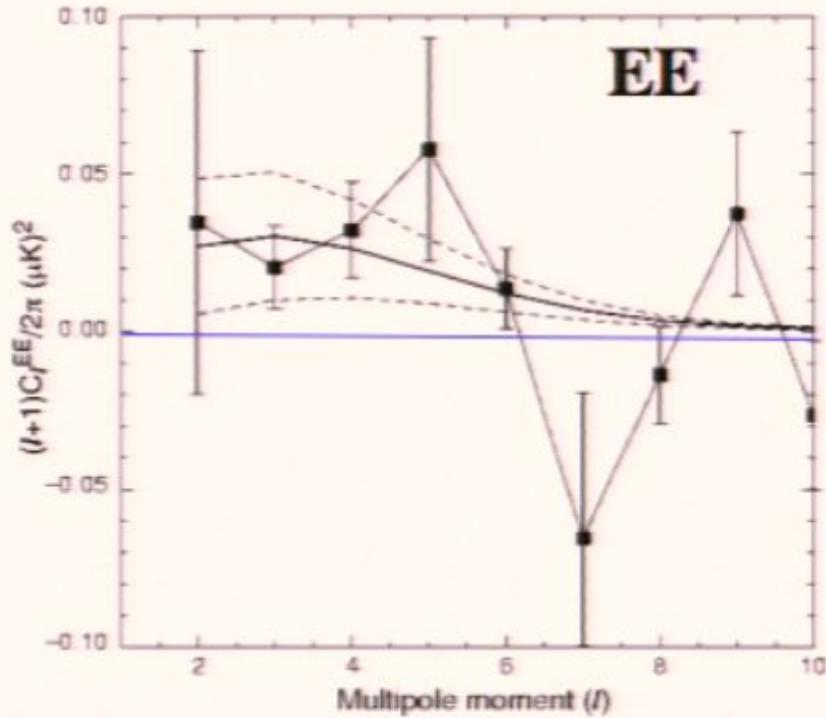
(1σ in 2d)

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, $\Delta\chi^2 = 6$ {but Eriksen & Huffenberger
- Model needs dark matter, $\Delta\chi^2 = 248$ (“15 sigma”)
- Model does not need: “running,” r , or massive neutrinos, $\Delta\chi^2 < 3$.

Low-l EE/BB



EE Polarization: from
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BB Polarization: null
check and limit on
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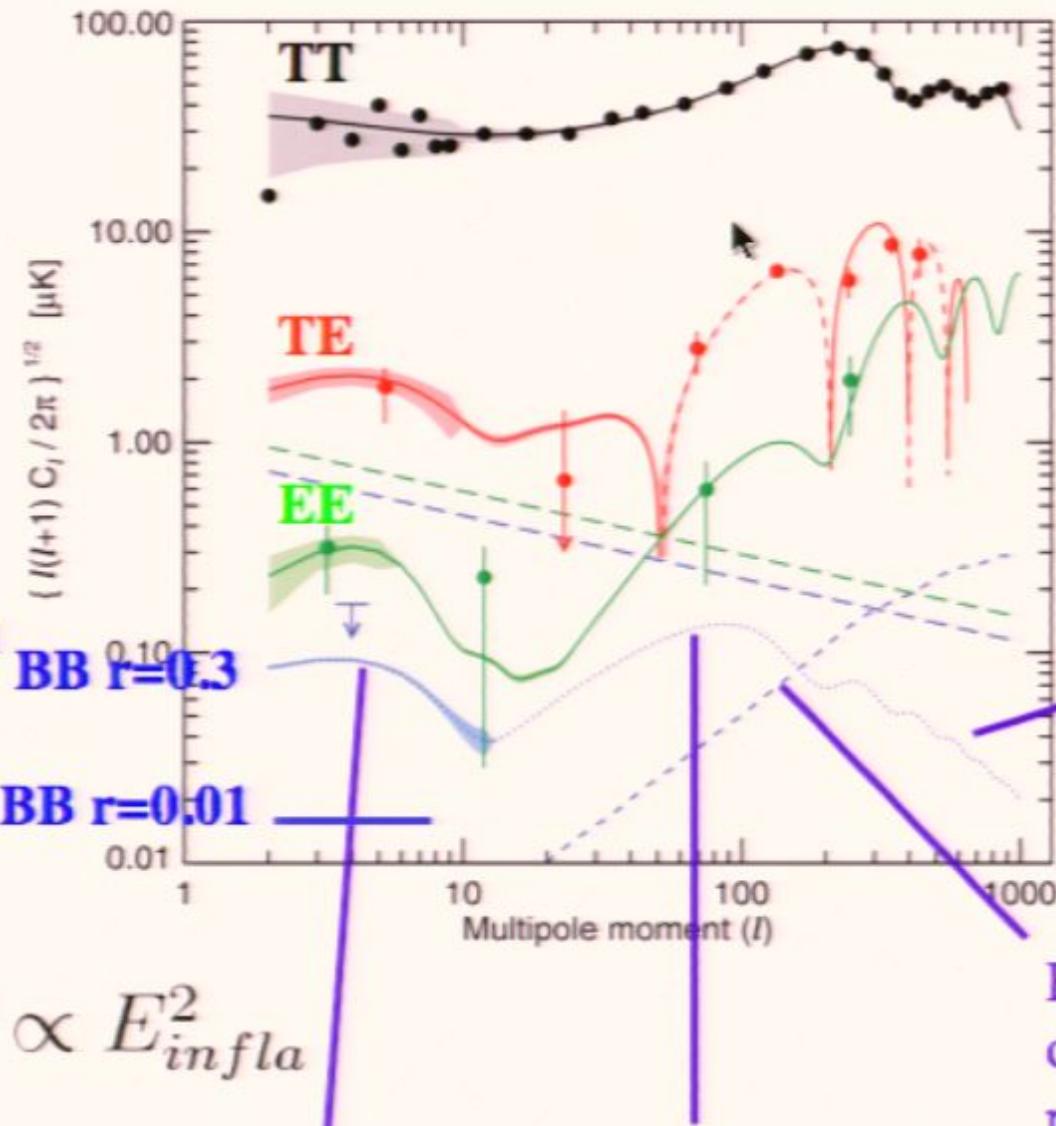
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-but Eriksen & Huffenberger

Gravitational Waves



Approx EE/BB
foreground averaged
over 75 % of the sky.

G-waves decay
once inside the
horizon.

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

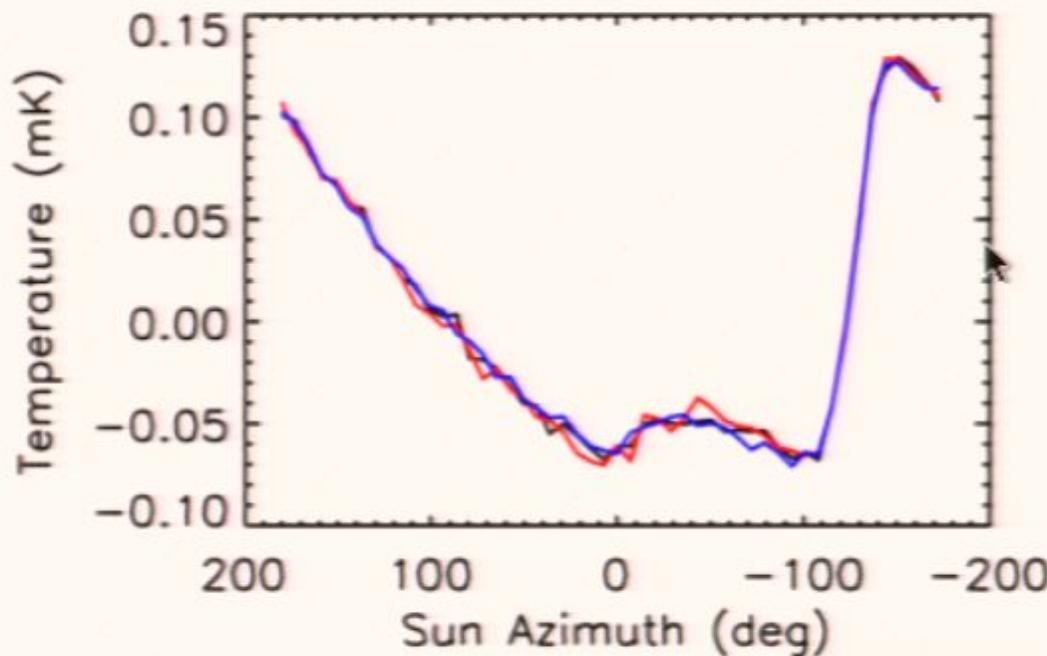
3 modes from
ensors only.

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

What limits how well one can determine r with the CMB?*

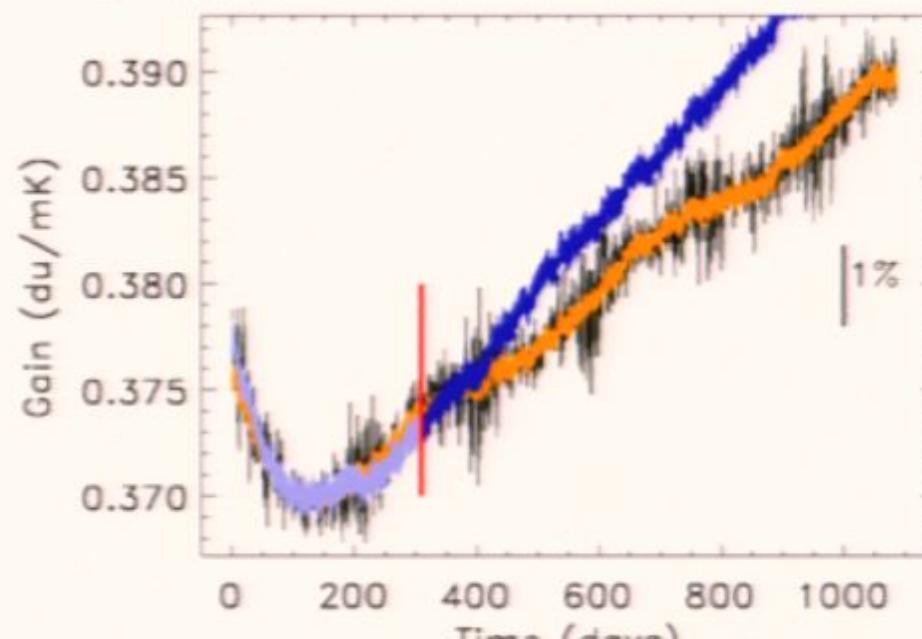
- A) Instrumental effects are mostly related to the instrument stability, scan strategy, knowledge of the beams.
- B) Foreground emission is likely to limit the determination of r to about 0.01.
- C) The best detection scheme has probably not been identified but the requisite sensitivity has been achieved.

Stability of instrument is critical



Physical temperature of B-side primary over three years. This is the largest change on the instrument.

Three parameter fit to gain over three years leads to a clean separation of gain and offset drifts.



Scan Pattern

- Most important modulation for polarization is sky (Q/U) rotation through one pointing. This allows for identification of systematic problems with the polarization measurement. “Spurious” terms show up as an offset in this modulation.
- There can be subtle couplings between the instrument stability requirements and scan strategy.
- For example, in WMAP an offset in the polarization signal time stream is strongly covariant with $l=3$ BB. In other words, a misidentified offset shows up as a signal. This is why the $l=3$ BB error bar is so large. A corollary: one cannot remove an offset from a Q or U map. It is signal. (Nolta: “you’ll remove an offset over my dead body.”)

Noise: Full F_{lm} Required

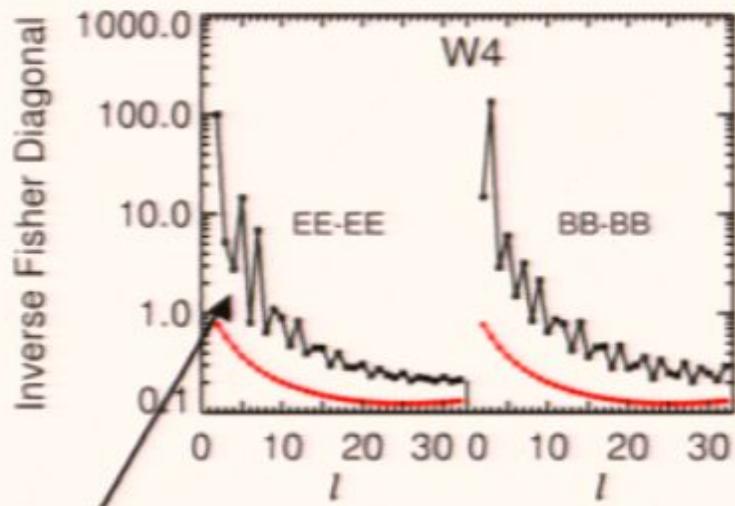
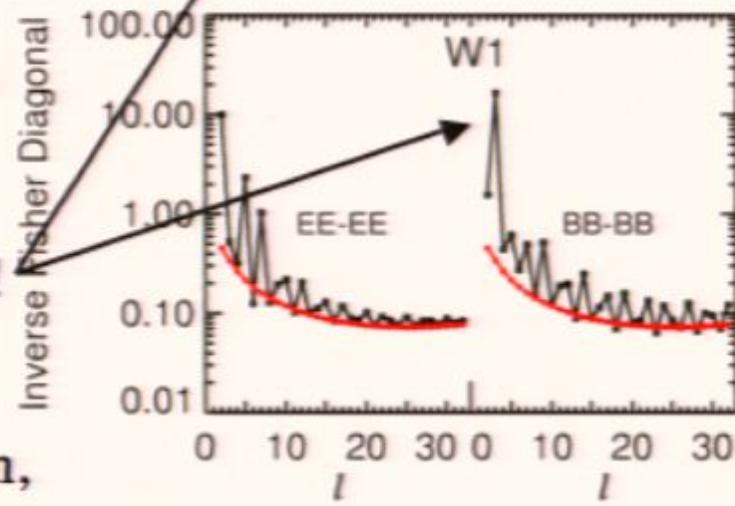
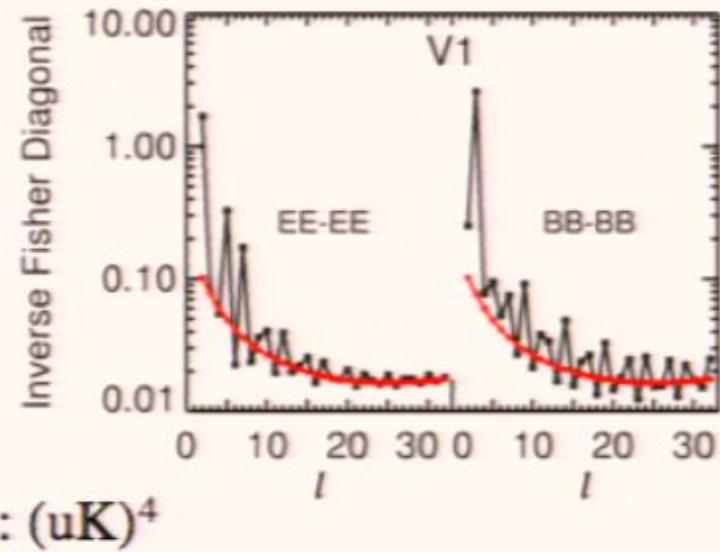
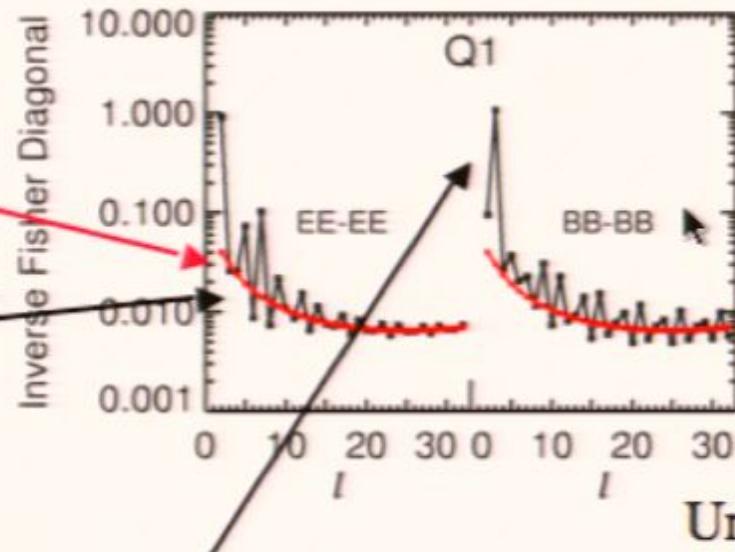
Uncorrelated
“ N_{obs} ” noise.

Covariance matrix
diagonal noise
(jagged line)

Scan pattern leads
to jagged line.

Note high $l=3$ BB!

For our scan pattern,
BB is better behaved
than EE



Note that 1/f, which is highest in W4, interacts with the scan pattern. Without full matrix noise C_1 would be off by X10.

Instrumental Effects

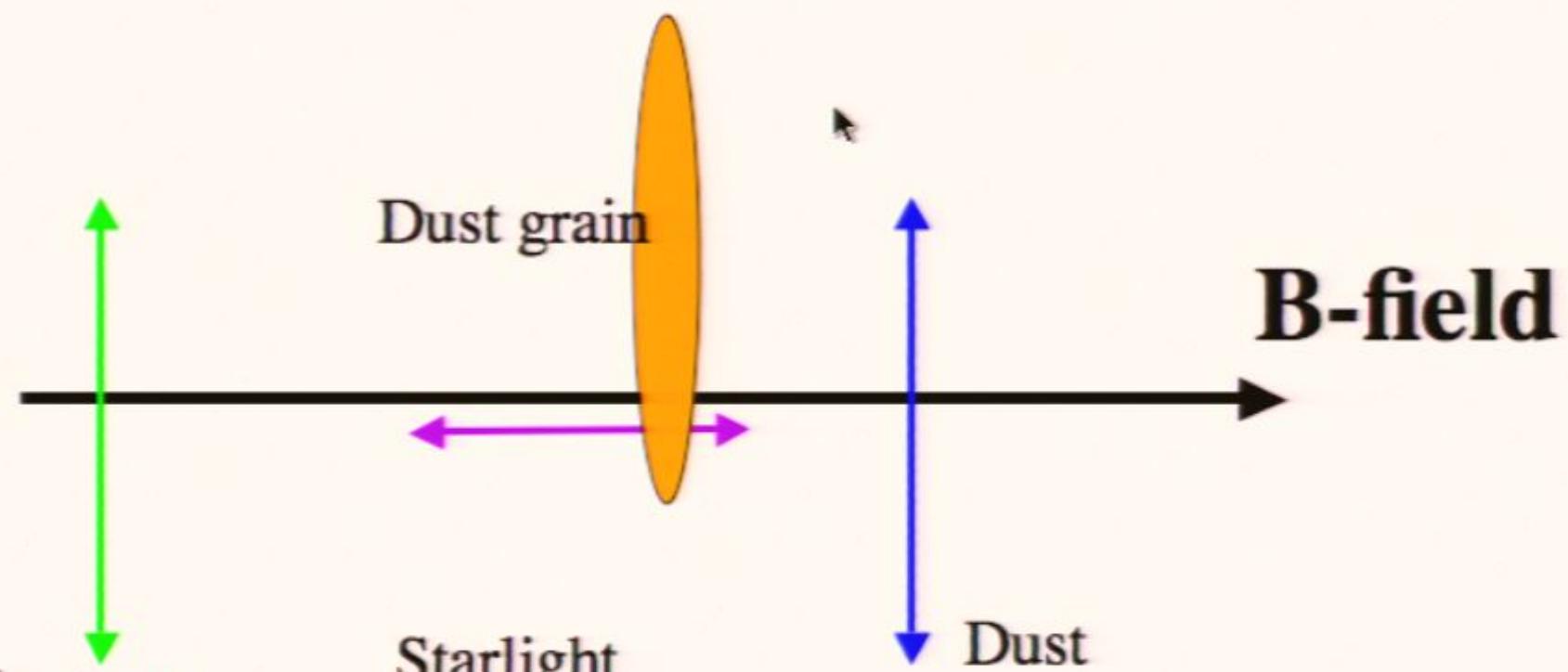
The easiest one is minimizing cross-pol or polarization isolation!

For WMAP, the largest instrumental systematic effect is from the passband mismatch. Foreground emission has a different effective frequency centroid than does the CMB (by up to a few GHz). Thus if the CMB is “nulled” the foreground may not be. A map of the spurious term S looks like the galaxy.

For each pixel we needed the full covariance matrix

$$\left\{ \begin{array}{cccc} II & IQ & IU & IS \\ QI & QQ & QU & QS \\ UI & UQ & UU & US \\ SI & SQ & SU & SS \end{array} \right\}$$

Polarized Foreground Emission



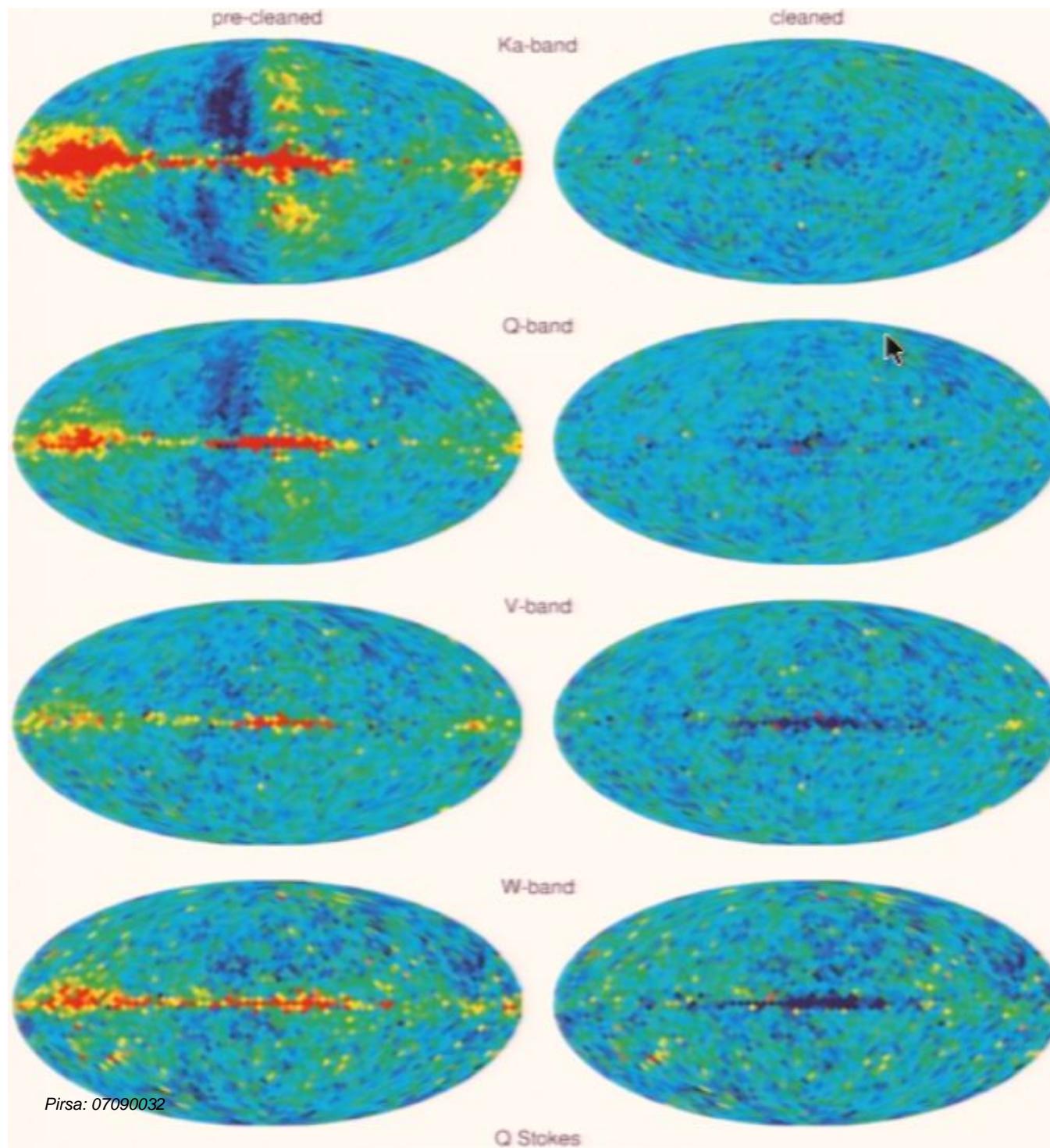
Max pol about
75%

Starlight
polarization

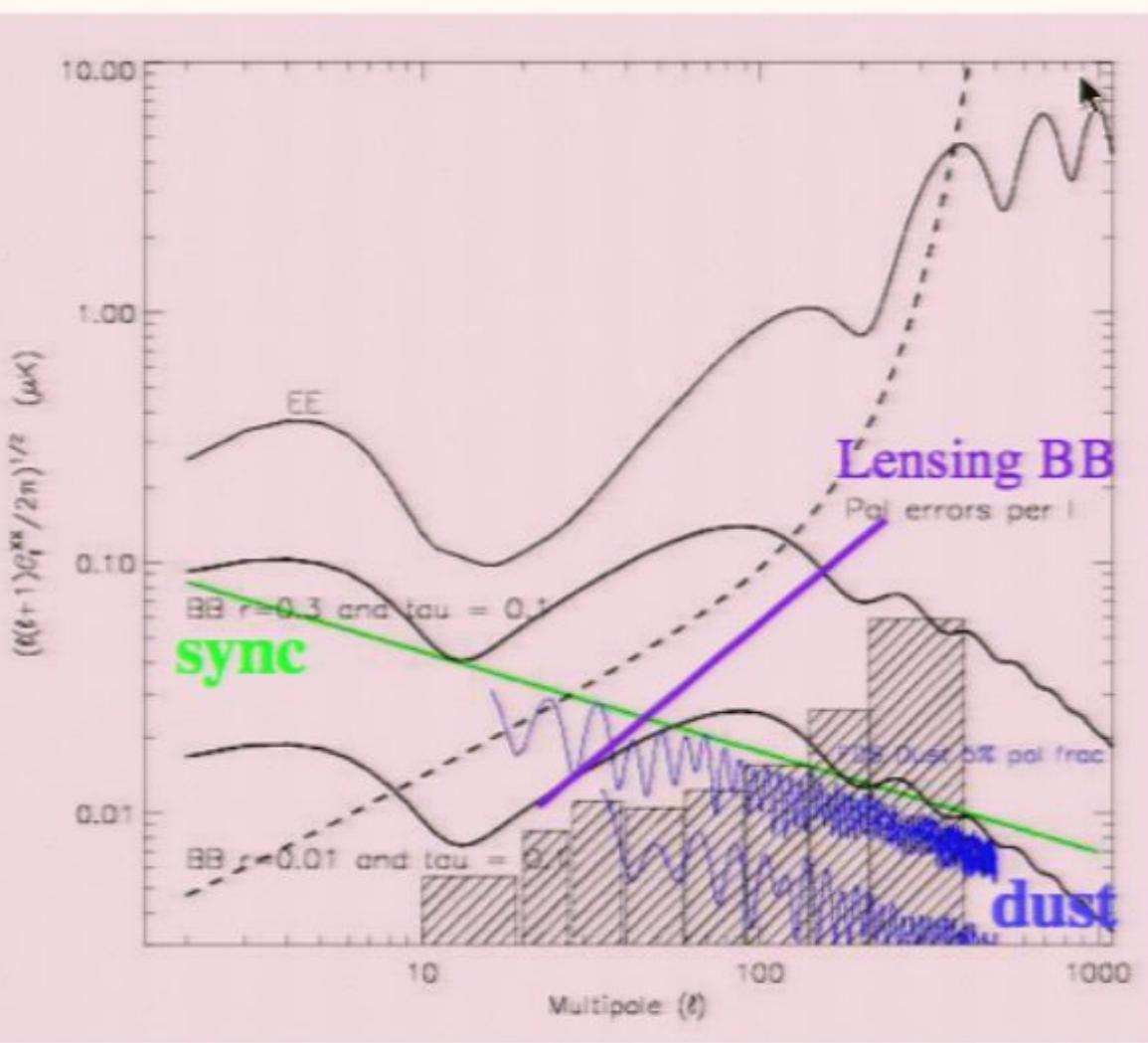
Max pol about 15% but
low pol for spinning dust.

Raw vs. Cleaned Maps

Galaxy masked in
analysis



Expectations at $l=100$



Foreground
“free” window !

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.

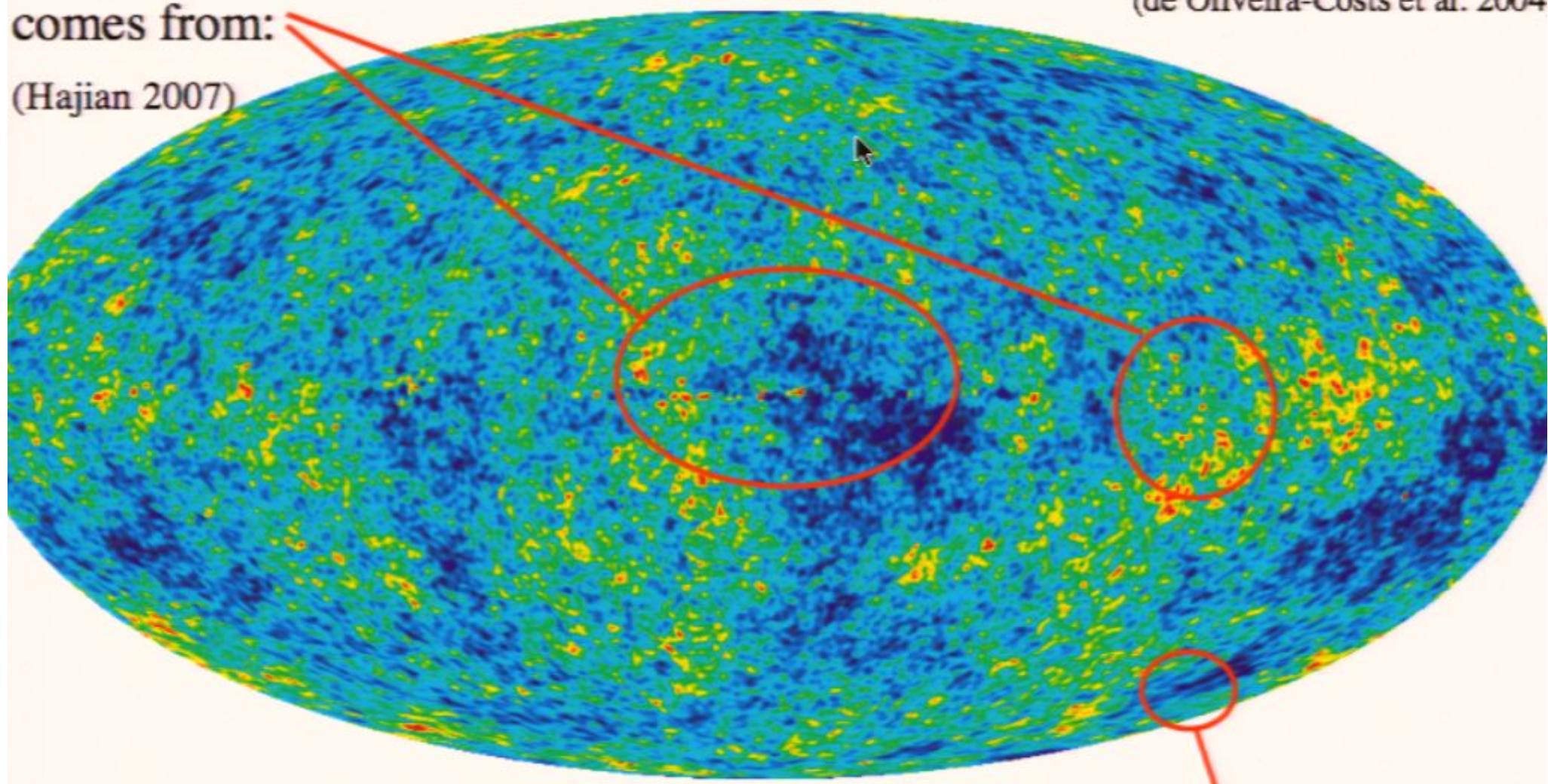
Non-Gaussianity

- The quadrupole is not anomalously low. For the full sky, the 2-pt correlation function is not anomalous.
- All “detections” of non-Gaussianity 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-Gaussianity. The WMAP team has not found one.

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

(Hajian 2007)



Note “fingers” present in the southern Galactic hemisphere.
Largest effect in ecliptic coord

Alignment?

(de Oliveira-Costa et al. 2004)

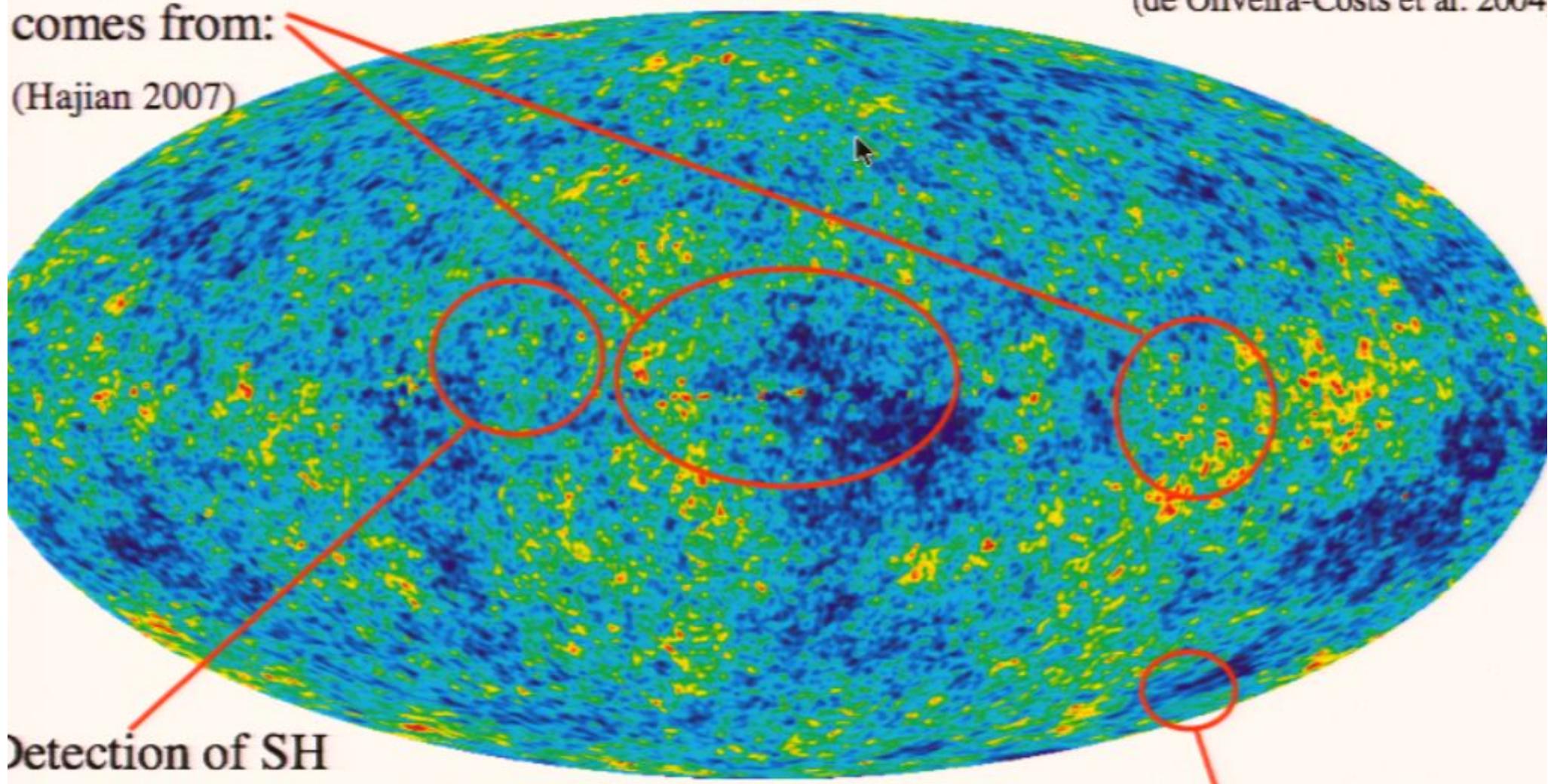
Extra cold spot:
(Vielva et al. 2004, Cruz et
al. 2004, 1.8% peak 2002)

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

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Detection of SH
persists!

Pirsa: 07090032



Alignment?

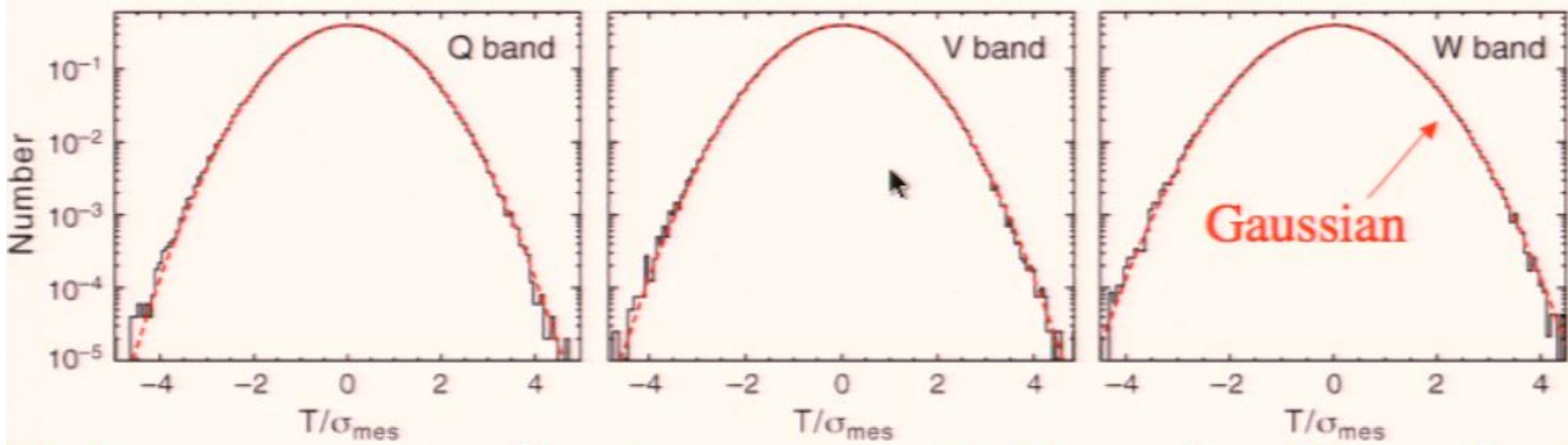
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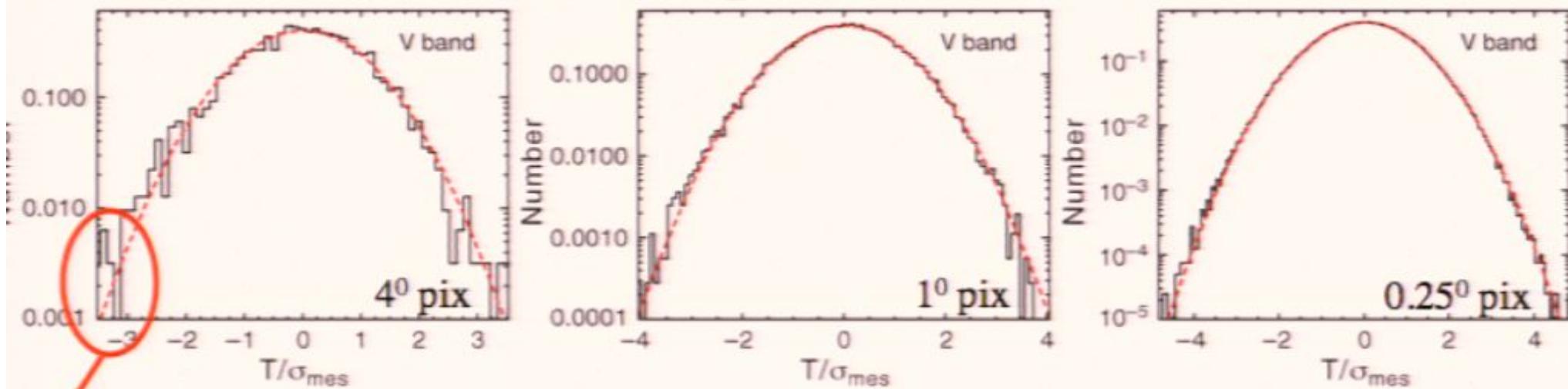
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Distribution by map temp. by frequency (accounting for uneven weighting)



Data are an excellent representation of a Gaussian!



One WMAP Characterization of non-Gaussianity

$$\Phi(x) = \Psi(x) + f_{NL} \Psi^2(x)$$

Curvature potential Gaussian random field

Komatsu et al.

$$f_{NL} = 30 \pm 42 \text{ or } -34 < f_{NL} < 114 \text{ (95% cl)}$$

Limit f_{NL} through the analysis of the bispectrum.

- Inflation gives $f_{NL} \sim 0.01$
- Some form of ekpyrosis gives $f_{NL} \sim 100$ (Preliminary)

- ▲ WMAP's K-band will be essential for the Planck polarization analysis.
- ▲ WMAP is a calibration source for all balloon and ground based measurements.
- ▲ Improvements in τ and n_s

B-Modes

Current WMAP limit: $r < 0.67$ (95% cl) mostly from TT&EE

WMAP+SDSS: $r < 0.30$ (95% cl)

With 12 years of WMAP and say SDSS we estimate that a 4σ detection of $r=0.2$ is possible.

Non-Gaussianity

With 12 years the 1σ limit on f_{NL} will be ~ 20 (currently 30)

What's the future of WMAP?

Present plan (from last senior review): observe through Sept. 2008. The tentative plan, to be reviewed, is to stop observations in Sept. 2009 after collecting 8 years of data.

WMAP has the fuel to last many more years!

... the best preparation for the Inflation Probe is through continued operations of WMAP. We also believe the best way to optimize Planck's pursuit of B-modes is through continued operation of WMAP. The most sensible time to cease WMAP observations is when Planck is working.

- ▲ WMAP's K-band will be essential for the Planck polarization analysis.
- ▲ WMAP is a calibration source for all balloon and ground based measurements.
- ▲ Improvements in τ and n_s

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