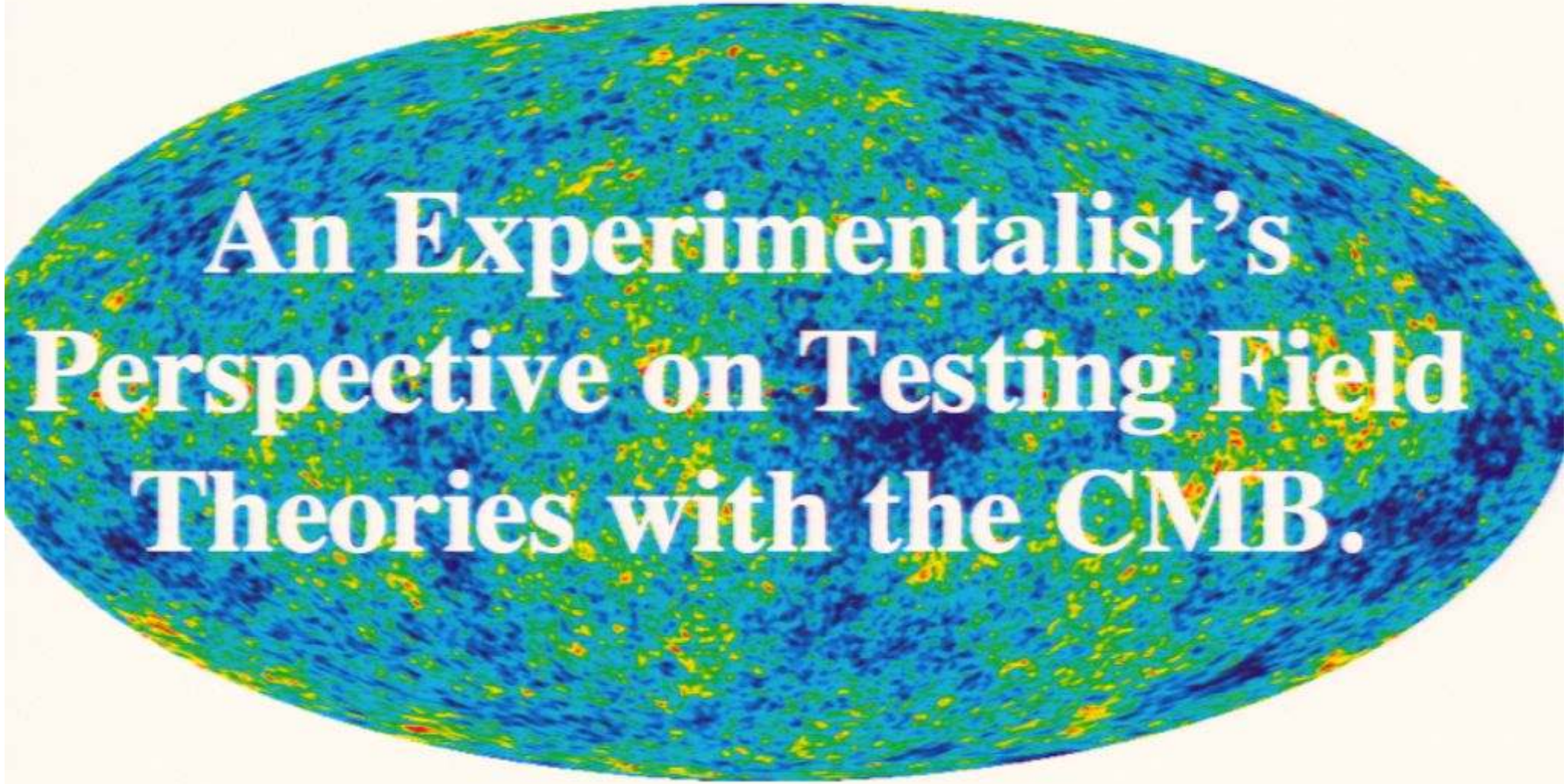
Title: An Experimentalist\'s Perspective on Testing Field Theories with the CMB

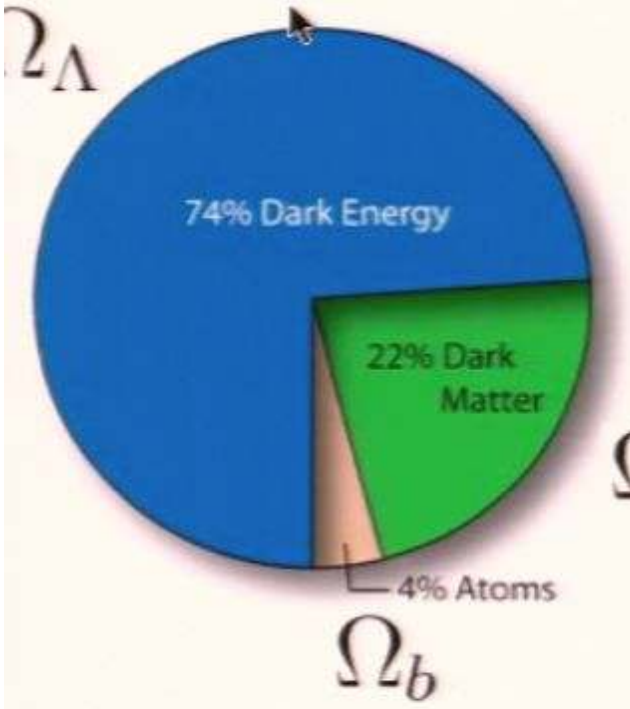
Date: Sep 10, 2007 08:30 AM

URL: http://pirsa.org/07090032

Abstract:



Page Perimeter Institute September 2007

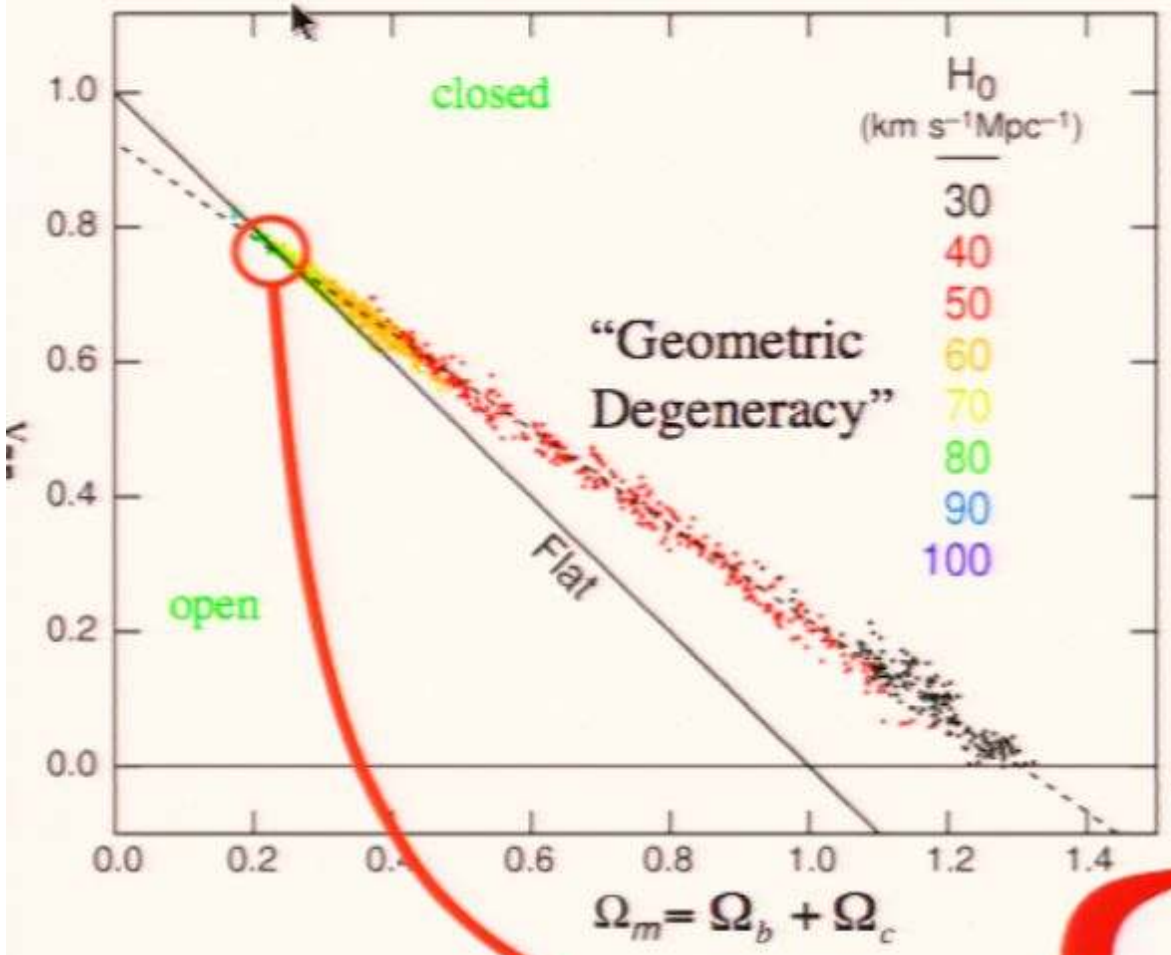


The current cosmological model agrees with virtually all cosmological measurements regardless of redshift or method.

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 ($P(k) \propto k^{n_s=1}$, ~3σ).

WMAP3 only			WMAP3 + all		
$\Omega_b h^2$	=	0.02233 ± 0.0008	$\Omega_b h^2$	=	0.02186 ± 0.0007
$\Omega_m h^2$	=	0.126 ± 0.009	$\Omega_m h^2$	=	0.132 ± 0.004
h	=	0.735 ± 0.032	h	=	0.704 ± 0.015
σ_8	=	0.76 ± 0.05	σ_8	=	0.776 ± 0.031
τ	=	0.088 ± 0.03	τ	=	0.073 ± 0.03
n_s	=	0.961 ± 0.017	n_s	=	0.947 ± 0.015

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 $\chi^2 = 1.037$

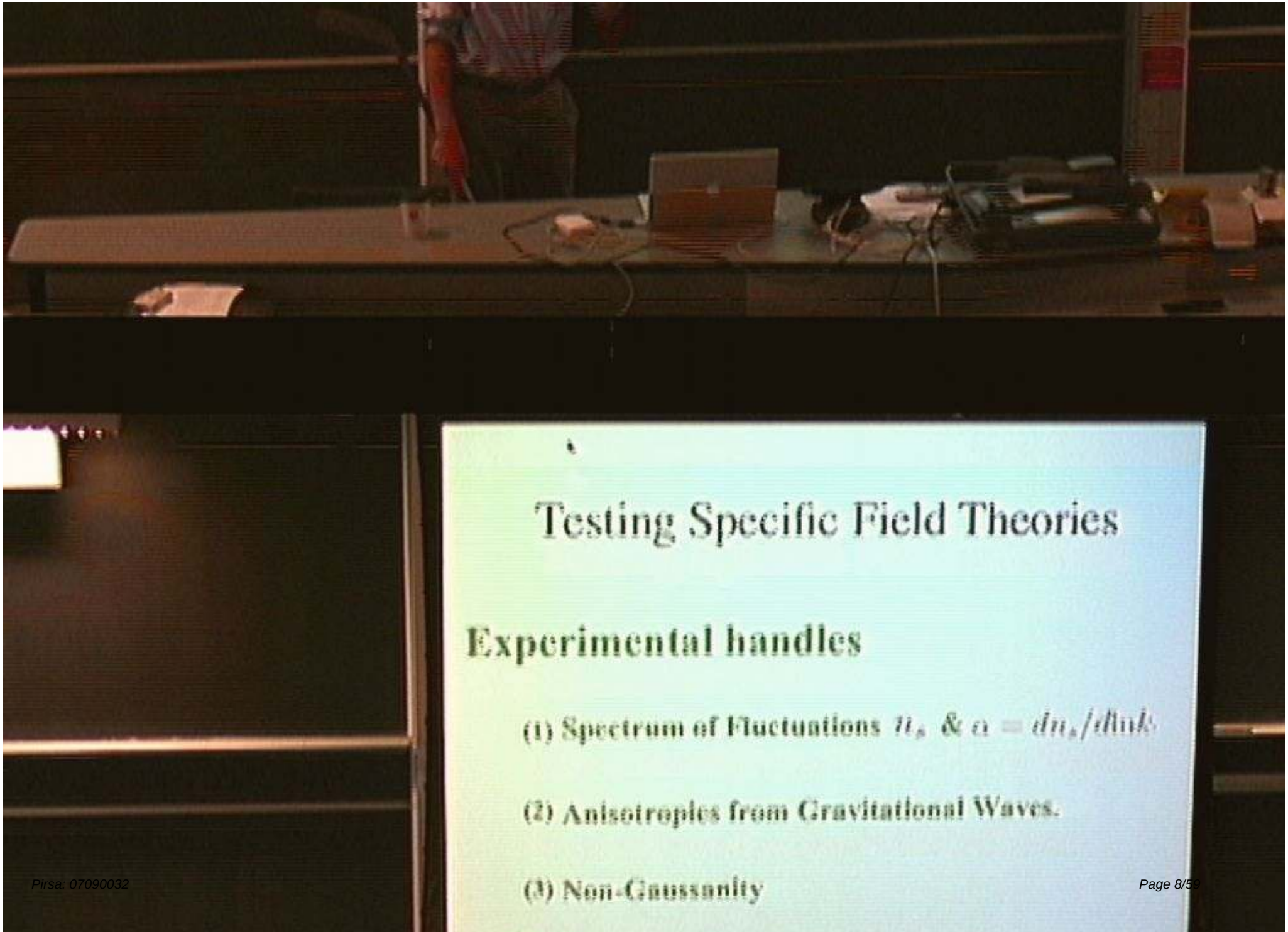
Testing Specific Field Theories

Experimental handles

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

(2) Anisotropies from Gravitational Waves.

(3) Non-Gaussanity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Testing Specific Field Theories

Experimental handles

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

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Types of Cosmological Perturbations

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

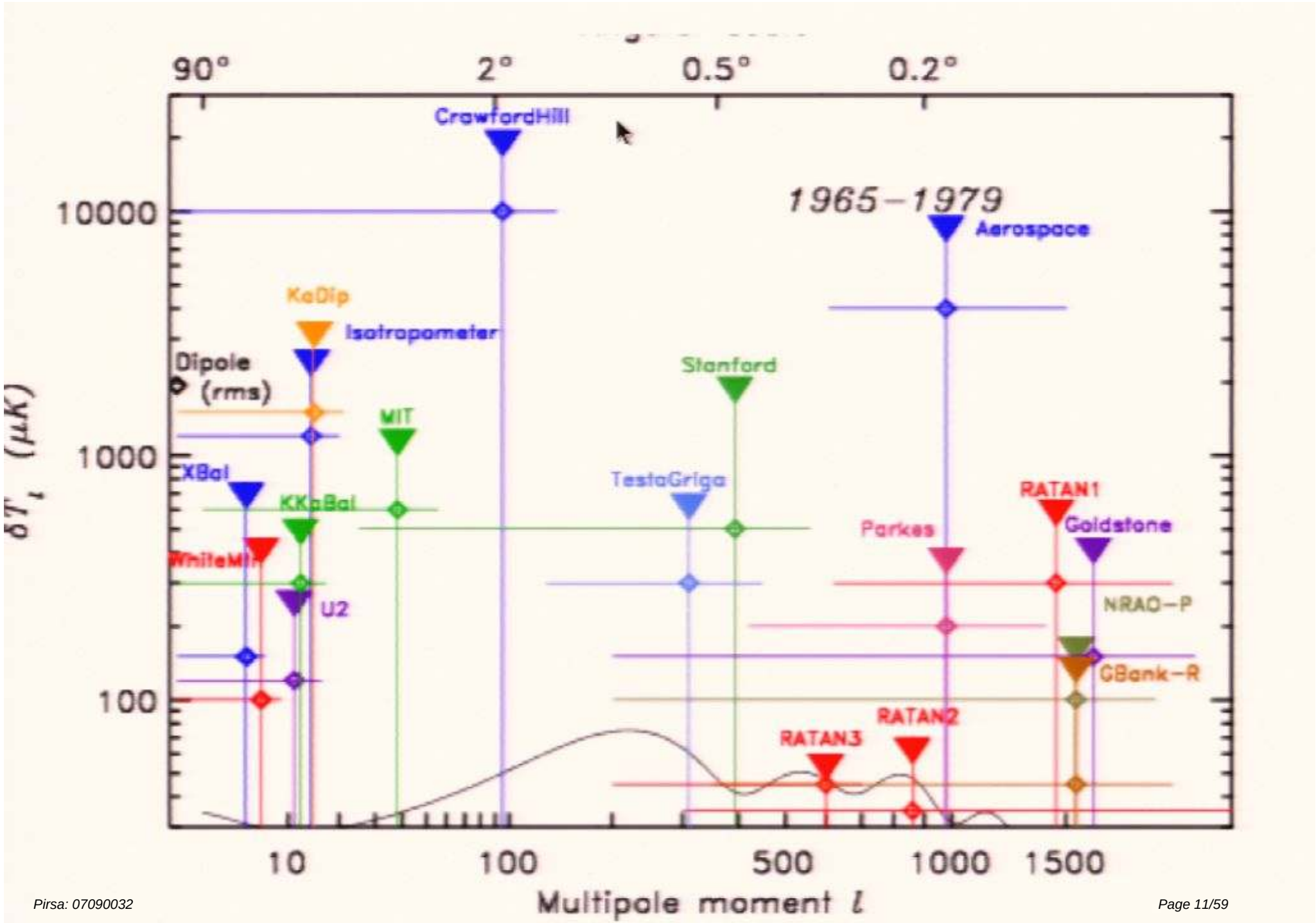
- Temperature
- E polarization

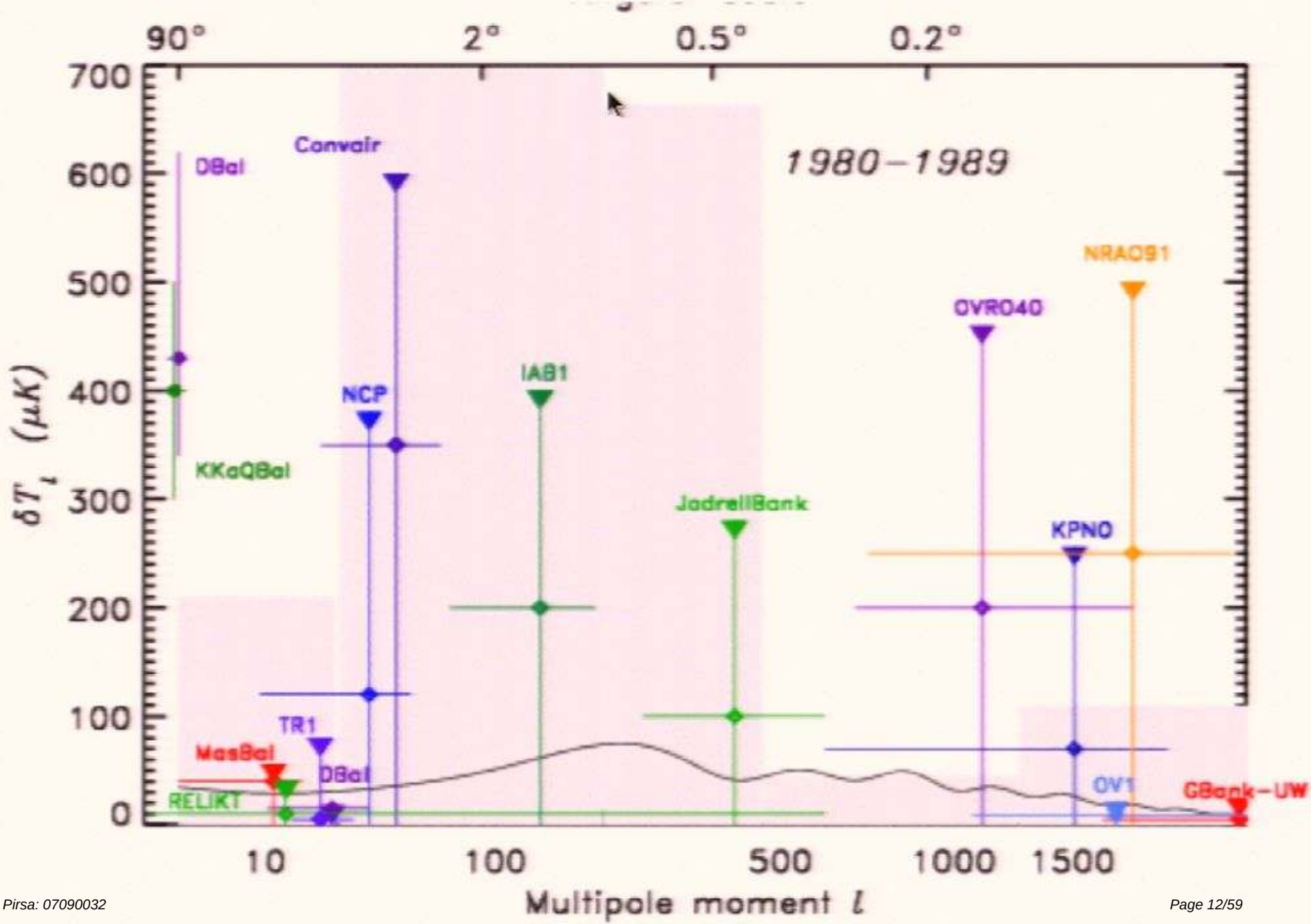
Tensors: h (GW strain)

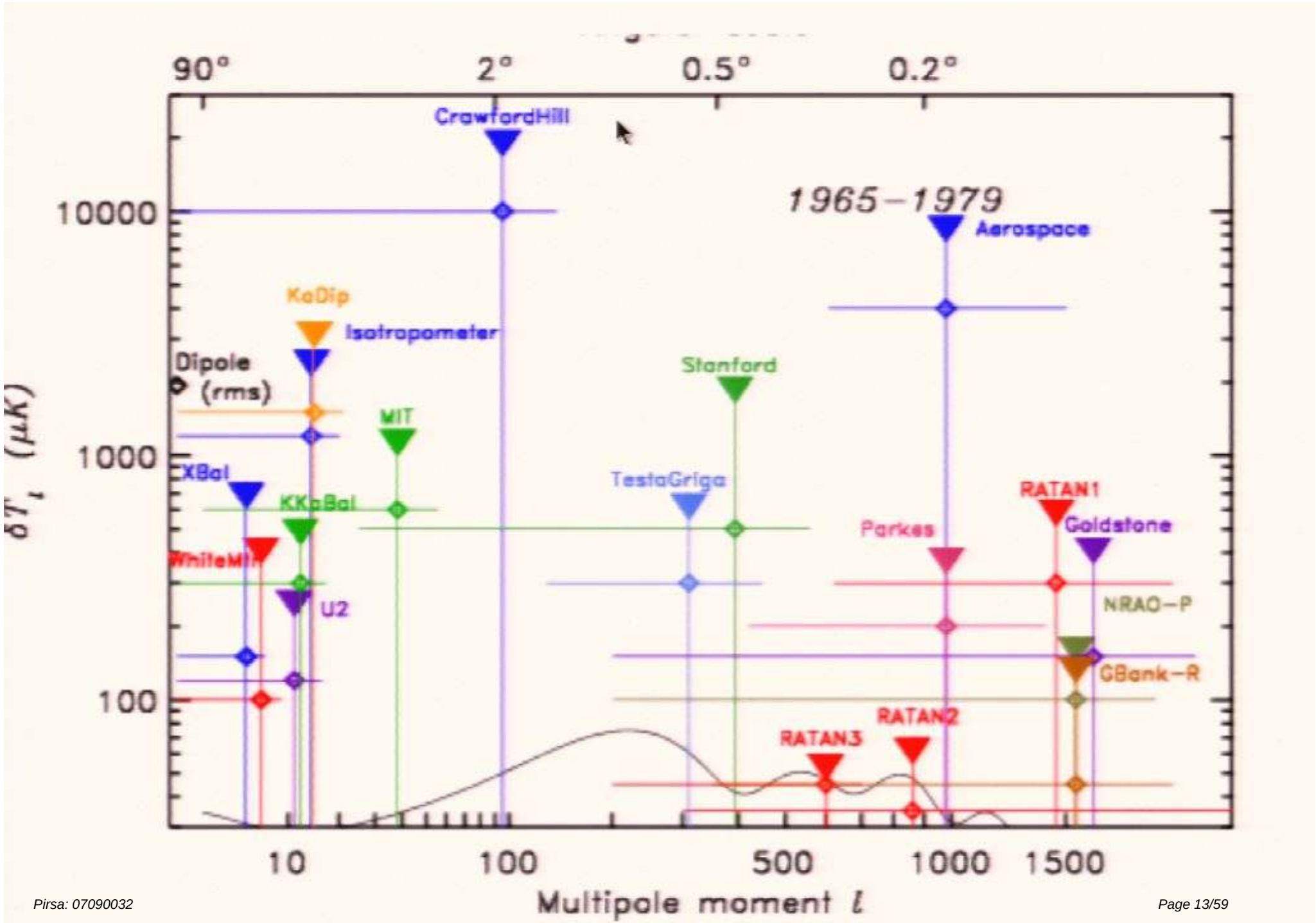
- Temperature
- E polarization
- B polarization

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

n and r are predicted by models of the early universe


90°
2°
0.5°
0.2°
CrawfordHill
1965–1979
Aerospace
KaDip
Isotropometer
Dipole
(rms)
Stanford
MIT
XBal
TestaGriga
RATAN1
KKaBal
Parkes
Goldstone
WhiteMtn
U2
NRAO–P
GBank–R
RATAN2
RATAN3
10000
1000
100
δT_l (μK)
10
100
500
1000
1500
Multipole moment l


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


90°
2°
0.5°
0.2°
CrawfordHill
1965–1979
Aerospace
KaDip
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Dipole
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MIT
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U2
NRAO–P
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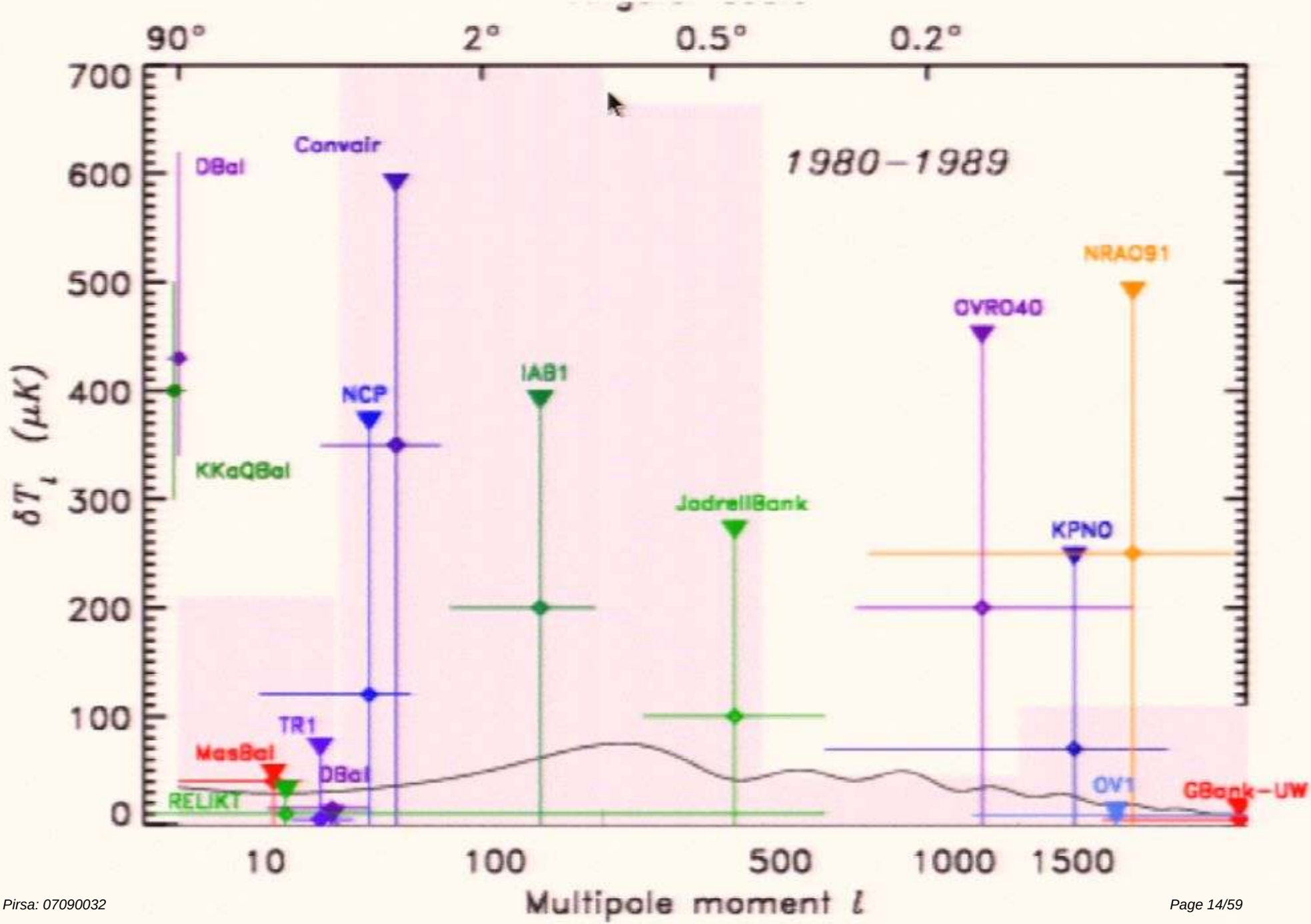
RATAN2
RATAN3
10000
1000
100
δT_l (μK)
10
100
500
1000
1500
Multipole moment l


90°
2°
0.5°
0.2°
700
600
500
400
300
200
100
0
δT_l (μK)
1980–1989
DBal
Convair
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RELIKT
OV1
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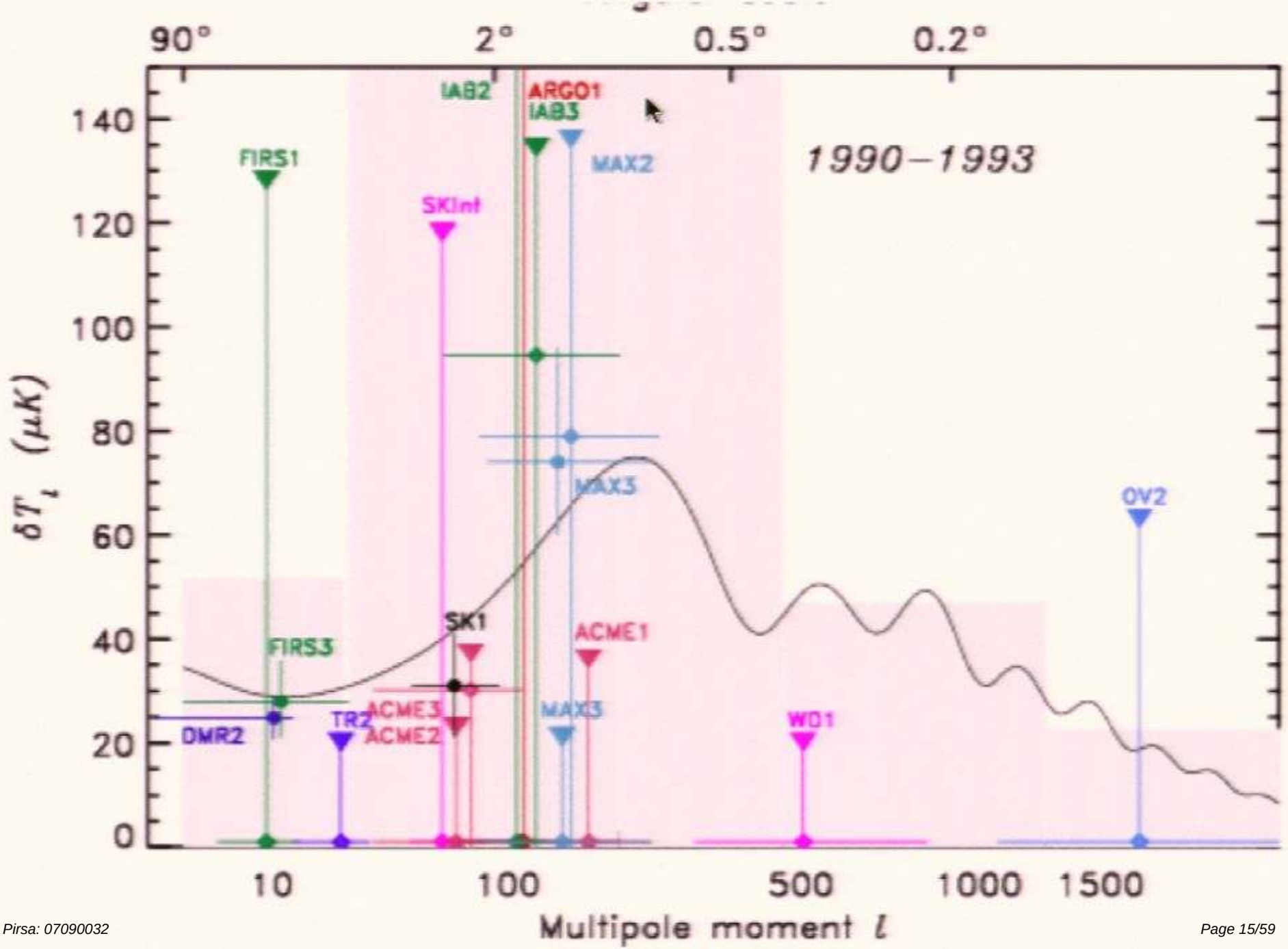
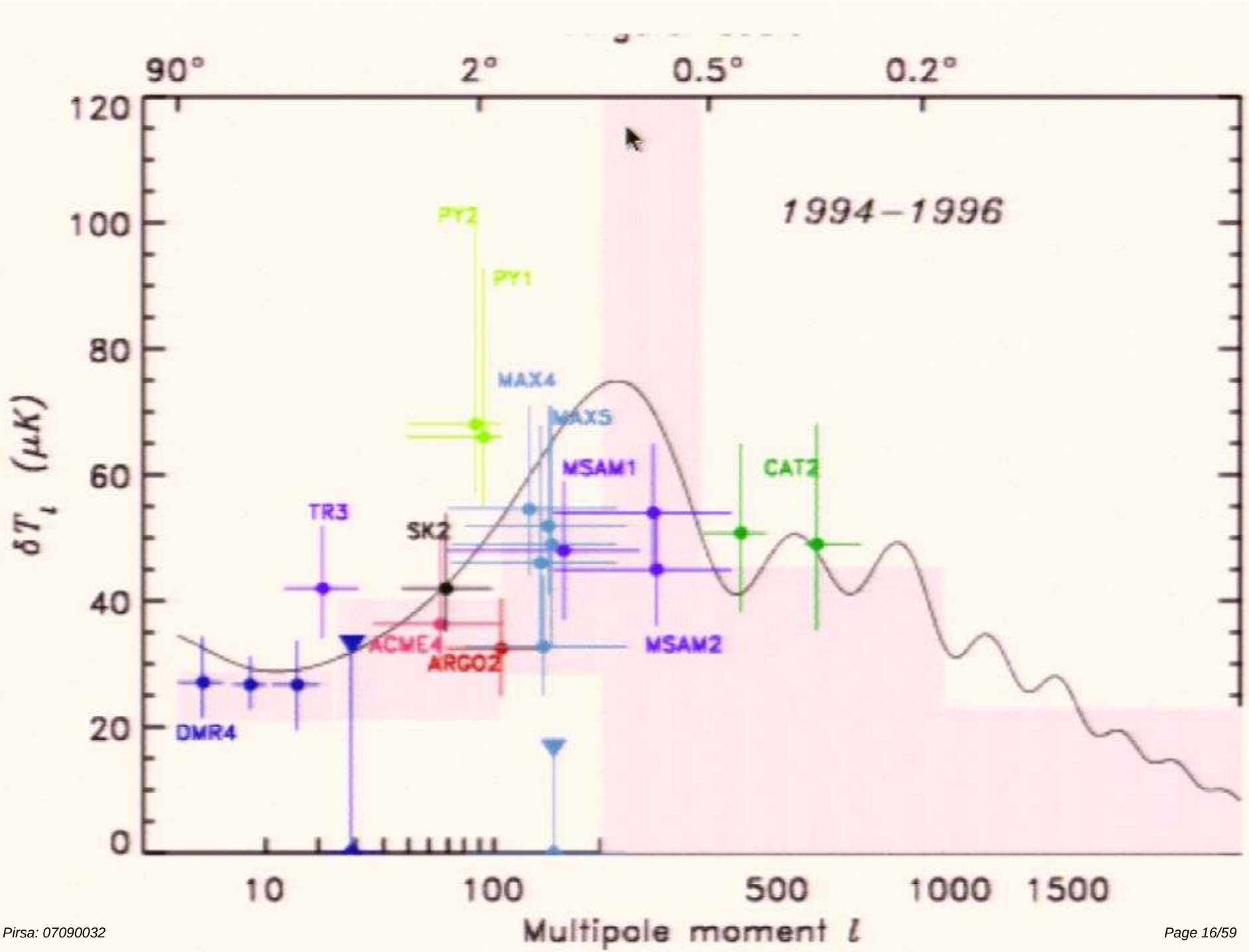
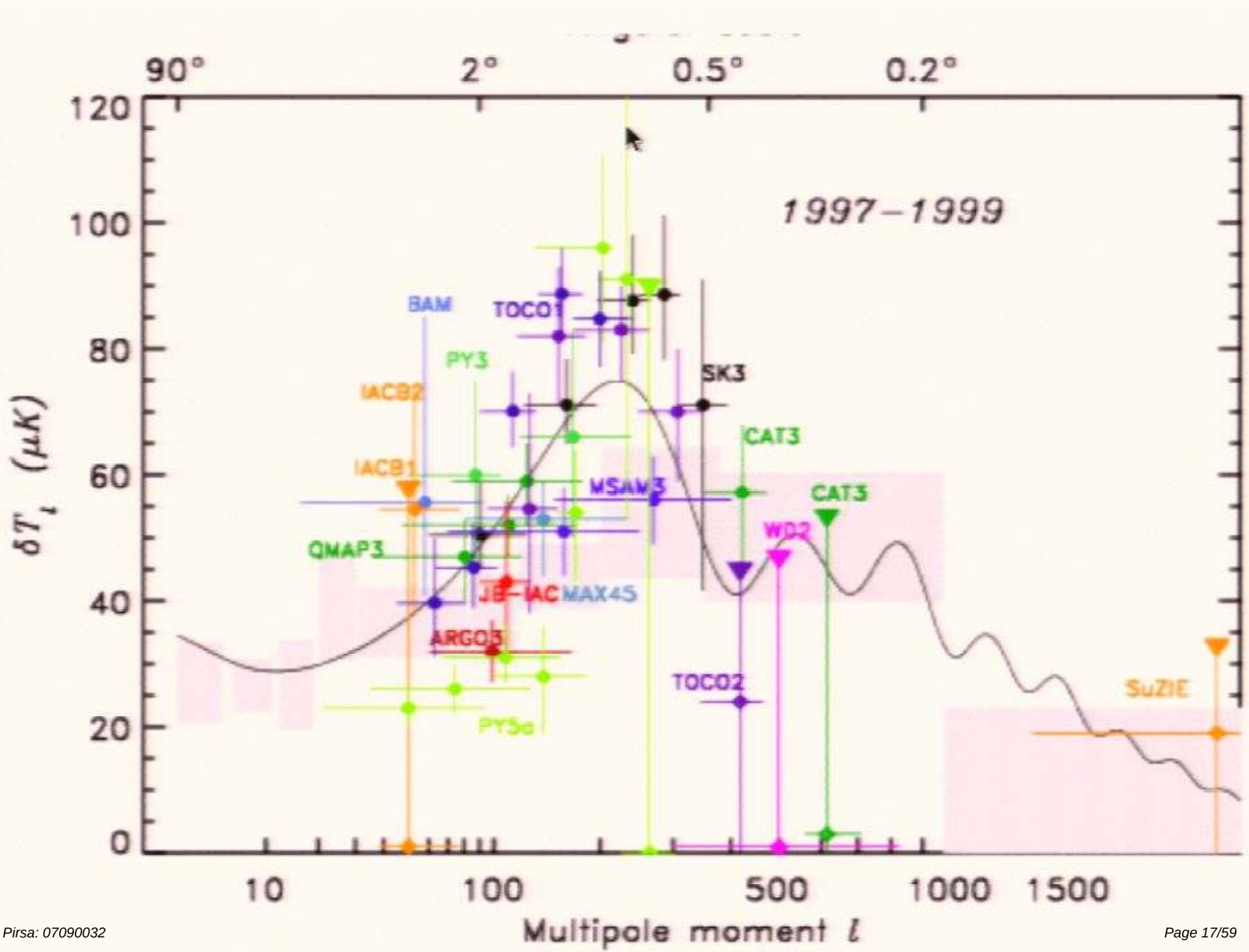
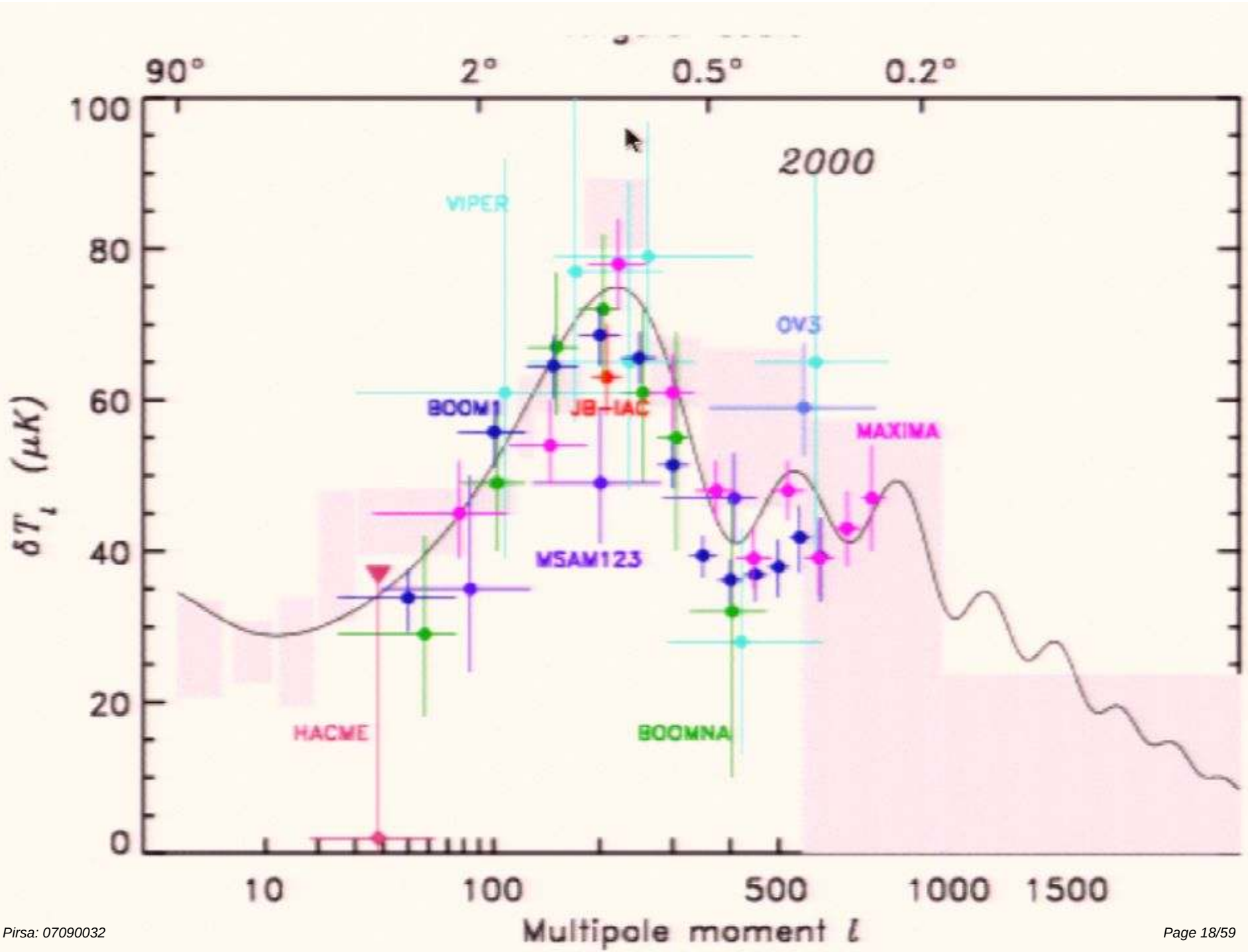
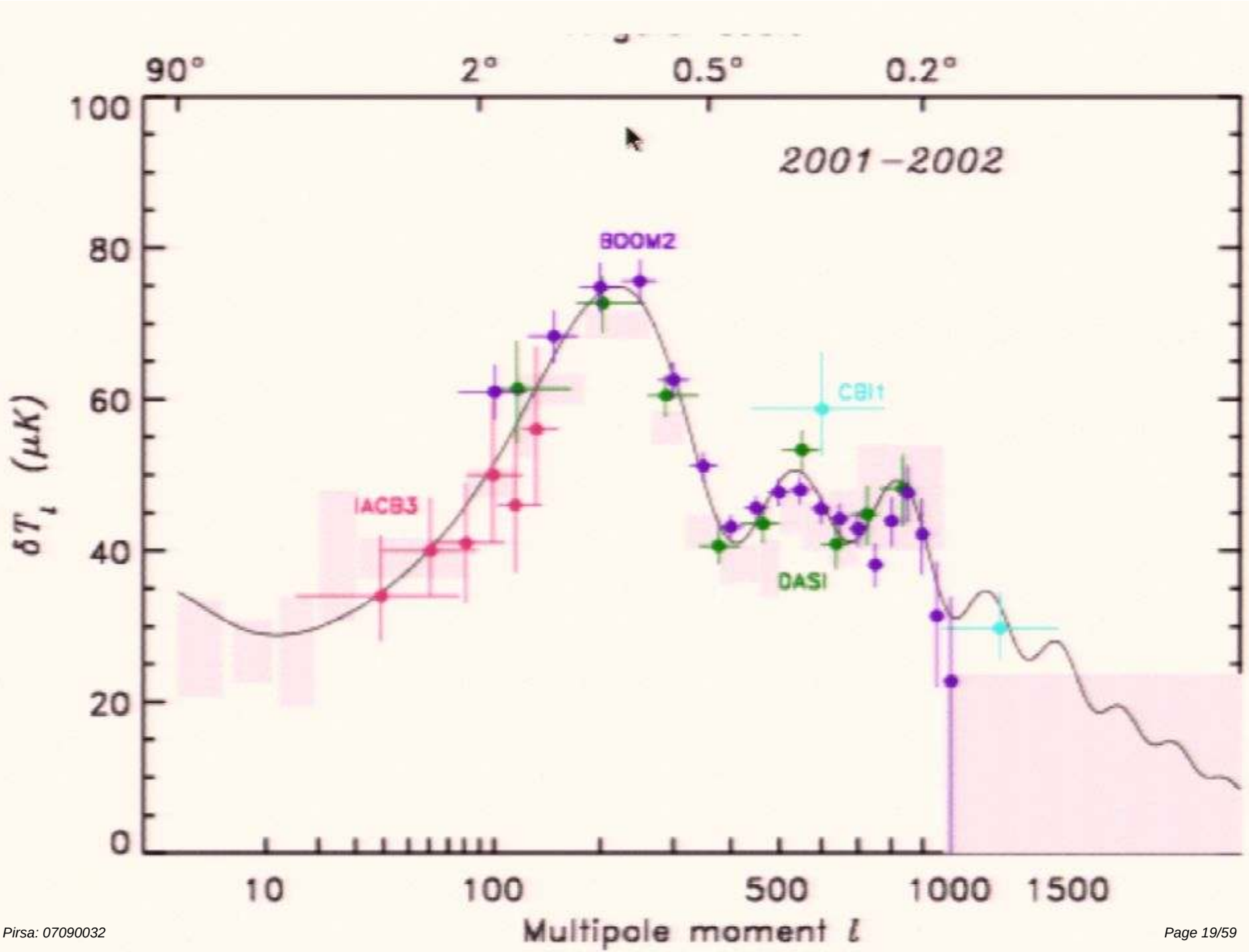
10
100
500
1000
1500
Multipole moment l

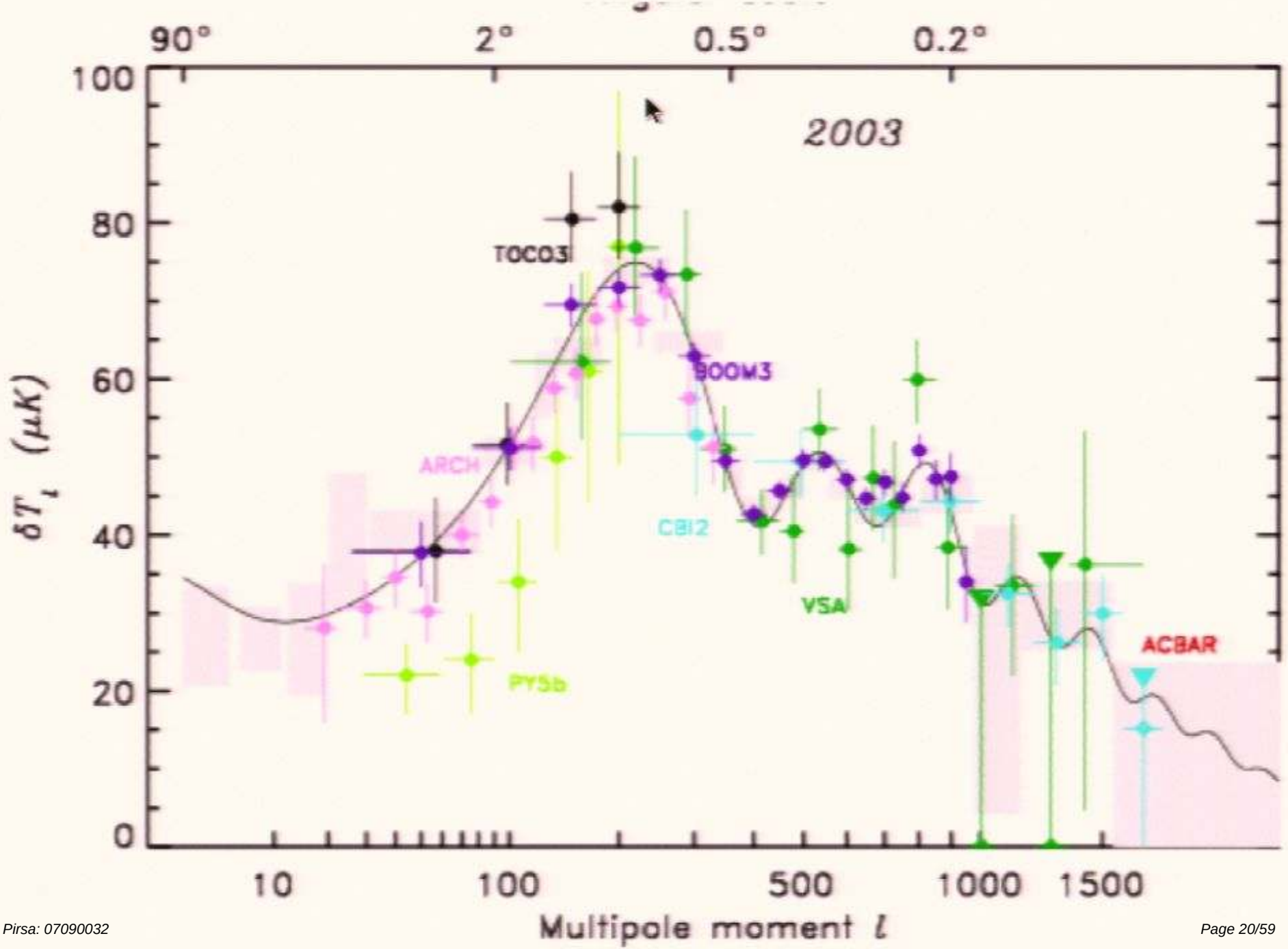

90°
2°
0.5°
0.2°
IAB2
ARGO1
IAB3
MAX2
1990–1993
FIRS1
SKInt
MAX3
OV2
SK1
ACME1
FIRS3
ACME3
ACME2
MAX3
TR2
WD1
DMR2
140
120
100
80
60
40
20
0
δT_l (μK)
10
100
500
1000
1500
Multipole moment l

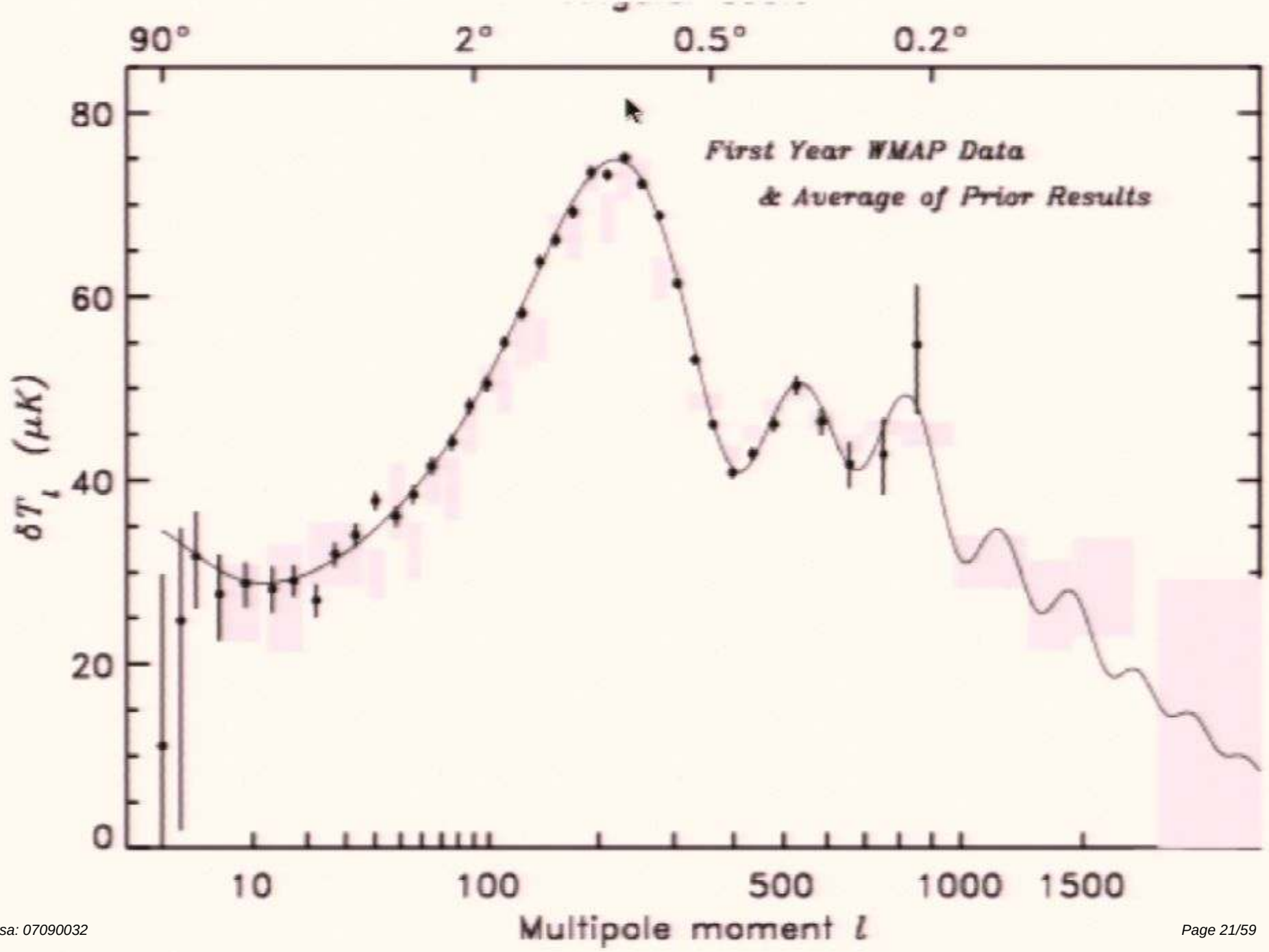

90°
2°
0.5°
0.2°
120
100
80
60
40
20
0
δT_l (μK)
1994–1996
PY2
PY1
MAX4
MAX5
MSAM1
CAT2
TR3
SK2
ACME4
ARGO2
MSAM2
DMR4
10
100
500
1000
1500
Multipole moment l


90°
2°
0.5°
0.2°
120
100
80
60
40
20
0
δT_l (μK)
1997–1999
BAM
TOCO1
PY3
SK3
IACB2
CAT3
IACB1
MSAM3
CAT3
WD2
QMAP3
JB-IAC
MAX4S
ARGO5
TOCO2
SuZIE
PY3o
10
100
500
1000
1500
Multipole moment l

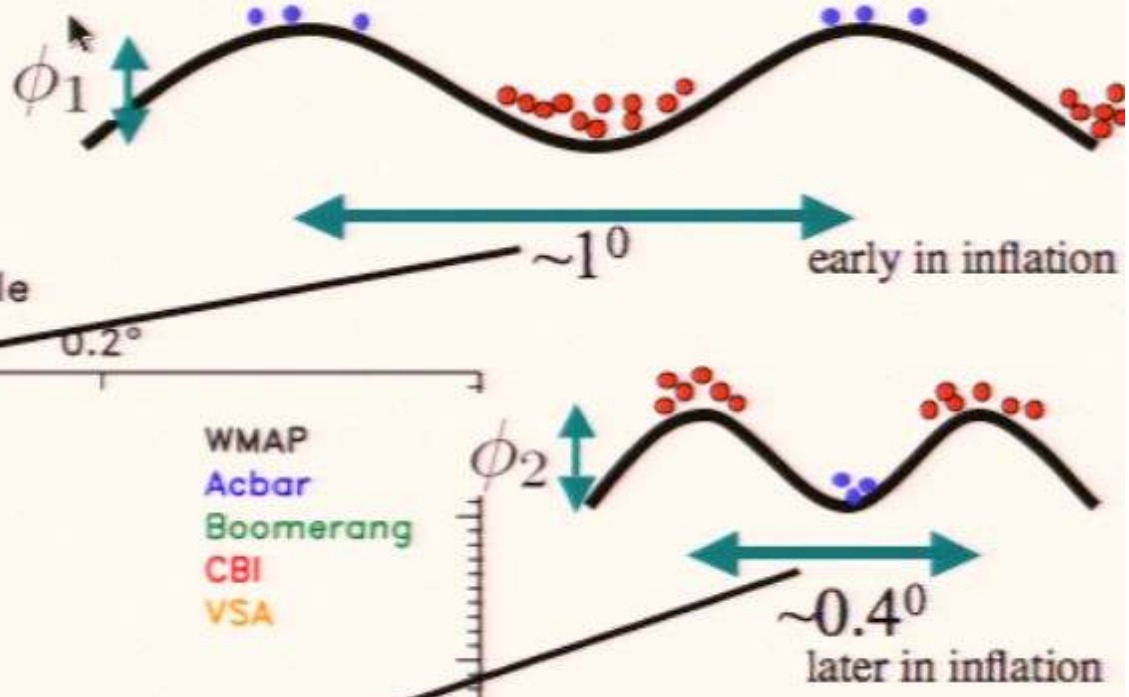

90°
2°
0.5°
0.2°
2000
VIPER
OV3
BOOM1
JB-IAC
MAXIMA
MSAM123
HACME
BOOMNA
100
80
60
40
20
0
δT_l (μK)
10
100
500
1000
1500
Multipole moment l

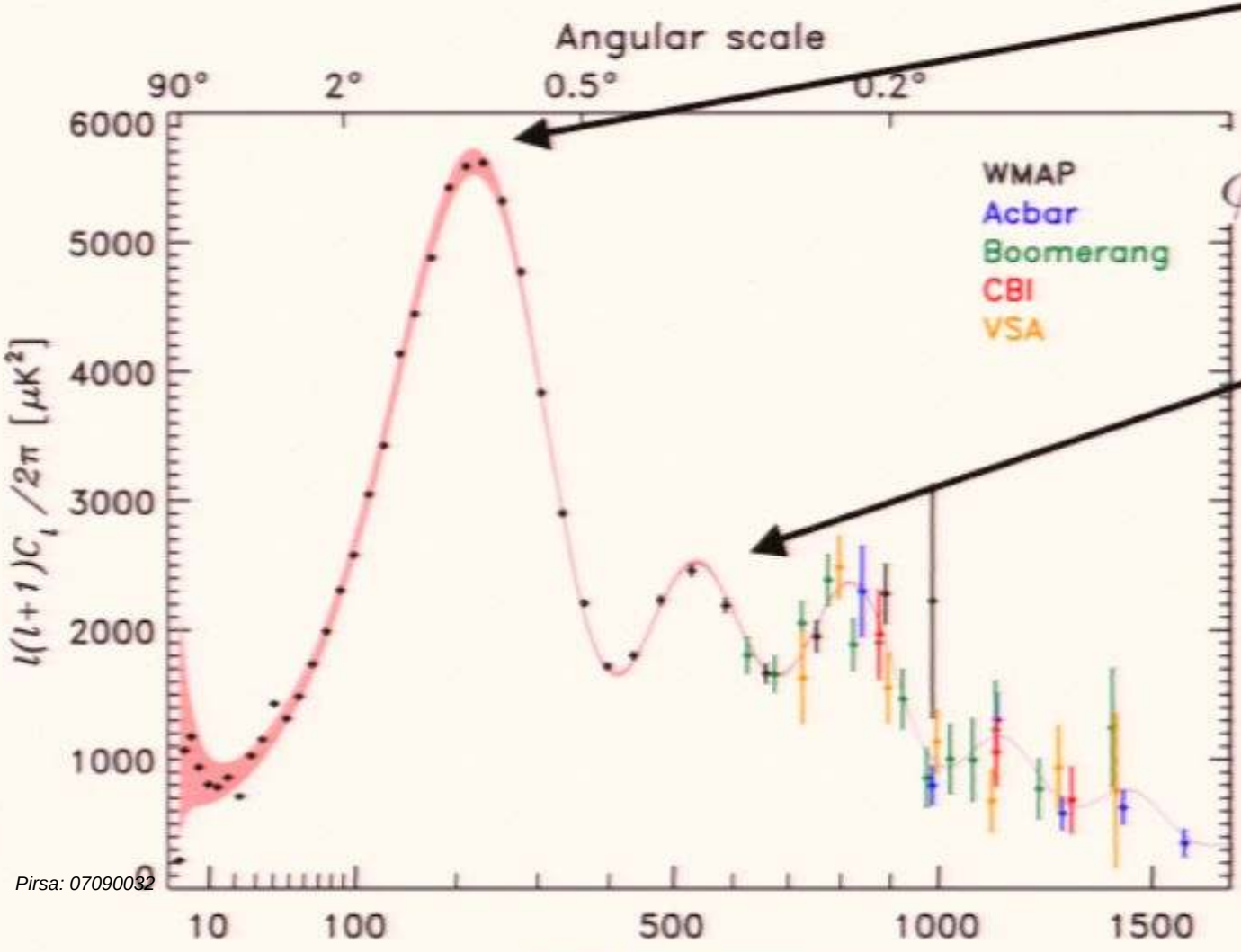

90°
2°
0.5°
0.2°
2001–2002
BOOM2
CBI1
ACBI3
DASI
δT_l (μK)
100
80
60
40
20
0
10
100
500
1000
1500
Multipole moment l


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

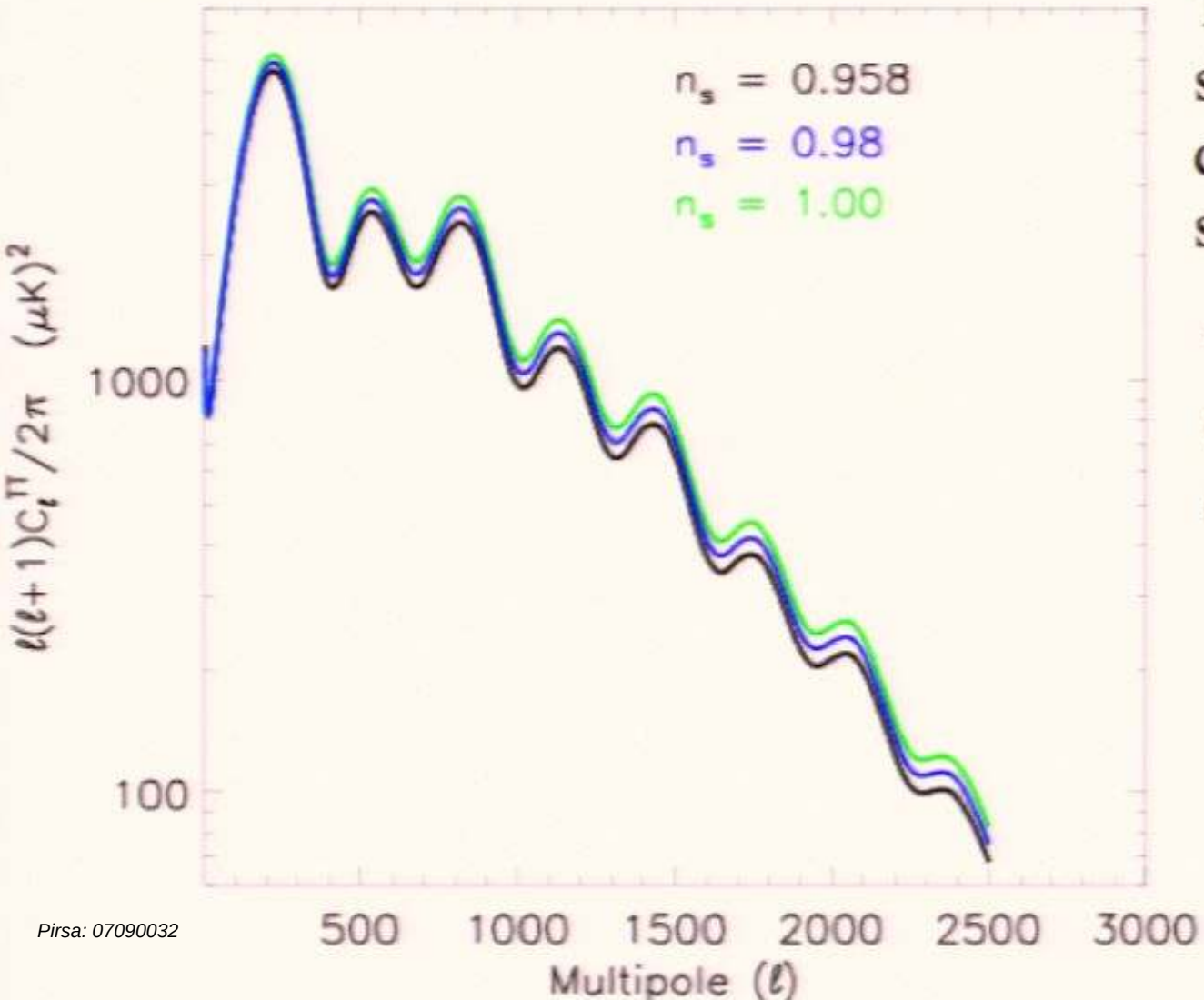
Angular Power Spectrum.





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

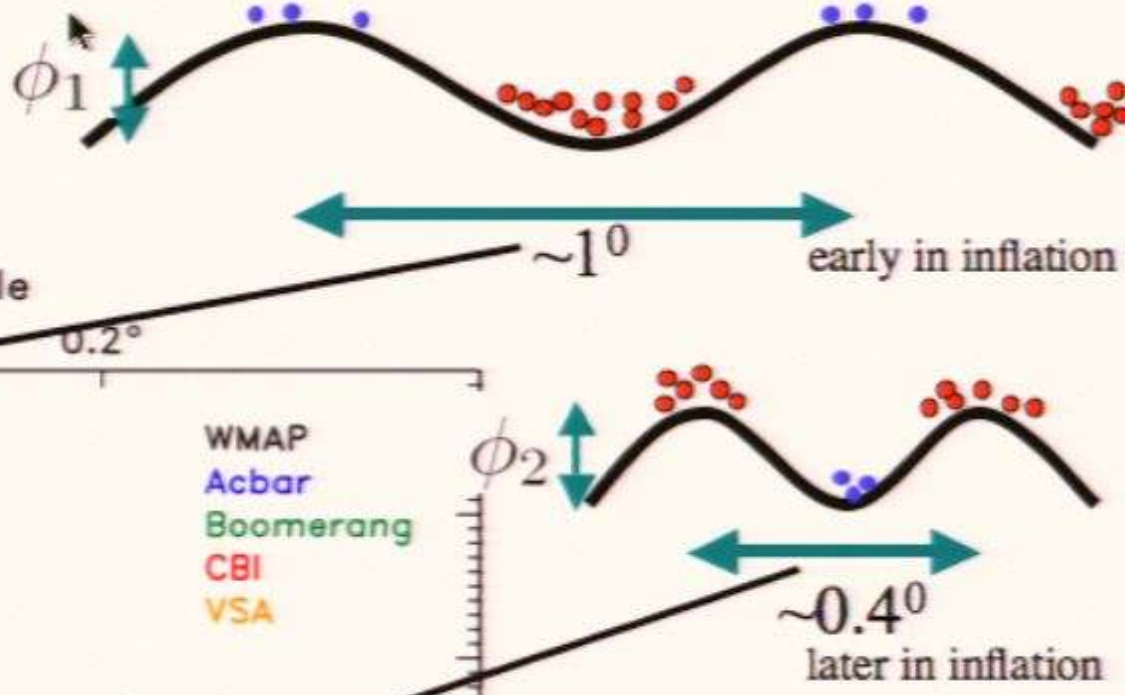
Spectral Index, Experimental Challenges

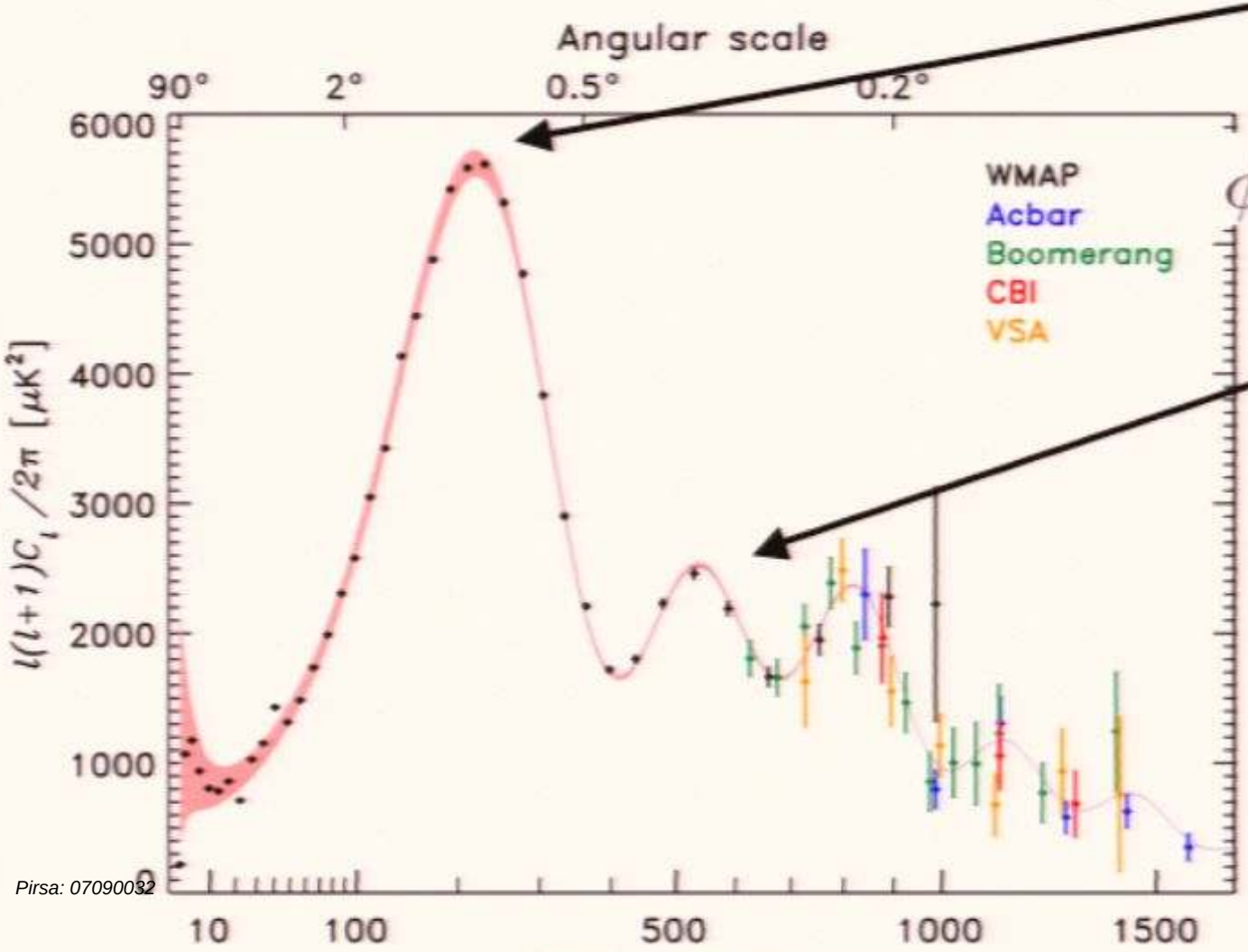


Three different spectra that differ only in spectral index.

The black line is the best WMAP model.

Angular Power Spectrum.





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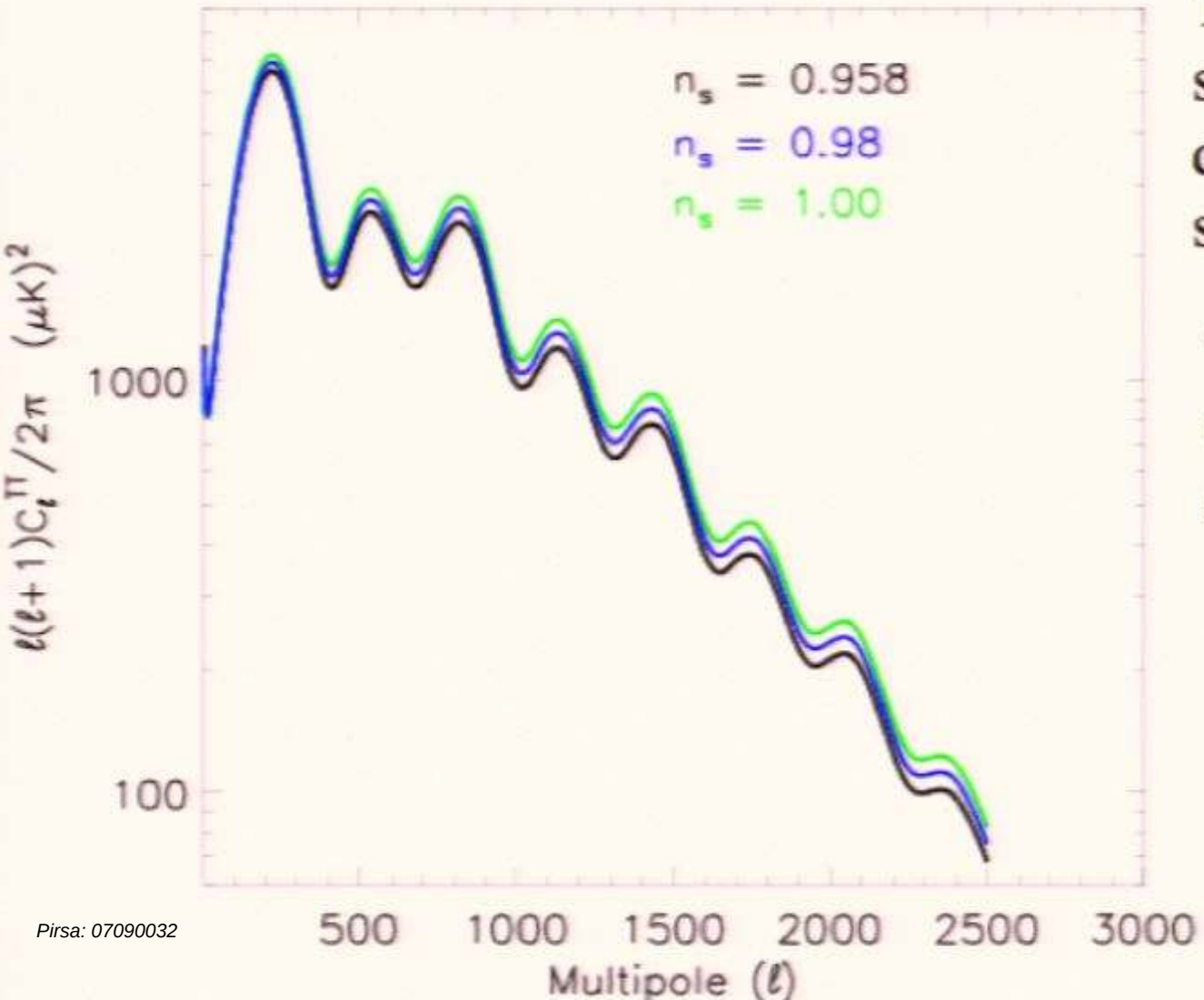

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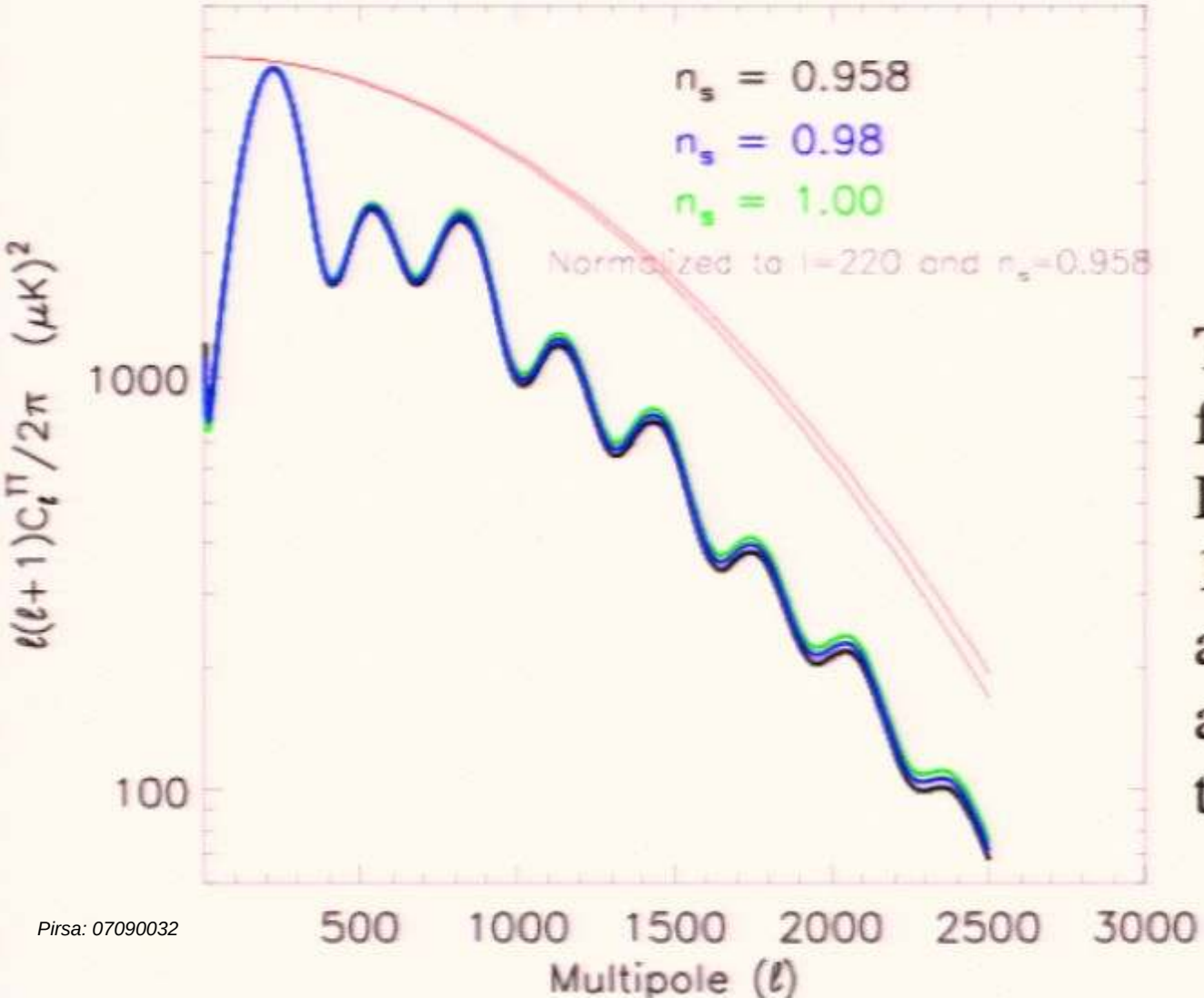
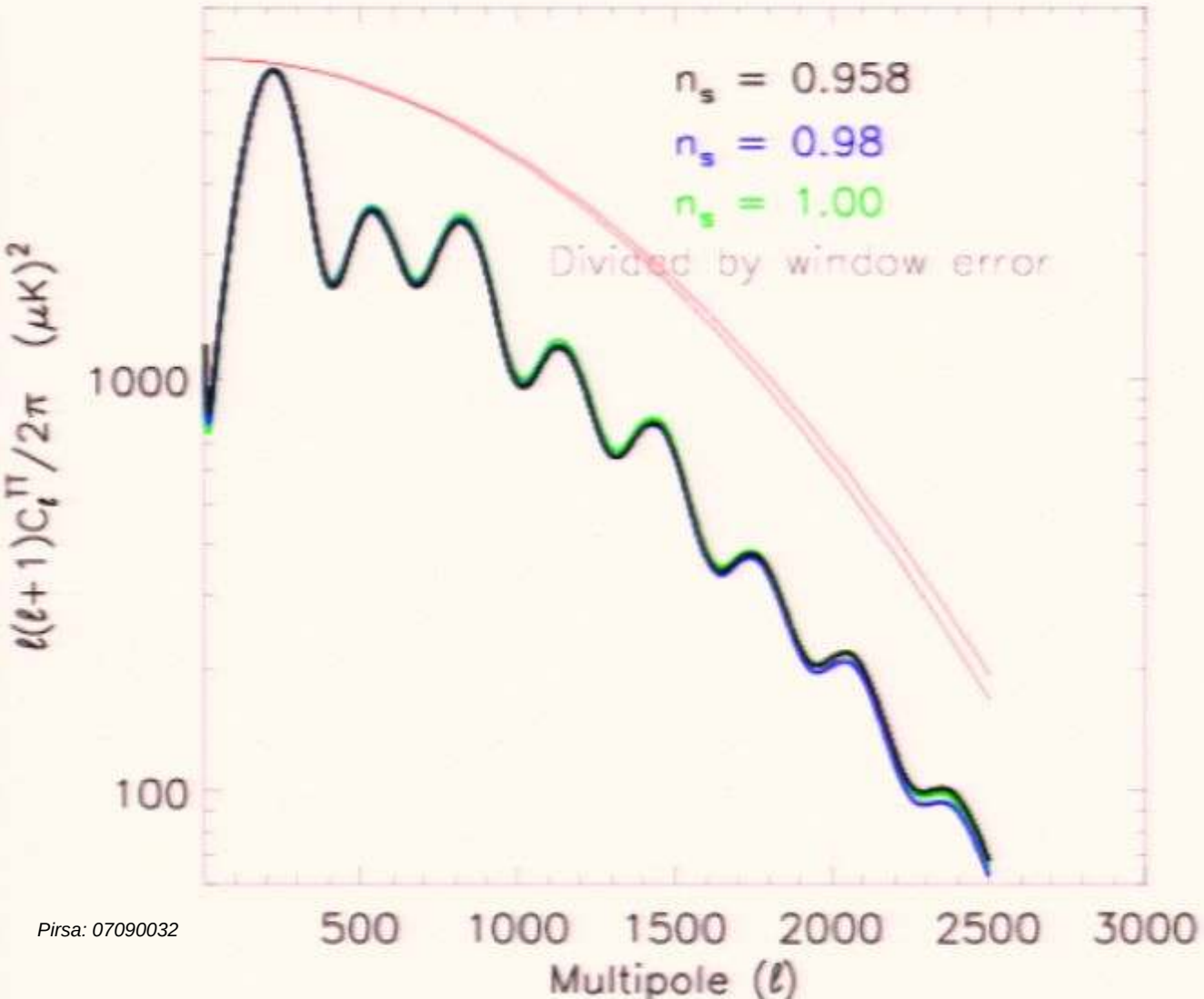
Spectral Index



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

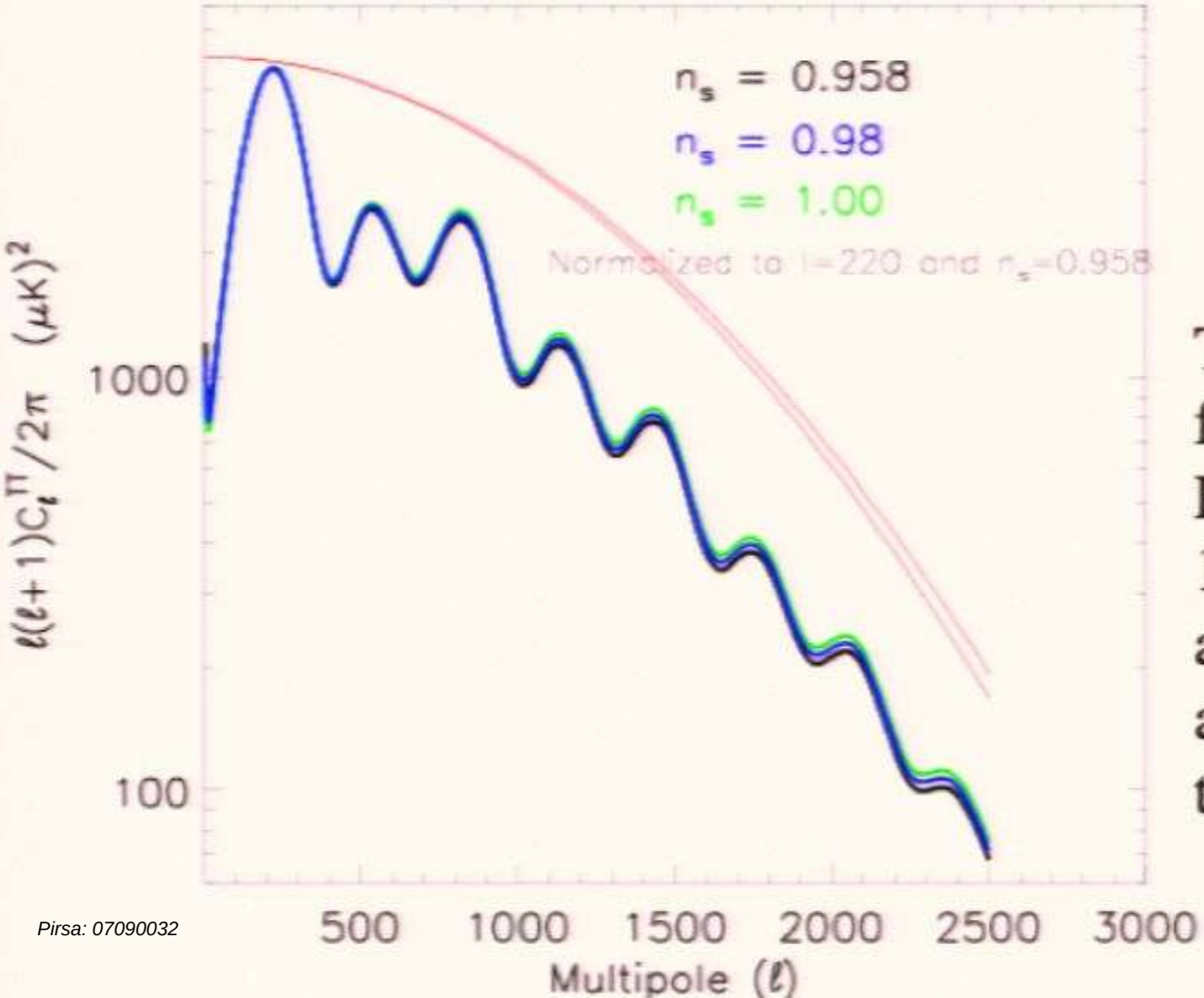


Divide by fractional window function.

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

In addition, there are astrophysical challenges.

Spectral Index



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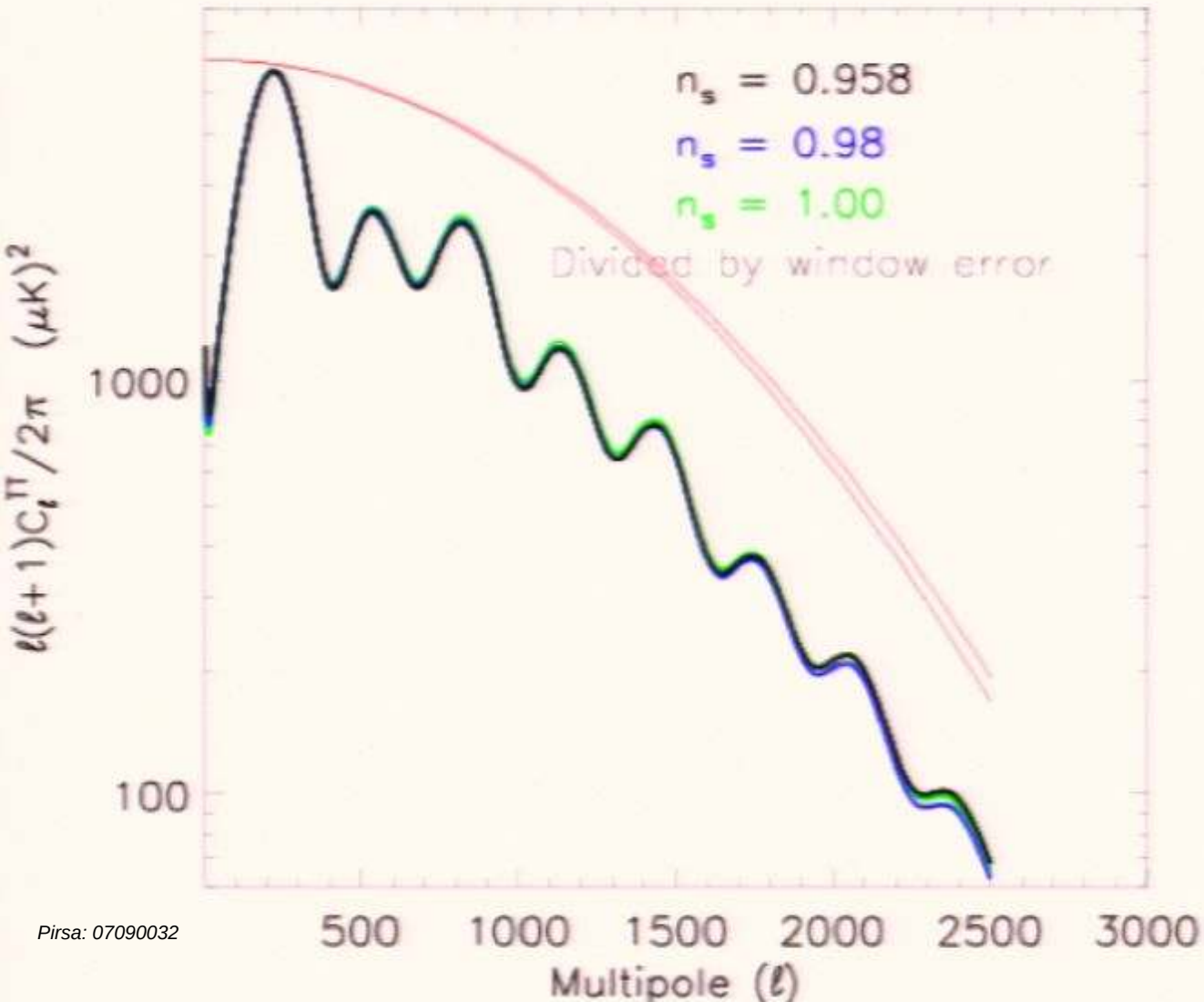


Divide by fractional window function.

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:

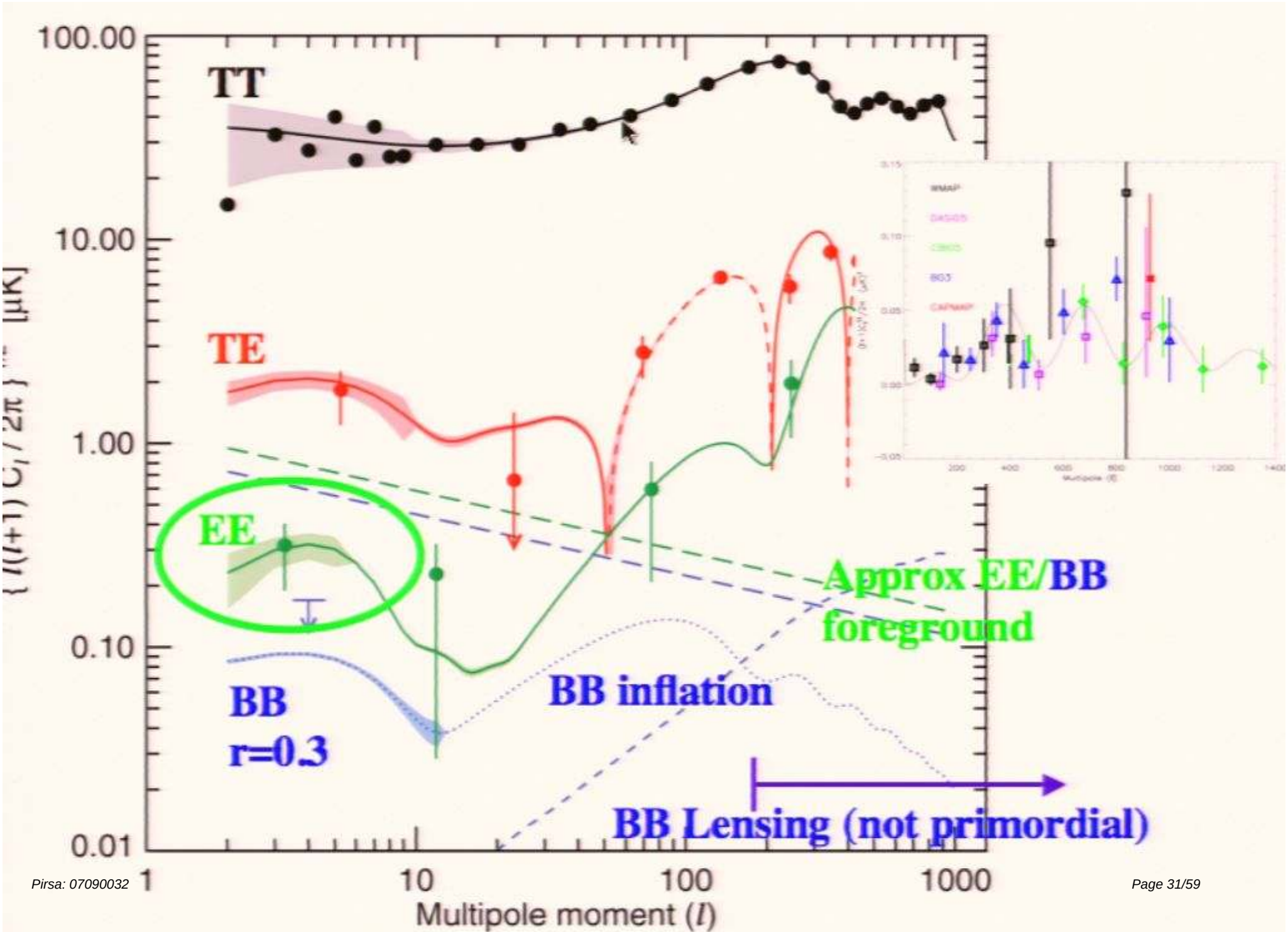
(1) rescatter CMB photons thereby reducing the anisotropy and

(2) polarize the CMB at large angular scales.

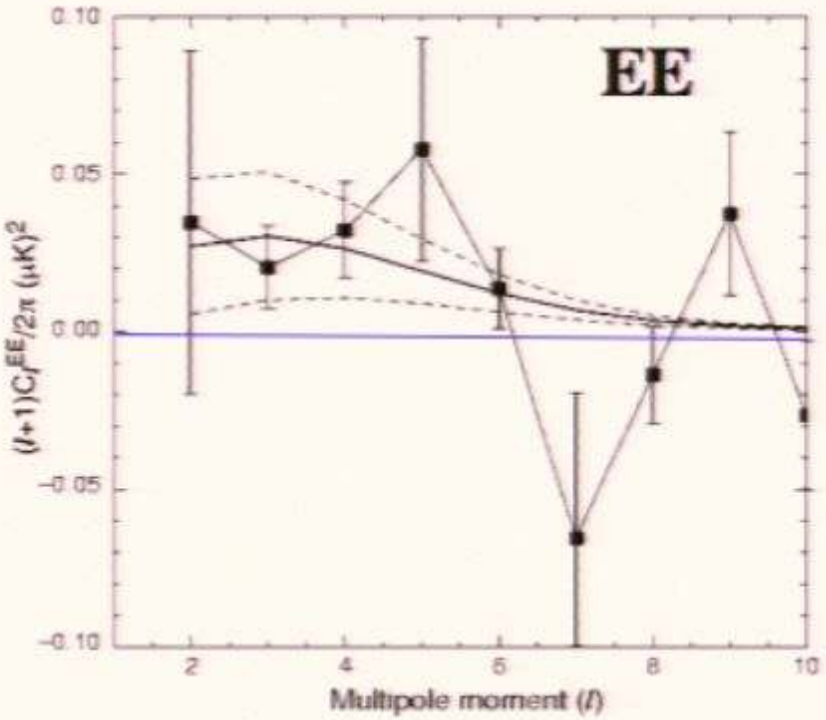
These effects mimic a change in n_s:

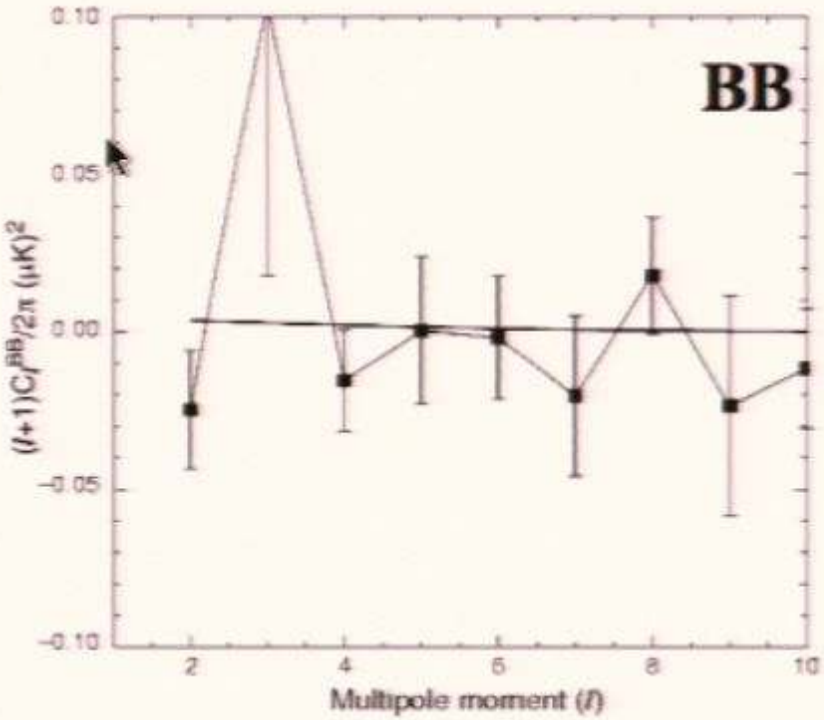
"the n_s - tau" degeneracy

WMAP measures (2) to break the degeneracy


100.00
10.00
1.00
0.10
0.01
TT
TE
EE
BB
r=0.3
BB inflation
Approx EE/BB
foreground
BB Lensing (not primordial)
1
10
100
1000
Multipole moment (l)
[μK]

Low-l EE/BB





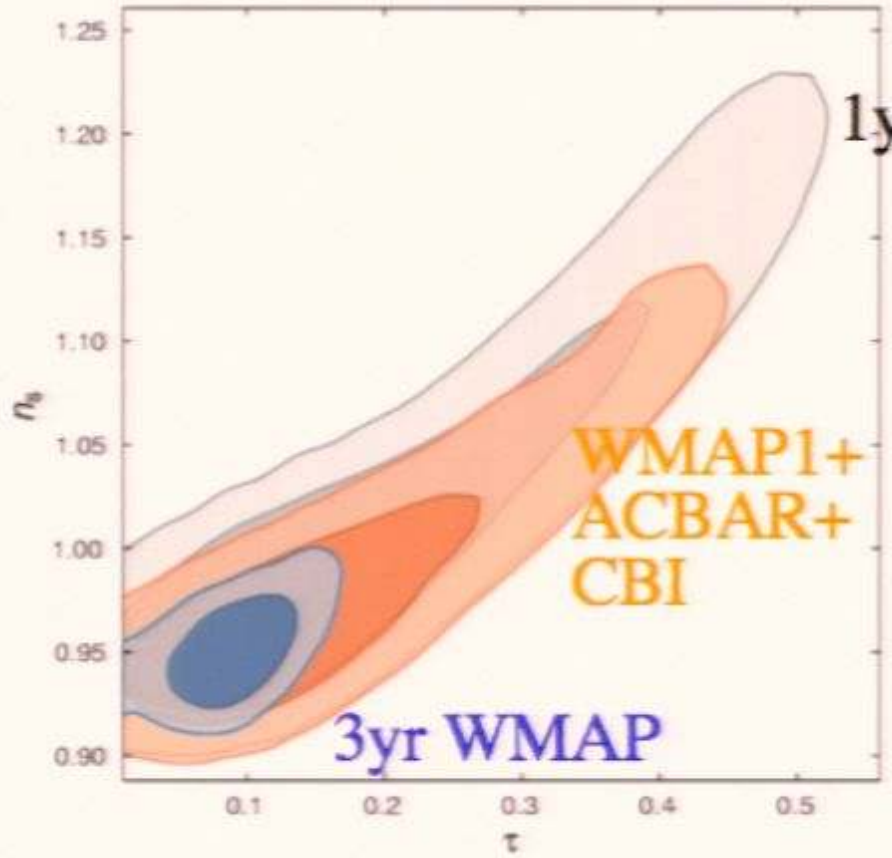
EE Polarization: from reionization by the first stars

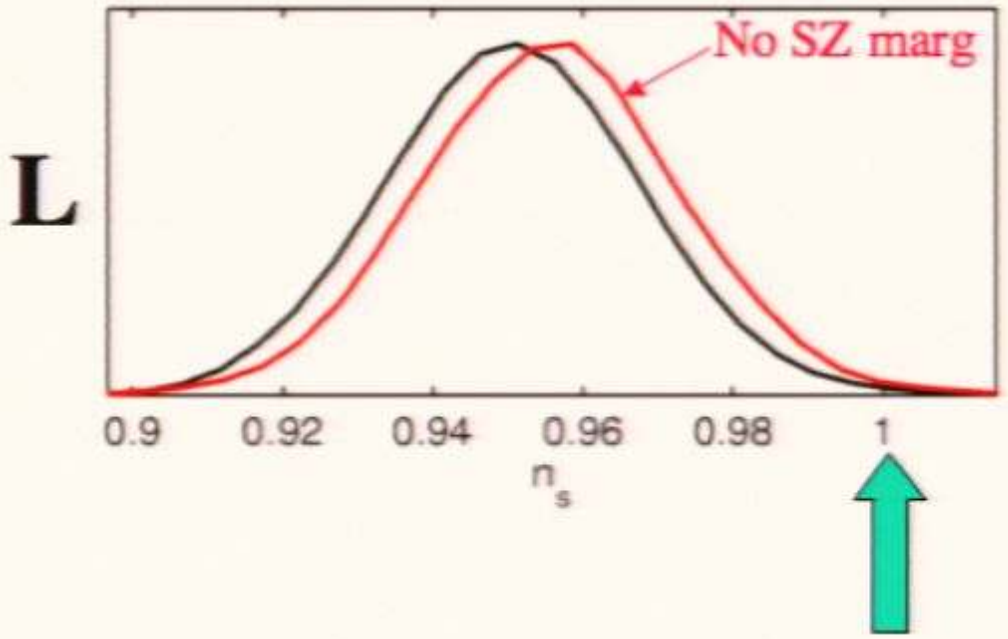
BB Polarization: null check and limit on gravitational waves.

Just Q and V bands.

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

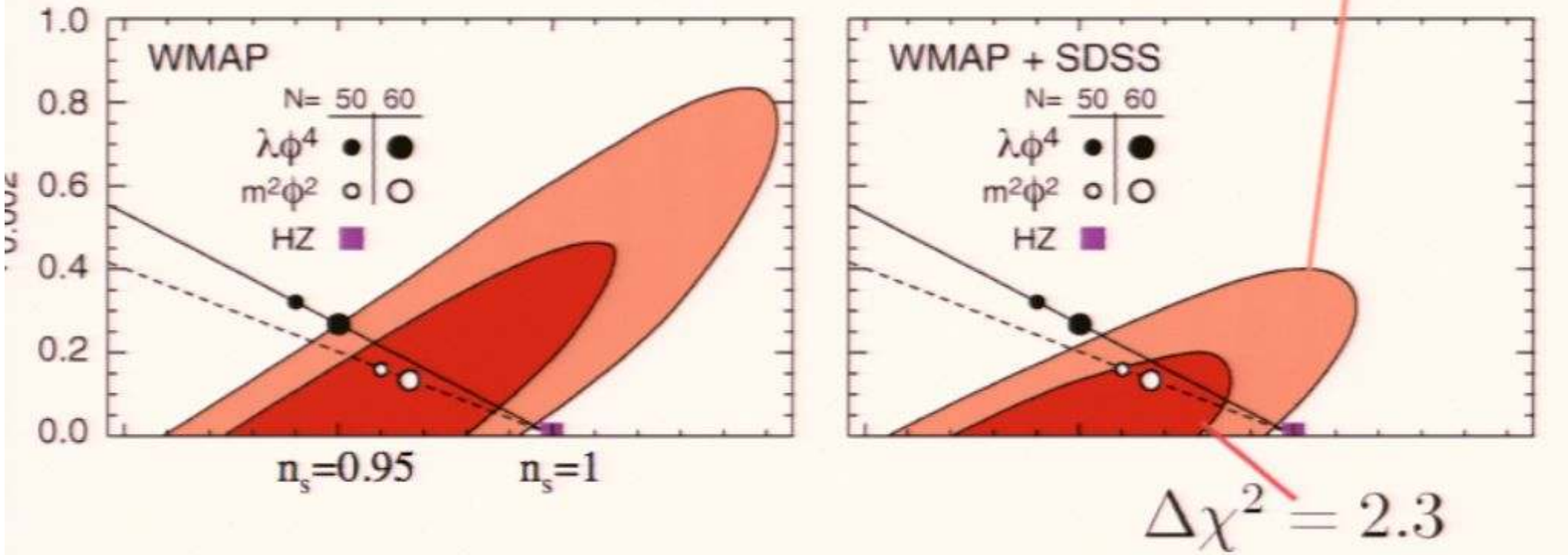
$n_s - \tau$ Degeneracy

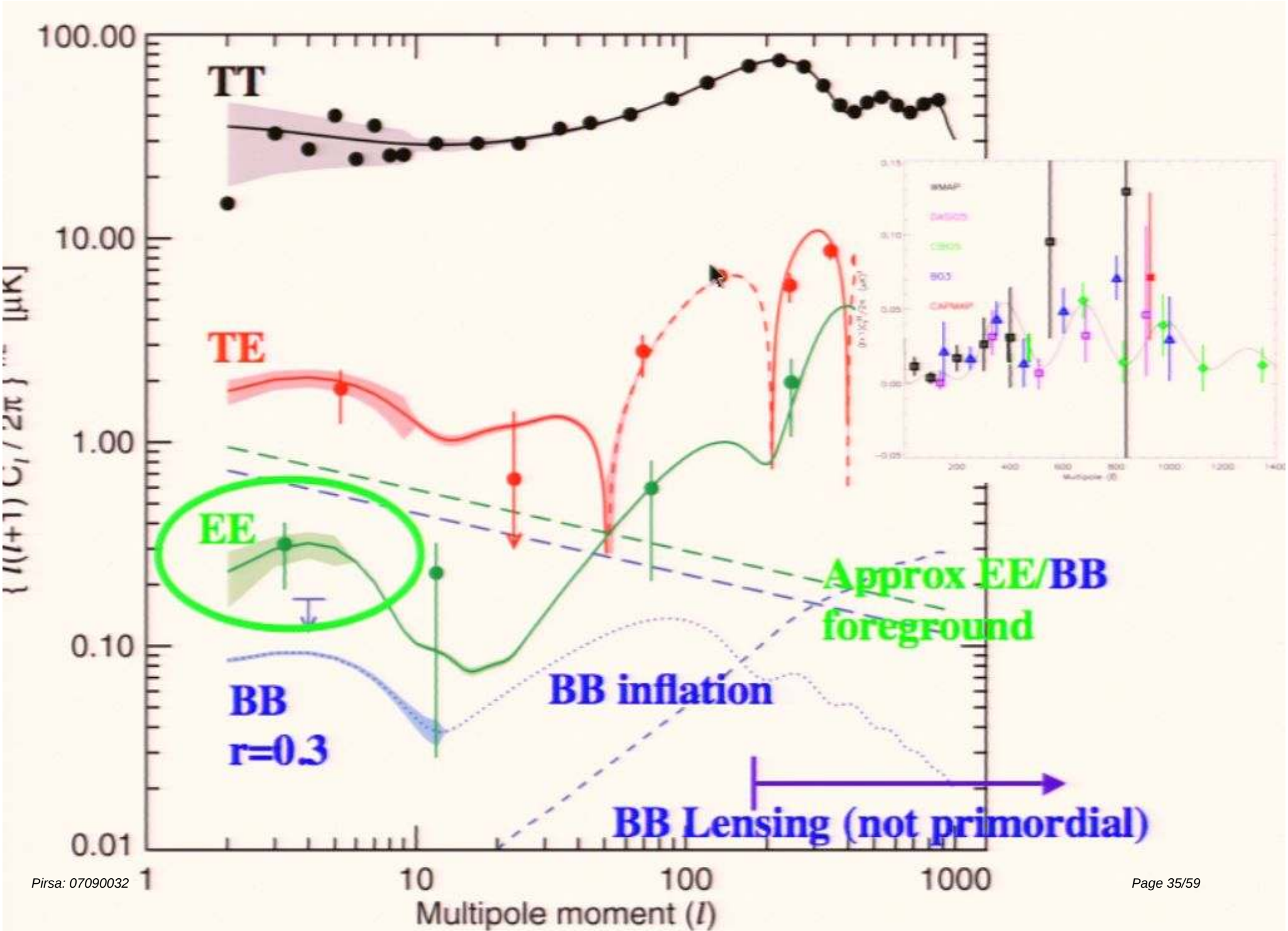




Knowledge of optical depth breaks the $n_s - \tau$ degeneracy

Index and Tensors




100.00
10.00
1.00
0.10
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TT
TE
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r=0.3
BB inflation
Approx EE/BB
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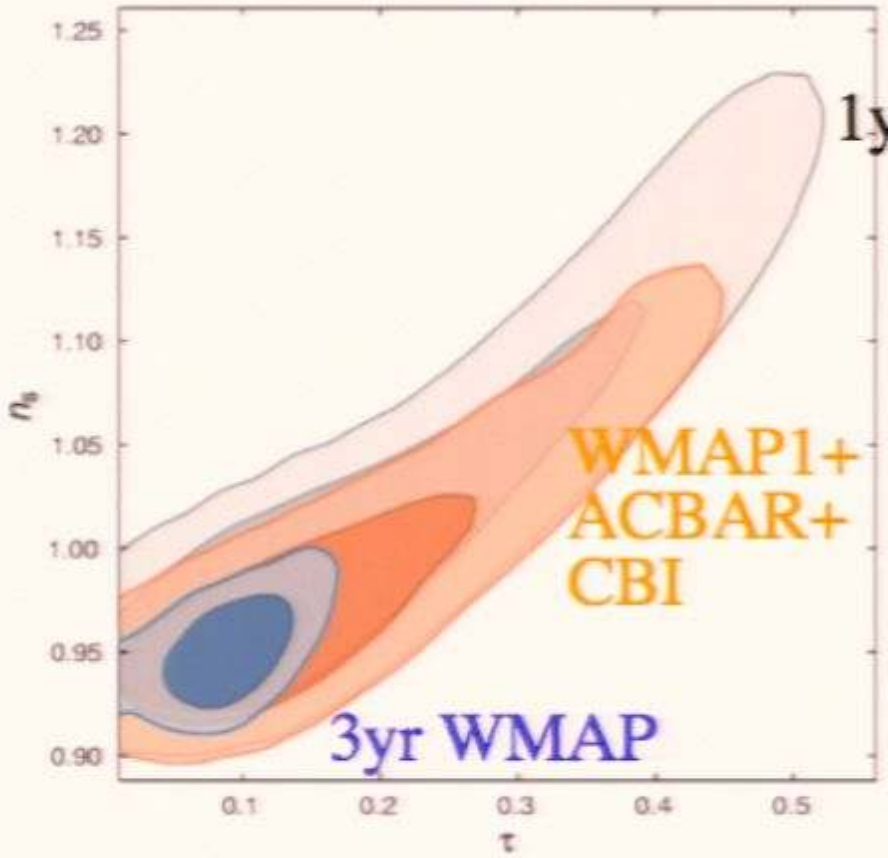
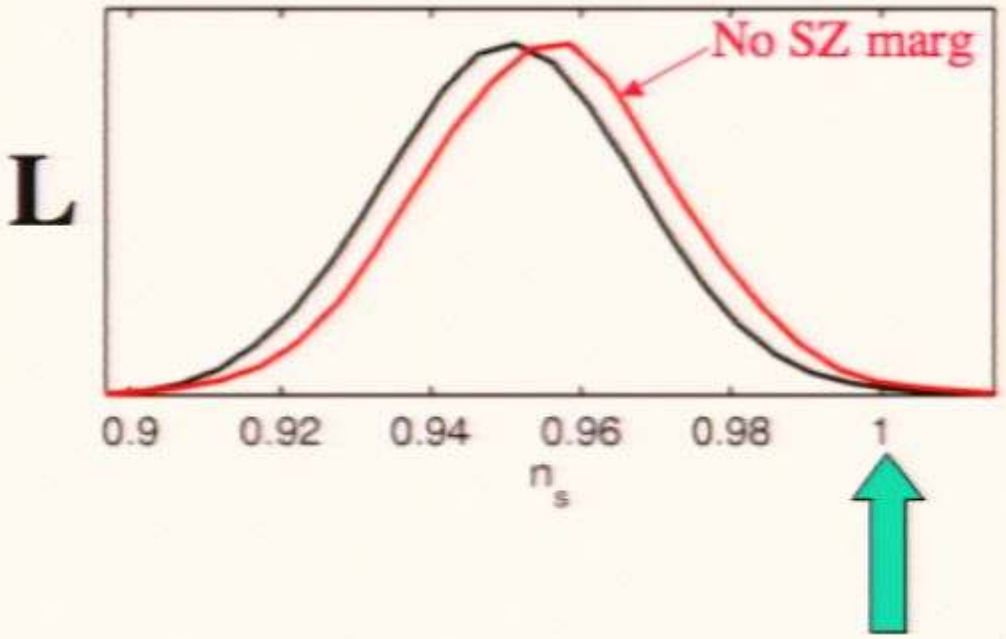
BB Lensing (not primordial)
1
10
100
1000
Multipole moment (l)
[μK]

$n_s - \tau$ Degeneracy





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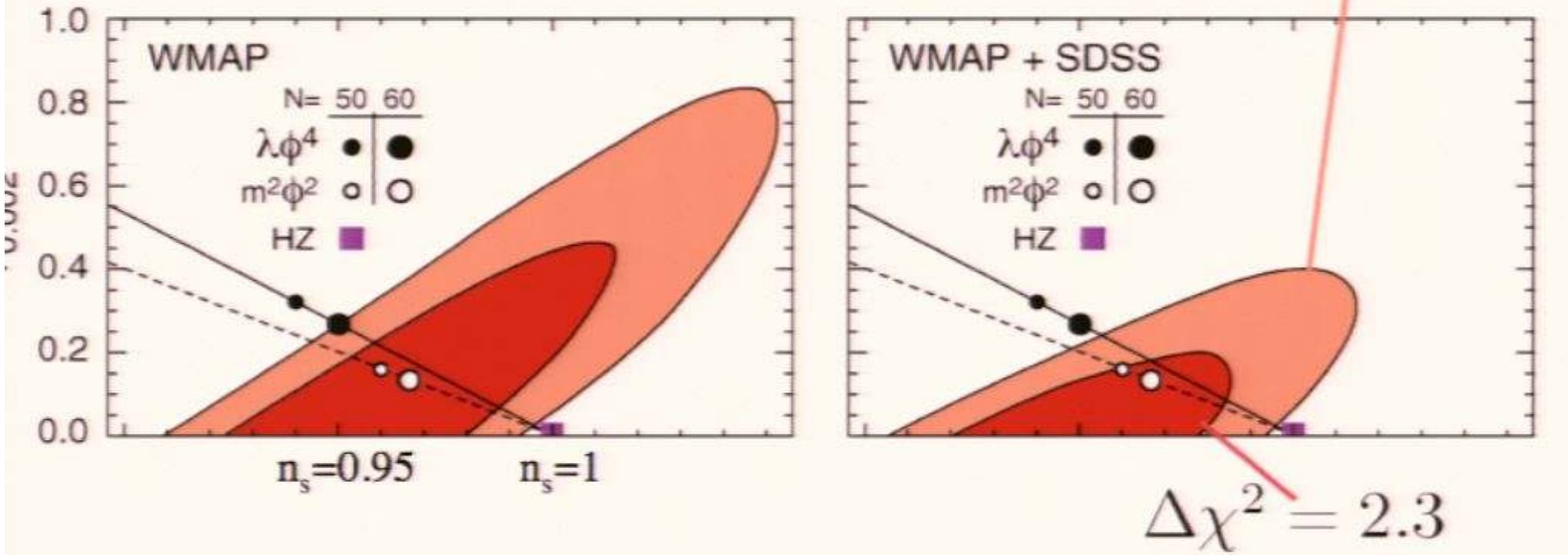
Index and Tensors



What Does the Model Need to Describe the Data?

changing one of the 6 parameters at a time….

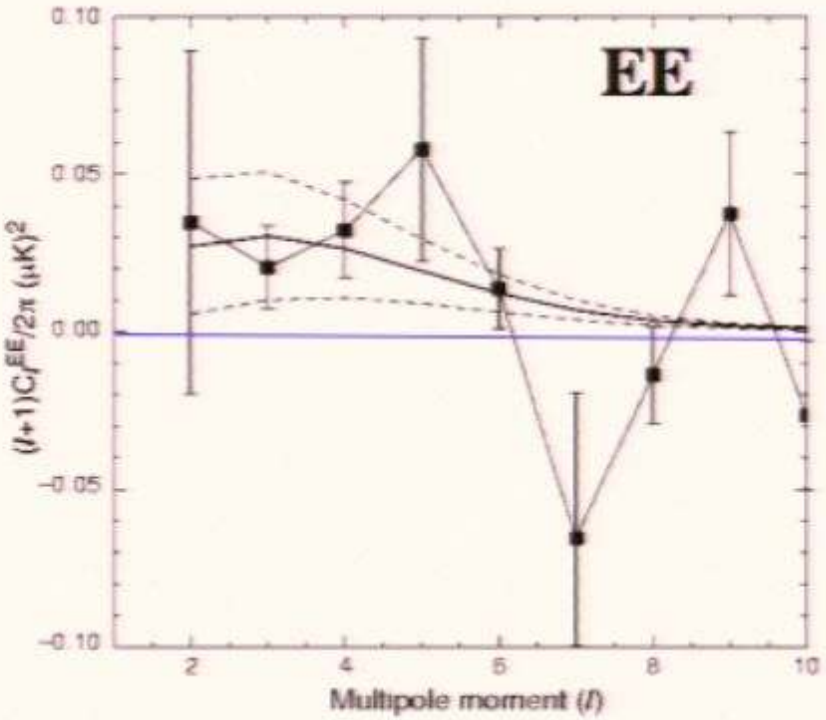
- Model needs τ, $\Delta\chi^2 = 8$ ("2.8 sigma")
- Model needs n_s not unity, $\Delta\chi^2 = 6$
- Model needs dark matter, $\Delta\chi^2 = 248$ ("15 sigma")

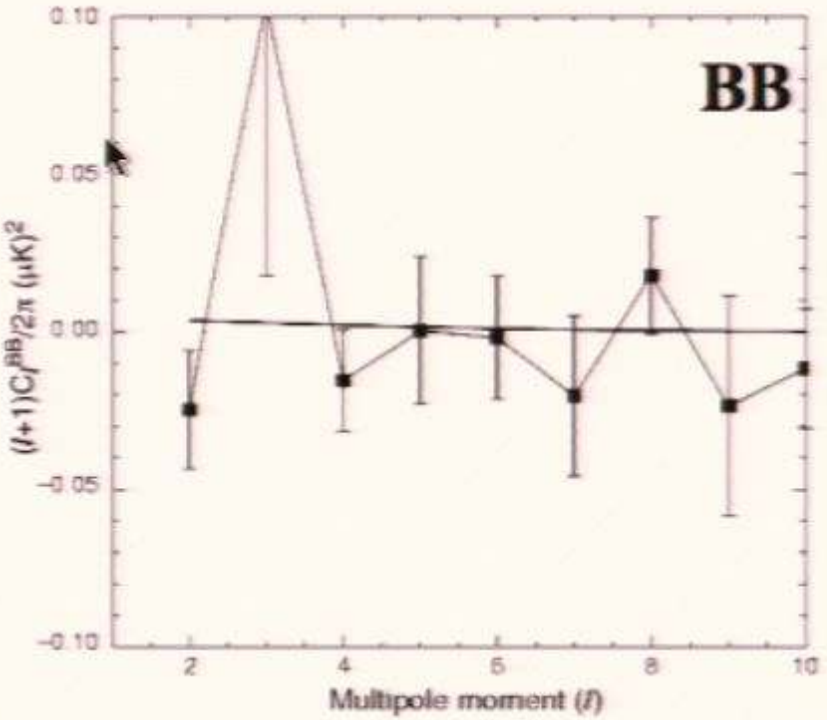
} ….but Eriksen & Huffenberger

- 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

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

What Does the Model Need to Describe the Data?

changing one of the 6 parameters at a time….

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

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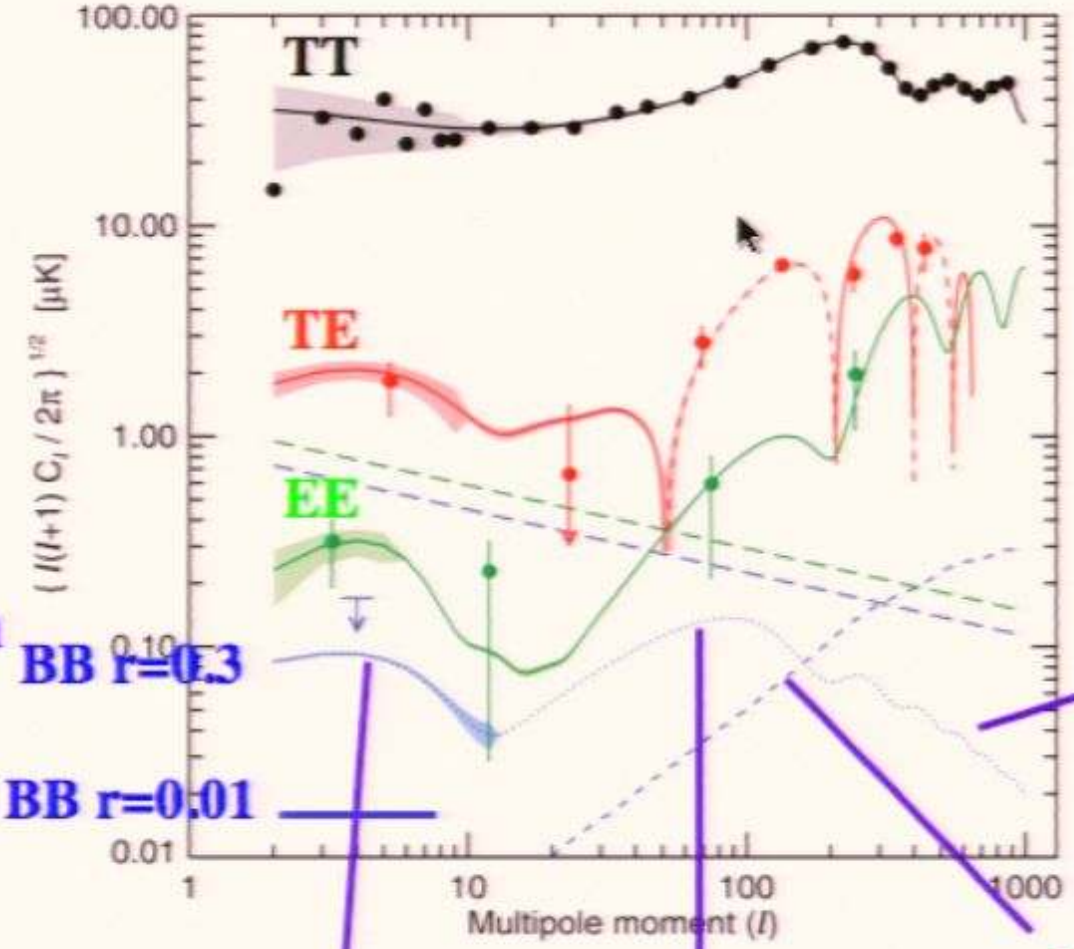
Gravitational Waves



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

B modes from tensors only.

G-waves decay once inside the horizon.

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

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

Reionization peak (z_r=10)

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

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

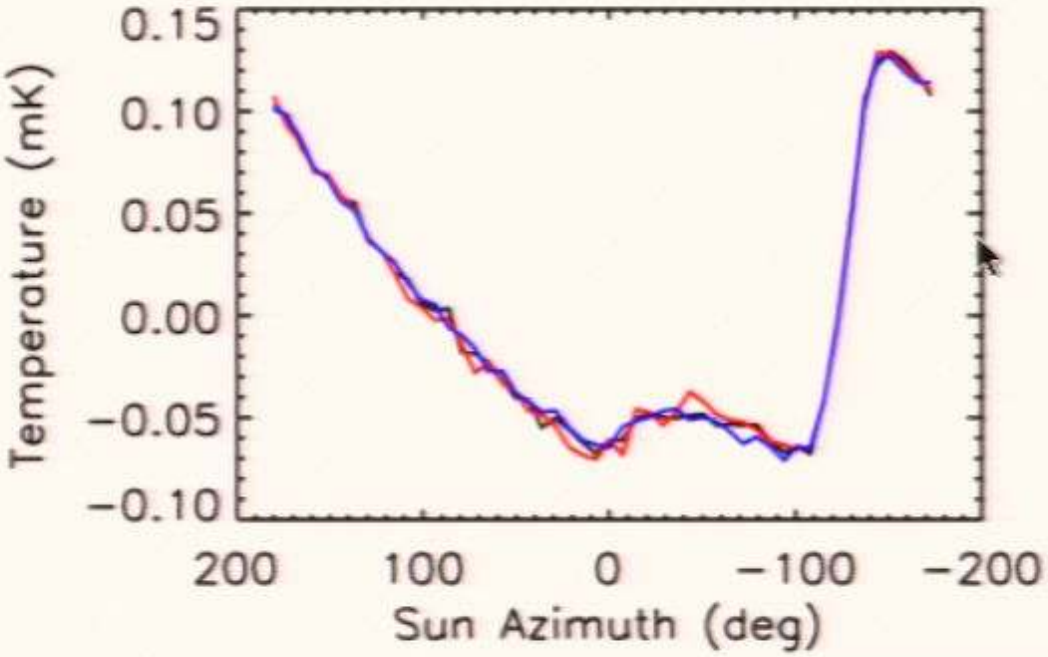
A) Instrumental effects are mostly related to the instrument stability, scan strategy, knowledge of the beams.

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.

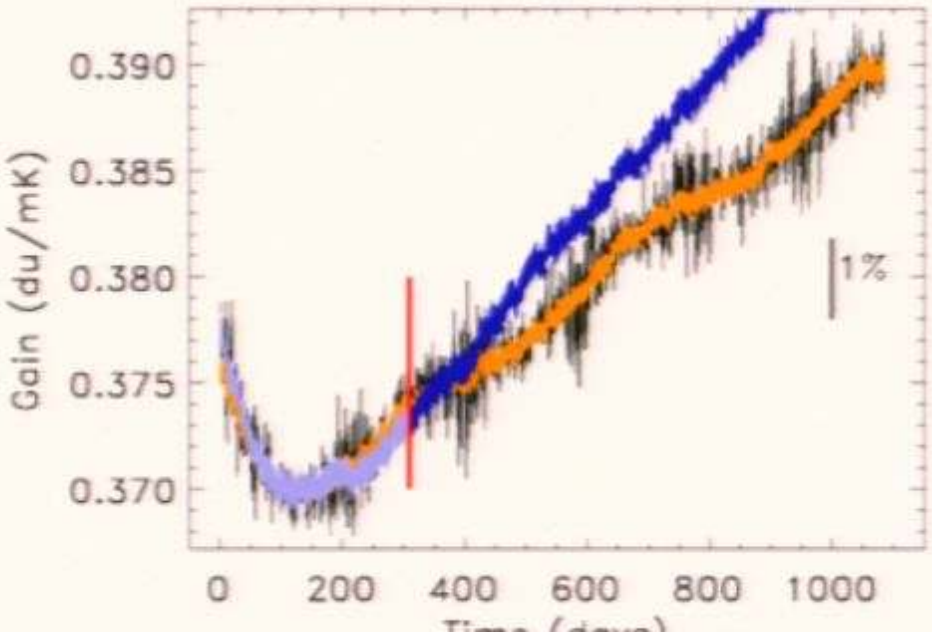
*From the Weiss report

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.



Jarosik et al

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.")

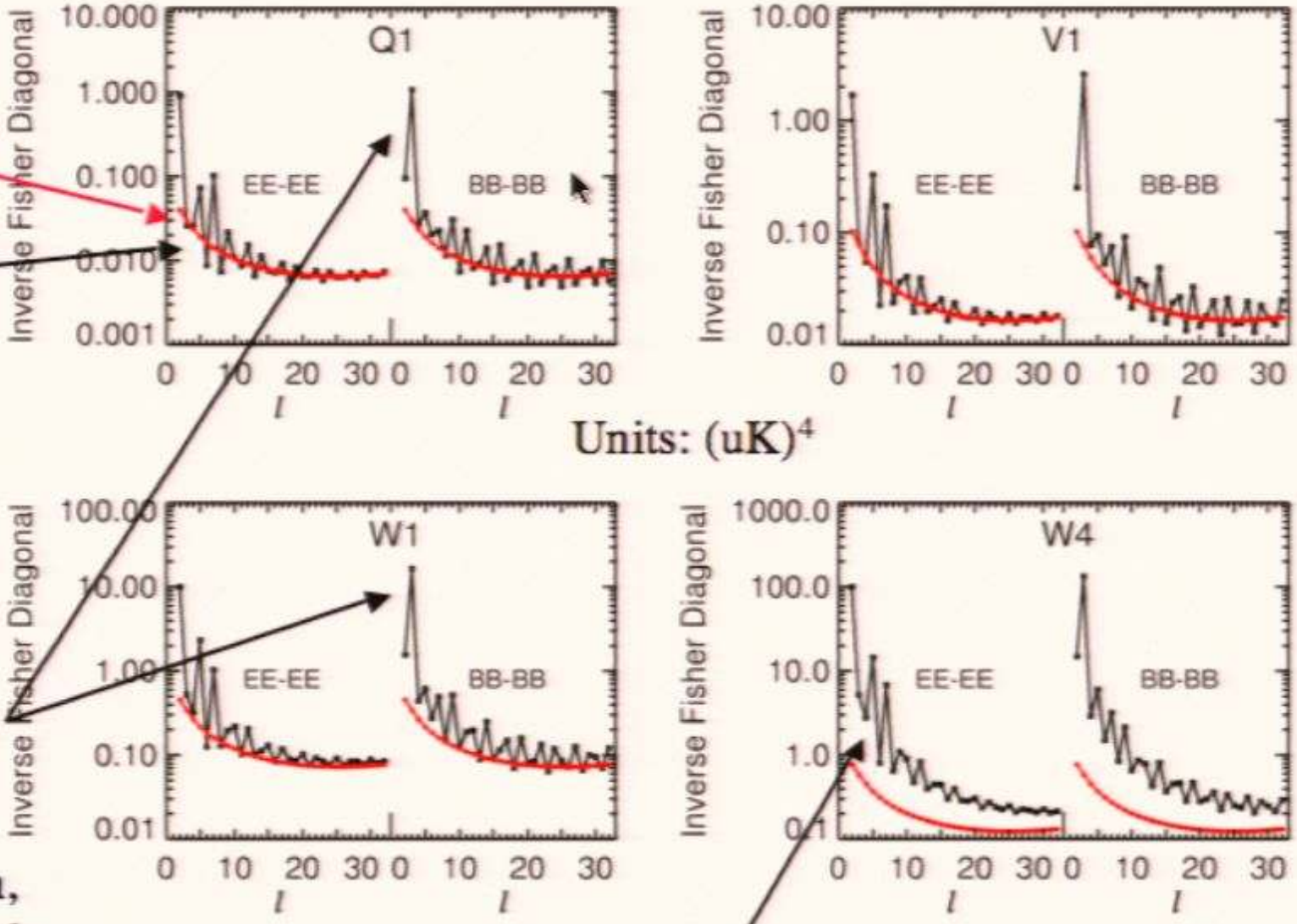
Noise: Full F_{lm} Required

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_l would be off by X10.

Instrumental Effects

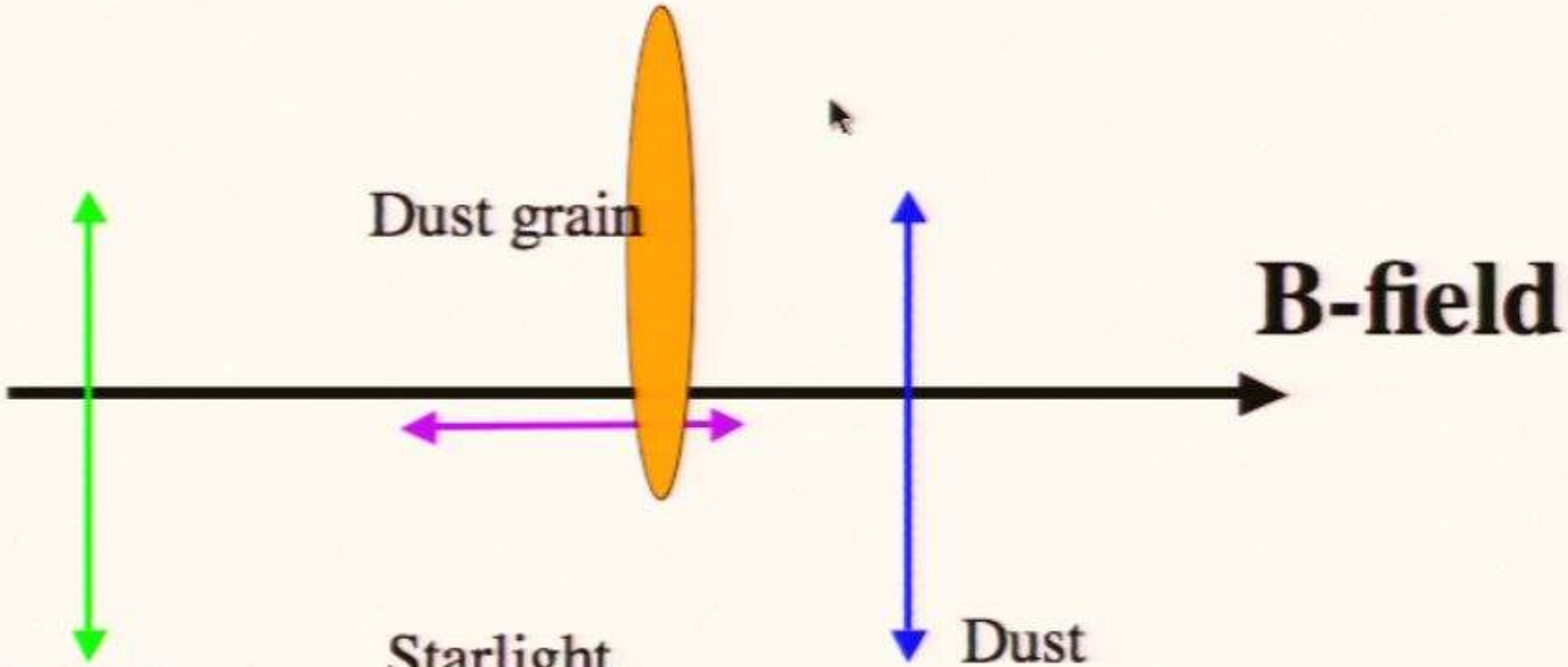
The easiest one is minimizing cross-pol or polarization isolation!

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

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

Polarized Foreground Emission



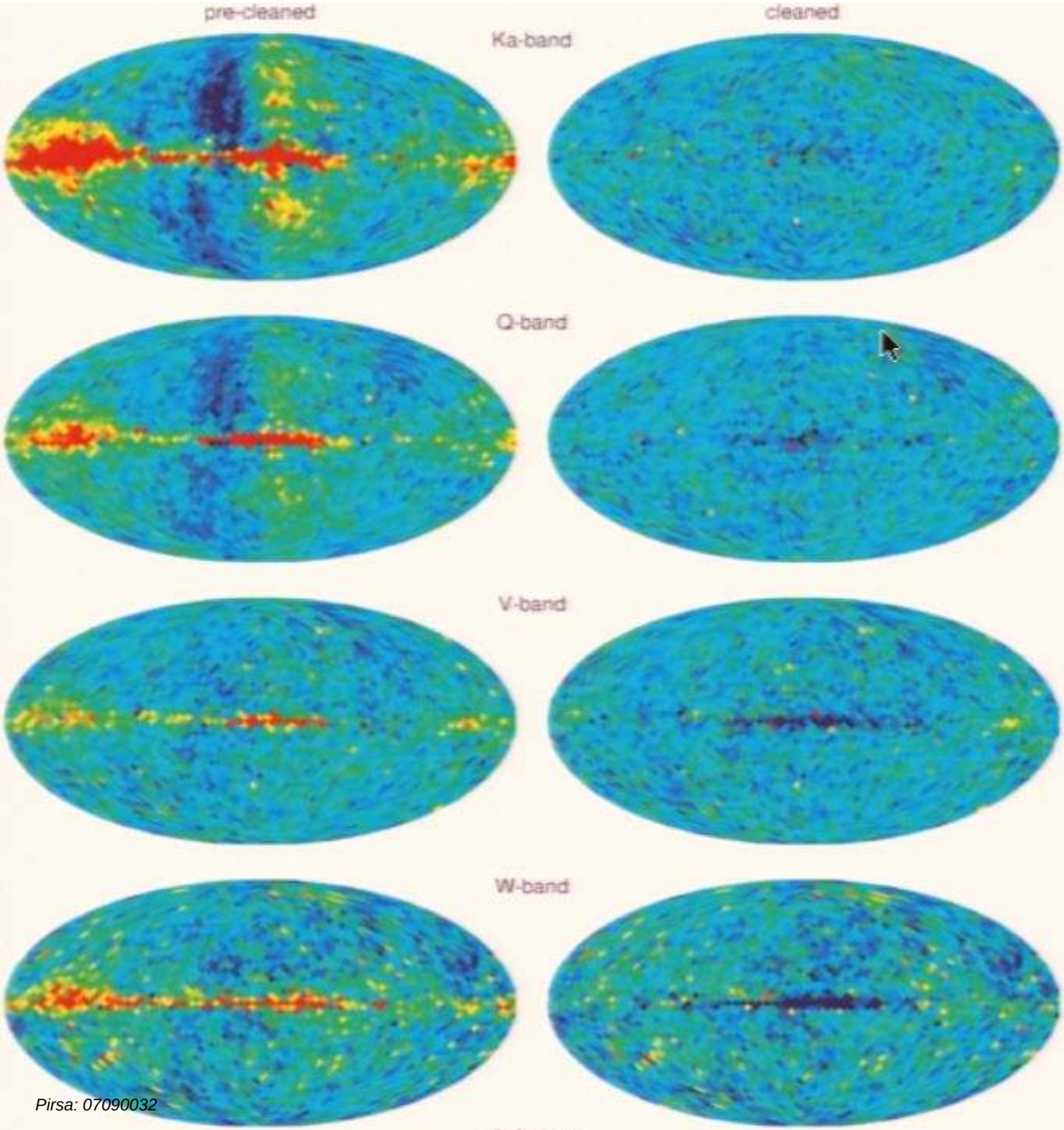
Synchrotron emission

Starlight polarization

Dust emission

Max pol about 75%

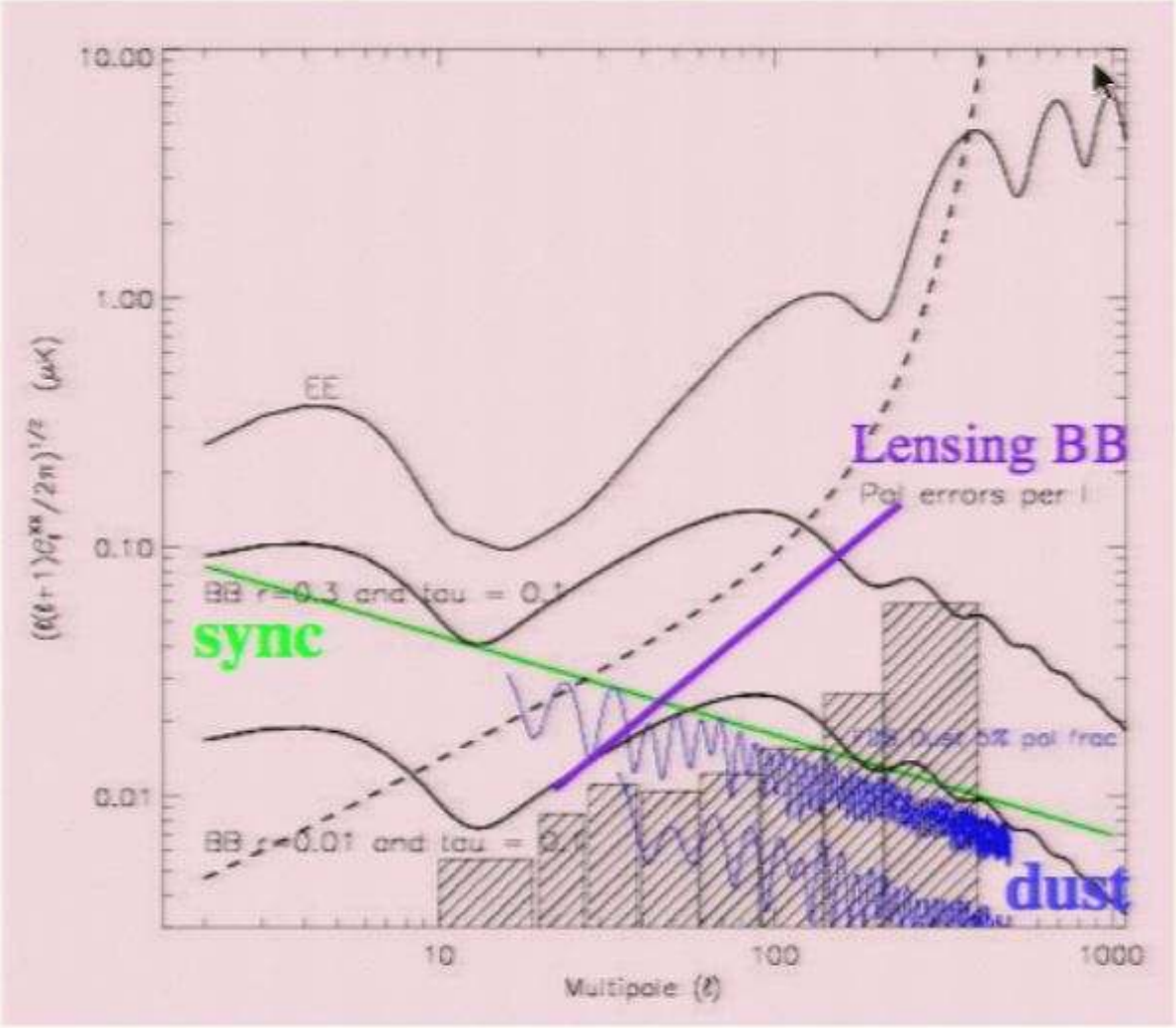
Max pol about 15% but low pol for spinning dust.



Raw vs. Cleaned Maps

Galaxy masked in analysis

Expectations at l=100



From Jo Dunkley

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-Gaussanity

- The quadrupole 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.

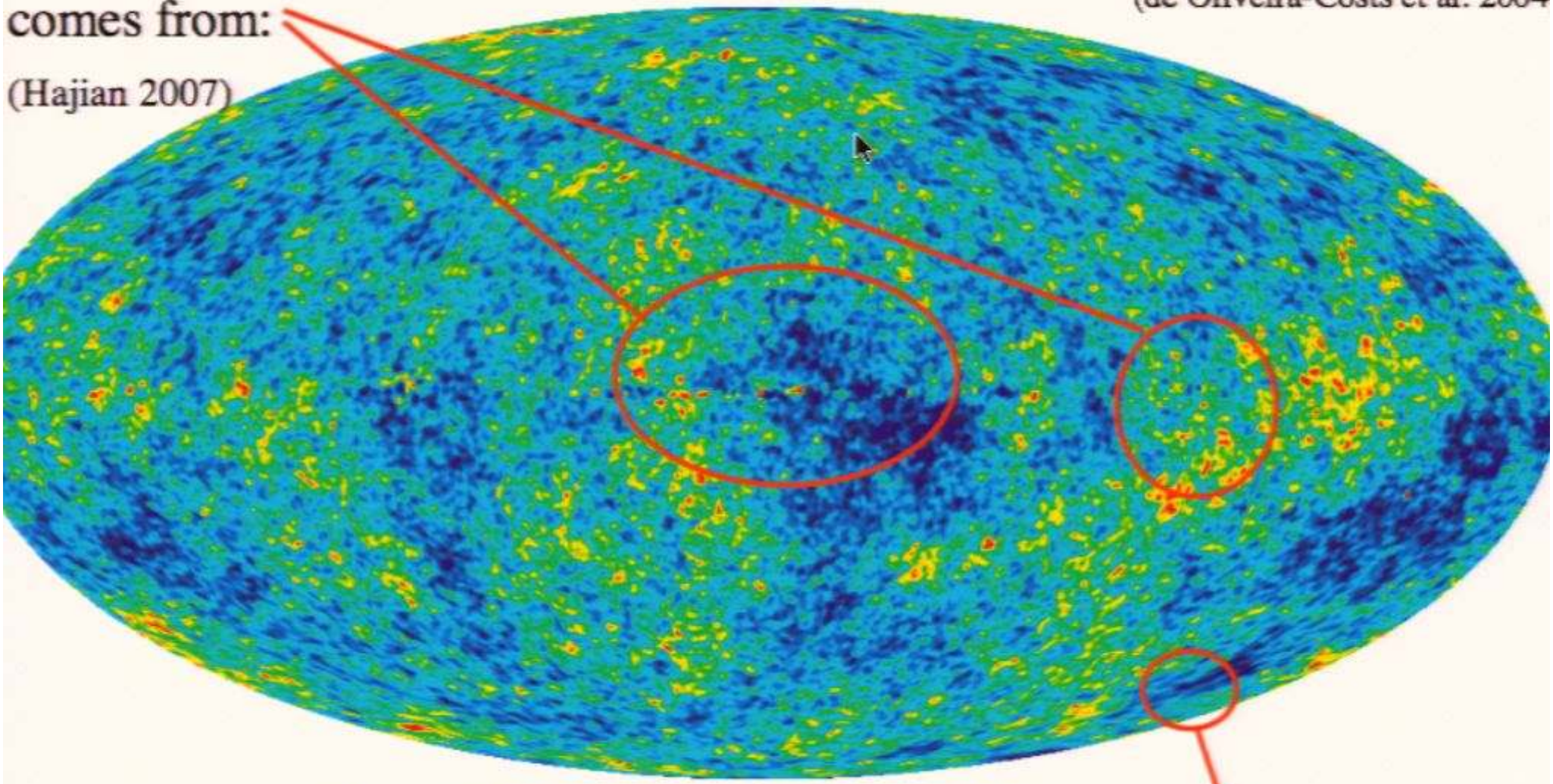
t would be fantastic to find a clear signature of cosmic non-Gaussanity. The WMAP team has not found one.

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

(Hajian 2007)

Alignment?

(de Oliveira-Costs et al. 2004



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

Extra cold spot:

(Vielva et al. 2004, Cruz et

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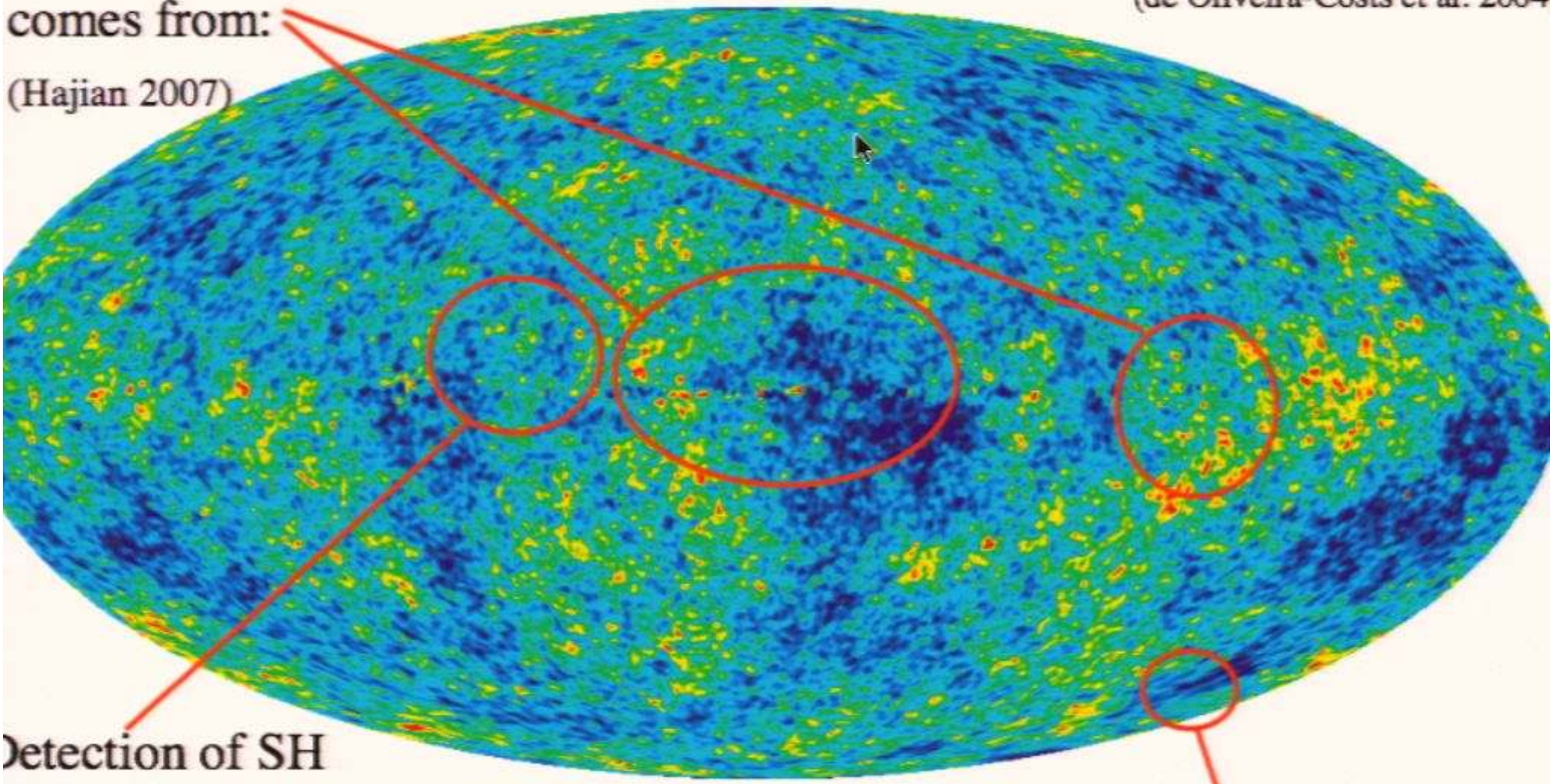

)etection of SH
ersists!

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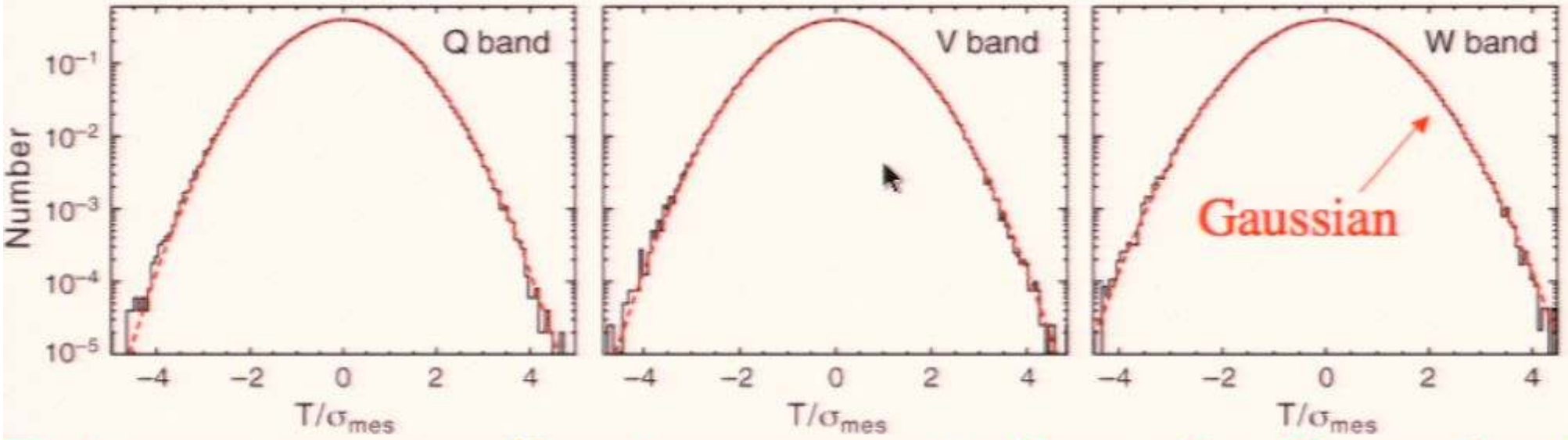
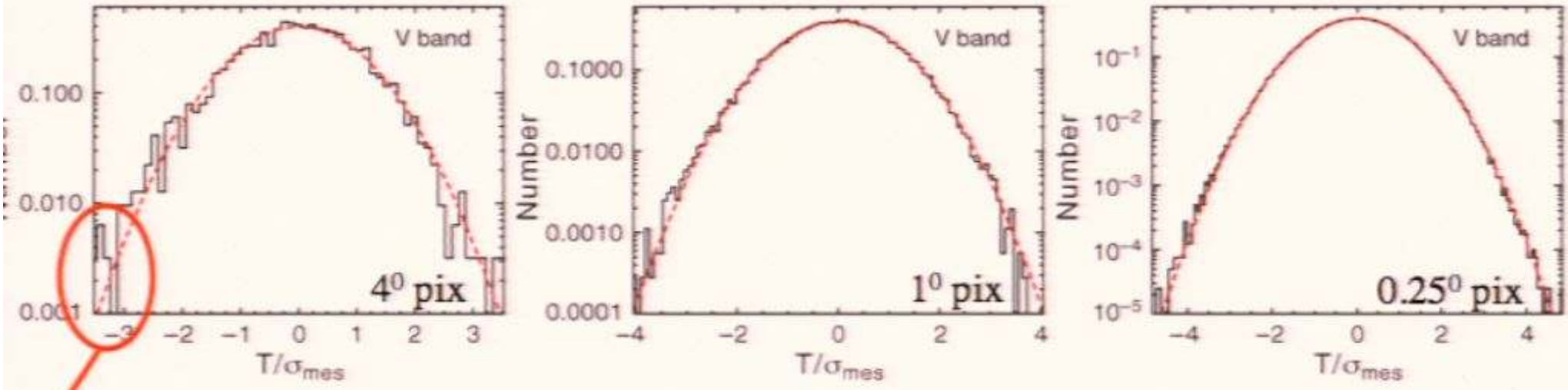
Distribution by map temp. by frequency (accounting for uneven weighting)



Data are an excellent representation of a Gaussian!



Cold spot

Distribution by resolution.

One WMAP Characterization of non-Gaussanity

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

Komatsu et al.

Curvature potential — Gaussian random field

$f_{NL} = 30 +/- 42$ or $-34 < f_{NL} < 114$ (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-Gaussanity

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.

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Pirsa: 07090032