Title: If the CMB is right, it is inconsistent with standard inflationary Lambda CDM

Date: Oct 30, 2008 04:00 PM

URL: http://pirsa.org/08100080

Abstract: The Cosmic Microwave Background Radiation is our most important source of information about the early universe. Many of its features are in good agreement with the predictions of the so-called standard model of cosmology -- the Lambda Cold Dark Matter Inflationary Big Bang. However, the large-angle correlations in the microwave background exhibit several statistically significant anomalies compared to the predictions of the standard model. On the one hand, the lowest multipoles seem to be correlated not just with each other but with the geometry of the solar system. On the other hand, when we look at the part of the sky that we most trust -- the part outside the galactic plane, there is a dramatic lack of large angle correlations. So much so that no choice of angular powerspectrum can explain it if the alms are Gaussian random statistically isotropic variables of zero mean.

If the CMB is right, it's inconsistent with standard inflationary ΛCDM

Glenn D. Starkman

Craig Copi, Dragan Huterer & Dominik Schwarz

Neil Cornish, David Spergel, & Eiichiro Komatsu;

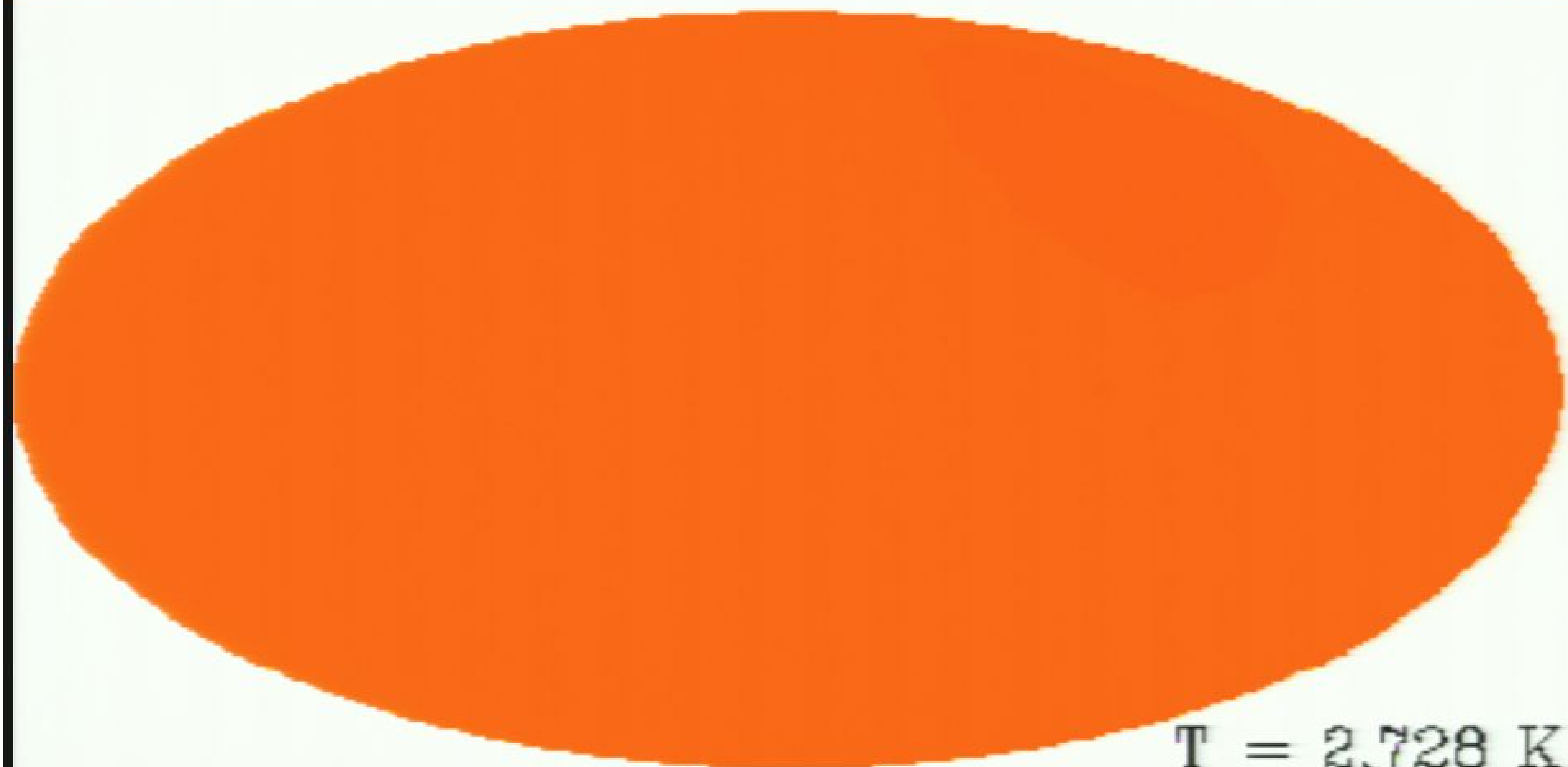
Jean-Philippe Uzan, Alain Riazuelo, Jeff Weeks,

Sam Leach, R. Trotta, Ben Wandel

Bob Nicho[illegible] Freeman

Kaiki Inoue, Joe Silk, Andrew Jaffe, Anastasia[illegible]

COBE - DMR



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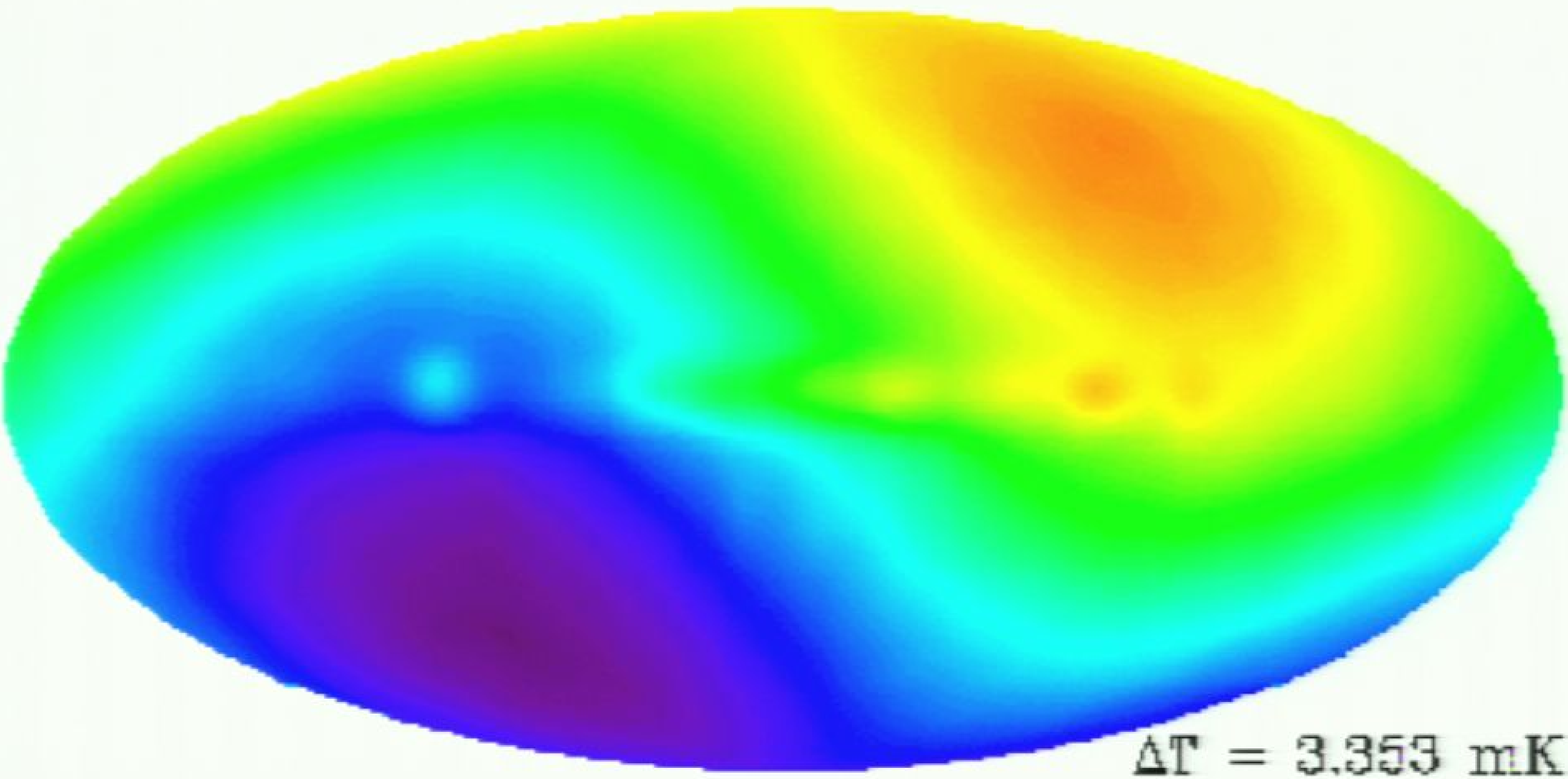

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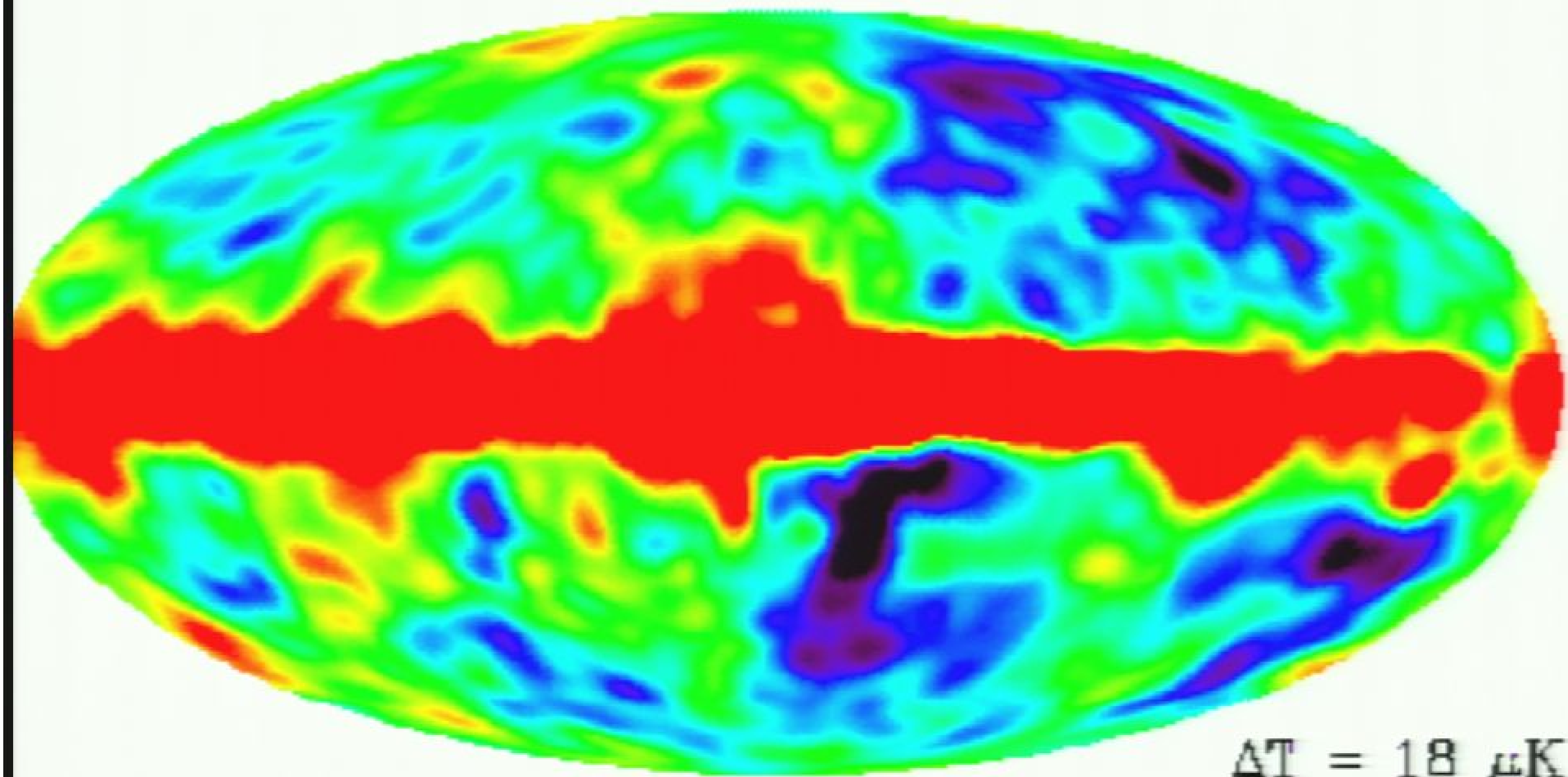

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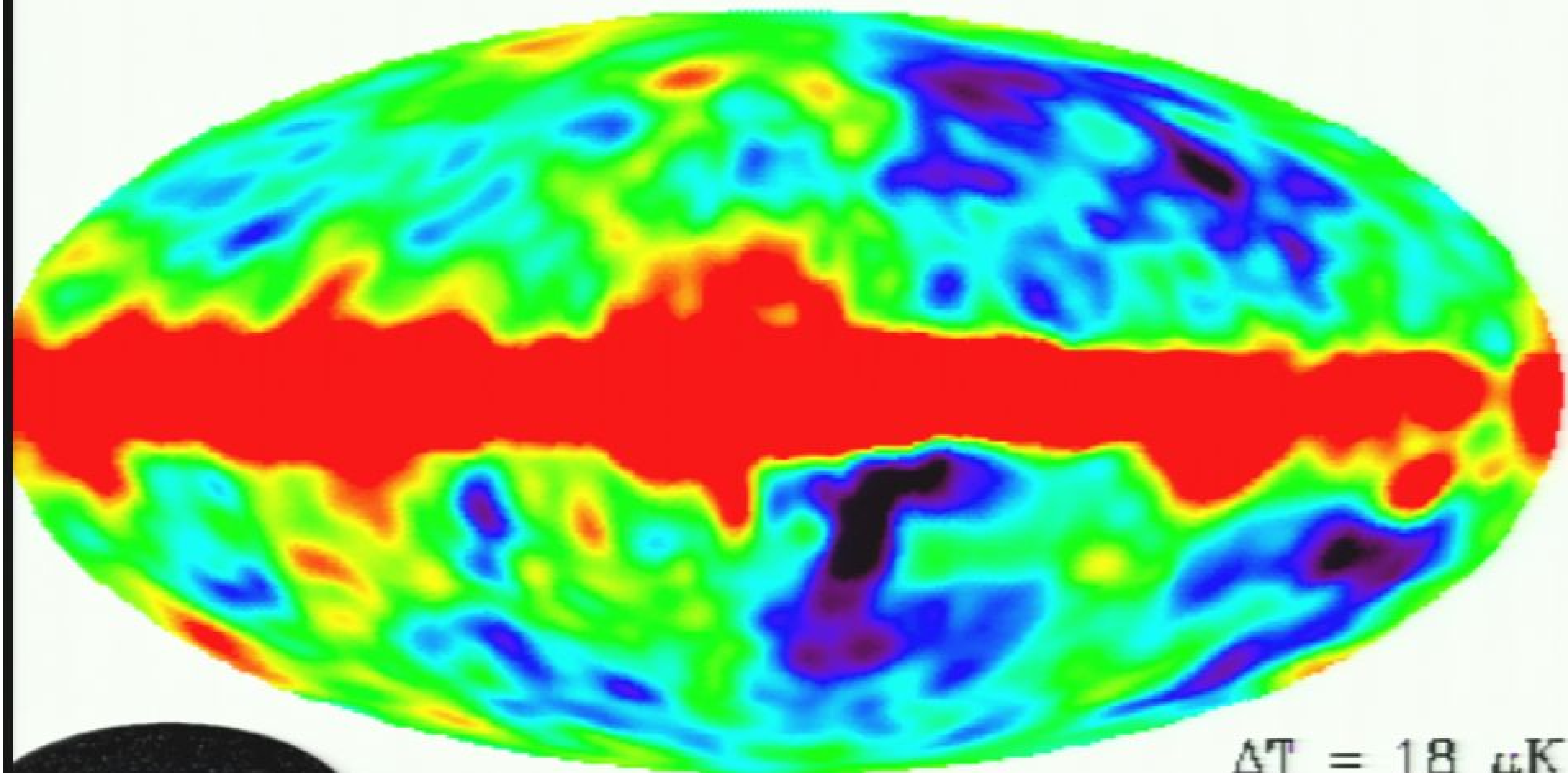
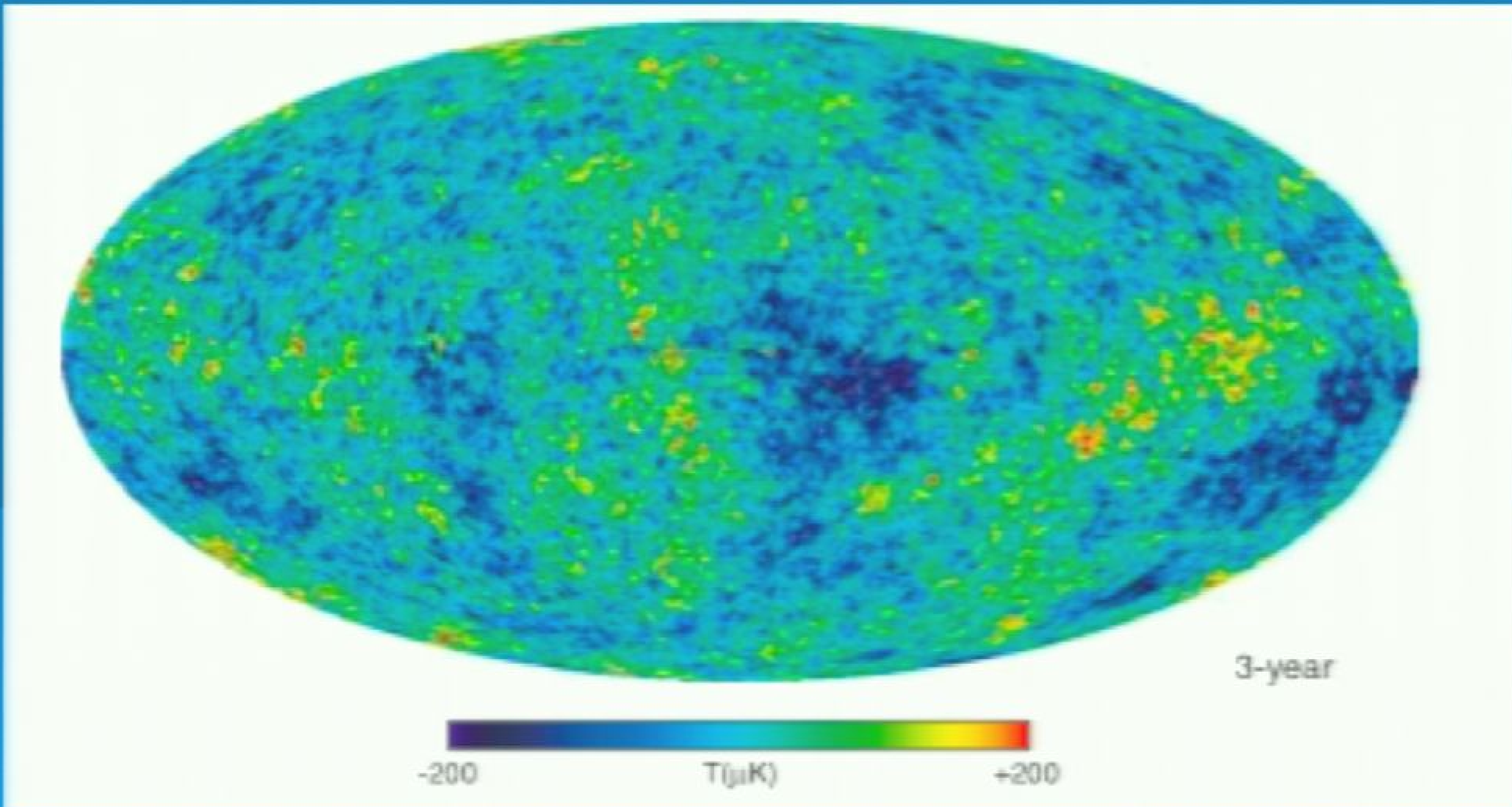
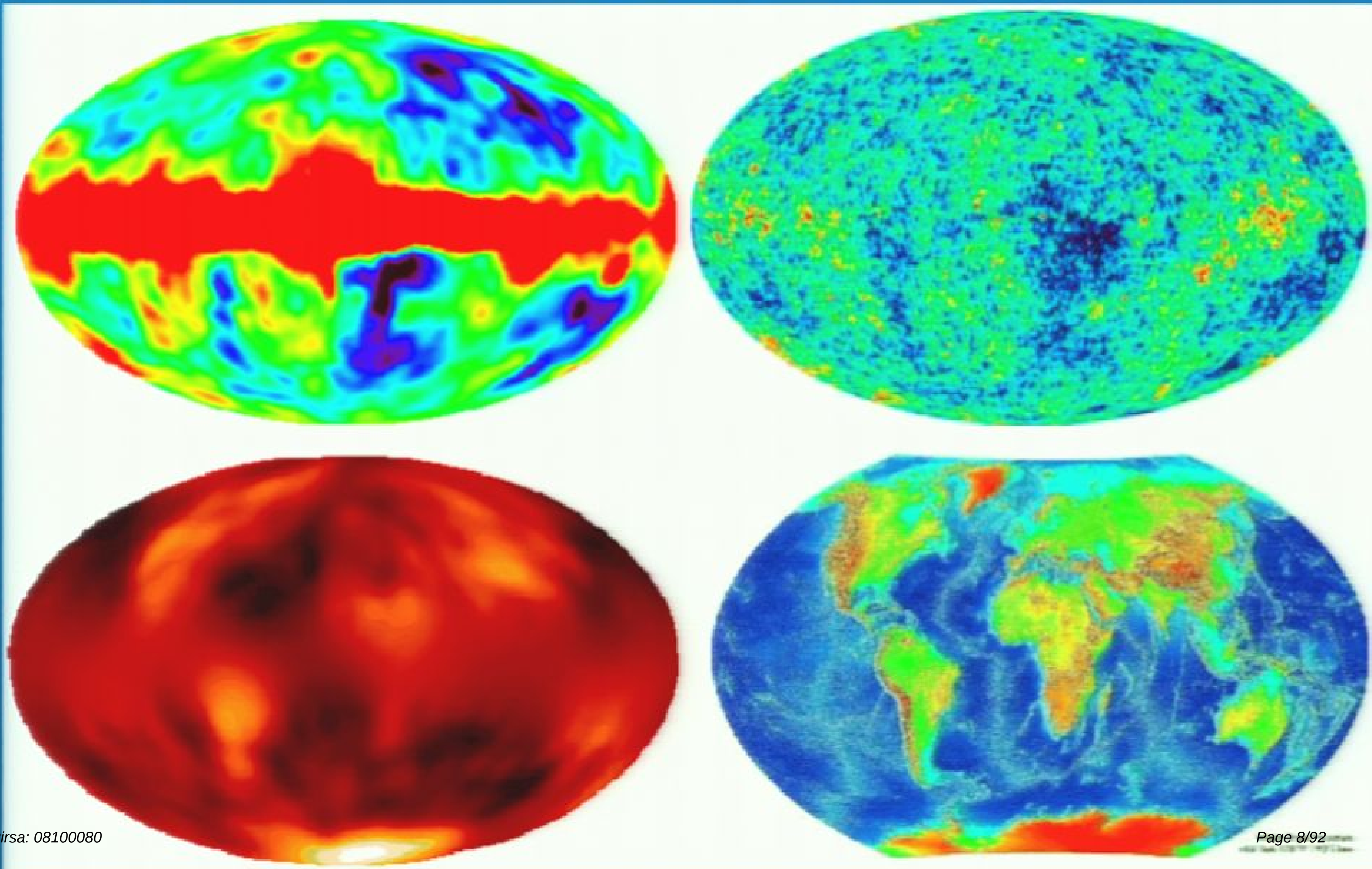


The WMAP Sky



COBE vs. WMAP



Outline

Largest scale properties of the universe:

- Curvature
- Topology

The low-ℓ / large-angle problem

- from C_ℓ to $C(\theta)$

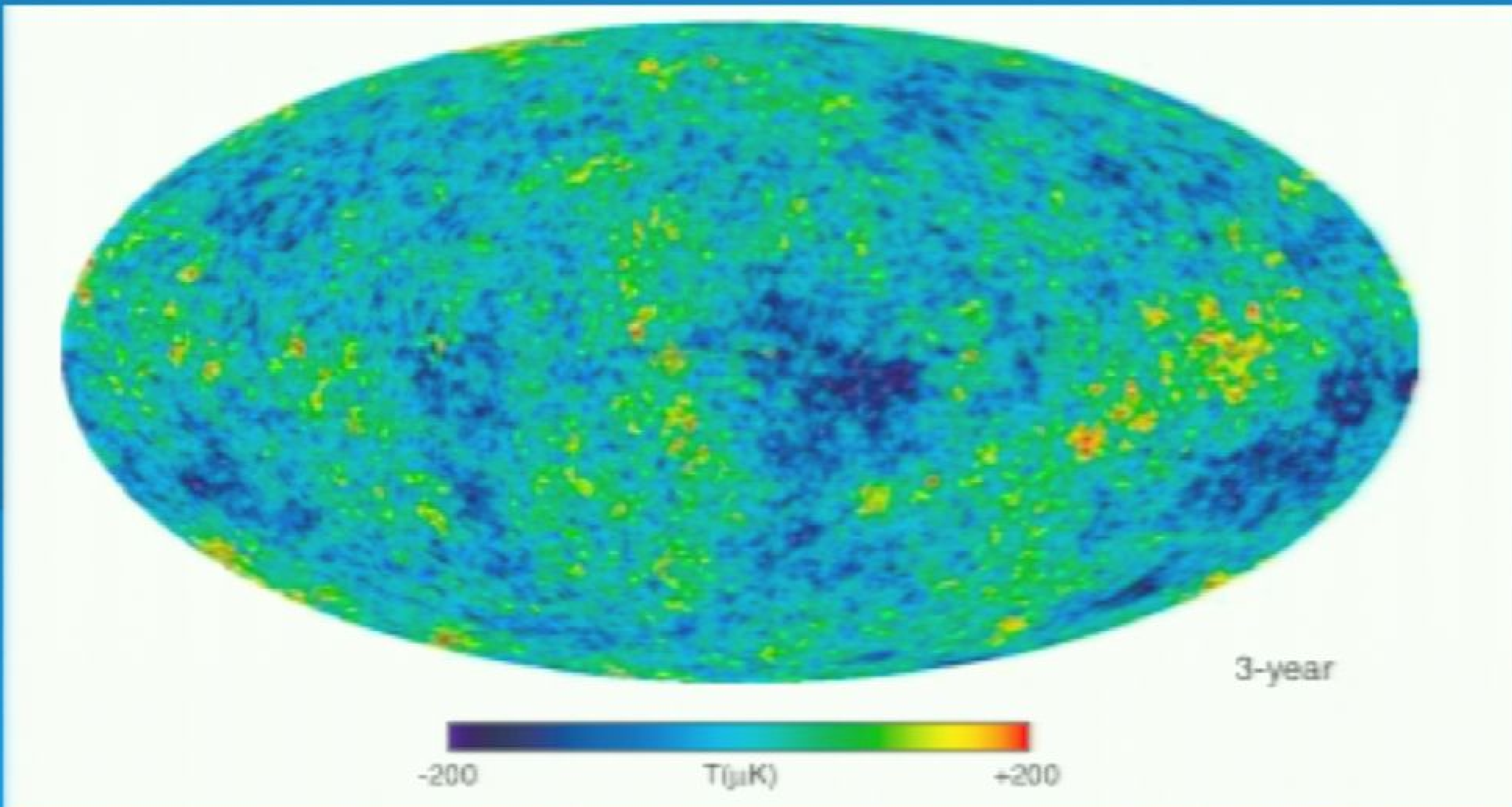
Beyond $C(\theta)$

- seeing the solar system in the microwave background

And back:

troubles in cosmological paradise

The WMAP Sky



Angular Power Spectrum

$\Delta T = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\varphi)$

Standard model for the origin of fluctuations (inflation):

$a_{\ell m}$ are independent Gaussian random variables, with $< a_{\ell m}\, a_{\ell' m'} > = C_\ell \delta_{\ell\ell'} \delta_{mm'}$

$\Rightarrow$Sky is statistically isotropic and Gaussian random

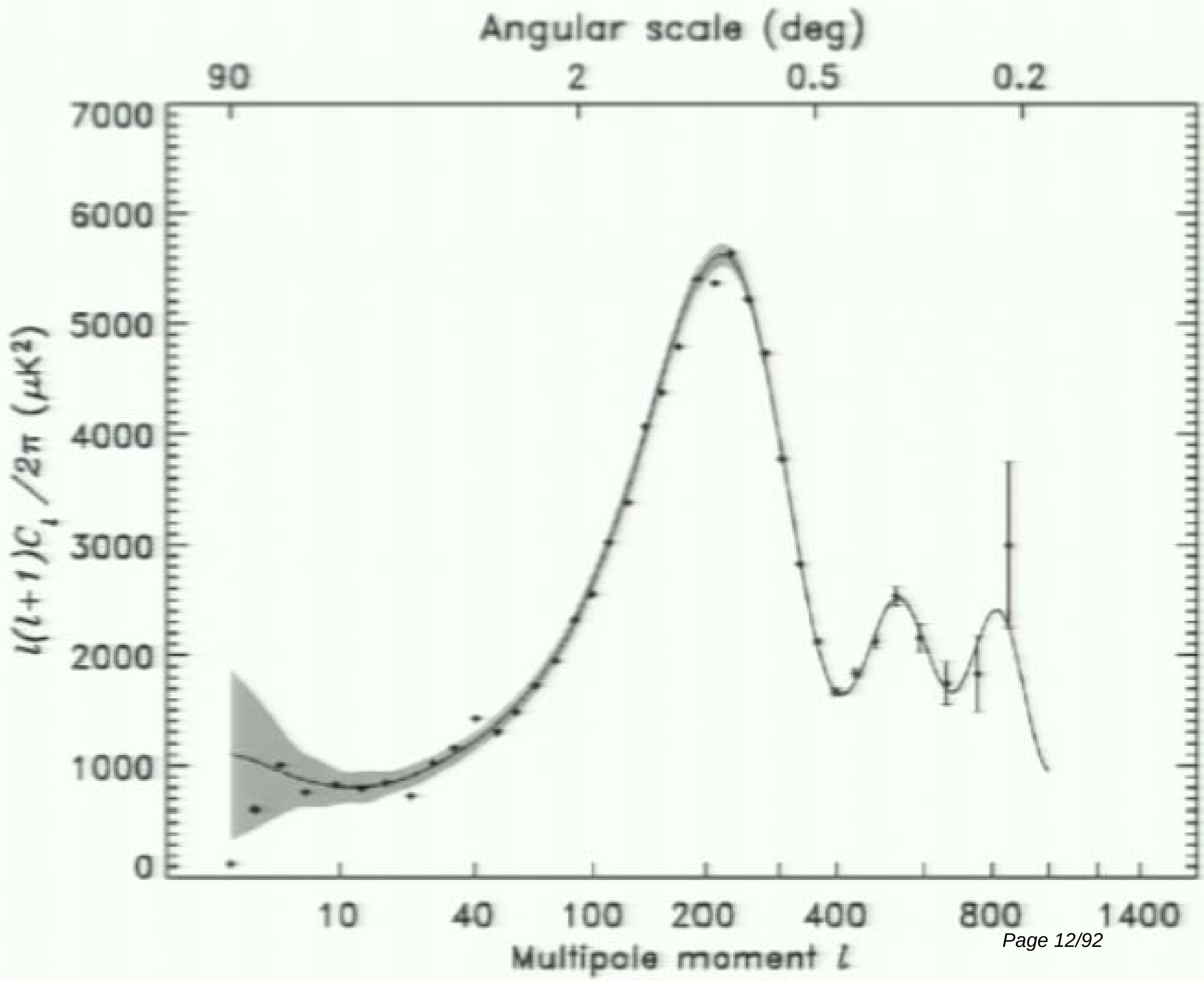
ALL interesting information in the sky is contained in C_ℓ

$C_\ell = (2\ell+1)^{-1} \sum_m |a_{\ell m}|^2$

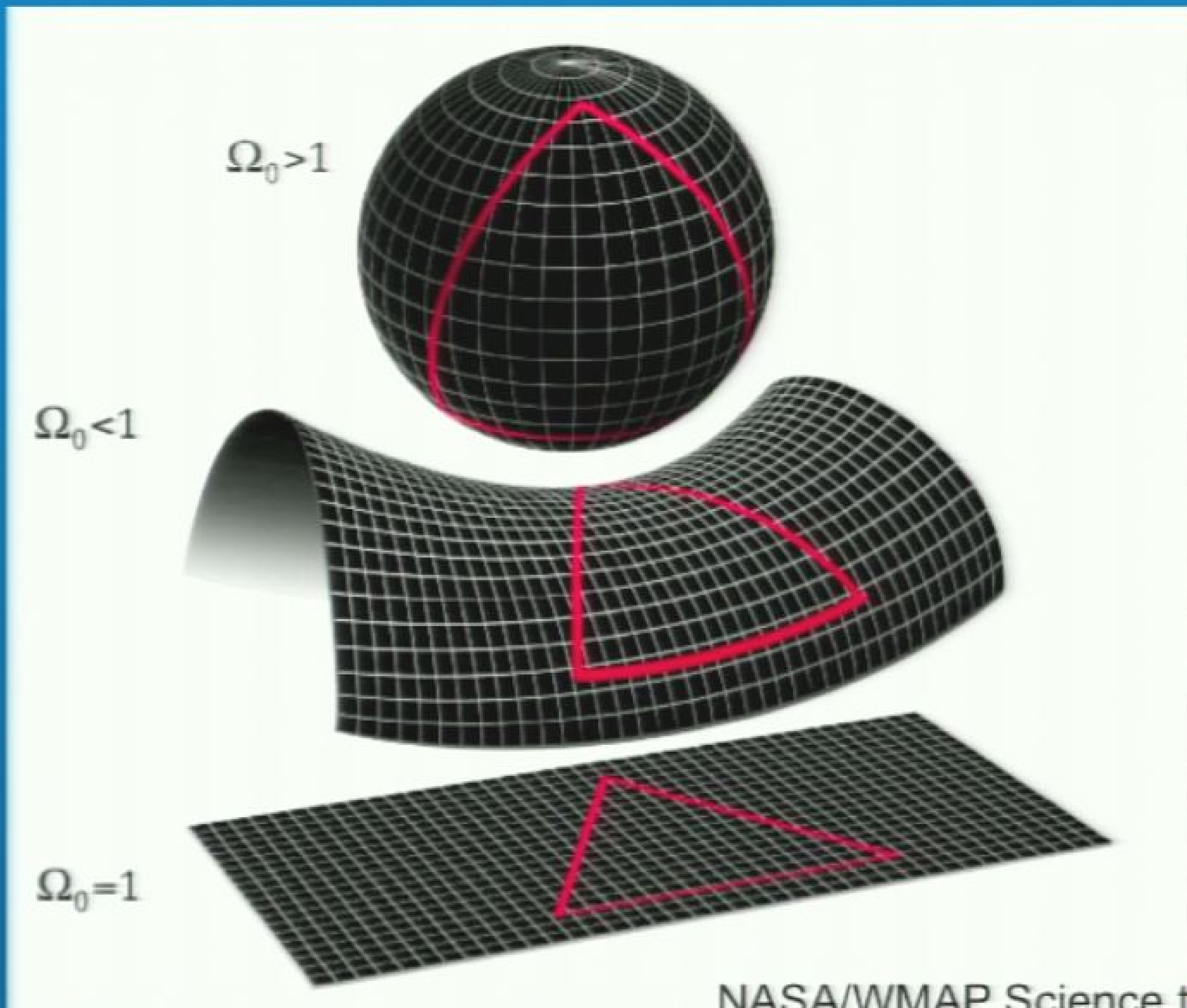
Angular Power Spectrum

$$T = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$

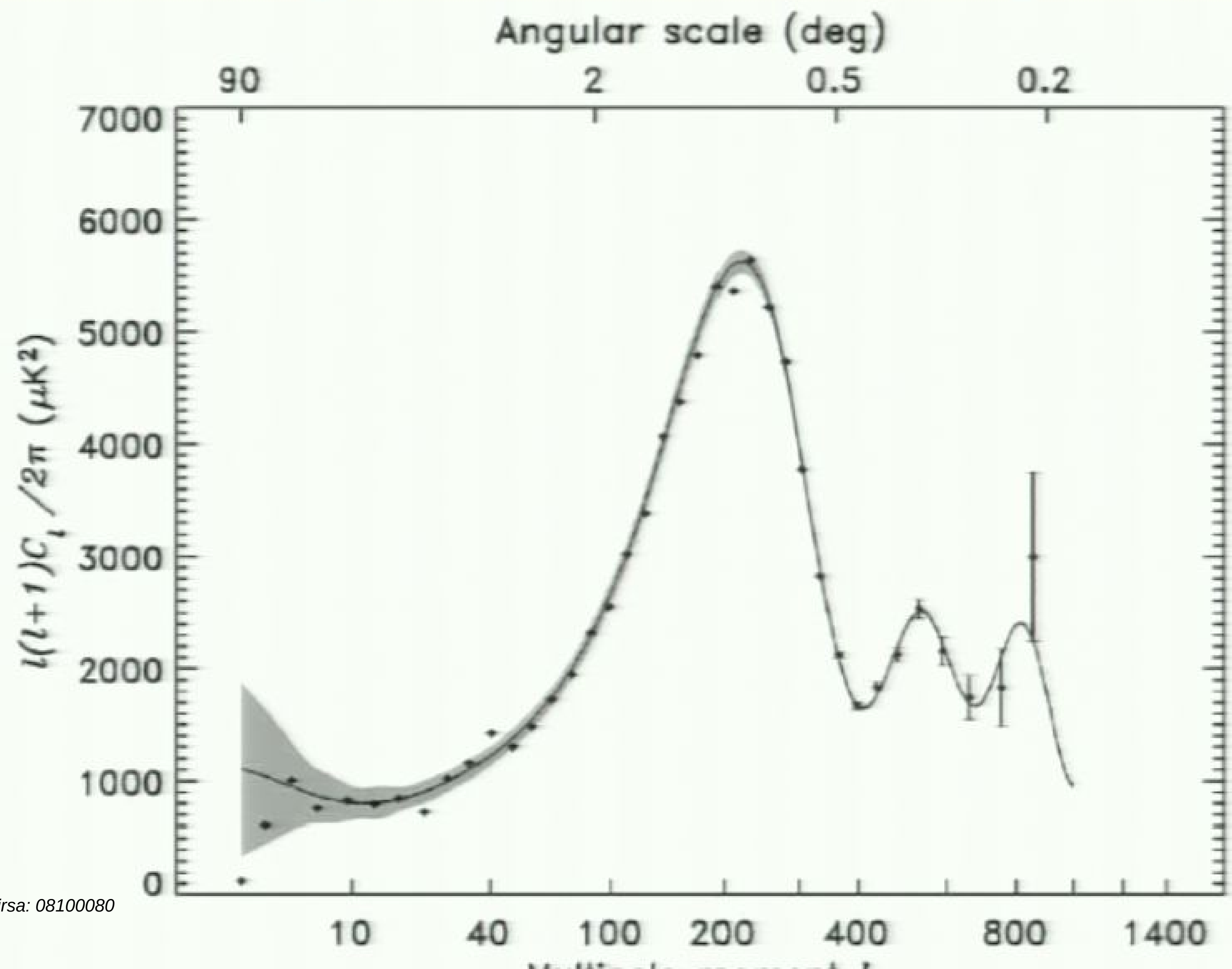
$$_{\ell} = (2\ell+1)^{-1} \sum_m |a_{\ell m}|^2$$



Measuring the shape of space



Angular Power Spectrum



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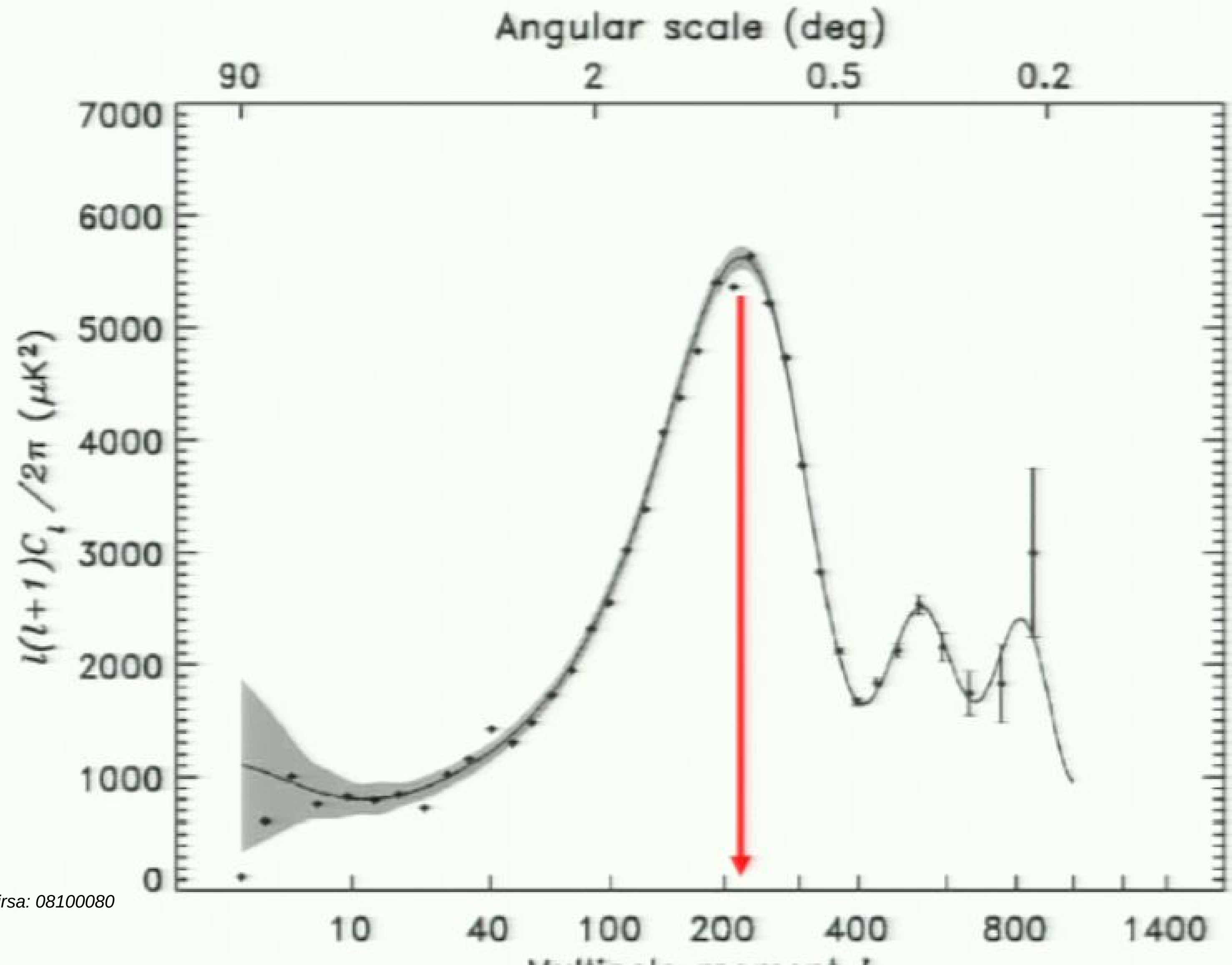
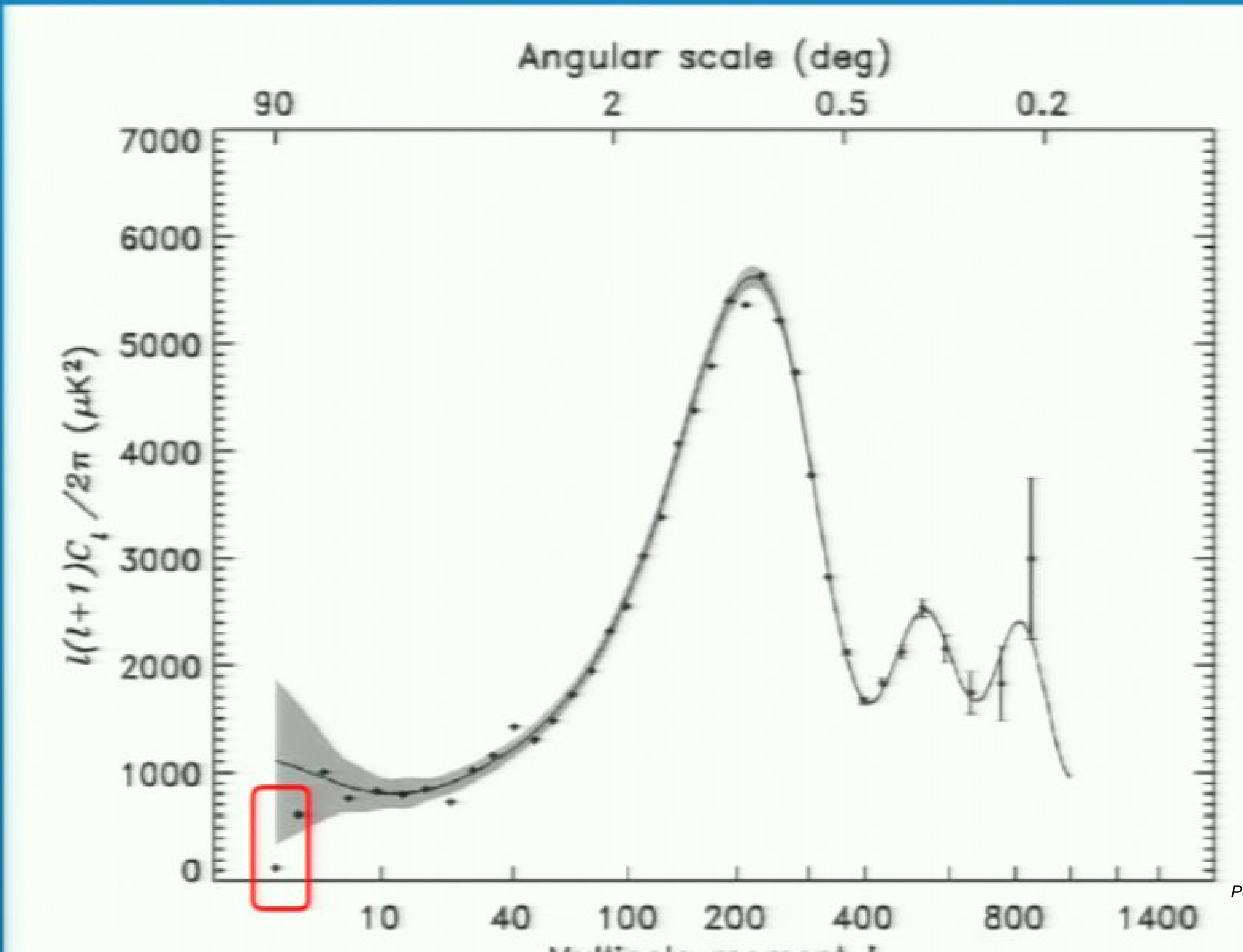


$\Omega = 1.02 \pm .02$

(with other data)

Is there anything interesting left to learn about the Universe on large scales?

Motivation: "The Low-l Anomaly"



Explaining the Low-l Anomaly

1. "Didn't that go away?"
2. "I never believe *a posteori* statistics."
3. Cosmic variance -- "I never believe anything less than a (choose one:) 5σ 10σ 20σ result."
4. "Inflation can do that"
5. Other new physics

$\Rightarrow$ We must look beyond C_l's

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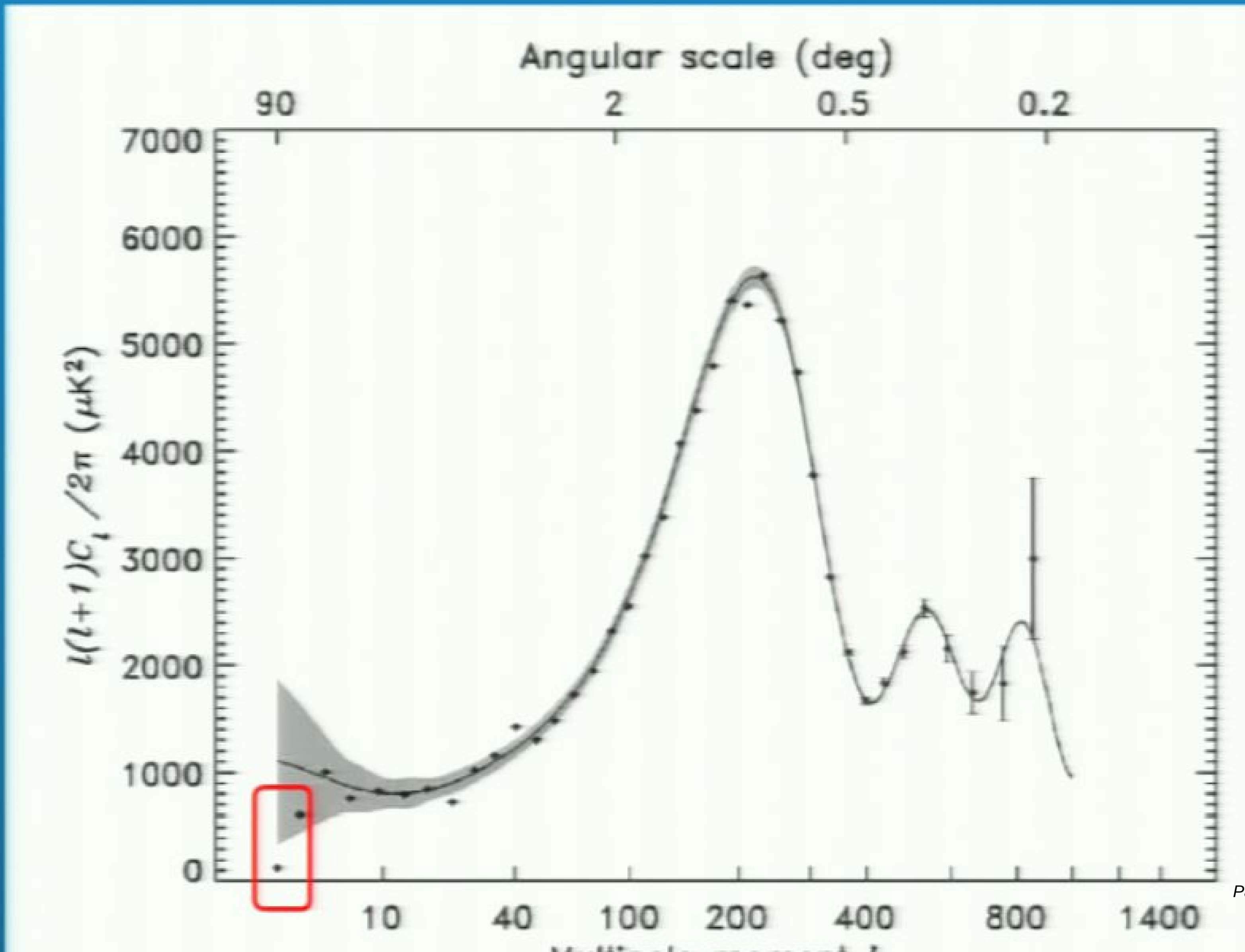

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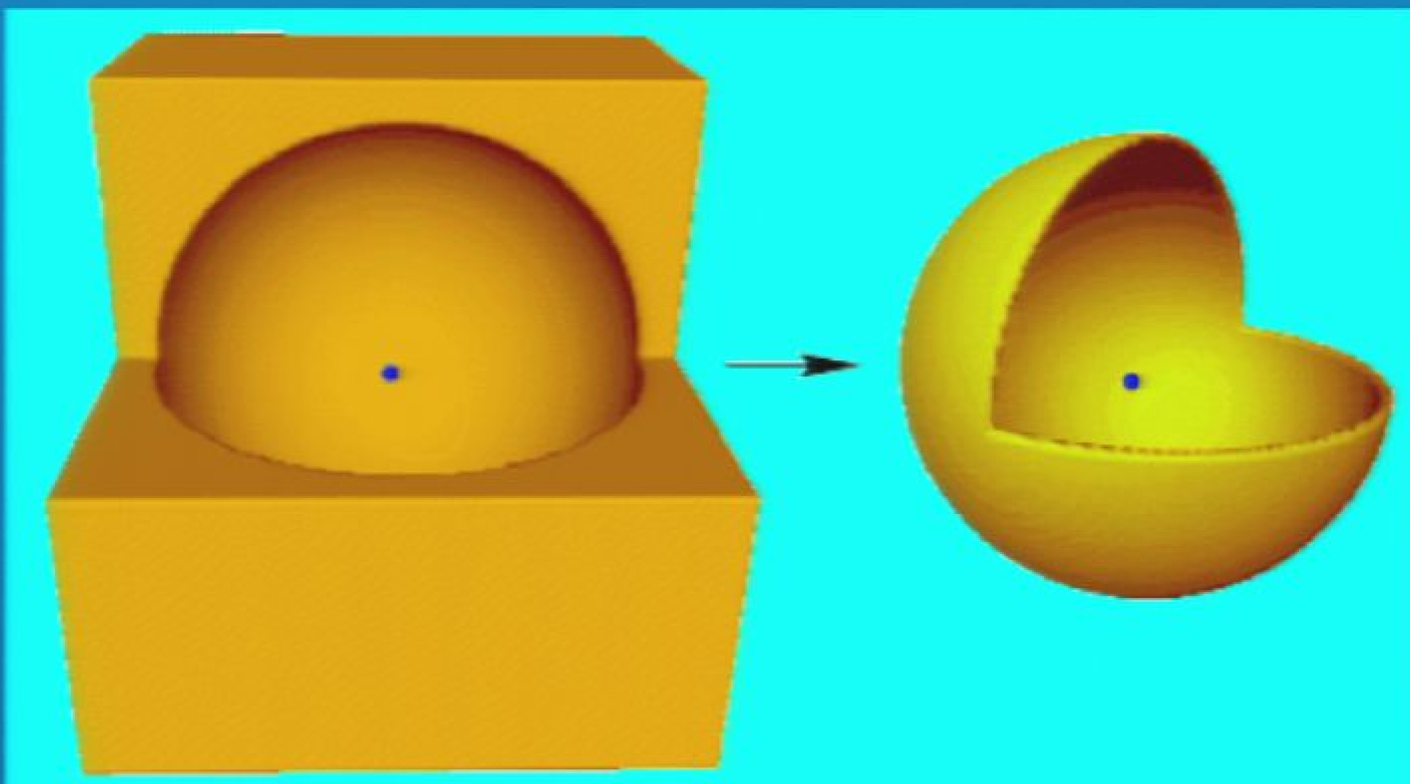
The microwave background in a "small" universe



Absence of long wavelength modes ⇒

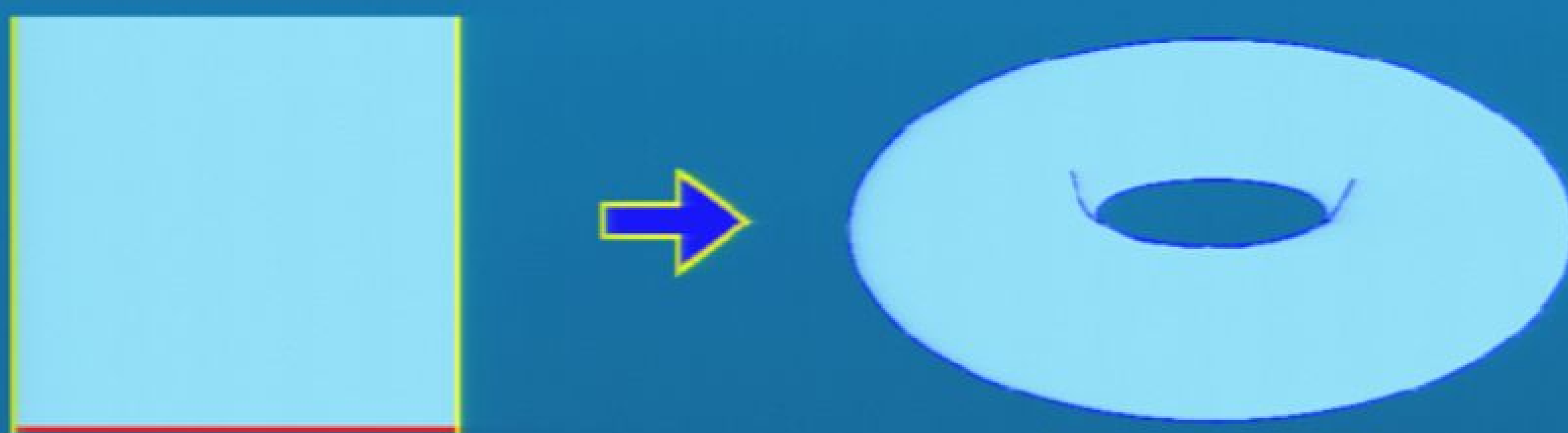
Absence of large angle correlations

Measuring the shape of space

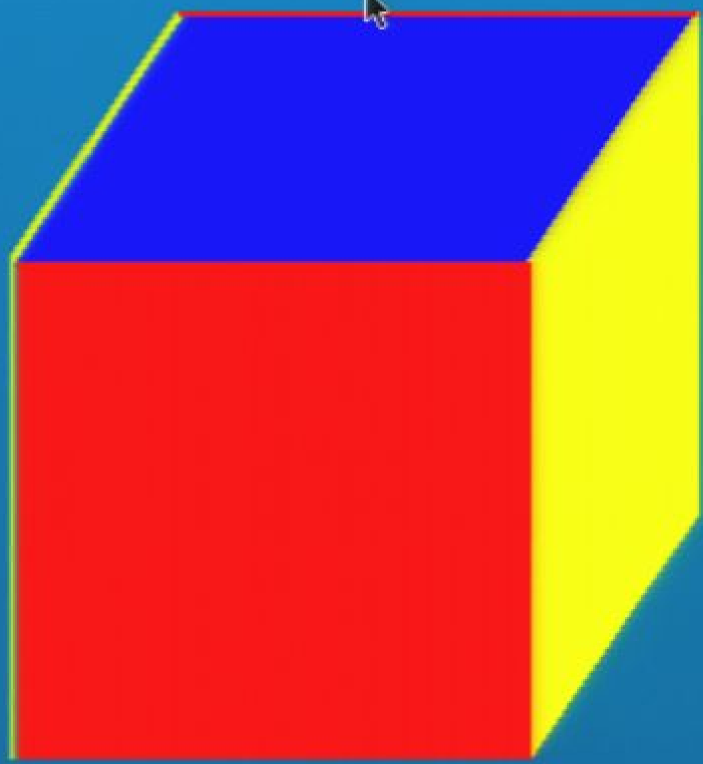
Curvature

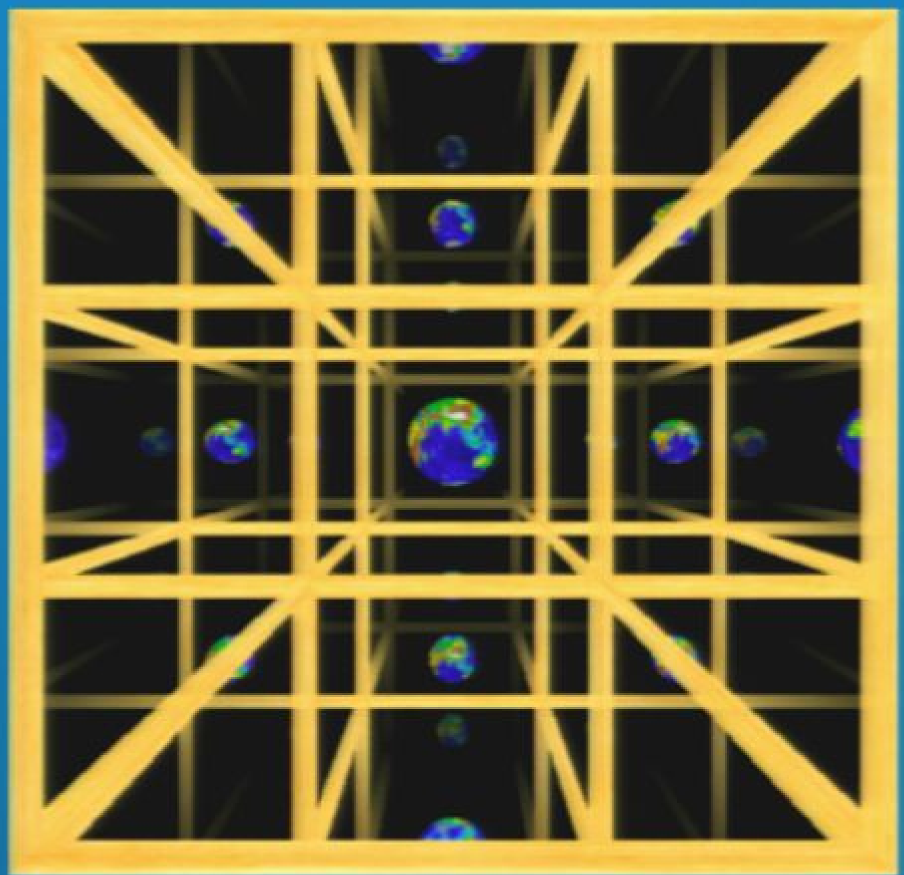
Measuring the shape of space

Curvature



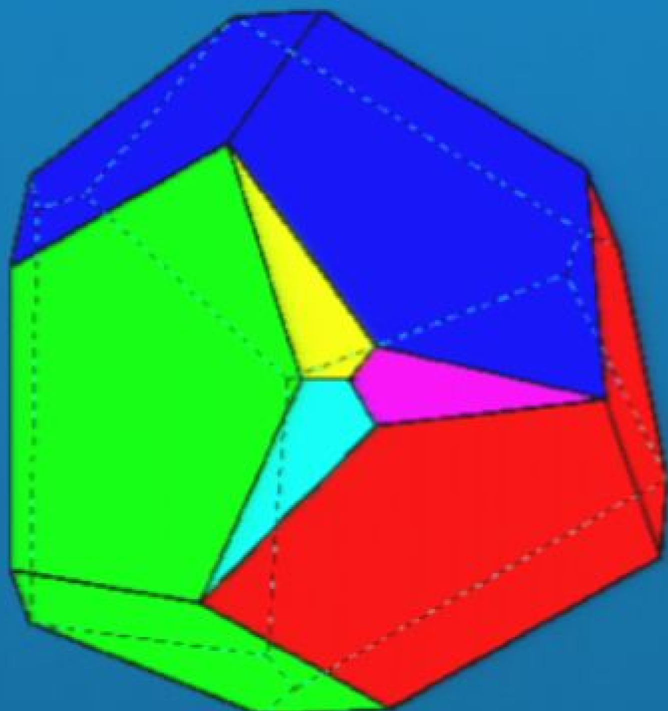
Three Torus

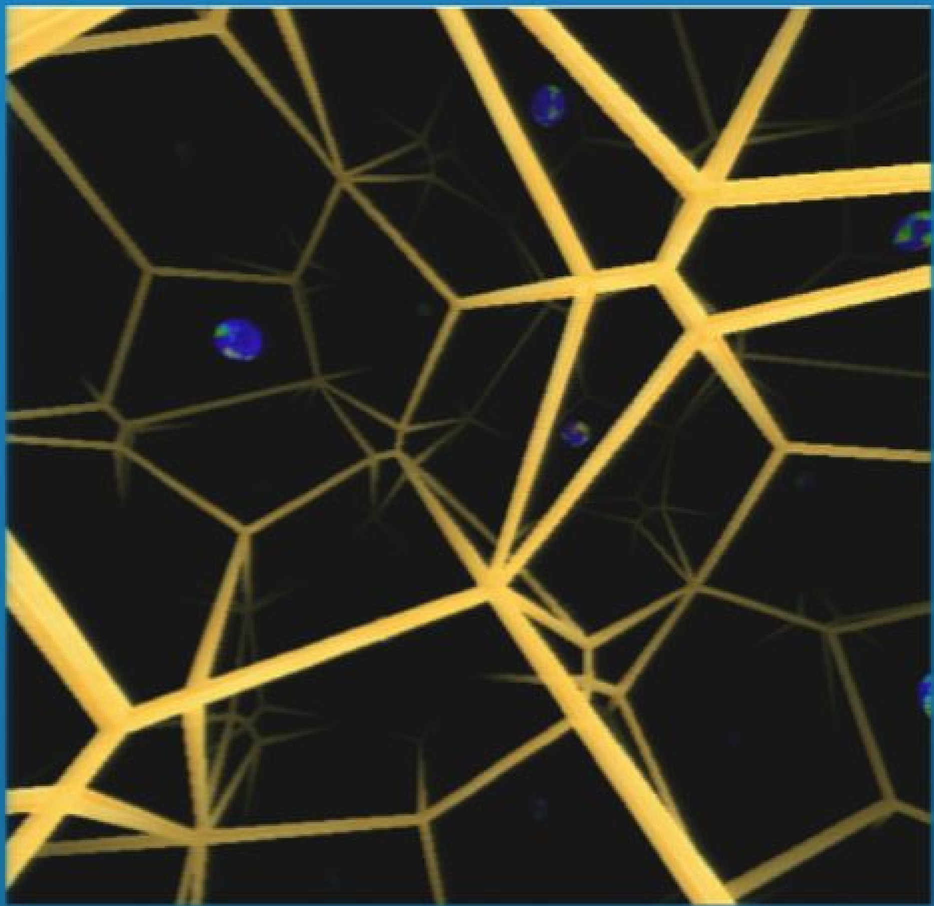




Same idea works in three space dimensions

Infinite number of tiling patterns

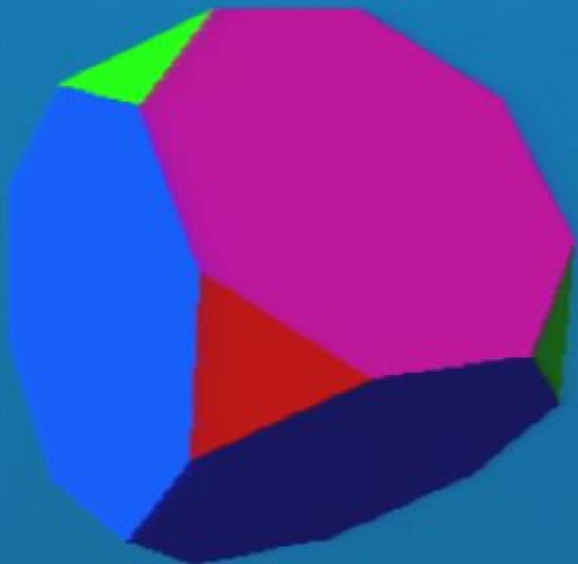


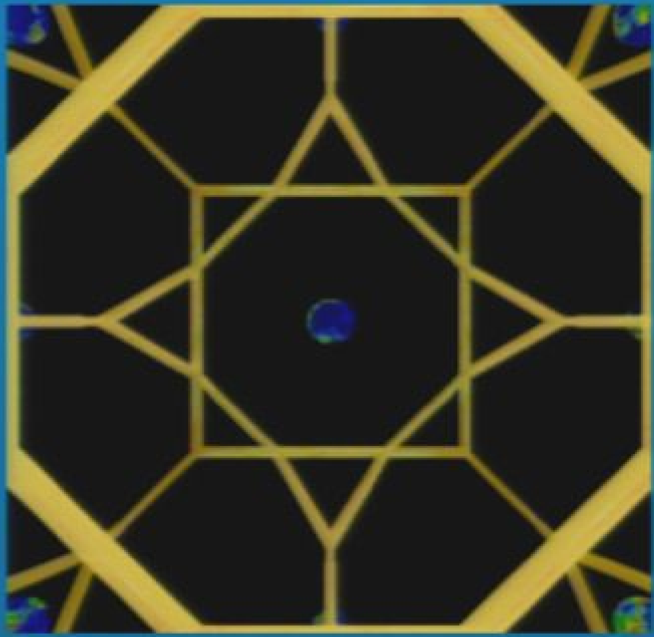


This one only works in hyperbolic space

Spherical Topologies

This example only works in spherical space





The microwave background in a multi-connected universe

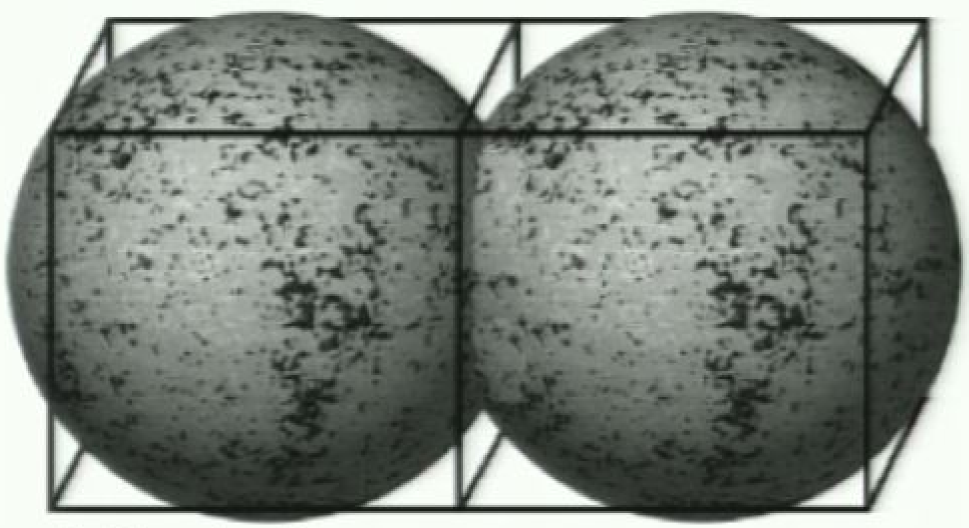
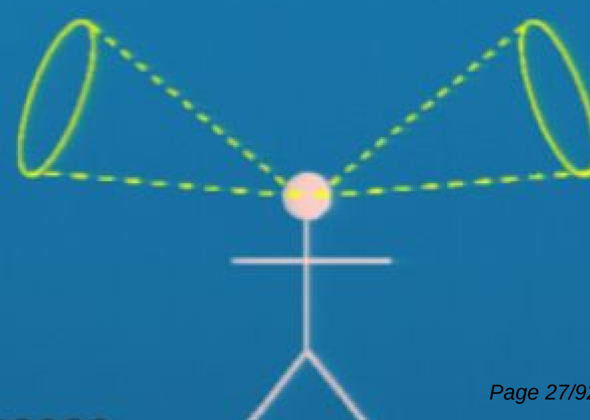
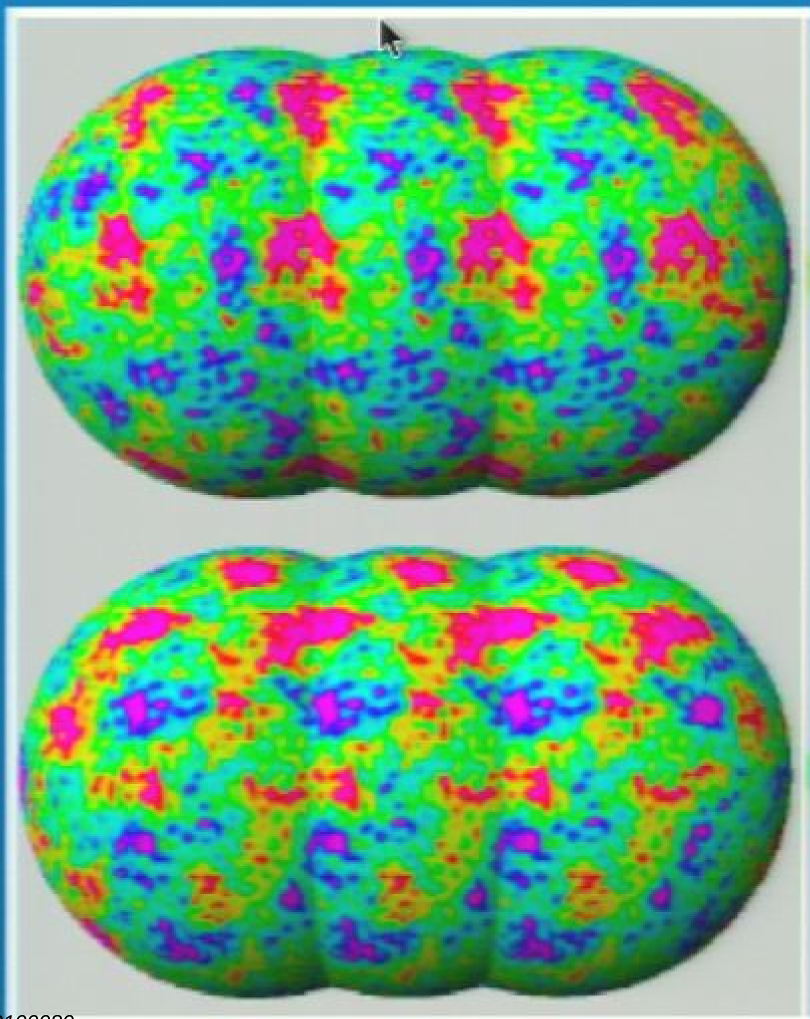


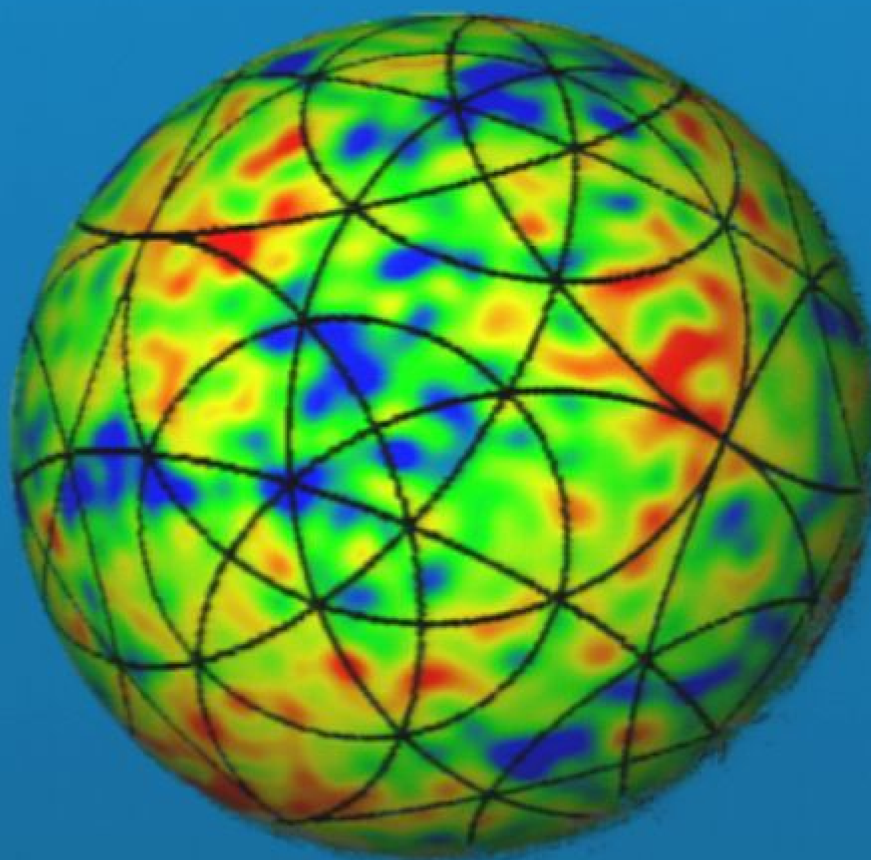
figure: J. Shapiro-Key



N. Cornish, D. Spergel, GDS **gr-qc/9602039, astro-ph/9708083,**

Matched circles in a three torus universe





The search for matched circles

General 6 parameter search:

- Location of first circle center (2)
- Location of second circle center (2)
- Radius of the circle (1)
- Relative phase of the two circles (1)

Reduced 4 parameter search (back-to-back circles):

- Location of first circle center (2)
- Radius of the circle (1)
- Relative phase of the two circles (1)

Statistics for matched circles

Spatial comparisons:

Use a RES r Healpix grid ($3 \times 2^{2r+2}$ pixels)

Draw a circle radius α around center,

linearly interpolate values at 2^{r+1} points around circle

$$S_{12} = 2\langle T_1(\phi)\, T_2(\phi) \rangle_\phi / (\langle T_1(\phi)^2 \rangle_\phi + \langle T_2(\phi)^2 \rangle_\phi)$$

Perfect match $S_{12} = 1$ Random circles $\langle S_{12} \rangle = 0$

Fourier space comparisons:

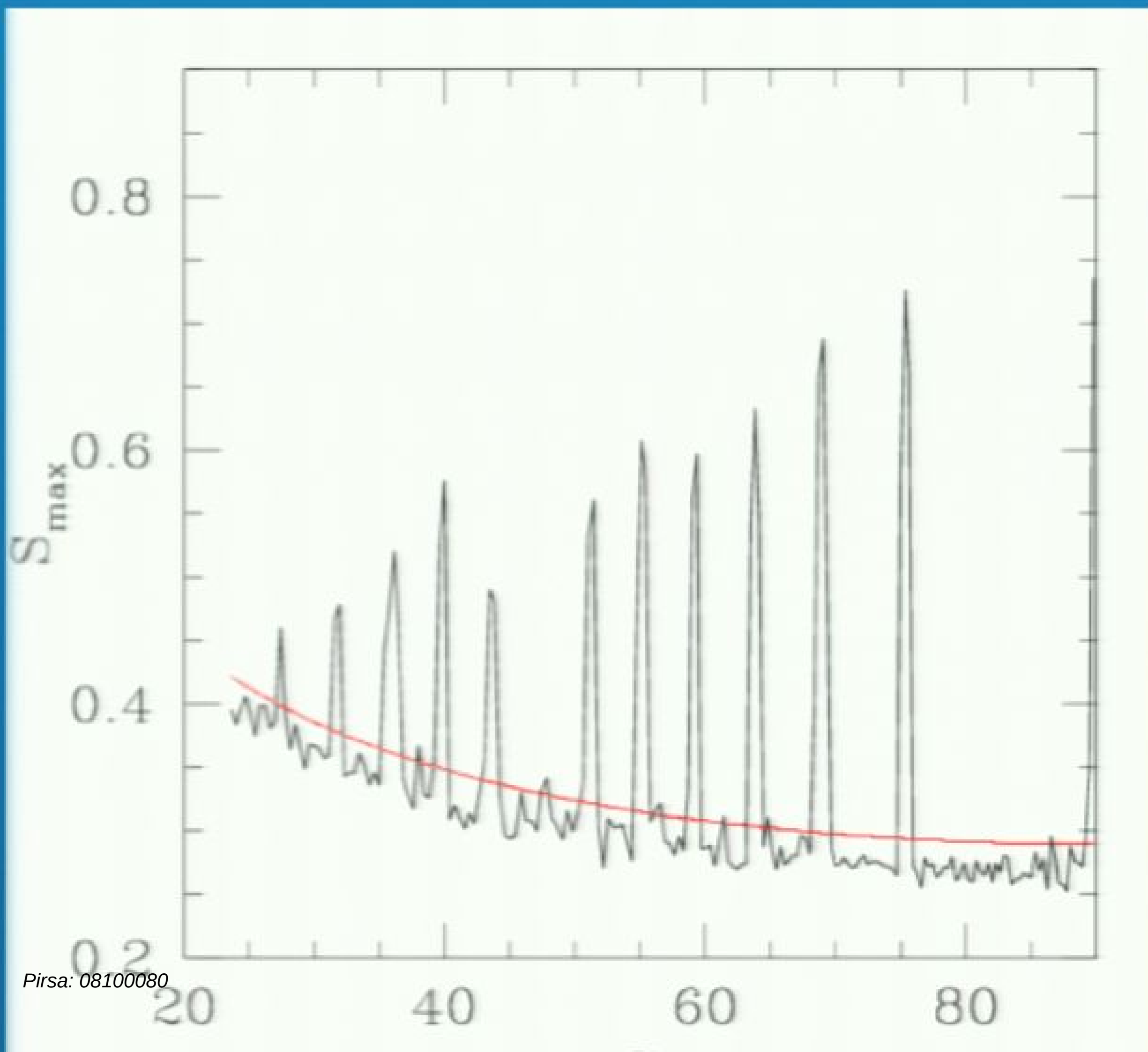
$T_i(\phi) = \sum_m T_{im} e^{im\phi}$

$S_{ij}(\beta) = 2\sum_m m T_{im} T_{jm} e^{-im\beta} / \sum_m m(|T_{im}|^2 + |T_{jm}|^2)$ β is relative phase

We write as: $S_{ij}(\beta) = \sum_m s_m e^{-im\beta}$ and calculate $S_{ij}(\beta)$ as an FFT of s_m

for a $n / \log n$ speed-up (to $n^4 \log(n)$)

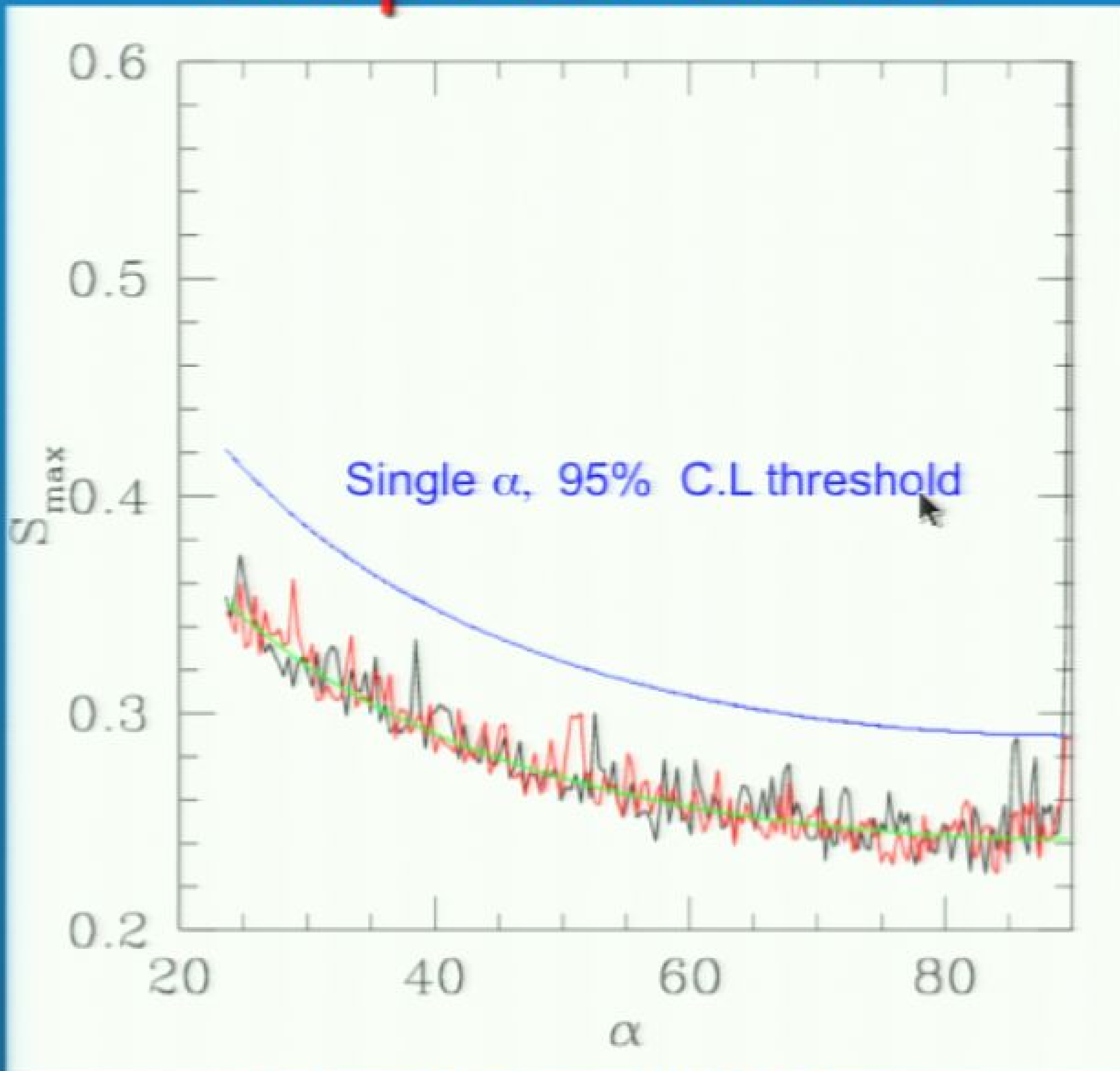
Matched Circles in Simulations



In a blind test >99% of circles found in a "deliberately difficult" universe

Searching the WMAP Sky: antipodal circles

Searching the WMAP Sky: antipodal circles



Implications

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- No antipodal matched circles larger than 25^{o} at > 99% confidence
  - now extended to 20^{o} by pre-filtering.

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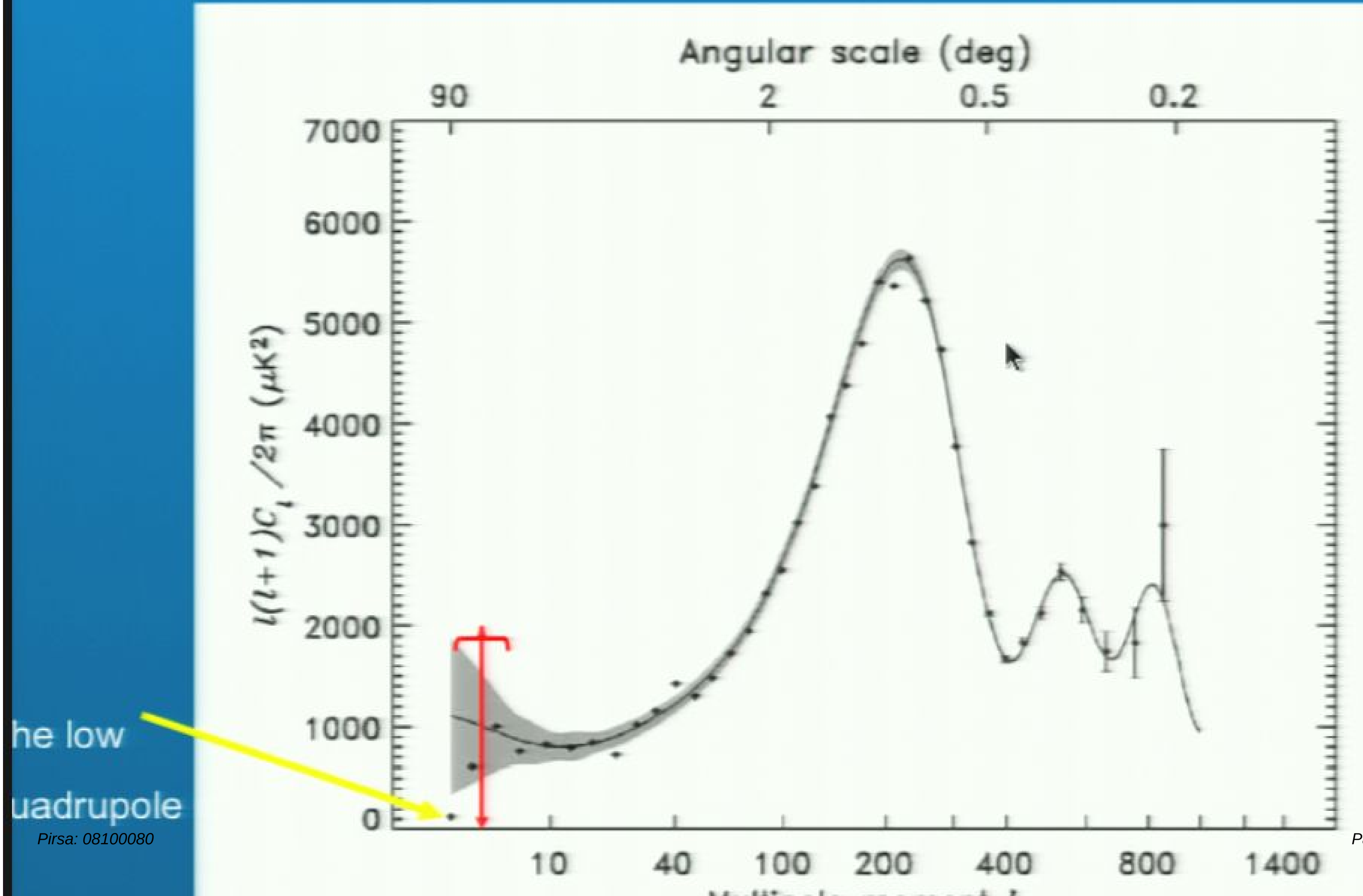
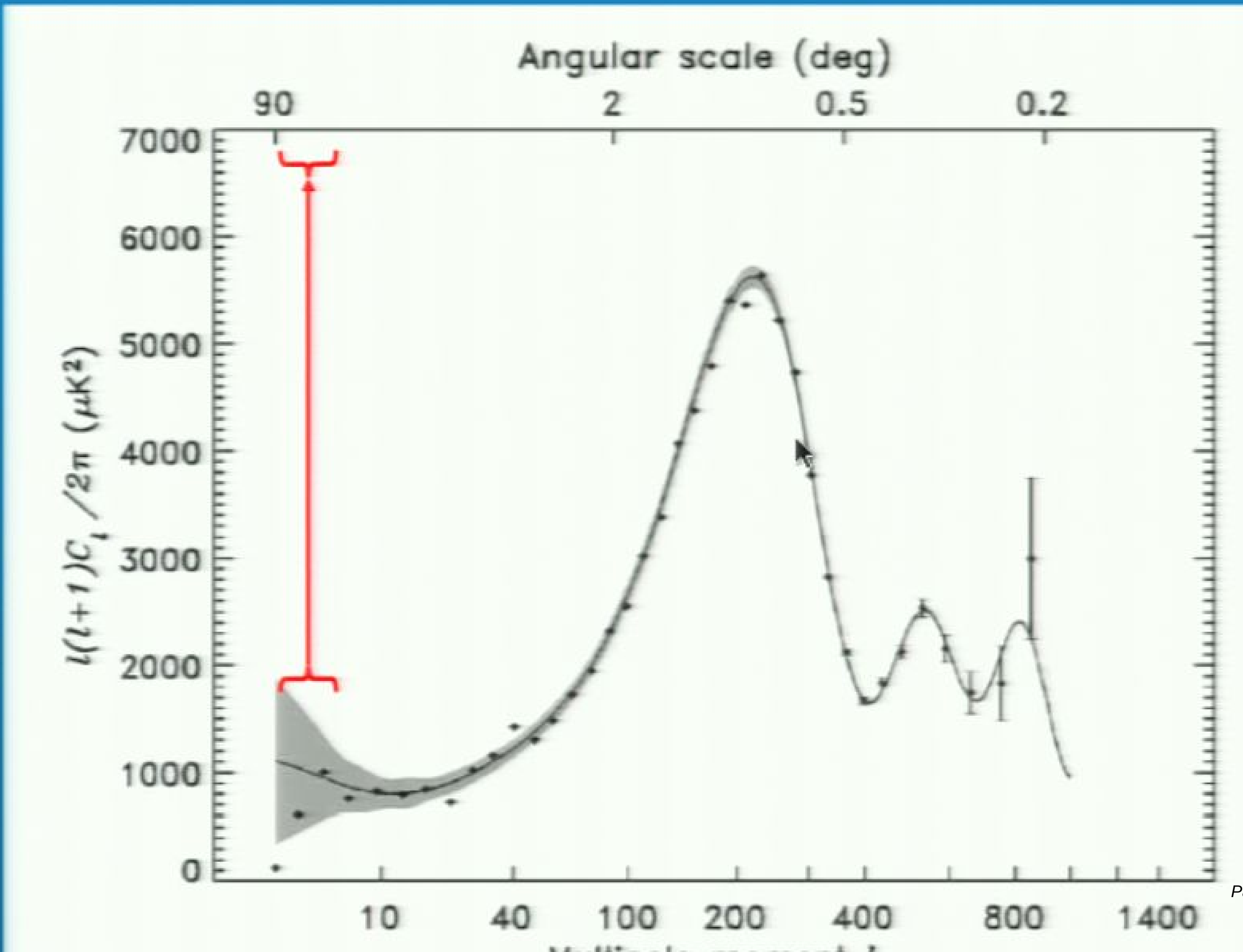
- Unpublished: no matched circles > 25^o.
  - Universe is >90% of the LSS diameter (24 Gpc) across
  - Search is being repeated on 5-year data
  - Sensitivity should improve to 10^o-15^o

"The Low-l Anomaly"



"The Large-Angle Anomaly"



The Angular Correlation Function, $C(\theta)$

$$C(\theta) = \langle T(\Omega_1)T(\Omega_2)\rangle_{\Omega_1.\Omega_2=\cos\theta}$$

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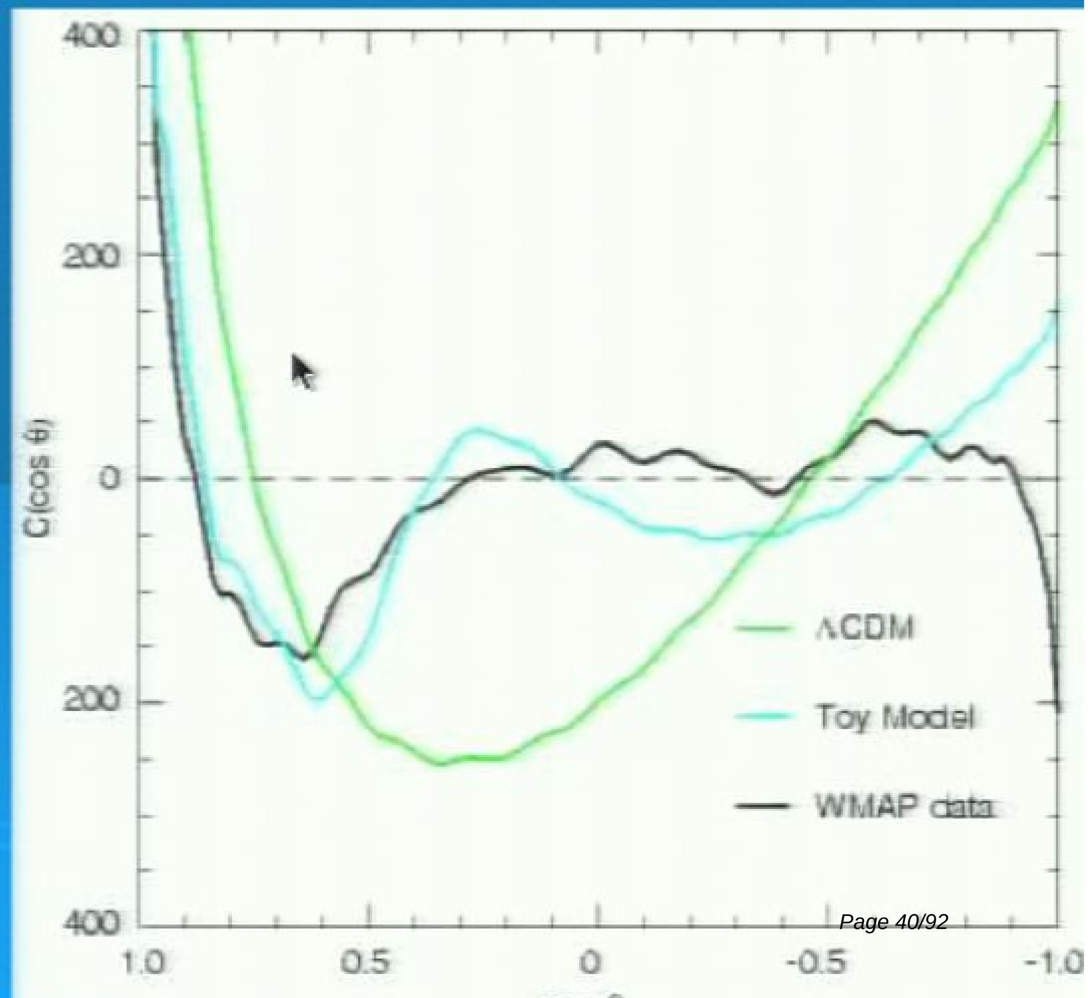

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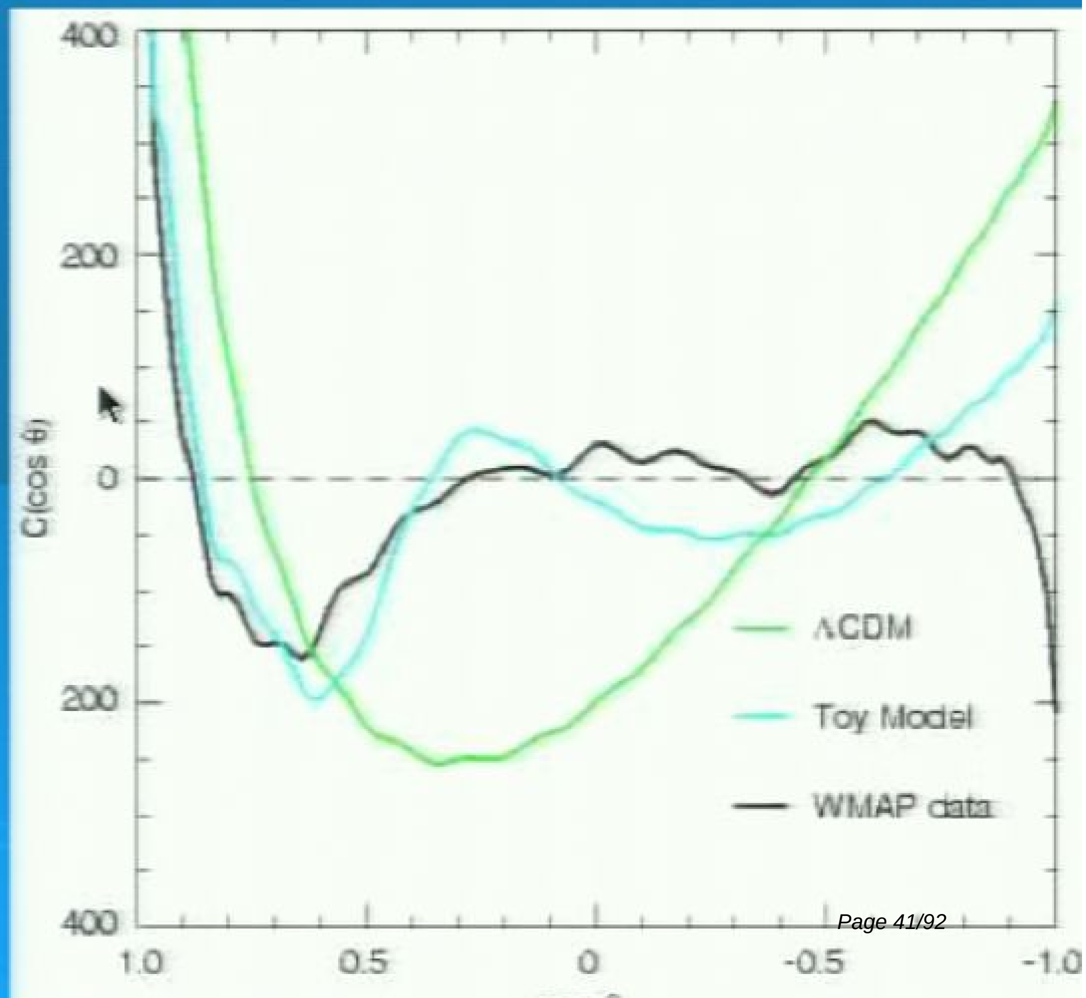
But (established lore):

$C(\theta) = \sum_l C_l P_l(\cos(\theta))$



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⇒ Same information as C_l, just
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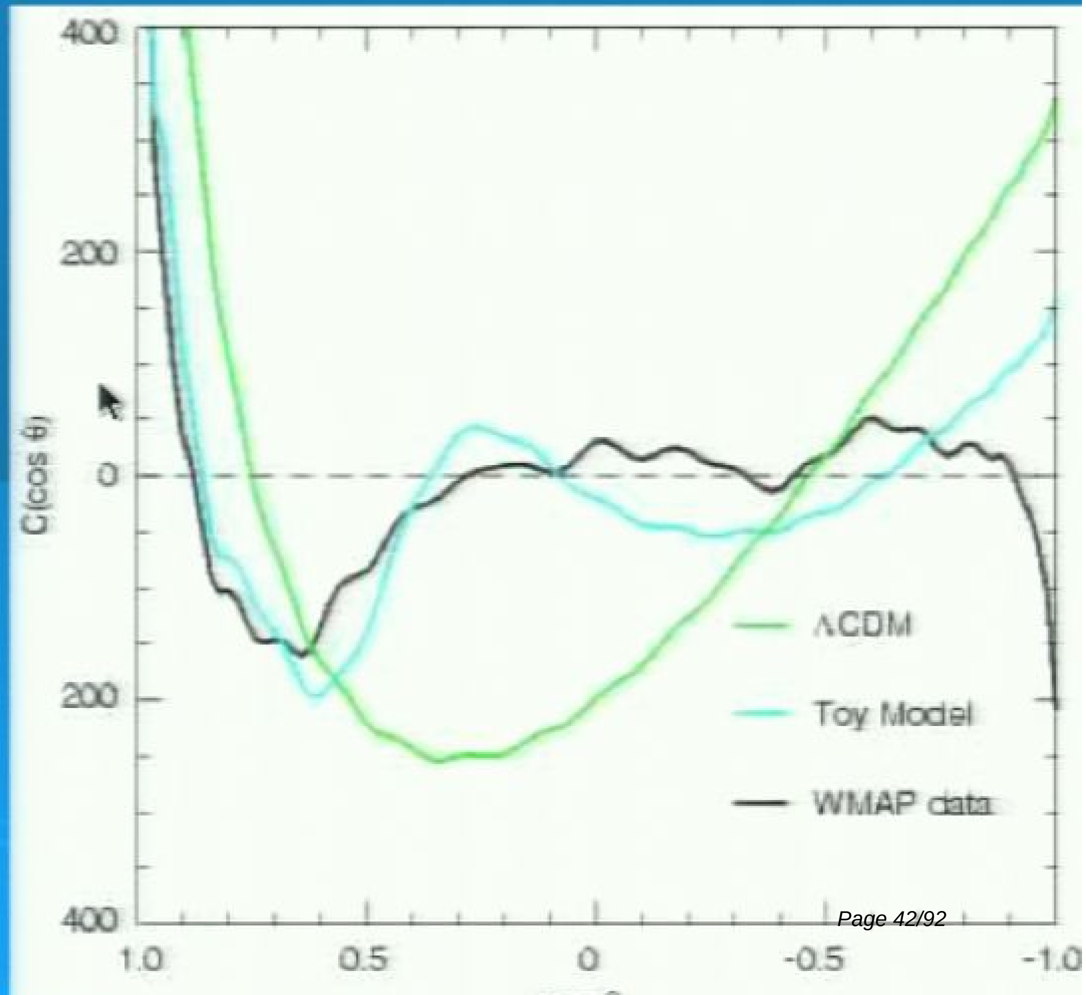

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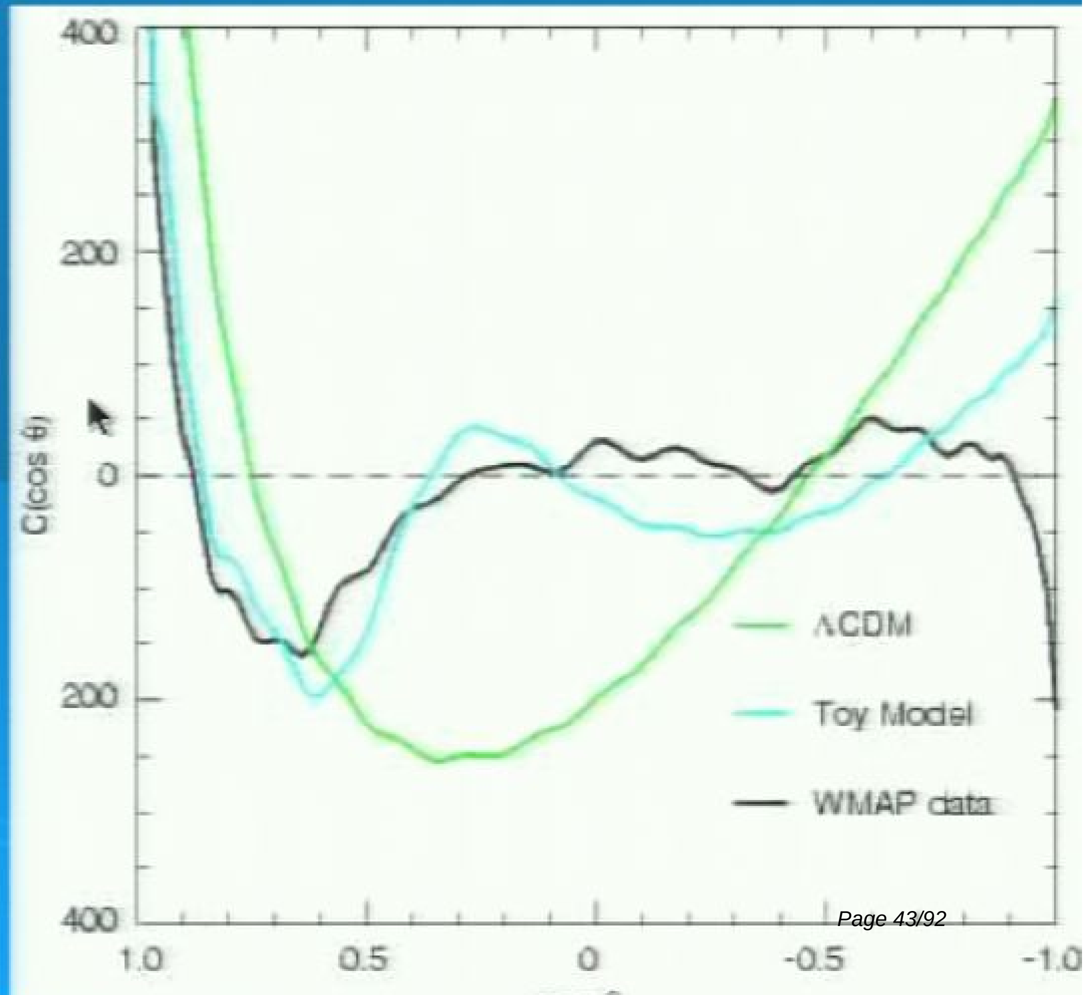
F

$C(\theta)$ is obtained by a full sky verage

r

the sky is statistically isotropic,

e. if $\langle a_{lm}\, a^*_{l'm'}\rangle = \delta_{ll'}\delta_{mm'} C_l$



Is the Large-Angle Anomaly Significant?

WMAP1:

$$S_{1/2} = \int_{-1}^{1/2} [C(\theta)]^2 \, d\cos\theta$$

Only 0.15% of realizations of **inflationary** ΛCDM universe with the best-fit parameters

Beyond C_ℓ and $C(\theta)$:

Searches for Departures from Gaussianity/ Statistical Isotropy

- angular momentum dispersion axes (da Oliveira-Costa, *et al.*)
- Genus curves (Park)
- Spherical Mexican-hat wavelets (Vielva *et al.*)
- Bispectrum (Souradeep *et al.*)
- North-South asymmetries in multipoint functions
  (Eriksen *et al.*, Hansen *et al.*)
- Cold hot spots, hot cold spots (Larson and Wandelt)
- Land & Magueijo scalars/vectors
- **multipole vectors**
  (Copi, Huterer & GDS; Schwarz, SCH; CHSS;
  also Weeks; Seljak and Slosar; Dennis)

Shape and Alignment of the Quadrupole and Octopole

A. de Oliveira-Costa, M. Tegmark, M. Zaldarriaga, A. Hamilton. **Phys.Rev.D69:063516,2004**
astro-ph/0307282

For each ℓ, find the axis $\mathbf{n}_\ell$ around which the angular momentum dispersion :

$$(\Delta L)^2 \equiv \sum_m m^2 \, |a^{\ell m}(\mathbf{n}_\ell)|^2$$

is maximized

Results:

	Probability
•octopole is unusually "planar" (dominated by $\lvert m \rvert = 3$ if $z \equiv \mathbf{n}_3$).	1/20??
• $\mathbf{n}_2 \cdot \mathbf{n}_3 = 0.9838$	1/60

Multipole Vectors

Q: What are the directions associated

with the ℓ^{th} multipole:

$$\Delta T_\ell(\theta,\phi) \equiv \sum_m a_{\ell m} Y_{\ell m}(\theta,\phi) \quad ?$$

Dipole (ℓ=1) :

$$\sum_m a_{1m} Y_{1m}(\theta,\phi) =$$

$$A^{(1)} (\hat{u}_x^{(1,1)}, \hat{u}_y^{(1,1)}, \hat{u}_z^{(1,1)}) . (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

Advantages: 1) $\hat{u}^{(1,1)}$ is a vector, $A^{(1)}$ is a scalar

Multipole Vectors

General ℓ, write:

$$\sum_m a_{\ell m} Y_{\ell m}(\theta,\phi) \approx$$

$$A^{(\ell)} \left[(\hat{u}^{(\ell,1)} \cdot \hat{e}) \ldots (\hat{u}^{(\ell,\ell)} \cdot \hat{e}) \text{ - all traces} \right]$$

$$\{a_{\ell m,}\ m = -\ell, \ldots, \ell\},\ \ell = (0,1,)2, \ldots\} \Rightarrow$$

$$\{A^{(\ell)}, \{\hat{u}^{(\ell,i)}, \ell = 1, \ldots \ell\},\ \ell = (0,1,)2, \ldots\}$$

Advantages: 1) $\hat{\mathbf{u}}^{(\ell,i)}$ are vectors, $\mathbf{A}^{(\ell)}$ is a scalar

2) Only $\mathbf{A}^{(\ell)}$ depends on C_ℓ

$$\sum_m a_{\ell m} Y_{\ell m}(\theta,\phi) = \left[(\mathbf{u}^{(\ell,1)} \cdot \nabla) \ldots (\mathbf{u}^{(\ell,\ell)} \cdot \nabla) r^{-1} \right]_{r=1}$$

manifestly symmetric AND trace free:

$$\nabla^2 (1/r) \propto \delta(r)$$

Maxwell Multipole Vectors

$$\sum_m a_{\ell m} Y_{\ell m}(\theta,\phi) = \left[(\mathbf{u}^{(\ell,1)}\cdot\nabla)\ldots(\mathbf{u}^{(\ell,\ell)}\cdot\nabla) r^{-1} \right]_{r=1}$$

manifestly symmetric AND trace free:

$$\nabla^2 (1/r) \propto \delta(r)$$

J.C. Maxwell, *A Treatise on Electricity and Magnetism*, v.1, 1873 (1st ed.)

Area Vectors

Notice:

- Quadrupole has 2 vectors, *i.e.* quadrupole is a plane
  - $n_2 \parallel (\hat{u}^{(2,1)} \times \hat{u}^{(2,2)})$
- Octopole has 3 vectors, *i.e.* octopole is 3 planes
  - octopole is perfectly planar if

    $(\hat{u}^{(3,1)} \times \hat{u}^{(3,2)}) \parallel (\hat{u}^{(3,2)} \times \hat{u}^{(3,3)}) \parallel (\hat{u}^{(3,3)} \times \hat{u}^{(3,1)})$

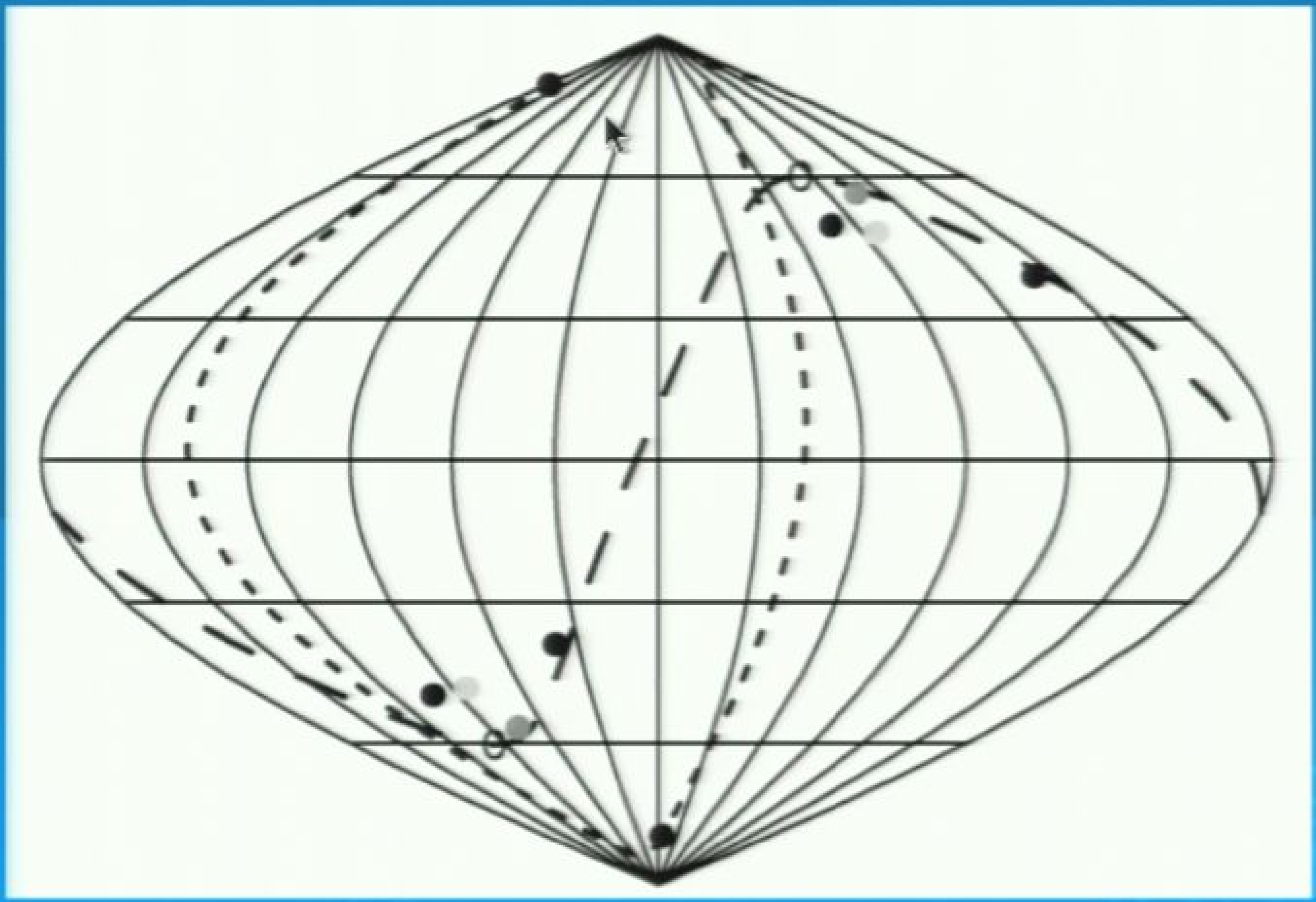
    and then: $n_3 \parallel (\hat{u}^{(3,1)} \times \hat{u}^{(3,2)})$

Suggests defining:

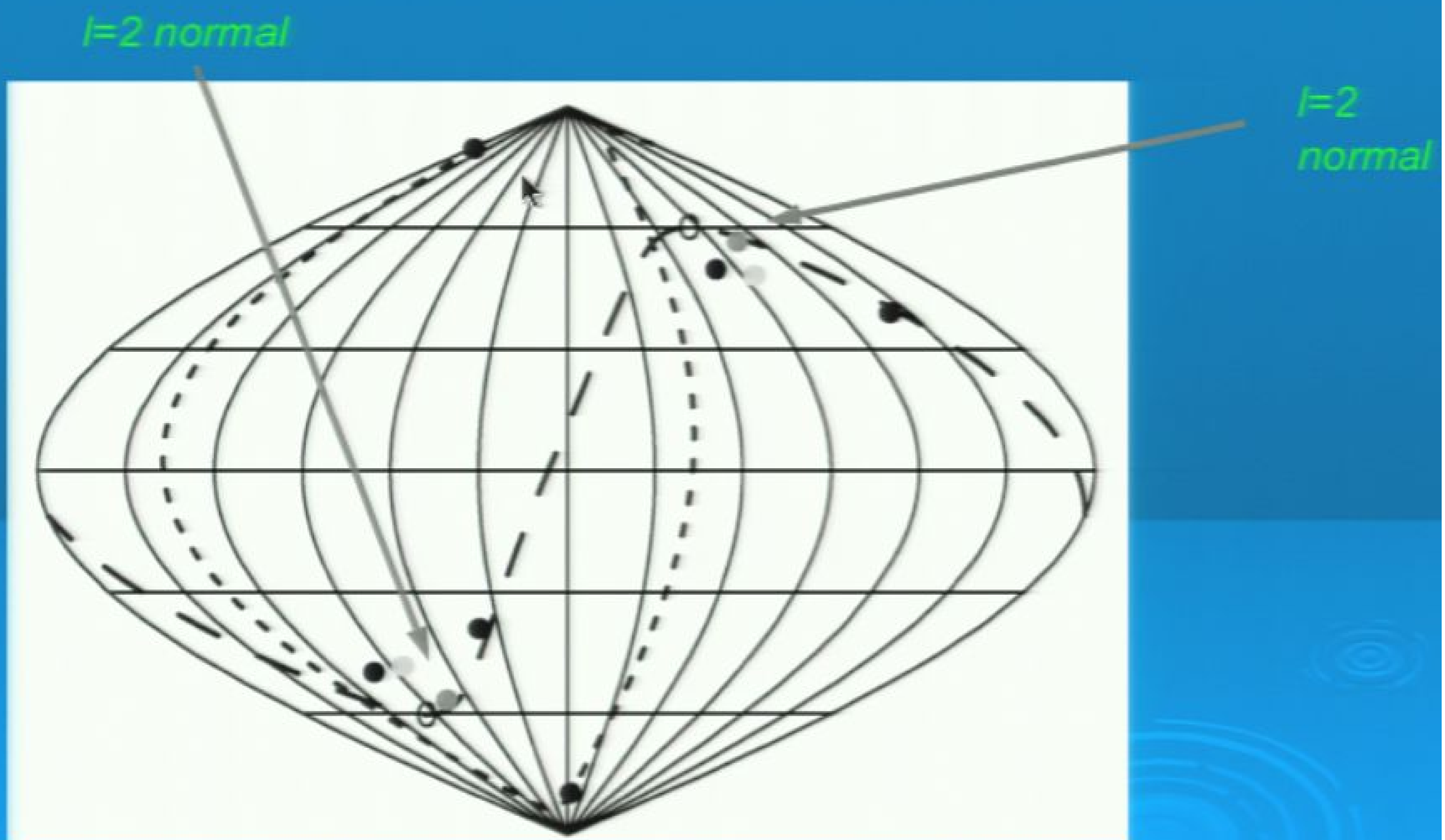
$\mathbf{w}^{(\ell,i,j)} \equiv (\hat{u}^{(\ell,i)} \times \hat{u}^{(\ell,j)})$ "area vectors"

Carry some, but not all, of the information

l=2&3 Multiple Vectors



l=2&3 Multiple Vectors



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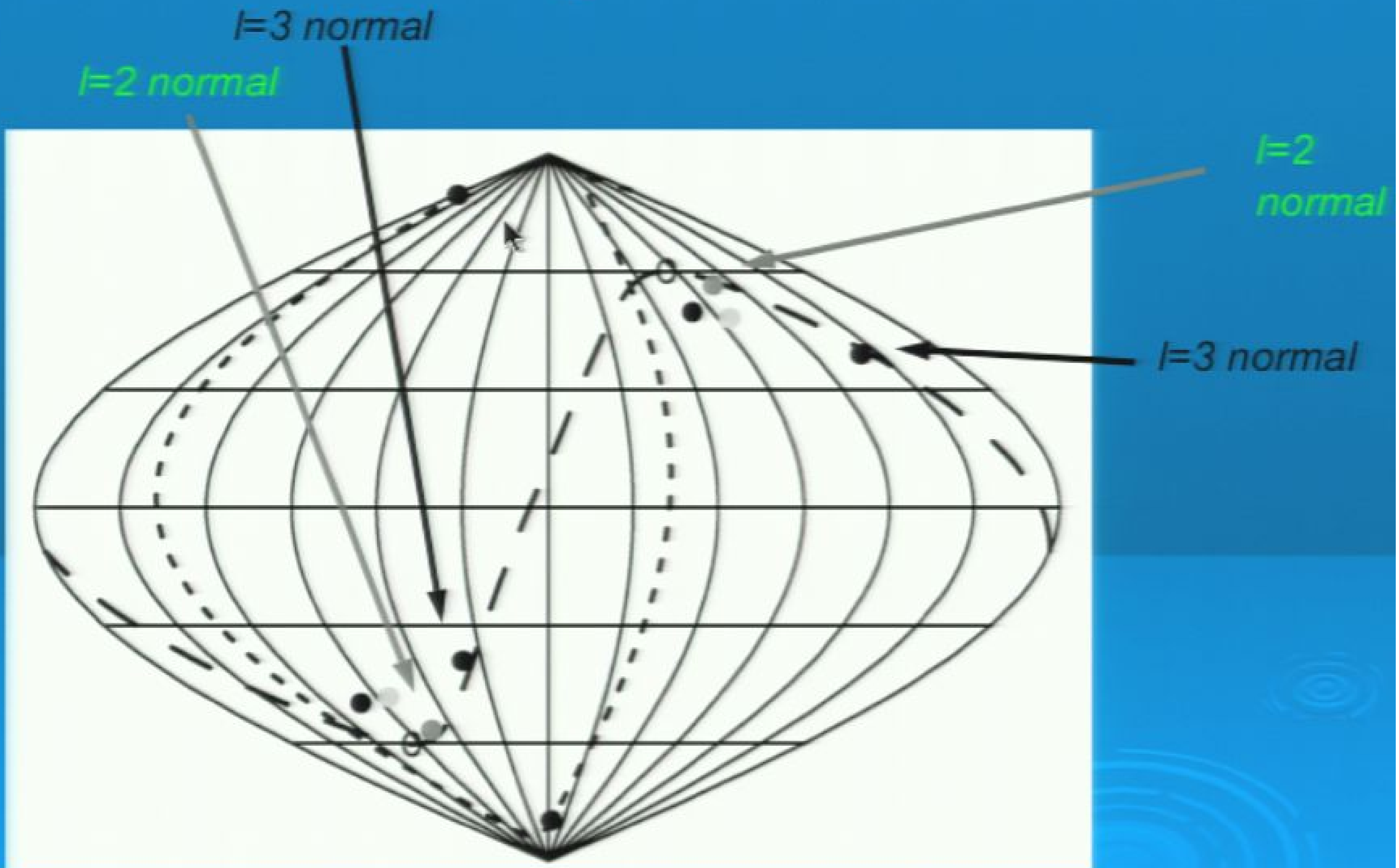
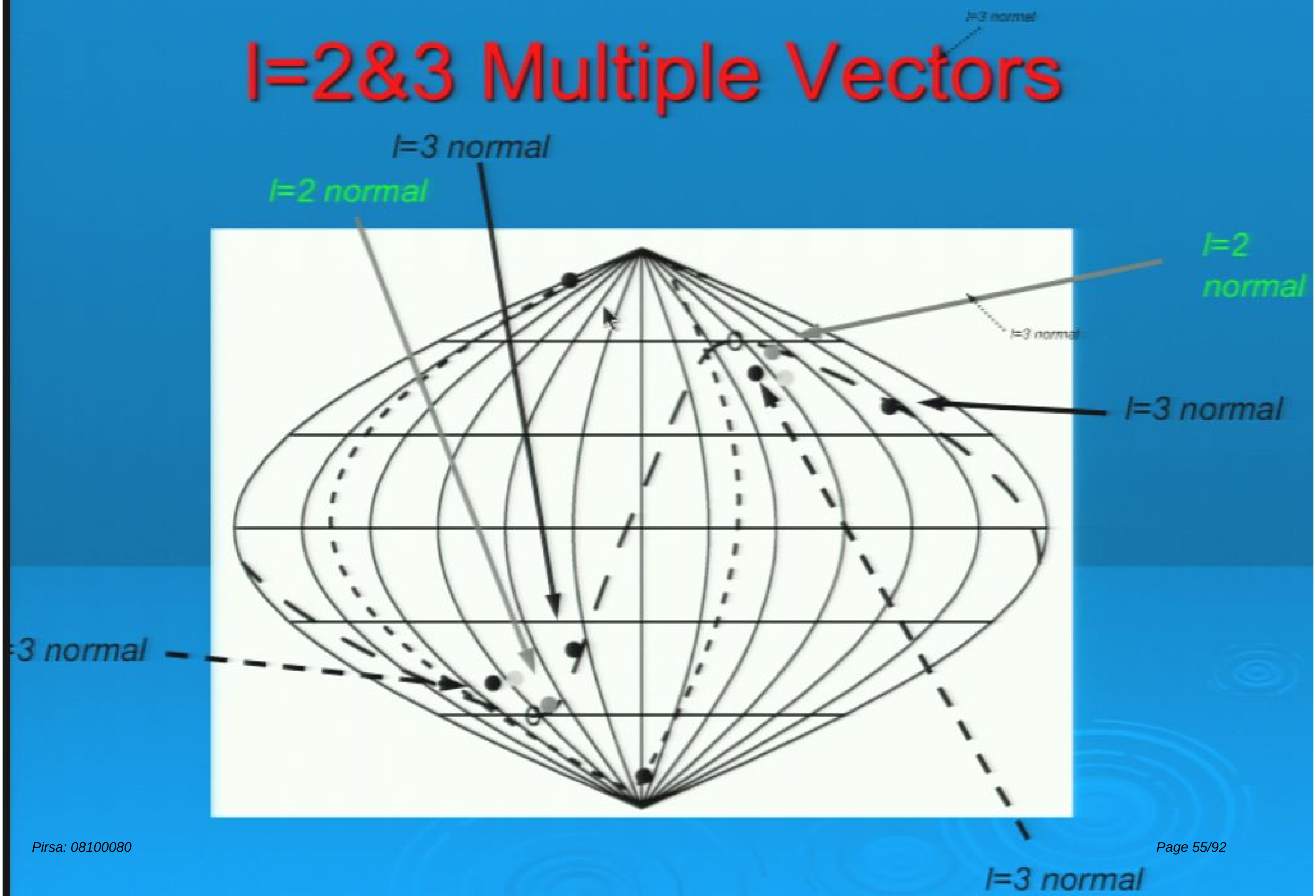
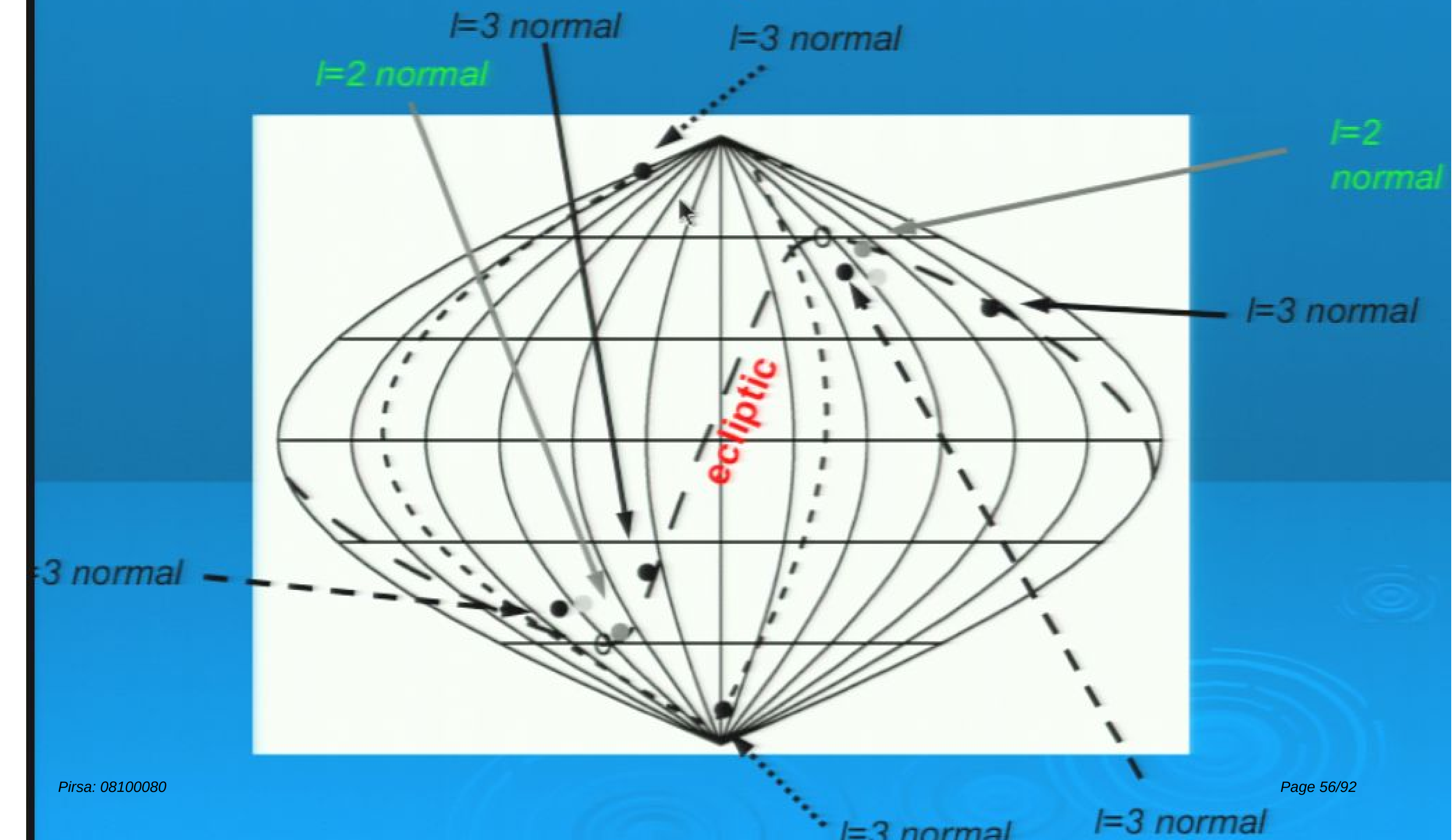


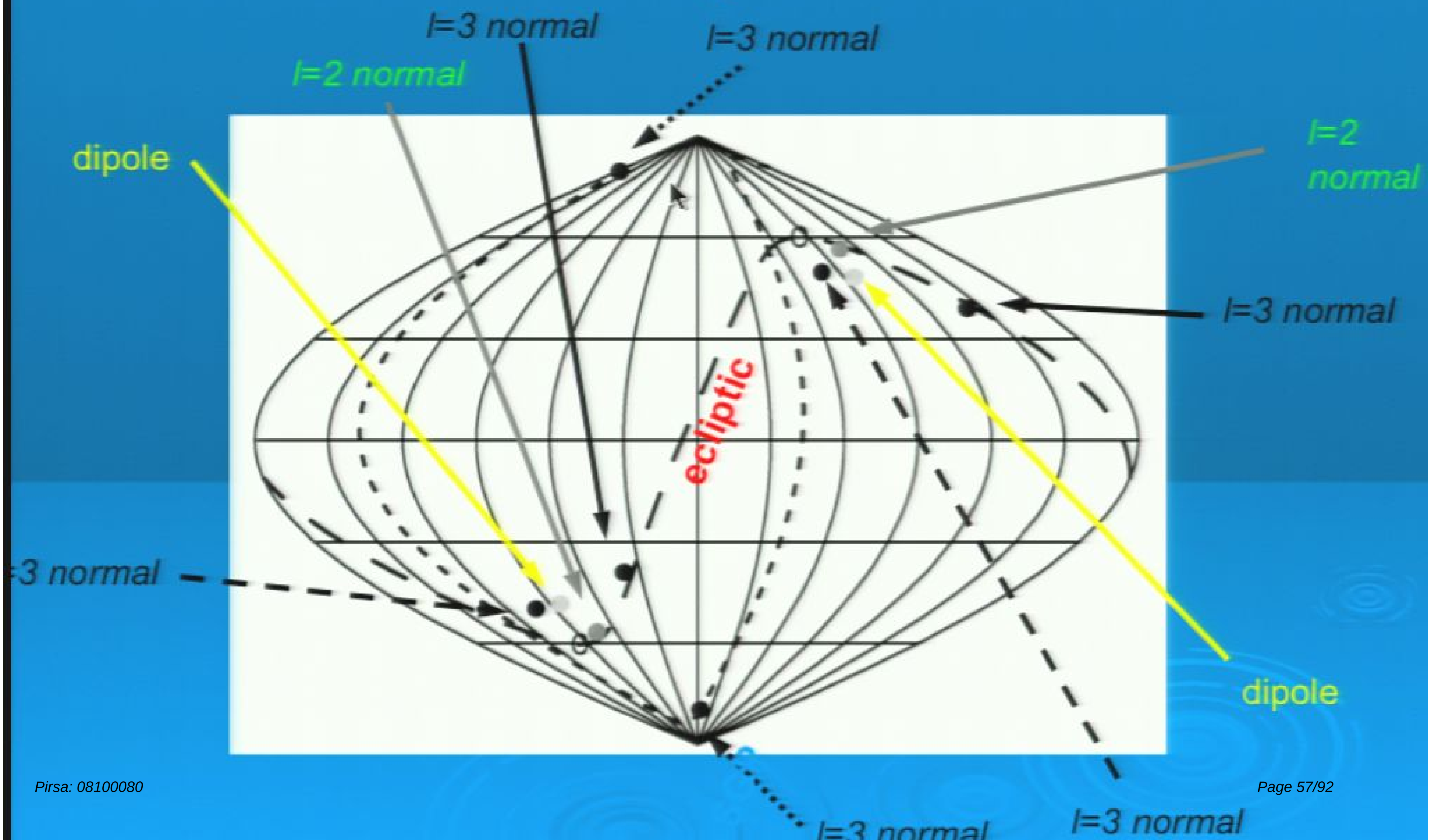
l=2&3 Multiple Vectors



l=2&3 Multiple Vectors



l=2&3 Multiple Vectors



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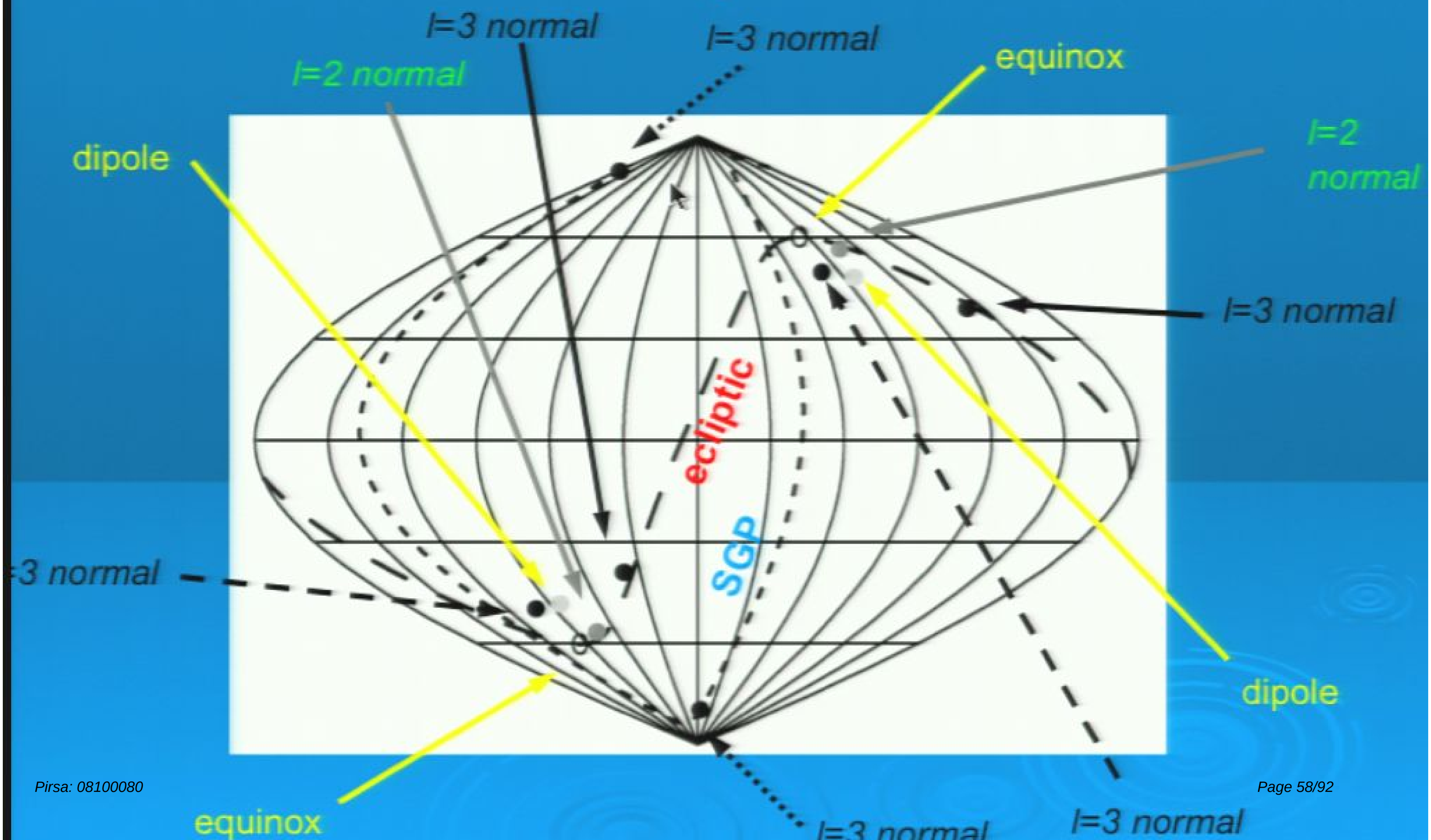
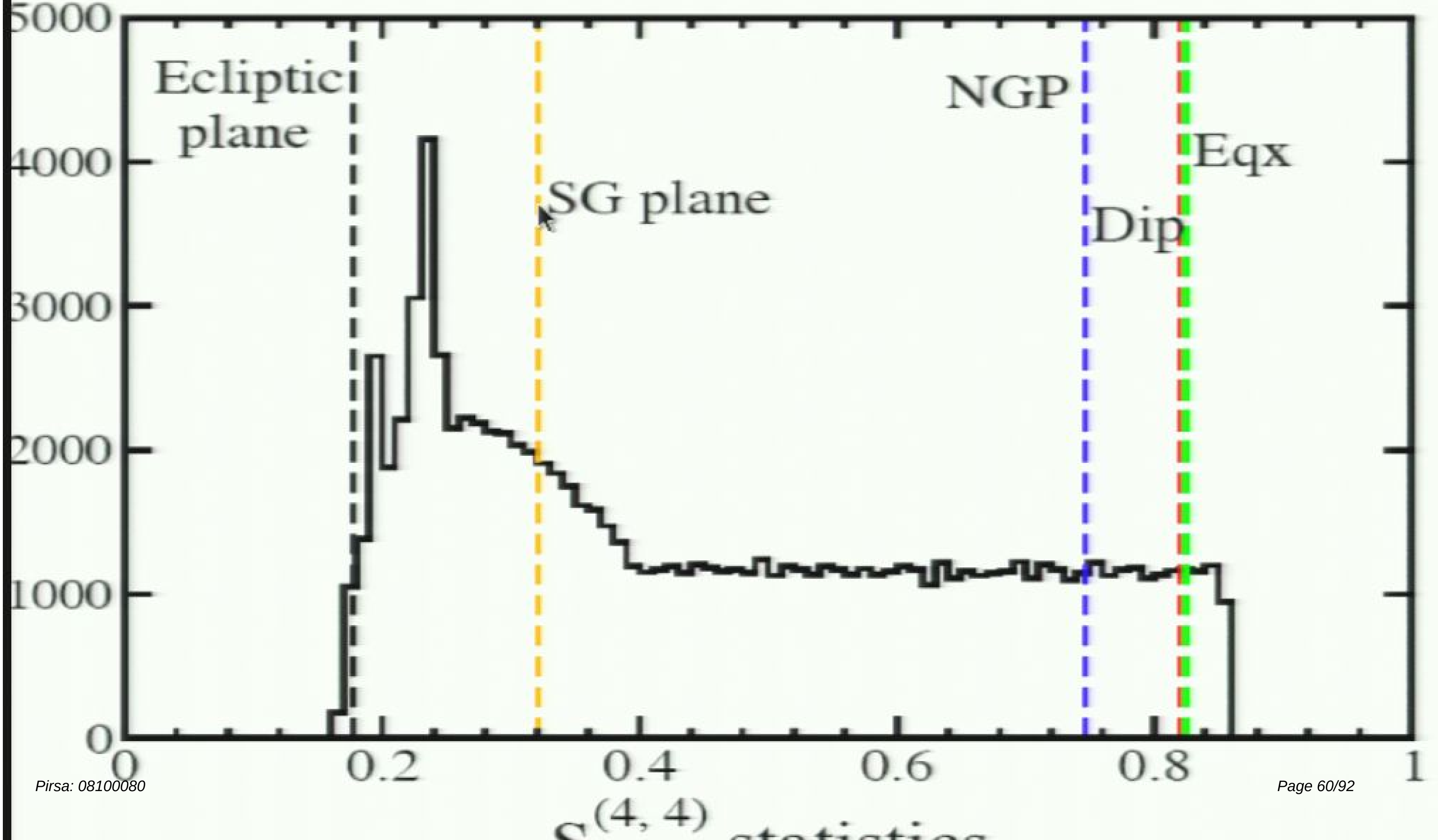


Alignment probabilities

Test	TOH DQ-corr	LILC DQ-corr	ILC DQ-corr	TOH uncorr	LILC uncorr	ILC uncorr
A_i	0.117	0.602	0.289	0.582	2.622	0.713
D_i	1.246	1.309	2.240	1.262	1.309	2.567
ecliptic plane	1.425	1.480	2.006	1.228	1.735	2.724
NGP	0.734	0.940	0.508	0.909	1.265	0.497
SG plane	14.4	13.4	8.9	11.6	10.2	6.5
dipole	0.045	0.214	0.110	0.093	0.431	0.207
equinox	0.031	0.167	0.055	0.064	0.315	0.080

All values in %, in a sample of 100,000 MC realisations of Gaussian-random $a_{\ell m}$

Additional alignment of the observed quadrupole+octopole with physical directions



Percentile of additional alignment with physical directions

Test	TOH DQ-corr	LILC DQ-corr	ILC DQ-corr
ecliptic plane	1.0	0.2	1.7
NGP	87	88	90
SG plane	34	33	25
dipole	95.6	93.8	94.5
equinox	96.1	94.4	96.4

- $S^{(4,4)}$ percentiles **given** the observed "shape" of l=2&3

Percentile of additional alignment with physical directions

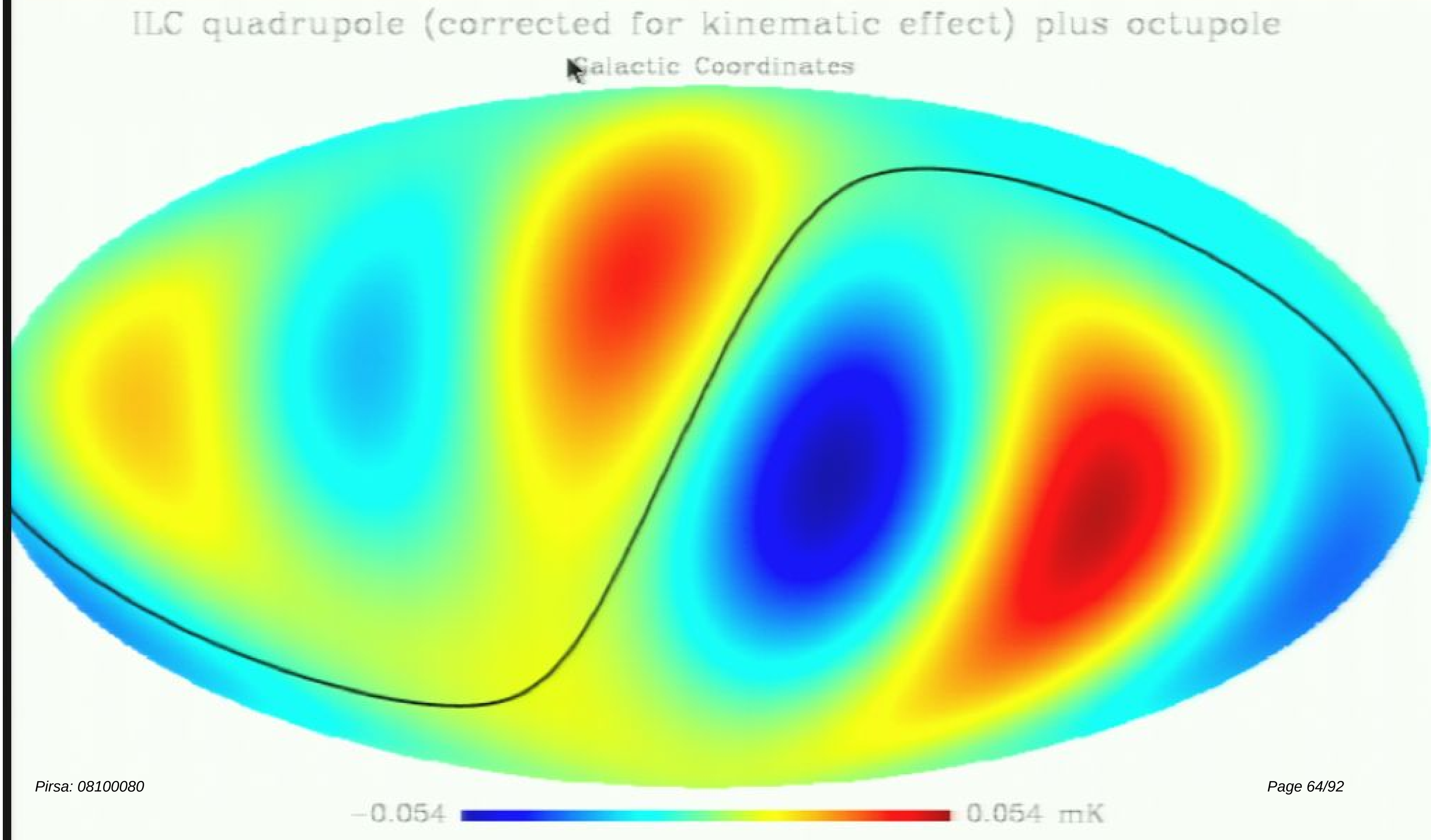
	ILC1	TOH1	LILC1	ILC123
ecliptic	1.7	1.0	0.2	10.3
NGP	90	87	88	88
SG plane	25	34	33	32
dipole	94.5	95.6	93.8	93.0
equinox	96.4	96.1	94.4	94.0

Area vectors tell about the orientations of the normals of the multipole planes

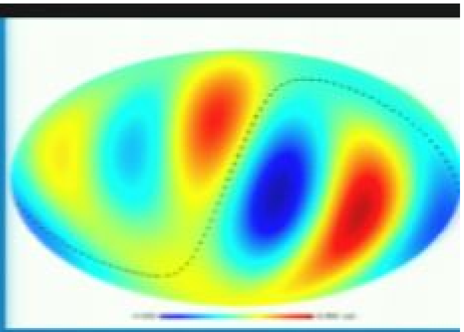
DON'T include all the information (multipole vectors do)

Can rotate the aligned planes about their common axis!

l=2&3 : The Map

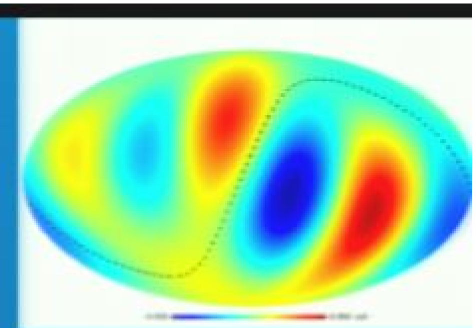

ILC quadrupole (corrected for kinematic effect) plus octupole
Galactic Coordinates
−0.054
0.054 mK

Quadrupole+Octopole Correlations -- Explanations: Cosmology?



- Cosmology -- you've got to be kidding? you choose: the dipole or the ecliptic ?

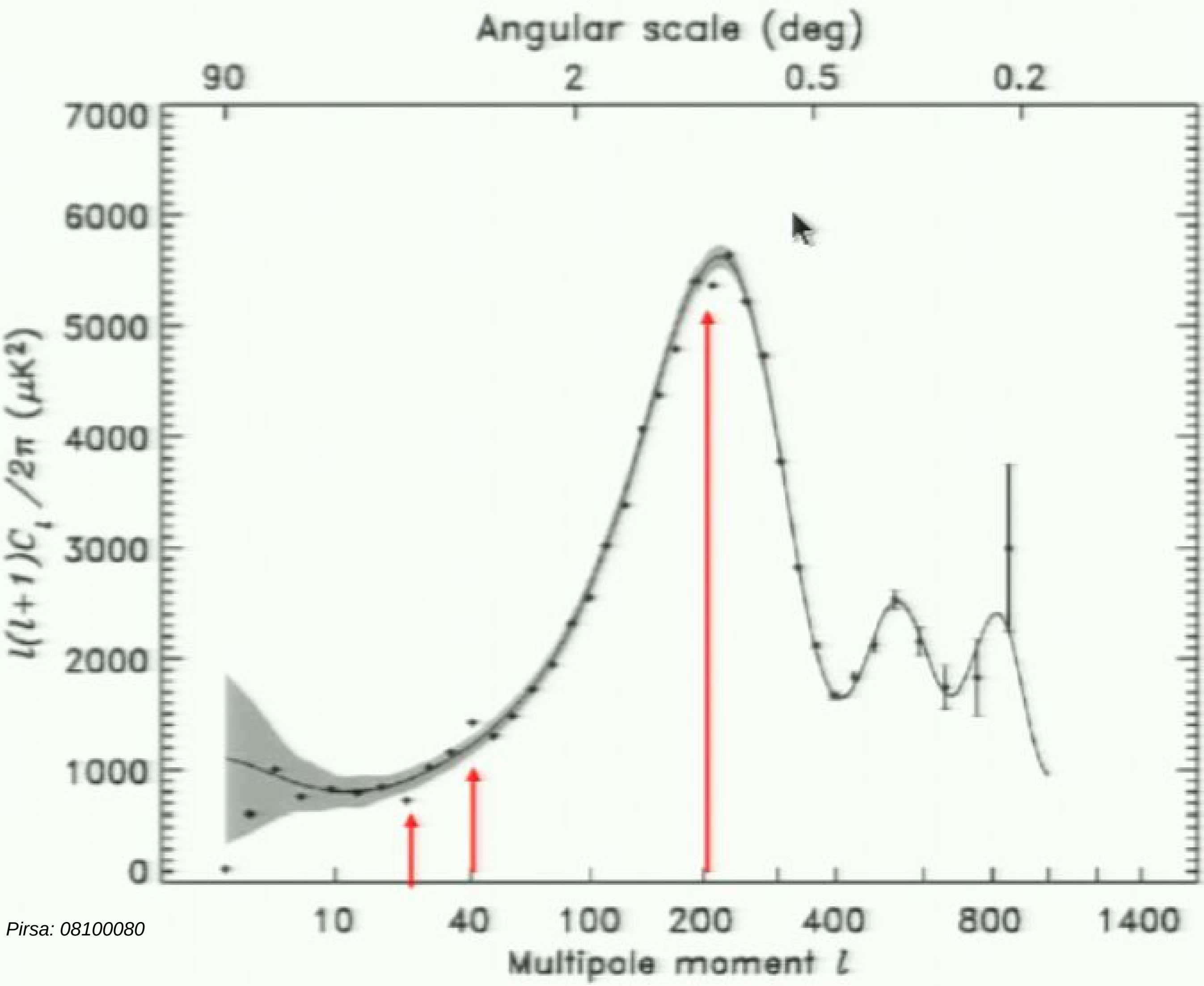
Quadrupole+Octopole Correlations -- Explanations: Systematics?



- Cosmology

- Systematics -- but …
  how do you get such an effect?
  esp., how do you get a N-S ecliptic asymmetry? (dipole mis-subtraction?)
  how do you avoid oscillations in the time-ordered data?
  possibilities -- correlation of beam asymmetry with observing pattern (S. Myer)

Angular Power Spectrum



At least 3 other major deviations in the C_l in 1st year data

Power spectrum: ecliptic plane vs. poles

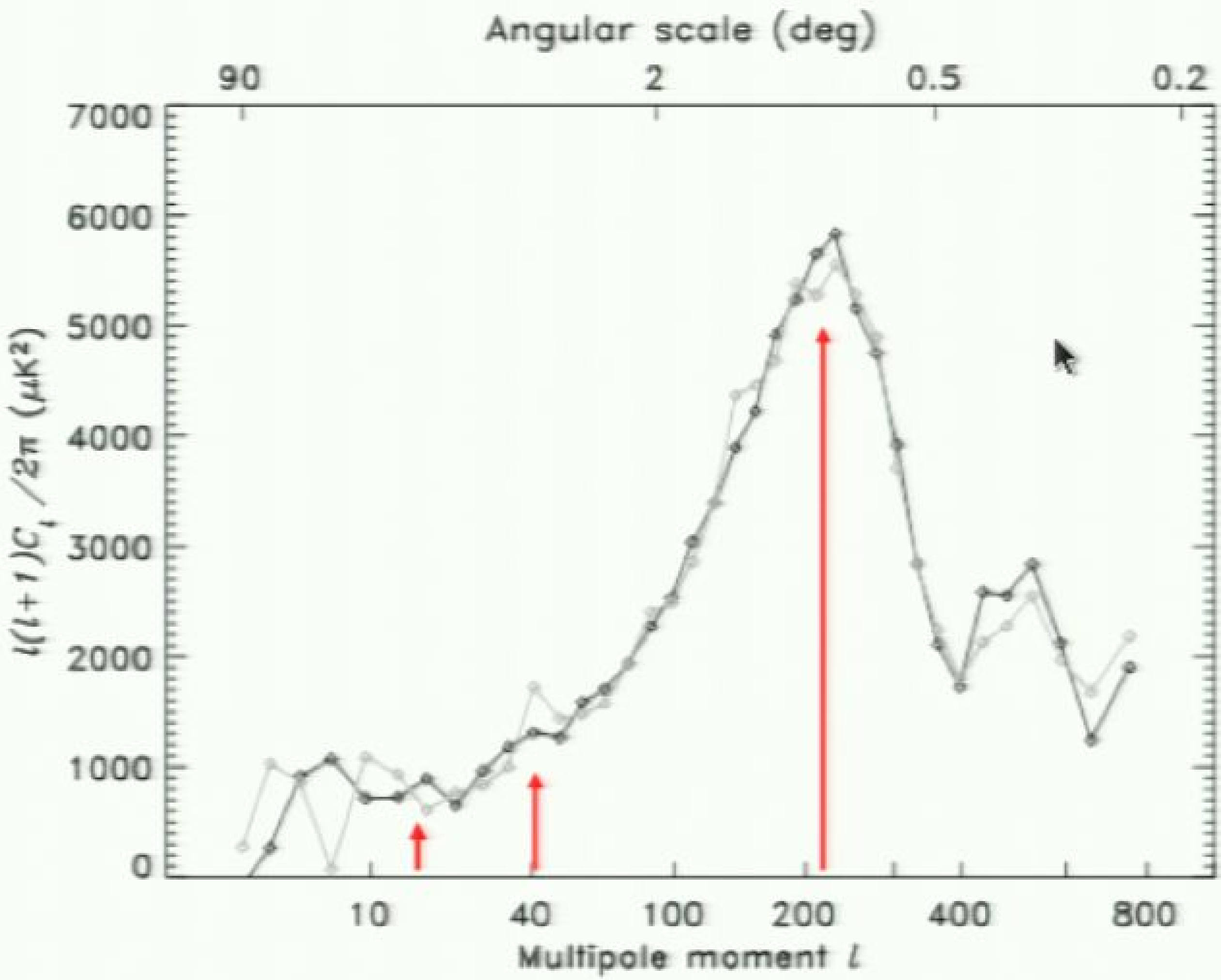
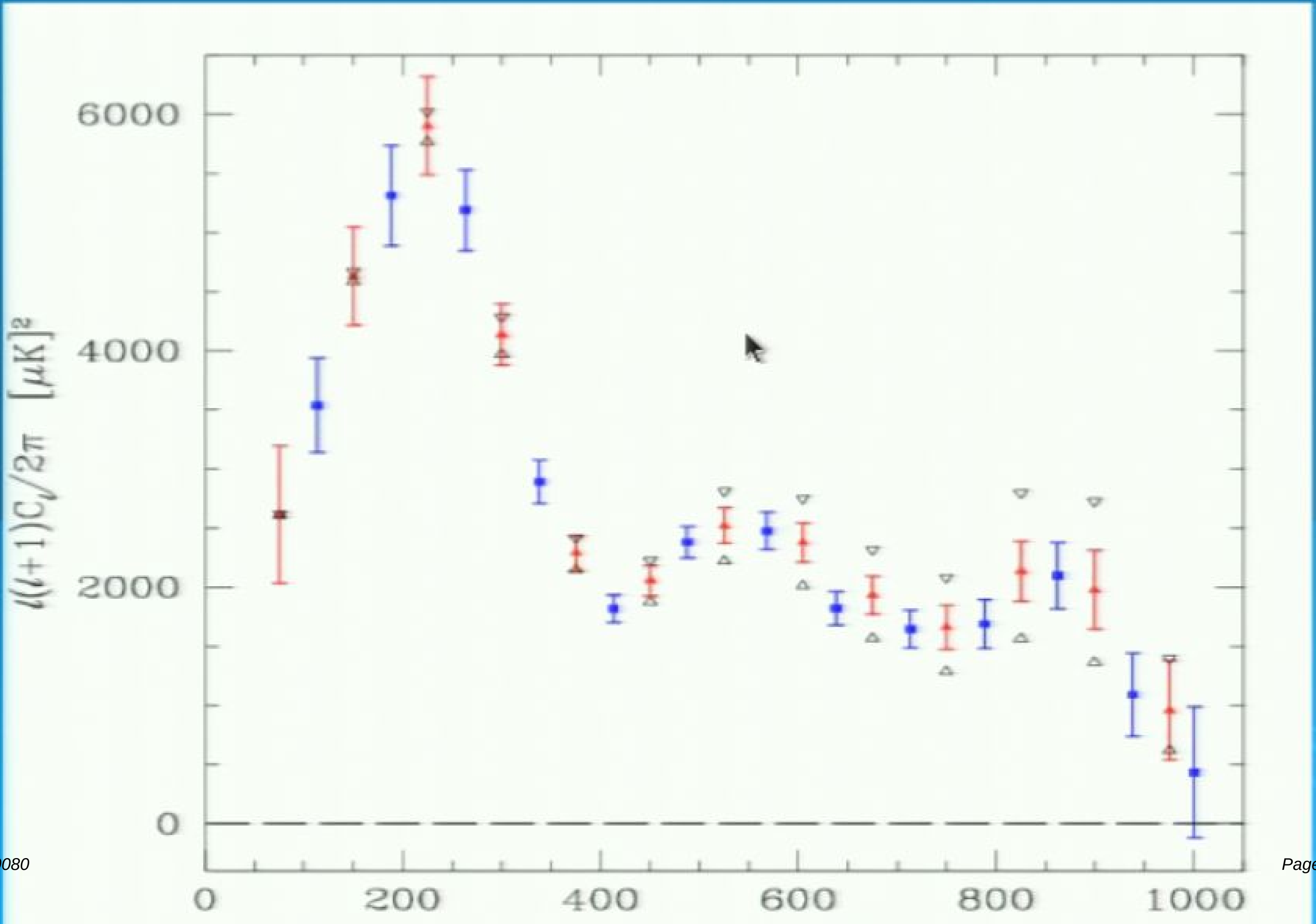


Fig. 7.— A comparison of the power spectrum computed with data from the ecliptic plane (black) vs. data from the ecliptic poles (grey). Note that some of the "bite" features that appear in the combined spectrum are not robust to data excision. There is also no evidence that beam ellipticity, which would be more manifest in the plane than in the poles.

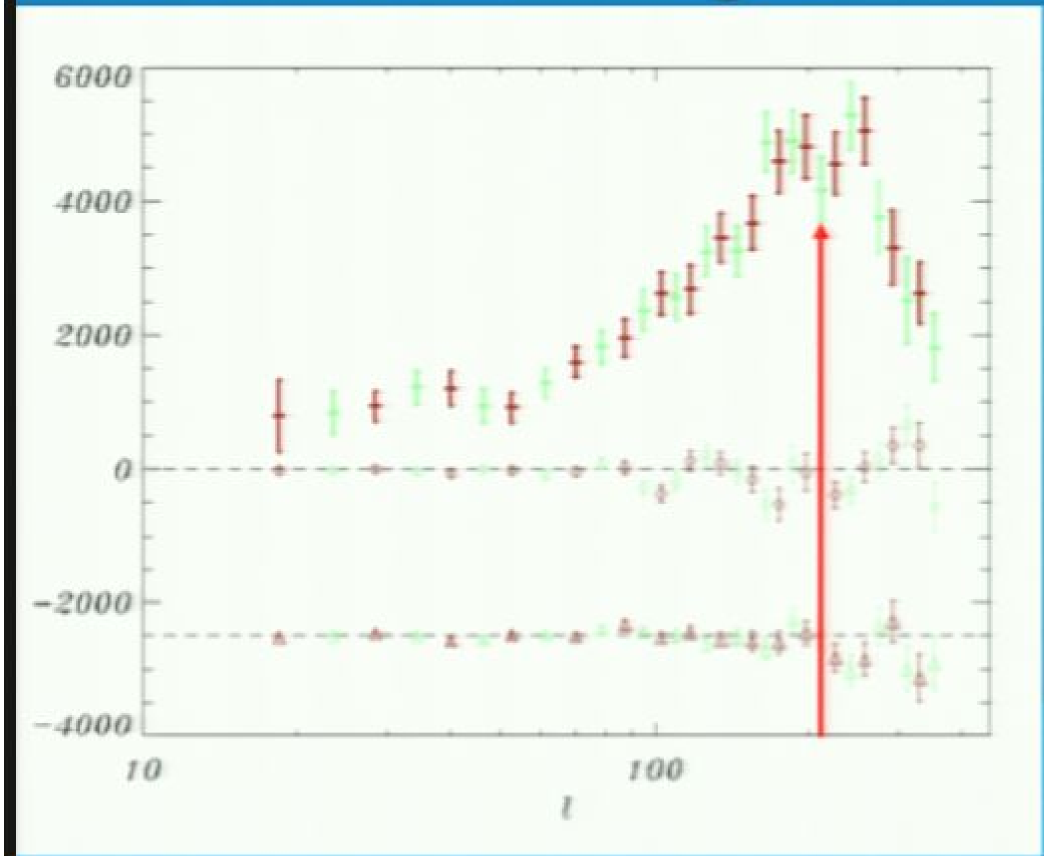
"First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: The Angular Power Spectrum"
G. Hinshaw, et.al., 2003, ApJS, **148**, 135 -- only v.1 on archive

All 3 other major deviations are in the ecliptic polar C_l only!!

No Dip?

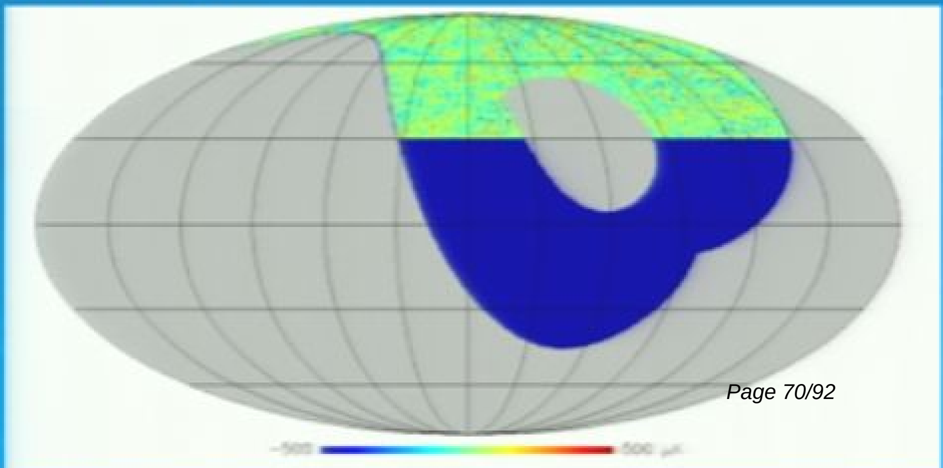


The case against a systematic (cont.)

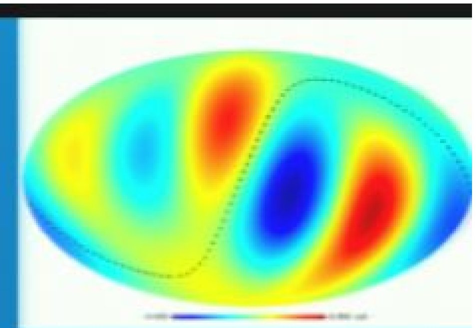


Archeops

Archeops

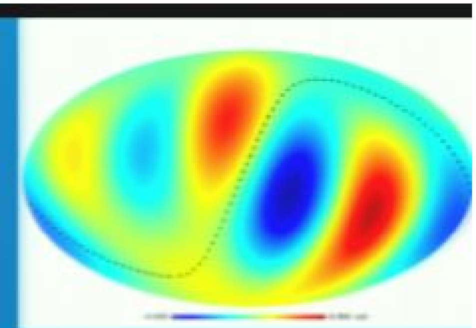


Quadrupole+Octopole Correlations -- Explanations: more galaxy?



- Cosmology
- Systematics
- The Galaxy:
  - has the wrong multipole structure (shape)
  - is likely to lead to GALACTIC not ECLIPTIC/DIPOLE/EQUINOX correlations

Quadrupole+Octopole Correlations -- Explanations: Foregrounds?



- Systematics
- Cosmology
- The Galaxy
- Foregrounds -- difficulties:
  1. Changing a patch of the sky typically gives you: Y_{l0}
  2. Sky has 5x more octopole than quadrupole
  3. How do you get a physical ring perpendicular to the ecliptic
     Caution: can add essentially arbitrary dipole, which can entirely distort the ring! (Silk & Inoue)
  4. How do you hide the foreground from detection? $T \approx T_{CMB}$

Did WMAP123 change the (large angle) story?

Mildly changed quadrupole:

- time dependence of satellite temperature
- "galaxy bias correction" -- add power inside "galaxy cut"

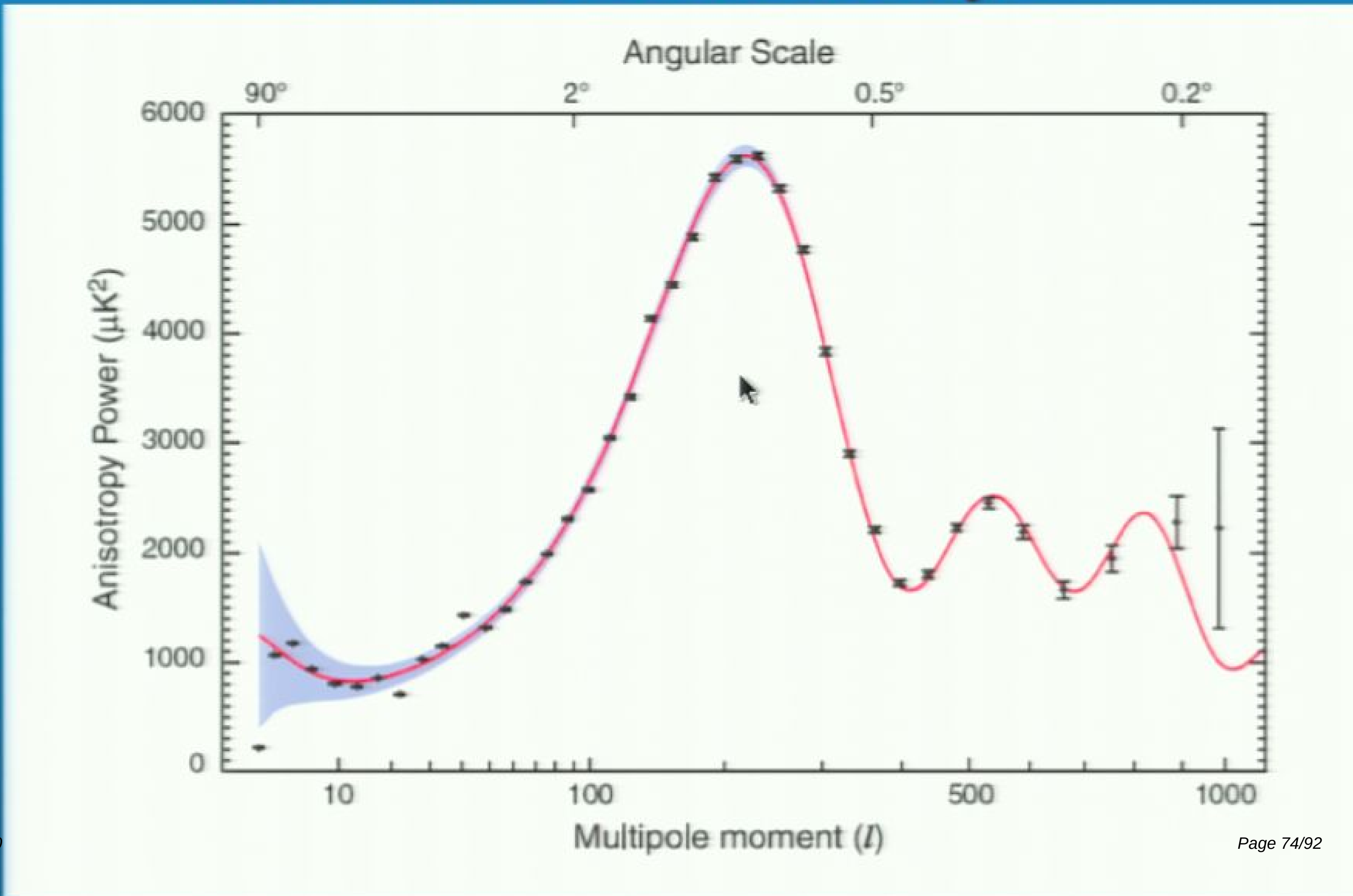
Reported something different for C_l:

- maximum likelihood estimate of coefficients of Legendre polynomial expansion of $C(\theta)$ instead of $(2\ell+1)^{-1}\sum_m |a_{\ell m}|^2$

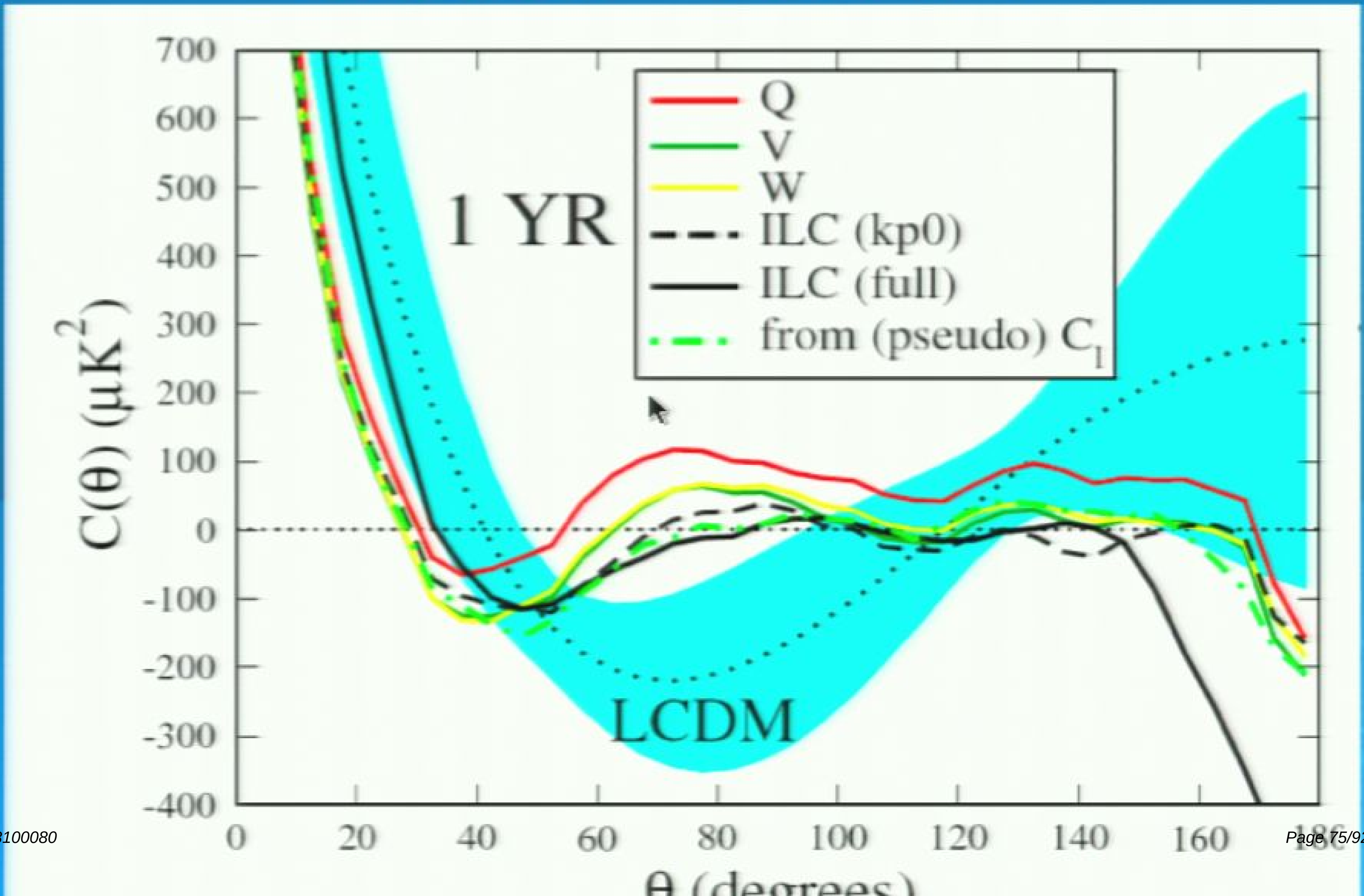
Quadrupole and Octopole still strange:

- planar (octopole)
- aligned with each other
- perpendicular to ecliptic
- normal points toward equinox/dipole
- oriented so that ecliptic separates extrema

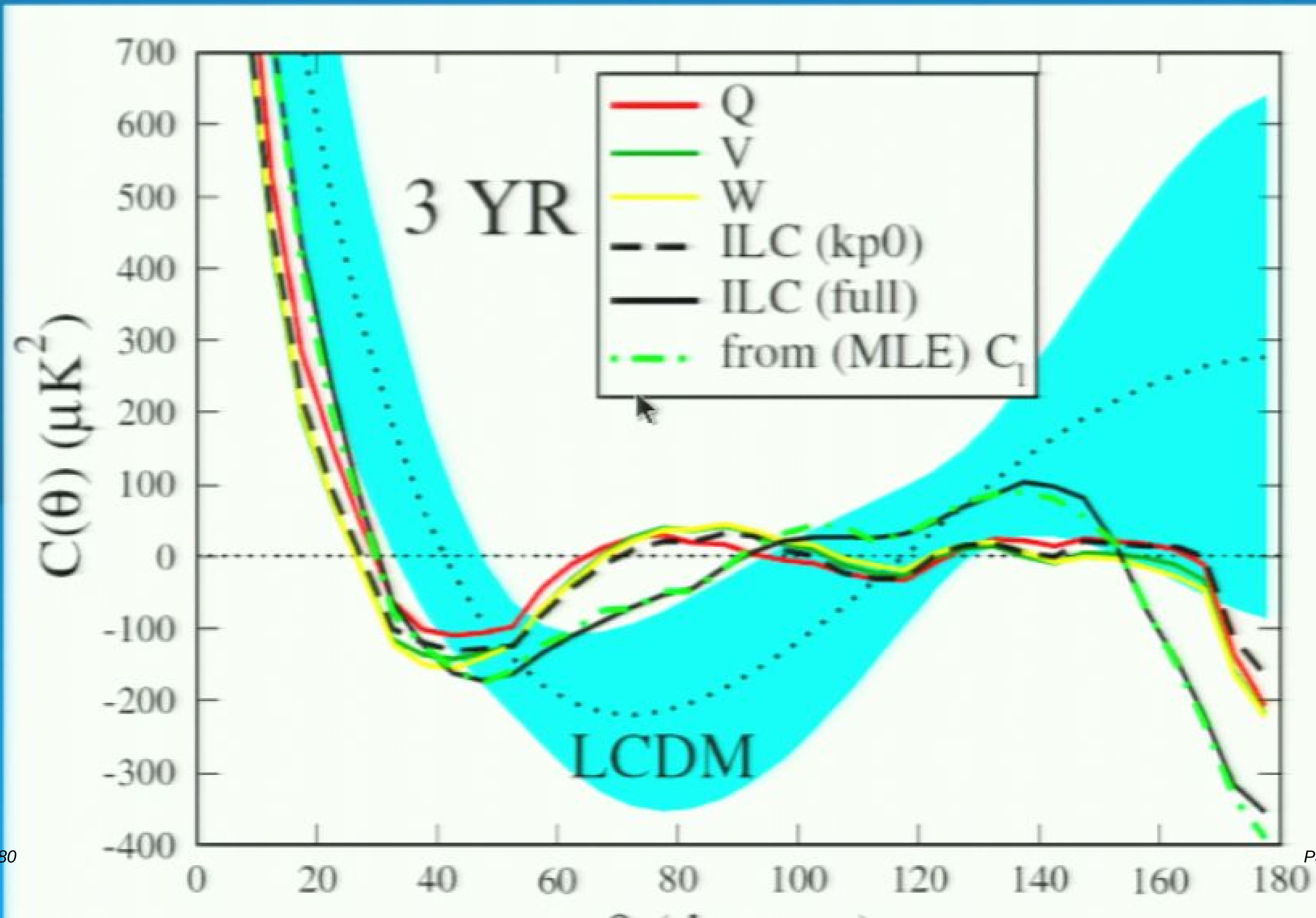
"The Low-l Anomaly? What Low-l Anomaly?"



Two point angular correlation function -- WMAP1



Two point angular correlation function -- WMAP3



Two point angular correlation function statistics

$$S_{1/2} = \int_{-1}^{1/2} [C(\theta)]^2 \, d\cos\theta$$

Two point angular correlation function statistics

Table 1. The C_ℓ calculated from $C(\theta)$ for the various data maps. The WMAP (pseudo and reported MLE) and best-fit theory C_ℓ are included for reference in the bottom five rows.

Data Source	$S_{1/2}$ $(\mu K)^4$	$P(S_{1/2})$ (per cent)	$6C_2/2\pi$ $(\mu K)^2$	$12C_3/2\pi$ $(\mu K)^2$	$20C_4/2\pi$ $(\mu K)^2$	$30C_5/2\pi$ $(\mu K)^2$
V3 (kp0, DQ)	1288	0.04	77	410	762	1254
W3 (kp0, DQ)	1322	0.04	68	450	771	1302
ILC3 (kp0, DQ)	1026	0.017	128	442	762	1180
ILC3 (kp0), $C(>60°)=0$	0	—	84	394	875	1135
ILC3 (full, DQ)	8413	4.9	239	1051	756	1588
V5 (KQ75)	1346	0.042	60	339	745	1248
W5 (KQ75)	1330	0.038	47	379	752	1287
V5 (KQ75, DQ)	1304	0.037	77	340	746	1249
W5 (KQ75, DQ)	1284	0.034	59	379	753	1289
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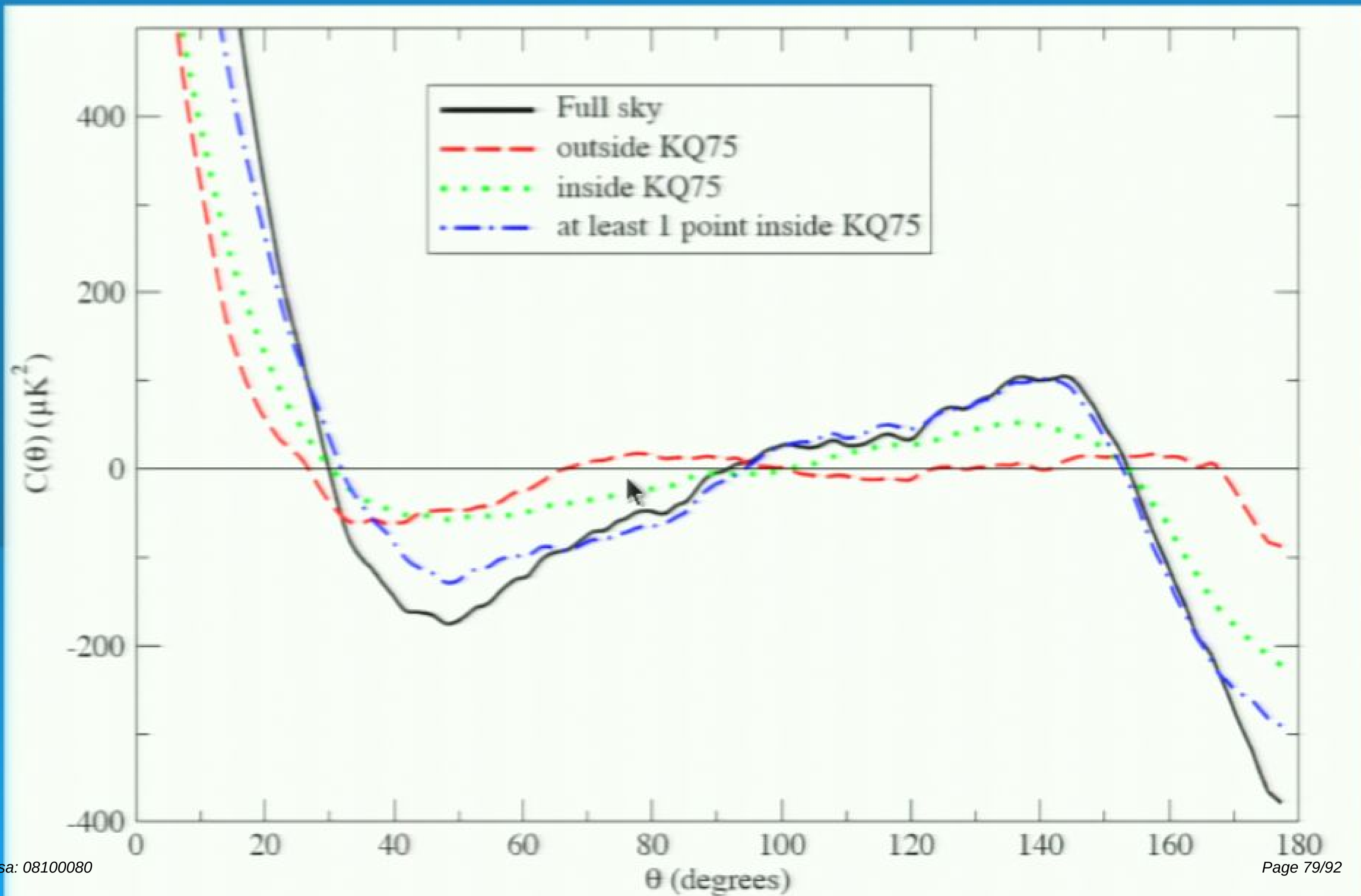
ILC5 (KQ75, DQ)	1152	0.025	95	320	768	1158
ILC5 (full, DQ)	8583	5.1	253	1052	730	1590
WMAP3 pseudo-C_ℓ	2093	0.18	120	602	701	1346
WMAP3 MLE C_ℓ	8334	4.2	211	1041	731	1521
Theory3 C_ℓ	52857	43	1250	1143	1051	981
WMAP5 C_ℓ	8833	4.6	213	1039	674	1527
Theory5 C_ℓ	49096	41	1207	1114	1031	968

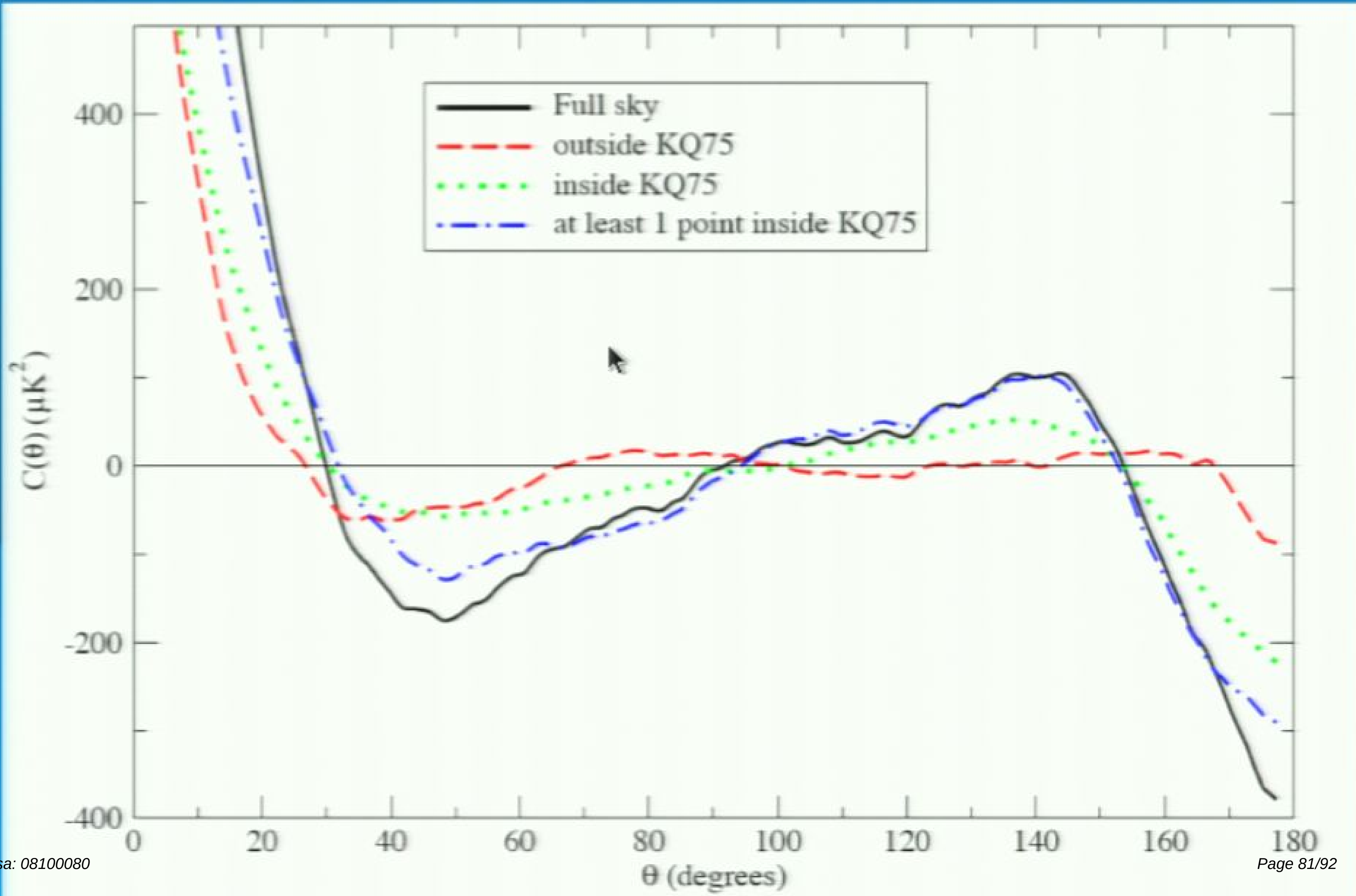
Where is C(θ) coming from?



Is it an accident?

Only 2% of rotated then cut full skies have this low an $S_{1/2}$

Where is C(θ) coming from?



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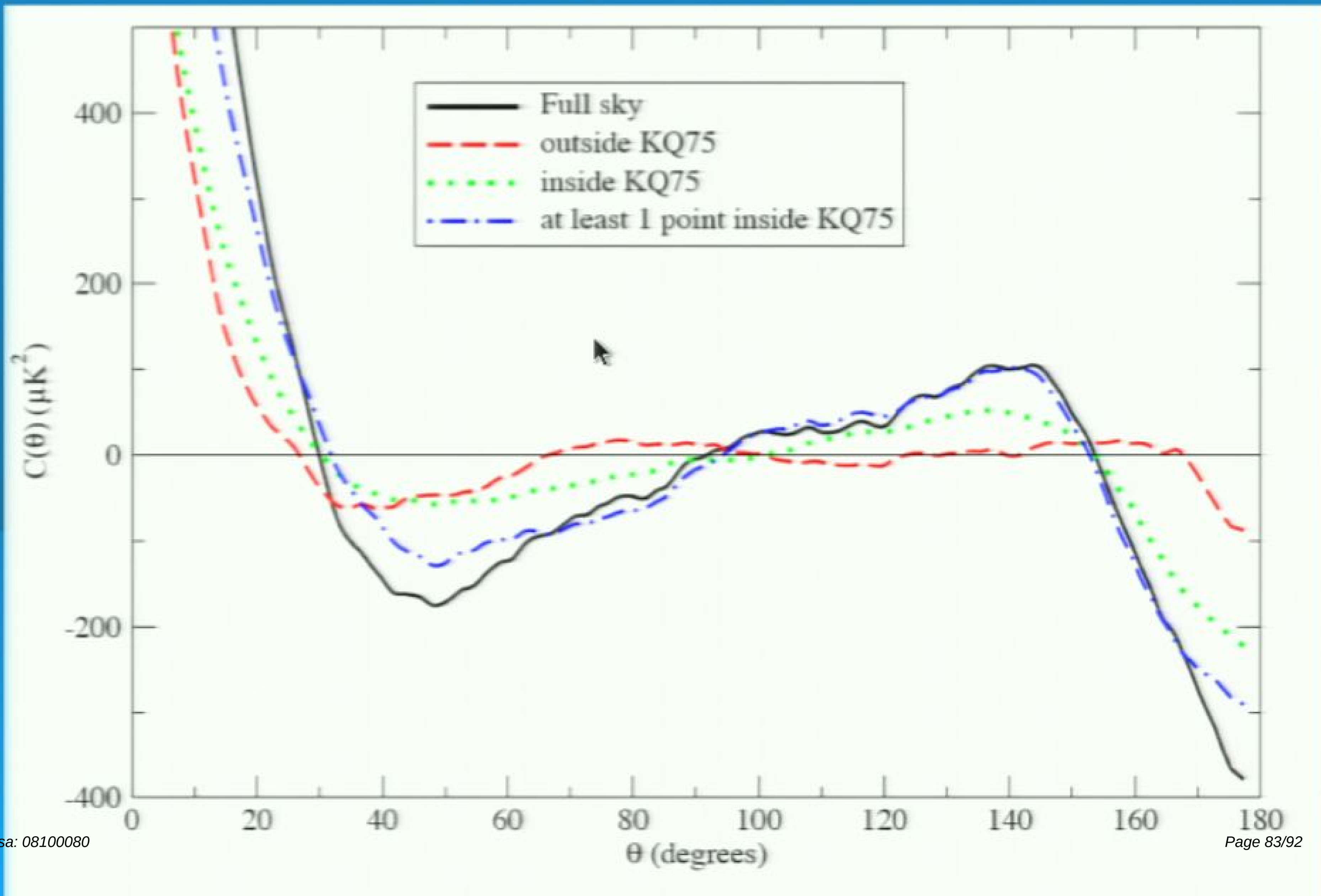


Is it an accident?

Only 2% of rotated then cut full skies have this low an $S_{1/2}$

The Conspiracy theory: minimizing $S_{1/2}$

able 3. Minimum $S_{1/2}$ in $(\mu\mathrm{K})^4$ for the best fit theory and WMAP C_ℓ as a function of
ie cutoff multipole, L. Also shown is the 95% confidence region of the minimum $S_{1/2}$
erived from chain 1 of the WMAP MCMC parameter fit.

C_ℓ	L						
Source	2	3	4	5	6	7	8
Theory	7624	922	118	23	7	3	0.7
Theory 95%	6300–1400	770–1600	100–200	20–40	7–14	3–6	1–2
WMAP	8290	2530	2280	800	350	150	130

To obtain $S_{1/2} < 971$ with the WMAP C_l requires varying C_2, C_3, C_4 & C_5!

Violation of the GRSI assumption

Even if we replace the theoretical C_ℓ by their observed values (up to ℓ=20), cosmic variance implies that only 3% of realizations will have $S_{1/2} \leq S_{1/2}^{observed}$

SUMMARY

If you believe the full sky CMB maps:

- There are signs of the failure of statistical isotropy
  - These are VERY statistically significant 99.9%-99.995%
  - The observed fluctuations seem to be correlated to the solar system (but not to other directions with great statistical significance)

SUMMARY

If you don't believe the CMB inside the galaxy (and you probably shouldn't) then:

- CMB shows signs of distinct lack of large angle correlations
  - this was first seen by COBE, but is now statistically much stronger – 99.975%C.L.
  - the low-ℓ C_ℓ are therefore measuring SMALL ANGLE not large angle correlations
  - This lack of correlations is inconsistent with Gaussian random statistically isotropic a_{lm} at ~97% C.L.

- This lack of correlations/power could be due to:
  - Statistical fluctuation -- incredibly unlikely
  - Topology -- not (yet?) seen
  - features in the inflaton potential -- contrived and still only a 3% chance that the large angle correlations would be this small

Conclusions

- We can't trust the reported low-ℓ microwave to be cosmic =>
  - inferred parameters may be suspect (τ, A, σ_8,…)
- The low-ℓ multipoles are measuring structure at smaller than expected scales.

Removal of a foreground will mean

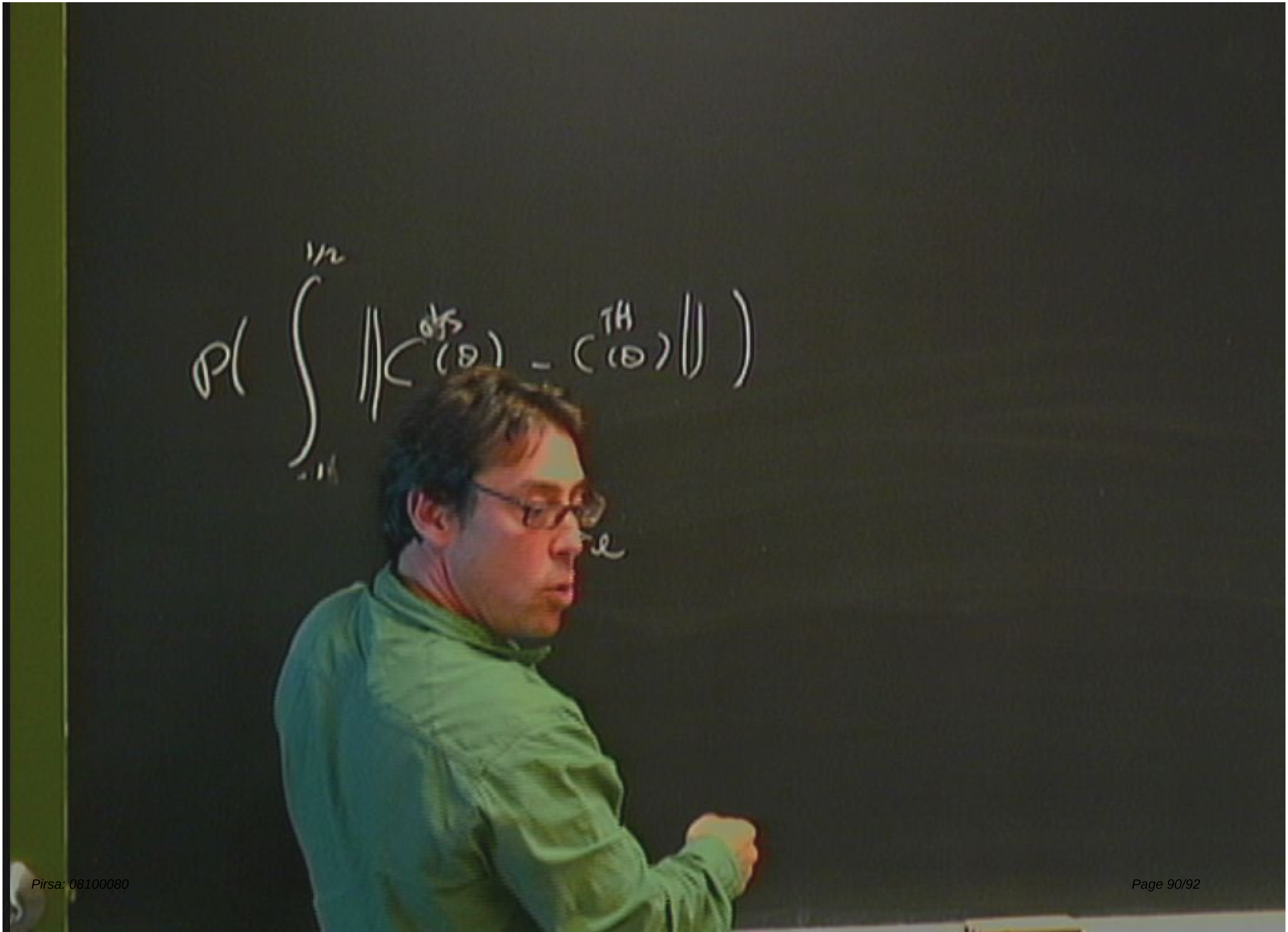
even lower $C(\theta)$ at large angles

expect $P(S^{wmap}|$ Standard model$)<<0.03\%$

Contradict predictions of generic

nflationary models at >99.97% C.L., and

of contrived models at ~97%


$P\left(\int_{-1/2}^{1/2} \| C^{obs}(\theta) - C^{TH}(\theta) \| \right)$

$$P\left(\int_{-1/2}^{1/2} \left\| C^{obs}(\theta) - \cancel{C^{TH}(\theta)} \right\| \right) \sim 10\%$$

C_2

$$P(C_2) \sim 10\%$$

$$P\left(\int_{-1}^{1/2} \left\| C^{obs}(\theta) - \overset{0}{\cancel{C^{TH}(\theta)}} \right\| \right) \sim 5\,\Sigma$$

$$0.02\,\%$$

$$C_\ell$$

$$P(C_2) \sim 10\,\%$$