Title: WMAP-1: 2 years after

Date: Oct 24, 2005 12:00 PM

URL: http://pirsa.org/05100039

Abstract:

Cosmology as enlightened by WMAP-1: 2 years after

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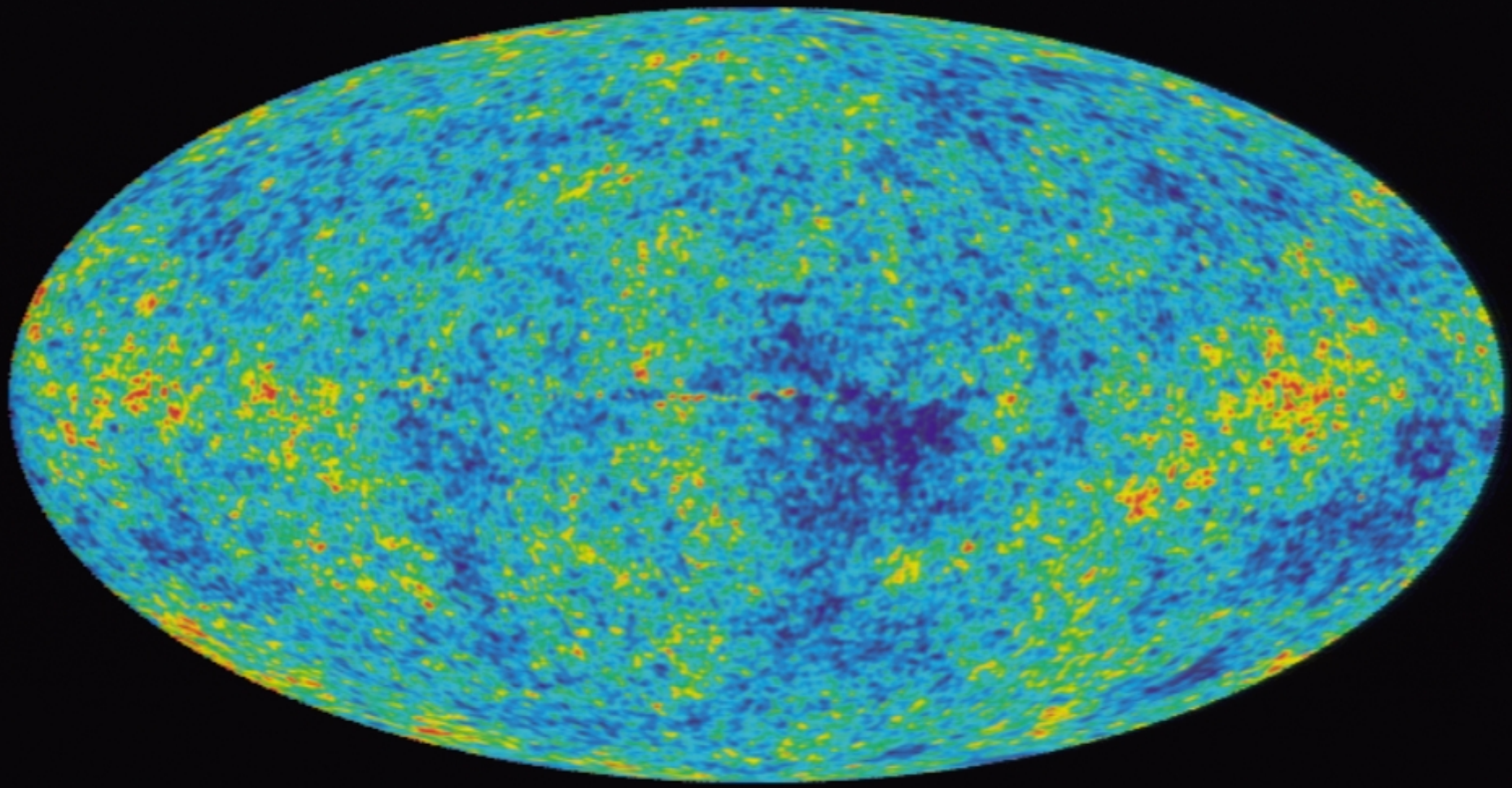
What has WMAP done for us ?



- WMAP improved over COBE by a factor of 45 in sensitivity and 33 in angular resolution
- Color codes temperature (intensity) : here fluctuations ± 100 μK
- Temperature traces the gravitational potential then
- The statistical analysis of this map yields detailed cosmological information

Where are we now ?

The current phenomenological success means :

1. *The initial primordial spectrum of inhomogeneities is close to scale invariant and predominantly adiabatic*
2. *We have a successful GR based theory of cosmological linear perturbations to evolve them*
3. *We have a correct effective description of the main components even if we do not know what they are*

It is now healthy to adopt 2 distinct attitudes :

- Use better observations to address open questions within this model:
  - What is Dark Energy ?
  - What is Dark Matter ?
  - Did we really undergo an Inflationary phase?
    (Physics we don't know yet)
  - First stars and how did the Universe get reionized ?
    (Physics we don't know how to compute)
  - Are we really leaving in a inflationary universe ?
- Explore further the data and test for anomalies or hint of anomalies

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Do the data hint at any flaw in this model or at new physics?

Maybe in WMAP…

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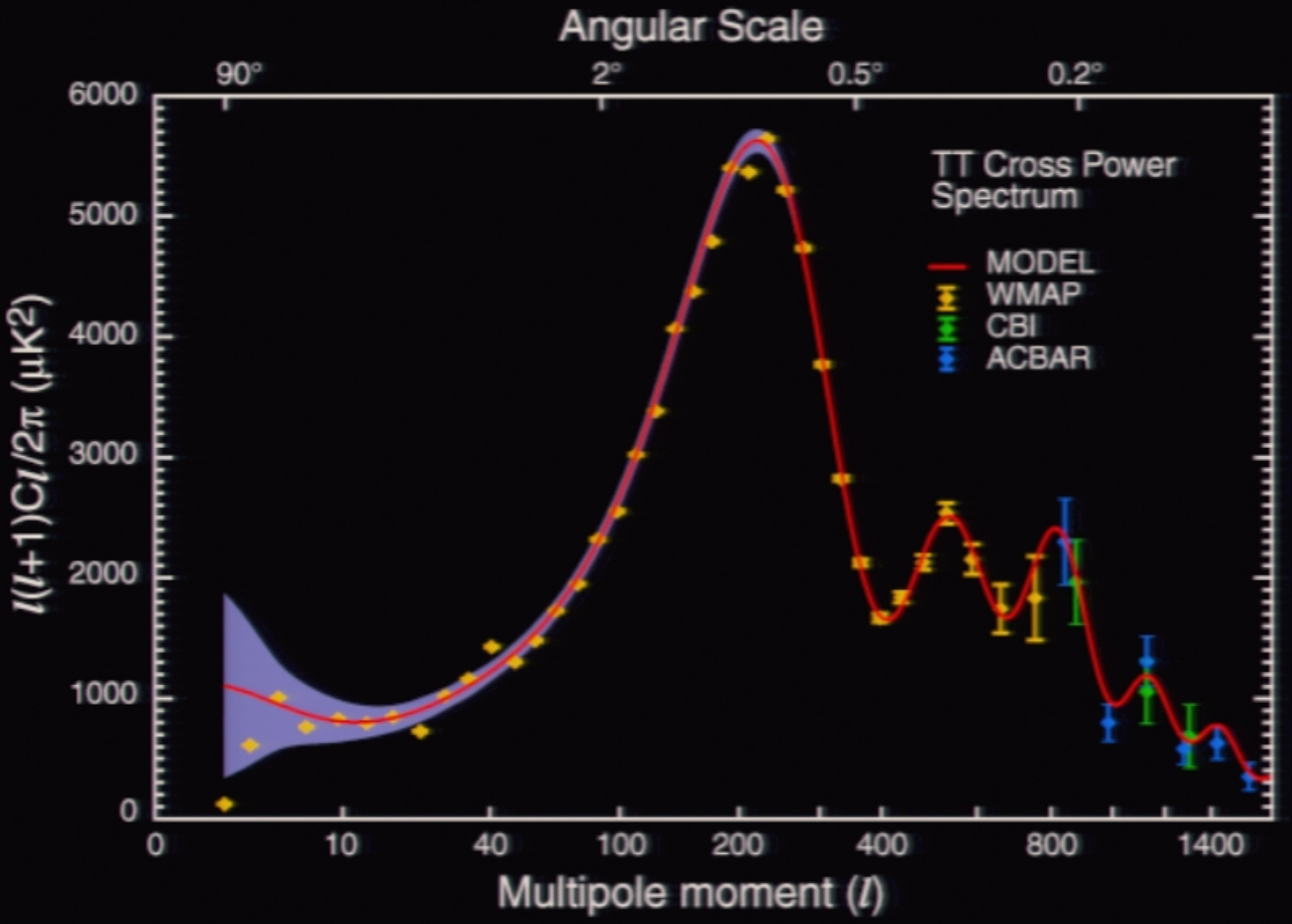
"Odd" Features Noted in 1st-year Sky Maps

- Amplitude of signal:
  - –Fourier space: the low quadrupole
  - –Position space: the 2-pt correlation function
  - –Other "bites" in the spectrum
- Phase of signal:
  - –Alignment of quadrupole & octupole (l=2,3)
  - –Asymmetry of large-scale power
  - –Features in skewness, bispectrum
  - –Features in wavelets

Angular Power Spectrum at low *l*



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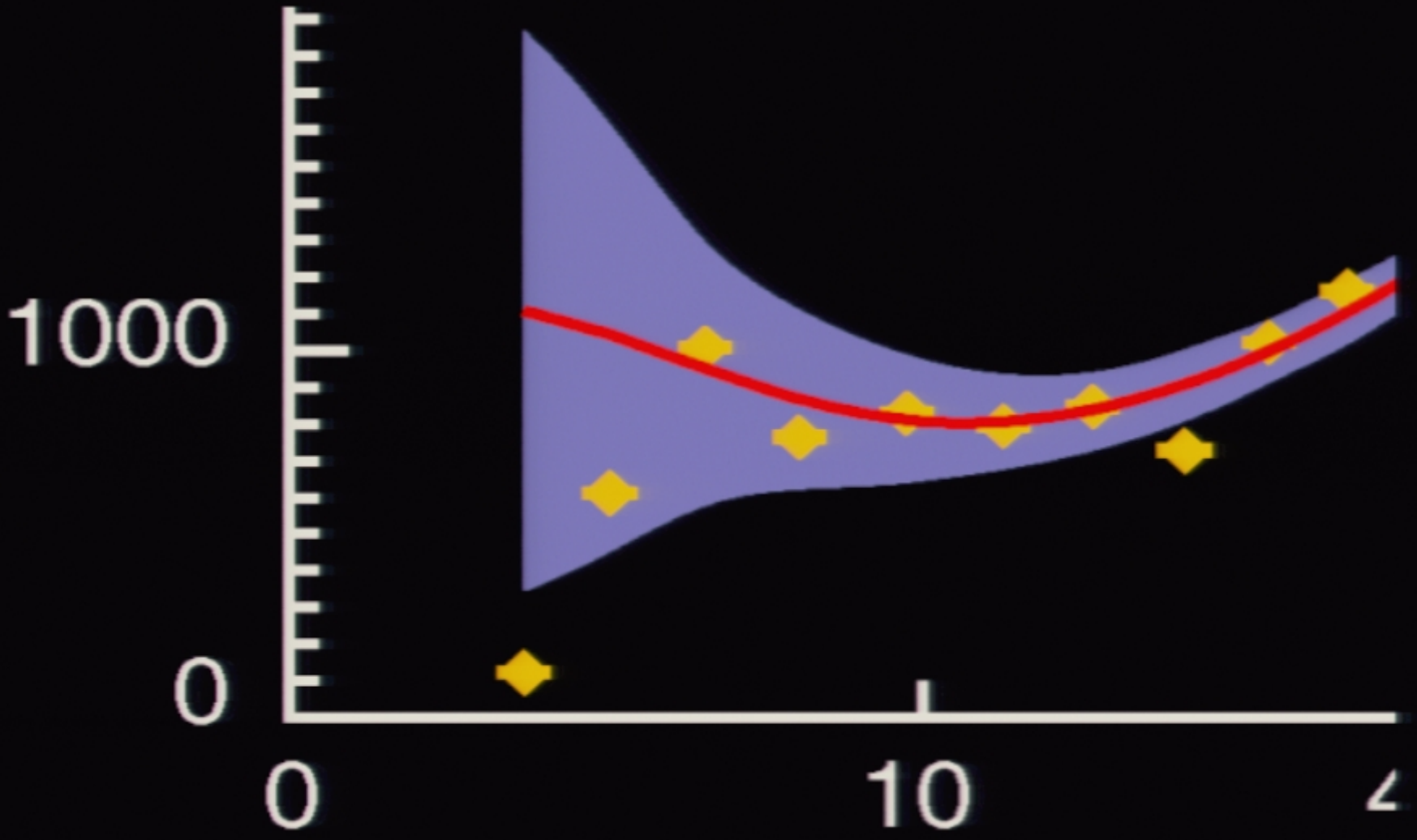


Already see in COBE

Low Quadrupole Power

- Expected (mean) values for selected best-fit ΛCDM models -
  - Pure power-law, WMAP+CBI+ACBAR: 1221 μK^2*
  - Running index, WMAP+CBI+ACBAR: 870 μK^2
  - Power-law, CMB+2dF+Ly-α: 1107 μK^2

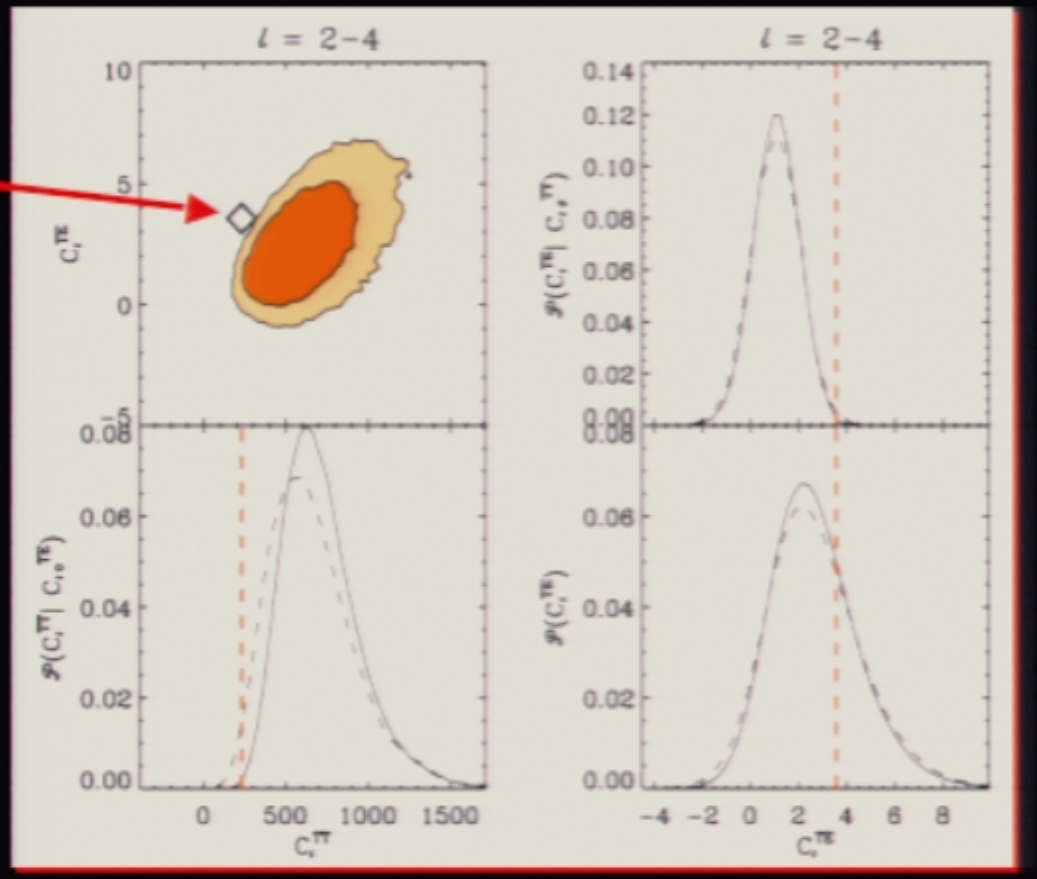
- Measured value(s) of quadrupole -
  - Quadratic estimator, V+W band, galaxy template & cut: 123 μK^2
    (Hinshaw, et al., ApJS, 148, 135, 2003)
  - Full-sky estimate, Galaxy-cleaned map: 184 μK^2
    (Tegmark et al, astro-ph/0302496)
  - Full-sky estimate, Linear Combination map: 154 ± 70 μK^2
    Error based on spread of values by galaxy cut and frequency
    (Bennett, et al., ApJS, 148, 1, 2003)
  - Max. likelihood estimate, Galaxy-cleaned map(s): 176-250 μK^2
    (Efstathiou, astro-ph/0310207)
  - Max. likelihood estimate, Galaxy template marginalization: <300 μK^2
    (Bielewicz, astro-ph/0405007; Slosar & Seljak, astro-ph/04??)

- Likelihood of low quadrupole given power-law ΛCDM model -
  ~2% - 10%

Fine print: estimates of significance depend on
1) quadrupole estimation method
2) handling of foreground errors
3) handling of cosmic variance errors
4) handling of cosmological parameter errors.

The quadrupole on a polarized light

Year 1 WMAP



- Test the consistency of *l*=2 TT and *l*=2 TE using the theoretically well known correlation between both
- Given the low C_2^{TT} you would expect a high C_2^{TE}
- This consistency test gives another handle on the low *l* quadrupole

Doré, Holder & Loeb 03

Hint for new physics ?

- If we consider this low COBE/WMAP quadrupole significantly anomalous, then one has to come with some new physical explanations

- Various physical mechanism to truncate the power at large scales has been proposed

  - Modifying the Sachs-Wolfe contribution
    - Closed Universe with a P(k) truncation corresponding to the curvature scale (Eftshatiou 03, Uzan *et al*. 03)
    - Truncation scale in the primordial P(k) inflation motivated (Contaldi *et al*. 03), scale which appears naturally if you try to reconstruct the primordial power spectra (Lewis et al. 03)

  - Modifying the Integrated Sachs-Wolfe *(motivated by the fact that l=2-3 corresponds to the Horizon size at DE domination)*
    - DE clustering (Hu 99, Bean & Doré 03)
    - Dark Energy isocurvature perturbations (Moroi & Takahashi 04, Gordon et al. 04)

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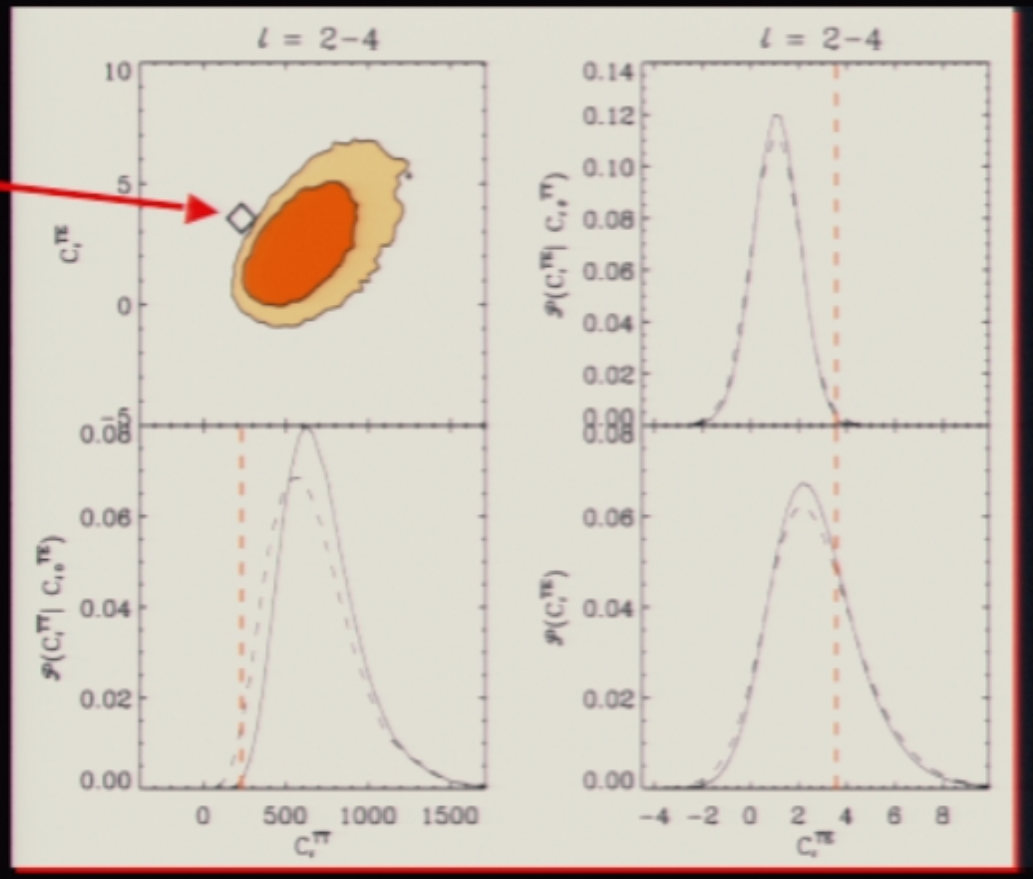

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Are some WMAP outliers another signatures of Inflation?

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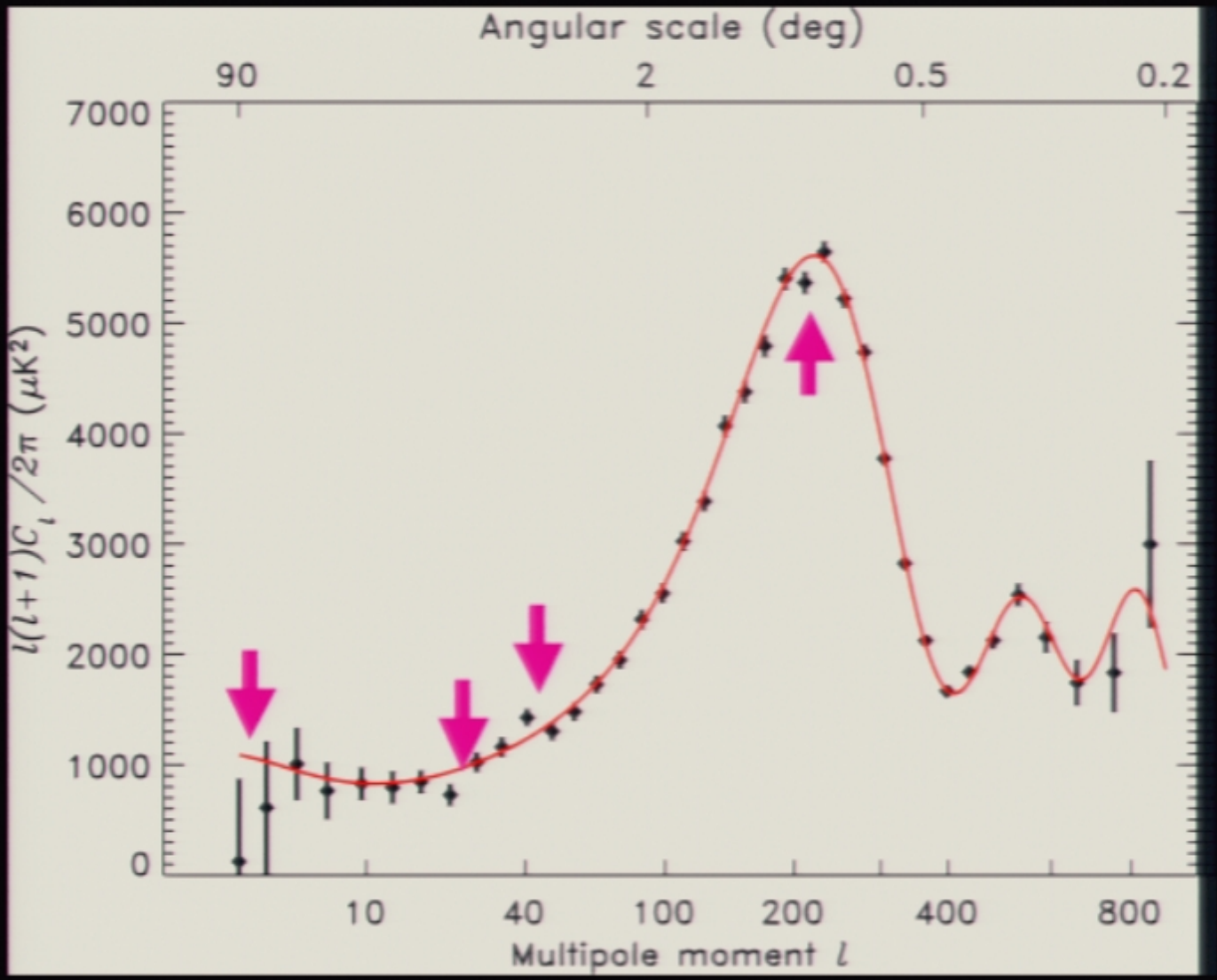


- Reduced χ^2 for TT only 1.09
- Lewis (astro-ph/0310186) observes that the number of 3σ points (above) is high. Notes that only 3/16000 simulations have a lower value of C_{181} (arrow)

Some questions to ask first

- Is the signal real ?
  - Various systematic effects: beams, foregrounds, etc.

- Are the statistics right ?
  - An underestimation of the Fisher matrix, which is a particular form of the 4pt function could account for this χ^2
  - Underestimated known terms (lensing, pt sources)
  - Could also be some particular form of NG non due to some new physics that creates some 4pt contribution without violating the 3pt limits, *e.g.* with a potential like

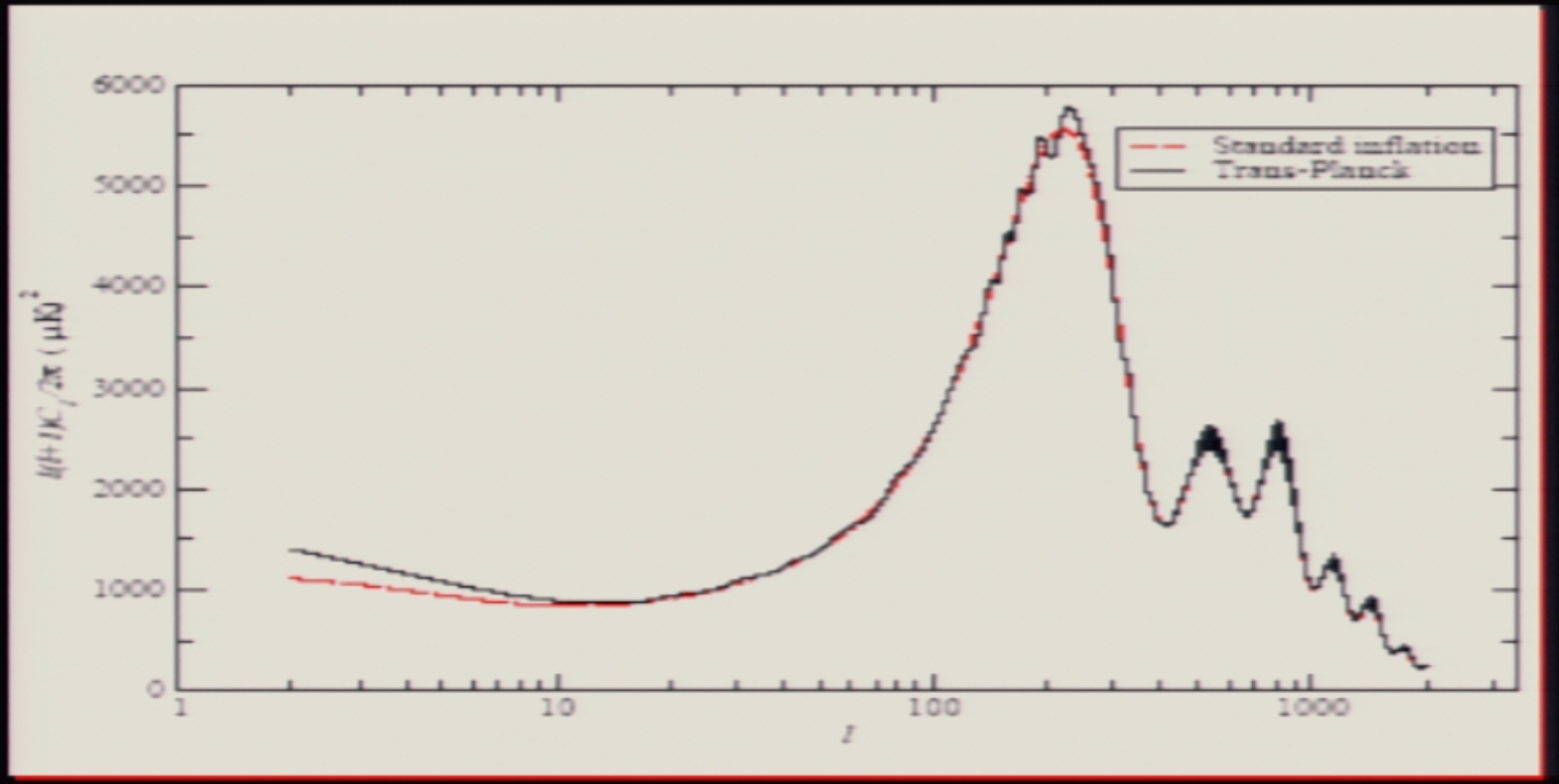
$$\Phi(\vec{x}) = \phi(\vec{x})\left(1 + g_{NL}\psi(\vec{x})\right)$$

(analogous to the Komatsu et al. 03, f_{nl})

  - It is thus also worth to probe this kind of NG

- Then, we can ask… is it one more signature of Inflation?

A specific signature of Trans-Planckians ?



- Martin & Ringeval 03 and Okamoto and Lim 03 fit toy trans-Planckian model to spectrum $\Delta\chi^2 = 16$ for 3(?) parameters and $H/M_c < 6.6\times10^{-3}$
- Significant hard to assess
- See *e.g.* Easther et al. 03, Greene et al. 05 for more theoretical arguments and

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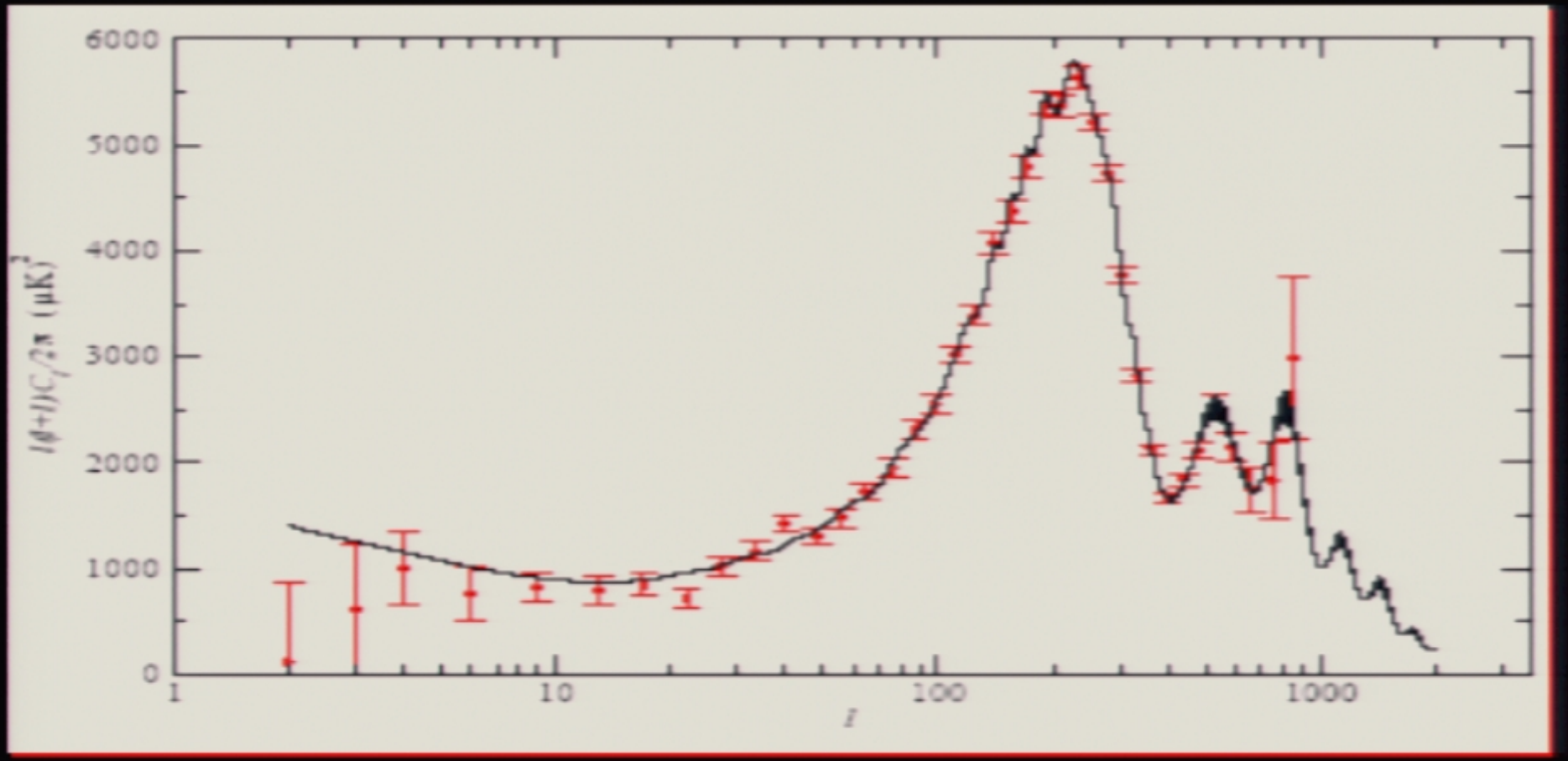

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Are TP effects observable even in principle?

Simple dimensional Analysis

Relevant Scales

- Assume a fundamental mass scale M where new physics kicks in
- Quantum Gravity/Planck scale - 10^{19} GeV
- String Scale up to two orders of magnitude lower? M ~ 10^{17} GeV
- Inflationary scale H ~ 10^{15} GeV

Dimensionless combination: (H/M)

- Impact of fundamental scale ~ $(H/M)^p$
- Key question: is p=1 or p=2?

Effects on the power spectrum are proportional to $(H/M)^p$, so at most a 1% effect

Note that Martin & Ringeval have an upper limit of $H/M < 10^{-3}$ in their model

How well can we measure Power Spectra?

The accuracy achievable can simply be written as

$$\frac{\delta P}{P} = \frac{1}{\sqrt{N_{modes}}}$$

Measuring the power spectrum with the CMB

$$N_\ell = \sum_\ell \frac{(2\ell+1)C_\ell}{C_\ell + n_\ell}$$

WMAP (1 yr): $l_{max} = 300$

WMAP (6 yr): $l_{max} = 600$

PLANCK : $l_{max} = 1500$

IDEAL : $l_{max} = 2000$

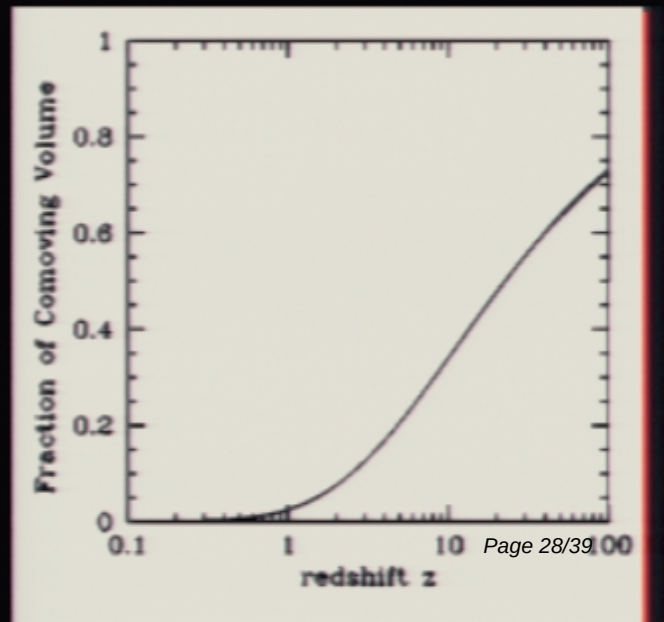
Gives about 10^{-2} for WMAP today and about ~10^{-3} for WMAP/Planck in the future. Limited by the 2D nature of the signal

Measuring the power spectrum with the LSS

$$N_k = \int_0^{k_{max}} \frac{k^2 dk\, P(k)}{P(k) + \frac{V}{N_{gal}}}$$

- k_{max} chosen to be at the non-linear scale
- 3D mode counting
- $V = (13000)^3\ \mathrm{Mpc}^3\ v(z) \sim 10^{13}\ v(z)\ \mathrm{Mpc}^3$

$$v(z < z_0) = \frac{4\pi}{3}(\Delta\eta)^3 \propto \left(1 - \frac{1}{\sqrt{1+z}}\right)^3$$



e.g. SDSS volume (z=0.2, 10% of the sky)

$\sim 10^8\ (\mathrm{Mpc})^3$ (so room for improvement!)

TP Power Spectrum prospect summary

- Today: 10^{-2}
- Soon (WMAP/Planck) : 10^{-3}
- Planned Galaxy Surveys (KAOS, LSST, Pan-Starr): 10^{-4}
- Future Galaxy Surveys (21 cm survey up to z~30) : 10^{-5}
- Theoretical Bound: 10^{-6}
- So in principle TP effects as we "understand" them now might be probed in a not so far future, ignoring all the galaxy evolution related complications...
- We need to know what to look for !

Phase space constraints

• Level of gaussianity is quite well constrained by inflation theory with a non linear coupling parameter f_{NL}~10^{-2}-10^{-1}

(Komatsu et al. 03, Mataresse 04, Maldacena 04)

$$\Phi(x) = \Phi_L(x) + f_{NL}\left(\Phi_L^2(x) - \langle\Phi_L^2(x)\rangle\right)$$

where Φ is gravitational potential

• Current best limit from WMAP alone using bispectrum or Minkowski functionals are

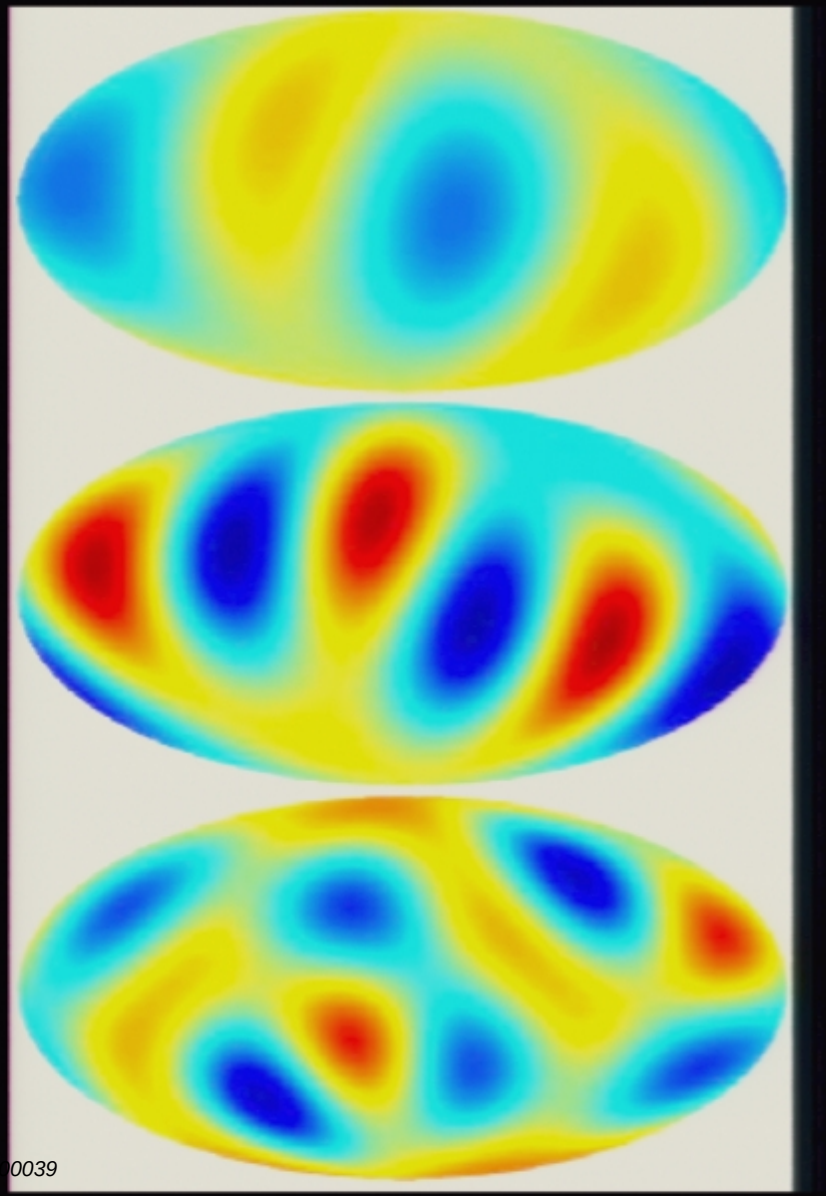
$-58 < f_{NL} < 134$ (95%)

(see Paolo Creminelli talk)

• Worth noting that is by nature a delicate measurements since the maps ARE non-gaussian and isotropic because of point sources, foregrounds and inhomogeneous noise

• Although the inflation theory predictions are somewhat clear, going beyond that is a theoretical no-man's land (except for topology type studies)

Alignment of Low *l* Power - I

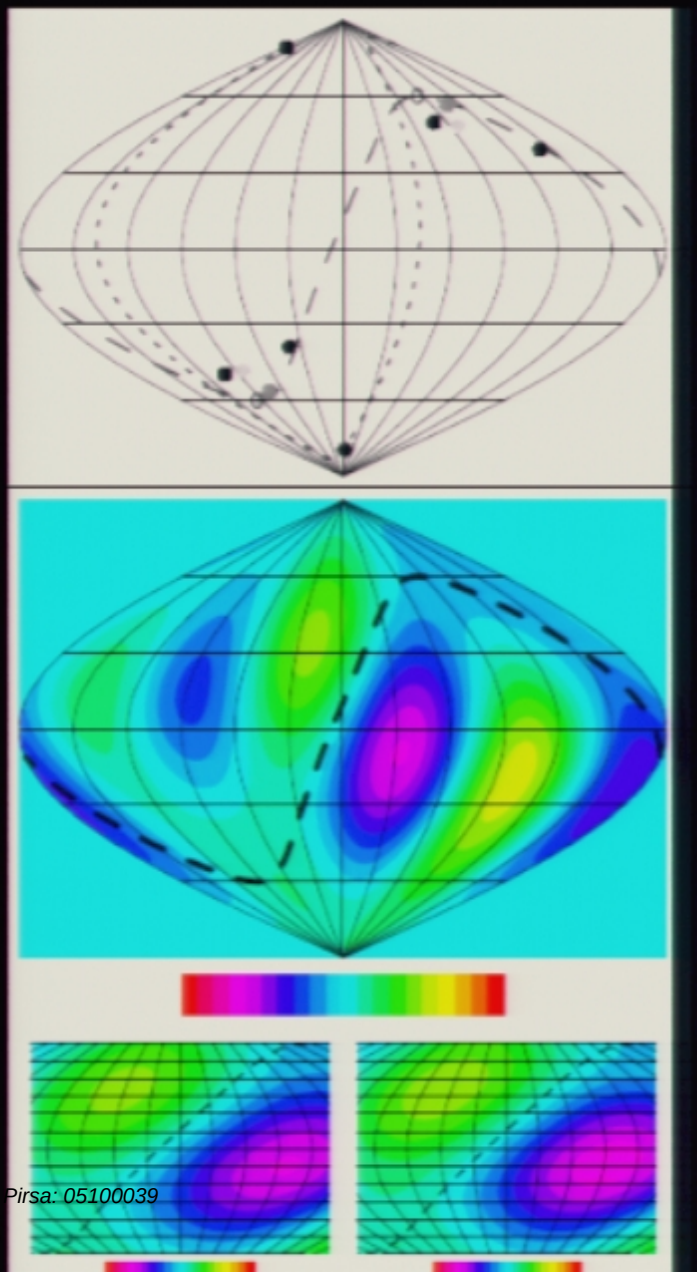


- 3 features at play here:
  - Low power at the lowest l =2,3
  - Tegmark et al. (astro-ph/0302496) note alignment of l=2,3 moments.
  - Power concentrated in plane ~30° from the Galactic plane: $m=\pm l$ in suitable coordinate system.

- de Oliveira-Costa et al. (astro-ph/0307282) estimate the probability of the combination:
low quadrupole + alignment + "planarity":
~4×10^{-5}

- This result is *a posteriori* and is thus potentially biased, but also potentially physically significant.

Alignment of Low *l* Power - III



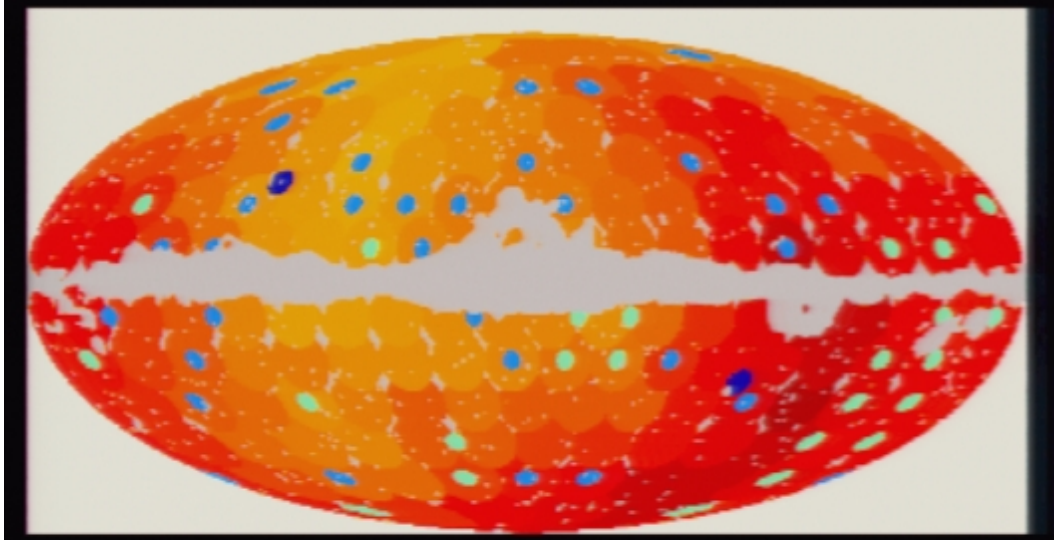
Schwarz et al. (astro-ph/0403353) also note alignment of l=2,3 moments with each other and with: a) the ecliptic coordinate frame, b) the vernal equinoxes, and c) the CMB dipole axis. Significance > ~99.9% is claimed

Analysis based on "multipole vectors" (Copi et al., astro-ph/0310511) that define geometry of l modes in coordinate invariant sense. See also Katz & Weeks (astro-ph/0405631), Land & Magueijo (astro-ph/0405519).

Notes:

- Foreground uncertainty is probably underestimated.
- If it was a zodi like signal at the 100μK level, it would have to have a black body spectrum and would appear easily at the TOD level because of annual modulations
- Magnitude of "posterior bias" is hard to estimate for these anomalies.
- Why only *l*=2,3 aligned with celestial frame?

Asymmetry of Low *l* Power - I



Eriksen *et al.* (astro-ph/0307507) note asymmetry of low *l* power in the sky.

They compute the ratio of low *l* power in northern and southern hemispheres over a complete set of coordinate systems:

Map of R for coordinate system pole centered in each ~10˚ circle

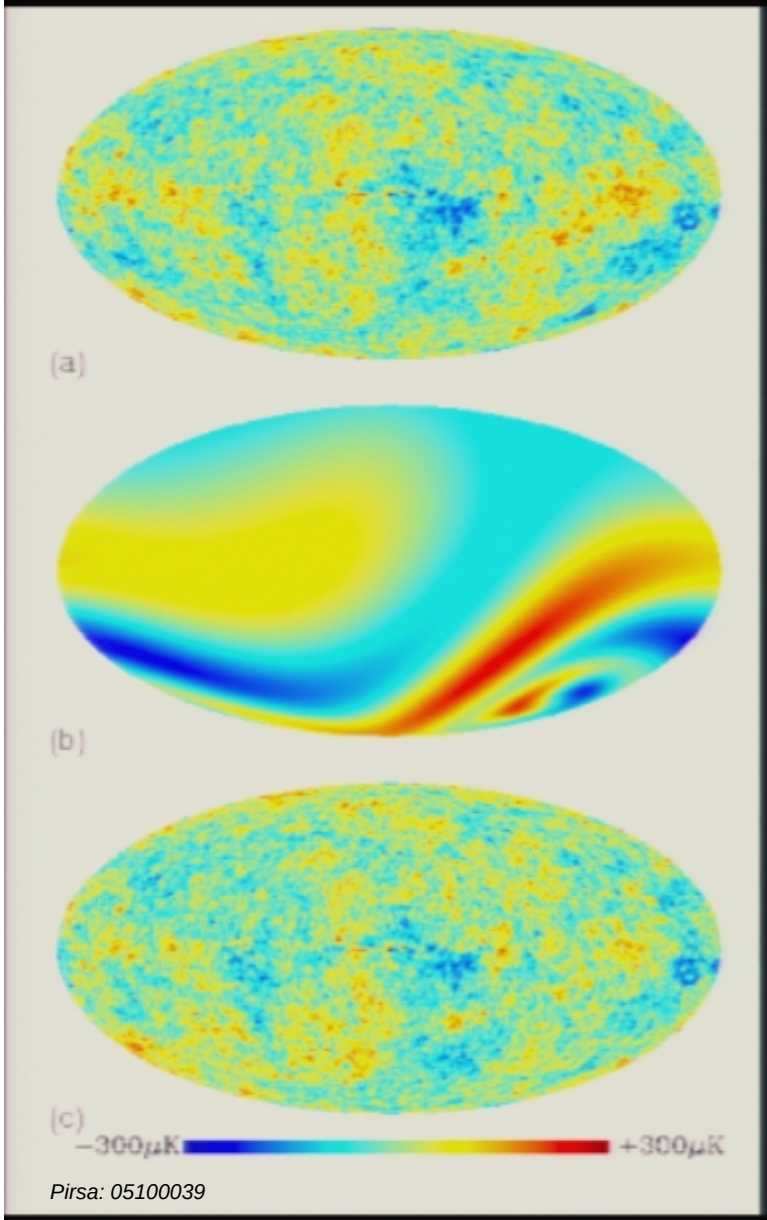
Plane of maximum asymmetry appears to be closed to the ecliptic plane

R is minimized for pole near the ecliptic pole. Only ~0.3% of simulated skies have as low a ratio as observed.

Also Hansen et al. (astro-ph/0404206)

Not really seen with other *l* space statistics (Souradeep *et al* 04)

Proposed mechanisms for alignment



1. Anisotropic Bianchi VII_h models have been studied and claimed to be significant at the 3σ level (7 new parameters) (T Jaffe et al. 04)
   - But best fit models fails at higher *l*
   - Appeal is that it provides explanation for alignment, asymmetry and one cold spot
   - Statistics revisited by Land & Mageijo 05 who fund that the detection is not statistically significant but still removes some anomalies in the map (discuss also template fitting statistics)
   - McEwen & Hobson 05 claims a enhanced NG signal

2. Lensing of CMB dipole by moving local structure (Vale et al. 04) leaks coherent power into lowest *l*
   - Uncertainties in lens mass distribution
   - Explain alignment but makes low l power situation worse

3. Gordon et al. 05 studied the *modulation* of a Gaussian field by an arbitrary function, here dipolar (mechanism unclear yet). See also Land & Mageijo 05

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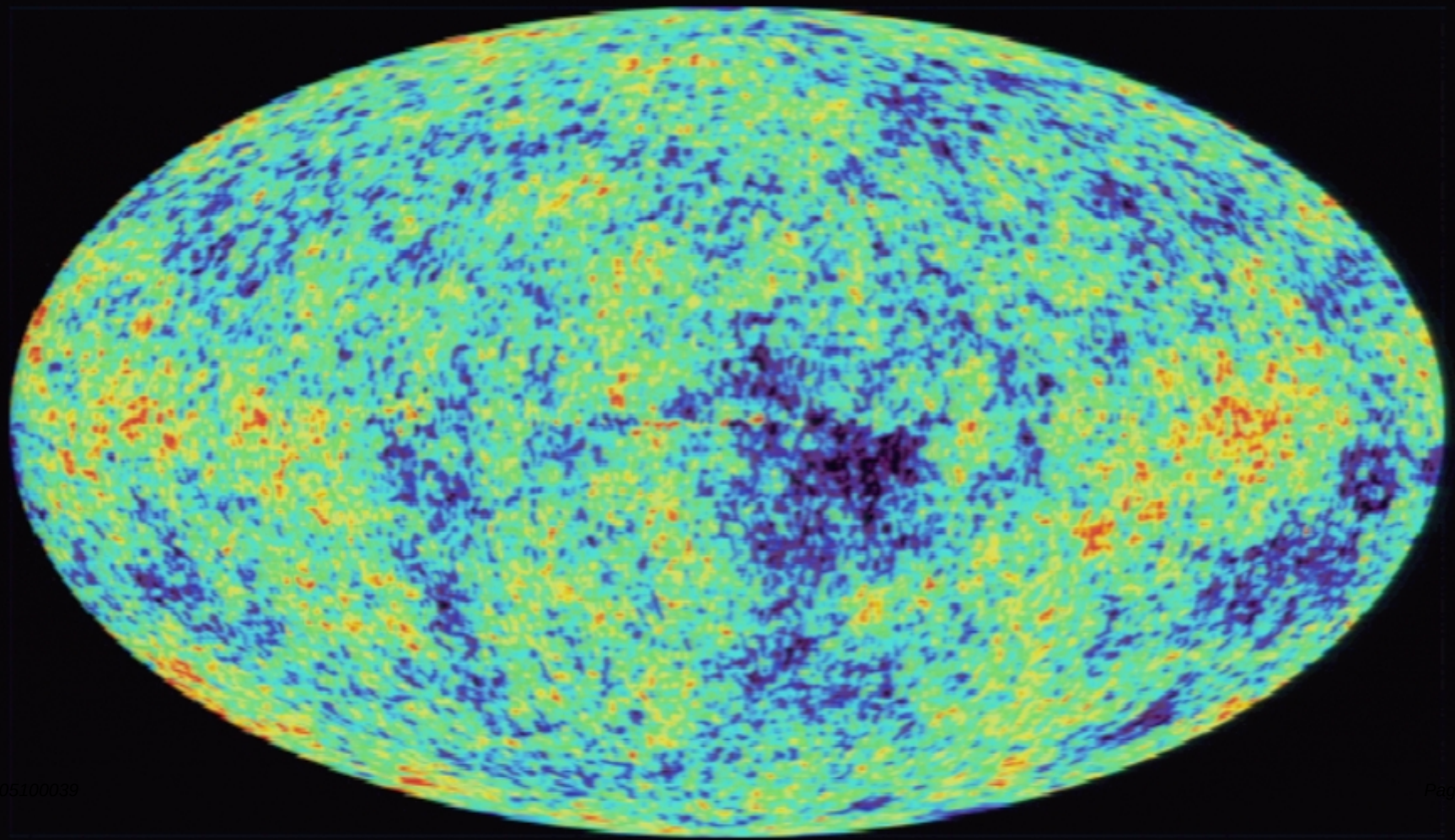
Another question we could ask



What to think of these results ?

- Acoustic peak structure gives *remarkable* endorsement of basic inflationary (read: gaussian, adiabatic) picture.
- The CMB provides the *only* probe of structure on scales of the Hubble radius, so far
- Low *l* results *may* be consistent with "standard model", but alternatives should still be considered. Examples:
  - *k*-space cutoff, ringing in *P(k)*, trans-Planckian effects?
  - String/brane - inspired models?
  - Compact topologies?
  - Any connection to Dark energy ?
- Hard to assess the significance of *a posteriori* statistics
- We are in need of new theoretical motivations that will come for sure

Future Plans

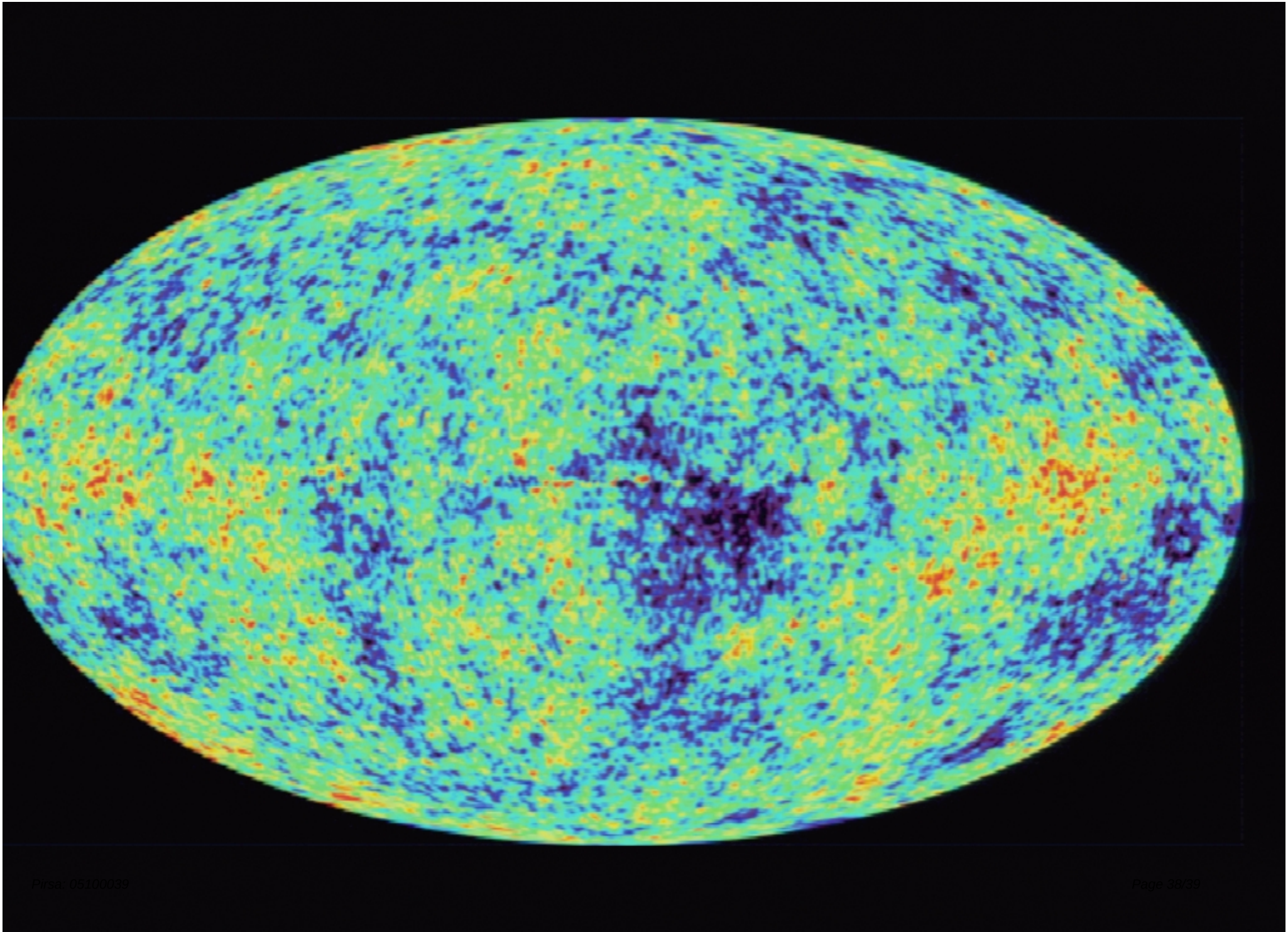
- WMAP completed another NASA "Senior Review" cycle in summer 2004 and received approval for 8 years of operation.

- Next data release is "soon" (ASAP!):
  - Temperature and polarization maps
    - 5 bands, full-sky, (yr1, yr2, yr3)
    - TT, TE, EE, BB, EB power spectra
  - Foreground models
  - Ancillary products: beam maps, sidelobe response, sky masks

- New data sets should teach us a lot about those various anomalies/ (~3σ) effects: if they are genuine, the significance should improve in most cases

- Already new polarized detections from CBI, B2K, DASI, CAPMAP

- Other CMB Temperature/Polarization Experiments, over 20 current/planned measurements, Planck, Beyond Einstein Inflation Probe, SPIDER...



Another question we could ask

What is the likelihood of seeing the initials of Stephen Hawking imprinted on the sky ?