Cosmology as enlightened by WMAP: 1.8 year after

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Outline

1. Fast pace partial review of WMAP, the first year results and their cosmological interpretations
2. Somewhat more thorough review of the subsequent literature

No results of the 2yr analysis

Quick **WMAP status**:

- The instrument is still working nominally
- WMAP is funded to operate for 6-8 years
- Virtually all aspects of the year one analysis have been reassessed. The next release will include all about polarization.
- The next data release is… "soon"

WMAP Science Team

- **Goddard (NASA)**

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  Robert Hill
  Gary Hinshaw, Co-I
  Al Kogut
  Michele Limon
  Nils Odegard
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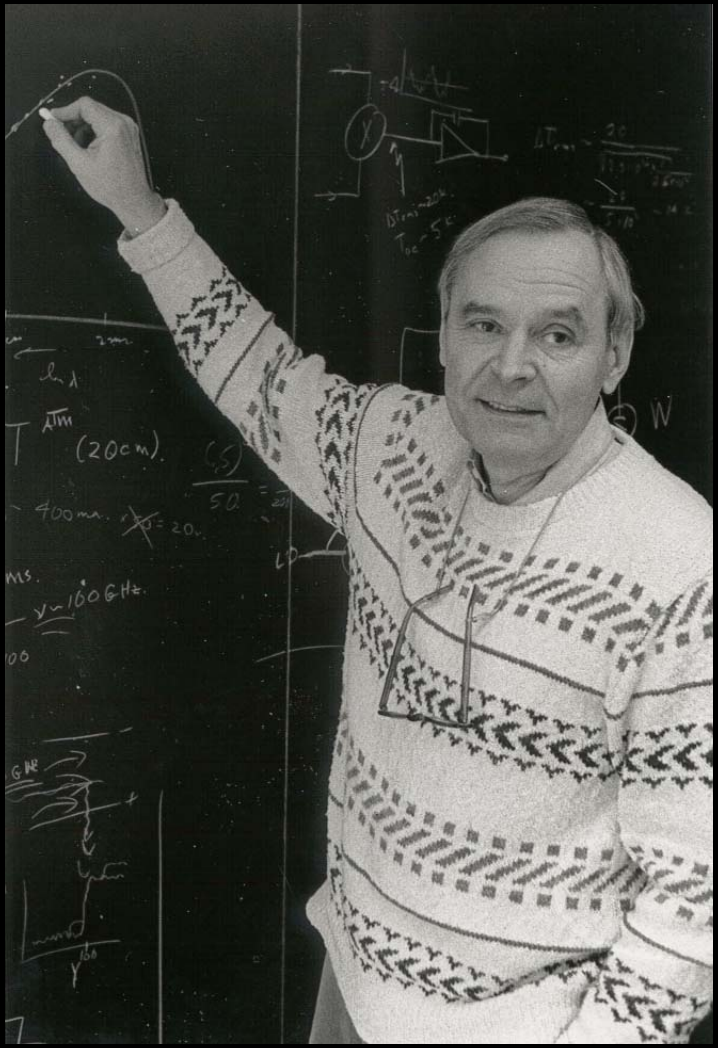


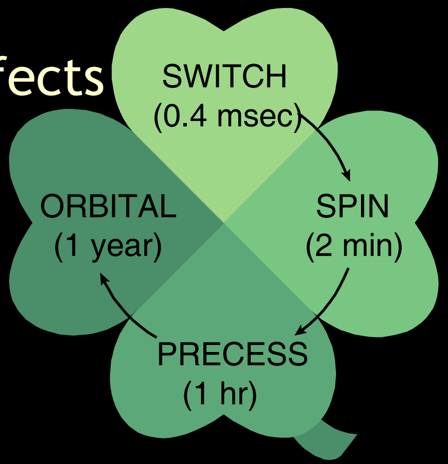
David Wilkinson 1935-2002

WMAP's *raison d'être*

To make a detailed full-sky map of the cosmic microwave background (CMB) radiation to constrain the cosmology of our universe.

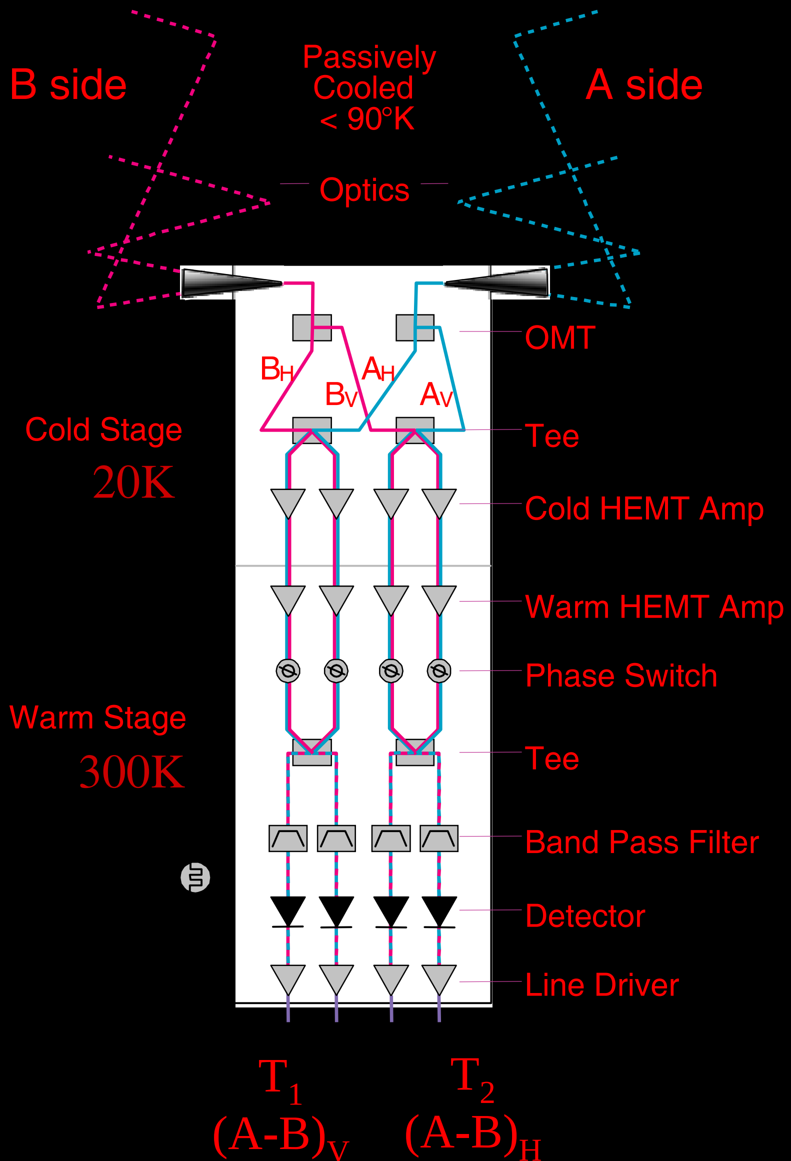
Design philosophy:
Minimize Systematic Measurement Errors

- Differential design to minimize systematic errors
- 5 microwave frequencies to understand foregrounds
- 20 radiometers to allow multiple cross checks
- Sensitivity to polarization
- Accurate calibration (<0.5%)
  → in-flight calibration using modulation of the dipole
- In-flight beam measurements on Jupiter
- Minimize sidelobes & diffracted signals from Earth, Sun, Moon
  → L2 orbit
- Multiple modulation periods to identify systematic effects
- Minimize all observatory changes
  → L2 orbit; constant survey mode operations
- Thermal stability / Passive thermal control → L2
- Rapid and complex sky scan, heavily connected
  → observe 30% of the sky in an hour
  → most of the pixels are observed with evenly distributed orientations

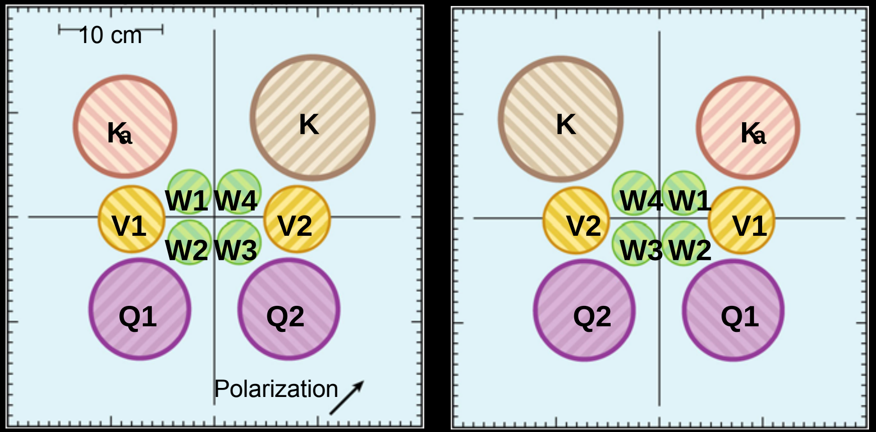


SPIN-SYNCHRONOUS NON-SKY SIGNALS WERE THE LEADING CONCERN

This philosophy embodied as WMAP

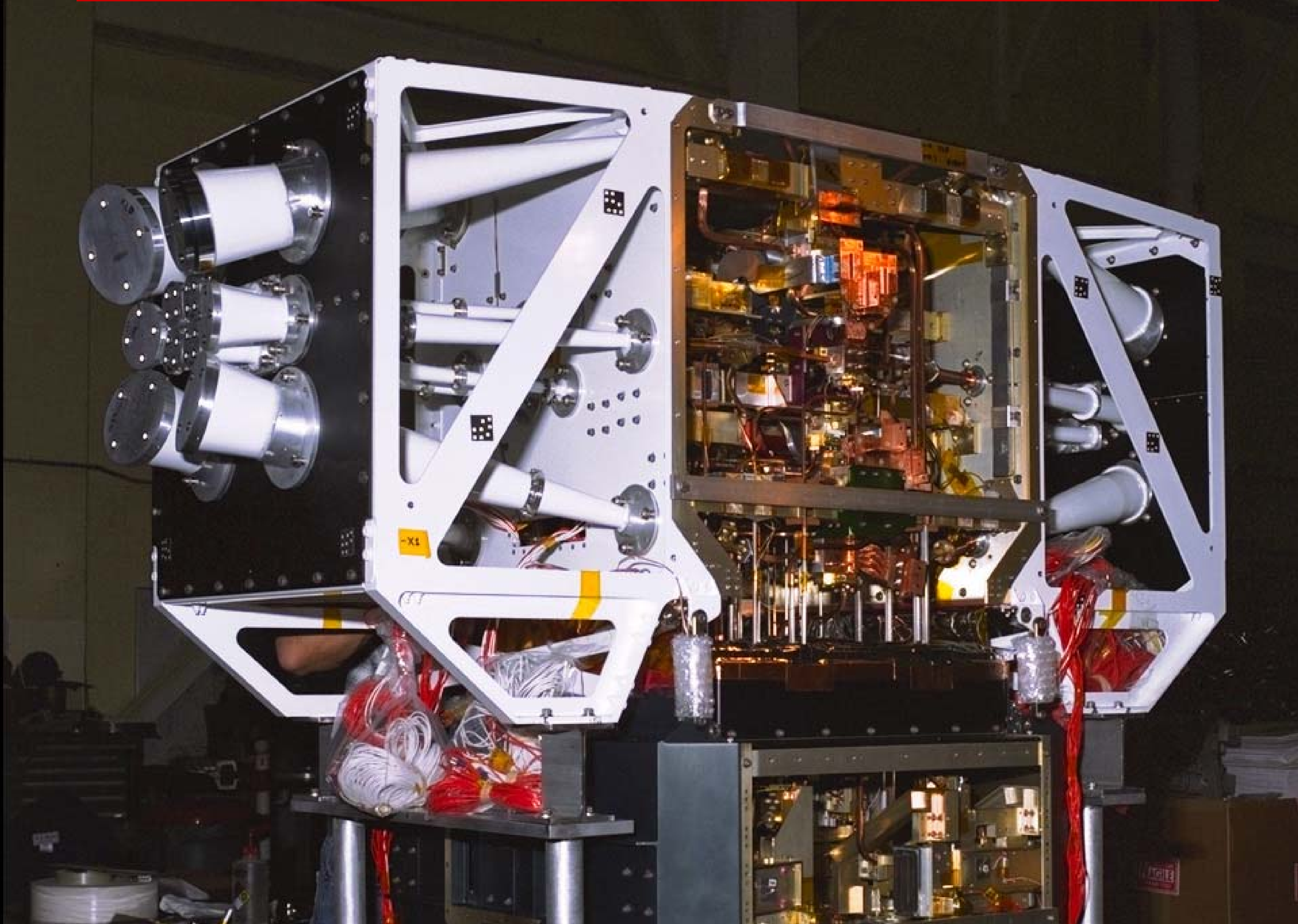


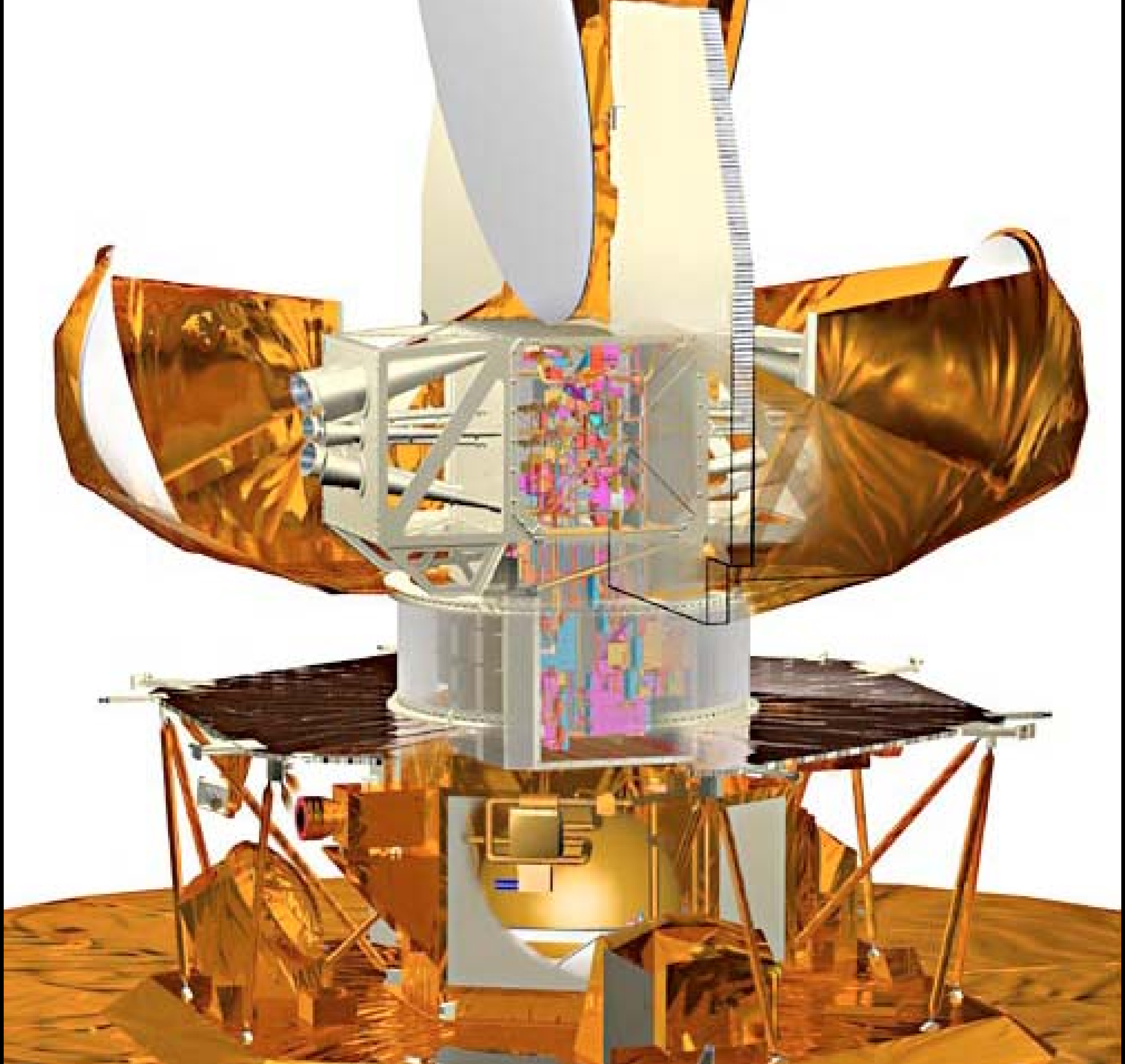
- Two Radiometers per Feed
  - Sum $(T_1 + T_2) \propto$ Intensity
  - Difference $(T_1 - T_2) \propto$ Polarization
- Spacecraft spin/precession combine to separate Stokes Q/U on sky
- Natural sensitivity to *I* and Polarization
- Only differences are measured
- Most of the common modes cancel



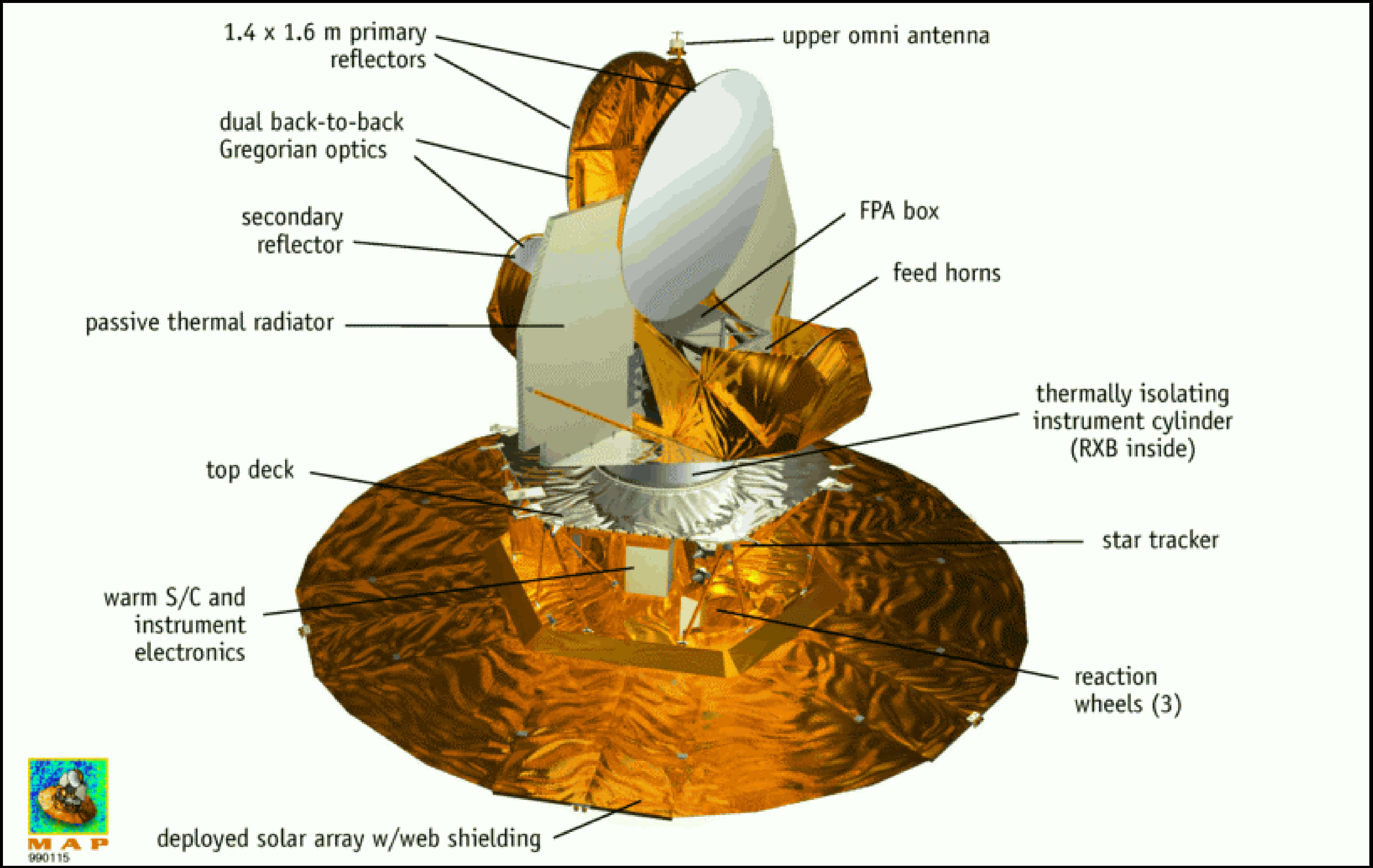
One differential assembly DA (one of 10)

Prototype WMAP Instrument

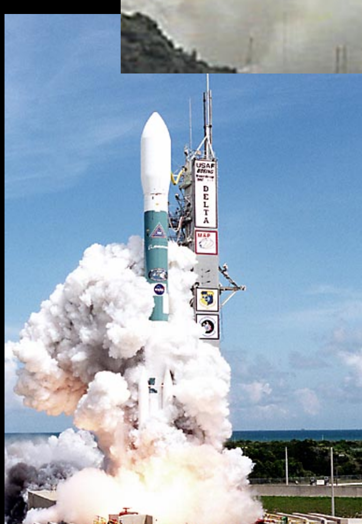


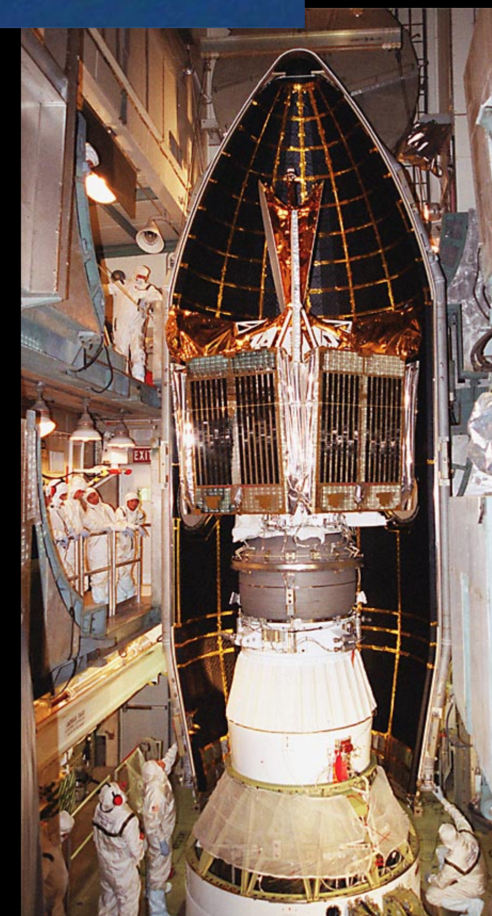


The spacecraft



WMAP Launch

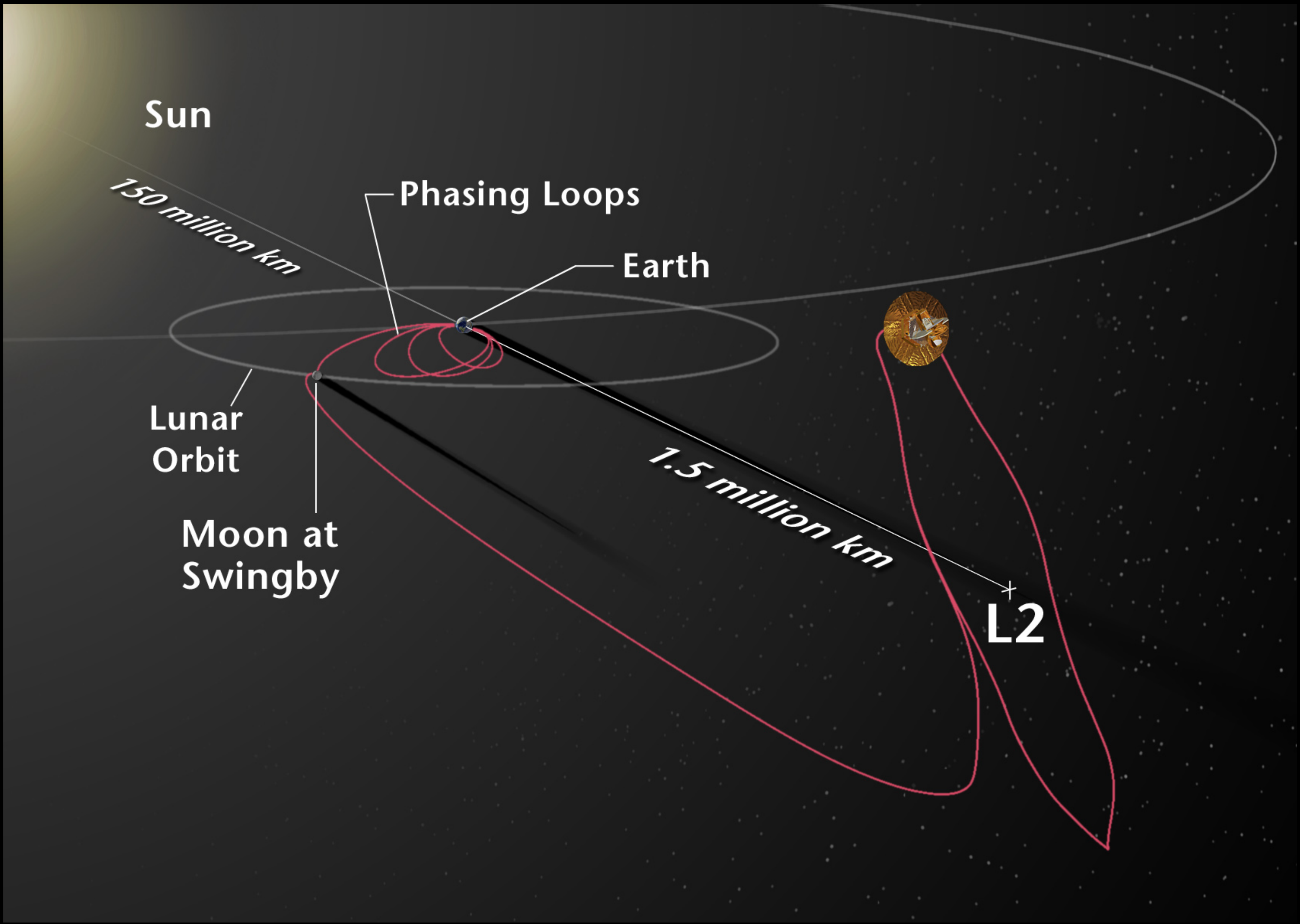




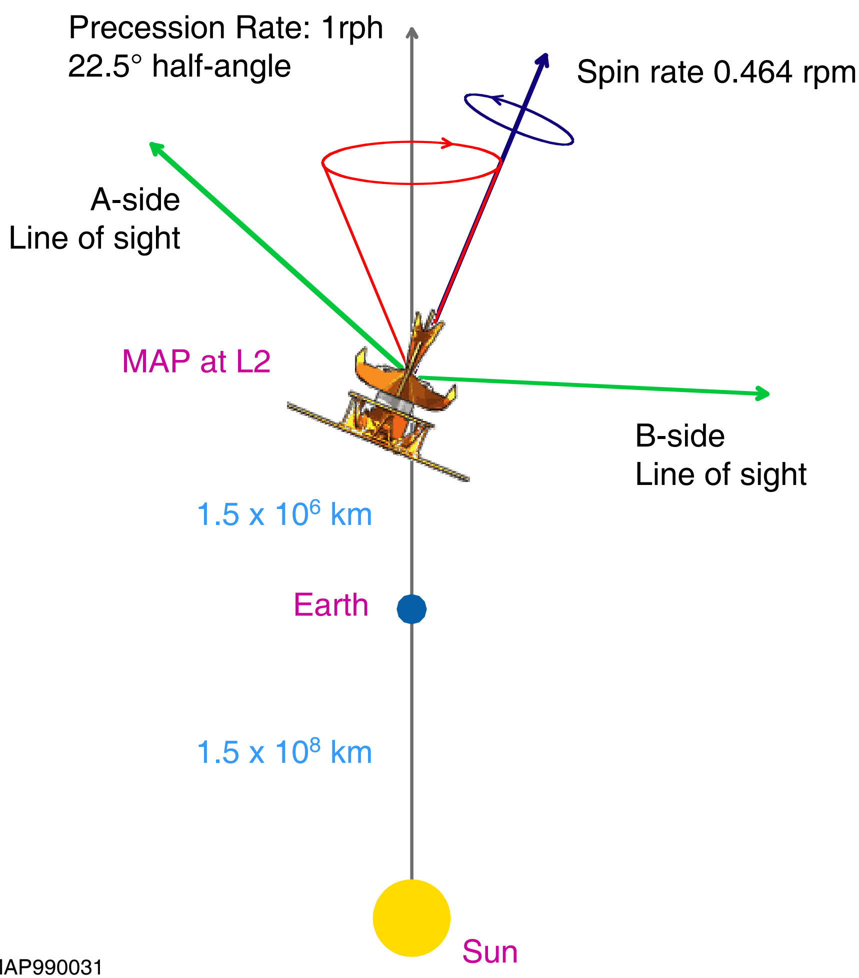
June 30, 2001 at 3:47 EDT

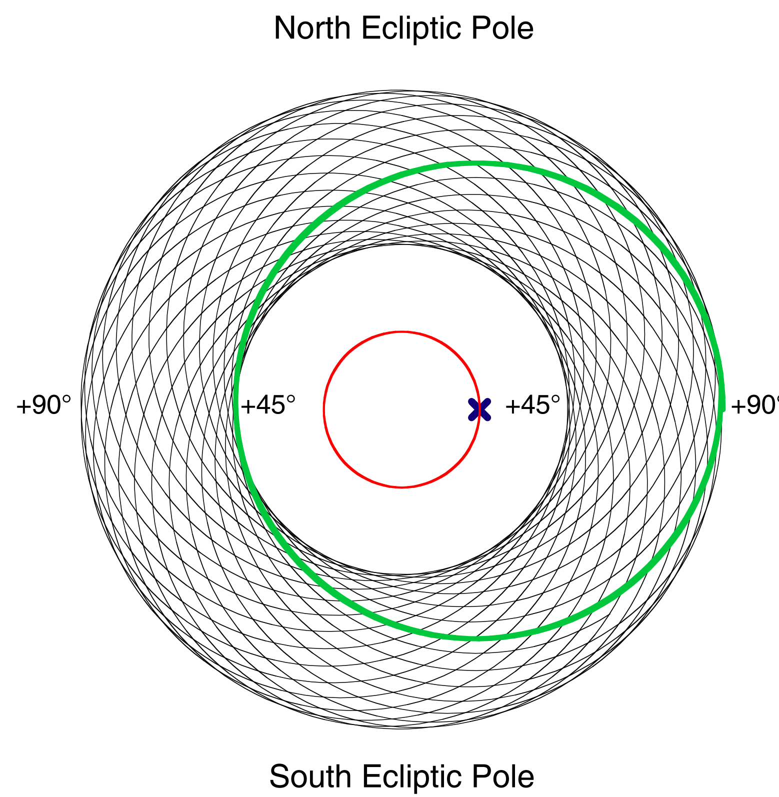
Delta II Model 7425-10
Delta Launch Number 286
Star-48 third stage motor
Cape Canaveral Air Force Station
Pad SLC-17B

Trajectory to L2



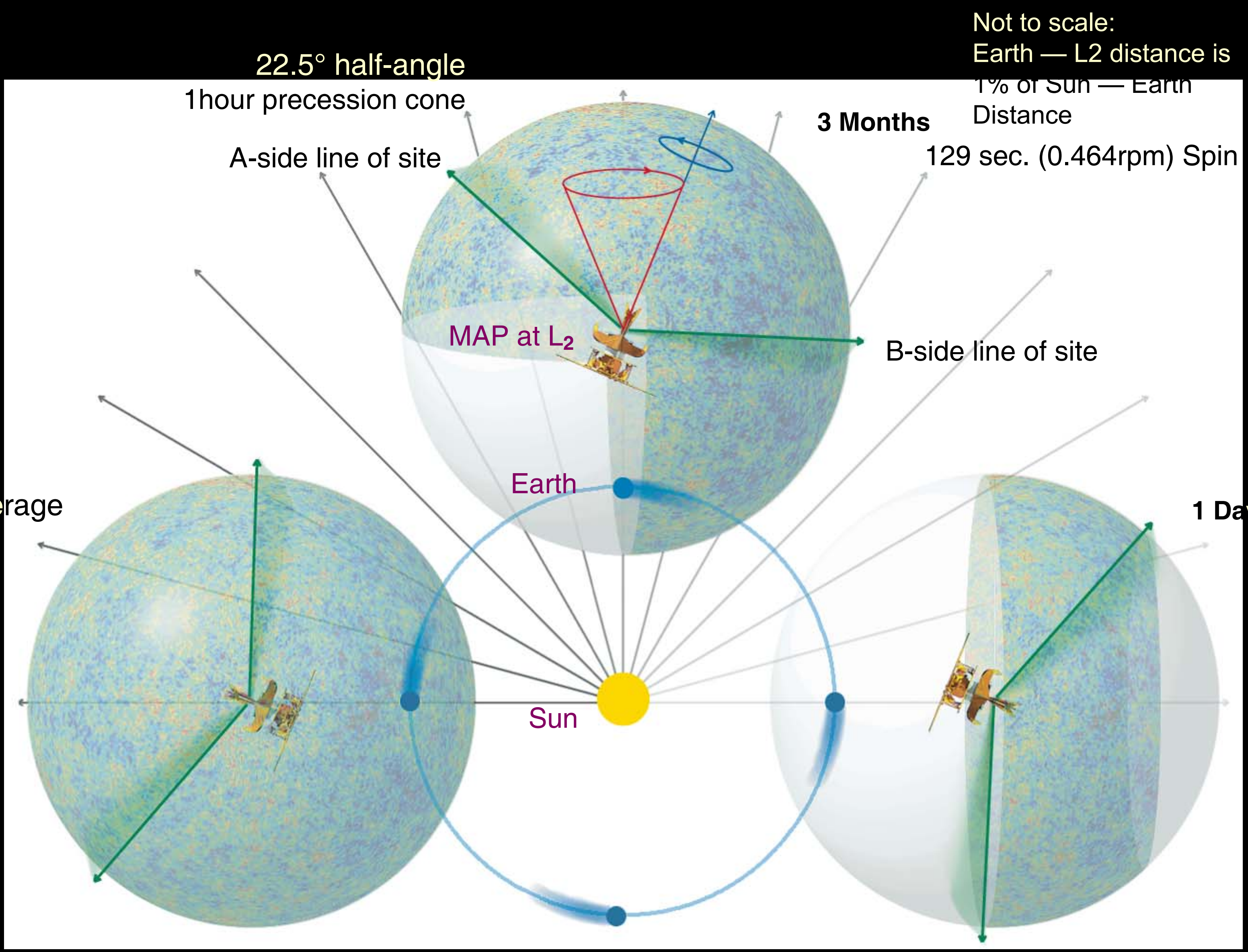
Scan Pattern



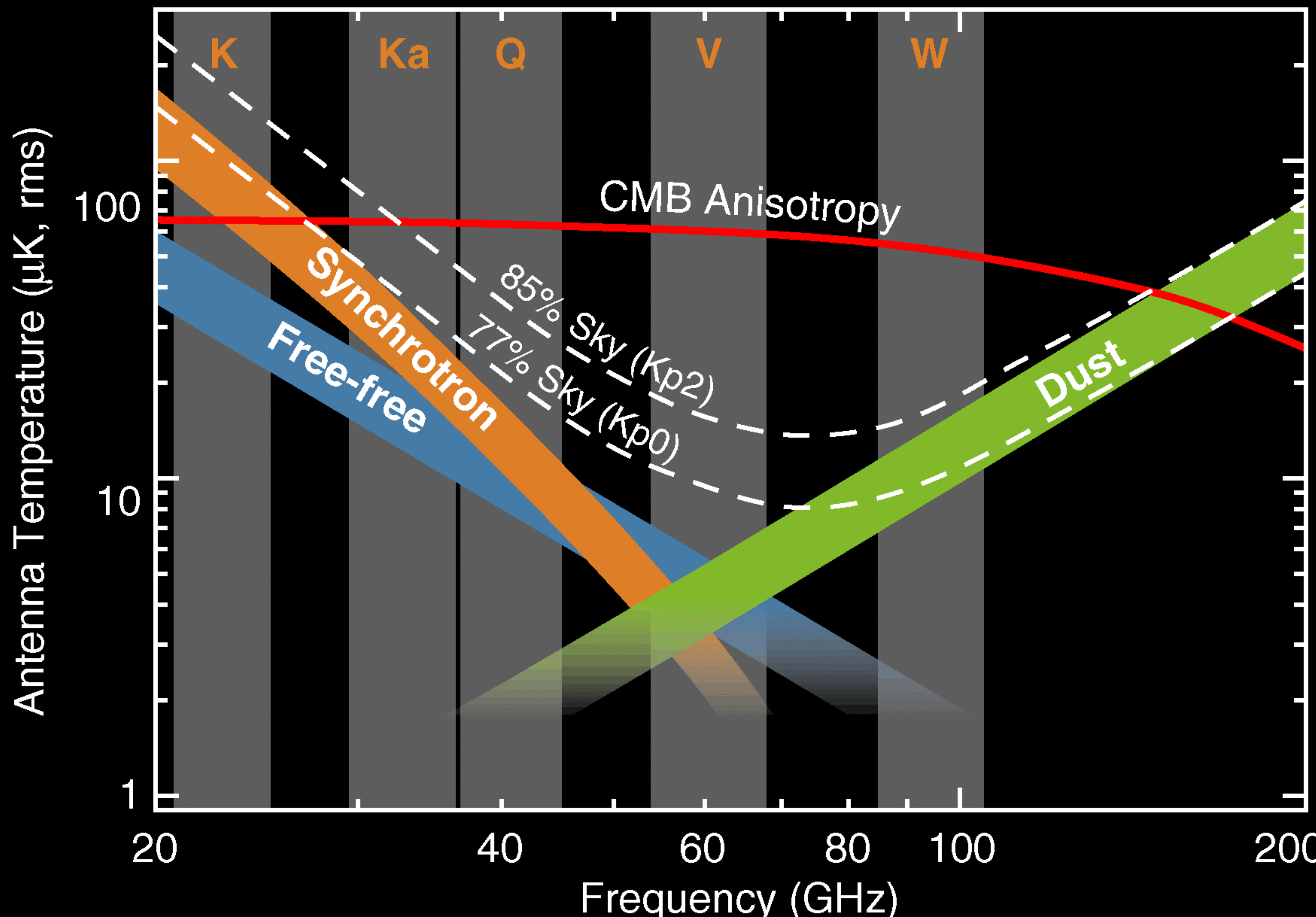


MAP990031

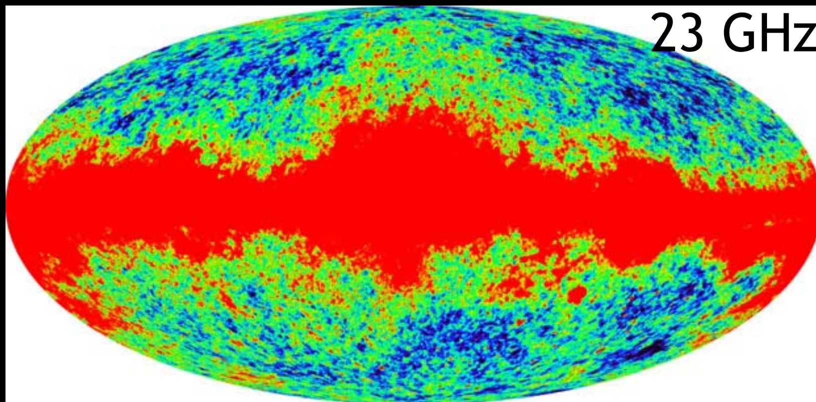
Scanning Strategy

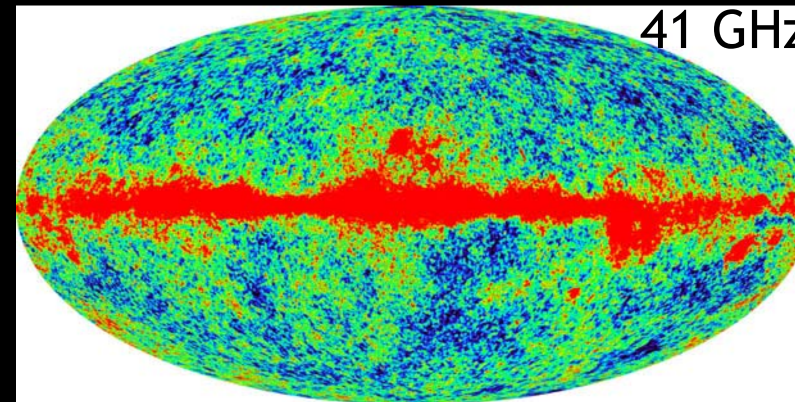


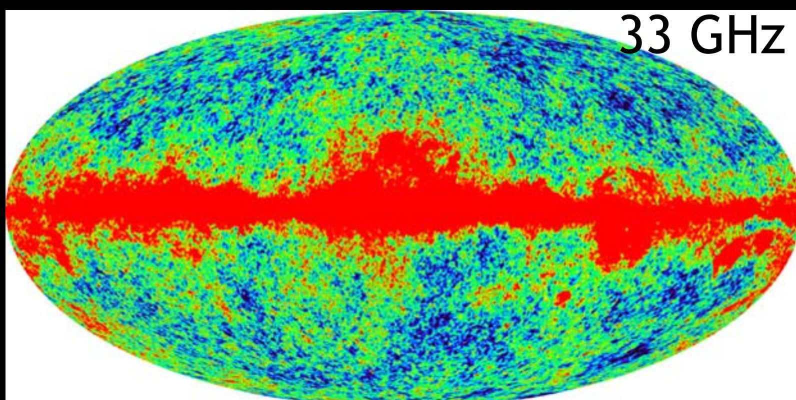
Foreground Spectra

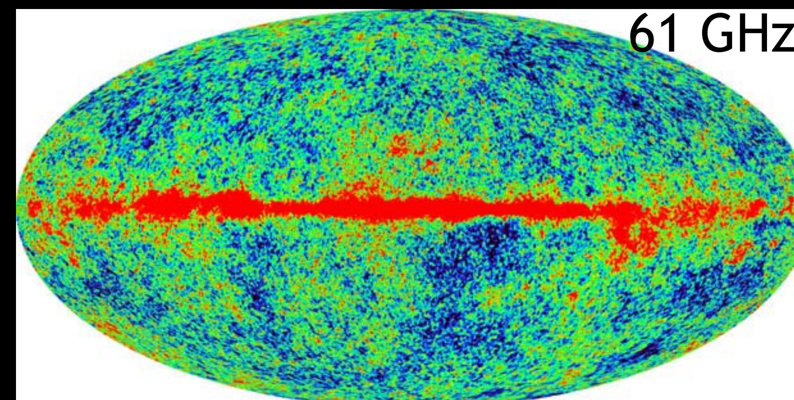


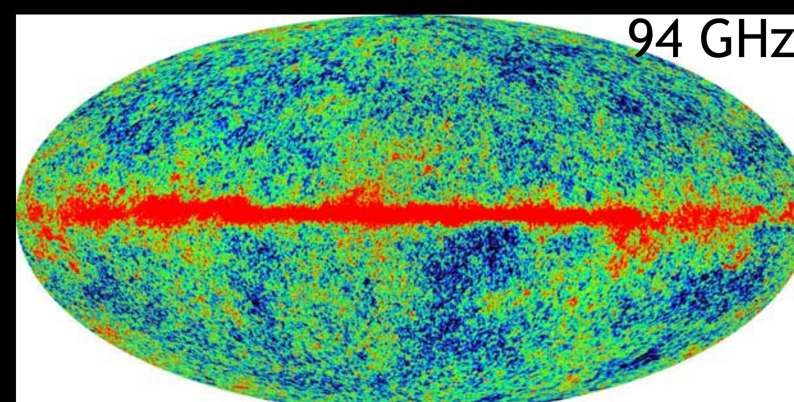
WMAP Sky Maps: 23 to 94 GHz





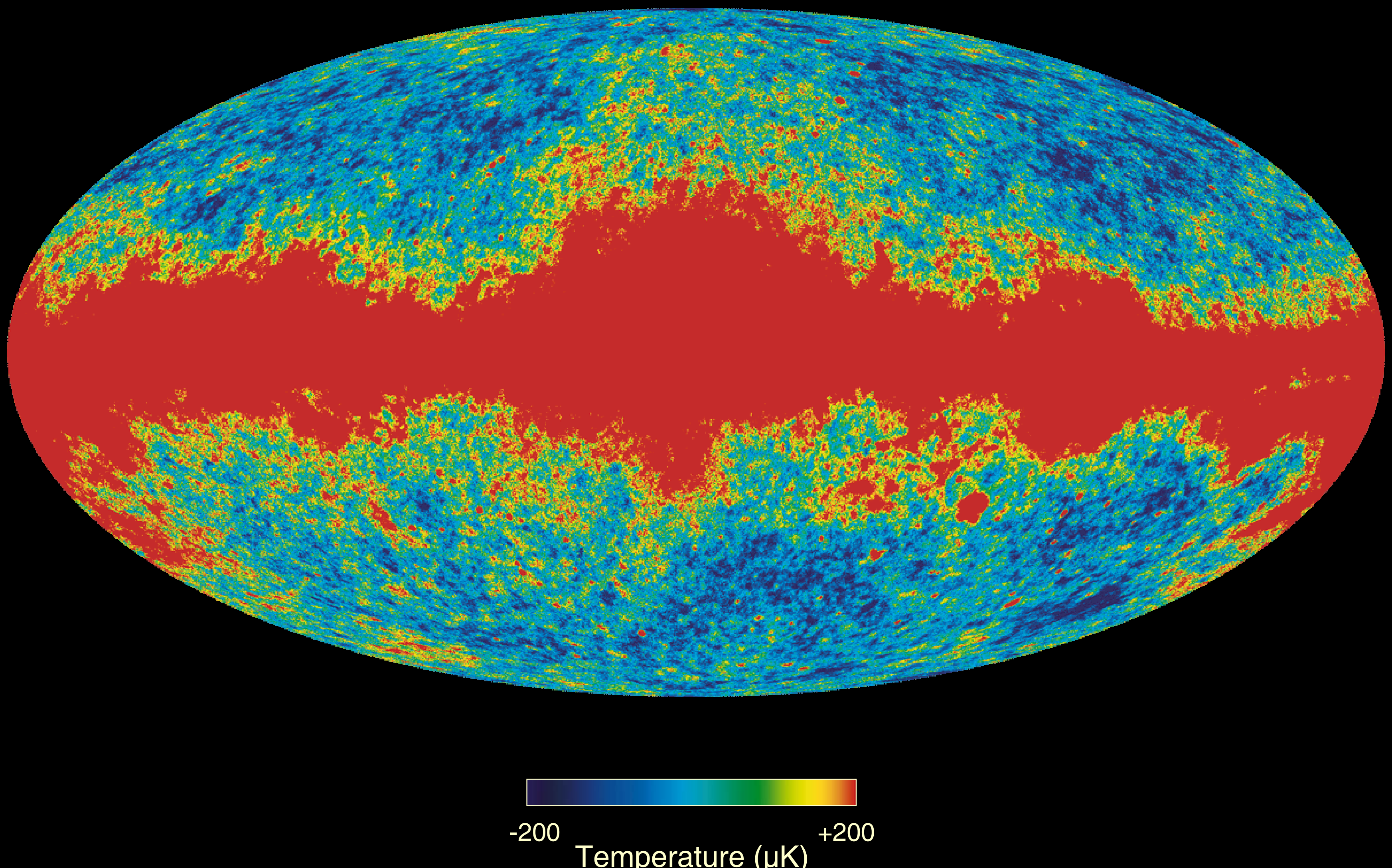




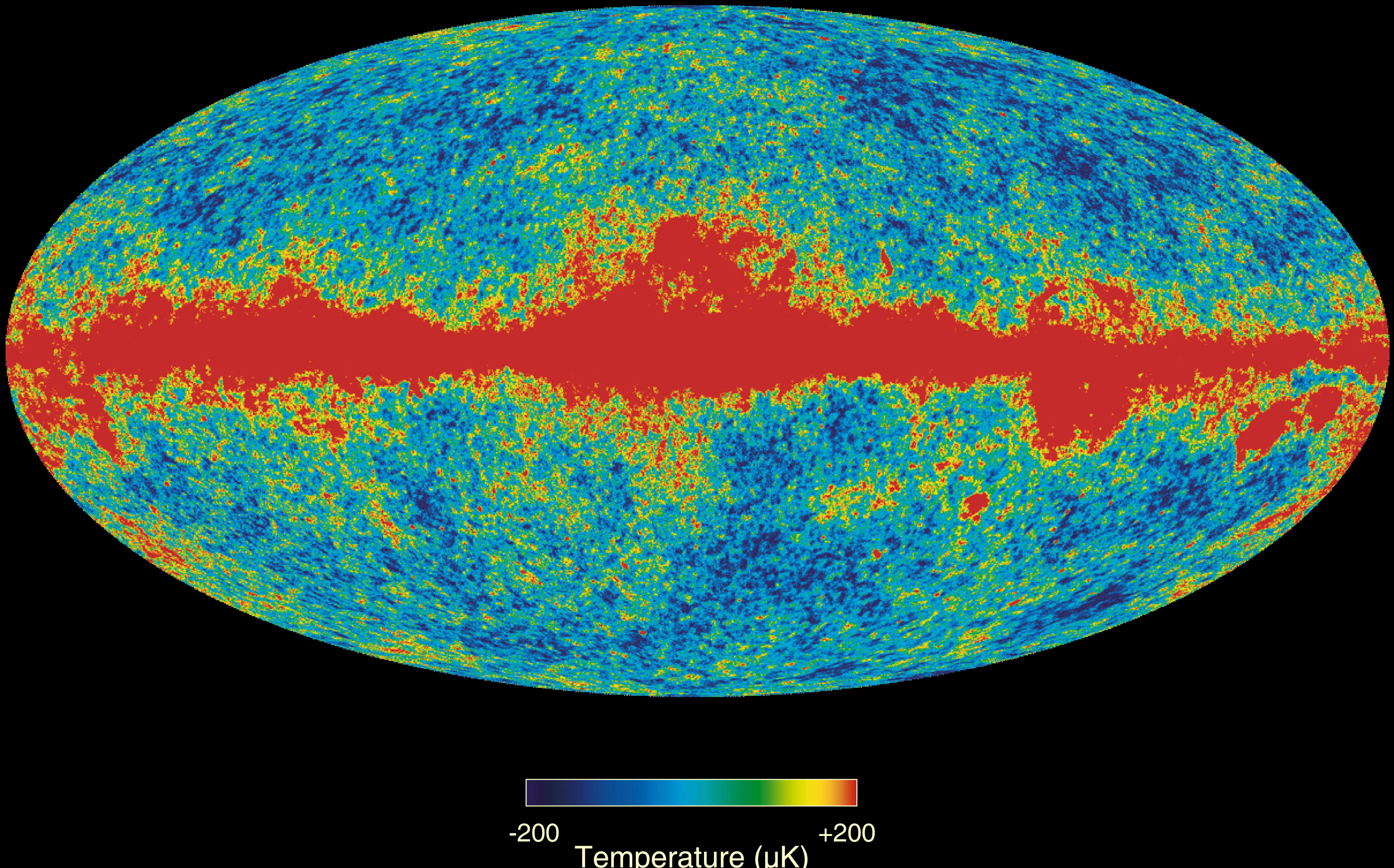


- Absolute Calibration: 0.5%
- Bandwidth: ~20%
- Beam FWHM: 0.85˚ (23 GHz) to 0.21˚(94 GHz)
- Systematic around 15μK^2 for C_2^{TT} vs the ~1000 μK^2 nominal TT and ~100 (EE), and less for higher l

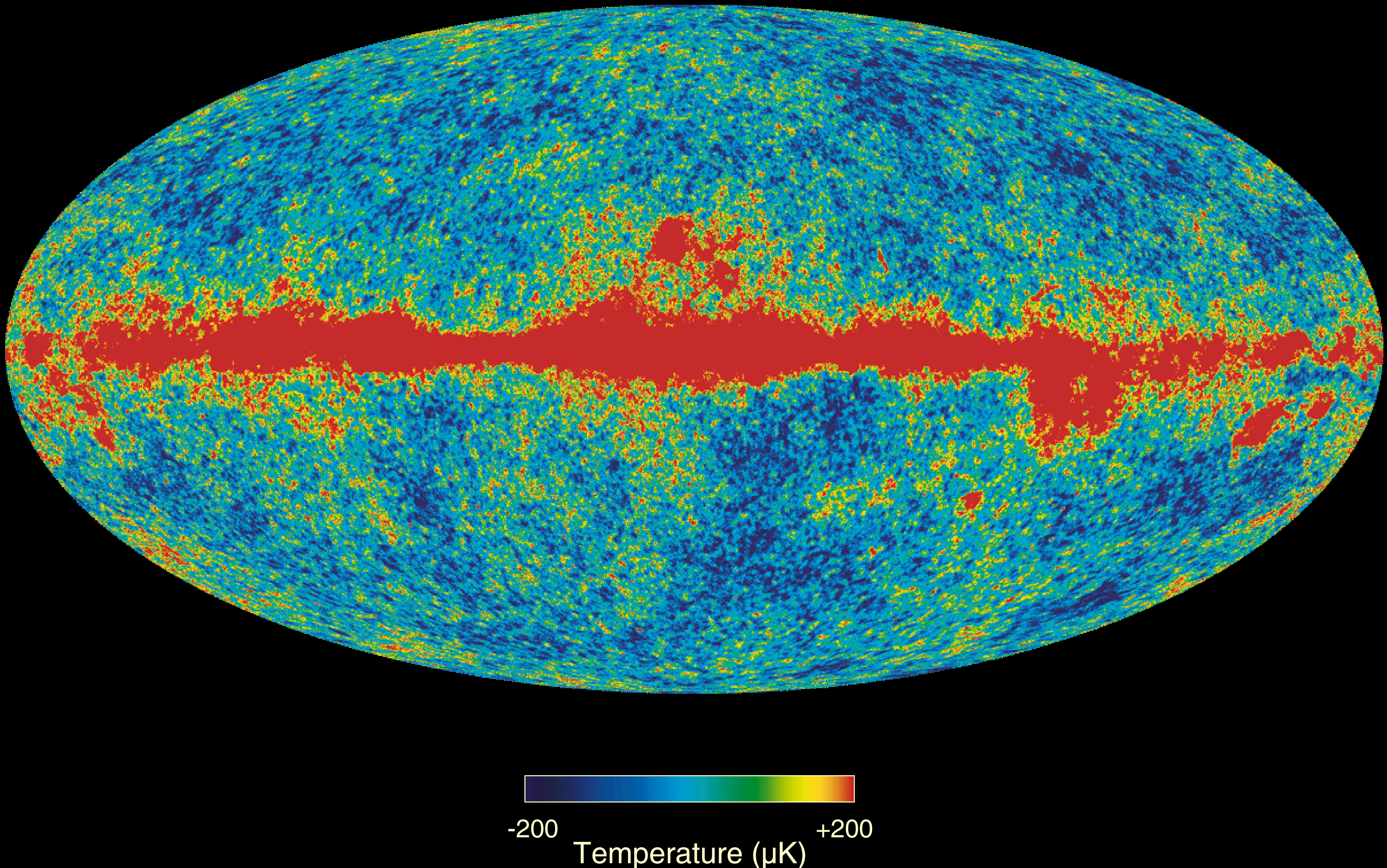
K Band (23 GHz)



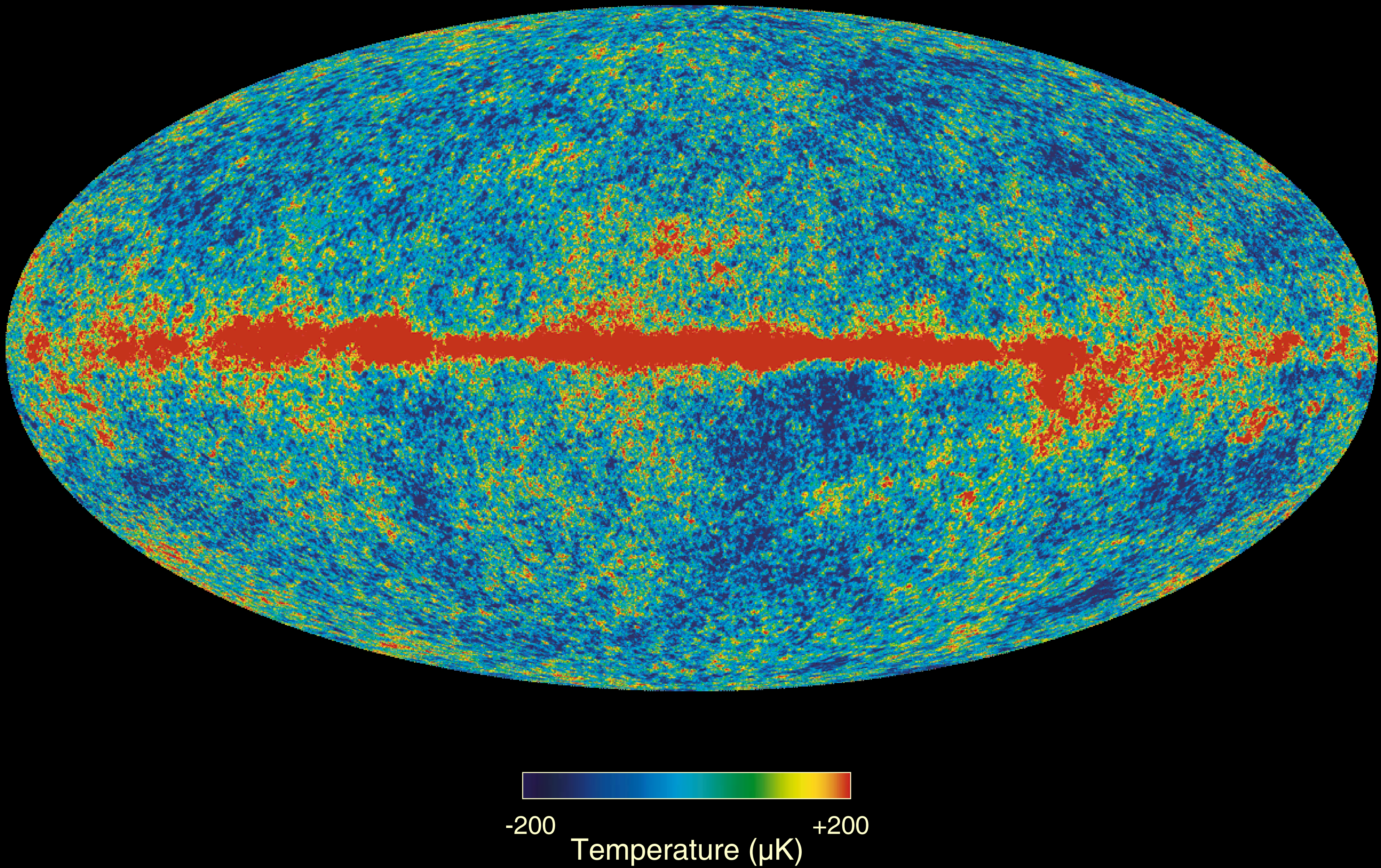
Ka Band (33 GHz)



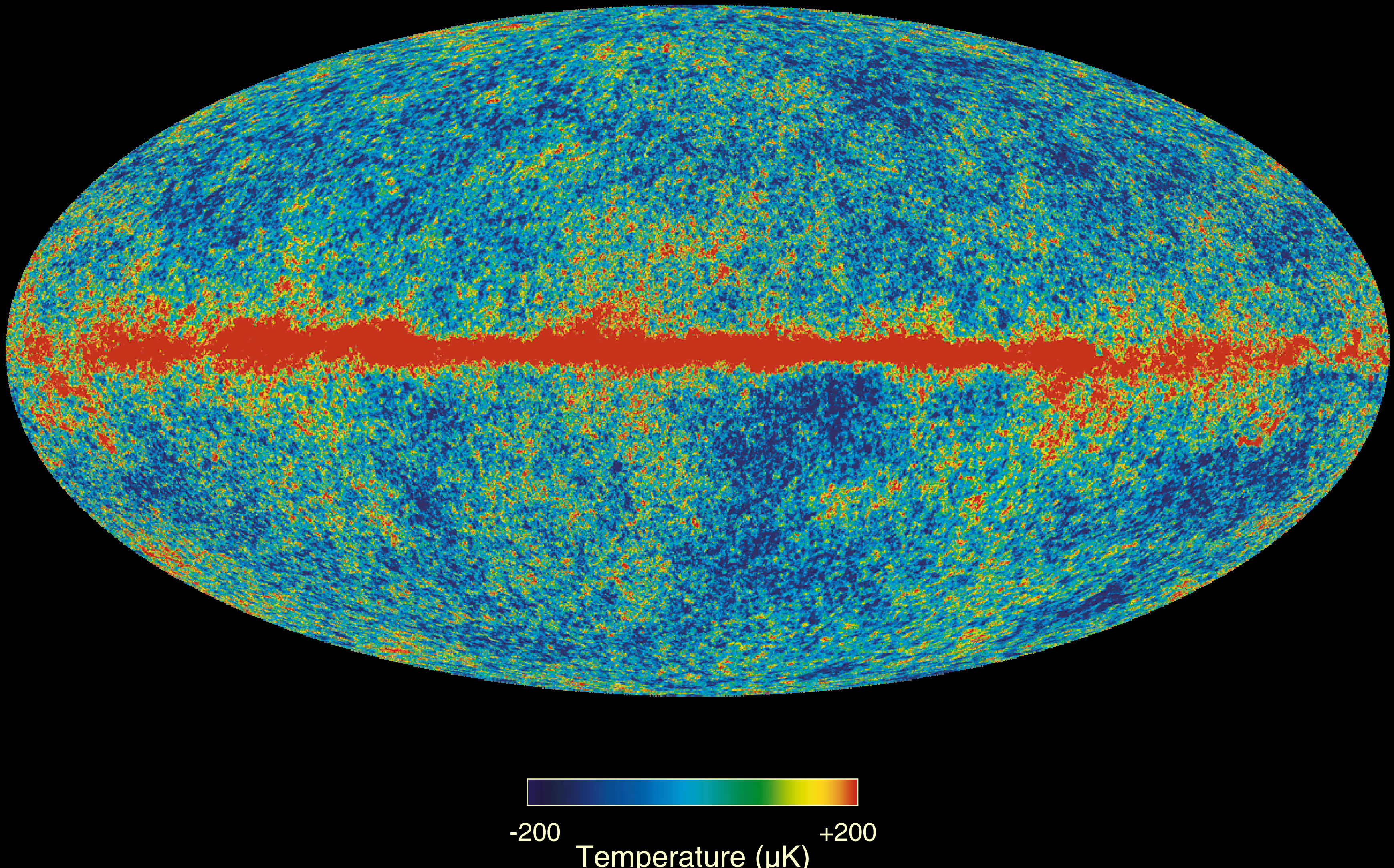
Q Band (41 GHz)



V Band (61 GHz)

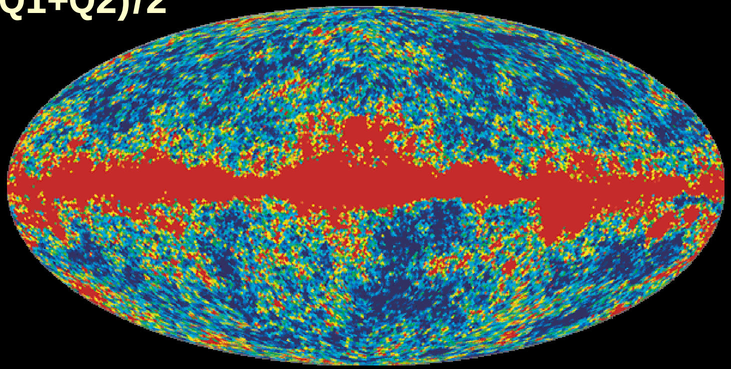


W Band (94 GHz)

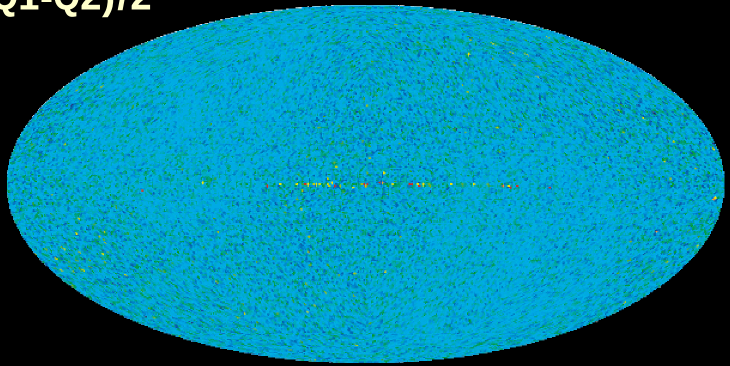


Systematic Error Cross-Checks

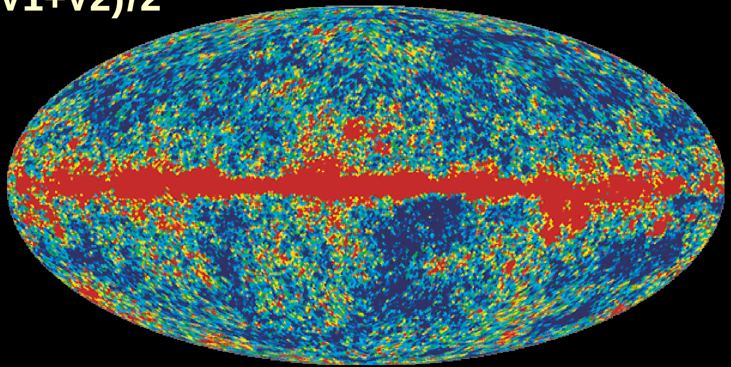
(Q1+Q2)/2



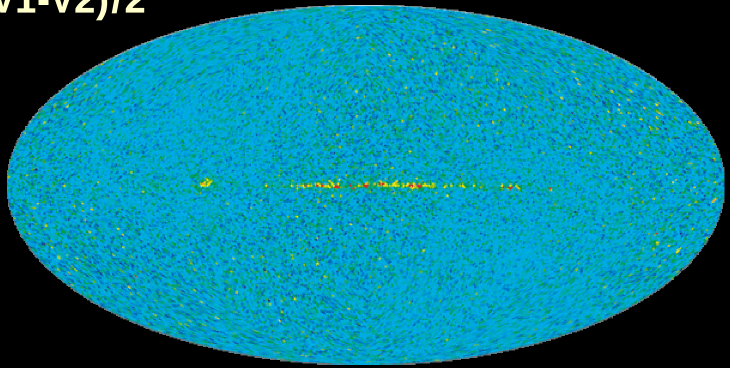
(Q1-Q2)/2



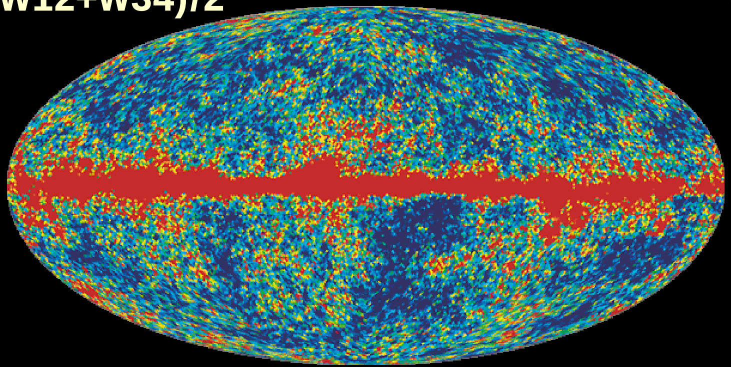
(V1+V2)/2



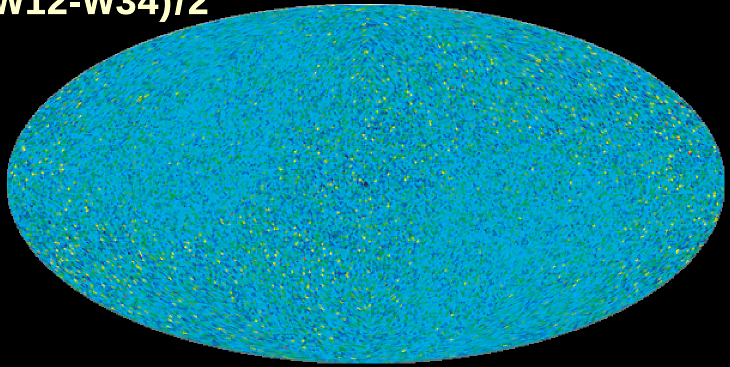
(V1-V2)/2



(W12+W34)/2

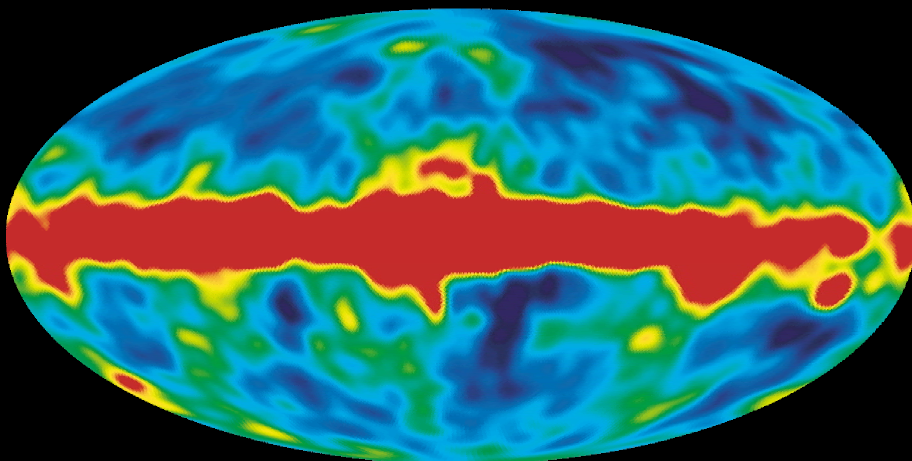


(W12-W34)/2

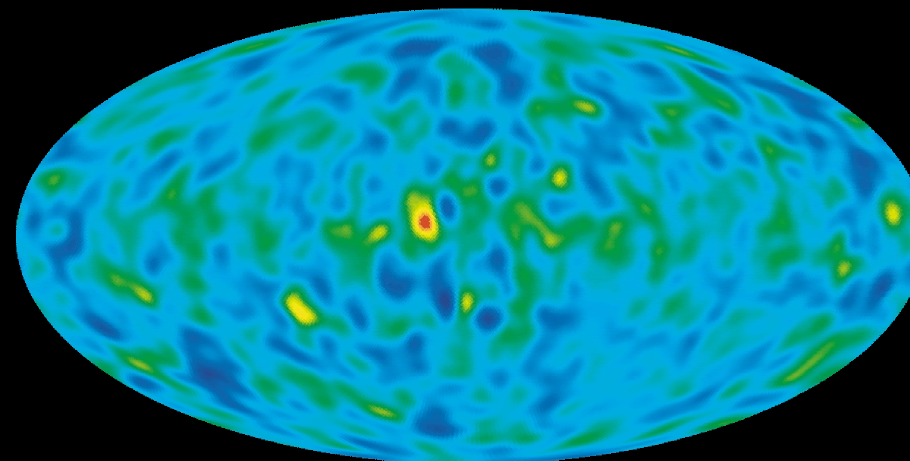


COBE-WMAP Comparison

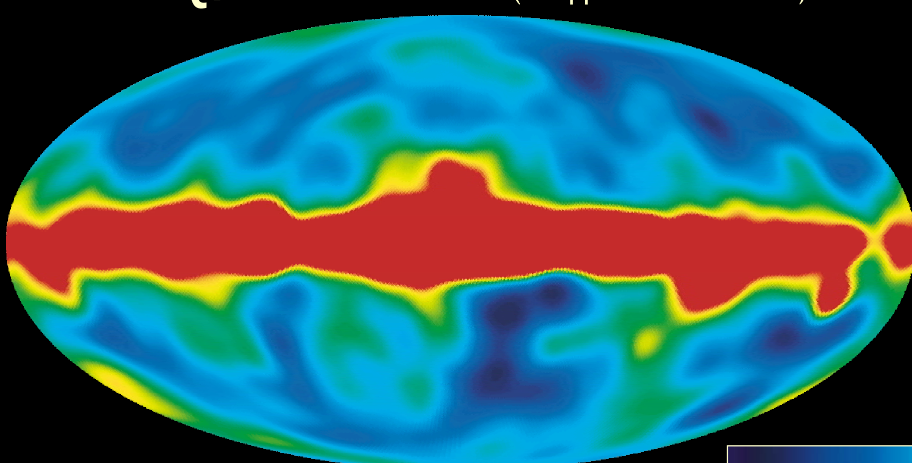
COBE DMR 53 GHz



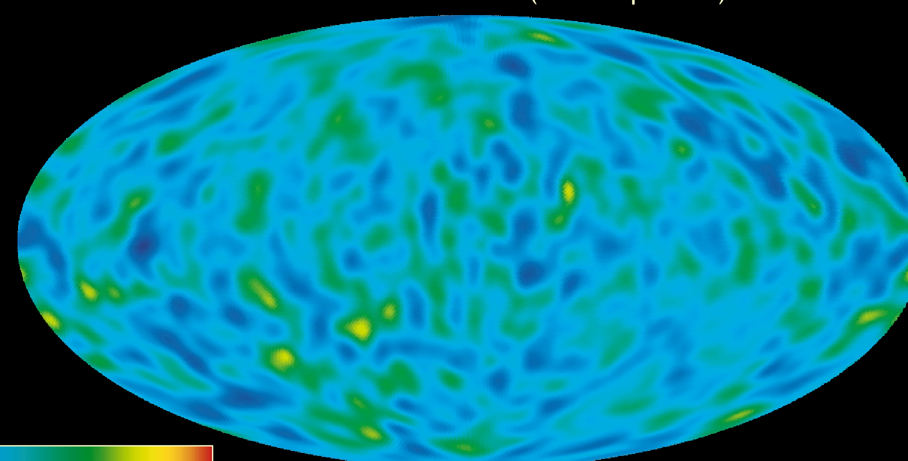
Difference: WMAP - DMR



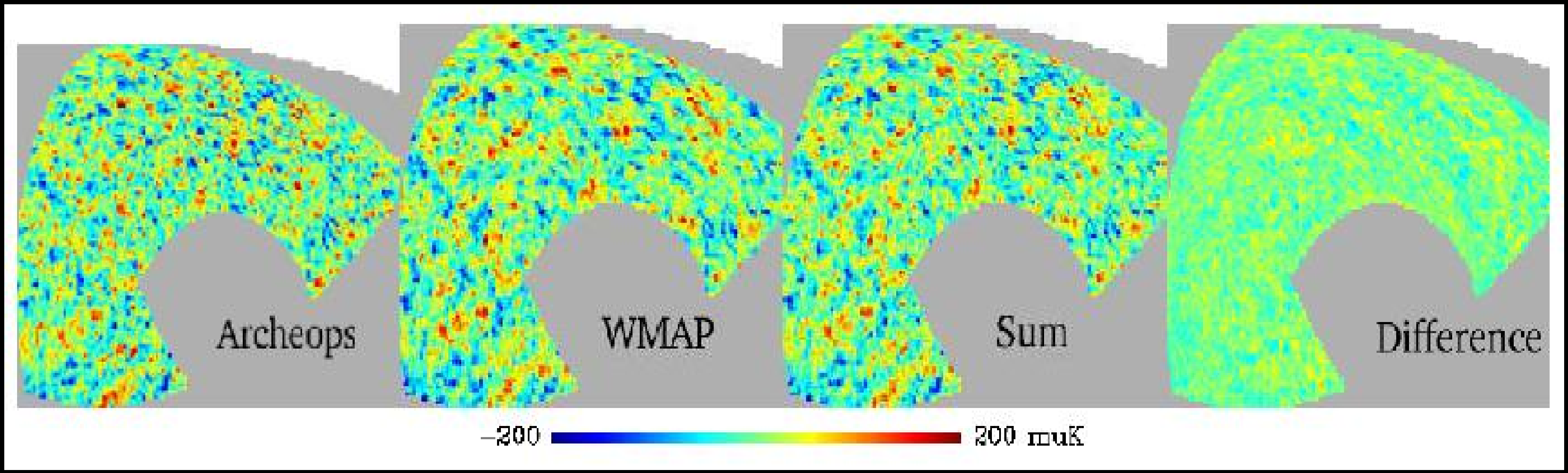
WMAP Q/V Combined (to approximate 53 GHz)



Simulated DMR Noise (for comparison)



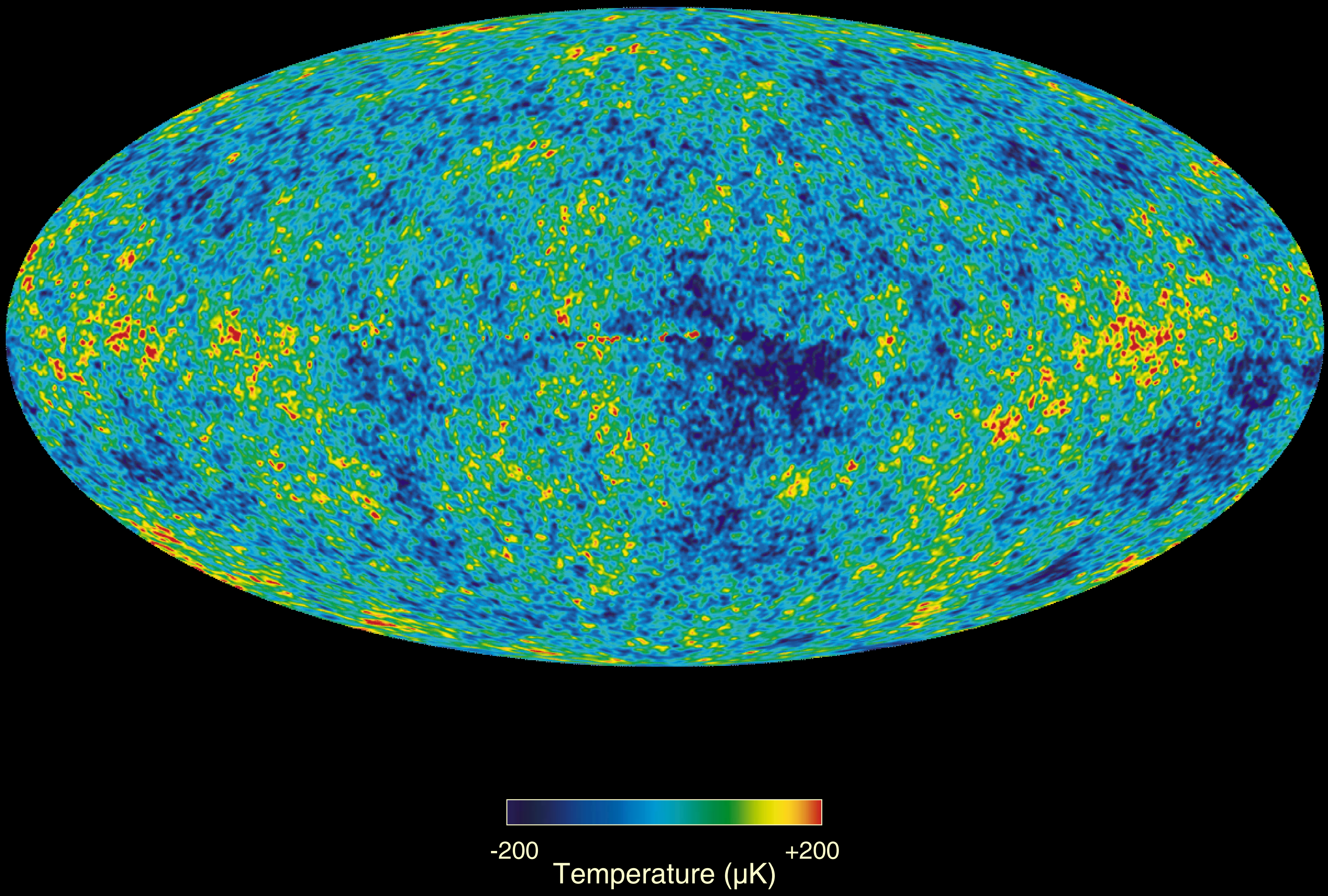
ARCHEOPS vs WMAP



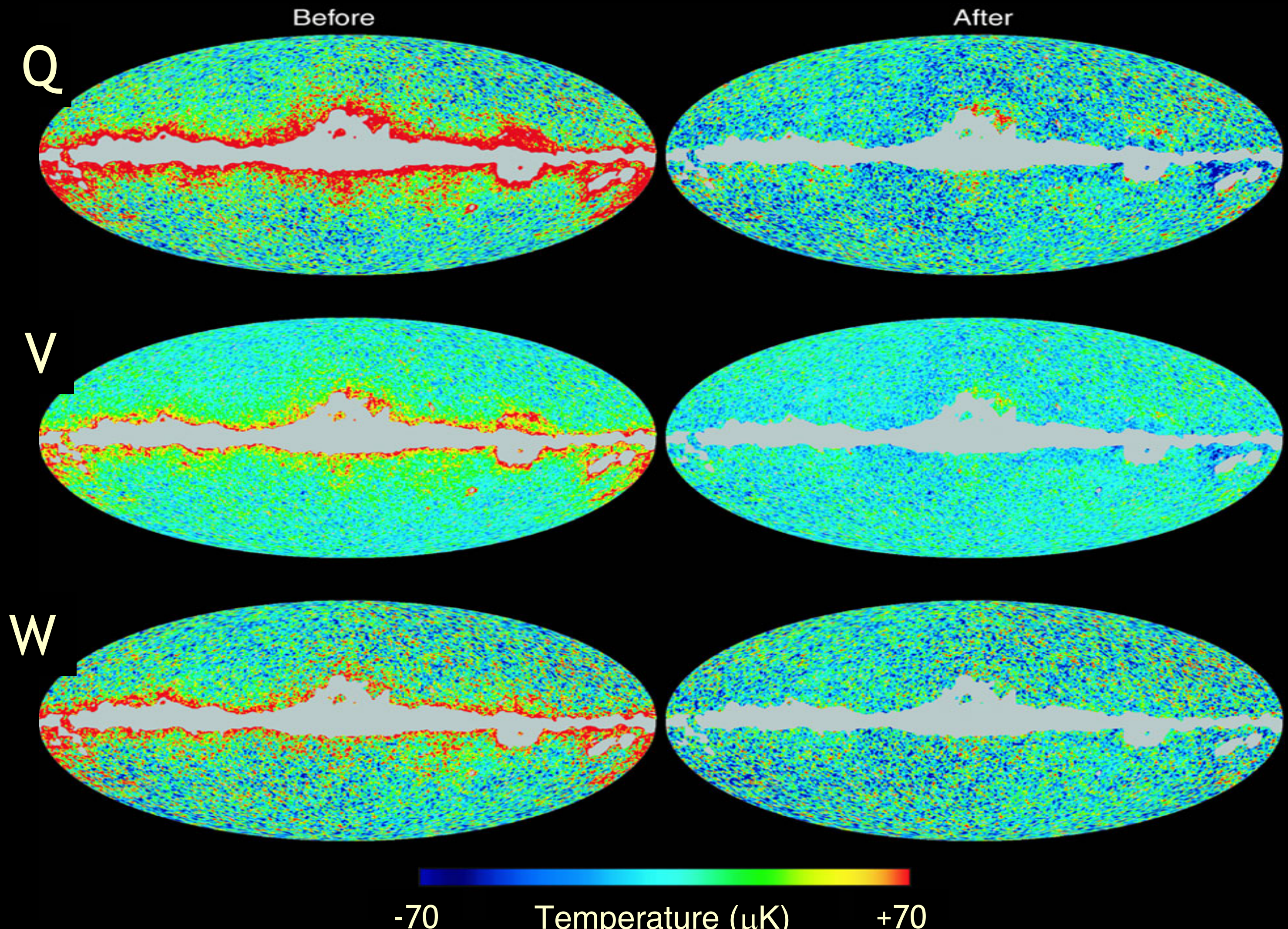
- ARCHEOPS (Benoit et al. 02) observed same ΔT at 143 & 217 GHz.
- Also consistent with WMAP at 94 GHz.
- See in particular the new C_ls of Tristram *et al.* 03
- Therefore thermal Sunyaev-Zeldovich effect is insignificant at $l < 500$

from Hamilton et al. 03

Internal Linear Combination CMB

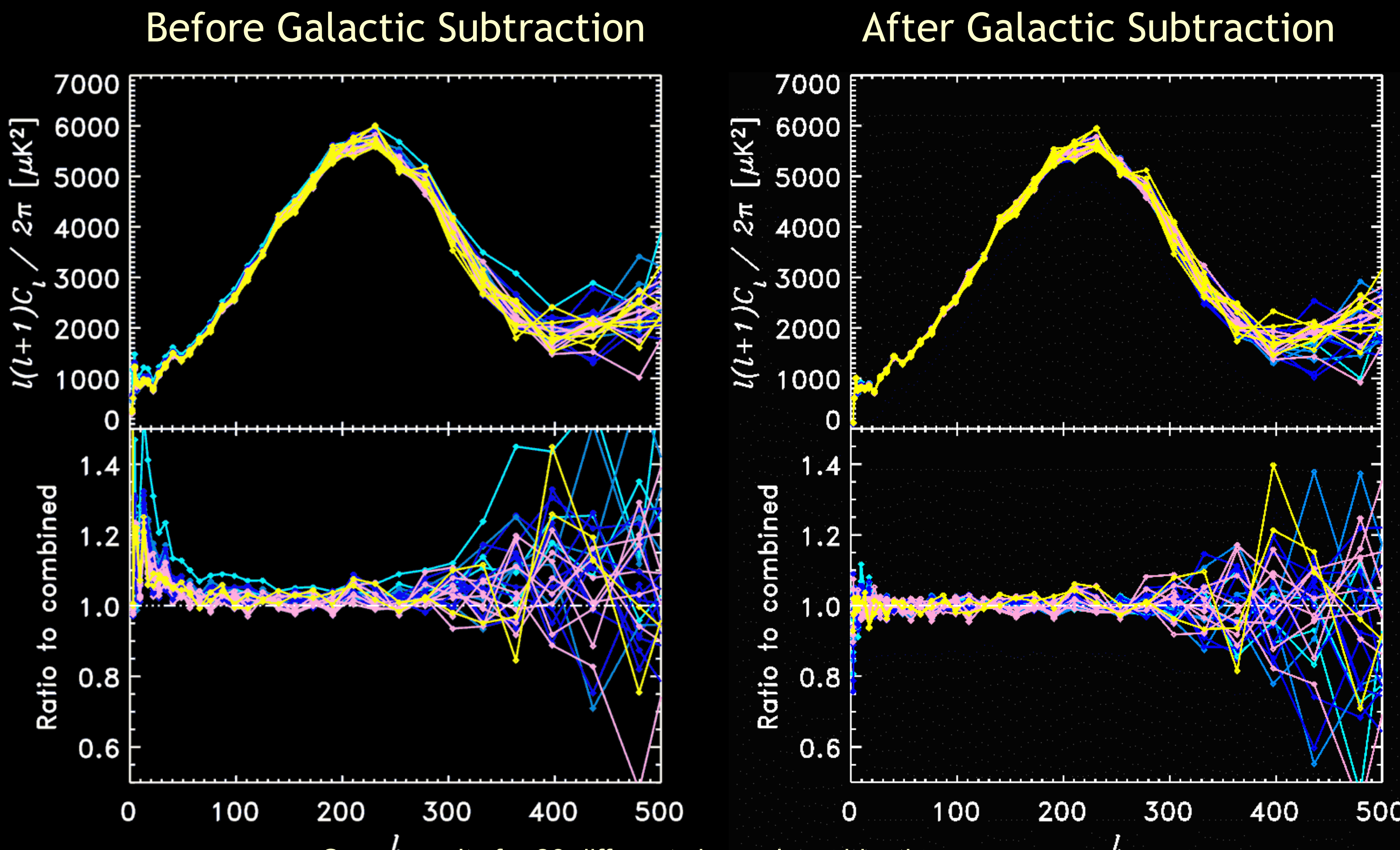


Foreground Removal for Spectrum Analysis



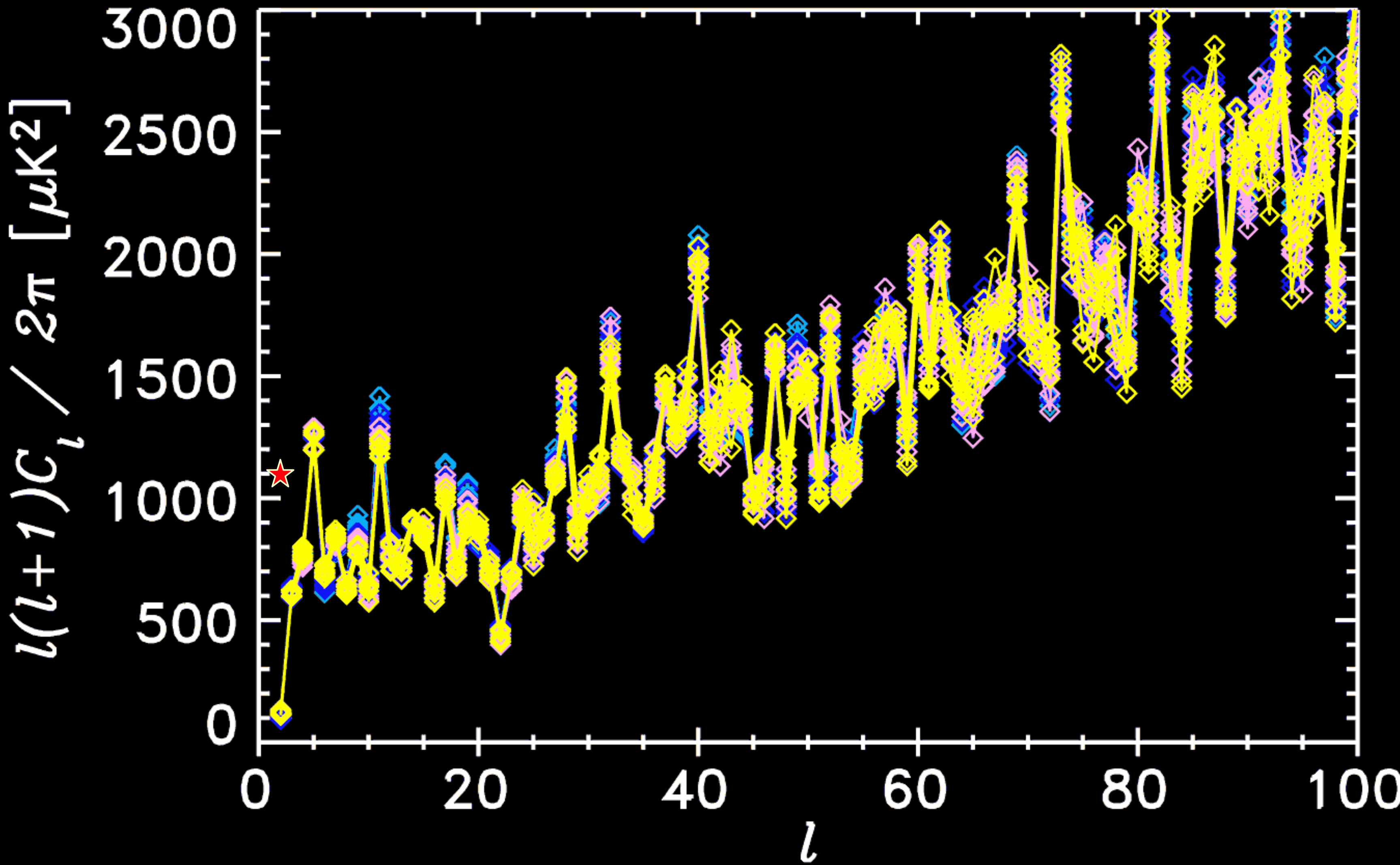
External templates
Hα maps from Finkbeiner et al. 03
WHAM Haslam et al. 1981
Finkbeiner, Davis & Schlegel 2001

Power Spectrum

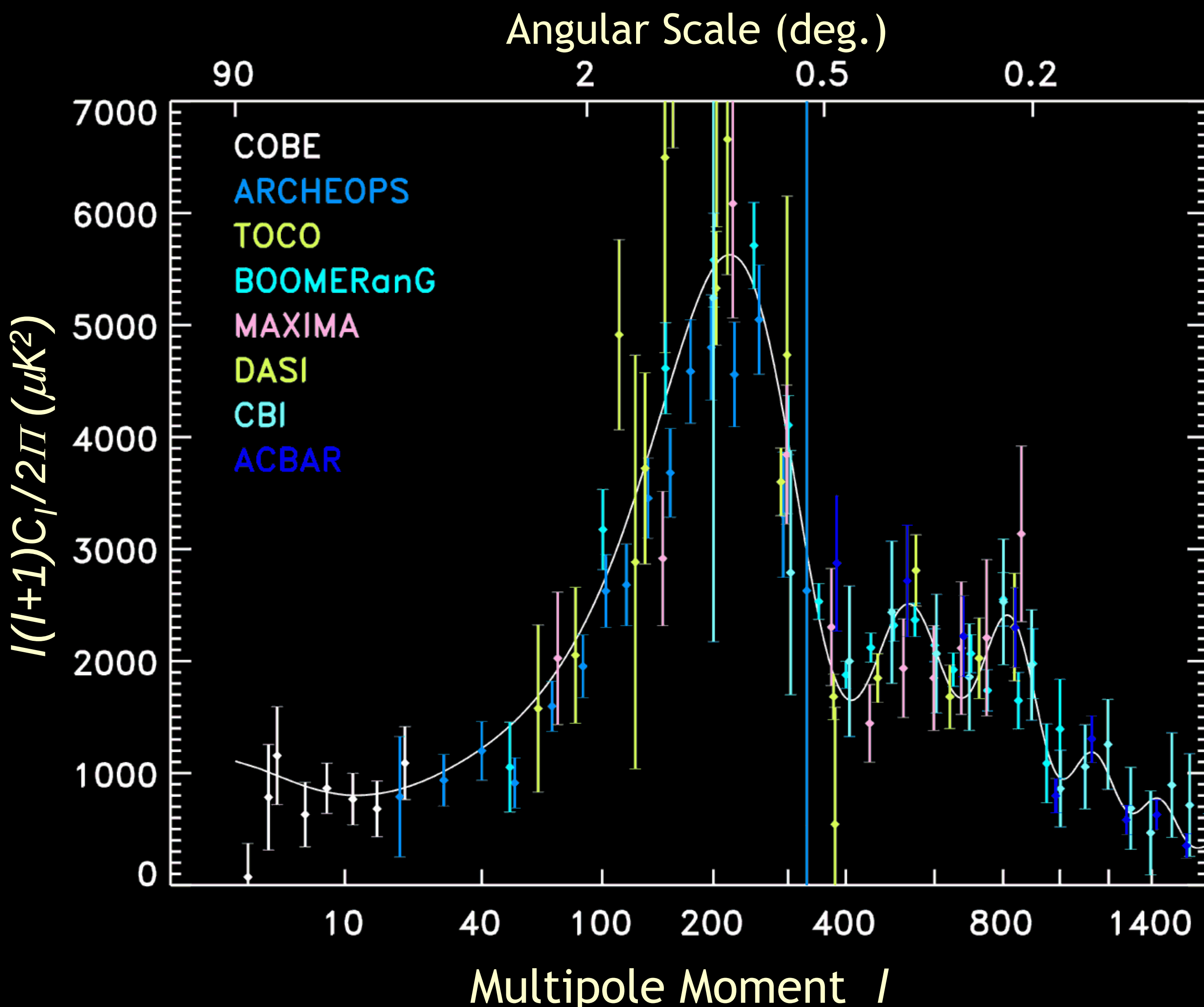


- Same results for 28 different channel combinations
- Same results for auto and cross-correlations
- Same results for different weightings, measurement schemes, foreground masks

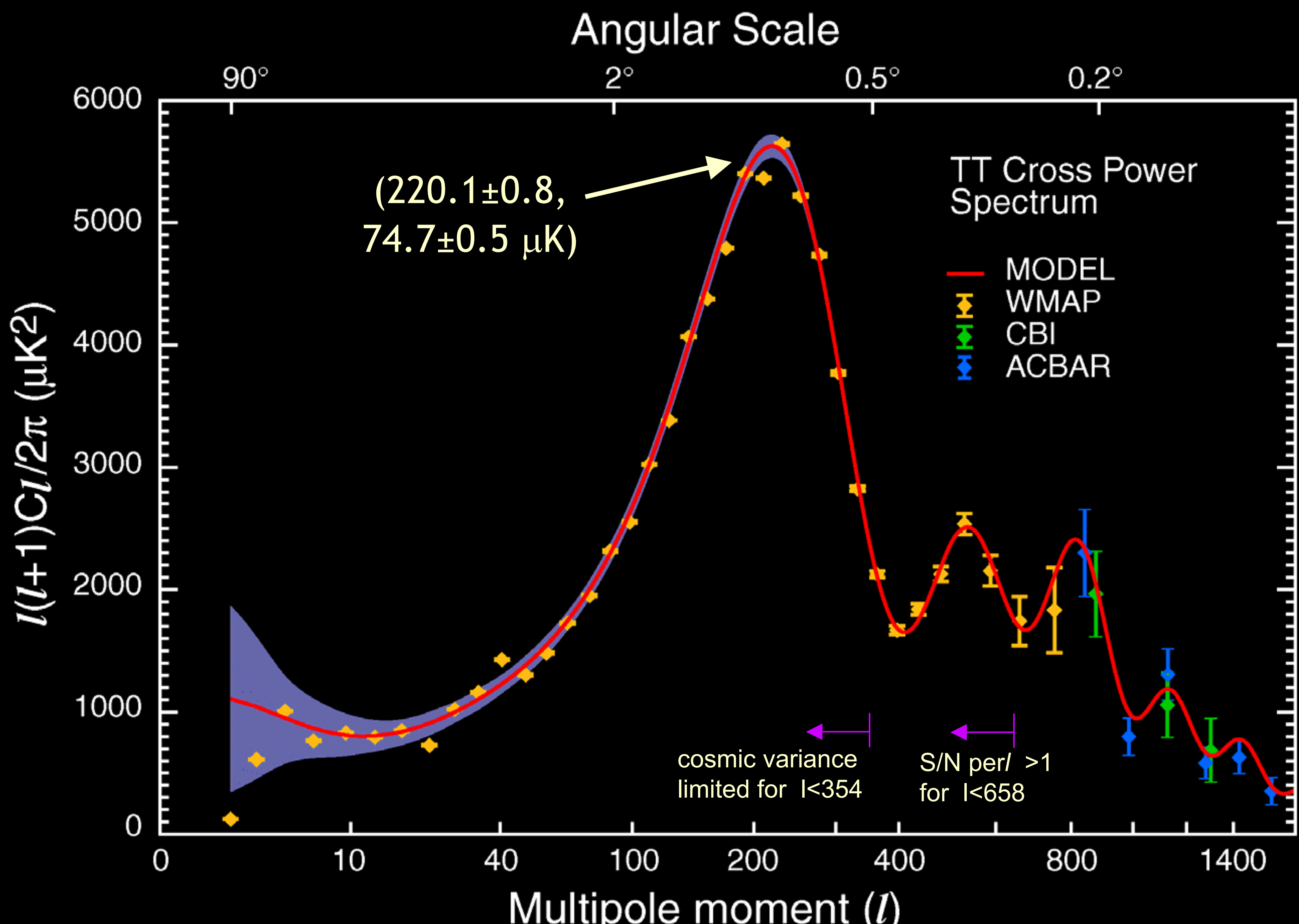
Unbinned Low-l Power Spectrum



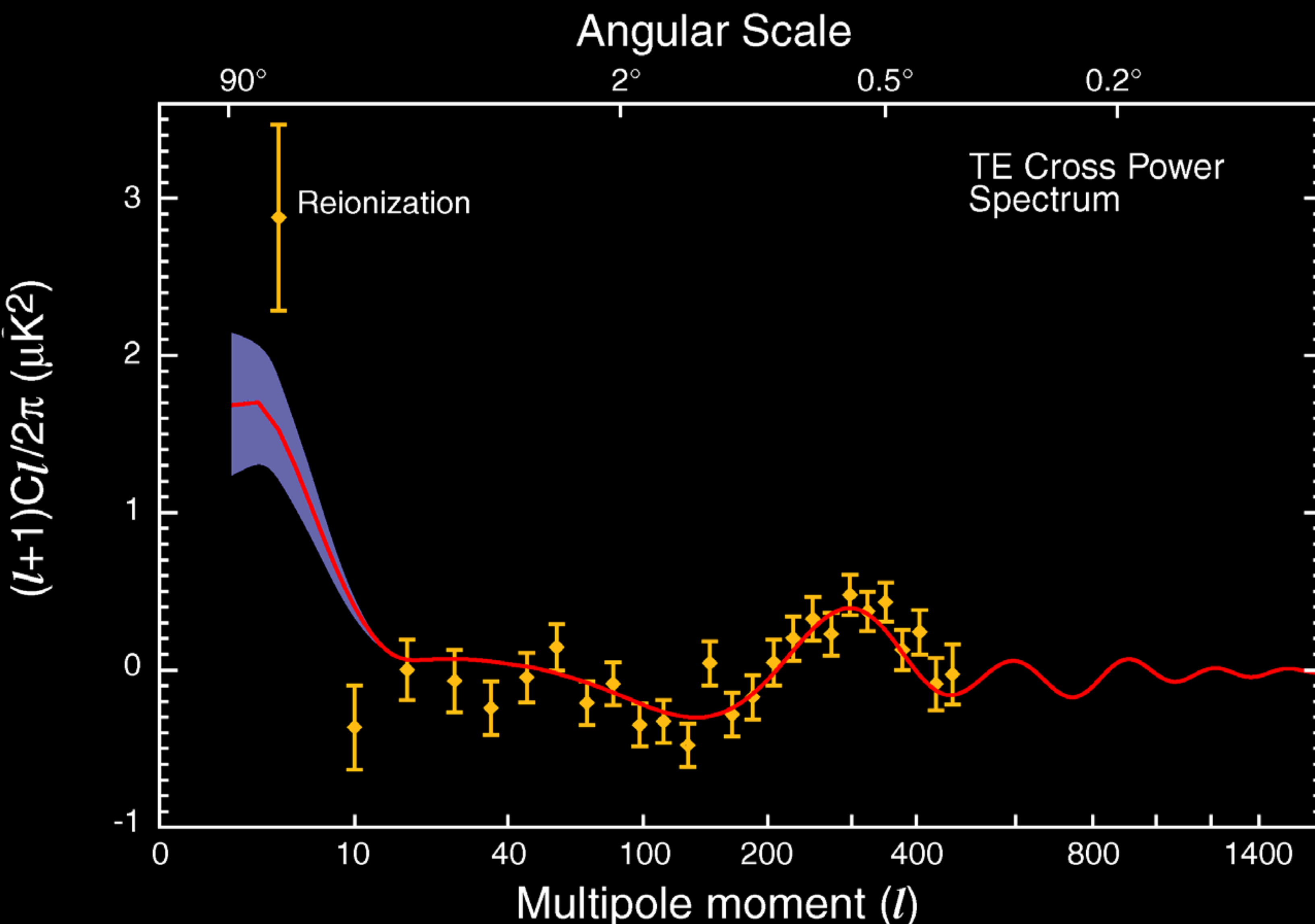
Power Spectrum: Previous CMB Measurements



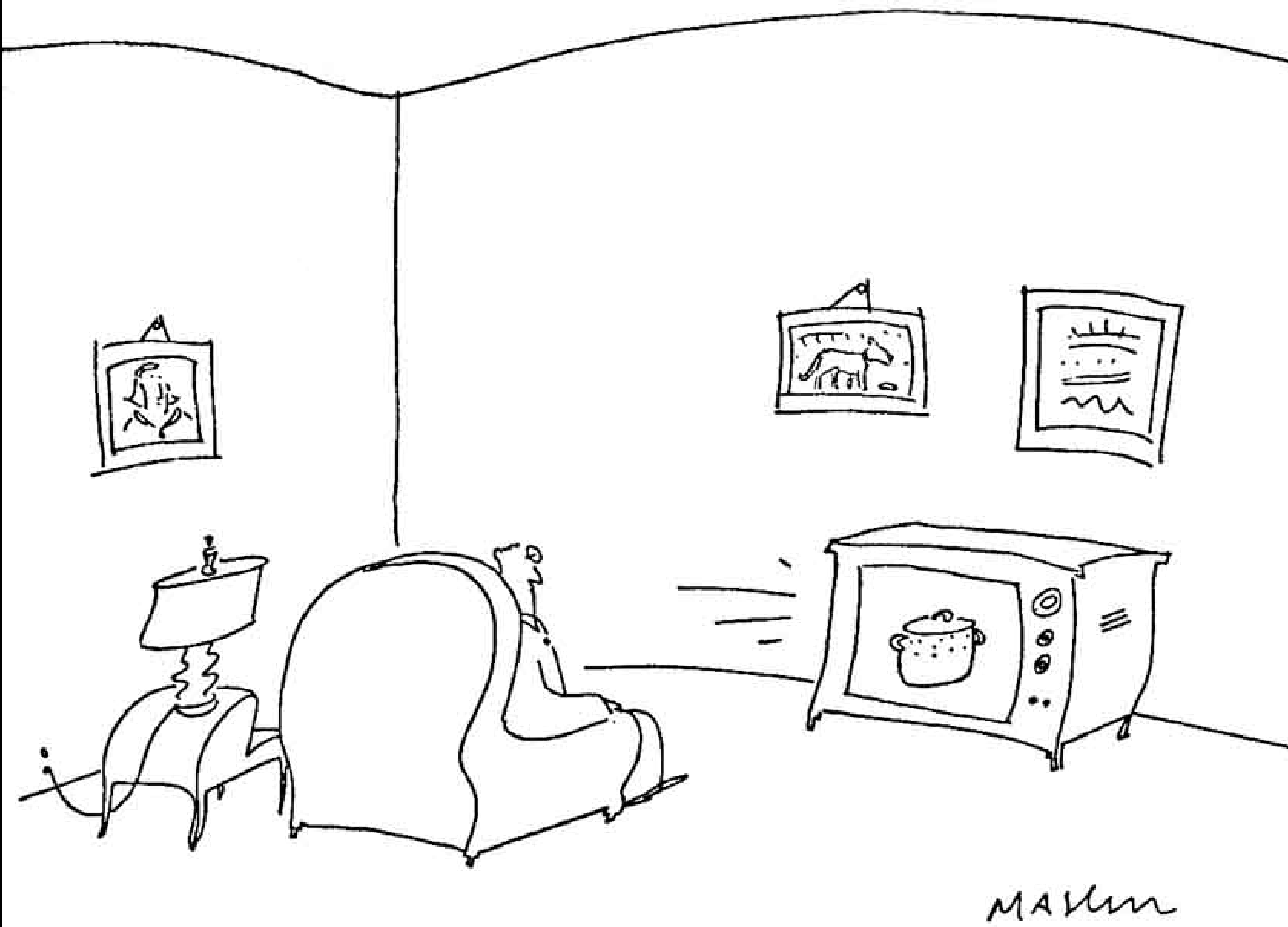
Power Spectrum



Temp x E-Polarization Power Spectrum

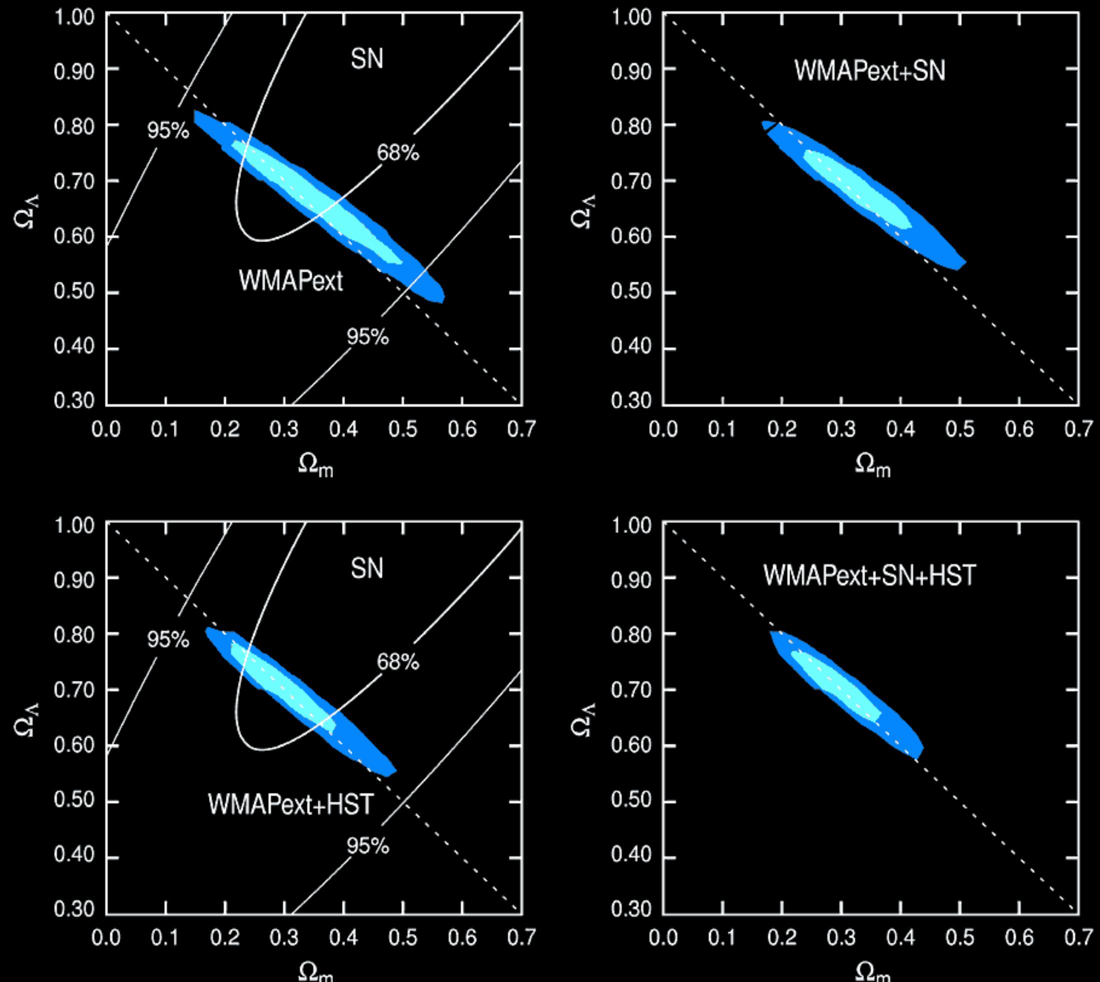


See Asantha's talk for more on physics at stake here



"How much would you pay for all the secrets of the universe? Wait, don't answer yet. You also get this six-quart covered combination spaghetti pot and clam steamer. Now how much would you pay?"

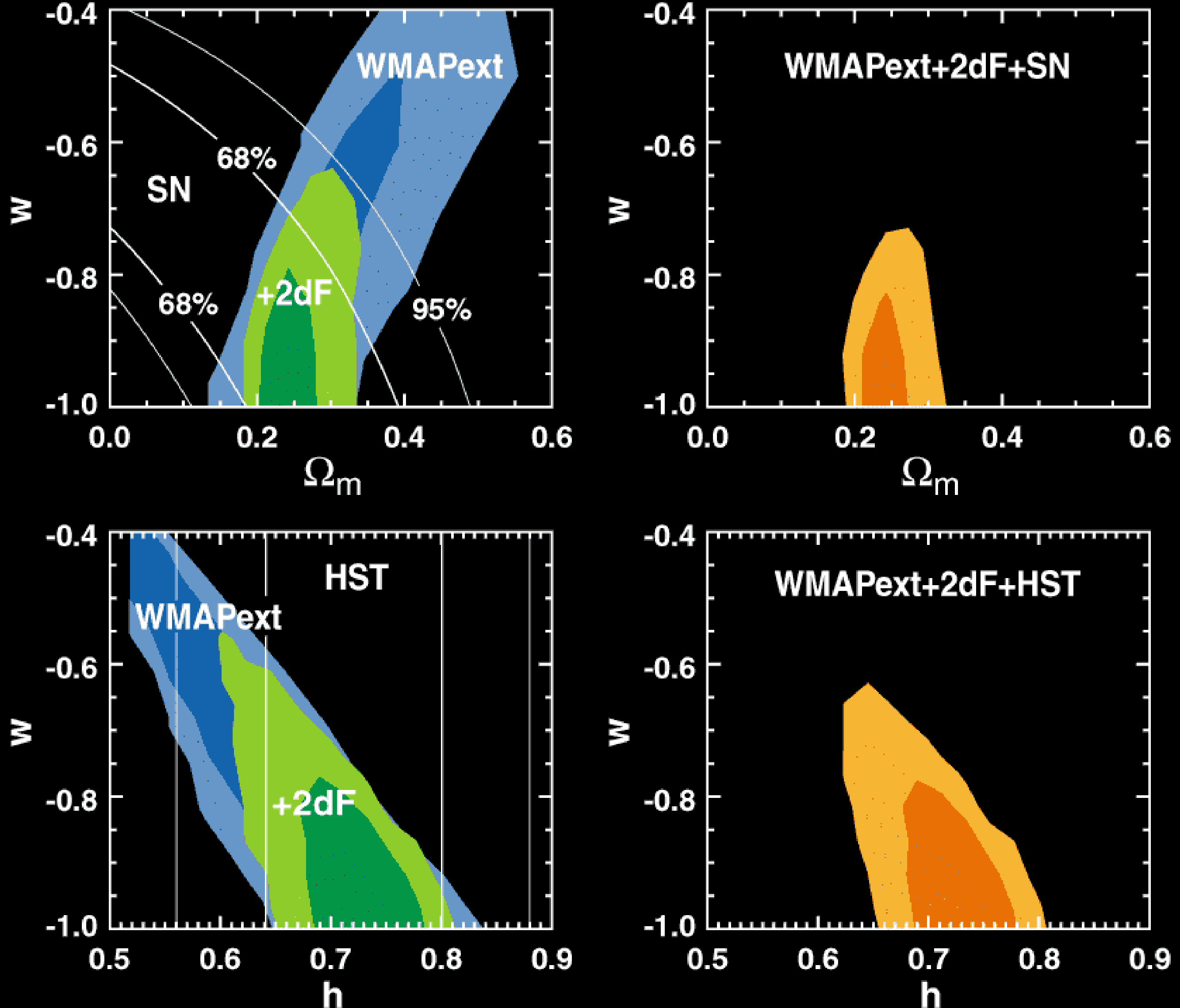
Constraining the geometry: Ω_Λ vs. Ω_m



- We here move along the D_A degeneracy
- With no priors and WMAP only model consistent but Ω_{tot}=1.28 and h=0.32
- With prior h>0.5 , WMAP alone 0.98< Ω_{tot}<1.08 (95%)
- With SN plus WMAP+CMB 0.98< Ω_{tot}<1.06 (95%)
- HST key project (72±3±7) value lead to **Ω_{tot} = 1.02±0.02**

Dark Energy Equation of State

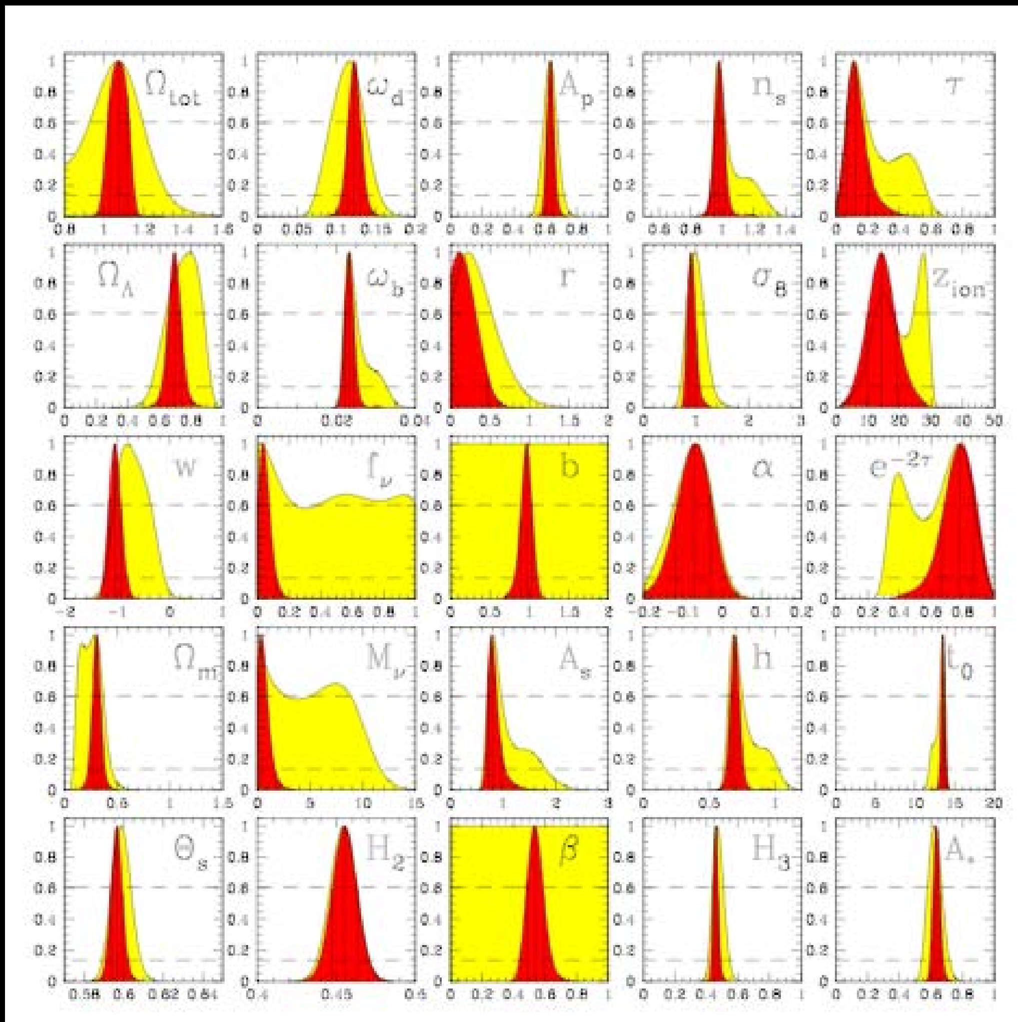
w = pressure (tension) / density = $p/\rho c^2$



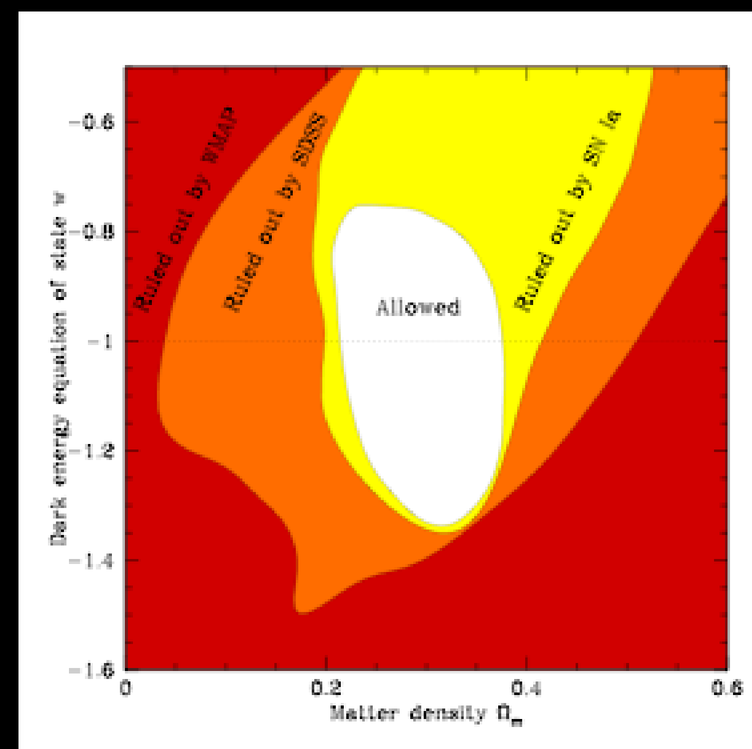
Note consistency

Ignore in these plots w<-1

SDSS + WMAP



Tegmark et al. 03



Inflation

- Flat Ω_{tot}=1.02±0.02
- $n_s \approx 1$ WMAP data only: n_s=0.99±0.04
  All combined data: n_s=0.96±0.02
  (or $dn_s / d \ln k = -0.031^{+0.016}_{-0.018}$)
- Adiabatic isocurvature modes do not improve fit
- Gaussian random phases -58<f_{NL}<134 (95% CL)
- TE anti-correlation velocities beyond horizon scale
- Tensor-to-Scalar ratio r<0.90 (95% CL)
  (at k_0 = 0.002 Mpc^{-1})

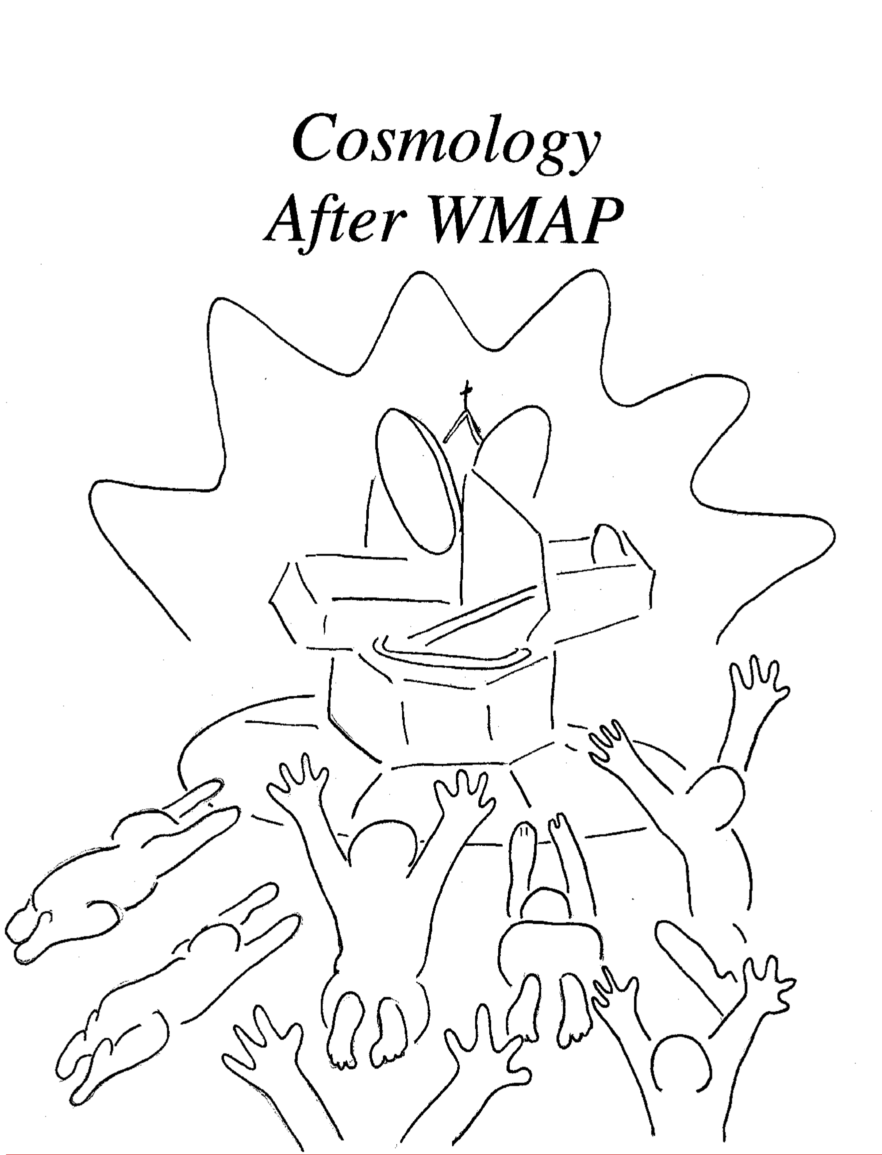
Hiranya will cover this in much greater details

Summary

- Results from 1-year survey
- First detailed (~0.2°) full-sky CMB map
- Support for Big Bang
- First measurement of TE cross power spectrum
  - Newly observed anti-correlation at l~100 is additional evidence of super-horizon velocity perturbations
  - First detection of polarization from reionization
- New limits on non-Gaussianity:

  $-58 < f_{NL} < 134$ (95% CL)
- Support for scale-invariant, adiabatic fluctuations
- Beginning to rule out specific Inflation models
- Cosmic concordance, with new accurate set of numbers
- Intriguing hints of the unexpected…?

What happened after ?



But it also receives some further scrutiny and some “anomalies” were pointed out

Various types of follow-up papers

- >600 papers since 1st data release based on WMAP results (1800 quotations each for the main 3 parameters)

- Very few people challenged the official wmap analysis (only one C_l measurements Fosalba & Szapudi 04)

- Some **refinements** of the standard cosmological analysis (more on neutrino mass, isocurvature modes, etc. (see Julien Lesgourgues talk))

- Some use of maps in conjunctions with other surveys (ISW, SZ or lensing probe)

- Some focusing on "anomalies"

    - Accepting gaussianity but focusing on the power spectrum oddities, ie looking at the amplitude $C_l=\langle a_{lm}a_{lm}^*\rangle$

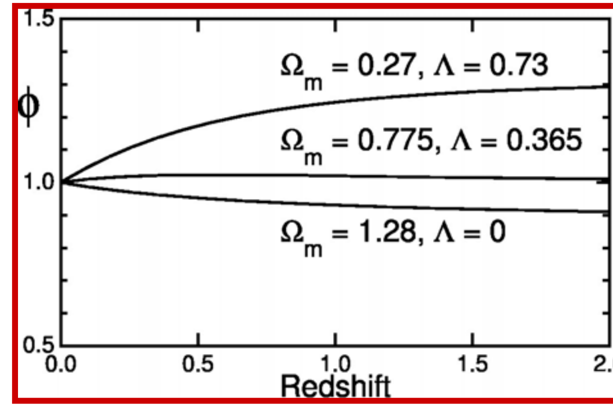
    - Several questioning validity of standard model, specifically gaussianity of fluctuations, ie investigating the phase structure of the maps, a_{lm}

Probing the Integrated Sachs-Wolfe effect with CMB x LSS

- Dark energy slows down the growth of perturbations

- CMB is sensitive to this through the Integrated Sachs-Wolfe effect (Rees-Sciama when non-linear)

$$\frac{\delta T(\hat{n})}{T_0} = -2 \int_0^{\eta_{dec}} d\eta \frac{d\Phi}{d\eta}(\eta \hat{n})$$



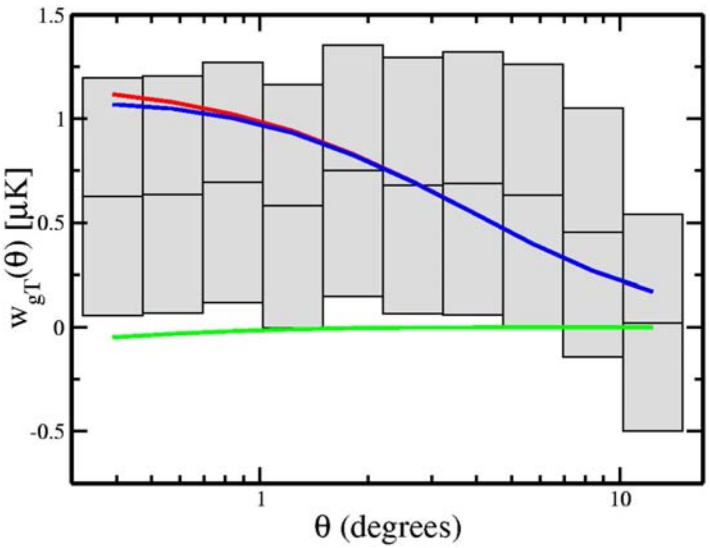
- Large scale effects because of small scales cancellations and late DE domination
- WMAP already provide the best measurements at those scales
- Difficult to measure directly from the C_l because of cosmic variance and contribution from primordial anisotropies
- But correlate with any other tracer of the potential

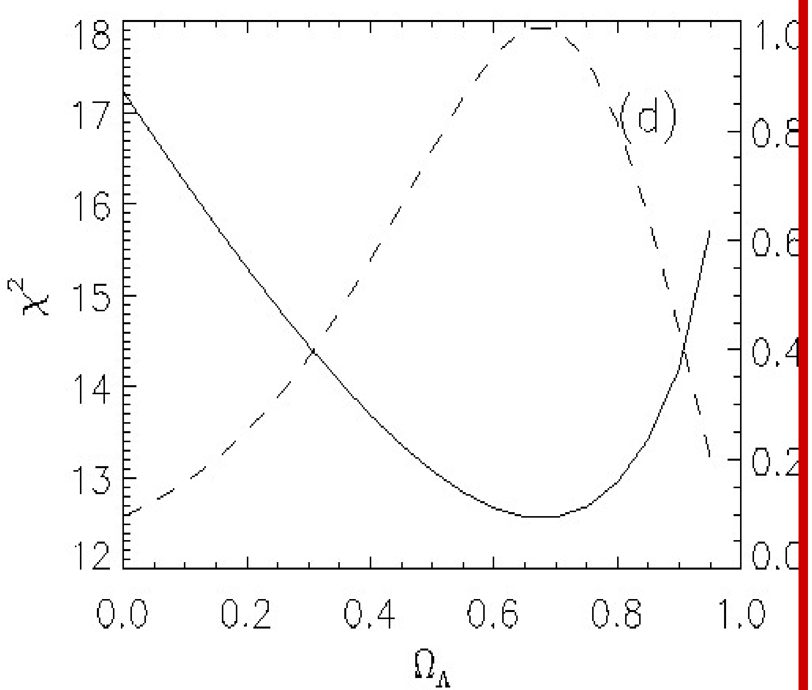
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Crittenden & Turok 96

Probing the Integrated Sachs-Wolfe effect with CMB x LSS

- Various catalogues have been used NVSS, SDSS, APM, 2MASS
- Each with about ~2σ detections and independent galaxy populations so ~6σ total
- Currently limited by galaxy surveys coverage and uncertainties





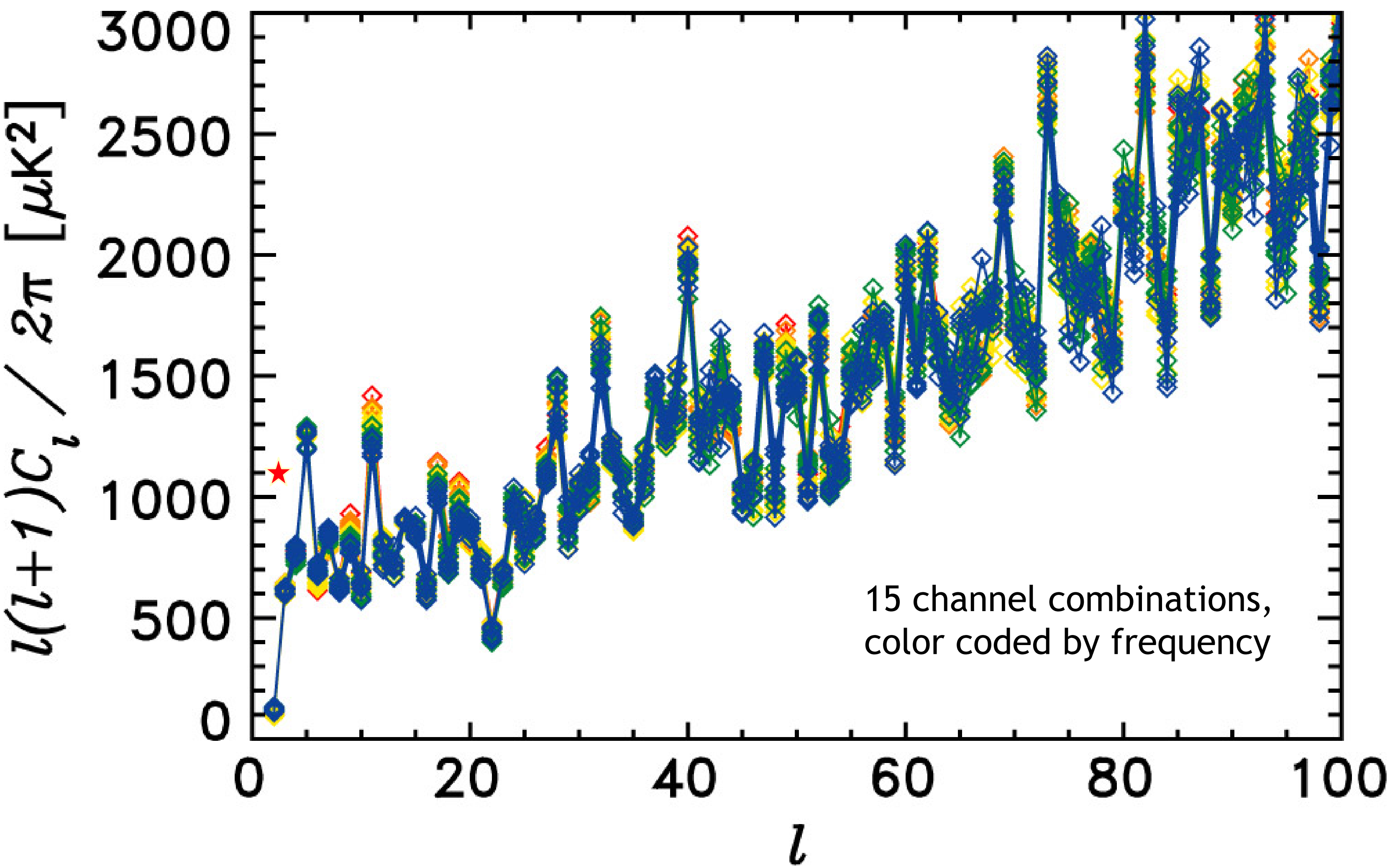
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Nolta *et al.* 03, Scranton *et al.* 03, Fosalba *et al.* 03, etc

“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: low *l*, un-binned



Low Quadrupole Power

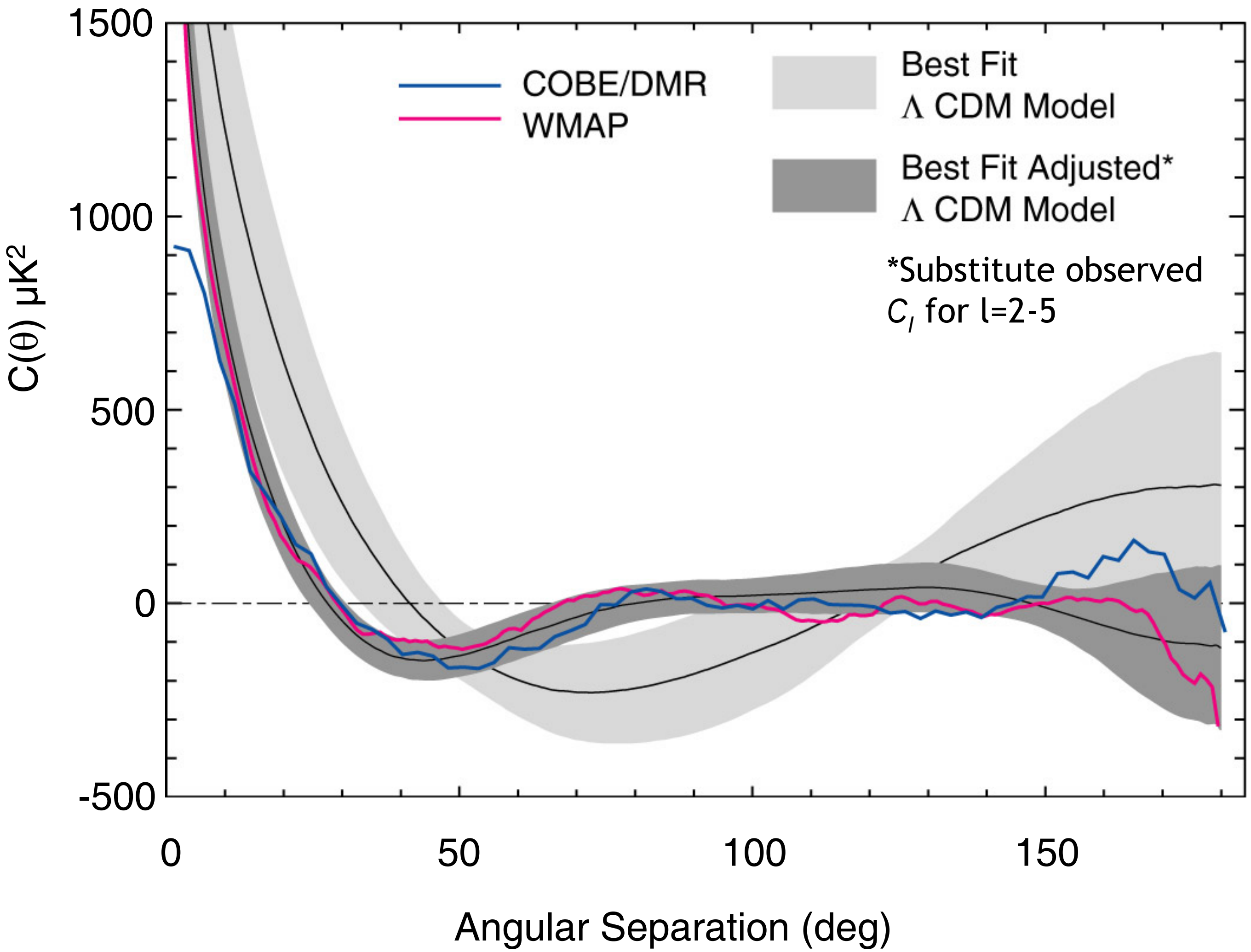
- Expected (mean) values for selected best-fit ΛCDM models -
  - Pure power-law, WMAP+CBI+ACBAR: 1221 μK^{2*}
  - Running index, WMAP+CBI+ACBAR: 870 μK^2
  - Power-law, CMB+2dF+Ly-α: 1107 μK^2

- 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.

2-pt Correlation Function



*WMAP C(θ) computed from Linear Combination map, Kp0 cut

Definition:*

$$C(\theta) = \langle T(n_i) T(n_j) \rangle$$

$$n_i \cdot n_j = \cos\theta$$

Posterior statistic:

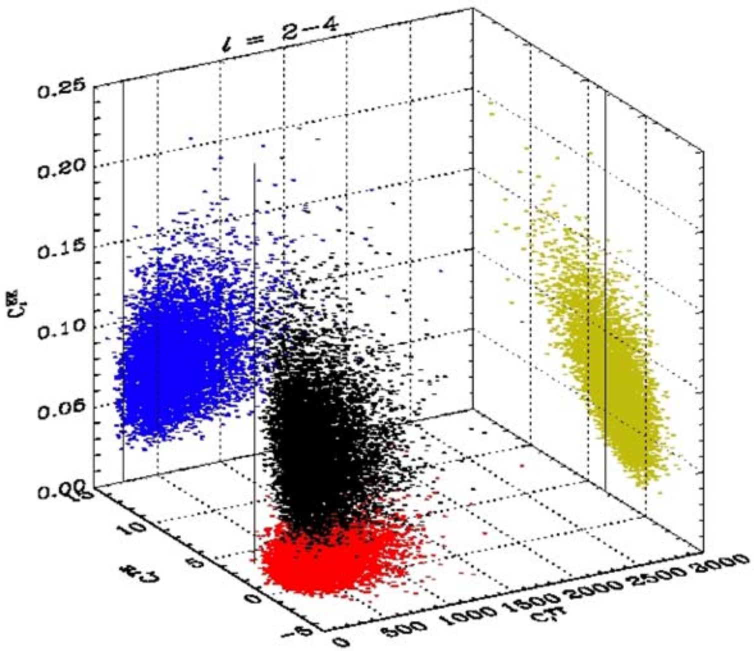
$$S = \int_{60^\circ}^{180^\circ} C(\theta)^2 d\theta$$

Likelihood of low *S* for best-fit LCDM:

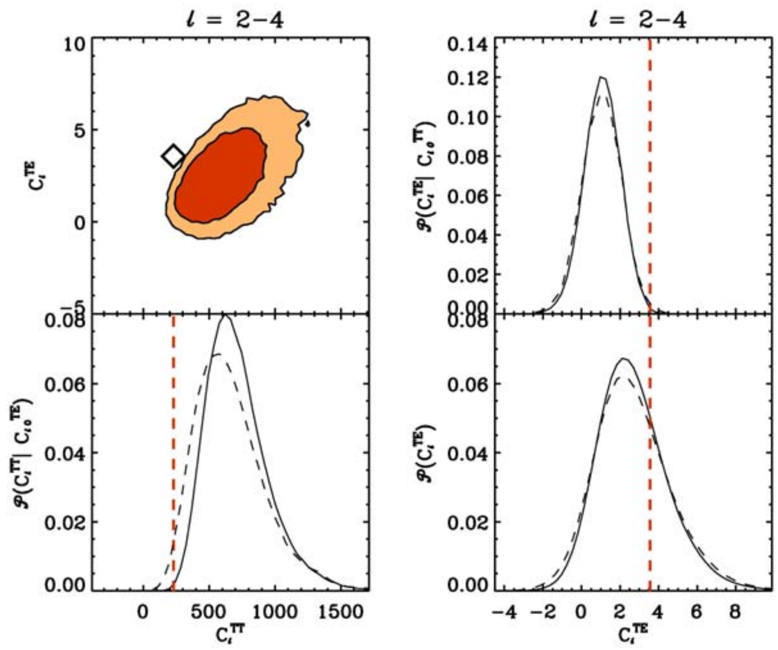
0.15%-0.3%

(Spergel et al. ApJS, 148, 175, 2003)

The quadrupole on a polarized light



- You can 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}
- It turns out that there are discrepant at high significance
- Foregrounds issues at low *l*



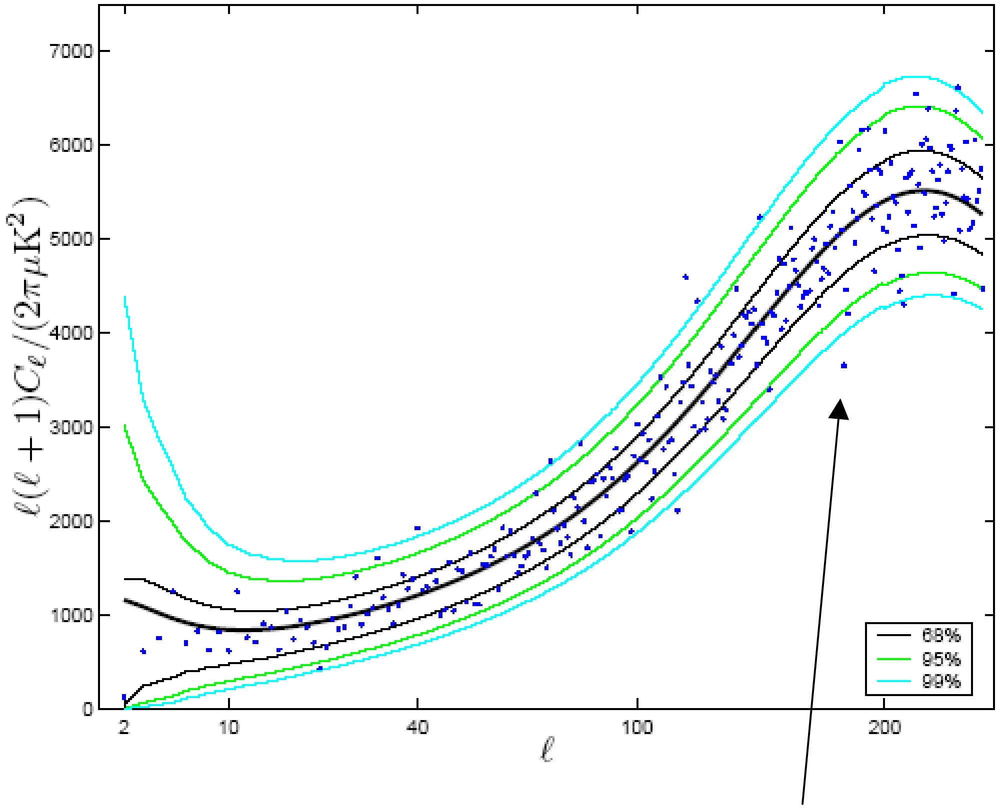
Doré, Holder & Loeb 03

Hint for new physics ?

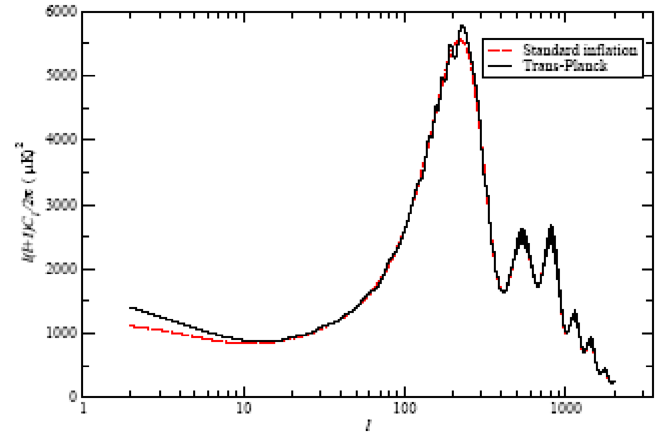
- If we consider this low COBE/WMAP quadrupole significant, then one has to come with some new physical explanations

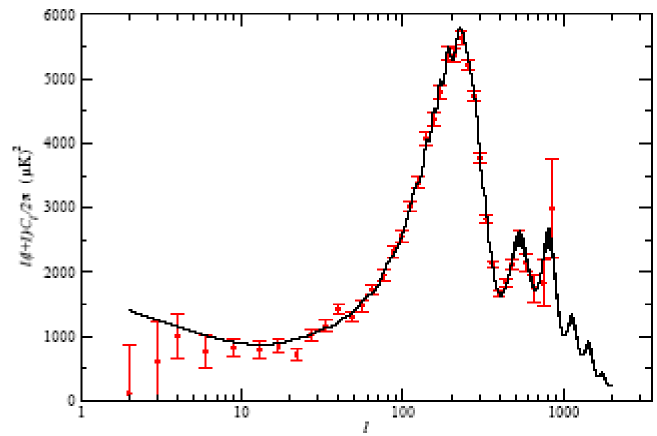
- Various physical mechanism to truncate the power at large scales has been proposed
  - Closed Universe with a P(k) truncation corresponding to the curvature scale (Eftshatiou 03, Uzan *et al*. 03)
  - Arbitrary truncation scale in the primordial P(k) inflation motivated (Contaldi *et al*. 03), scale which appearsnaturally if you try to reconstruct the primordial power spectra (Lewis et al. 03)
  - DE clustering (Hu 99, Bean & Doré 03)
  - …

More Power Spectrum Outliers



WMAP team noted outlying features in 1st year spectrum -- adopt "wait and see" attitude. 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).





Martin & Ringeval (astro-ph/0310382) fit toy trans-Planckian model to spectrum: $\Delta\chi^2 = 16$ for 3(?) parameters (initially $r\chi^2$ = 1431/1342=1.07 vs $r\chi^2$ =1415/1340=1.06)

Note talk by Hiranya for more on the trans-planckian effects in CMB

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)

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

where Φ is gravitational potential

(see Sabino Matarrese talk)

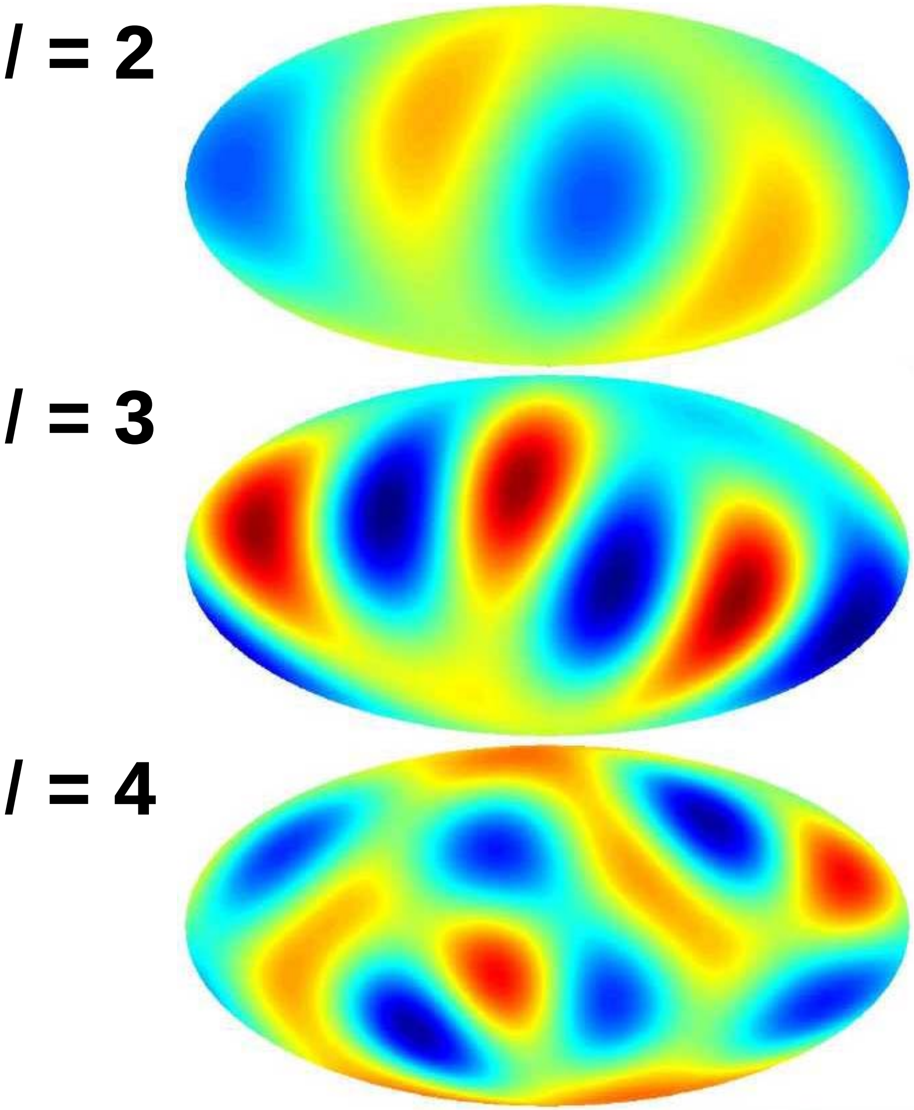
• Current best limit from WMAP alone using bispectrum or Minkowski functionals are

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

• Worth noting that is by nature a delicate measurements since the maps ARE non-gaussian 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:

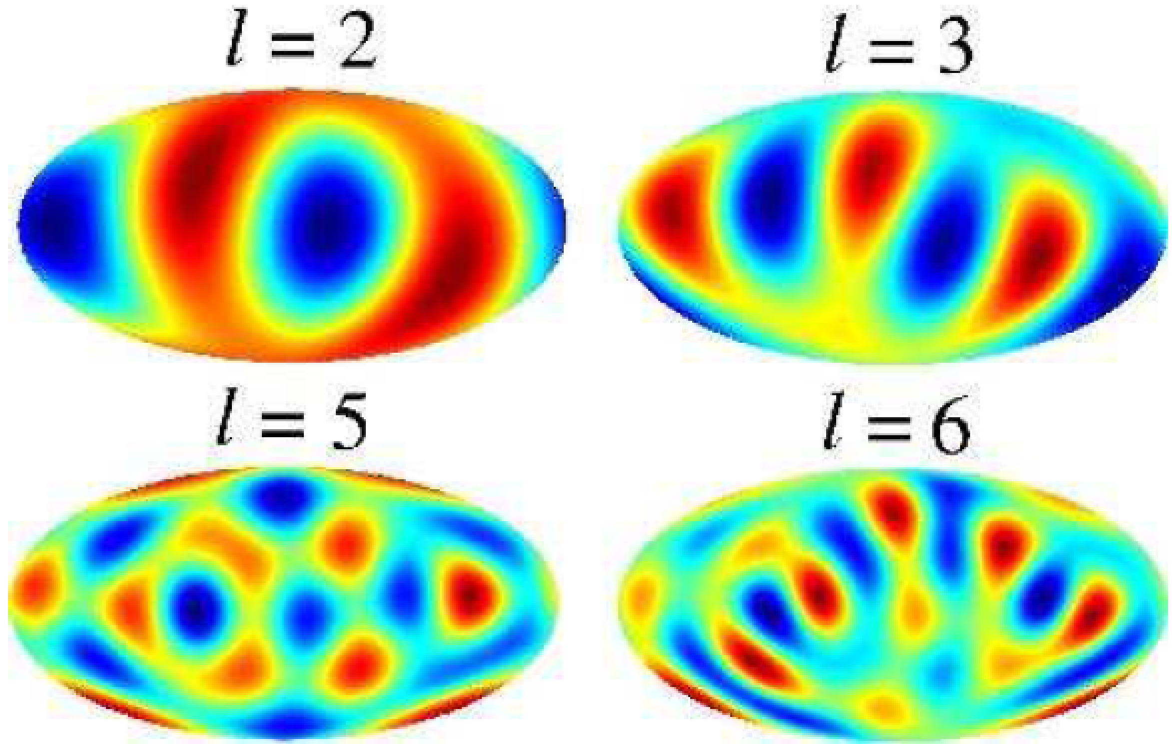
  - Low power at the lowest *l* =2,3
  - Tegmark et al. (astro-ph/0302496) note alignment of l=2,3 moments.
  - Power concentrated in plane ~30˚ from the Galactic plane: $m=\pm l$ in suitable coordinate system.

- de Oliveira-Costa et al. (astro-ph/0307282) estimate the probability of the combination: low quadrupole + alignment + "planarity":

  $\sim 4 \times 10^{-5}$

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

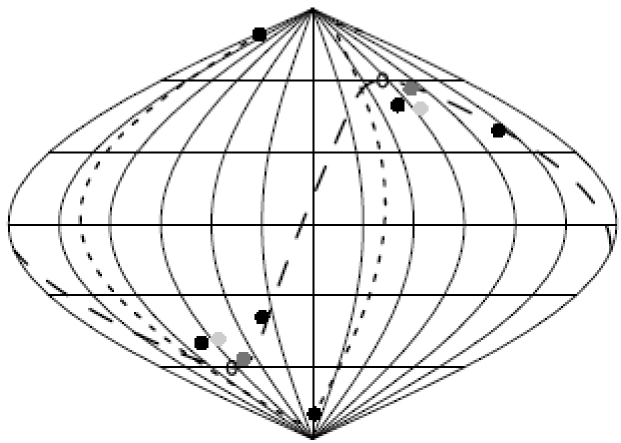
Alignment of Low *l* Power - II

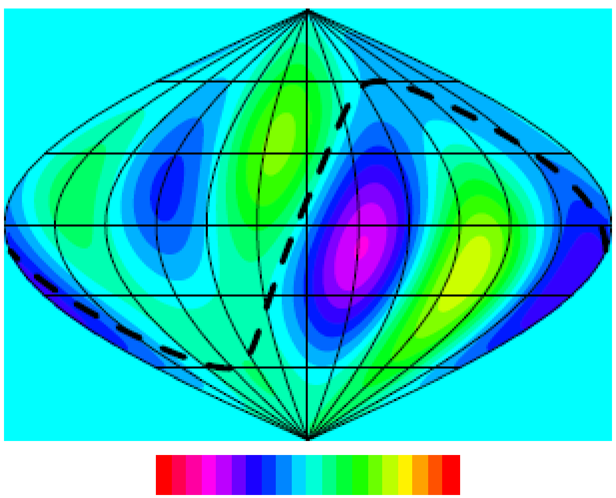


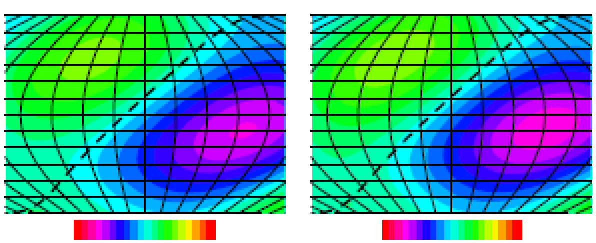
Eriksen et al. (astro-ph/0403098) study Galaxy removal using WMAP team's internal linear combination (ILC) method. While cautious, they note alignment of l=2,3 moments and further note the "spherical symmetry" of *l*=5 (~3σ) and the "planarity" of *l*=6 (~2σ), as measured by concentration of power in $a_{l\pm l}$ in a particular coordinate frame:

$$t = \max \ \mathrm{R}\left(\frac{|a_{l-l}|^2 + |a_{ll}|^2}{\sum_m |a_{lm}|^2} \right)$$

Alignment of Low *l* Power - III







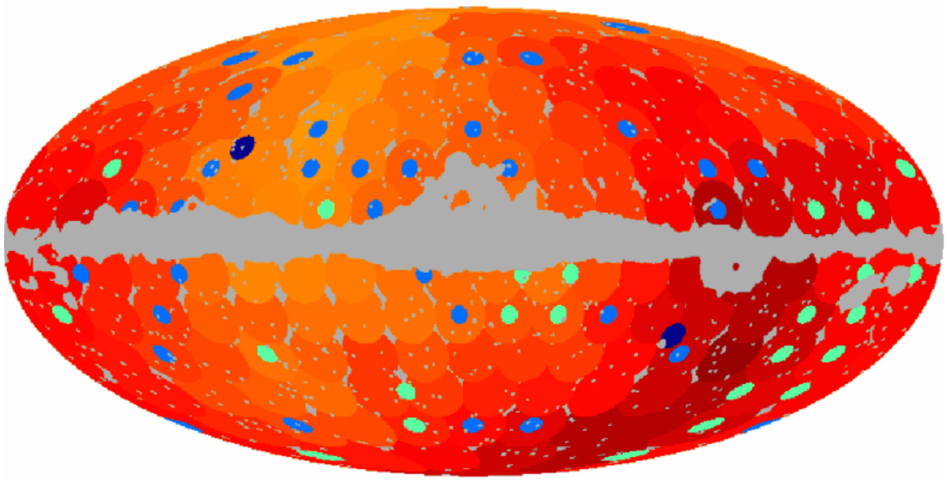
Schwarz et al. (astro-ph/0403353) also note alignment of l=2,3 moments with each other and with: a) the ecliptic coordinate frame, b) the vernal equinoxes, and c) the CMB dipole axis. Significance > ~99.9% is claimed.

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



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

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

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:

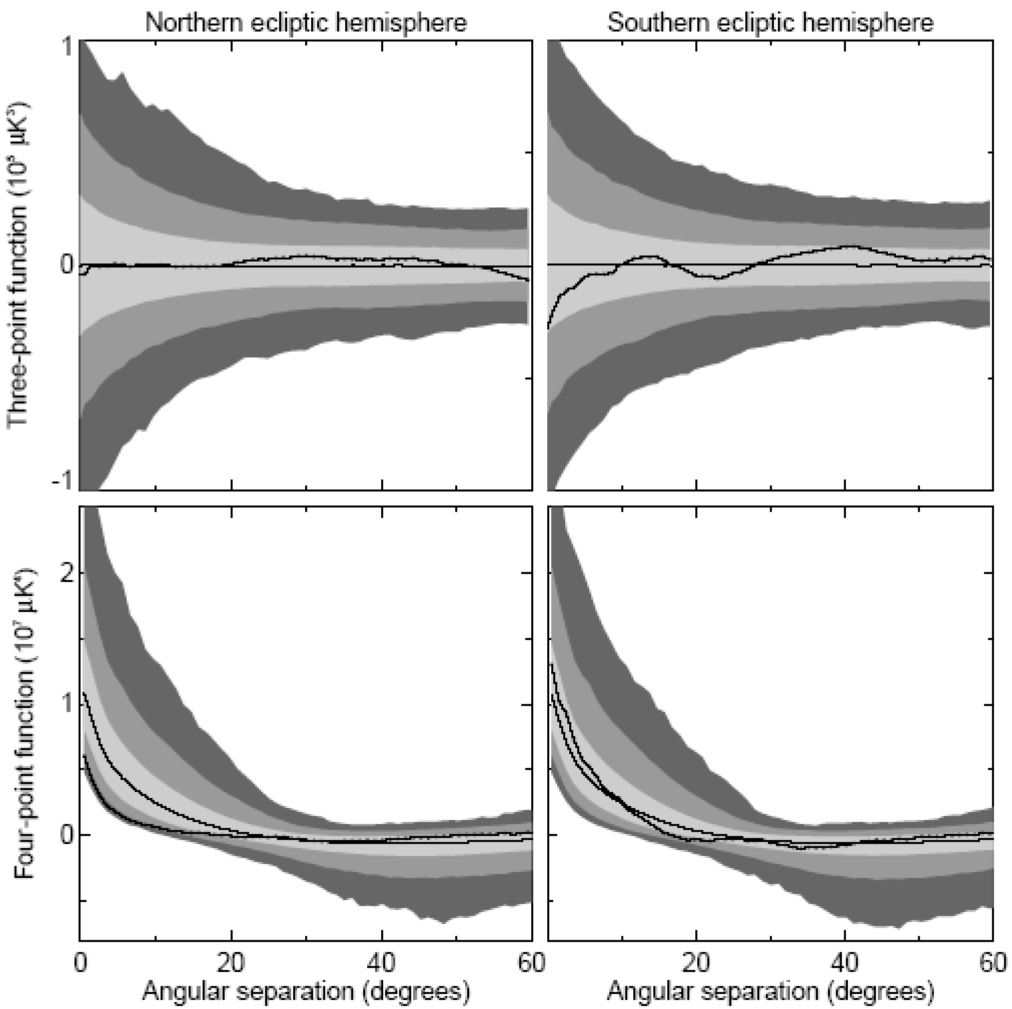
$$R = \frac{\left\langle \Delta T_l^2 \right\rangle_{l=2-34}^{(north)}}{\left\langle \Delta T_l^2 \right\rangle_{l=2-34}^{(south)}}$$

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)

Asymmetry of low *l* Power



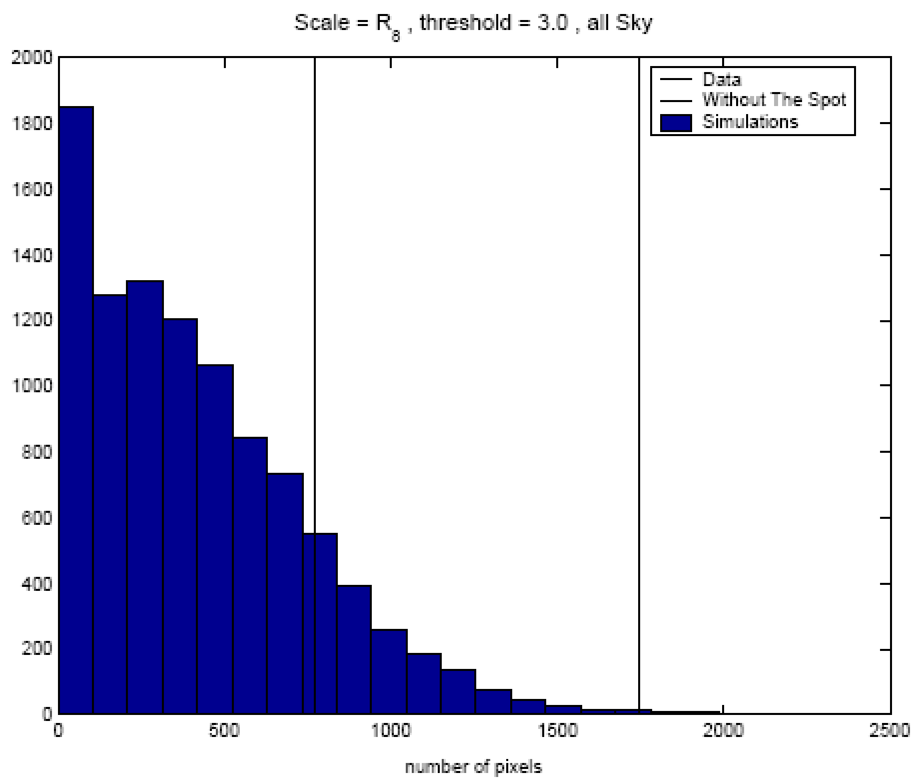
Eriksen et al. (astro-ph/0307507) also note asymmetry of *n*-point correlation functions computed in ecliptic hemispheres.

Northern ecliptic hemisphere has less 3-point (skewness) and 4-point (kurtosis) amplitude than in the south, as measured by a χ^2 ratio statistic:

Only ~2% of simulated skies have as low a 3-point χ^2 ratio, and only ~0.2% of simulations have as low a 4-point χ^2 ratio.

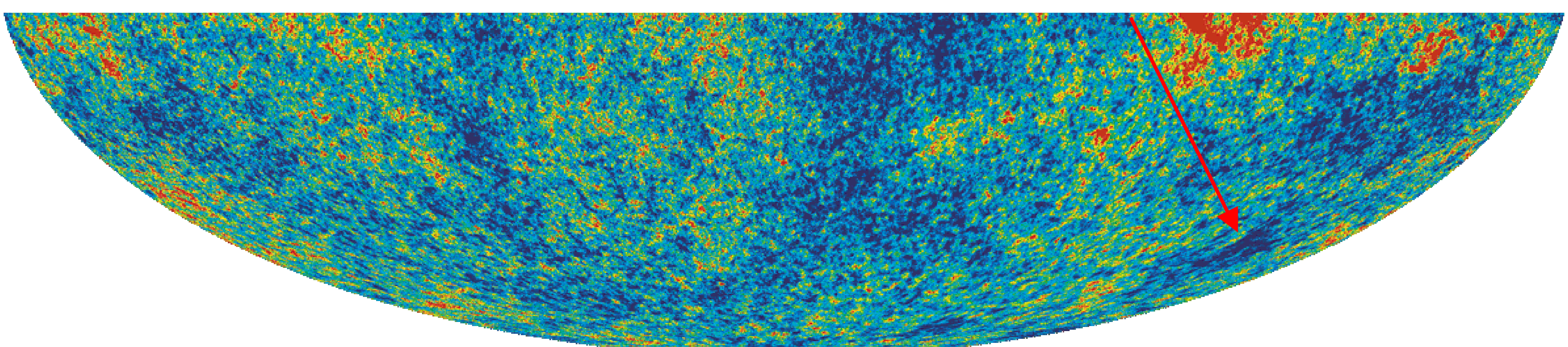
Also Land & Magueijo further discuss "Cubic Anomalies in WMAP": see afternoon talk.

A Big, Cold Spot



Vielva et al (astro-ph/0310273) and Cruz et al. (astro-ph/0405341) perform a Spherical Mexican Hat Wavelet (SMHW) analysis of the 1^{st} year WMAP data. They find significant deviation from gaussian, random-phase hypothesis on scales of 10° on the sky.

They isolate a spot (~10° in size) centered at (l,b) = (209°,-57°) as the main source of the deviation, at ~99.8% CL.



Another question we could ask

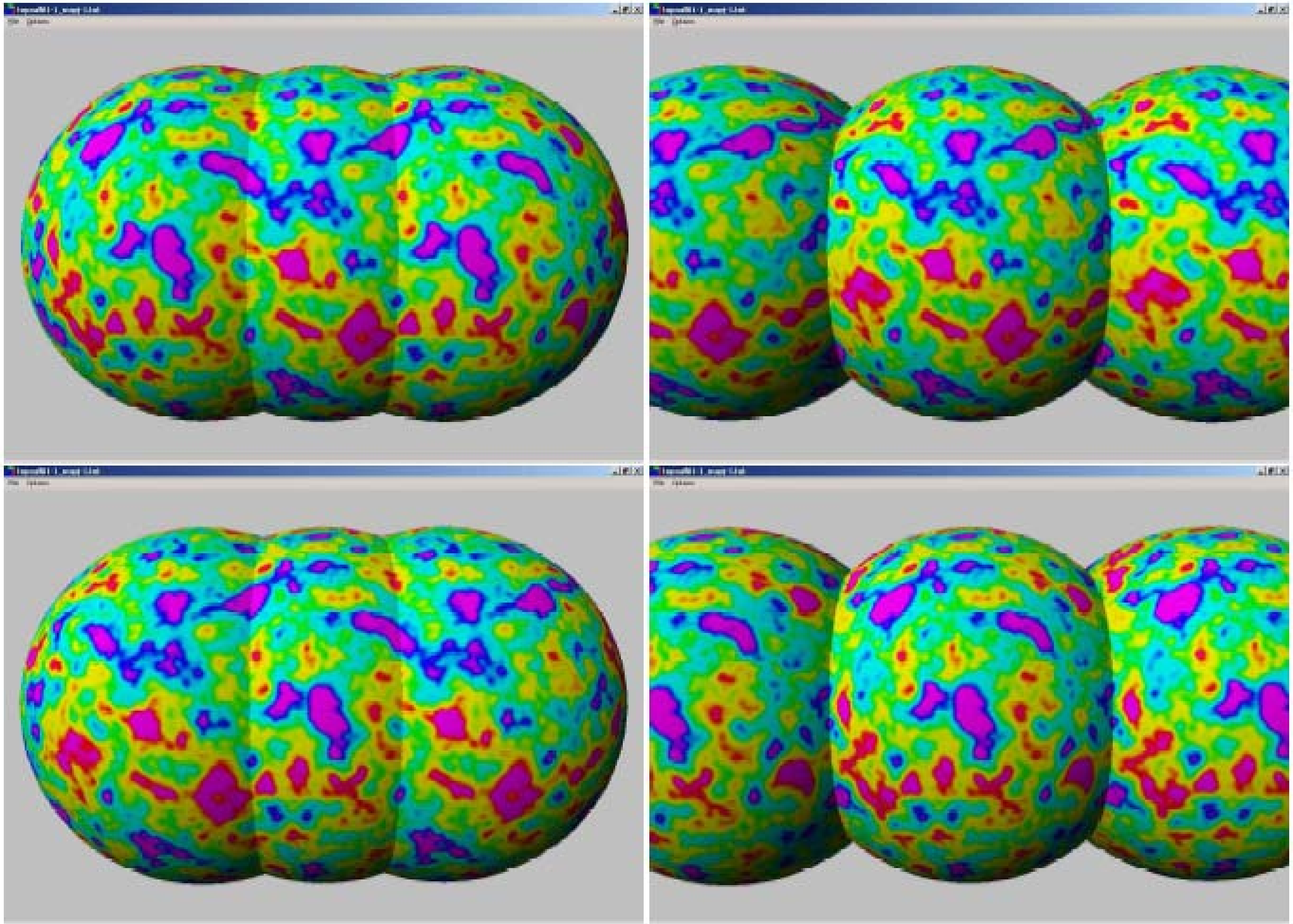
- What is the likelihood of seeing the initials of Stephen Hawking imprinted on the sky ?

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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?
  - Compact topologies?
  - String/brane - inspired models?
  - Holographic information bounds?
  - 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

Compact Topologies



Compact topology models have been weakly motivated by the data, but mostly studied because they are cool and of course theoretically sound.

Many models of multi-connected topologies predict one or more pairs of matched circles in the CMB sky temperature.

Riazuelo et al., astro-ph/0311314

Circle Search in WMAP

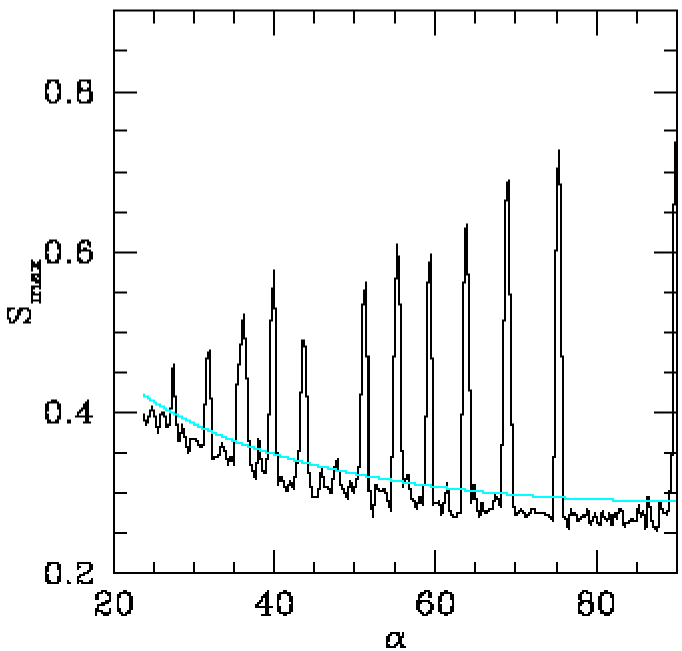


FIG. 1: The maximum value of the circle statistic as a function of radius, α, for a simulated finite universe model. The peaks in the plots correspond to positions of matched circles. The cyan line corresponds to the detection threshold discussed below. α is measured in degrees in all figures. $S_{max}(\alpha)$ is the best match value found at each radius.

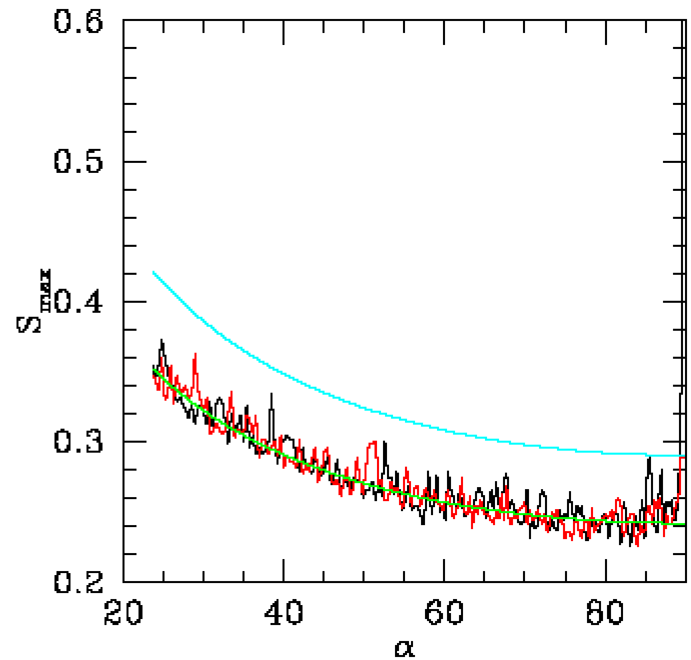
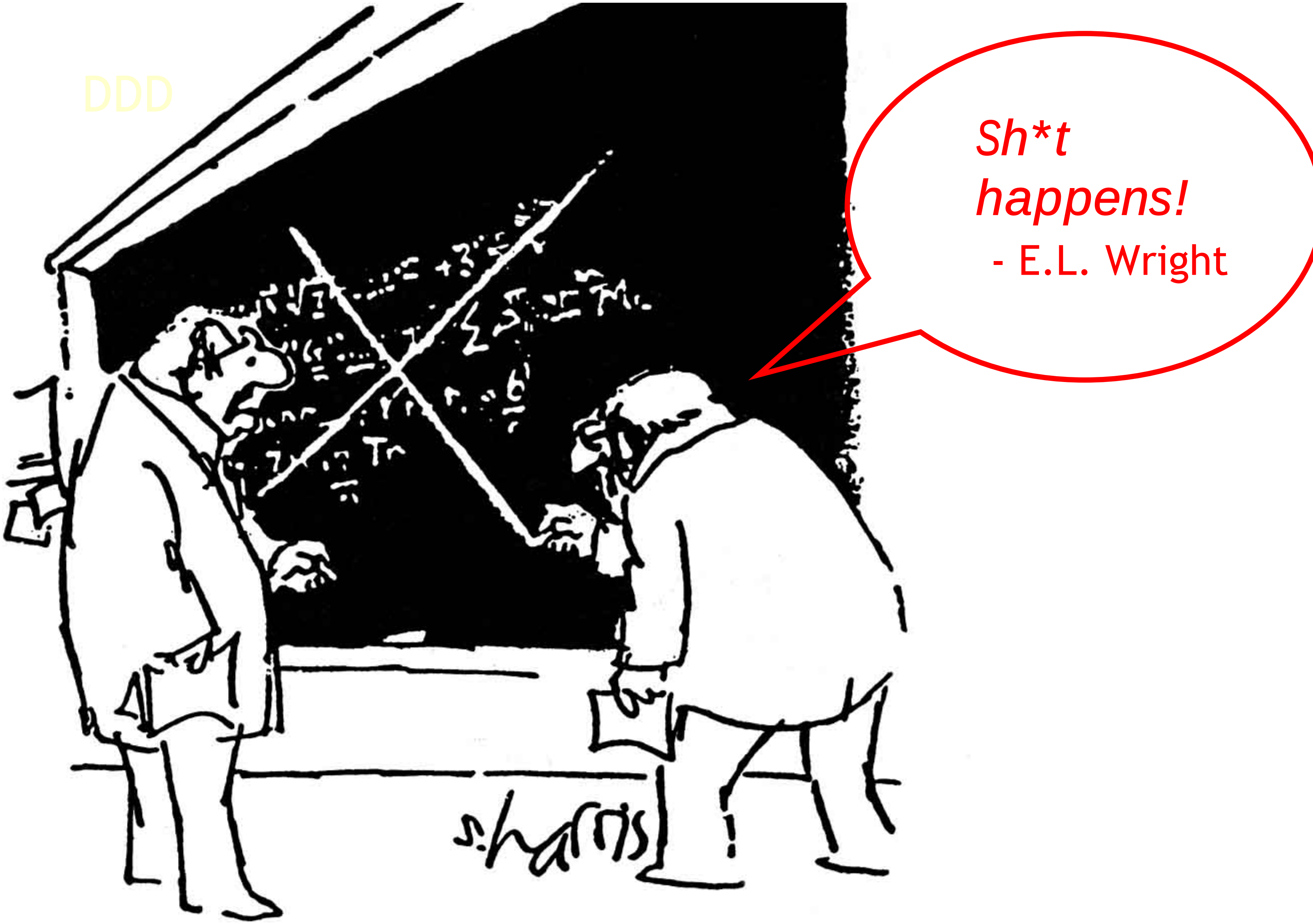


FIG. 3: The maximum value of the circle statistic as a function of radius for the *WMAP* data for back-to-back circles. The solid line in the figure is for a orientable topology. The red line is for non-oriented topologies. The green line is the expected false detection level. The cyan line is the detection threshold. The spike at 90° is due to a trivial match between a circle of radius 90° centered around a point and a copy of the same circle centered around its antipodal point.

Cornish et al. (astro-ph/0310233) performed a comprehensive circle search with null results.



"That's it? That's peer review?"

Future Plans

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

- Two-year data release is "soon" (ASAP!):
  - Temperature and polarization maps
    - 5 bands, full-sky, (yr1, yr2 & 2yr), (N_{side}=512, N_{side}=1024)
  - 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, DASI, CAPMAP

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

"You can't keep running in here and demanding data every two years!"

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.


THE END