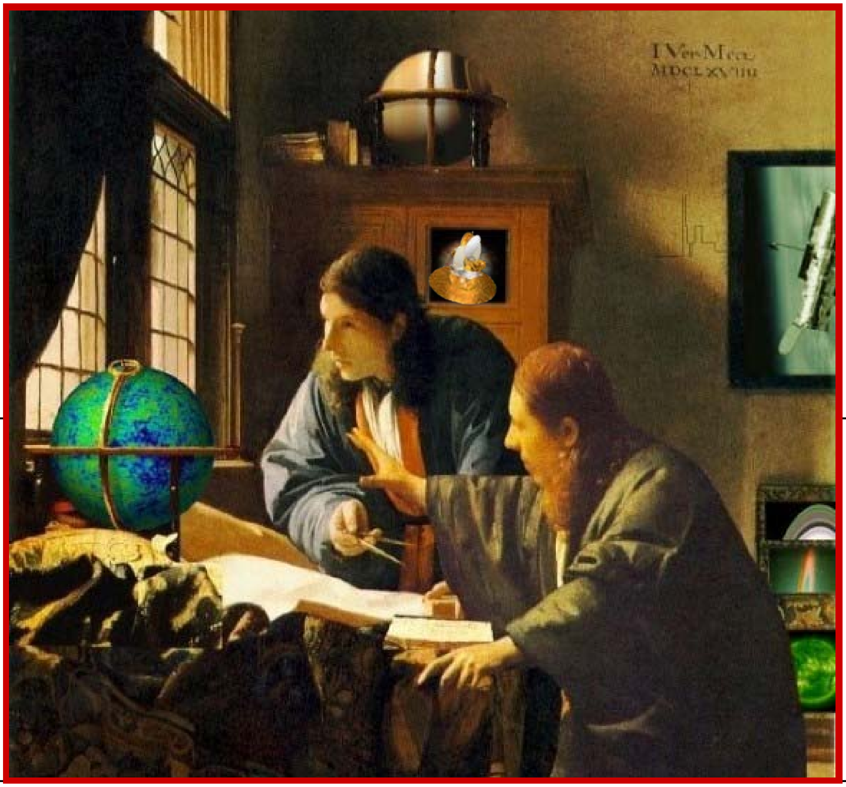
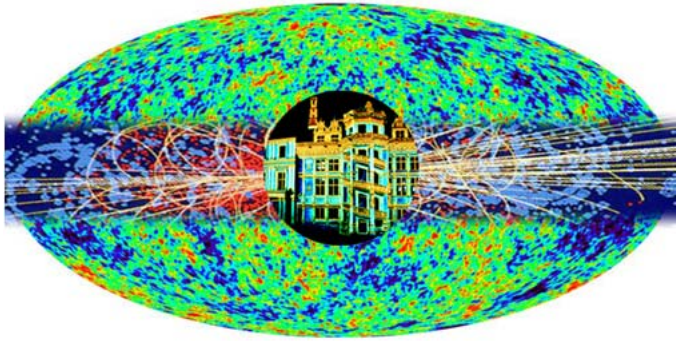
Observing the Cosmic Microwave Background - 7-year Results from WMAP

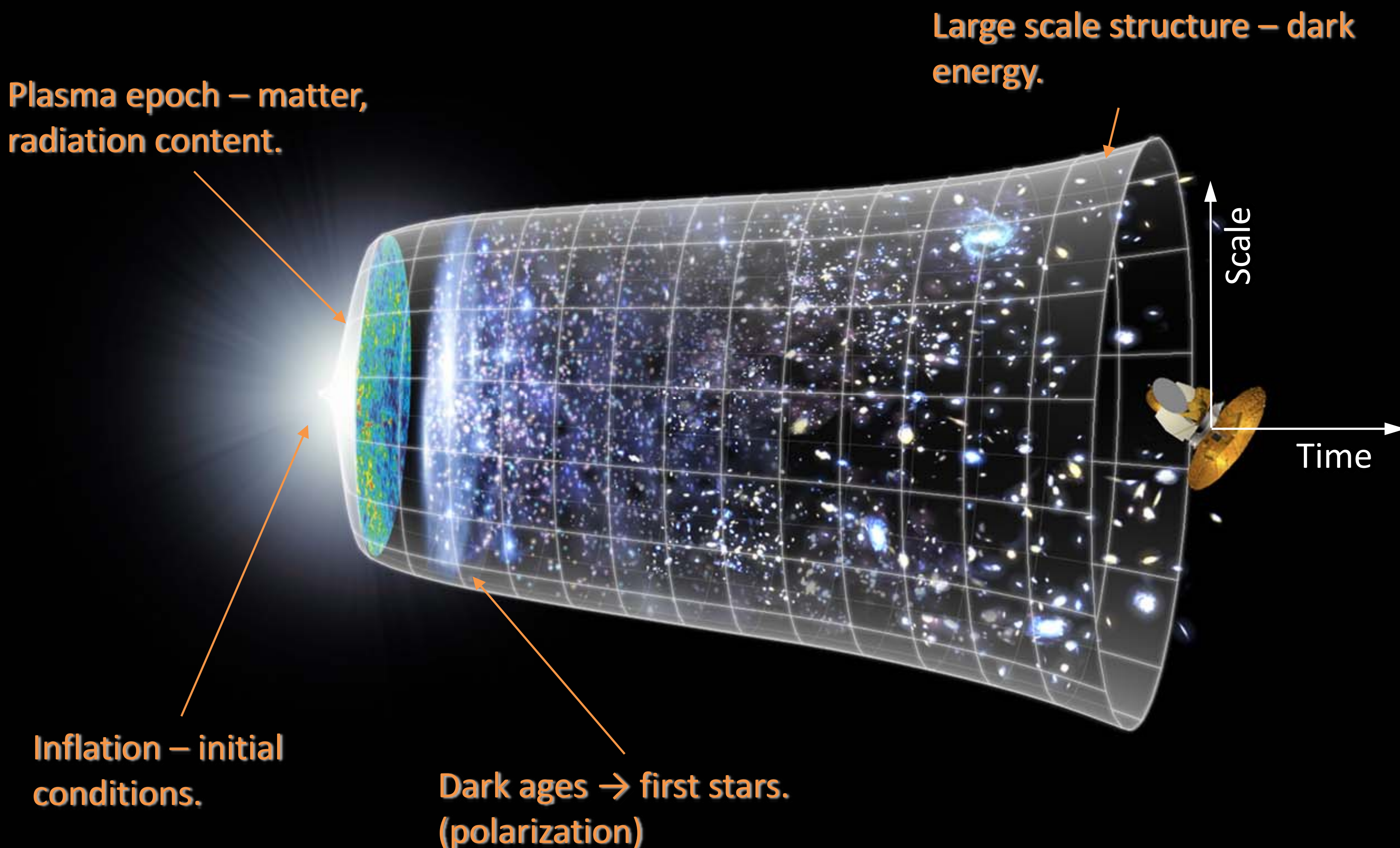




Gary Hinshaw NASA/GSFC

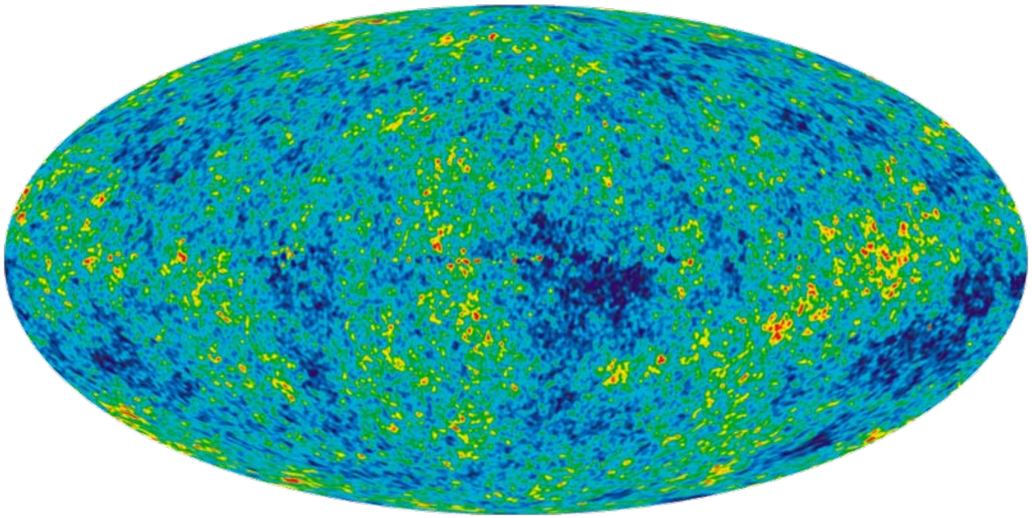
20 July 2010 XXII[nd] Rencontres de Blois, Particle Physics & Cosmology

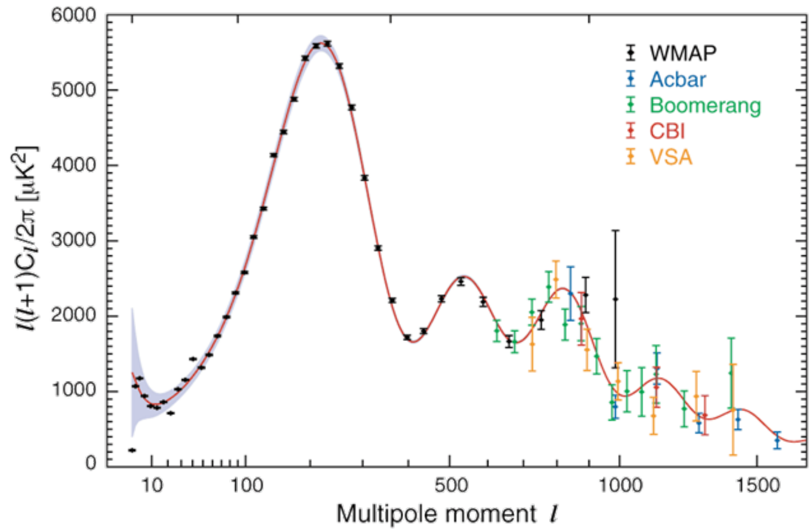
Why the CMB?



It is the oldest light in the Universe.

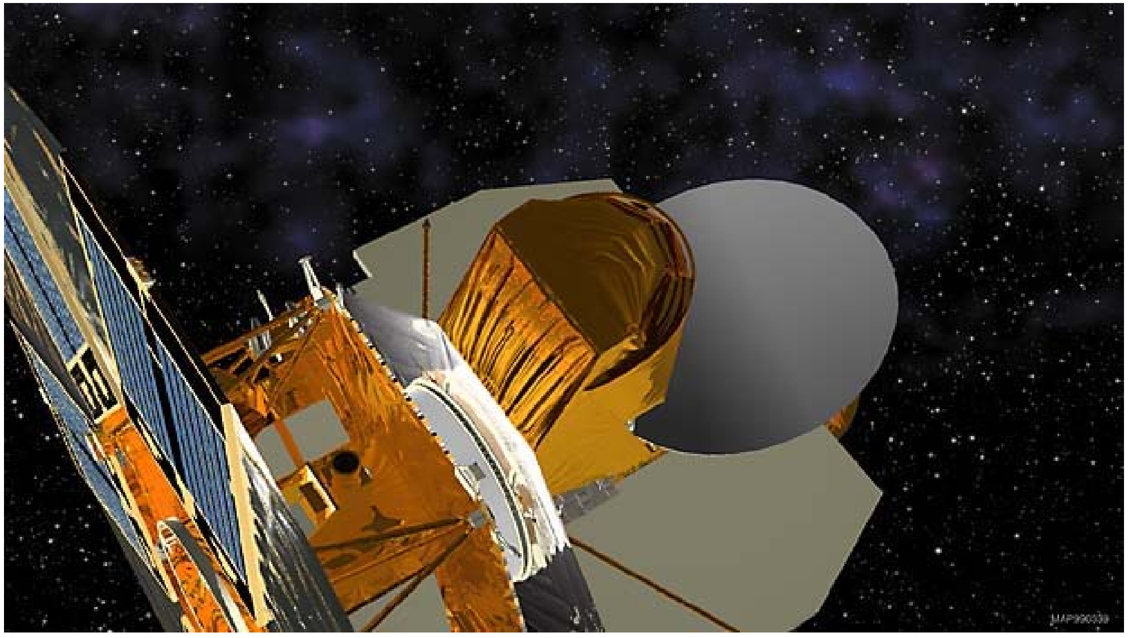
1996: MAP Mission Selected





MAP'S PURPOSE –

To make a detailed full-sky map of the CMB radiation anisotropy (temperature and polarization) to constrain the cosmology of our universe.



WMAP's Differential Receivers*

10 "Differencing Assemblies"

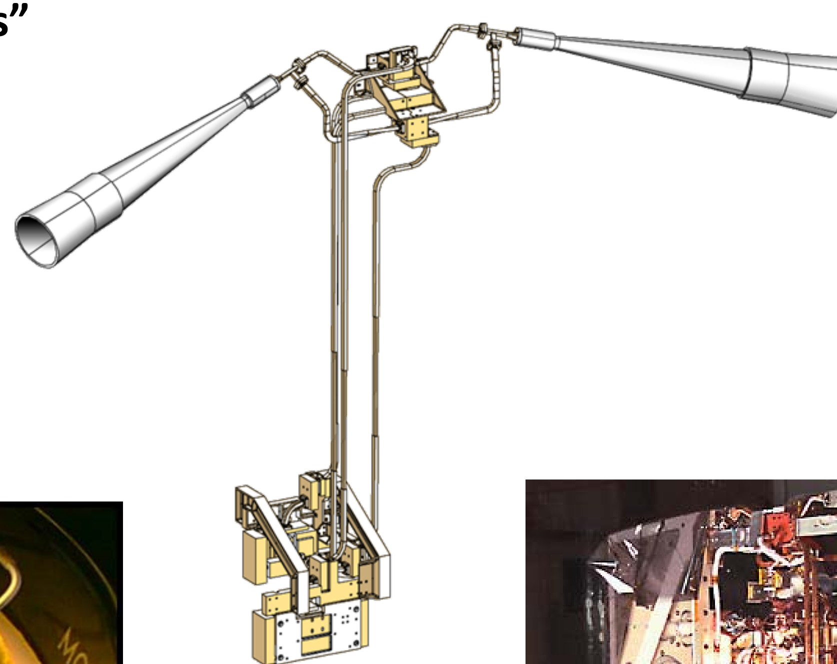
4 @ 94 GHz W-band

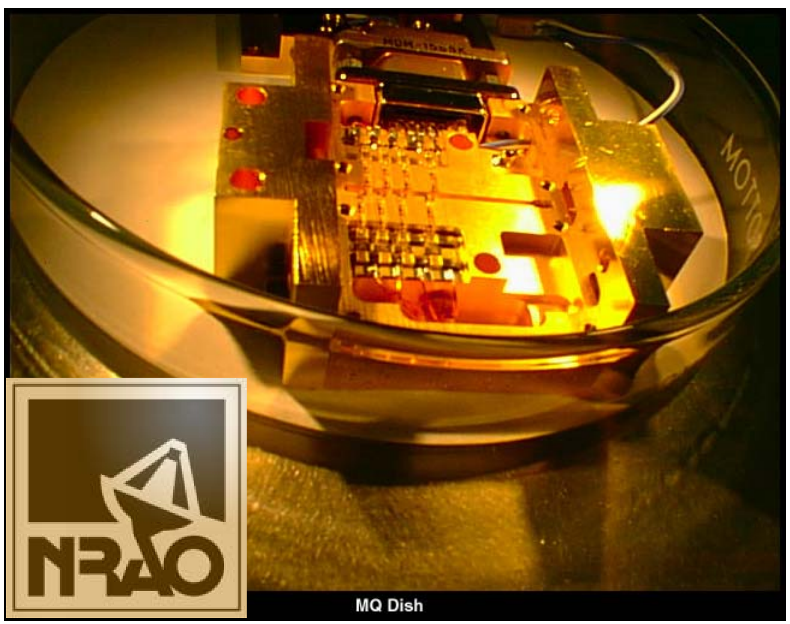
2 @ 61 GHz V-band

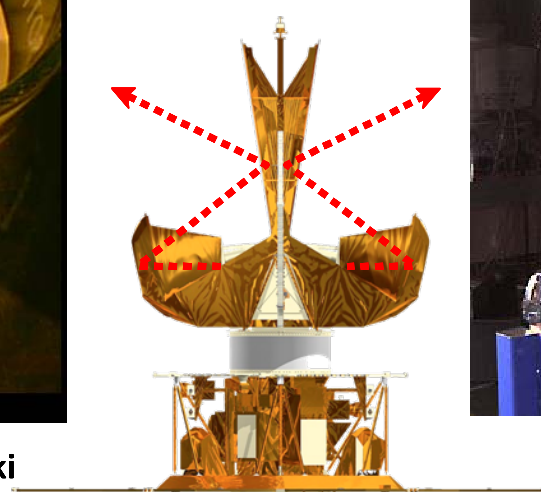
2 @ 41 GHz Q-band

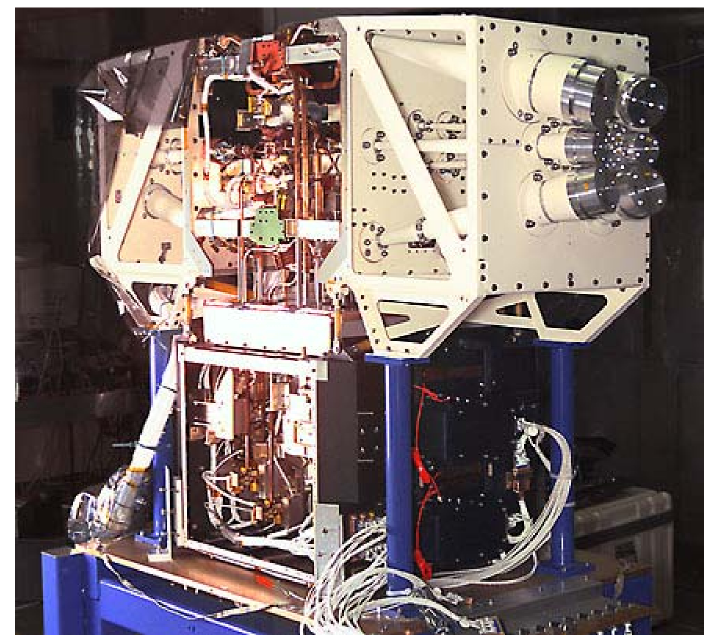
1 @ 33 GHz Ka-band

1 @ 23 GHz K-band



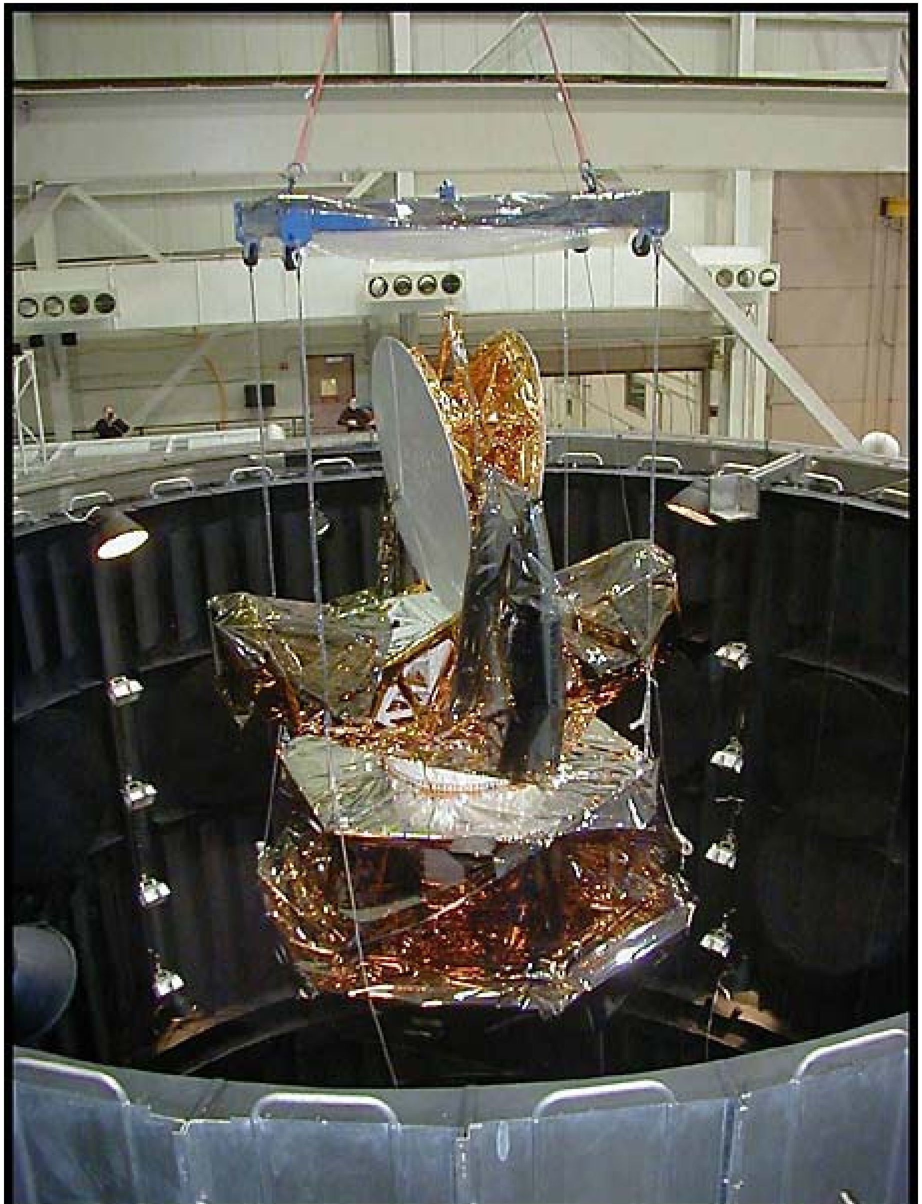


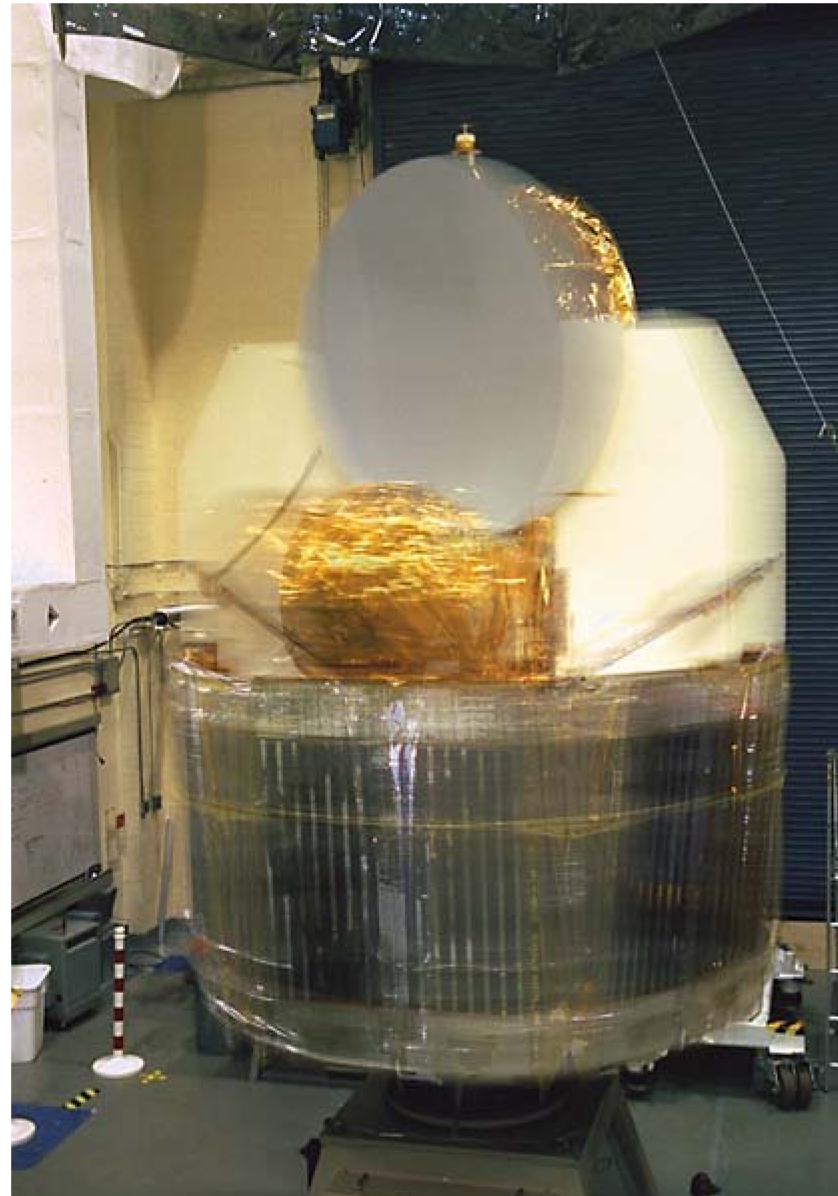




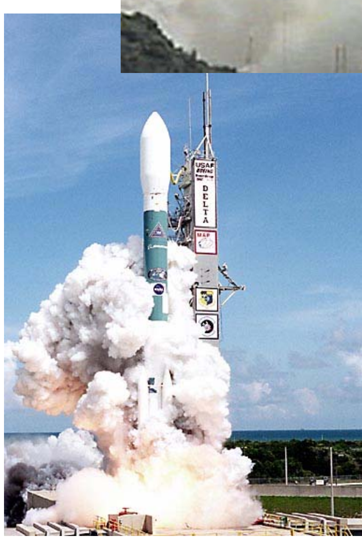
*based on HEMT design of M. Pospieszalski

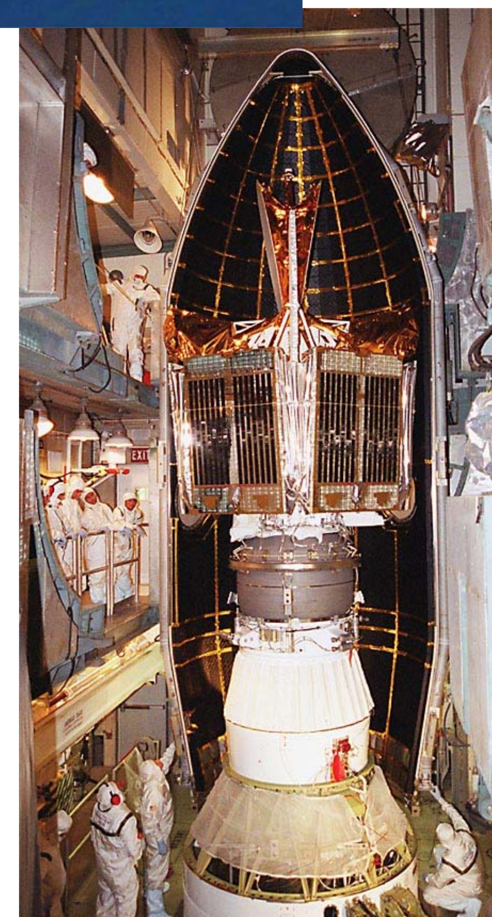
WMAP I&T at Goddard





WMAP Launch

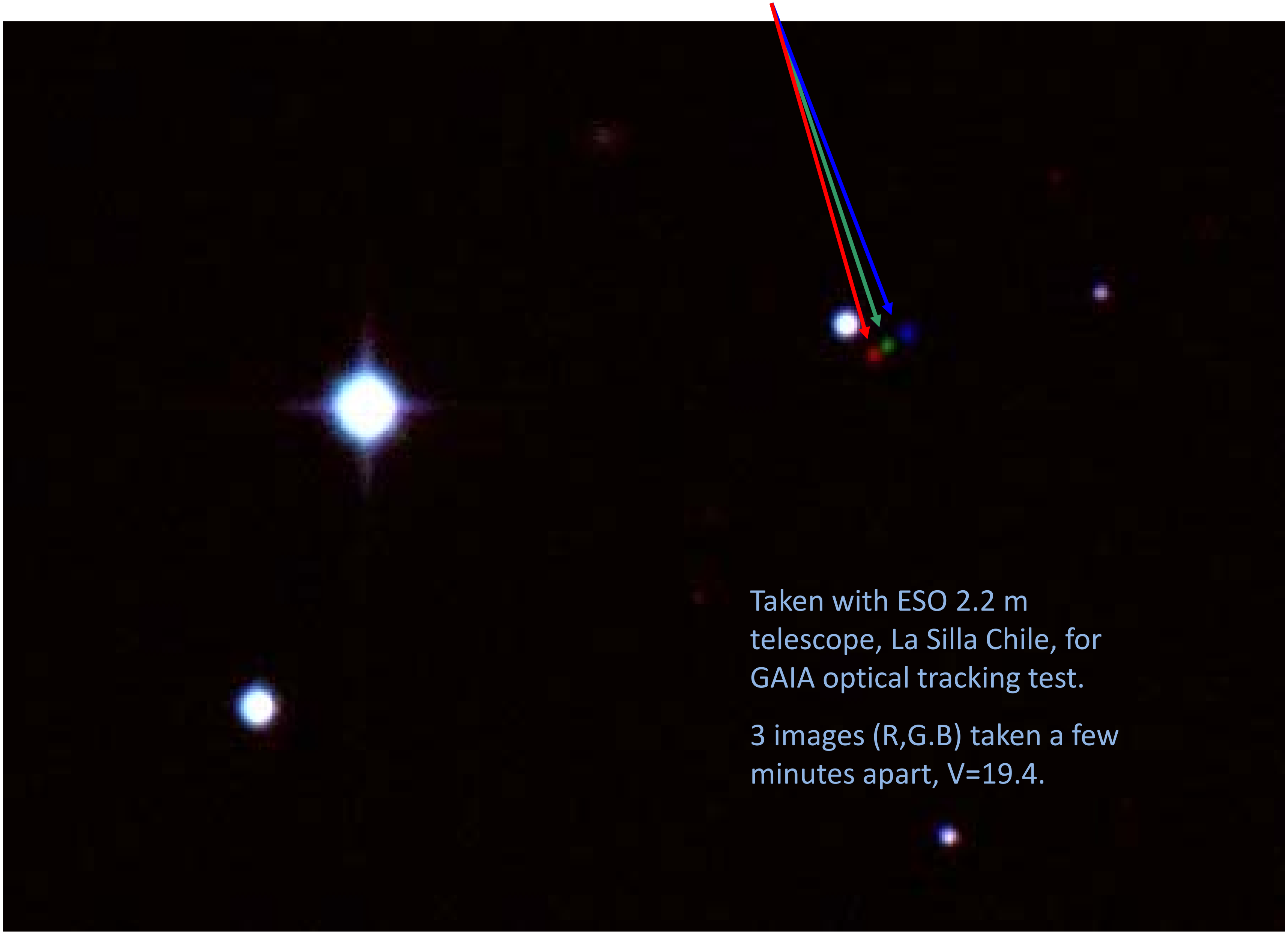




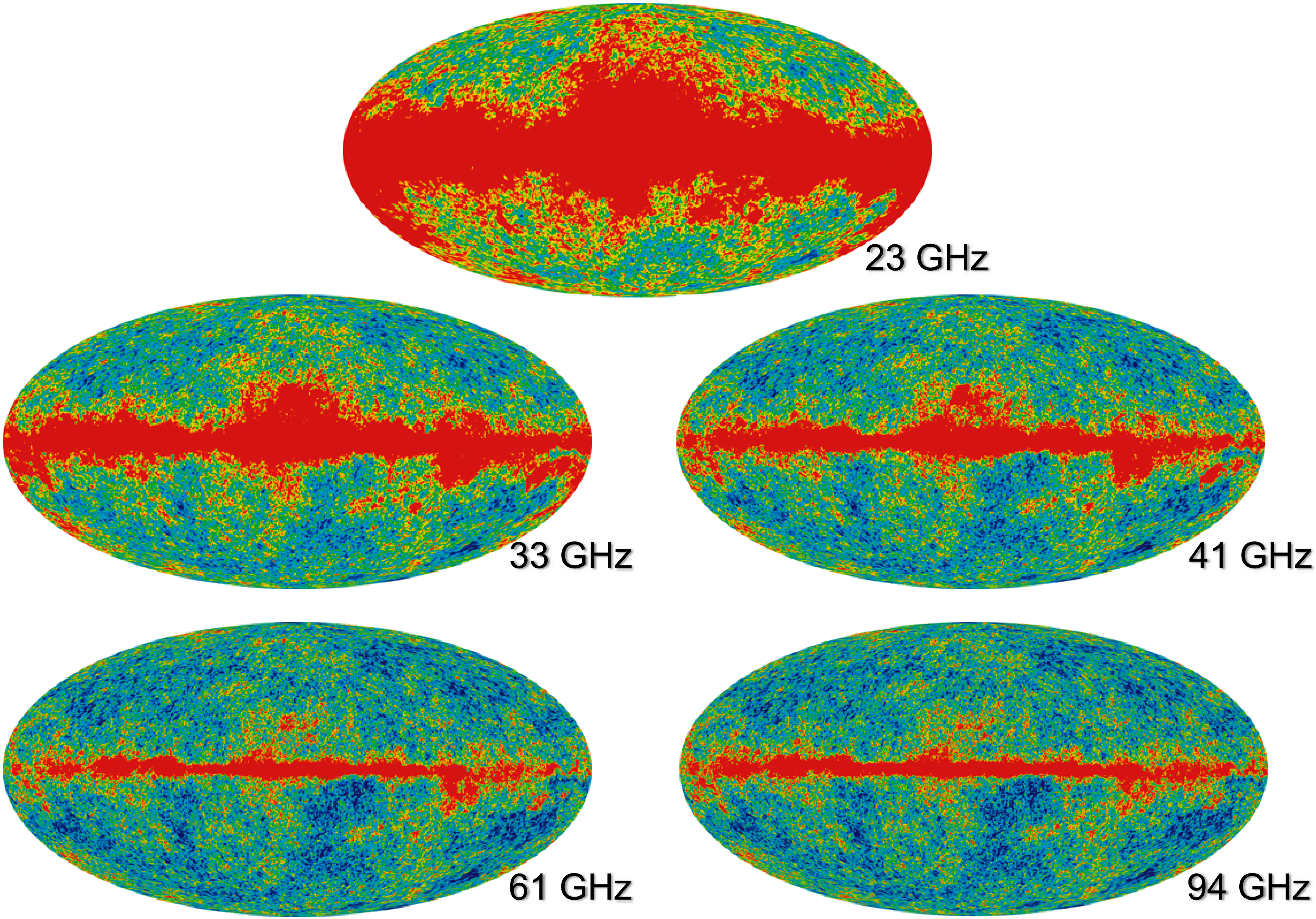
June 30, 2001 at 15:47 EDT

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

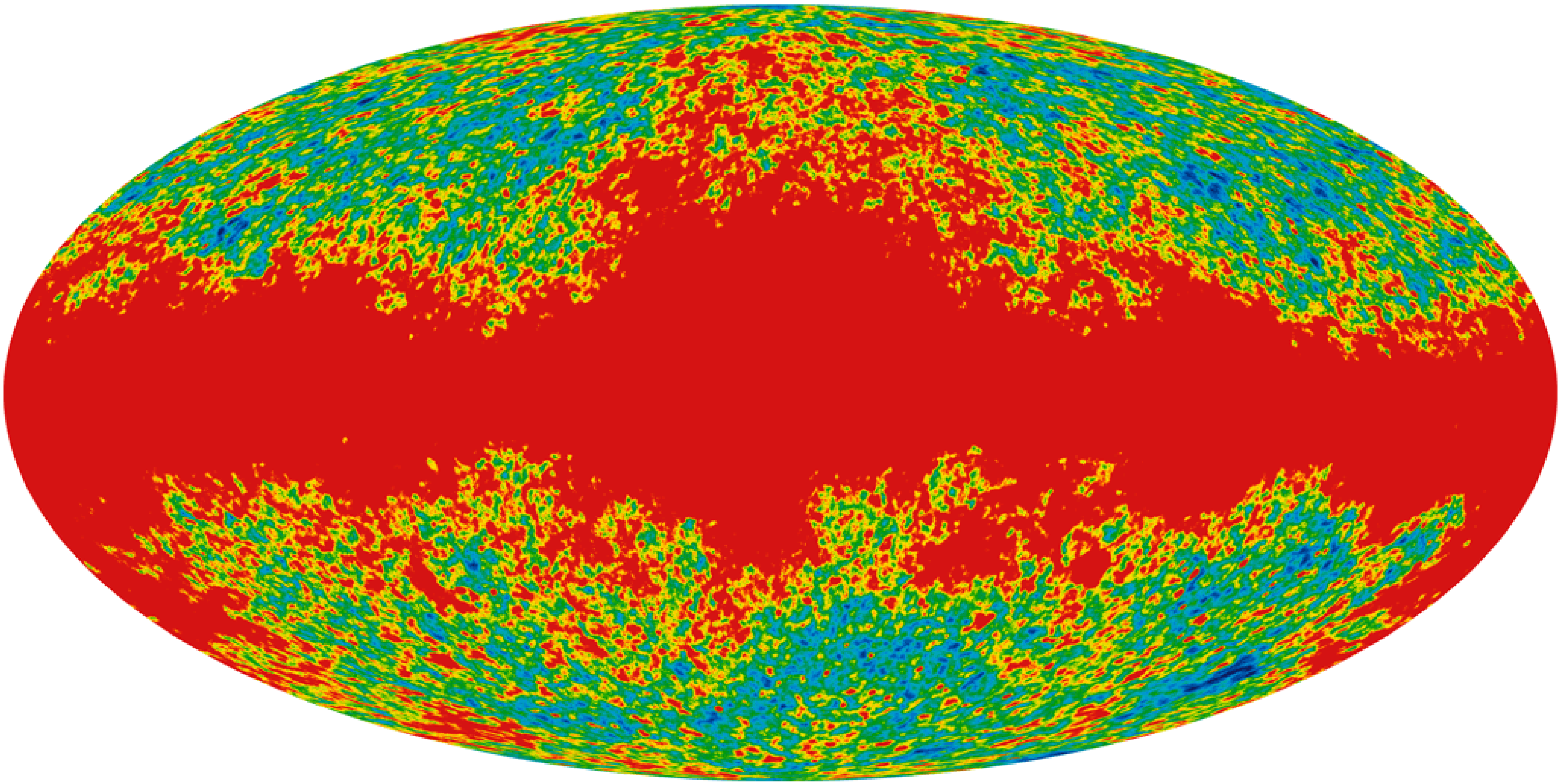
WMAP at L2


Taken with ESO 2.2 m telescope, La Silla Chile, for GAIA optical tracking test.
3 images (R,G.B) taken a few minutes apart, V=19.4.

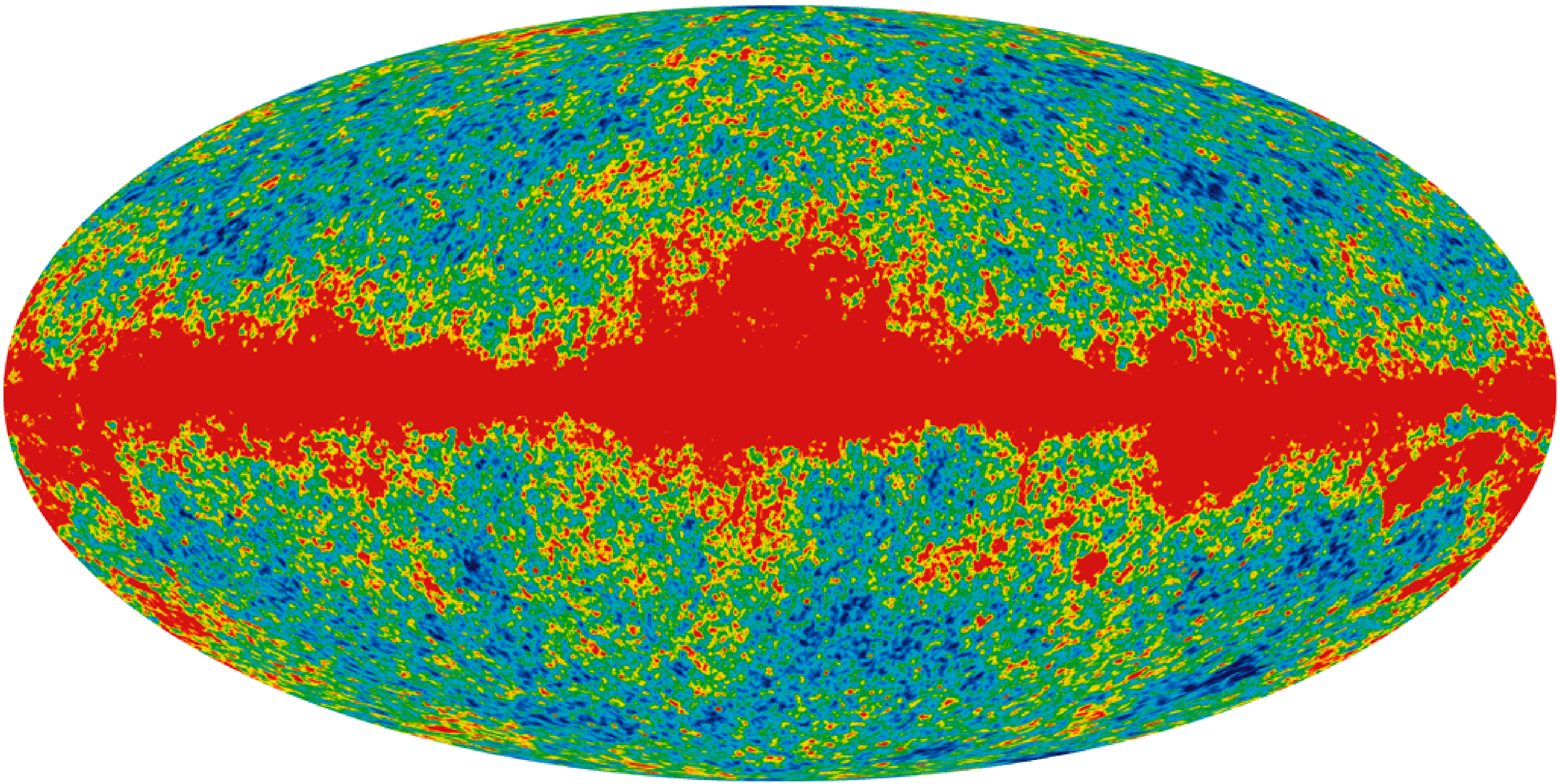
7-year Temperature Maps



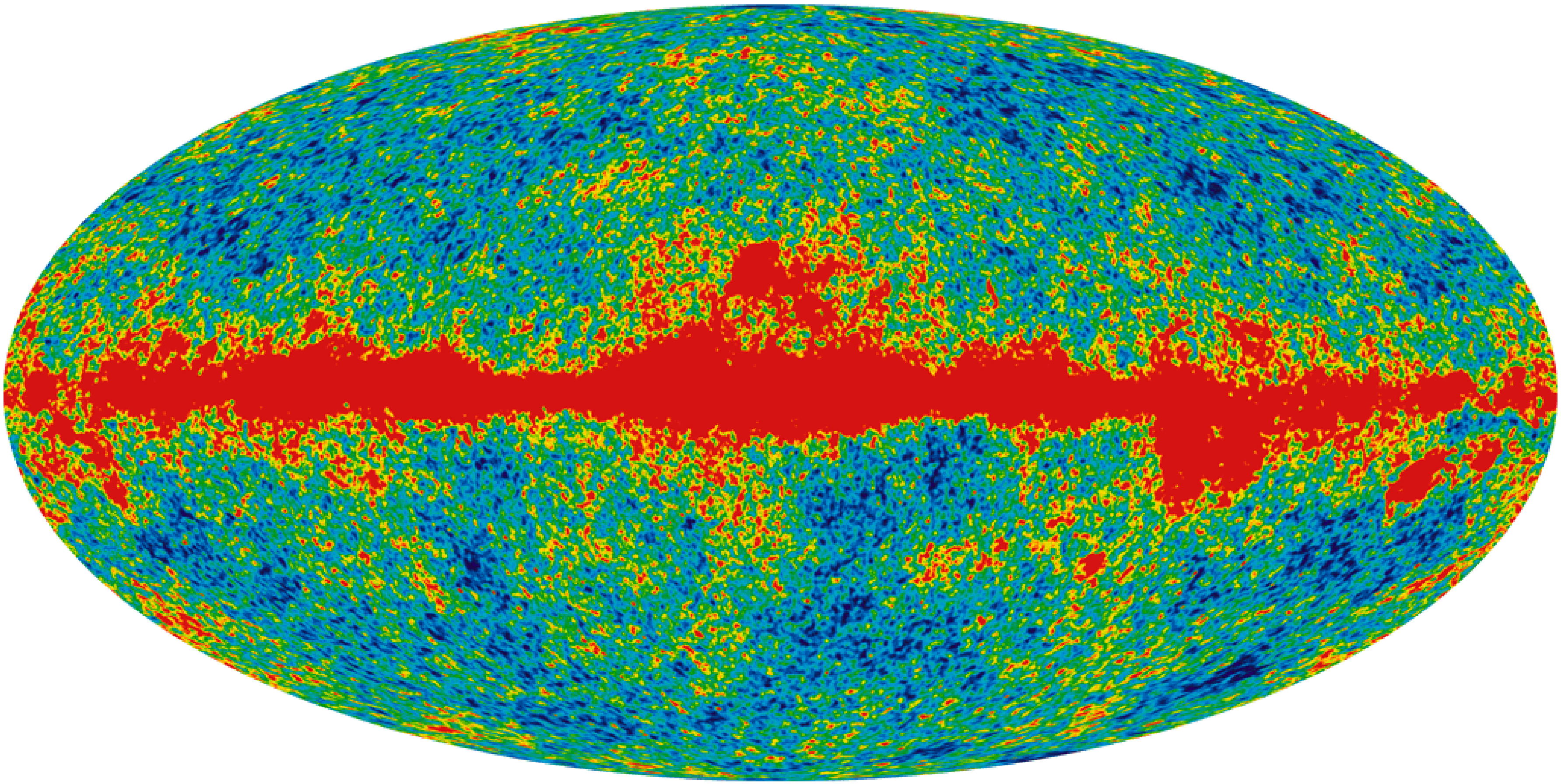
K Band Temperature, 23 GHz



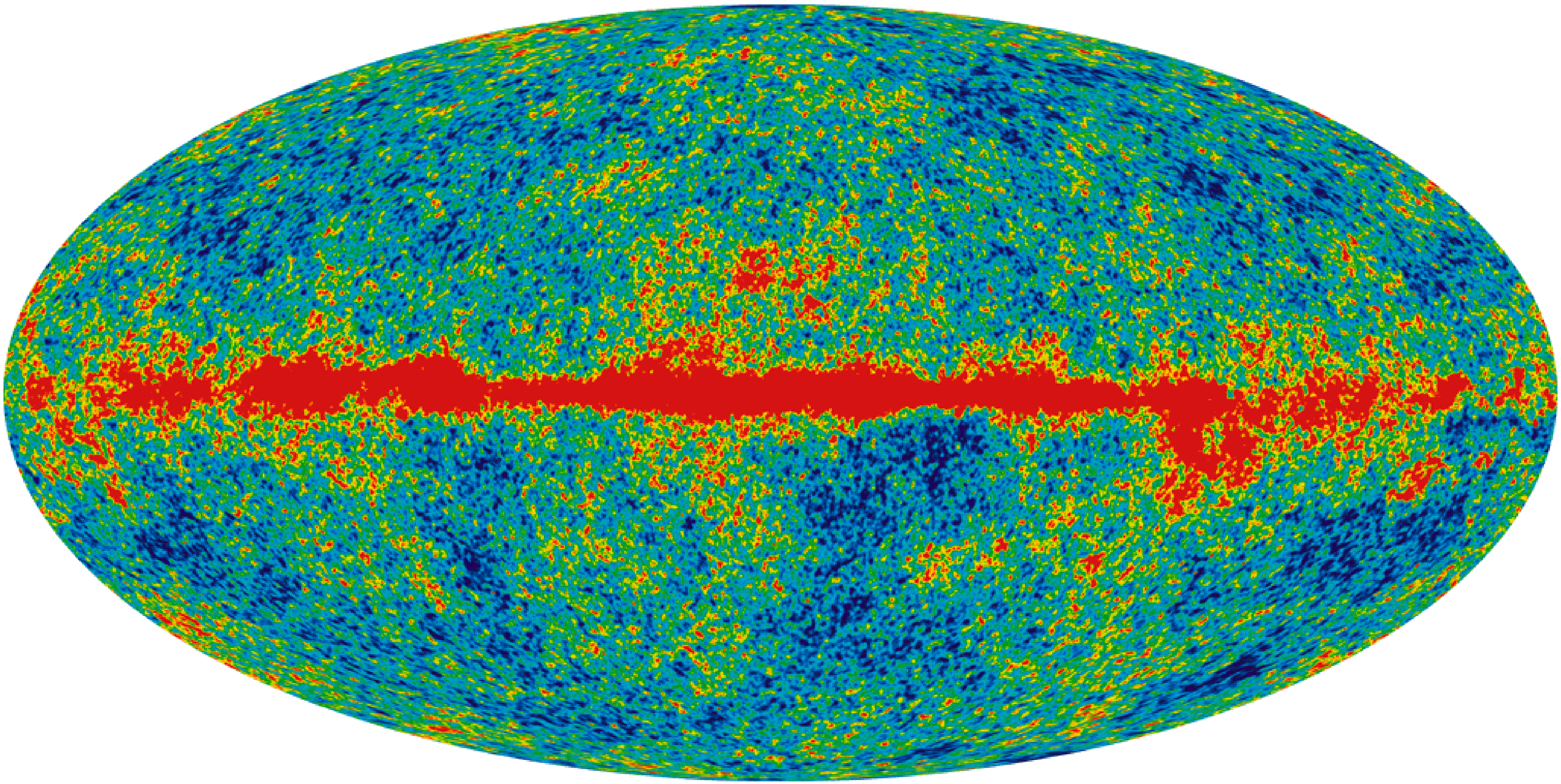
Ka Band Temperature, 33 GHz



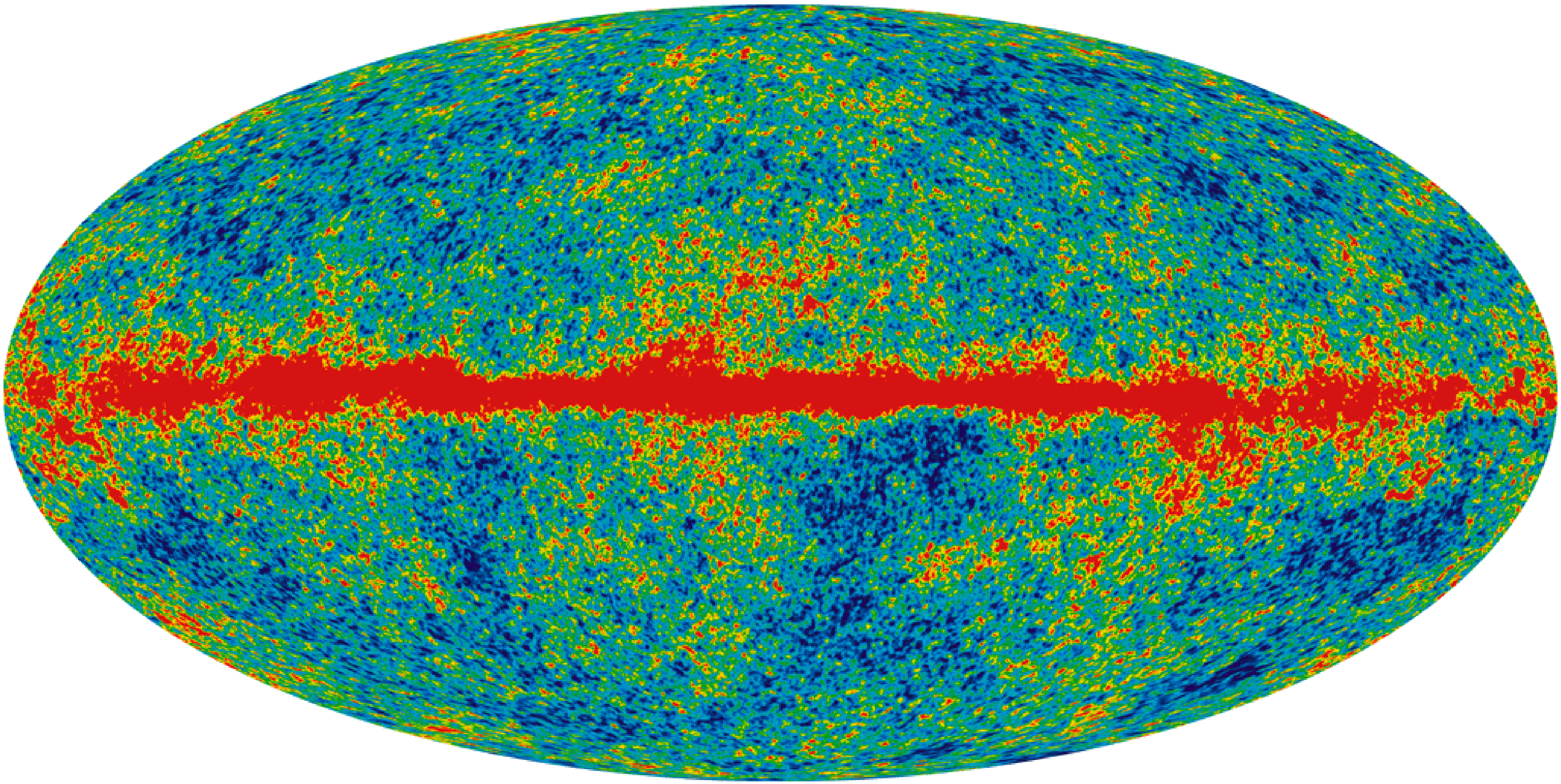
Q Band Temperature, 41 GHz



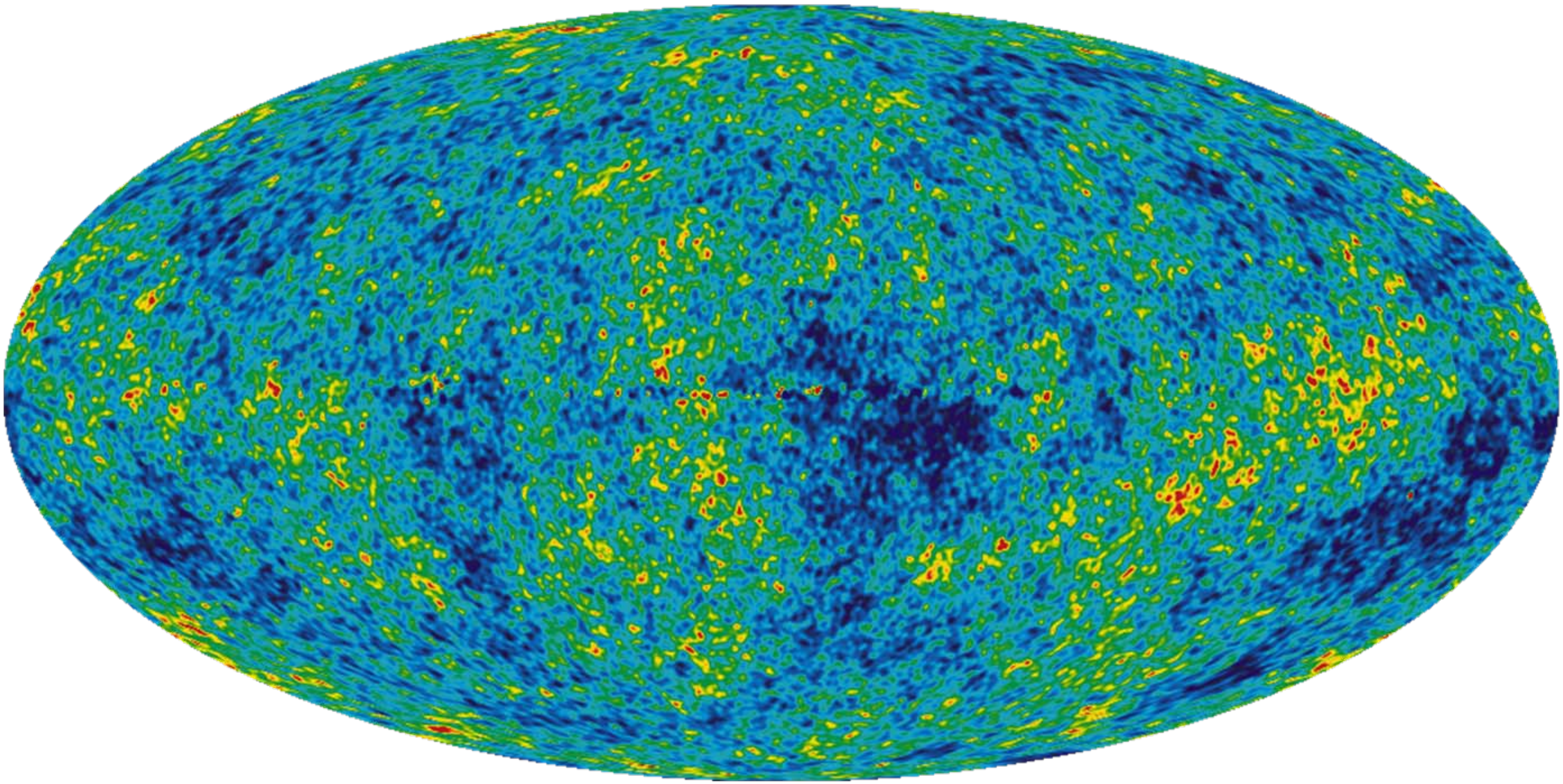
V Band Temperature, 61 GHz



W7 Band Temperature, 94 GHz

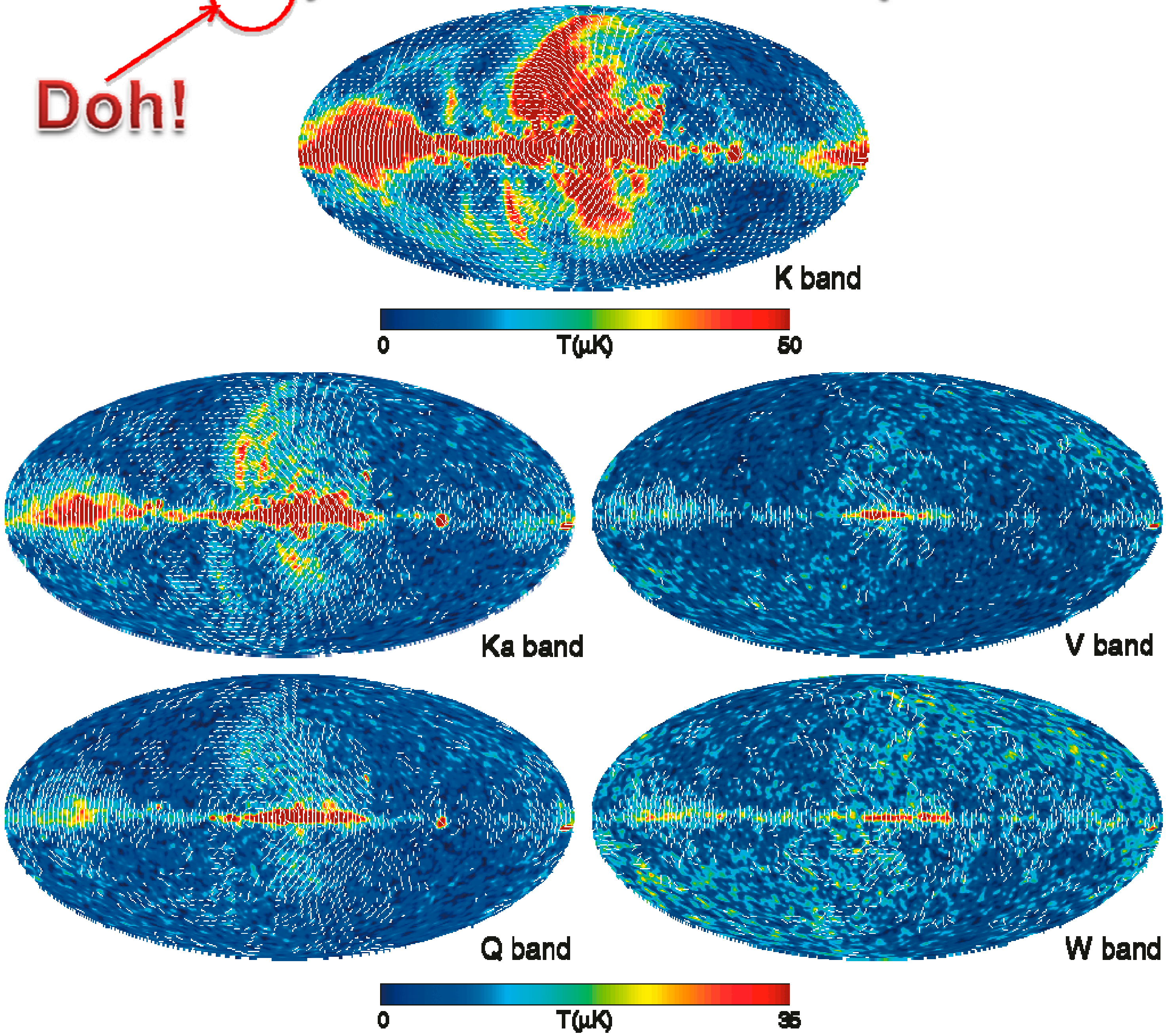


5 Frequency Linear Combination ("ILC")



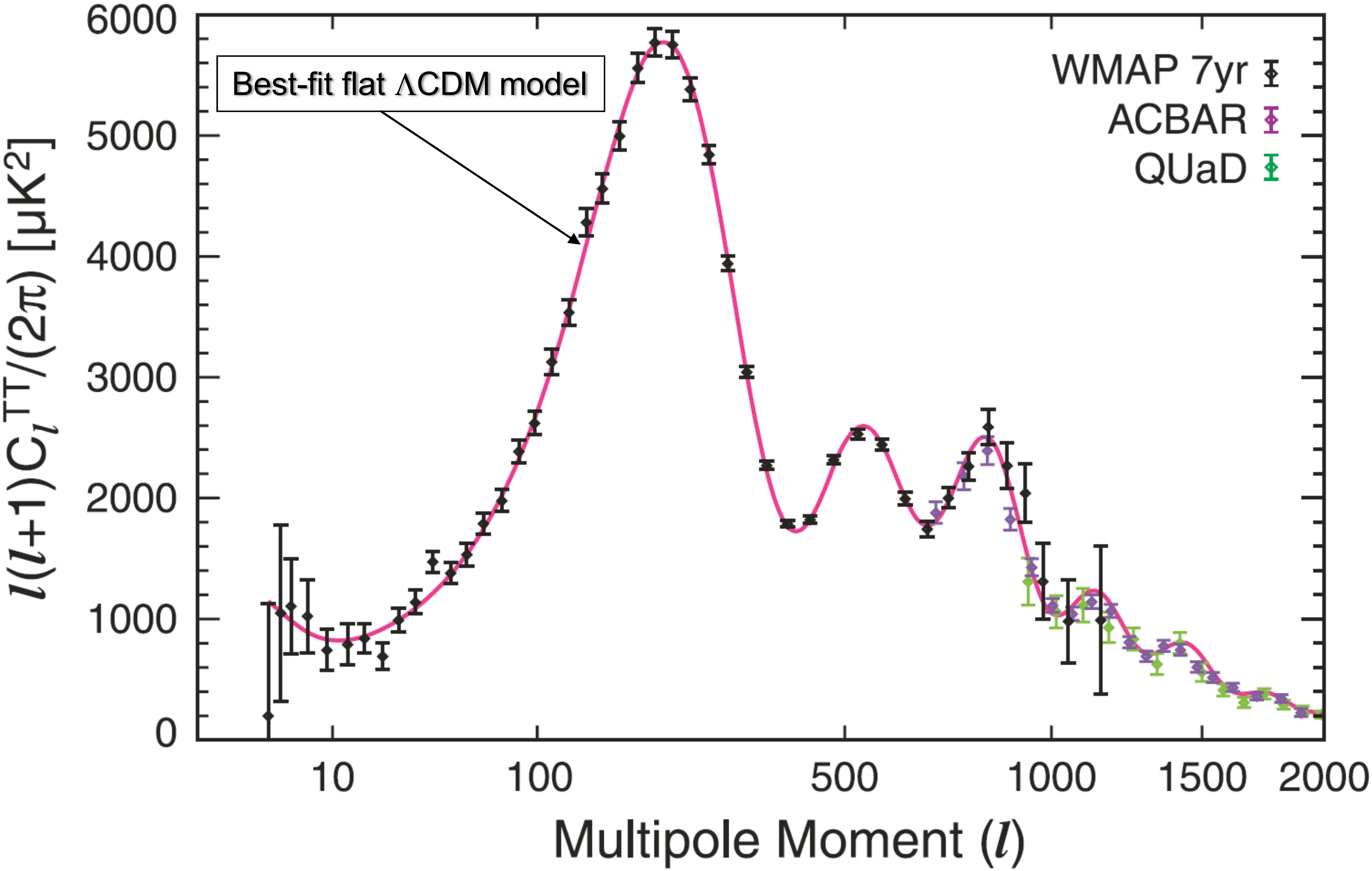
5-year Polarization Maps

Doh!

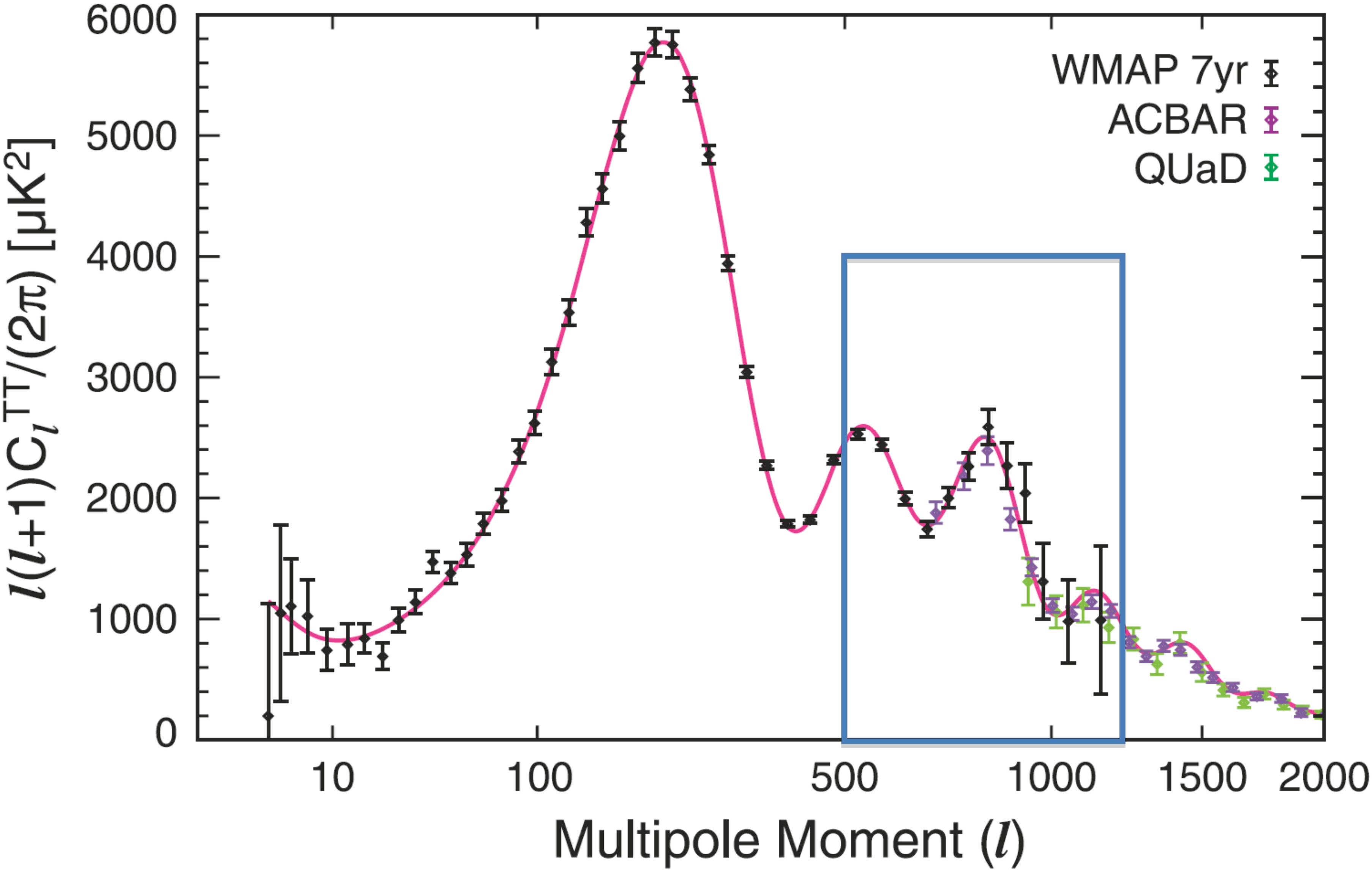


Analysis

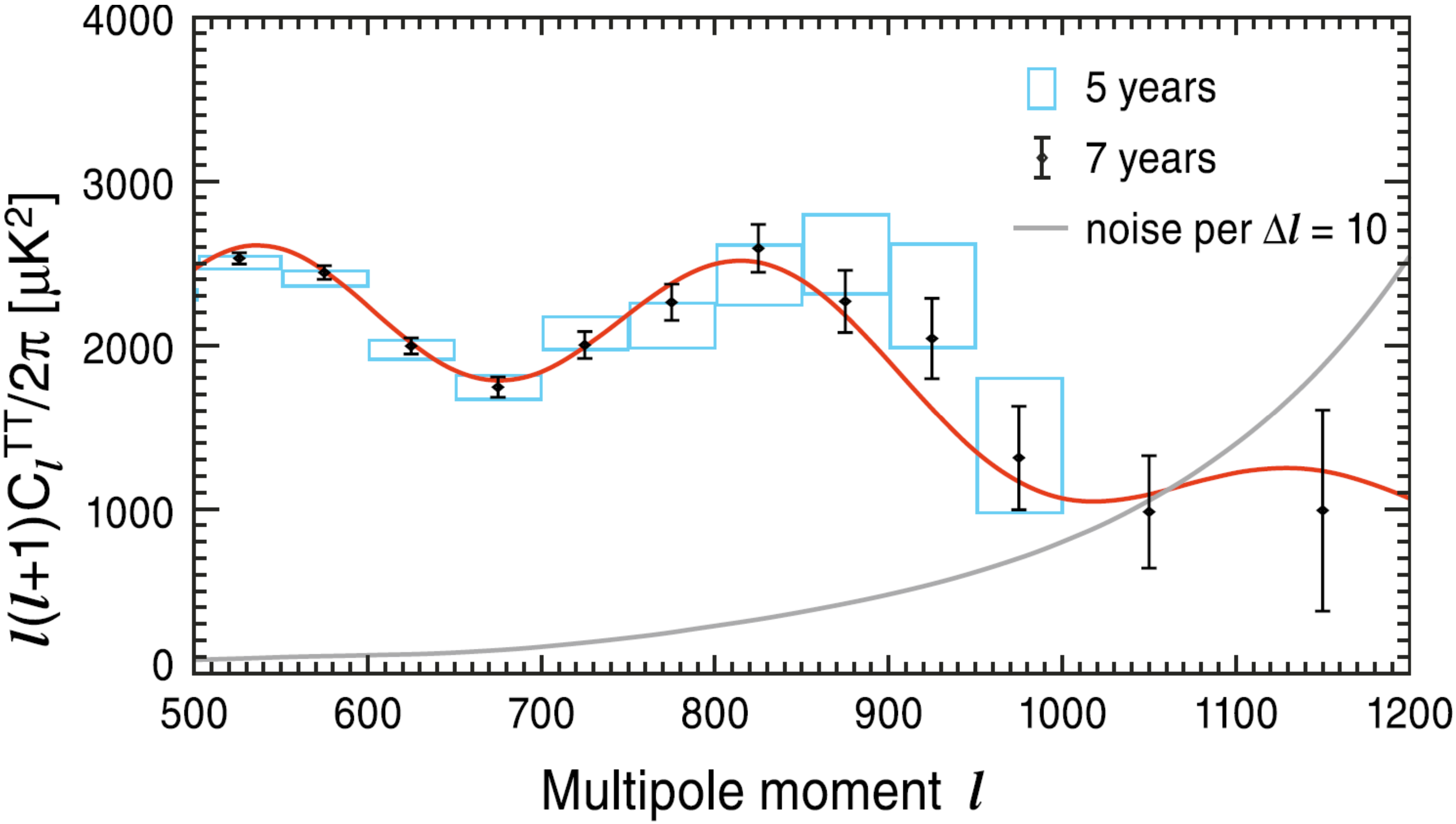
The CMB Temperature Spectrum, c. 2010



Improving the Third Acoustic Peak

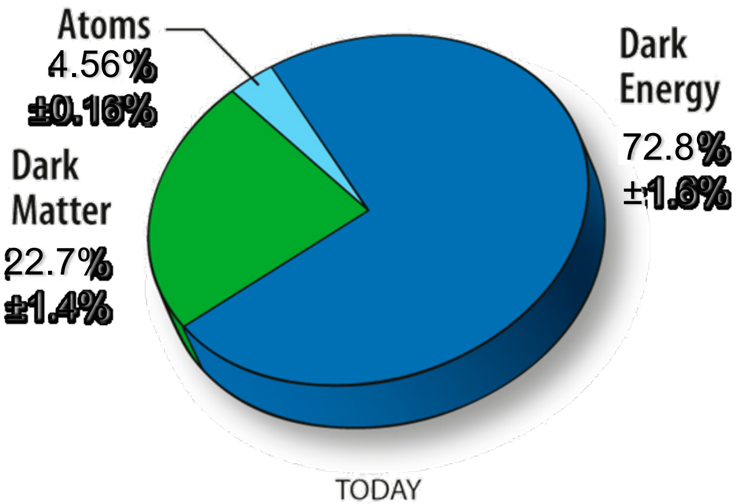


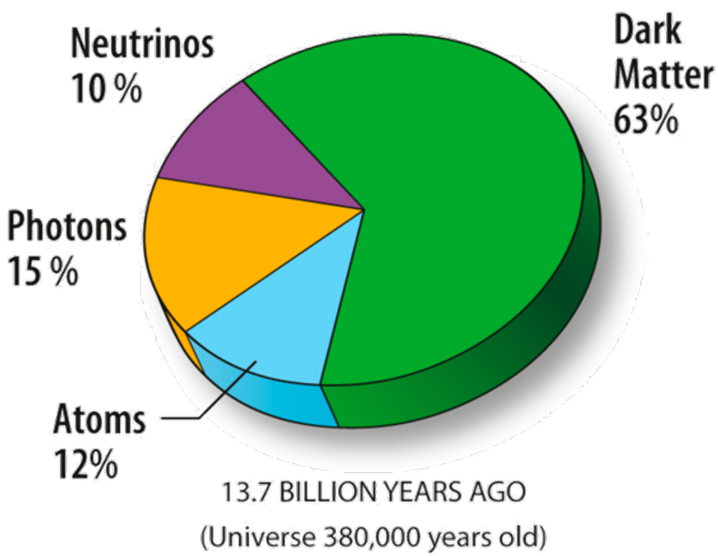
Improving the Third Acoustic Peak



Signal/noise ratio > 1 for l<1060 (Δl=10).

The Big Picture – c.2010





Hubble –

H_0 = 70.4 ± 1.4 $kms^{-1}Mpc^{-1}$

Age –

t_0 = 13.75 ± 0.11 Gyr

Selected 7-year Science Highlights

- Direct visualization of the predicted oscillation and **polarization** pattern around hot/cold spots (next vu-graph).

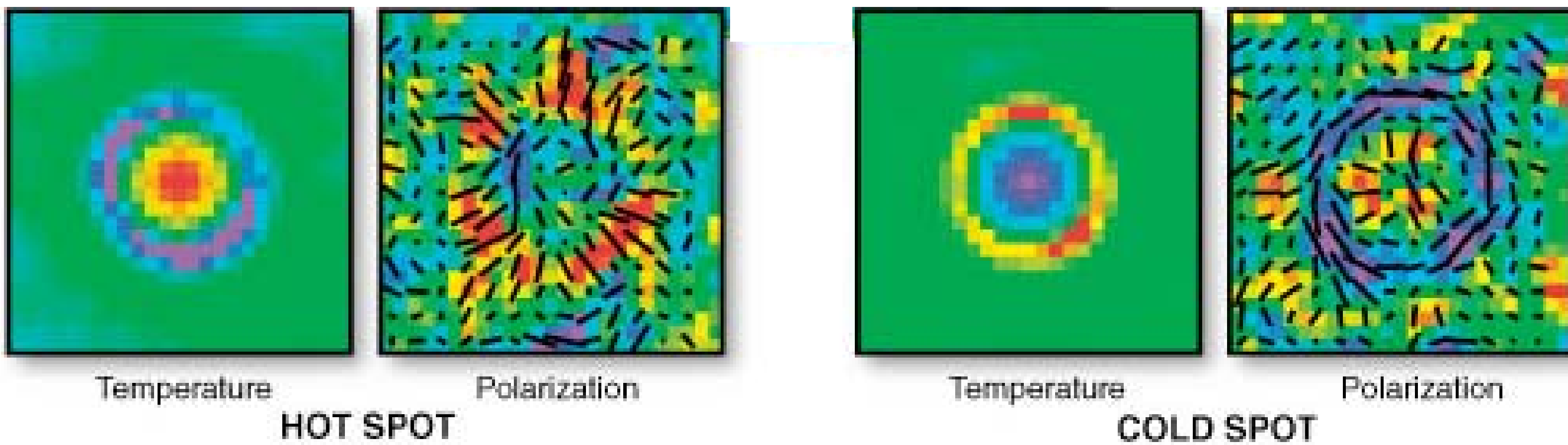
- ~50% reduction in allowable volume of 6-d ΛCDM parameter space.

- 1st detection (>3σ) of the effect of **pre-stellar helium** on the temperature power spectrum (w/ Acbar+QUaD)

- Improved limits on **neutrino** parameters:
  $\Sigma m_\nu < 0.58$eV (95% CL) $N_{eff} = 4.3 \pm 0.9$ (68% CL)

- The primordial spectral **tilt** (in standard ΛCDM model):
  $n_s<1$ (99.5% CL).

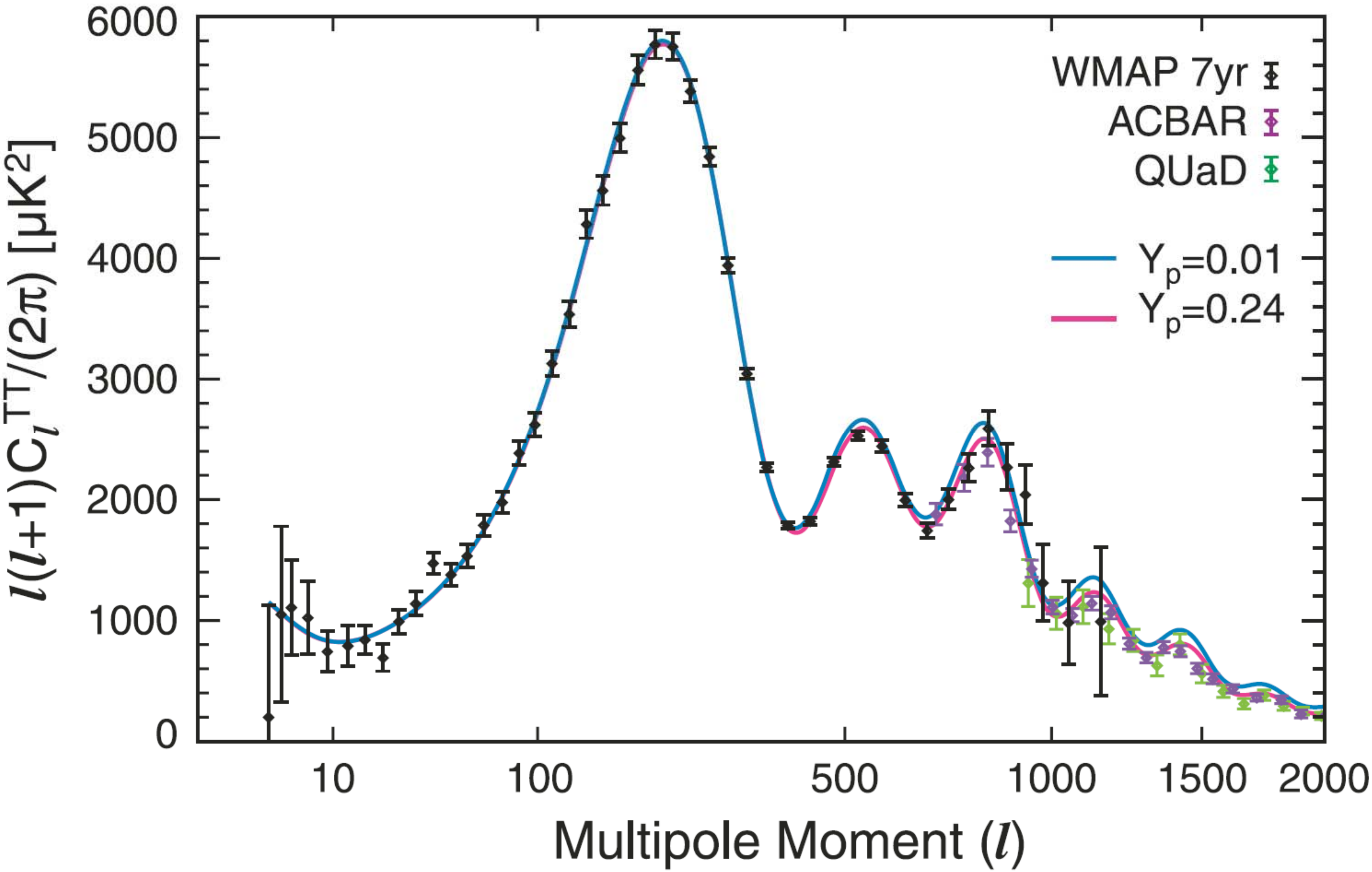
Acoustic Oscillations in T & E



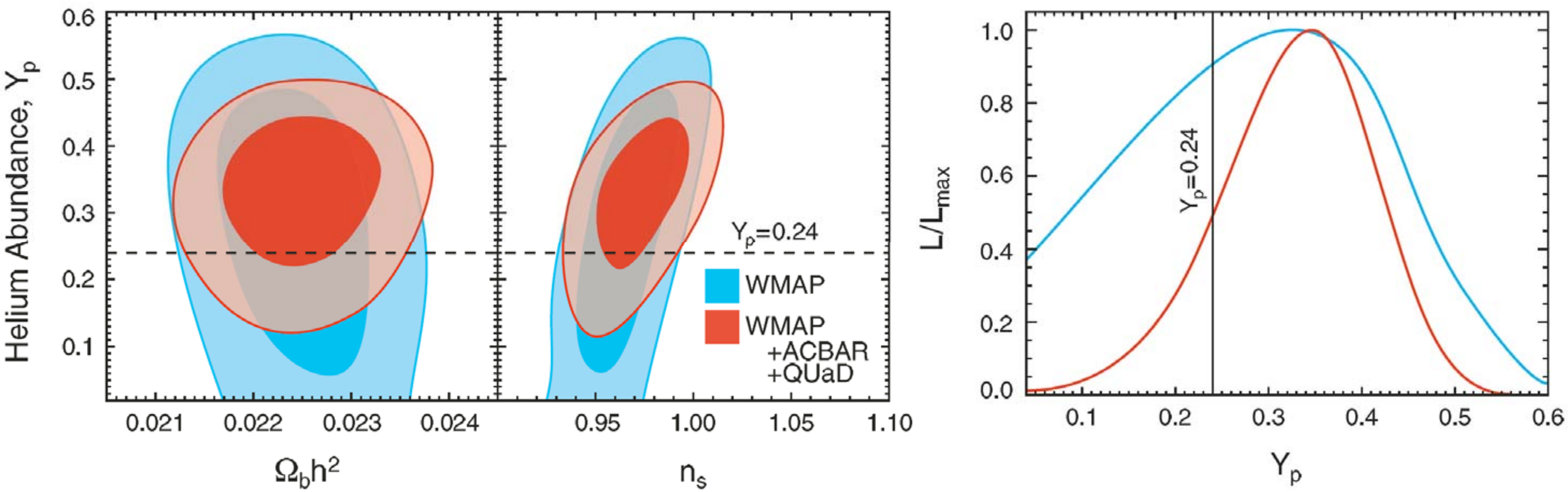
The imprint of sound waves is visible in the co-added degree-scale hot (left) & cold (right) spots. The expected radial/tangential polarization pattern around these extrema is now clearly seen in the 7-year WMAP data.

This pattern is also imprinted on the baryon gas (baryon acoustic oscillations or BAO) that evolves to form large scale structure.

Detection of Pre-Stellar Helium - I

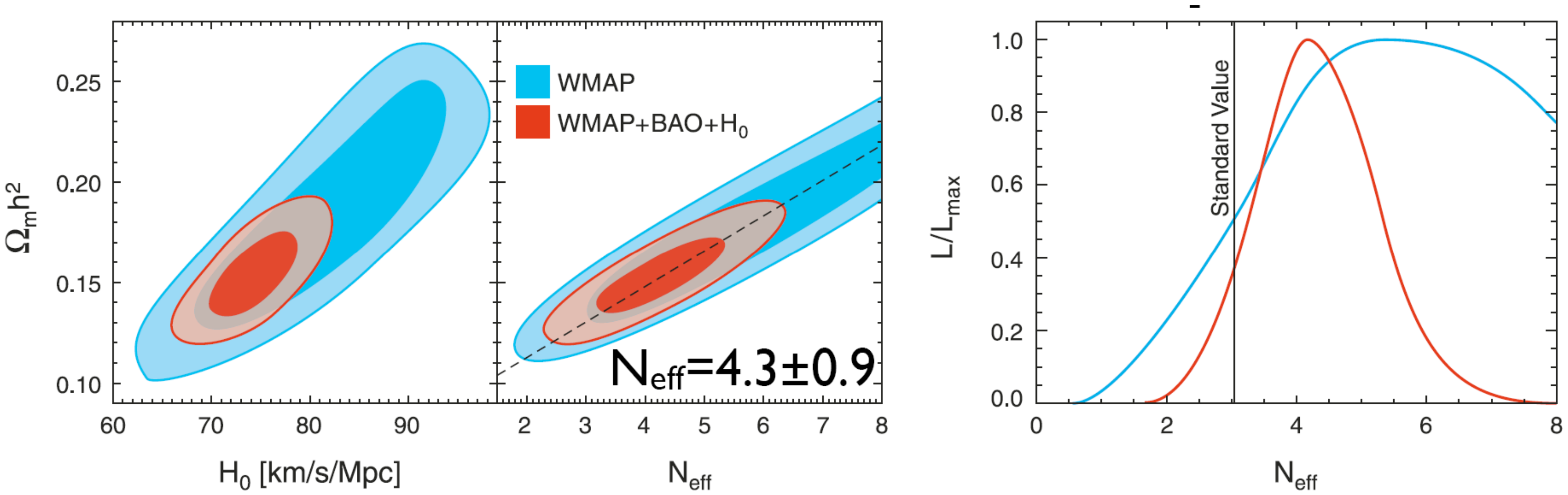


Detection of Pre-Stellar Helium - II



The combination of WMAP and high-*l* CMB data (ACBAR and QUaD) is powerful enough to isolate the effect of helium: $Y_p = 0.33 \pm 0.08$ (68% CL).

Number of Relativistic Species*



*Number of effective relativistic species after matter-radiation equality
Standard model of particle physics has 3.04 effective neutrino species.
WMAP7+BAO+H0 measure 4.3 ± 0.9.

Also limit sum of neutrino masses: $\Sigma m_\nu < 0.58$ eV

Inflation Scorecard

Flatness – $\Omega_{tot} = 1.0023 \pm 0.0056$

Tilt – $n_s = 0.963 \pm 0.012$ ($n_s < 1$ @ 99.5% CL)

Adiabatic - inclusion of isocurvature modes does not improve fits

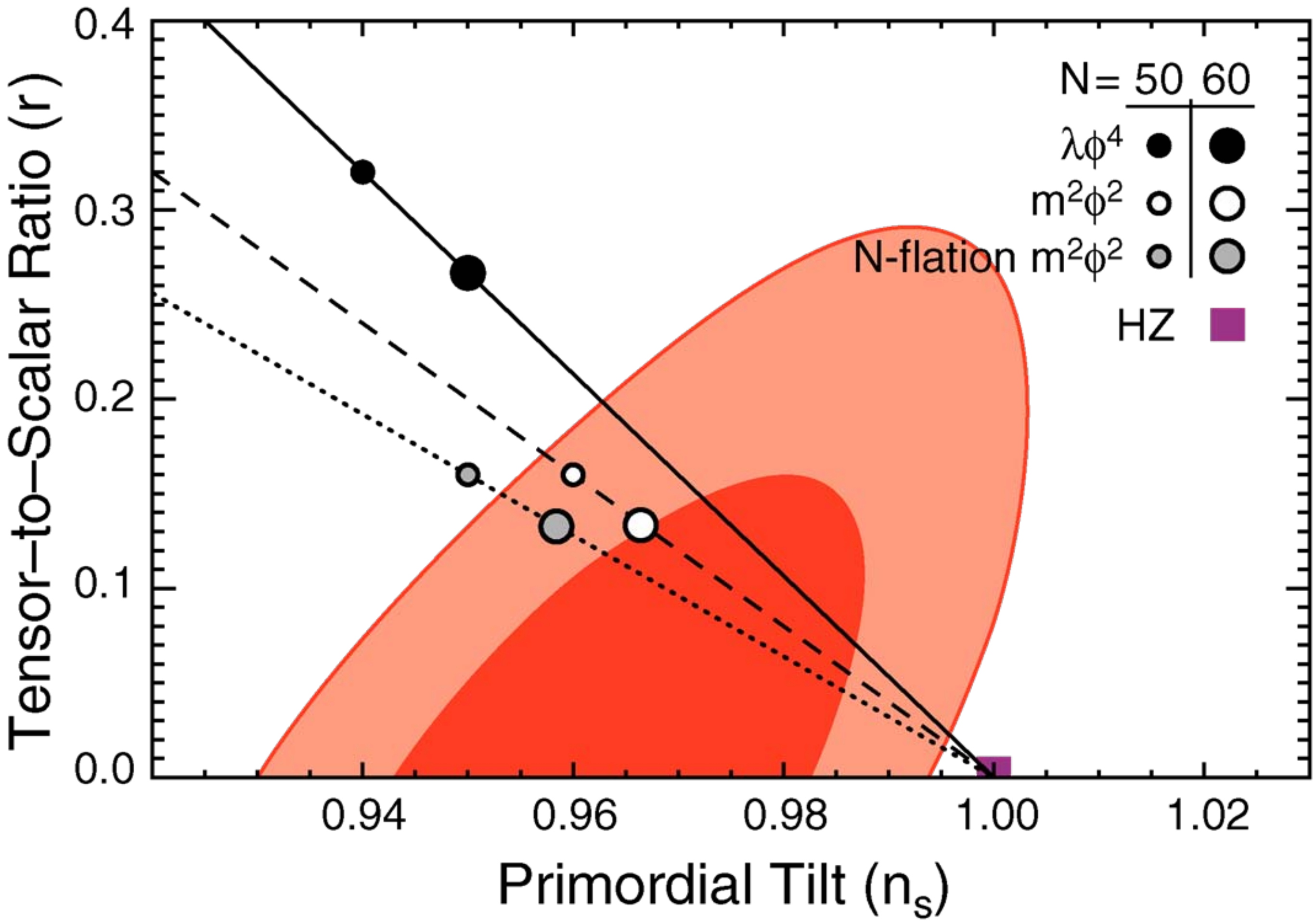
Non-gaussianity –

$-10 < f_{NL}^{loc} < 74$ $\quad -214 < f_{NL}^{eq} < 266$ $\quad -410 < f_{NL}^{ortho} < 6$ (95% CL)

Tensor-to-Scalar ratio –

$r < 0.24$ (95% CL) w/o using Sne data
$r < 0.20$ (95% CL) using Sne data

Testing Inflation



Inflation models are being put to the test.

Many of the models predict an observable gravitational wave background (via the CMB B-mode polarization).

Errors in the data?...
Anomalies in the CMB?...
My take on a few recent claims

Lui & Li – WMAP Maps are Flawed

- Lui & Li have (impressively) developed an independent map-making code that they have used to make sky maps from the WMAP calibrated time-ordered data.
- In recent papers they argue that they don't reproduce our maps and they strongly assert that our released maps are flawed.
- In their most recent paper, they cite a specific code difference:
  - They assign sky pixels based on the pointing at the start time of data integration,
  - We assign sky pixels based on the pointing at the mid-point of data integration.
- The magnitude of the difference is frequency-dependent, but is ~7 arcmin, which is very large compared to our spacecraft pointing knowledge.
- The correctness of the latter prescription should be obvious, but it can be independently confirmed by comparing the location of known radio sources to the positions measured by WMAP (as a function of frequency).
- Roukema (arXiv:1004.4506) has tested the source positions in both cases and finds better source "focus" with the WMAP team's pointing.

We have very high confidence that the WMAP sky maps are accurate within their stated errors.

Sawangwit & Shanks - WMAP Beams are Flawed

S&S (arXiv:0912.0524) try an alternate approach to measuring instrument point spread function (PSF): they stack the sky maps by the location of detected point sources and compare the measured beam profile to the profile measured from Jupiter.

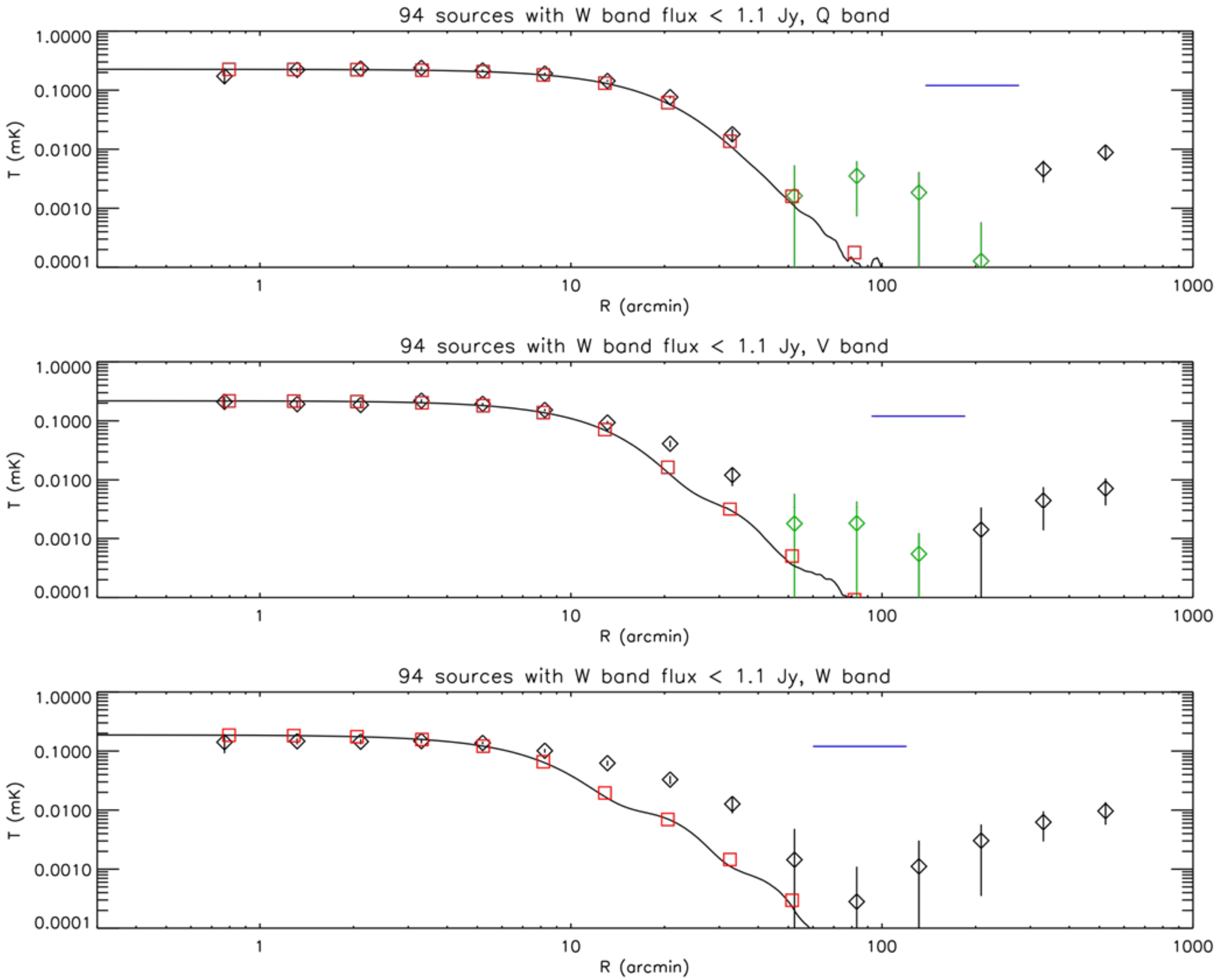
They find the beam response measured from stacked sources to be higher than the beam response measured from Jupiter by a factor of 2-3 in the range of ~1°. They conclude that the CMB power spectrum has been improperly deconvolved and that all cosmological conclusions derived from the CMB power spectrum are suspect.

We have reproduced their analysis and we **do** reproduce their beam response measurement (see following page).

Notes:

- W band (94 GHz) is most important band for beam response (highest resolution).
- Jupiter is about 200 mK in W band.
- There are ~100 detected radio sources at W band, from ~100 μK to ~2 mK.
- The CMB fluctuations are ~100 μK rms, comparable to most radio sources.
- Radio sources must be detected in the data, while the position of Jupiter is known a priori.

Beam Comparison by WMAP Team – Flight Data



Top to bottom:

41 GHz (Q band)

61 GHz (V band)

94 GHz (W band)

Red squares/solid lines:

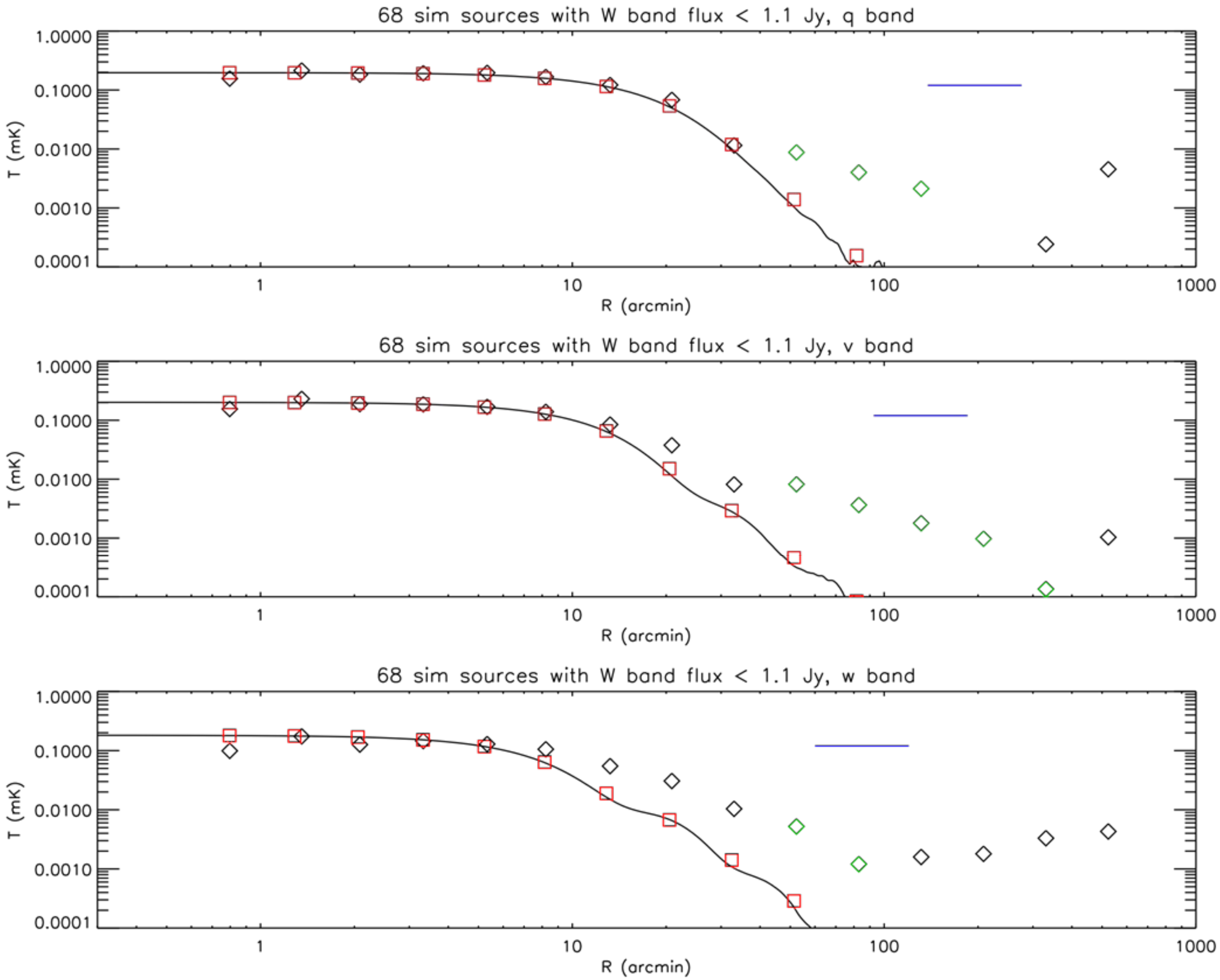
Profile measured from Jupiter

Black diamonds:

Profile measured from stacked sources

Discrepancy increases with decreasing sources brightness – in agreement w/ S&S

Beam Comparison by WMAP Team – Simulated Data



Top to bottom:

41 GHz (Q band)

61 GHz (V band)

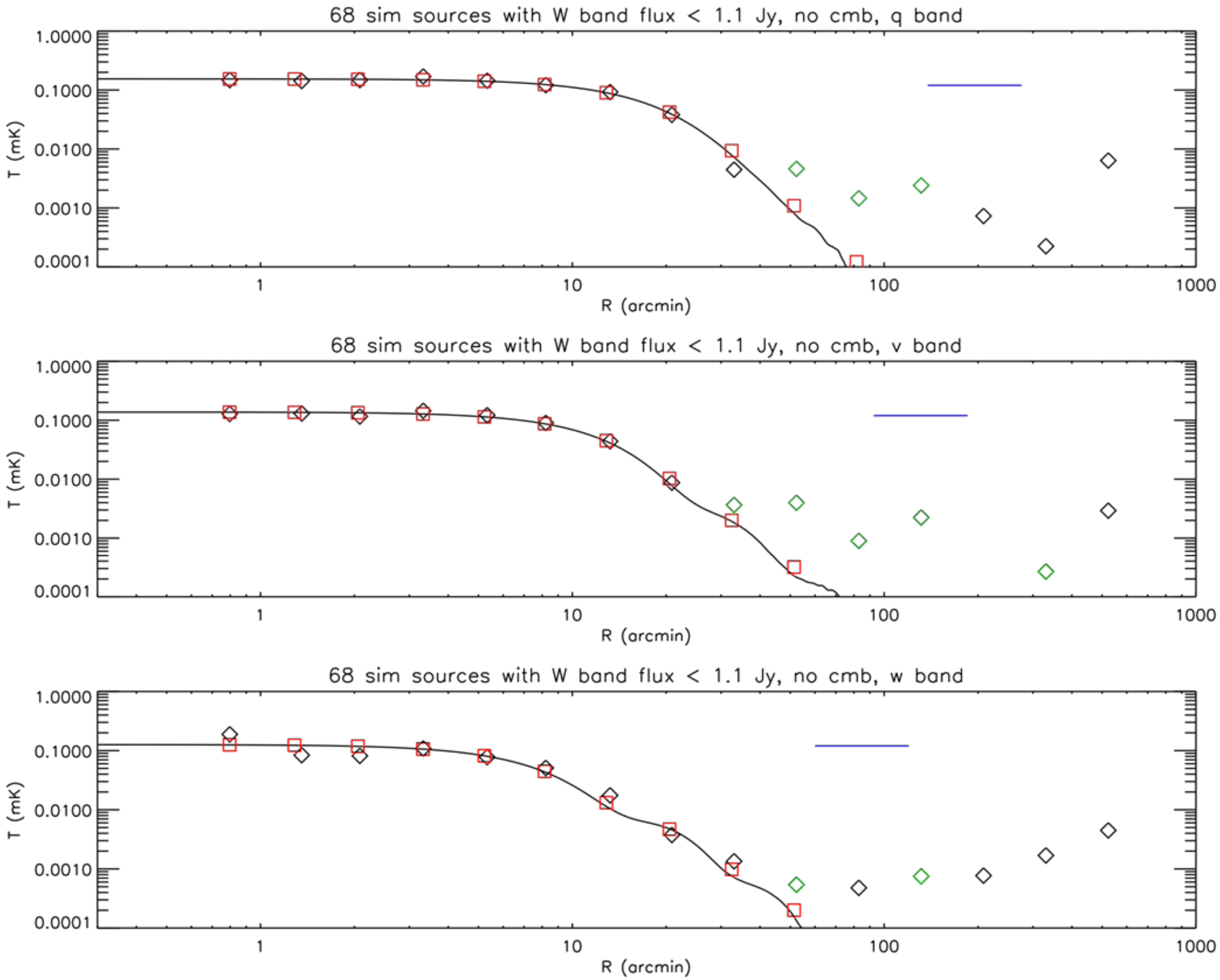
94 GHz (W band)

Same format as flight data. In this case solid lines are **input** beam model.

Very similar discrepancy between Jupiter and stacked-source profiles.

This suggests a bias in the source stacking.

Beam Comparison – Simulated Sources w/o CMB



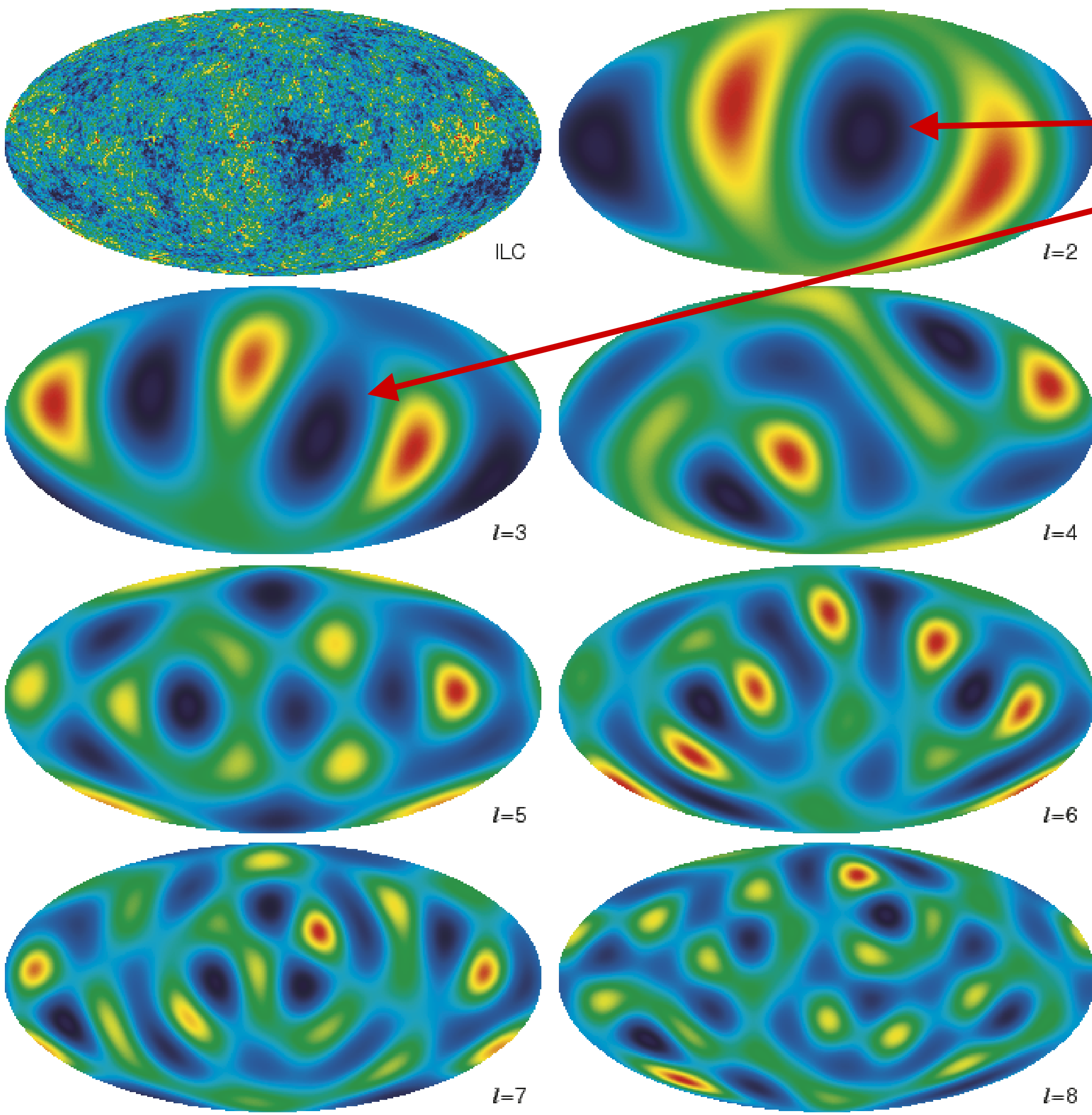
Top to bottom:
41 GHz (Q band)
61 GHz (V band)
94 GHz (W band)

In this case CMB signal is removed from the simulation.

Profiles agree within errors of stacked sources.

Source sample is not complete – we preferentially detect sources on peaks of CMB, which biases stacked sources

Alignment of Low *l* Power - I



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.

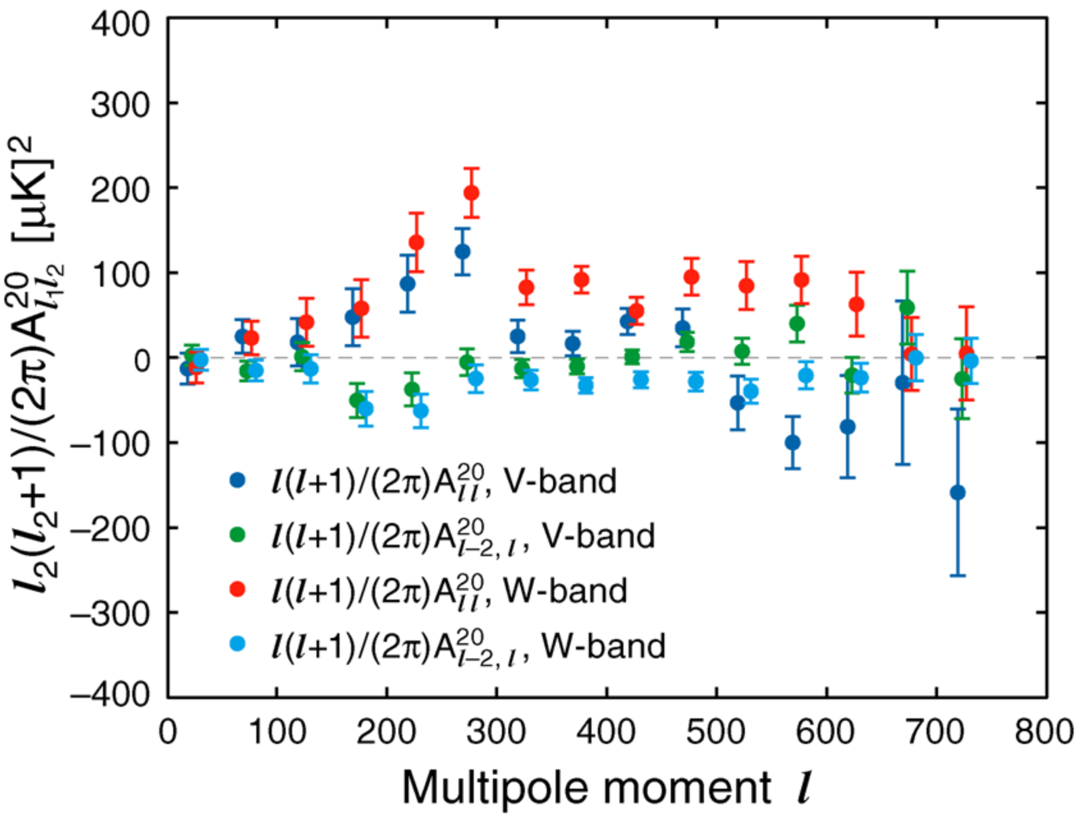
de Oliveira-Costa et al. (astro-ph/0307282) estimate the probability of the combination: low quadrupole + alignment + "planarity":

~4 x 10^{-5}

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

The alignment persists in the 7-year data.

Statistical Anisotropy



Quadrupolar modulation –

Groeneboom et al. (0911.0150) and Hanson et al. (0908.0963) search for quadrupolar modulation of the Gaussian anisotropy in WMAP5 and find evidence for an effect in mode (l=2,m=0) in ecliptic coordinates. Komatsu et al. (1001.4538) confirm the result in WMAP7 (left).

Effect is likely due to asymmetry in the beam response (PSF). Hanson et al (1003.0198) argue convincingly that this is the case.

9-year analysis will attempt to correct for this beam asymmetry.

WMAP Status – 2010

WMAP will complete 9 years of operations at L2 this summer (Aug. 10, 2010) and will cease survey operations at that time.

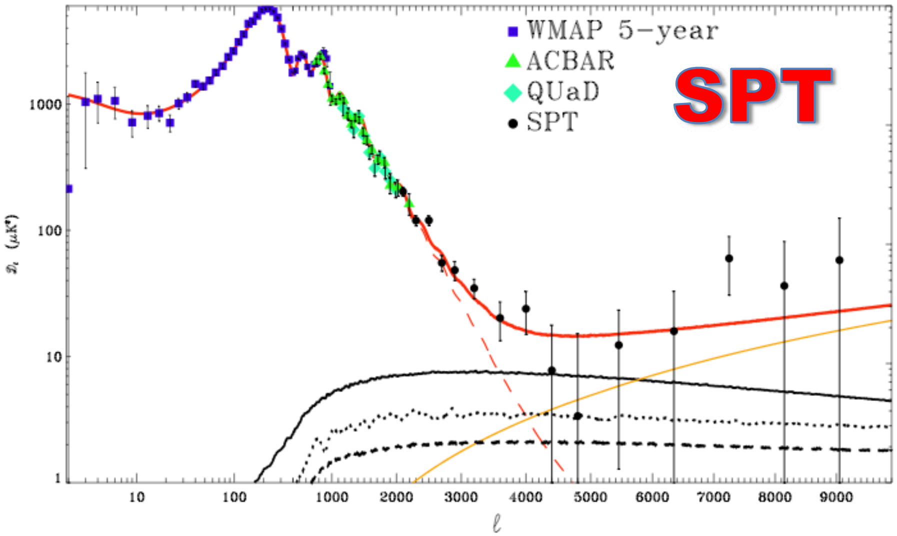
21 days from now.

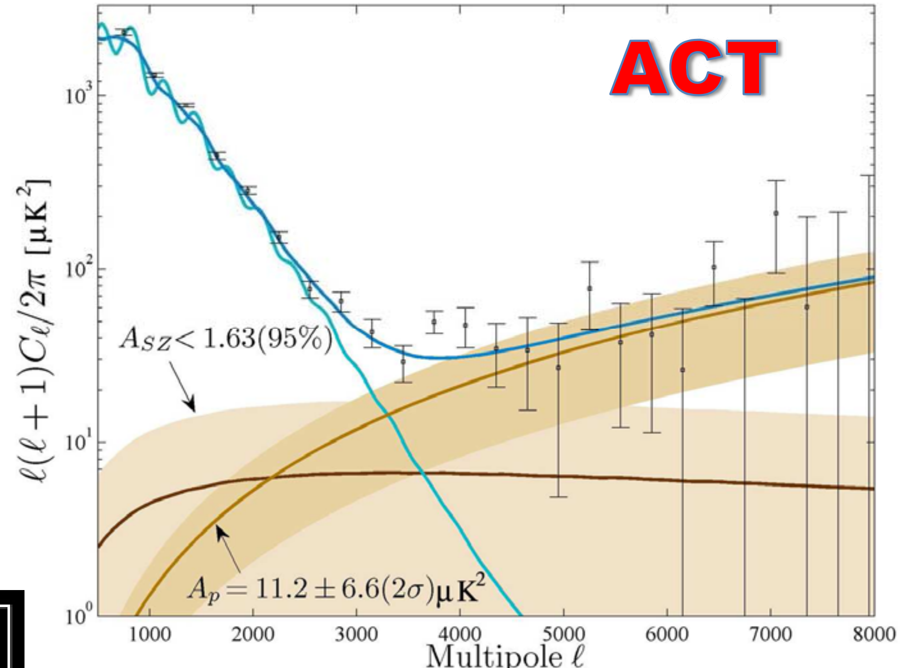
We are planning a 10-day test in which we increase WMAP's angle off sun line from 22.5° to 30° to measure or limit solar interference.

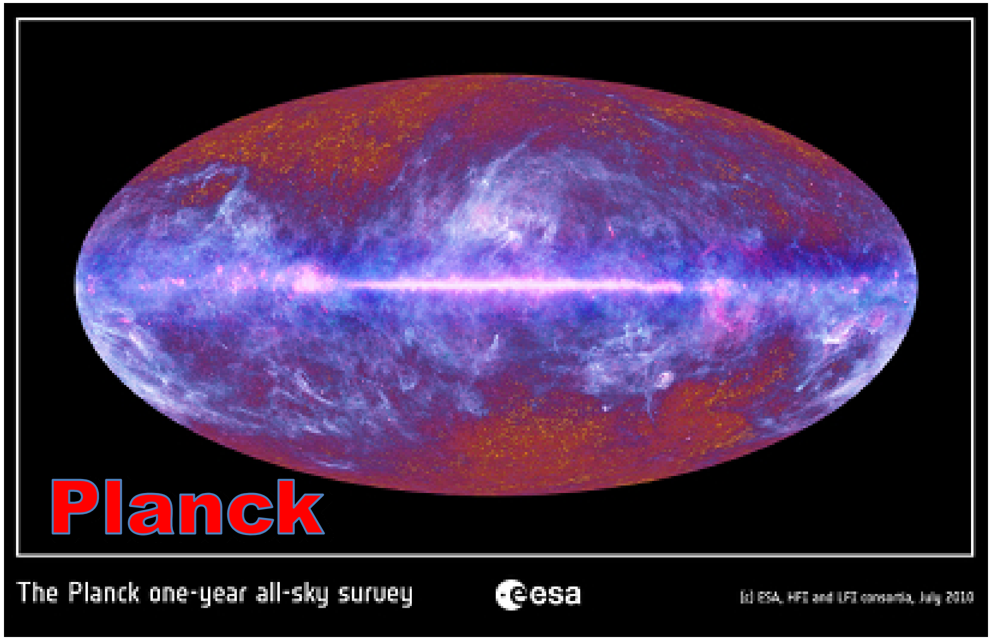
After that, WMAP will either be given a Viking Funeral (a final thruster burn will inject it into a drift away solar orbit), or it will be crashed into the Moon and observed by LRO (Lunar Reconnaissance Orbiter). Final disposition is still pending.

NASA guidelines provide sufficient funding to complete the analysis of the full 9-year science data set. Preliminary processing is well underway – we anticipate a final data release around Jan. 2012.

A Bright Future for CMB Observations





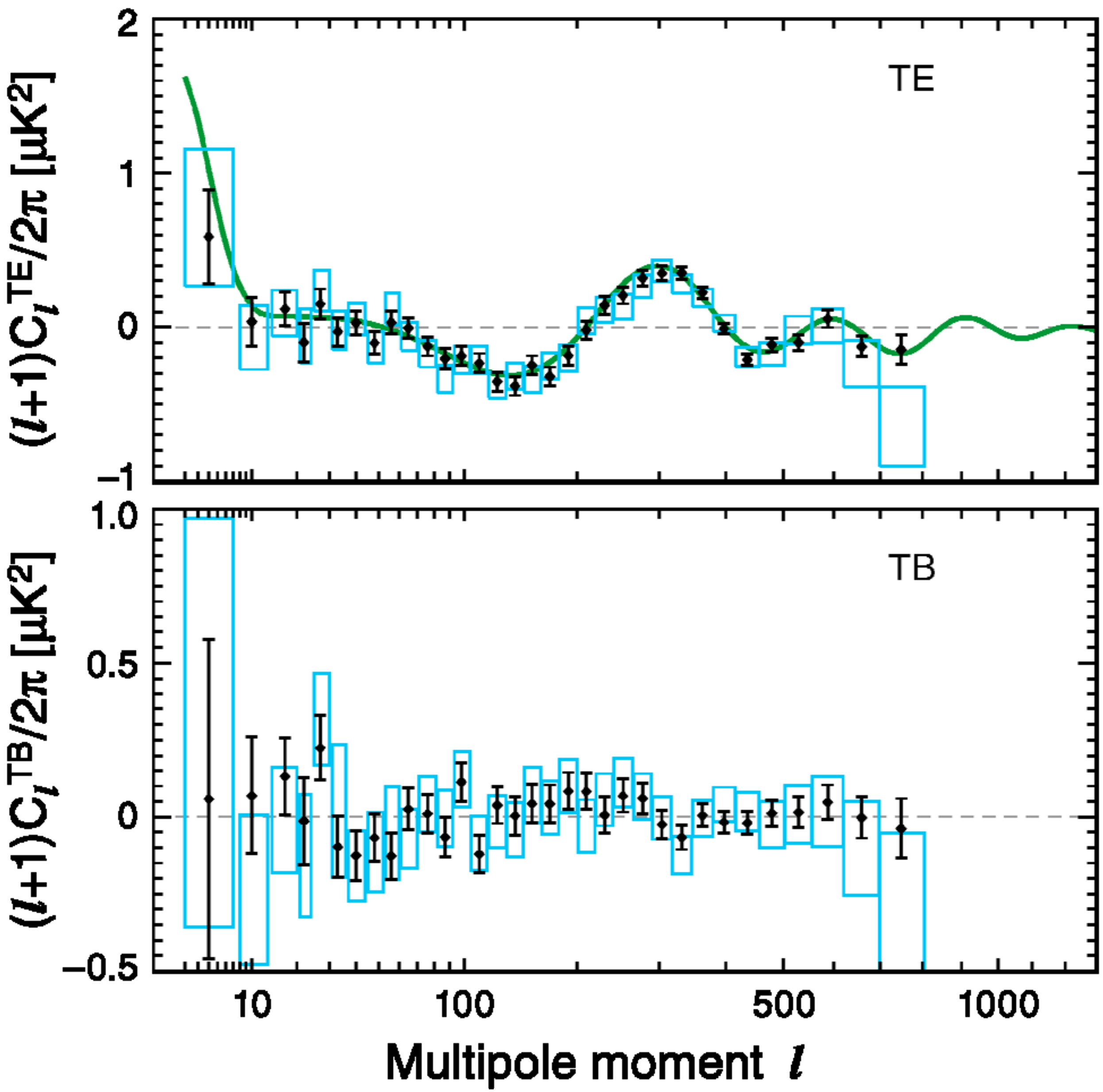


- Planck (left), SPT (top-left), & ACT (top-right) have all started science data acquisition.
- Ground- and balloon-based polarization experiments in development to search for B-mode polarization & gravitational wave background from inflation. Lead-up to CMBPol mission.


COSMOLOGY MARCHES ON
Where did it all come from?
Where did it all come from?
S. Harris

The End

Improvements in High-*l* TE & TB

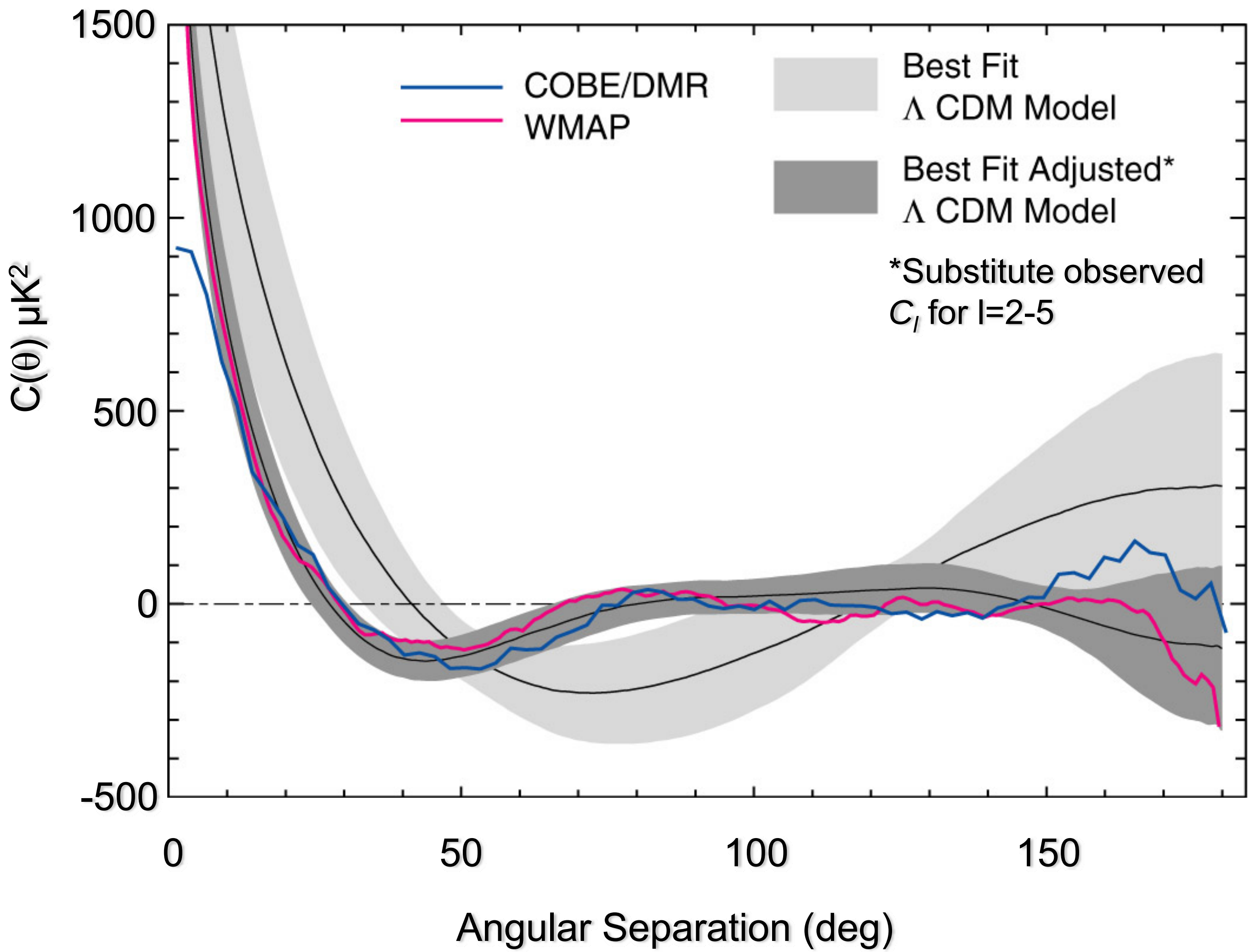


Black pts. – 7yr
Blue boxes – 5yr

High-l polarization data was improved by the inclusion of W-band (94 GHz) data in the WMAP7 release.

Gives a factor of ~2 improvement in high-l sensitivity.

2-pt Correlation Function – Cut Sky



Definition:*

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

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

Posterior statistic:

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

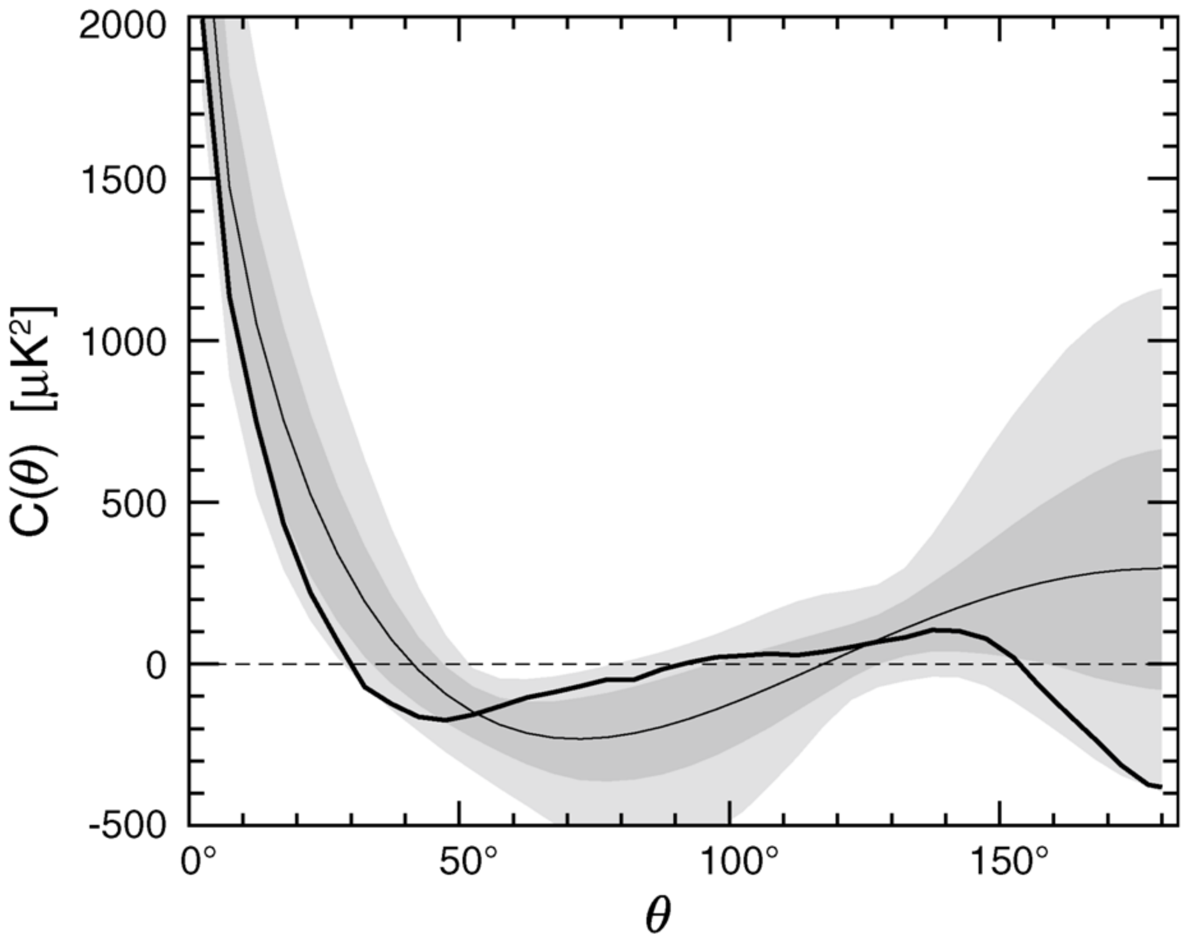
Likelihood of low *S* for best-fit LCDM:

0.15%-0.3%

Spergel et al.
ApJS, 148, 175, 2003

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

2-pt Correlation Function – Full Sky



Definition:*

$$C(\theta) = \sum_{l} \frac{4\pi}{2l+1} C_l W_l P_l(\cos\theta)$$

Likelihood of low *S* for this estimate is a few percent, not unusual.

Same conclusion follows using $\langle T_i T_j \rangle$ estimate on full-sky ILC map.

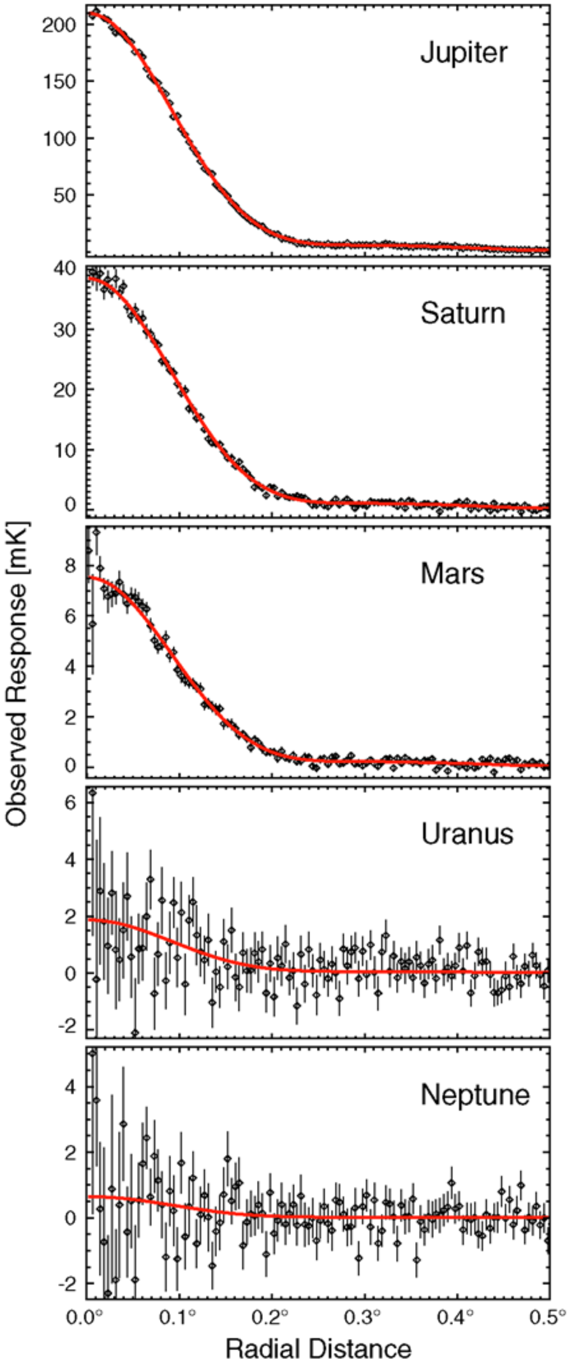
So – cut-sky result for lack-of-large-angle-power **is** unusual relative to an ensemble of ΛCDM simulations, but full-sky result is not.

Is this an anomaly?

Kashlinsky et al – "Dark Flow"

- Kashlinsky et al. attempt to use the kinetic Sunyaev-Zeldovich (kSZ) effect to measure the bulk velocity of ~1200 X-ray clusters out to z~0.3.
- Note: $\Delta T_{kSZ} \sim \tau V_{cluster,}$;   V relative to CMB rest frame.
- Cluster bulk flow manifests as a dipole in ΔT_{ksz} when evaluated over an ~isotropic sample of cluster locations.
- After filtering primary CMB anisotropy, a residual dipole of order 5 μK is seen (~3σ).
- Conversion to V is model dependent: it depends on the average cluster radial profile after filtering. Beta model produces different *sign* for <τ> than NFW profile, after filtering.
- Method assumes that the CMB rest frame is also the zero-dipole frame.

The outer planets – selected results



The Outer Planets in WMAP

The outer planets are important calibration sources for small-scale wave experiments.

WMAP data reduction for outer planets:

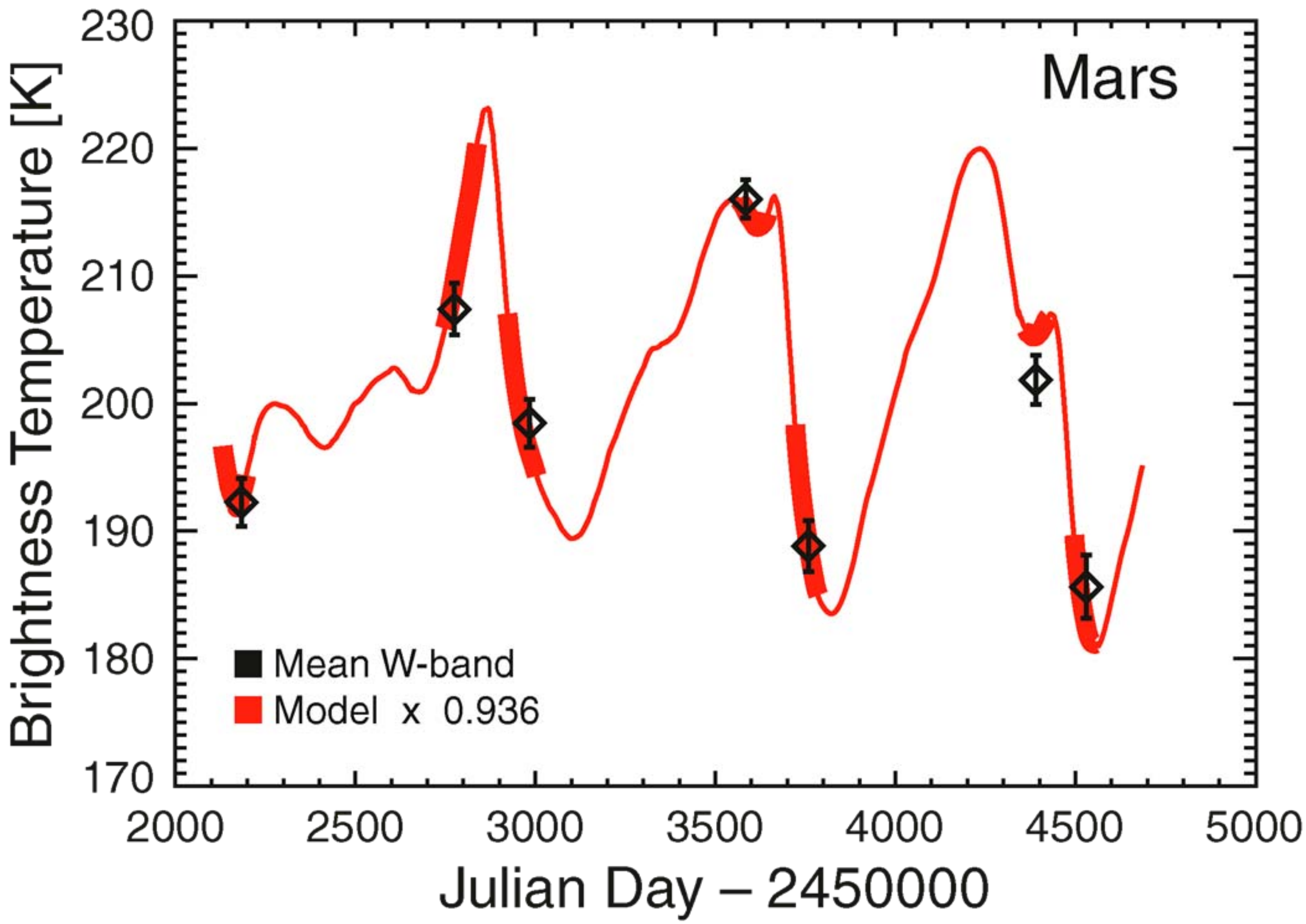
• Derive beam profiles from Jupiter modeling.

• Fit amplitude of profile to each “season” of planet data to obtain a brightness vs. season.

• At left is data for one channel and one season for 5 planets. 1 season is ~45 days.

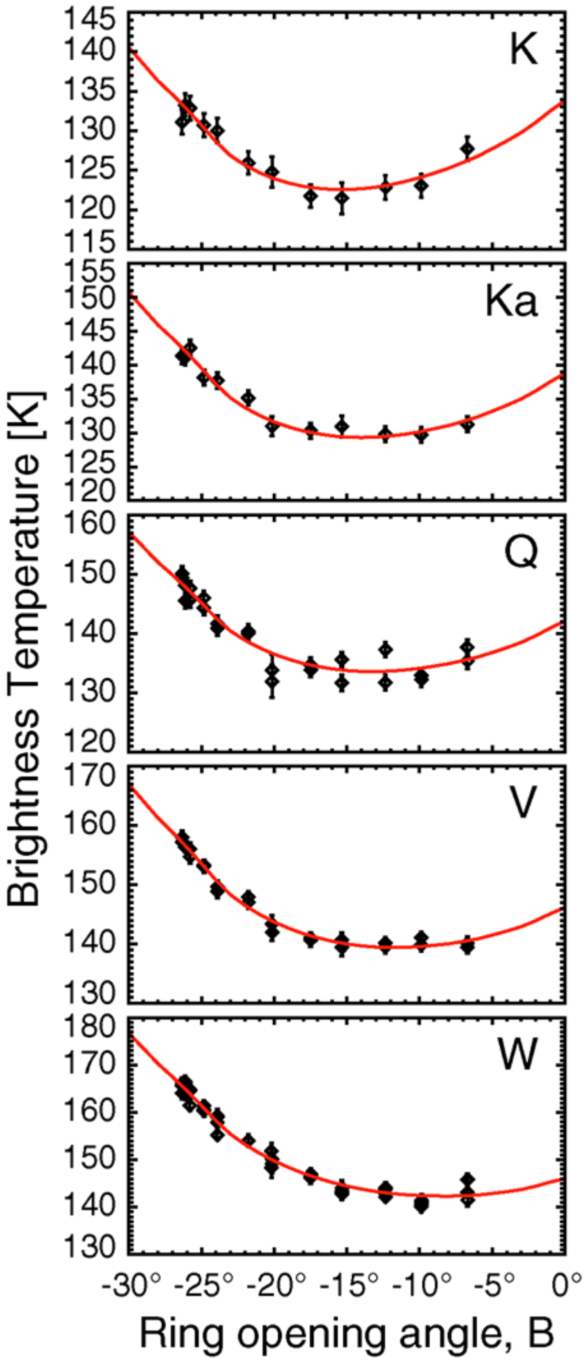
• Study planet properties with this reduced data.

Mars from WMAP



Black points are 94 GHz Mars data over 7 years of observations. Red model is Wright's IR Mars model scaled by 0.936, suggesting a frequency-dependent surface emissivity.

Saturn from WMAP

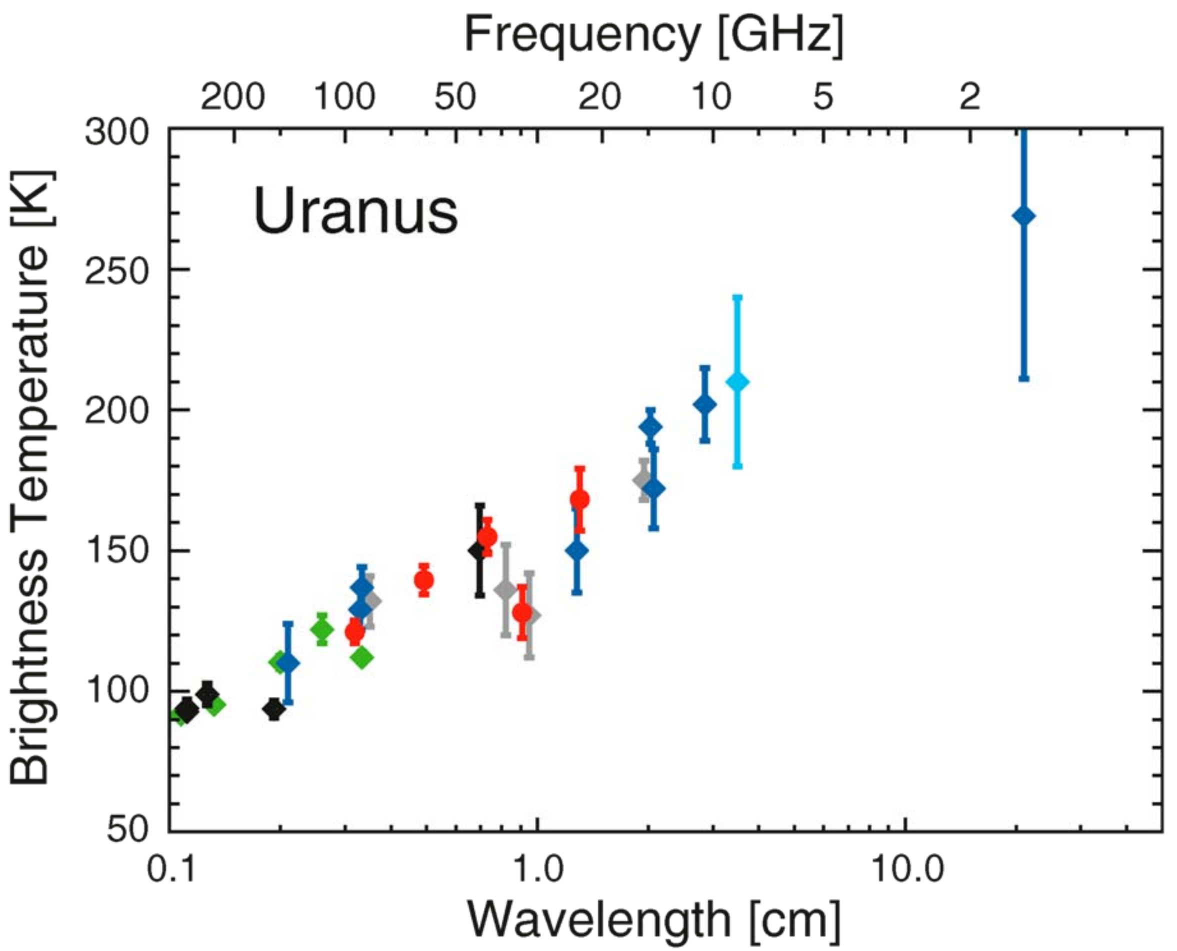


Black points are Saturn data as a function of ring inclination, B.

Red curves are a simple model with fixed disk brightness temp., a separate but common temperature and optical depth for the rings.

We have a ring plane crossing in 2009/10 that will break some degeneracy in the model.

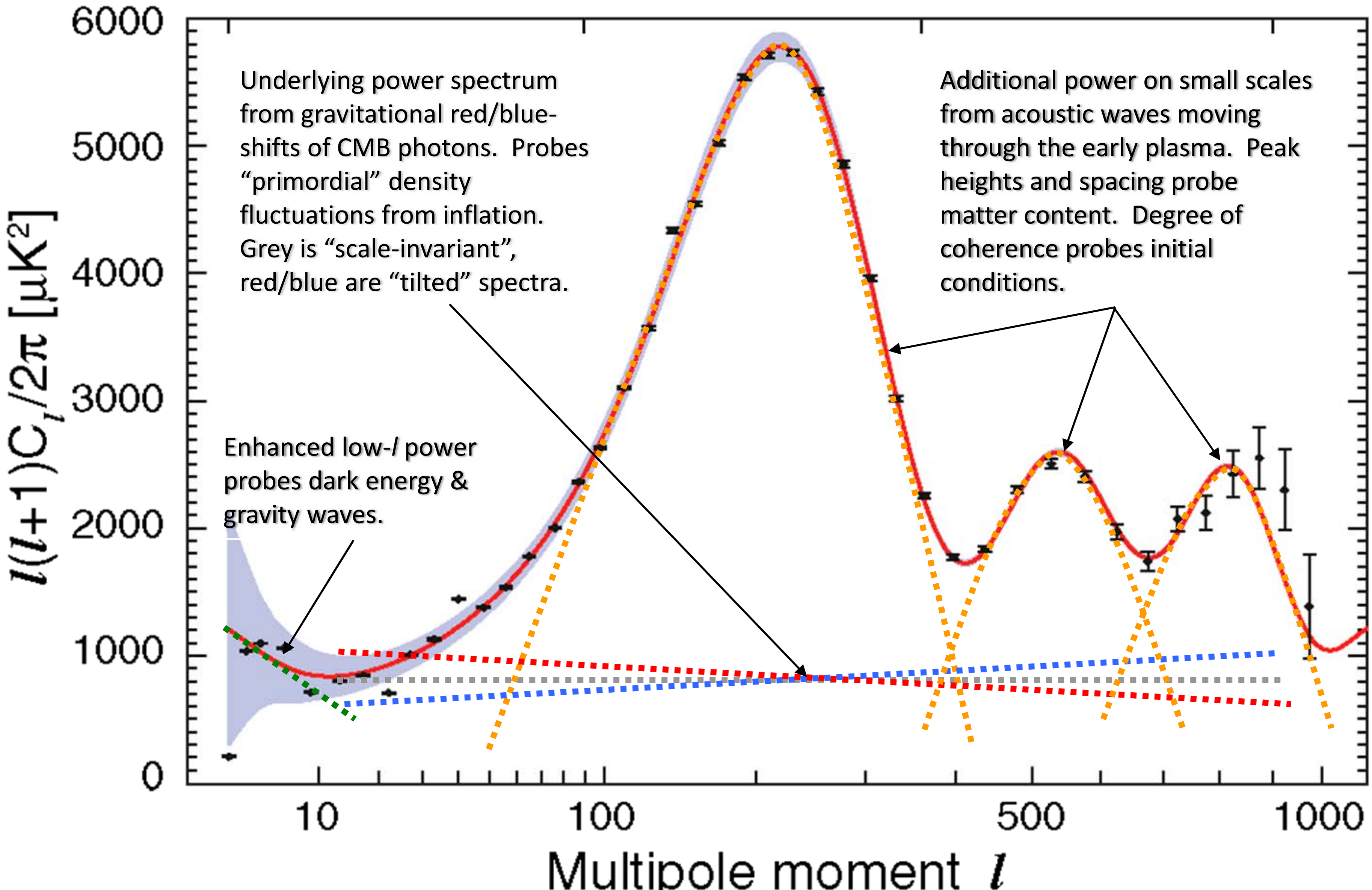
Uranus from WMAP



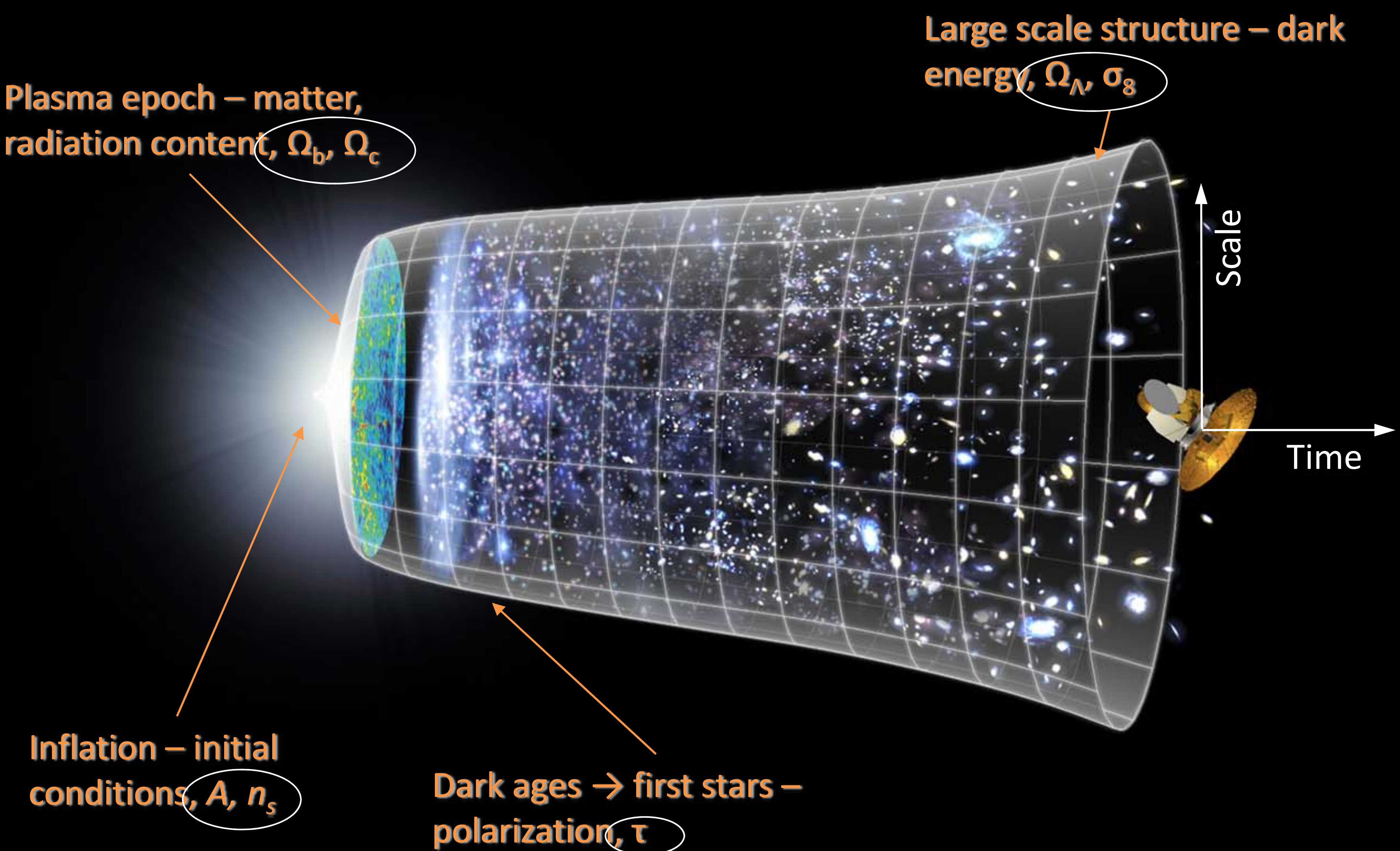
Red points are WMAP Uranus data co-added over all 7 years of observations. Prior measurements are shown for comparison.

What is causing the dip at ~1 cm? Not ammonia or methane…

3 Elements of the Power Spectrum

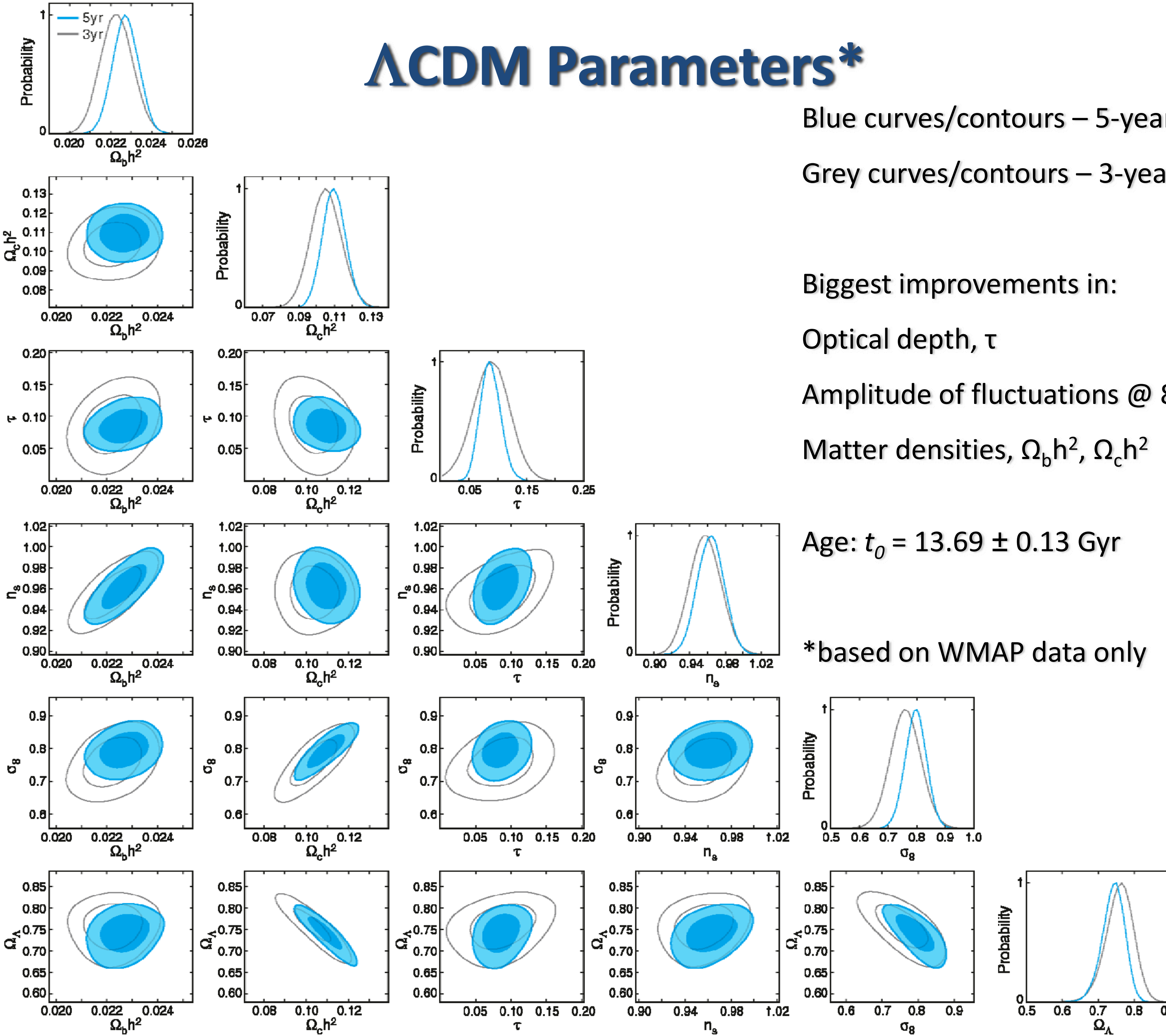


The 6 Parameters of ΛCDM*



*The amplitude parameters A and σ_8 are not are independent; flatness of the universe is assumed in ΛCDM.

ΛCDM Parameters*



Blue curves/contours – 5-year data

Grey curves/contours – 3-year data

Biggest improvements in:

Optical depth, τ

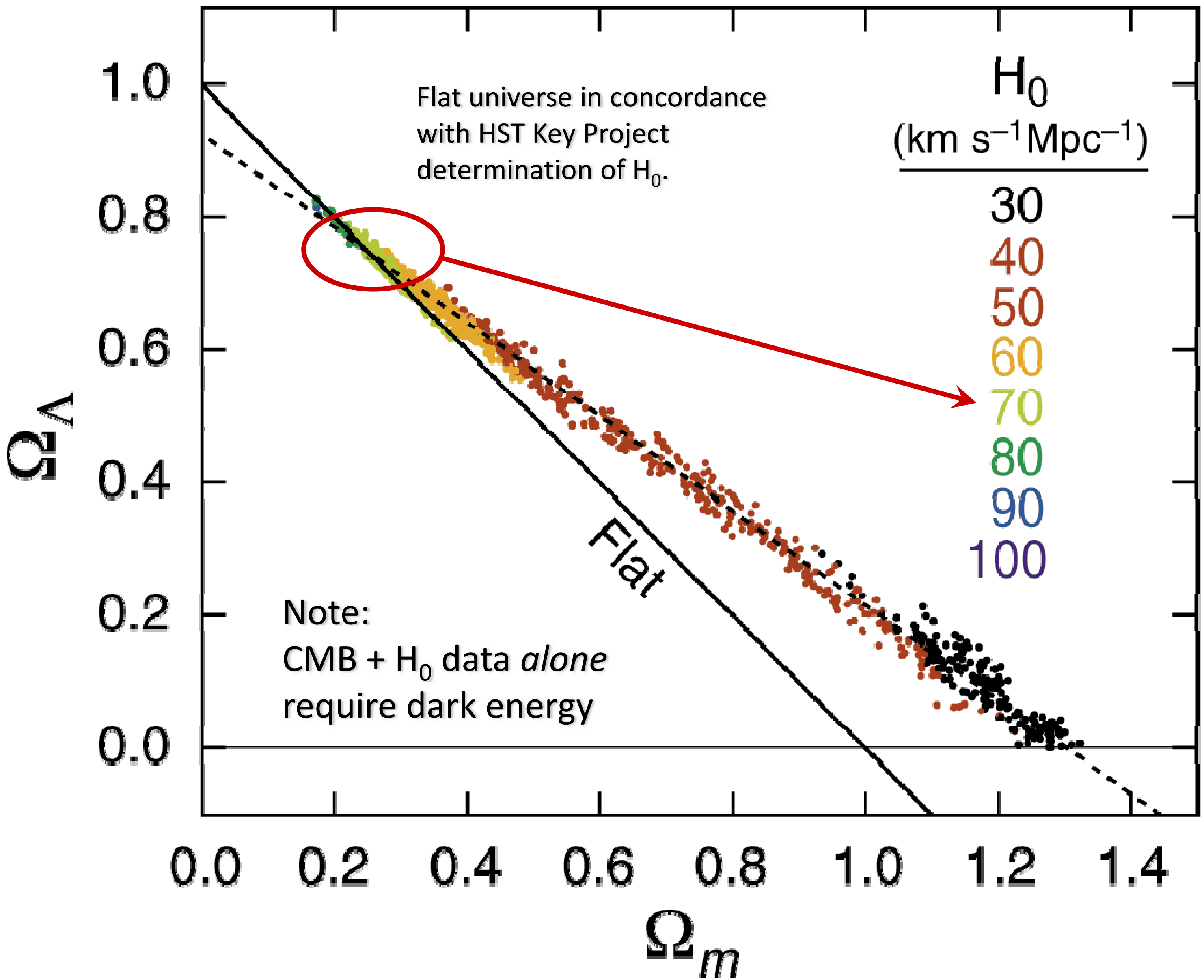
Amplitude of fluctuations @ 8 Mpc, σ_8

Matter densities, $\Omega_b h^2$, $\Omega_c h^2$

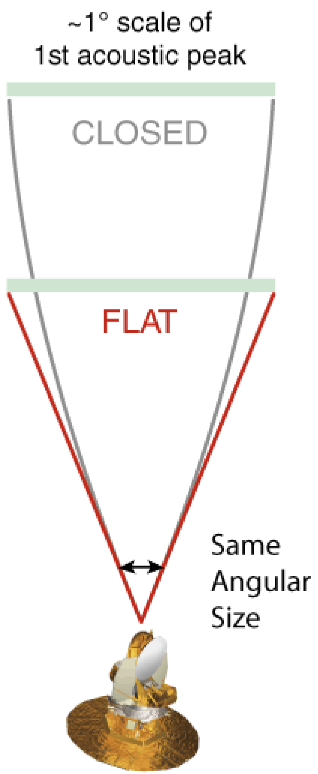
Age: t_0 = 13.69 ± 0.13 Gyr

*based on WMAP data only

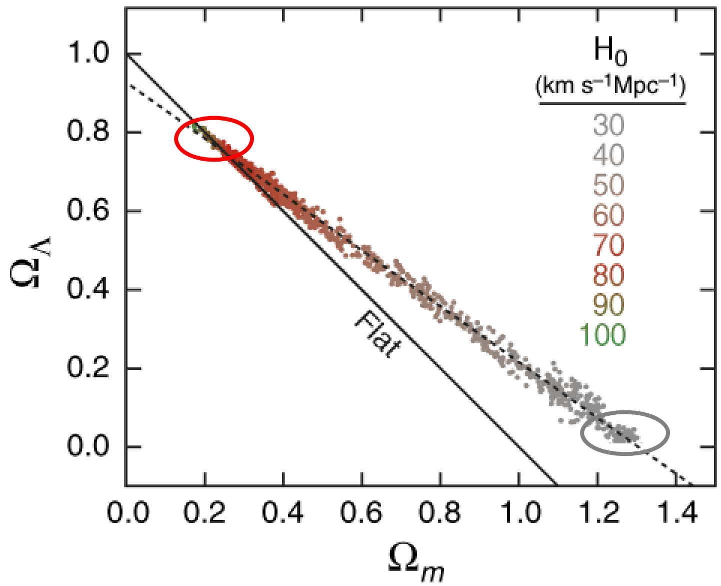
Testing Assumptions: Flatness

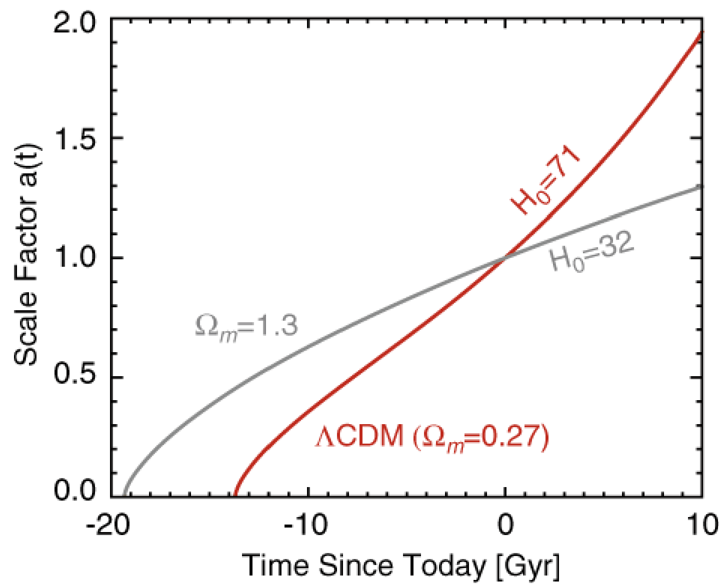


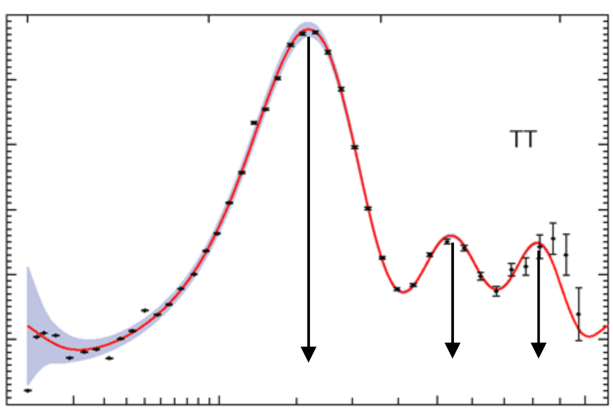
Testing Assumptions: Flatness



Geometric degeneracy in the CMB

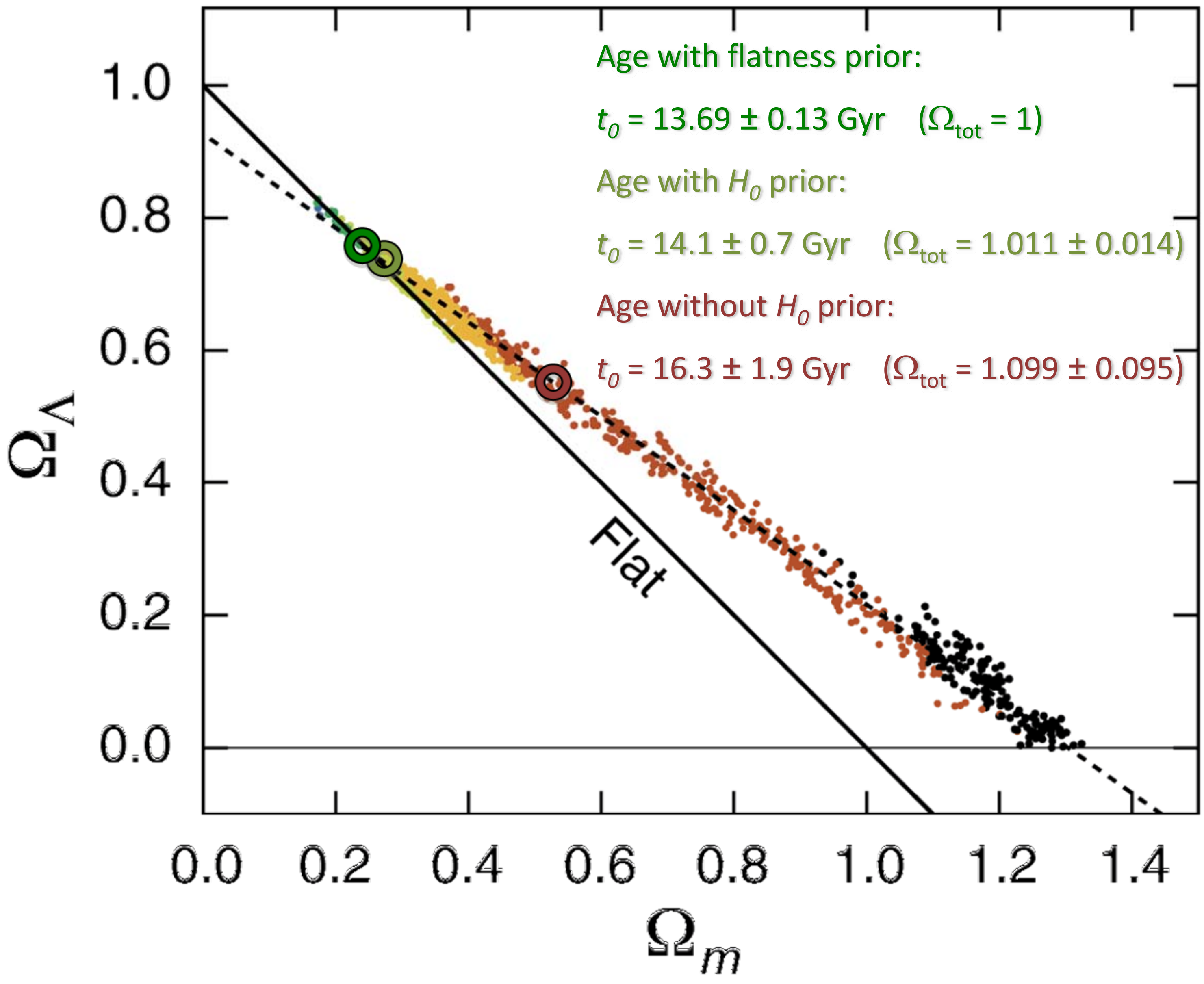




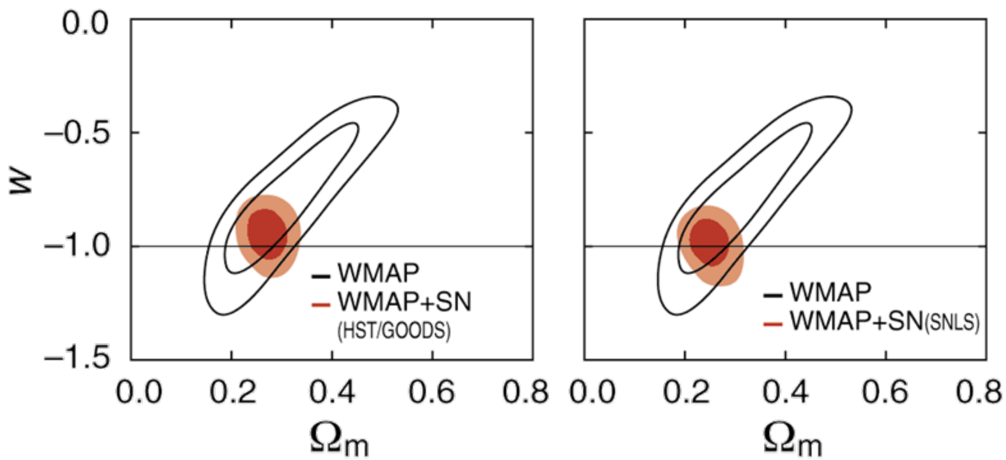


- Acoustic scale is the proper distance a sound wave travels during plasma epoch (~379,000 yr).
- Set mostly by matter / radiation ratio.
- Measured by peak locations, but this is degenerate with distance to last-scattering surface (hence H_0).

Testing Assumptions: Flatness & Age

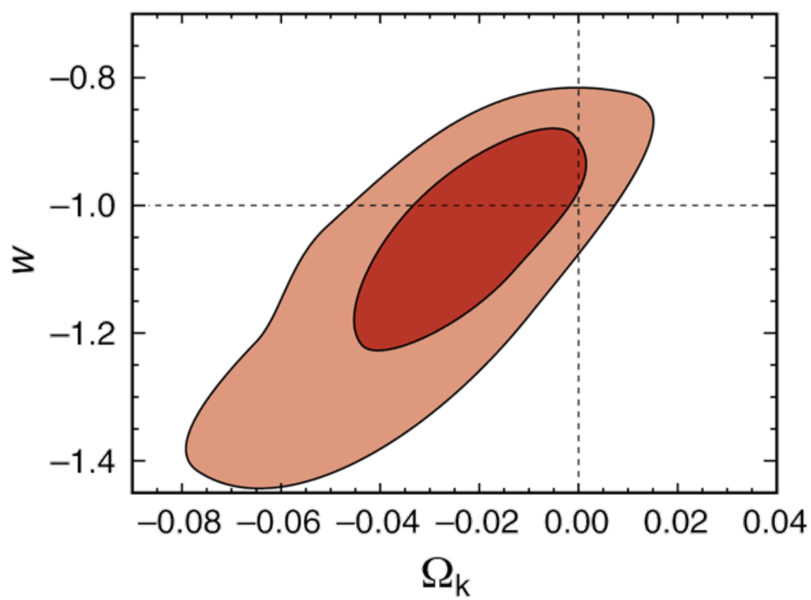


Testing Assumptions: Dark Energy



Constraints on (Ω_m,w) assuming:
1) a flat universe,
2) w´ = 0,
3) dark energy does not cluster.

WMAP-only and WMAP+SNe data from two different surveys.

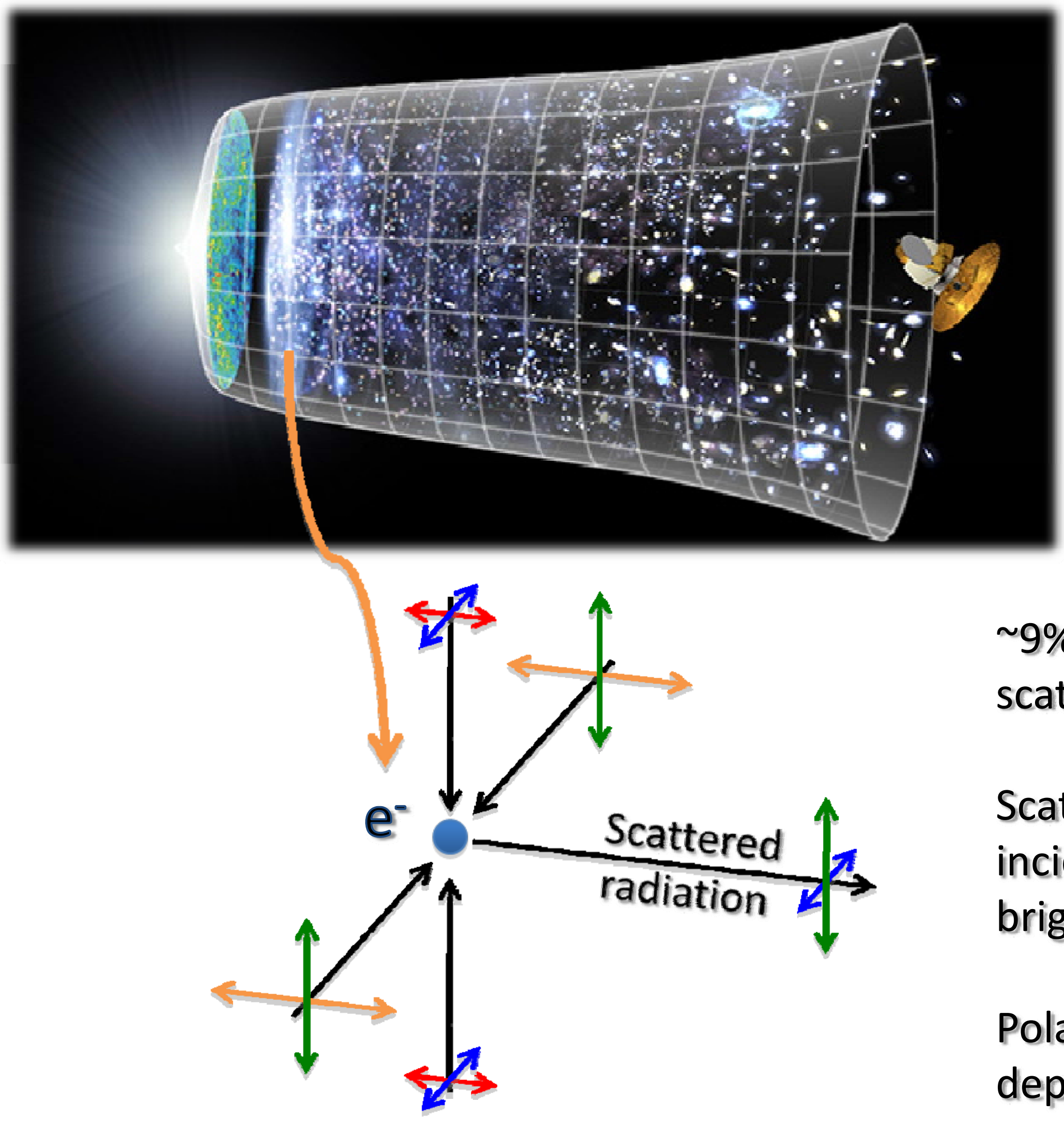


Constraints on (Ω_k,w) assuming:
1) w´ = 0,
3) dark energy does not cluster.

WMAP + all other data.

Constraints still weak – more data needed, e.g., JDEM.

Probing Reionization

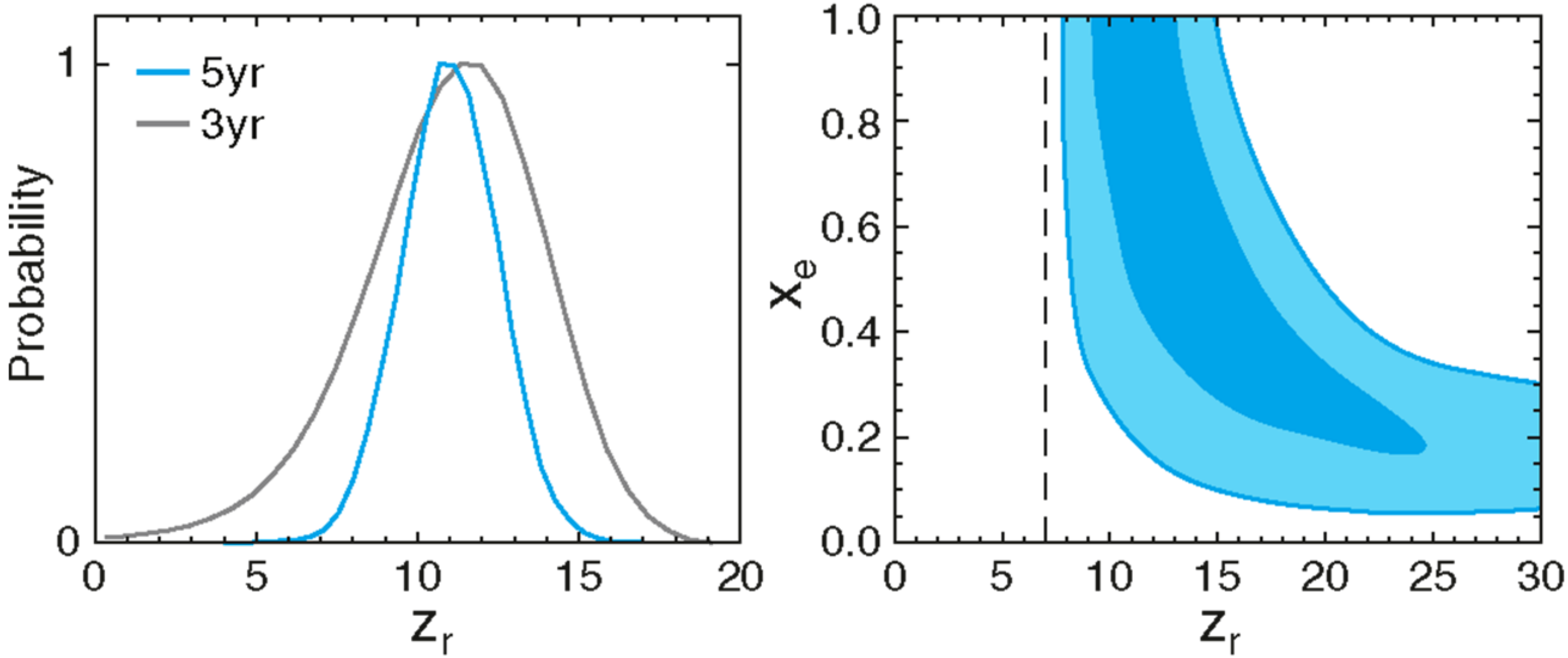


~9% of CMB photons are Thompson-scattered by free electrons at z>6.

Scattered radiation is polarized if incident radiation has a quadrupoler brightness distribution.

Polarization strength probes optical depth of reionized gas.

Reionization History



Improved polarization data improves measurement of optical depth and/or reionization redshift. Also begin to probe 2nd reionization parameter.

The **bulk** of the reionization had to occur at z>6, thus it had to be an extended process.

Six Tests of Inflation

- The following are "generic" predictions of inflation, items for which we had little evidence when inflation was introduced (from Steinhardt):
  - **near scale invariance**
    - slope of spectrum, measured with ~20% precision by COBE
  - **flatness**
    - position of 1st acoustic peak, measured by TOCO, Boomerang,WMAP1
  - **adiabatic fluctuations**
    - width of 1st acoustic peak, measured by Boomerang, …, WMAP1+
  - **gaussian fluctuations**
    - modest limits on f_{NL}, measured by WMAP1+
  - **super-horizon fluctuations**
    - TE anti-correlation on >2° scales, measured by WMAP1+
  - **spectral tilt, $n_s < 1$**
    - favored by WMAP3+, n_s=0.965 @ ~2.5 σ from 1
  - **gravity waves (tensors)**
    - measured by CMBPOL?

Low Quadrupole Power

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

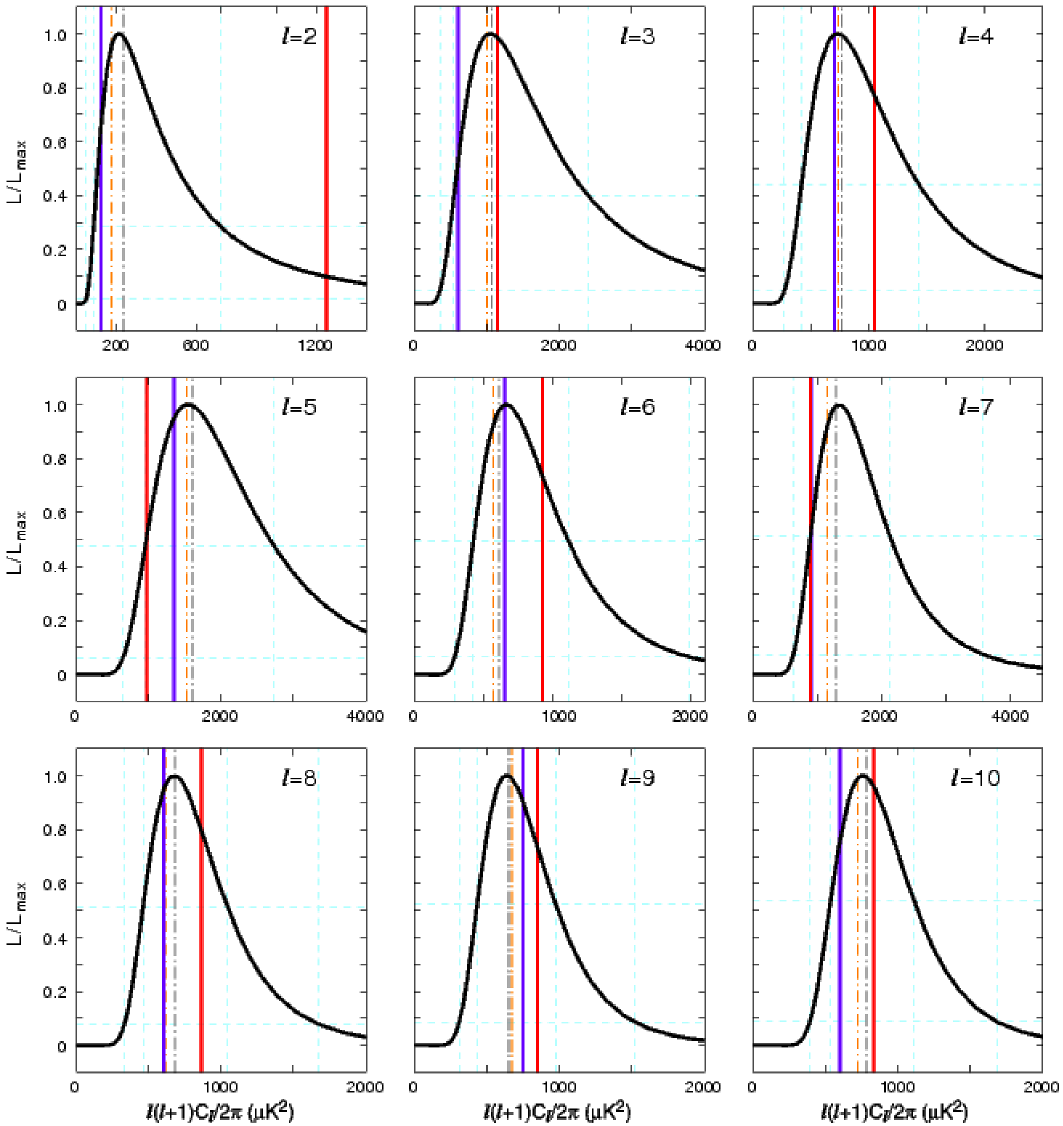
- Measured value(s) of quadrupole -
  - Quadratic estimator, V+W band, galaxy template & cut: 123 μK^2
    (Hinshaw, et al., ApJS, 148, 135, 2003)
  - Full-sky estimate, Galaxy-cleaned map: 184 μK^2
    (Tegmark et al, astro-ph/0302496)
  - Full-sky estimate, Linear Combination map: 154 ± 70 μK^2
    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 LCDM 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.

Posterior Power Spectrum Likelihood, *l*=2-10

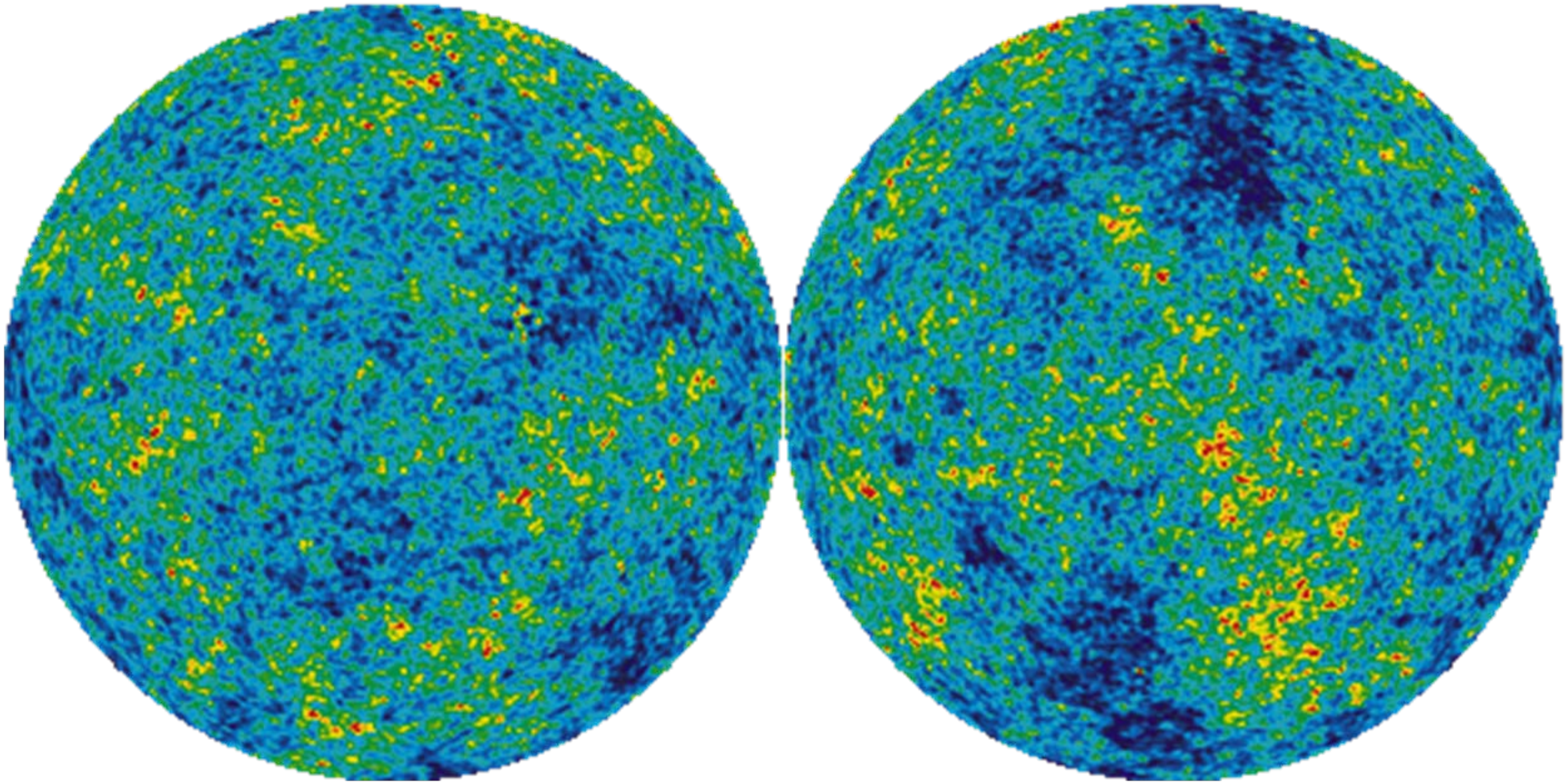


Maximum likelihood:
black curve –
ILC map, Kp2 cut

Psuedo-C_l:
purple line –
ILC map, Kp2 cut
orange dashed line –
V-band map, Kp2 cut
gray dashed line –
ILC map, full sky

Best fit model, MCMC:
red line –
LCDM (6 parameters)

Significant North-South Power Asymmetry?

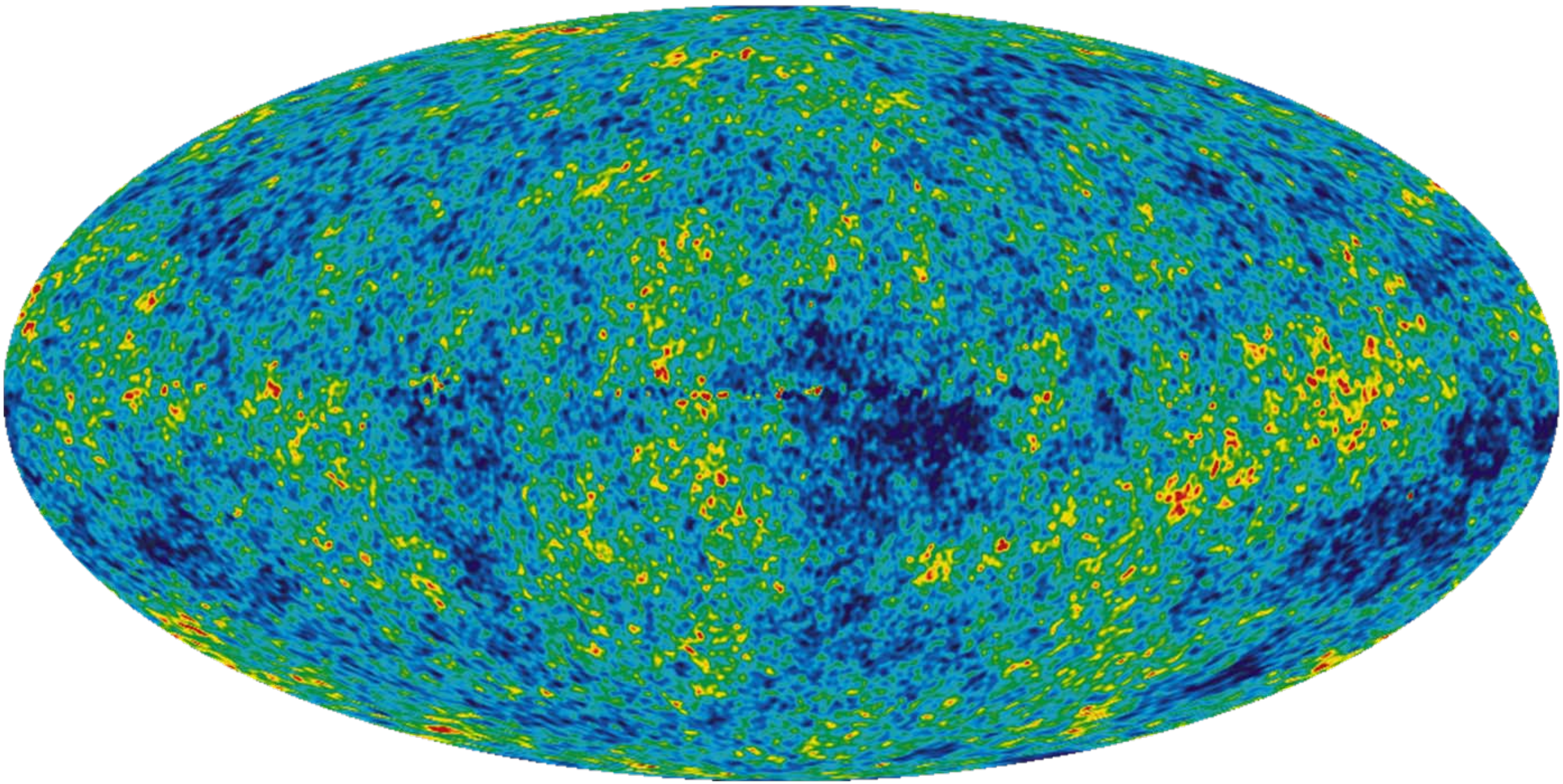


North Ecliptic Hemisphere   South Ecliptic Hemisphere

Note difference in North/South appearance.
WMAP observations are symmetric w.r.t. the ecliptic equator.
Unlikely at the ~0.3% level (Eriksen et al.)*.

*See fine print in later slides.

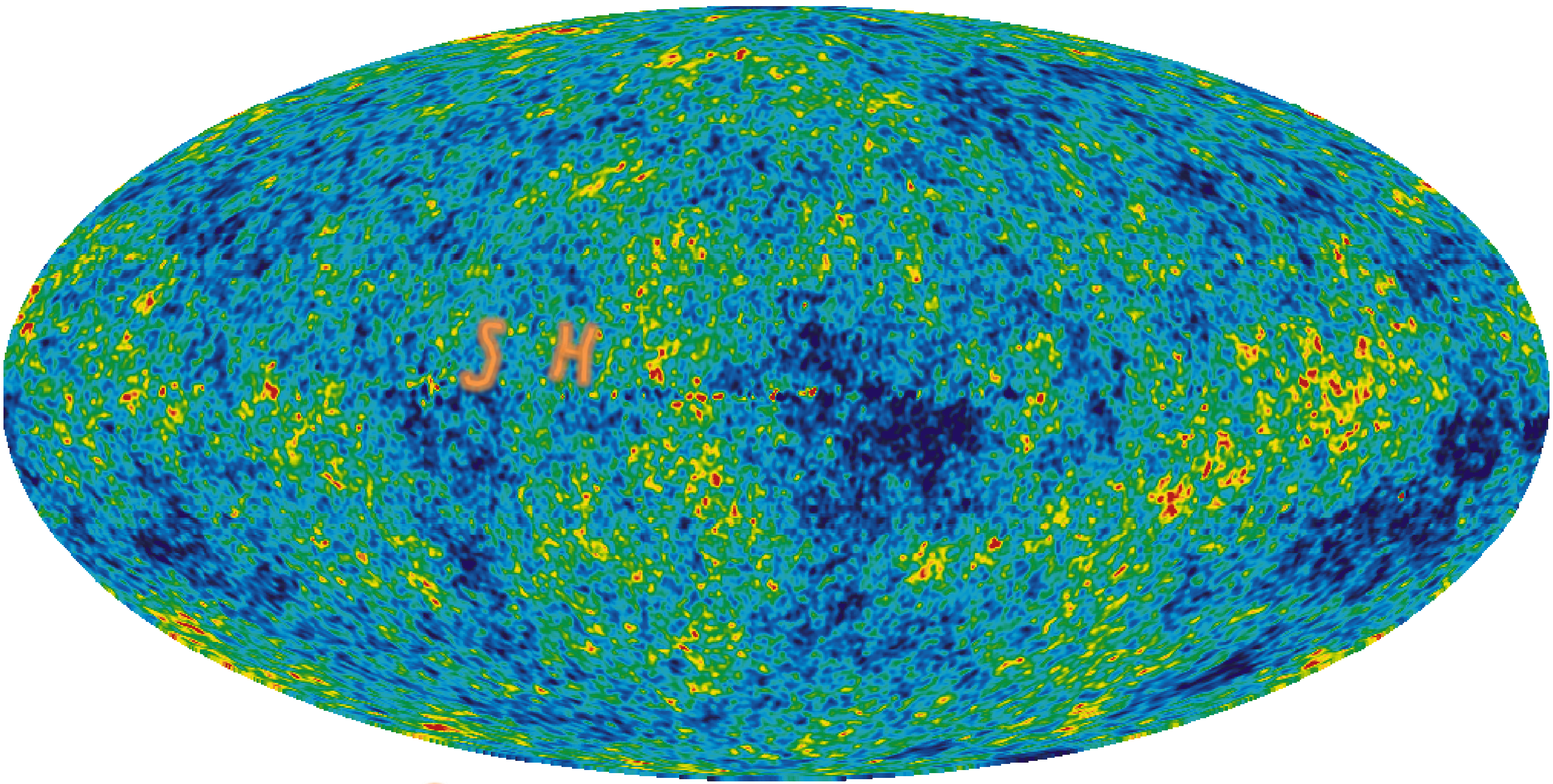
Fluctuations are Gaussian & Random Phase*



Consistent with a gaussian distribution and random phases*: it looks “random”.

*Fine print: many authors have commented on unusual features on largest scales.

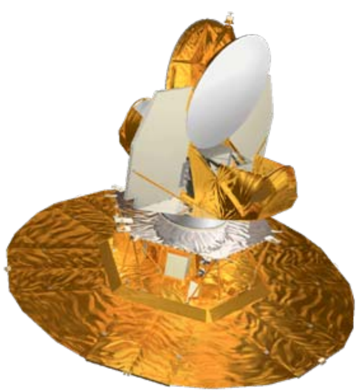
Fluctuations are Gaussian & Random Phase?



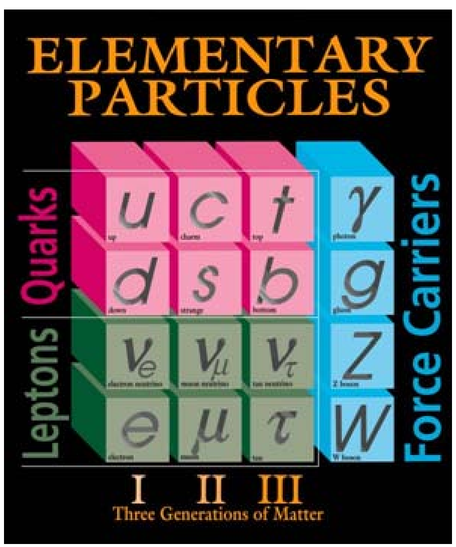
Stephen Hawking

Do These Anomalies Mean Anything?

- 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.
- 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?
  - Bianchi models?
- Any connection to dark energy?
- Any predictions for large scale structure?



Progress in Cosmology



The culmination of this ~two decade old program to measure CMB anisotropy, large-scale structure, and other cosmological probes has produced a remarkable "concordance" model that fits *all* of the major data sets in cosmology.

96% of the stress-energy in this model is in the form of dark matter and dark energy. Fundamental insight to the nature of these constituents may well be very difficult to come by, just as in the standard model of particle physics.

The data should be scoured for hints of discordance.

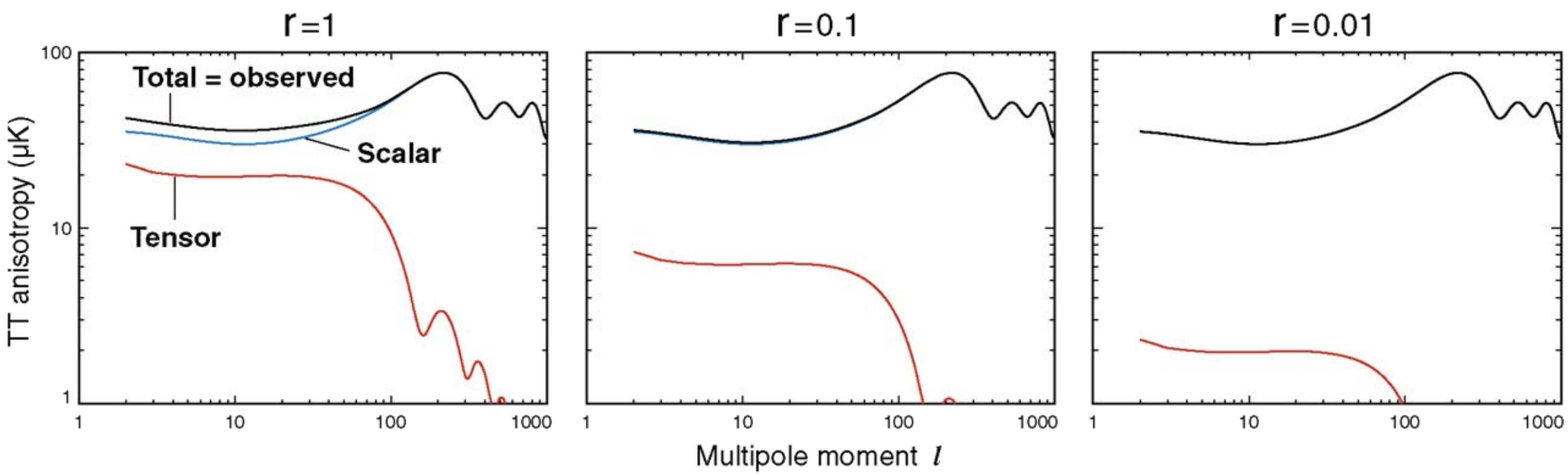
"WMAP didn't change what we think,
it changed what we know."
- gfh

Inflation and Gravity Waves - I

- Inflation predicts two forms of fluctuations:
  - Scalar modes (density perturbations) with slope n_s:
    - generate CMB anisotropy and lead to structure formation
  - Tensor modes (gravity waves) with slope n_t:
    - generate CMB anisotropy but do not contribute to structure formation
- Gravity wave amplitude, *r*, proportional to energy scale of inflation:

$$r^{1/4} \propto \frac{V_\phi^{1/4}}{m_{pl}} = \frac{E_{\rm infl}}{3.3\times10^{16}\,\mathrm{GeV}} \quad \text{with} \quad r \equiv \frac{P(k_0)_{tensor}}{P(k_0)_{scalar}}$$

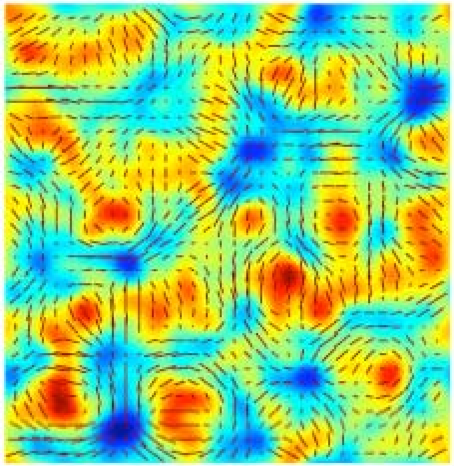
- Both types of fluctuations contribute to CMB temperature anisotropy:

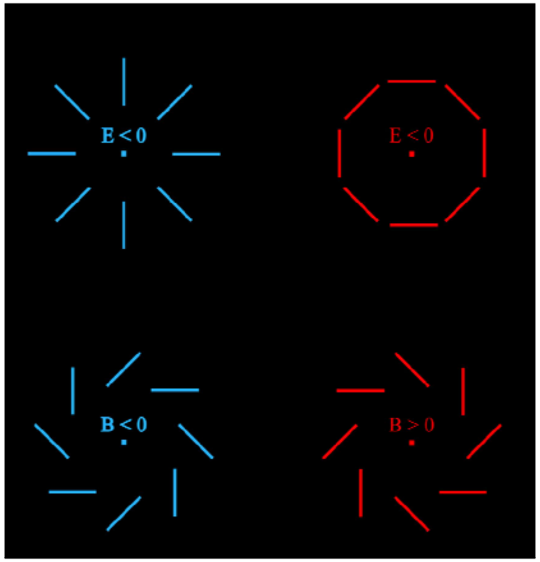


Inflation and Gravity Waves – II

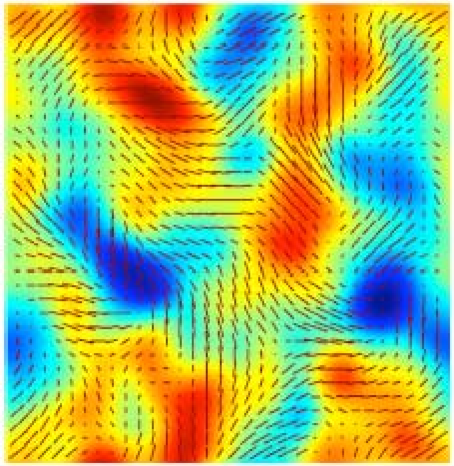
- Both types of fluctuations contribute to CMB polarization anisotropy:
  - Scalar modes produce only "E-mode" polarization patterns, by symmetry
  - Tensor modes produce both "E-mode" and "B-mode" polarization patterns (see below)
- The observation of B-mode polarization uniquely separates scalar and tensor modes from inflation and measures the energy scale of inflation.
- *Only* known probe of physics at E ~ 10^{16} GeV… *12 orders of magnitude higher than planned accelerators.*

E – scalar+tensor

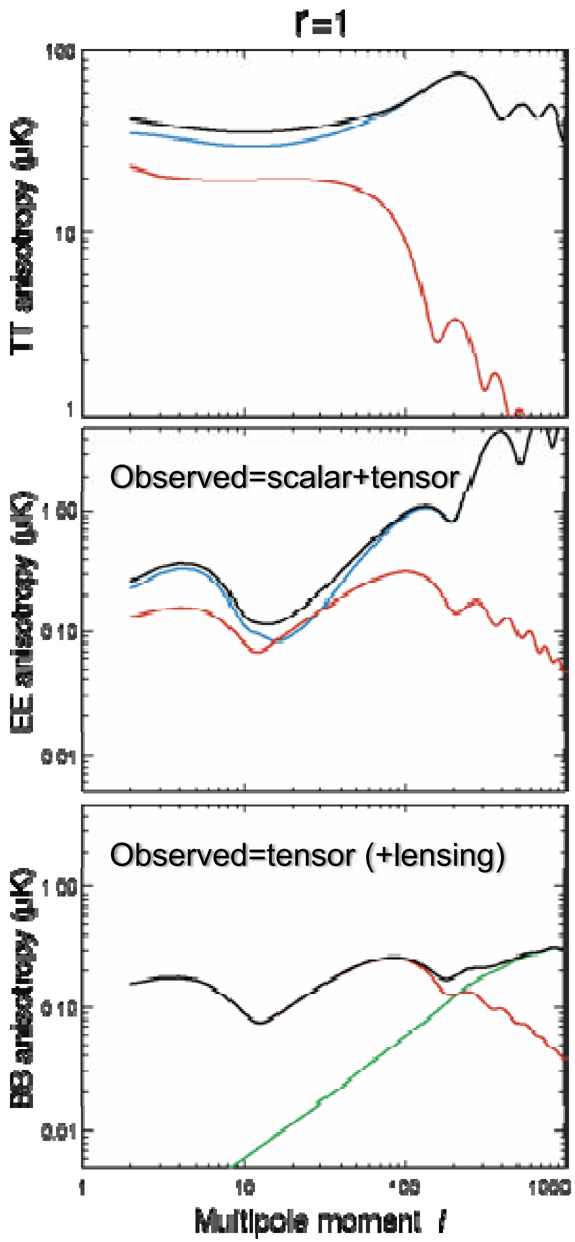




B – tensor only



Predicted Polarization Signal, r=1.00

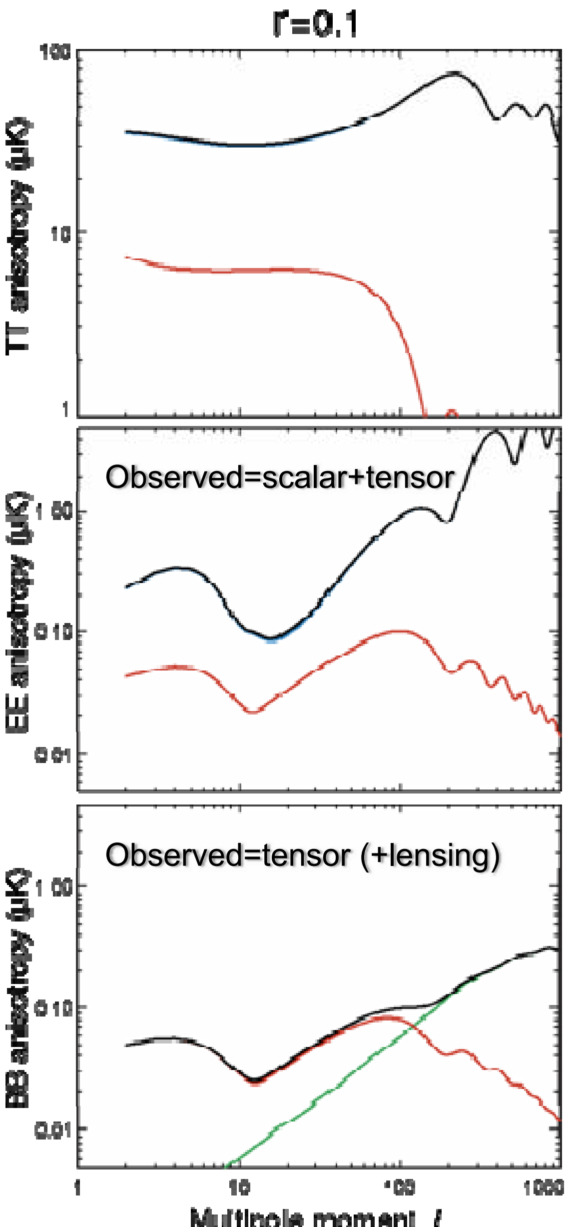


Temperature spectrum
(as before)

E-mode polarization spectrum,
scalar (blue) & tensor (red) terms

B-mode polarization spectrum,
tensor (red) & gravitational lensing (green) terms

Predicted Polarization Signal, r=0.10

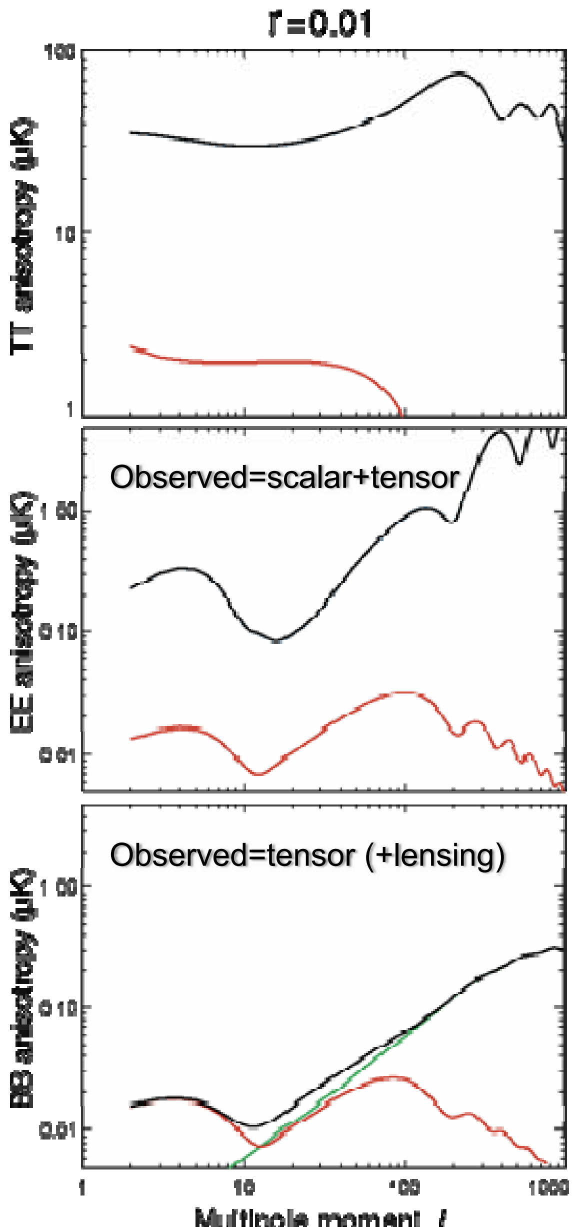


Temperature spectrum
(as before)

E-mode polarization spectrum,
scalar (blue) & tensor (red) terms

B-mode polarization spectrum,
tensor (red) & gravitational lensing (green) terms

Predicted Polarization Signal, r=0.01

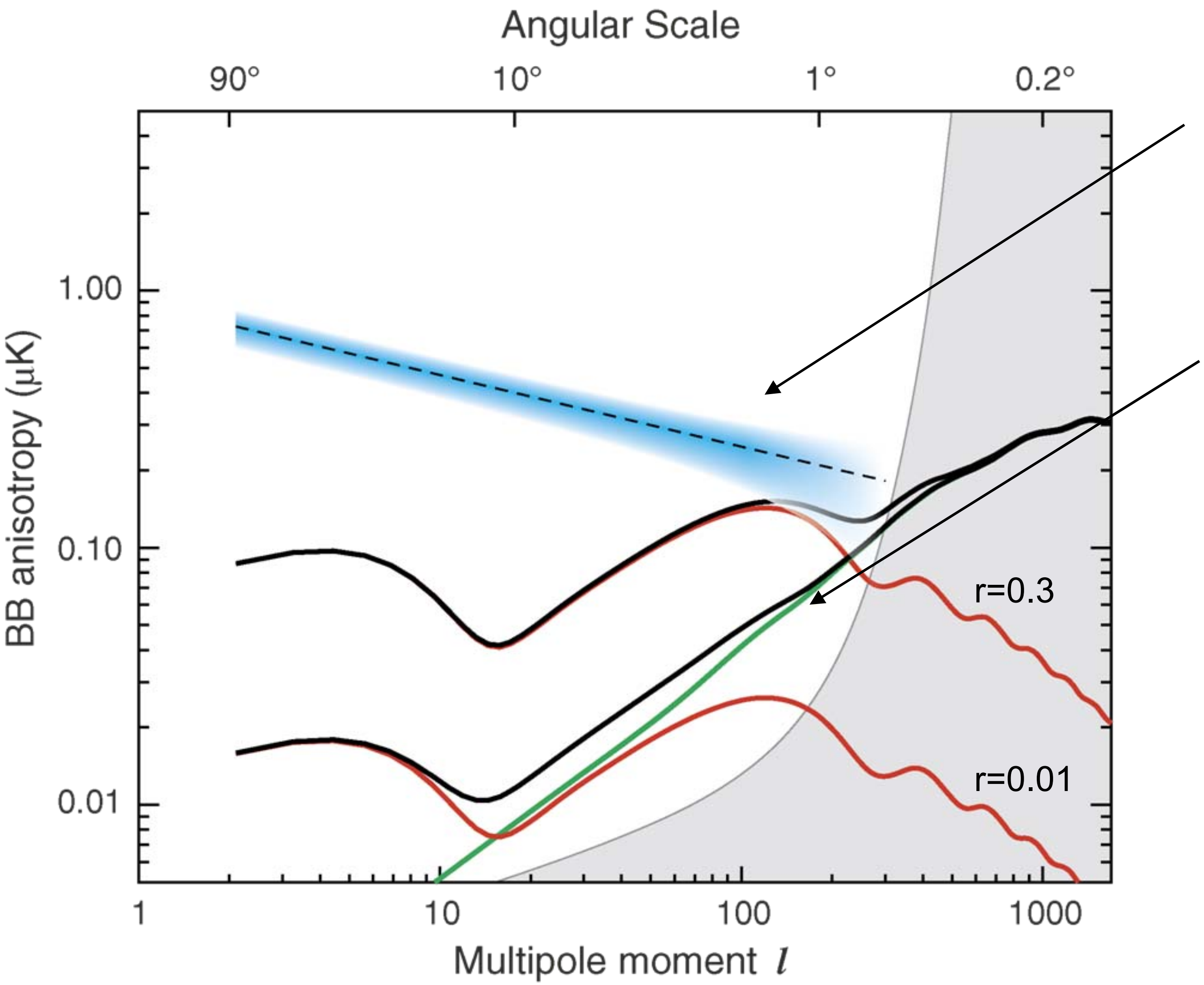


Temperature spectrum
(as before)

E-mode polarization spectrum,
scalar (blue) & tensor (red) terms

B-mode polarization spectrum,
tensor (red) & gravitational lensing (green) terms

Sensitivity & Foreground Estimates



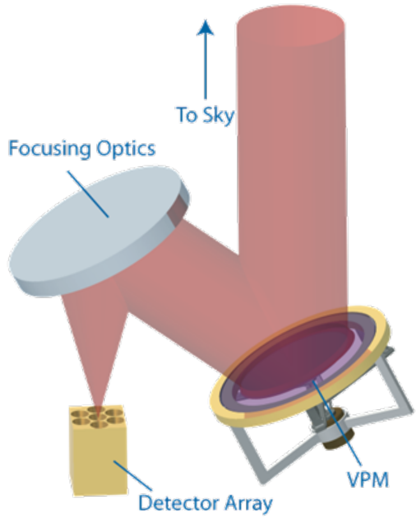
Blue band -
Galactic foreground estimate from WMAP3, frequency dependent

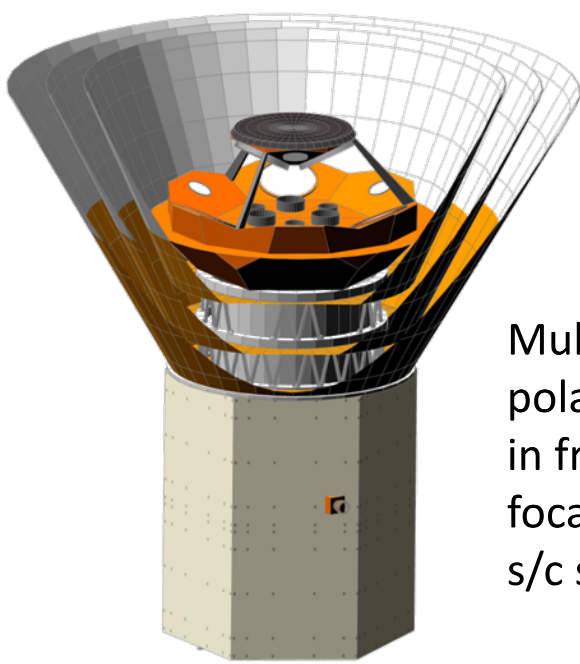
Green line -
Lensing (EE→BB), frequency independent

Red lines -
Gravity wave signal(s)

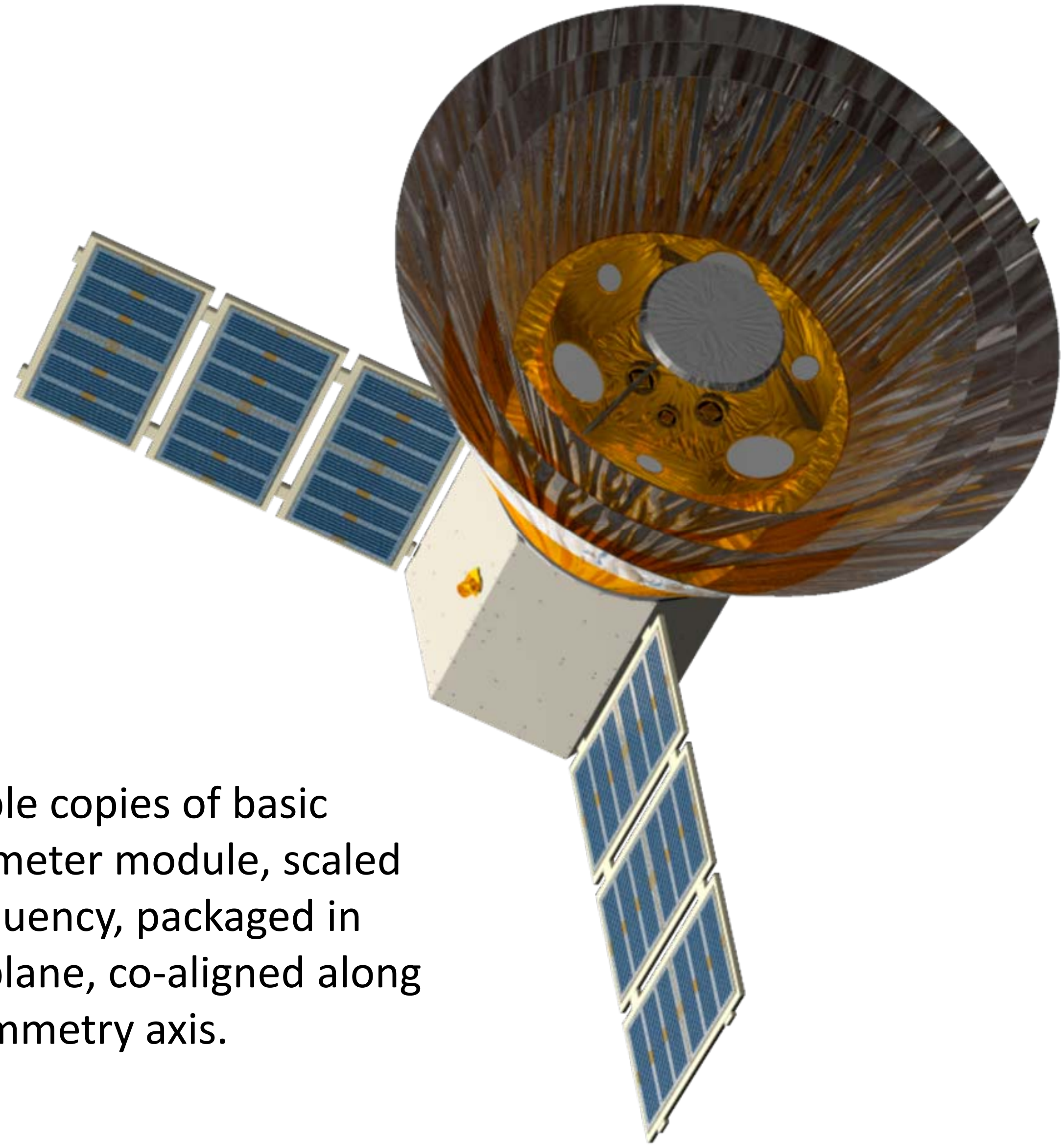
Grey shaded band -
1-sigma sensitivity for 1000-channel system with 1-yr integration, 1°FWHM resolution

Candidate CMBPol Concept





Multiple copies of basic polarimeter module, scaled in frequency, packaged in focal plane, co-aligned along s/c symmetry axis.



Monodromy in the CMB: Gravity Waves and String Inflation

Eva Silverstein and Alexander Westphal

http://arxiv.org/abs/0803.3085v2

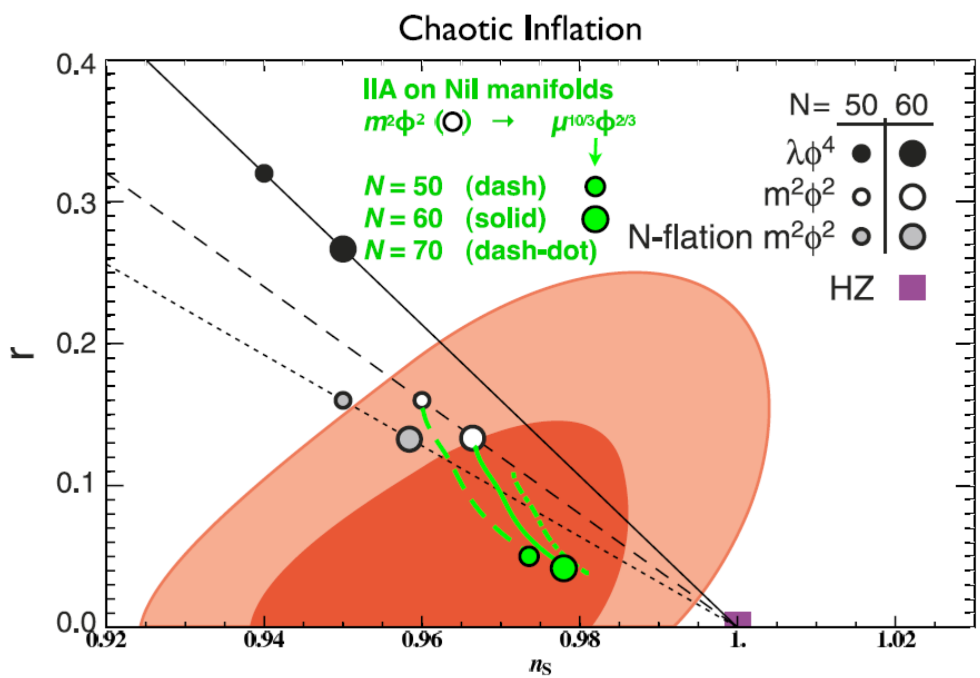


Figure 4: Red: 5-year WMAP+BAO+SN [9] combined joint 68 % and 95 % error contours on (n_s, r). Green: General prediction of the potential $V_{\mathcal{R}}(\phi)$ (2.14) as one formally varies β to interpolate between $m^2\phi^2$ (black hollow circles) and $\mu^{10/3}\phi^{2/3}$ (green solid circles). Only the latter regime is viable in our setup as discussed in the text, so the solid green circles (for $N = 50, 60$ efolds before the end of inflation) denote our prediction.

Large-field inflation (hence gravitational waves) from string theory compactified on twisted tori.

“Odd” Features Noted in WMAP Sky Maps

- Amplitude of signal:
  - Fourier space: the low quadrupole
  - Position space: the 2-pt correlation function
  - Other “bites & dips” 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
- Both…
  - Additive template fits
  - Multiplicative (non-linear) contributions

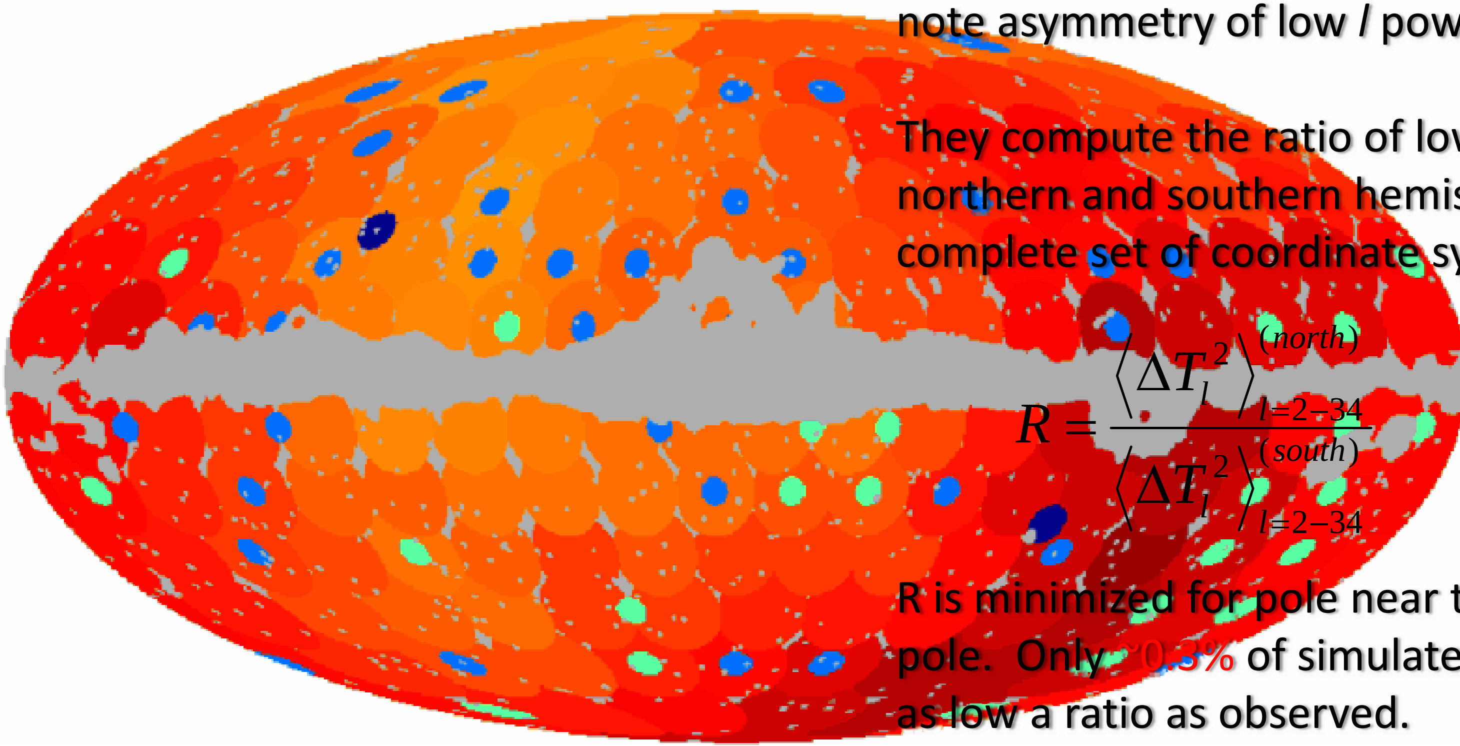
Asymmetry of Low *l* Power – I

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:

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

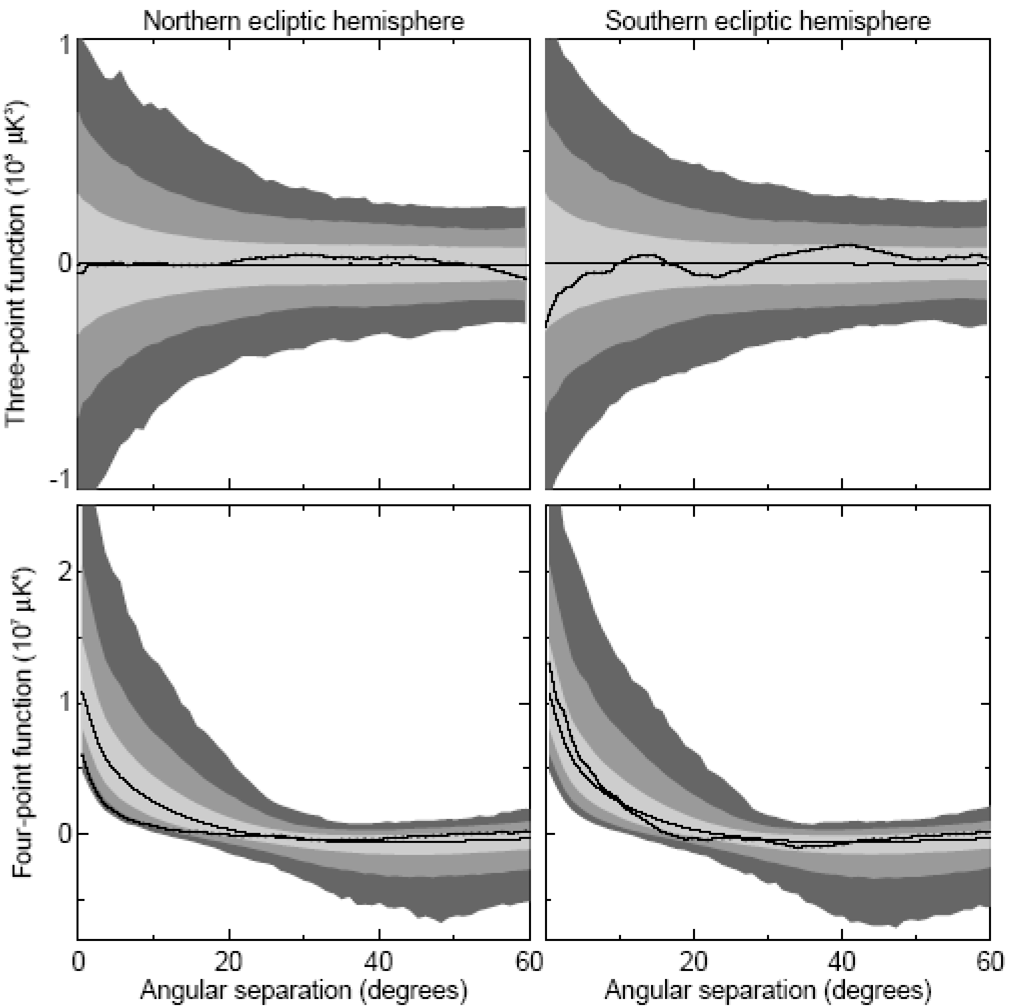
R is minimized for pole near the ecliptic pole. Only ~0.3% of simulated skies have as low a ratio as observed.



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

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

Asymmetry of Low *l* Power – II



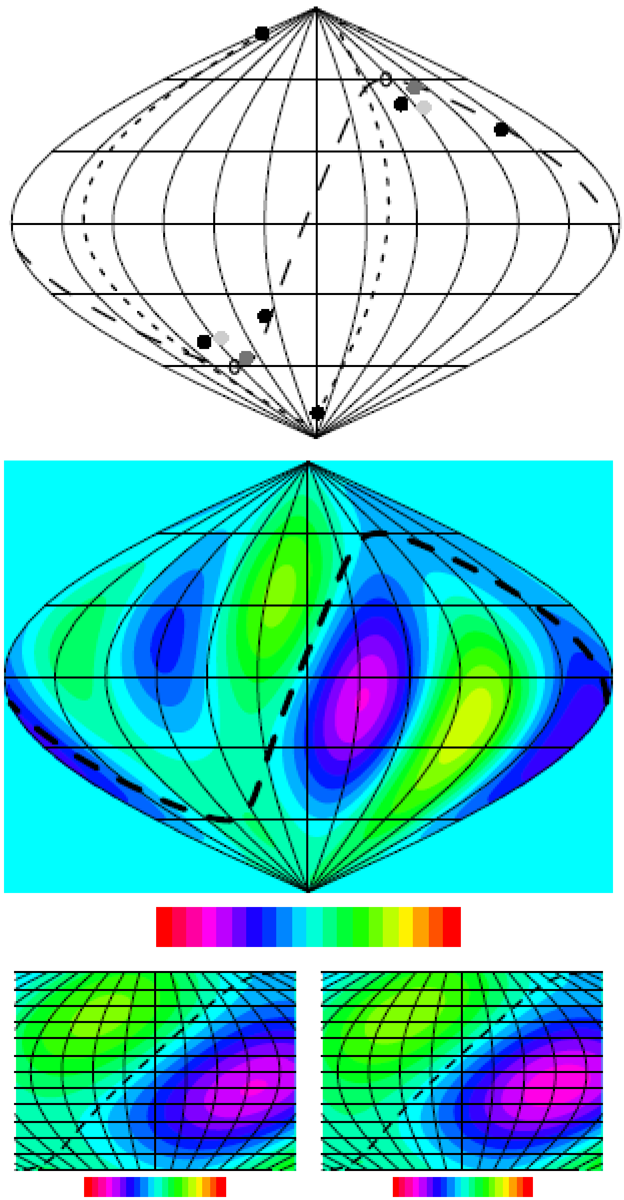
Eriksen et al. (astro-ph/0307507) also note asymmetry of *n*-point correlation functions computed in ecliptic hemispheres.

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.

Land & Magueijo also discuss "Cubic Anomalies in WMAP"

Alignment of Low l Power - II

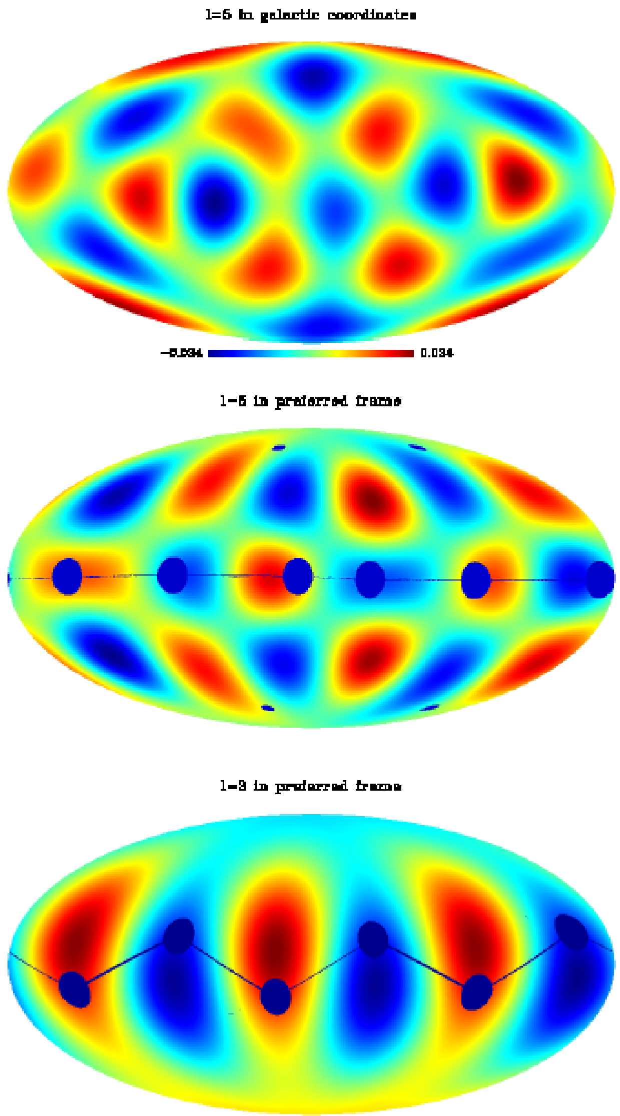


Schwarz et al. (astro-ph/0403353) also note alignment of l=2,3 moments with each other and with: a) the ecliptic coordinate frame, b) the vernal equinoxes, and c) the CMB dipole axis. Significance > ~99.9% is claimed.

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:
- Magnitude of “posterior bias” is hard to estimate for these anomalies.
- Why only l=2,3 aligned with celestial frame?
- Model with local origin extends “low quadrupole” problem to l=3.

Alignment of Low l Power – III ("Axis of Evil")



Further analysis by Land & Magueijo (astro-ph/0502237) claim preferred axis of large scale fluctuations along

(l,b) = (-91°,+50°)

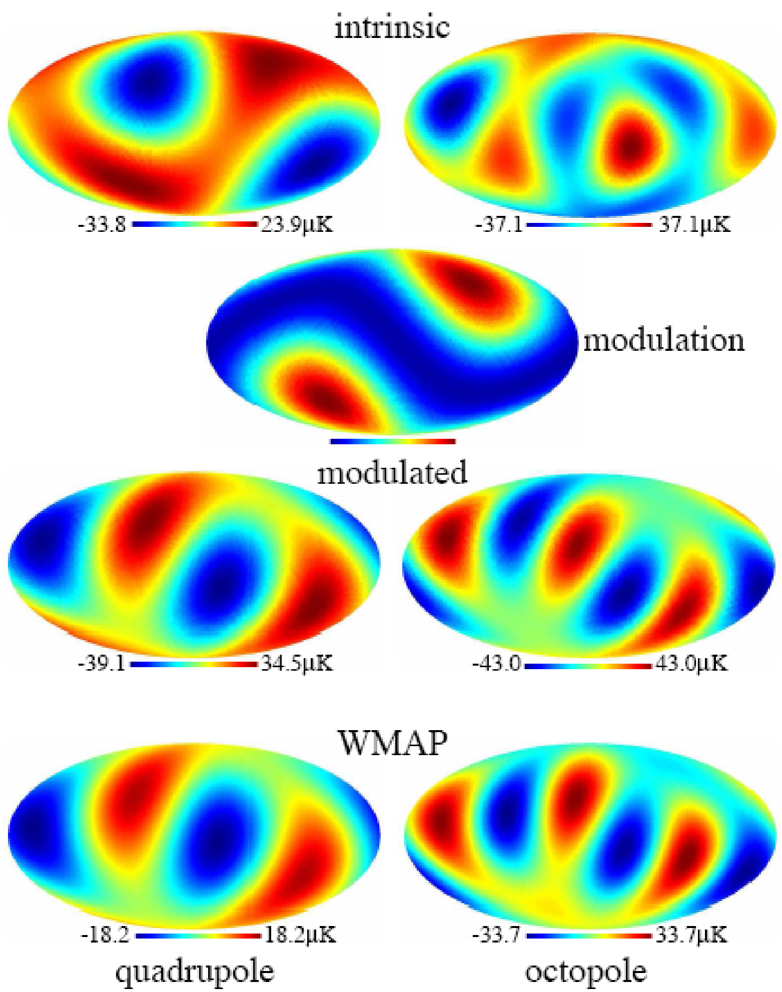
with modes up to l=5 being included in the alignment.

Notes:

- Power in l=5 concentrated in m=3 in this frame.
- Also, l=3 mode has nodes aligned with l=5 mode.
- Perhaps a "frame of evil" rather than merely an axis of evil.

Later analysis by L&M with new methodology reduces claimed significance.
See also Frommert & Enβlin (0908.0435) for polarization analysis. (Talk today)

Alignment of Low *l* Power – IV



Gordon et al. (astro-ph/0509301) point out that alignments and power deficits could be induced by nonlinear effects in the process of anisotropy formation.

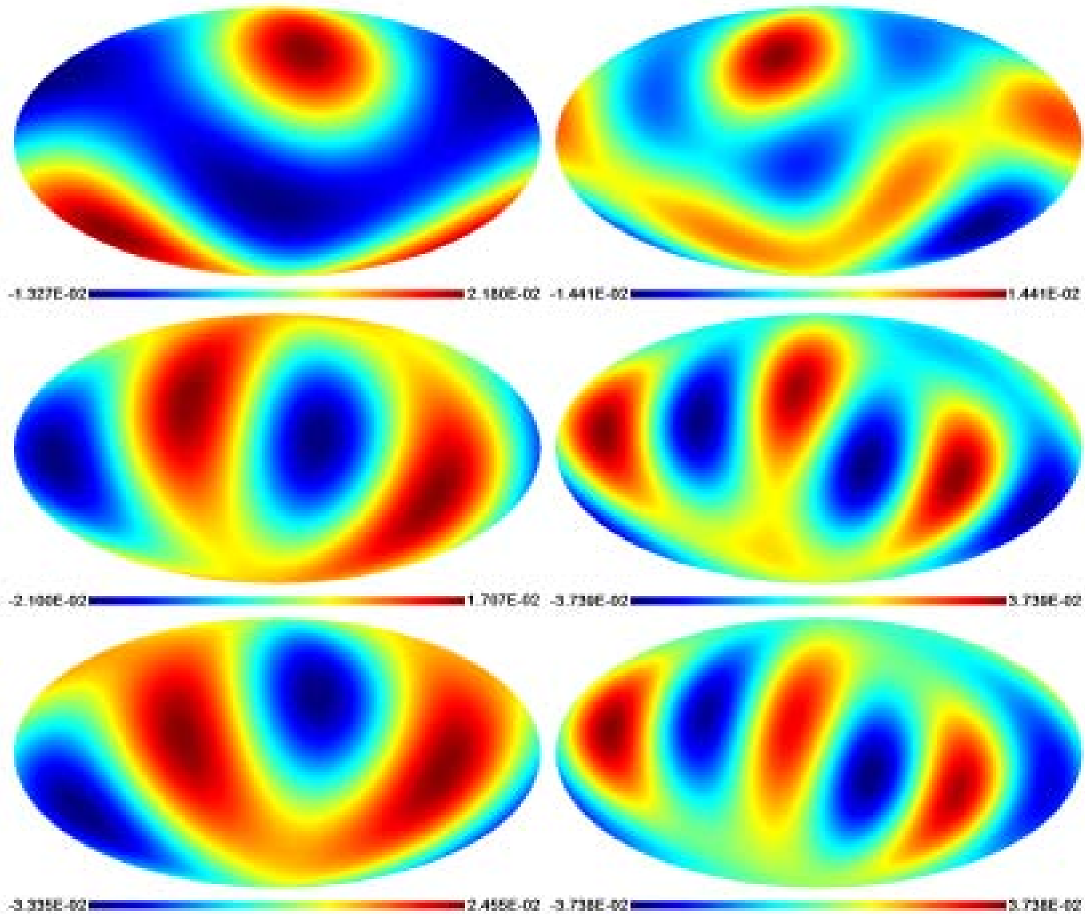
Model:

$$T(\hat{n}) = A(\hat{n}) + f[1 + w(\hat{n})]B(\hat{n})$$

where A and B are linear, gaussian fields and w is a "modulation" field.

Figure at left shows effect for a toy model with w aligned along dipole axis. Physical source of the modulation is unspecified, but they mention super-horizon-scale dark energy perturbations.

Alignment of Low ℓ Power – V



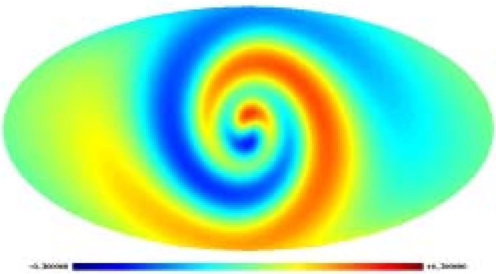
Francis & Peacock (0909.2495) use 2MASS & COSMOS data to estimate the ISW effect from local structure.

Top row:
Estimated ISW contribution to l=2,3 anisotropy.

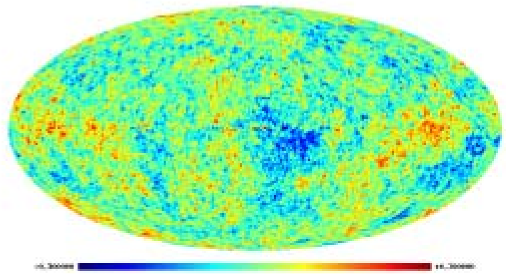
Middle row:
Raw WMAP l=2,3 moments.

Bottom row:
WMAP anisotropy corrected for local ISW.

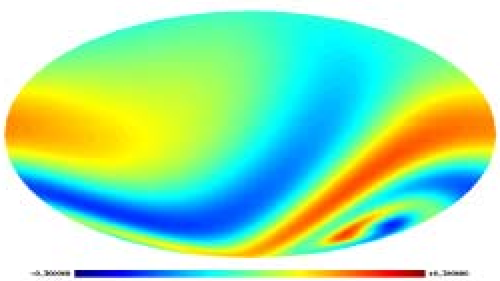
“Old” Physics?



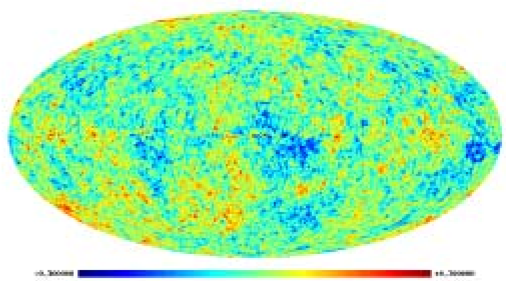
(a) Best-fit Bianchi template (scaled by four) rotated to the Galactic centre for illustration



(b) ILC map



(d) Best-fit Bianchi template (scaled by four)

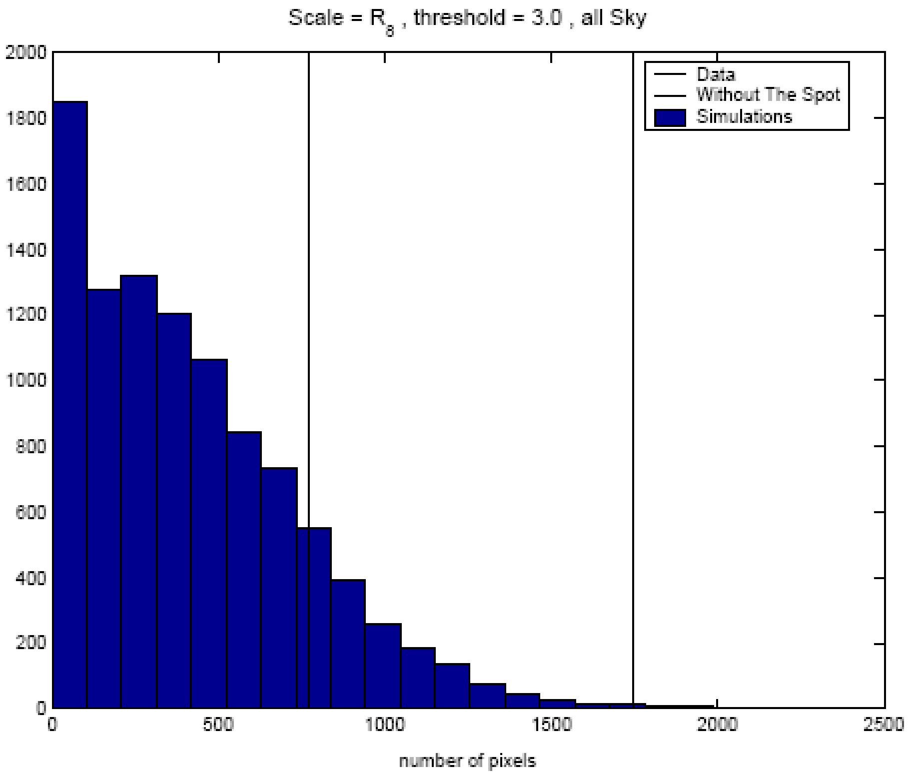


(e) Bianchi corrected ILC map

Jaffe et al. (astro-ph/0503213) fit CMB maps to templates of anisotropy generated in inhomogeneous Bianchi type VII_h cosmological models.

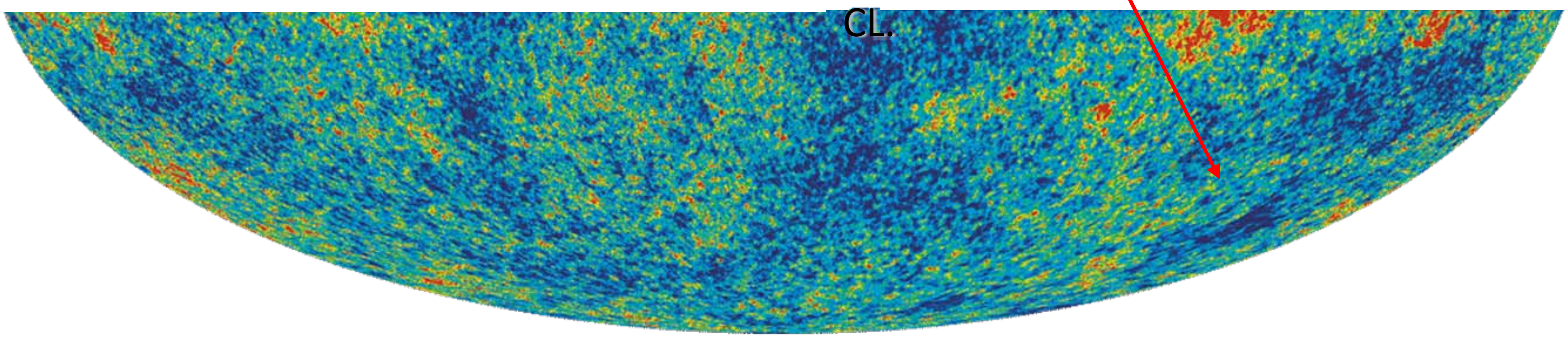
Results for Bianchi type VII, shown here, are striking, almost spooky, but not without problems…

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 1st 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.



New: Zhang & Huterer (0908.3988) use disk weights; find less significance

With Apologies to…

- Topologies…
  - The topic is very interesting, but the results have been inconclusive. Can the 2-pt function teach us anything new?

- Liu & Li (0907.2731), “Improved CMB Maps from WMAP Data”
  - The WMAP team has tried at length to reproduce the results of this paper and have been unable to do so. We are confident in our map-making pipeline, a violation of Fixsen’s Law:

“The difference between an experimentalist and a theorist is as follows: when a theorist gives a talk, s/he is the only one in the room who believes it; when an experimentalist gives a talk, s/he is the only one who doesn’t.”

- Cover (0908.xxxx), Uncalibrated data give a better fit to the WMAP images.
  - I’m sorry, but I just don’t understand the analysis yet. I hope to learn more today.

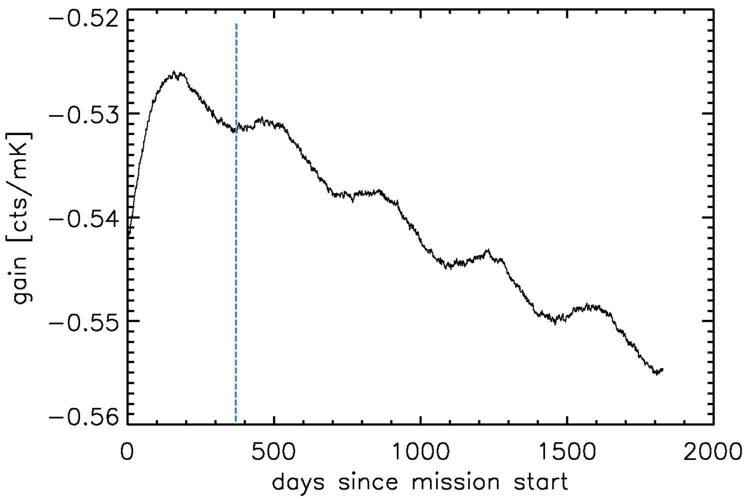
Future WMAP Operations

WMAP is nearing 7 years at L2 and has been approved for 2 final years of operation.

What important questions will more WMAP data help address?

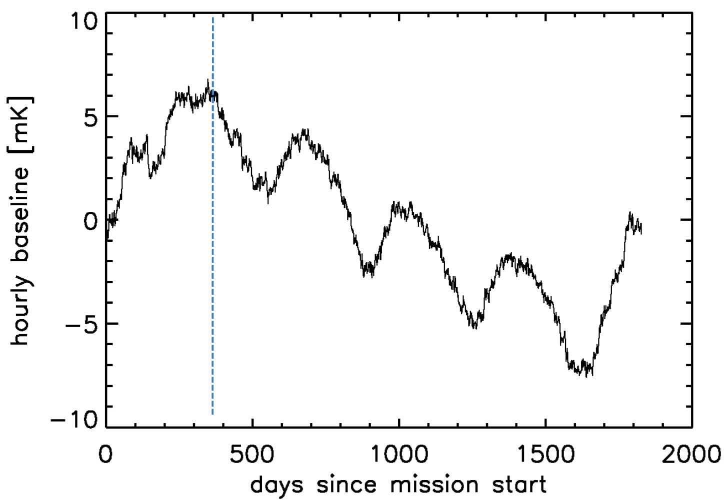
- Reionization - was reionization an extended process? Was the universe partially reionized at $z = 20$ or 30?
- Dark Energy - upcoming dark energy experiments will be limited by WMAP cosmological parameter uncertainties. Additional WMAP data will improve these uncertainties.
- Physics of Inflation - primordial gravity waves, primordial non-Gaussianity, deviations from scale invariance.
- Also: polarized synchrotron data, radio source & planet data, calibration source for ground/balloon-based experiments

Detailed Understanding of Instrument

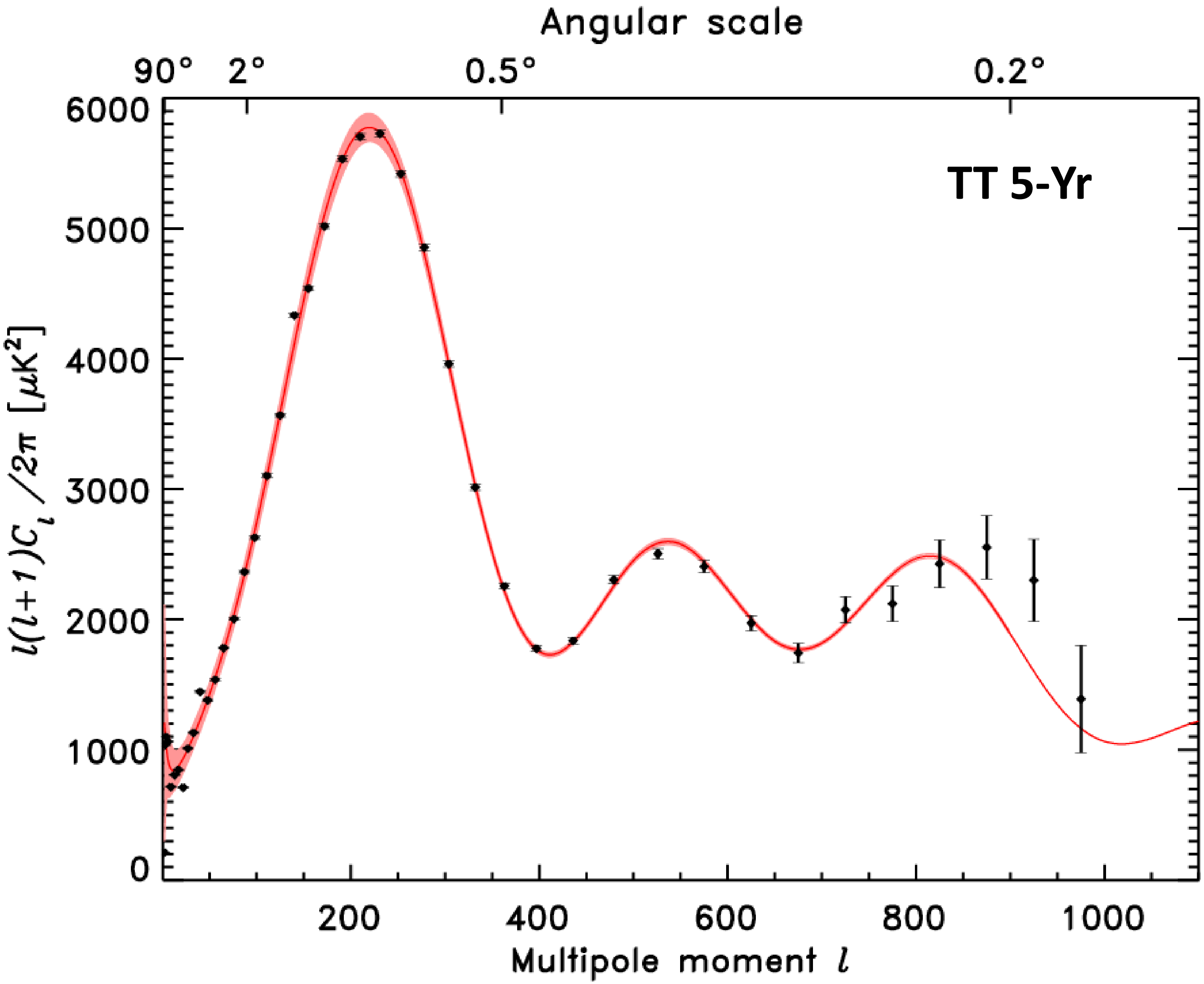


Output counts per unit of input temperature difference changes with time due to changes in spacecraft temperature and amplifier properties.

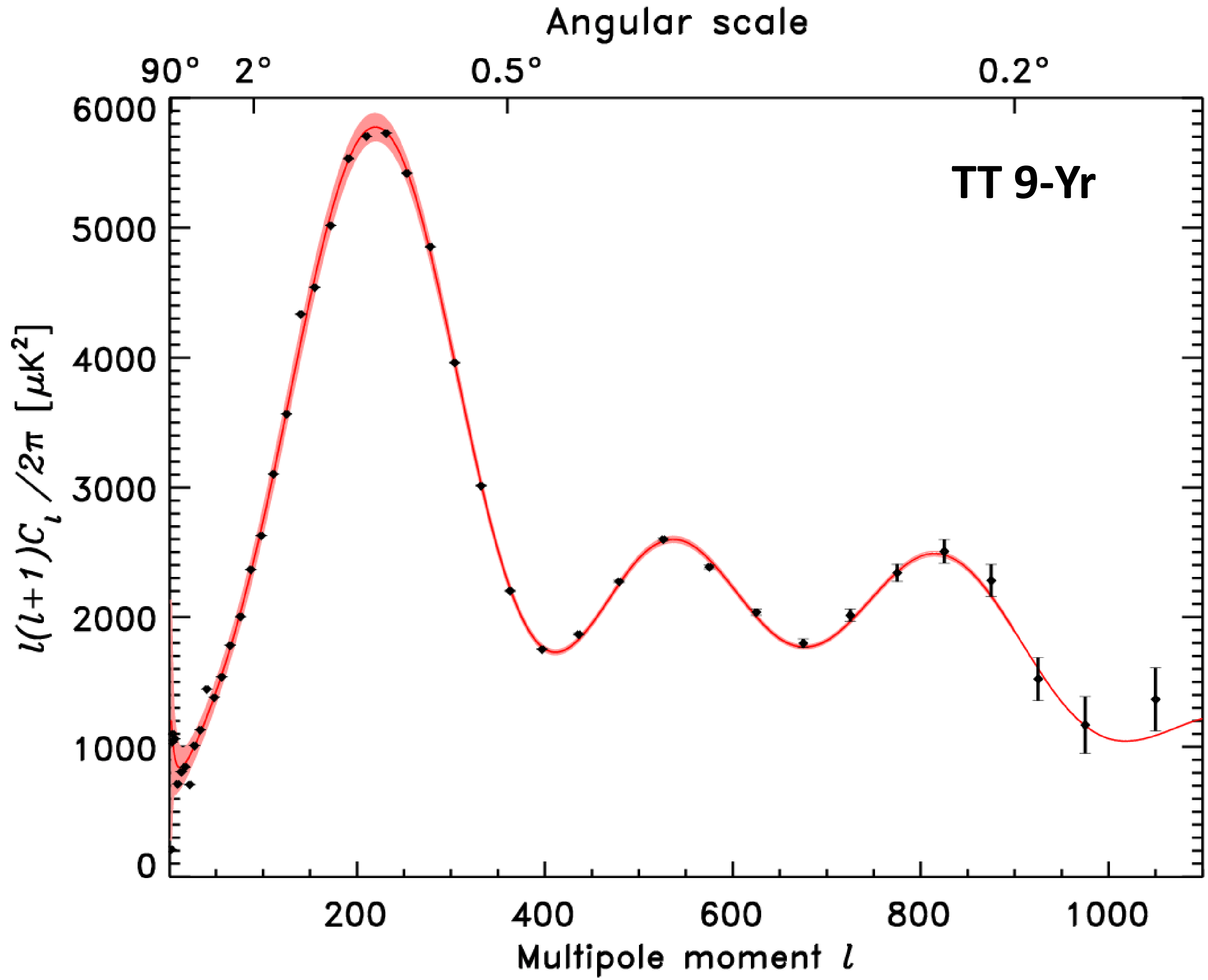
Multiple years of data help to separate these effects and improve uncertainty in the gain model.

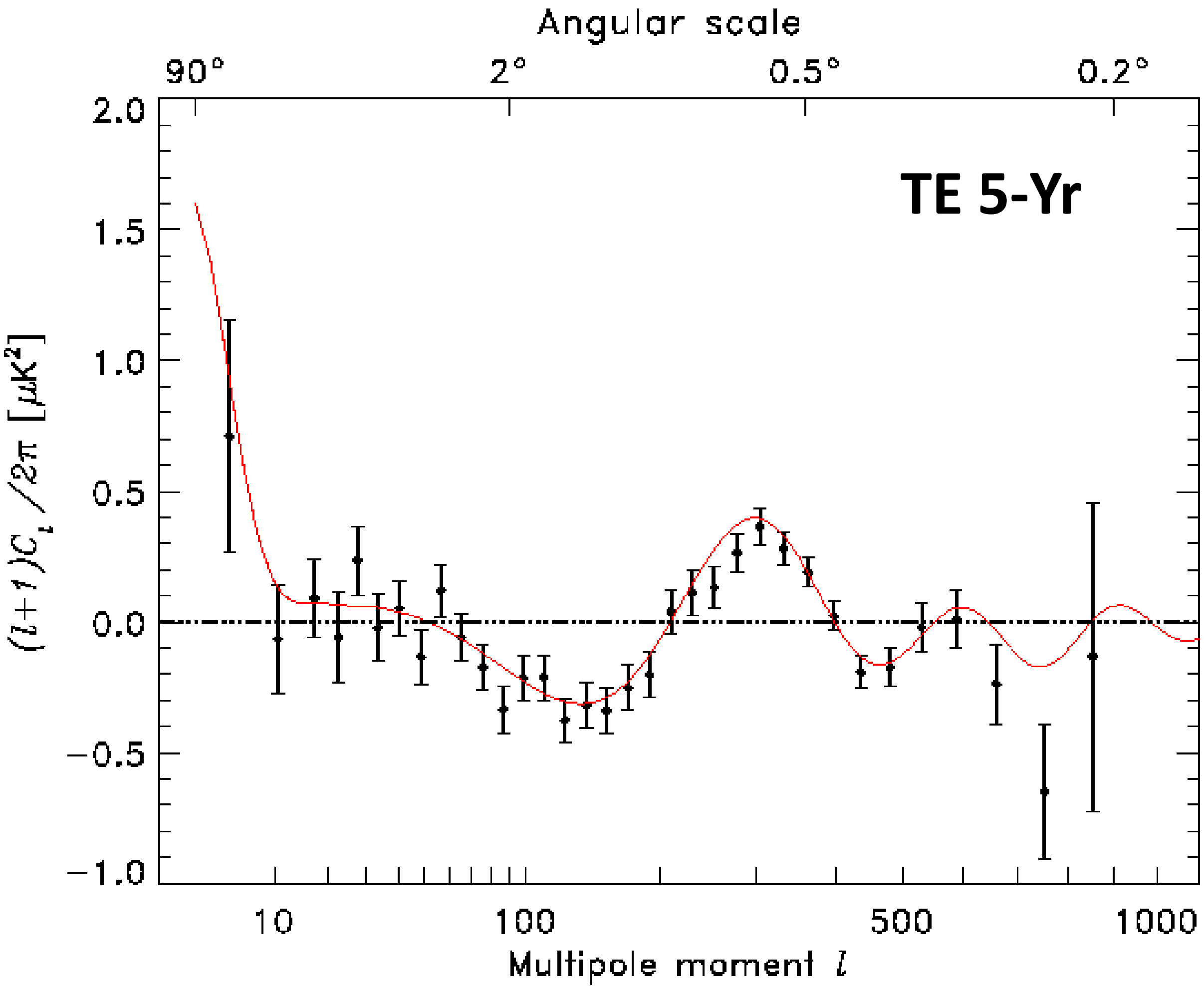


Change in instrument offset vs. time. Additional years of data improve our knowledge of the sources of offset: thermal emission, gain variation, etc.

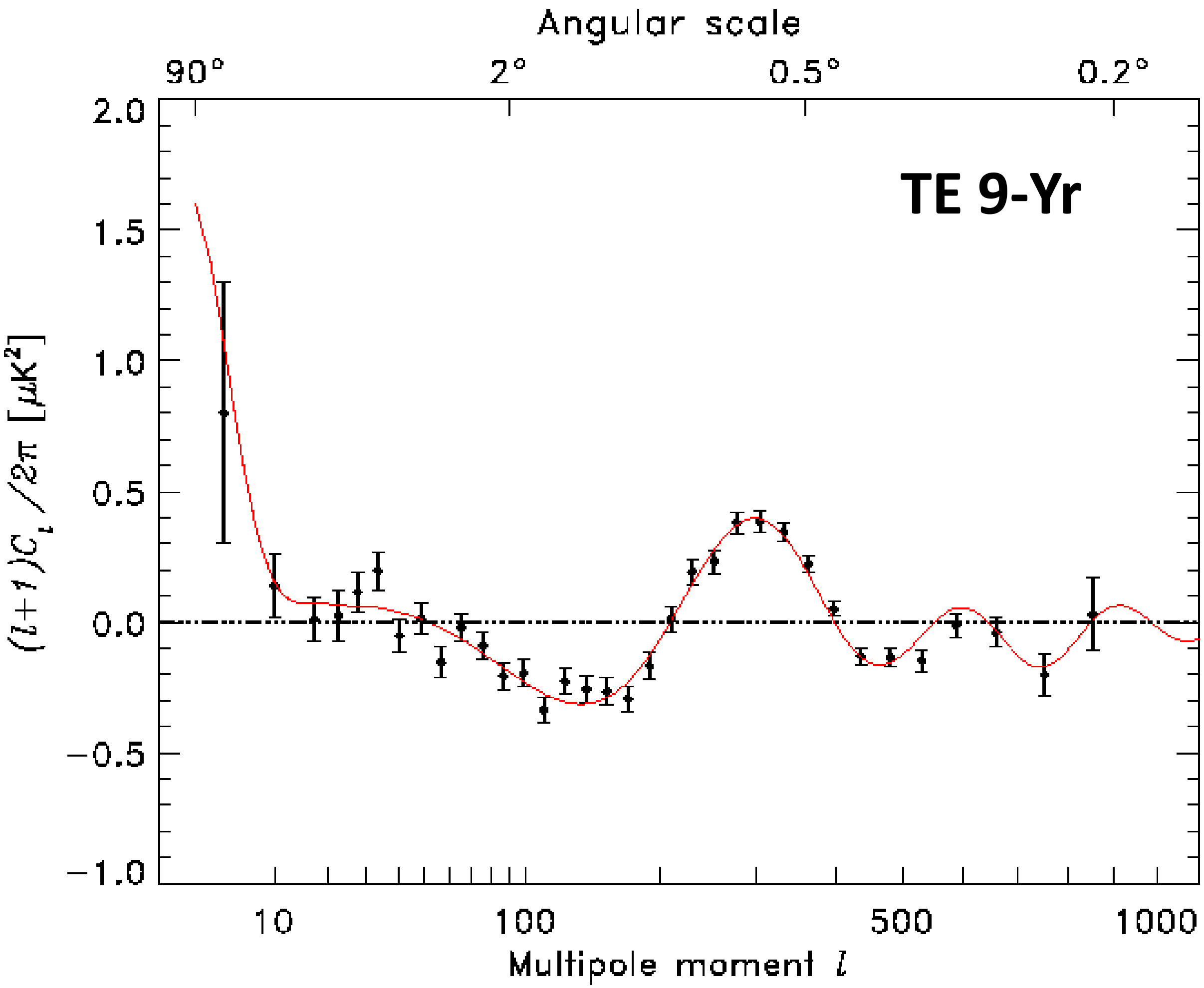


Angular scale
90°
2°
0.5°
0.2°
TT 5-Yr
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
200
400
600
800
1000
Multipole moment l

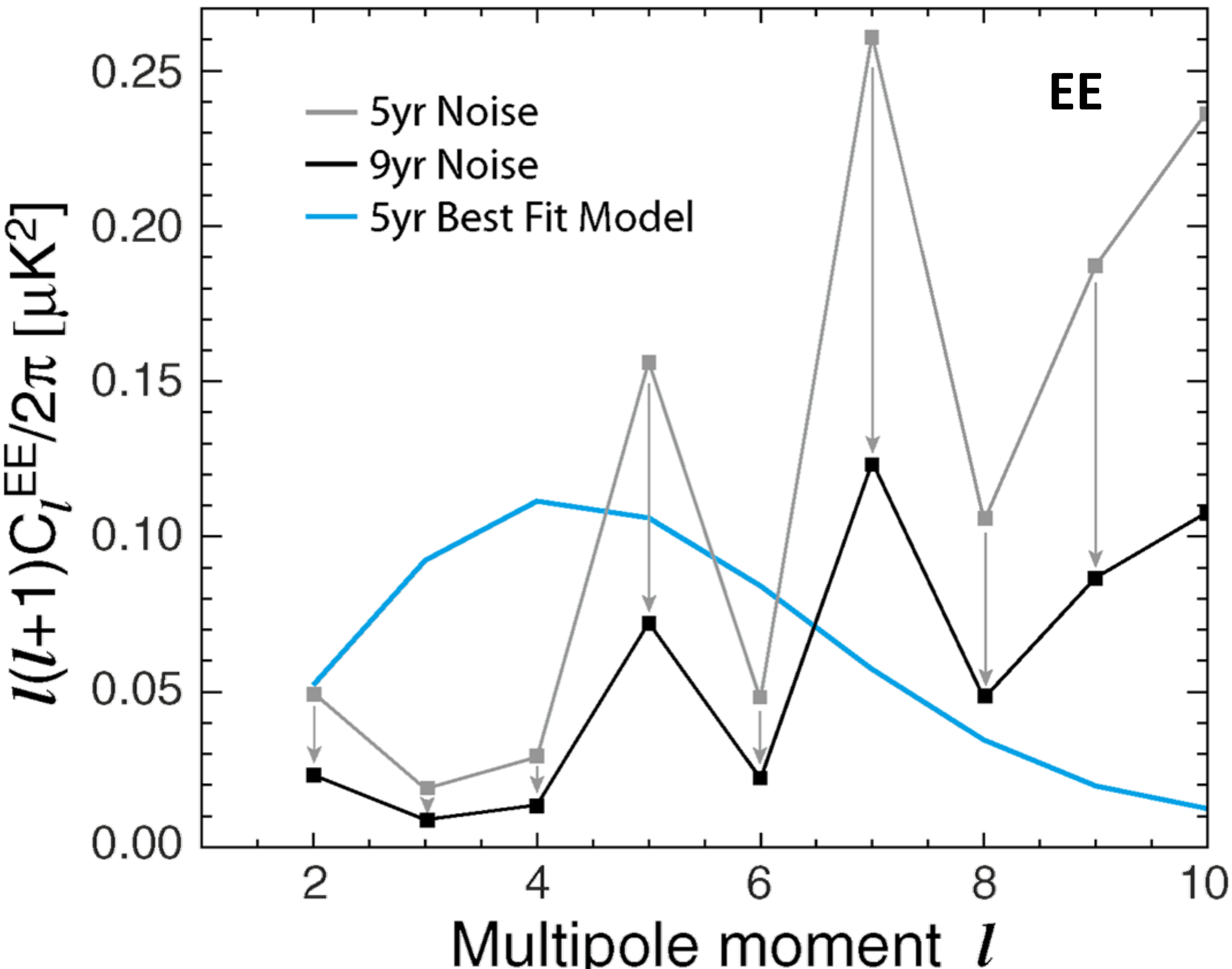

Angular scale
90°
2°
0.5°
0.2°
TT 9-Yr
6000
5000
4000
3000
2000
1000
0
200
400
600
800
1000
Multipole moment l
l(l+1)C_l /2π [μK²]



Angular scale
90°
2°
0.5°
0.2°
TE 5-Yr
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
$(l+1)C_l\ /2\pi\ [\mu K^2]$
10
100
500
1000
Multipole moment l

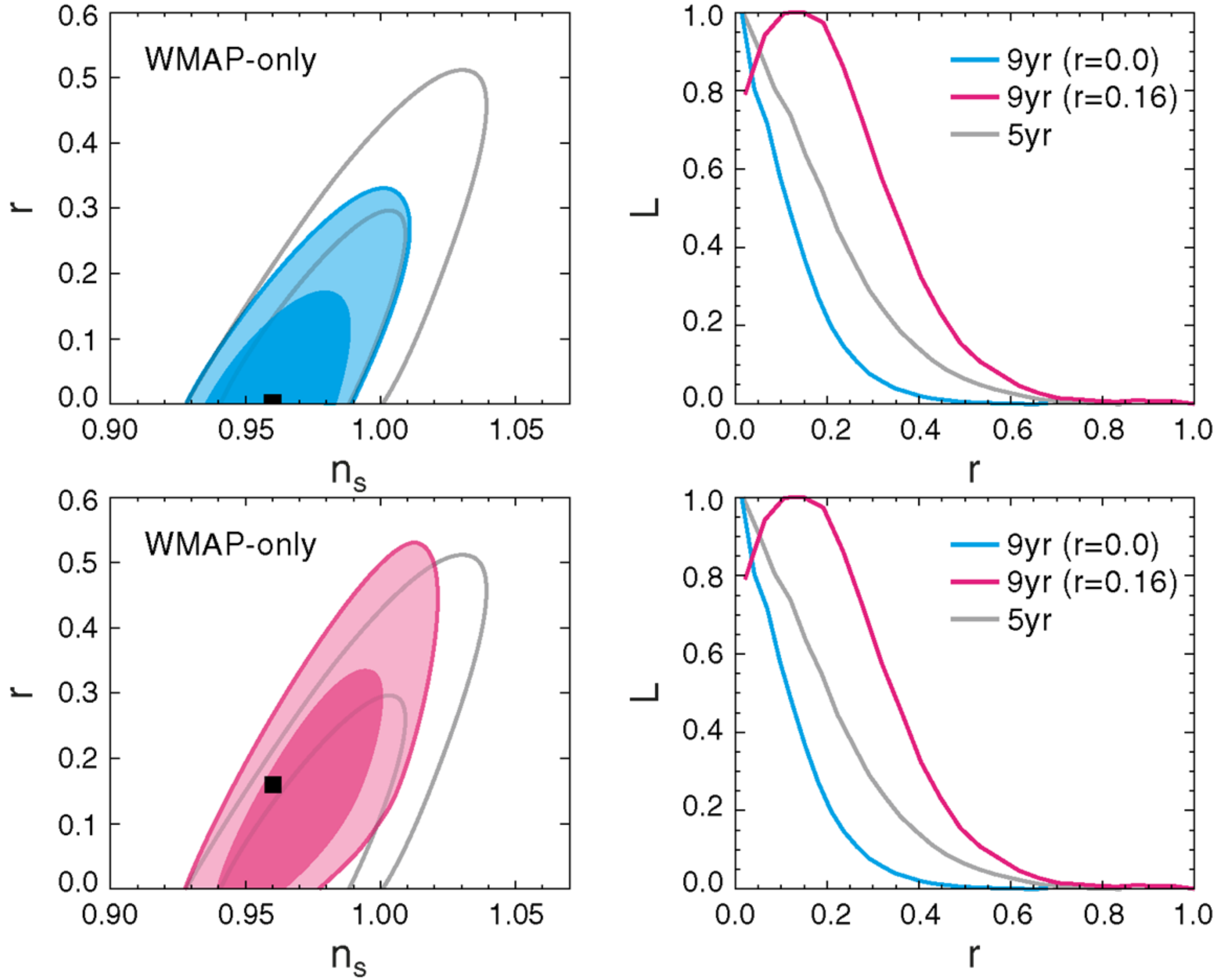


Angular scale
90°
2°
0.5°
0.2°
TE 9-Yr
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
$(l+1)C_l/2\pi$ [μK^2]
10
100
500
1000
Multipole moment l



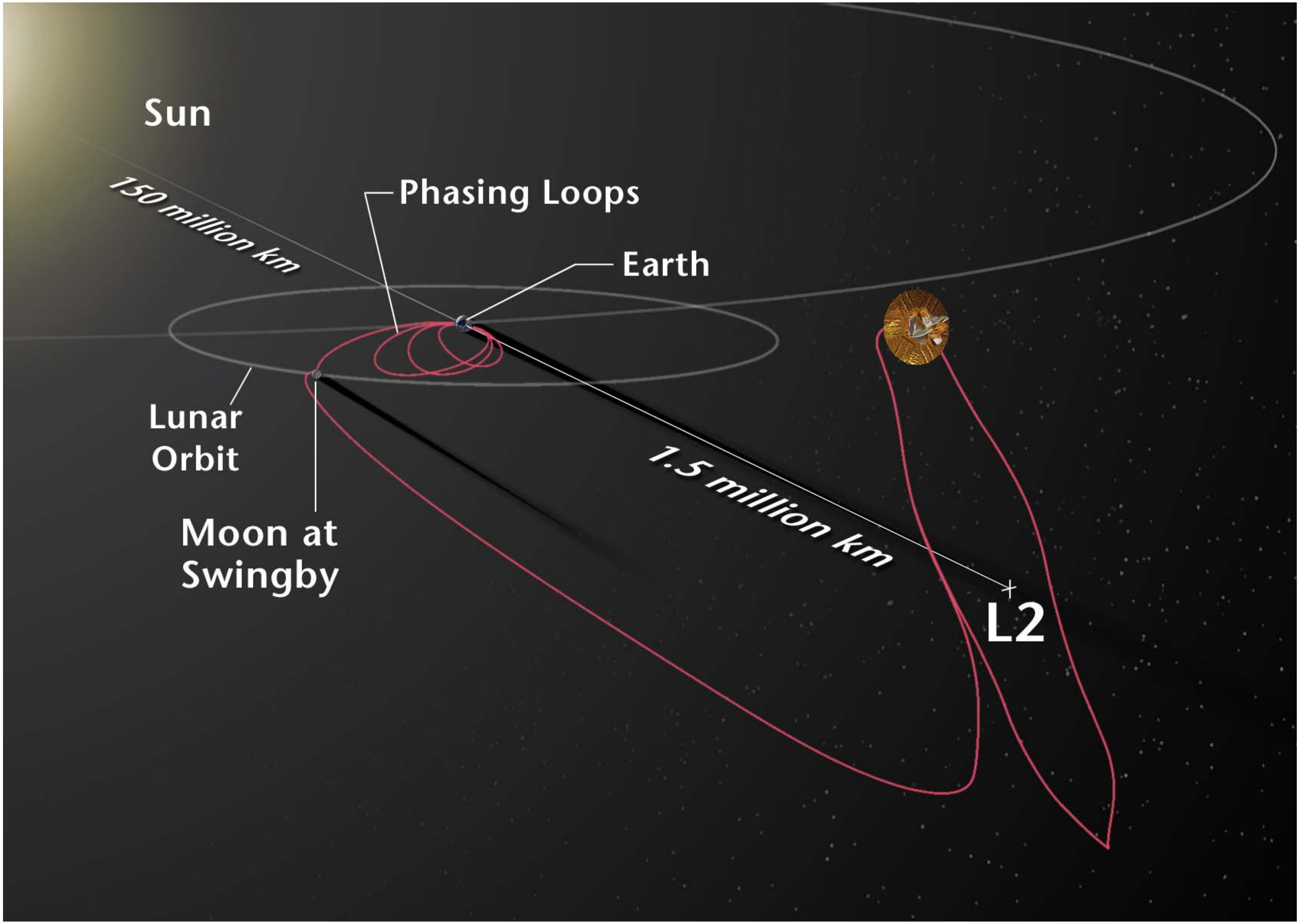
EE
5yr Noise
9yr Noise
5yr Best Fit Model
$l(l+1)C_l^{EE}/2\pi$ [μK^2]
0.25
0.20
0.15
0.10
0.05
0.00
2
4
6
8
10
Multipole moment l

Testing Inflation



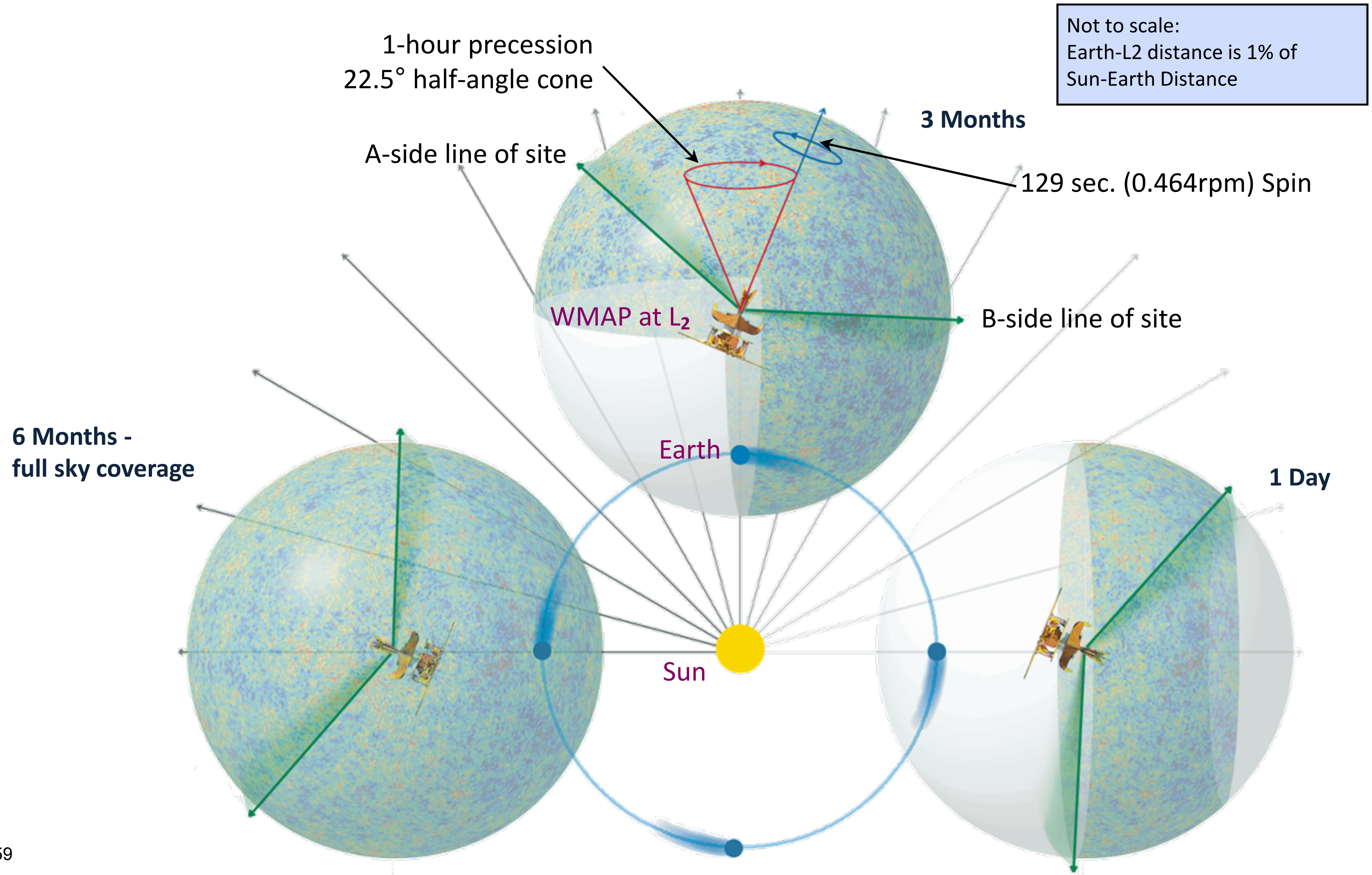

THE END

WMAP at L2



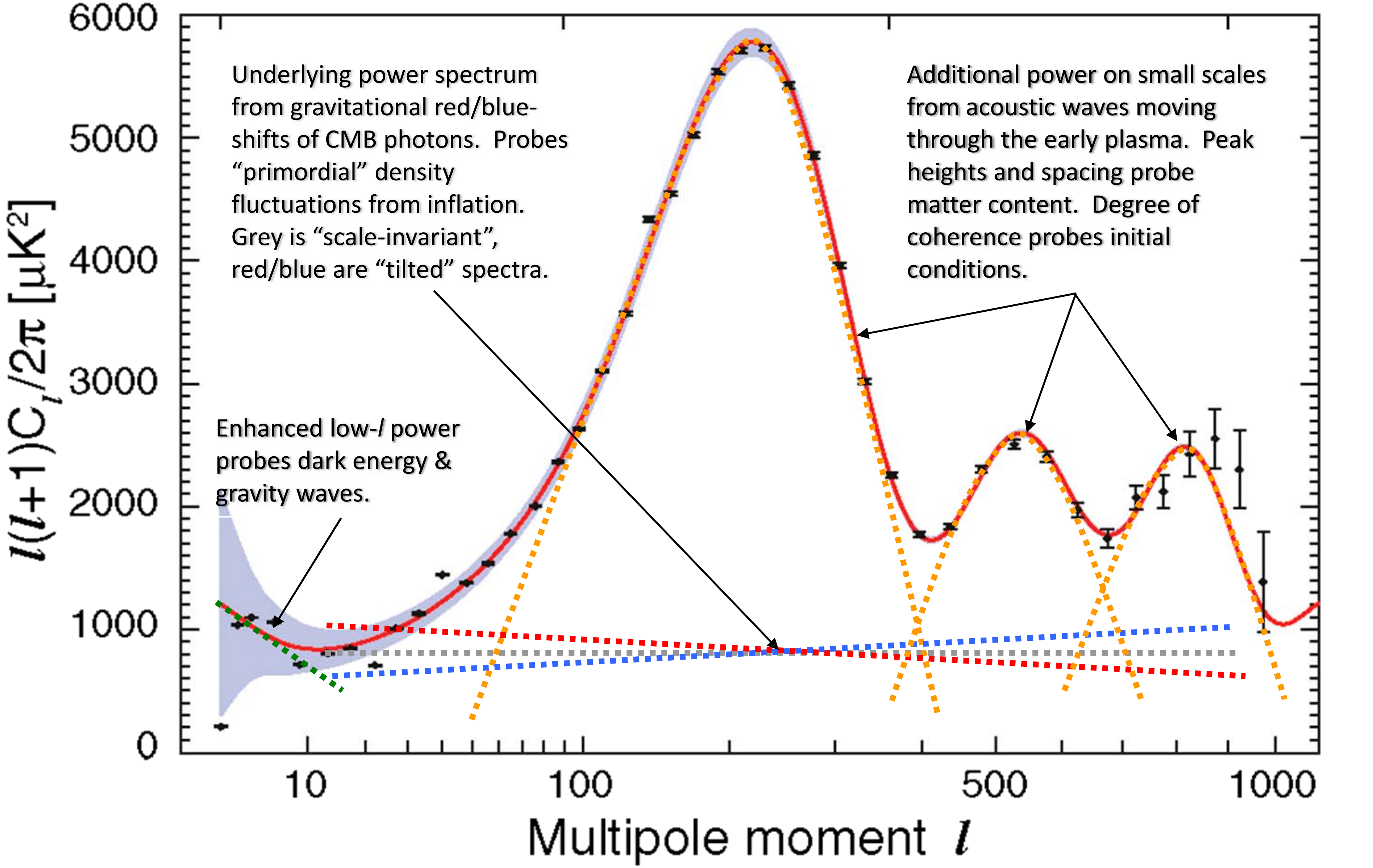
Sun
150 million km
Phasing Loops
Earth
Lunar
Orbit
Moon at
Swingby
1.5 million km
L2

WMAP Sky Coverage



MAP990159

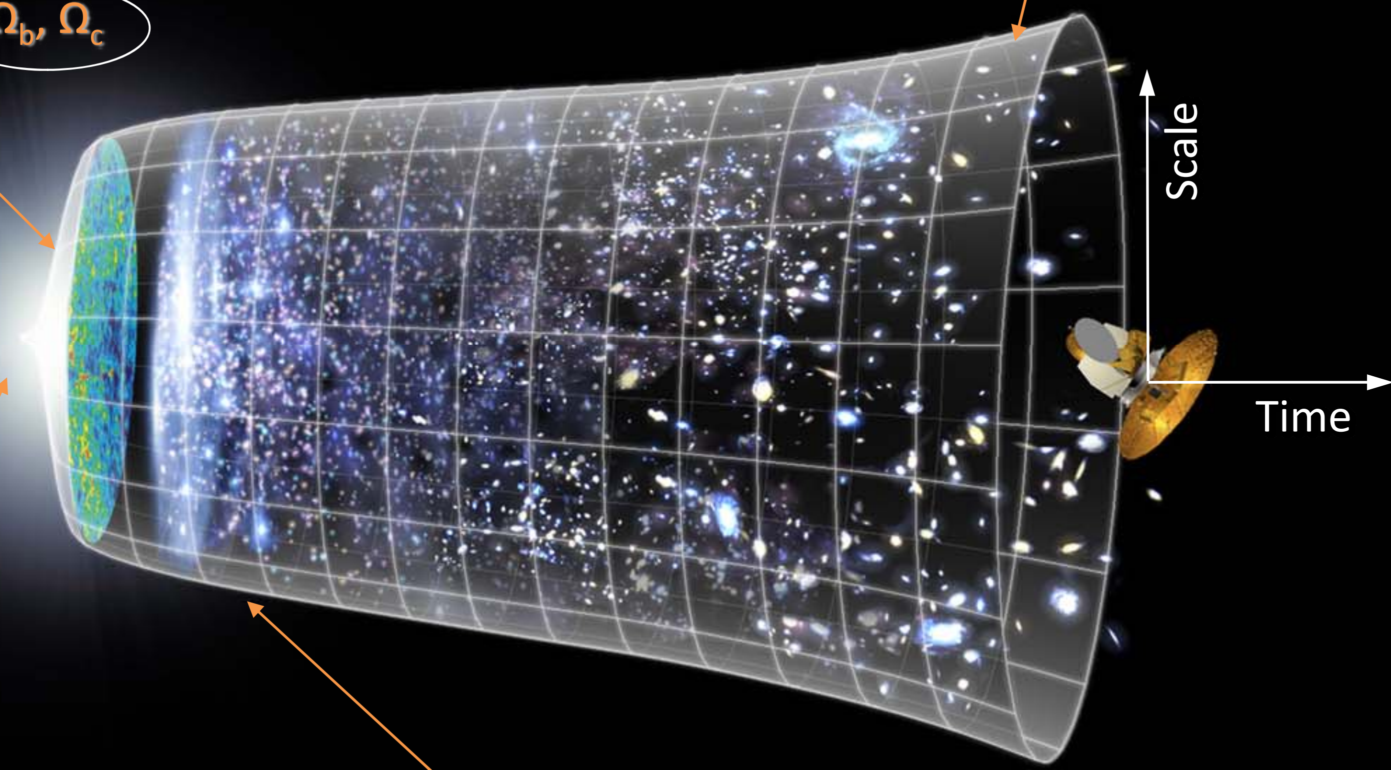
3 Elements of the Power Spectrum



The 6 Parameters of ΛCDM*

Large scale structure – dark energy, Ω_Λ, σ_8

Plasma epoch – matter, radiation content, Ω_b, Ω_c

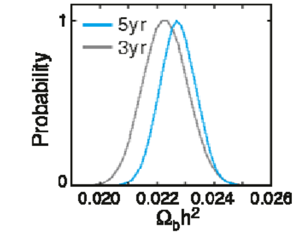


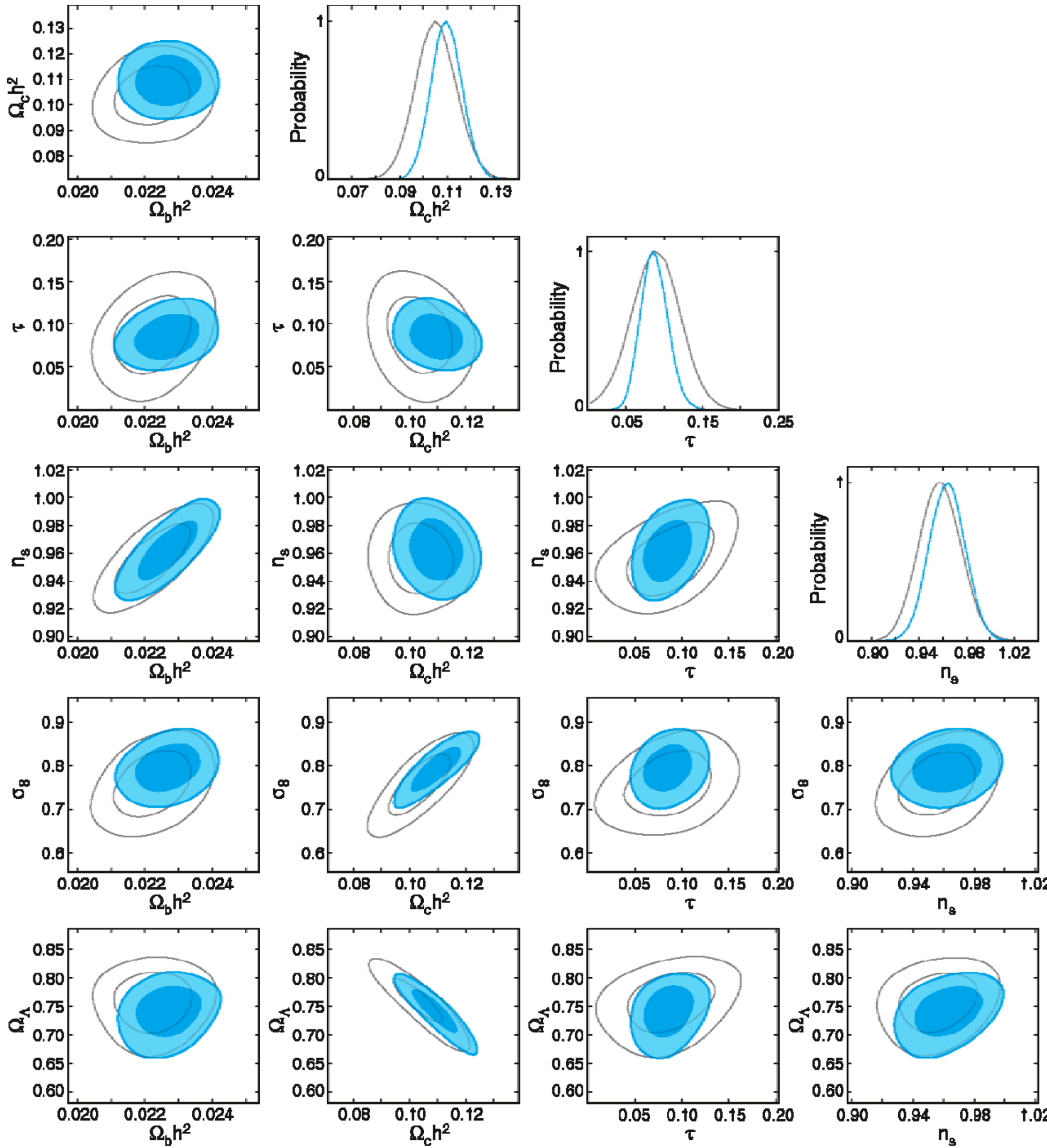
Inflation – initial conditions, A, n_s

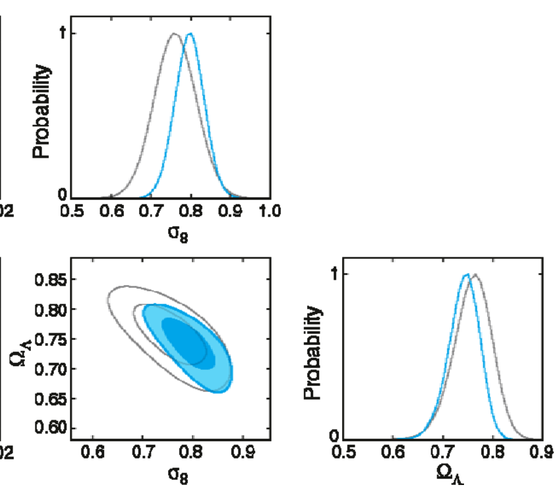
Dark ages → first stars – polarization, τ

*The amplitude parameters A and σ_8 are not are independent; flatness of the universe is assumed in ΛCDM.

ΛCDM Parameters*







Blue curves/contours – 5-year data

Grey curves/contours – 3-year data

Biggest improvements in:

Optical depth, τ

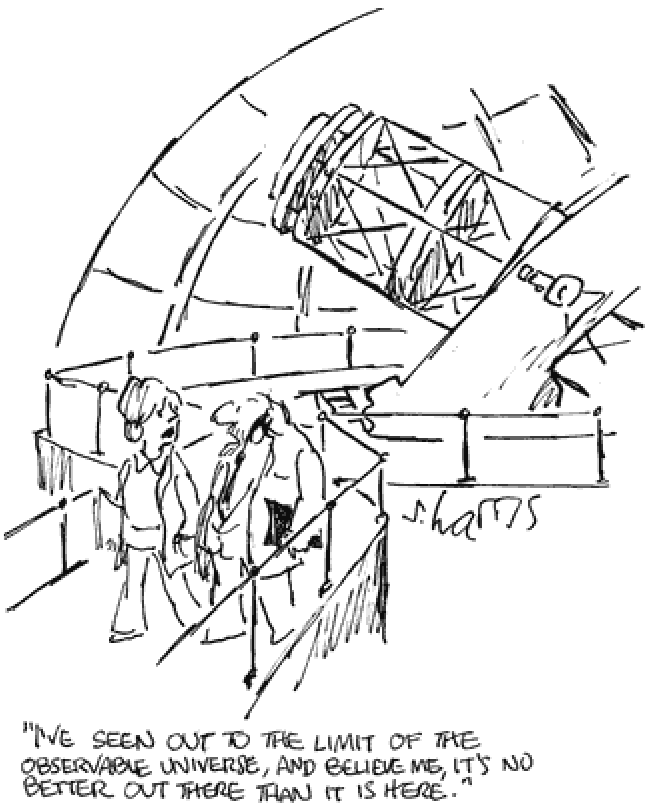
Amplitude of fluctuations @ 8 Mpc, σ_8

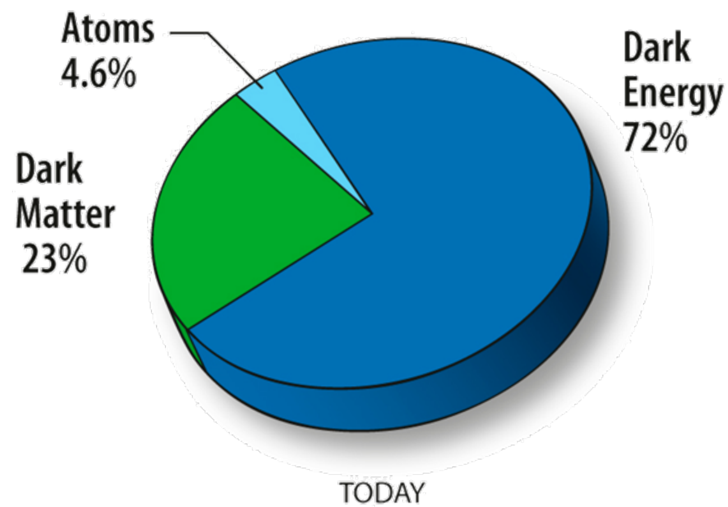
Matter densities, $\Omega_b h^2$, $\Omega_c h^2$

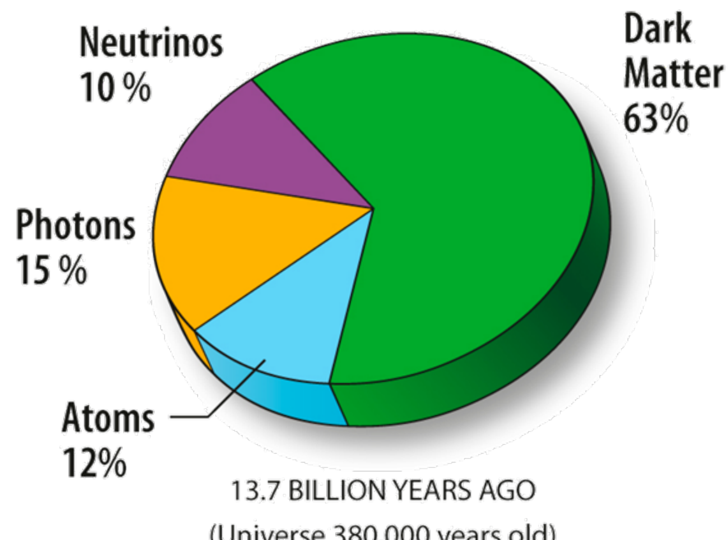
Age: t_0 = 13.69 ± 0.13 Gyr

*based on WMAP data only

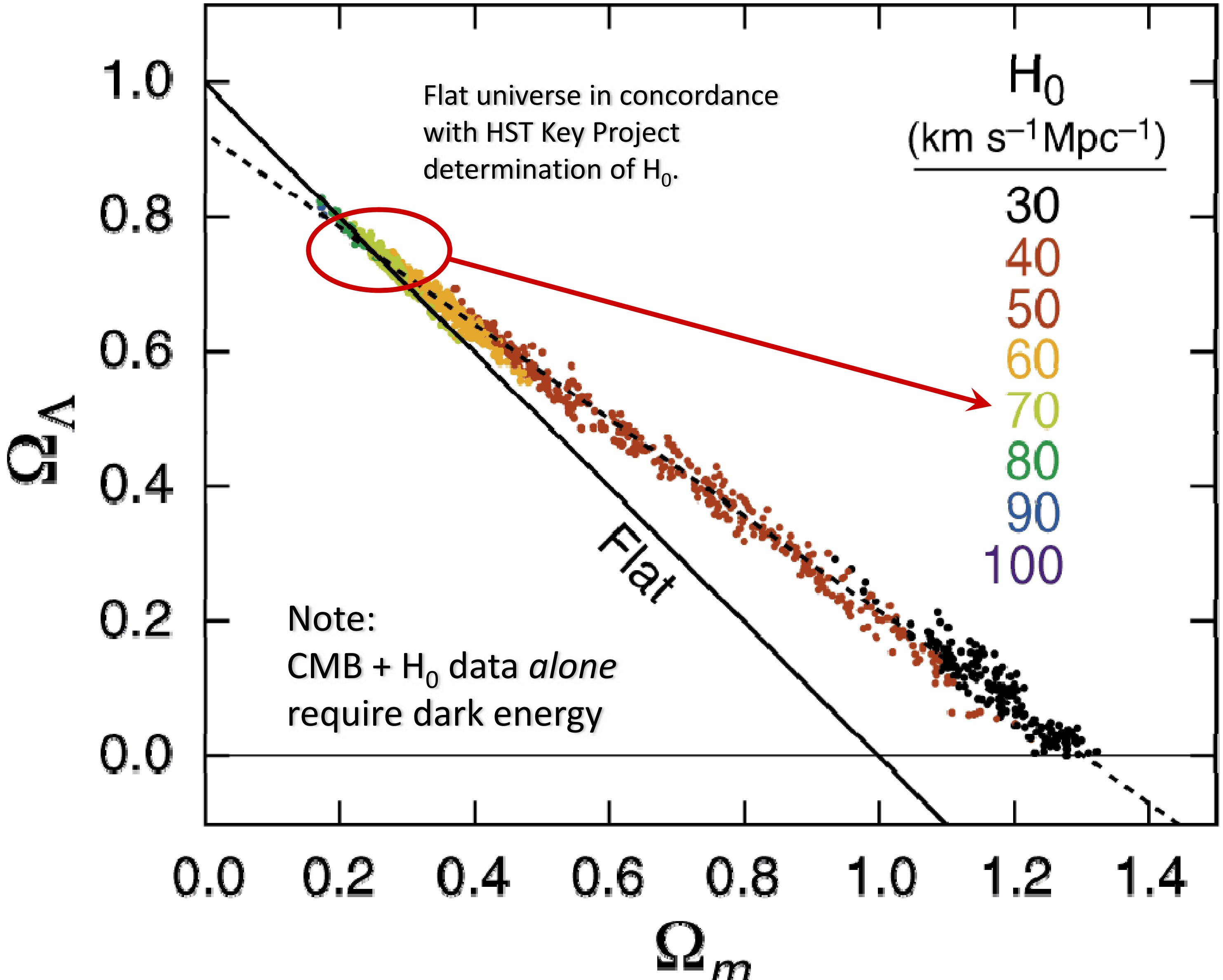
The Dark Side



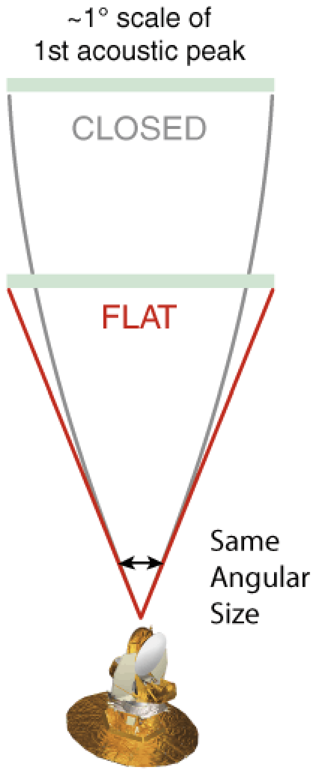




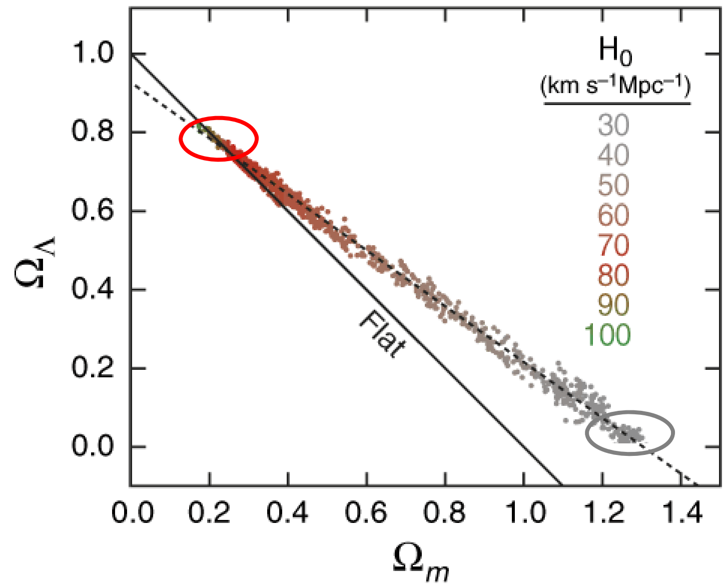
Testing Assumptions: Flatness

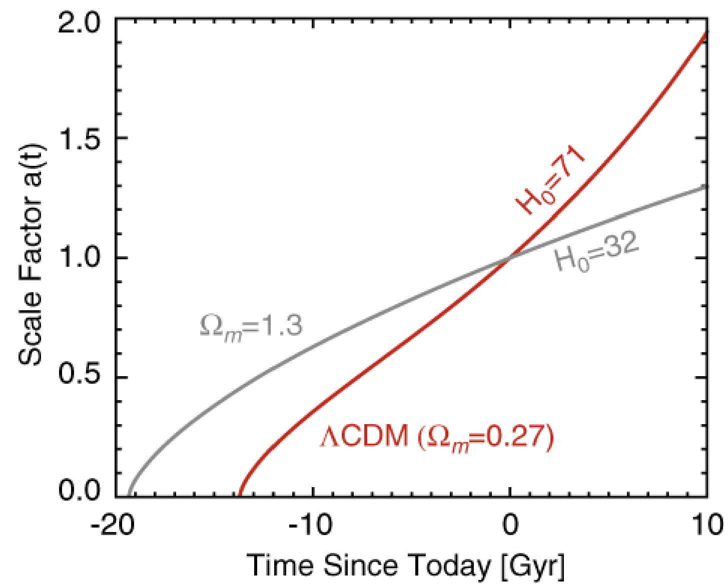


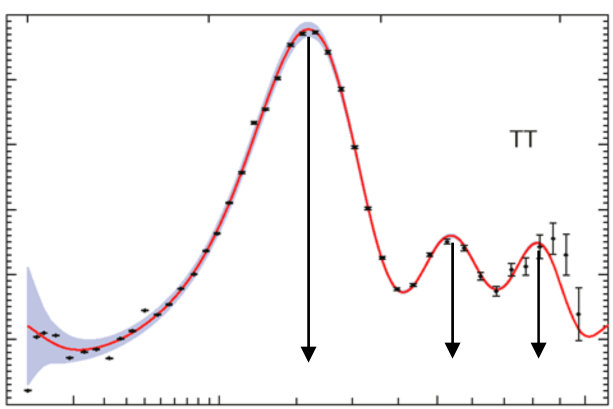
Testing Assumptions: Flatness



Geometric degeneracy in the CMB

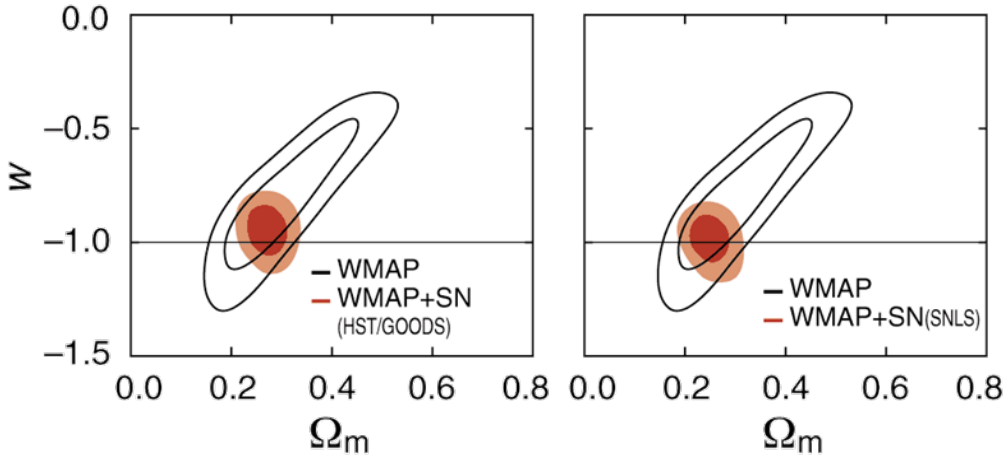






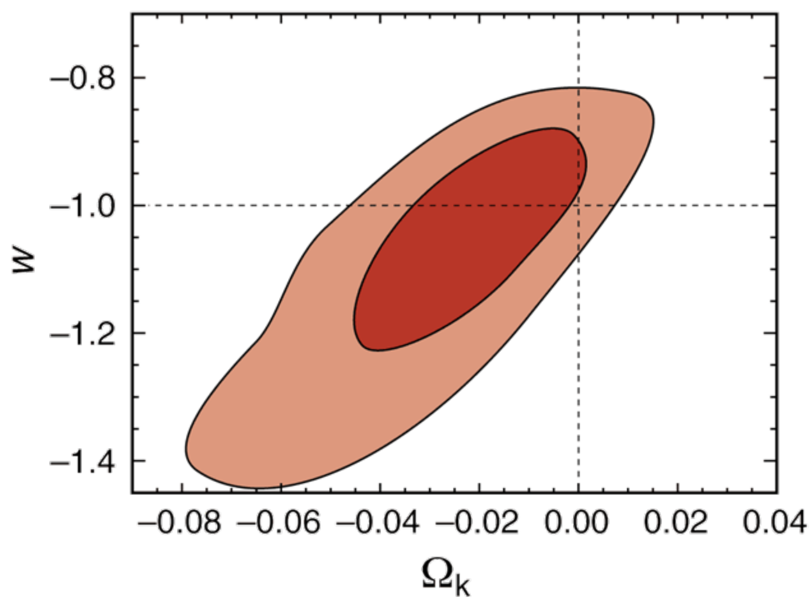
- Acoustic scale is the proper distance a sound wave travels during plasma epoch (~379,000 yr).
- Set mostly by matter / radiation ratio.
- Measured by peak locations, but this is degenerate with distance to last-scattering surface (hence H_0).

Testing Assumptions: Dark Energy



Constraints on (Ω_m,w) assuming:
1) a flat universe,
2) w´ = 0,
3) dark energy does not cluster.

WMAP-only and WMAP+SNe data from two different surveys.

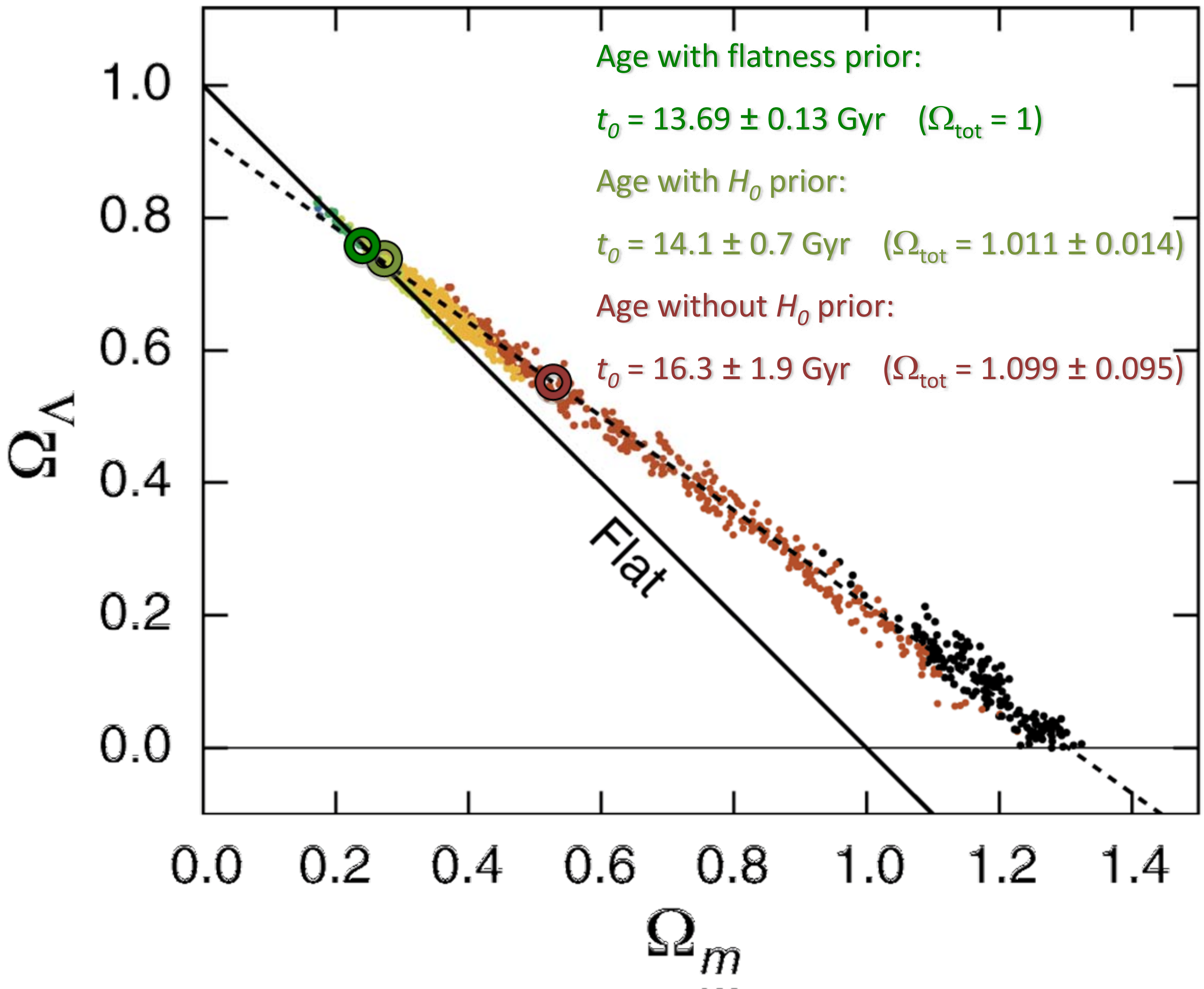


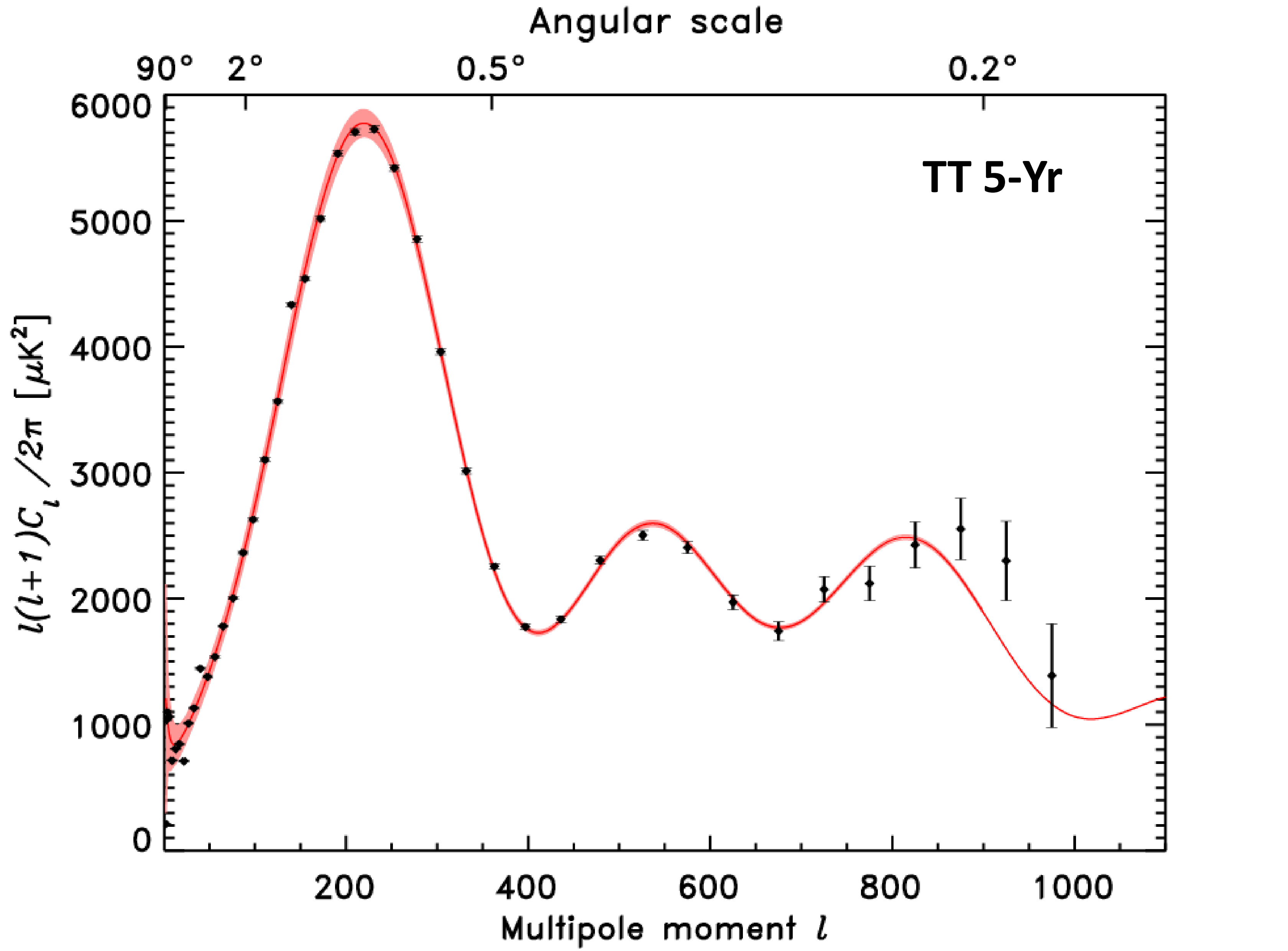
Constraints on (Ω_k,w) assuming:
1) w´ = 0,
3) dark energy does not cluster.

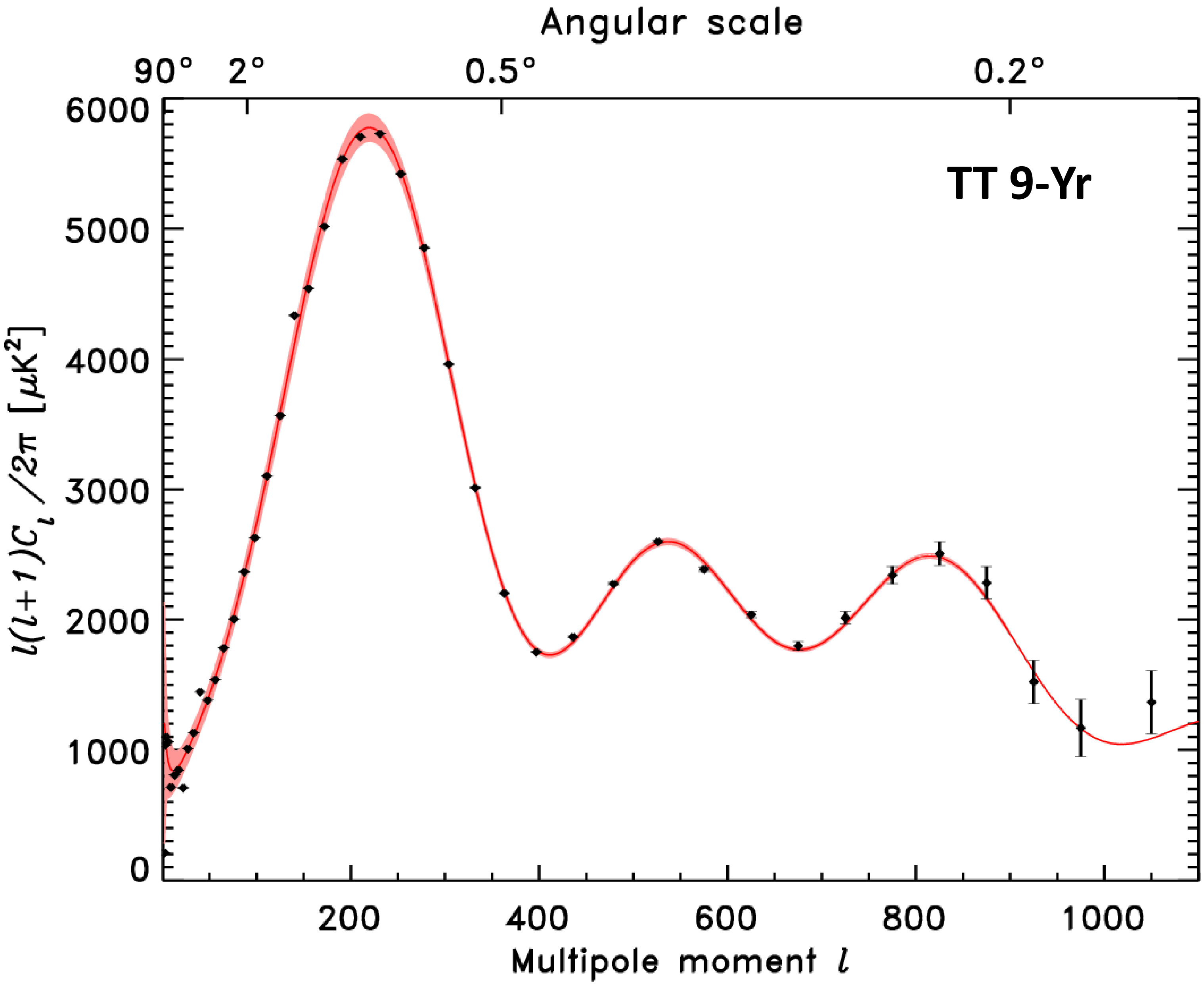
WMAP + all other data.

Constraints still weak – more data needed, e.g., JDEM.

Testing Assumptions: Flatness & Age




Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi\ [\mu K^2]$
TT 5-Yr
200
400
600
800
1000
Multipole moment l


Angular scale
90°
2°
0.5°
0.2°
TT 9-Yr
$l(l+1)C_l/2\pi$ [μK^2]
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1000
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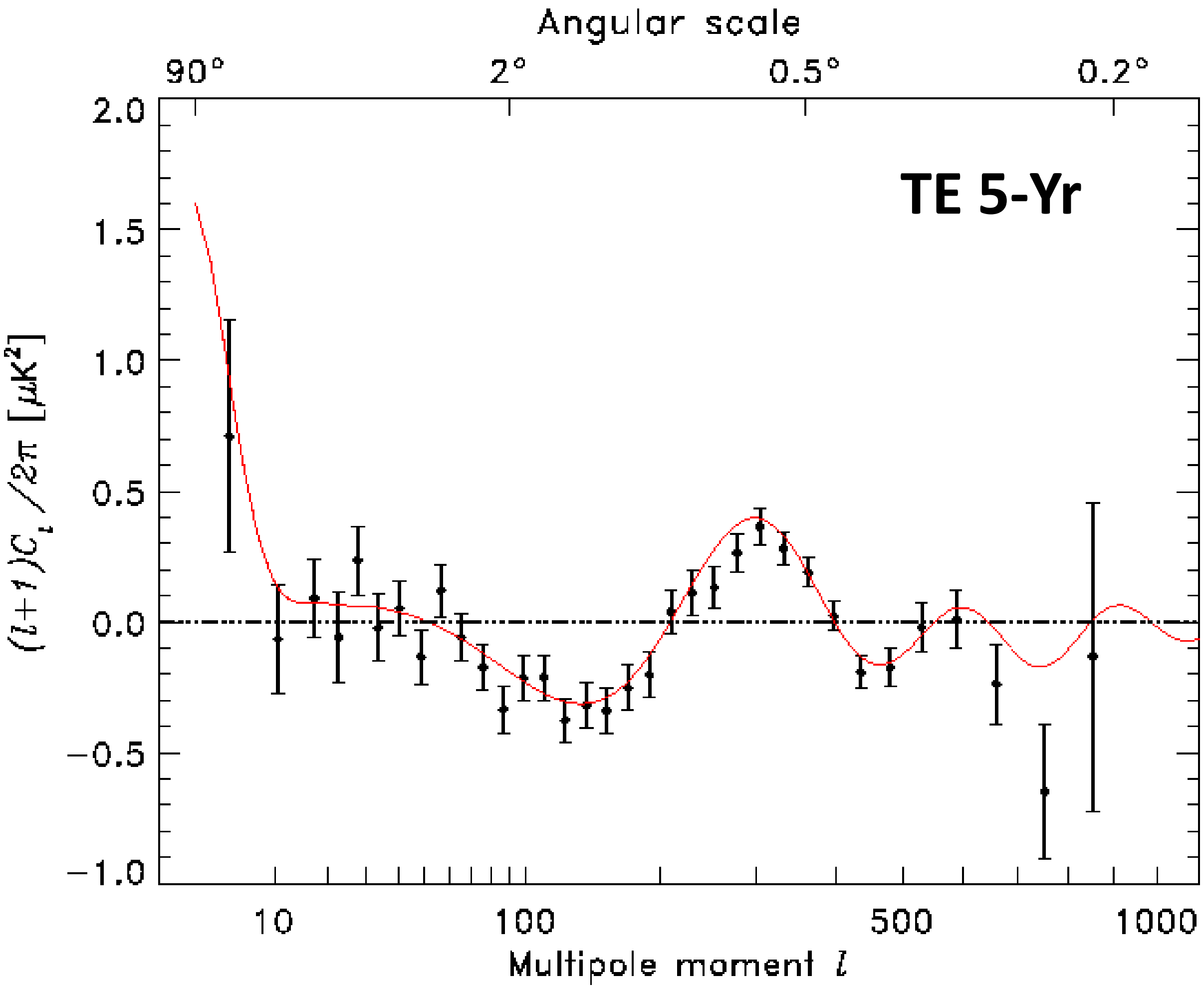
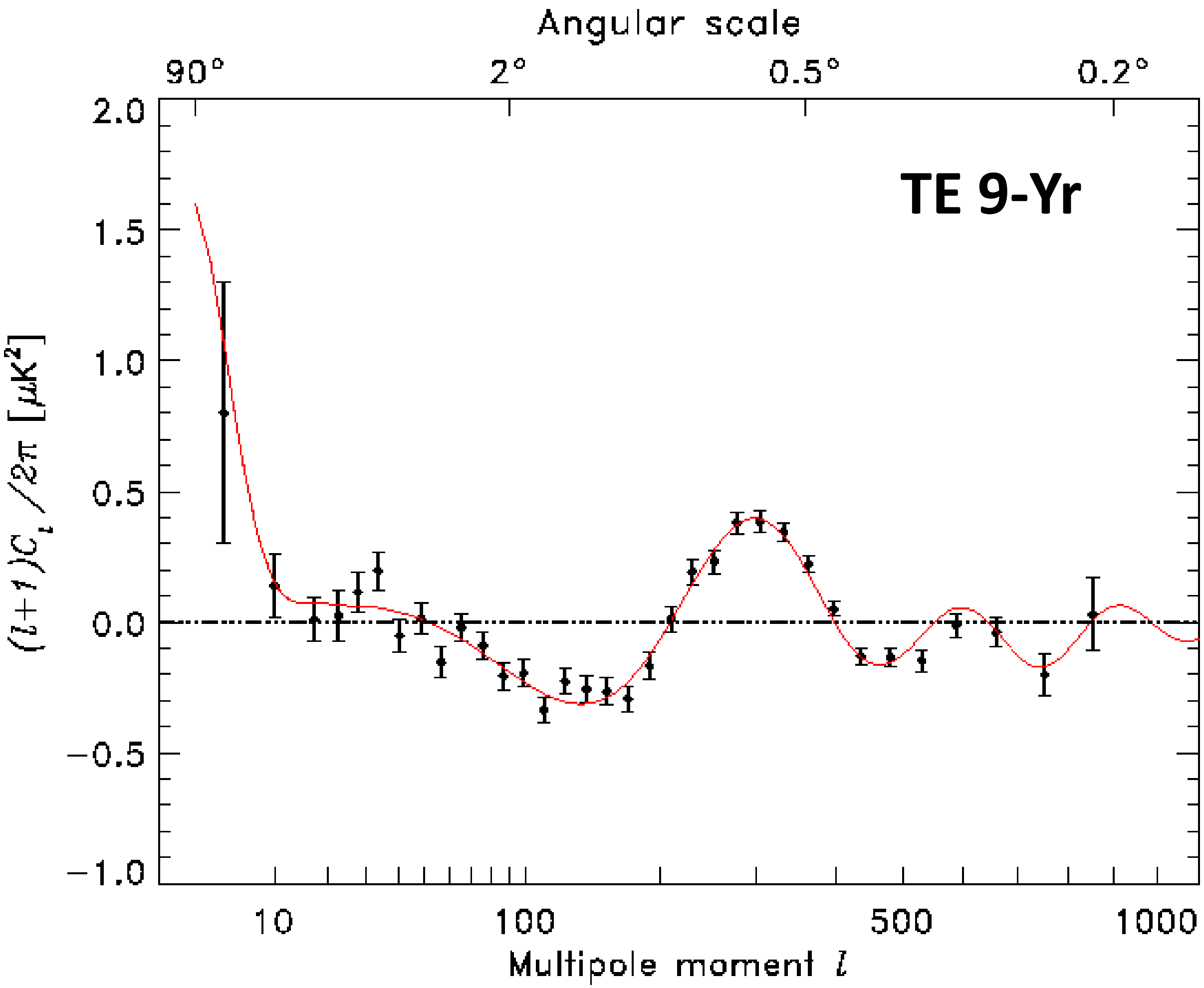
800
1000
Multipole moment l

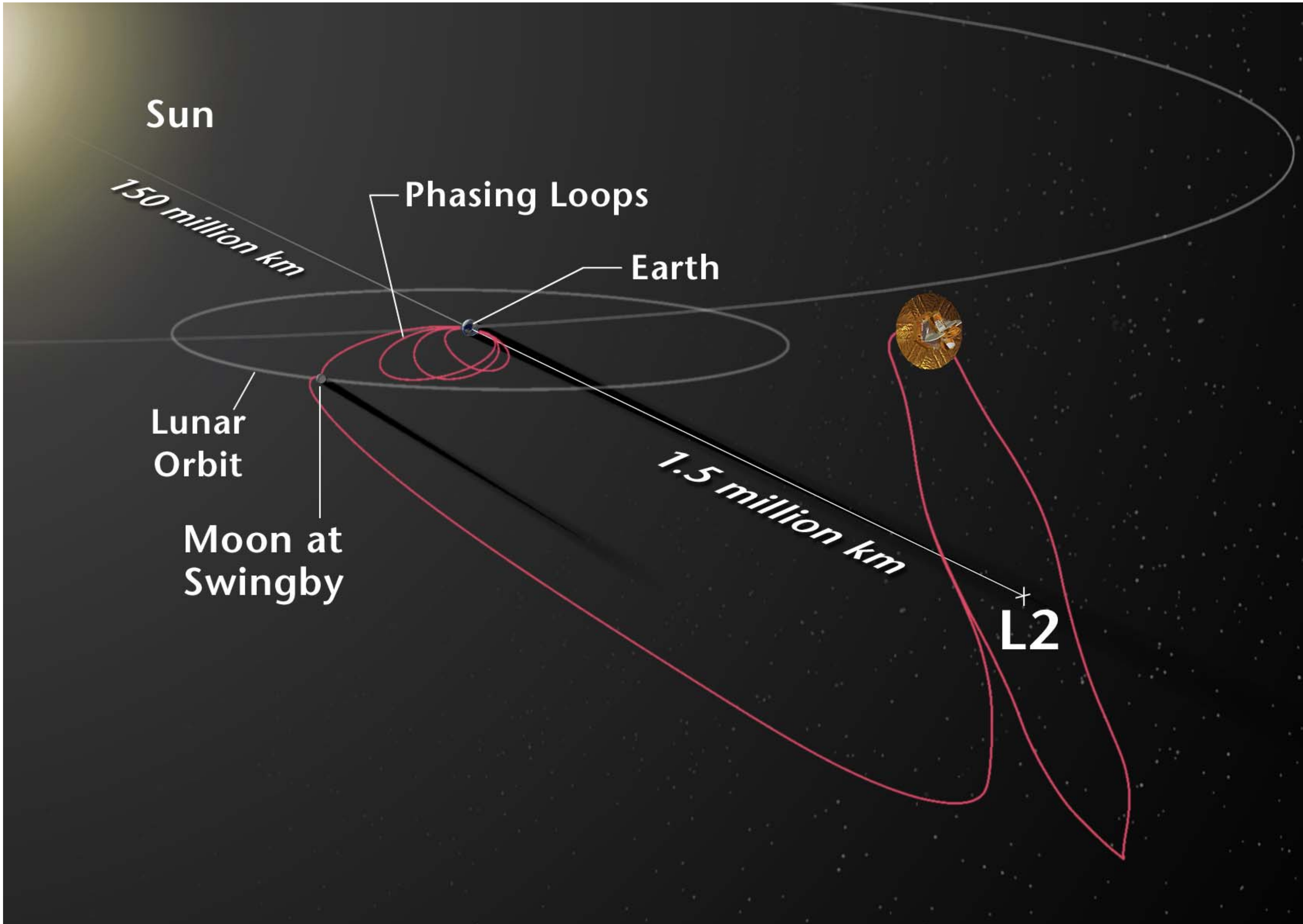


Angular scale
90°
2°
0.5°
0.2°
TE 5-Yr
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
$(l+1)C_l\ /2\pi\ [\mu K^2]$
10
100
500
1000
Multipole moment l



Angular scale
90°
2°
0.5°
0.2°
TE 9-Yr
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
$(l+1)C_l/2\pi$ [μK^2]
10
100
500
1000
Multipole moment l

WMAP at L2



Sun
150 million km
Phasing Loops
Earth
Lunar
Orbit
Moon at
Swingby
1.5 million km
L2

COSMIC BACKGROUND EXPLORER (COBE)

1974 COBE proposed
Spacecraft & all 3 instruments built at Goddard

1989 COBE Launched from Vandenberg AFB

1990 FIRAS - spectrum results favor blackbody

1992 DMR - anisotropy discovered at $\Delta T/T \sim 10^{-5}$

1990: Blackbody Spectrum of the CMB

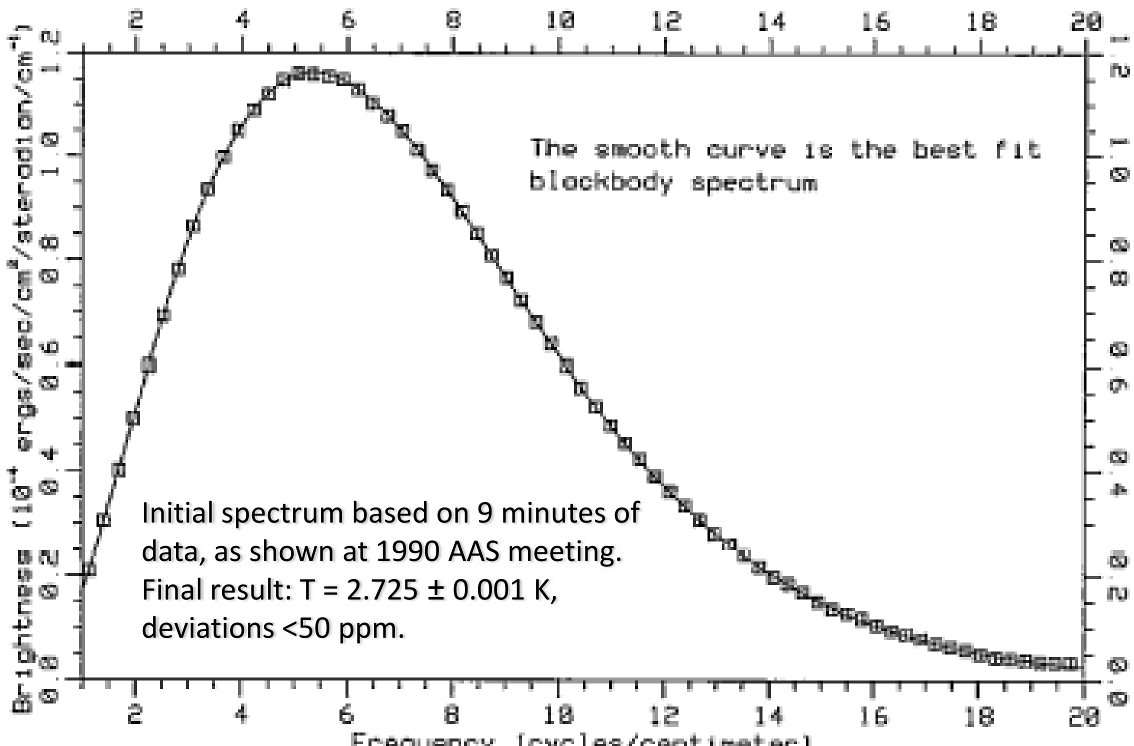
A PRELIMINARY MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM BY THE *COSMIC BACKGROUND EXPLORER* (*COBE*)[1] SATELLITE

J. C. Mather,[2] E. S. Cheng,[2] R. E. Eplee, Jr., [3] R. B. Isaacman,[3] S. S. Meyer,[4] R. A. Shafer,[2] R. Weiss,[4] E. L. Wright,[5] C. L. Bennett, N. W. Boggess,[2] E. Dwek,[2] S. Gulkis,[6] M. G. Hauser,[2] M. Janssen,[6] T. Kelsall,[2] P. M. Lubin,[7] S. H. Moseley, Jr.,[2] T. L. Murdock,[8] R. F. Silverberg,[2] G. F. Smoot,[9] and D. T. Wilkinson[10]

The Astrophysical Journal, 354:L37-40, 1990

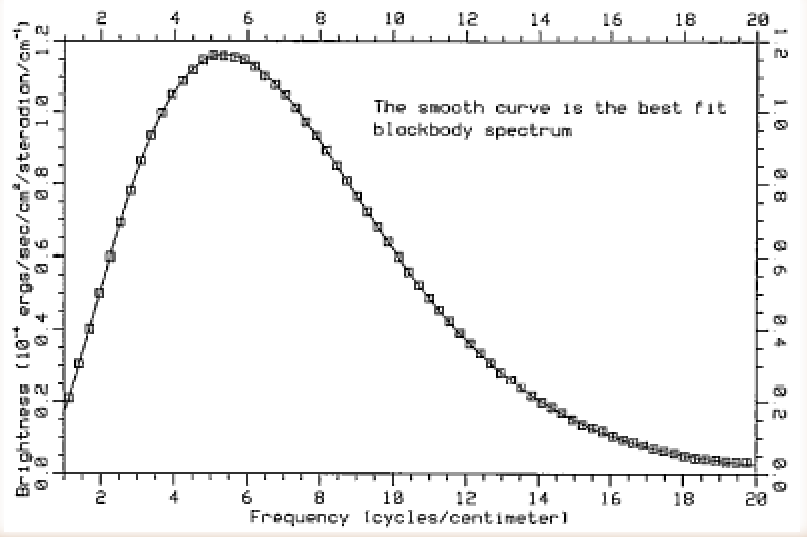
2006

A crucial test of Big Bang cosmology.



Initial spectrum based on 9 minutes of data, as shown at 1990 AAS meeting. Final result: T = 2.725 ± 0.001 K, deviations <50 ppm.

The Early Universe



At the time of recombination (t=379,000 yr) the universe is filled with warm gas (T~3000 K) in thermal equilibrium. There is no observable structure.

1992: CMB Anisotropy

STRUCTURE IN THE *COBE*[1] DIFFERENTIAL MICROWAVE RADIOMETER FIRST-YEAR MAPS

G. F. SMOOT,[2] C. L. BENNETT,[3] A. KOGUT,[4] E. L. WRIGHT,[5] J. AYMON,[2] N. W. BOGGESS,[3] E. S. CHENG,[3] G. DE AMICI,[2] S. GULKIS,[6] M. G. HAUSER,[3] G. HINSHAW,[4] P. D. JACKSON,[7] M. JANSSEN,[6] E. KAITA,[7] T. KELSALL,[3] P. KEEGSTRA,[7] C. LINEWEAVER,[2] K. LOEWENSTEIN,[7] P. LUBIN,[8] J. MATHER,[3] S. S. MEYER,[9] S. H. MOSELEY,[3] T. MURDOCK,[10] L. ROKKE,[7] R. F. SILVERBERG,[3] L. TENORIO,[2] R. WEISS,[9] AND D. T. WILKINSON[11]

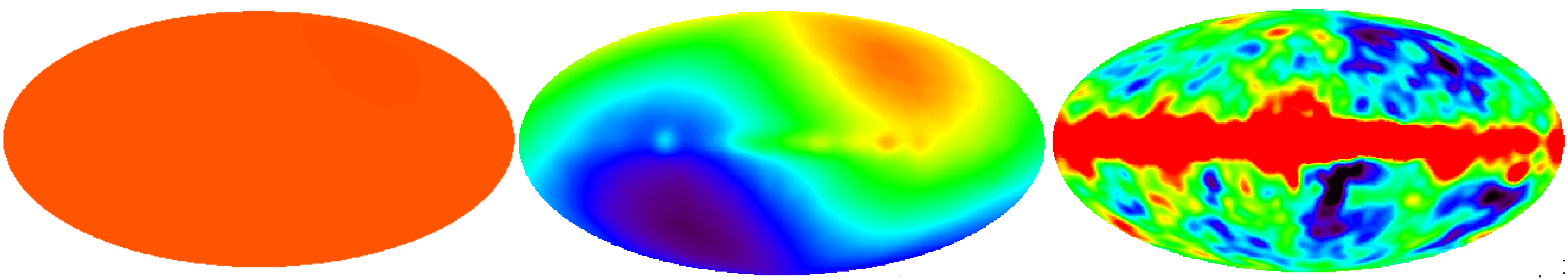
THE ASTROPHYSICAL JOURNAL, 396:L1-L5, 1992

2006

"PRELIMINARY SEPARATION OF GALACTIC AND COSMIC MICROWAVE EMISSION…"
BENNETT ET AL, THE ASTROPHYSICAL JOURNAL, 396:L1-L5, 1992

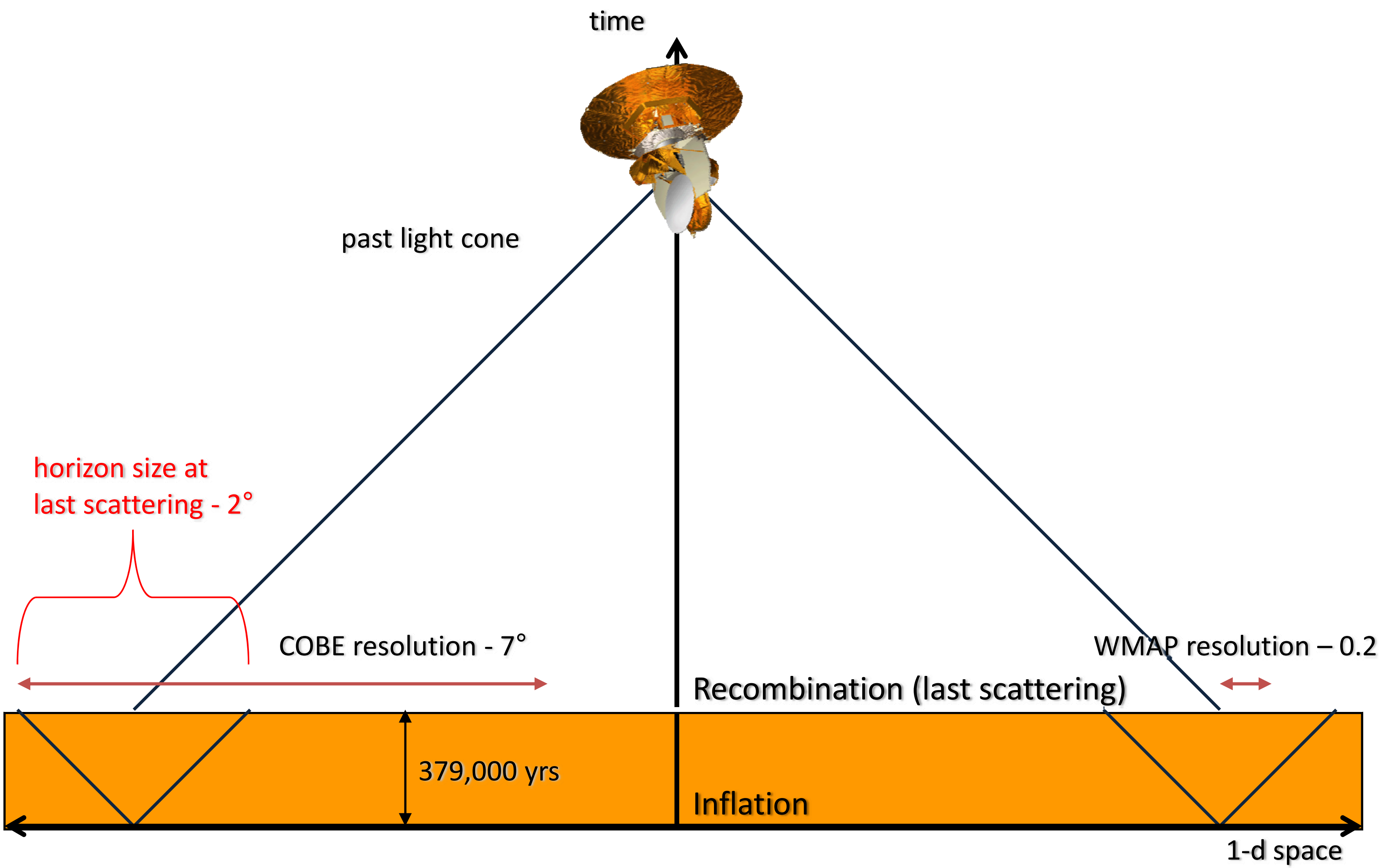
"INTERPRETATION OF THE COSMIC MICROWAVE BACKGROUND RADIATION ANISOTROPY…"
WRIGHT ET AL, THE ASTROPHYSICAL JOURNAL, 396:L1-L5, 1992

"COBE DIFFERENTIAL MICROWAVE RADIOMETERS – PRELIMINARY SYSTEMATIC ERROR…"
KOGUT ET AL, THE ASTROPHYSICAL JOURNAL, 401, 1-18, 1992



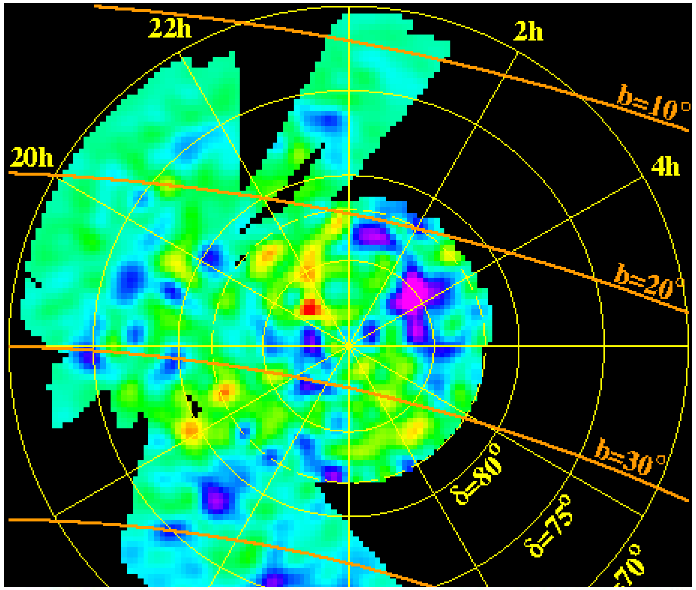
First detection of temperature fluctuations (anisotropy): sets the scale of the signal – brighter than the Galactic foreground!

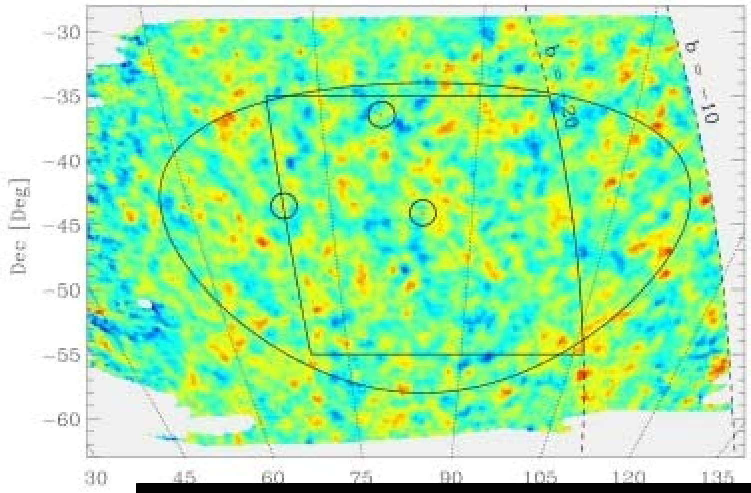
1990's: Push for Higher Resolution

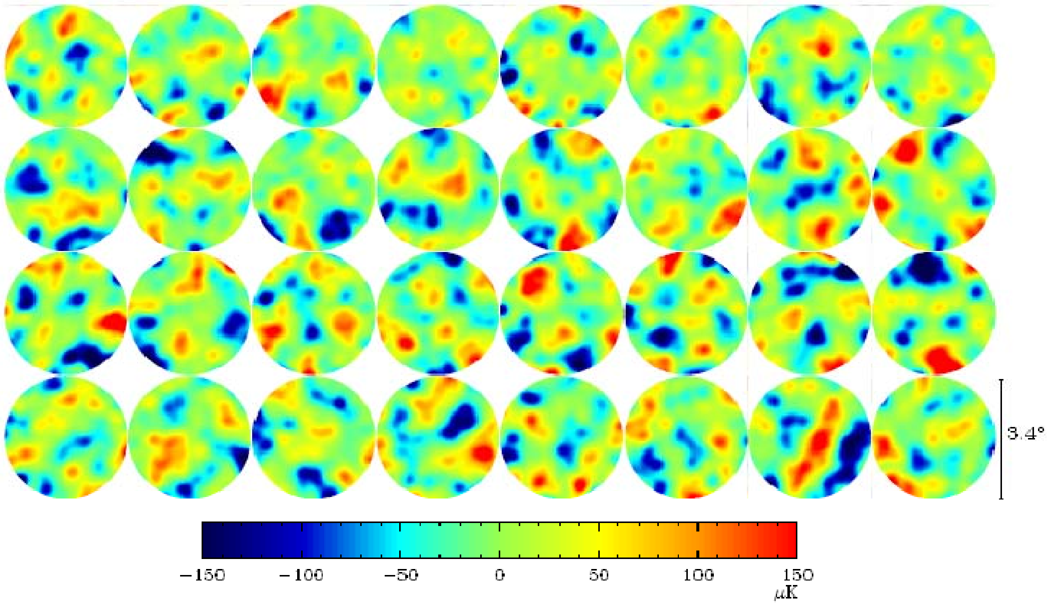


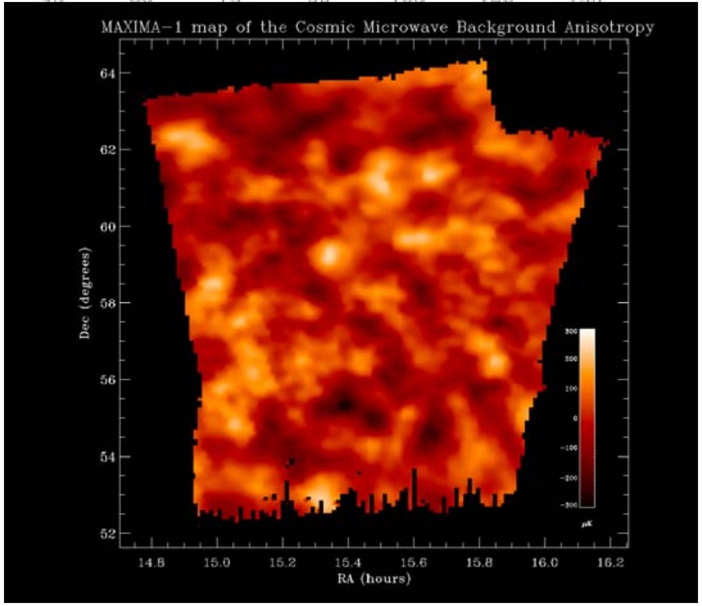
WMAP and other degree-scale experiments probe scales smaller than the horizon. COBE does not.

1990's: A Decade of Progress!







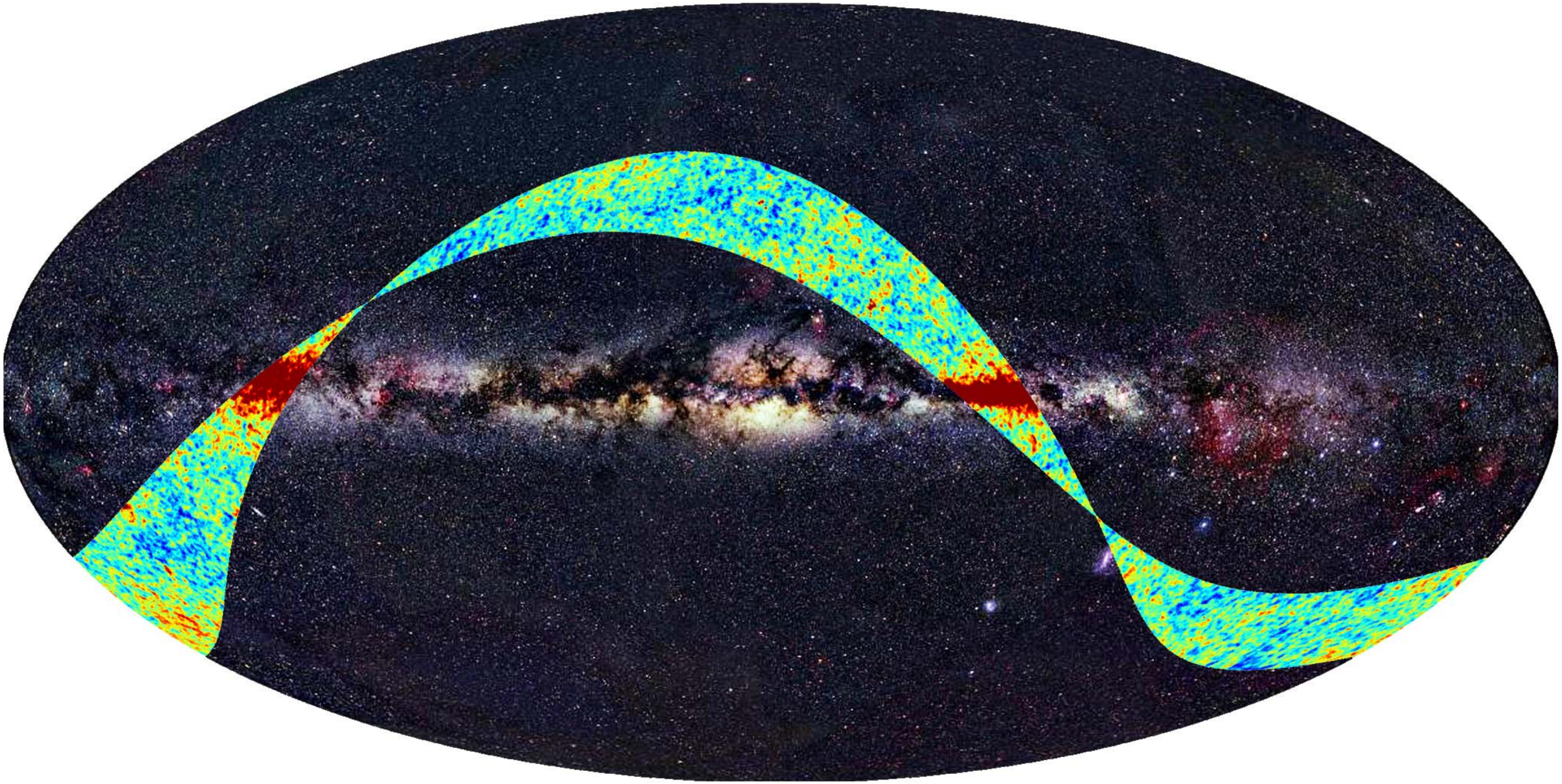


QMASK
DASI

Boomerang
Maxima

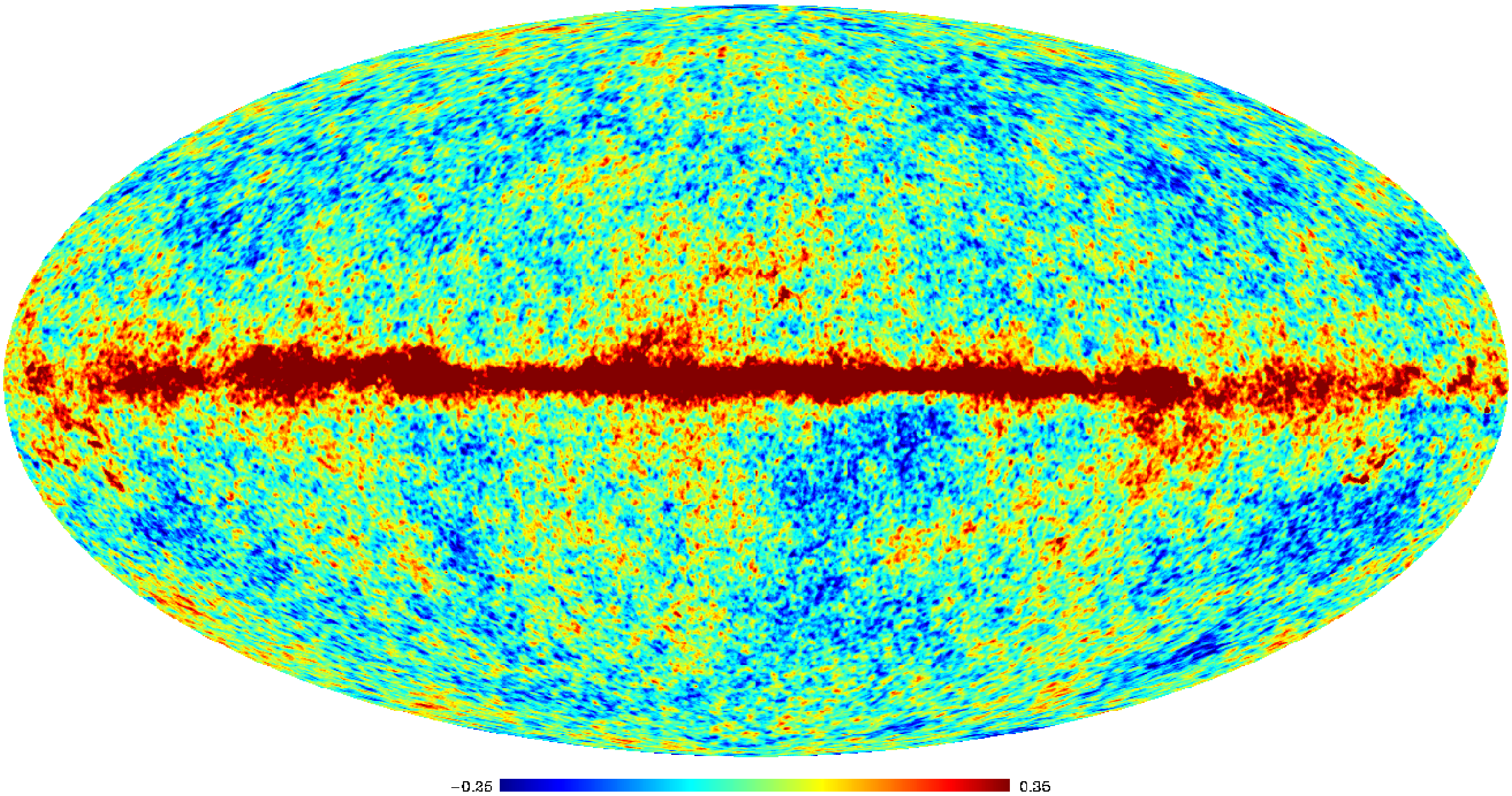
to name a few…

Planck First Light!



Source: ESA

WMAP-only



WMAP/Planck