Cosmic Microwave Background as a Probe of the Very Early Universe

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Colloquium, STScI, October 1, 2008

WMAP 5-Year Papers

- **Hinshaw et al.**, "*Data Processing, Sky Maps, and Basic Results*" 0803.0732
- **Hill et al.**, "*Beam Maps and Window Functions*" 0803.0570
- **Gold et al.**, "*Galactic Foreground Emission*" 0803.0715
- **Wright et al.**, "*Source Catalogue*" 0803.0577
- **Nolta et al.**, "*Angular Power Spectra*" 0803.0593
- **Dunkley et al.**, "*Likelihoods and Parameters from the WMAP data*" 0803.0586
- **Komatsu et al**., "*Cosmological Interpretation*" 0803.0547

WMAP 5-Year Science Team

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- D. Larson
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Special Thanks to **WMAP Graduates!**

- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

Night Sky in Optical (~0.5nm)

courtesy University of Arizona

Night Sky in Microwave (~1mm)

courtesy University of Arizona

A. Penzias & R. Wilson, 1965

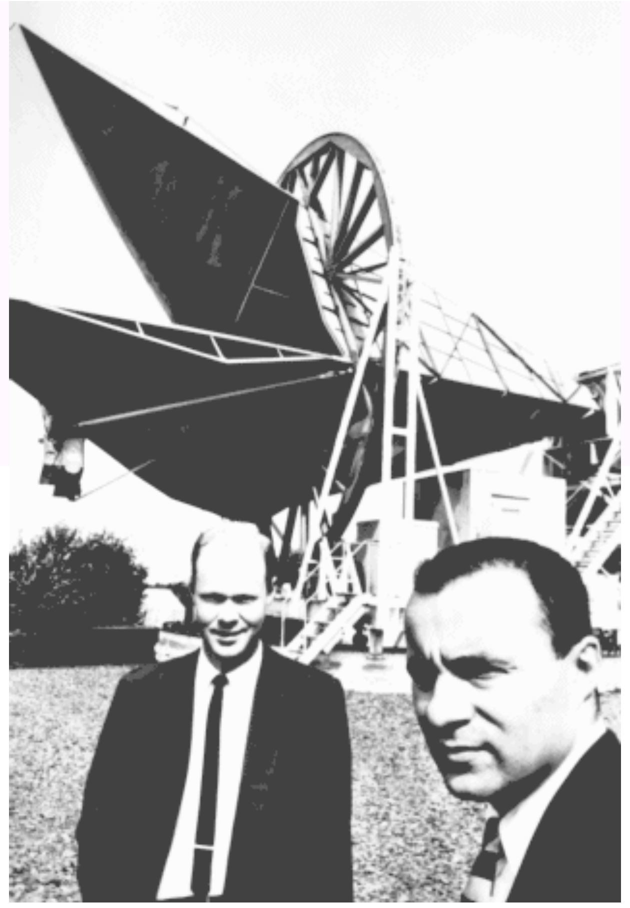
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

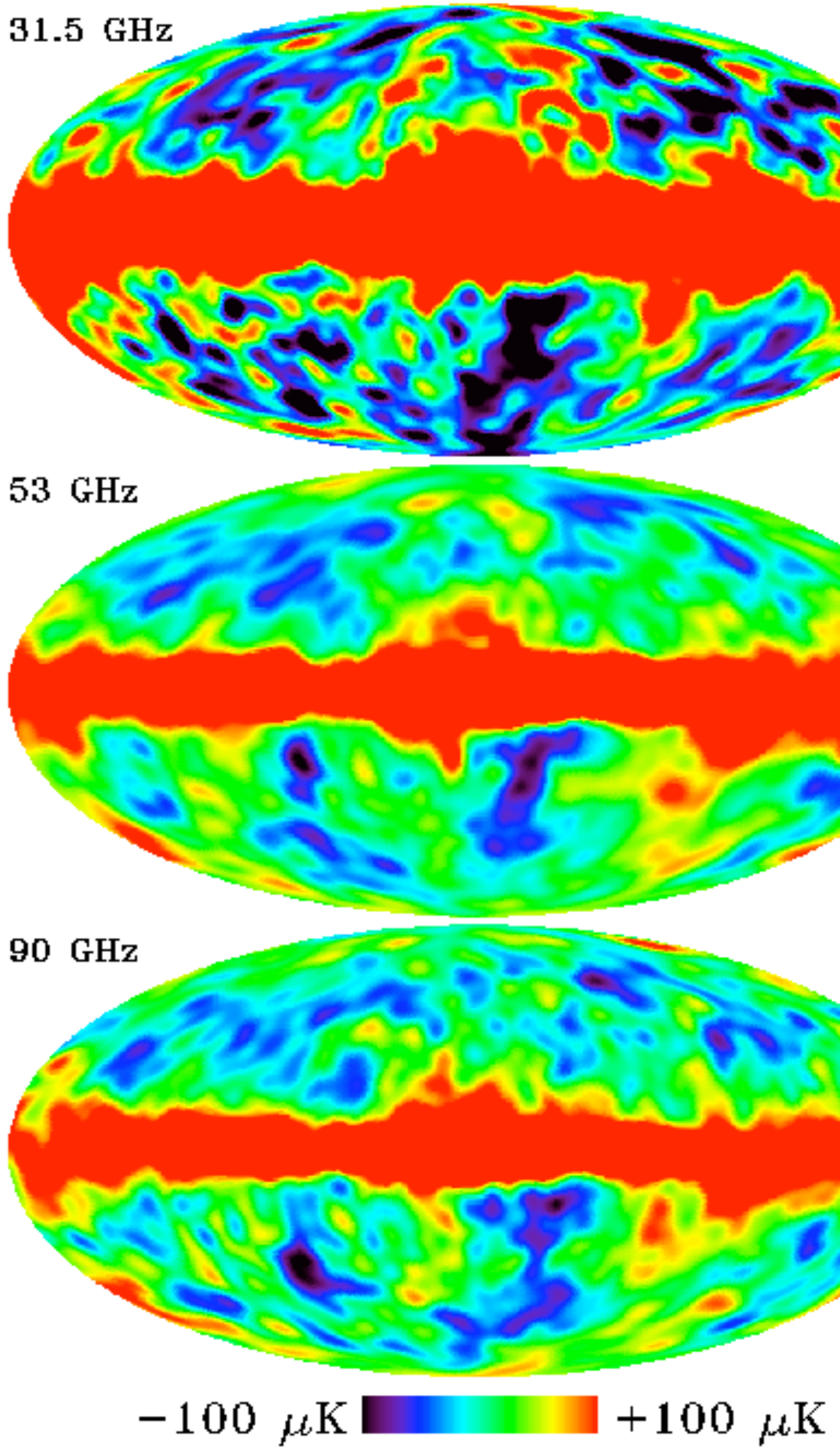
- **Isotropic**
- **Unpolarized**

A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey



COBE/DMR, 1992



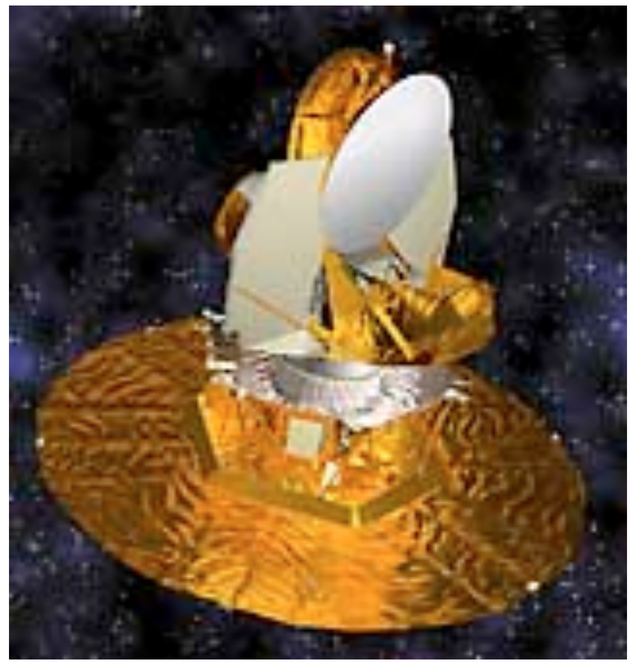
- Isotropic?
- CMB is anisotropic! (at the 1/100,000 level)

COBE to WMAP (x35 better resolution)

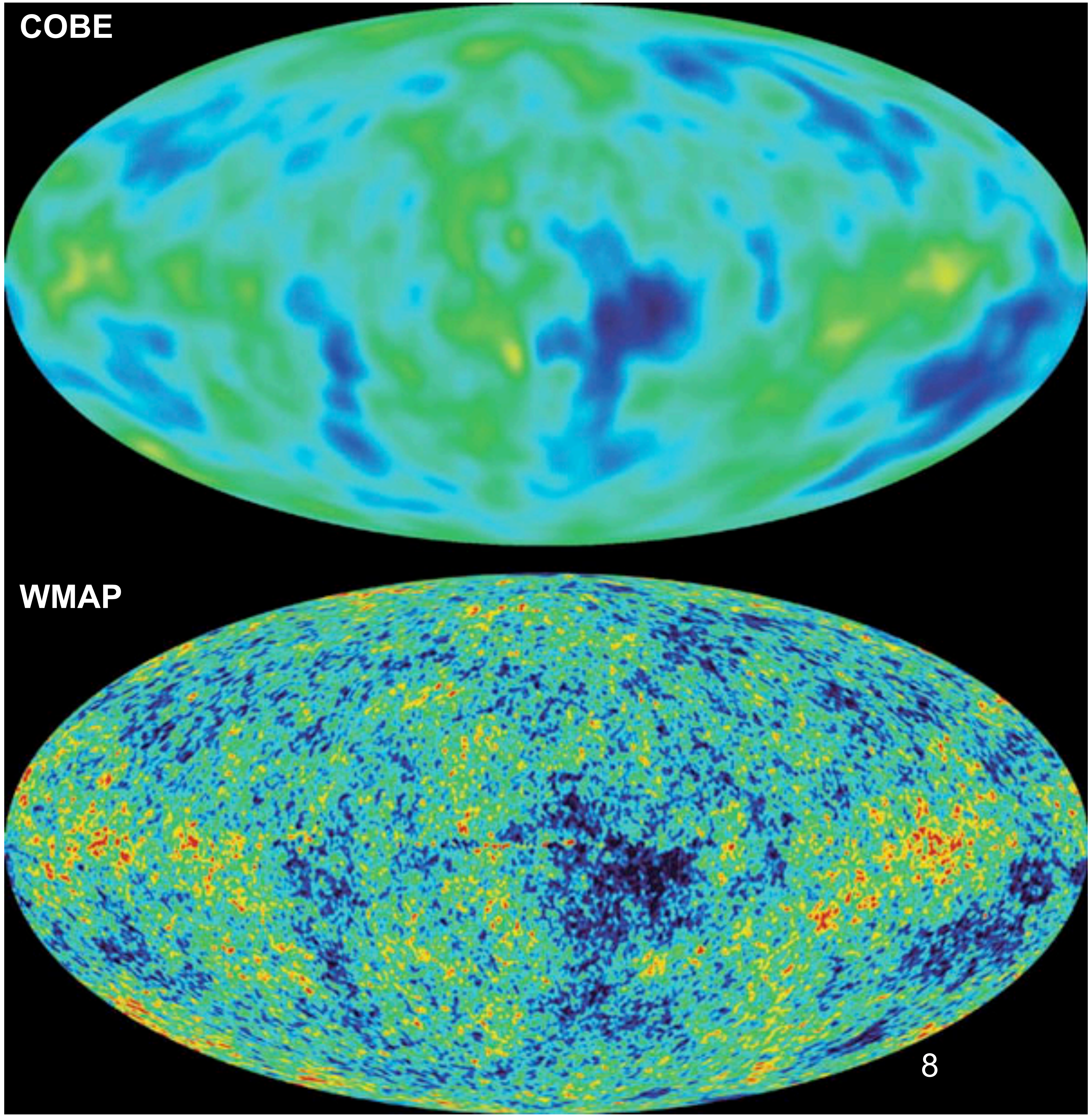
COBE
1989

Press Release from the Nobel Foundation

[COBE’s] measurements also marked the inception of cosmology as a precise science. It was not long before **it was followed up,** for instance **by the WMAP satellite, which yielded even clearer images of the background radiation**.



WMAP
2001



WMAP at Lagrange 2 (L2) Point

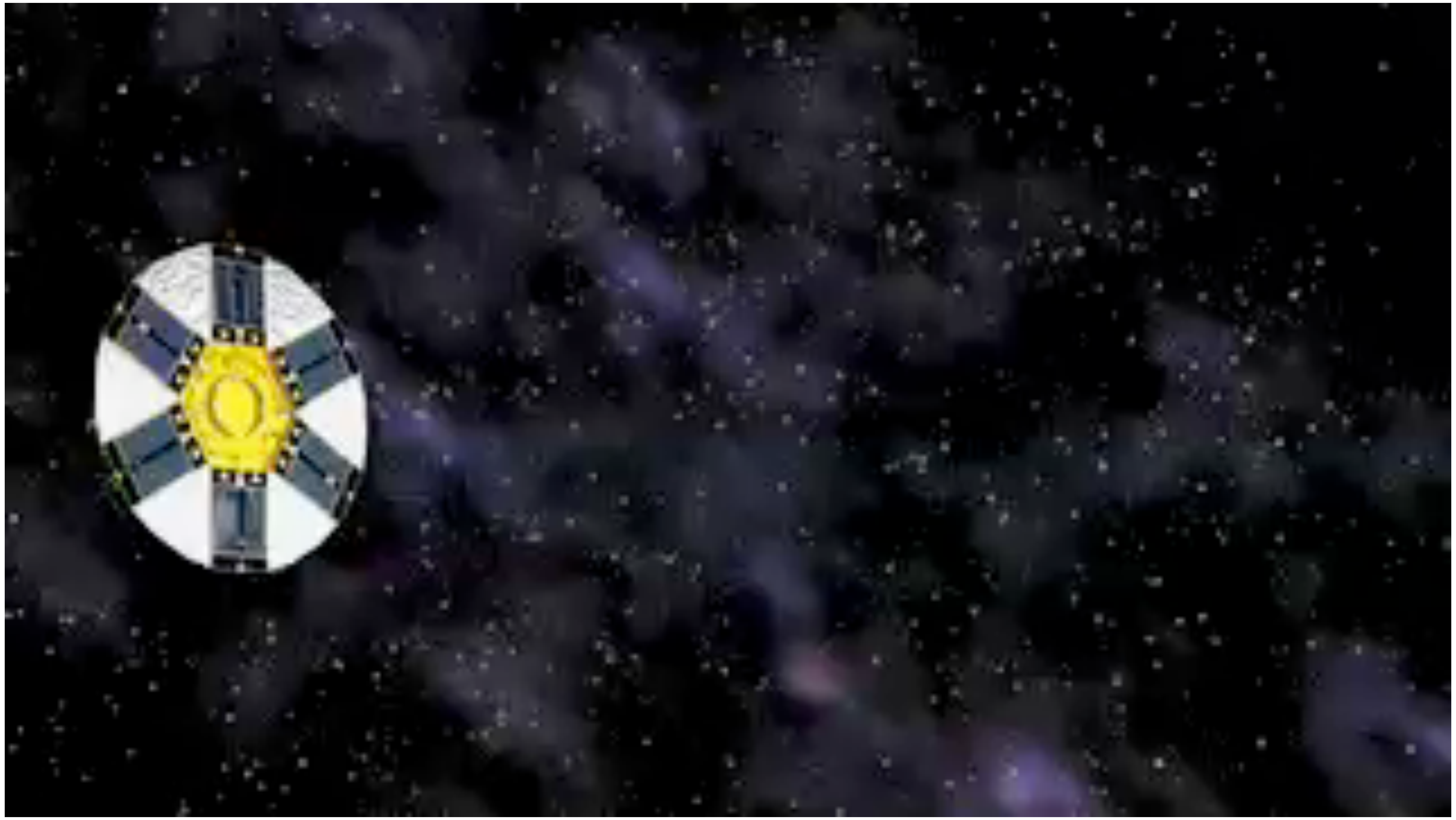
June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

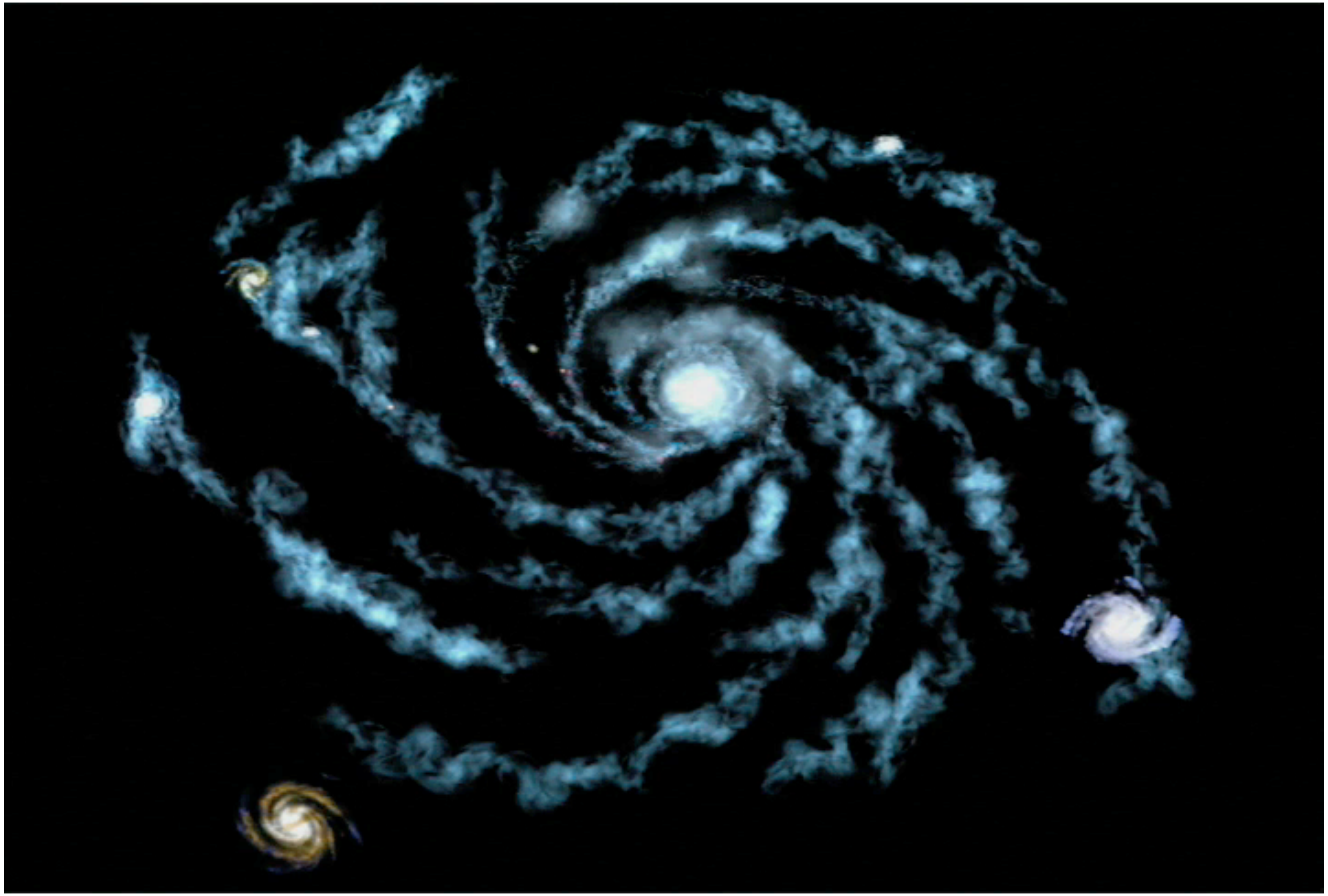
**March 2008:
The five-year data release**

9-year survey funded recently



- L2 is a million miles from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them

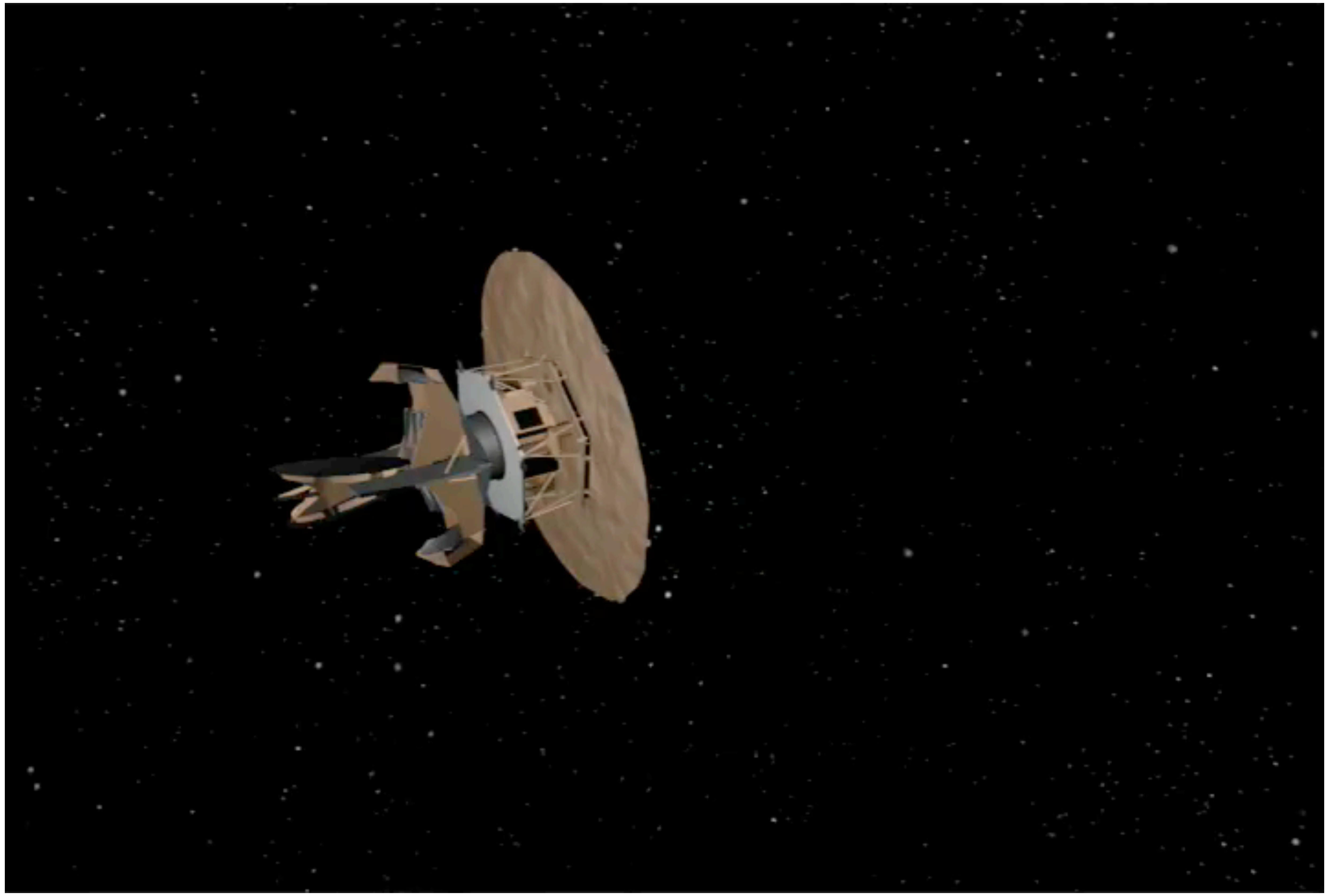
WMAP Measures Microwaves From the Universe



- The mean temperature of photons in the Universe today is 2.725 K
- WMAP is capable of measuring the temperature *contrast* down to better than **one part in millionth**

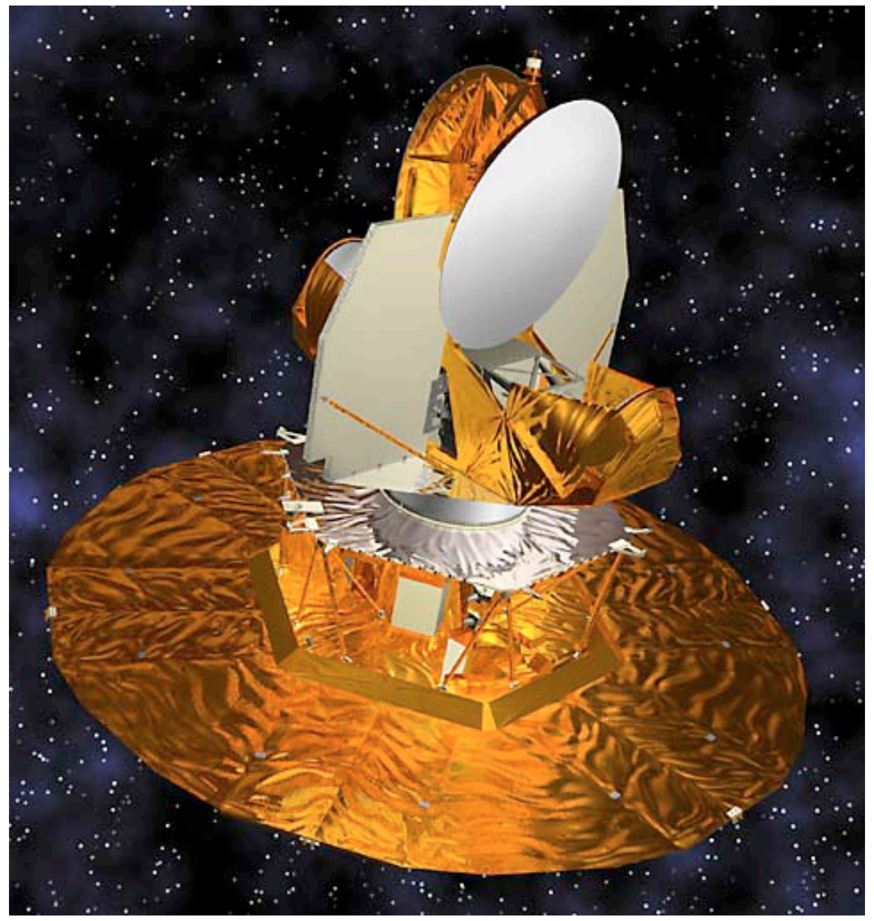
Journey Backwards in Time

- The Cosmic Microwave Background (**CMB**) is ***the fossil light from the Big Bang***
- This is the oldest light that one can ever hope to measure
- CMB is a ***direct*** image of the Universe when the Universe was only 380,000 years old



- CMB photons, after released from the cosmic plasma "soup," traveled for **13.7 billion years** to reach us.
- CMB collects information about the Universe as it travels through it.

The Wilkinson Microwave Anisotropy Probe (*WMAP*)



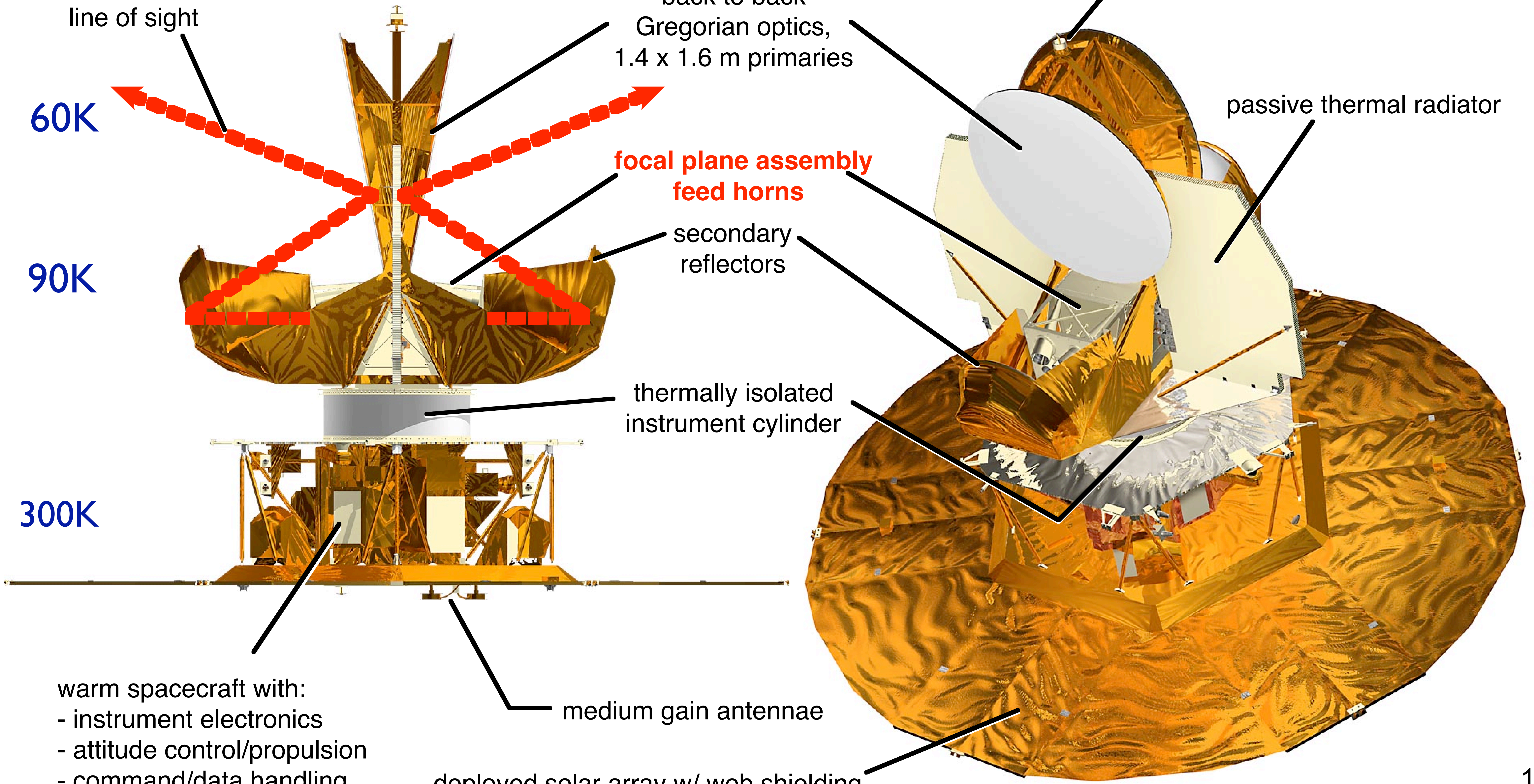
- A microwave satellite working at L2
- Five frequency bands
  - K (22GHz), Ka (33GHz), Q (41GHz), V (61GHz), W (94GHz)
  - Multi-frequency is crucial for cleaning the Galactic emission

- **The Key Feature: Differential Measurement**
  - The technique inherited from COBE
  - 10 “Differencing Assemblies” (DAs)
  - K1, Ka1, Q1, Q2, V1, V2, W1, W2, W3, & W4, each consisting of two radiometers that are sensitive to orthogonal linear polarization modes.
- Temperature anisotropy is measured by **single difference**.
- Polarization anisotropy is measured by **double difference**.

WMAP can measure polarization as well!

WMAP Spacecraft

Radiative Cooling: No Cryogenic System



line of sight

60K

90K

300K

back to back
Gregorian optics,
1.4 x 1.6 m primaries

upper omni antenna

passive thermal radiator

focal plane assembly
feed horns

secondary
reflectors

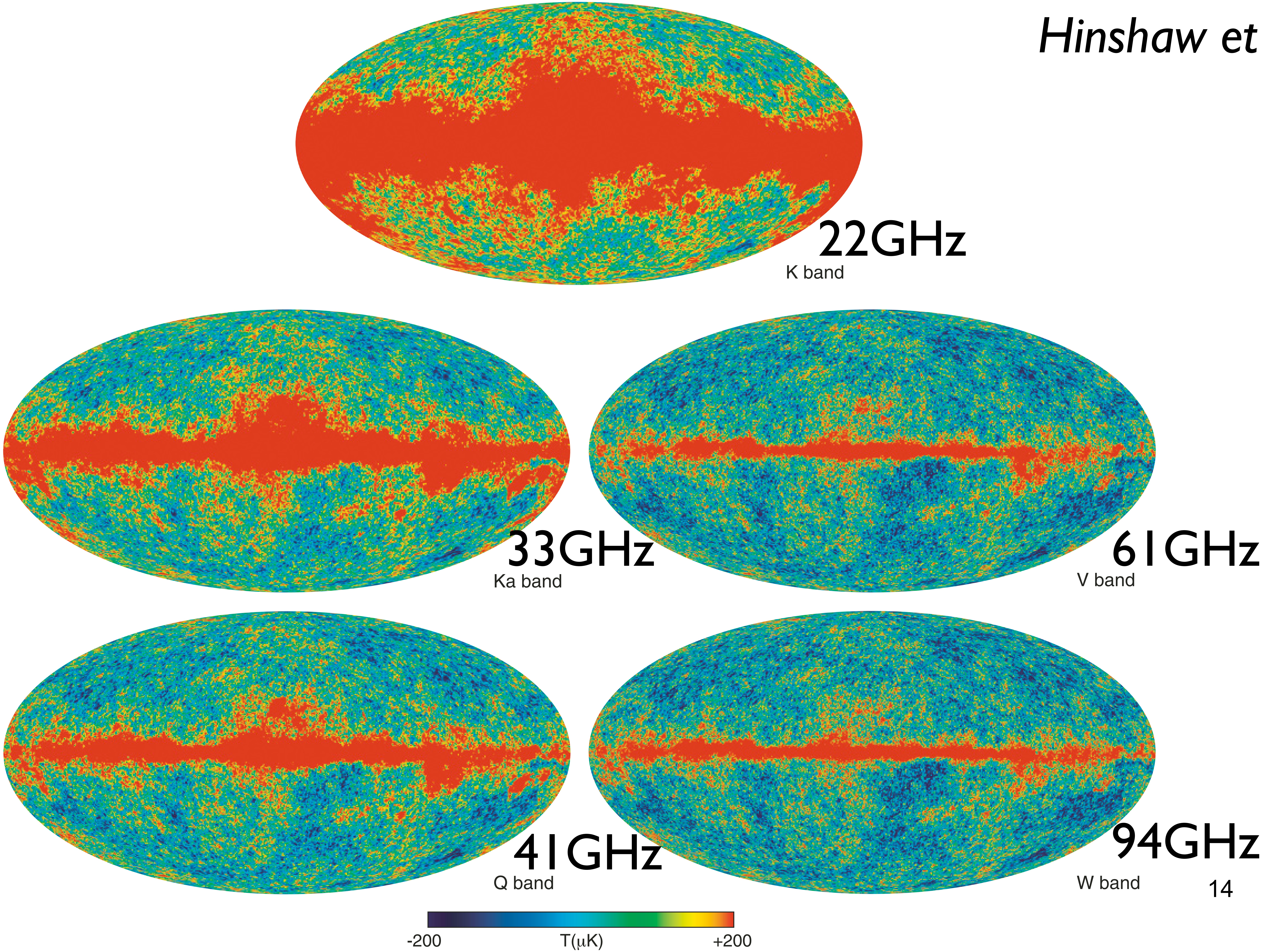
thermally isolated
instrument cylinder

warm spacecraft with:
- instrument electronics
- attitude control/propulsion
- command/data handling
- battery and power control

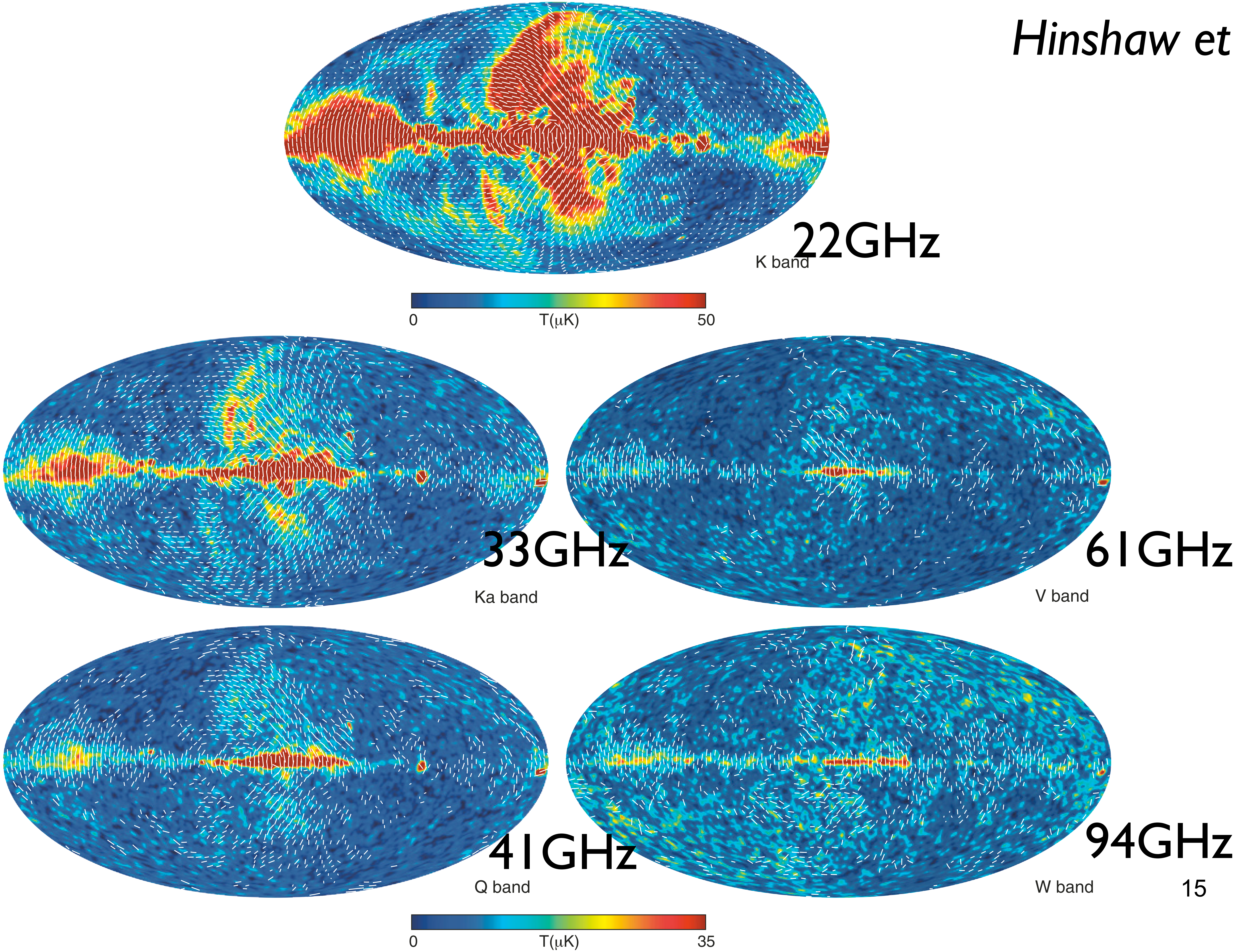
medium gain antennae

deployed solar array w/ web shielding

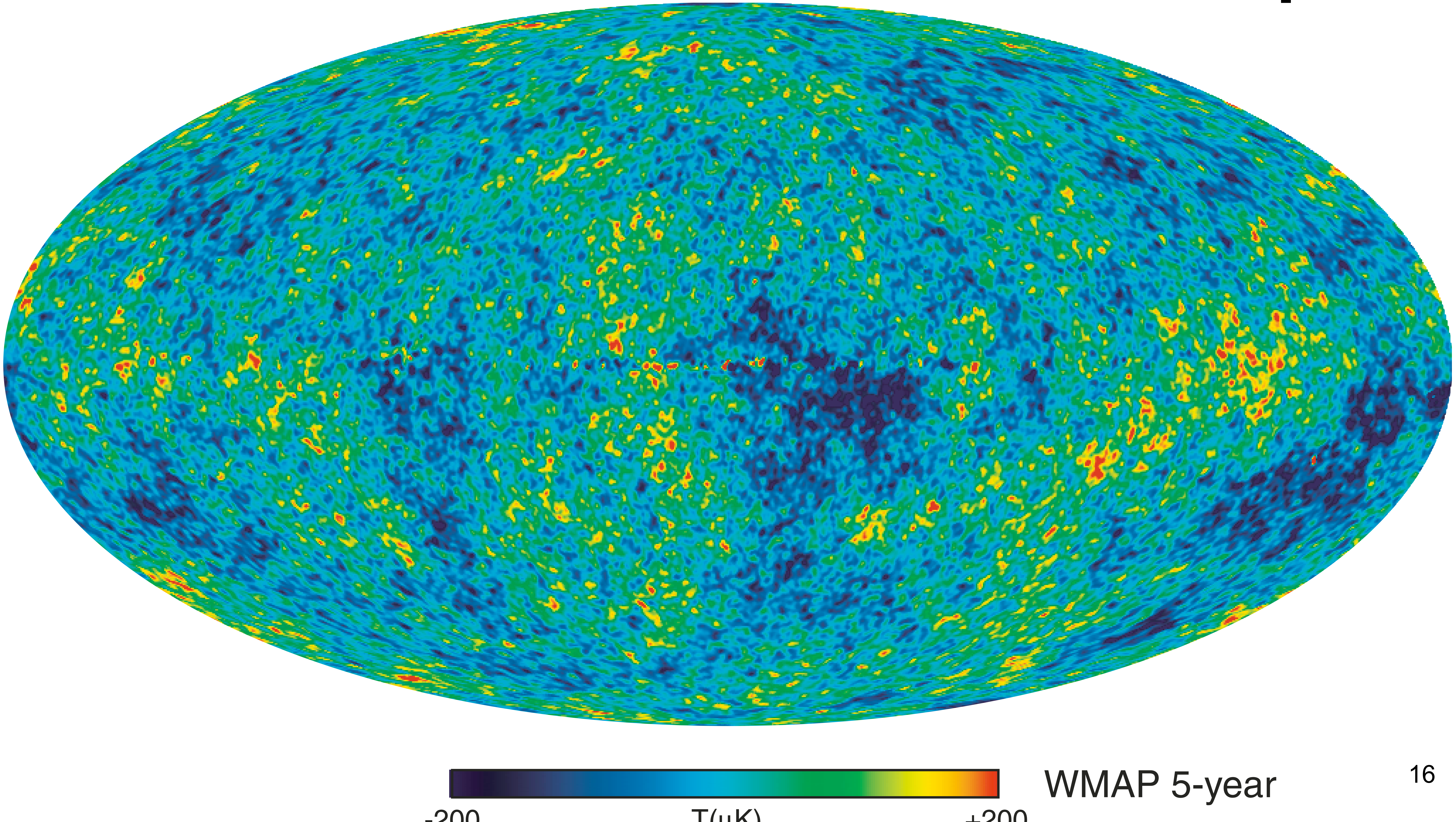
Hinshaw et al.



Hinshaw et al.



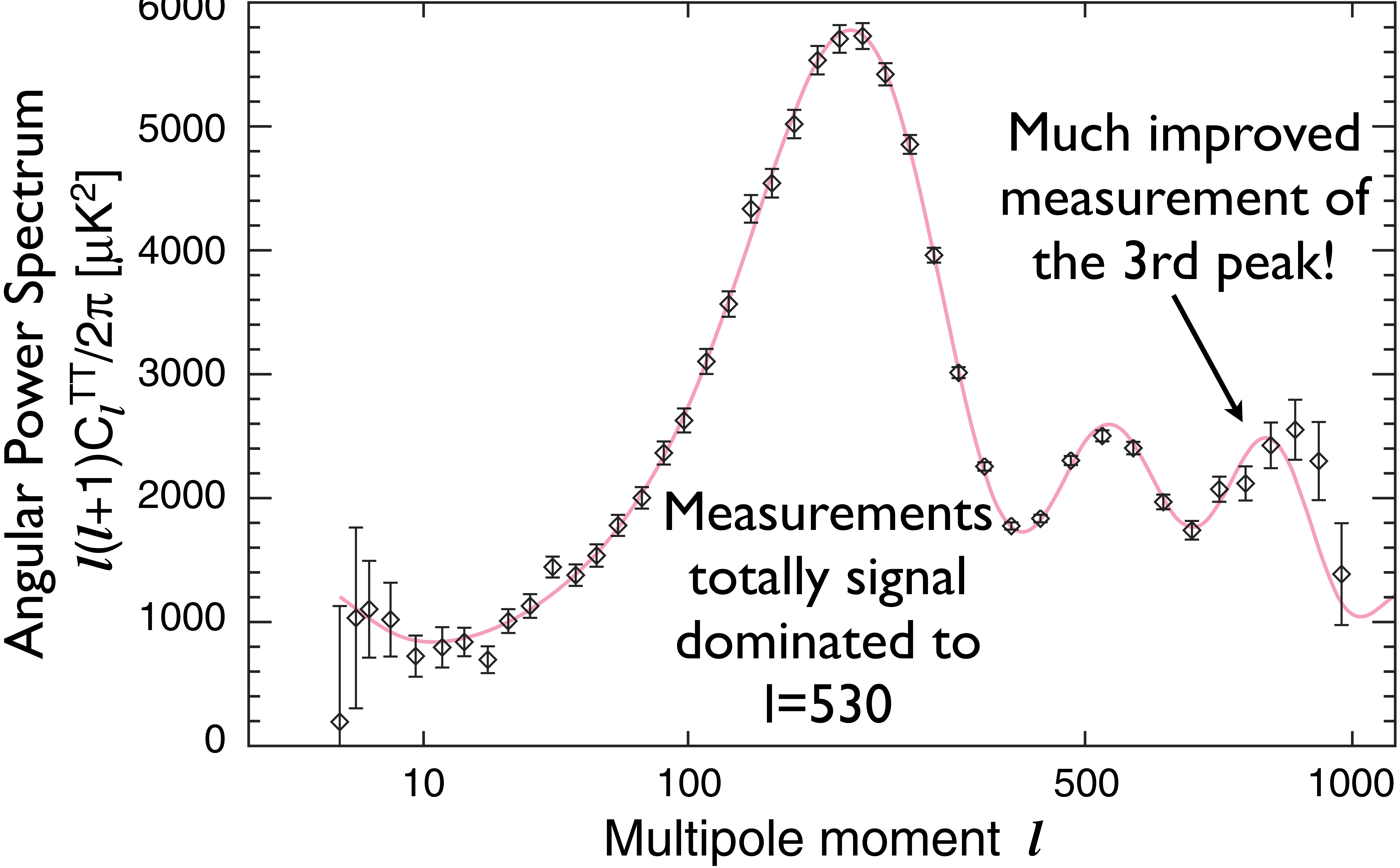
How Did We Use This Map?



WMAP 5-year

Nolta et al.

The Spectral Analysis

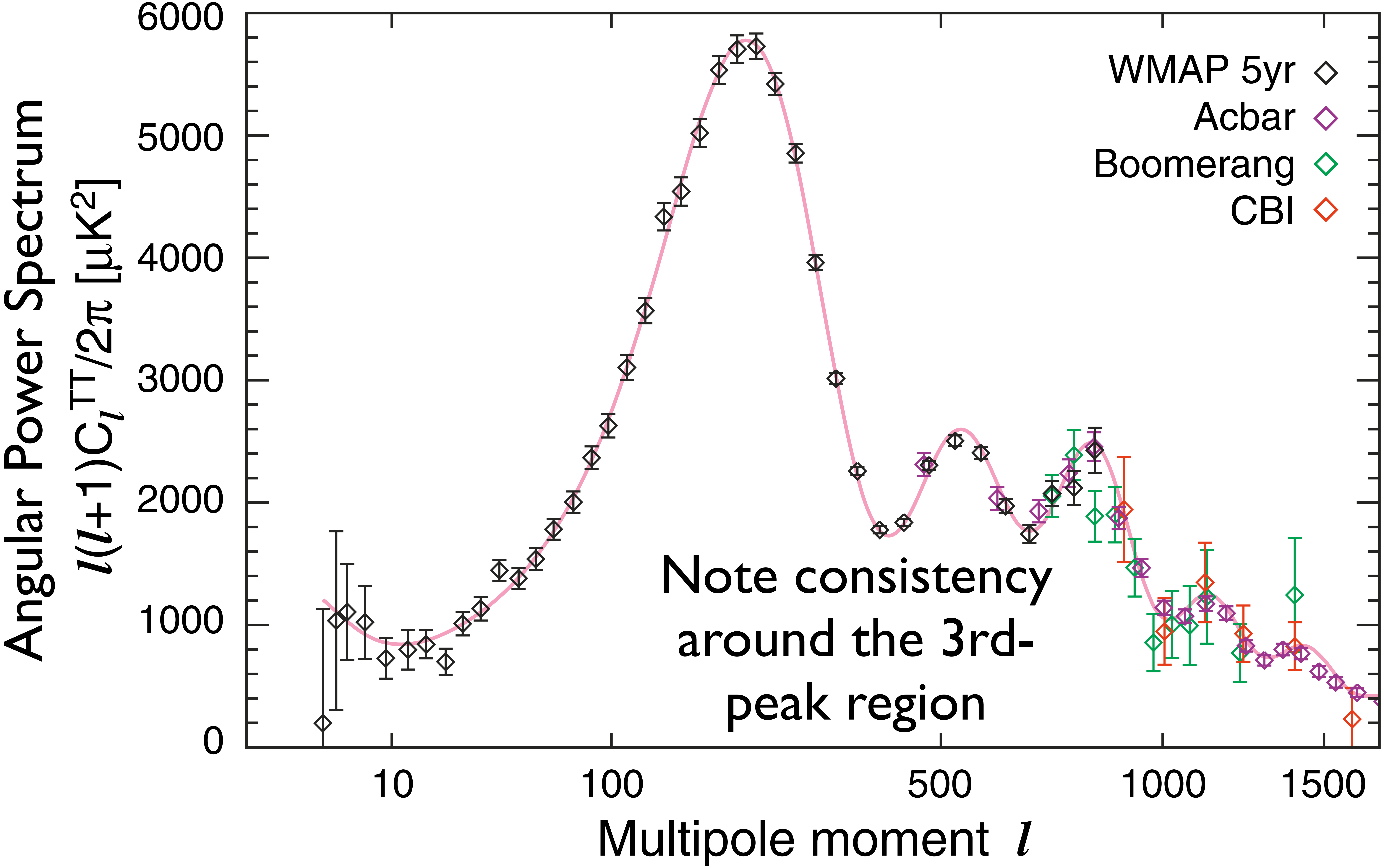


Much improved measurement of the 3rd peak!

Measurements totally signal dominated to l=530

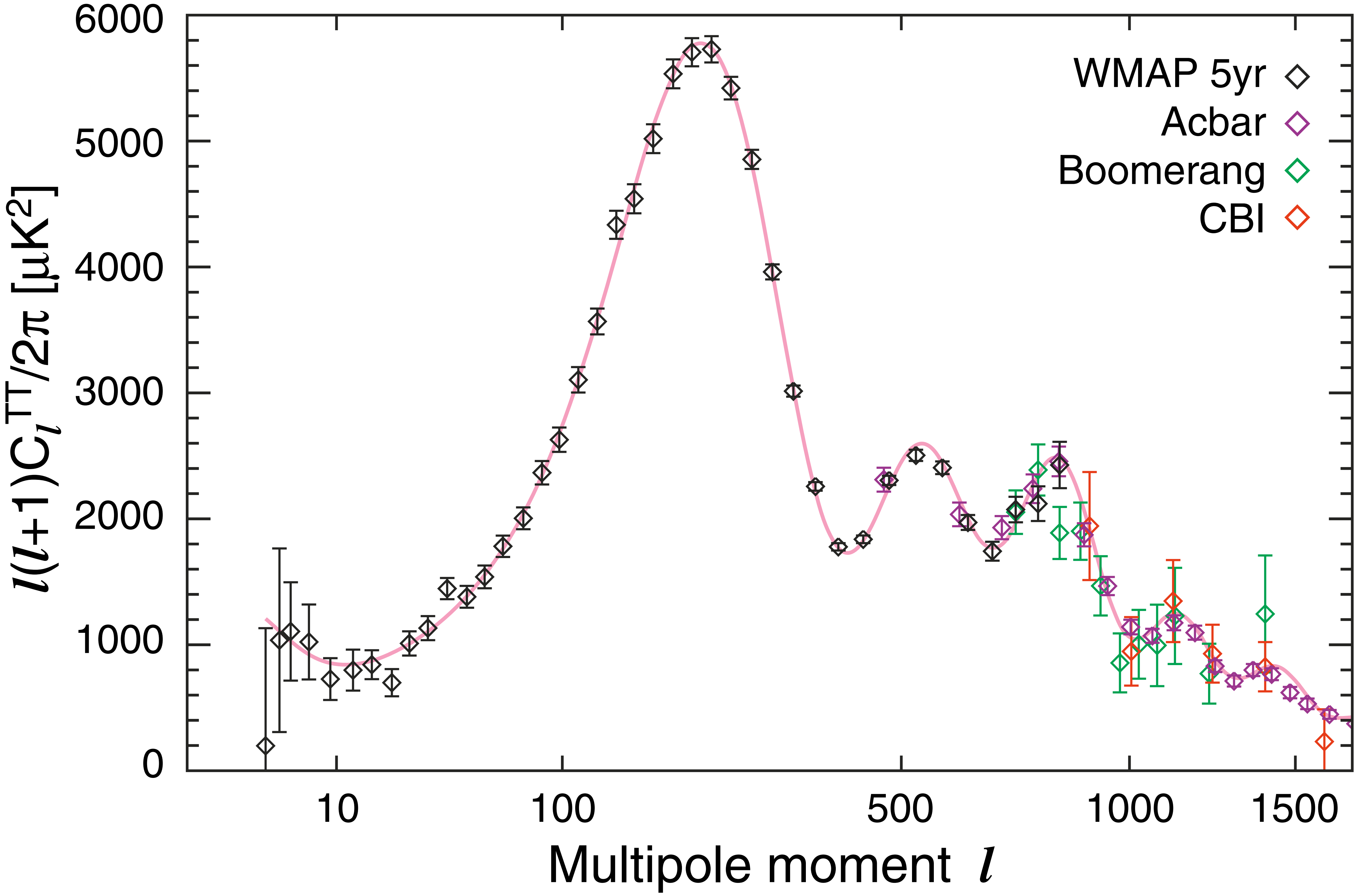
Nolta et al.

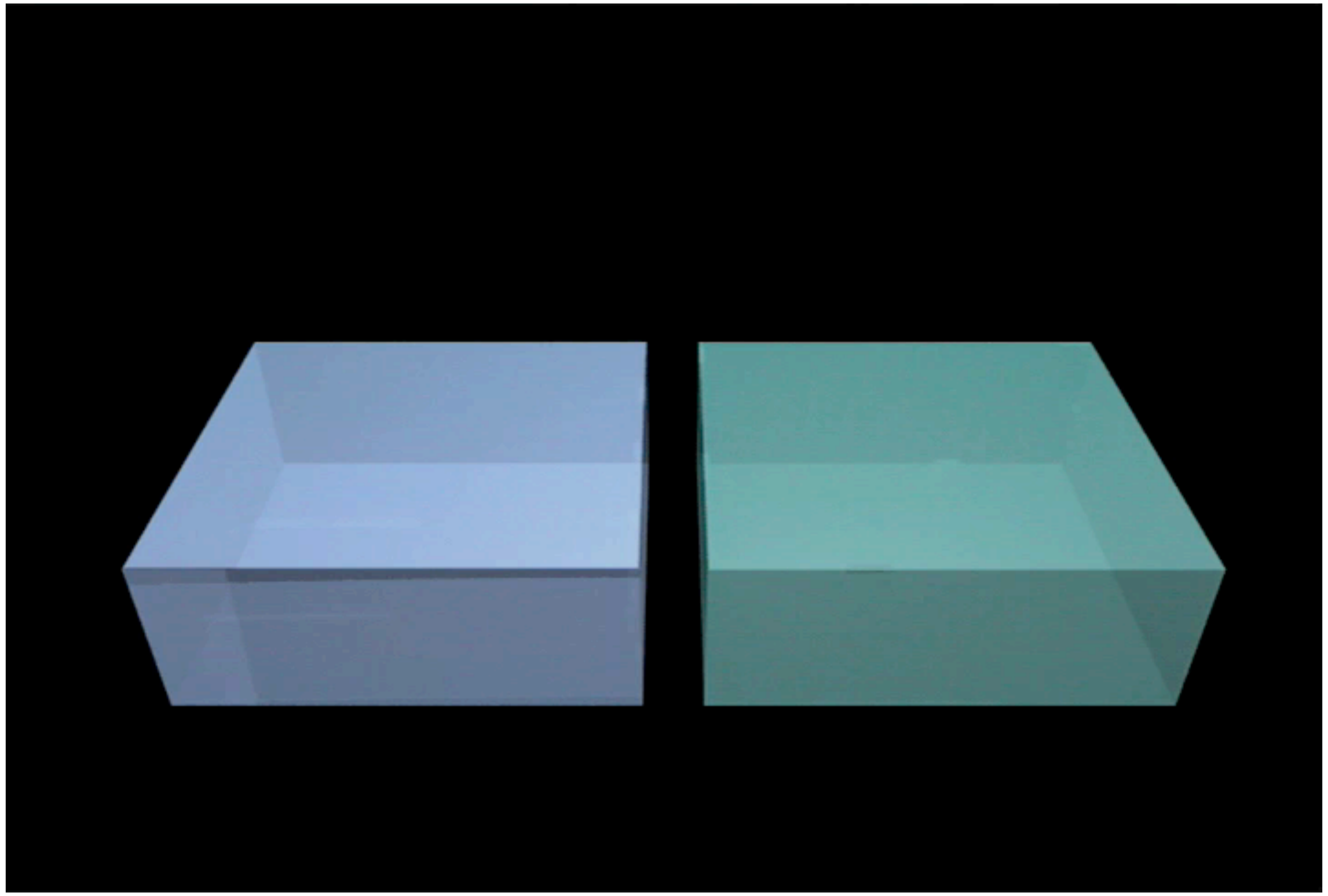
The Cosmic Sound Wave



Note consistency around the 3rd-peak region

The Cosmic Sound Wave

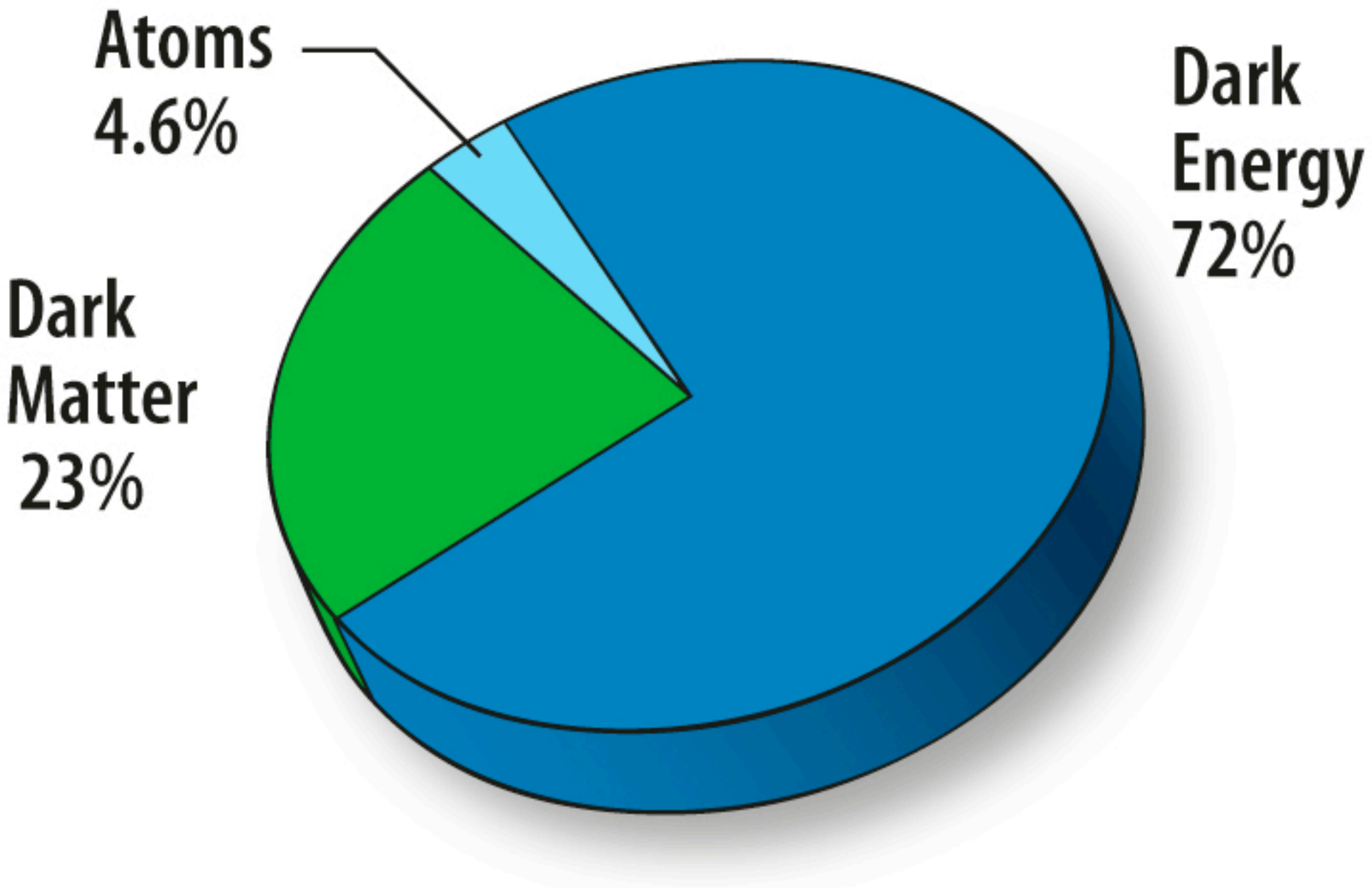




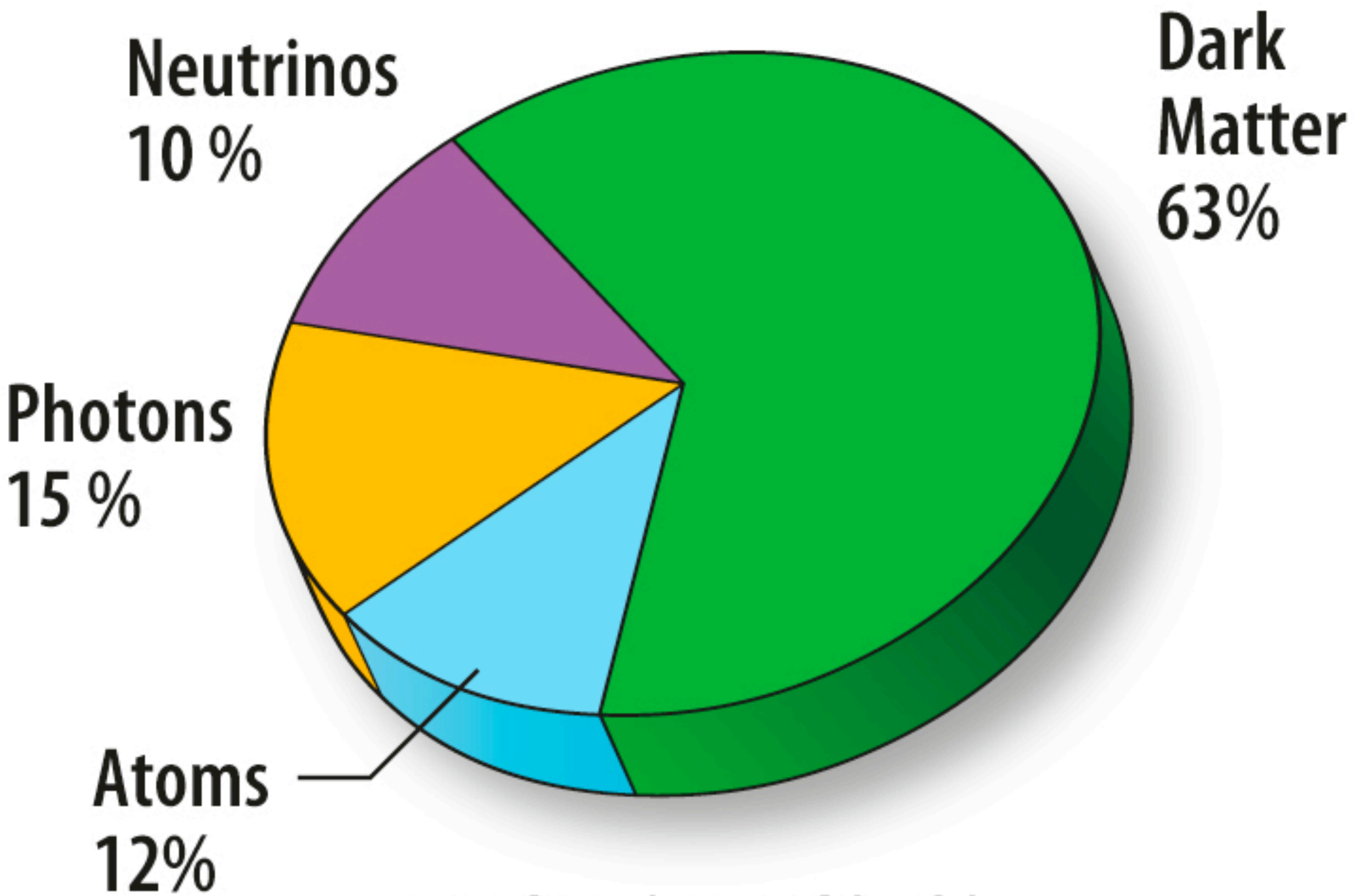
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves. E.g.,
  - **1st-to-2nd-peak** ratio: baryon-to-photon ratio
  - **1st-to-3rd-peak** ratio: total matter-to-total radiation ratio

Komatsu et al.

~WMAP 5-Year~ Pie Chart Update!



TODAY

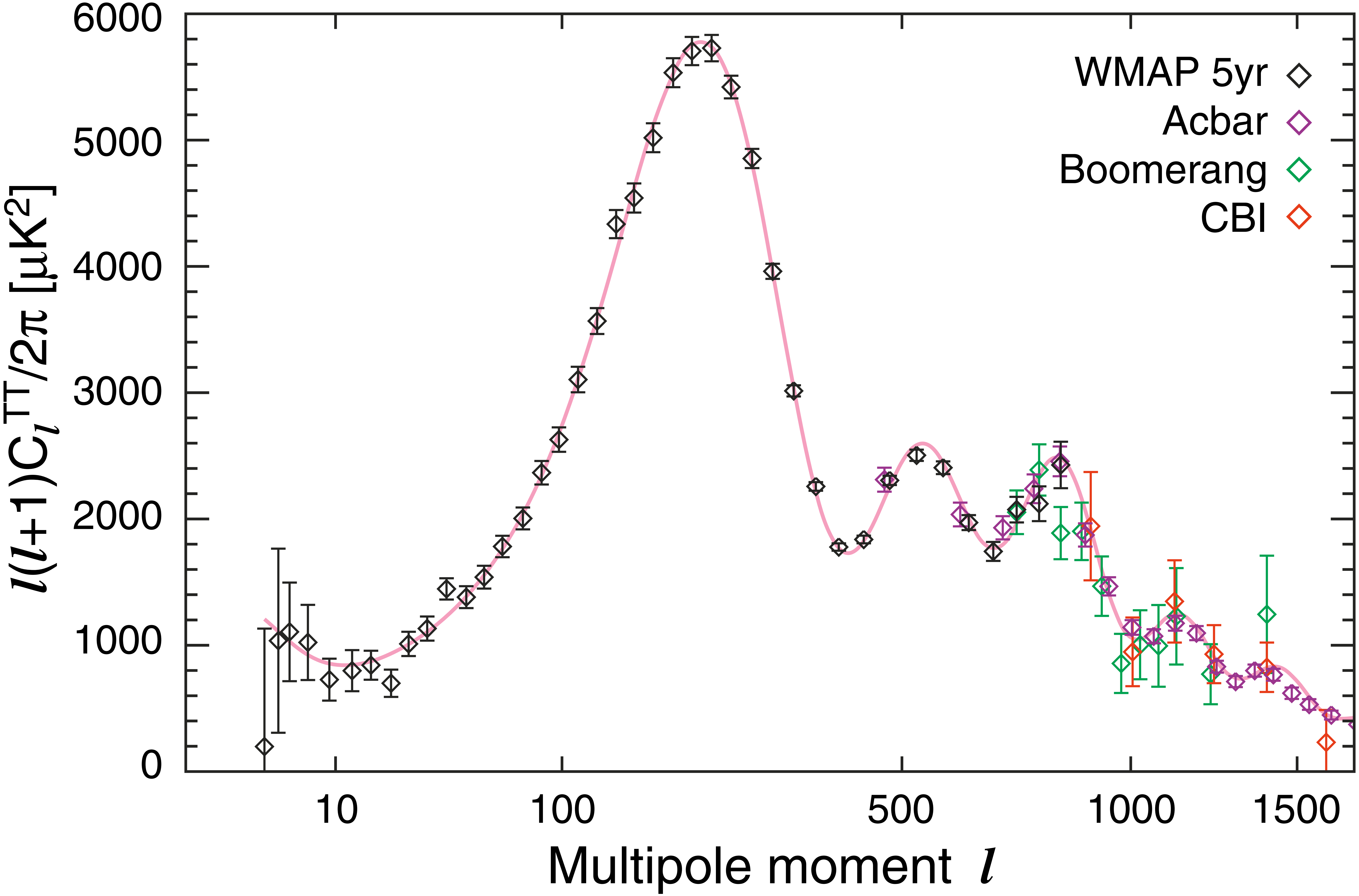


13.7 BILLION YEARS AGO

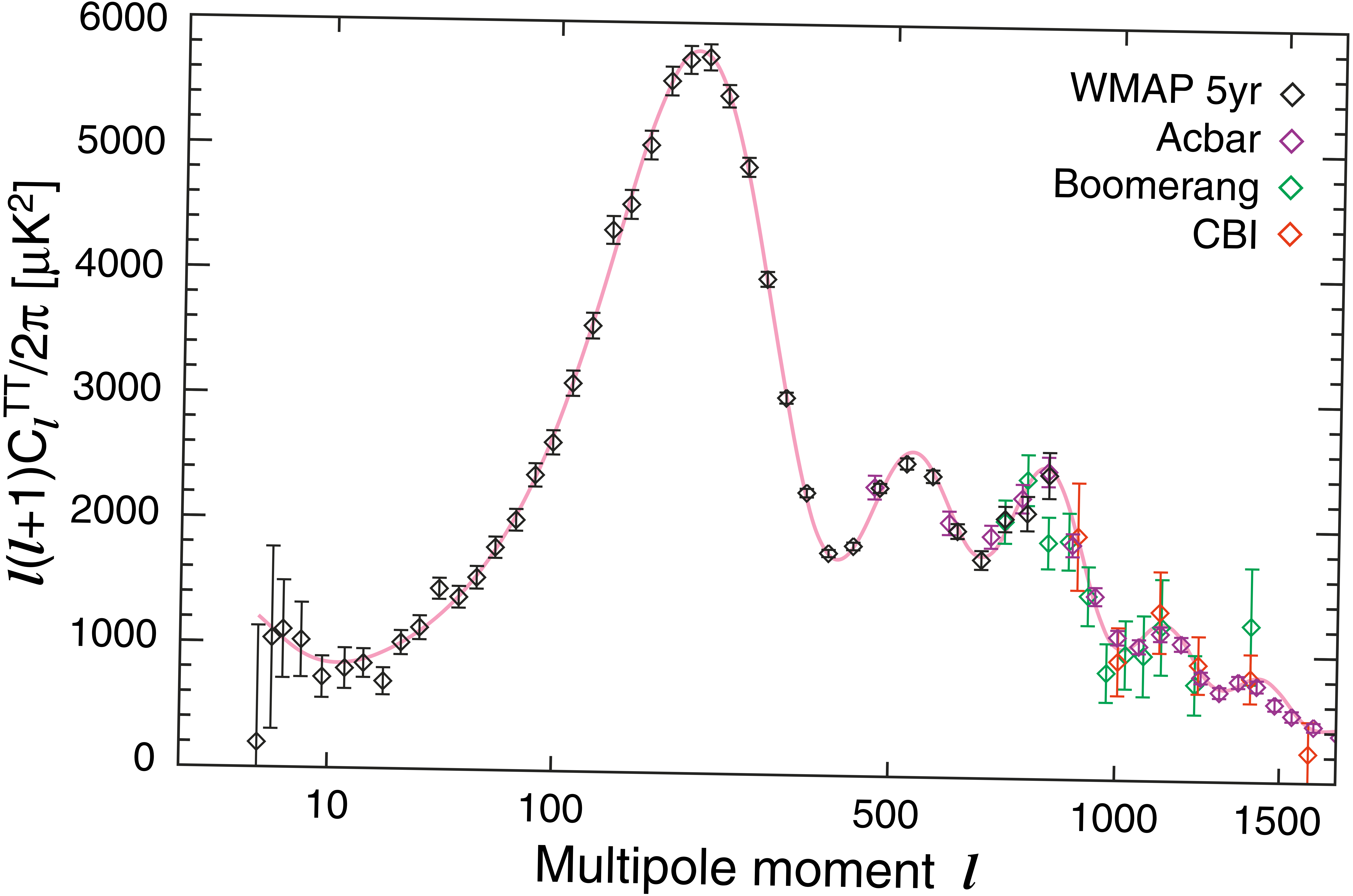
(Universe 380,000 years old)

- Universe today
  - Age: **13.72 +/- 0.12** Gyr
  - Atoms: **4.56 +/- 0.15 %**
  - Dark Matter: **22.8 +/- 1.3%**
  - Vacuum Energy: **72.6 +/- 1.5%**
- When CMB was released 13.7 B yrs ago
  - A significant contribution from the *cosmic neutrino background*

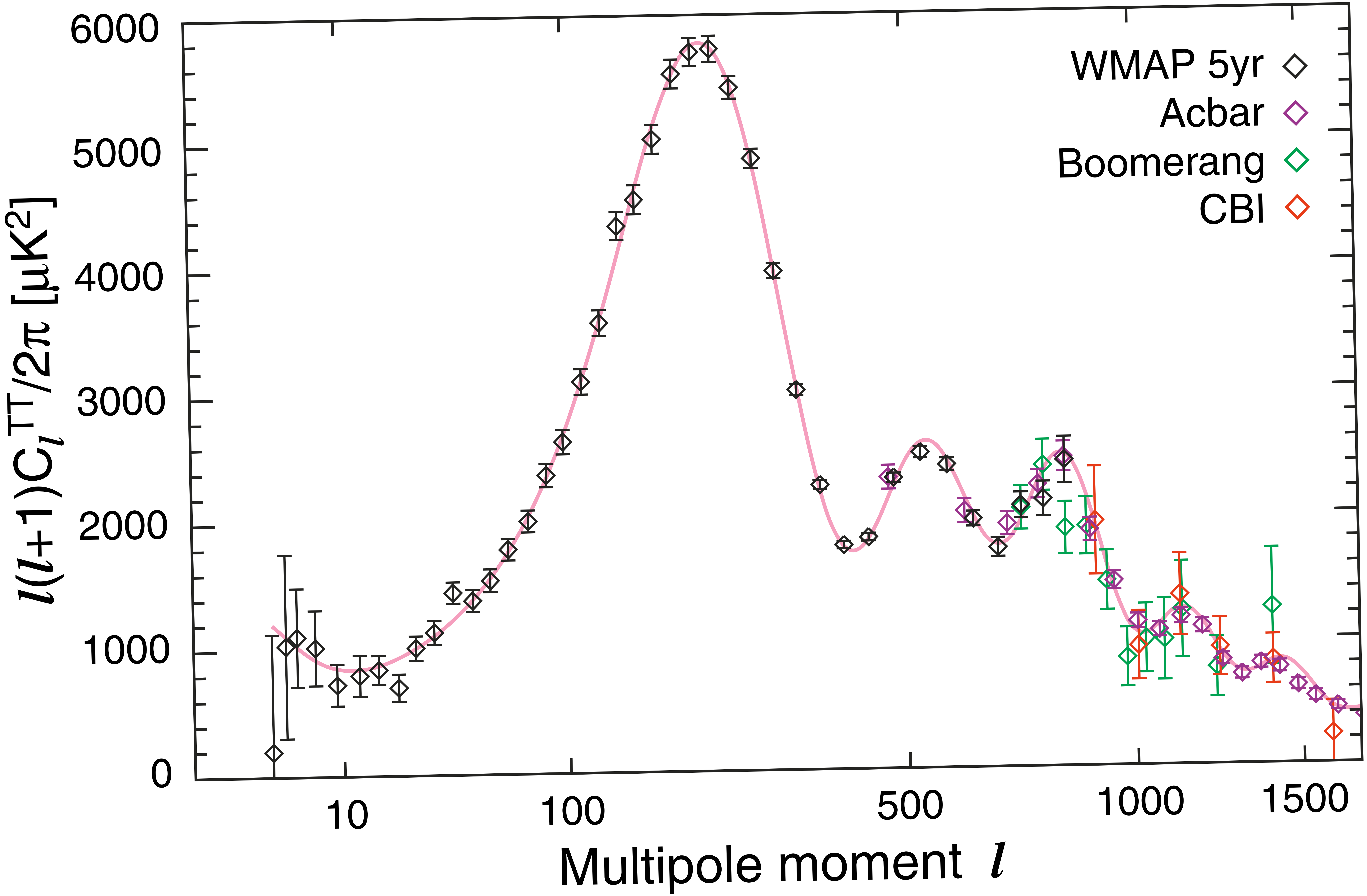
Tilting=Primordial Shape->Inflation



“Red” Spectrum: $n_s < 1$



“Blue” Spectrum: $n_s > 1$

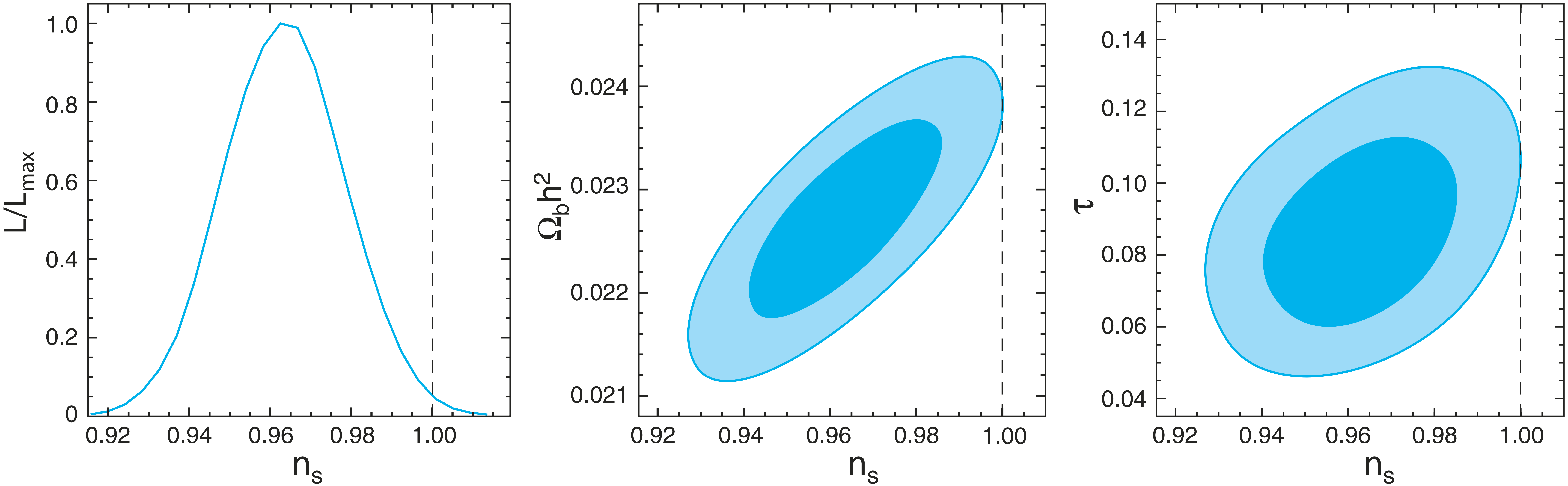


Expectations From 1970's: $n_s=1$

- Metric perturbations in g_{ij} (let's call that "curvature perturbations" Φ) is related to δ via
  - $k^2\Phi(k)=4\pi G\rho a^2\delta(k)$
- Variance of $\Phi(x)$ in position space is given by
  - $\langle\Phi^2(x)\rangle=\int \ln k\; \boldsymbol{k^3|\Phi(k)|^2}$
  - In order to avoid the situation in which curvature (geometry) diverges on small or large scales, a "scale-invariant spectrum" was proposed: $\boldsymbol{k^3|\Phi(k)|^2 = \mathrm{const.}}$
  - This leads to the expectation: $\boldsymbol{P(k)}=|\delta(k)|^2\boldsymbol{=k}$ **(n_s=1)**
    - *Harrison 1970; Zel'dovich 1972; Peebles&Yu 1970*

Is n_s different from ONE?

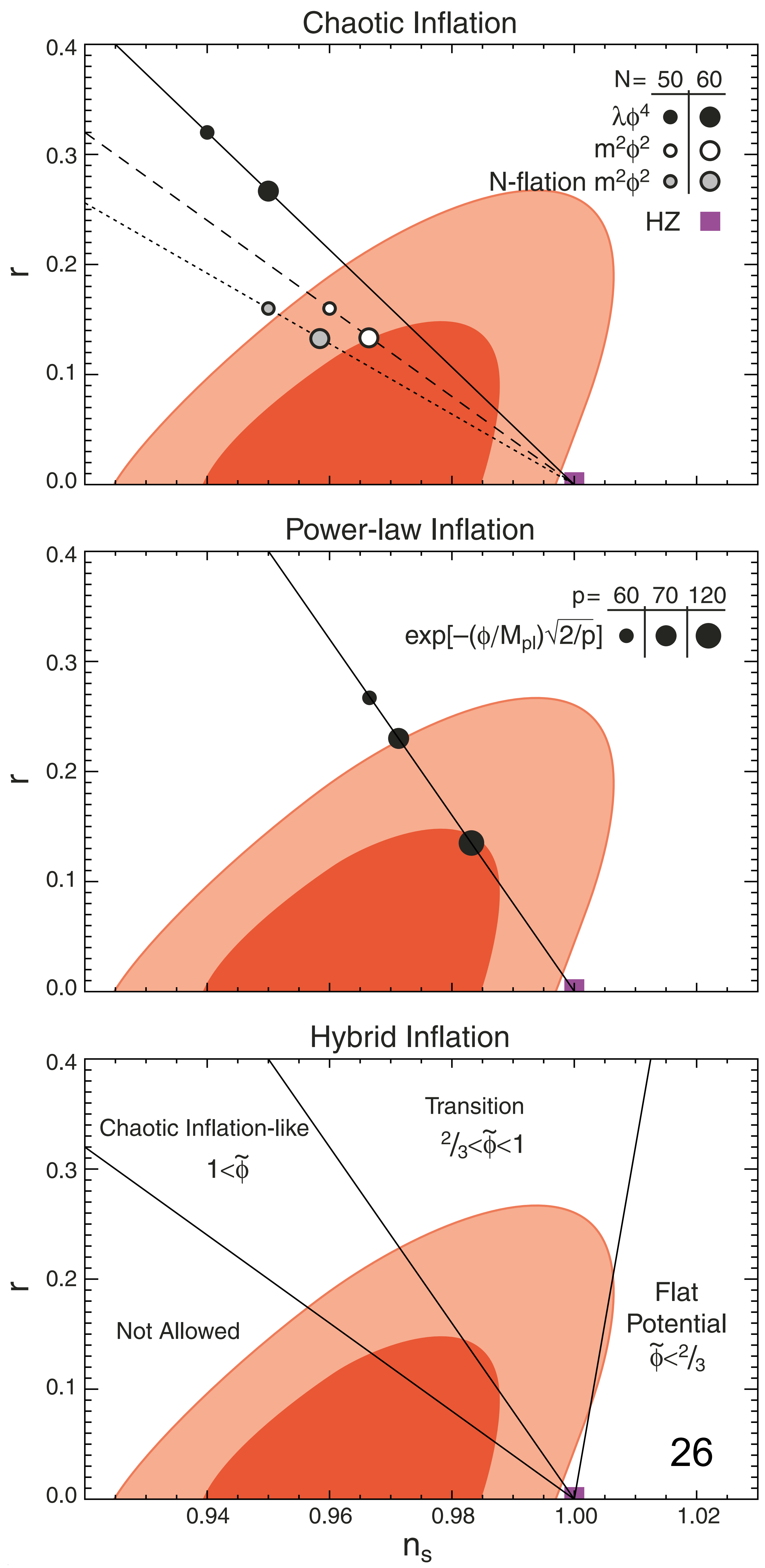
Komatsu et al.



- WMAP-alone: **n_s=0.963** (+0.014) (-0.015) (Dunkley et al.)
  - 2.5-sigma away from n_s=1, "scale invariant spectrum"
- n_s is degenerate with $\Omega_b h^2$; thus, we can't really improve upon n_s further unless we improve upon $\Omega_b h^2$

Deviation from n_s=1

- This was expected by many inflationary models
- In n_s–r plane (where r is called the "tensor-to-scalar ratio," which is P(k) of gravitational waves divided by P(k) of density fluctuations) **many inflationary models are compatible with the current data**
- Many models have been excluded also



Searching for Primordial Gravitational Waves in CMB

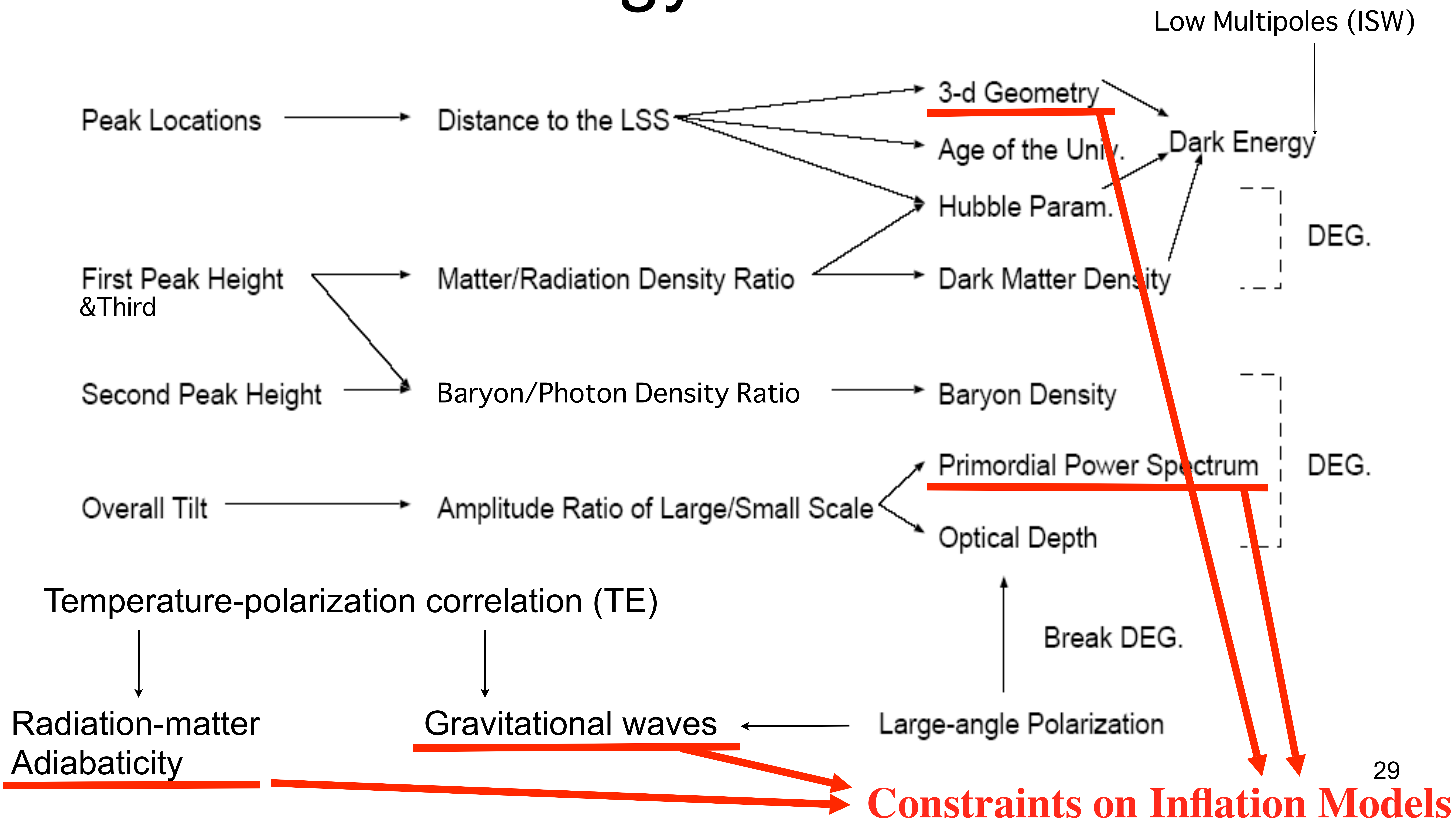
- Not only do inflation models produce density fluctuations, but also primordial gravitational waves
- Some predict the observable amount (r>0.01), some don't
  - Current limit: **r<0.22** (95%CL) (*WMAP5+BAO+SN*)
- Alternative scenarios (e.g., New Ekpyrotic) don't
- A powerful probe for testing inflation and testing specific models: next "Holy Grail" for CMBist

Testing Cosmic Inflation

~5 Tests~

- Is the observable universe flat?
- Are the primordial fluctuations adiabatic?
- Are the primordial fluctuations nearly Gaussian?
- Is the power spectrum nearly scale invariant?
- Is the amplitude of gravitational waves reasonable?

CMB to Cosmology to Inflation



Low Multipoles (ISW)

Peak Locations → Distance to the LSS → 3-d Geometry, Age of the Univ., Hubble Param.

3-d Geometry, Age of the Univ., Dark Matter Density, Low Multipoles (ISW) → Dark Energy

First Peak Height &Third → Matter/Radiation Density Ratio → Hubble Param., Dark Matter Density

First Peak Height &Third, Second Peak Height → Baryon/Photon Density Ratio → Baryon Density

Overall Tilt → Amplitude Ratio of Large/Small Scale → Primordial Power Spectrum, Optical Depth

Hubble Param., Dark Matter Density: DEG.

Baryon Density, Primordial Power Spectrum, Optical Depth: DEG.

Large-angle Polarization → Optical Depth: Break DEG.

Large-angle Polarization → Gravitational waves

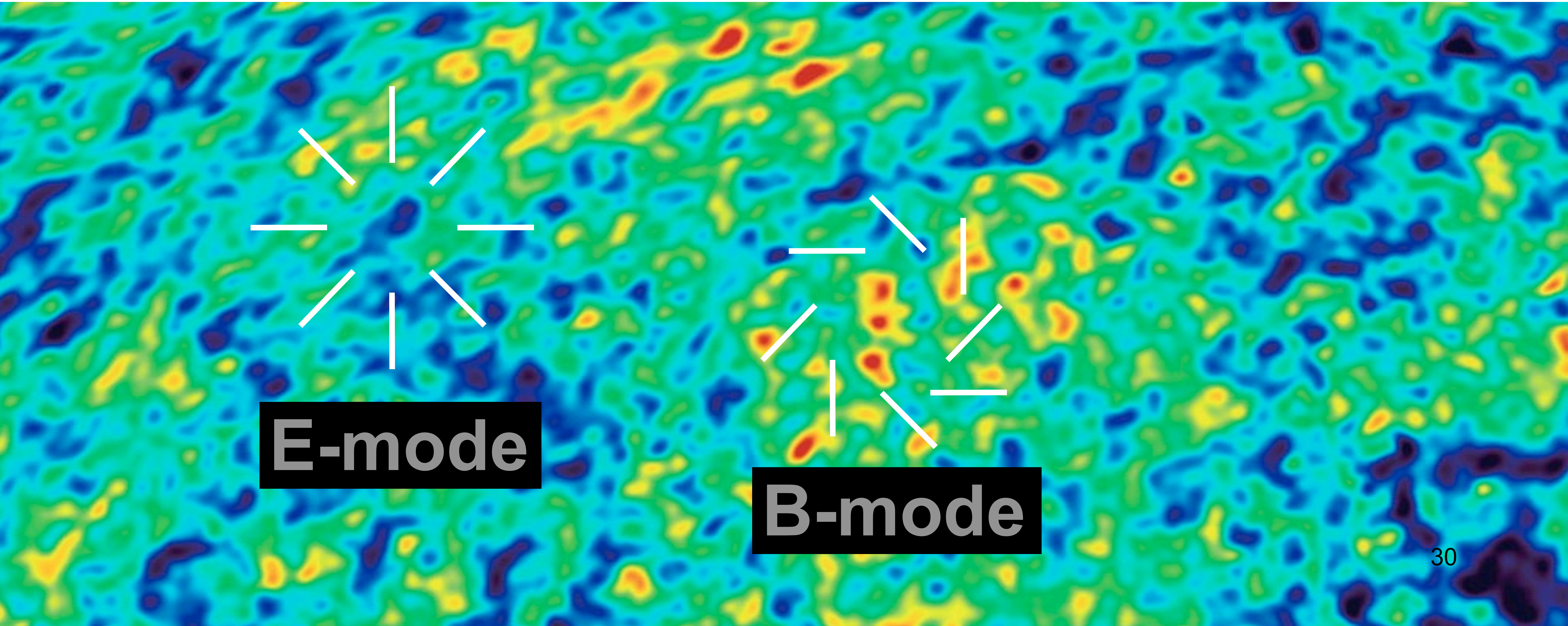
Temperature-polarization correlation (TE) → Radiation-matter Adiabaticity, Gravitational waves

3-d Geometry, Primordial Power Spectrum, Gravitational waves, Radiation-matter Adiabaticity → Constraints on Inflation Models

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky, Stebbins (1997)

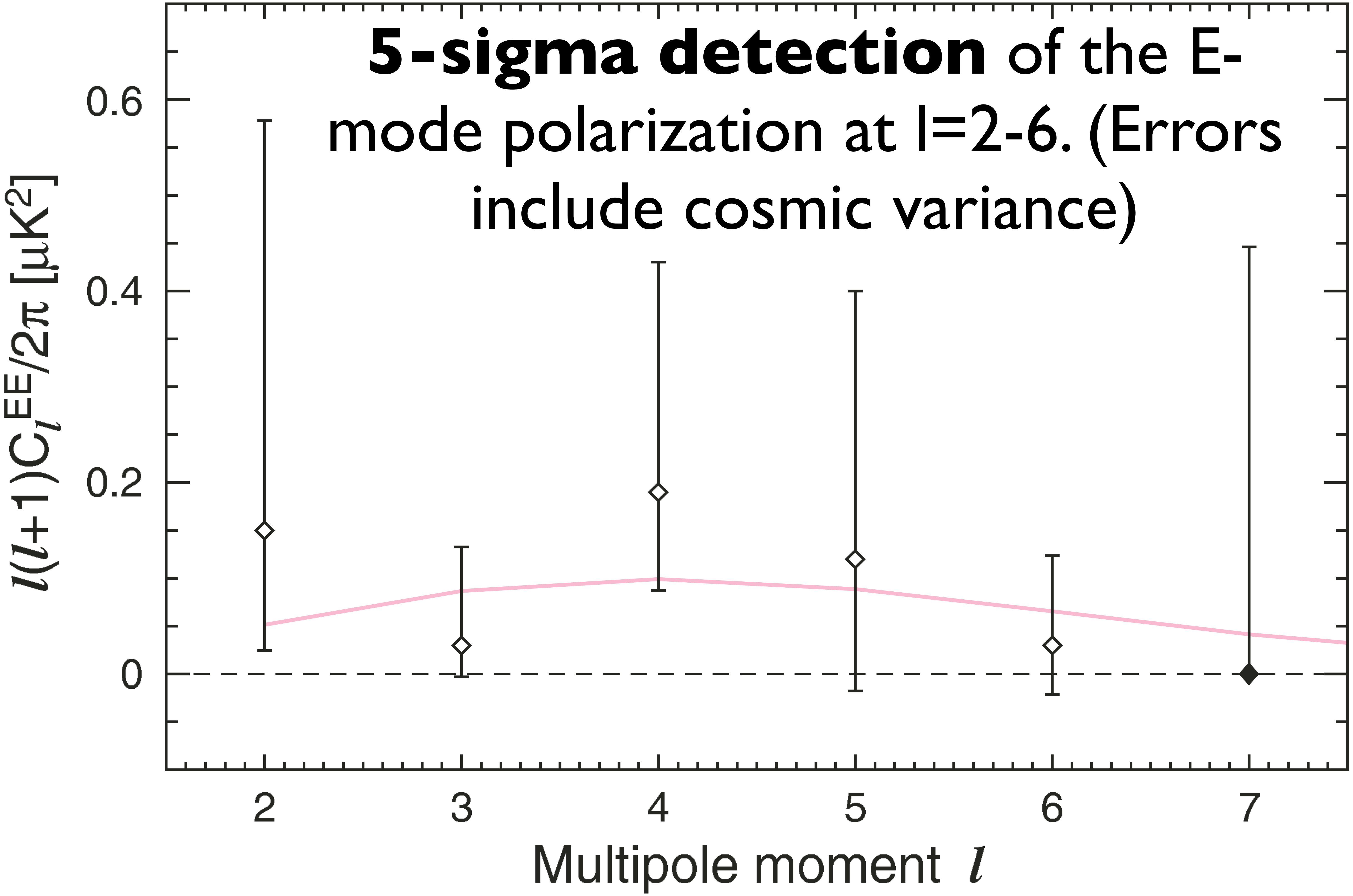
What About Polarization?

- Polarization is a rank-2 tensor field.
- One can decompose it into a divergence-like “E-mode” and a vorticity-like “B-mode”.



Nolta et al.

5-Year E-Mode Polarization Power Spectrum at Low l



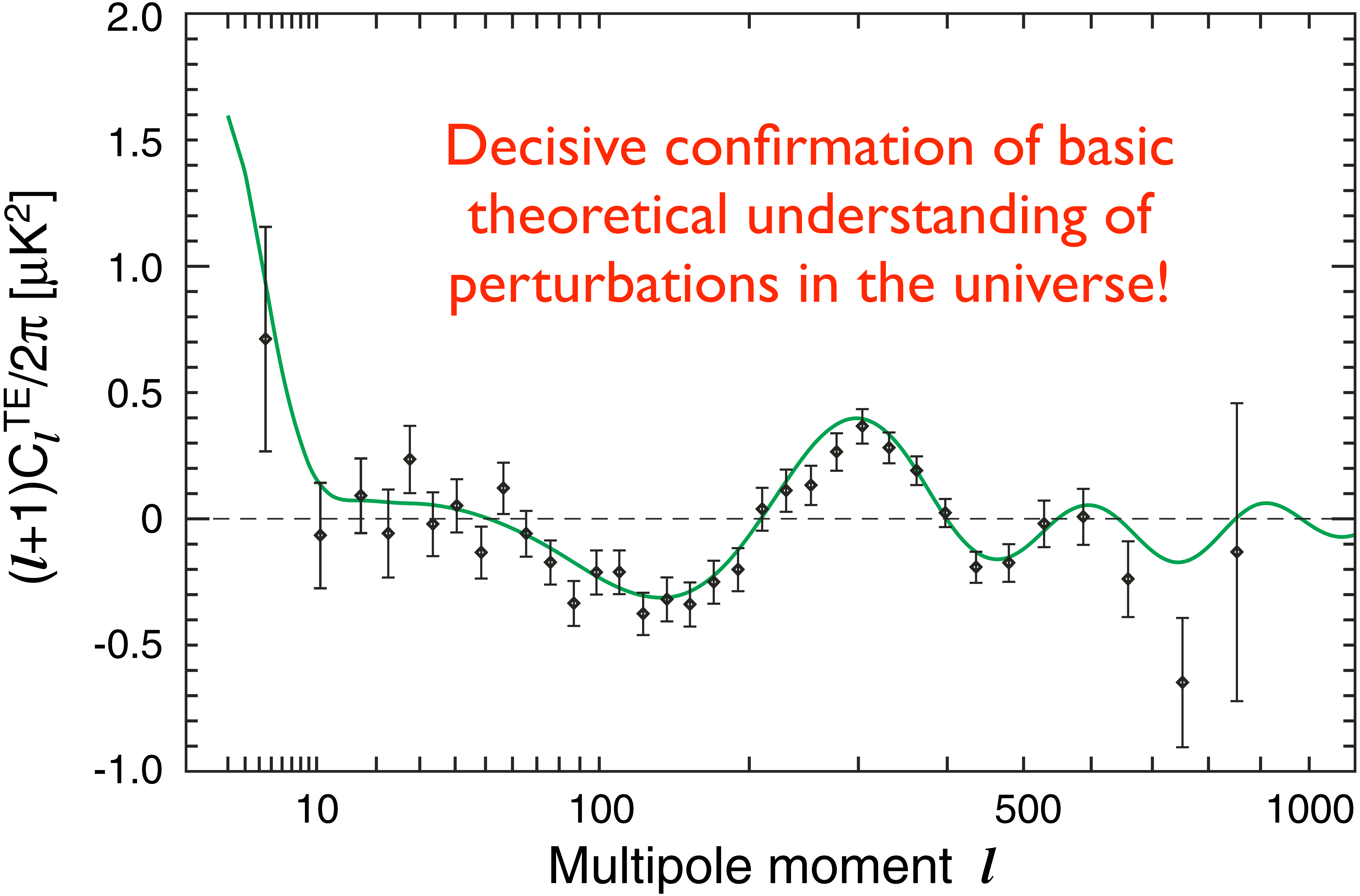
E-Mode Angular Power Spectrum

5-sigma detection of the E-mode polarization at l=2-6. (Errors include cosmic variance)

Black Symbols are upper limits

Nolta et al.

5-Year TxE Power Spectrum



Decisive confirmation of basic theoretical understanding of perturbations in the universe!

B-modes

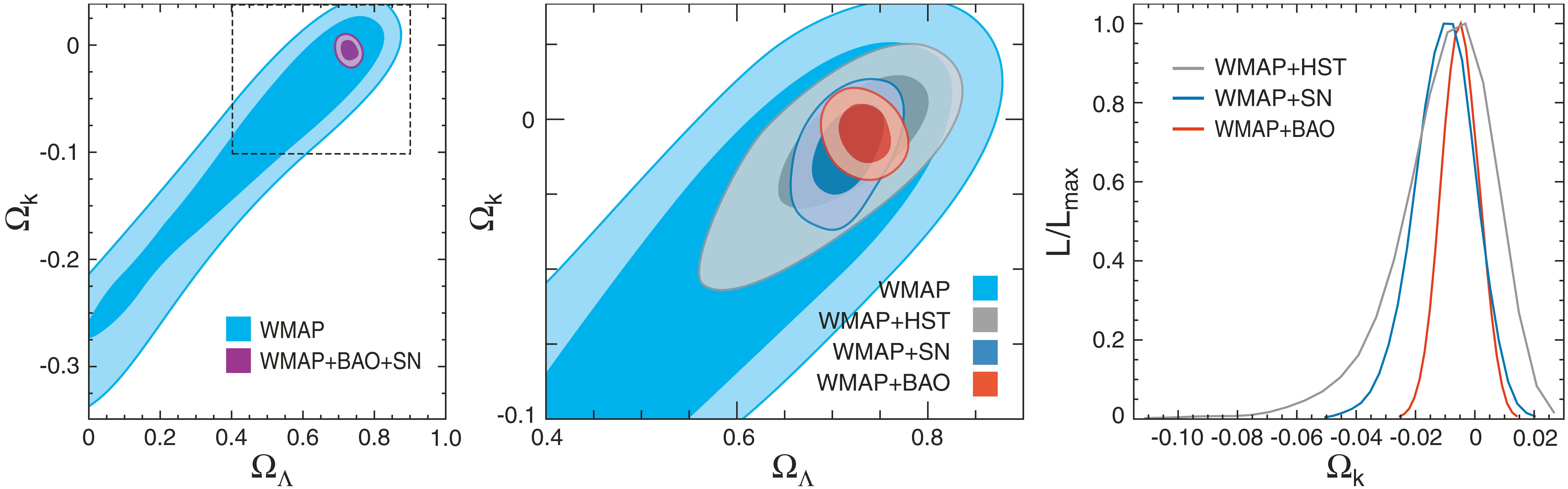
- No detection of B-mode polarization yet.
- I will come back to this later.

How Do We Test Inflation?

- The WMAP data alone can put tight limits on most of the items in the check list. (For the WMAP-only limits, see Dunkley et al.)
- However, we can improve the limits on many of these items by adding the extra information from the **cosmological distance measurements**:
  - *Luminosity Distances* from Type Ia Supernovae (SN)
  - *Angular Diameter Distances* from the Baryon Acoustic Oscillations (BAO) in the distribution of galaxies

Example: Flatness

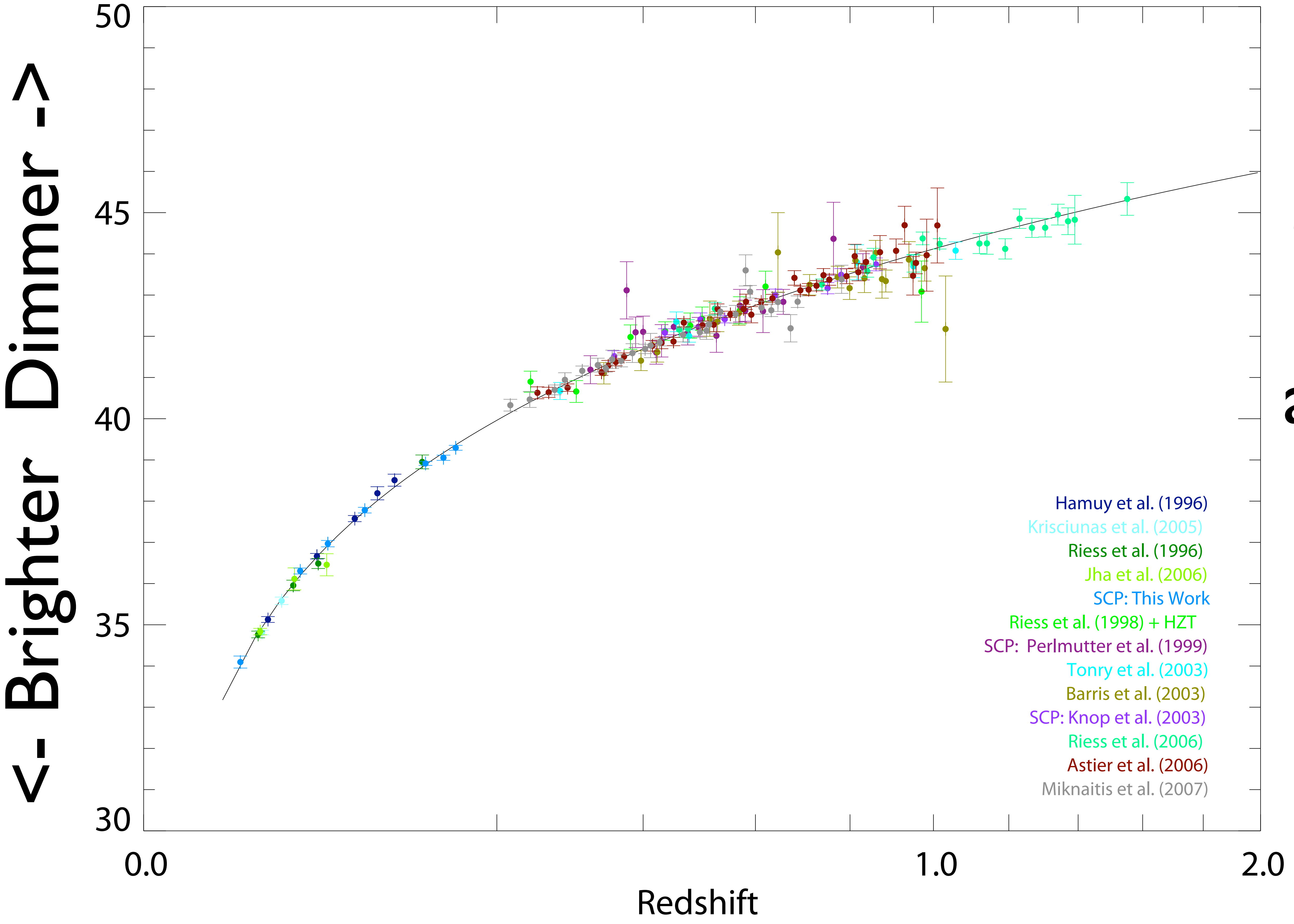
Komatsu et al.



- WMAP measures the angular diameter distance to the decoupling epoch at z=1090.
- The distance depends on curvature AND other things, like the energy content; thus, we need more than one distance indicators, in order to constrain, e.g., Ω_m and H_0

Kowalski et al.

Type Ia Supernova (SN) Data



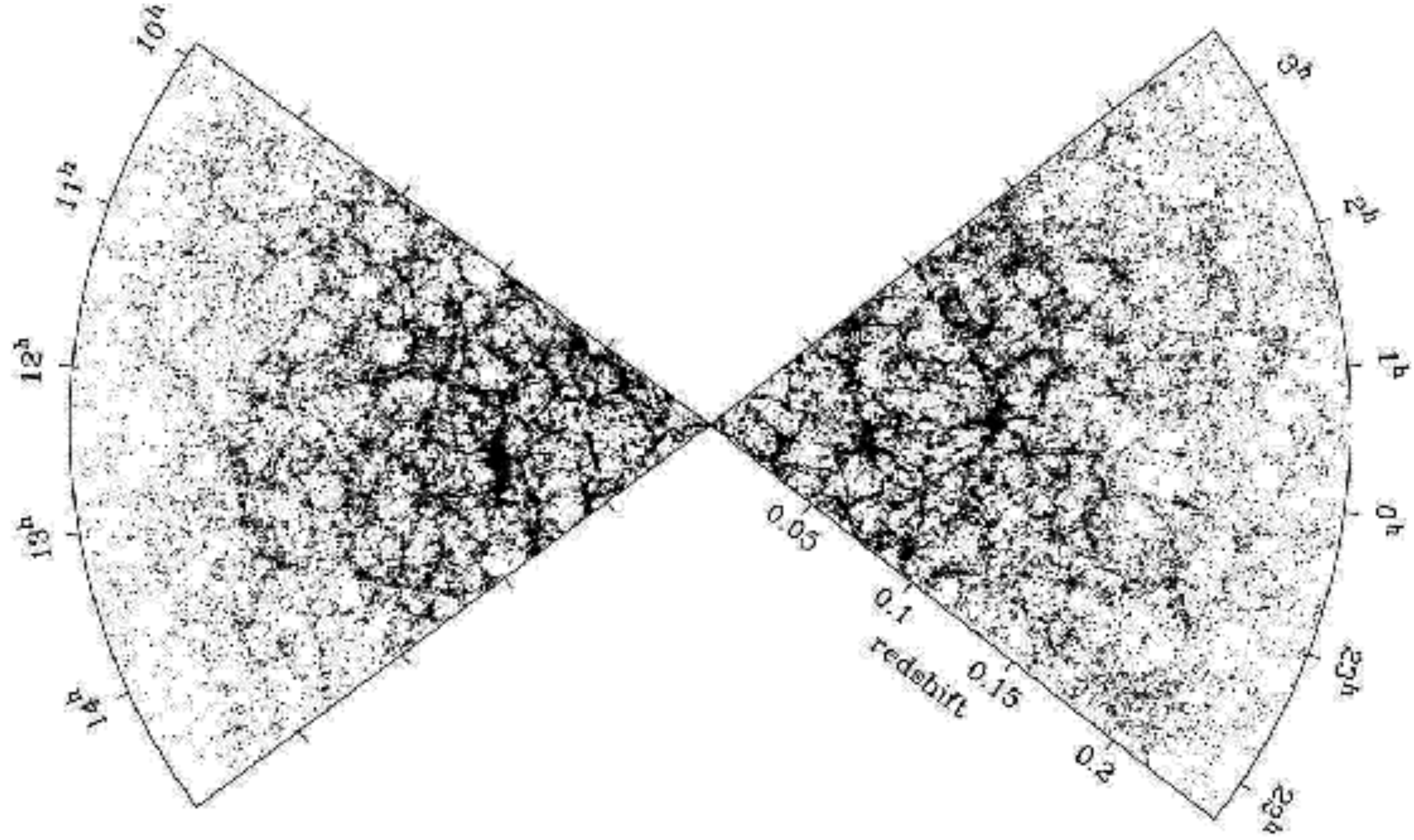
Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)

From these measurements, we get the **relative** luminosity distances between Type Ia SNe. Since we marginalize over the absolute magnitude, the current SN data are **<u>not</u>** sensitive to the absolute distances.

- Latest "Union" supernova compilation (Kowalski et al.)

BAO in Galaxy Distribution

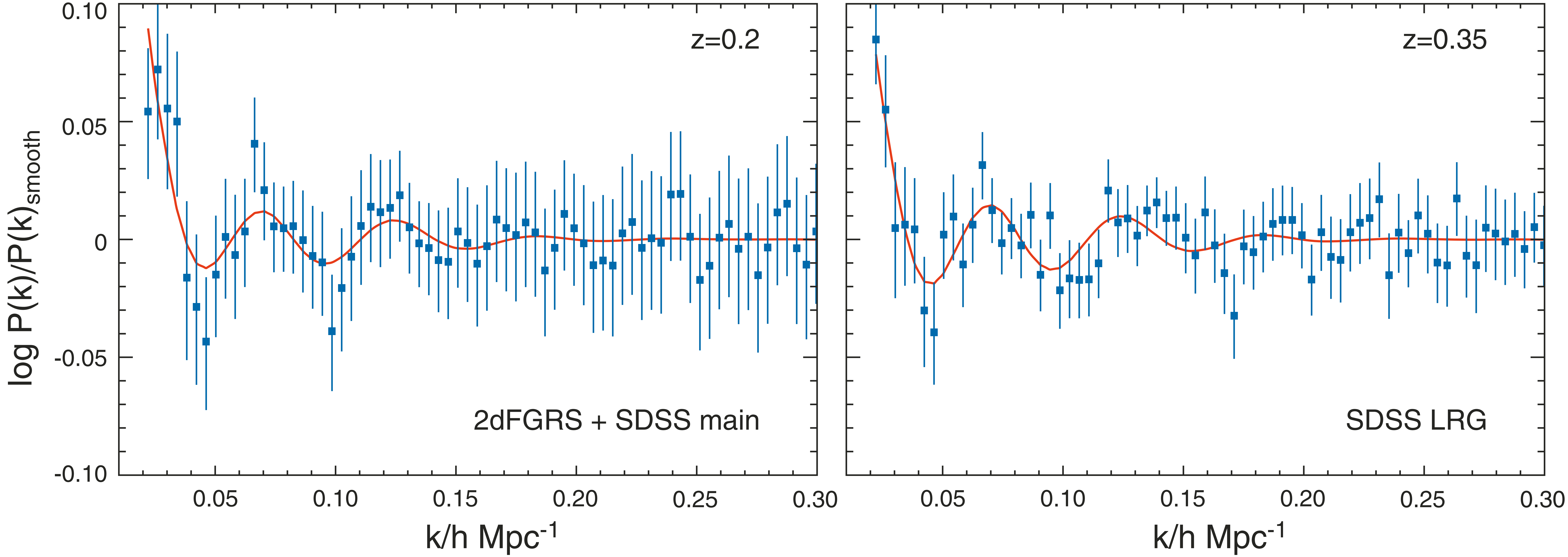
2dFGRS



- The same acoustic oscillations should be hidden in this galaxy distribution...

BAO in Galaxy Distribution

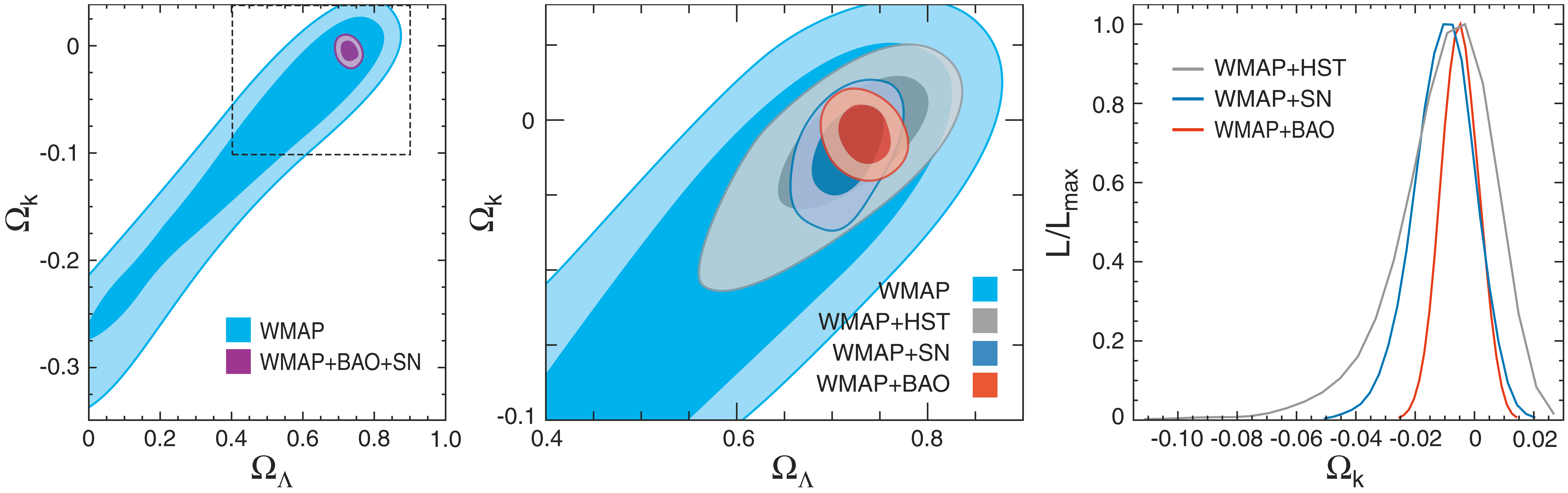
Dunkley et al.



- BAO measured from SDSS (main samples and LRGs) and 2dFGRS (Percival et al. 2007)
- Just like the acoustic oscillations in CMB, the galaxy BAOs can be used to measure the **absolute** distances

Komatsu et al.

As a result..



- **$-0.0181 < \Omega_k < 0.0071$** (95% CL) for w=-1 (i.e., dark energy being a cosmological constant)
- The constraint driven mostly by WMAP+BAO

Komatsu et al.

How Big Is Our Universe?

- By definition, the curvature radius of the universe is given by
  - R_{curv} = 3h^{-1}Gpc / sqrt(Ω_k)
  - For negatively curved space (Ω_k>0): R>33h^{-1}Gpc
  - For positively curved space (Ω_k<0): R>22h^{-1}Gpc
- The particle horizon today is 9.7h^{-1}Gpc
  - The curvature radius of the universe is at least 3 times as large as the observable universe.

Komatsu et al.

How Long Did Inflation Last?

- The universe had expanded by $\mathbf{e^{N_{tot}}}$ during inflation.
  - Q. How long should inflation have lasted to explain the observed flatness of the universe?
  - A. $\mathbf{N_{total} > 36}$ + $\ln(T_{\rm reheating}/1\ \mathrm{TeV})$
  - A factor of 10 improvement in Ω_k will raise this lower limit by 1.2.
  - Lower if the reheating temperature was < 1 TeV
- This is the check list #1

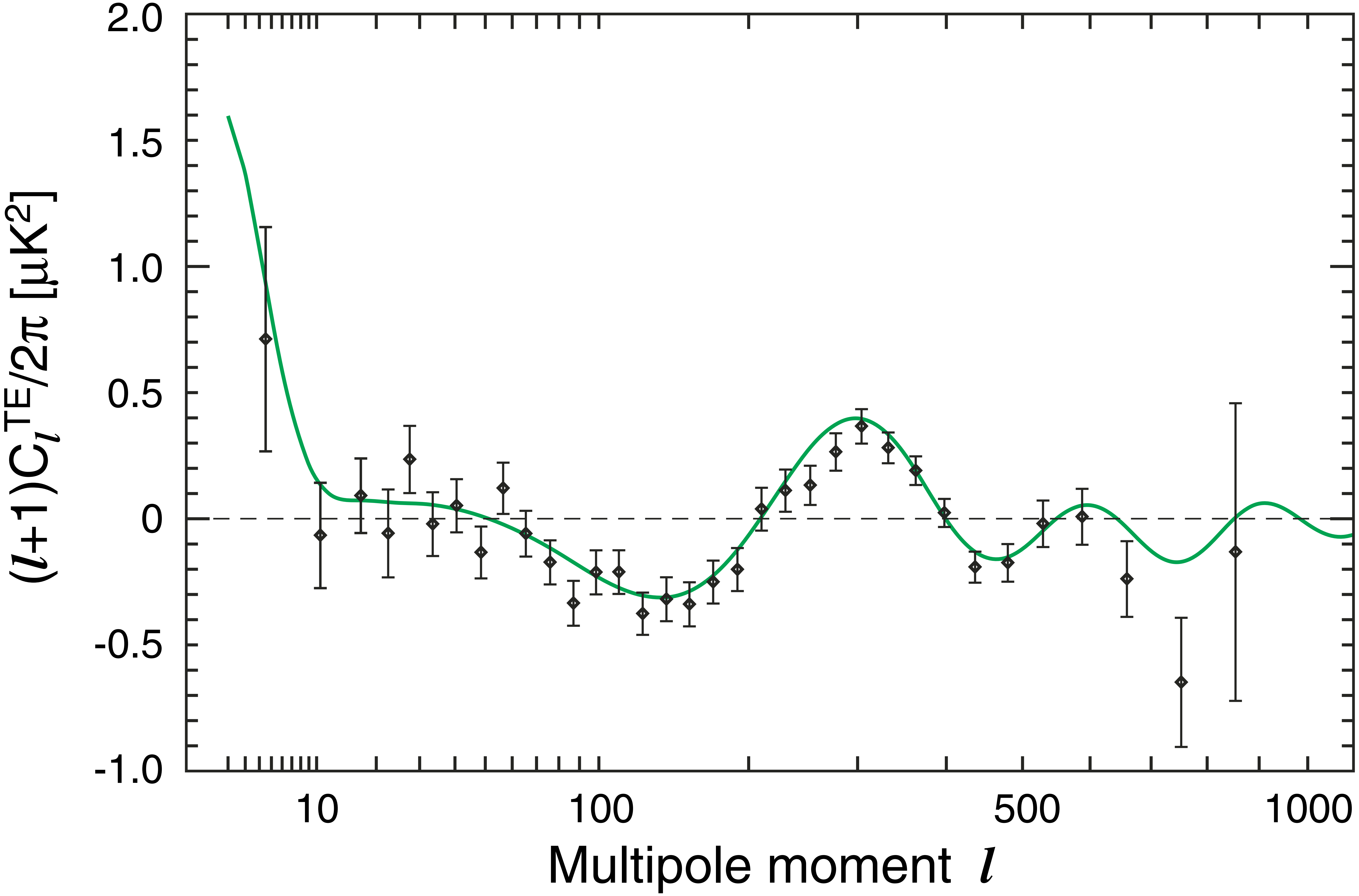
Komatsu et al.

Check List #2: Adiabaticity

- The **adiabatic relation** between radiation and matter:
  - $3\delta\rho_{\mathrm{radiation}}/(4\rho_{\mathrm{radiation}}) = \delta\rho_{\mathrm{matter}}/\rho_{\mathrm{matter}}$
- *Deviation from adiabaticity:* A simple-minded quantification
  - Fractional deviation of A from B = (A**-**B) / [(A**+**B)/2]
    - $\delta_{\mathrm{adi}} = [3\delta\rho_{\mathrm{radiation}}/(4\rho_{\mathrm{radiation}}) - \delta\rho_{\mathrm{matter}}/\rho_{\mathrm{matter}}] / \{[3\delta\rho_{\mathrm{radiation}}/(4\rho_{\mathrm{radiation}}) + \delta\rho_{\mathrm{matter}}/\rho_{\mathrm{matter}}]/2\}$
  - Call this the "***adiabaticity deviation parameter***"
    - "Radiation and matter obey the adiabatic relation to $(100\delta_{\mathrm{adi}})$% level."

Nolta et al.

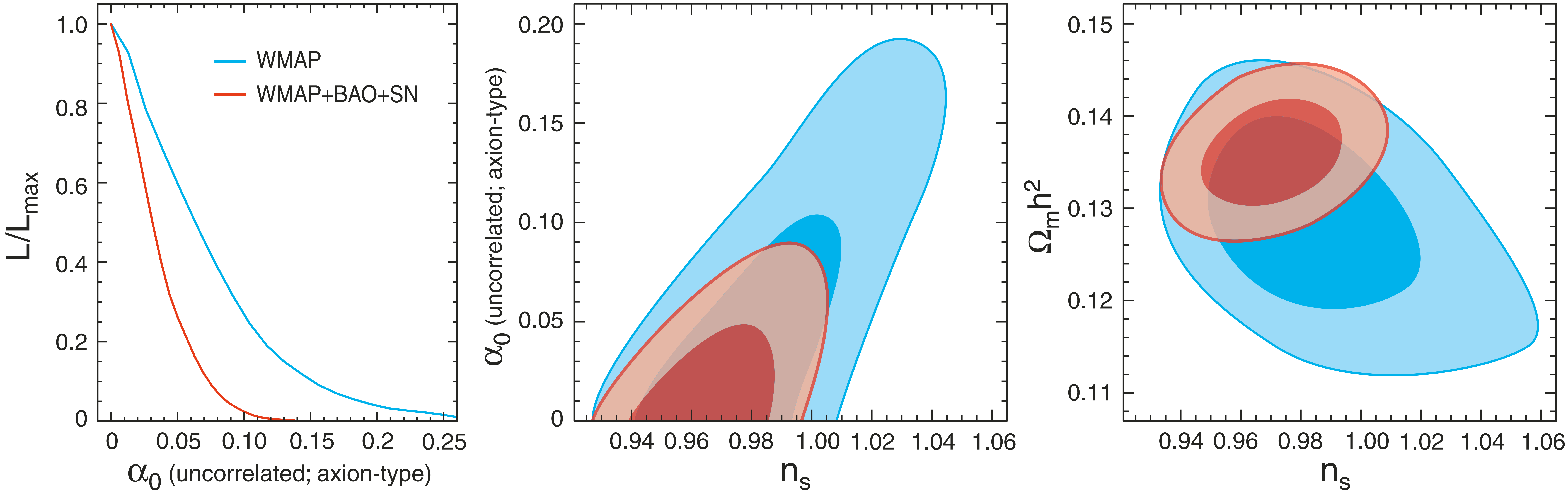
WMAP 5-Year TE Power Spectrum



- The negative TE at l~100 is the distinctive signature of super-horizon adiabatic perturbations (Spergel & Zaldarriaga 1997)
- Non-adiabatic perturbations would fill in the trough, and shift the zeros.

Axion Dark Matter

Komatsu et al.



- $\alpha_{axion} < 0.16$ [WMAP-only; 95% CL]
- $\alpha_{axion} < 0.072$ [WMAP+BAO+SN; 95% CL]
- CMB and axion-type dark matter are adiabatic to **8.9%**

Komatsu et al.

Axion Dark Matter?

- CMB and axion-type dark matter are adiabatic to **8.6%**
  - **This puts a severe limit on axions being the dominant dark matter candidate.**

$$\frac{\Omega_a}{\Omega_c} < \frac{3.0 \times 10^{-39}}{\theta_a^5 \gamma^6} \left(\frac{0.01}{r}\right)^{7/2}$$

The non-adiabatic perturbations, combined with the expression for Ω_a, constrain $\Omega_a^{1/7}$.

Check list #3: Gaussianity

- In the simplest model of inflation, the distribution of primordial fluctuations is close to a Gaussian with random phases.
- The level of non-Gaussianity predicted by the simplest model is well below the current detection limit.
- A convincing detection of primordial non-Gaussianity will rule out most of inflation models in the literature.
  - **Detection of non-Gaussianity would be a breakthrough in cosmology**

Getting the Most Out of Fluctuations, $\delta(x)$

- In Fourier space, $\delta(k) = A(k)\exp(i\varphi_k)$
  - **Power**: $P(k) = \langle|\delta(k)|^2\rangle = A^2(k)$
  - **Phase**: φ_k
- We can use the observed distribution of...
  - matter (e.g., galaxies, gas)
  - radiation (e.g., Cosmic Microwave Background)
- to learn about both $P(k)$ and φ_k.

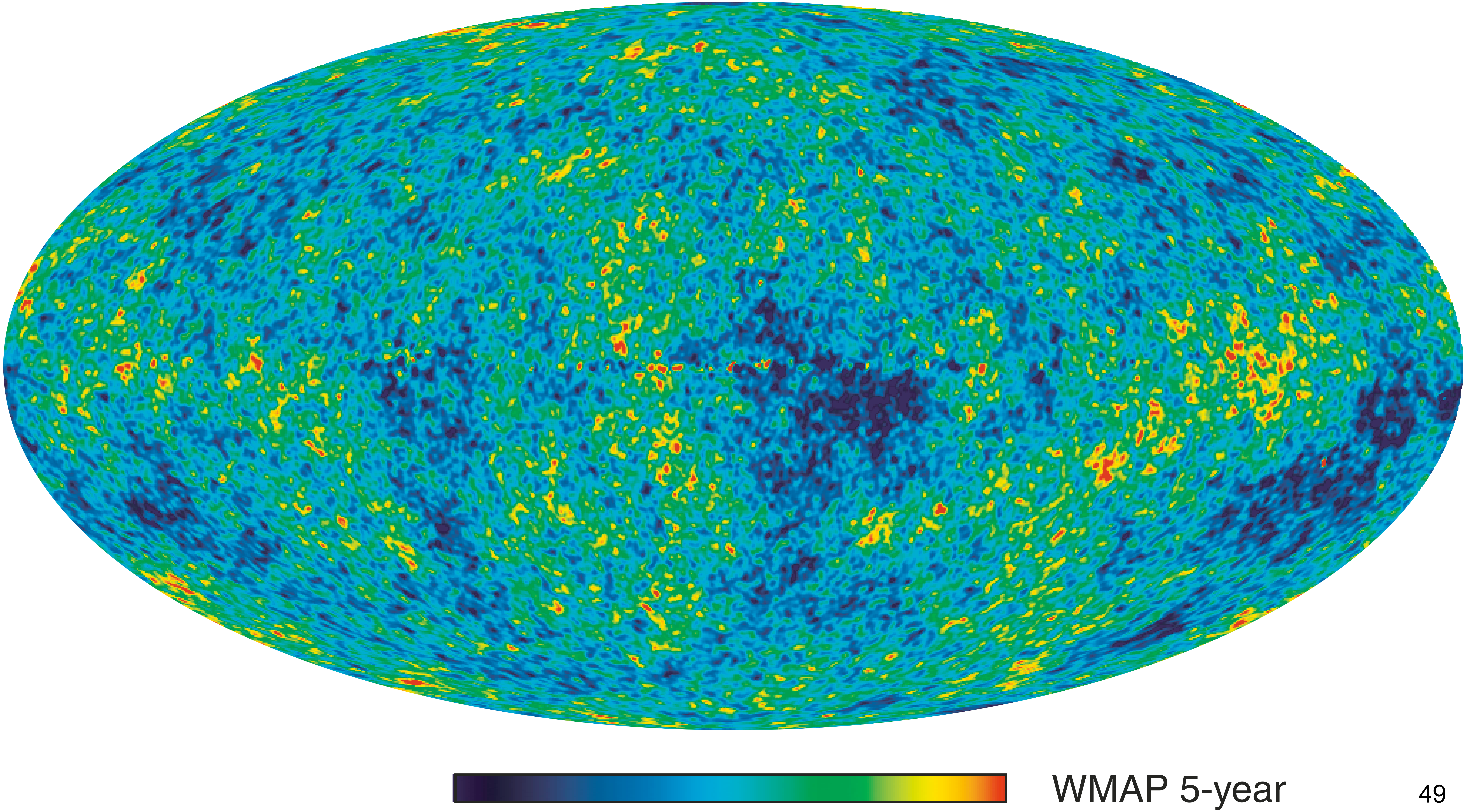
What About Phase, φ_k

- There were expectations also:
  - Random phases! (Peebles, ...)
- Collection of random, uncorrelated phases leads to the most famous probability distribution of δ:

Gaussian Distribution

WMAP5

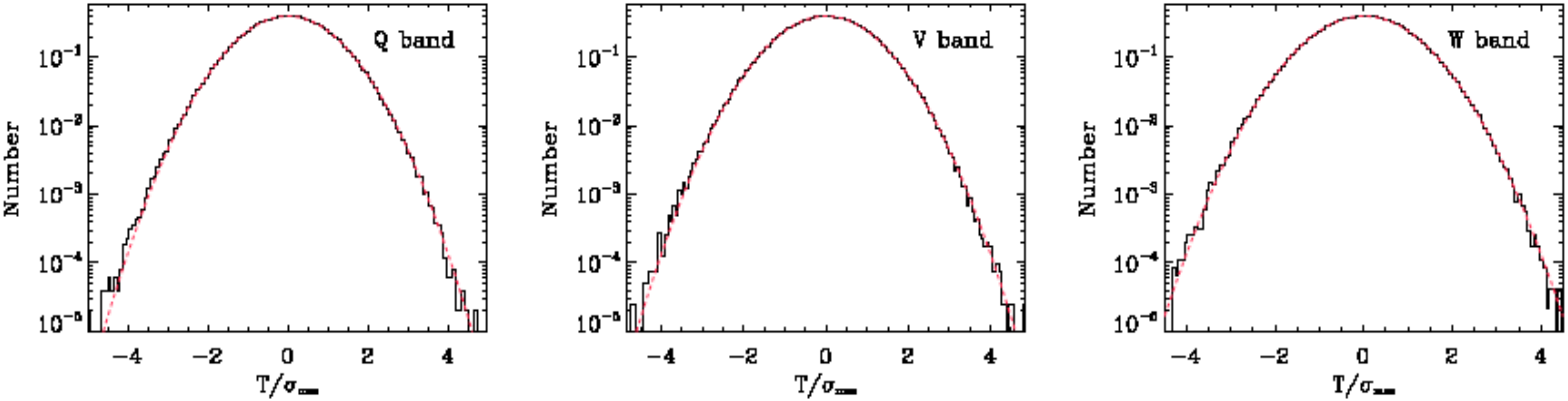
Gaussian?



WMAP 5-year

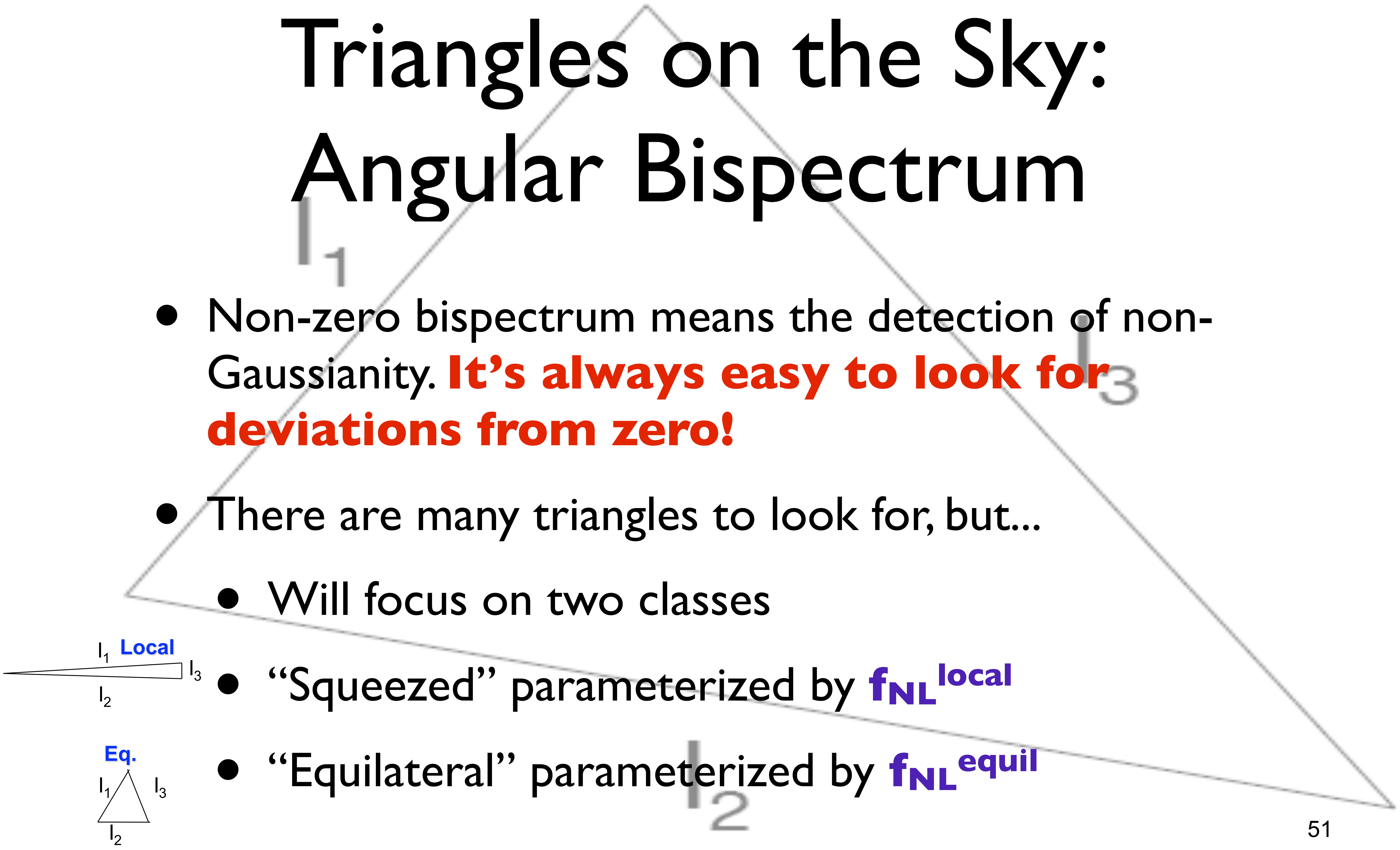
Spergel et al. (2008)

Take One-point Distribution Function



- The one-point distribution of WMAP map looks pretty Gaussian.
  - –Left to right: Q (41GHz), V (61GHz), W (94GHz).
- Deviation from Gaussianity is small, if any.

Triangles on the Sky: Angular Bispectrum



- Non-zero bispectrum means the detection of non-Gaussianity. **It's always easy to look for deviations from zero!**
- There are many triangles to look for, but...
  - Will focus on two classes
  - "Squeezed" parameterized by $\mathbf{f_{NL}^{local}}$
  - "Equilateral" parameterized by $\mathbf{f_{NL}^{equil}}$

Komatsu et al.

No Detection at >95%CL

- $-9 < f_{NL}(\text{local}) < 111$ (95% CL)
- $-151 < f_{NL}(\text{equilateral}) < 253$ (95% CL)

- These numbers mean that the primordial curvature perturbations are Gaussian to **0.1% level**.
  - This result provides the strongest evidence for quantum origin of primordial fluctuations during inflation.

Dunkley et al.; Komatsu et al.

Check List #4: Scale Invariance

- For a power-law power spectrum (no $dn_s/d\ln k$):
  - WMAP-only: $n_s=0.963\ (+0.014)\ (-0.015)$
  - WMAP+BAO+SN: $n_s=0.960 \pm 0.013$
    - **3.1 sigma away from $n_s=1$**

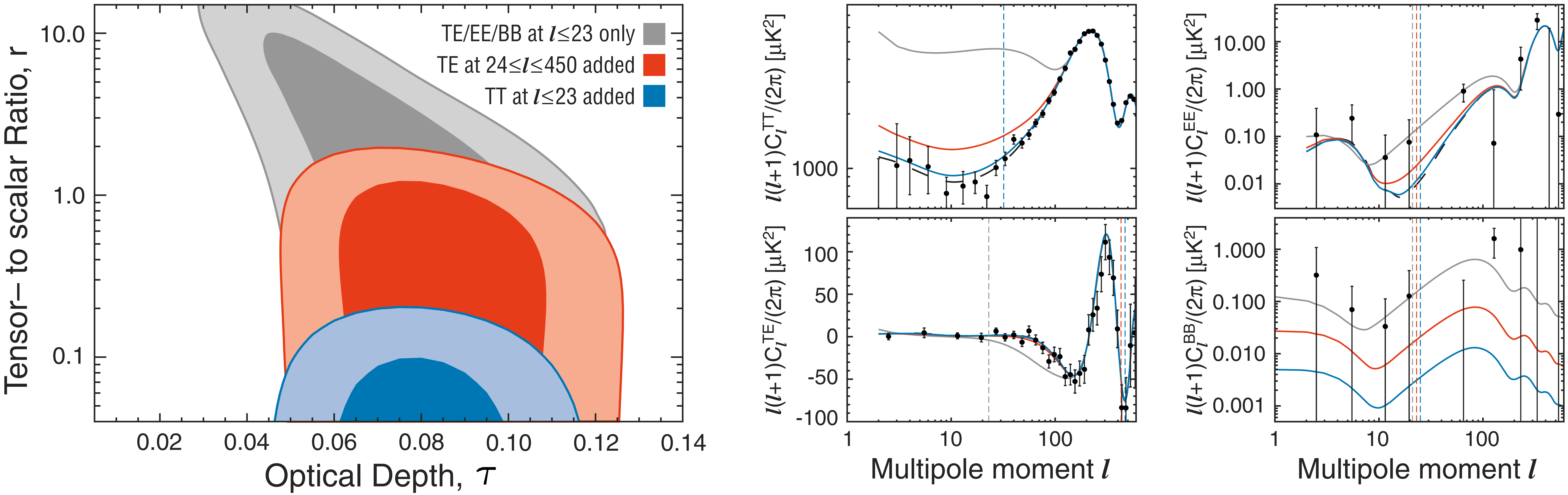
Check List #5: Gravitational Waves

- How do WMAP data constrain the amplitude of primordial gravitational waves?

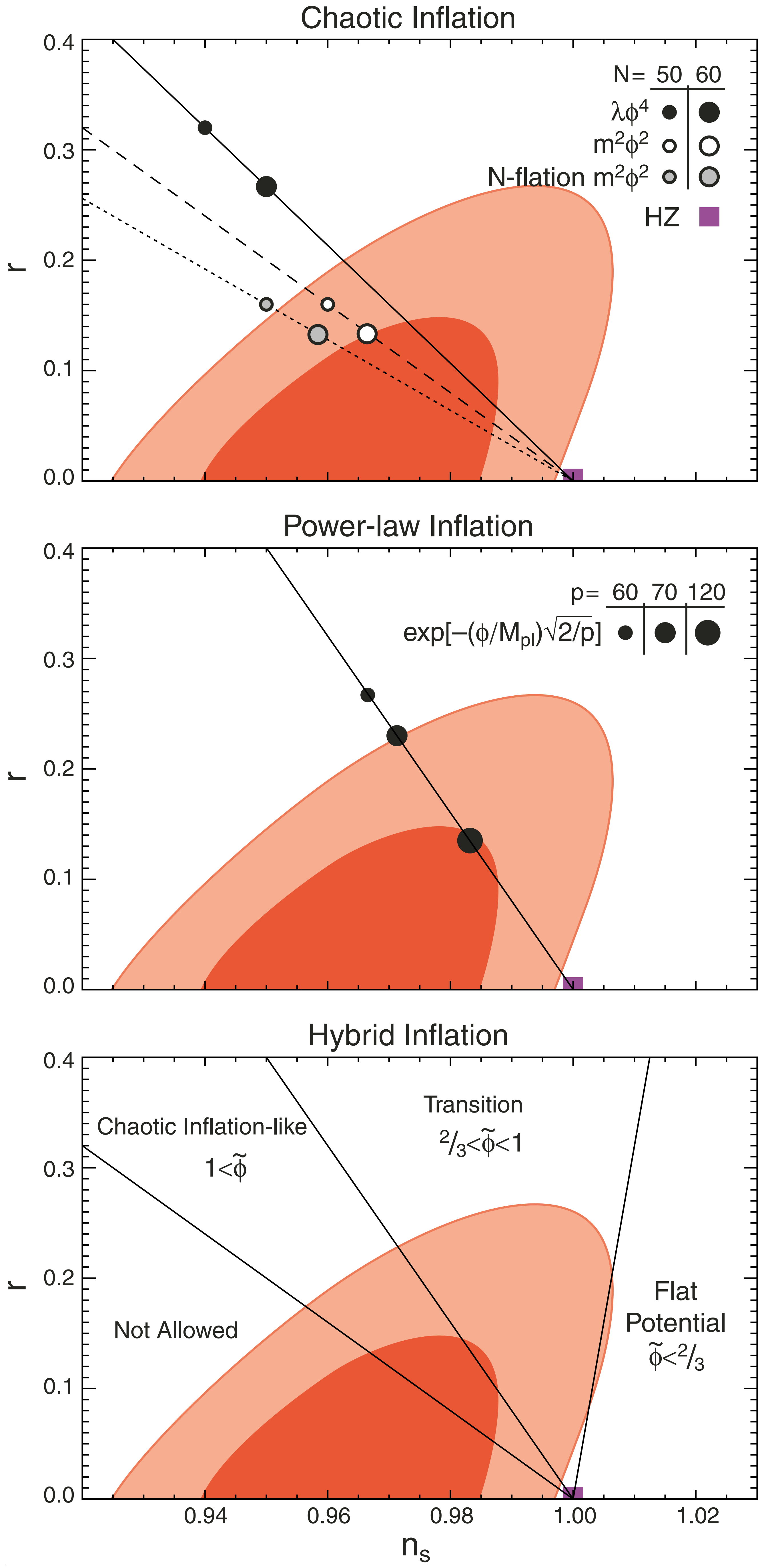
- We use “r” to parameterize the amplitude of GWs relative to the density fluctuations (or the scalar curvature (metric) perturbations)
    - When r=1, we have equal amount of scalar and tensor metric perturbations.

Pedagogical Explanation

Komatsu et al.



- If all the other parameters (n_s in particular) are fixed...
  - Low-l polarization gives r<20 (95% CL)
  - + high-l polarization gives r<2 (95% CL)
  - + low-l temperature gives r<0.2 (95% CL)



Komatsu et al.

Lowering a “Limbo Bar”

- $\lambda\varphi^4$ is totally out. (unless you invoke, e.g., non-minimal coupling, to suppress r...)
- $m^2\varphi^2$ is within 95% CL.
  - Future WMAP data would be able to push it to outside of 95% CL, if $m^2\varphi^2$ is not the right model.
- N-flation $m^2\varphi^2$ (Easther&McAllister) is being pushed out
- PL inflation [$a(t) \sim t^p$] with $p<60$ is out.
- A blue index ($n_s>1$) region of hybrid inflation is disfavored

Komatsu et al.

Grading Inflation

- Flatness: Curvature < 1.3%
- Non-adiabaticity: <8.9%
- Non-Gaussianity: <0.1%
- Tilt (for r=0): $n_s=0.960 \pm 0.013$ [68% CL]
- Gravitational waves: **$r < 0.22$**
  - $n_s=0.970 \pm 0.015$ [68% CL]
  - **$n_s>1$ disfavored at 95% CL regardless of r**

Summary

- A simple inflation model (~25 years old) fits the WMAP data, as well as the other astrophysical data sets.
- **We did everything we could do to find deviations from the simple inflation model (curvature, non-adiabaticity, non-gaussianity), but failed.**
- Significant improvements in limits on the deviations
  - Most notably, $r<0.22$ (95% CL), and $n_s>1$ is now disfavored regardless of r.
  - Good News: Many popular inflation models have been either ruled out, or being in danger!

Looking Ahead...

- With more WMAP observations, exciting discoveries may be waiting for us. Two examples for which we might be seeing some hints from the 5-year data:
  - Non-Gaussianity: If f_{NL}~50, we will see it at the 3 sigma level with 9 years of data.
  - Gravitational waves (r) and tilt (n_s) : $m^2\varphi^2$ can be pushed out of the favorable parameter region
    - $n_s>1$ would be convincingly ruled out regardless of r.
- Beyond WMAP: detection of gravitational waves?