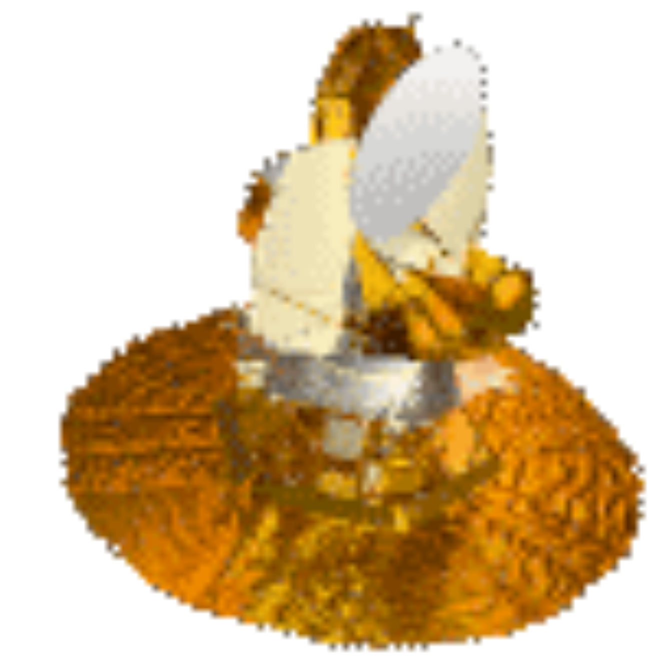


The 5-Year Wilkinson Microwave Anisotropy Probe (*WMAP*) Observations: Cosmological Interpretation

Eiichiro Komatsu (Department of Astronomy, UT Austin)
NUPAC Seminar, Univ. of New Mexico, May 6, 2008

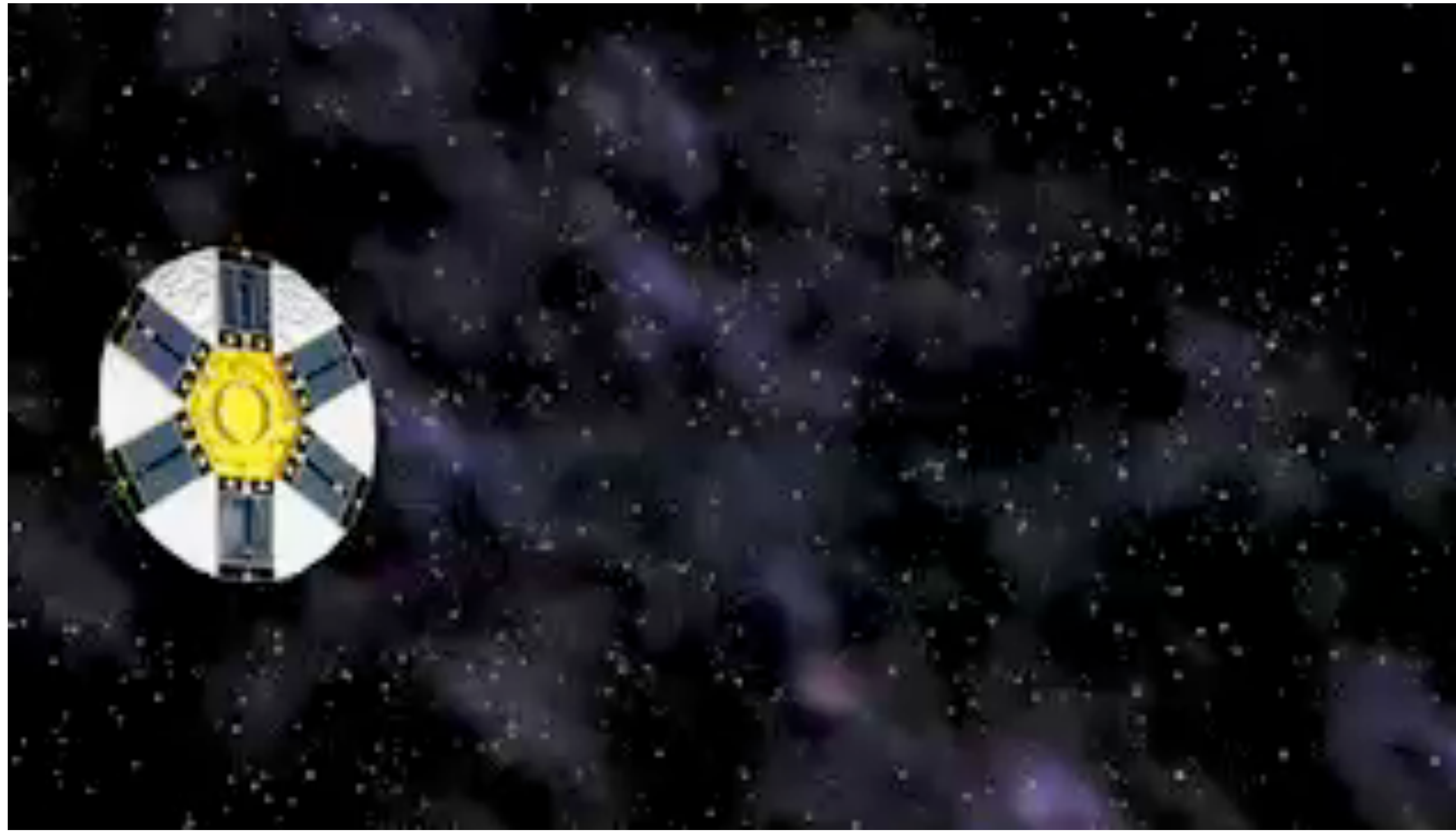
WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

February 2003:
The first-year data release

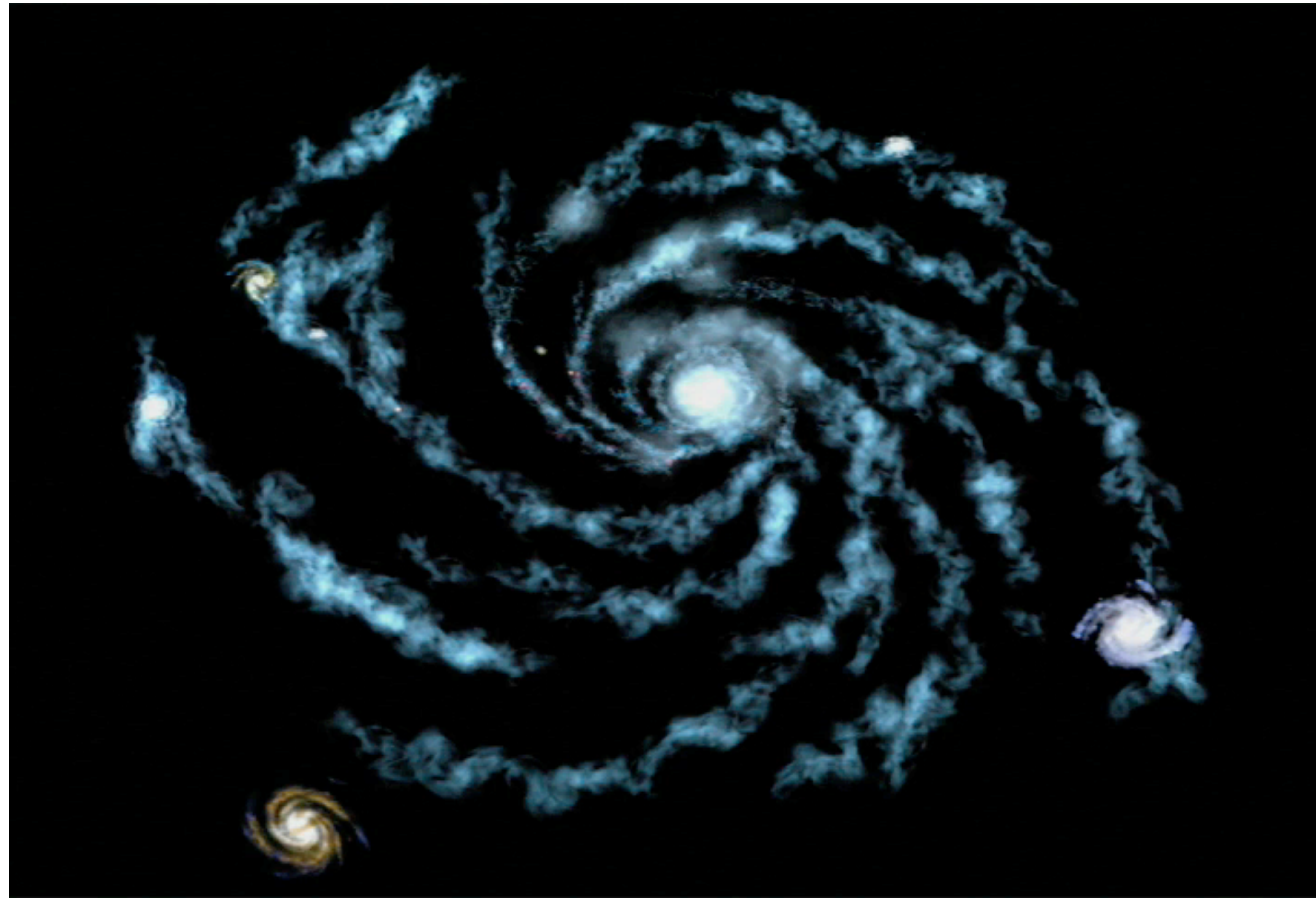
March 2006:
The three-year data release

March 2008:
The five-year data release



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

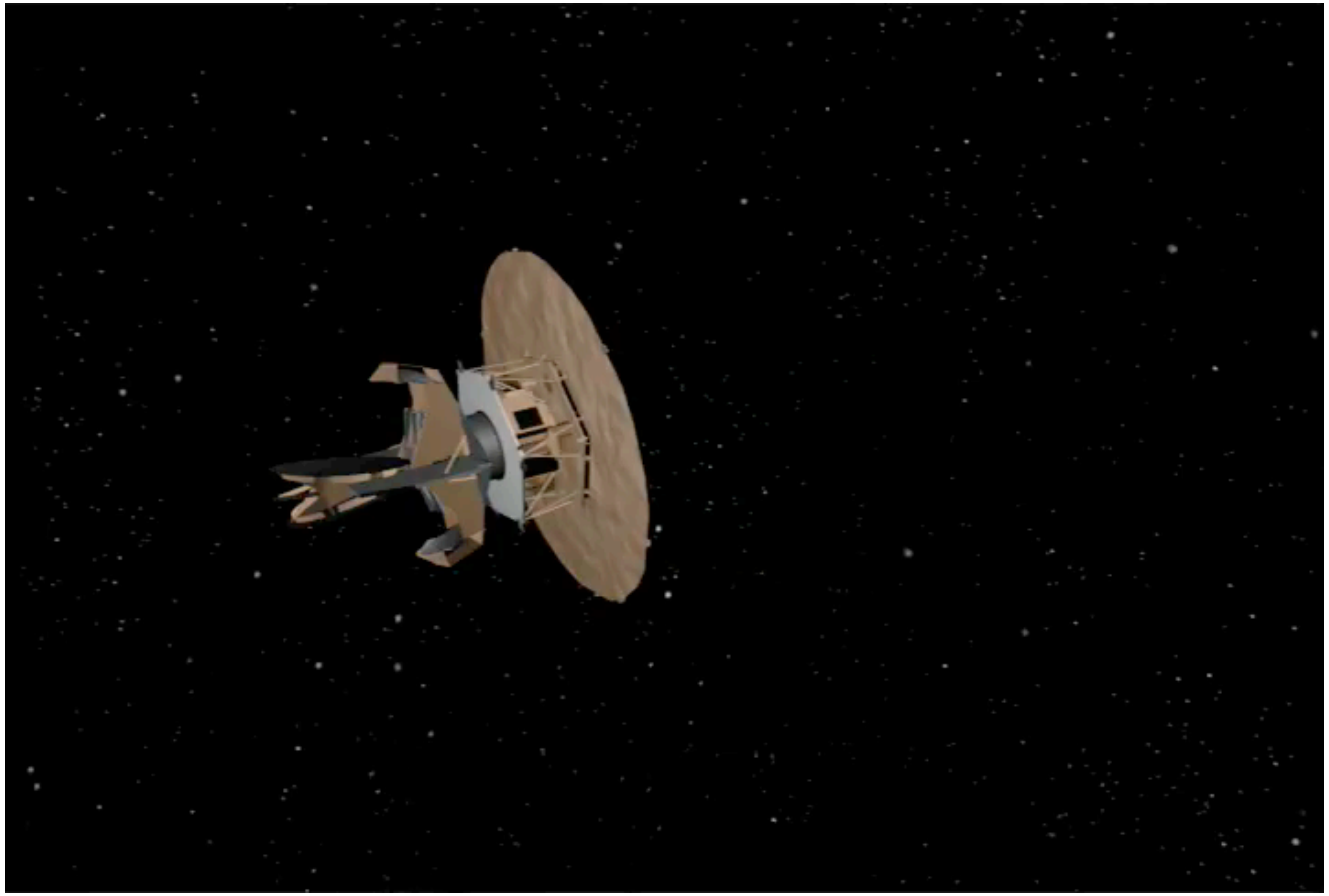
WMAP Measures Microwaves From the Universe



- 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

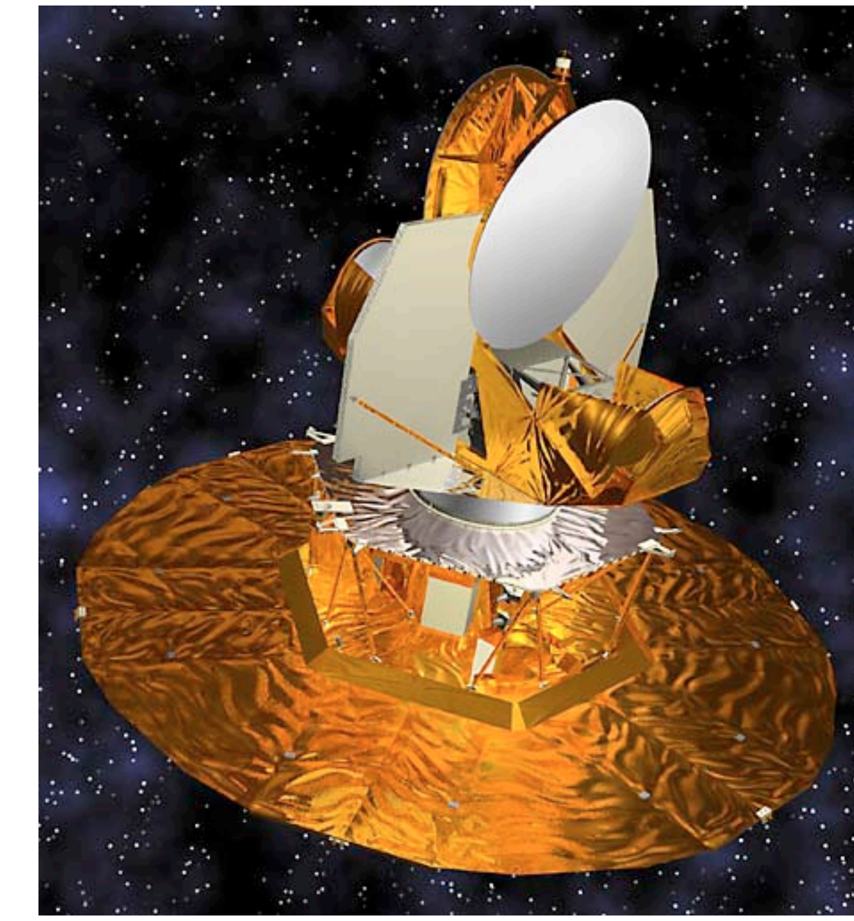
Journey Backwards in Time

- 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*)



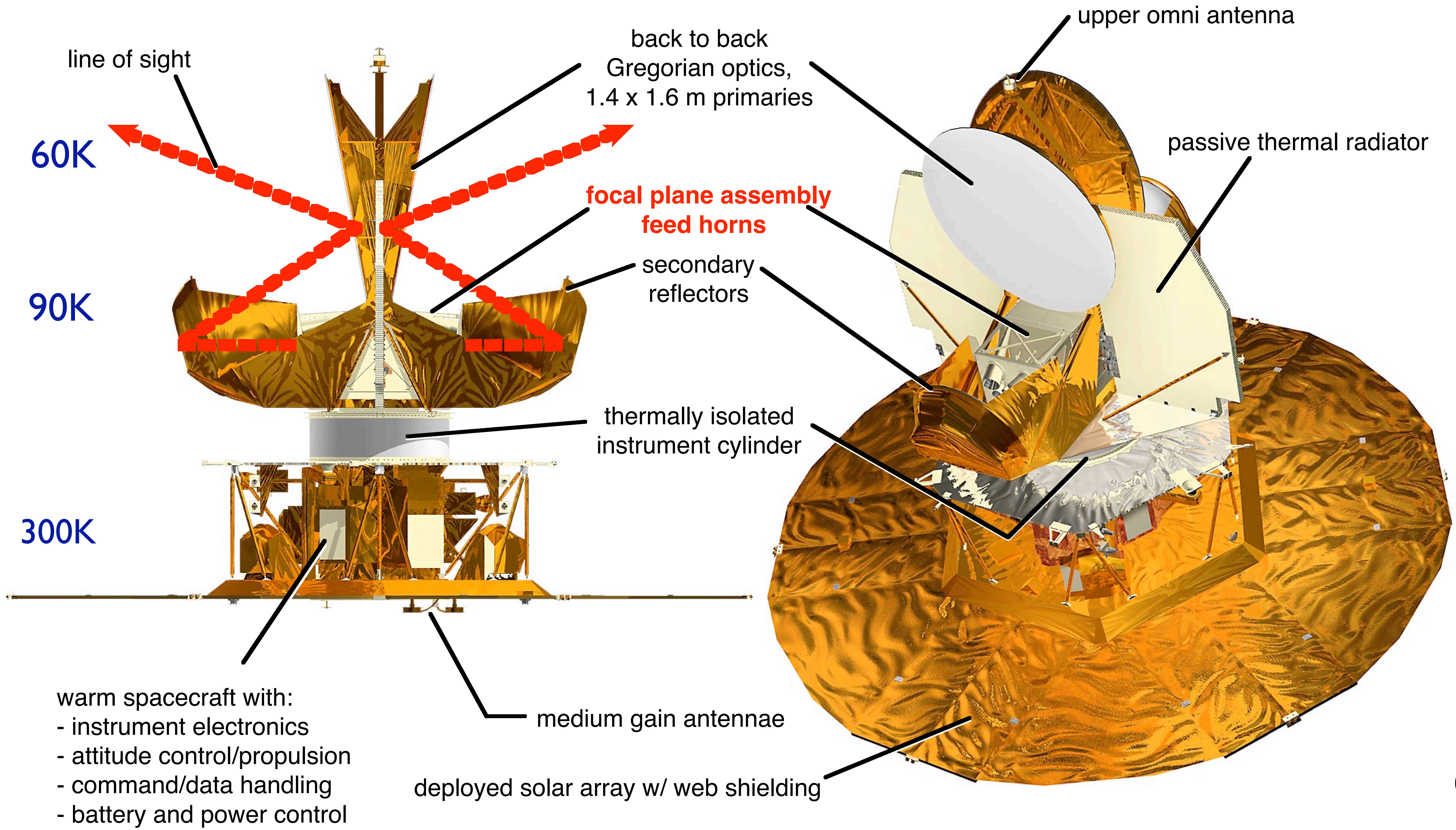
- A microwave satellite working at L2
- Five frequency bands
  - –K (22GHz), Ka (33GHz), Q (41GHz), V (61GHz), W (94GHz)
  - –Multi-frequency is crucial for cleaning the Galactic emission

- **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**.

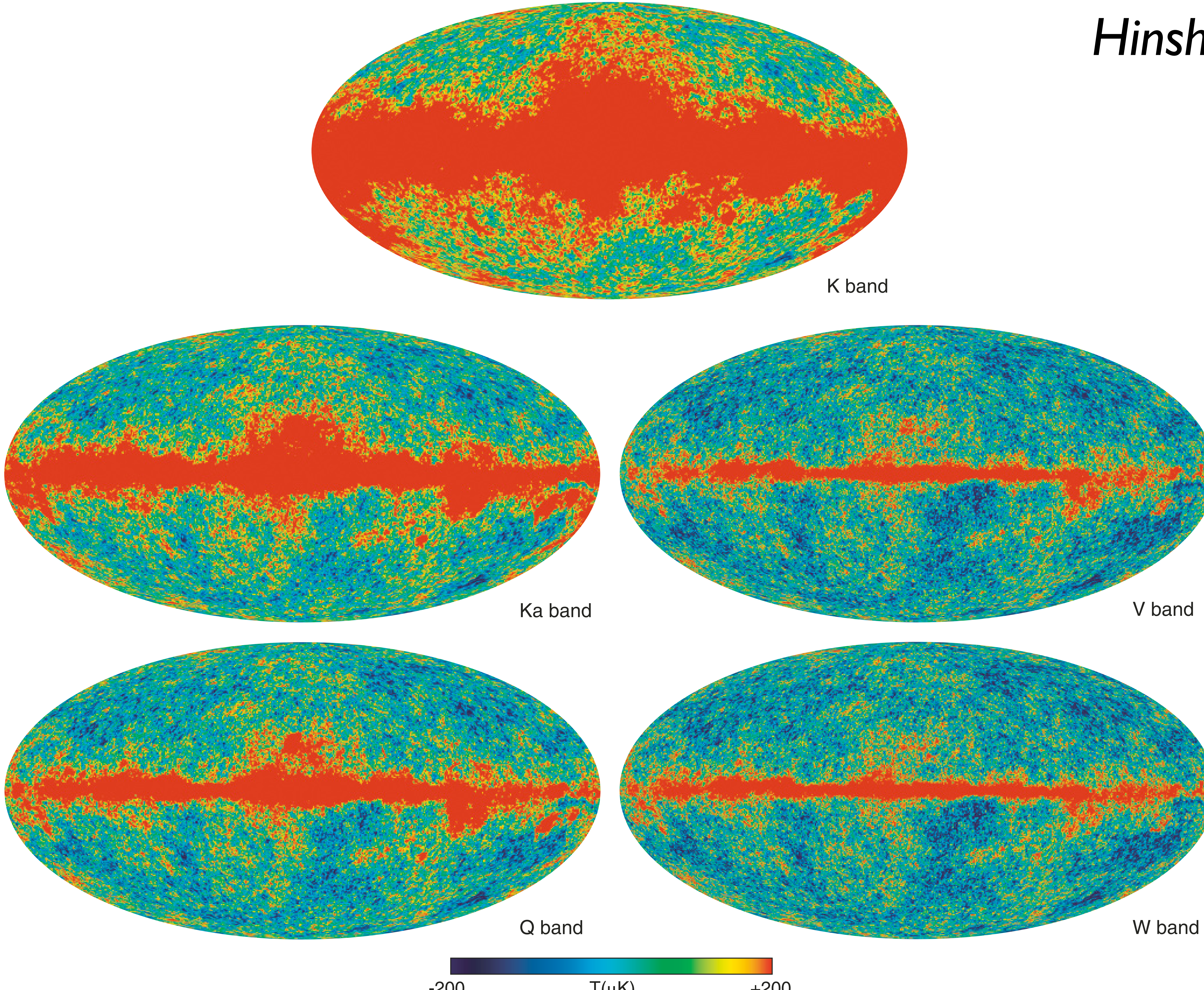
WMAP can measure polarization as well!

WMAP Spacecraft

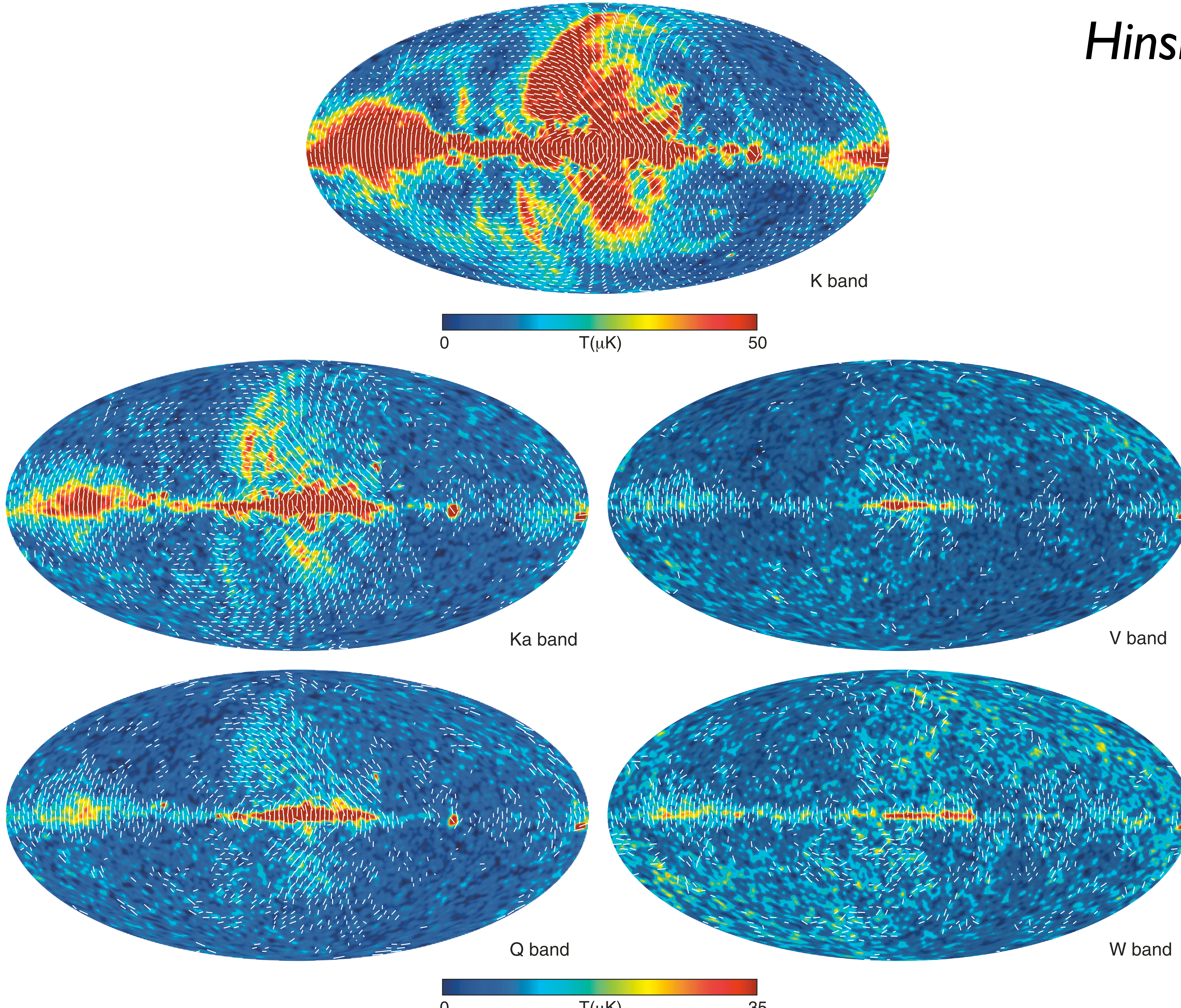
Radiative Cooling: No Cryogenic System



Hinshaw et al.

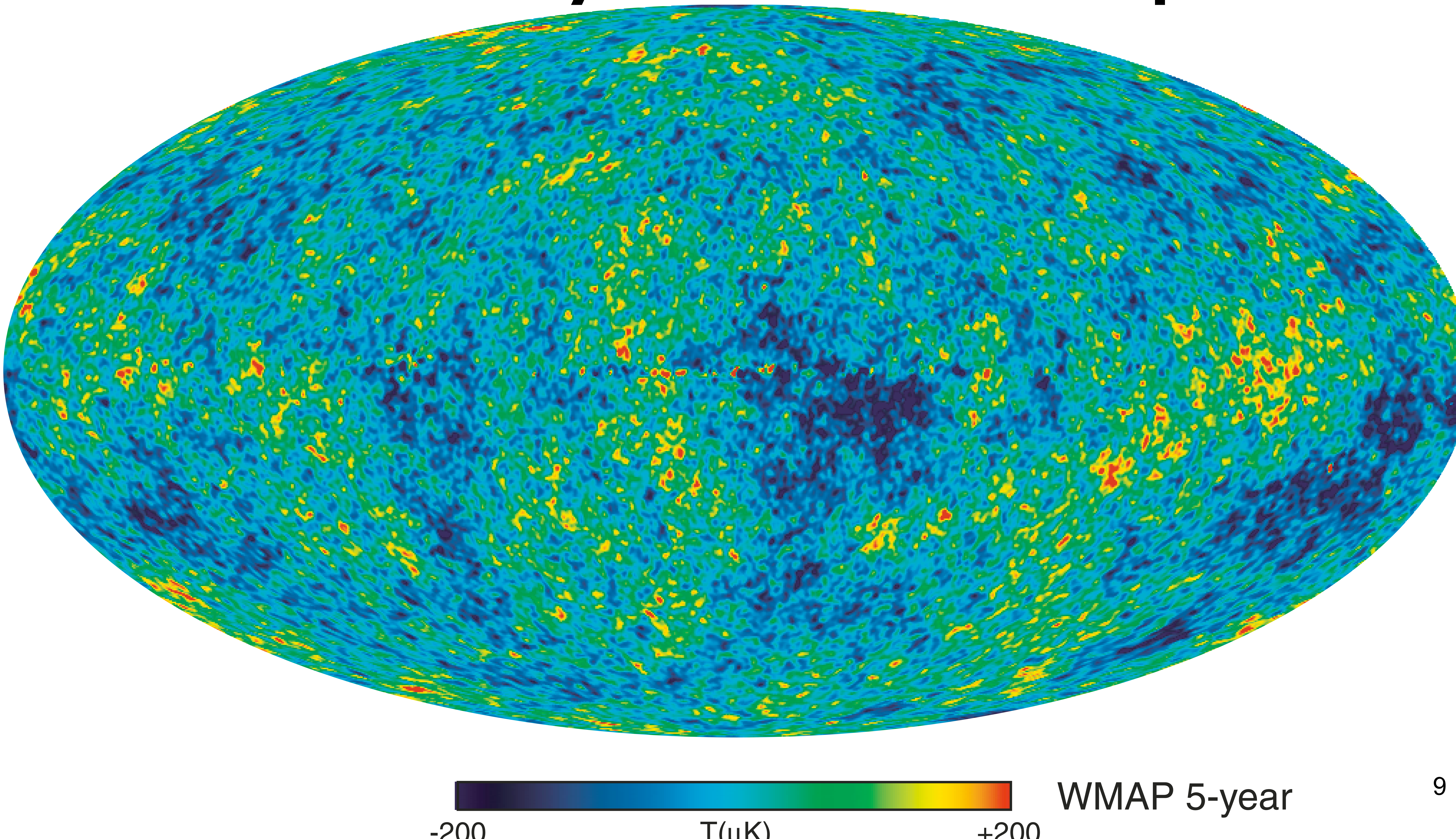


Hinshaw et al.

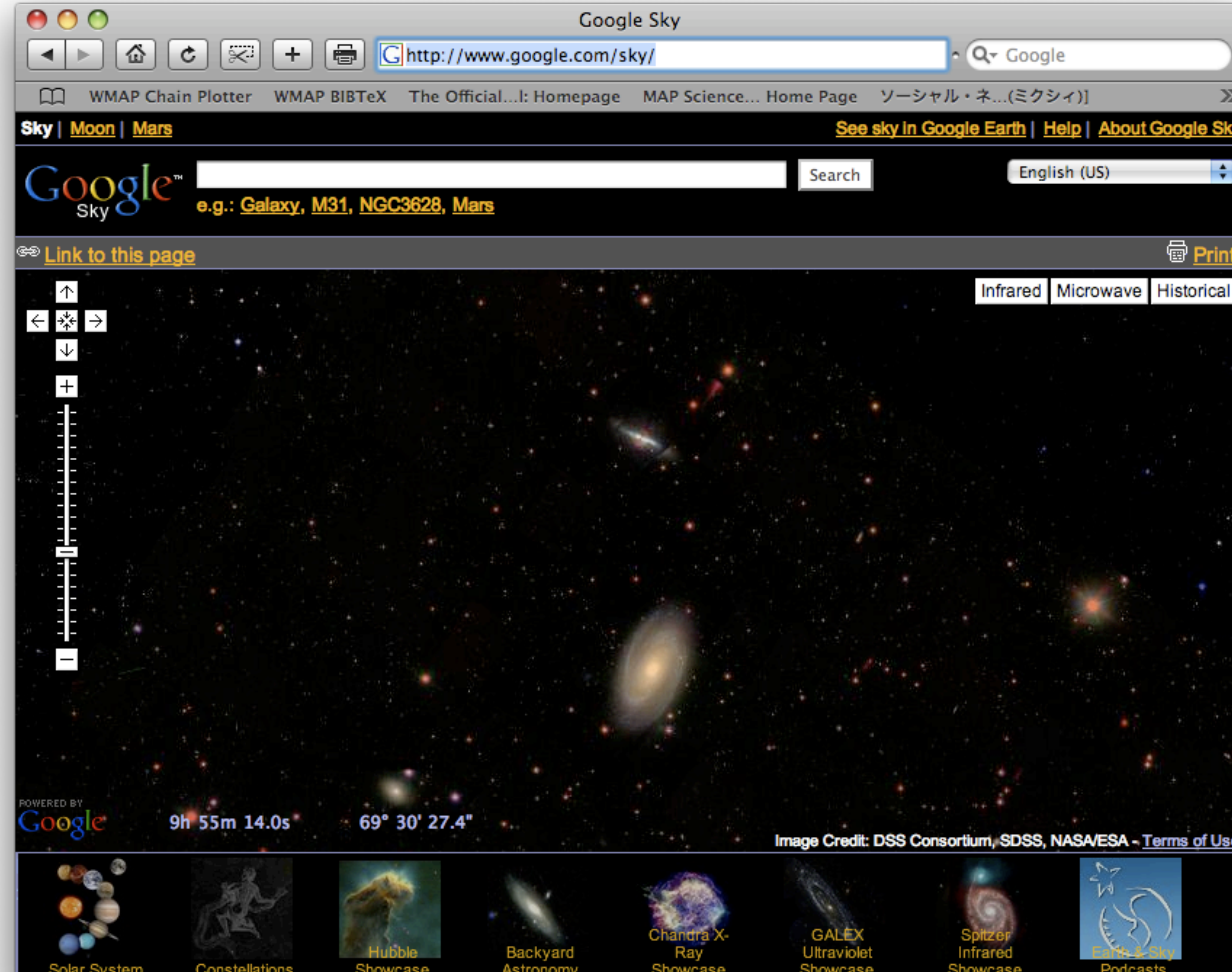


Galaxy-cleaned Map

Hinshaw et al.



WMAP on google.com/sky



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

- C.L. Bennett
- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright

- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
- M. Limon
- N. Odegard
- G.S. Tucker

- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta

Special Thanks to **WMAP Graduates!**

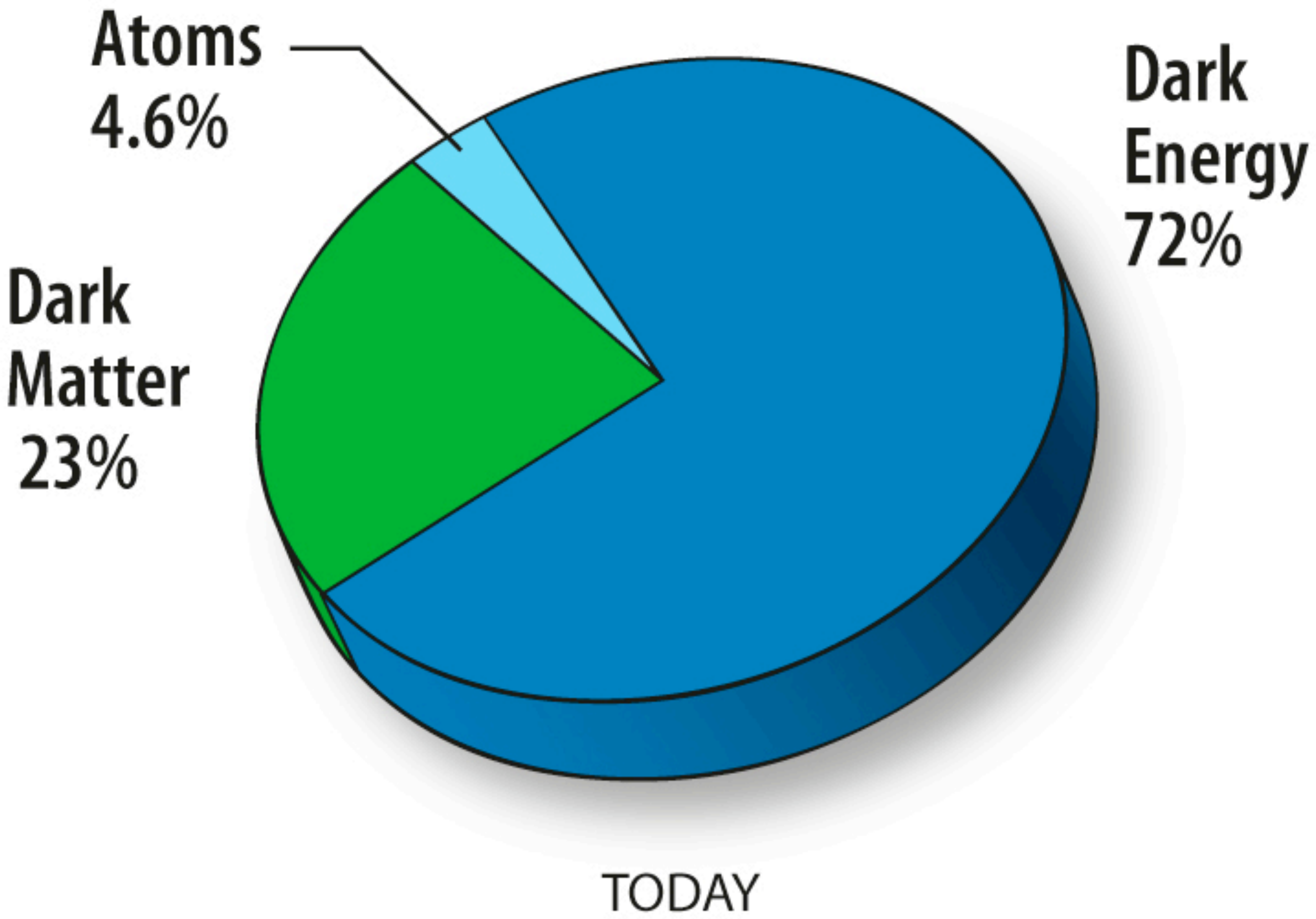
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

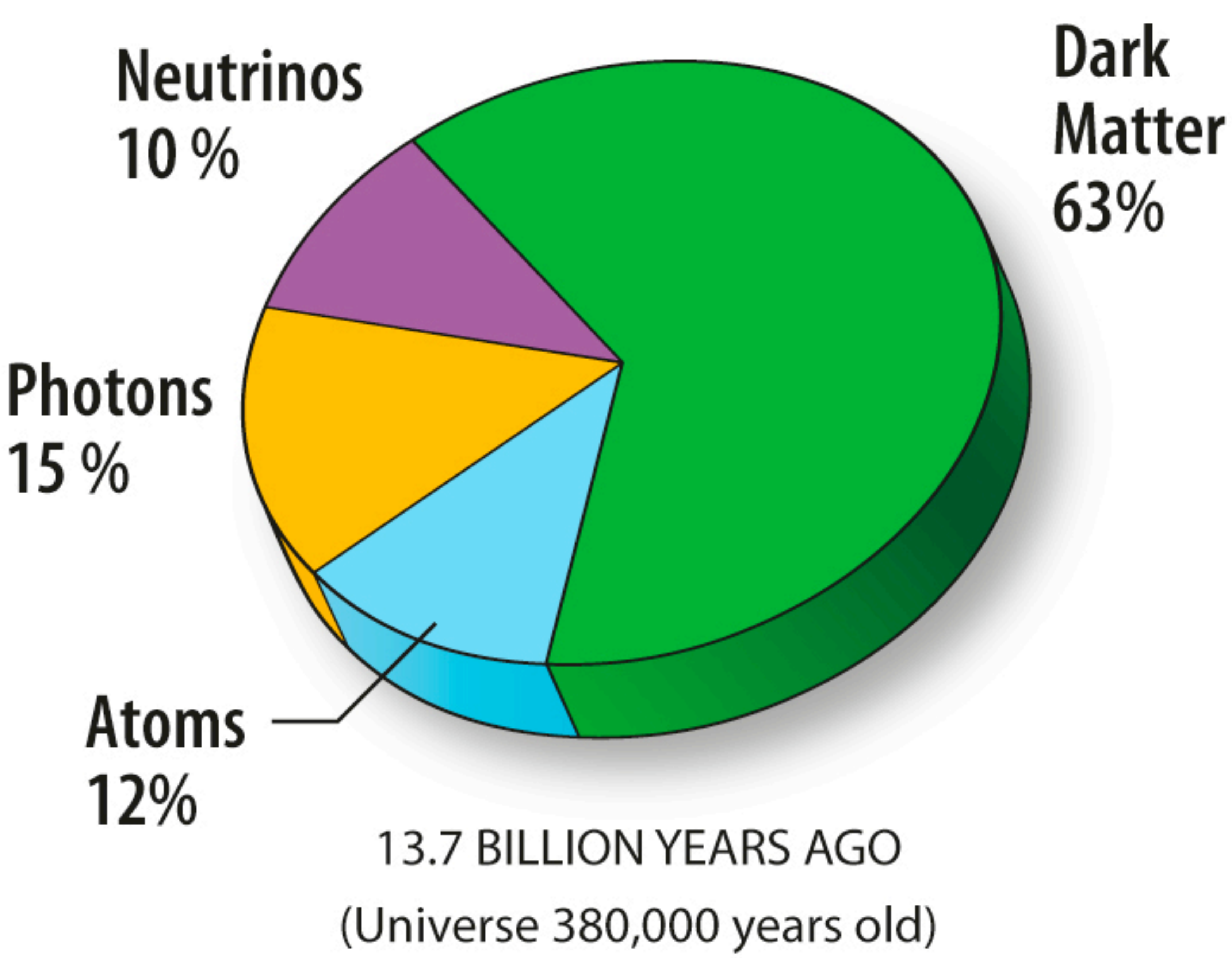
WMAP: Selected Results From the Previous Releases

- **2003: The first-year results**
- Age of the Universe: **13.7 (+/- 0.2)** billion years
- "Cosmic Pie Chart"
  - Atoms (baryons): **4.4 (+/- 0.4) %**
  - Dark Matter: **23 (+/- 4) %**
  - Dark Energy: **73 (+/- 4) %**
  - Erased lingering doubts about the existence of DE
- "Breakthrough of the Year #1" by Science Magazine

WMAP: Selected Results From the Previous Releases

- **2006: The three-year results**
- ***Polarization*** of the cosmic microwave background measured with the unprecedented accuracy
  - The epoch of the formation of first stars (onset of the "cosmic reionization")
  - ~400 million years after the Big Bang
- Evidence for a scale dependence of the amplitude of primordial fluctuations (the so-called "***tilt***")
  - Peering into the cosmic inflation (ultra early univ!)



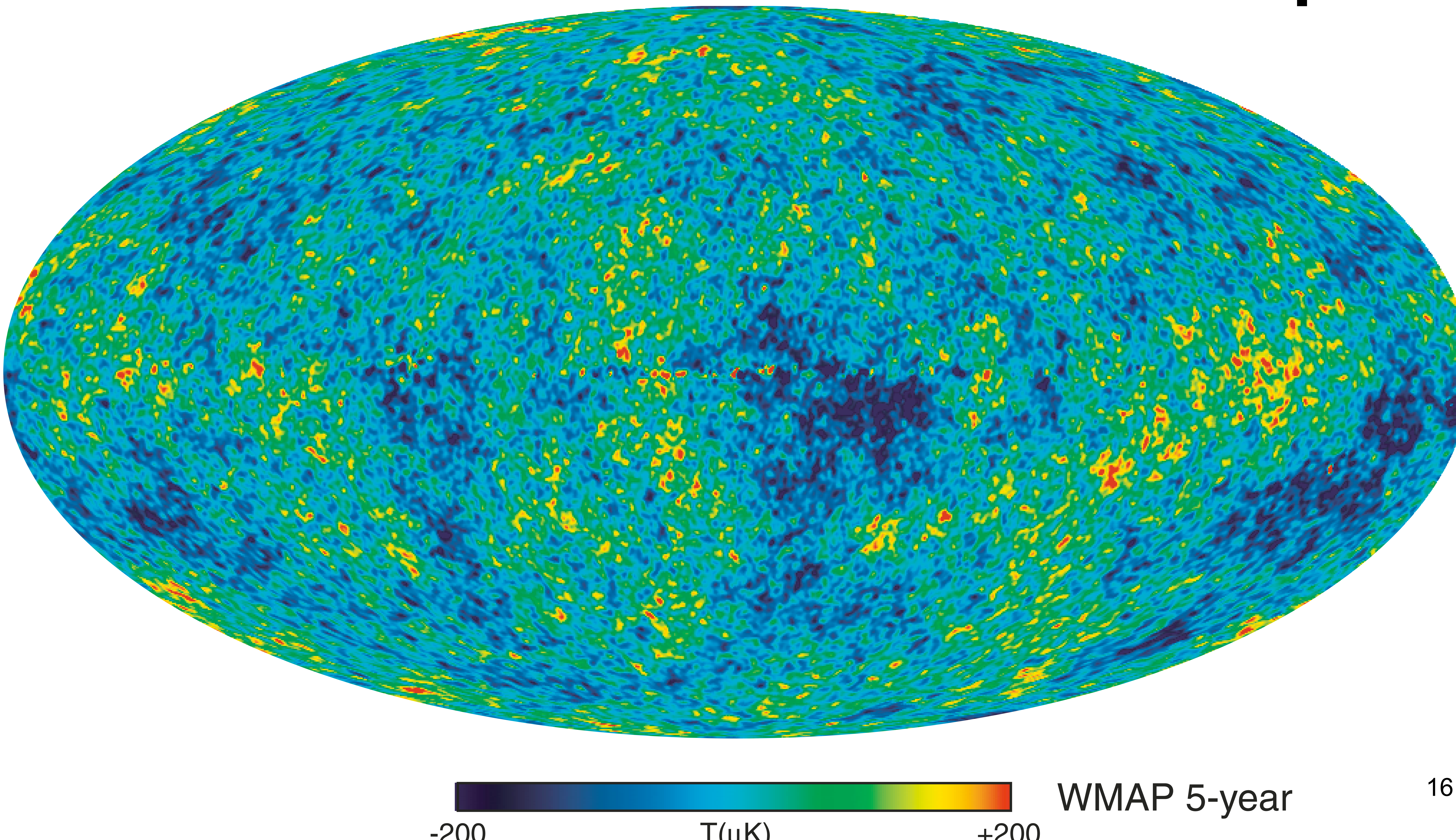


Komatsu et al.

~WMAP 5-Year~ Pie Chart Update!

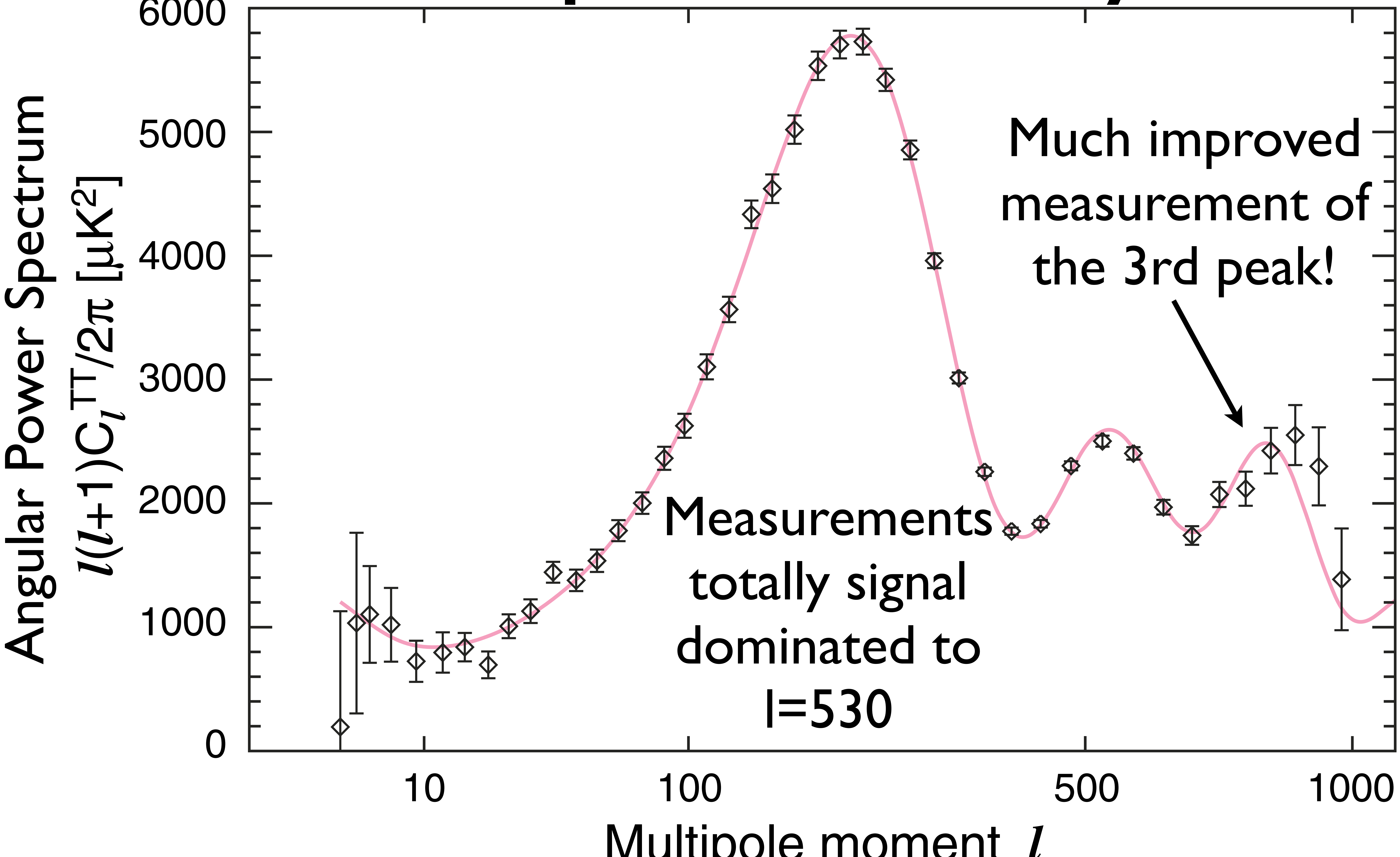
- <u>Universe today</u>
  - Age: **13.73 +/- 0.12** Gyr
  - Atoms: **4.62 +/- 0.15 %**
  - Dark Matter: **23.3 +/- 1.3%**
  - Vacuum Energy: **72.1 +/- 1.5%**
- <u>When CMB was released 13.7 B yrs ago</u>
  - A significant contribution from the *cosmic neutrino background*

How Did We Use This Map?



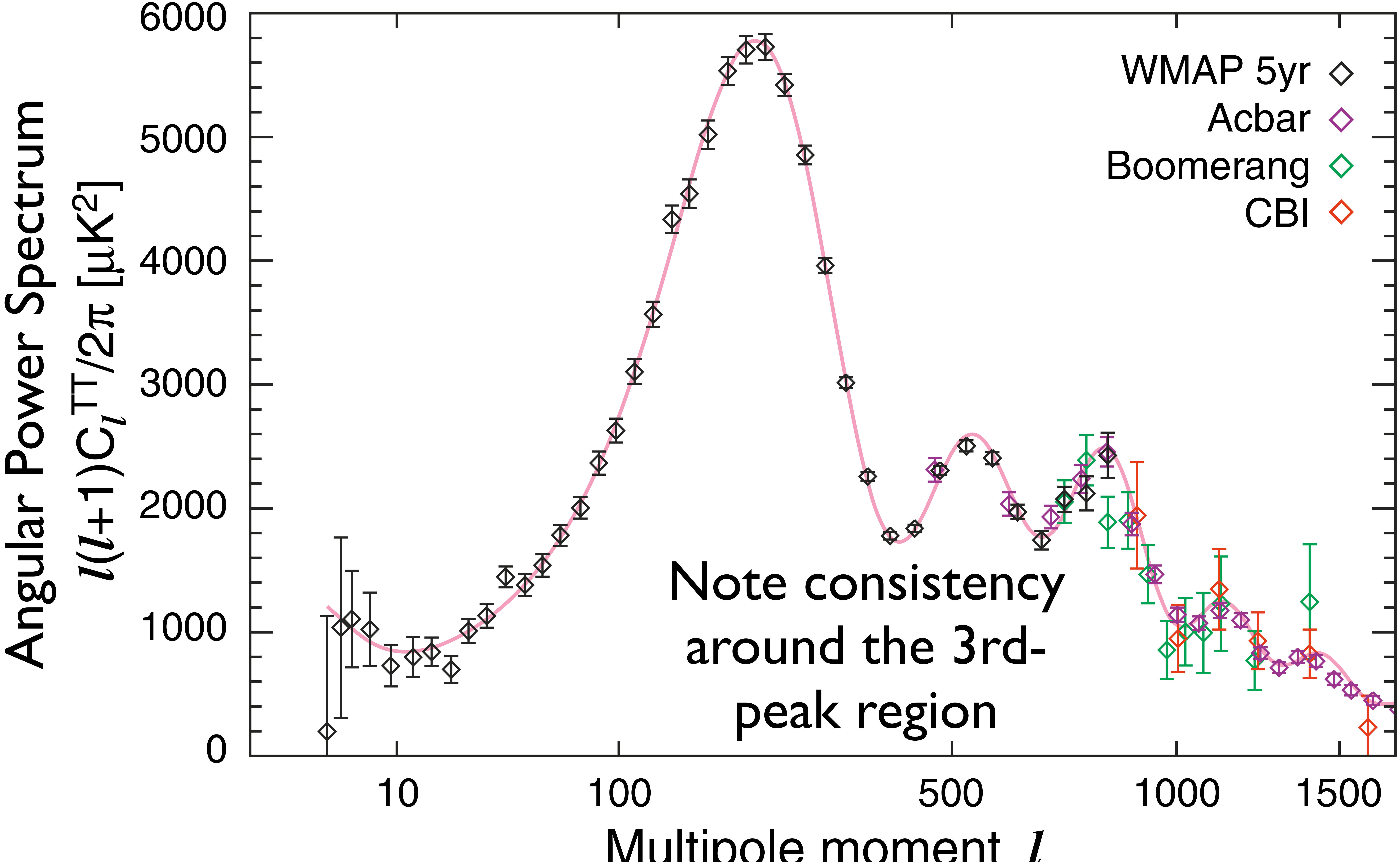
The Spectral Analysis

Nolta et al.



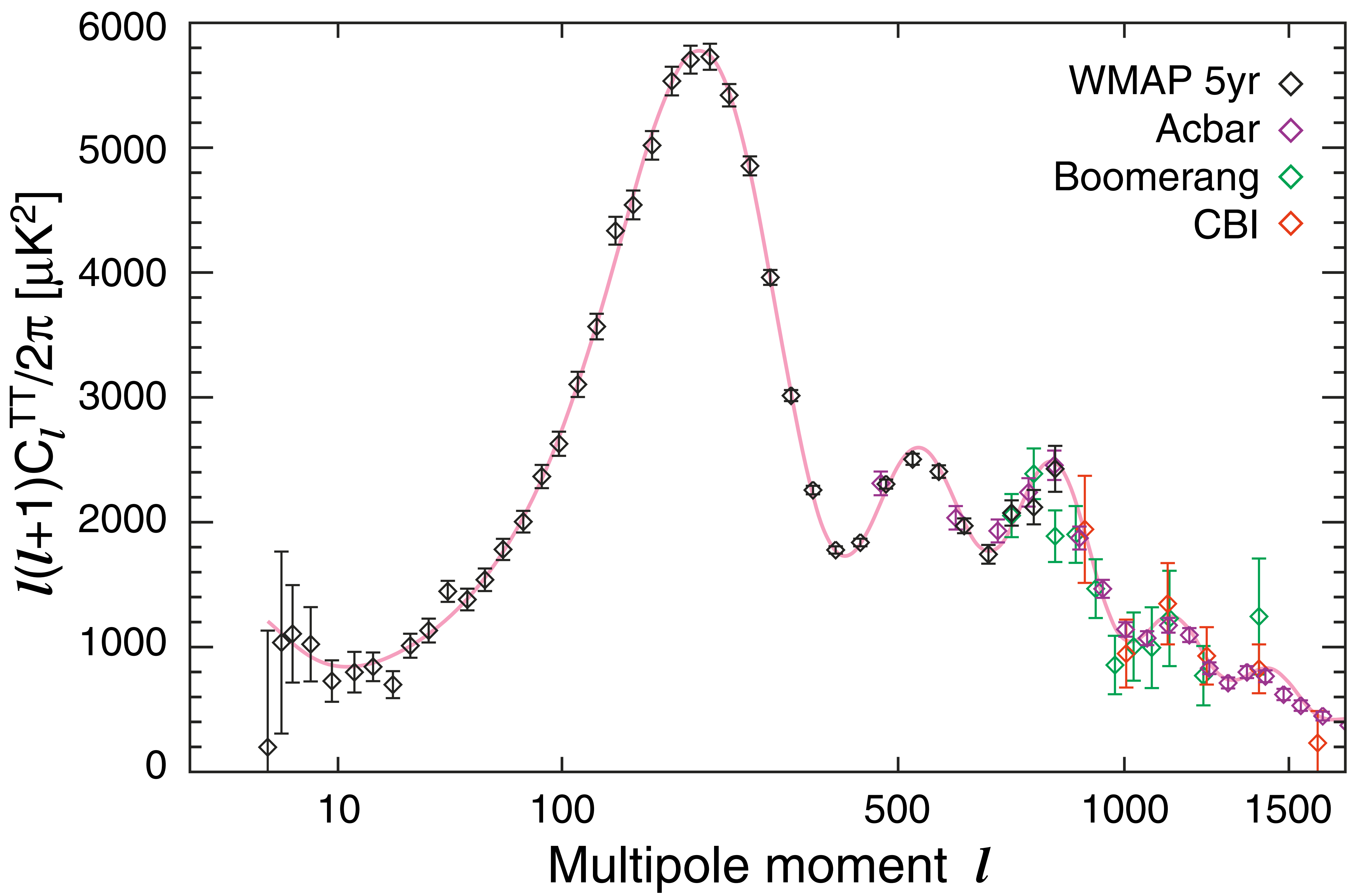
Nolta et al.

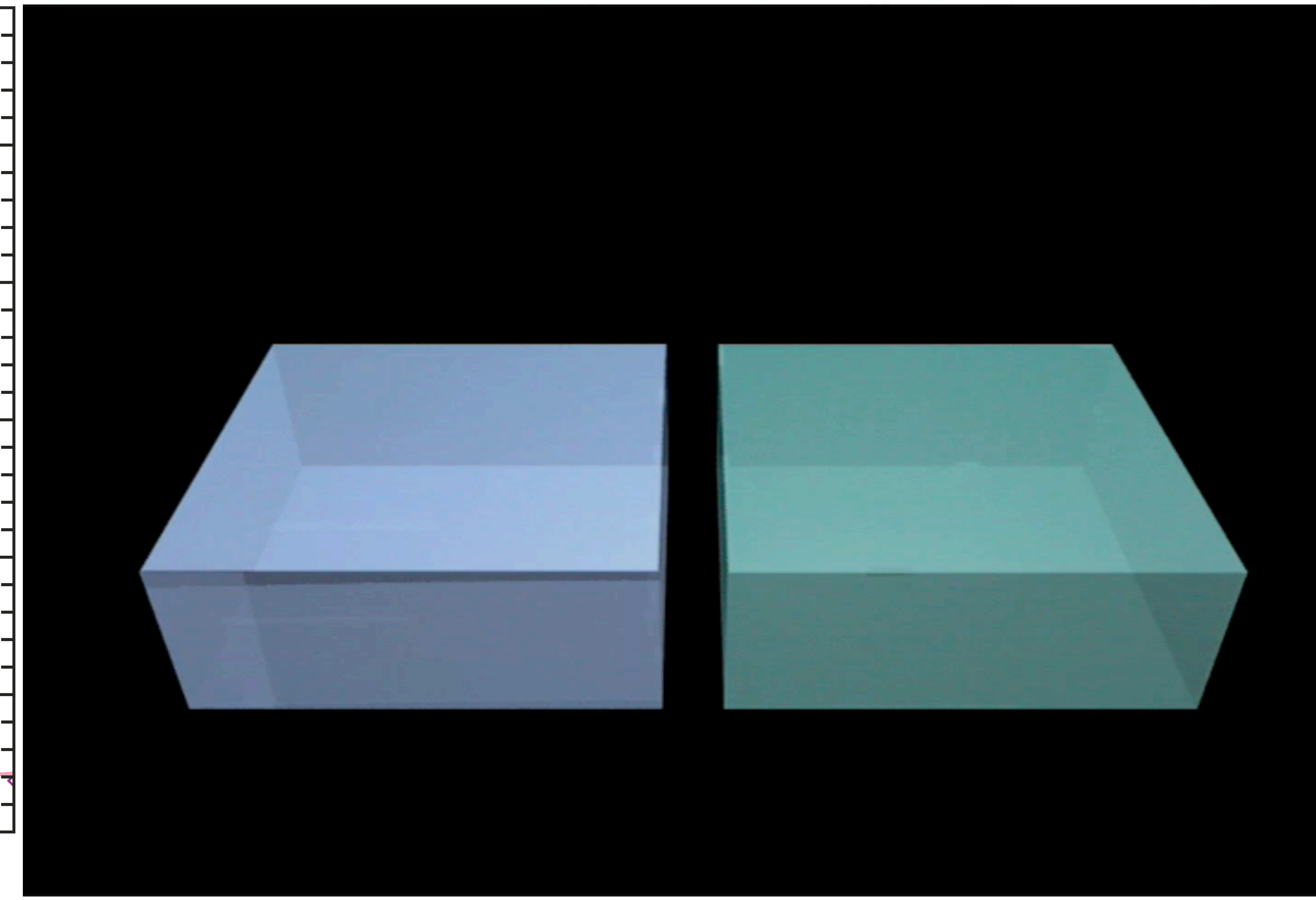
The Cosmic Sound Wave



Note consistency around the 3rd-peak region

The Cosmic Sound Wave



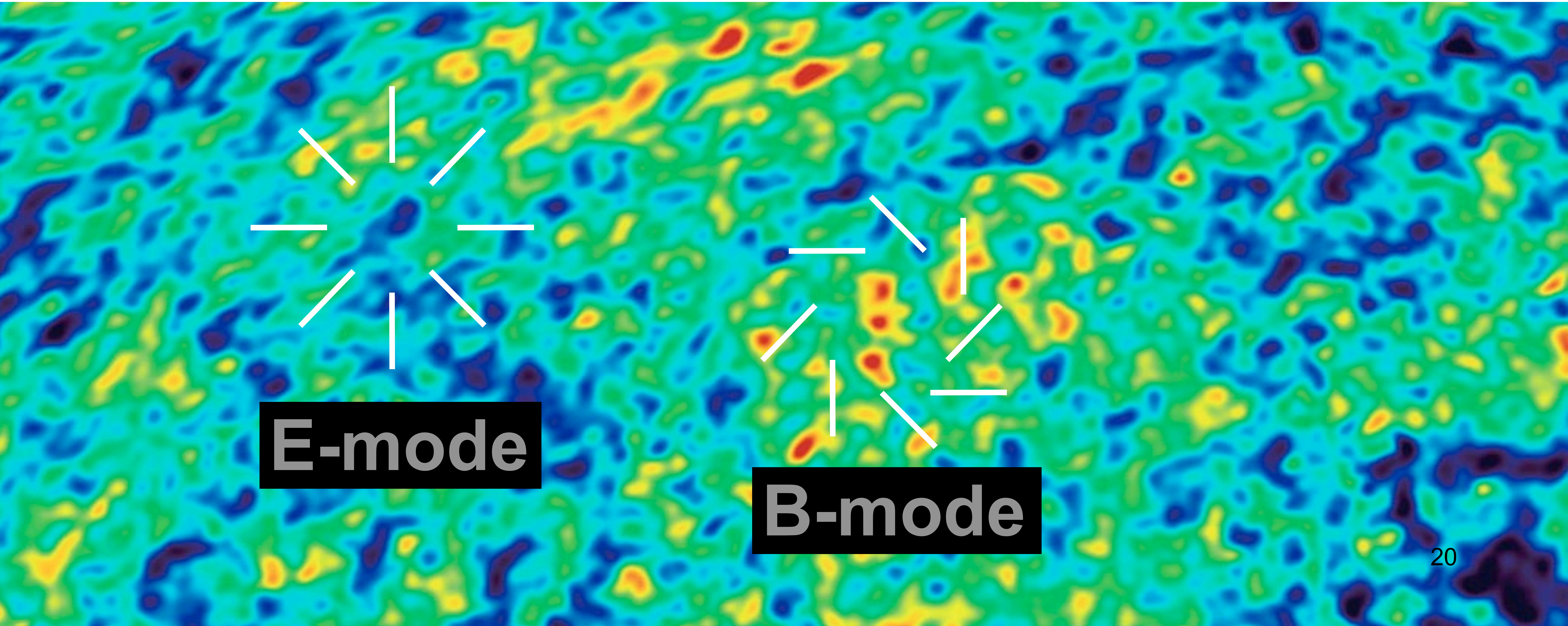


- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

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

How About Polarization?

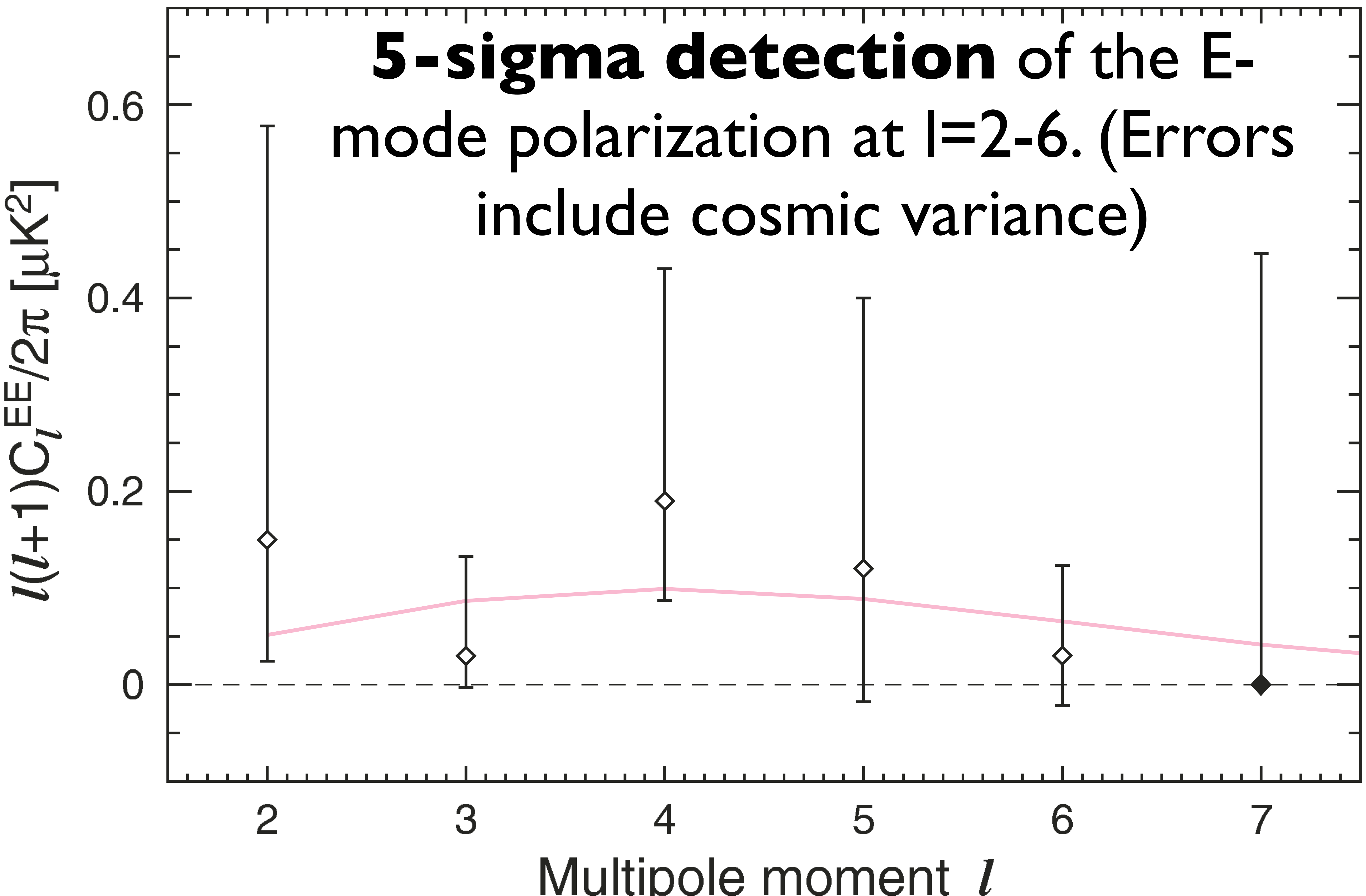
- Polarization is a rank-2 tensor field.
- One can decompose it into a divergence-like "E-mode" and a vorticity-like "B-mode".



Nolta et al.

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

E-Mode Angular Power Spectrum

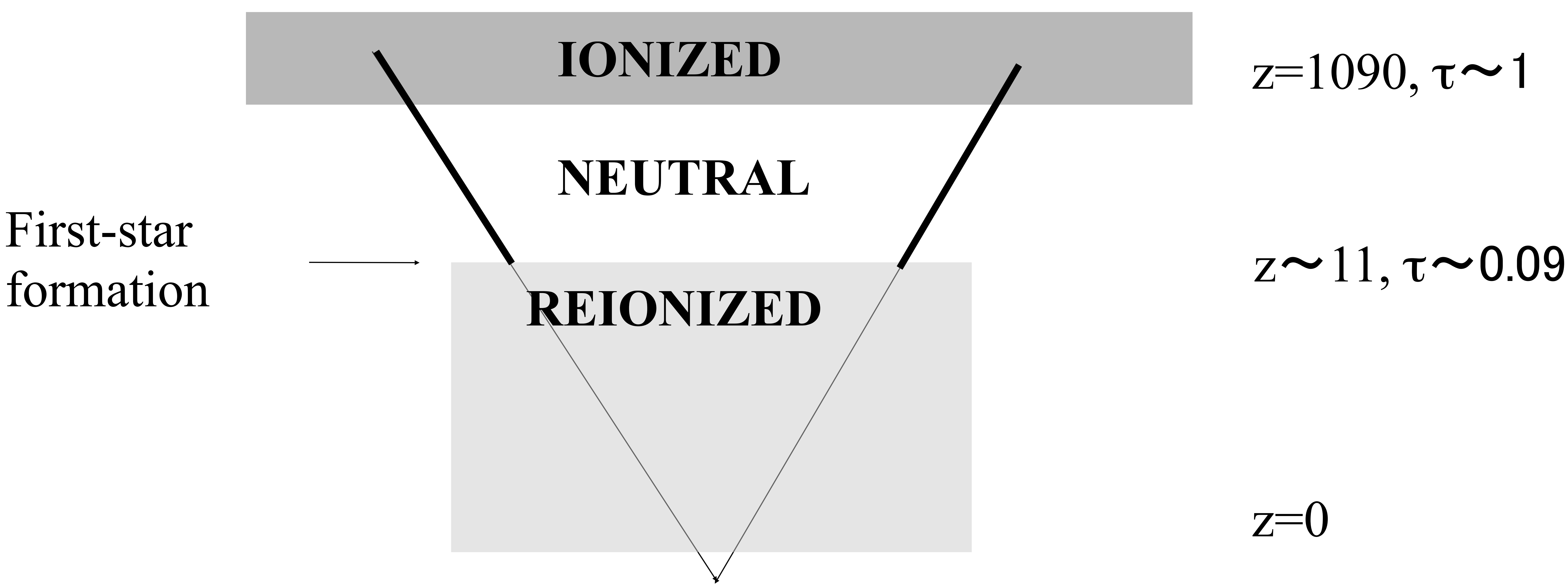


5-sigma detection of the E-mode polarization at l=2-6. (Errors include cosmic variance)

Black Symbols are upper limits

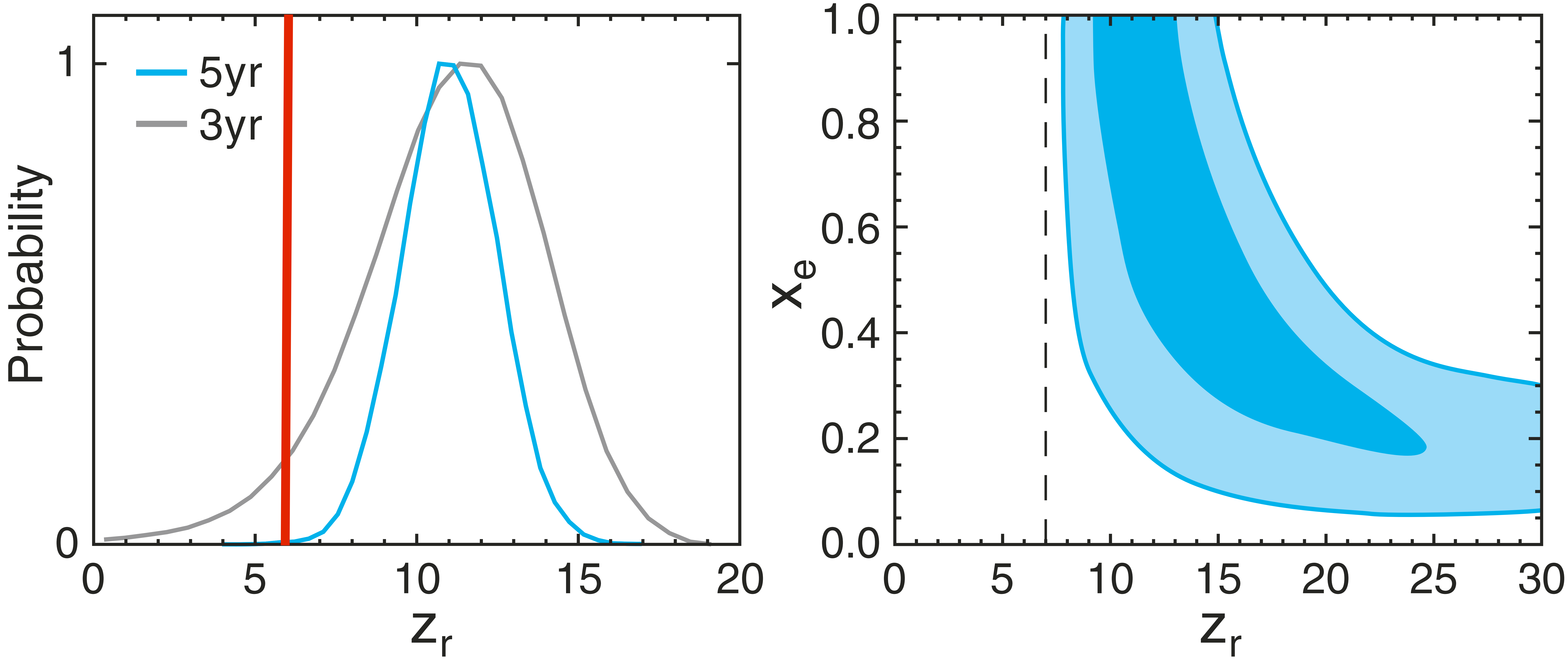
Polarization From Reionization

- CMB was emitted at z=1090.
- Some fraction (~9%) of CMB was re-scattered in a reionized universe: ***erased*** *temperature anisotropy, but* ***created*** *polarization.*
- The reionization redshift of ~11 would correspond to 400 million years after the Big-Bang.



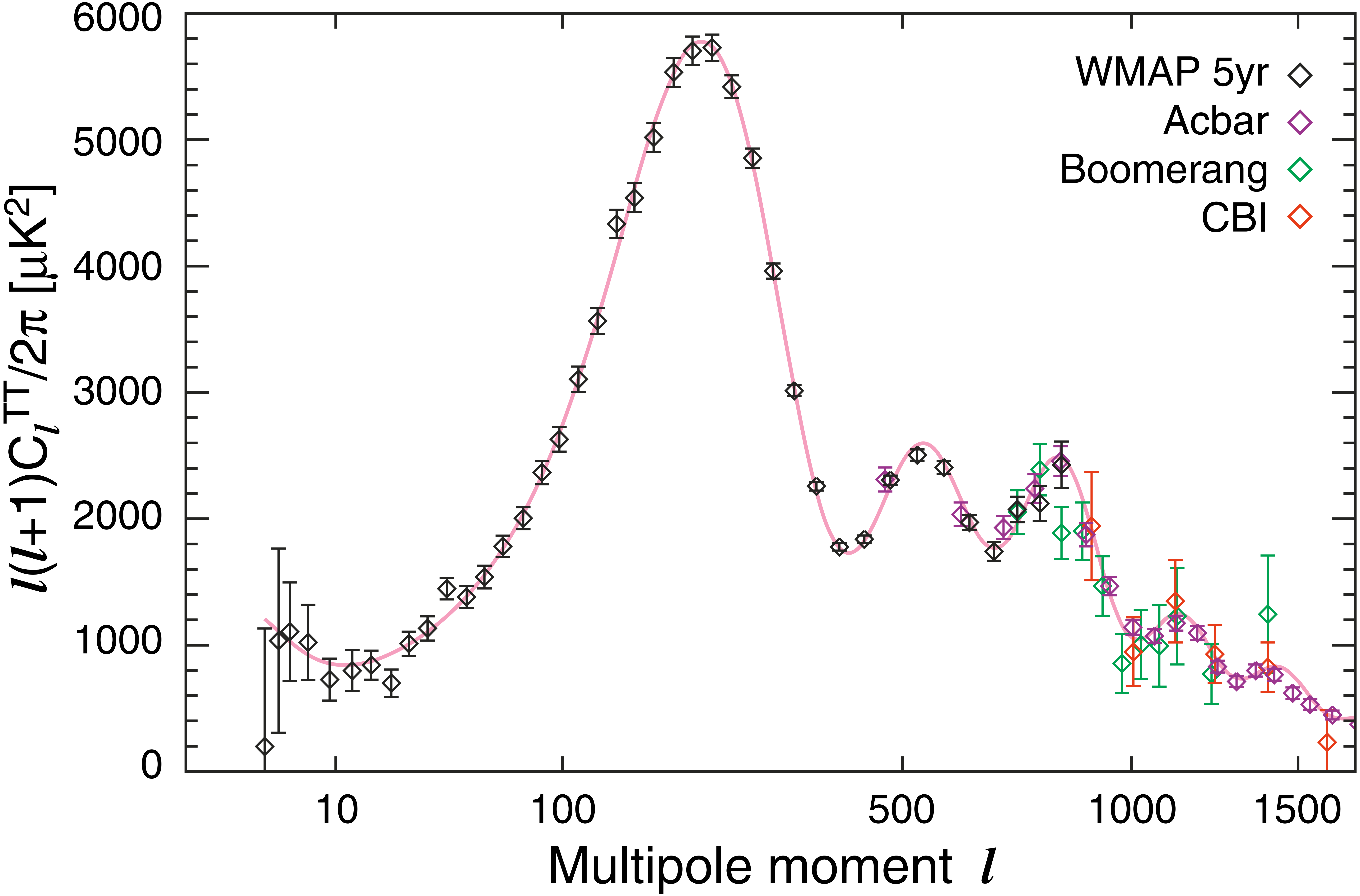
Z_{reion}=6 Is Excluded

Dunkley et al.

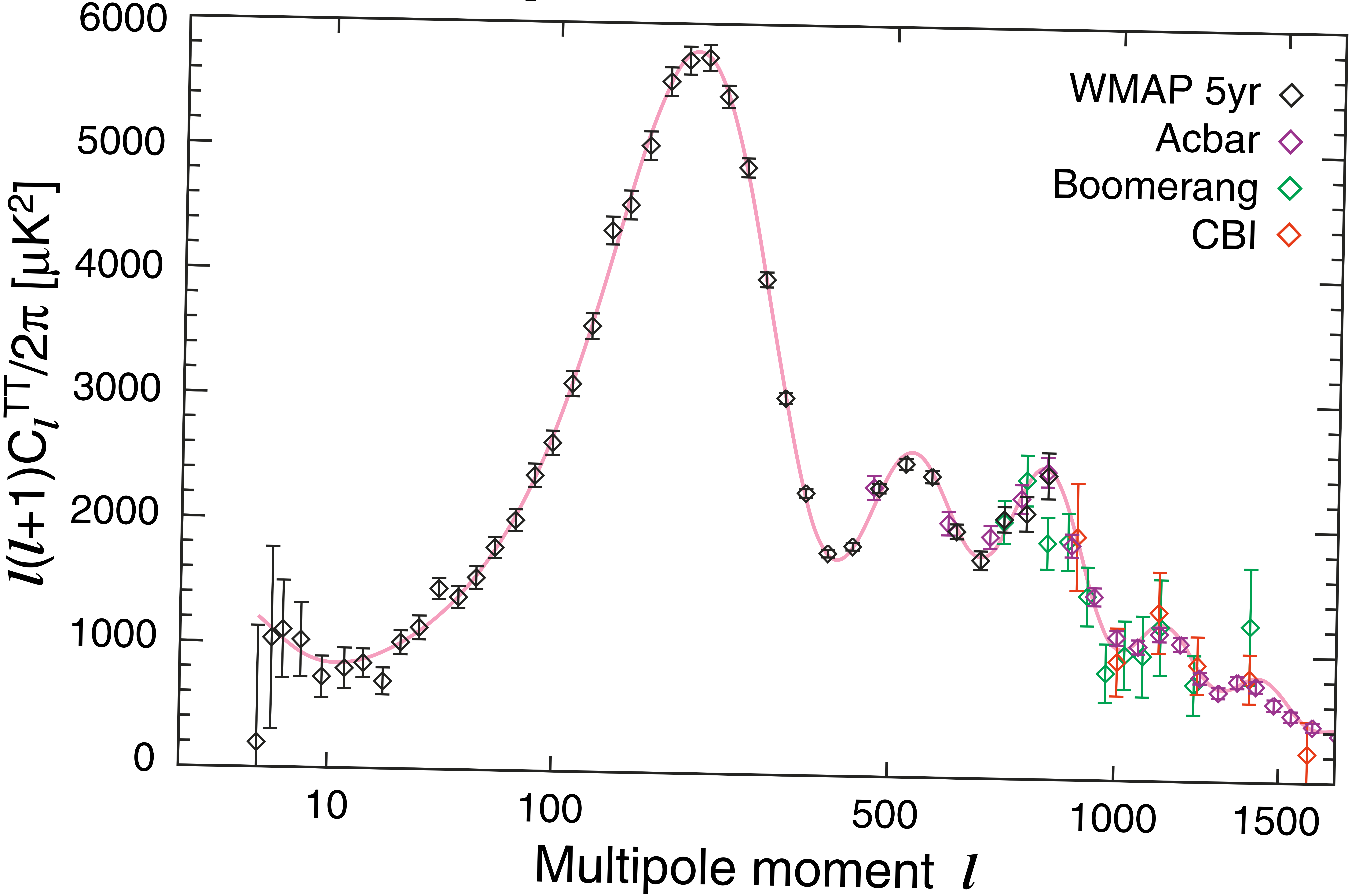


- Assuming an instantaneous reionization from x_e=0 to x_e=1 at z_{reion}, we find **z_{reion}=11.0 +/- 1.4** (68 % CL).
- The reionization was not an instantaneous process at z~6. (The 3-sigma lower bound is z_{reion}>6.7.)

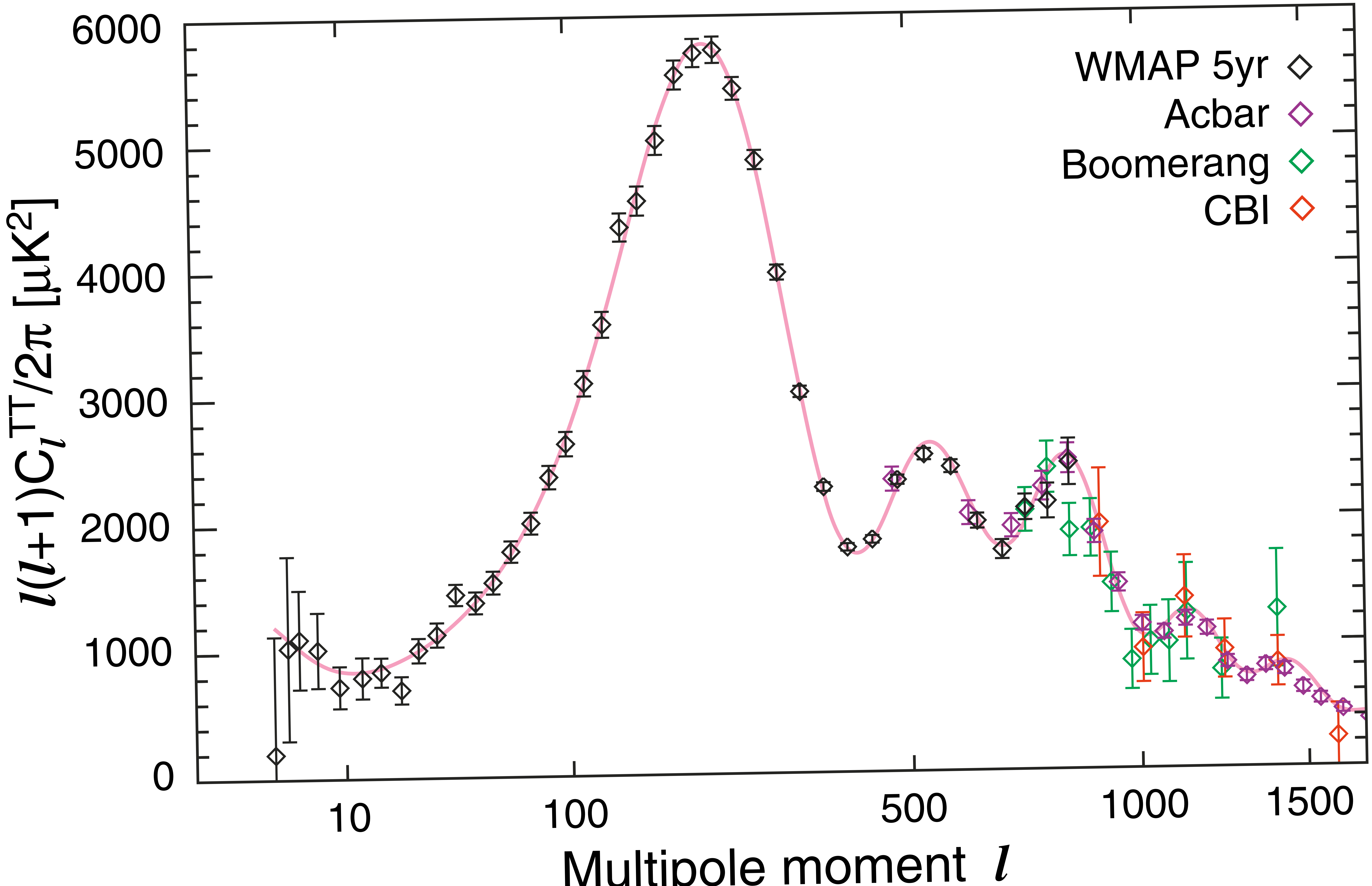
Tilting=Primordial Shape->Inflation



"Red" Spectrum: $n_s < 1$

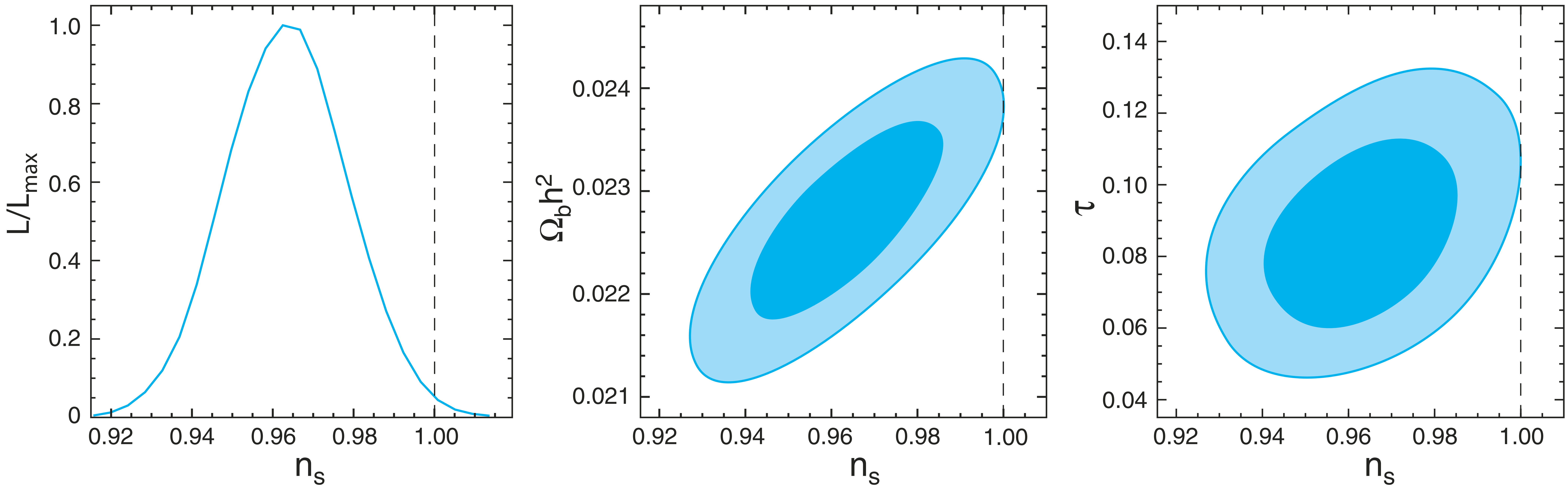


"Blue" Spectrum: $n_s > 1$



Is n_s different from ONE?

Komatsu et al.



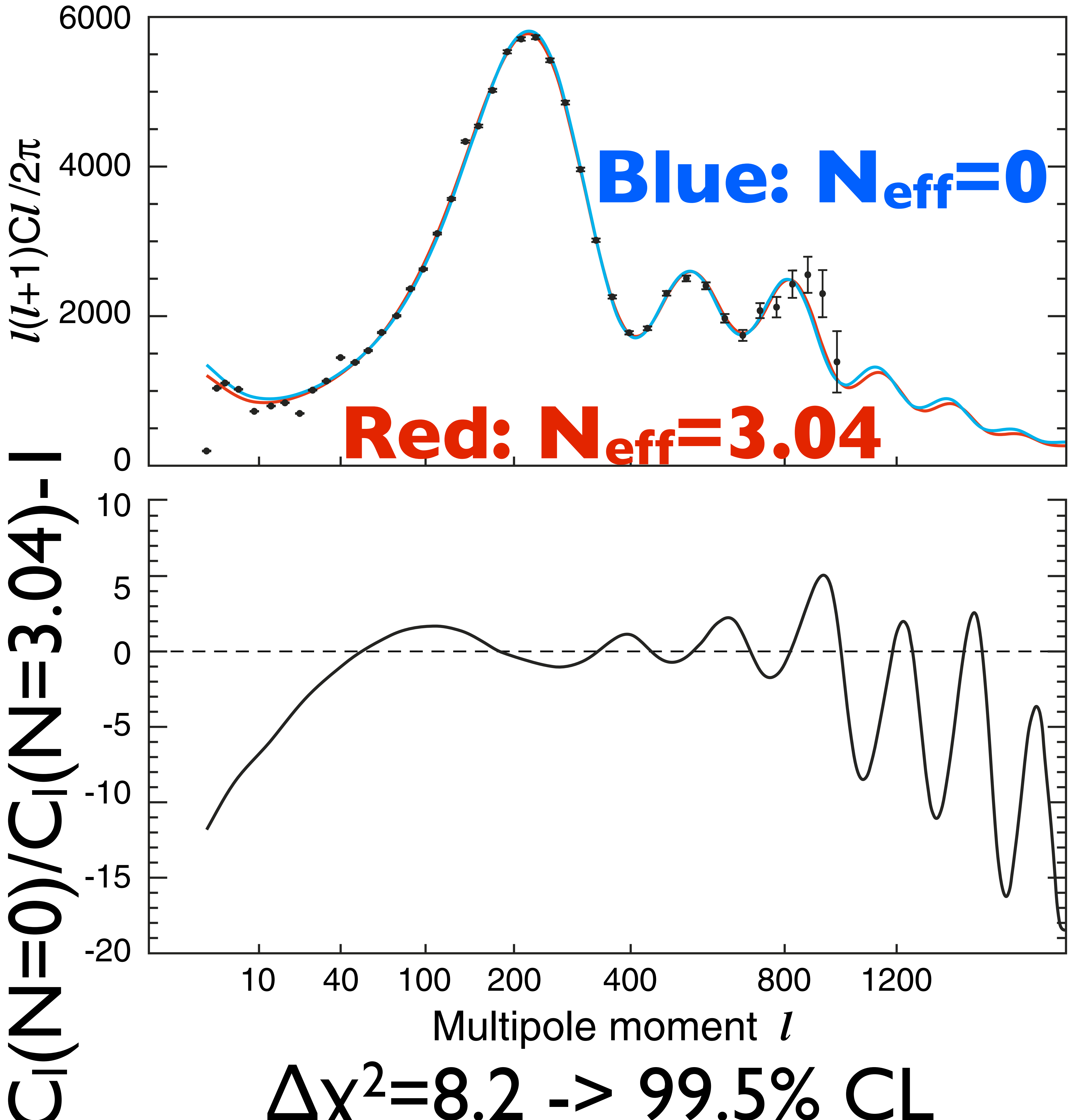
- WMAP-alone: n_s=0.963 (+0.014) (-0.015) (Dunkley et al.)
  - 2.5-sigma away from n_s=1, "scale invariant spectrum"
- n_s is degenerate with $\Omega_b h^2$; thus, we can't really improve upon n_s further unless we improve upon $\Omega_b h^2$

Cosmic Neutrino Background

- How do neutrinos affect the CMB?
  - *Neutrinos add to the radiation energy density*, which delays the epoch at which the Universe became matter-dominated. The larger the number of neutrino species is, the later the matter-radiation equality, $z_{equality}$, becomes.
    - This effect can be mimicked by lower matter density.
  - *Neutrino perturbations* affect metric perturbations as well as the photon-baryon plasma, through which CMB anisotropy is affected.

Dunkley et al.

CNB As Seen By WMAP



$\Delta\chi^2$=8.2 -> 99.5% CL

- Multiplicative phase shift is due to the change in $z_{equality}$
  - *Degenerate with $\Omega_m h^2$*
- Suppression is due to neutrino perturbations
  - *Degenerate with n_s*
- Additive phase shift is due to neutrino perturbations
  - **No degeneracy** (Bashinsky & Seljak 2004)

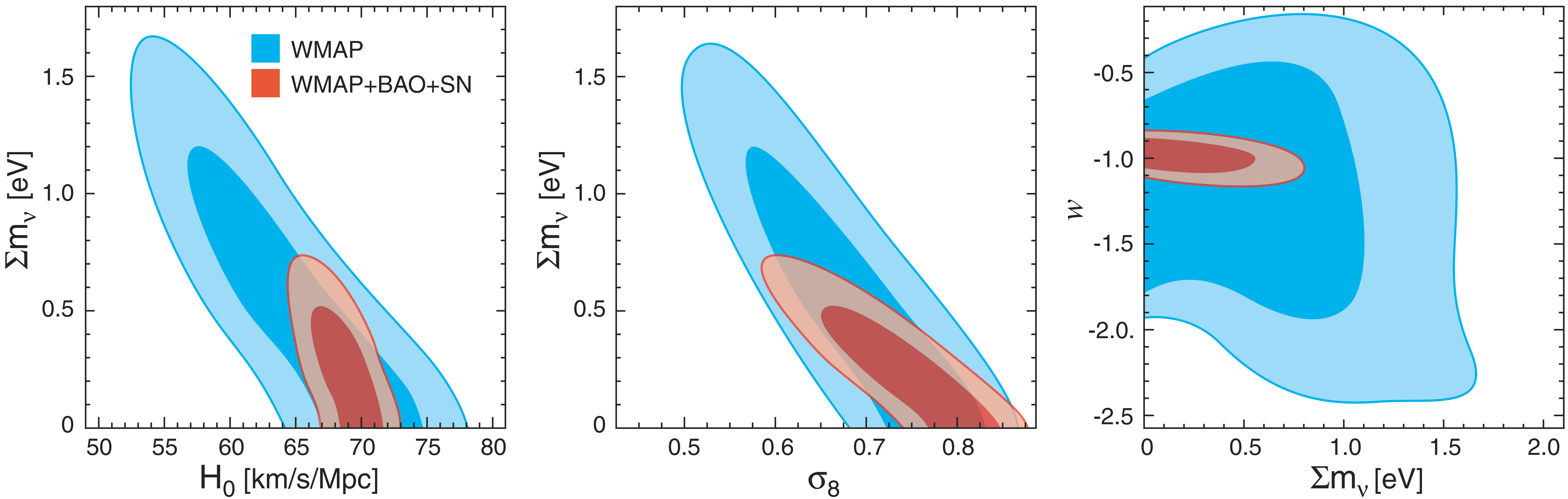
Komatsu et al.

Cosmic/Laboratory Consistency

- From WMAP+BAO+SN (I will explain what BAO and SN are shortly)
  - N_{eff} = 4.4 +/- 1.5
- From the Big Bang Nucleosynthesis
  - N_{eff} = 2.5 +/- 0.4
- From the decay width of Z bosons measured in LEP
  - $N_{neutrino}$ = 2.984 +/- 0.008

Komatsu et al.

Neutrino Mass



- BAO helps determine the neutrino mass by giving H_0.
- **Sum(m_ν) < 0.61 eV** (95% CL) -- independent of the normalization of the large scale structure.

Testing Cosmic Inflation

~5 Tests~

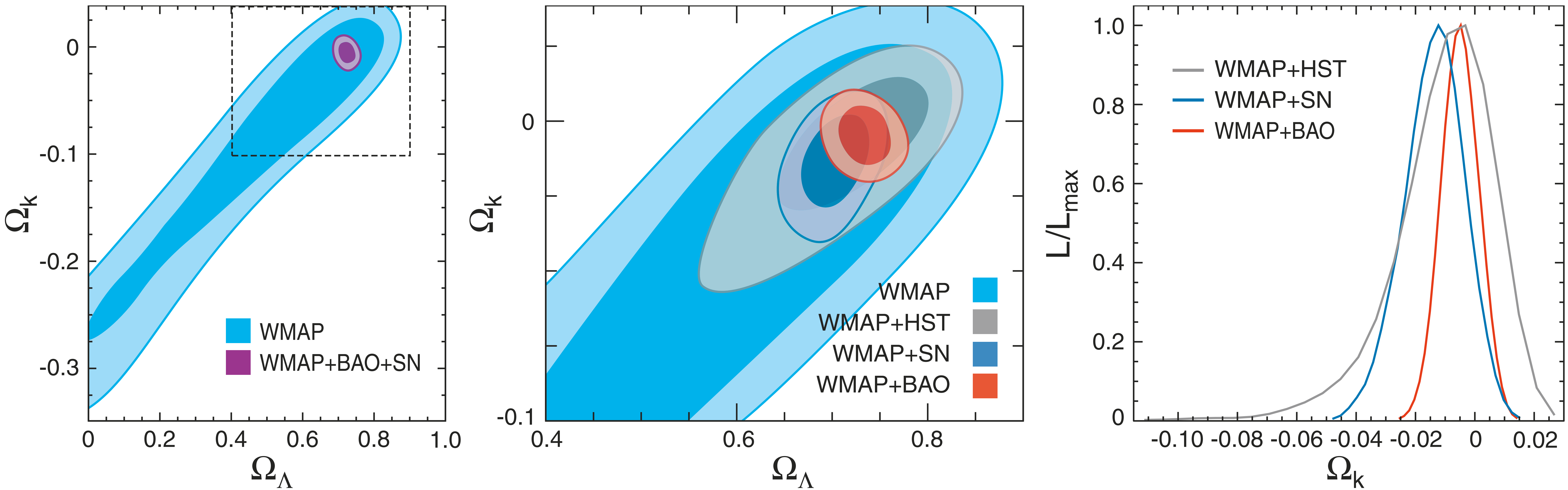
- Is the observable universe flat?
- Are the primordial fluctuations adiabatic?
- Are the primordial fluctuations nearly Gaussian?
- Is the power spectrum nearly scale invariant?
- Is the amplitude of gravitational waves reasonable?

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

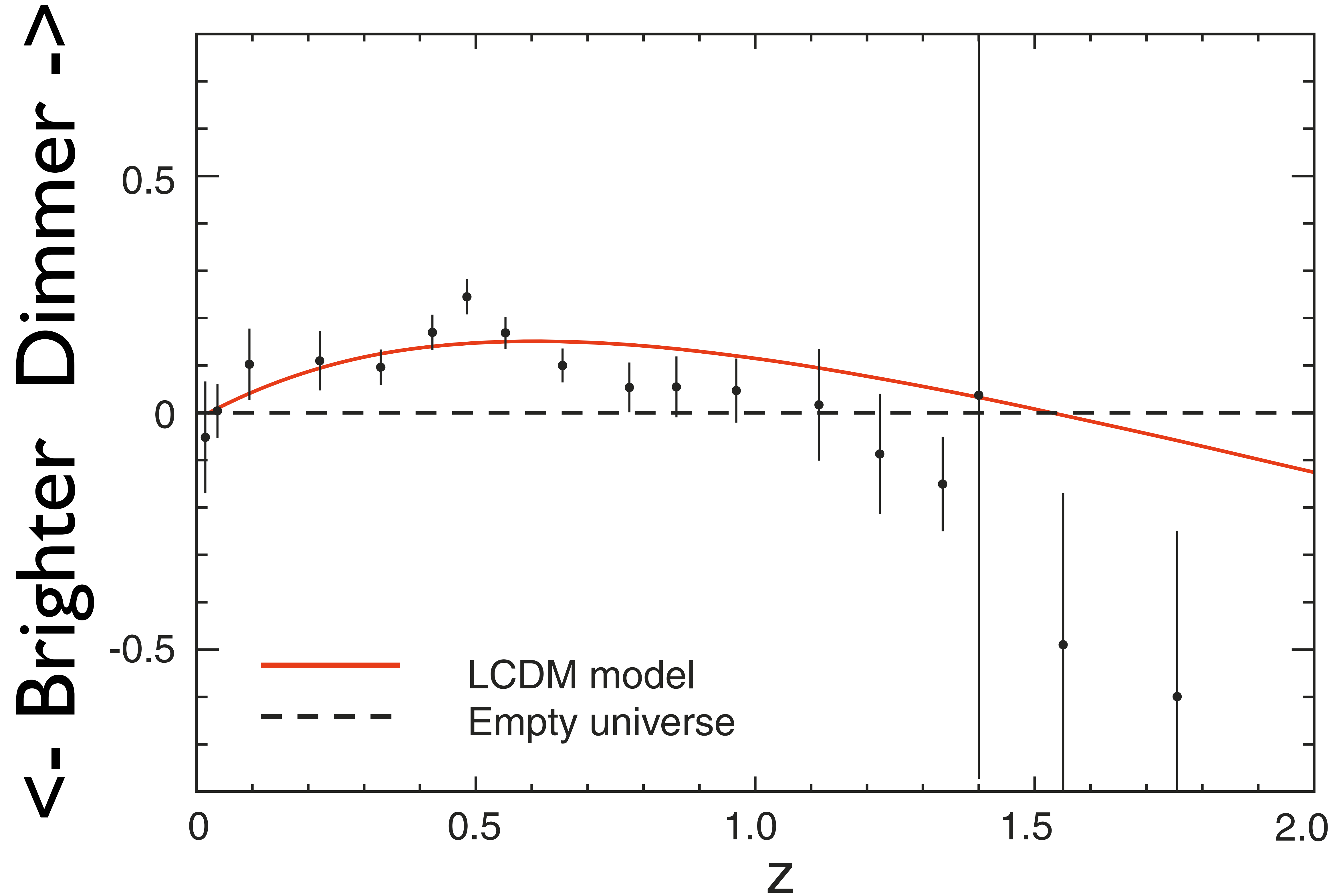
Komatsu et al.



- 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

Type Ia Supernova (SN) Data

Dunkley et al.

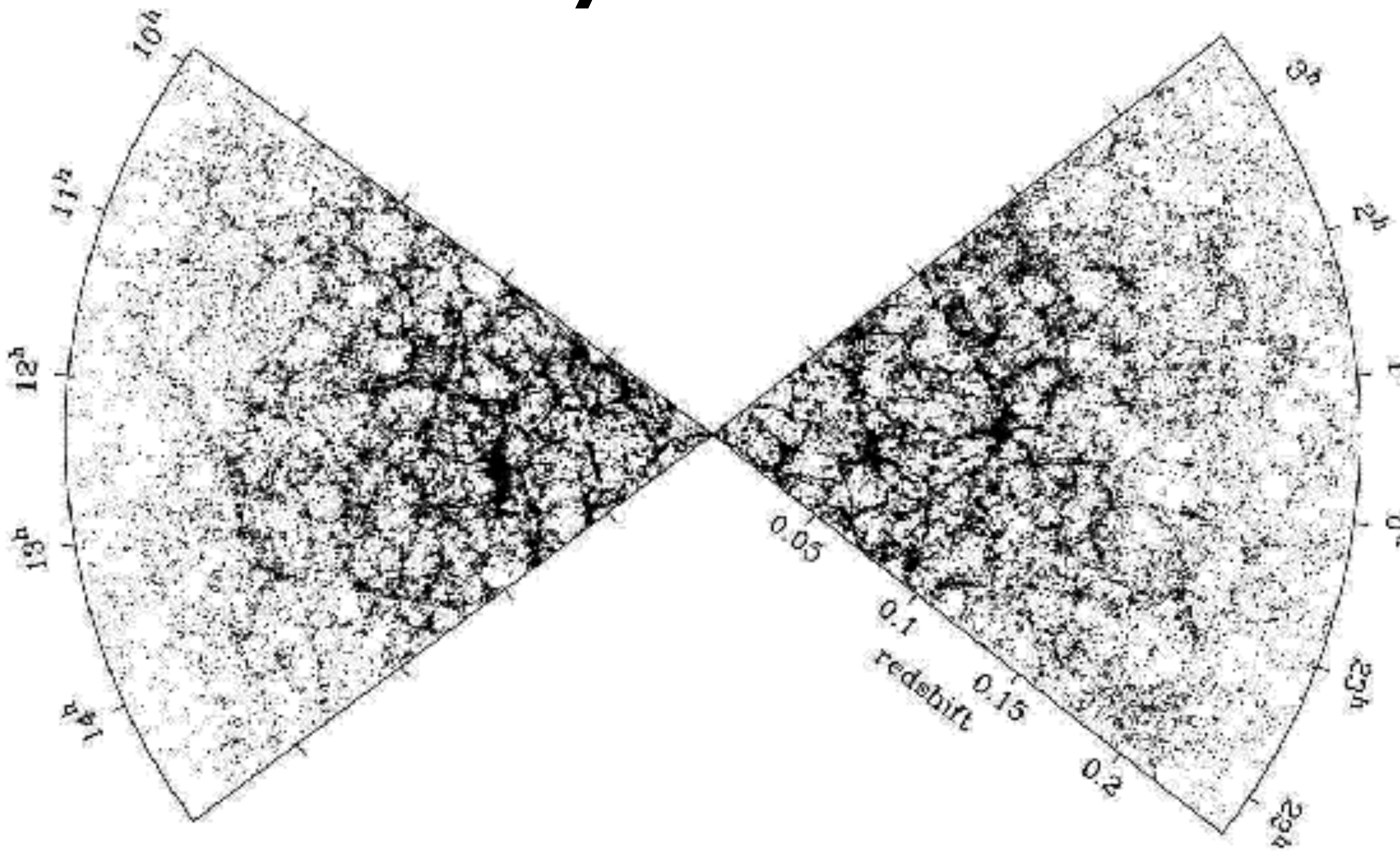


From these measurements, we get the **relative** luminosity distances between Type Ia SNe. Since we marginalize over the absolute magnitude, the current SN data are **<u>not</u>** sensitive to the absolute distances.

- Riess et al. (2004; 2006) HST data
- Astier et al. (2006) Supernova Legacy Survey (SNLS)
- Wood-Vasey et al. (2007) ESSENCE data

BAO in Galaxy Distribution

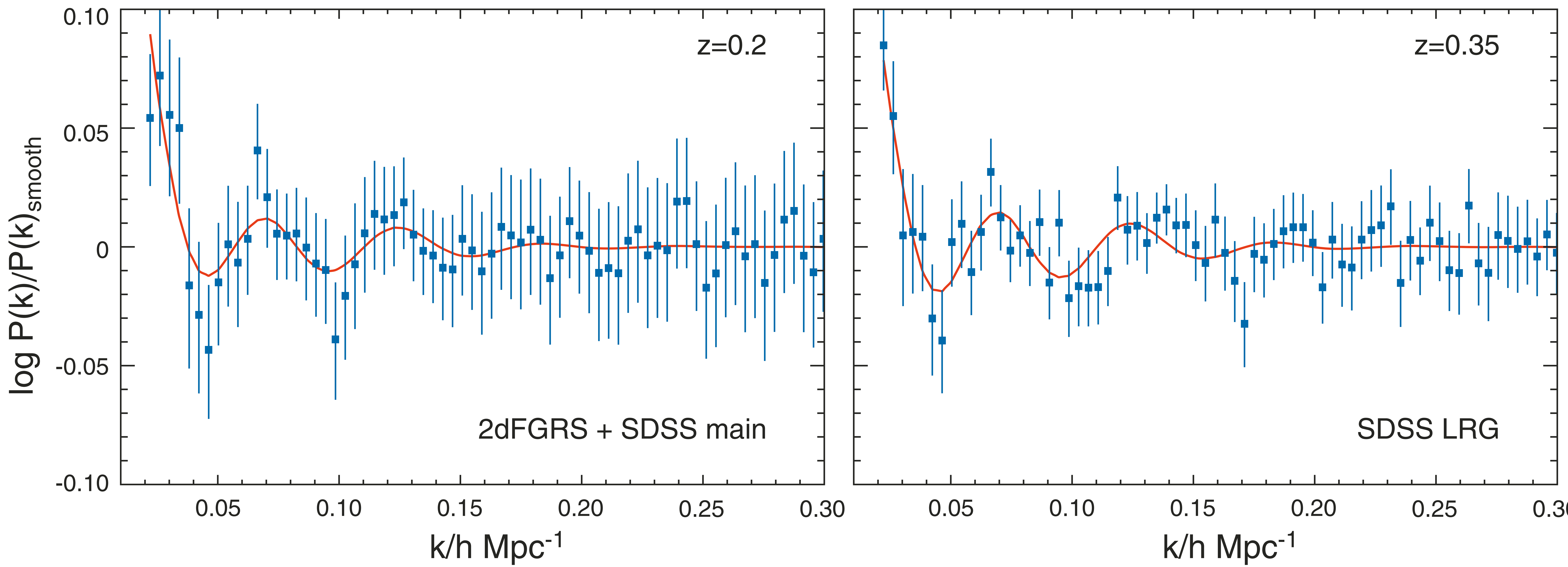
Tegmark et al.



- The same acoustic oscillations are hidden in this galaxy distribution...

BAO in Galaxy Distribution

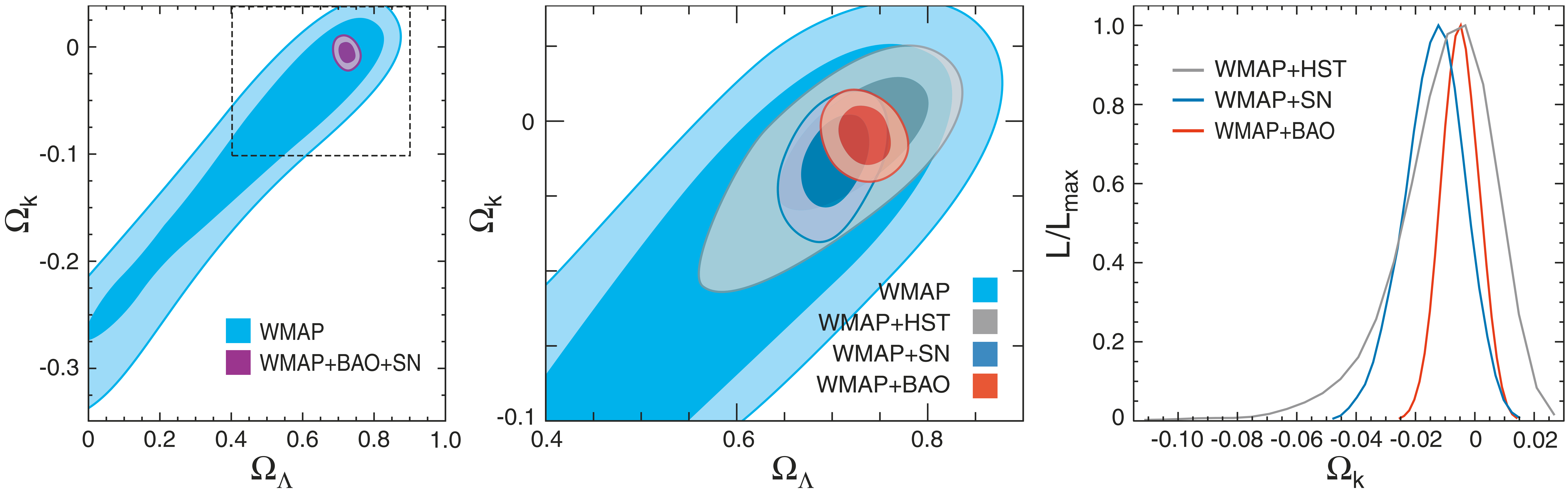
Dunkley et al.



- 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.

Fun Numbers to Quote

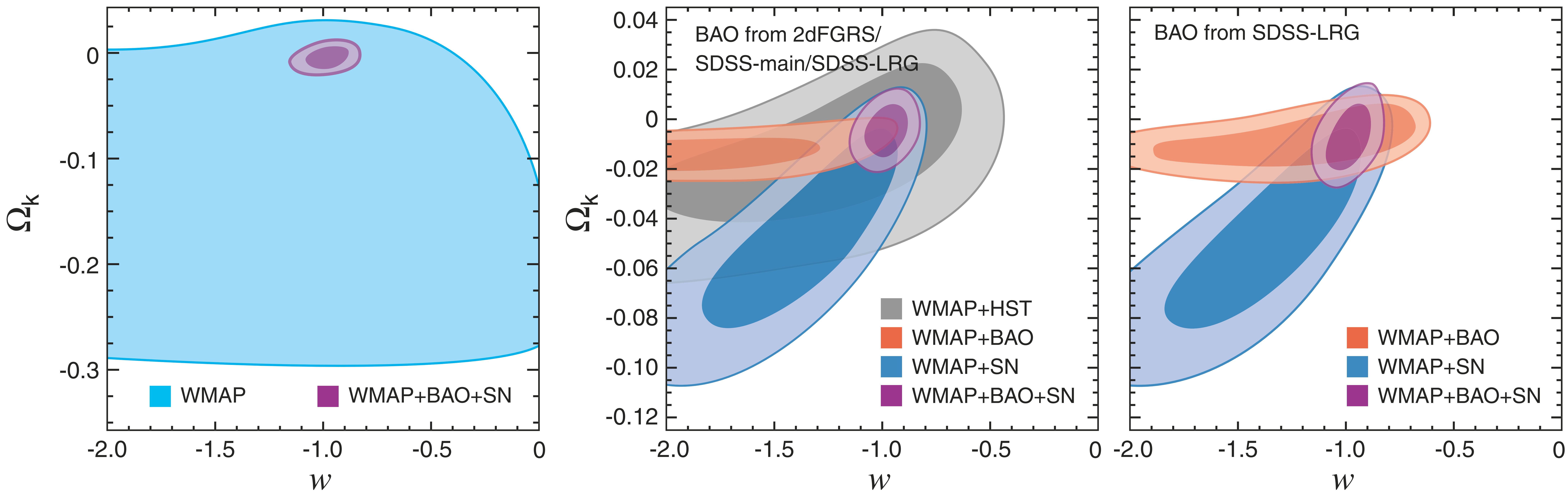
- The curvature radius of the universe is given, by definition, by
  - $R_{curv} = 3h^{-1}\text{Gpc} / \text{sqrt}(\Omega_k)$
  - For negatively curved space ($\Omega_k>0$): $R>33h^{-1}\text{Gpc}$
  - For positively curved space ($\Omega_k<0$): $R>23h^{-1}\text{Gpc}$
- The particle horizon today is $9.7h^{-1}\text{Gpc}$
  - The curvature radius of the universe is at least 3 times as large as the observable universe.

Implications for Inflation?

- Details aside...
  - Q. How long should inflation have lasted to explain the observed flatness of the universe?
  - A. $\mathbf{N_{total} > 36}$ + $\ln(T_{reheating}/1\ \mathrm{TeV})$
  - 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

What If Dark Energy Was Not Vacuum Energy (w/=-1)...

Komatsu et al.



- WMAP+BAO -> Curvature; WMAP+SN -> w
- WMAP+BAO+SN -> Simultaneous limit
- **$-0.0175 < \Omega_k < 0.0085$** ; **$-0.11 < 1+w < 0.14$** (95% CL)

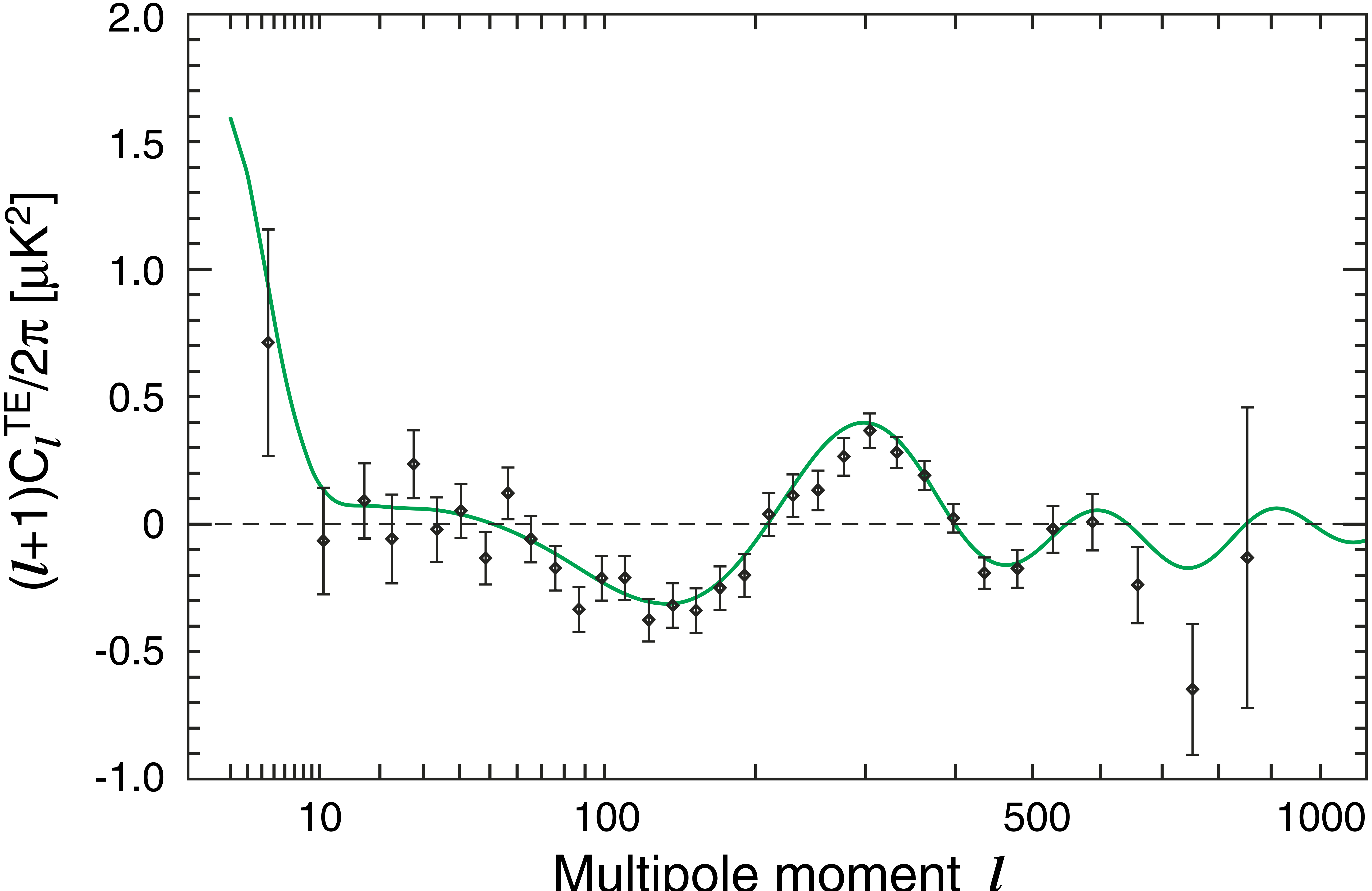
Komatsu et al.

Check List #2: Adiabaticity

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

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.**

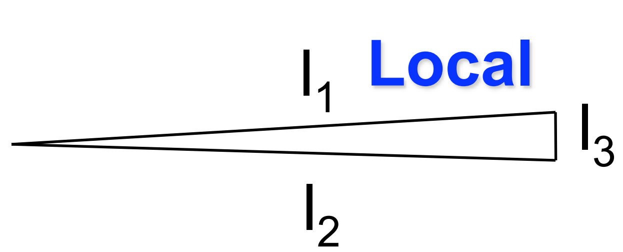
$$\frac{\Omega_a}{\Omega_c} < \frac{3.0 \times 10^{-39}}{\theta_a^5 \gamma^6} \left(\frac{0.01}{r}\right)^{7/2}$$

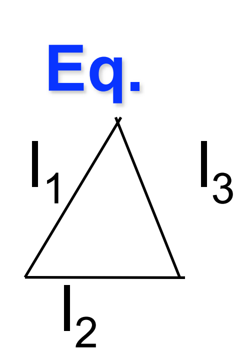
Check list #3: Gaussianity

- 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**

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 f_{NL}^{local}
  - "Equilateral" parameterized by f_{NL}^{equil}





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 (+0.014) (-0.013)
    - **2.9 sigma away from n_s=1**
    - No dramatic improvement from the WMAP-only result because neither BAO nor SN is sensitive to $\Omega_b h^2$

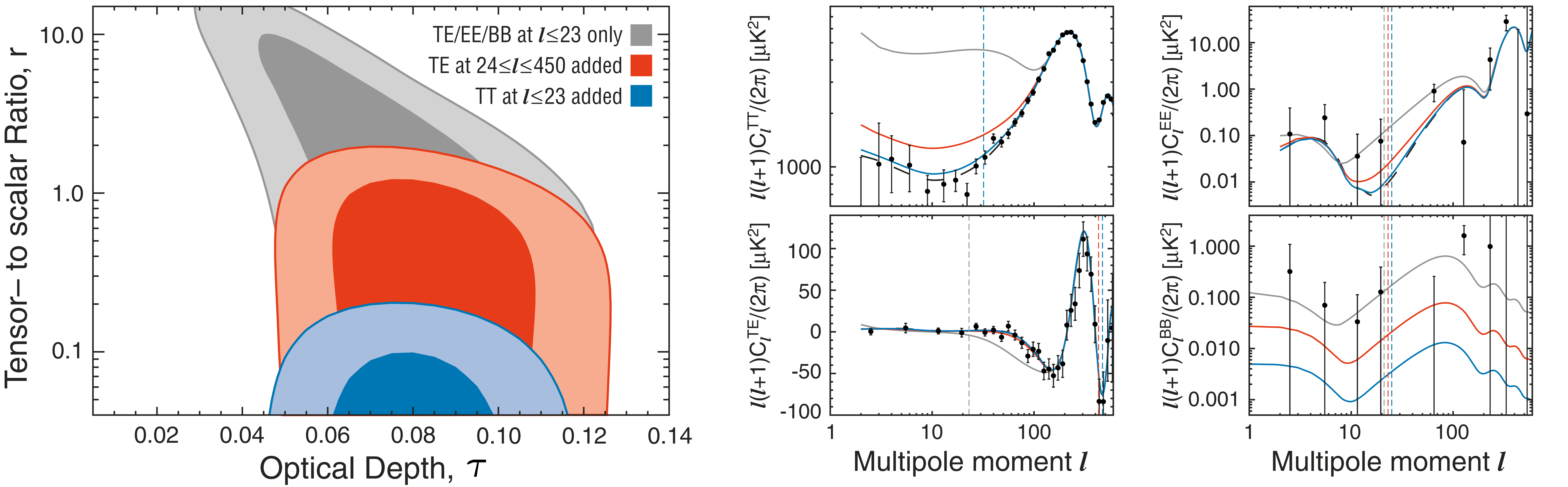
Check List #5: Gravitational Waves

- 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

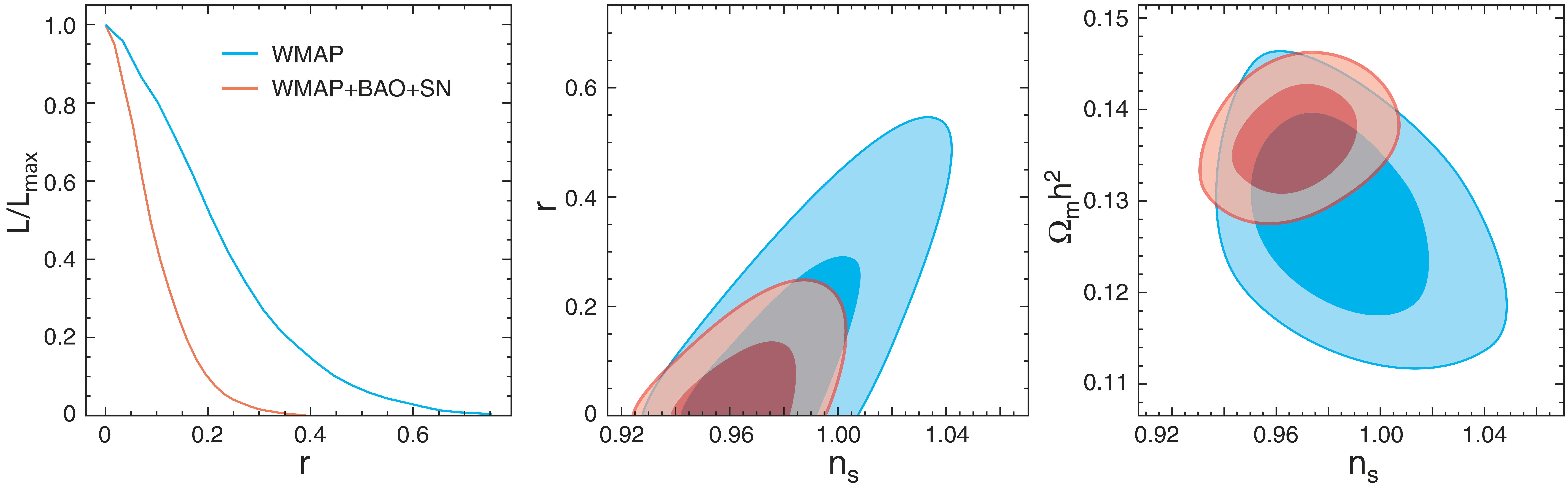
Komatsu et al.



- 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.

Real Life: Killer Degeneracy



- Since the limit on r relies on the low-l temperature, it is strongly degenerate with n_s.
- The degeneracy can be broken partially by BAO&SN
  - r<0.43 (WMAP-only) -> **r<0.20** (WMAP+BAO+SN)

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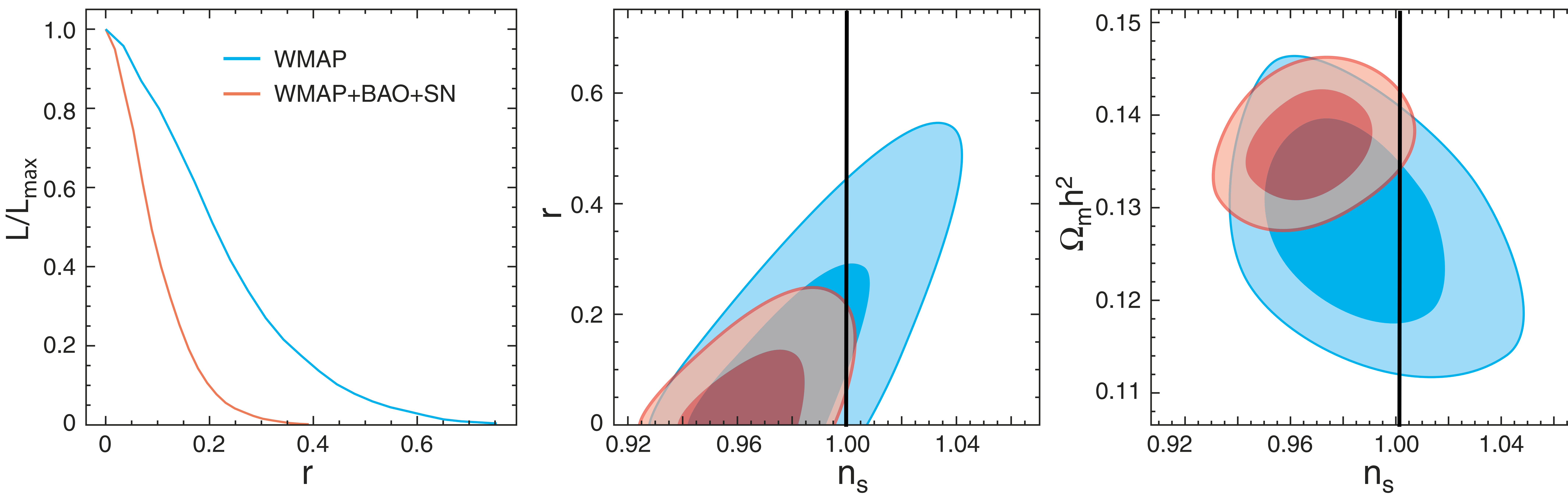
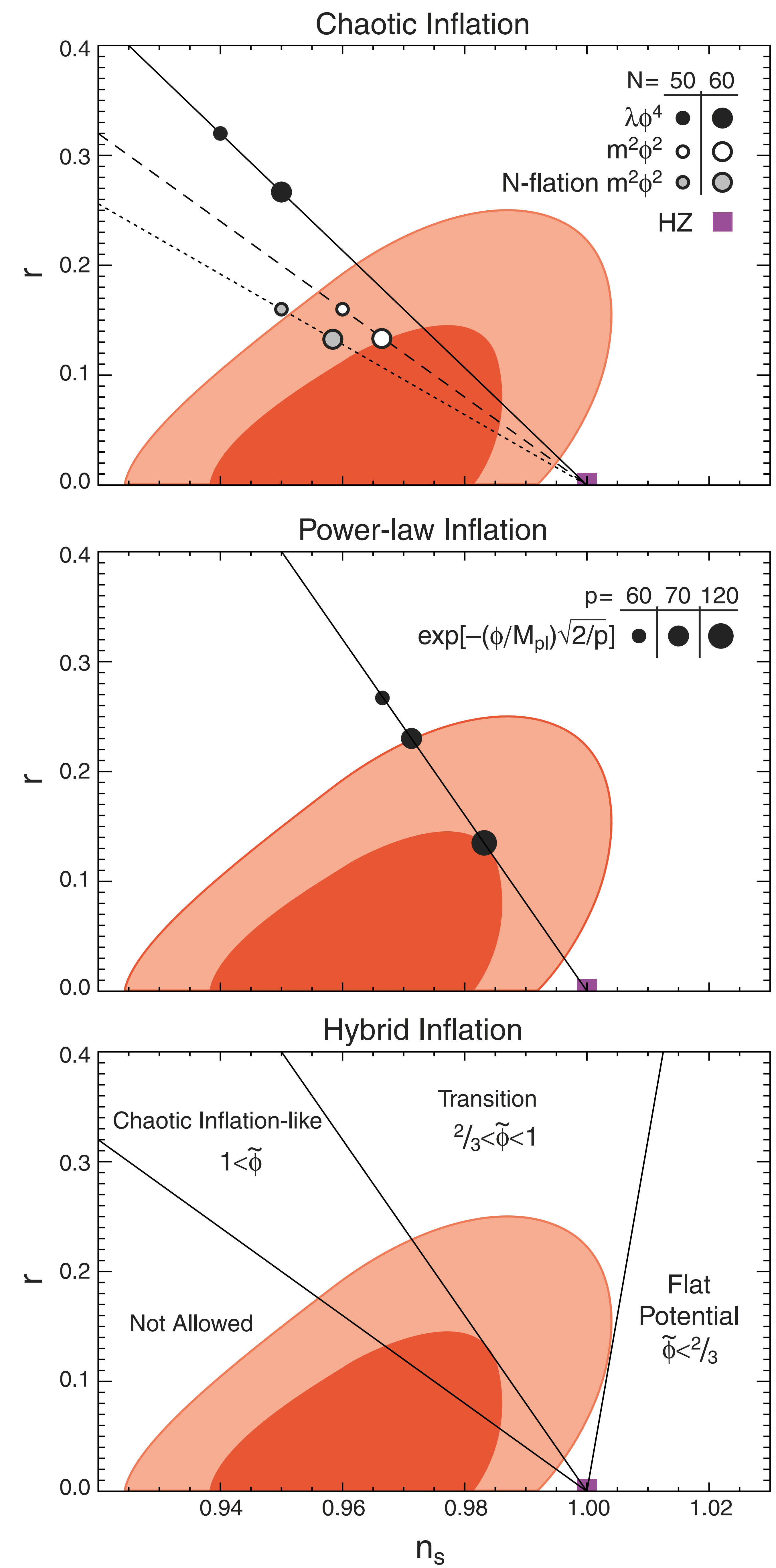
n_s>1.0 is Disfavored, Regardless of r



- The maximum n_s we find at 95% CL is **n_s=1.005 for r=0.16.**



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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

Grading Inflation

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- Flatness: $-0.0175 < \Omega_k < 0.0085$ (not assuming w=-1!)
- Non-adiabaticity: <8.6% (axion DM); <2.0% (curvaton DM)
- Non-Gaussianity: -9 < Local < 111; -151 < Equilateral < 253
- Tilt (for r=0): n_s=0.960 (+0.014) (-0.013) [68% CL]
- Gravitational waves: **r < 0.20**
    - n_s=0.968 (+/- 0.015) [68% CL]
    - **n_s>1 disfavored at 95% CL regardless of r**

Summary

- A simple, yet *mysterious* ΛCDM still fits the WMAP data, as well as the other astrophysical data sets.
- **We did everything we could do to find deviations from ΛCDM, but failed.**
  - Bad news... we still don't know what DE or DM is.
- Significant improvements in limits on the deviations
  - Most notably, $r<0.2$ (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!
- Significant improvements in ΛCDM parameters.

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.

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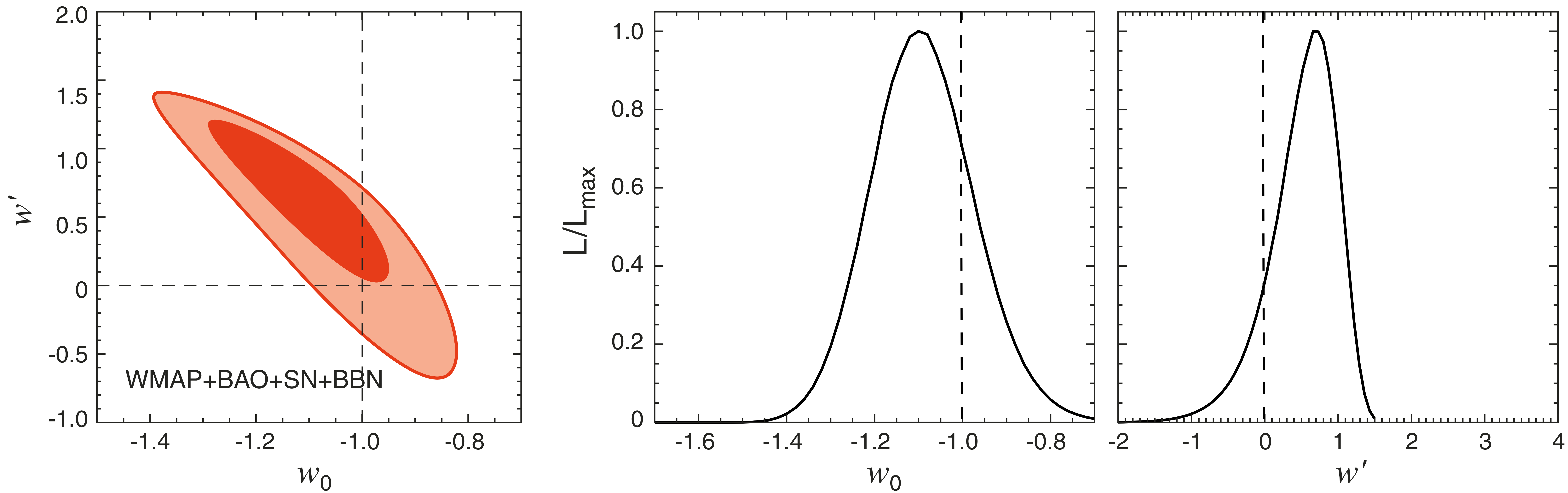
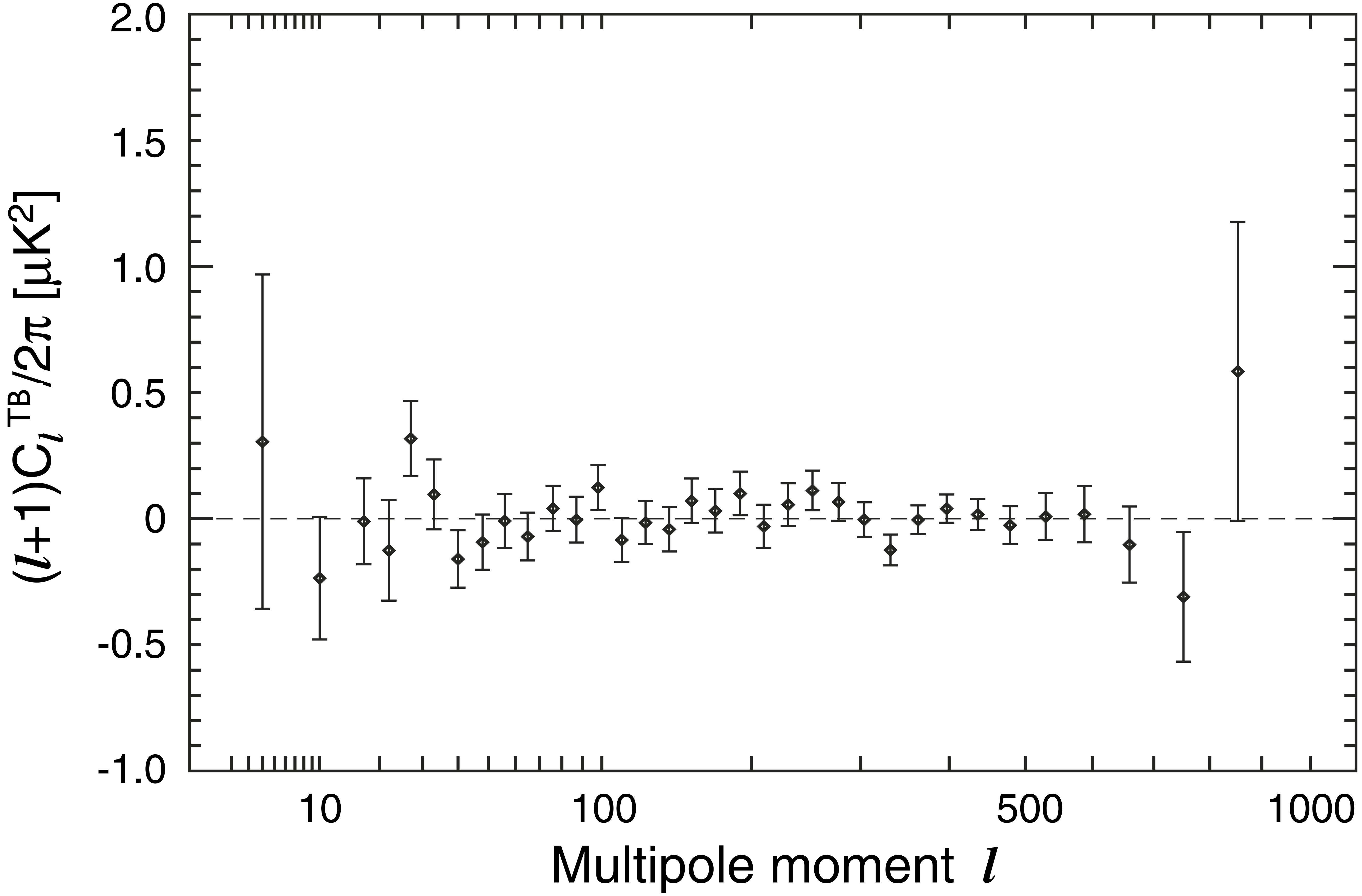
Dark Energy EOS: $w(z)=w_0+w'z/(1+z)$



- Dark energy is pretty consistent with cosmological constant: w_0=-1.09 +/- 0.12 & w'=0.52 +/- 0.46 (68%CL)

Probing Parity Violation

Nolta et al.



- Parity violating interactions that rotate the polarization angle of CMB can produce TB and EB correlations.

Lue, Wang & Kamionkowski (1999); Feng et al. (2005)

E -> B

$$C_l^{TE,obs} = C_l^{TE}\cos(2\Delta\alpha),$$
$$C_l^{TB,obs} = C_l^{TE}\sin(2\Delta\alpha),$$
$$C_l^{EE,obs} = C_l^{EE}\cos^2(2\Delta\alpha),$$
$$C_l^{BB,obs} = C_l^{EE}\sin^2(2\Delta\alpha),$$
$$C_l^{EB,obs} = \frac{1}{2}C_l^{EE}\sin(4\Delta\alpha).$$

- These are simpler relations when there was no primordial B-mode polarization.
- How much rotation would WMAP allow?

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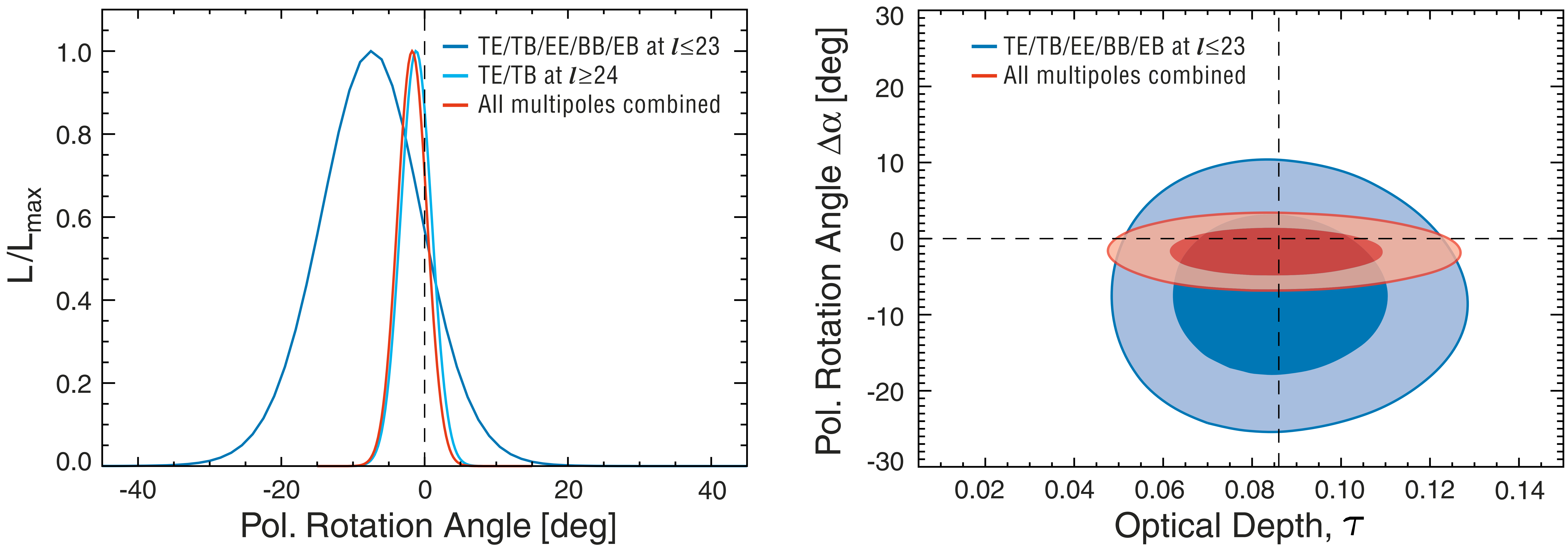

- **$\Delta\alpha$=(-1.7 +/- 2.1) degrees (68% CL)**
- Comparable to the astrophysical constraint from quasars and radio galaxies
  - $\Delta\alpha$=(-0.6 +/- 1.5) degrees (68% CL) (Carroll 1998)
- But, note the difference in path length!