



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

**Eiichiro Komatsu** (Department of Astronomy, UT Austin)  
ISCAP Seminar, Columbia University, May 1, 2008

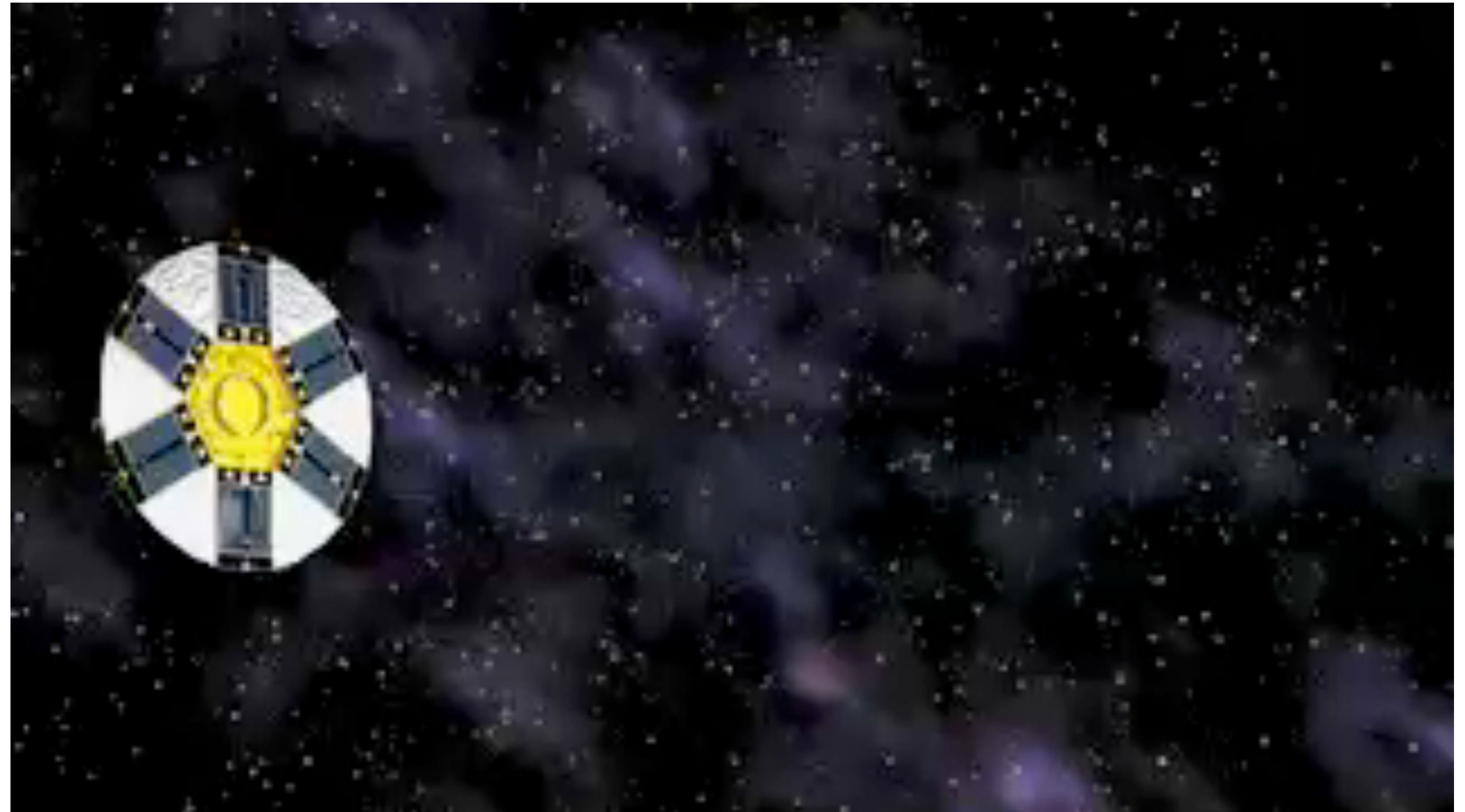
# WMAP at Lagrange 2 (L2) Point

June 2001:  
WMAP launched!

February 2003:  
The first-year data  
release

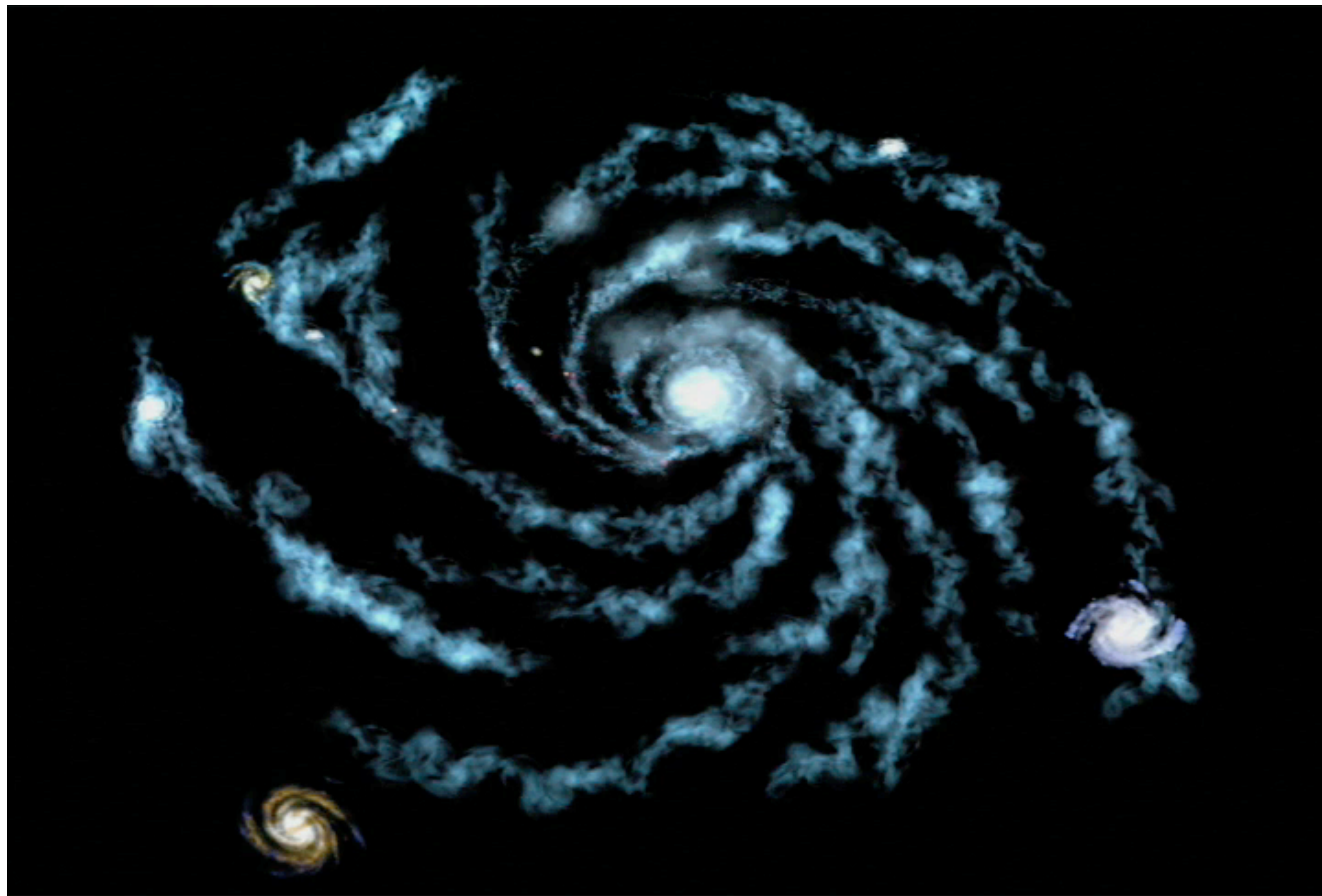
March 2006:  
The three-year data  
release

**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

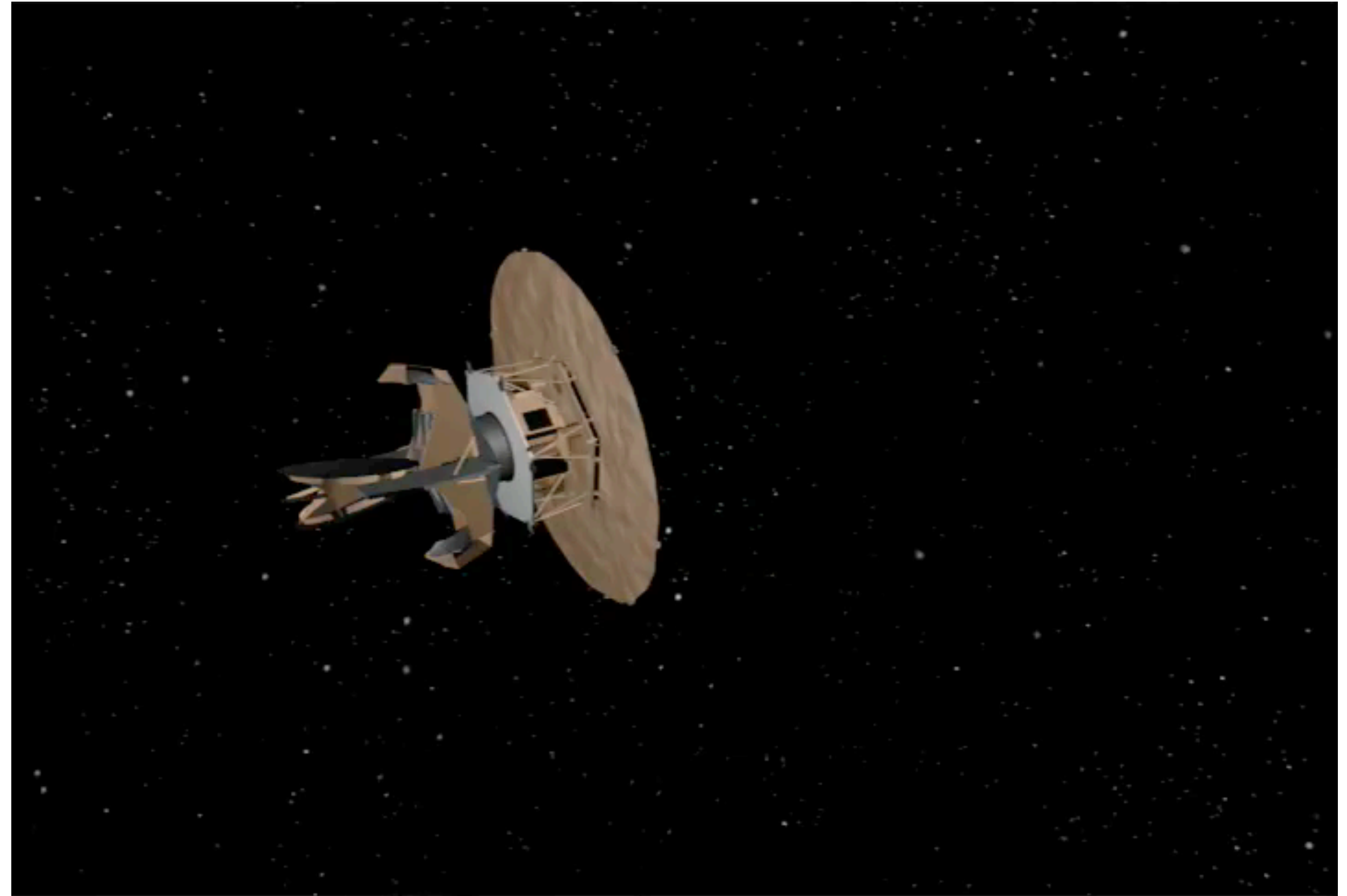
# WMAP Measures Microwaves From the Universe



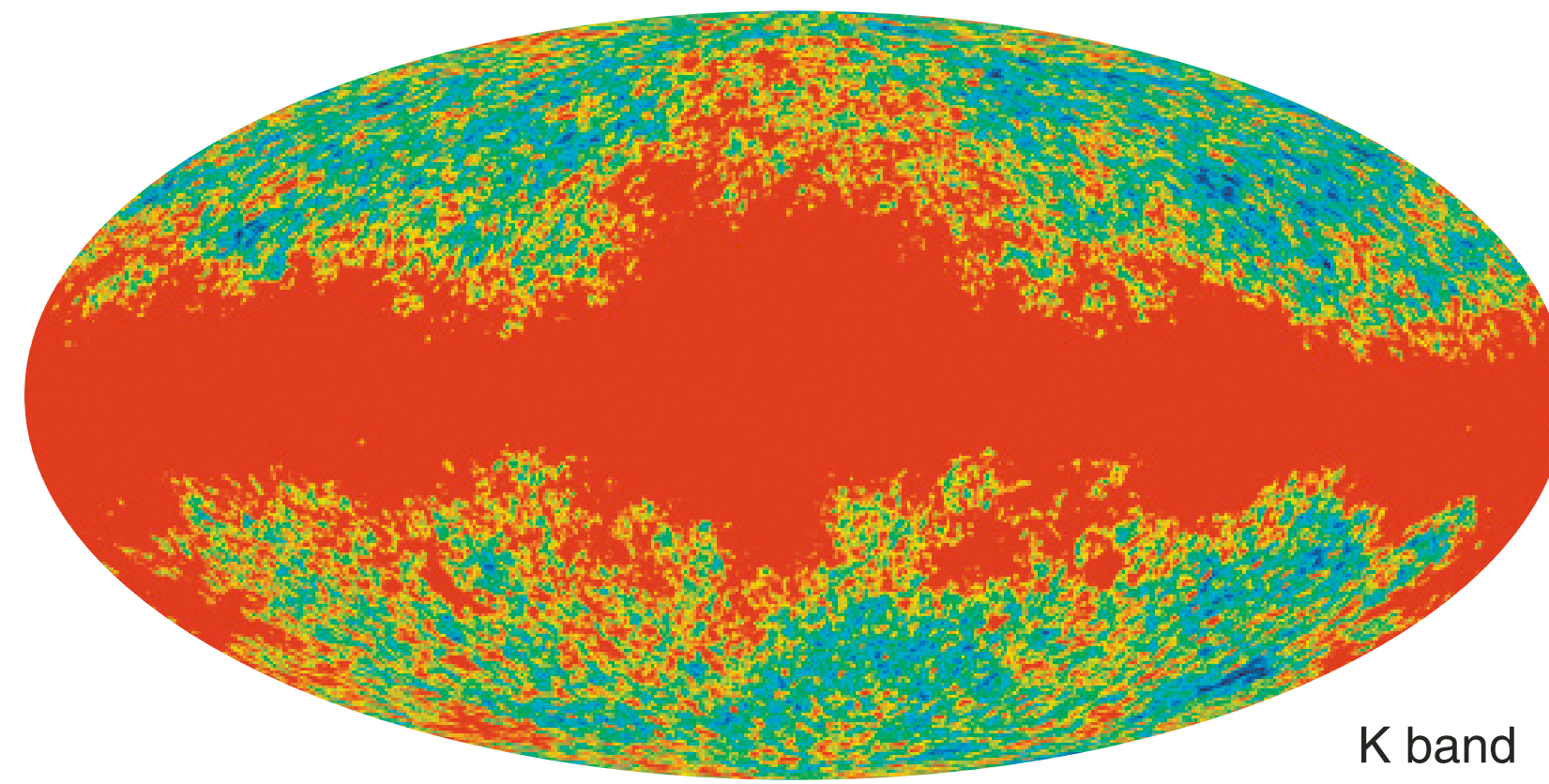
- The mean temperature of photons in the Universe today is 2.725 K
- WMAP is capable of measuring the temperature *contrast* down to better than one part in millionth

# Journey Backwards in Time

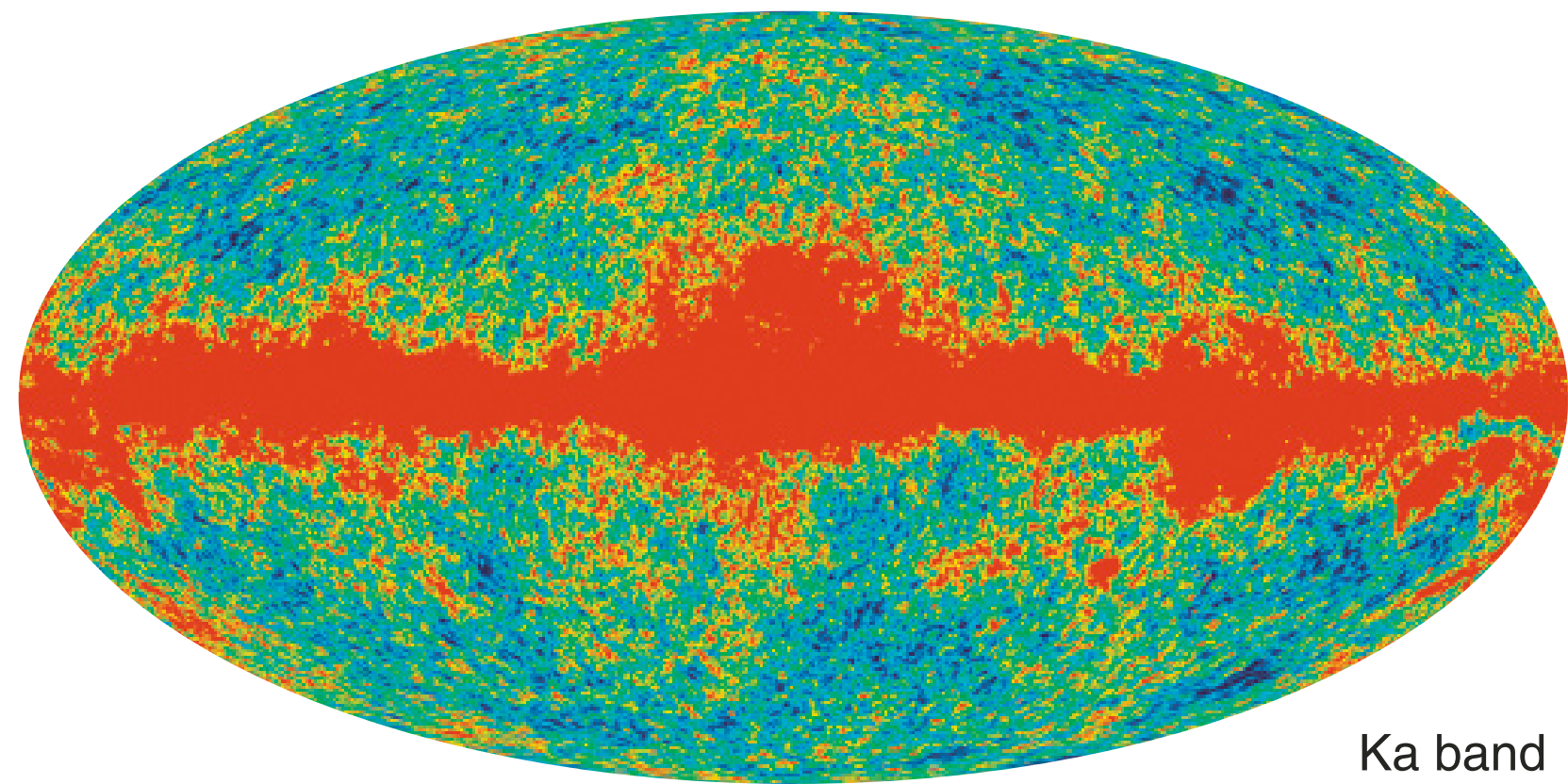
- The Cosmic Microwave Background (**CMB**) is *the fossil light from the Big Bang*
- This is the oldest light that one can ever hope to measure
- CMB is a direct image of the Universe when the Universe was only 380,000 years old



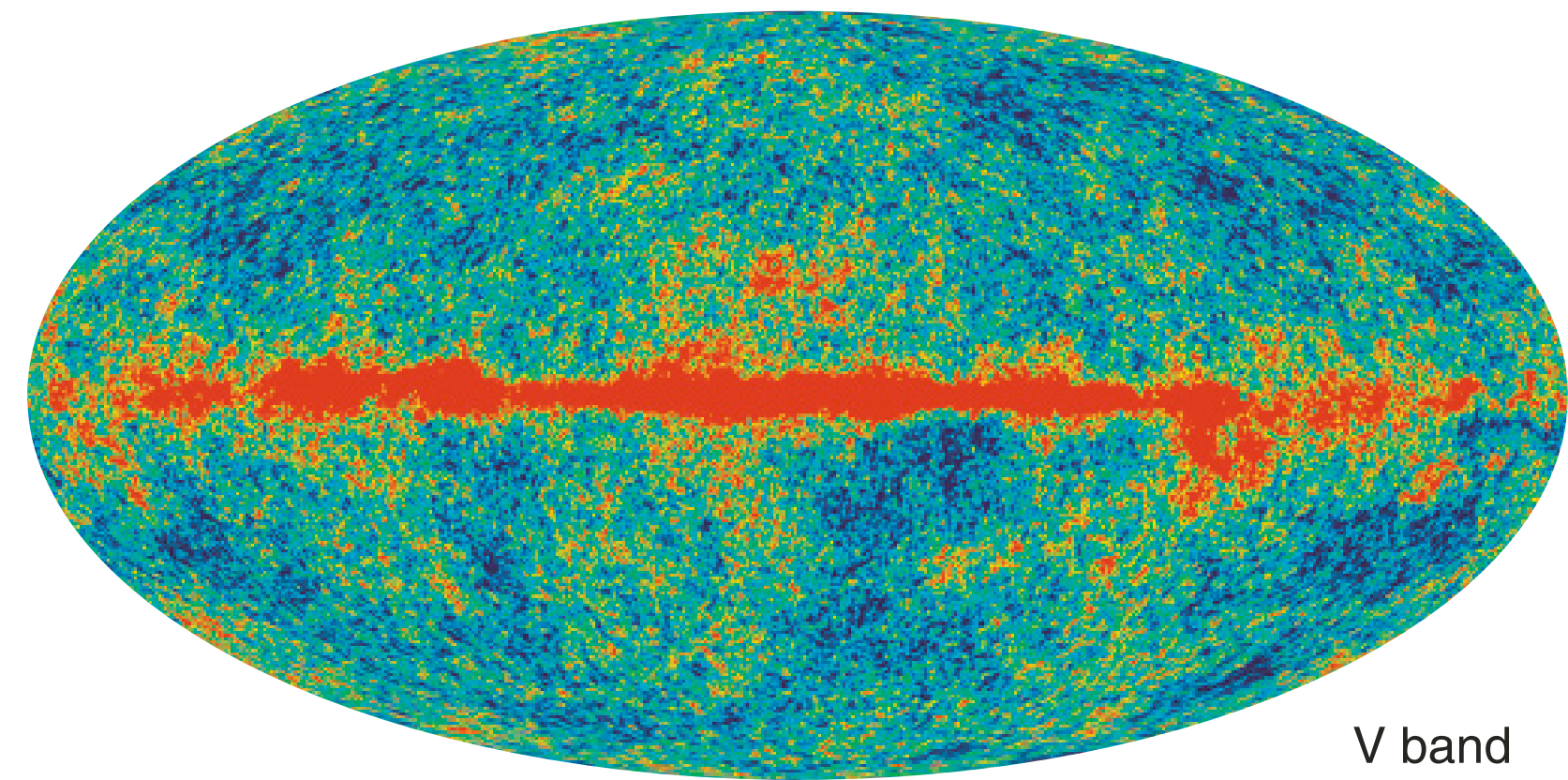
- CMB photons, after released from the cosmic plasma “soup,” traveled for **13.7 billion years** to reach us.
- CMB collects information about the Universe as it travels through it.



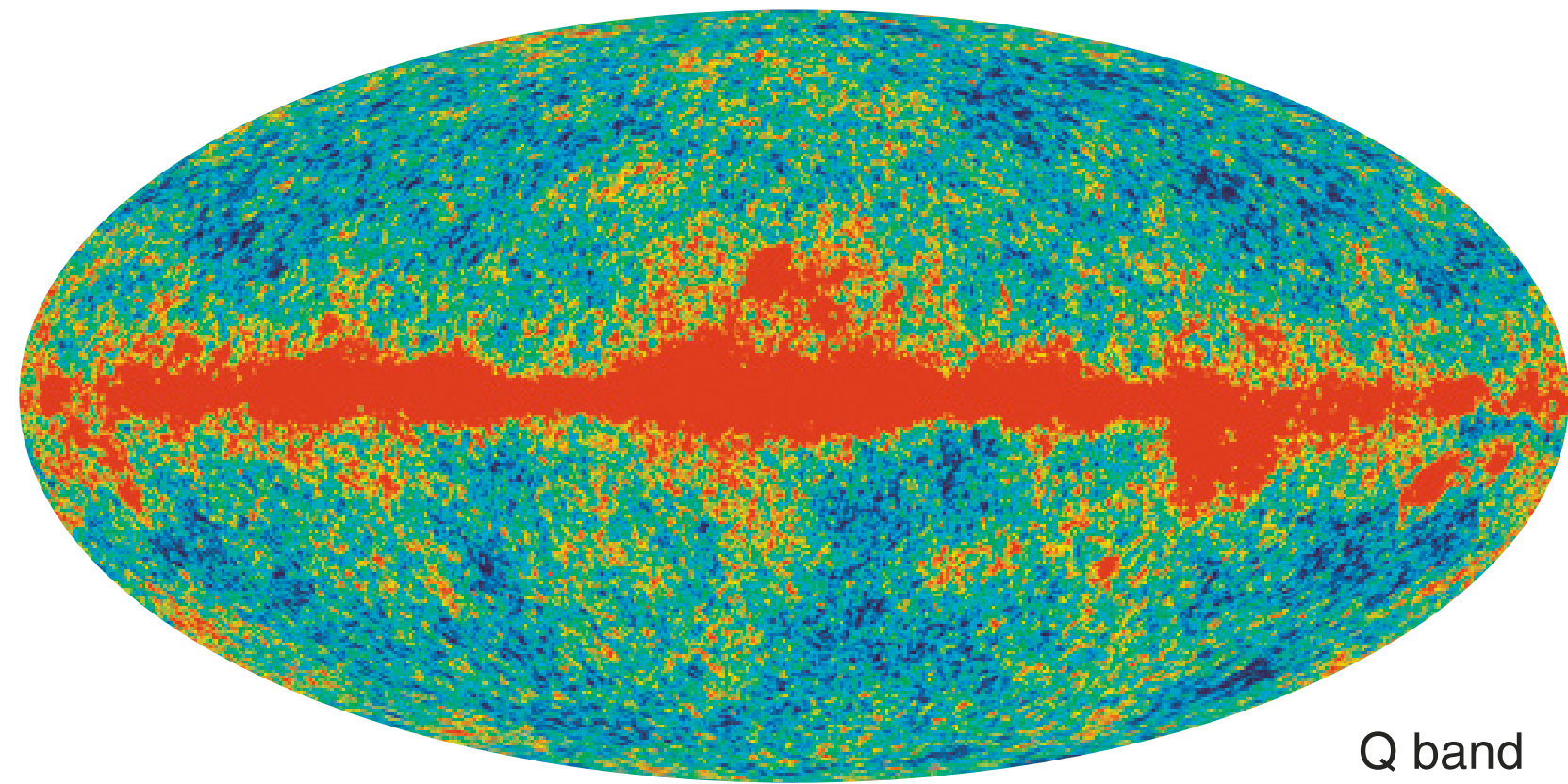
K band



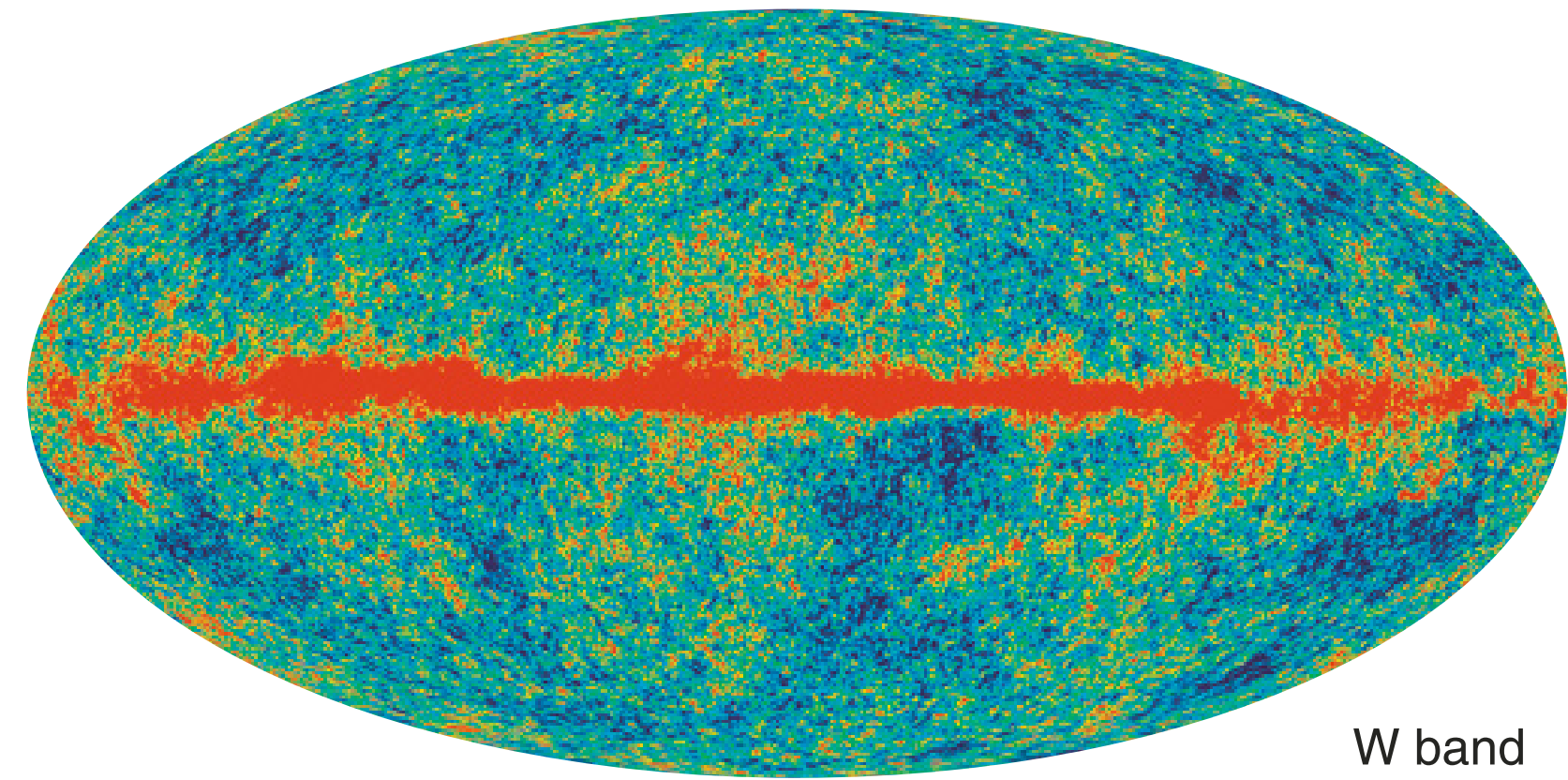
Ka band



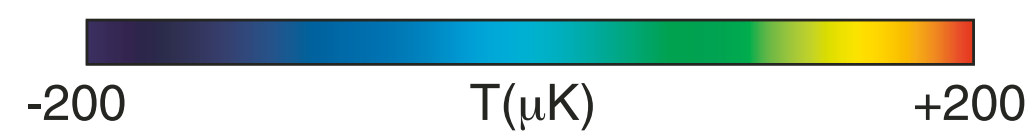
V band

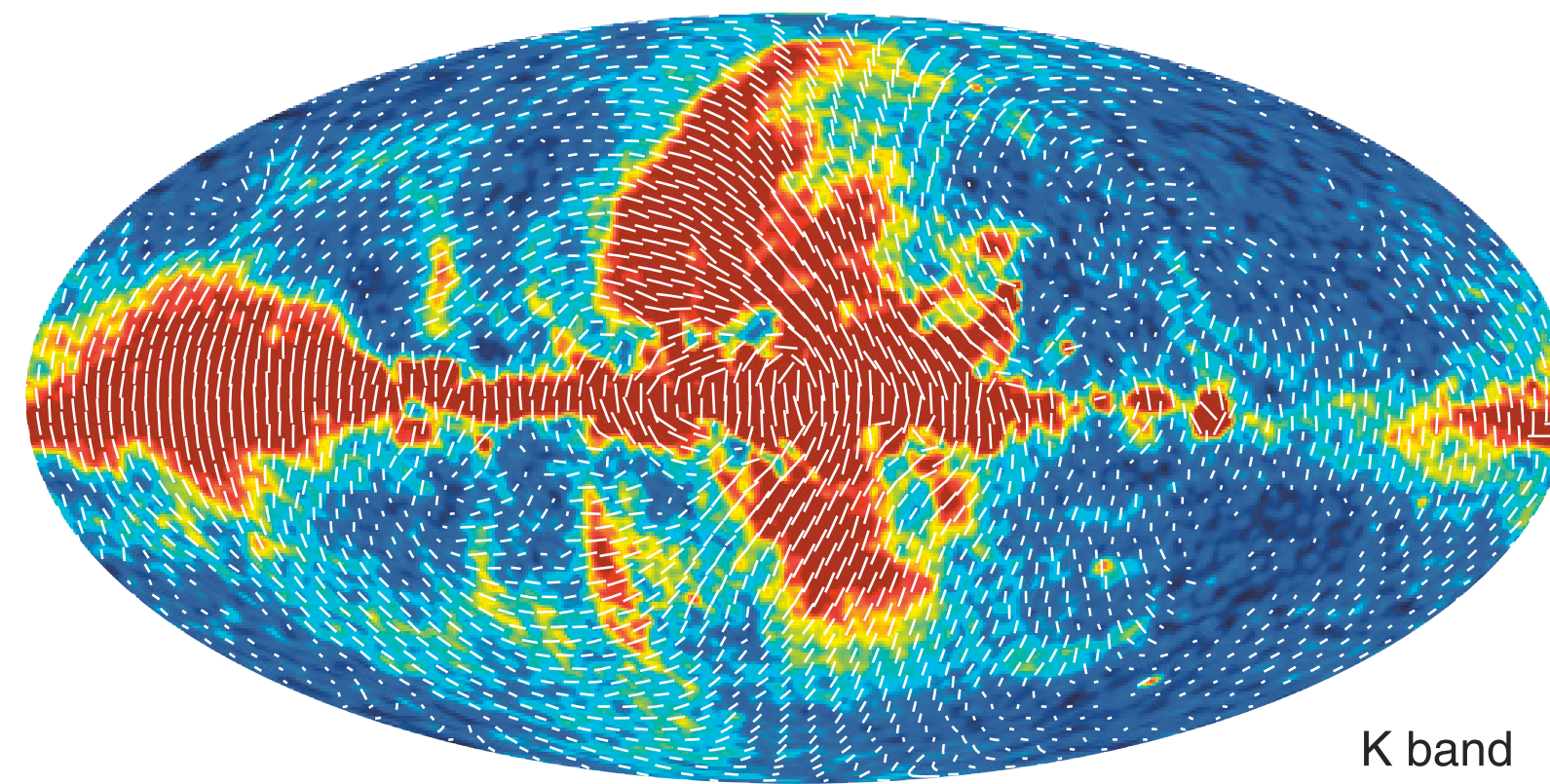


Q band

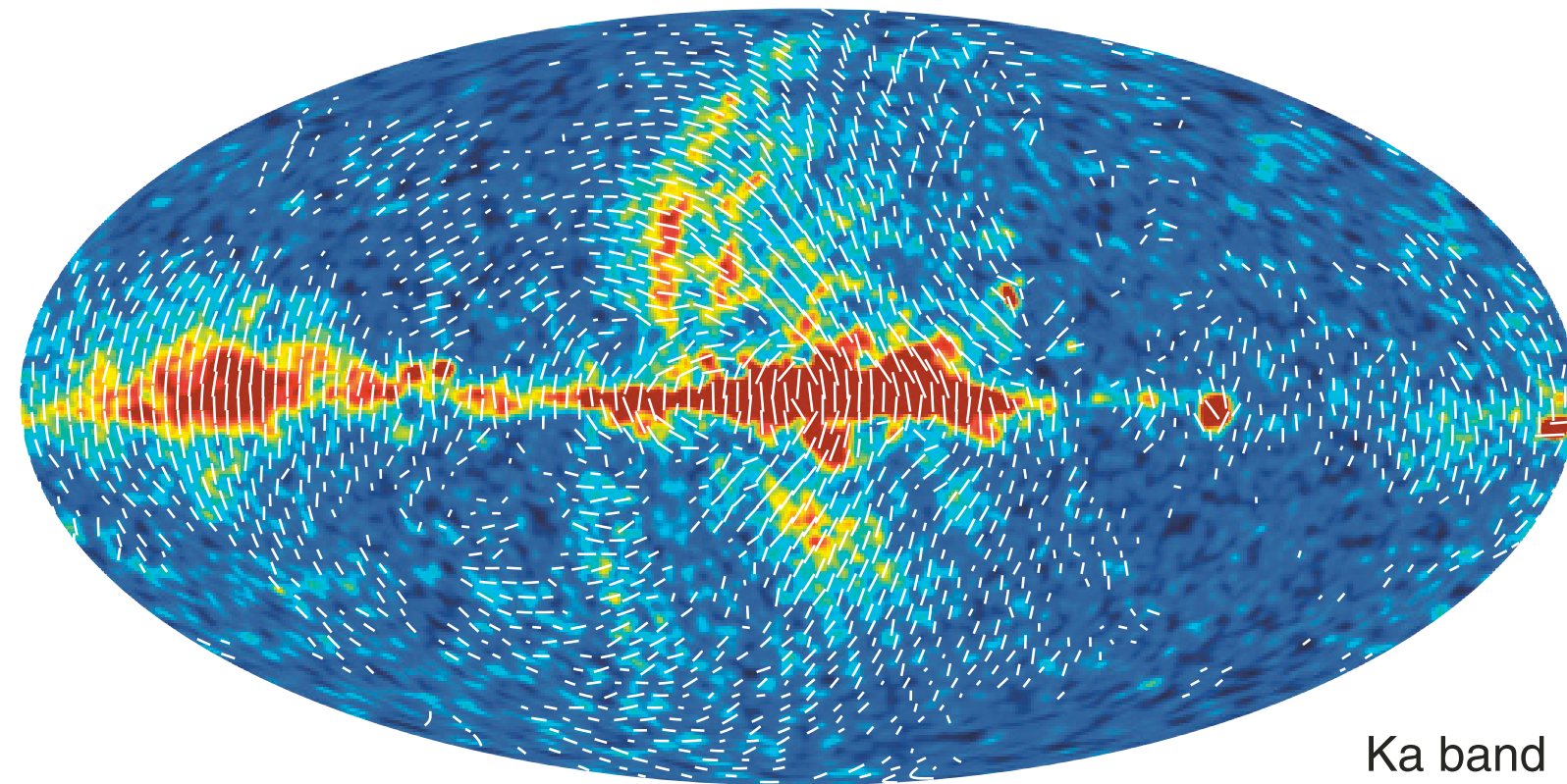
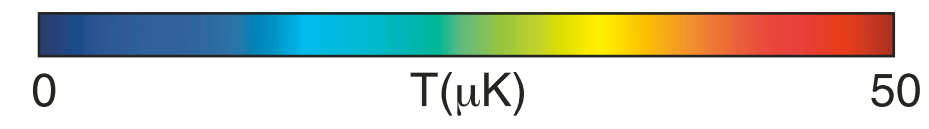


W band

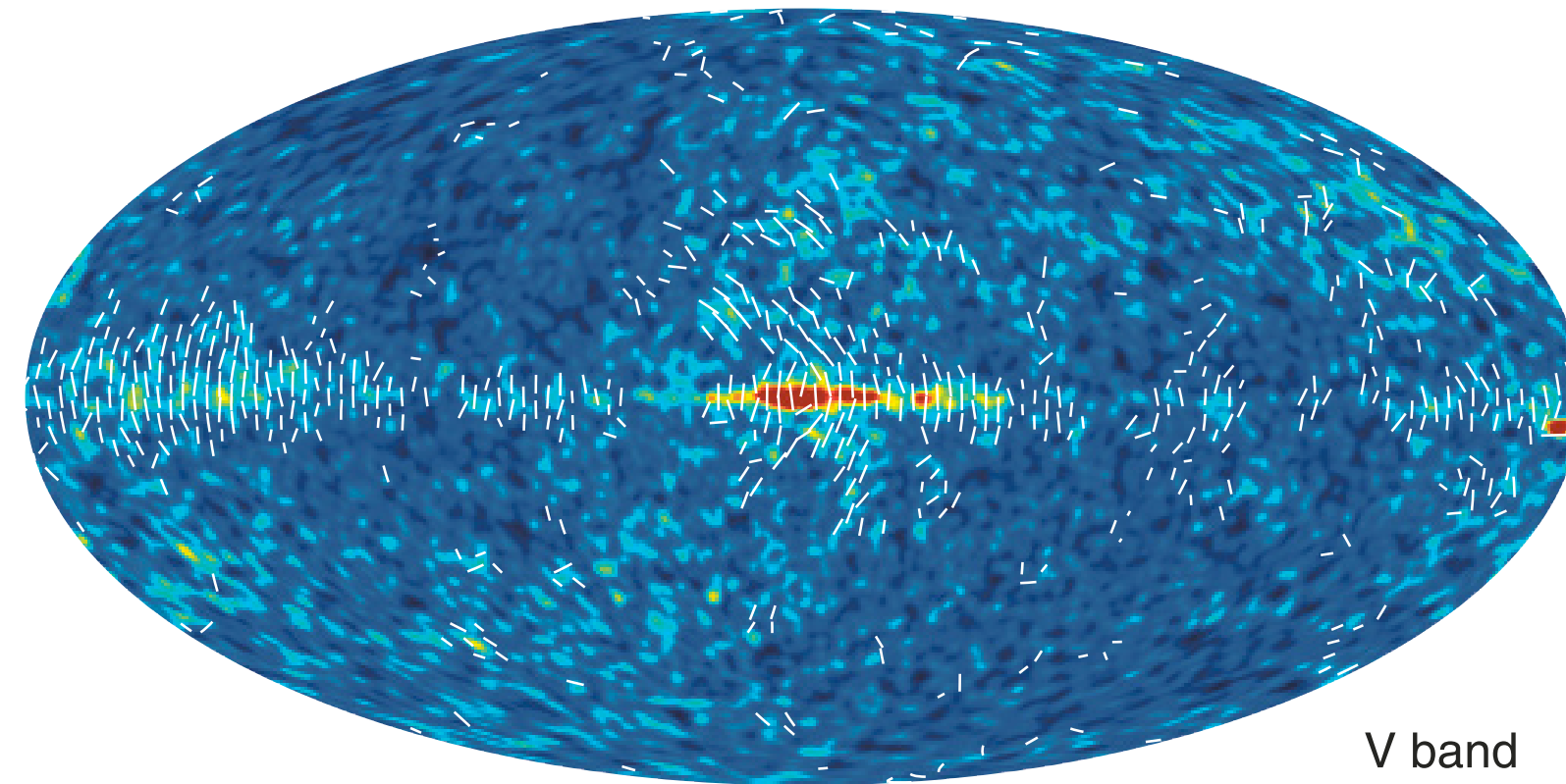




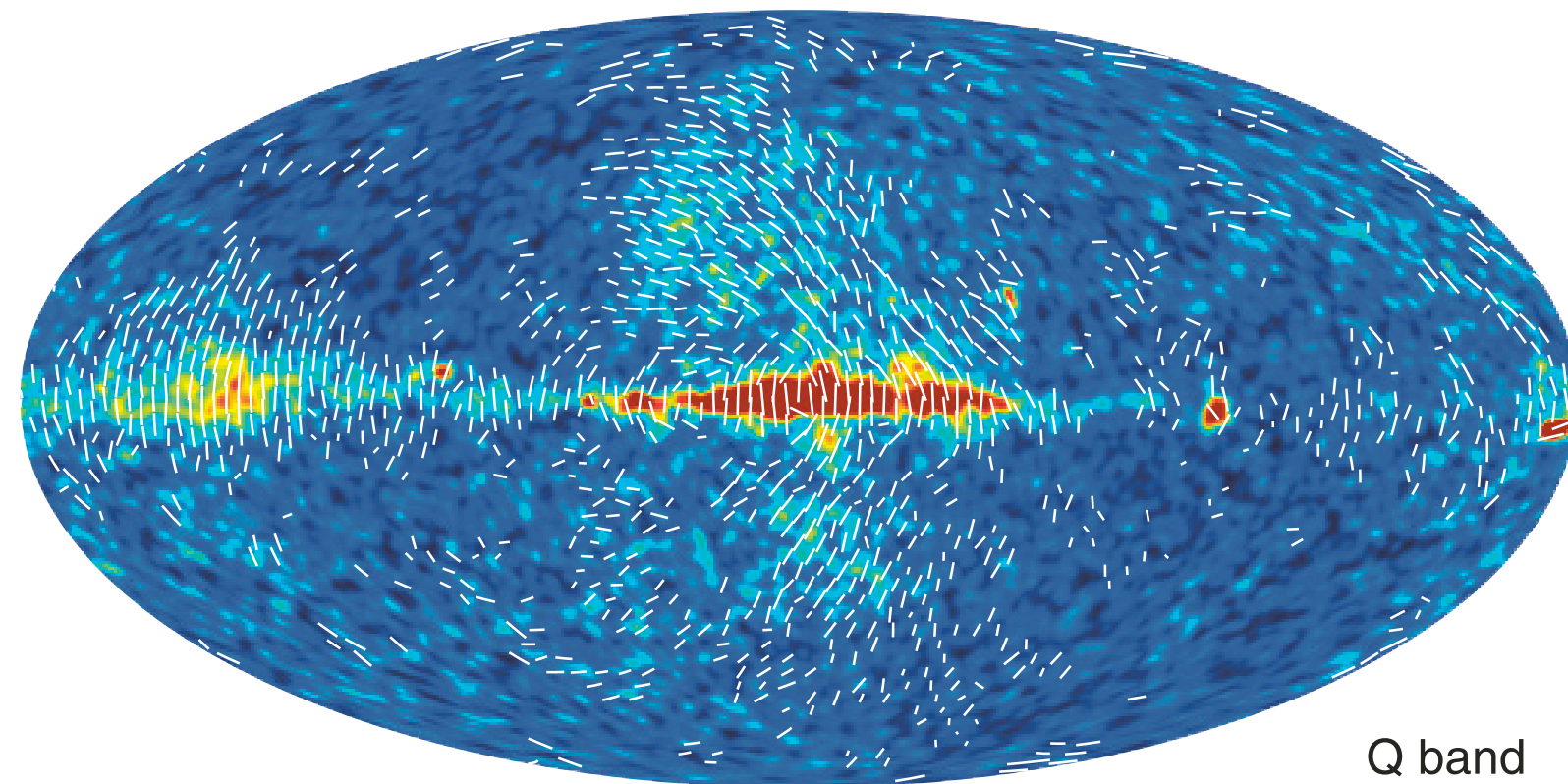
K band



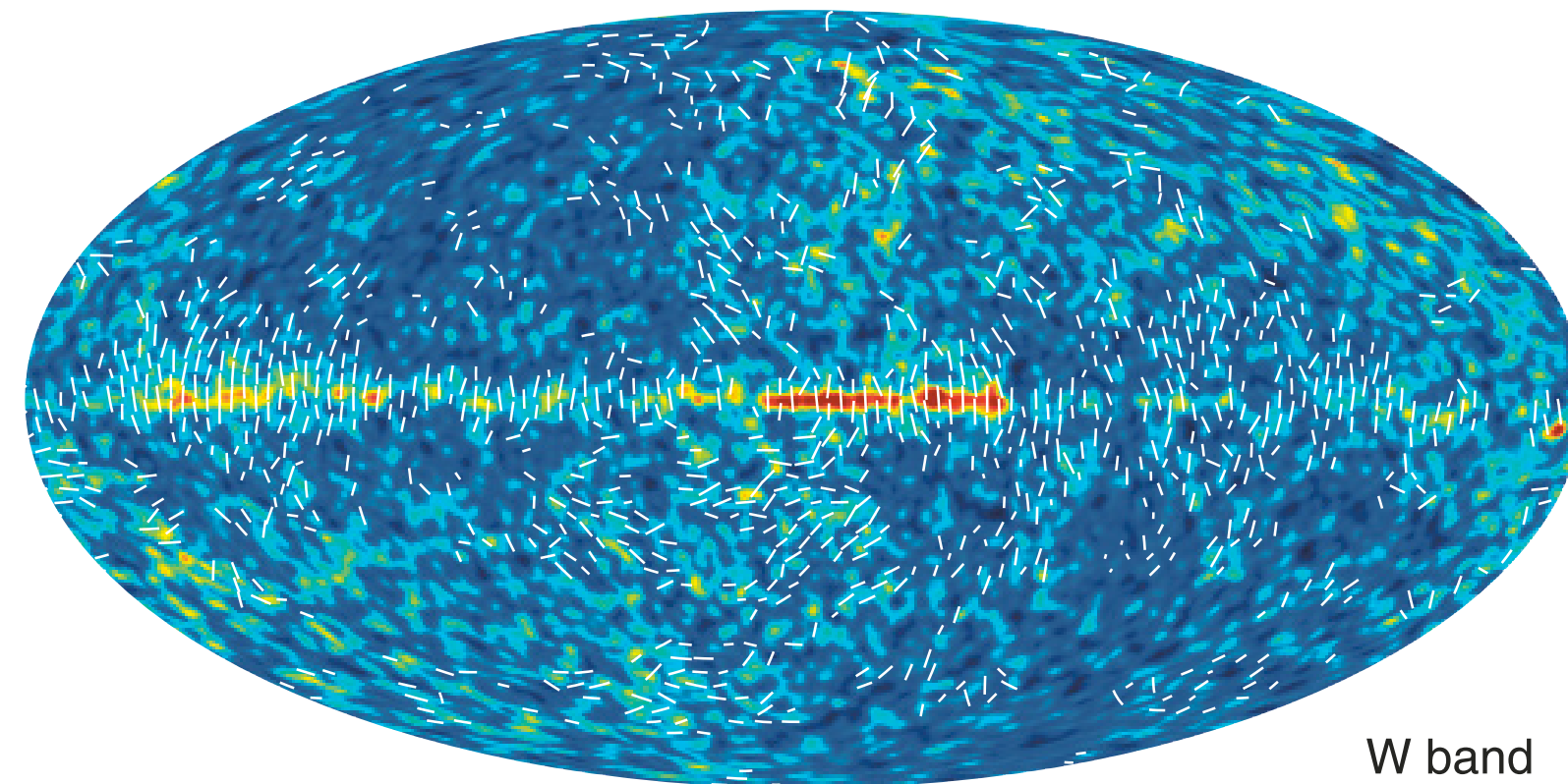
Ka band



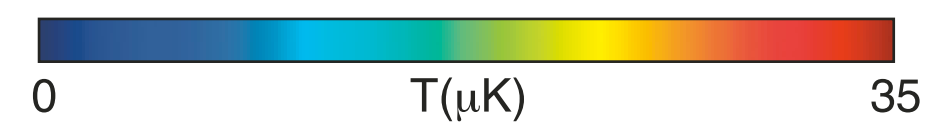
V band



Q band

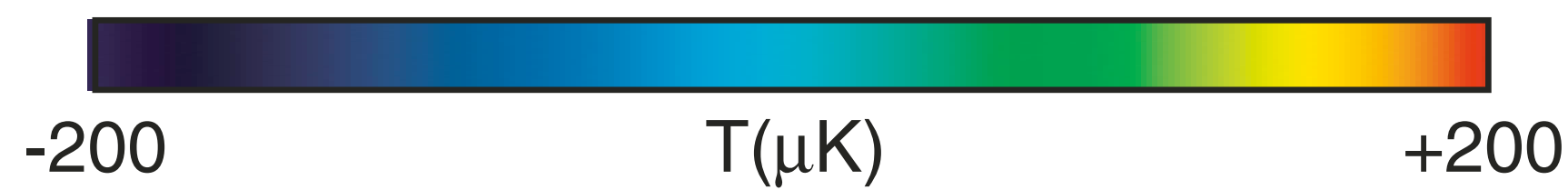
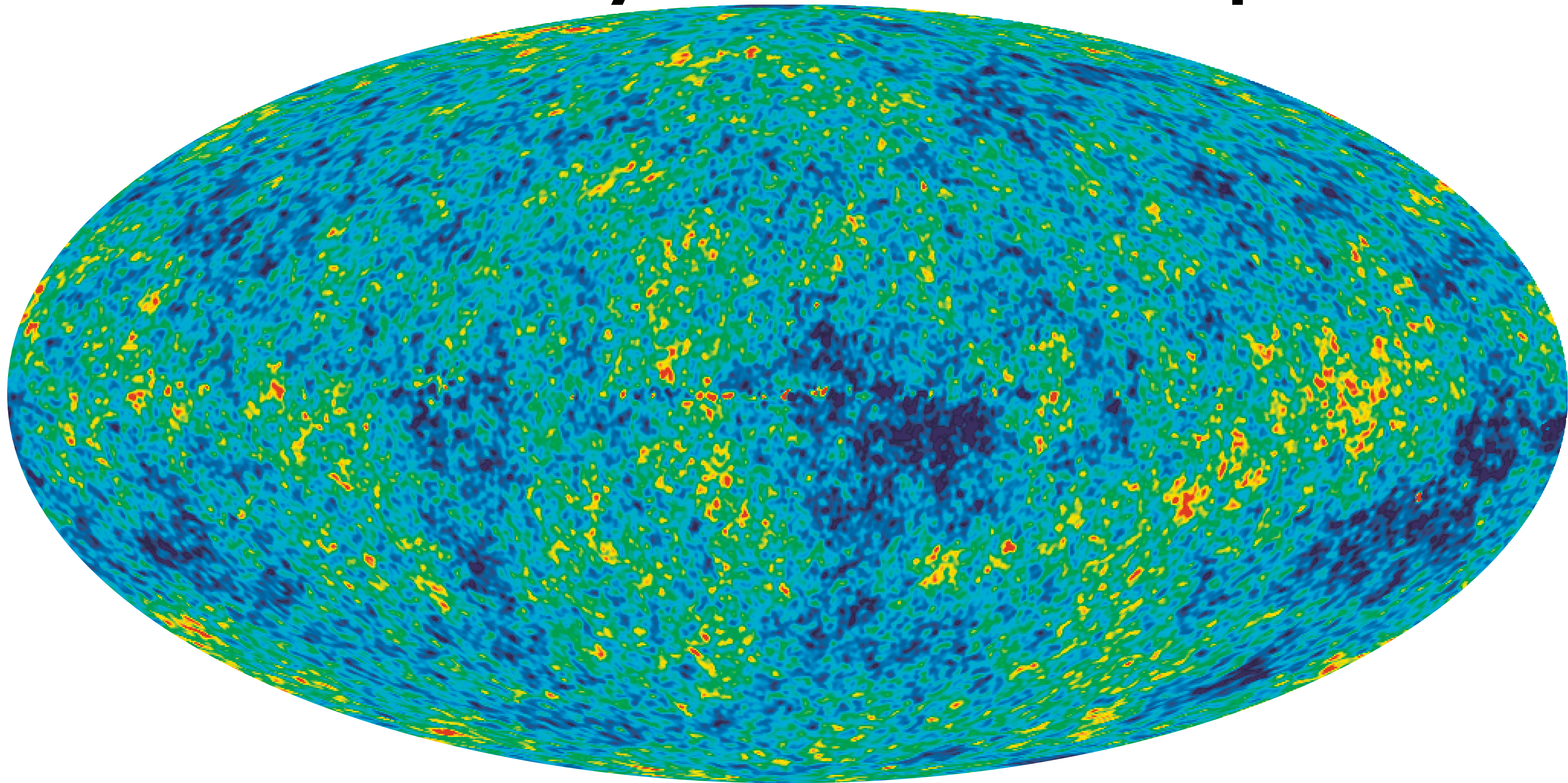


W band



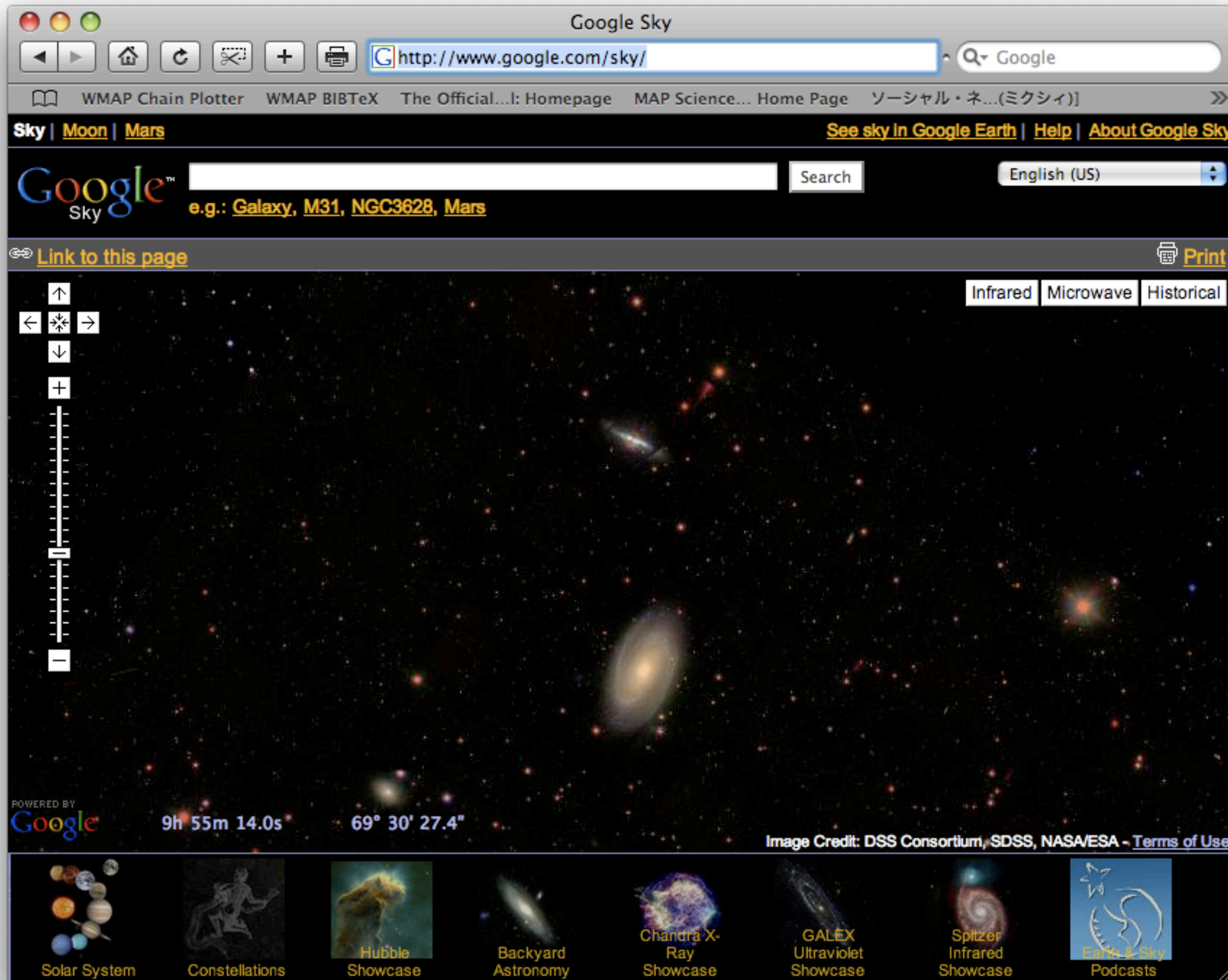
# Galaxy-cleaned Map

*Hinshaw et al.*



WMAP 5-year

# 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
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- M. Halpern
- R.S. Hill
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- M. Limon
- N. Odegard
- G.S. Tucker
- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R.olta

Special  
Thanks to  
**WMAP**  
**Graduates!**

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

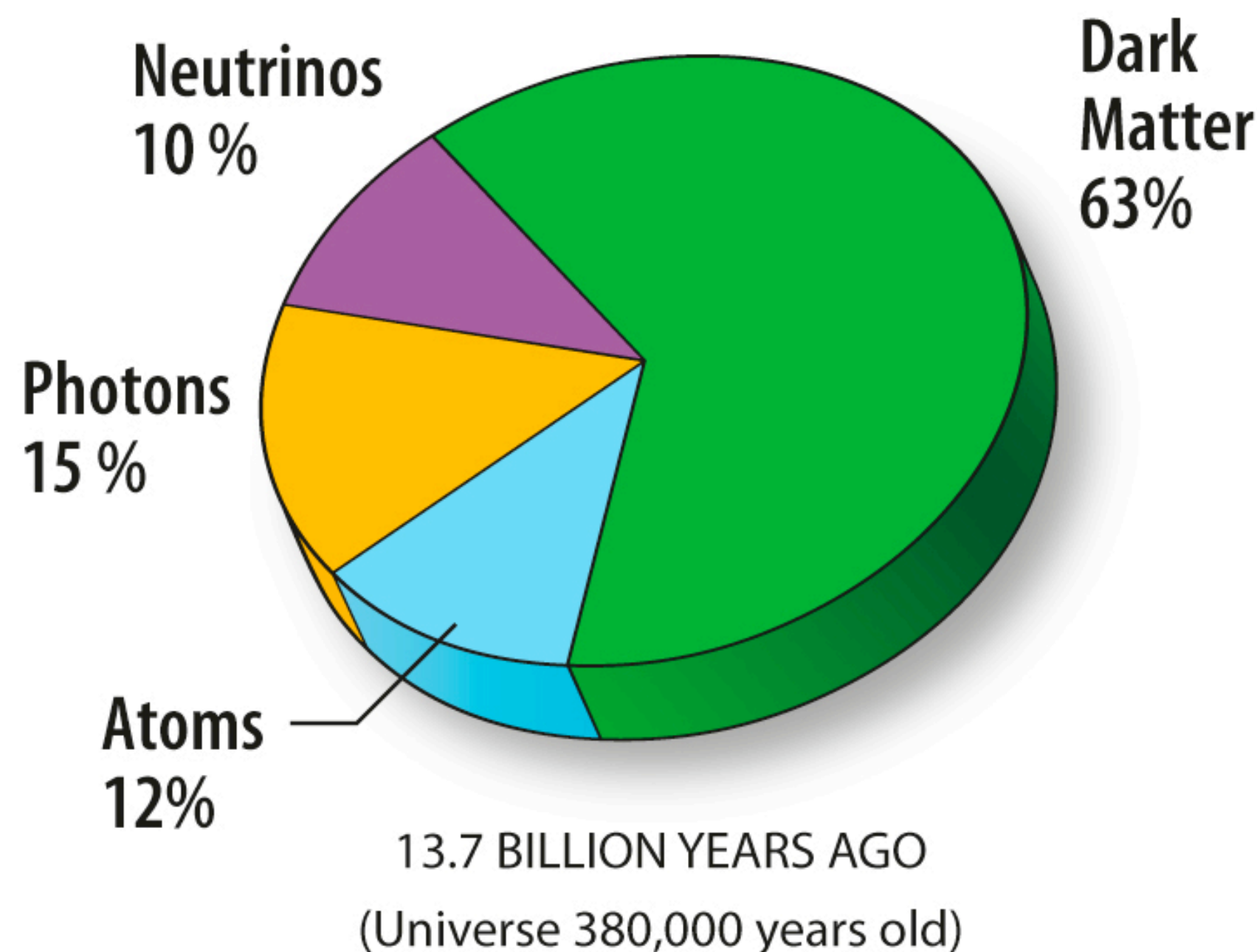
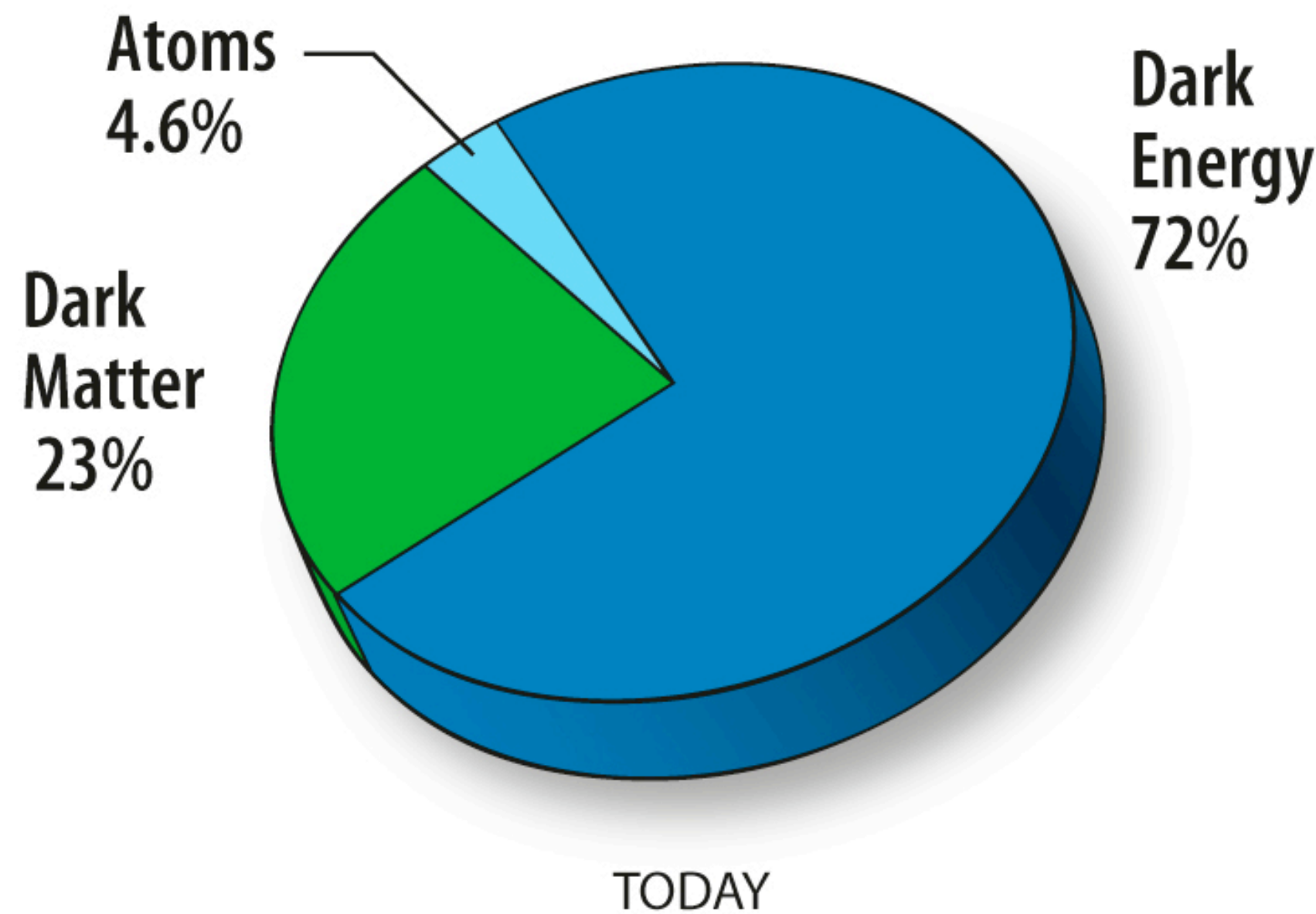
# WMAP: Selected Results From the Previous Releases

- **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

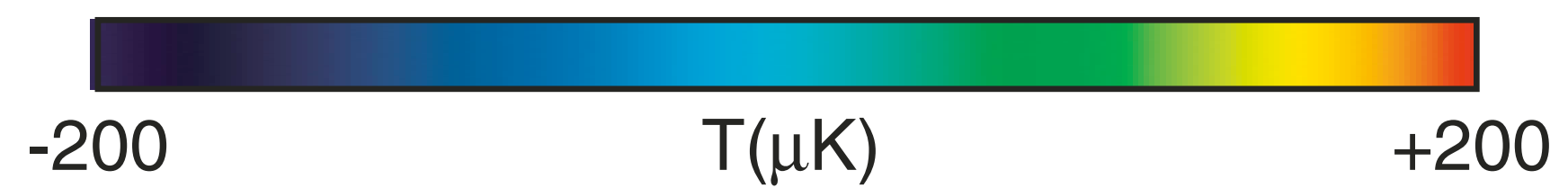
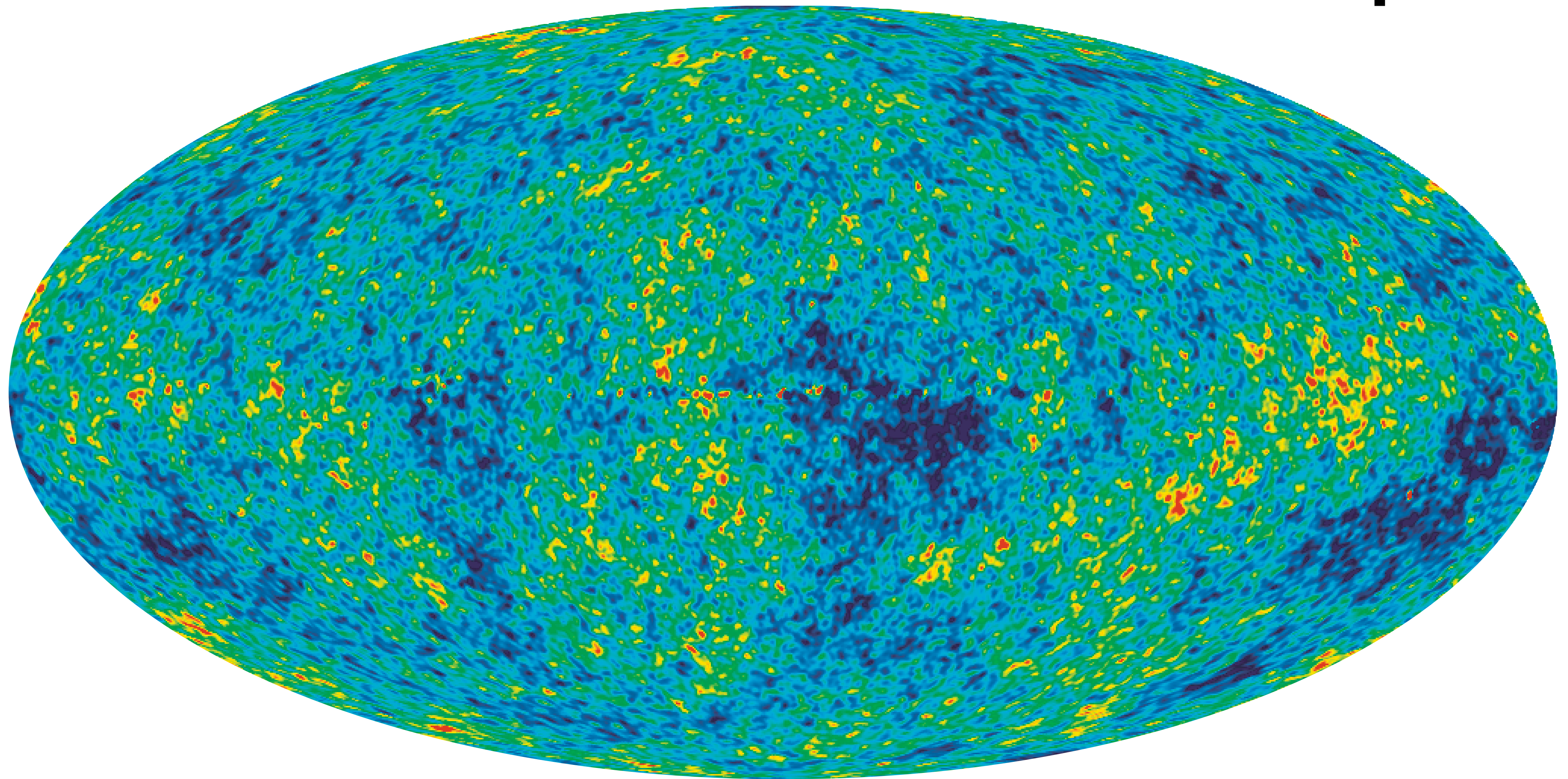
- **2006: The three-year results**
- **Polarization** of the cosmic microwave background measured with the unprecedented accuracy
  - The epoch of the formation of first stars (onset of the “cosmic reionization”)
    - ~400 million years after the Big Bang
- Evidence for a scale dependence of the amplitude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

# ~WMAP 5-Year~ Pie Chart Update!



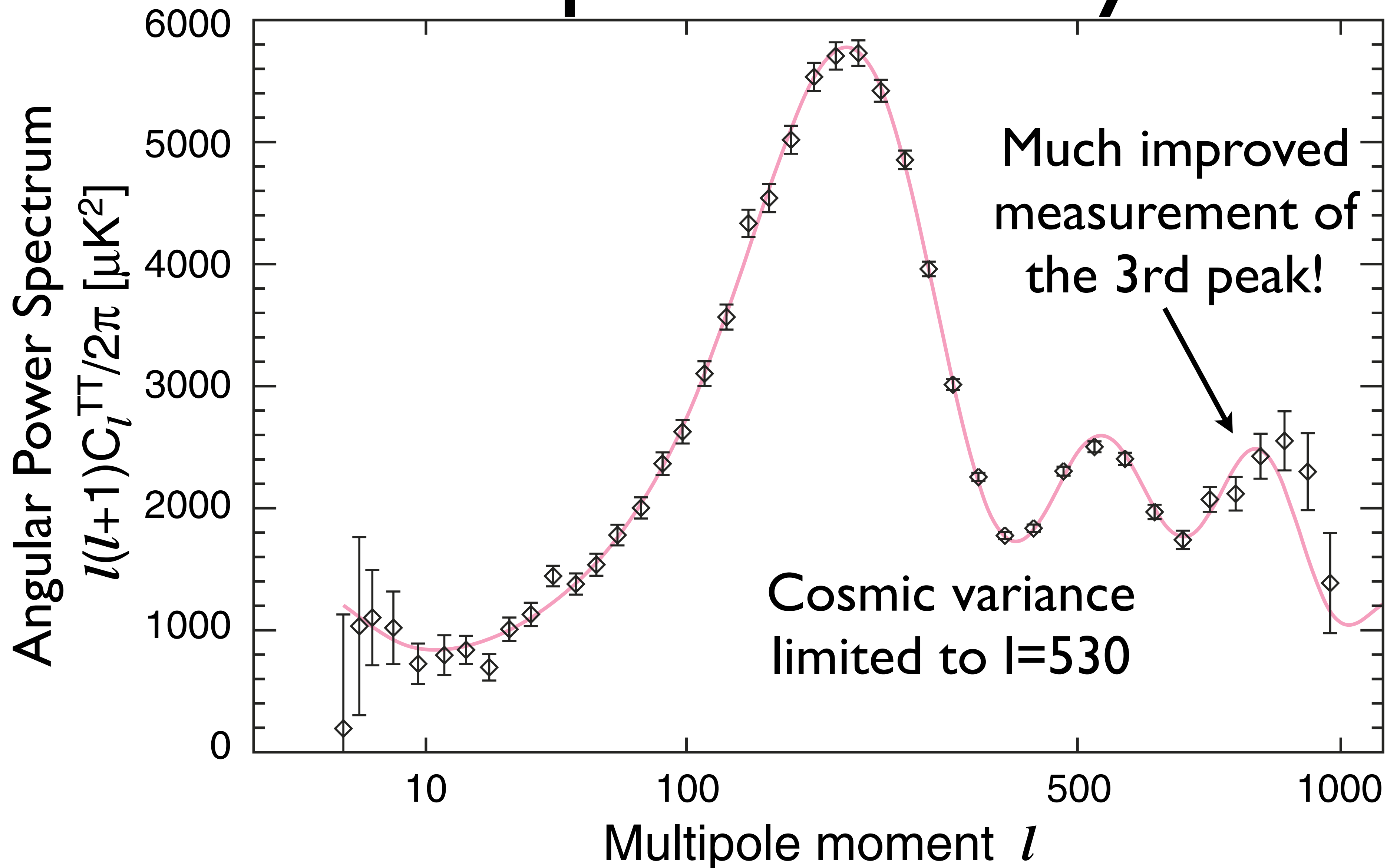
- Universe today
  - Age: **13.73 +/- 0.12 Gyr**
  - Atoms: **4.62 +/- 0.15 %**
  - Dark Matter: **23.3 +/- 1.3%**
  - Vacuum Energy: **72.1 +/- 1.5%**
- When CMB was released 13.7 B yrs ago
  - A significant contribution from the *cosmic neutrino background*

# How Did We Use This Map?

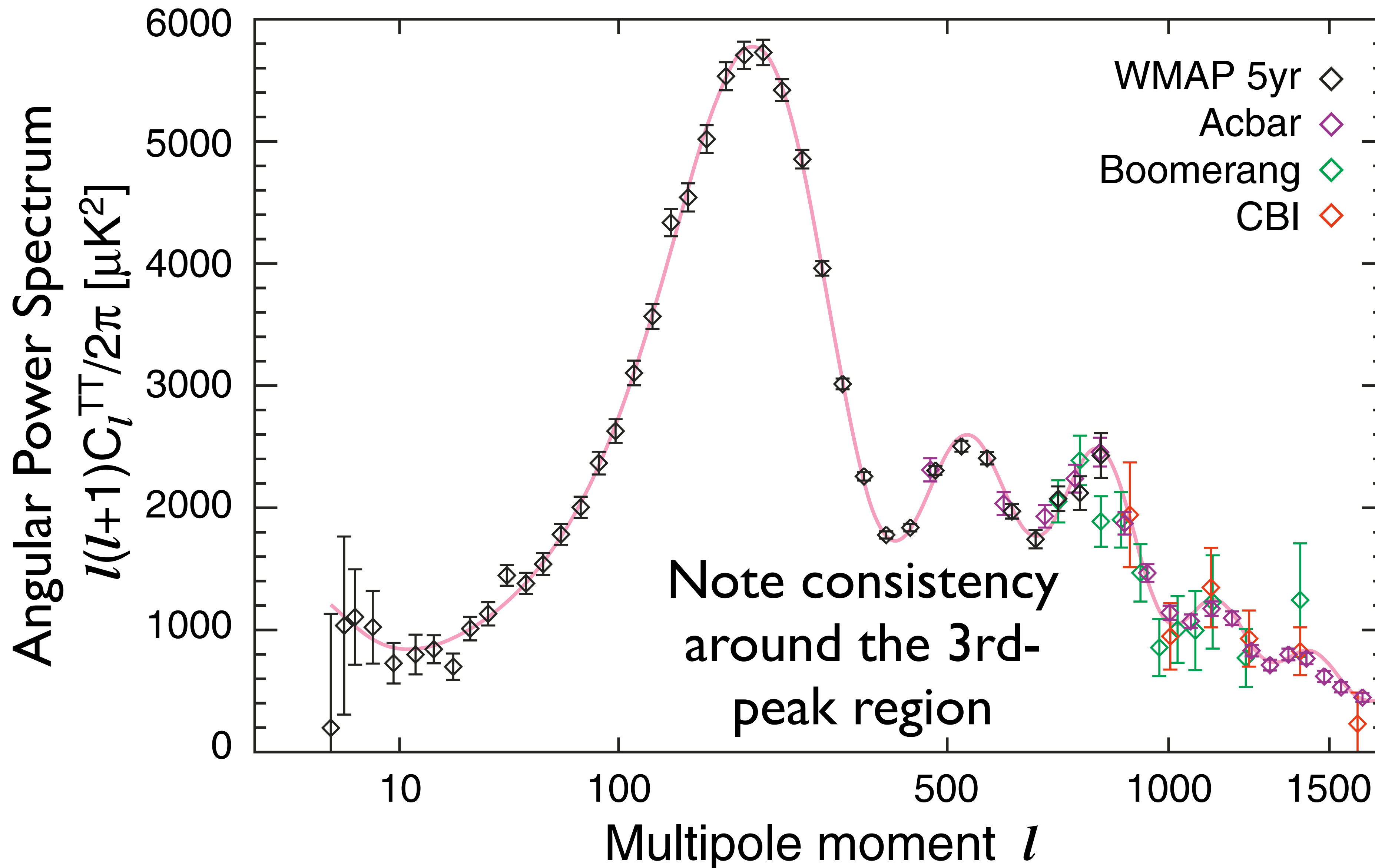


WMAP 5-year

# The Spectral Analysis

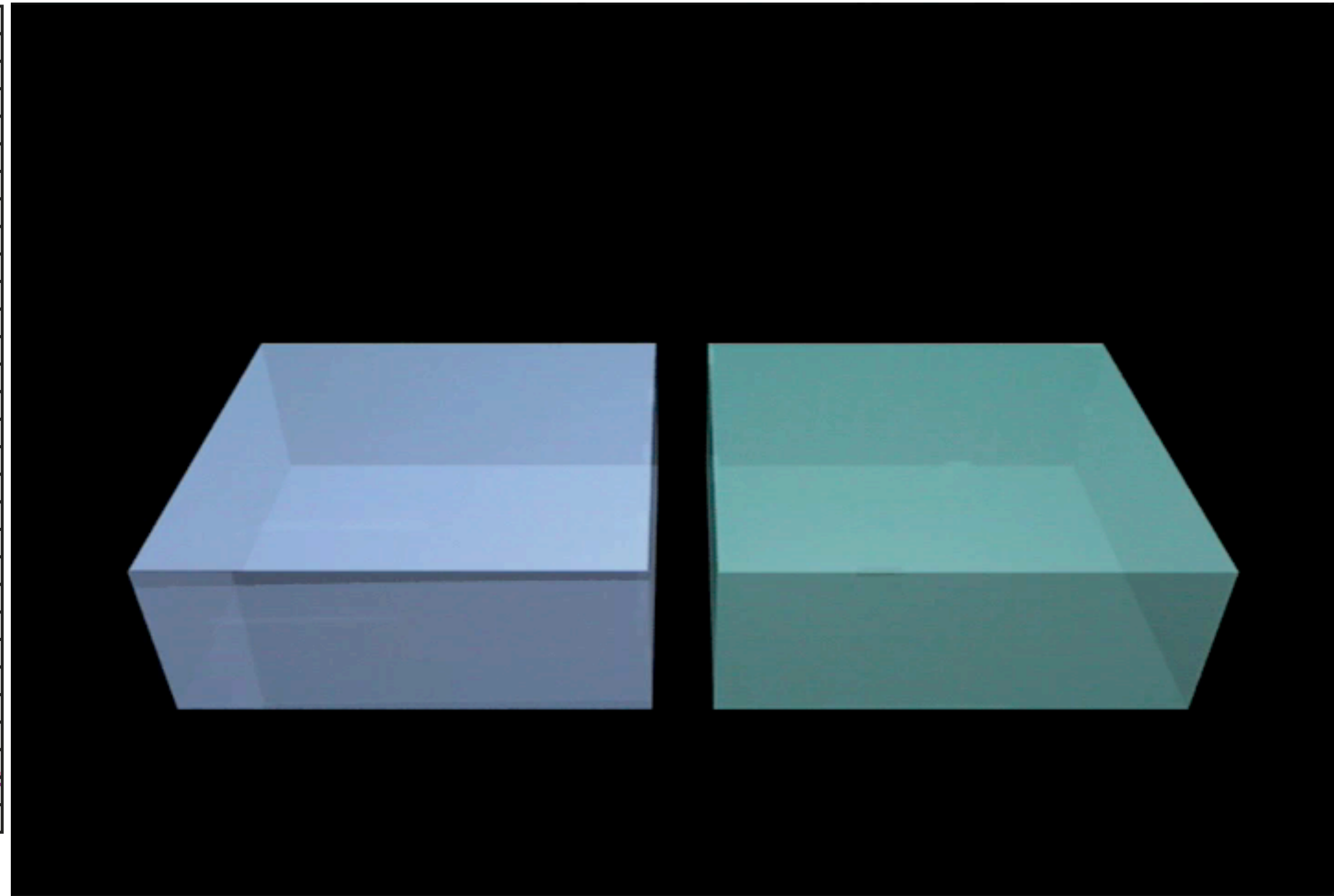
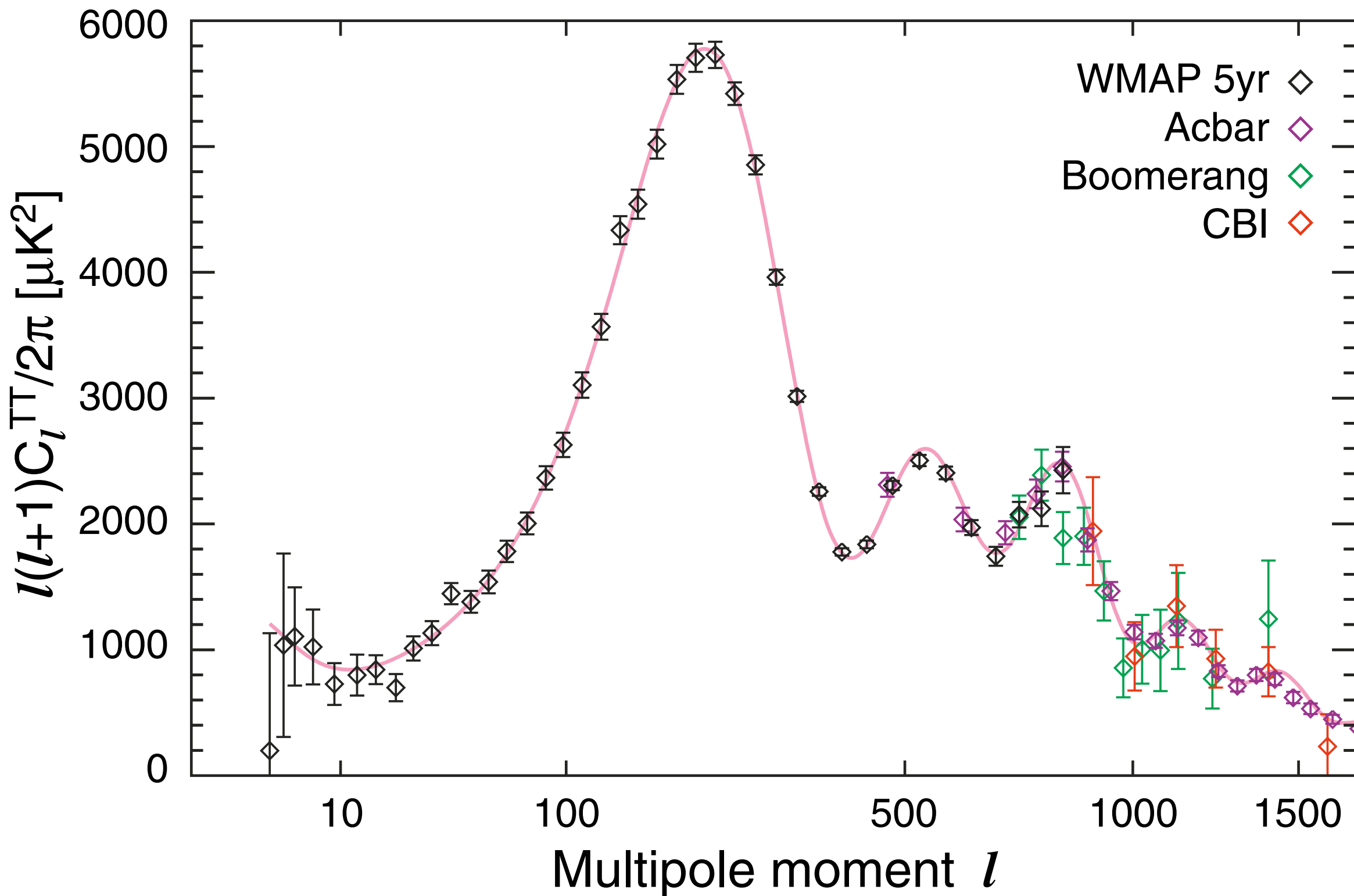


# The Cosmic Sound Wave





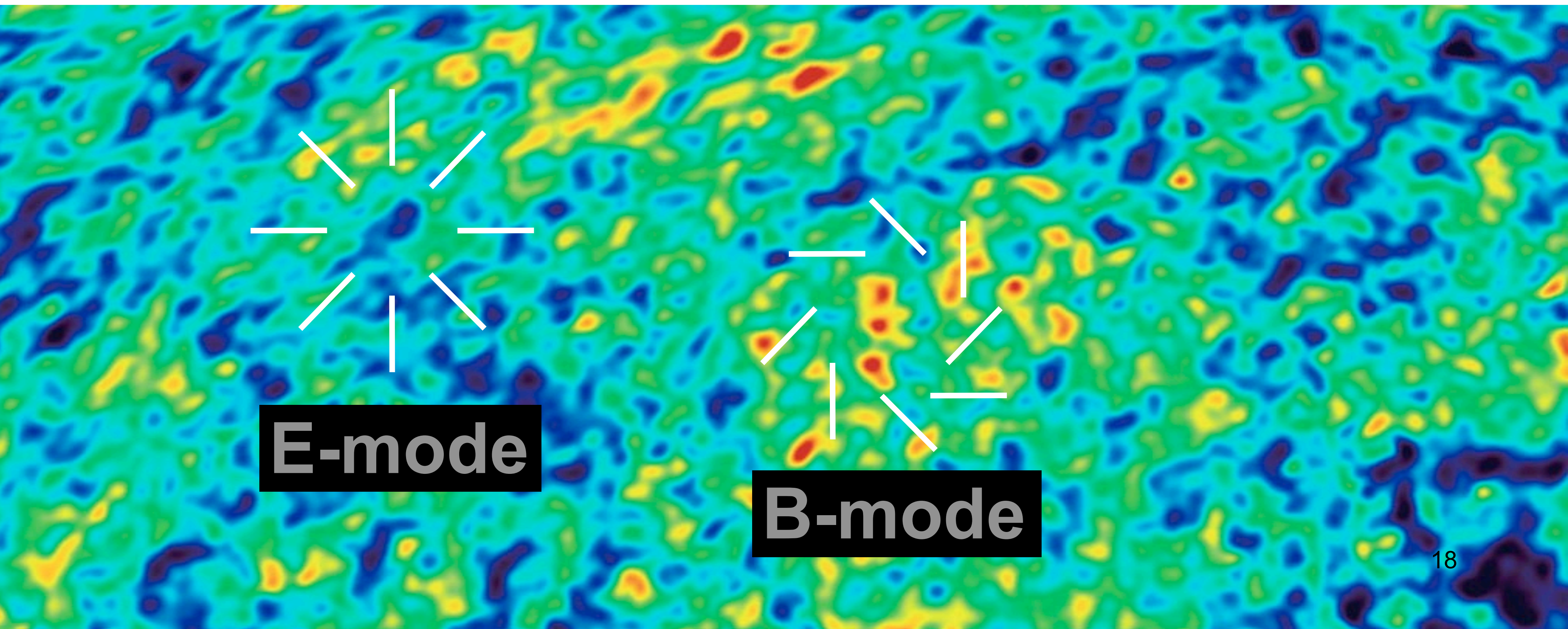
# The Cosmic Sound Wave



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

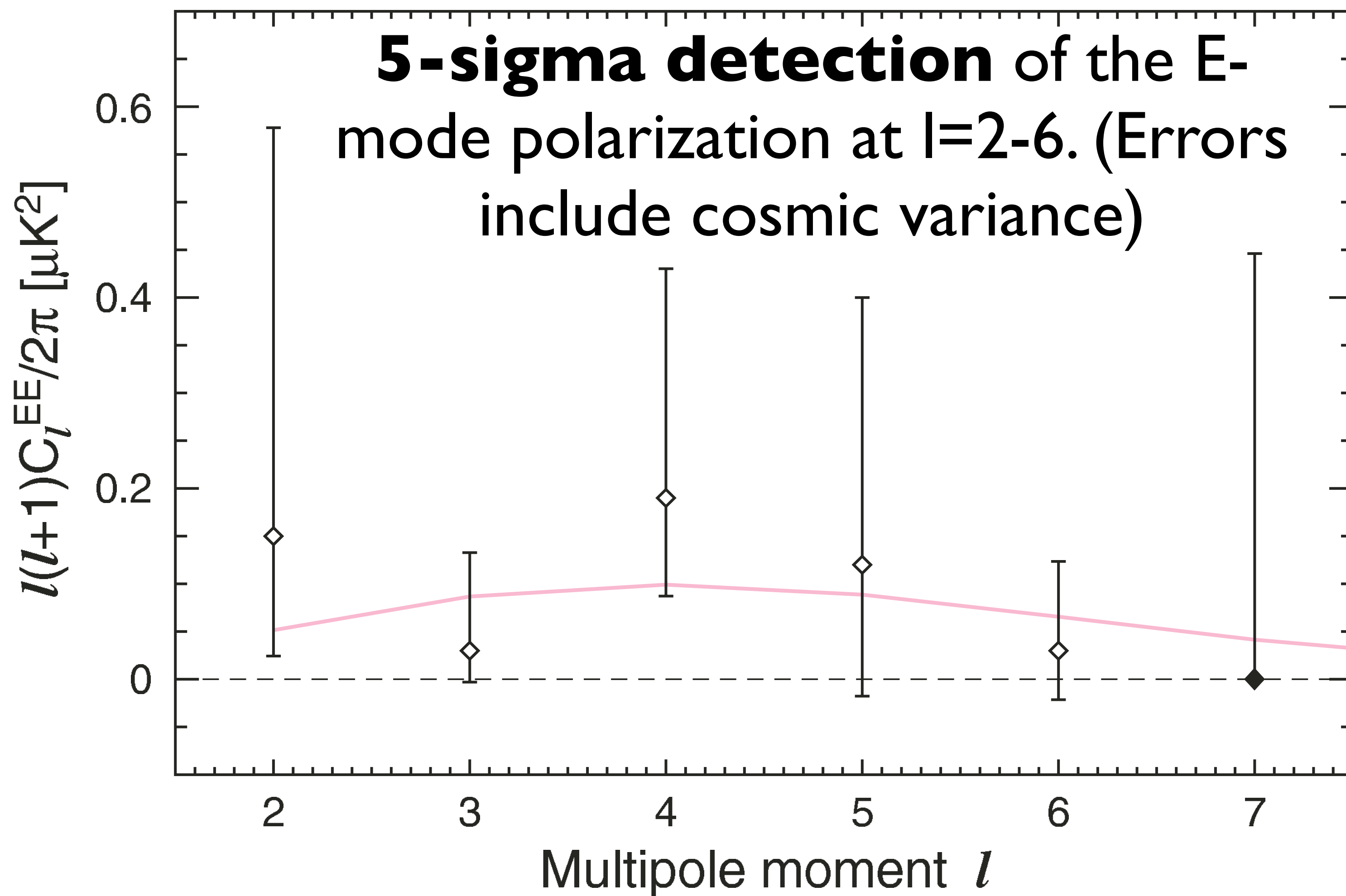
# *How About Polarization?*

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



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

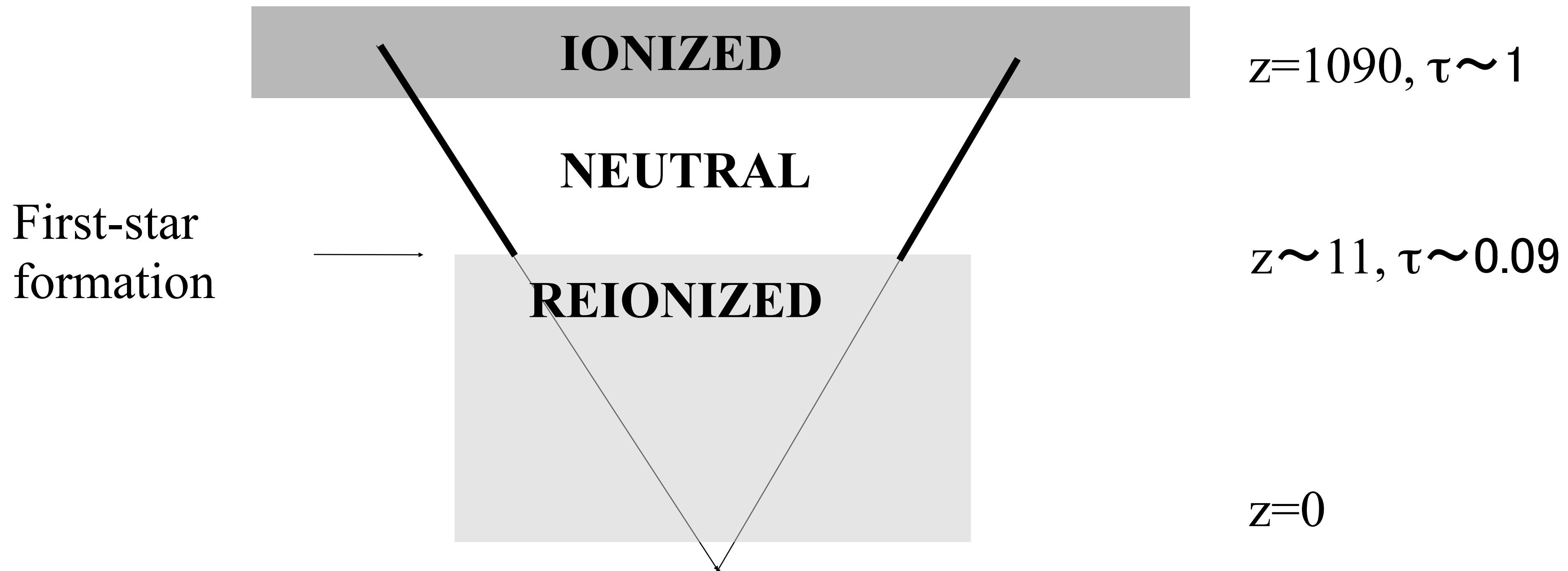
E-Mode Angular Power Spectrum



Black Symbols are upper limits

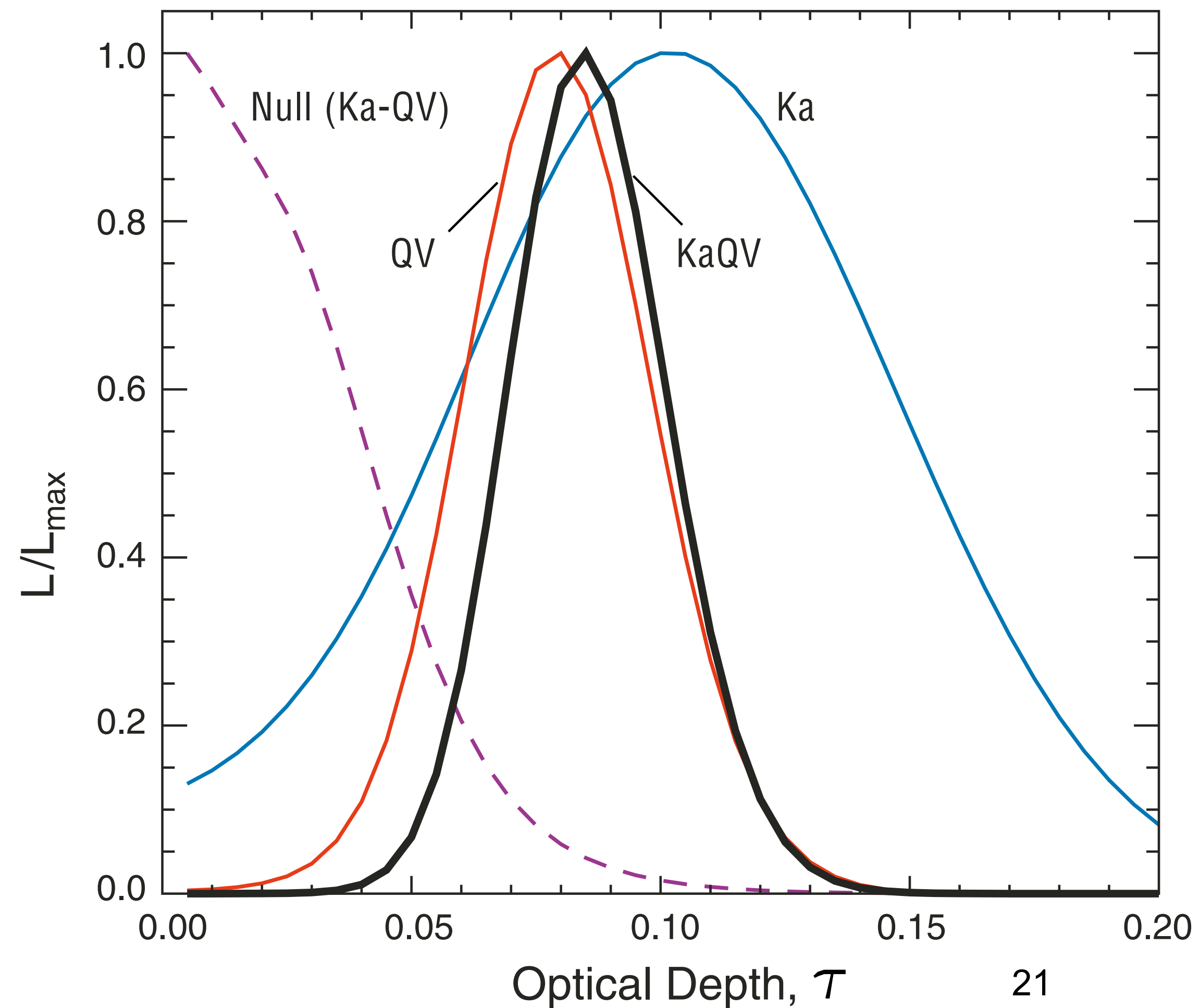
# Polarization From Reionization

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



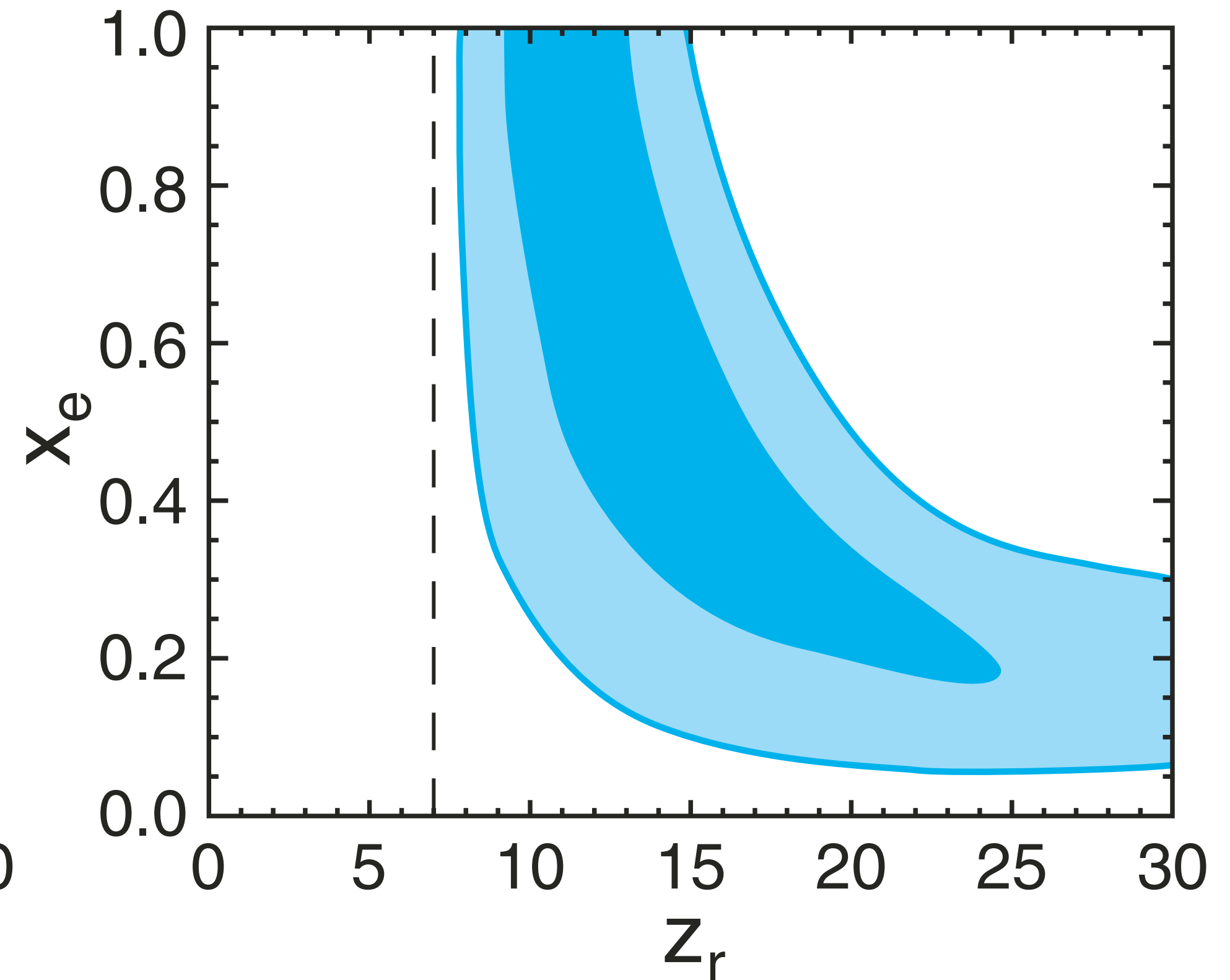
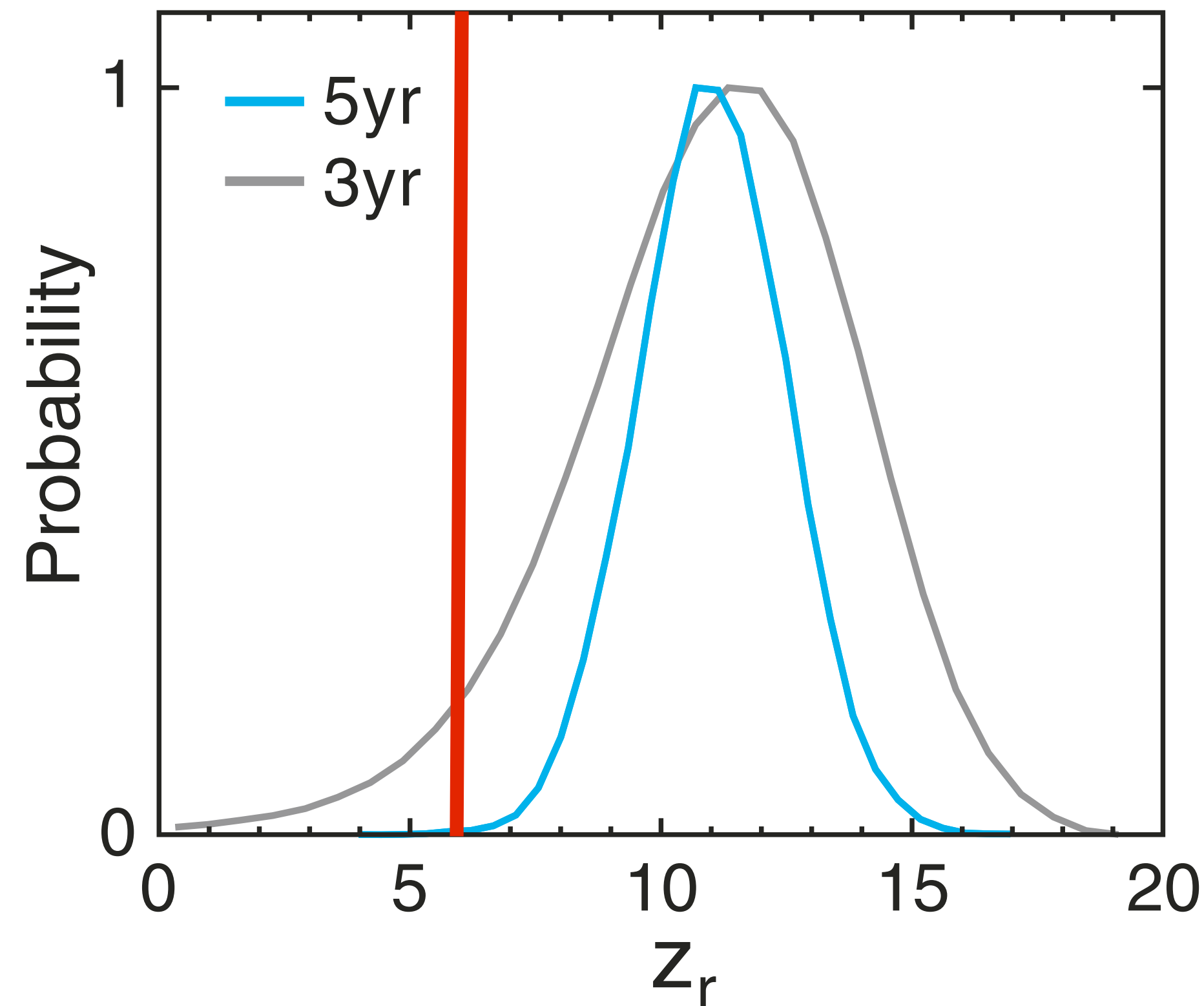
# Measuring The Optical Depth of the Universe

- Optical Depth measured from the E-mode power spectrum:
- $\tau(5\text{yr}) = 0.087 \pm 0.017$
- $\tau(3\text{yr}) = 0.089 \pm 0.030$  (Page et al.; QV only)
- 3-sigma improved to 5-sigma!
- Tau from the null map (Ka-QV) is consistent with zero



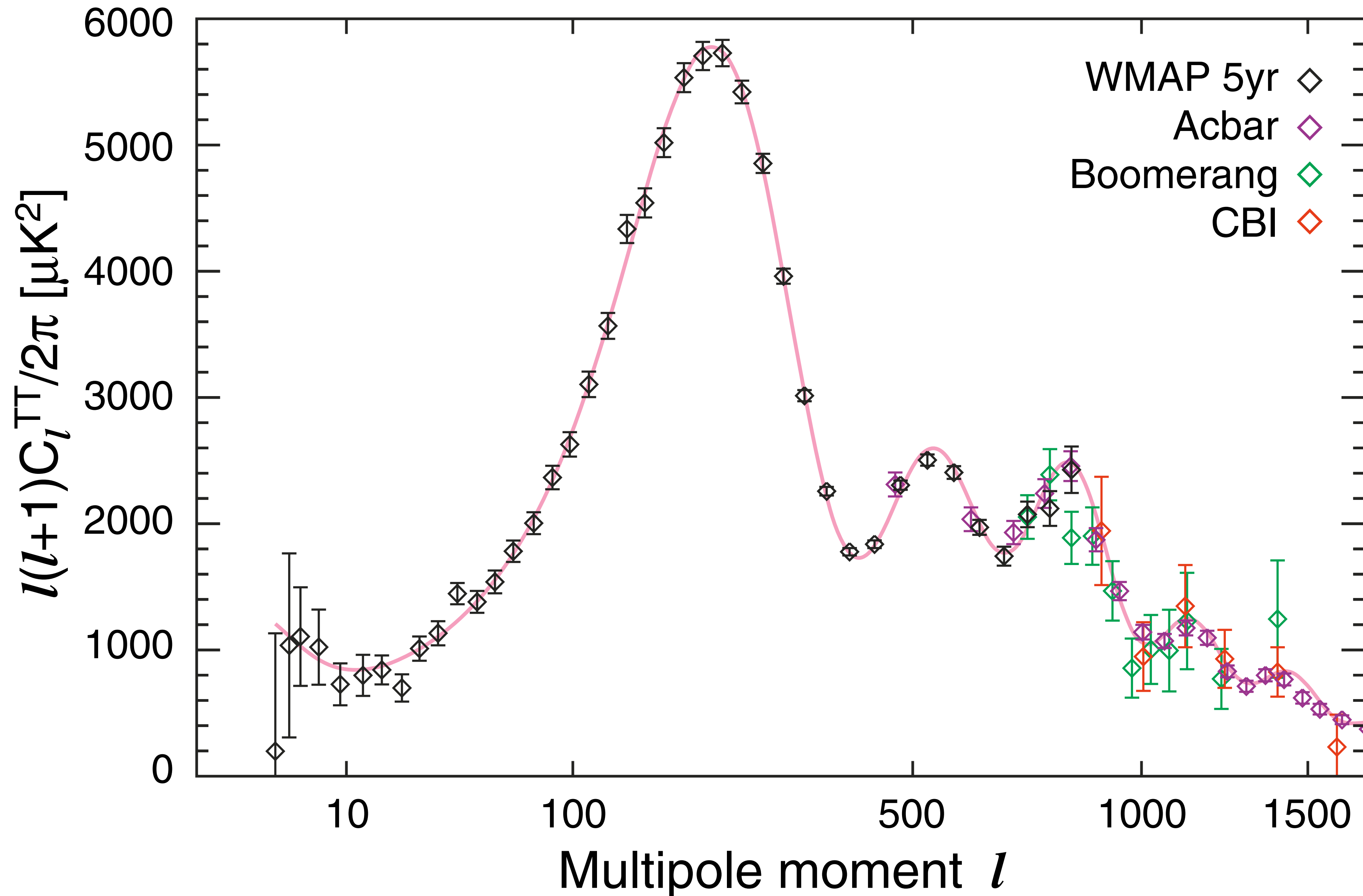
# $z_{\text{reion}}=6$ Is Excluded

*Dunkley et al.*

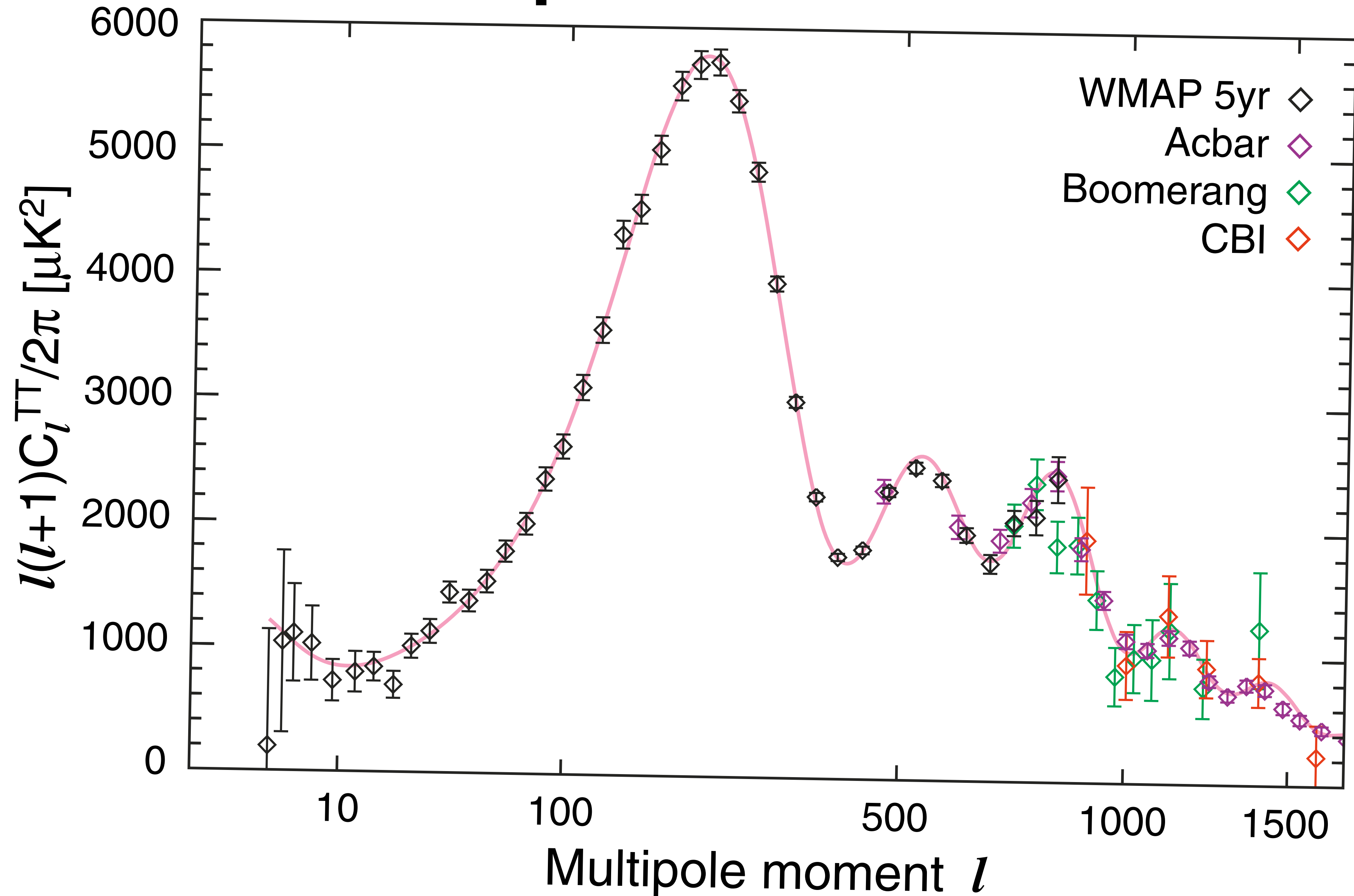


- Assuming an instantaneous reionization from  $x_e=0$  to  $x_e=1$  at  $z_{\text{reion}}$ , we find  $z_{\text{reion}}=11.0 \pm 1.4$  (68 % CL).
- The reionization was not an instantaneous process at  $z \sim 6$ . (The 3-sigma lower bound is  $z_{\text{reion}} > 6.7$ .)

# Tilting=Primordial Shape->Inflation

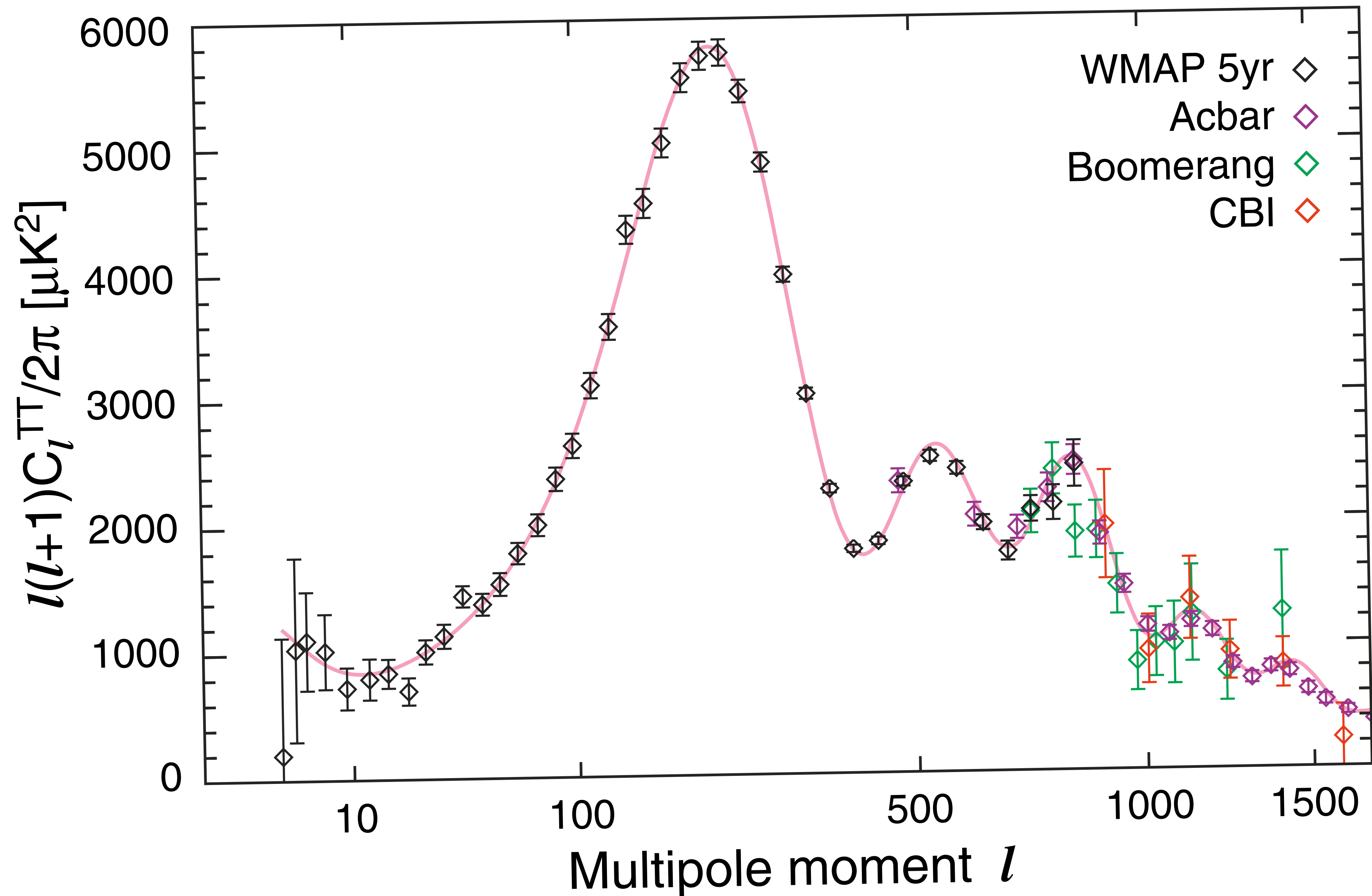


# “Red” Spectrum: $n_s < 1$

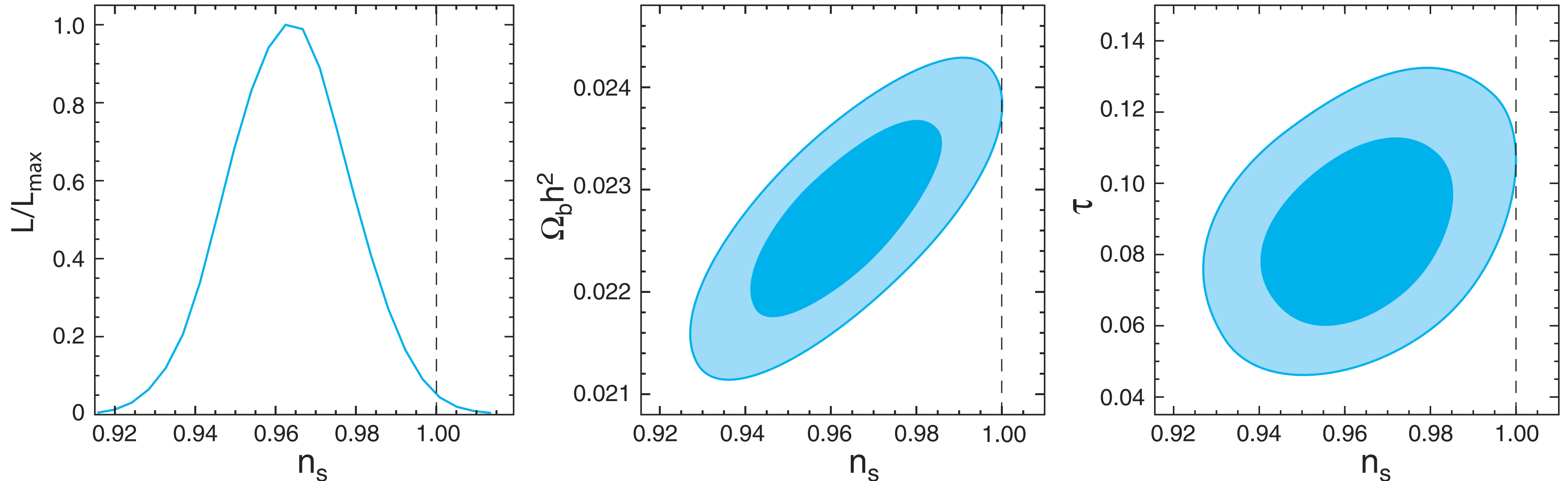




# “Blue” Spectrum: $n_s > 1$



# Tau: (Once) Important for $n_s$ *Komatsu et al.*

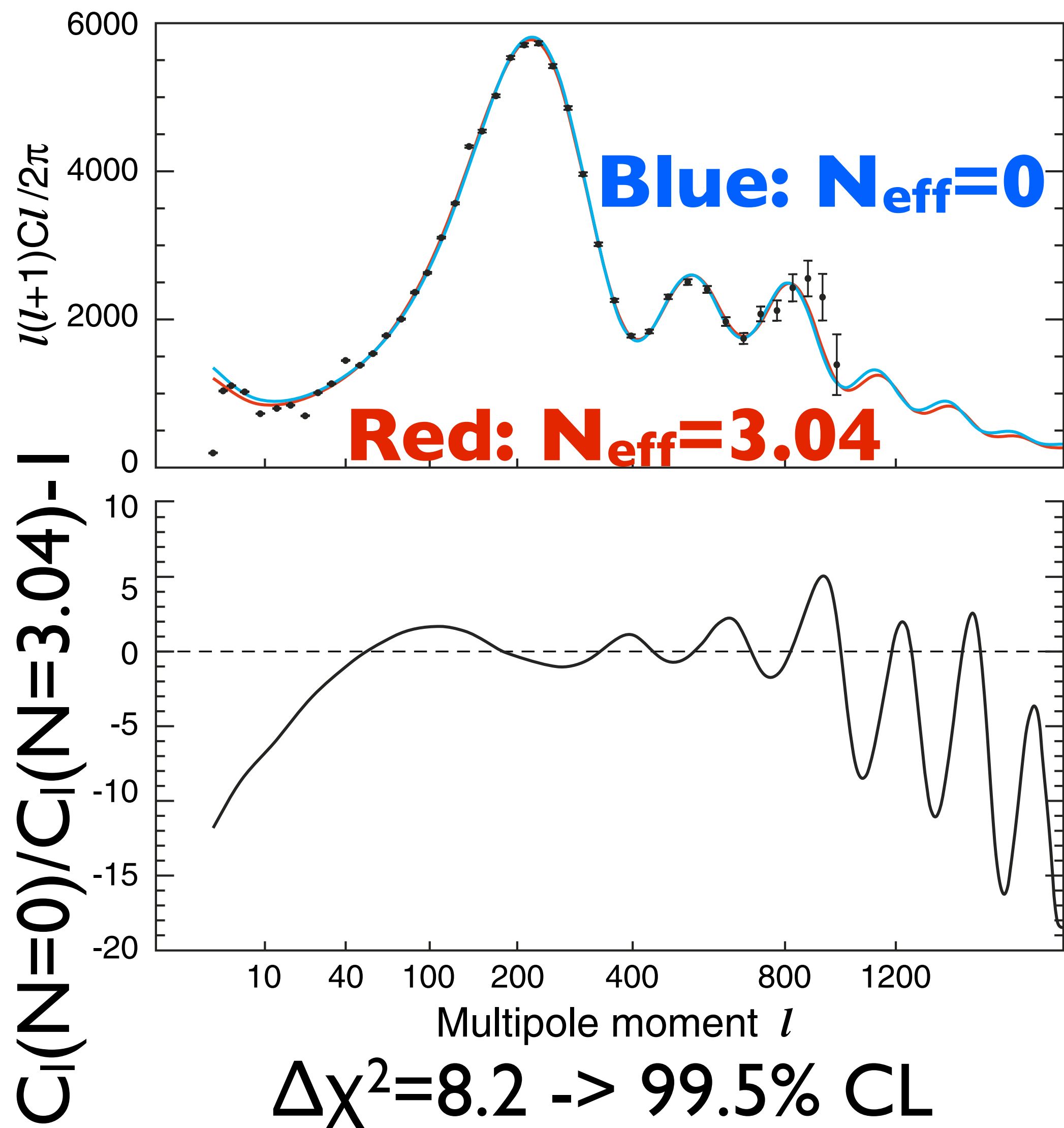


- With the 5-year determination of the optical depth ( $\tau$ ), the most dominant source of degeneracy is now  $\Omega_b h^2$ , rather than  $\tau$ .
- WMAP-alone:  $n_s = 0.963$  (+0.014) (-0.015) (Dunkley et al.)
  - 2.5-sigma away from  $n_s = 1$ , “scale invariant spectrum”

# 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,  $z_{\text{equality}}$ , 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.

# CNB As Seen By WMAP



- Multiplicative phase shift is due to the change in  $z_{\text{equality}}$ 
  - *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)

# Cosmic/Laboratory Consistency

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

# Testing Cosmic Inflation

~5 Tests~

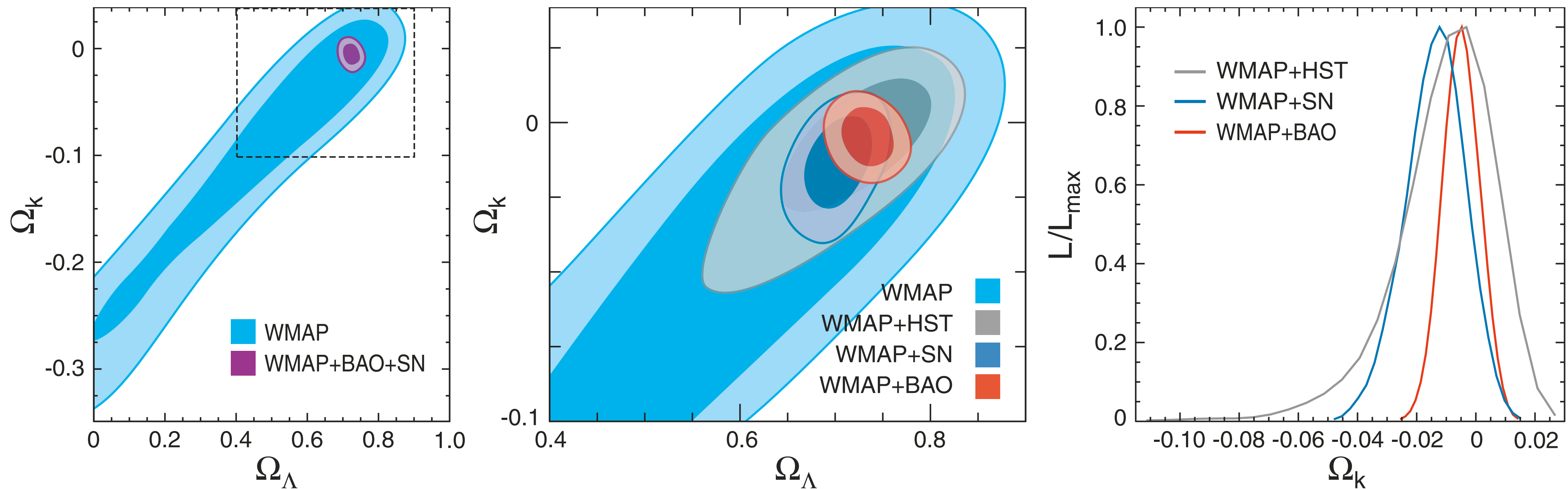
- Is the observable universe flat?
- Are the primordial fluctuations adiabatic?
- Are the primordial fluctuations nearly Gaussian?
- Is the power spectrum nearly scale invariant?
- Is the amplitude of gravitational waves reasonable?

# 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

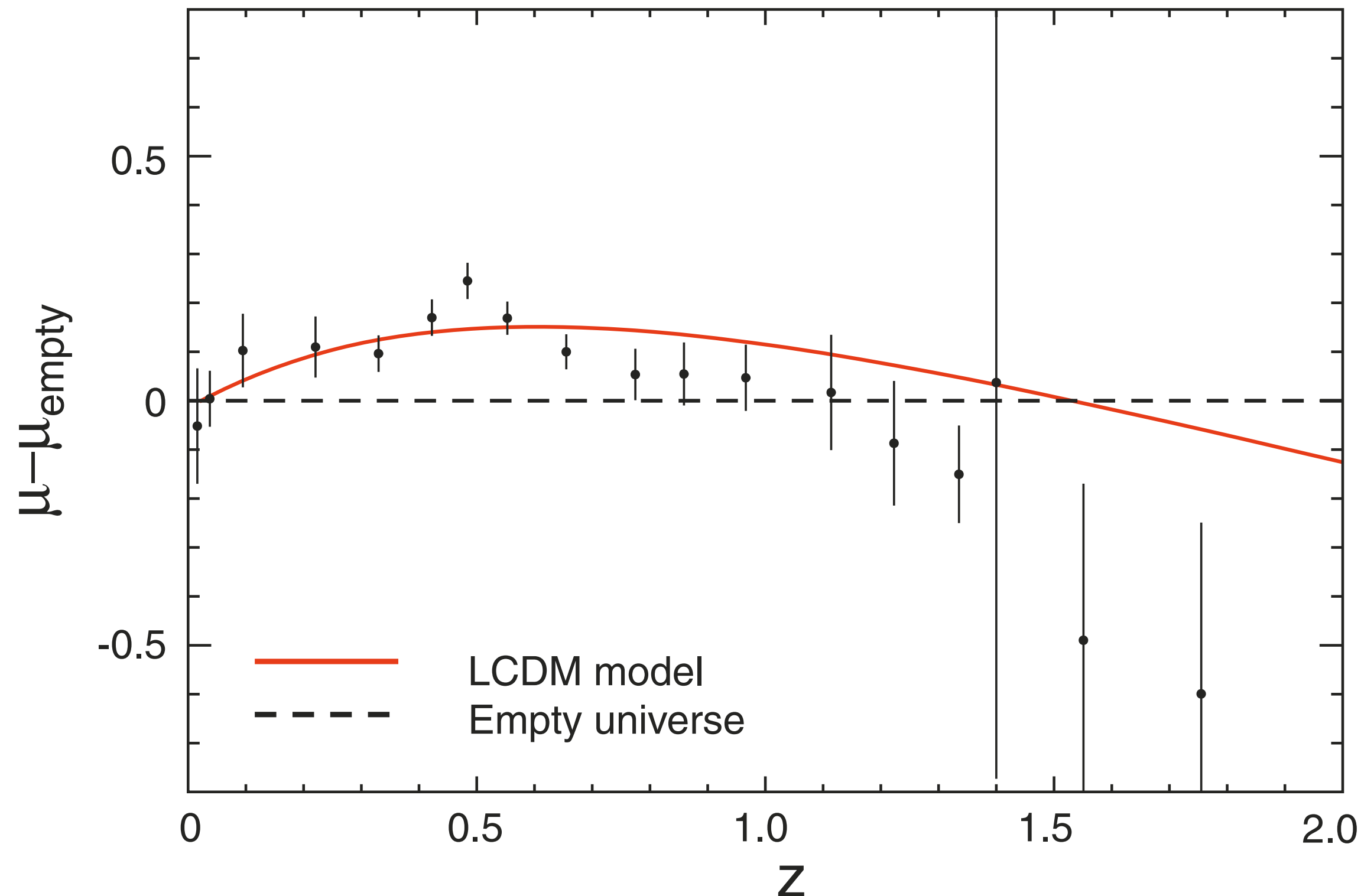
*Komatsu et al.*



- 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.,  $\Omega_m$  and  $H_0$



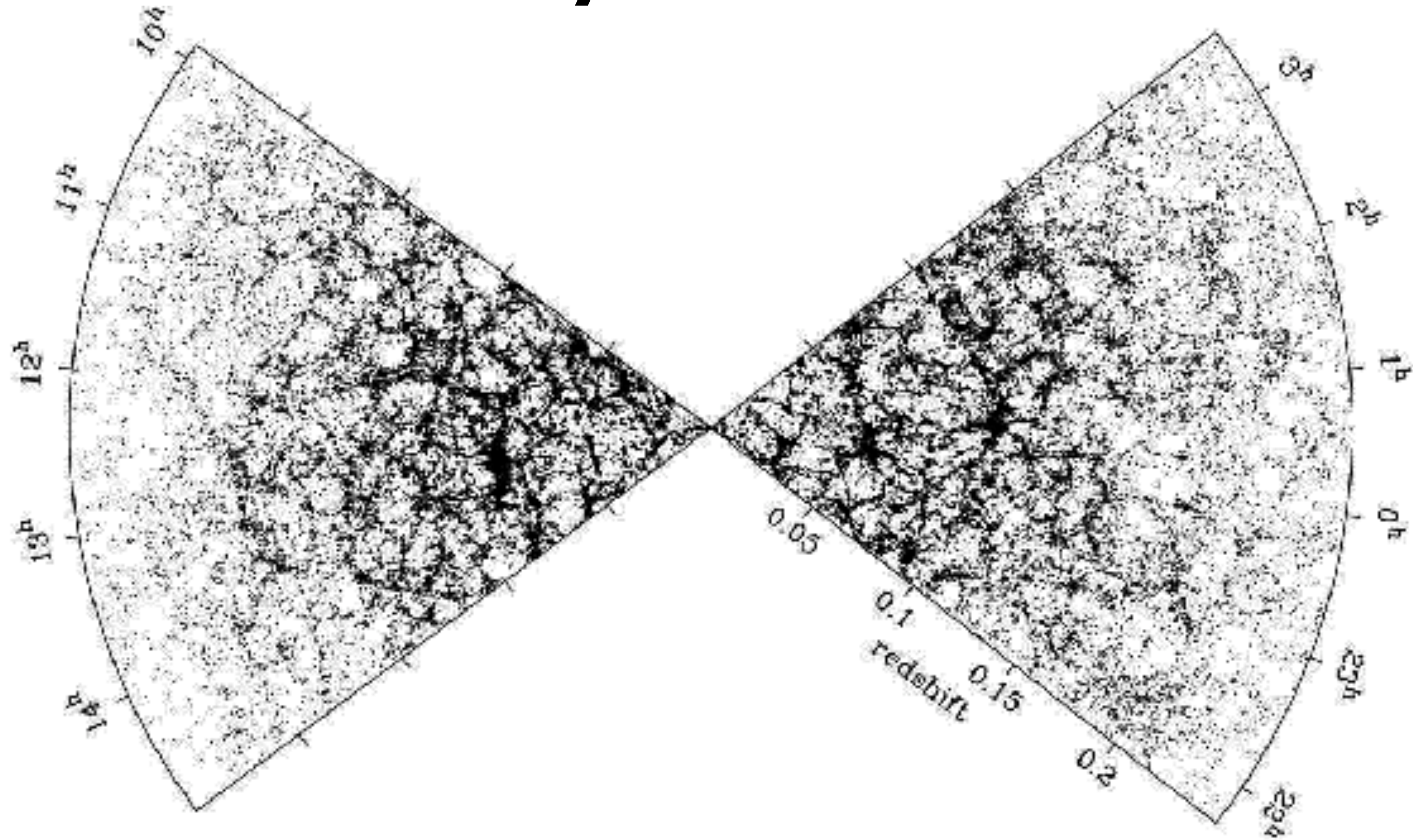
# Type Ia Supernova (SN) Data



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 **not** sensitive to the absolute distances.

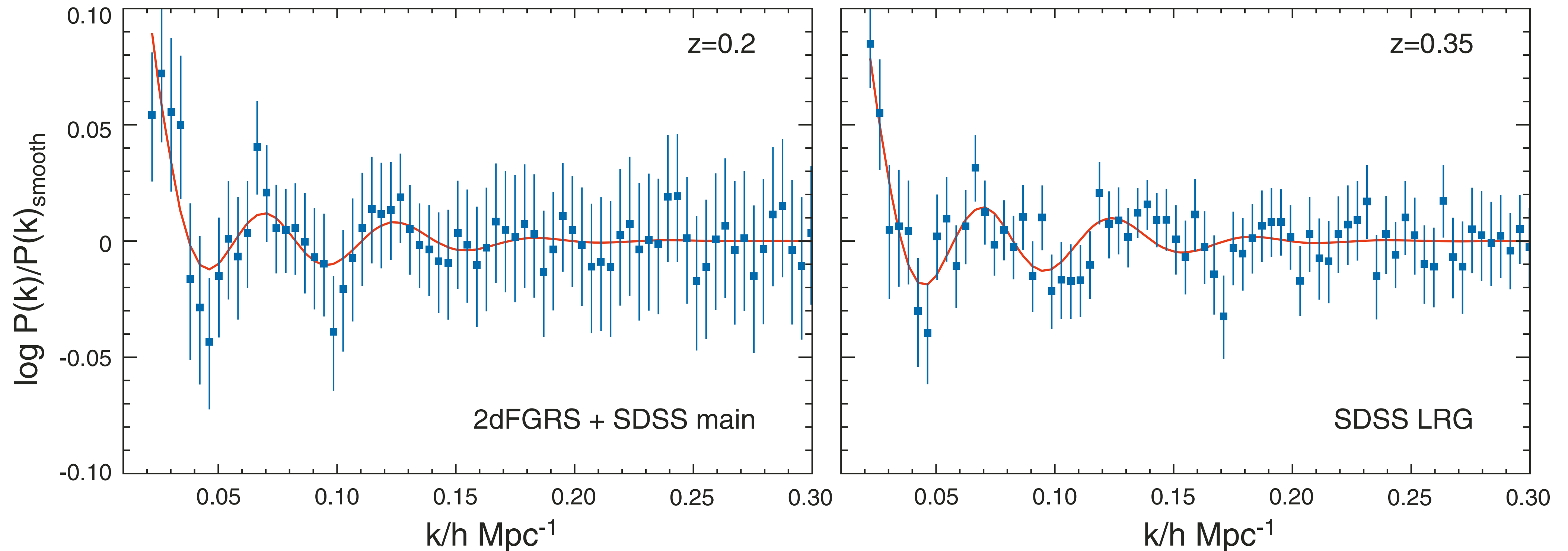
- Riess et al. (2004; 2006) HST data
- Astier et al. (2006) Supernova Legacy Survey (SNLS)
- Wood-Vasey et al. (2007) ESSENCE data

# BAO in Galaxy Distribution *Tegmark et al.*



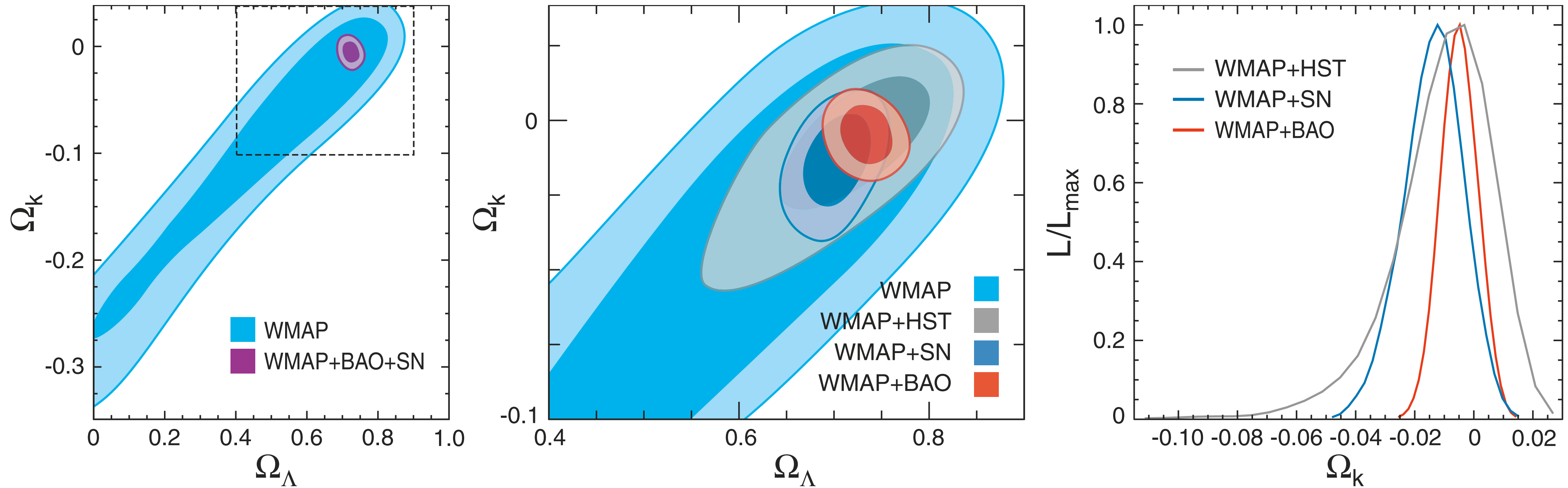
- The same acoustic oscillations are hidden in this galaxy distribution...

# BAO in Galaxy Distribution *Dunkley et al.*



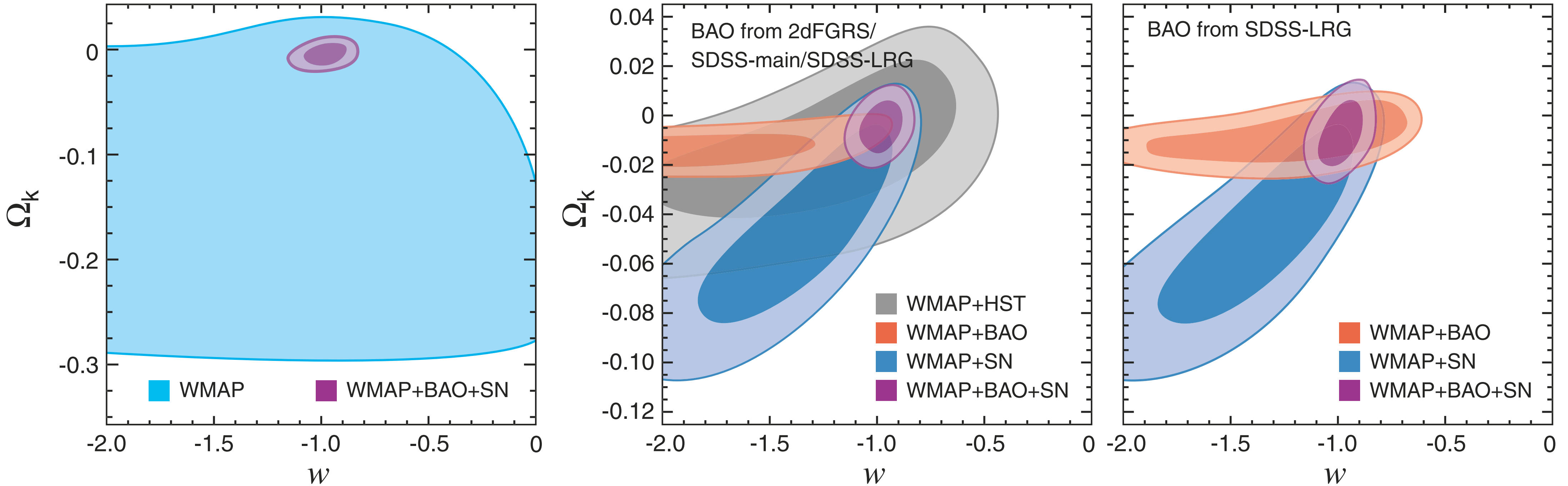
- BAO measured from SDSS (main samples and LRGs) and 2dFGRS (Percival et al. 2007)
- Just like the acoustic oscillations in CMB, the galaxy BAOs can be used to measure the **absolute** distances <sup>35</sup>

# 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

# What If Dark Energy Was Not Vacuum Energy ( $w \neq -1$ )...



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

# Fun Numbers to Quote

- The curvature radius of the universe is given, by definition, by
  - $R_{\text{curv}} = 3h^{-1}\text{Gpc} / \text{sqrt}(\Omega_k)$
  - 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 observable universe is pretty flat! (Fun to teach this in class)

# Implications for Inflation?

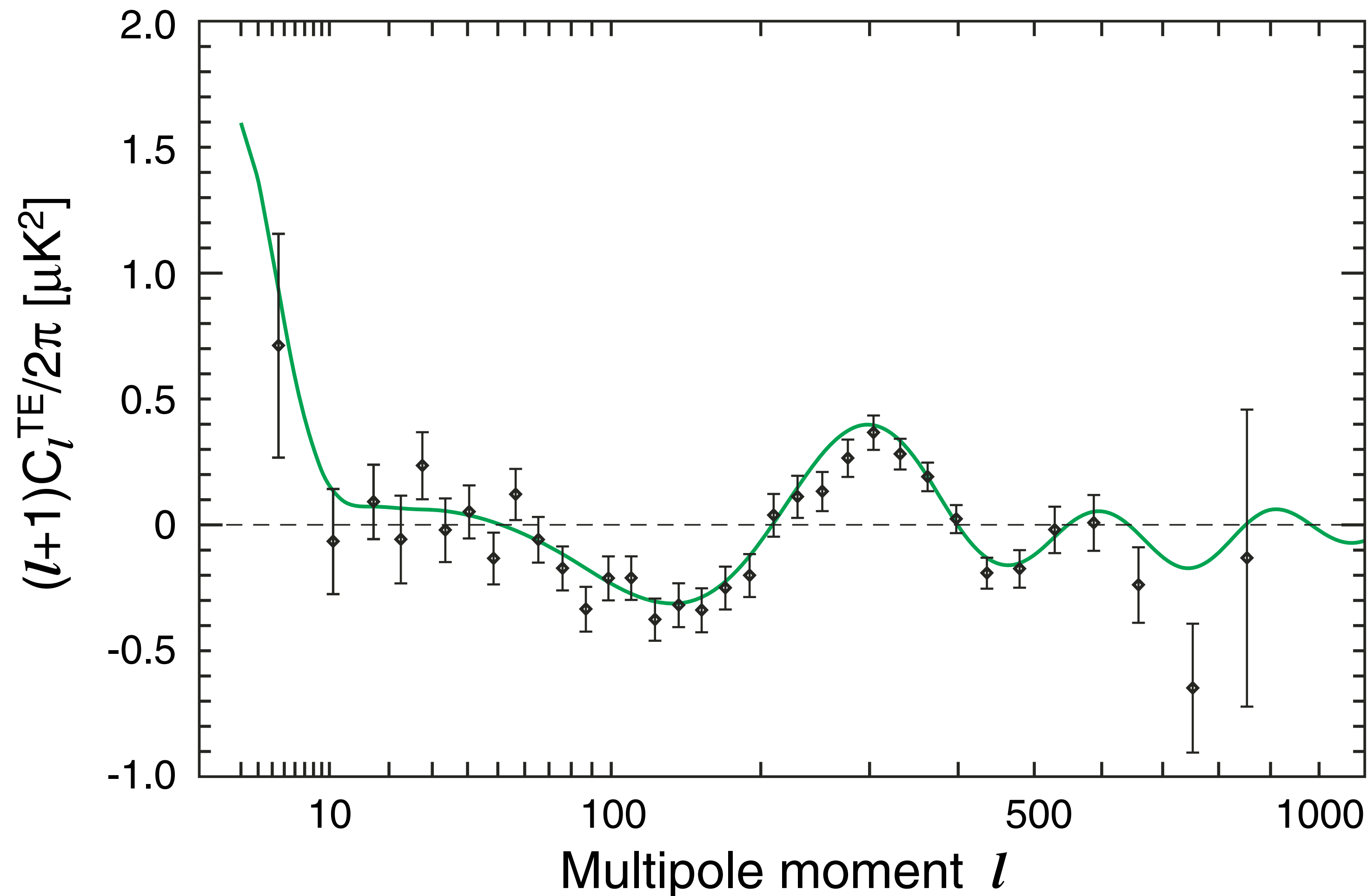
- Details aside...
  - Q. How long should inflation have lasted to explain the observed flatness of the universe?
  - A.  **$N_{\text{total}} > 36 + \ln(T_{\text{reheating}}/1 \text{ TeV})$**
  - A factor of 10 improvement in  $\Omega_k$  will raise this lower limit by 1.2.
  - Lower if the reheating temperature was  $< 1 \text{ TeV}$
- This is the check list #1

# Check List #2: Adiabaticity

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



# WMAP 5-Year TE Power Spectrum



- The negative TE at  $l \sim 100$  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?

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

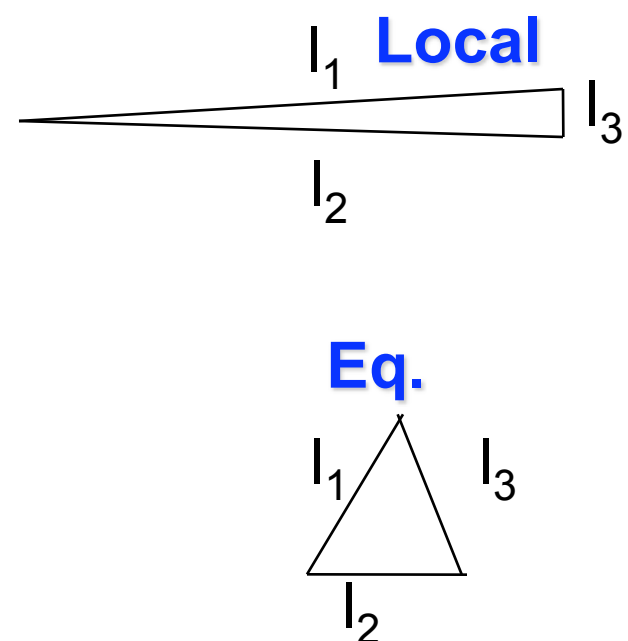
$$\frac{\Omega_a}{\Omega_c} < \frac{3.0 \times 10^{-39}}{\theta_a^5 \gamma^6} \left( \frac{0.01}{r} \right)^{7/2}$$

# 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.

# 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  $f_{\text{NL}}^{\text{local}}$
  - “Equilateral” parameterized by  $f_{\text{NL}}^{\text{equil}}$



# No Detection at $\geq 95\% \text{CL}$

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

# Check List #4: Scale Invariance

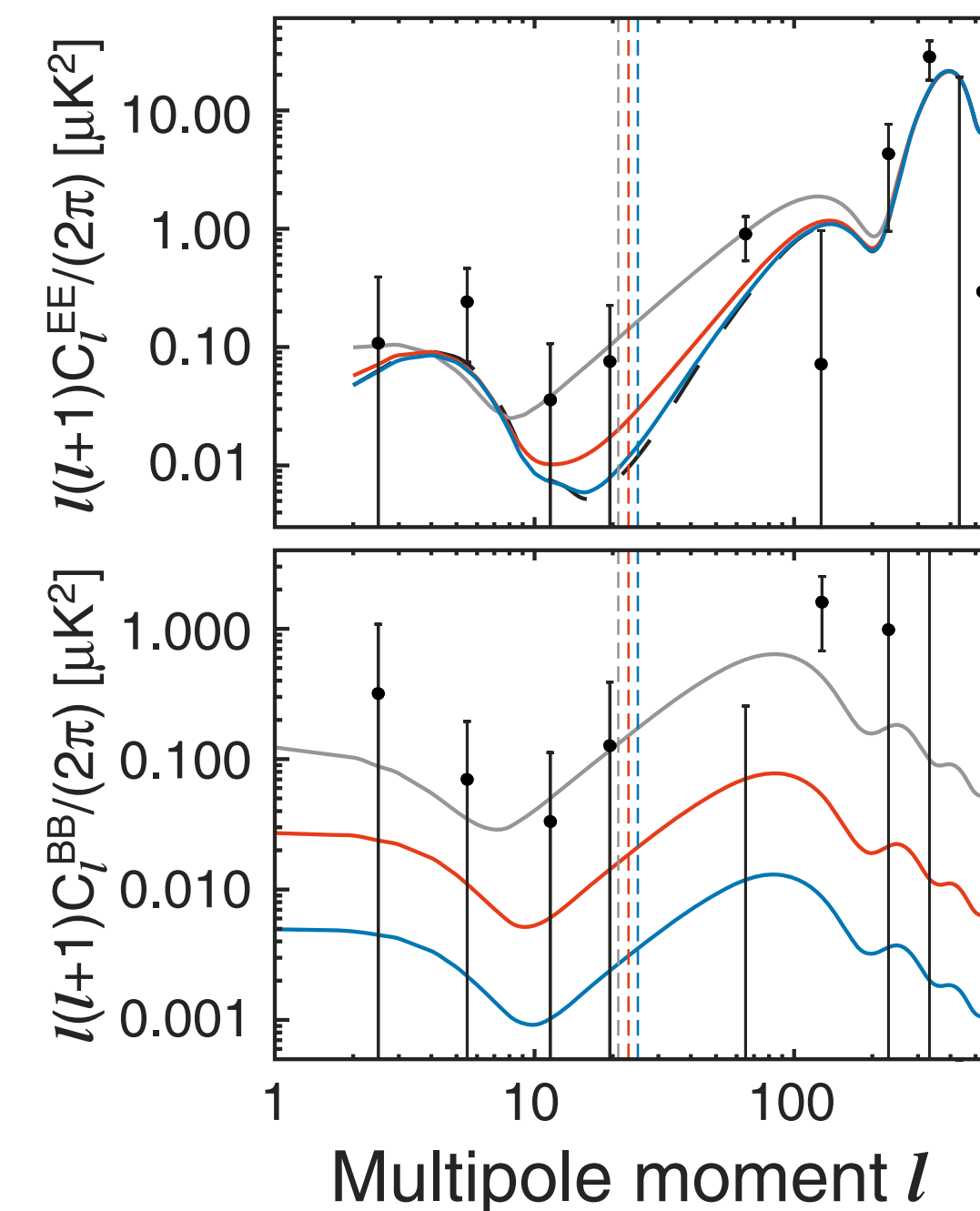
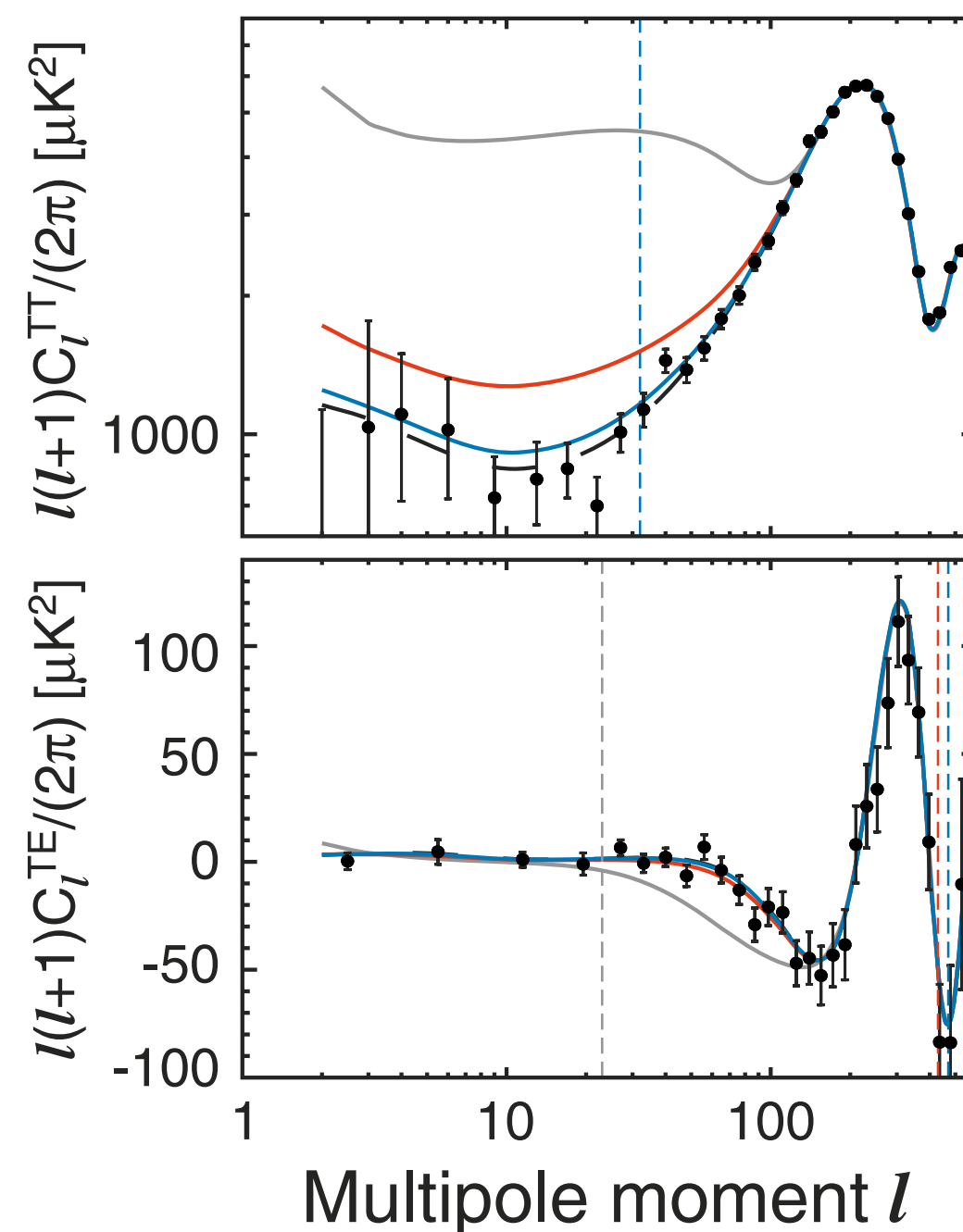
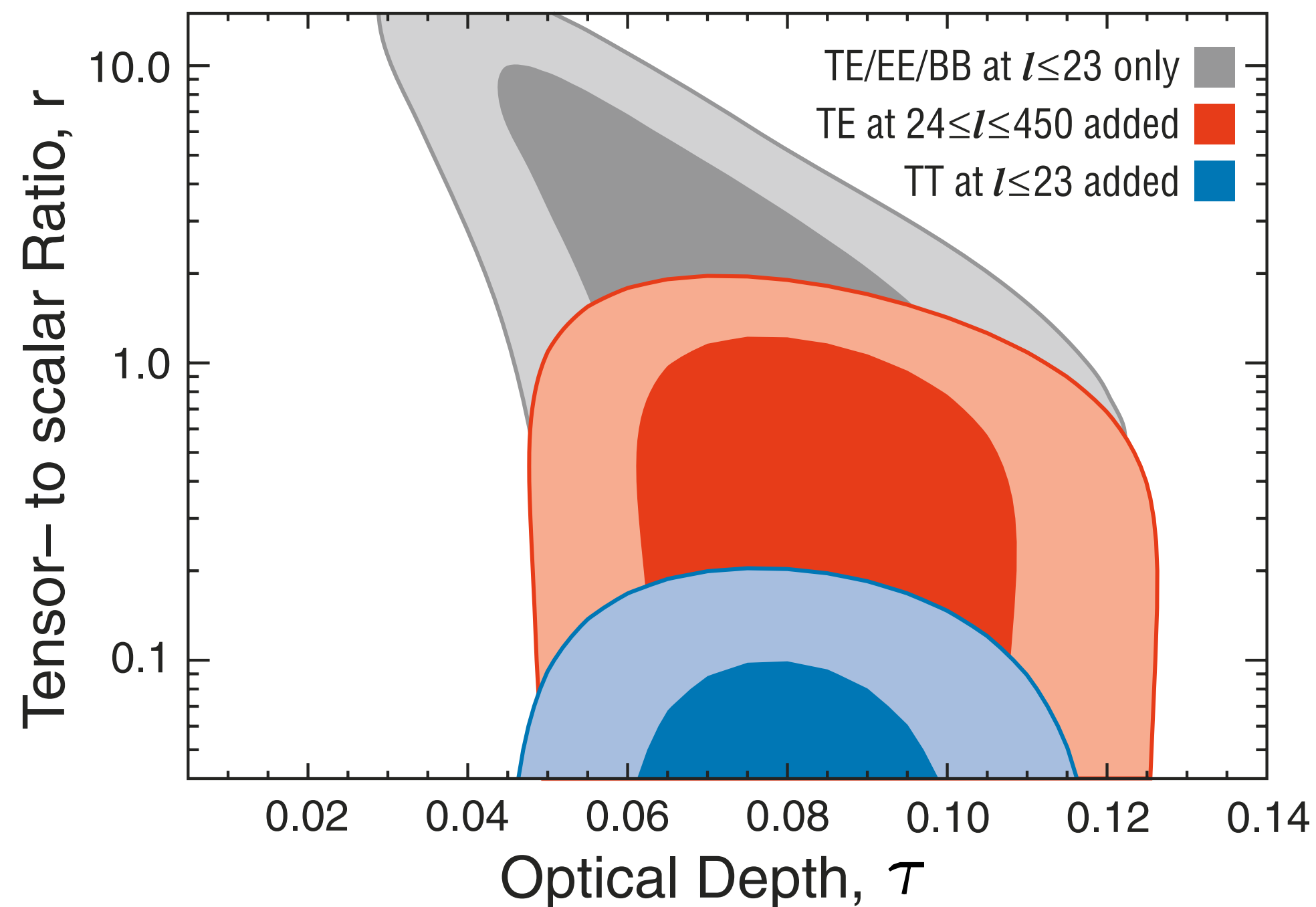
- For a power-law power spectrum (no  $dn_s/d\ln k$ ):
  - WMAP-only:  $n_s=0.963$  (+0.014) (-0.015)
  - WMAP+BAO+SN:  $n_s=0.960$  (+0.014) (-0.013)
    - **2.9 sigma away from  $n_s=1$**
  - No dramatic improvement from the WMAP-only result because neither BAO nor SN is sensitive to  $\Omega_b h^2$

# Check List #5: Gravitational Waves

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

# Pedagogical Explanation

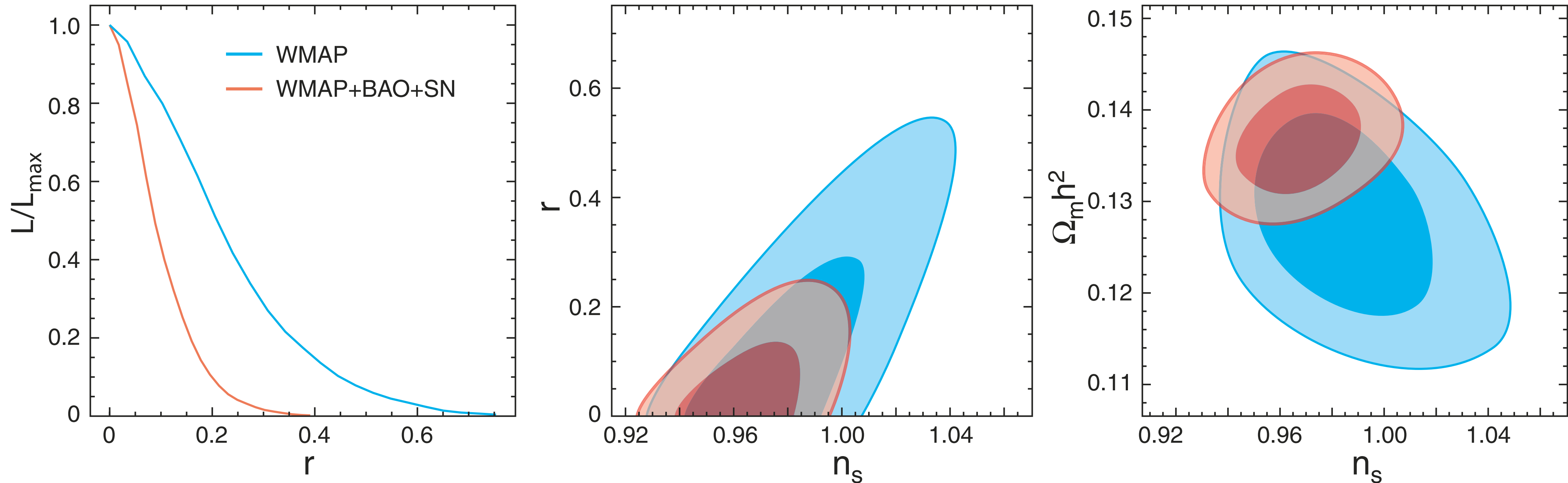
*Komatsu et al.*



- 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)

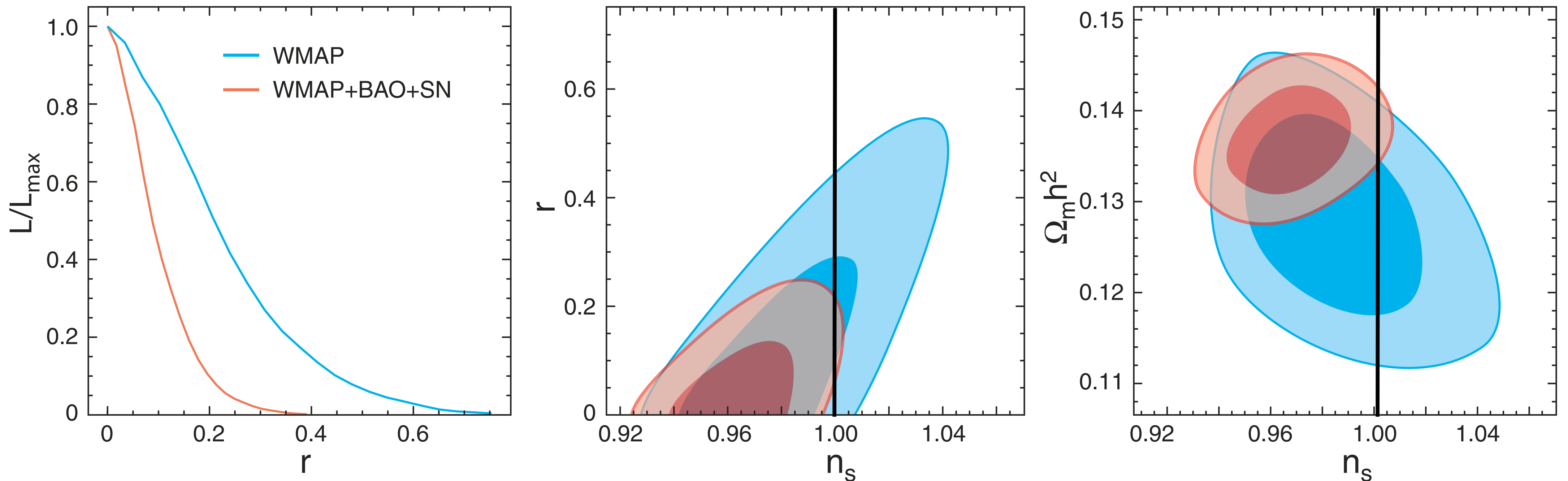


# Real Life: Killer Degeneracy



- 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)  $\rightarrow$   **$r < 0.20$**  (WMAP+BAO+SN)

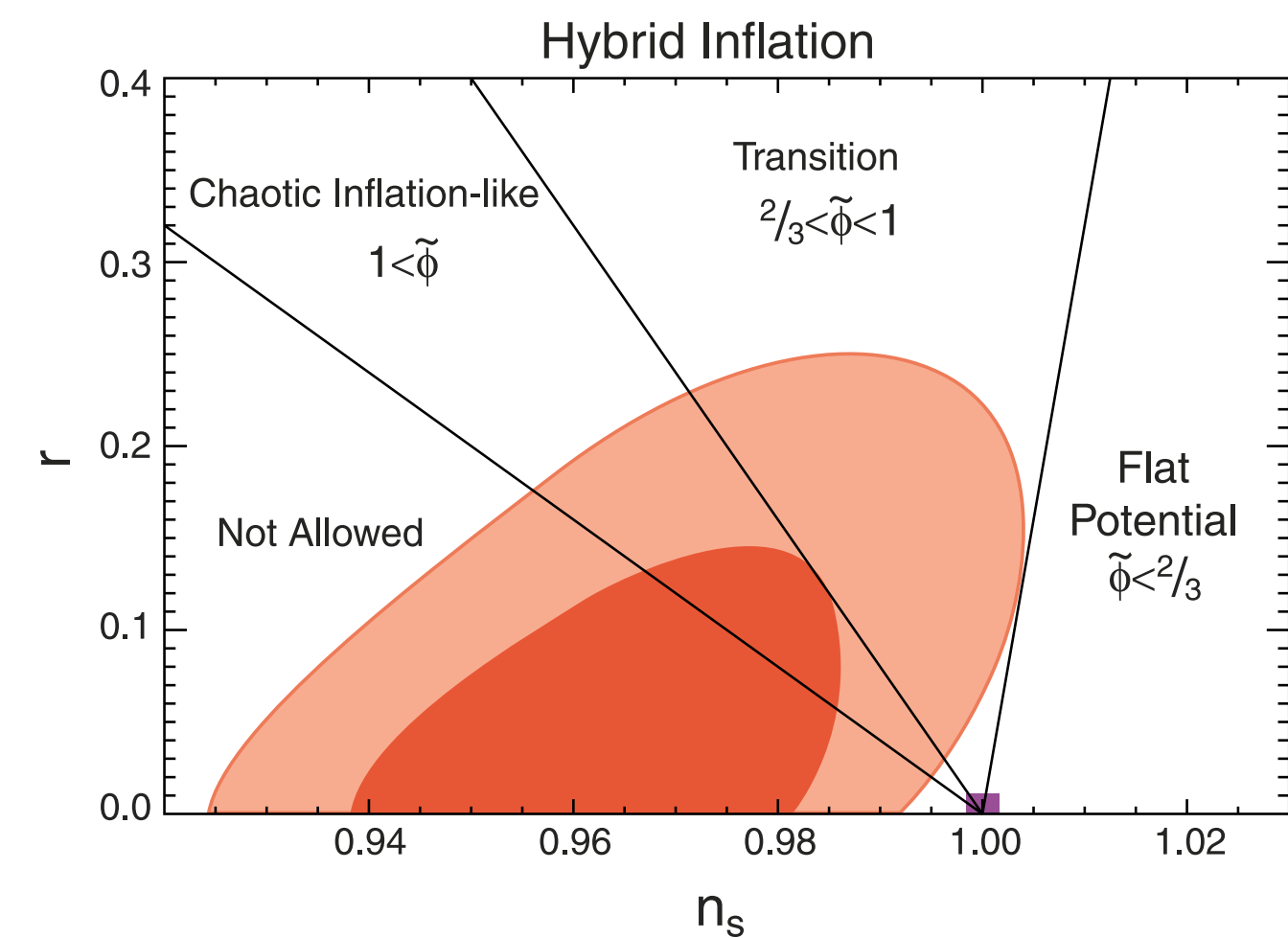
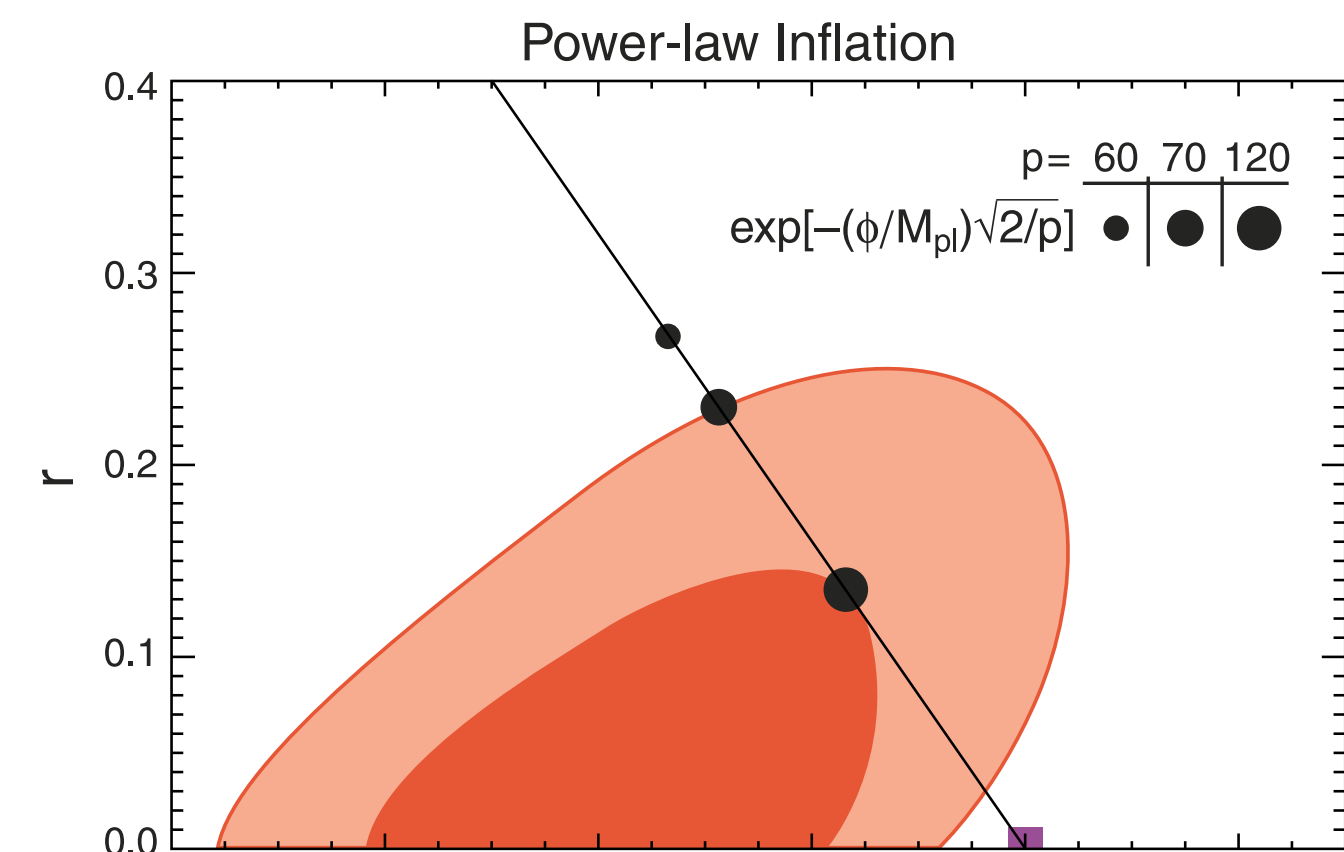
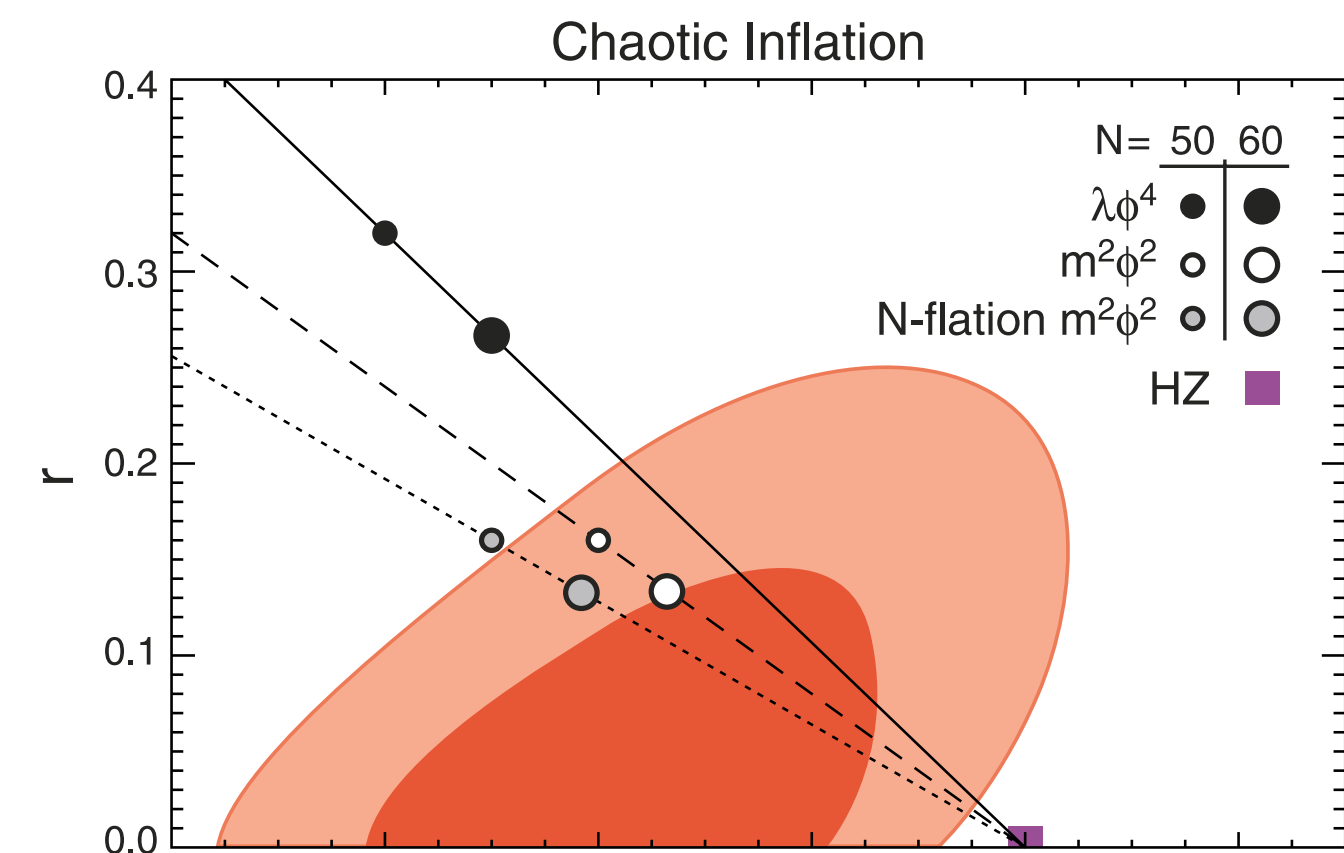
# $n_s > 1.0$ is Disfavored, Regardless of $r$



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

# 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  $m^2\varphi^2$  (Easter&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

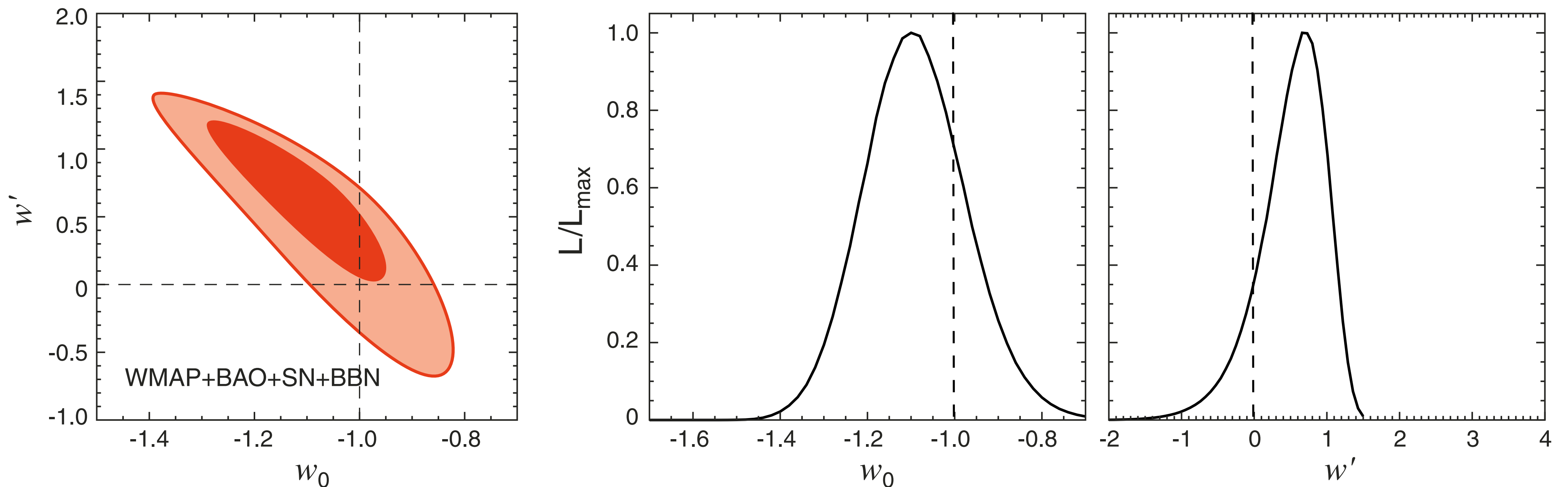


# Grading Inflation

- **Flatness:**  $-0.0175 < \Omega_k < 0.0085$  (not assuming  $w=-1$ !)
- **Non-adiabaticity:**  $<8.6\%$  (axion DM);  $<2.0\%$  (curvaton DM)
- **Non-Gaussianity:**  $-9 < \text{Local} < 111$ ;  $-151 < \text{Equilateral} < 253$
- **Tilt** (for  $r=0$ ):  $n_s=0.960 (+0.014) (-0.013)$  [68% CL]
- **Running** (for  $r=0$ ):  $-0.0728 < dn_s/d\ln k < 0.0087$
- **Gravitational waves:**  **$r < 0.20$** 
  - $n_s=0.968 (+/- 0.015)$  [68% CL]
  - **$n_s > 1$  disfavored at 95% CL regardless of  $r$**

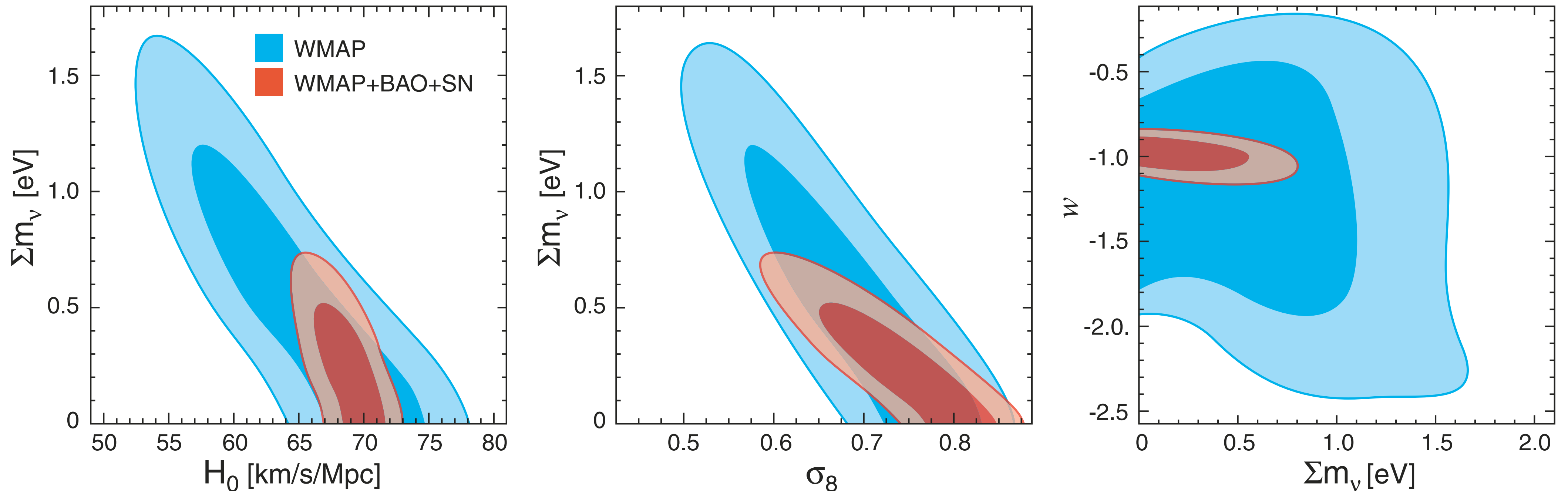
# Dark Energy EOS:

$$w(z) = w_0 + w'z / (1+z)$$



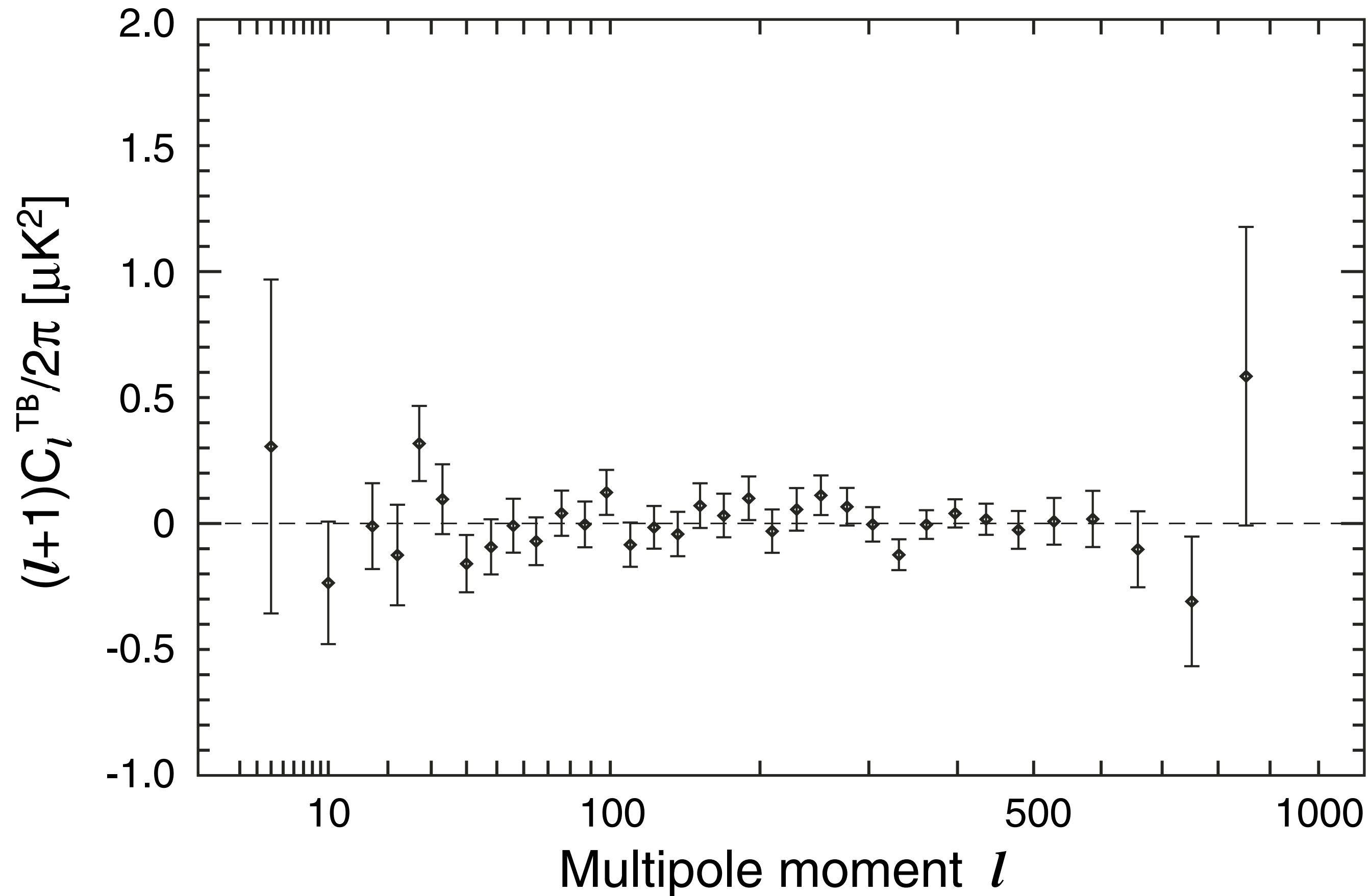
- Dark energy is pretty consistent with cosmological constant:  $w_0 = -1.09 \pm 0.12$  &  $w' = 0.52 \pm 0.46$  (68%CL)

# Neutrino Mass



- BAO helps determine the neutrino mass by giving  $H_0$ .
- **$\text{Sum}(m_\nu) < 0.61 \text{ eV}$**  (95% CL) -- independent of the normalization of the large scale structure.

# Probing Parity Violation *Nolta et al.*



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

# E $\rightarrow$ B

$$C_l^{TE,obs} = C_l^{TE} \cos(2\Delta\alpha),$$

$$C_l^{TB,obs} = C_l^{TE} \sin(2\Delta\alpha),$$

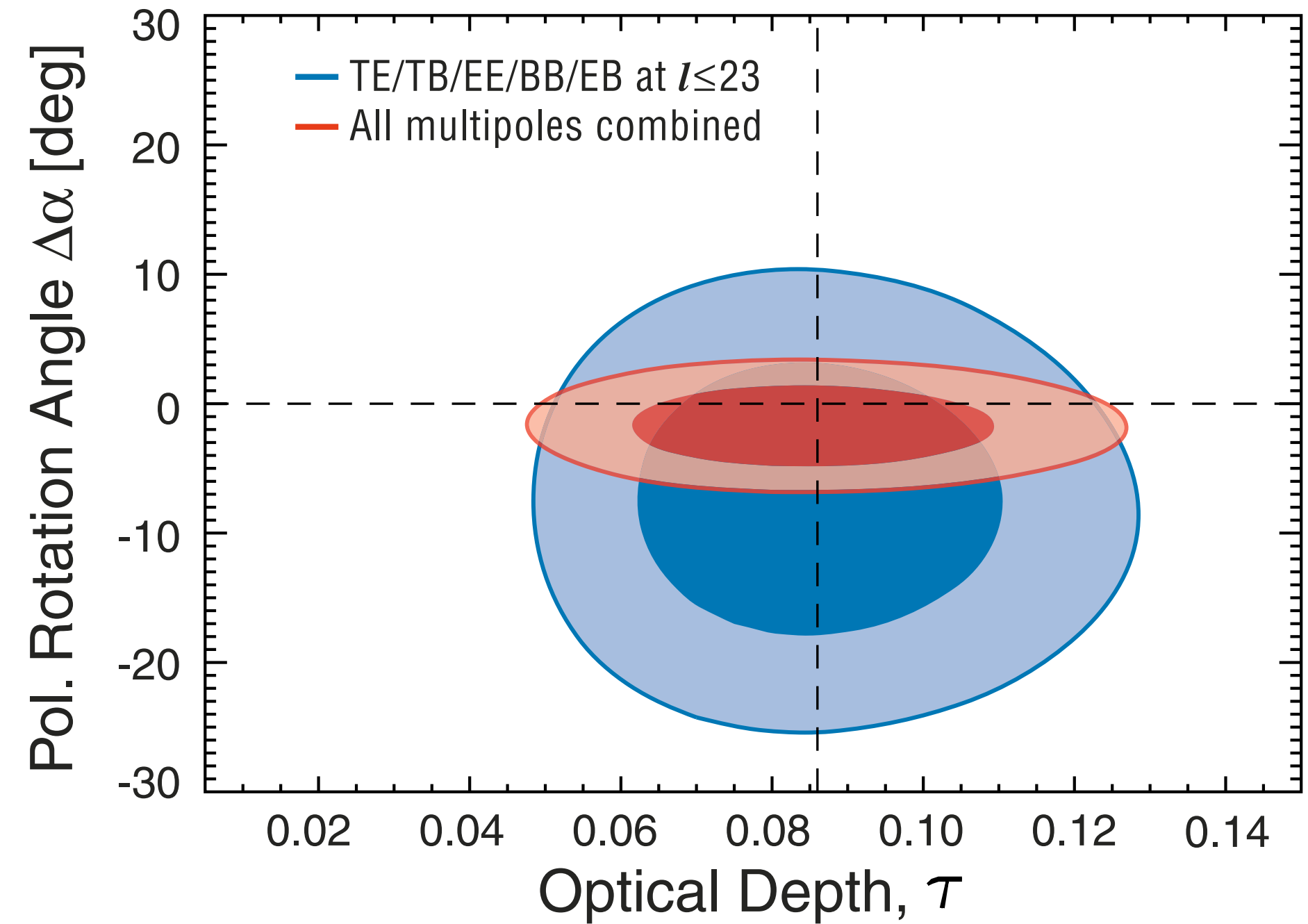
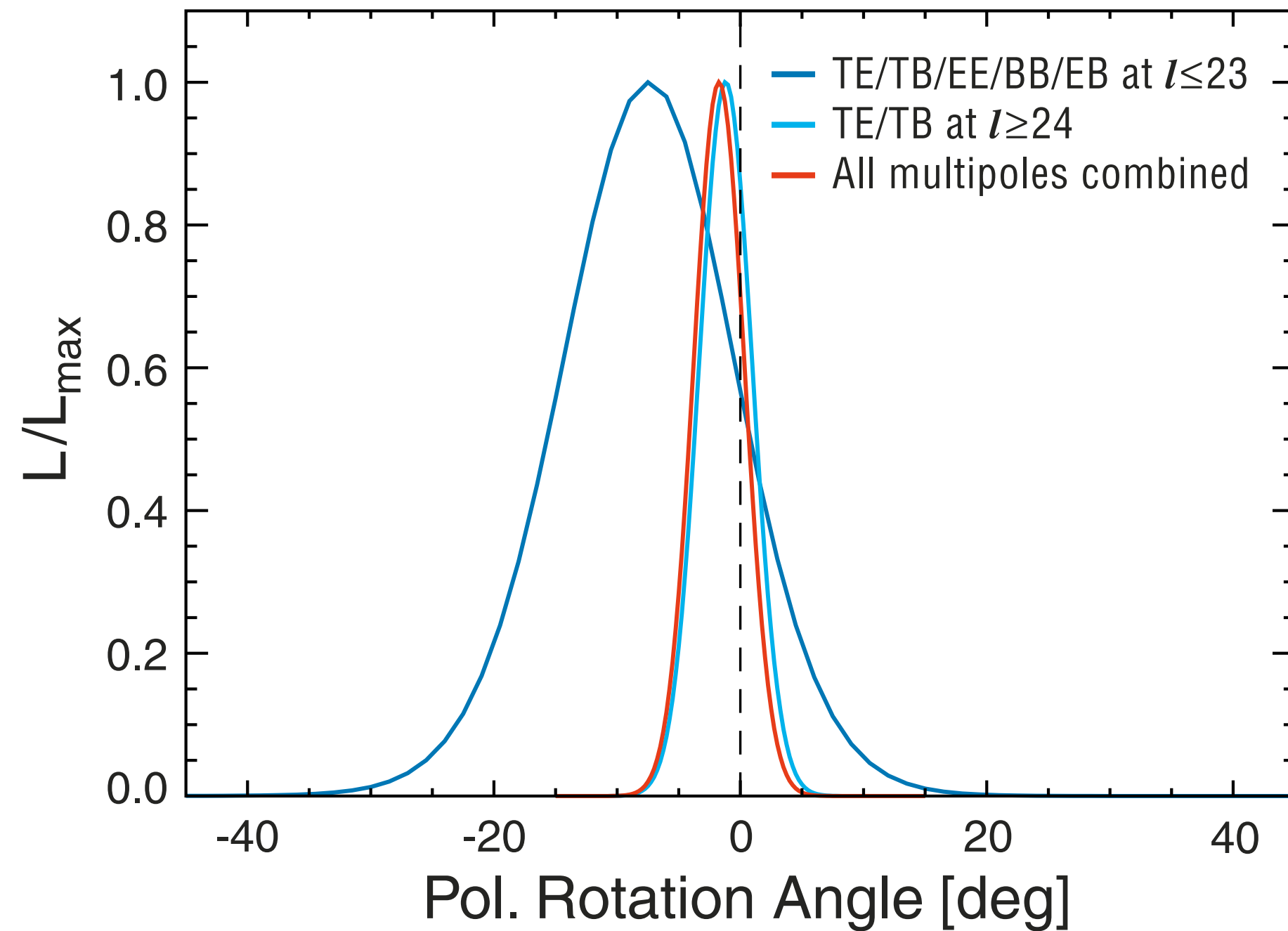
$$C_l^{EE,obs} = C_l^{EE} \cos^2(2\Delta\alpha),$$

$$C_l^{BB,obs} = C_l^{EE} \sin^2(2\Delta\alpha),$$

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

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





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

# Summary

- A simple, yet *mysterious*  $\Lambda$ CDM still fits the WMAP data, as well as the other astrophysical data sets.
- **We did everything we could do to find deviations from  $\Lambda$ CDM, 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  $\Lambda$ CDM 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  $f_{\text{NL}} \sim 50$ , we will see it at the 3 sigma level with 9 years of data.
  - Gravitational waves ( $r$ ) and tilt ( $n_s$ ) :  $m^2\phi^2$  can be pushed out of the favorable parameter region
    - $n_s > 1$  would be convincingly ruled out regardless of  $r$ .