



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

Eiichiro Komatsu (Department of Astronomy, UT Austin)
Colloquium, University of California Davis, May 12, 2008

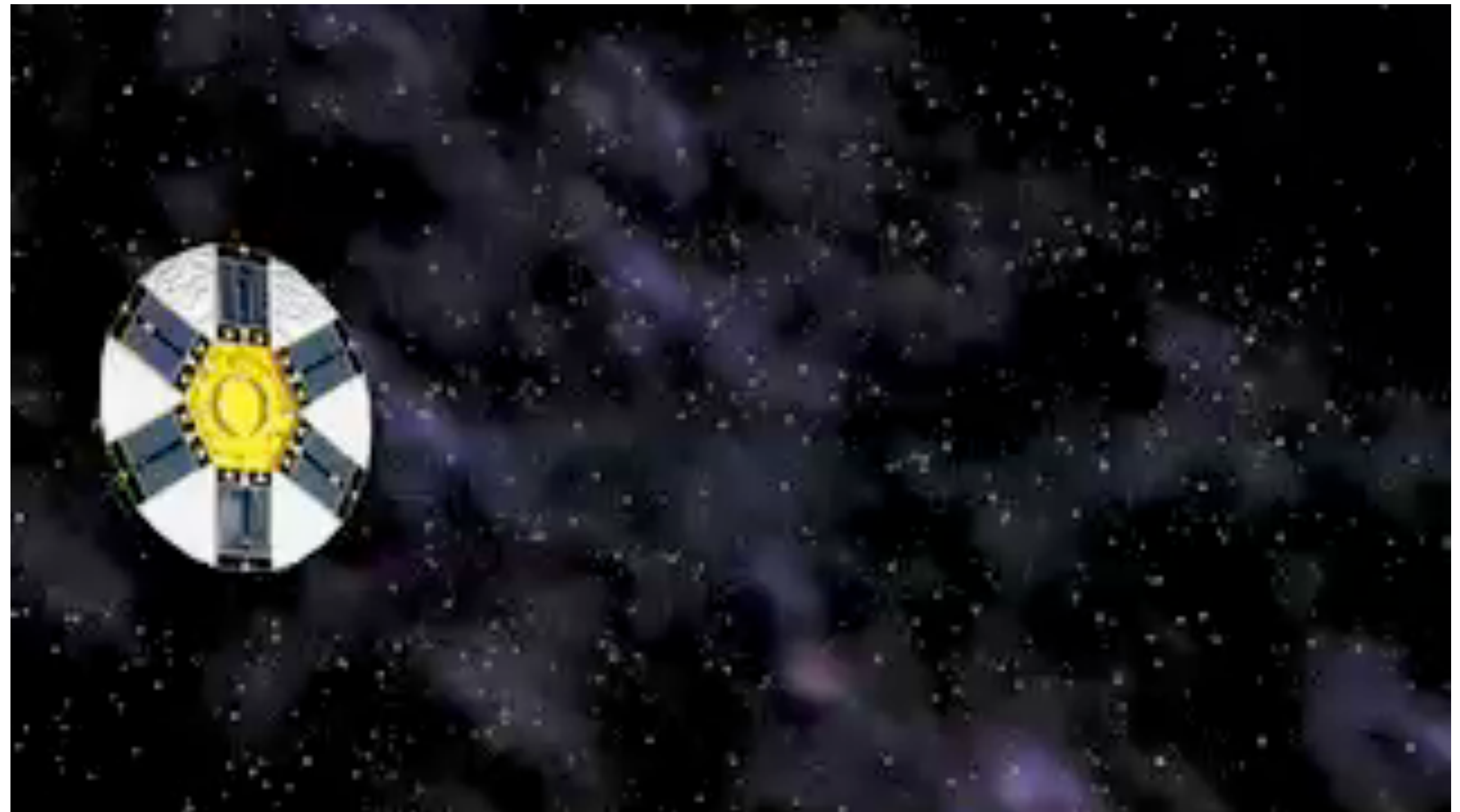
WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

February 2003:
The first-year data
release

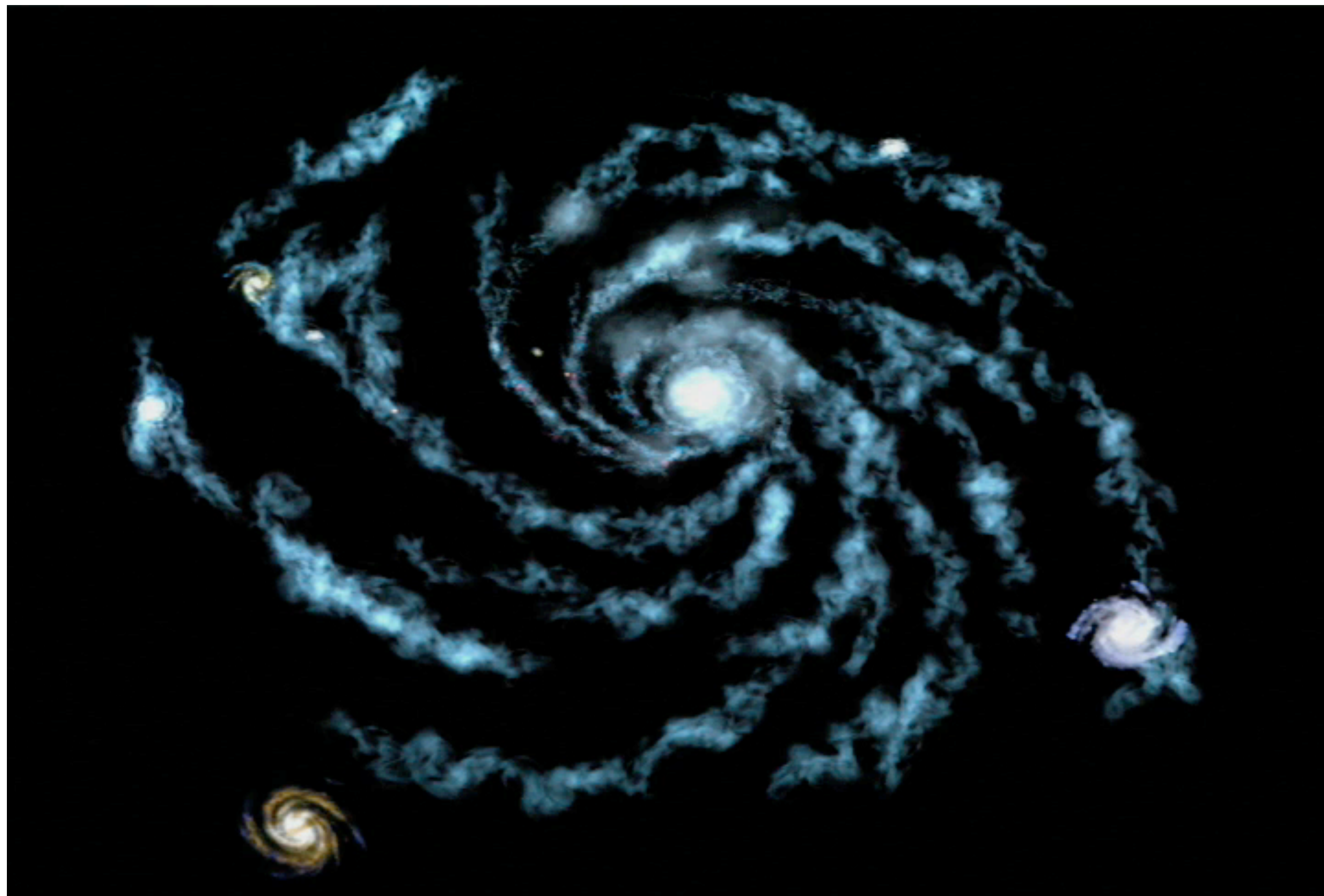
March 2006:
The three-year data
release

**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

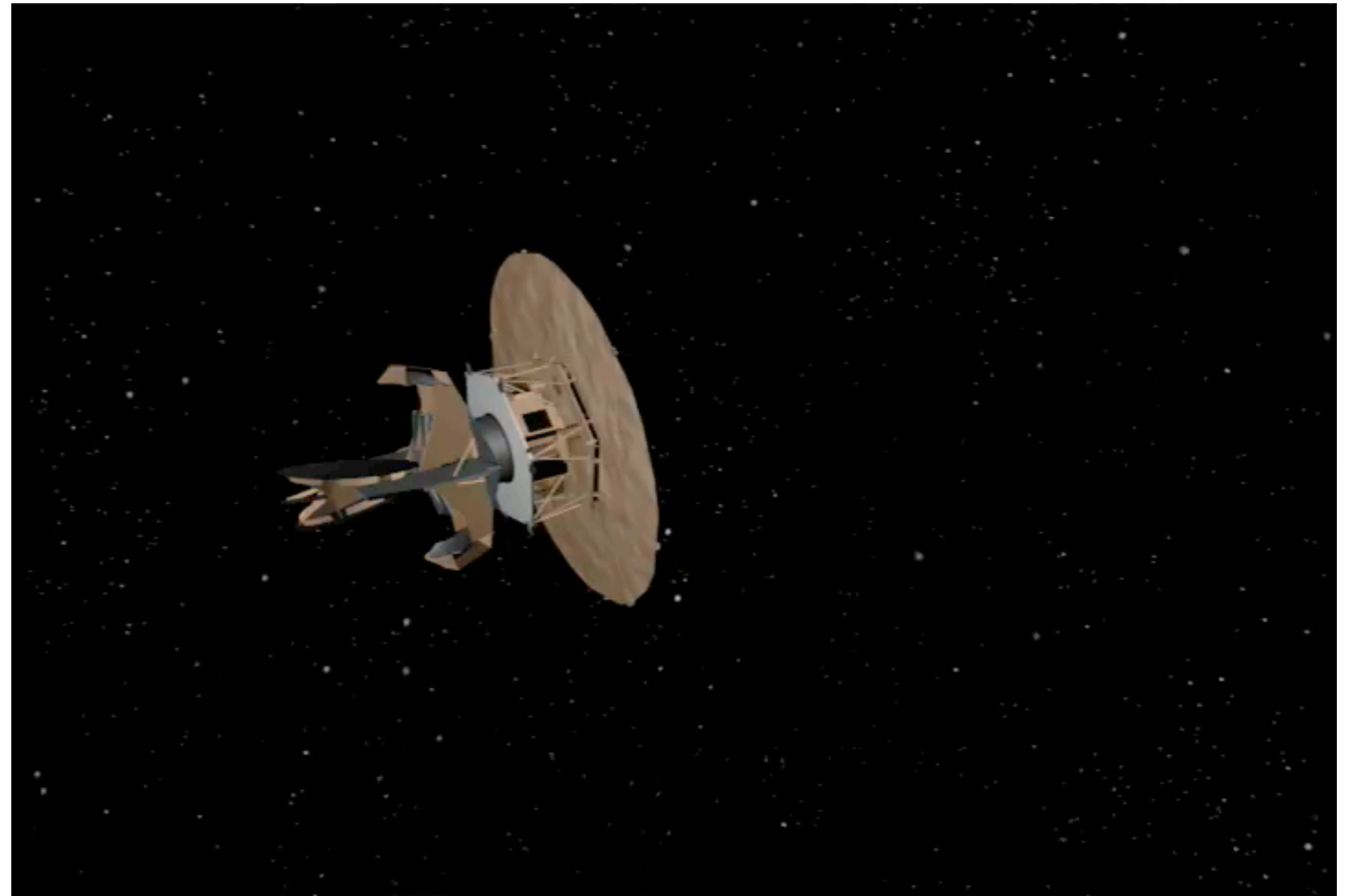
WMAP Measures Microwaves From the Universe



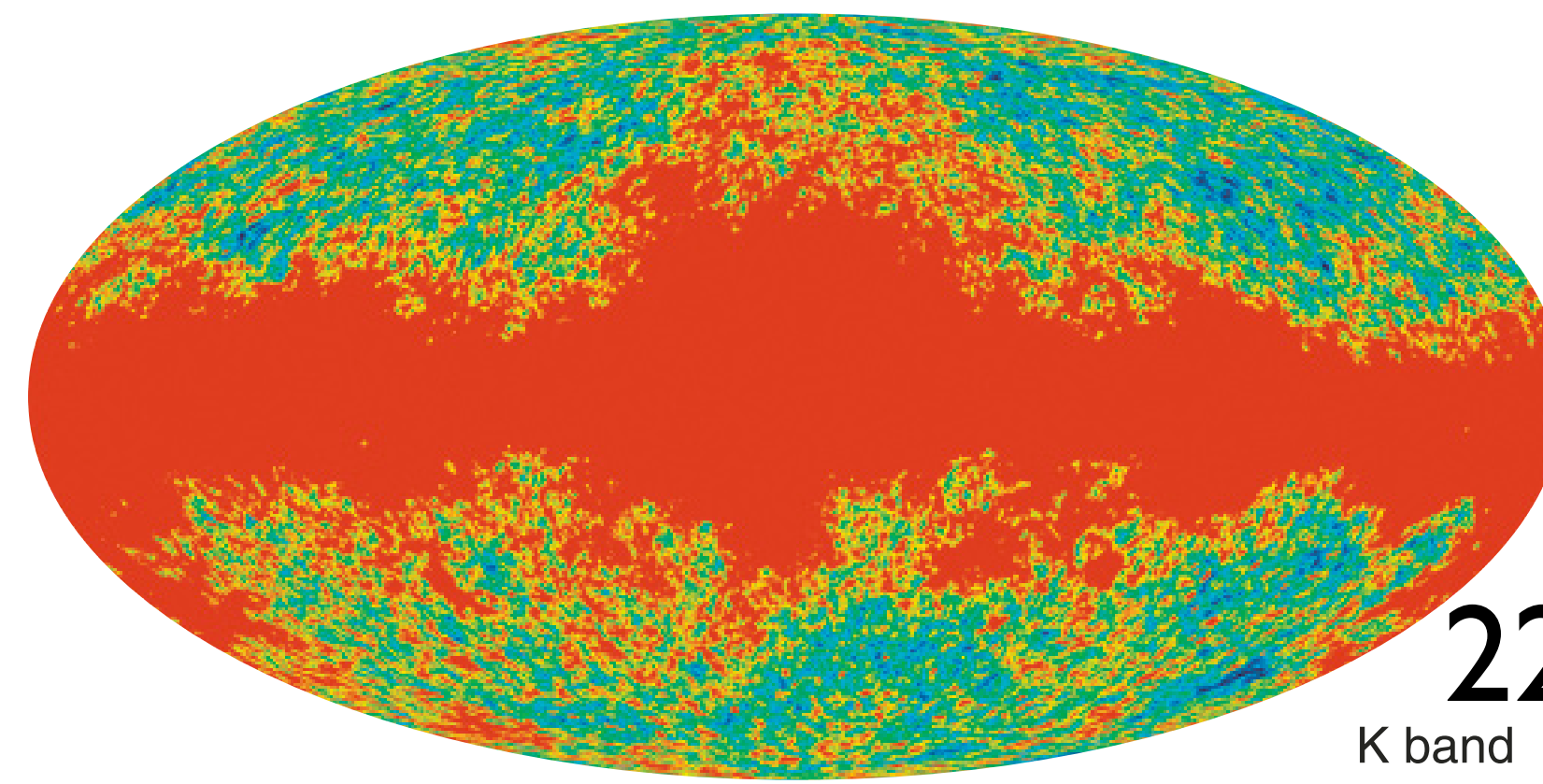
- The mean temperature of photons in the Universe today is 2.725 K
- WMAP is capable of measuring the temperature *contrast* down to better than **one part in millionth**³

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

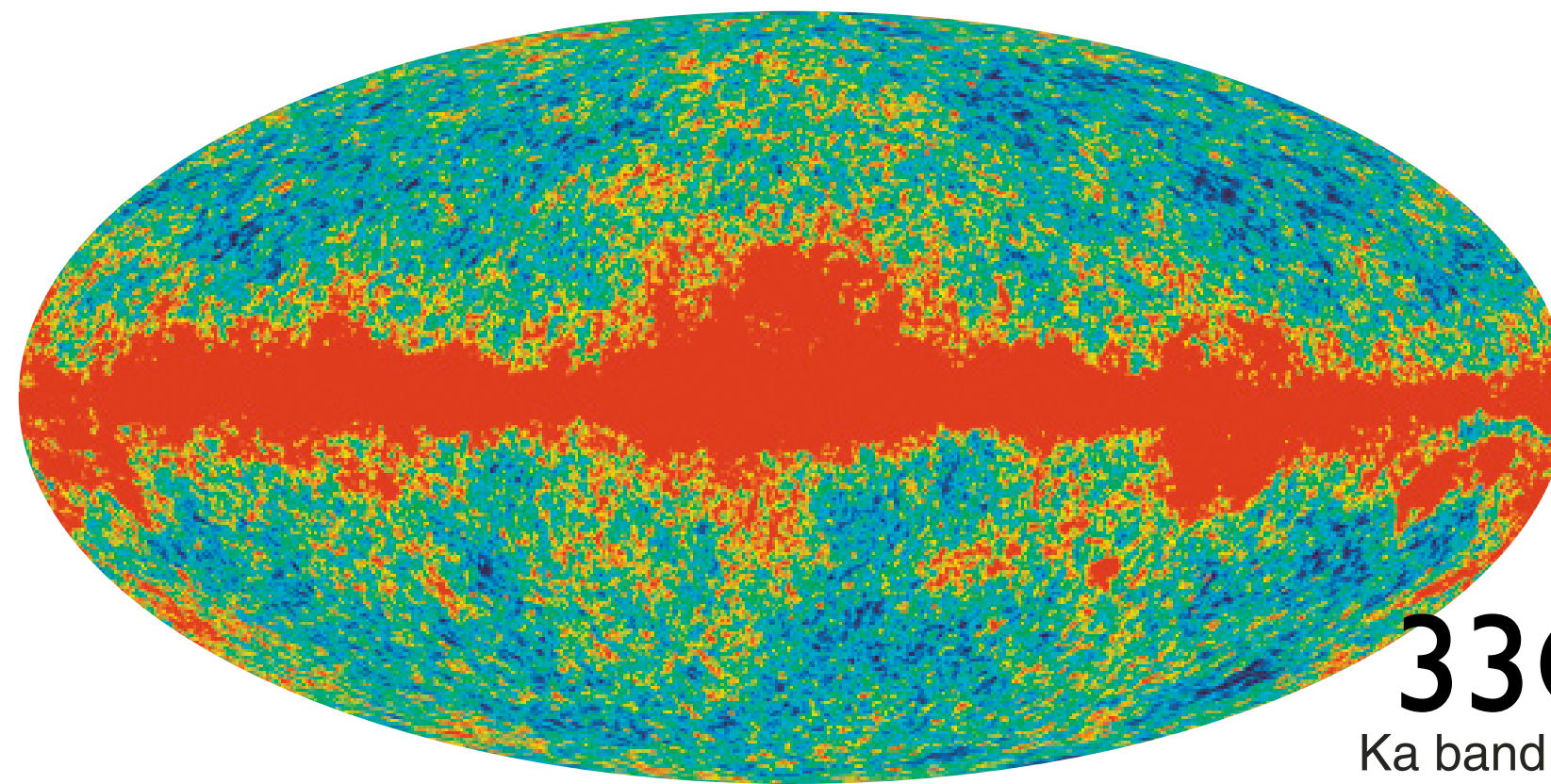


- CMB photons, after released from the cosmic plasma “soup,” traveled for **13.7 billion years** to reach us.
- CMB collects information about the Universe as it travels through it.



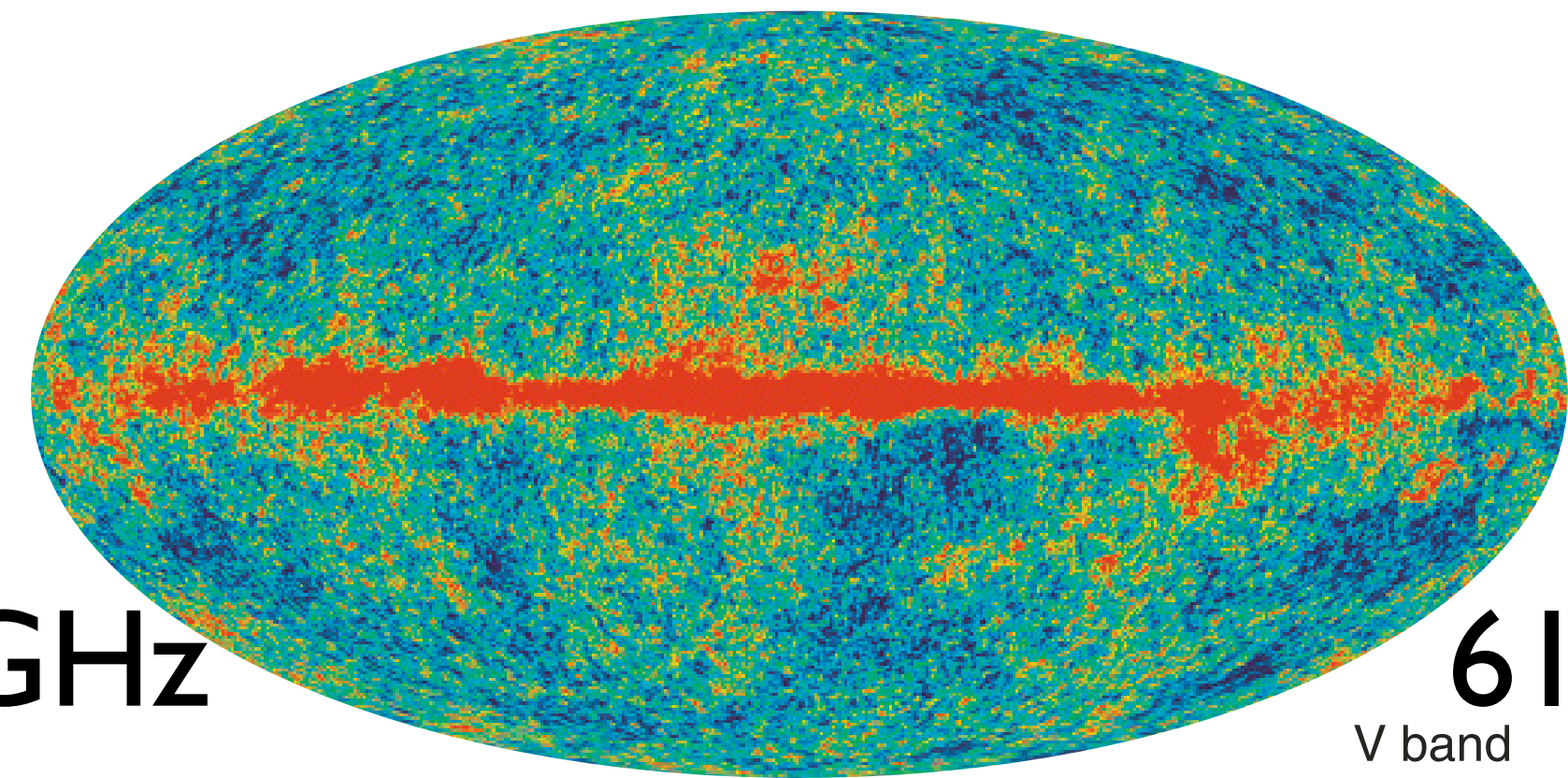
22GHz

K band



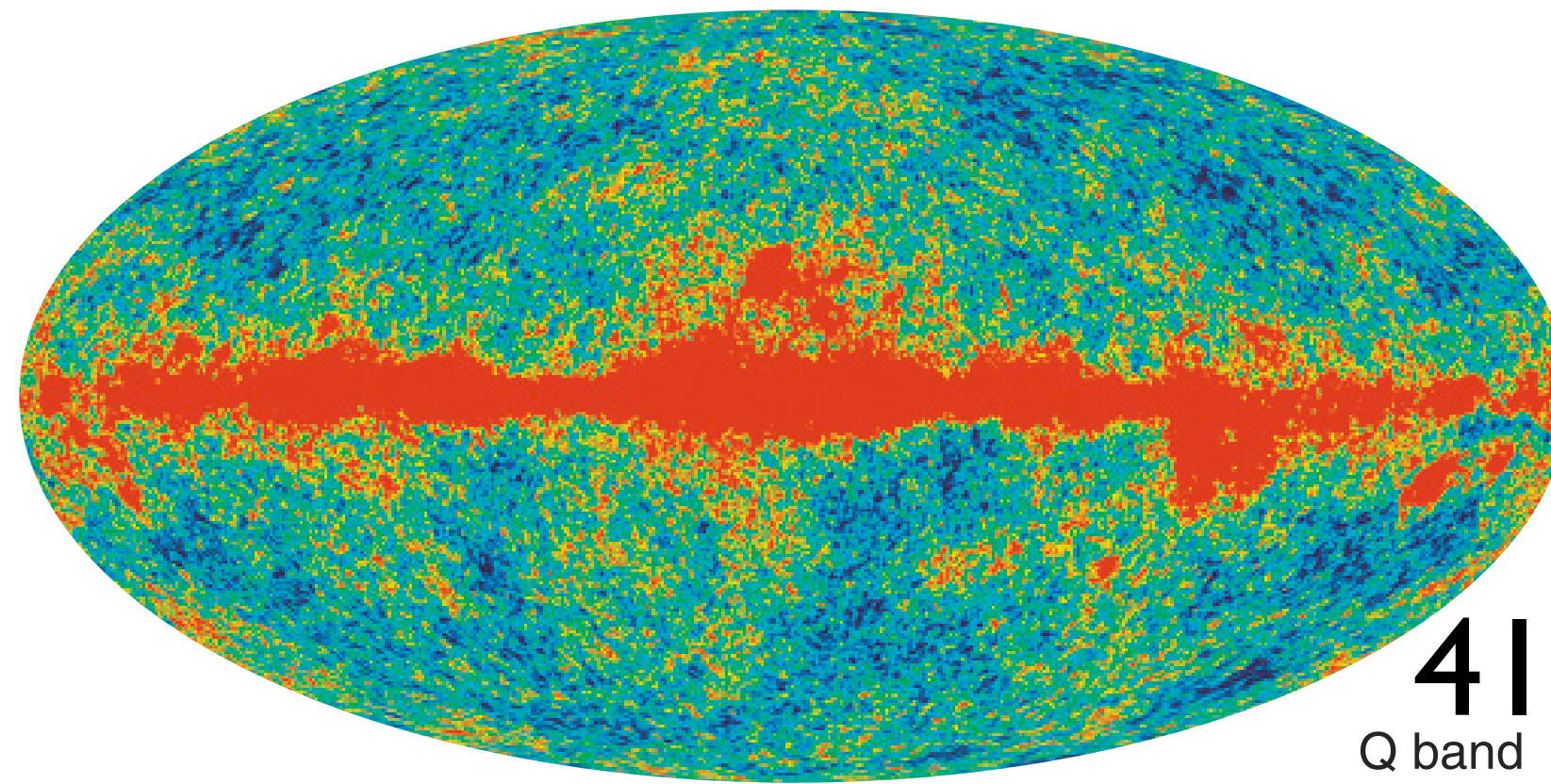
33GHz

Ka band



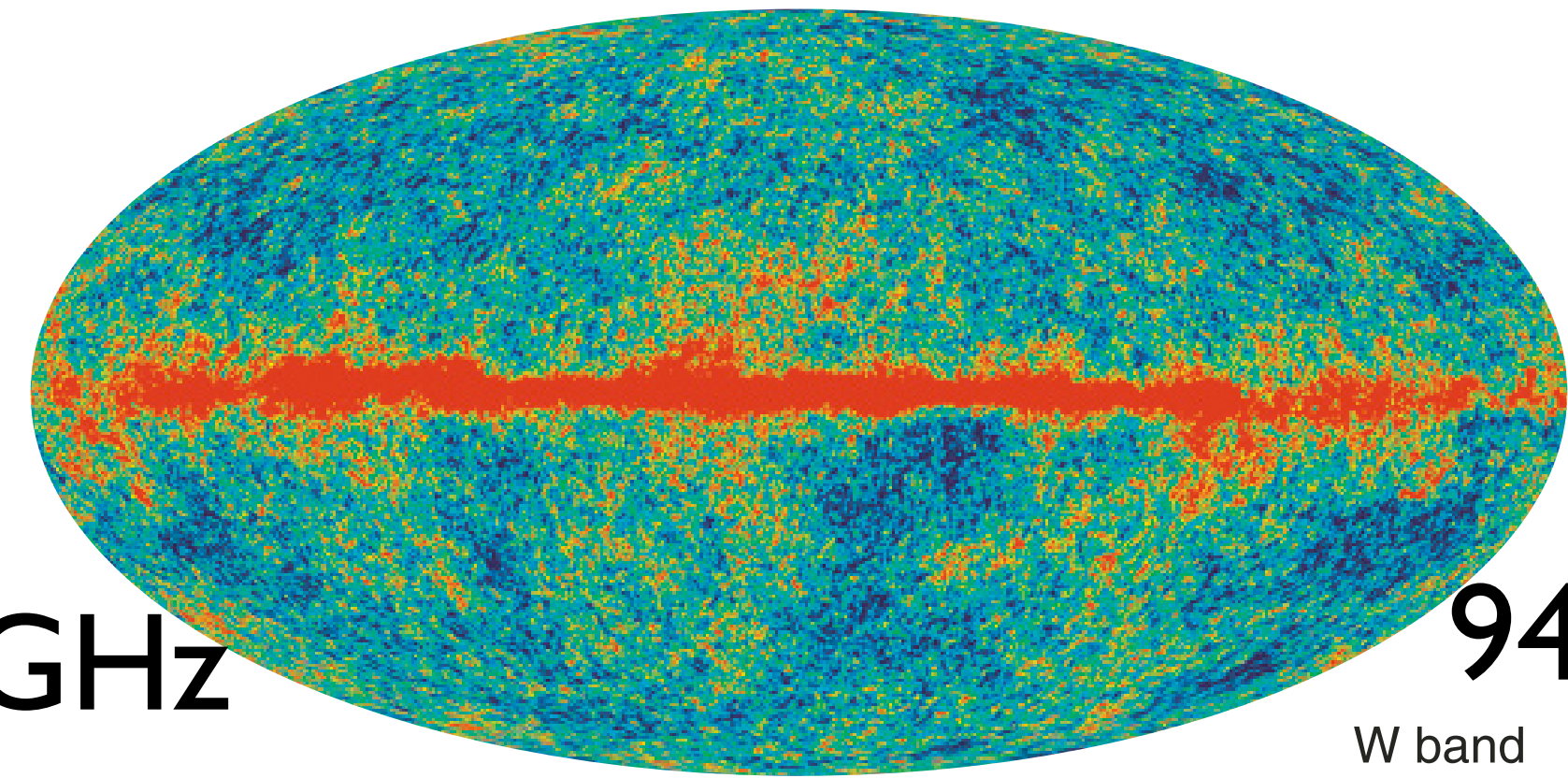
61GHz

V band



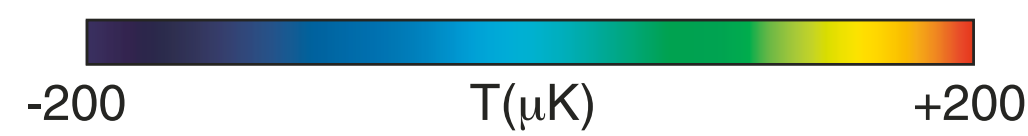
41GHz

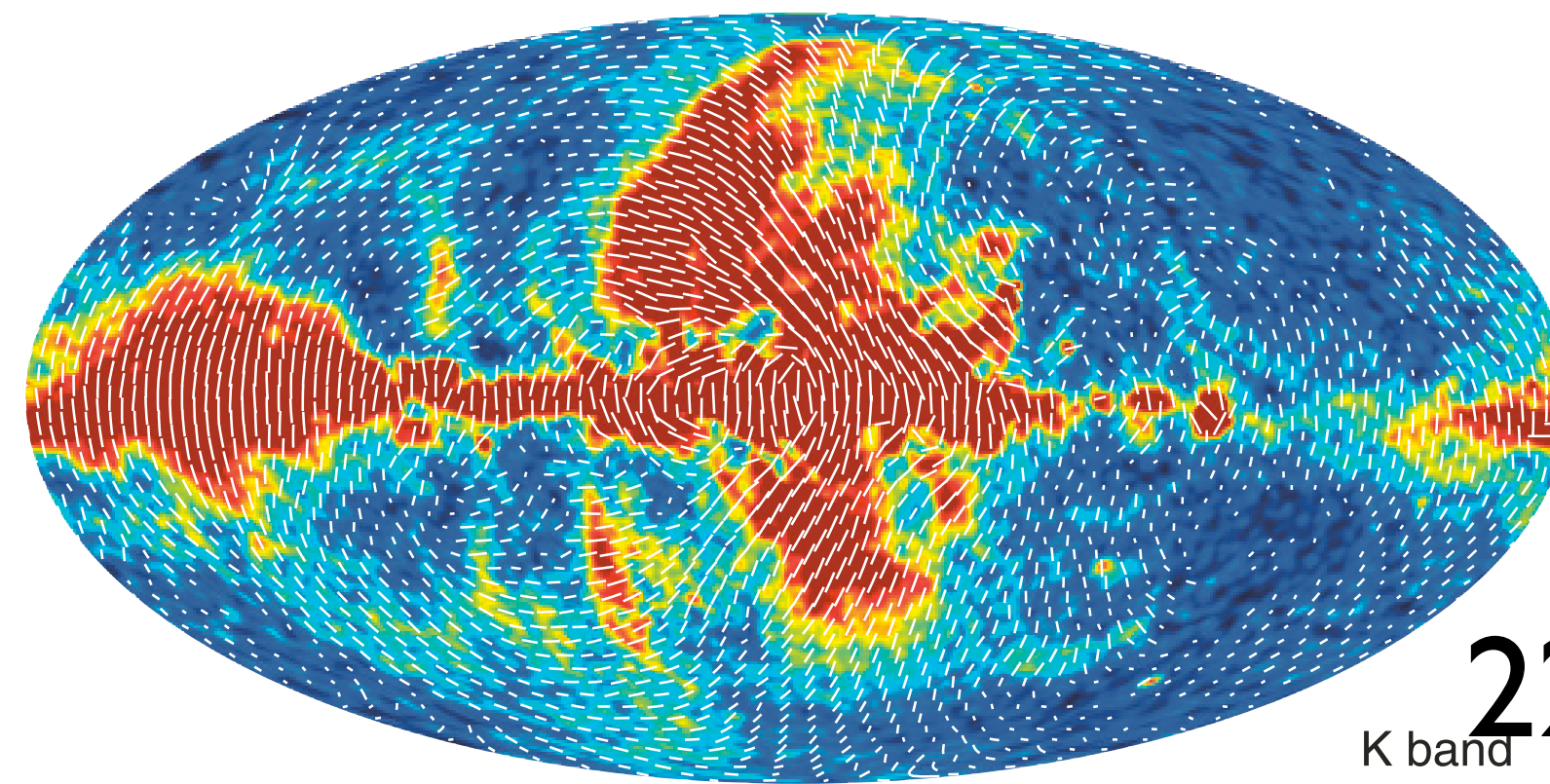
Q band



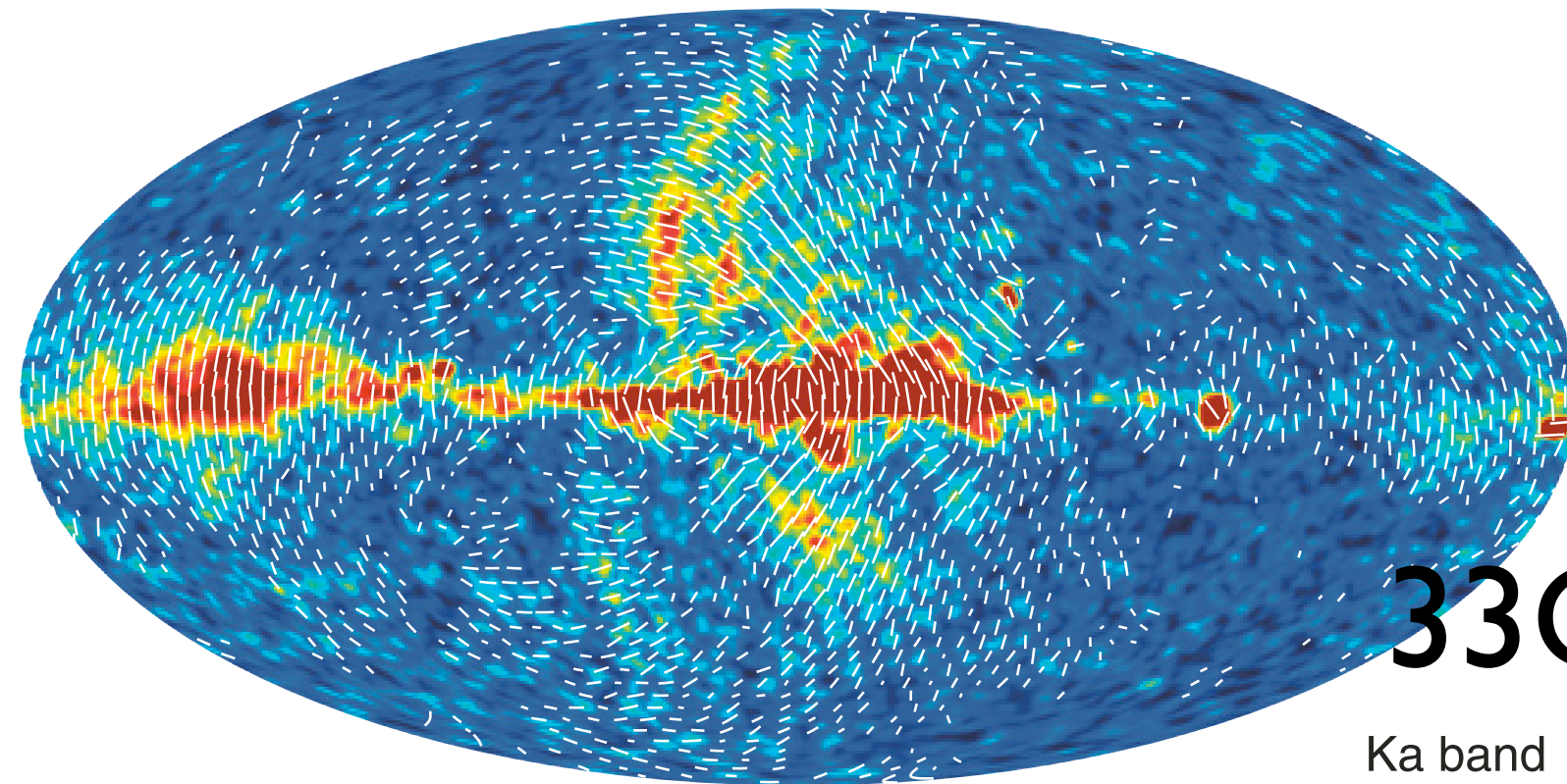
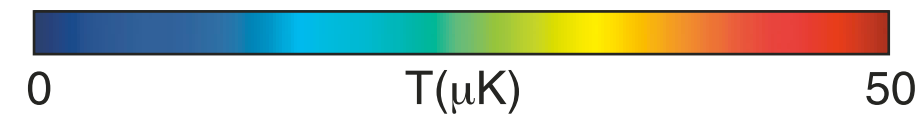
94GHz

W band

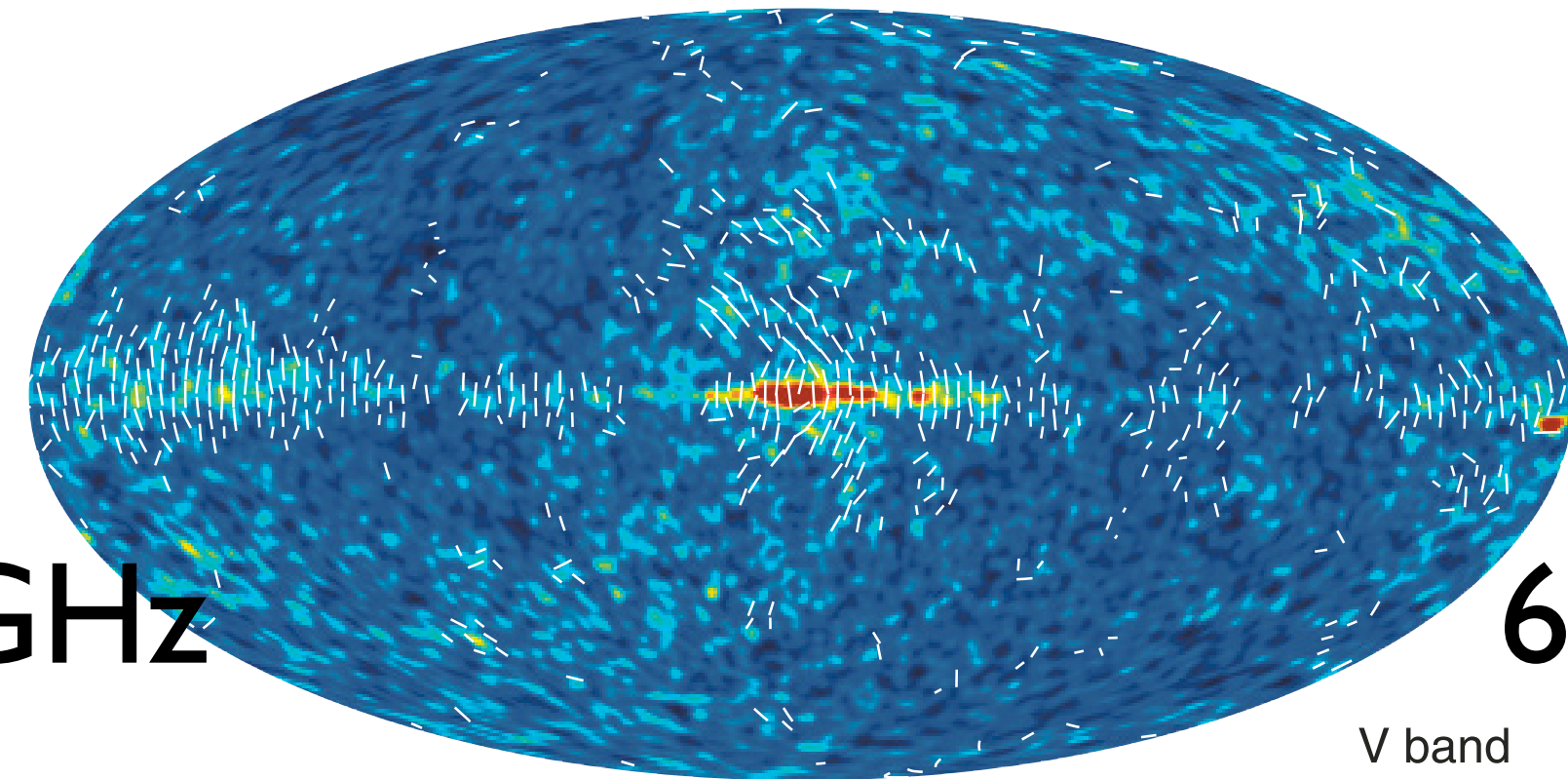




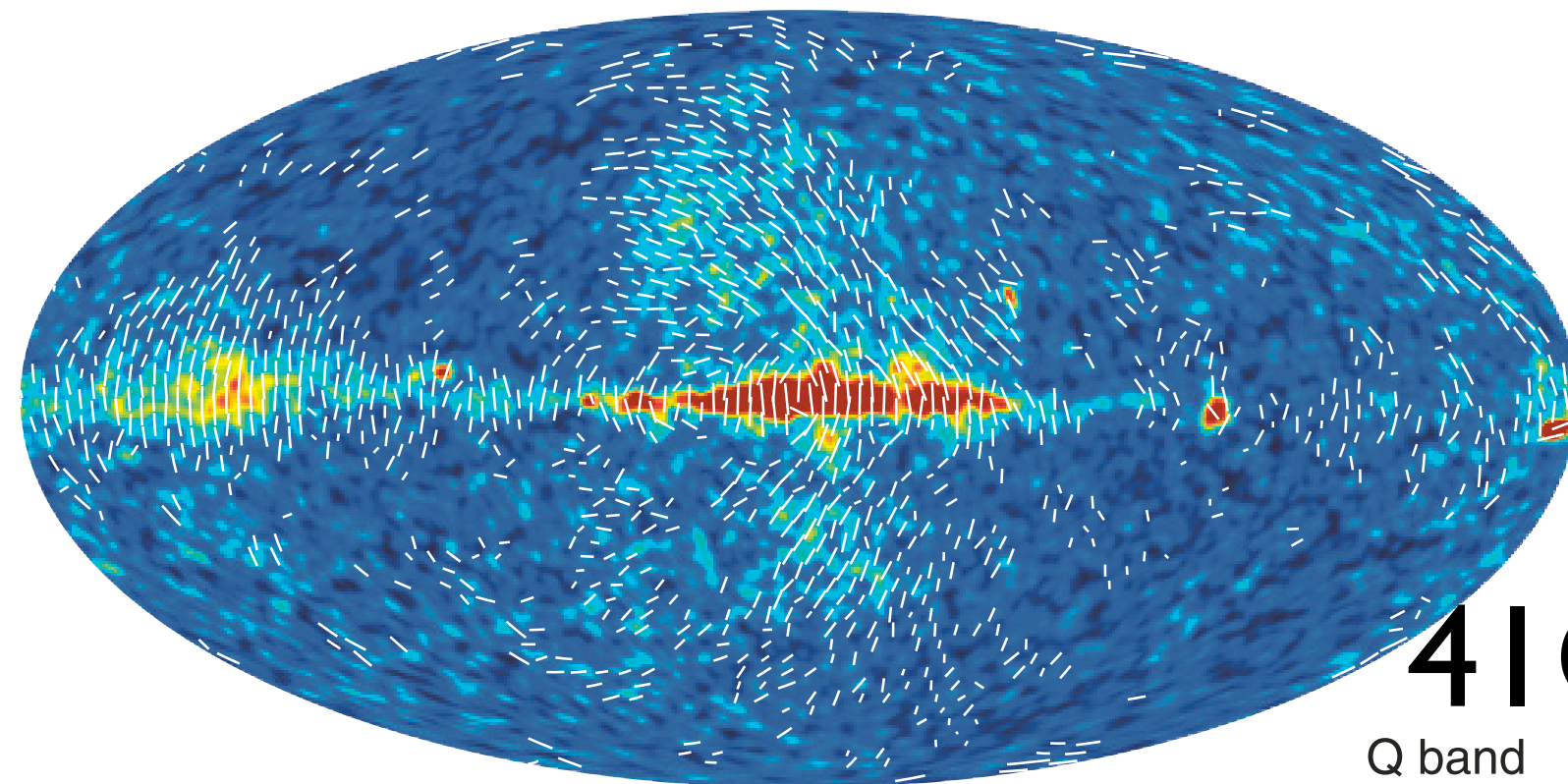
22GHz
K band



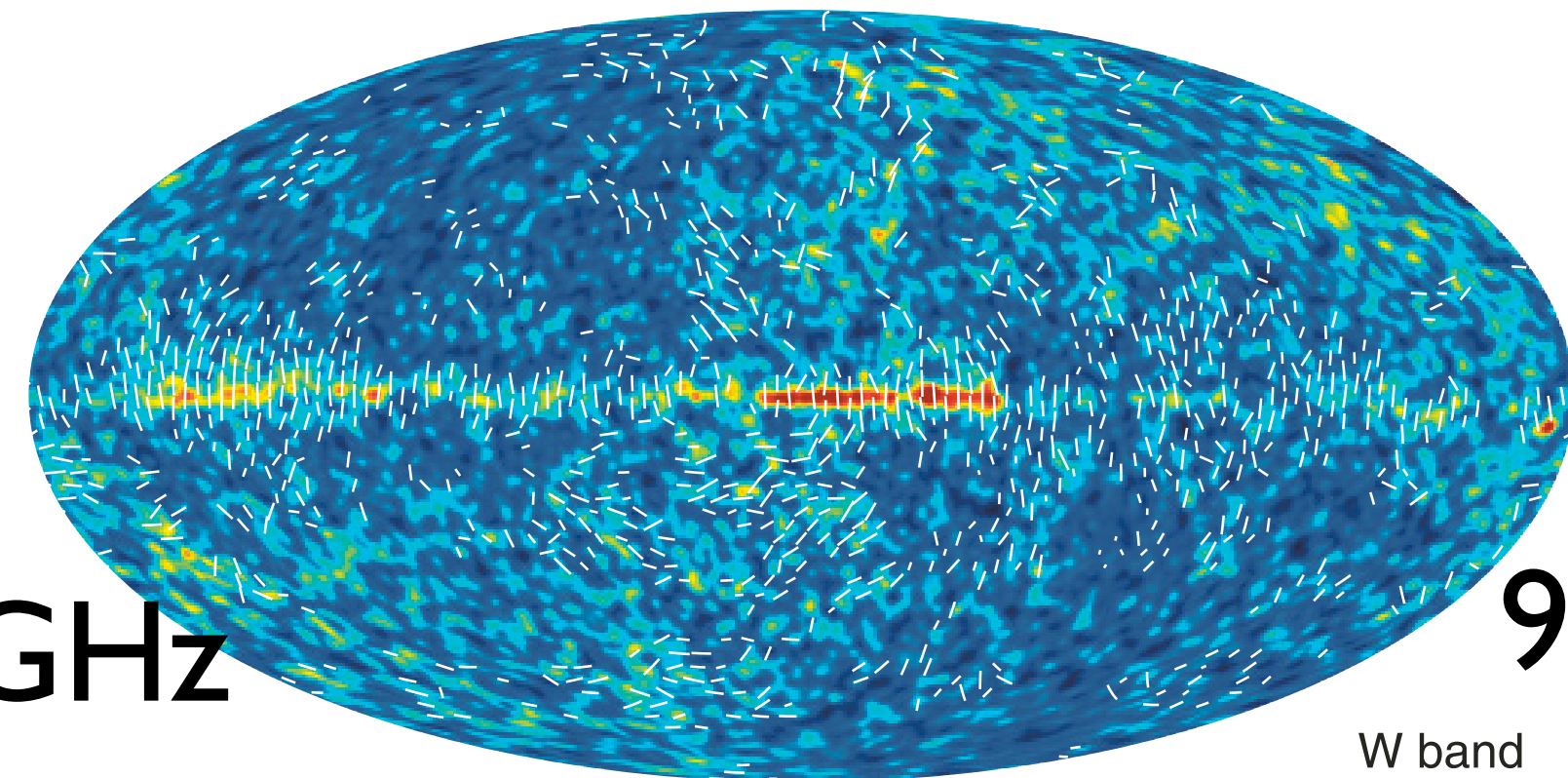
33GHz
Ka band



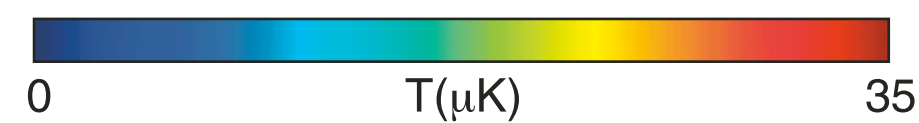
61GHz
V band



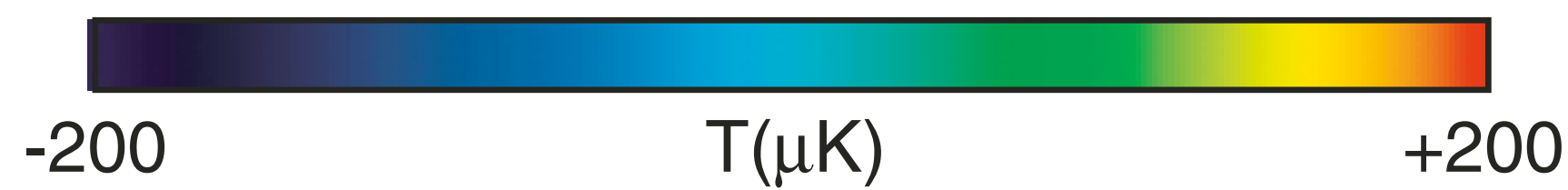
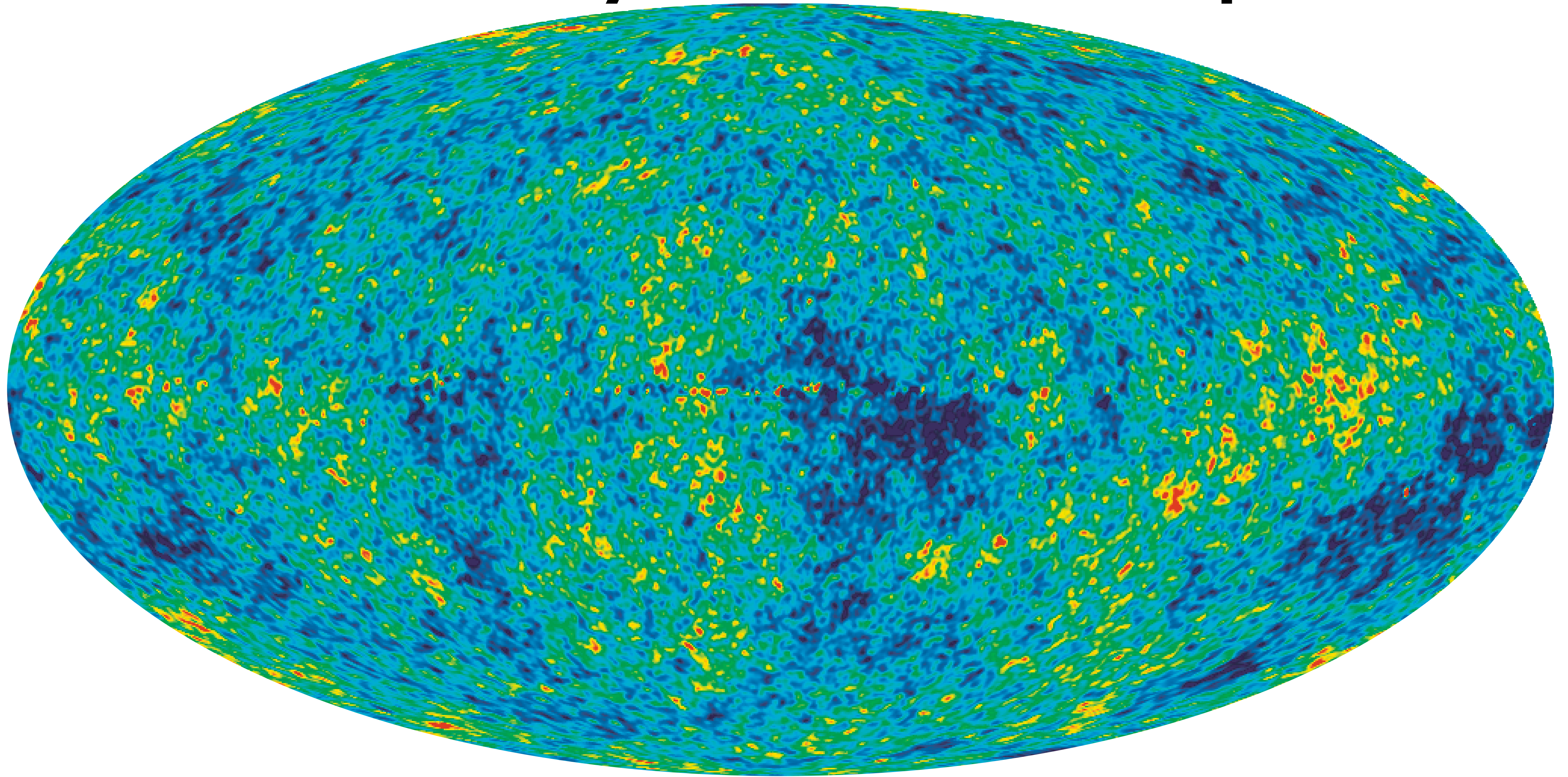
41GHz
Q band



94GHz
W band

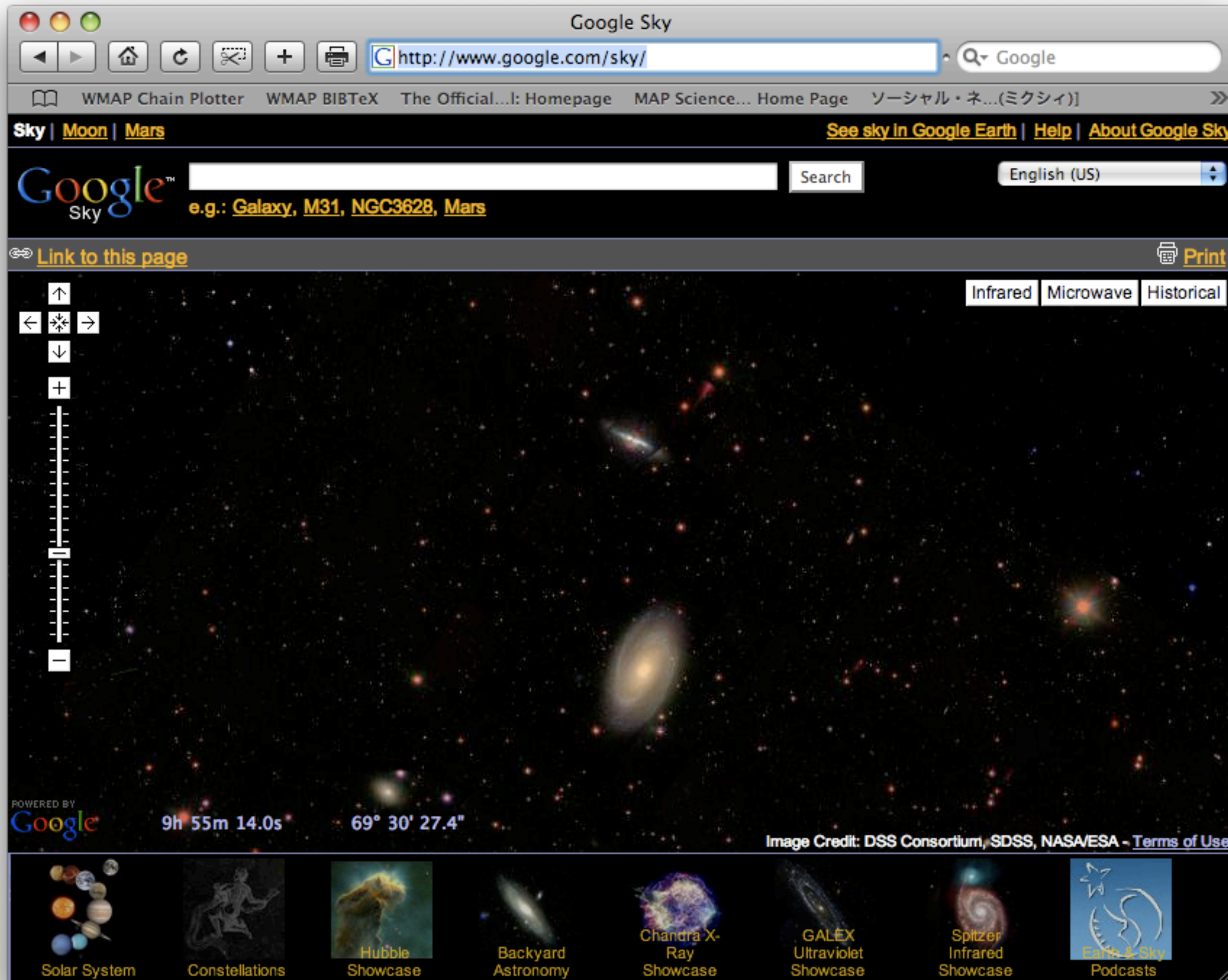


Galaxy-cleaned Map



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](#)

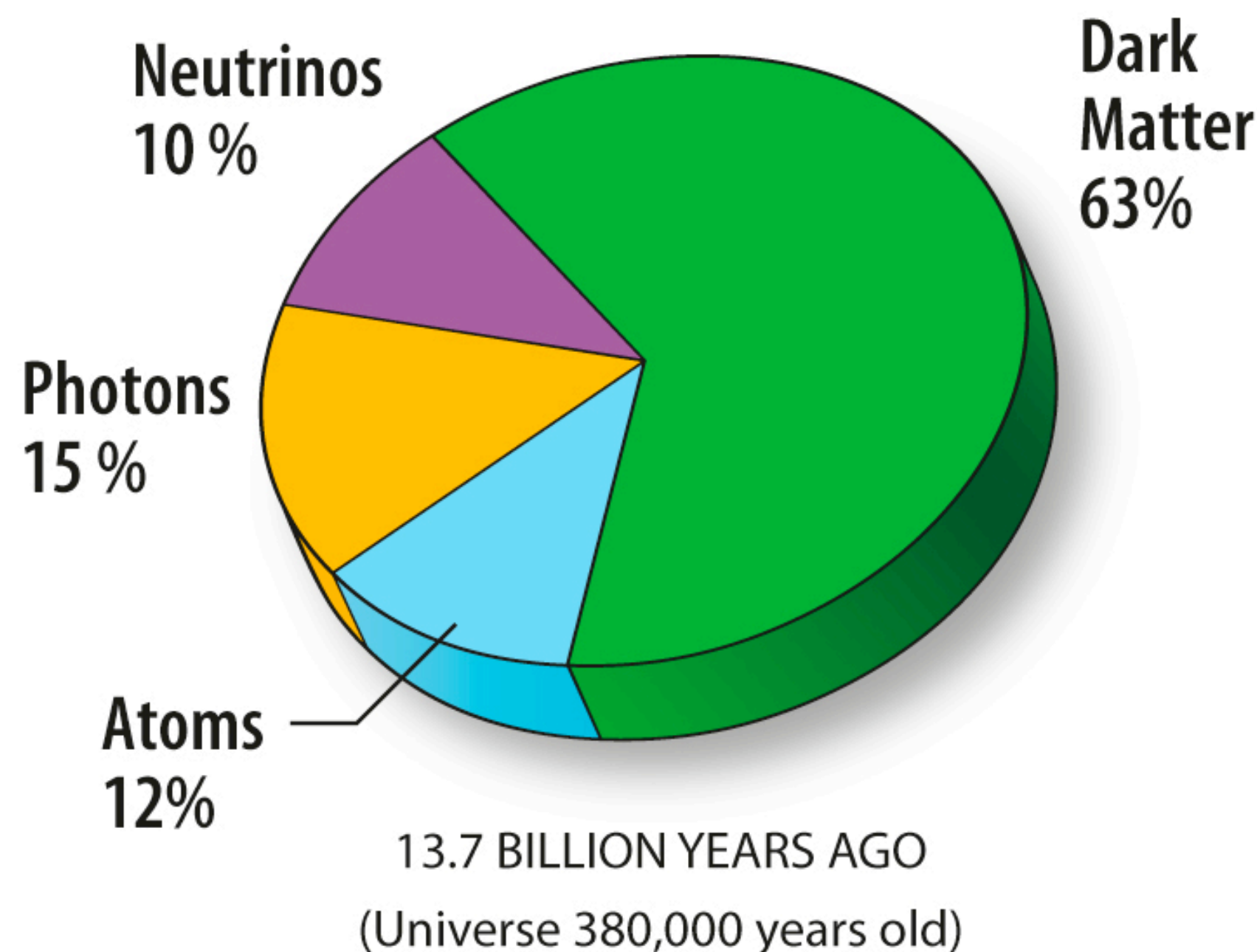
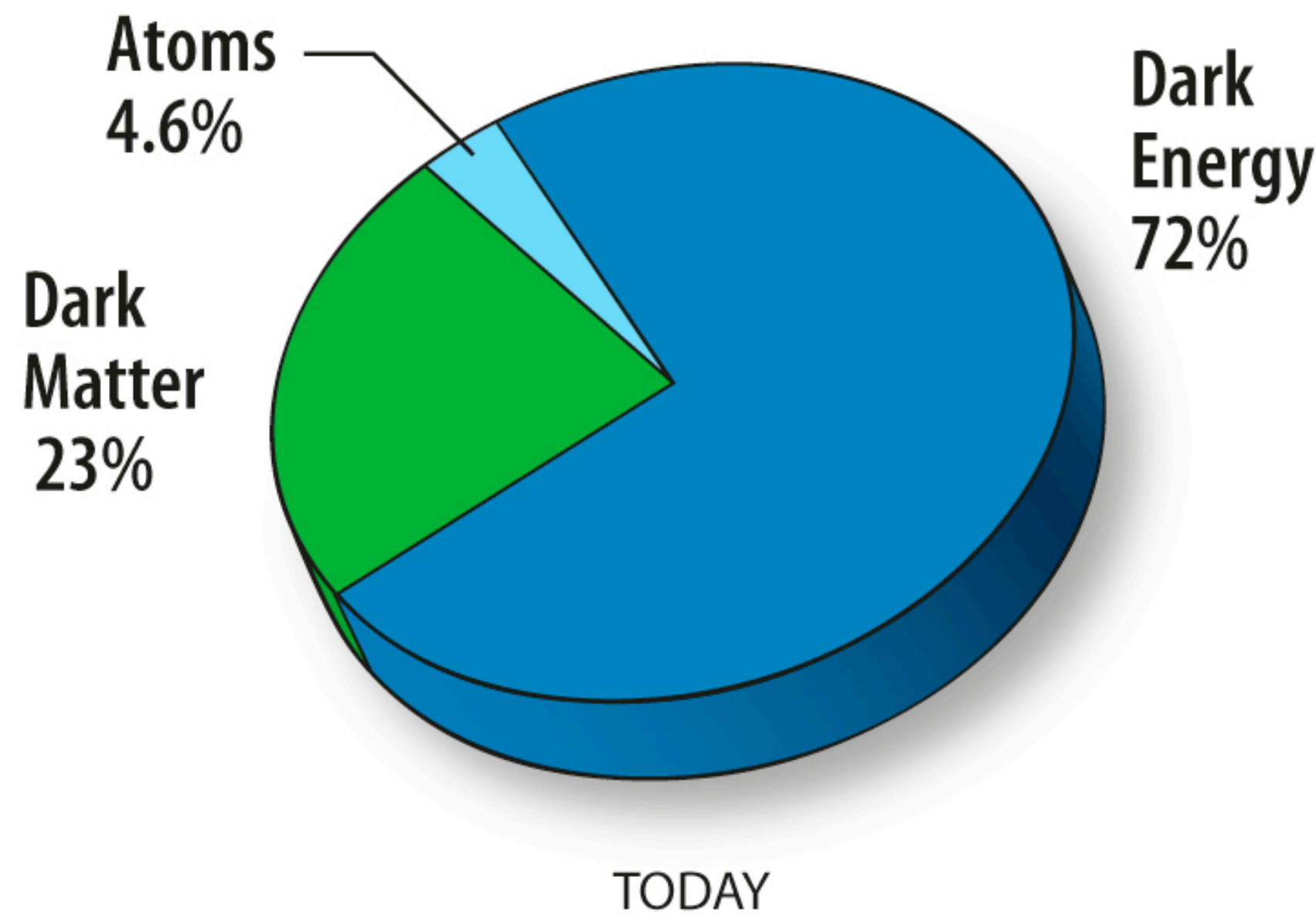
WMAP 5-Year Science Team

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

Special
Thanks to
WMAP
Graduates!

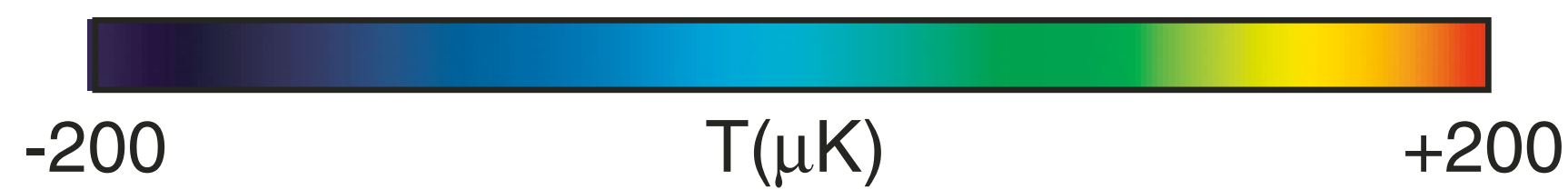
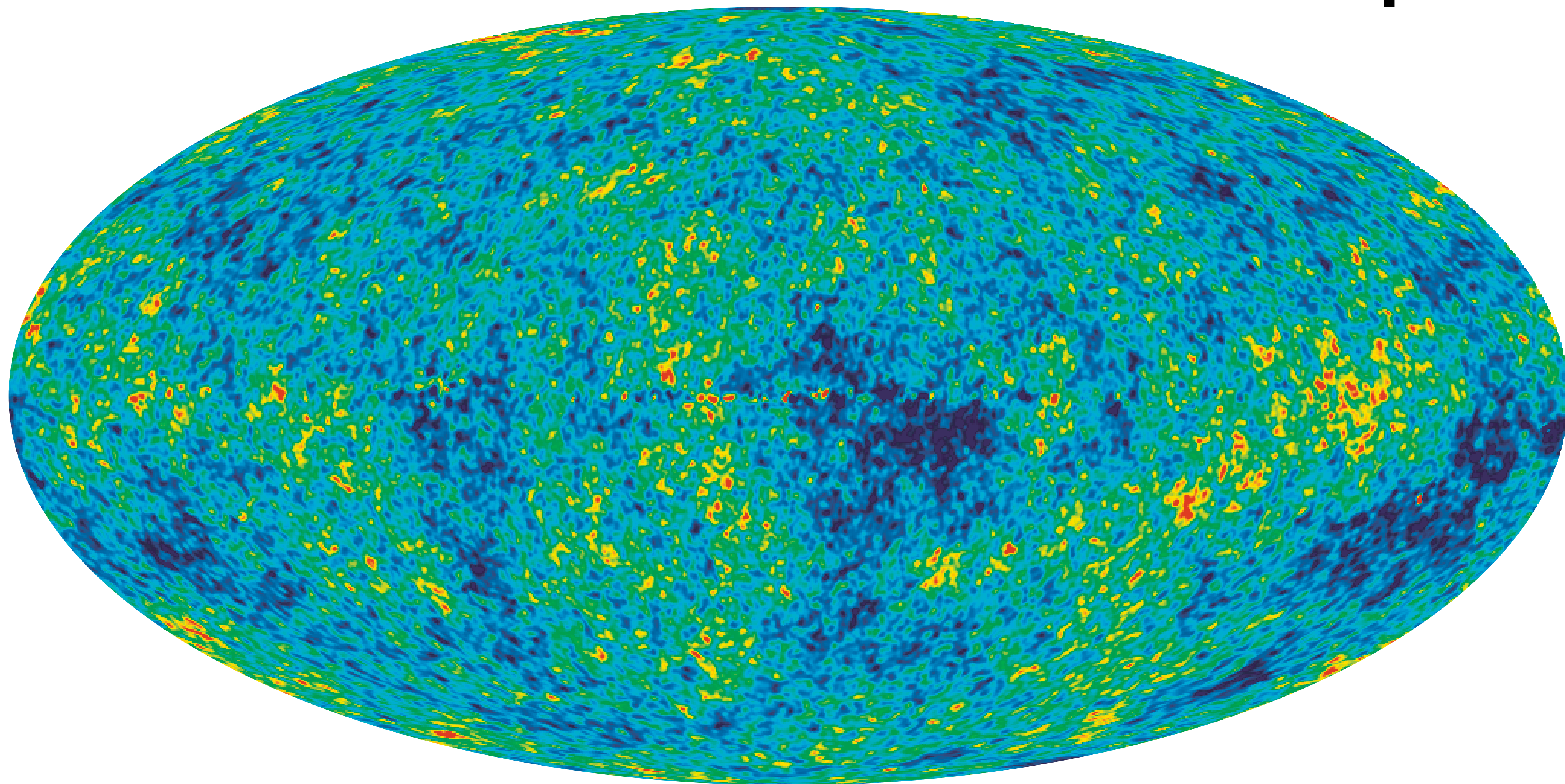
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

~WMAP 5-Year~ Pie Chart Update!



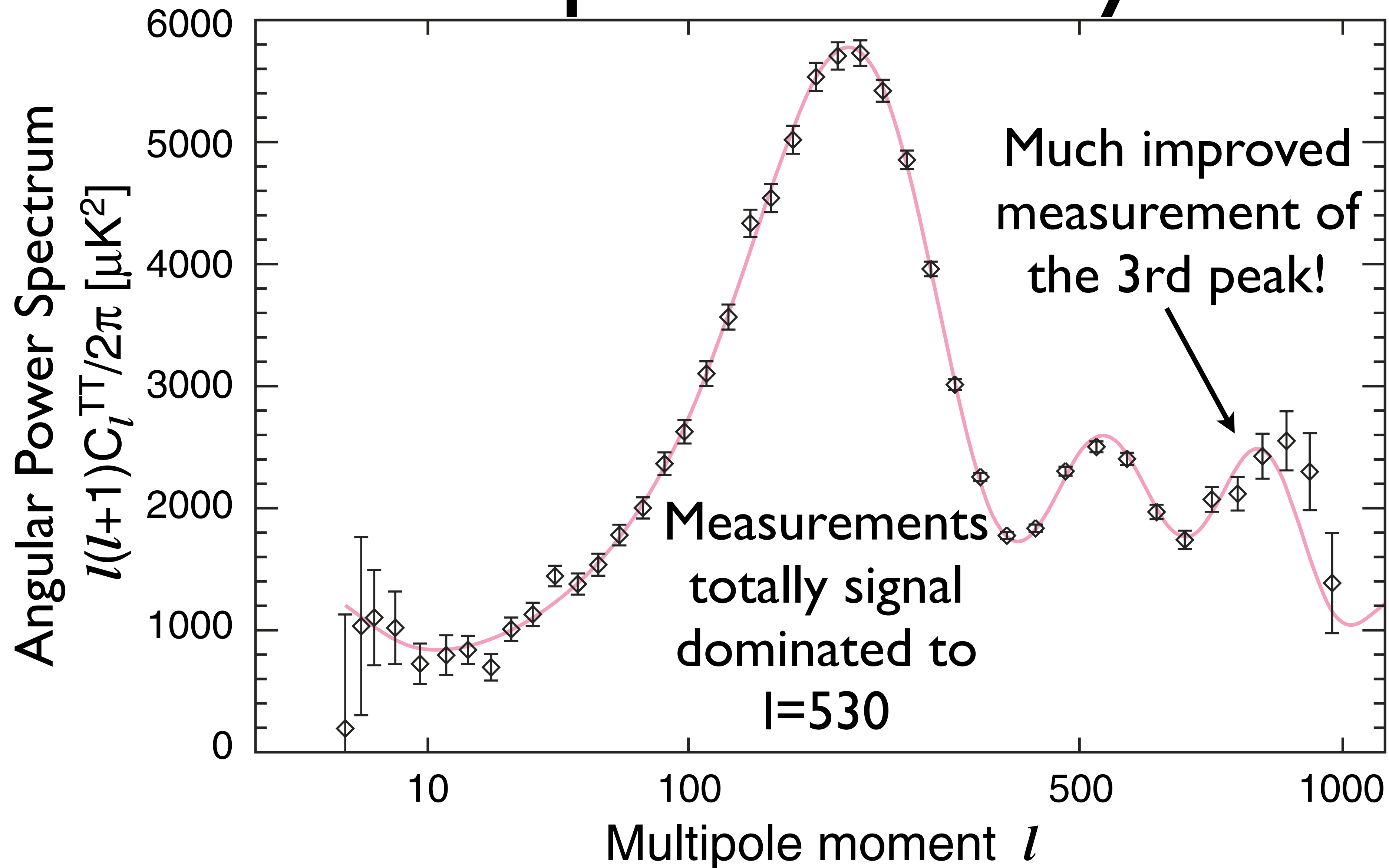
- Universe today
 - Age: **13.73 +/- 0.12 Gyr**
 - Atoms: **4.62 +/- 0.15 %**
 - Dark Matter: **23.3 +/- 1.3%**
 - Vacuum Energy: **72.1 +/- 1.5%**
- When CMB was released 13.7 B yrs ago
 - A significant contribution from the *cosmic neutrino background*

How Did We Use This Map?

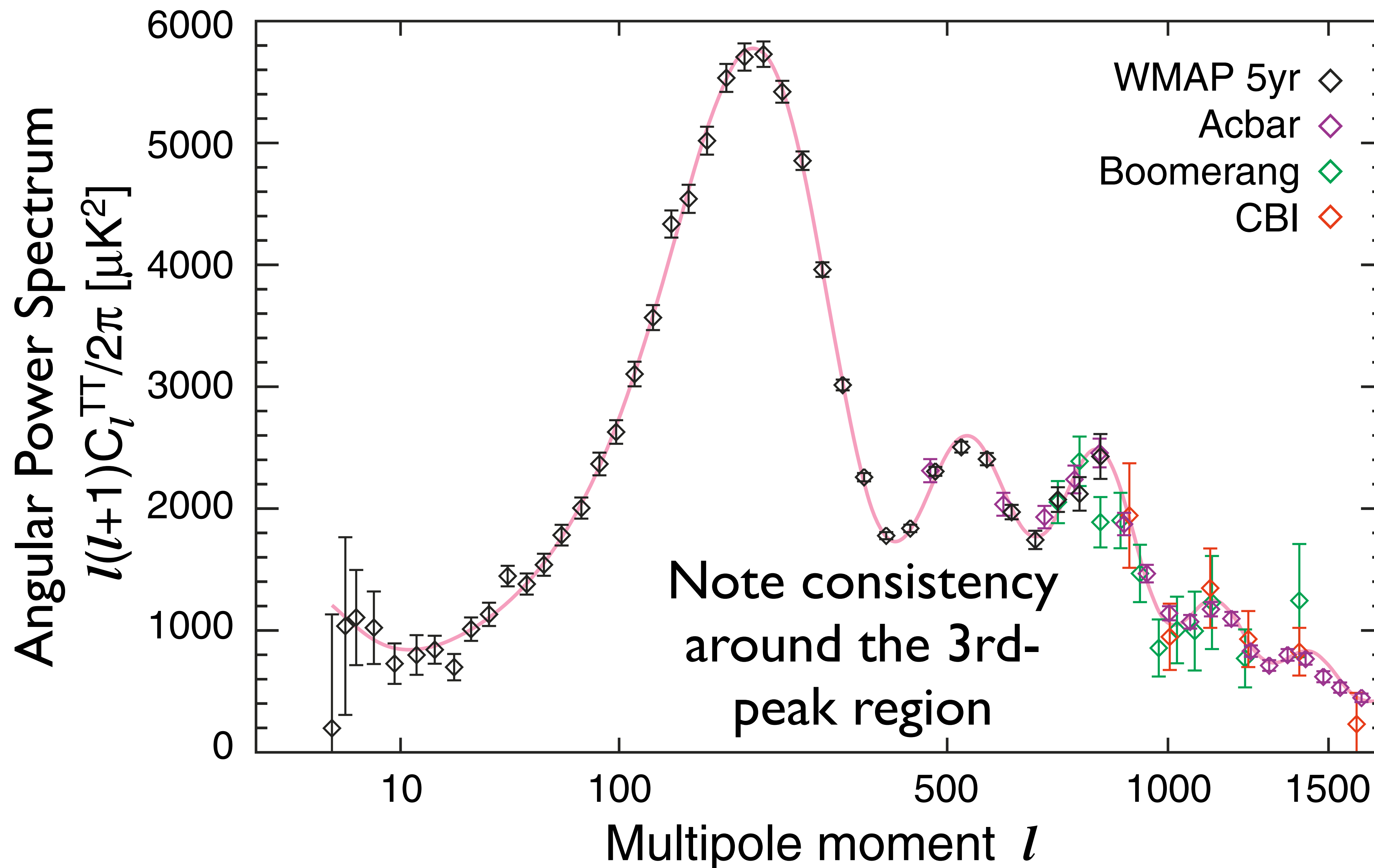


WMAP 5-year

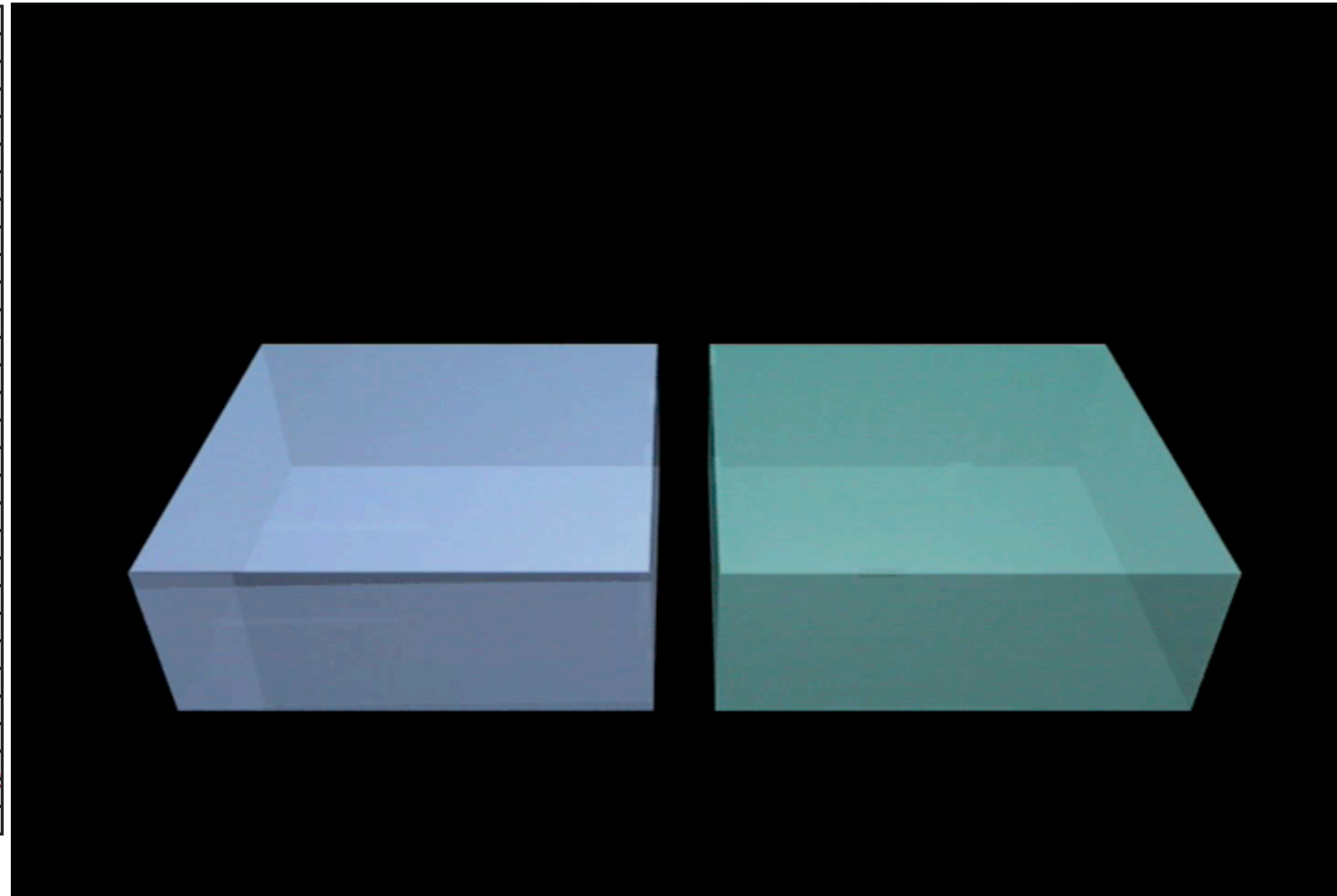
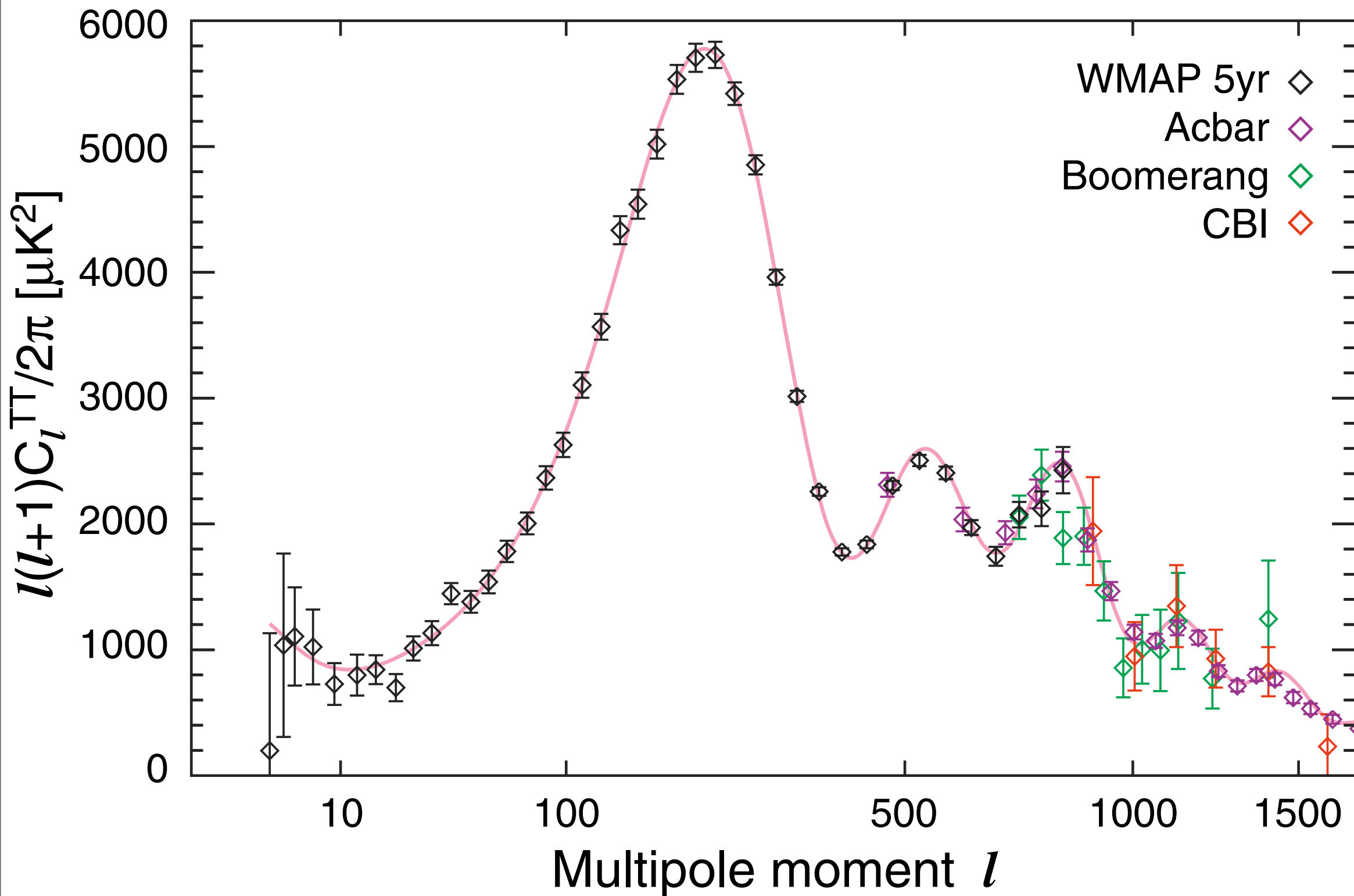
The Spectral Analysis



The Cosmic Sound Wave



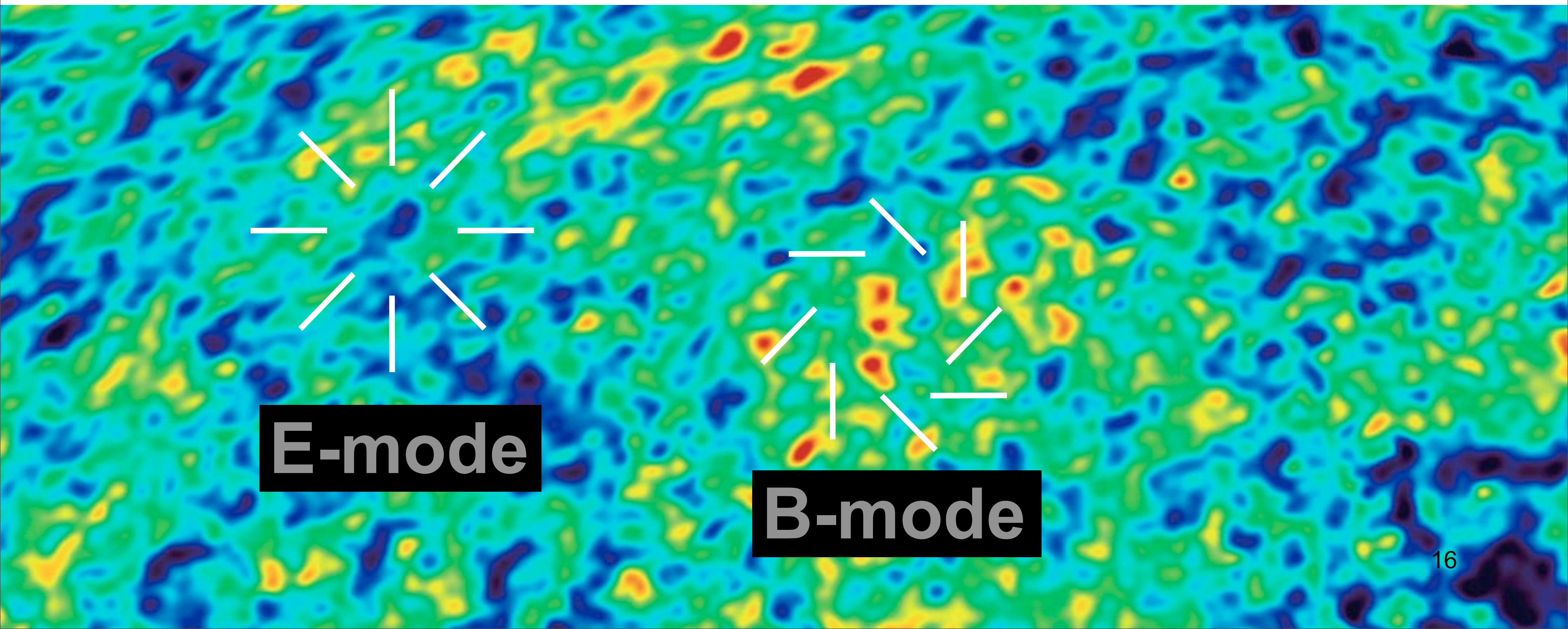
The Cosmic Sound Wave



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

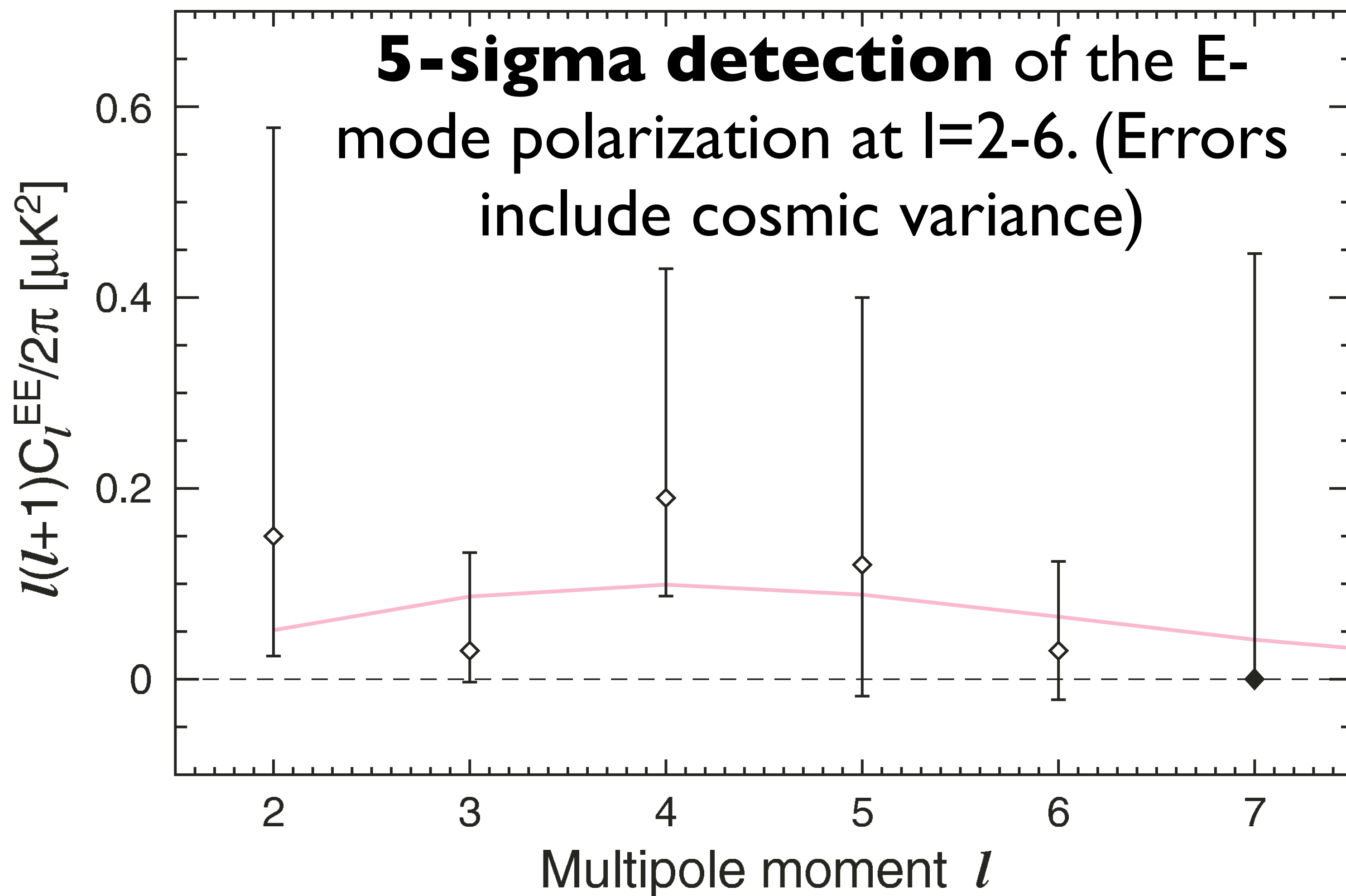
How About Polarization?

- 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

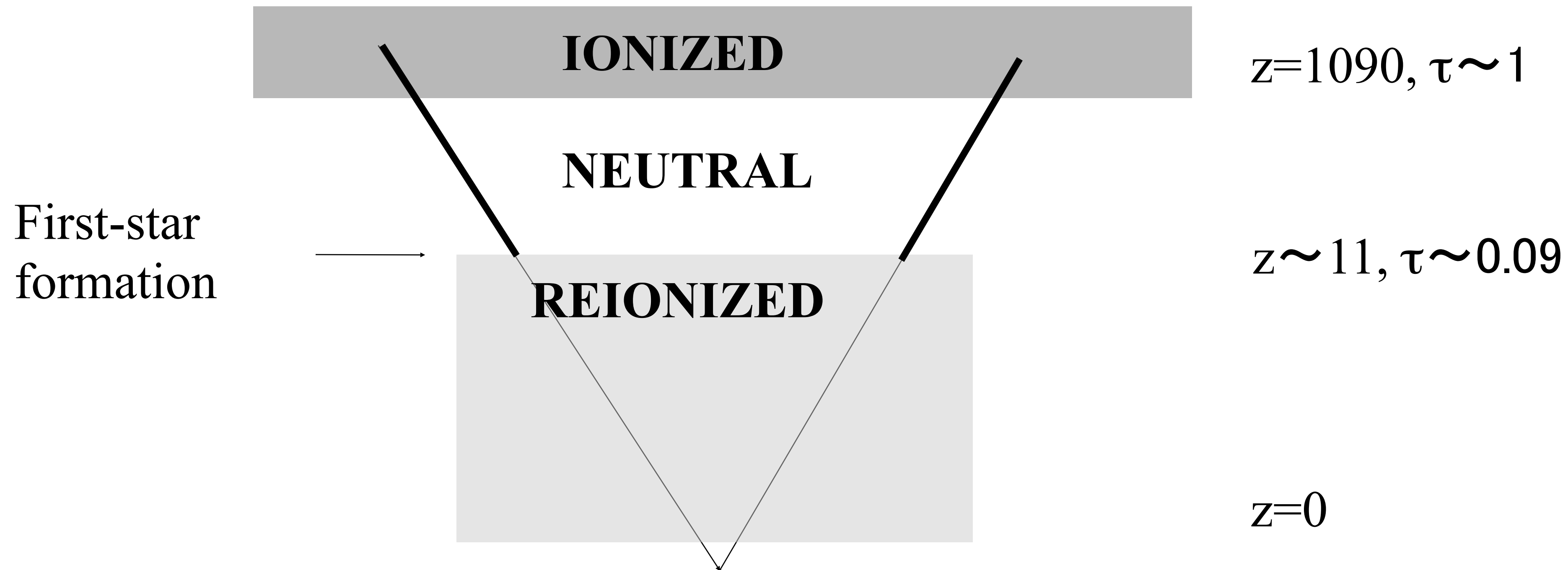
E-Mode Angular Power Spectrum



Black Symbols are upper limits

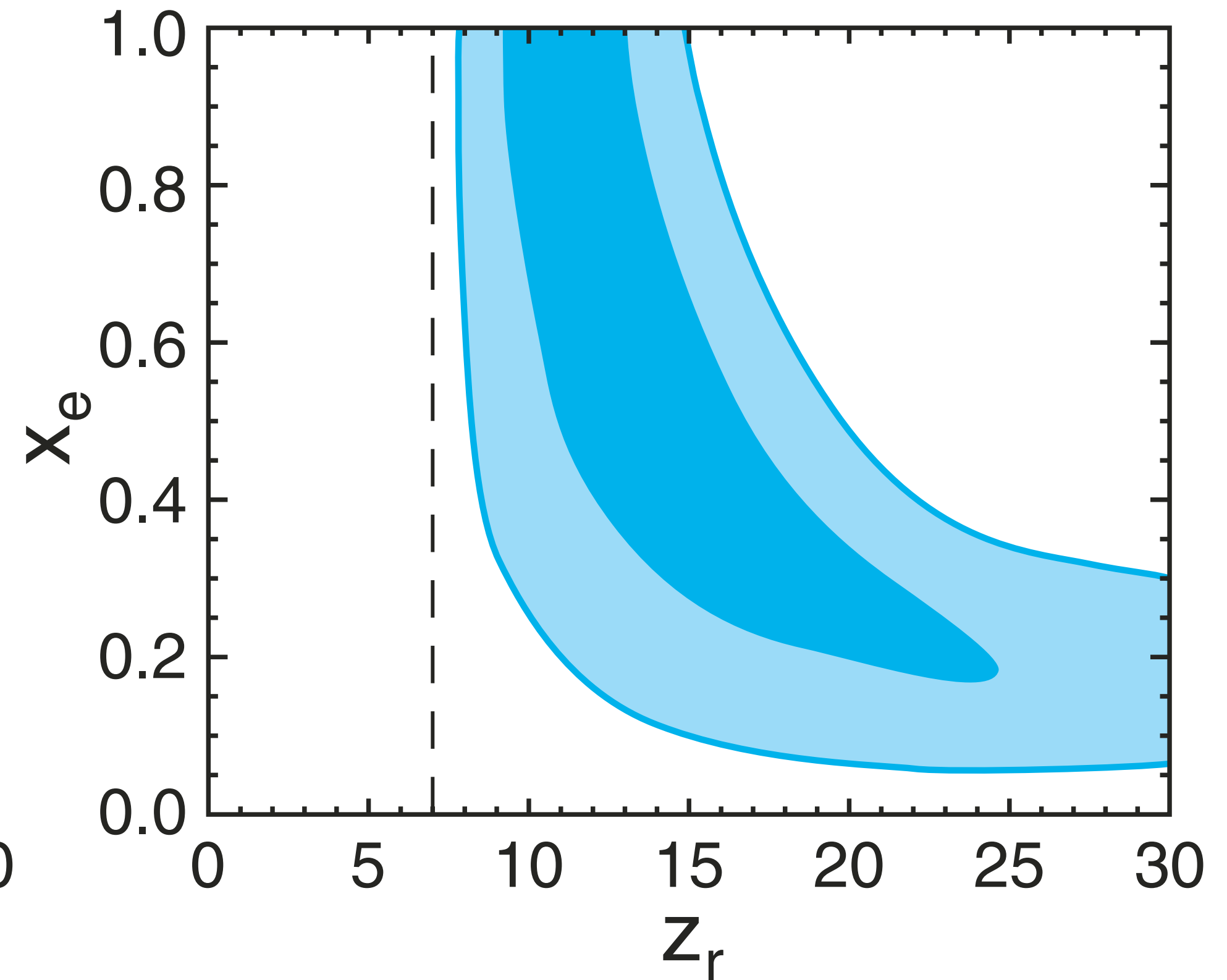
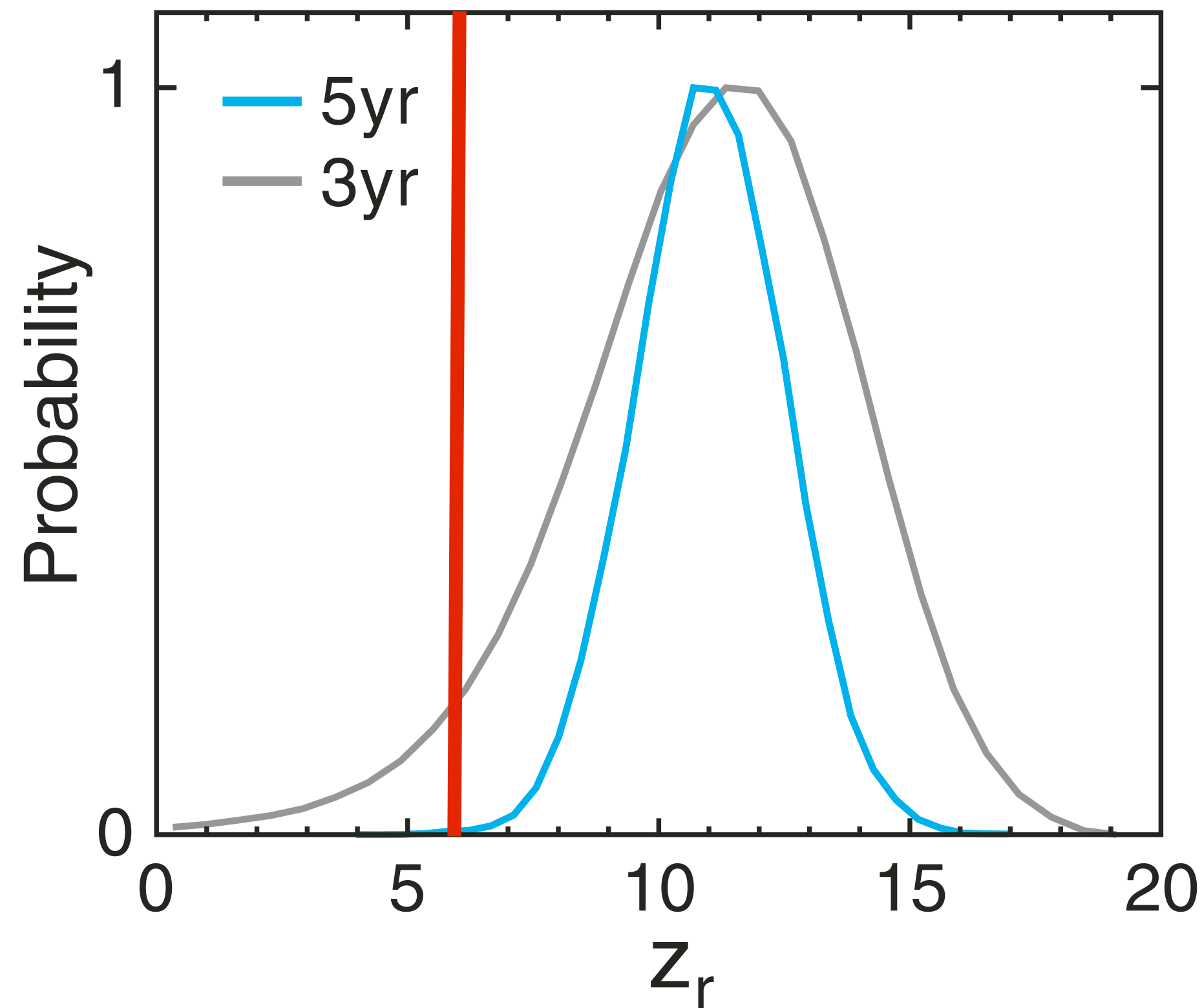
Polarization From Reionization

- 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 ~ 11 would correspond to 400 million years after the Big-Bang.



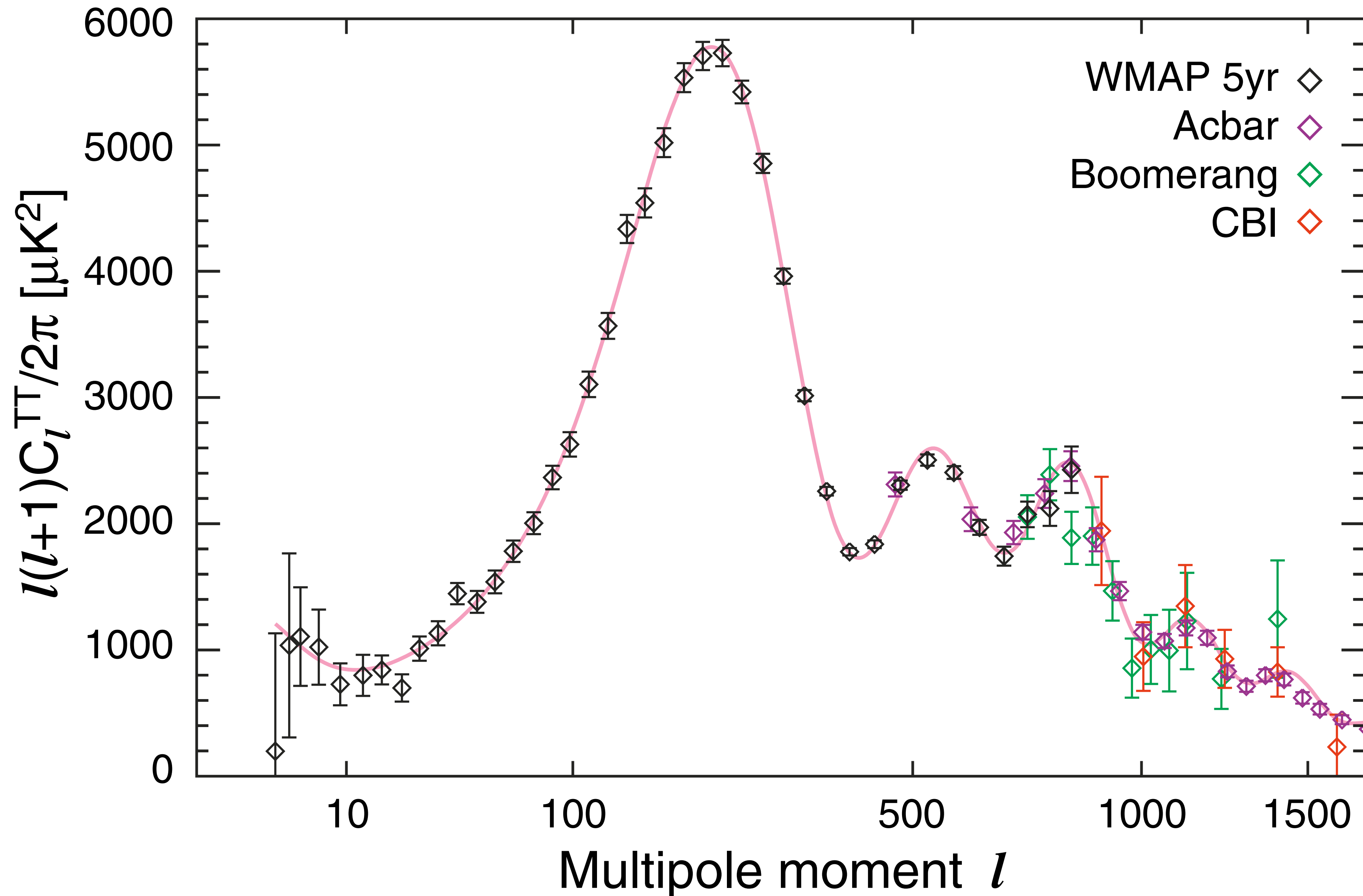
$z_{\text{reion}}=6$ Is Excluded

Dunkley et al.

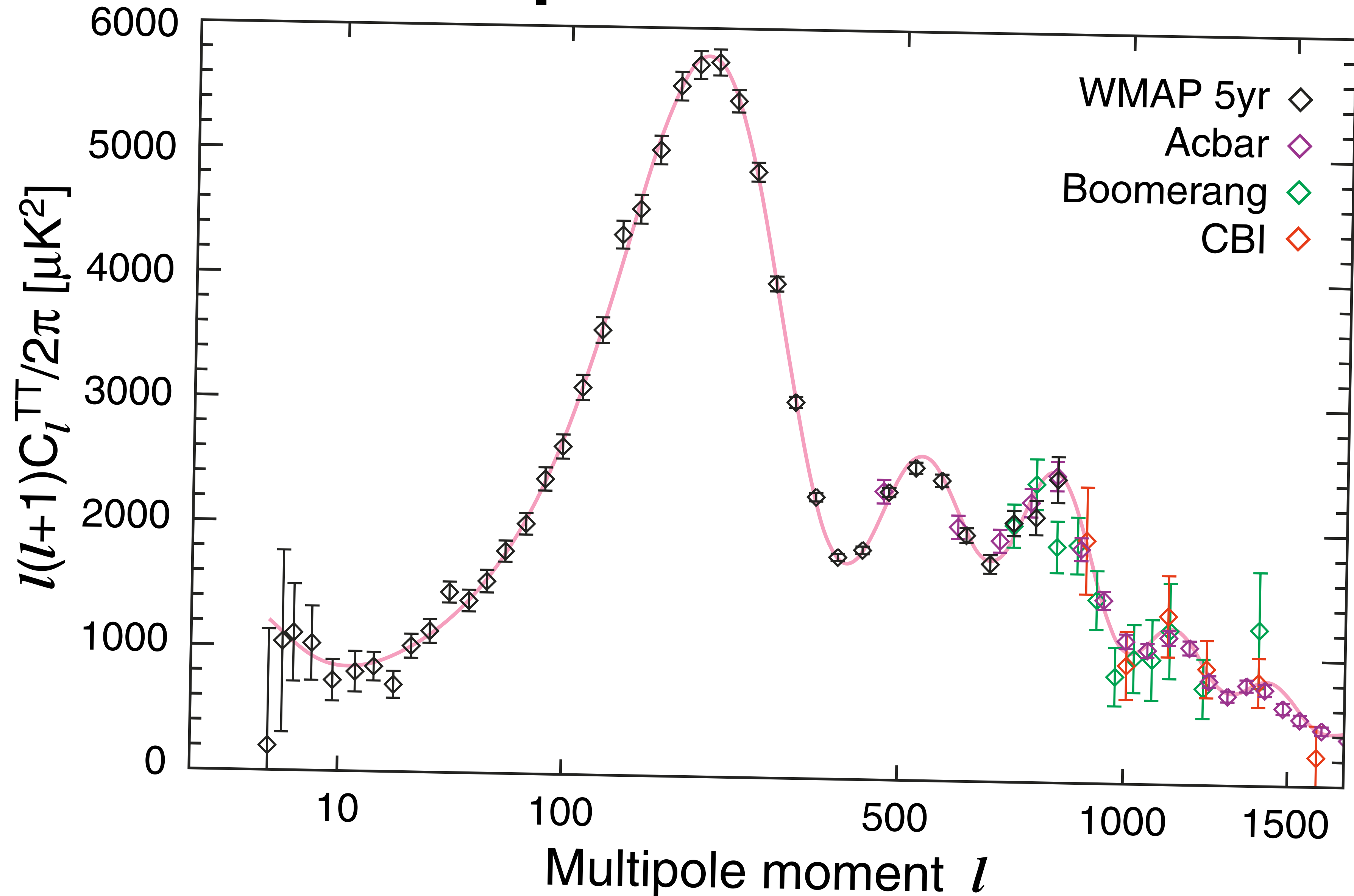


- Assuming an instantaneous reionization from $x_e=0$ to $x_e=1$ at z_{reion} , we find $z_{\text{reion}}=11.0 \pm 1.4$ (68 % CL).
- The reionization was not an instantaneous process at $z \sim 6$. (The 3-sigma lower bound is $z_{\text{reion}} > 6.7$.)

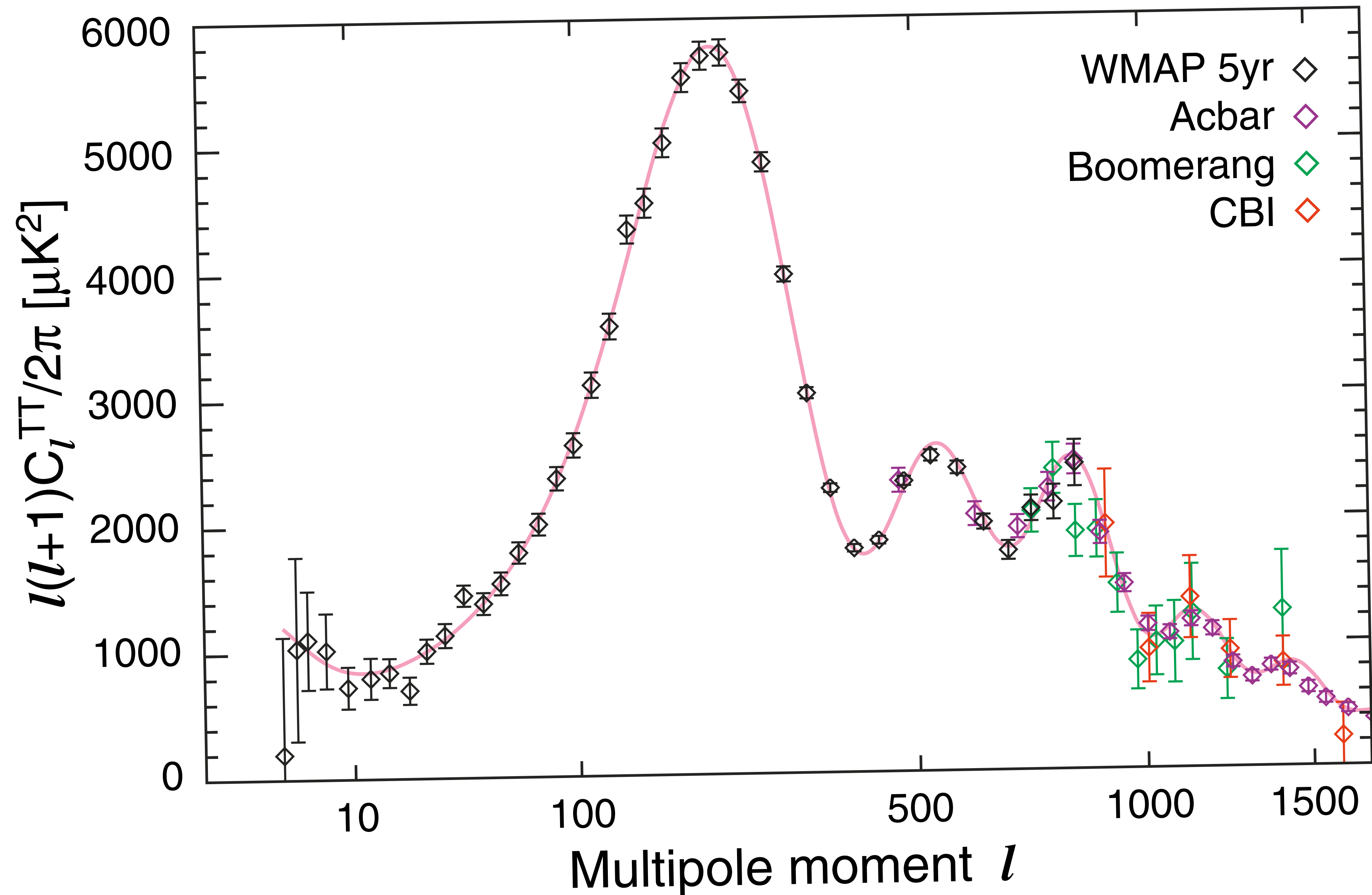
Tilting=Primordial Shape->Inflation



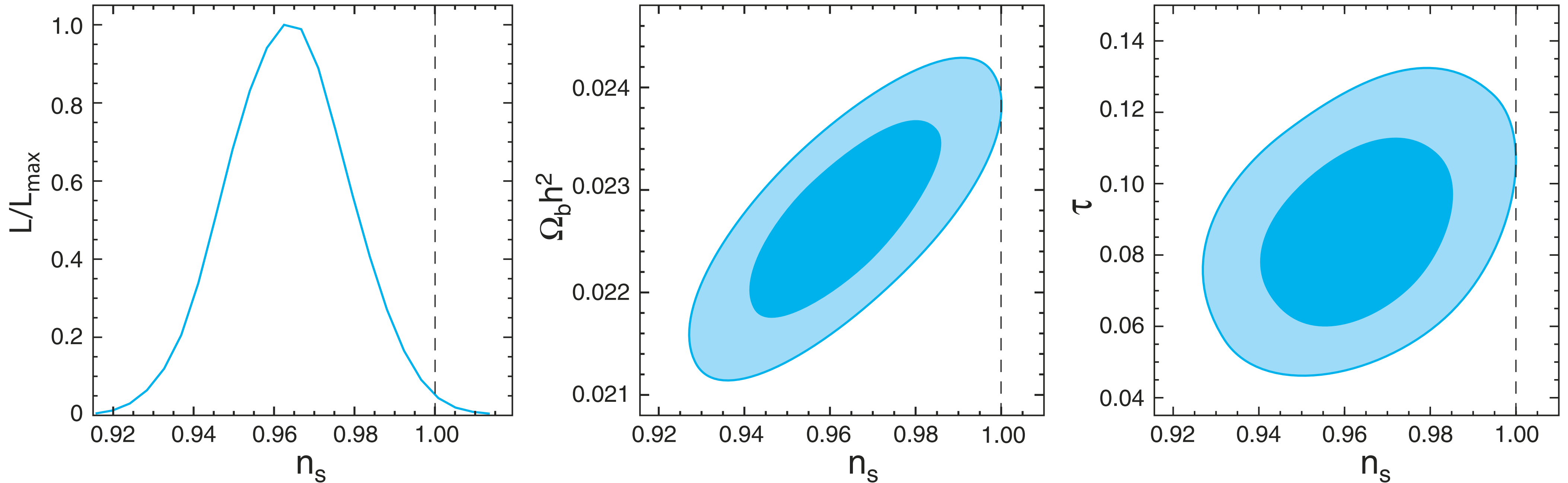
“Red” Spectrum: $n_s < 1$



“Blue” Spectrum: $n_s > 1$



Is n_s different from ONE?

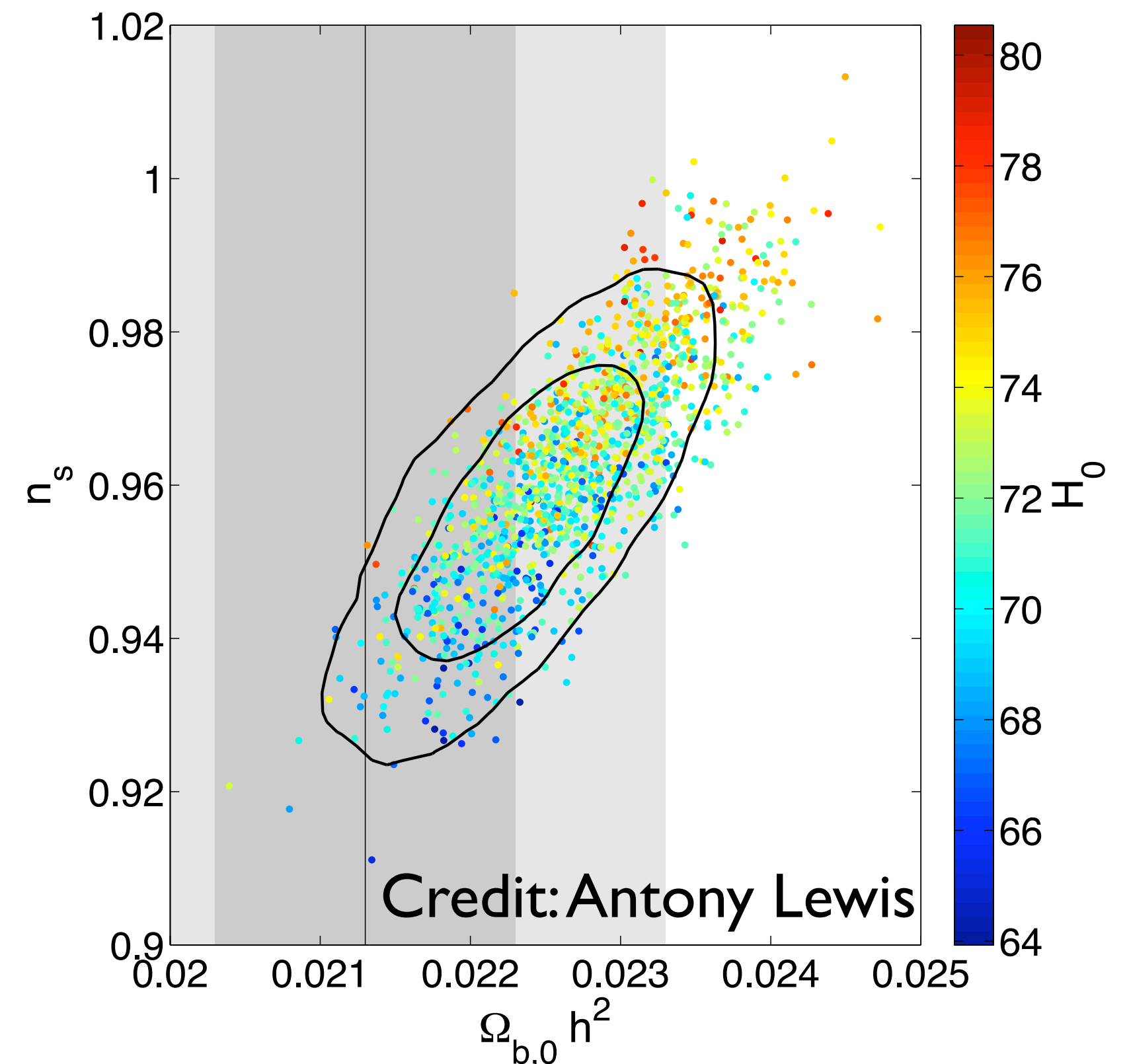


- WMAP-alone: $n_s = \mathbf{0.963}$ (+0.014) (-0.015) (Dunkley et al.)
 - 2.5-sigma away from $n_s = 1$, “scale invariant spectrum”
- n_s is degenerate with $\Omega_b h^2$; thus, we can't really improve upon n_s further unless we improve upon $\Omega_b h^2$

This One Just In!

Pettini et al. 0805.0594

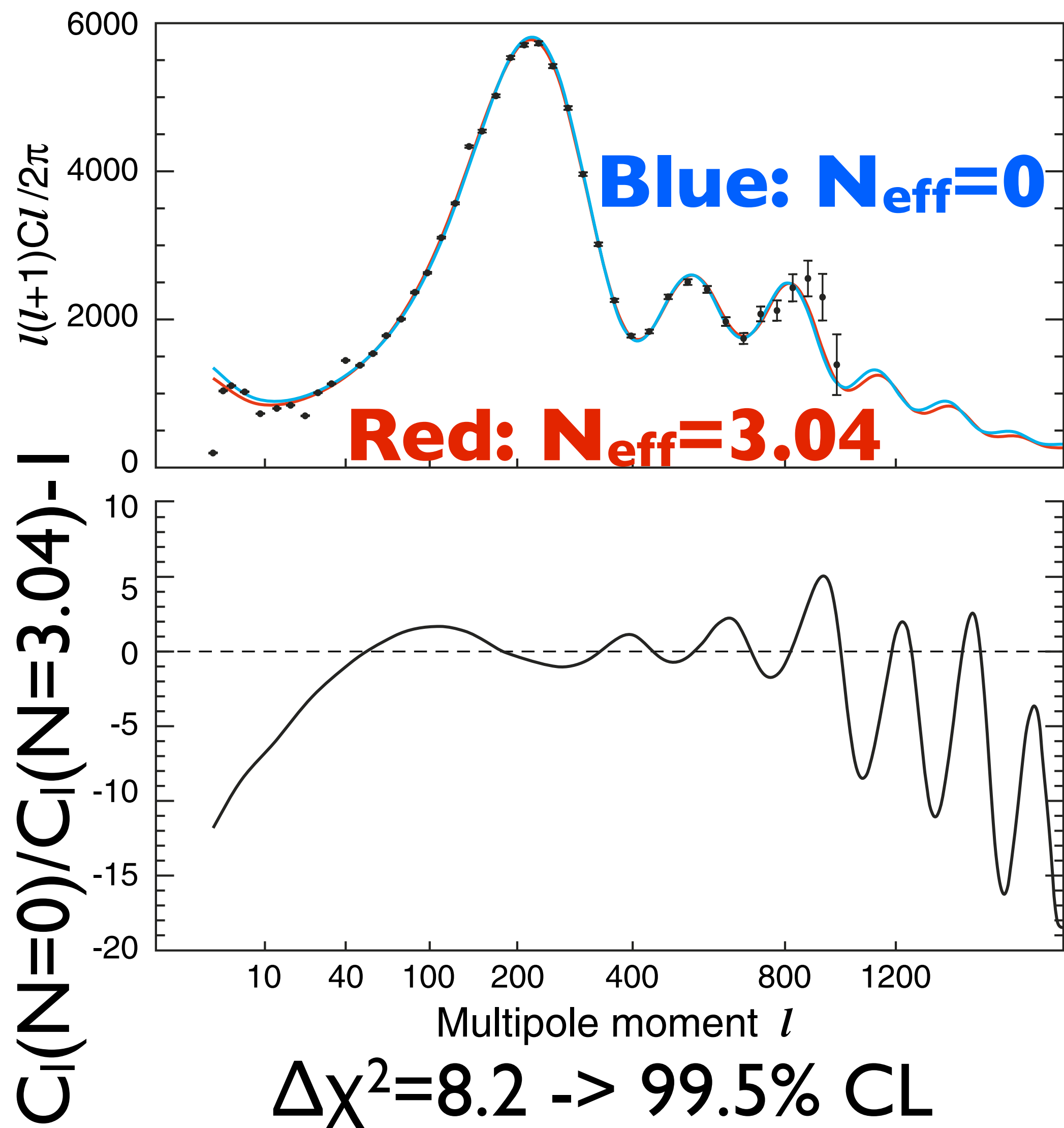
- The accuracy of $\Omega_b h^2$ inferred from the [D/H] measurement of the most-metal poor Damped Lyman-alpha system (towards QSO Q0913+072) is comparable to WMAP!
 - $\Omega_b h^2(\text{DLA}) = 0.0213 \pm 0.0010$ from $\log(\text{D}/\text{H}) = -4.55 \pm 0.03$
 - $\Omega_b h^2(\text{WMAP}) = 0.0227 \pm 0.0006$
- $\Omega_b h^2(\text{DLA})$ is totally independent of n_s
 - *Degeneracy reduced!*
 - $n_s(\text{DLA} + \text{WMAP}) = 0.956 \pm 0.013$
 - **3.4-sigma away from 1**
 - $n_s(\text{WMAP}) = 0.963 (+0.014) (-0.015)$



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.

CNB As Seen By WMAP

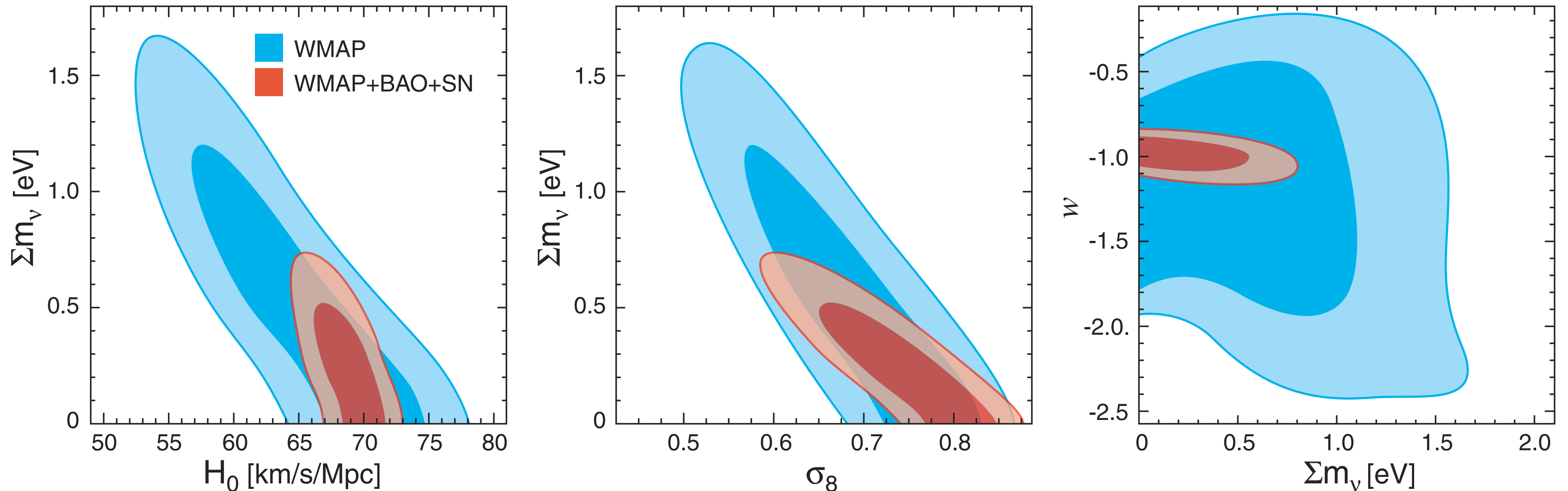


- Multiplicative phase shift is due to the change in z_{equality}
 - *Degenerate with $\Omega_m h^2$*
- Suppression is due to neutrino perturbations
 - *Degenerate with n_s*
- Additive phase shift is due to neutrino perturbations
 - **No degeneracy**
(Bashinsky & Seljak 2004)

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
 - $N_{\text{neutrino}} = 2.984 \pm 0.008$

Neutrino Mass



- The local distance measurements (BAO) help 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.

Testing Cosmic Inflation

~5 Tests~

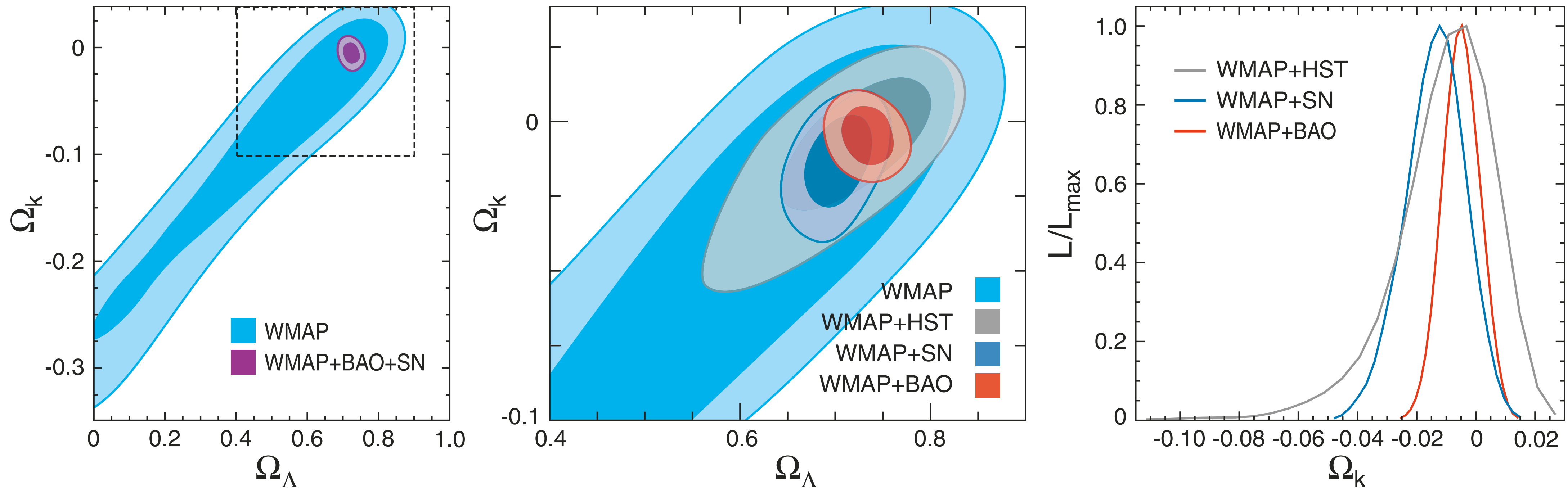
- Is the observable universe flat?
- Are the primordial fluctuations adiabatic?
- Are the primordial fluctuations nearly Gaussian?
- Is the power spectrum nearly scale invariant?
- Is the amplitude of gravitational waves reasonable?

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

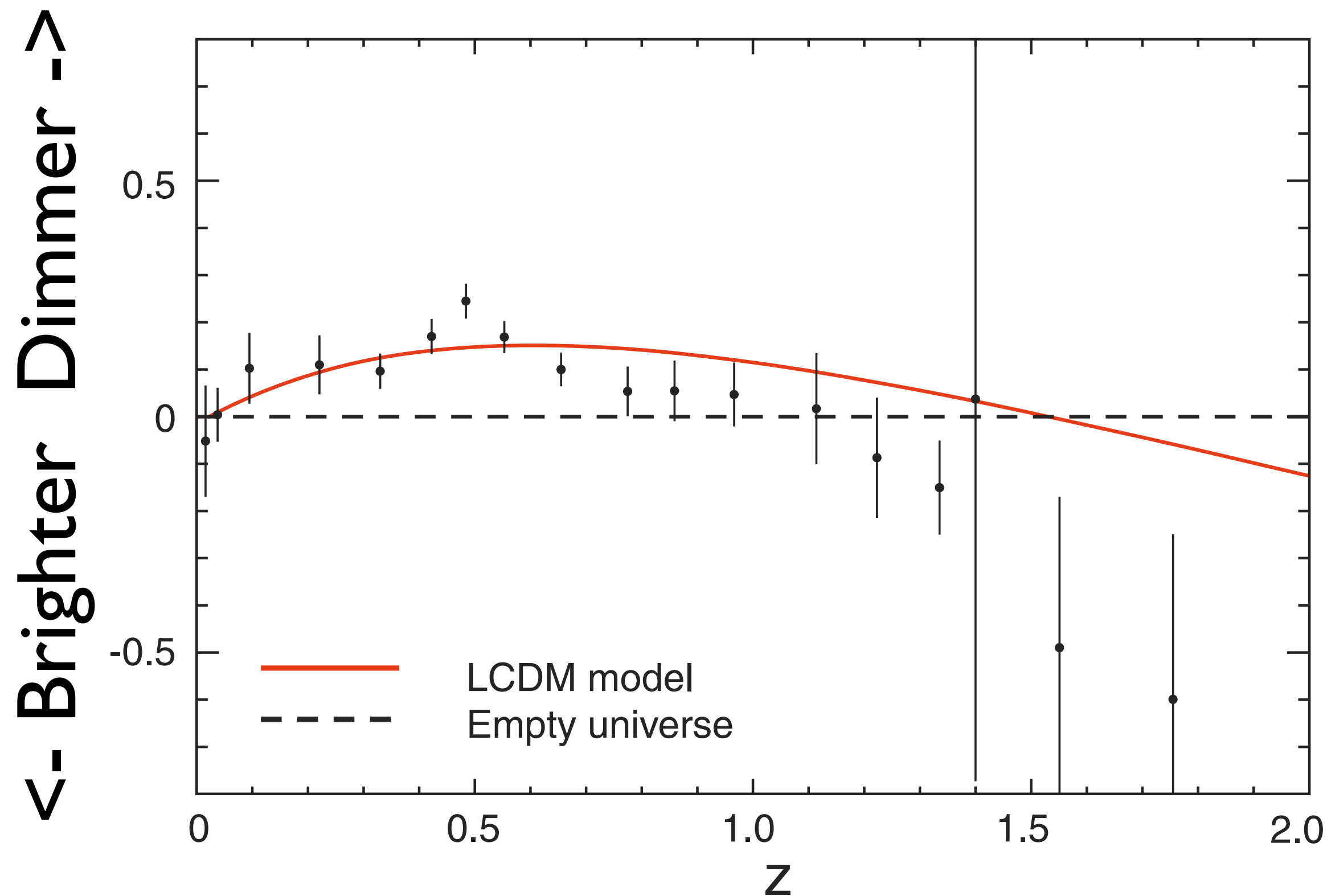
Example: Flatness

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

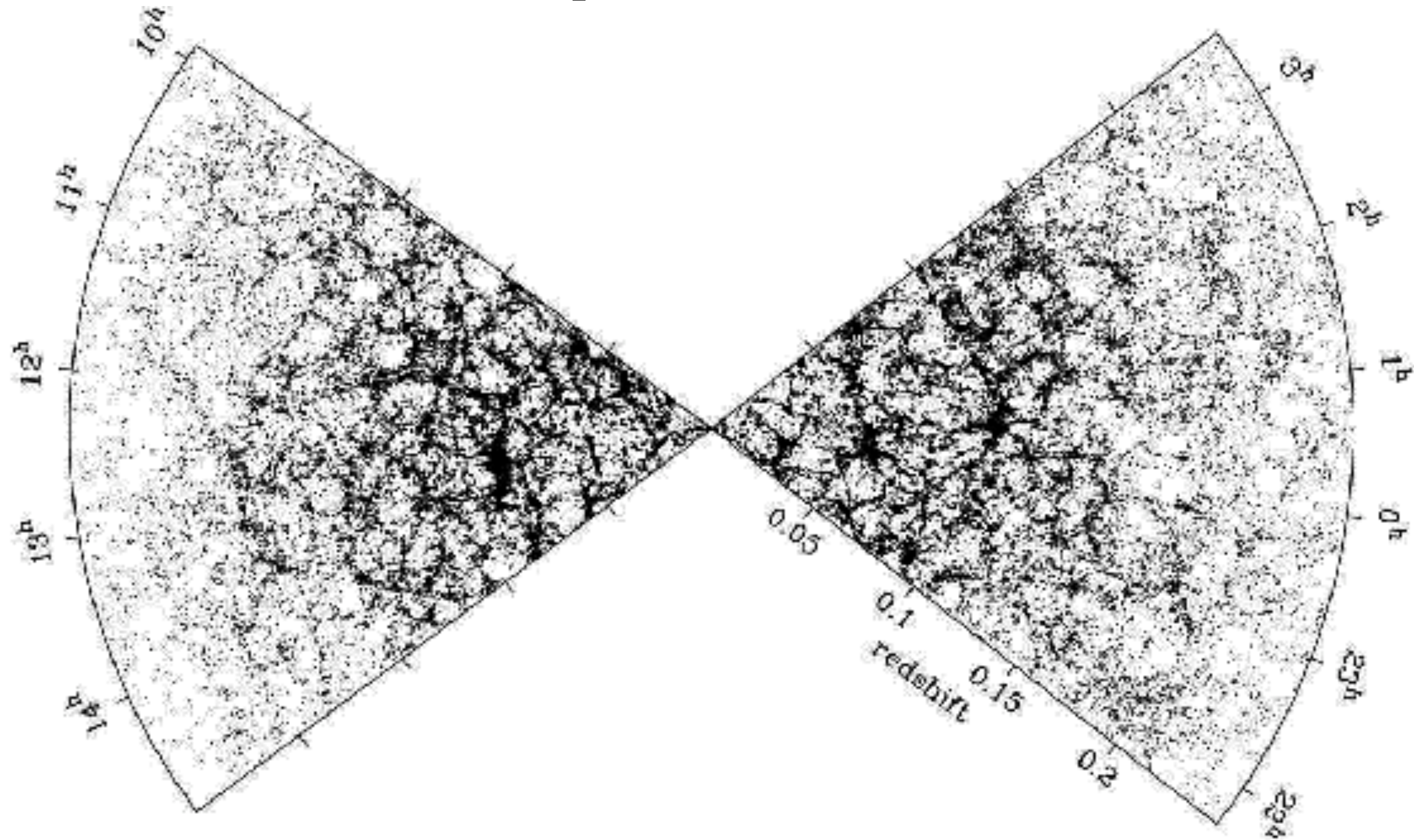
Type Ia Supernova (SN) Data



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.

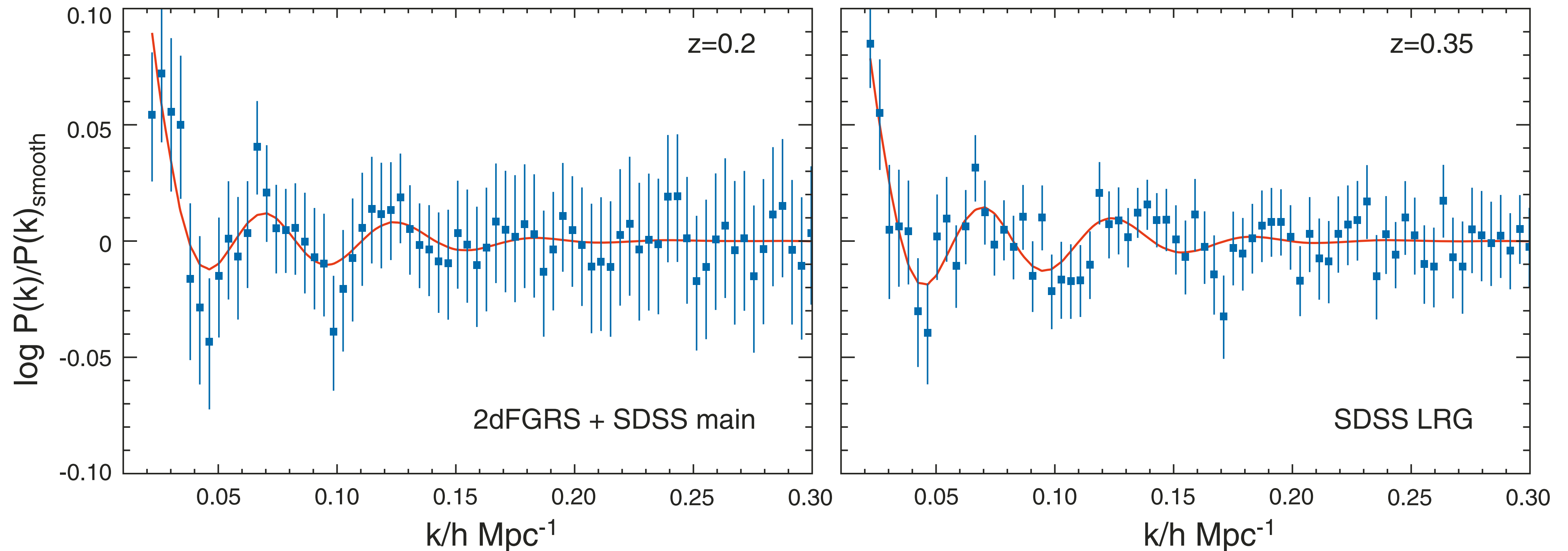
- Riess et al. (2004; 2006) HST data
- Astier et al. (2006) Supernova Legacy Survey (SNLS)
- Wood-Vasey et al. (2007) ESSENCE data

BAO in Galaxy Distribution *Tegmark et al.*



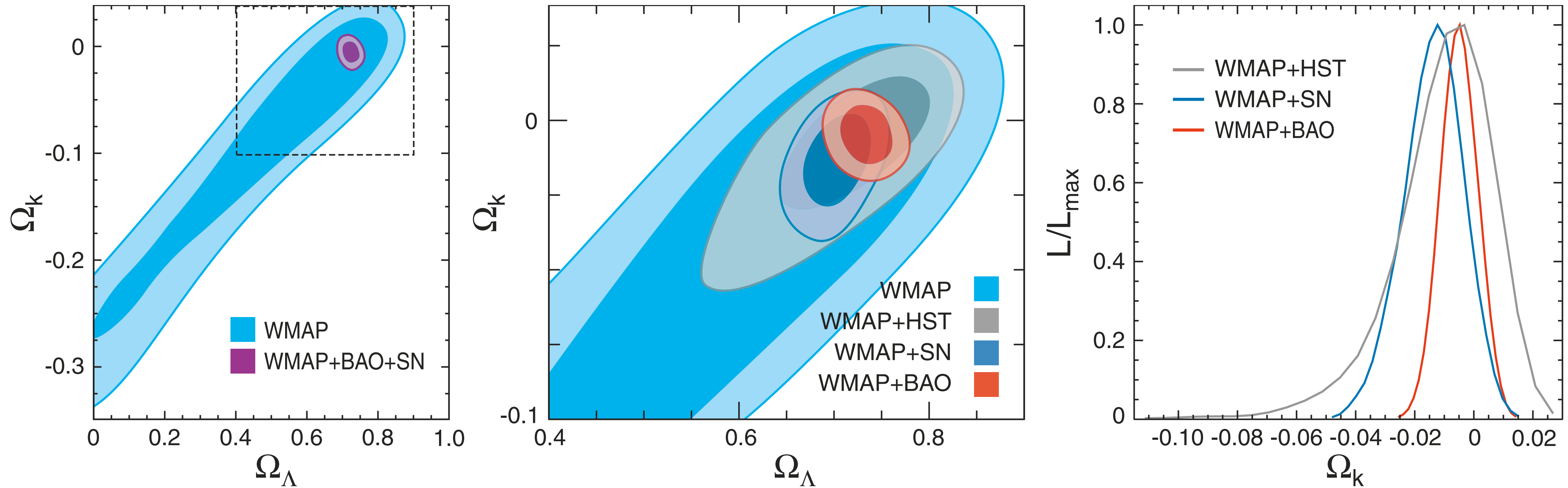
- The same acoustic oscillations should be hidden in this galaxy distribution...

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 ³⁴

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

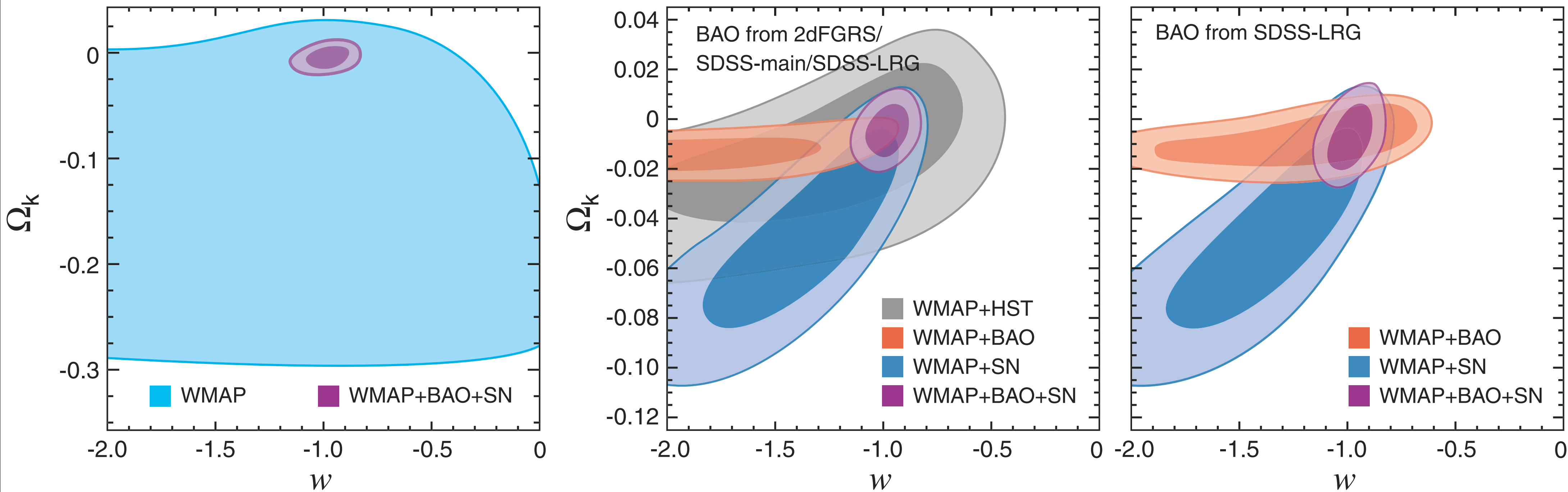
How Big Is Our Universe?

- By definition, the curvature radius of the universe is given 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 curvature radius of the universe is at least 3 times as large as the observable universe.

How Long Did Inflation Last?

- The universe had expanded by $e^{N_{\text{tot}}}$ during inflation.
 - 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 Ω_k will raise this lower limit by 1.2.
 - Lower if the reheating temperature was $< 1 \text{ TeV}$
- This is the check list #1

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



● WMAP+BAO -> Curvature; WMAP+SN -> w

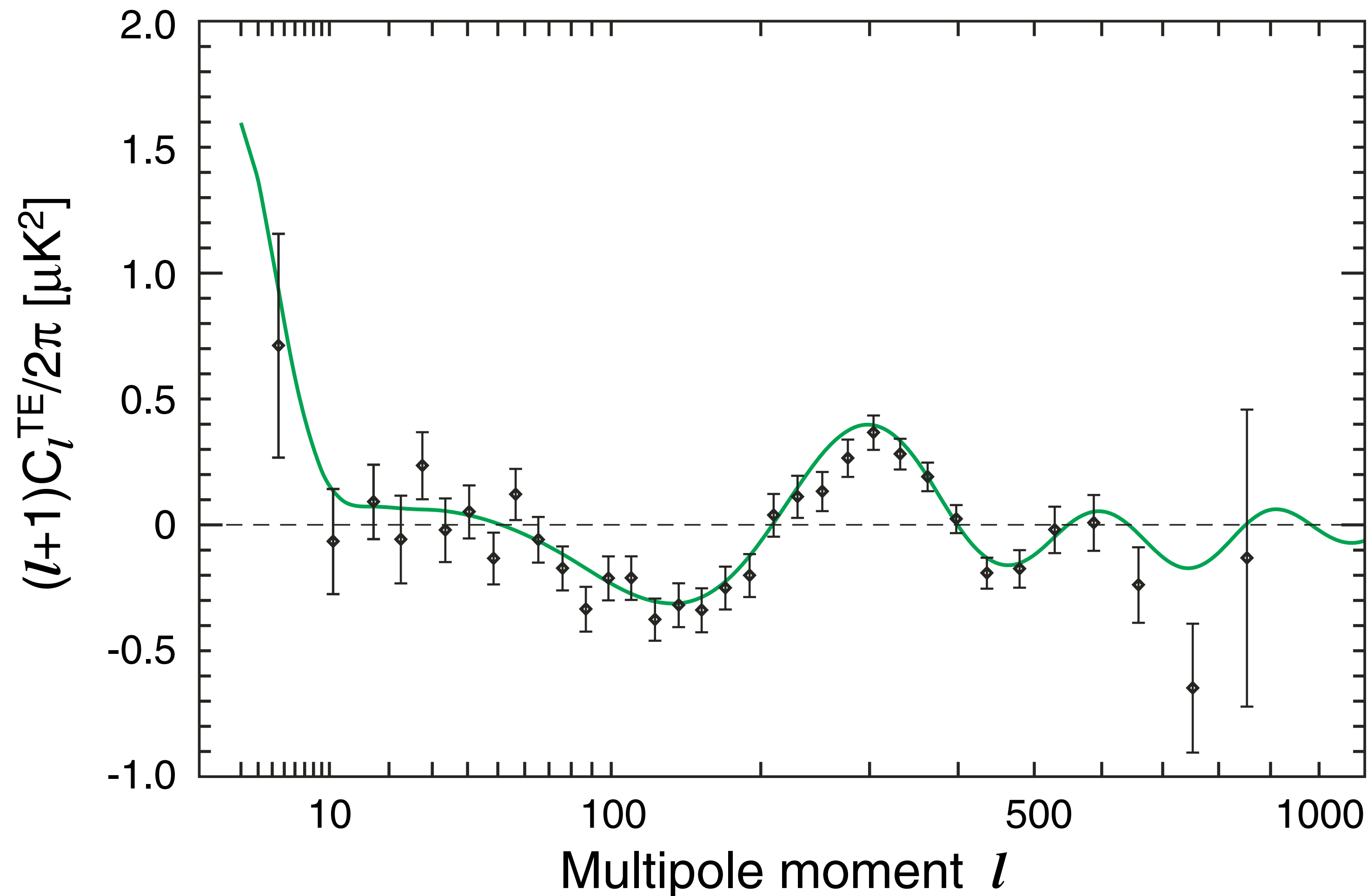
● WMAP+BAO+SN -> Simultaneous limit

● $-0.0175 < \Omega_k < 0.0085$; $-0.11 < 1+w < 0.14$ (95% CL)

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.**

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

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**

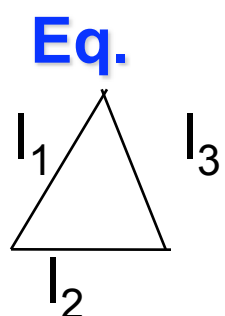
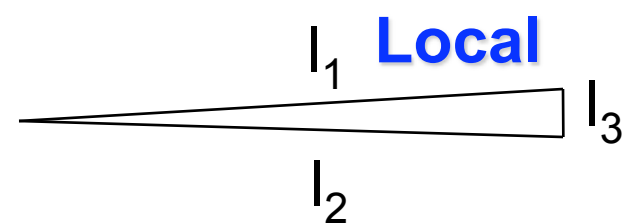
Triangles on the Sky: Angular Bispectrum

- 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 f_{NL}^{local}

- “Equilateral” parameterized by f_{NL}^{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

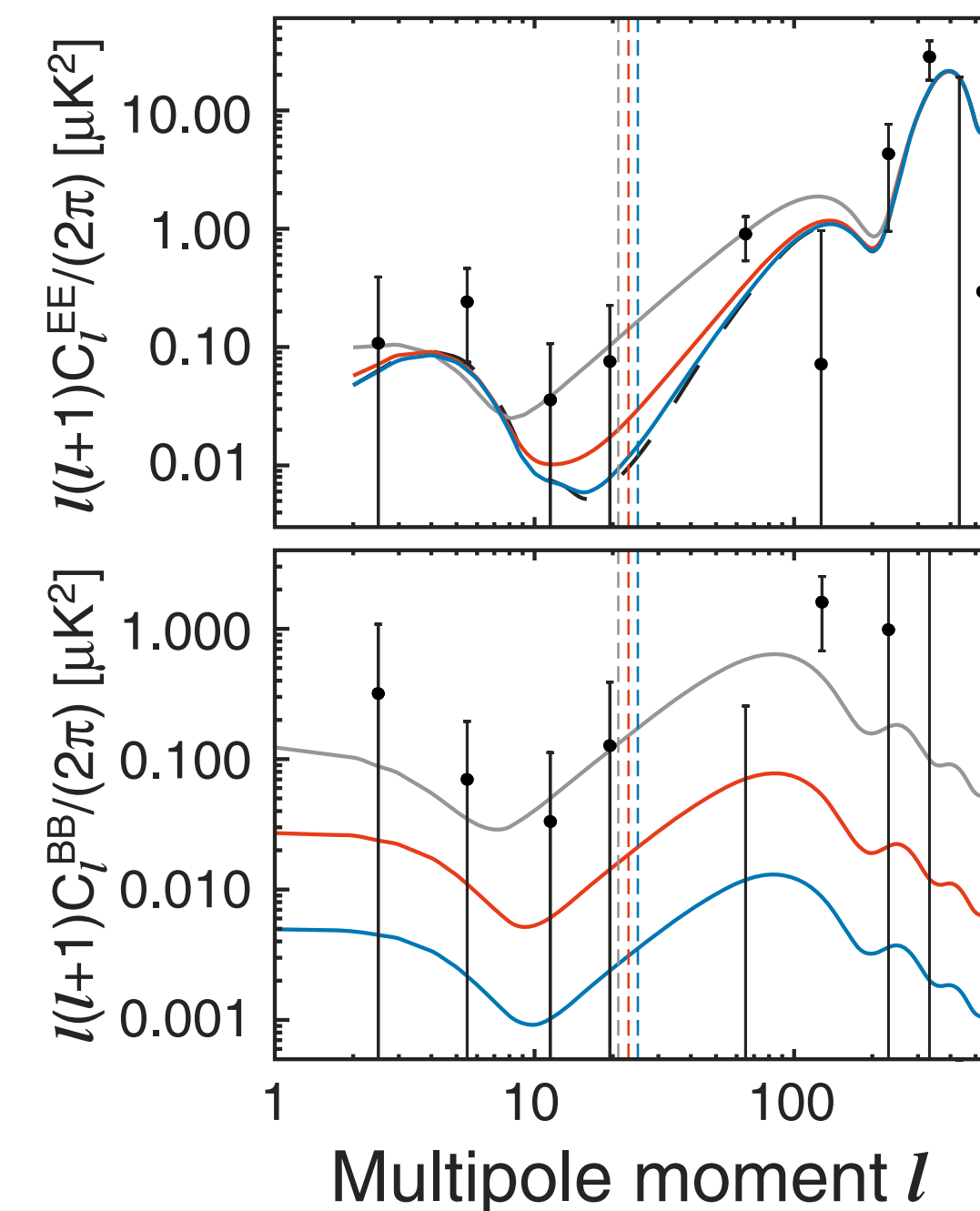
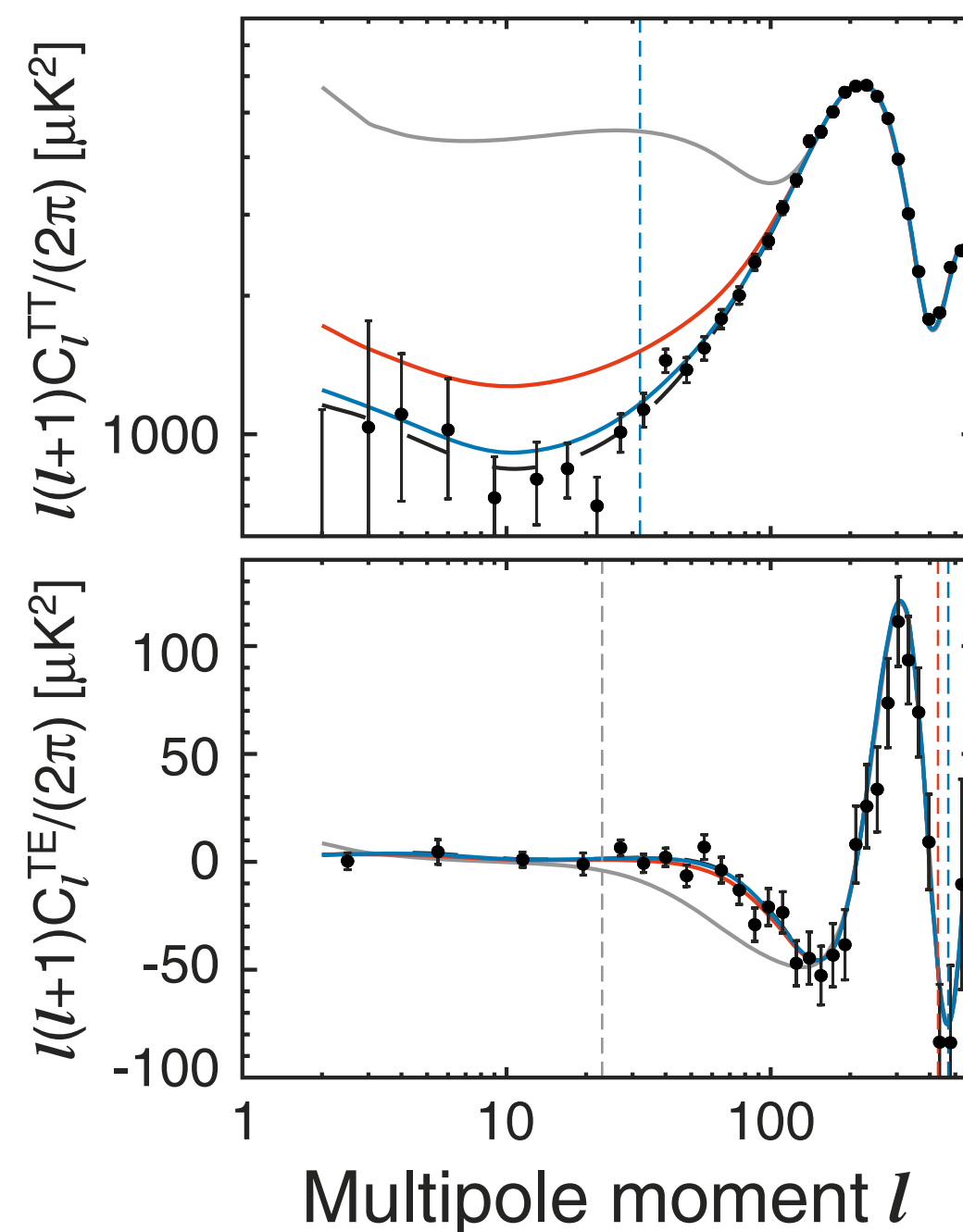
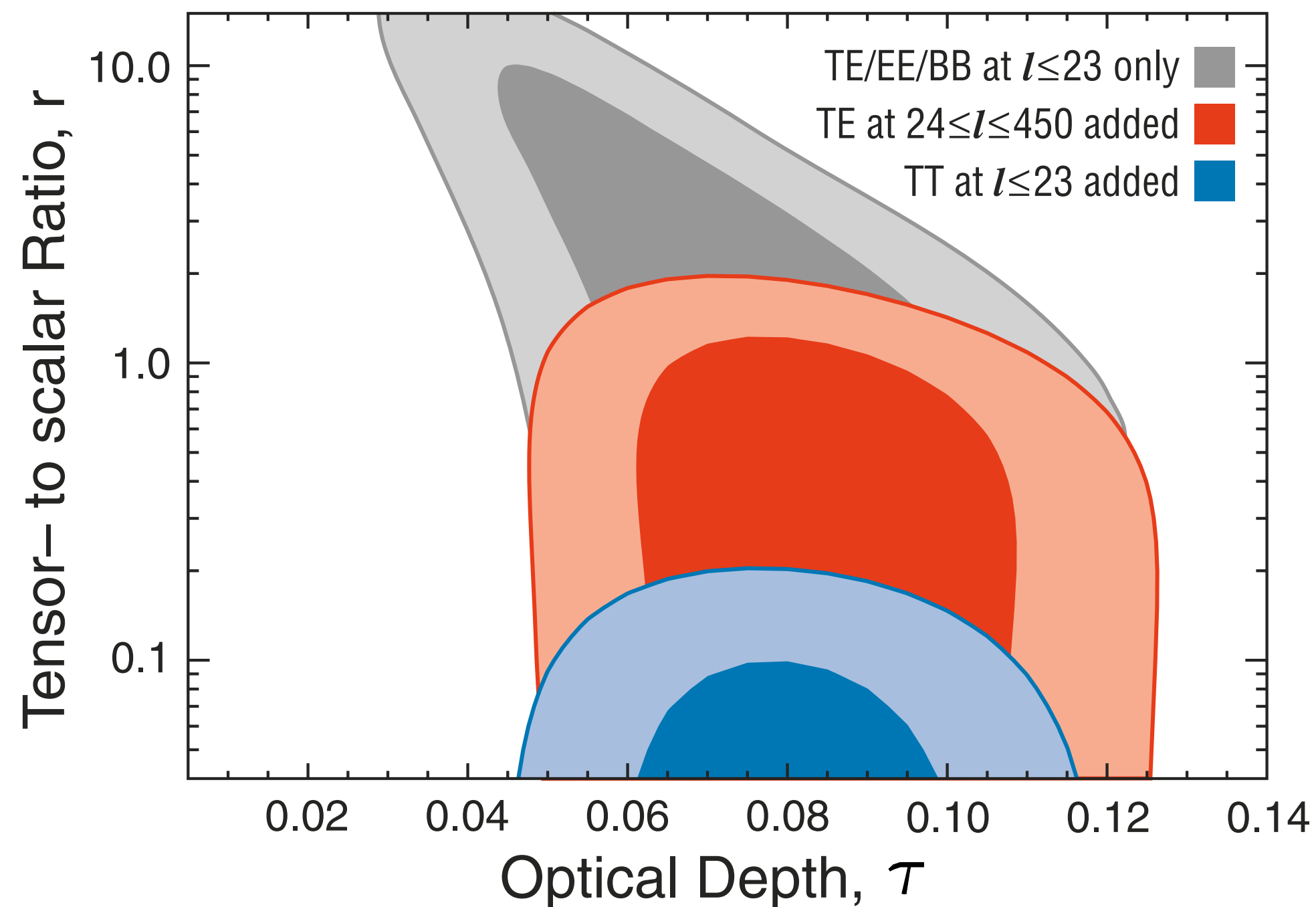
- For a power-law power spectrum (no $dn_s/d\ln k$):
 - WMAP-only: $n_s=0.963$ (+0.014) (-0.015)
 - WMAP+BAO+SN: $n_s=0.960$ (+0.014) (-0.013)
 - **2.9 sigma away from $n_s=1$**
 - No dramatic improvement from the WMAP-only result because neither BAO nor SN is sensitive to $\Omega_b h^2$
- BBN can help! (Pettini et al. 0805.0594)

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.

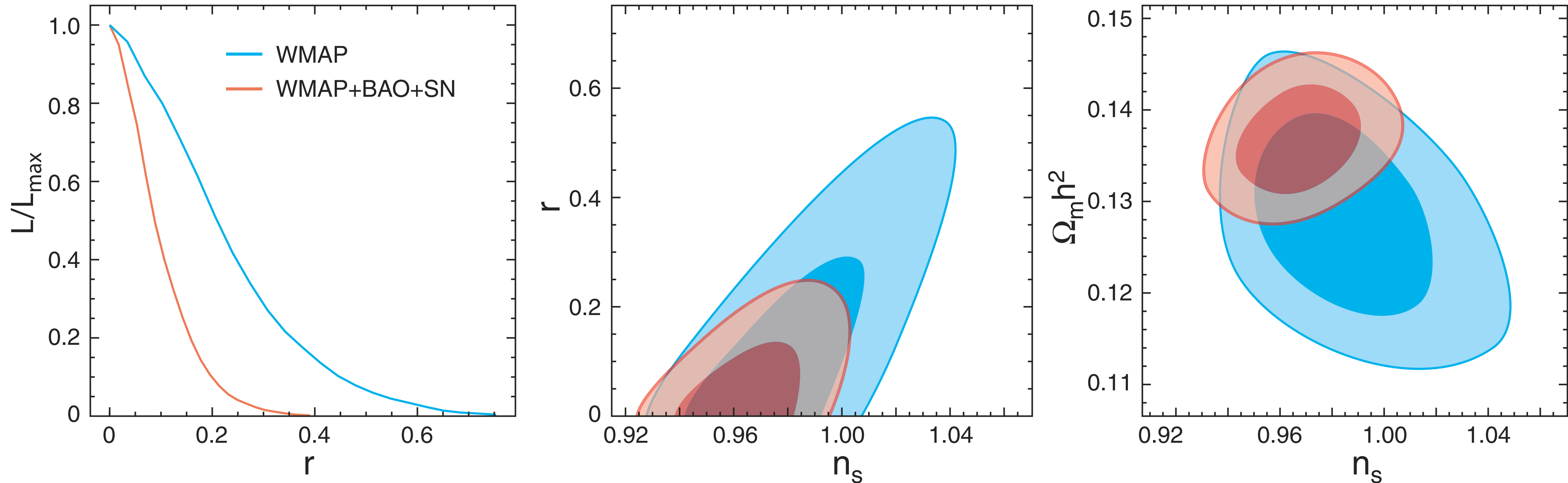
Pedagogical Explanation

Komatsu et al.



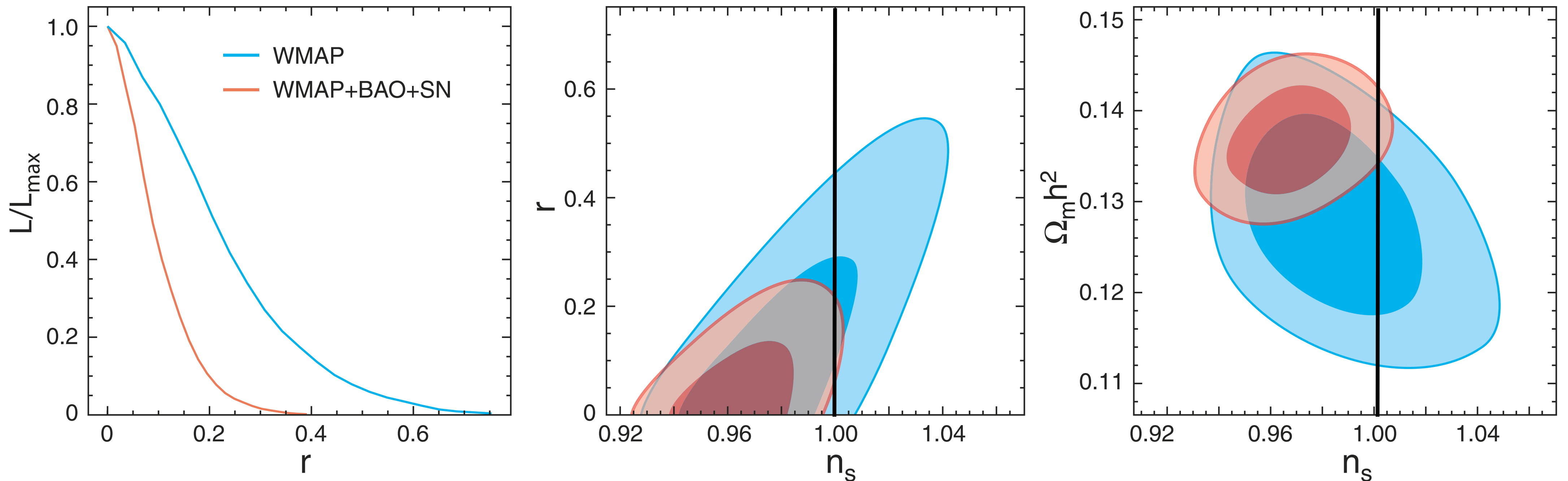
- If all the other parameters (n_s in particular) are fixed...
 - Low- l polarization gives $r < 20$ (95% CL)
 - + high- l polarization gives $r < 2$ (95% CL)
 - + low- l temperature gives $r < 0.2$ (95% CL)

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)

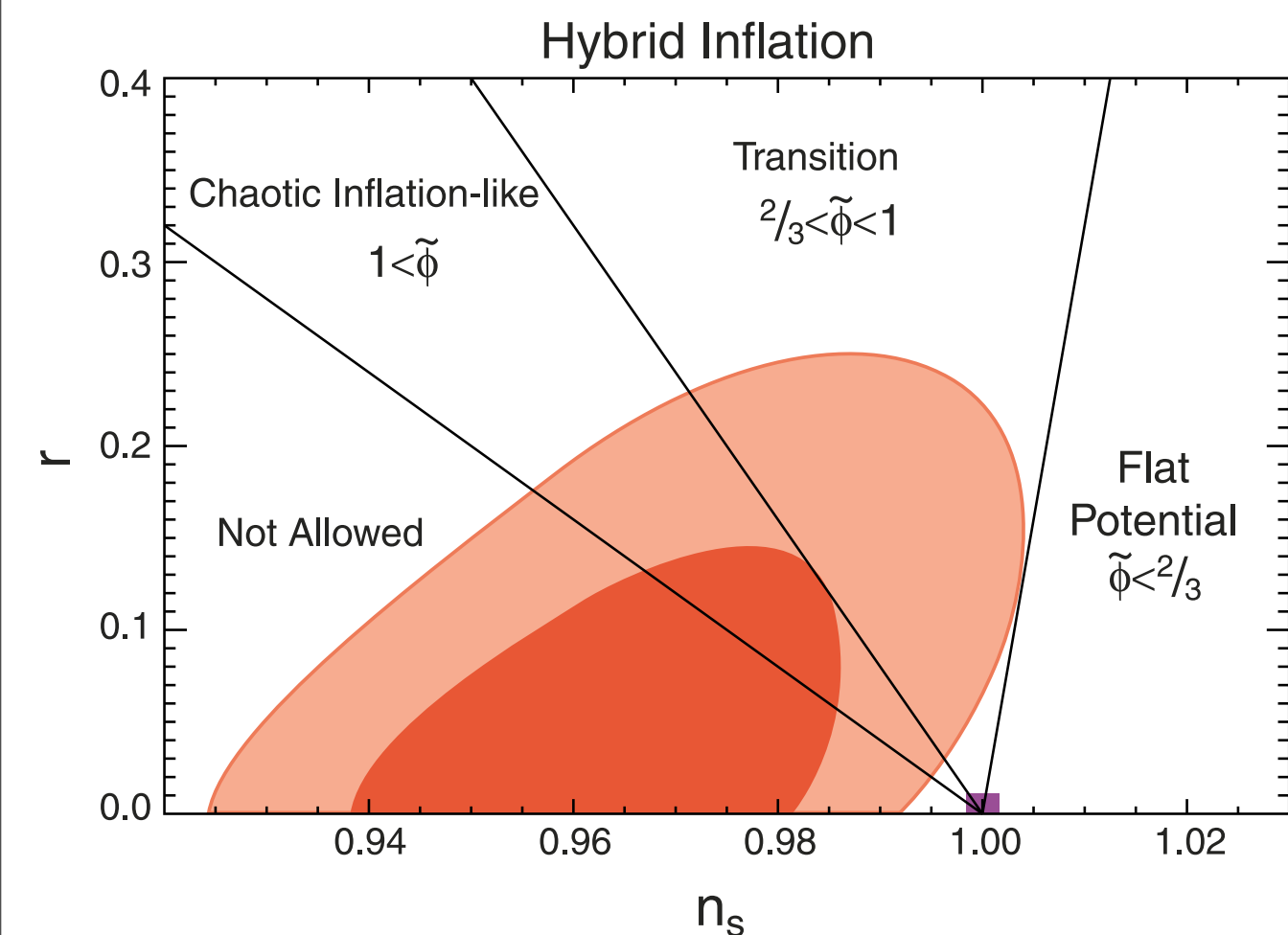
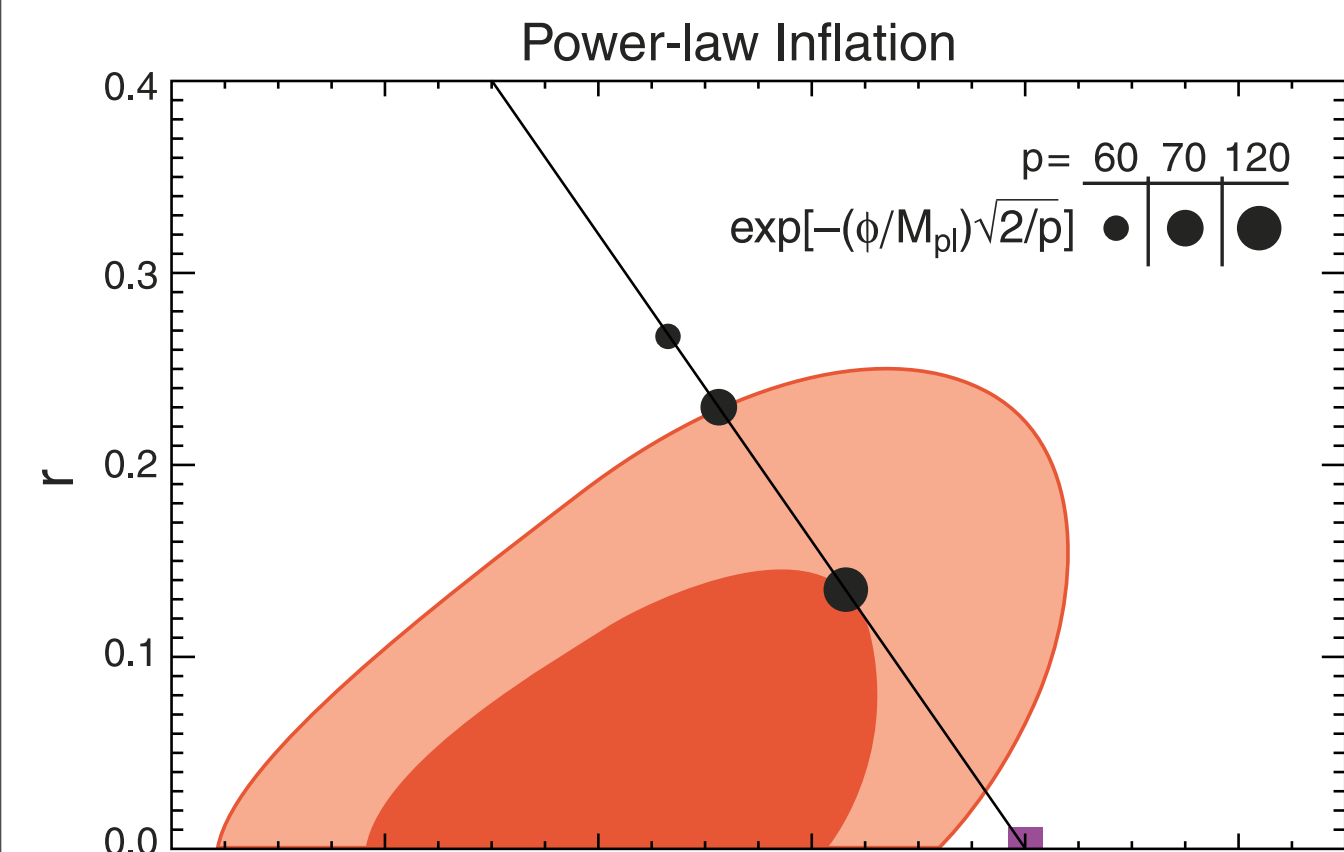
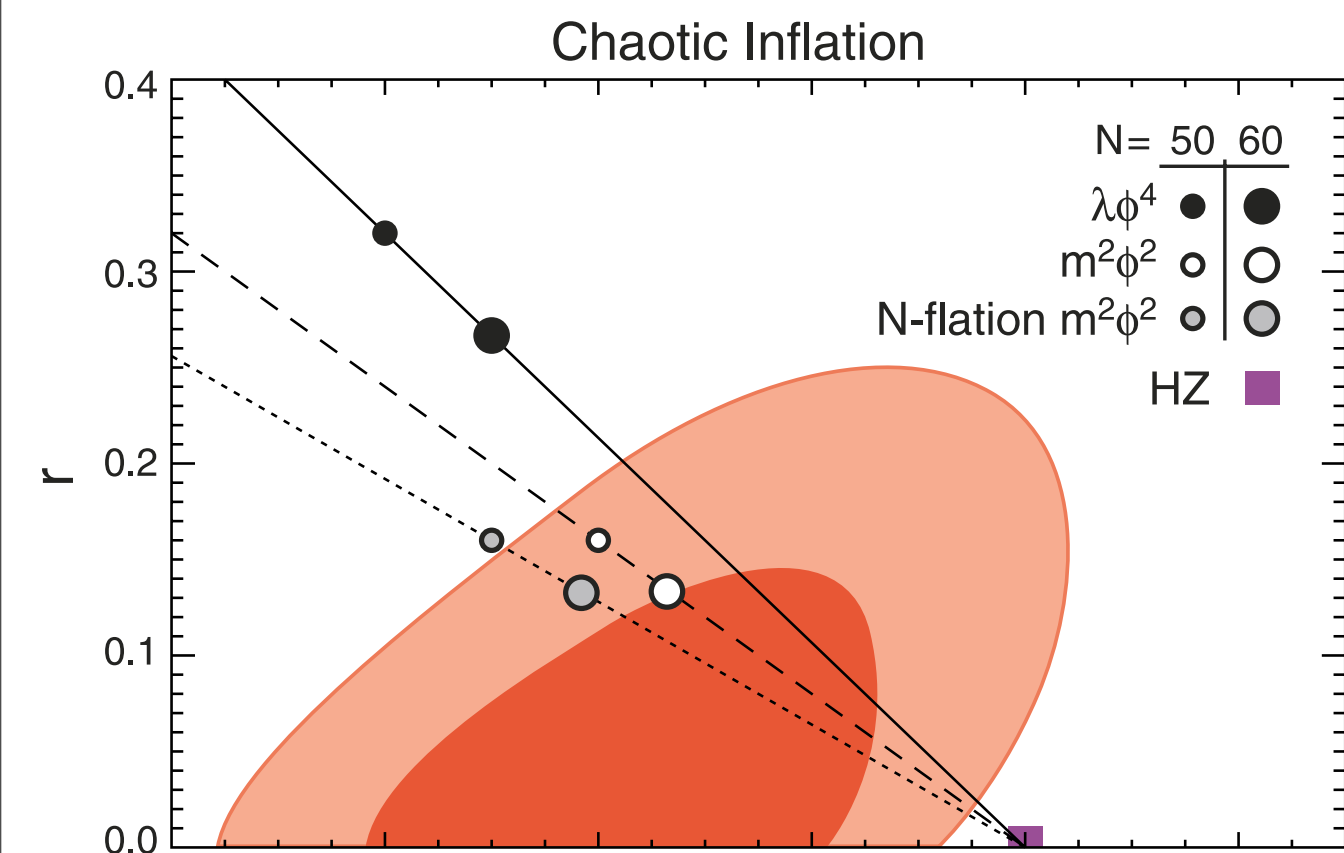
$n_s > 1.0$ is Disfavored, Regardless of r



- 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]
- **Gravitational waves:** **$r < 0.20$**
 - $n_s=0.968 (+/- 0.015)$ [68% CL]
 - **$n_s > 1$ disfavored at 95% CL regardless of r**

Summary

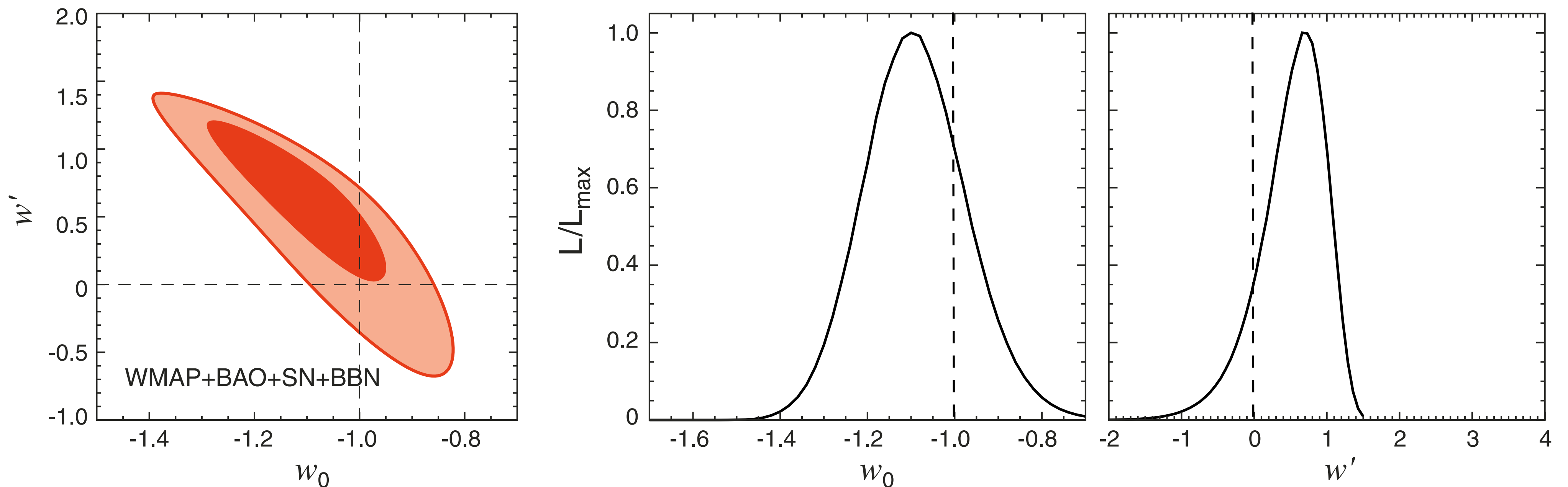
- A simple, yet *mysterious* Λ CDM still fits the WMAP data, as well as the other astrophysical data sets.
- **We did everything we could do to find deviations from Λ CDM, but failed.**
 - Bad news... we still don't know what DE or DM is.
- Significant improvements in limits on the deviations
 - Most 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 Λ 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) : $m^2\varphi^2$ can be pushed out of the favorable parameter region
 - $n_s > 1$ would be convincingly ruled out regardless of r .

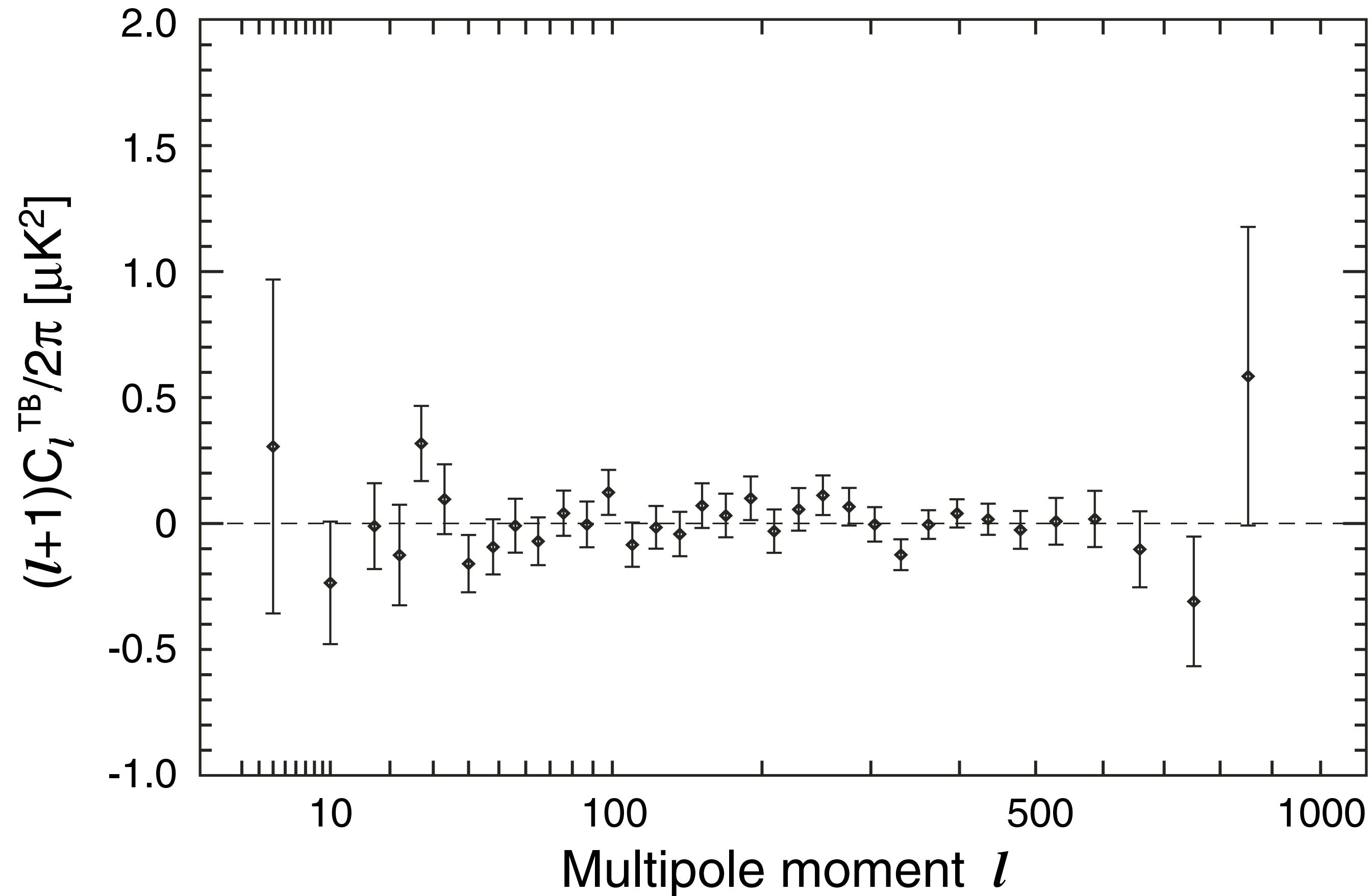
Dark Energy EOS:

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



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

Probing Parity Violation



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

E \rightarrow B

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

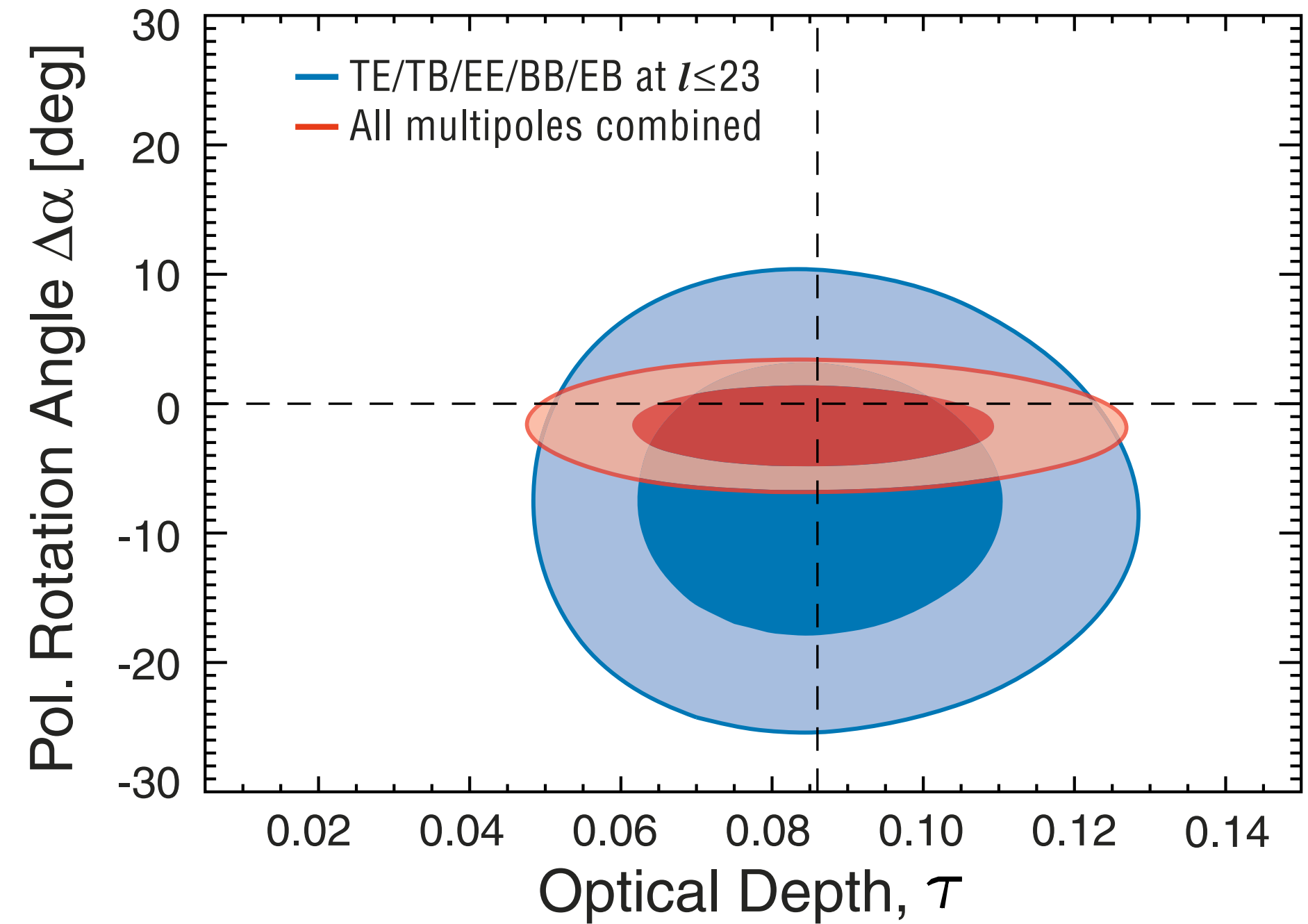
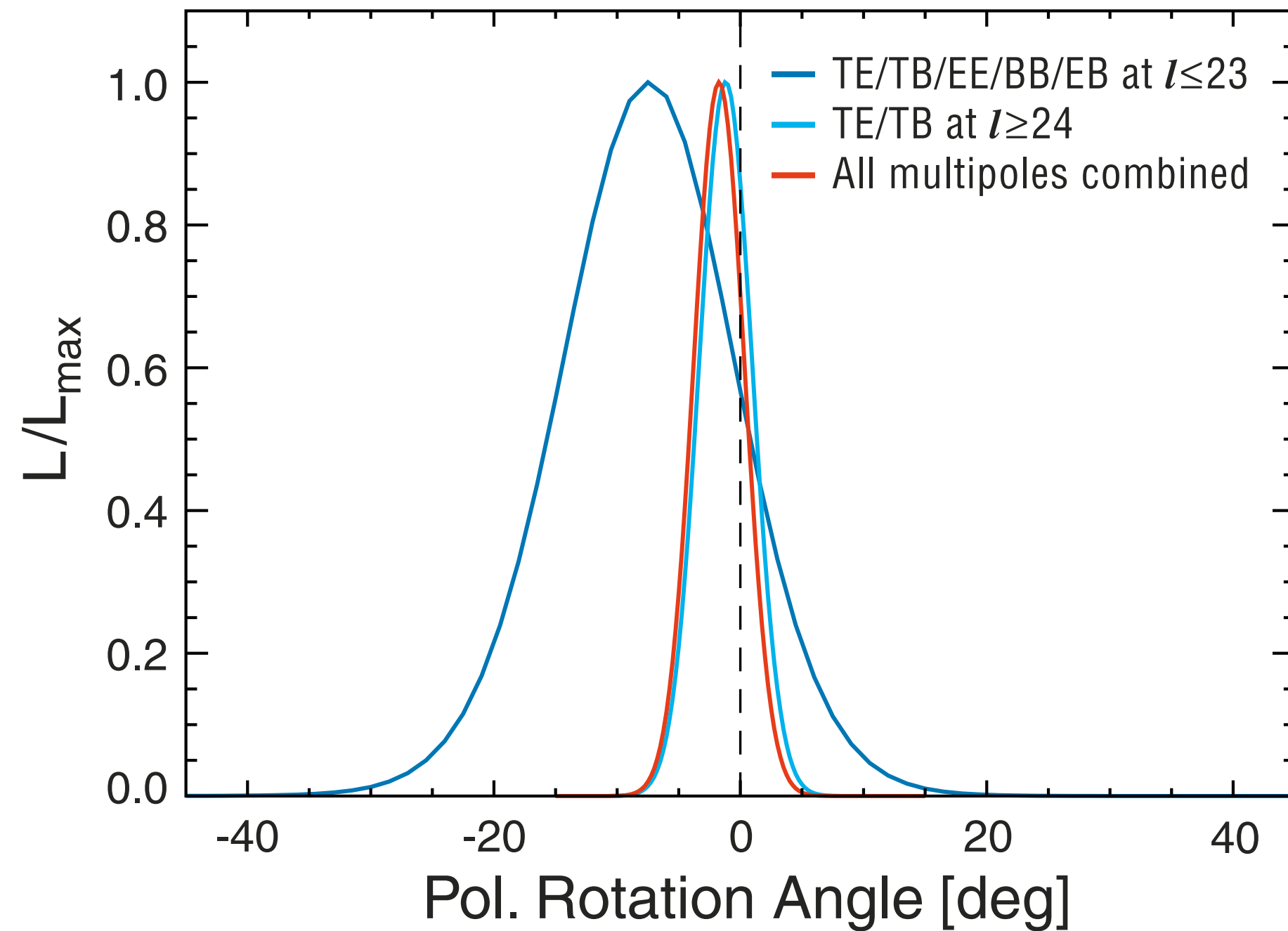
$$C_l^{TB,obs} = C_l^{TE} \sin(2\Delta\alpha),$$

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

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

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

- 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!