WMAP 5-Year Results: Implications for Inflation

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PPC 2008, May 19, 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

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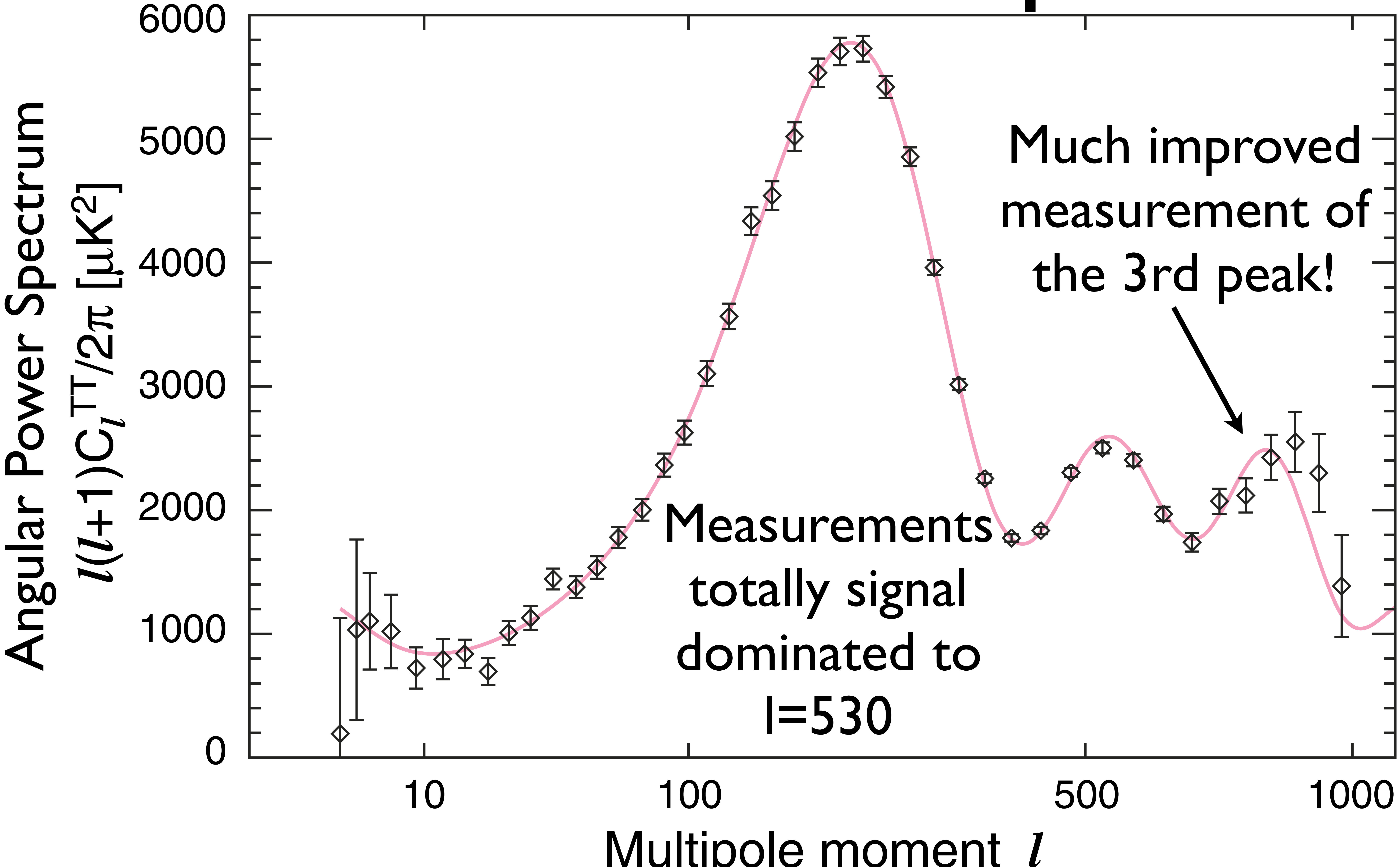
Special Thanks to **WMAP Graduates**!

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

Nolta et al.

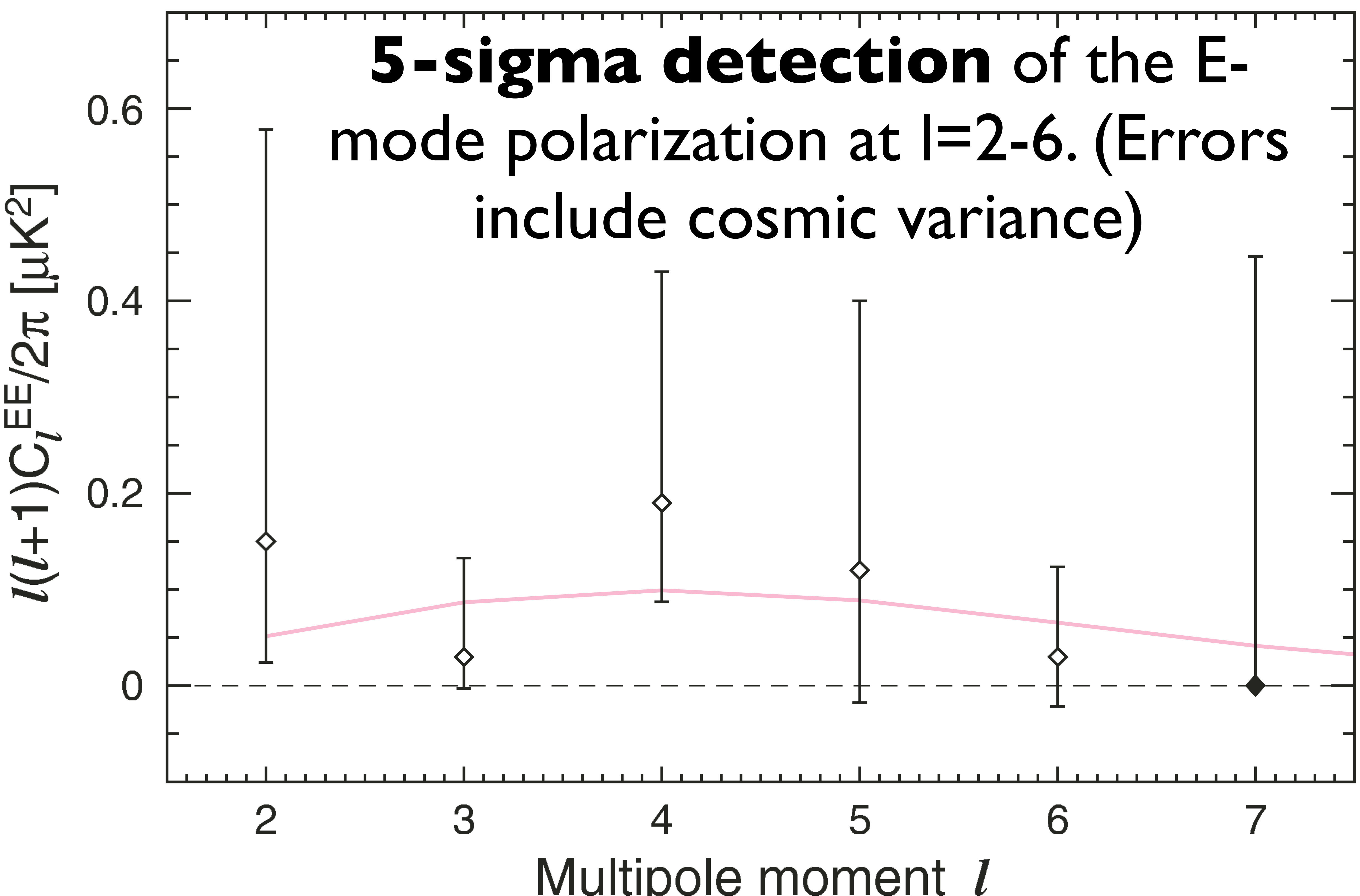
5-Year TT Power Spectrum



Nolta et al.

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

E-Mode Angular Power Spectrum

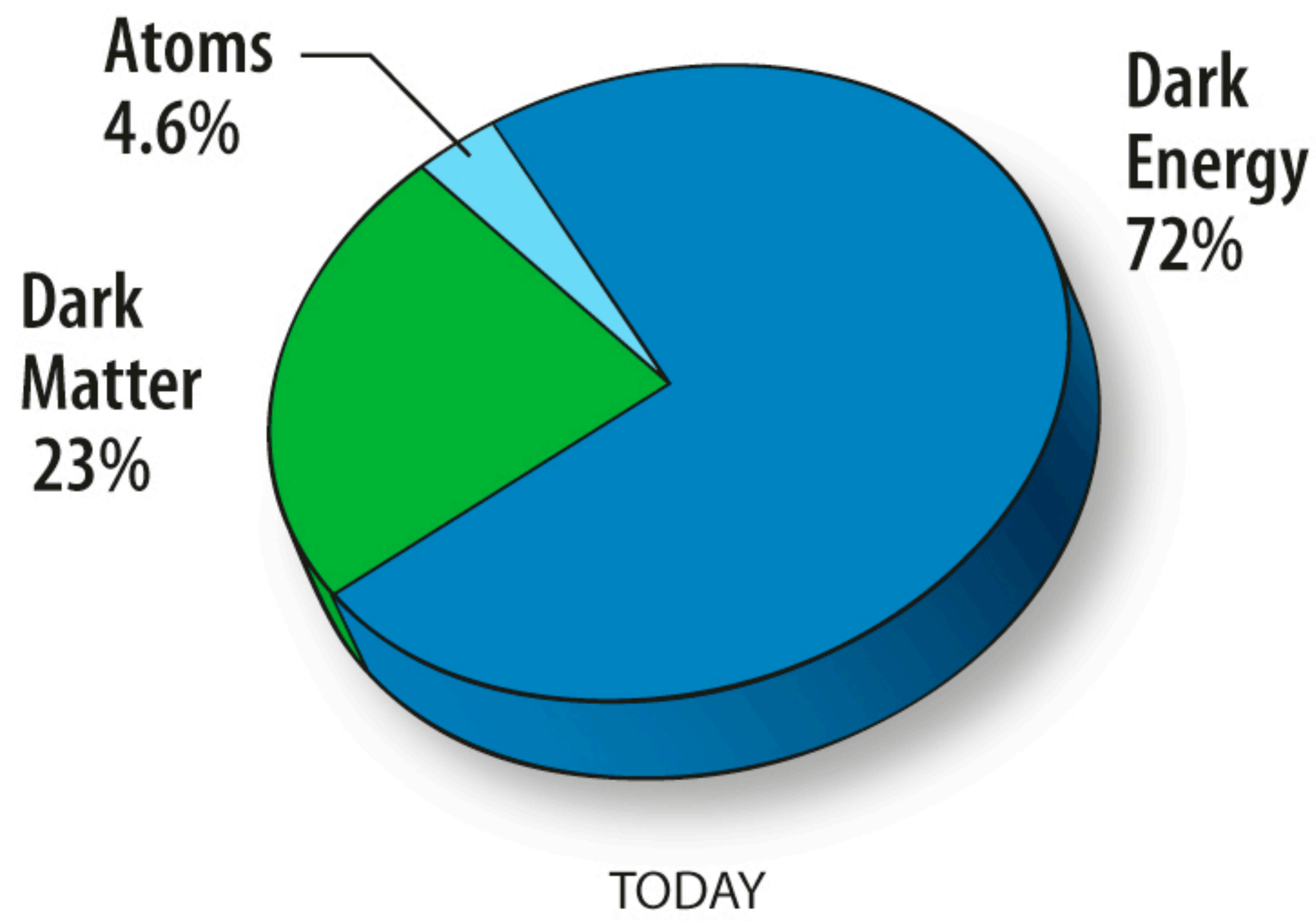


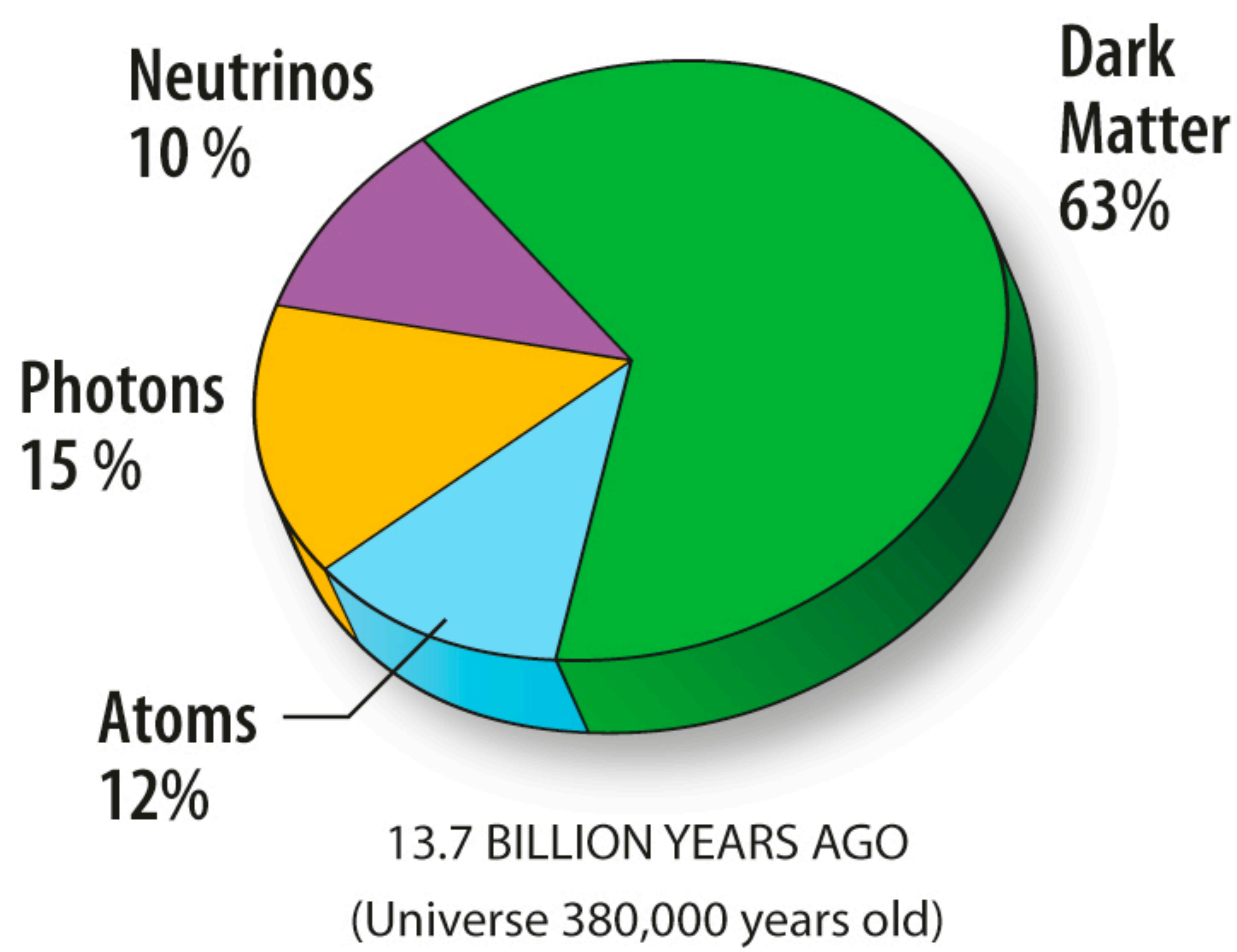
5-sigma detection of the E-mode polarization at l=2-6. (Errors include cosmic variance)

Black Symbols are upper limits

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*

Testing Cosmic Inflation

~5 Tests~

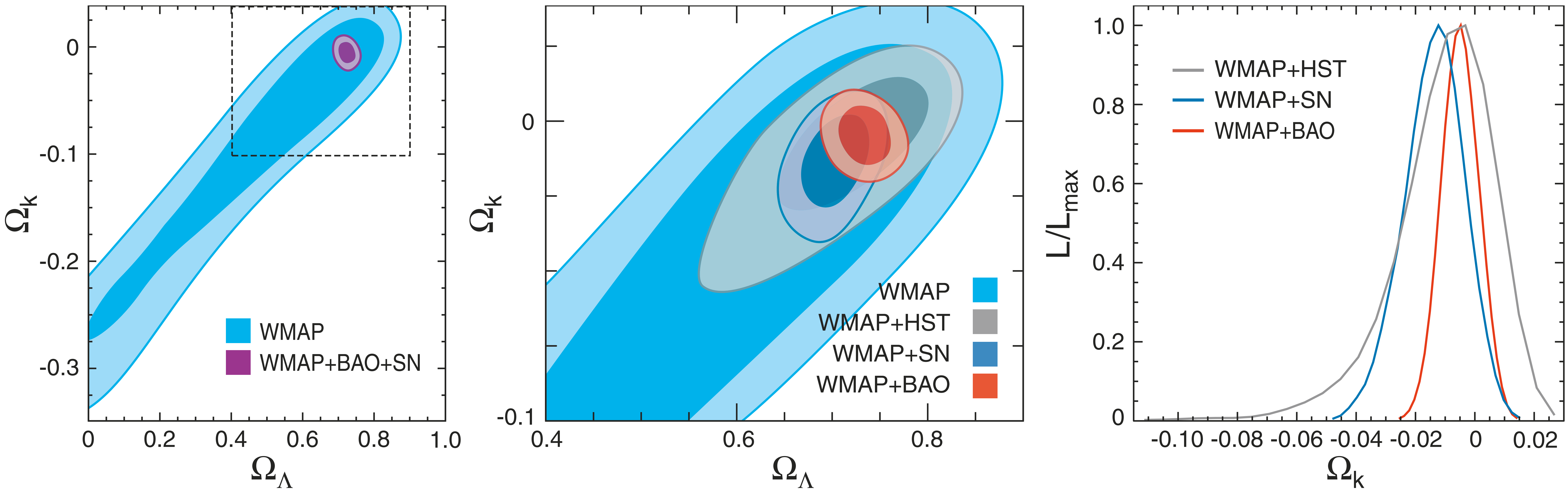
- Is the observable universe flat?
- Are the primordial fluctuations nearly Gaussian?
- Are the primordial fluctuations adiabatic?
- Is the power spectrum nearly scale invariant?
    - I talked about this already.
- Is the amplitude of gravitational waves reasonable?

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

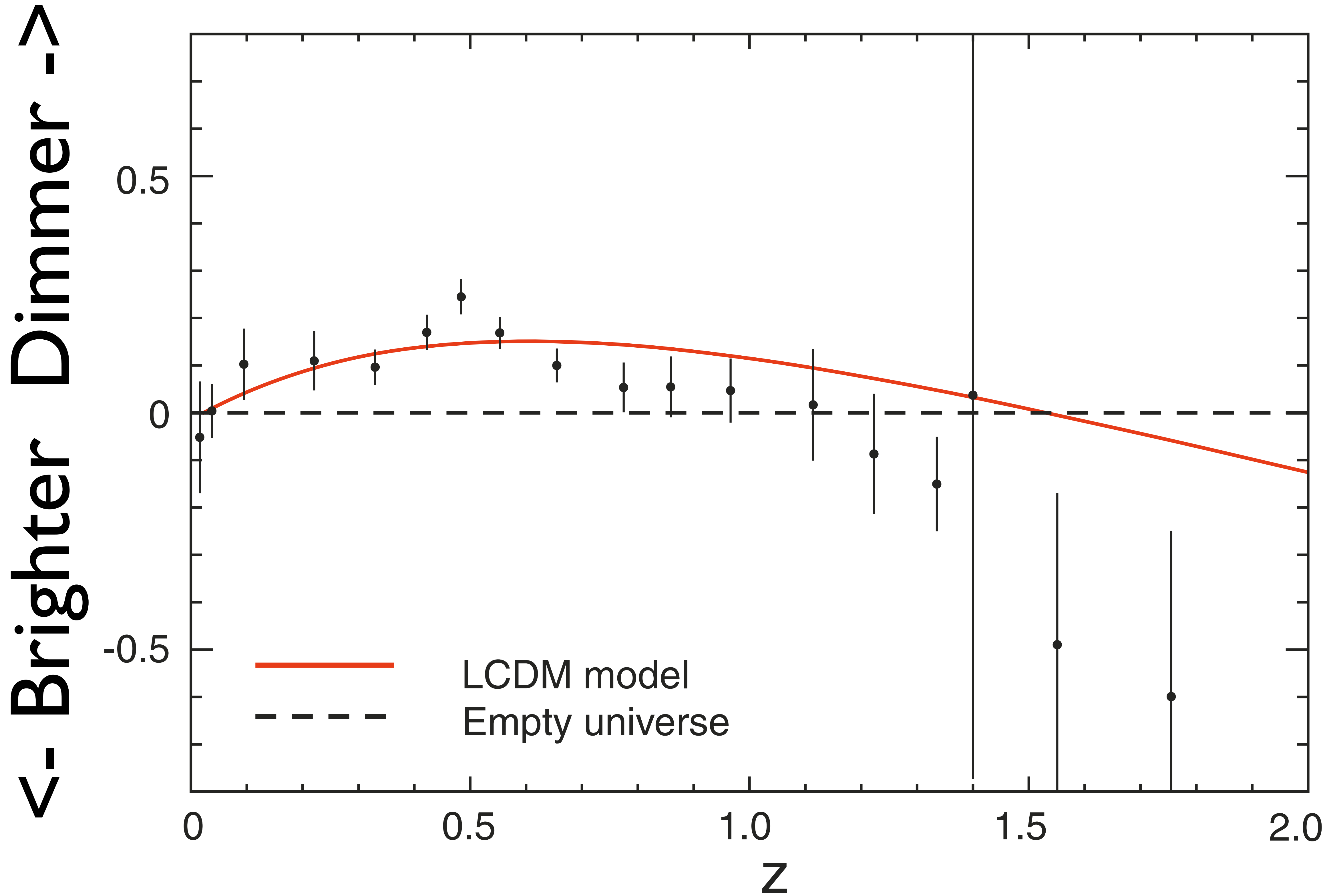
Komatsu et al.



- 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.

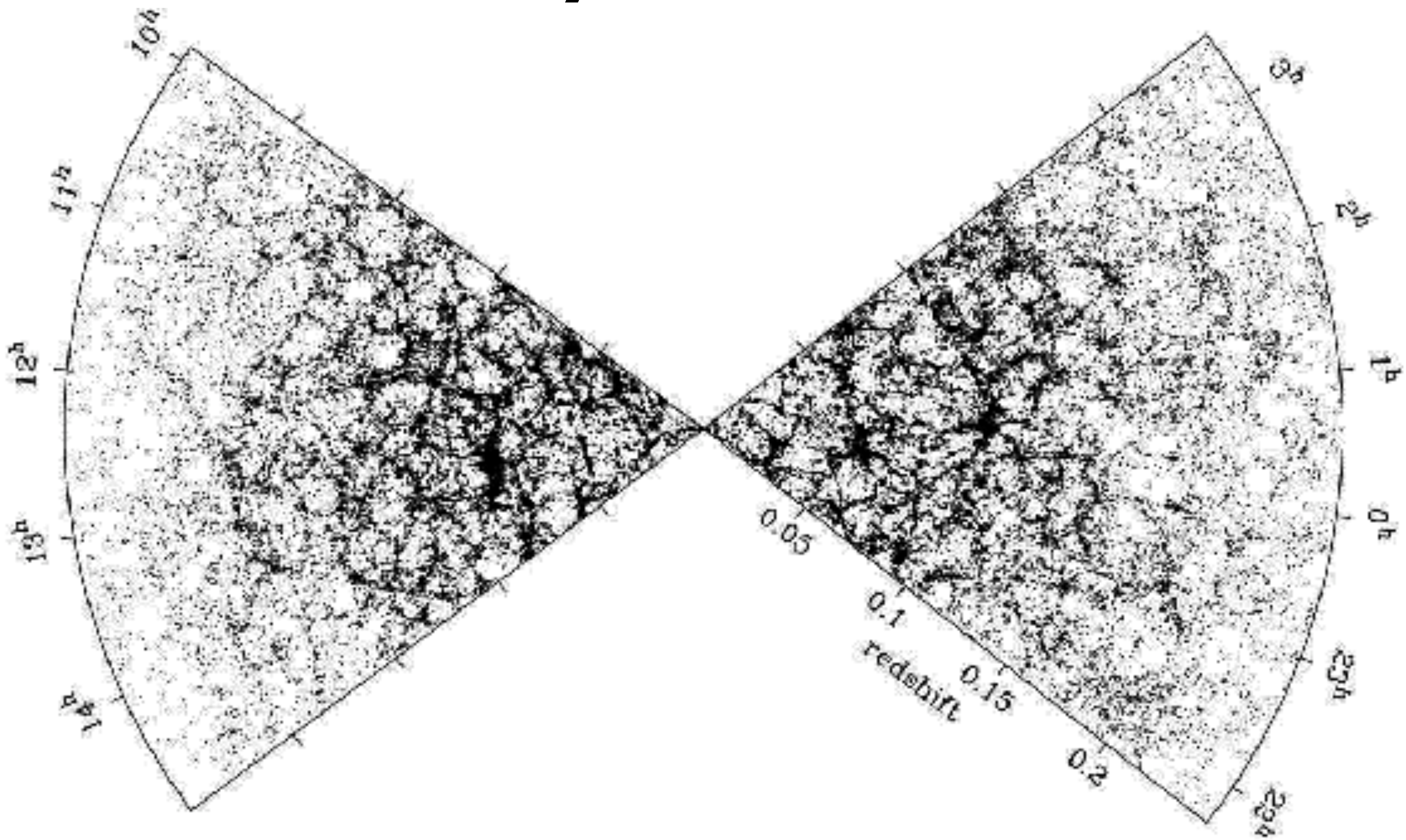


From these measurements, we get the **relative** luminosity distances between Type Ia SNe. Since we marginalize over the absolute magnitude, the current SN data are **<u>not</u>** sensitive to the absolute distances.

- 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

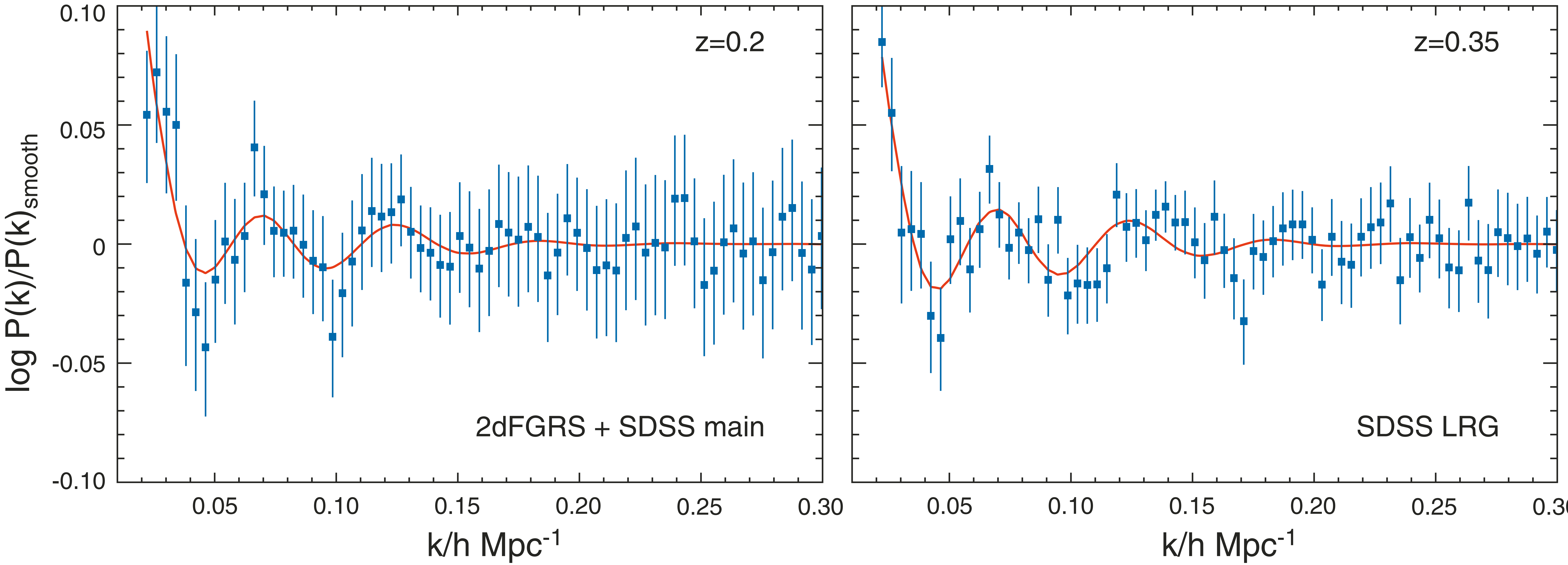
Tegmark et al.



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

BAO in Galaxy Distribution

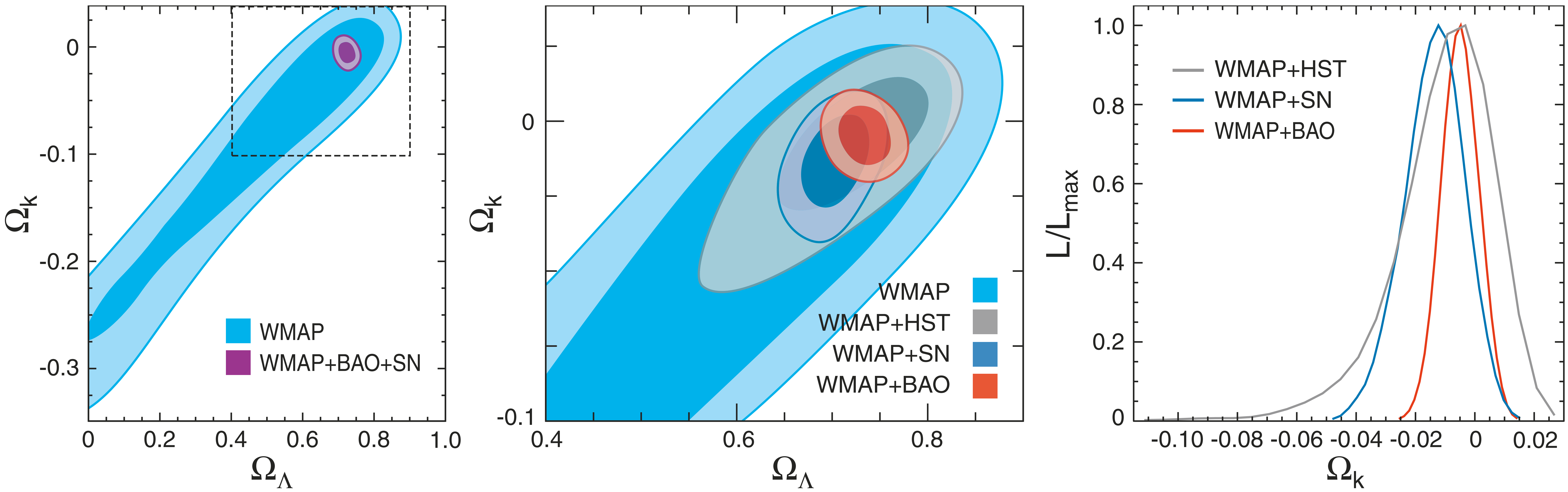
Dunkley et al.



- 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 ($\Omega_k>0$): $R>33h^{-1}$Gpc
    - For positively curved space ($\Omega_k<0$): $R>23h^{-1}$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.

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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. $\mathbf{N_{total} > 36}$ + $\ln(T_{reheating}/1\ \mathrm{TeV})$
  - 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)...

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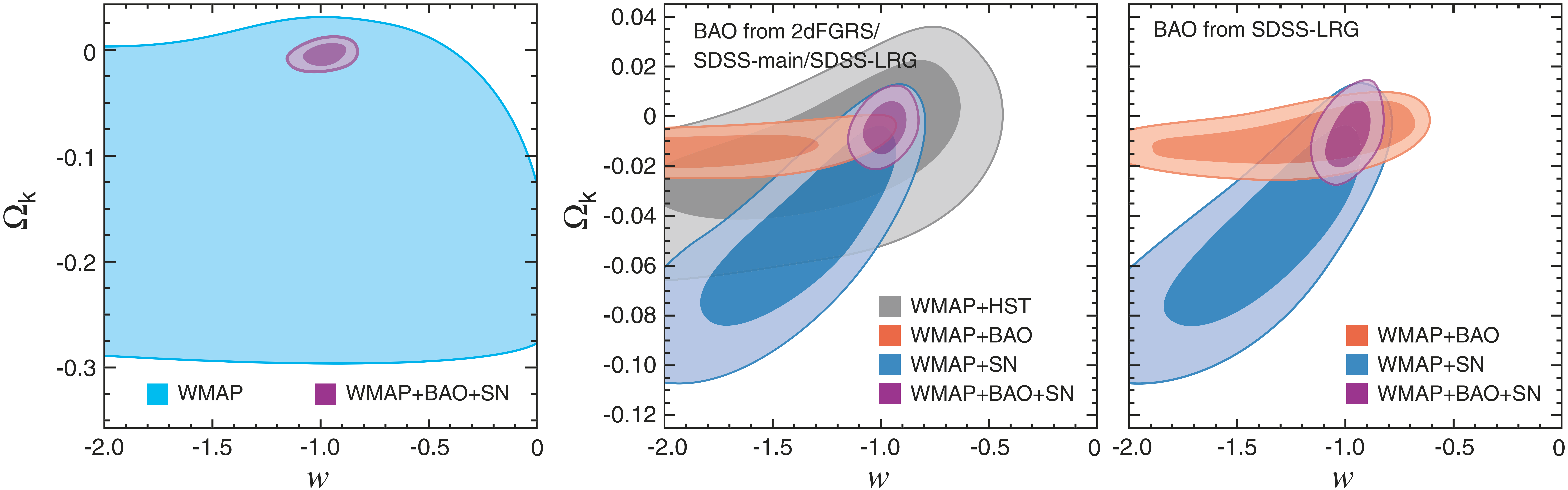
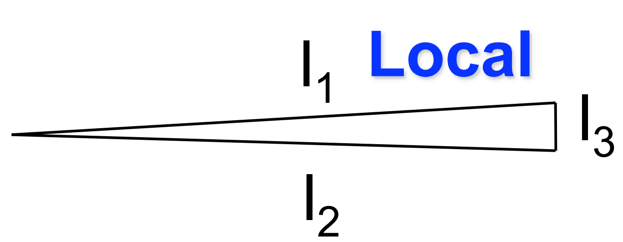


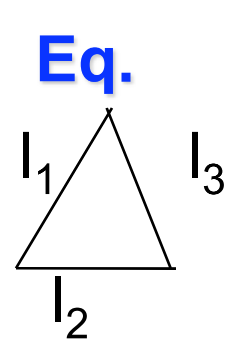
- WMAP+BAO -> Curvature; WMAP+SN -> w
- WMAP+BAO+SN -> Simultaneous limit
- **$-0.0175 < \Omega_k < 0.0085$** ; **$-0.11 < 1+w < 0.14$** (95% CL)

Check list #2: 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.
  - **Convincing 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 $\mathbf{f_{NL}^{local}}$
  - 

"Equilateral" parameterized by $\mathbf{f_{NL}^{equil}}$

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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.

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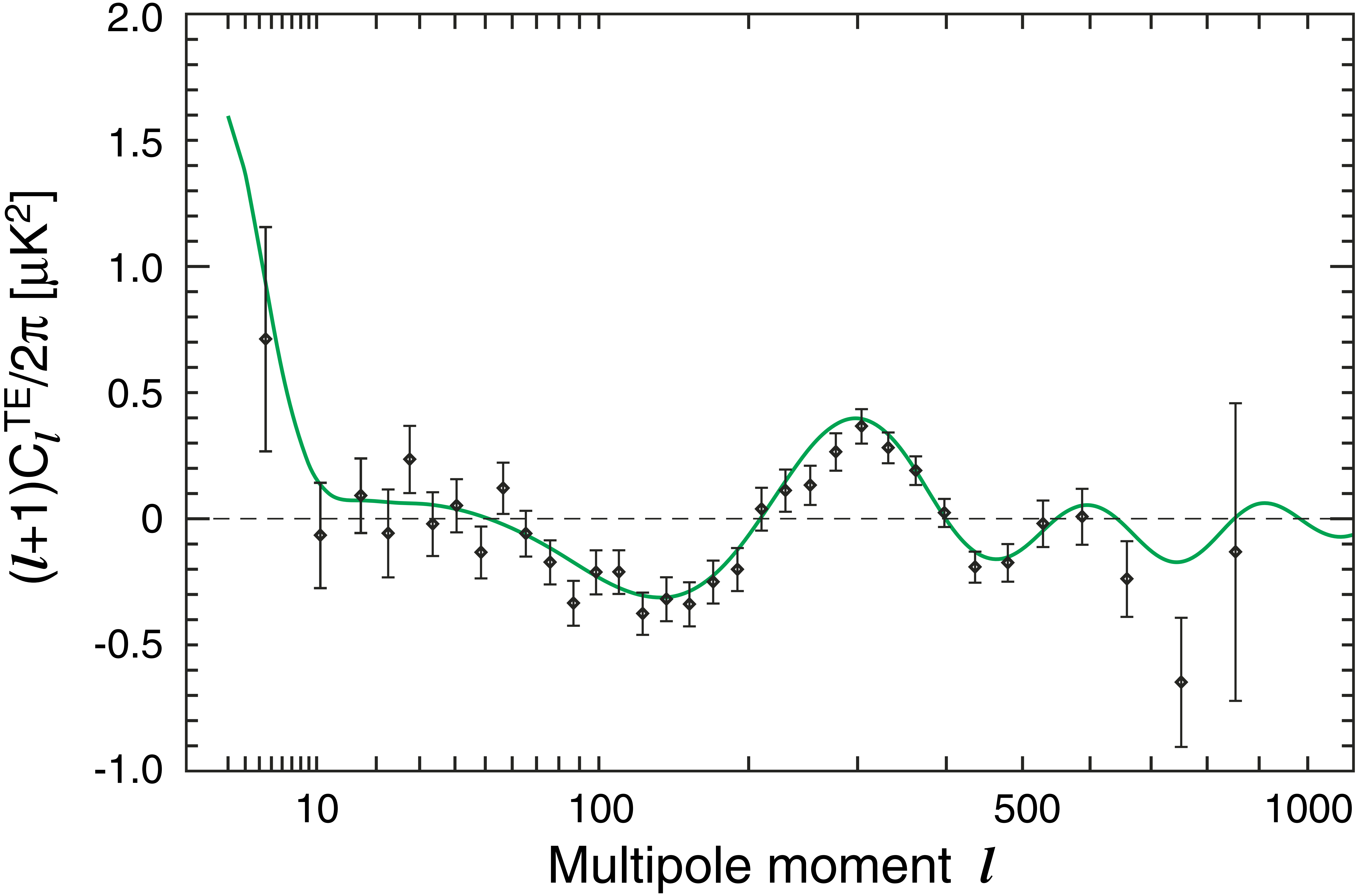
Check List #3: Adiabaticity

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

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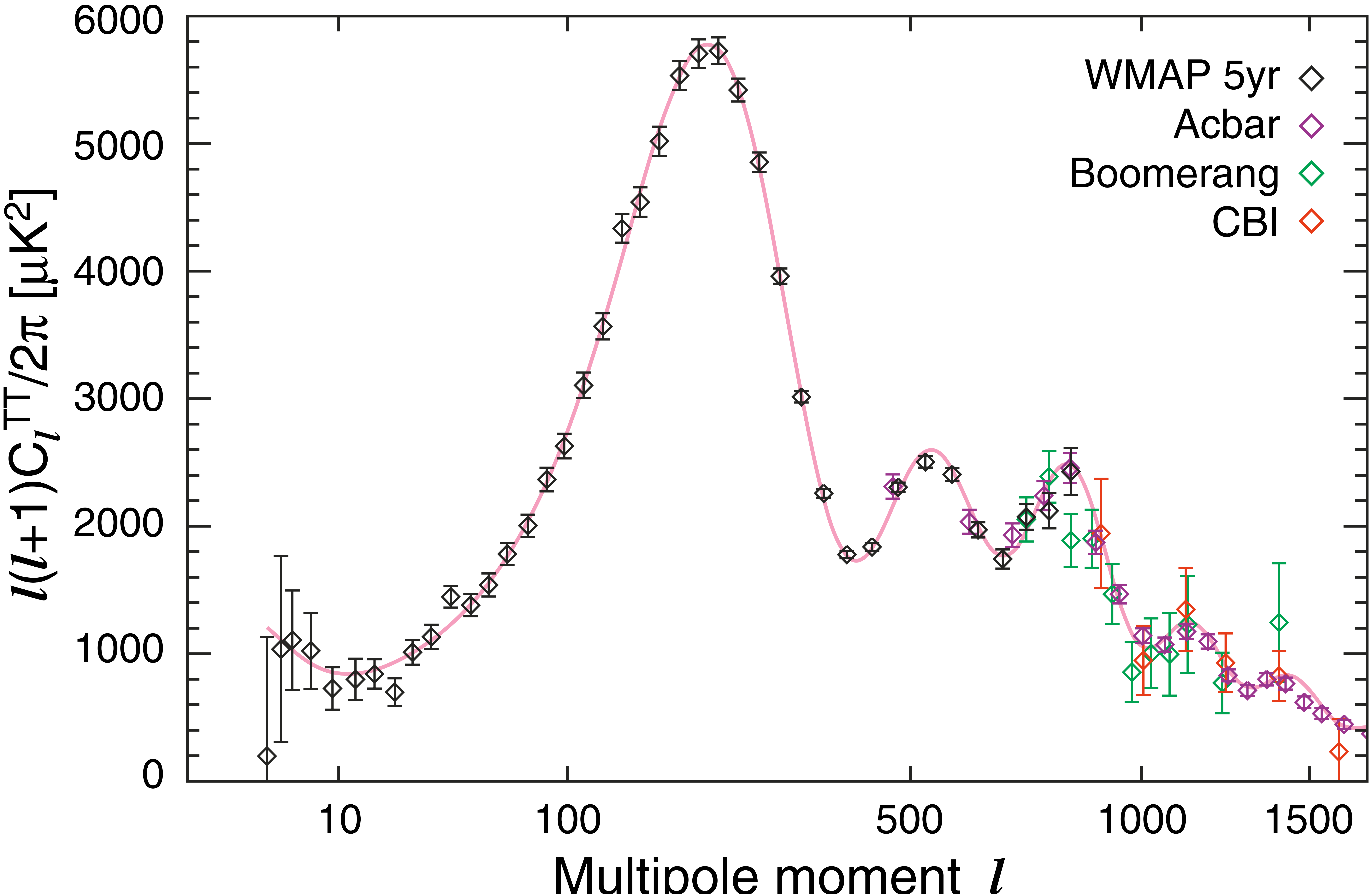
Axion Dark Matter?

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

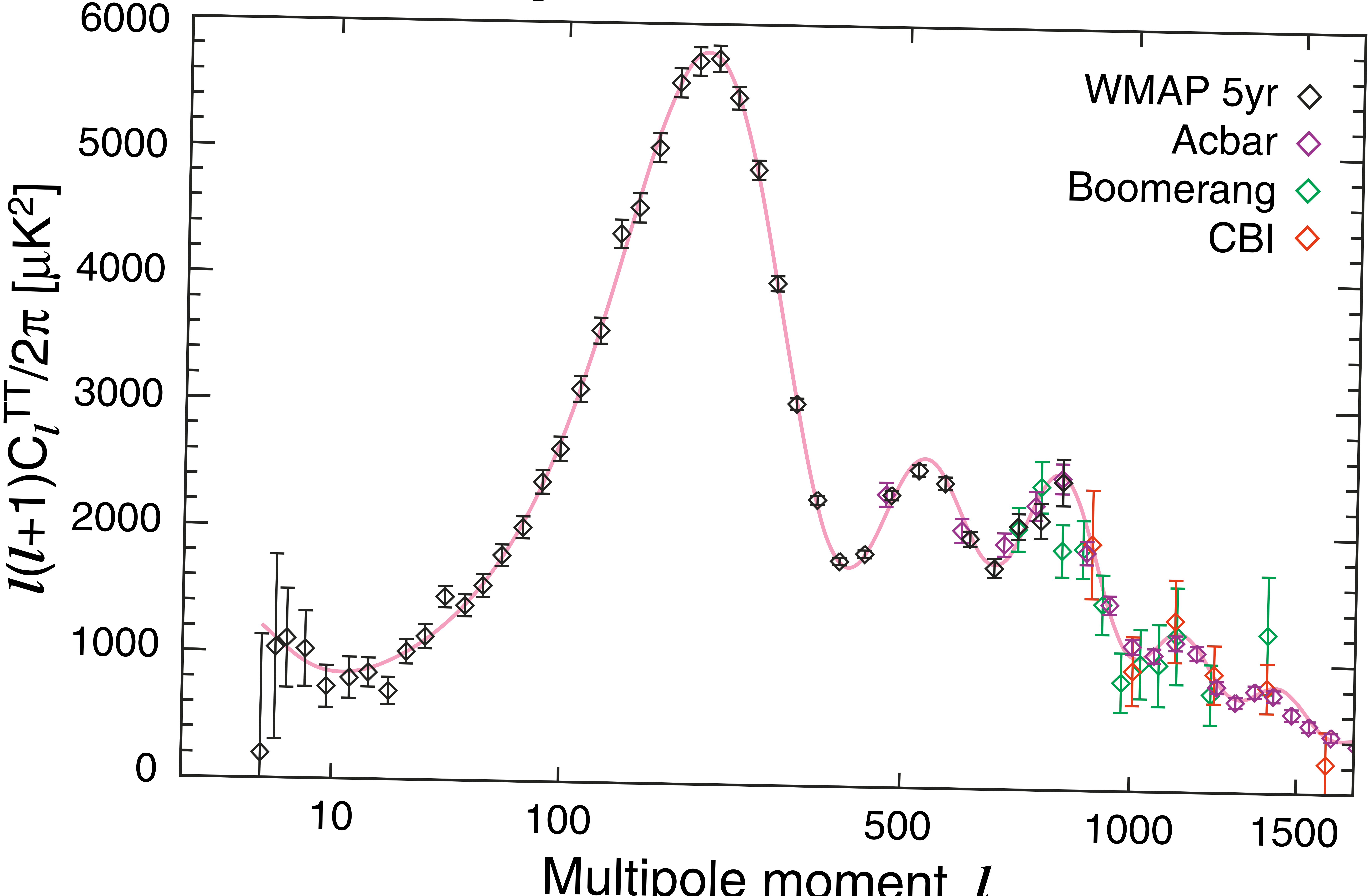
$$\frac{\Omega_a}{\Omega_c} < \frac{3.0 \times 10^{-39}}{\theta_a^5 \gamma^6} \left(\frac{0.01}{r}\right)^{7/2}$$

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

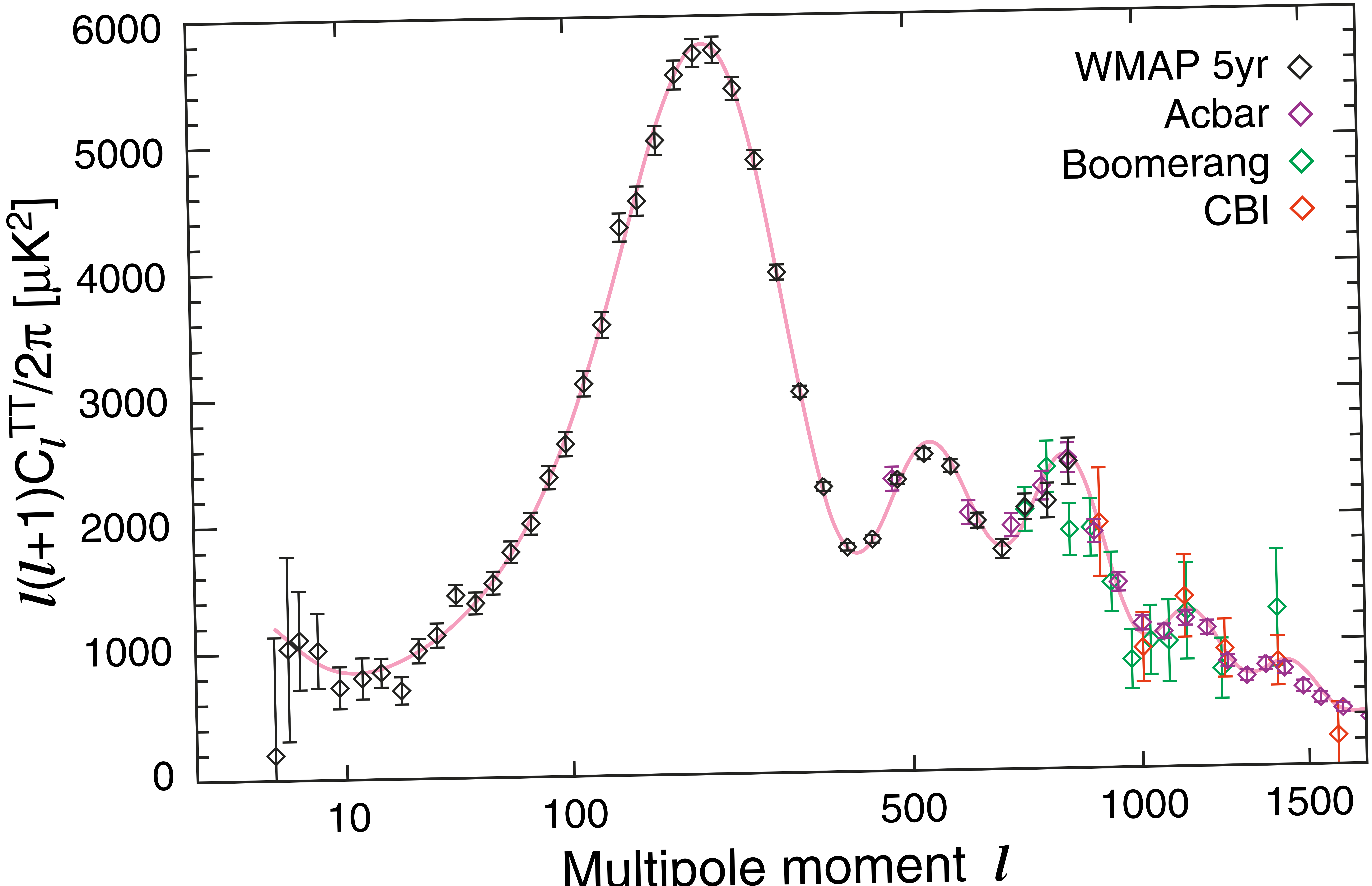
Check List #4: Scale Invariance



“Red” Spectrum: $n_s < 1$



“Blue” Spectrum: n_s > 1



Is n_s different from ONE?

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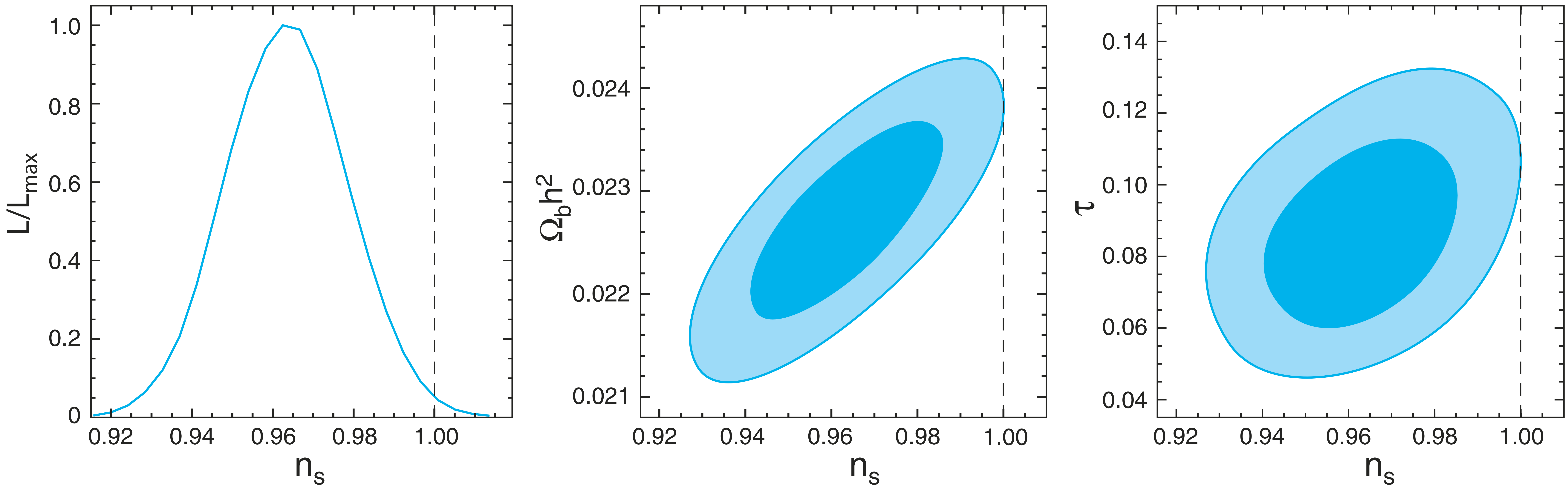
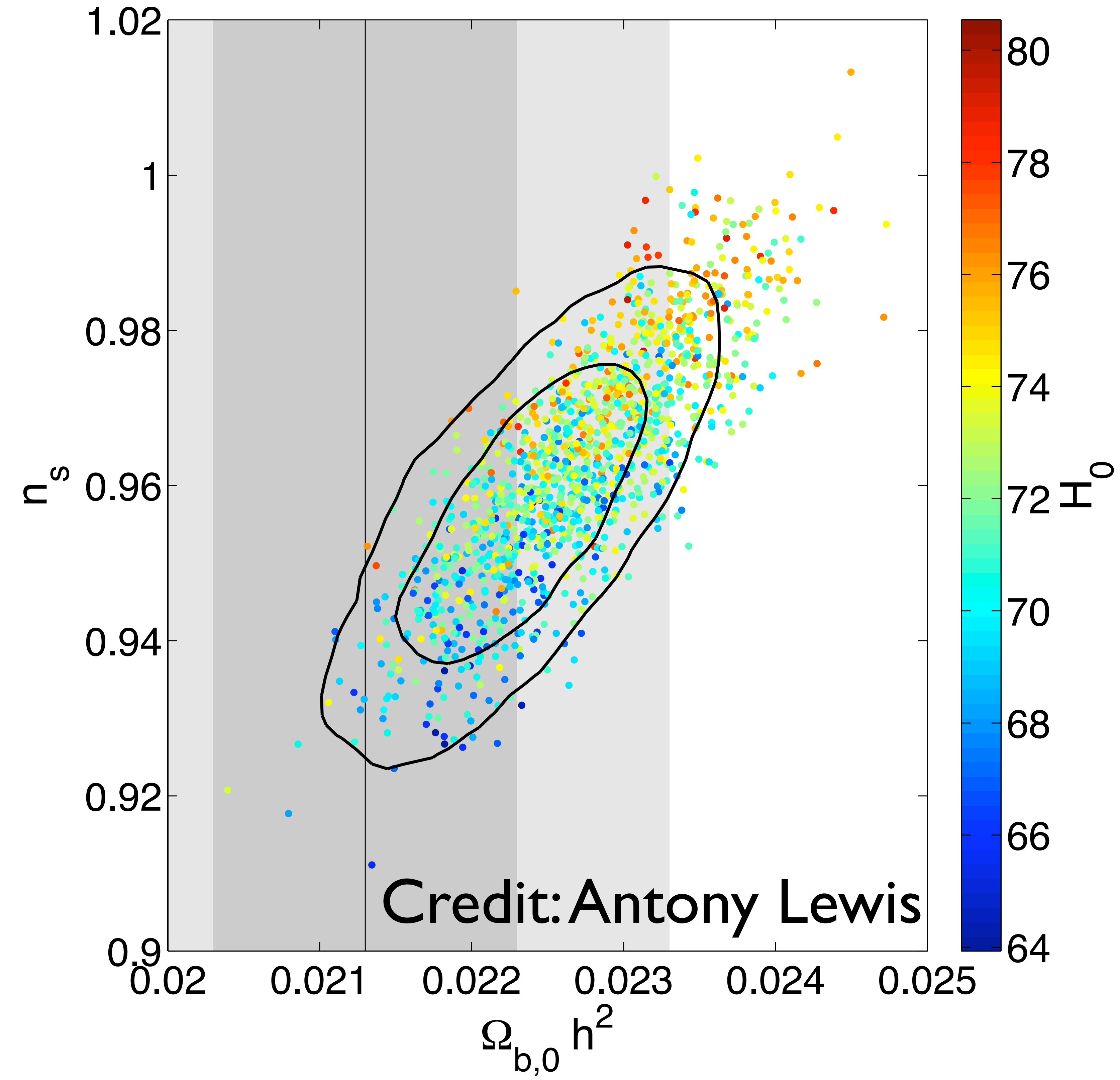


- WMAP-alone: **n_s=0.963** (+0.014) (-0.015) (Dunkley et al.)
  - 2.5-sigma away from n_s=1, "scale invariant spectrum"
- n_s is degenerate with $\Omega_b h^2$; thus, we can't really improve upon n_s further unless we improve upon $\Omega_b h^2$

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!
  - $\Omega_b h^2$(DLA)=0.0213±0.0010 from log(D/H)=-4.55±0.03
  - $\Omega_b h^2$(WMAP)=0.0227±0.0006
- $\Omega_b h^2$(DLA) is totally independent of n_s
  - *Degeneracy reduced!*
  - n_s(DLA+WMAP)=**0.956±0.013**
    - **3.4-sigma away from 1**
  - n_s(WMAP)=0.963 (+0.014) (-0.015)



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

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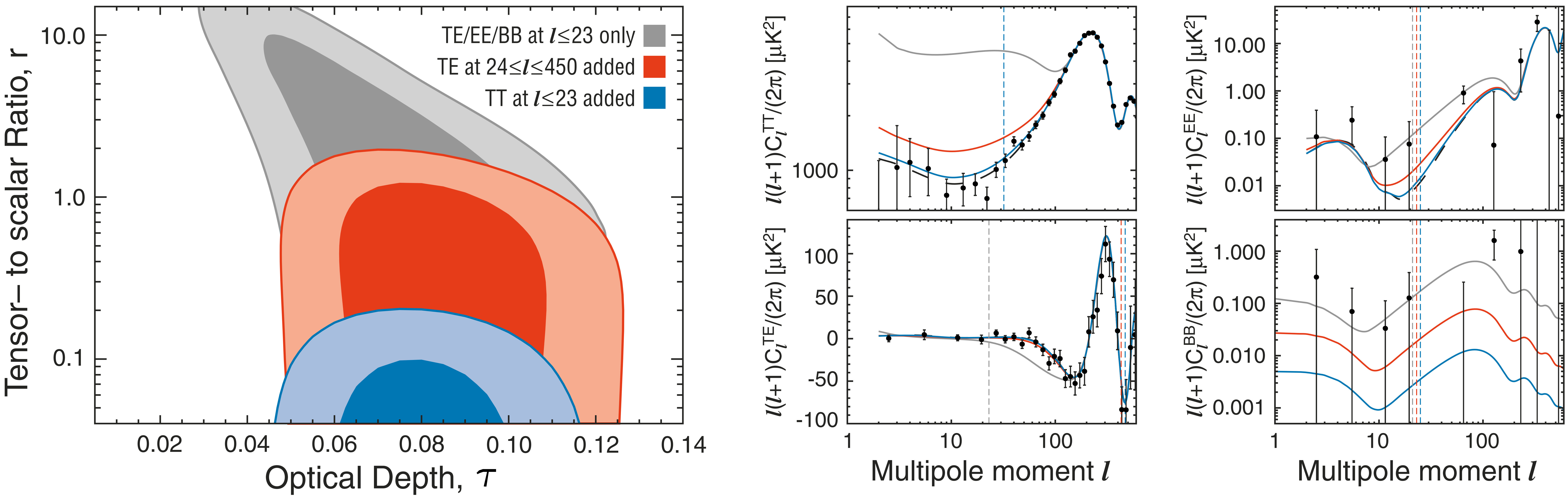
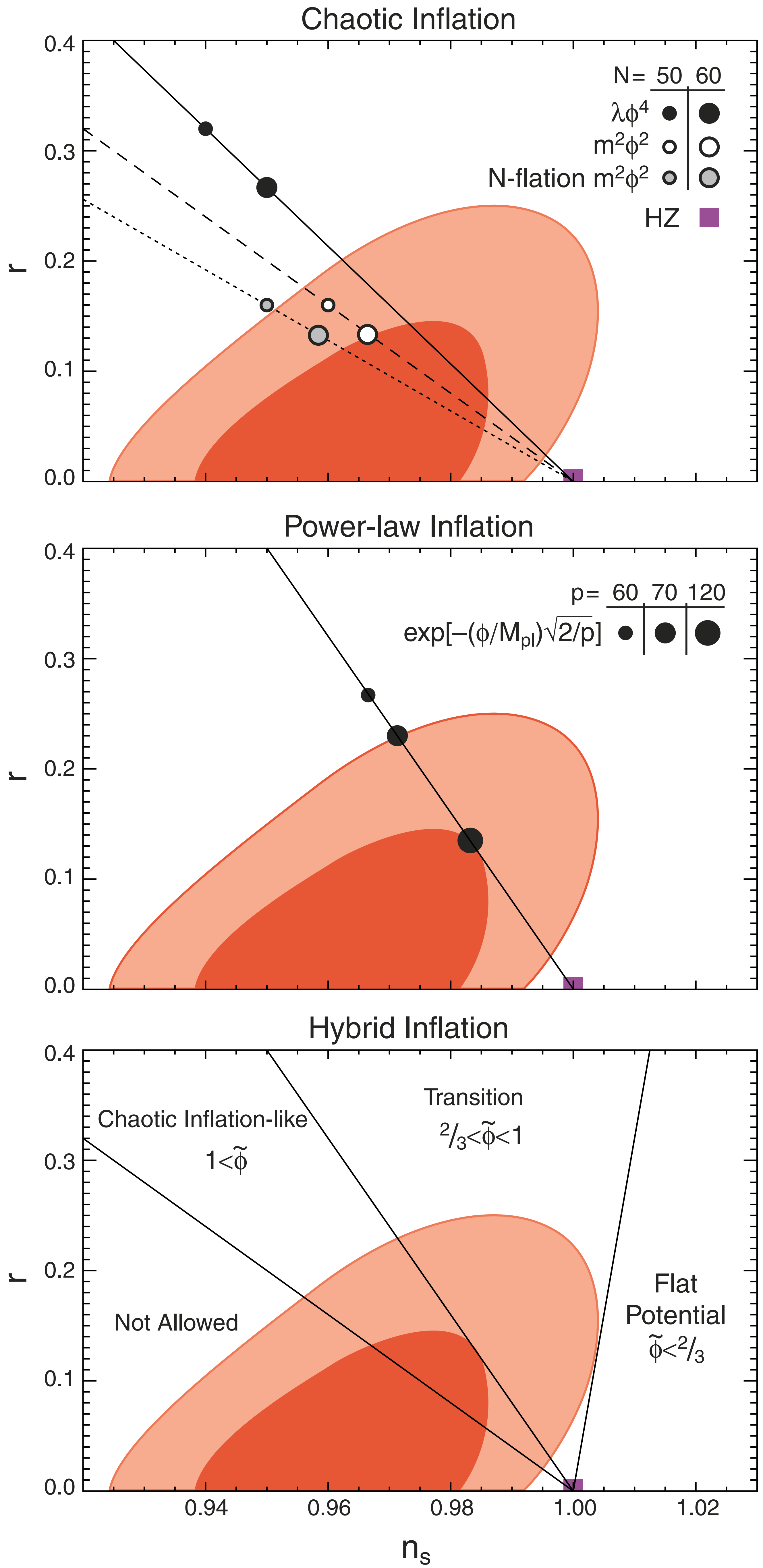


- If all the other parameters (n_s in particular) are fixed...
  - Low-l polarization gives r<20 (95% CL)
  - + high-l polarization gives r<2 (95% CL)
  - + low-l temperature gives r<0.2 (95% CL)



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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

Komatsu et al.

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 < 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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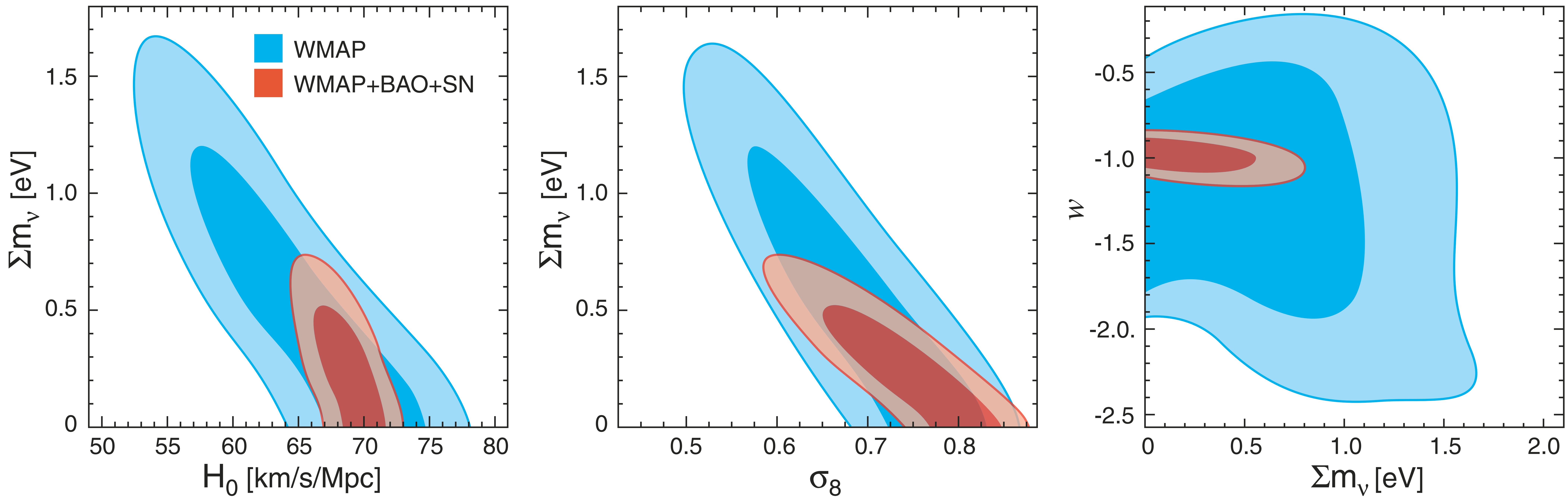
Neutrino Mass



- The local distance measurements (BAO) help 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.

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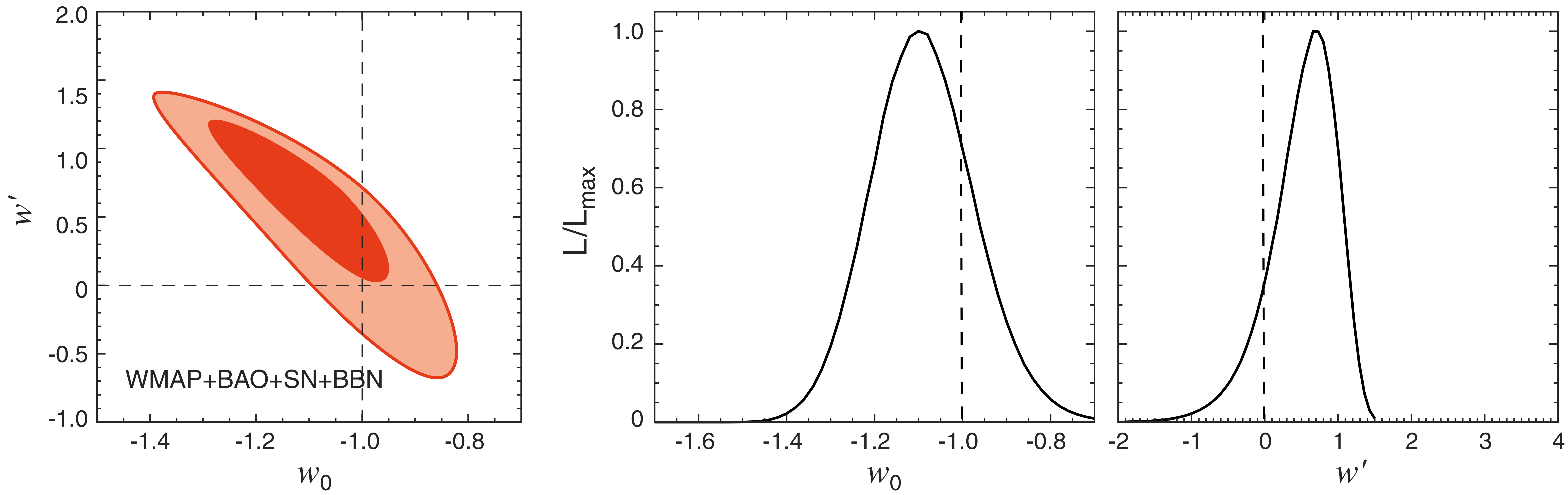
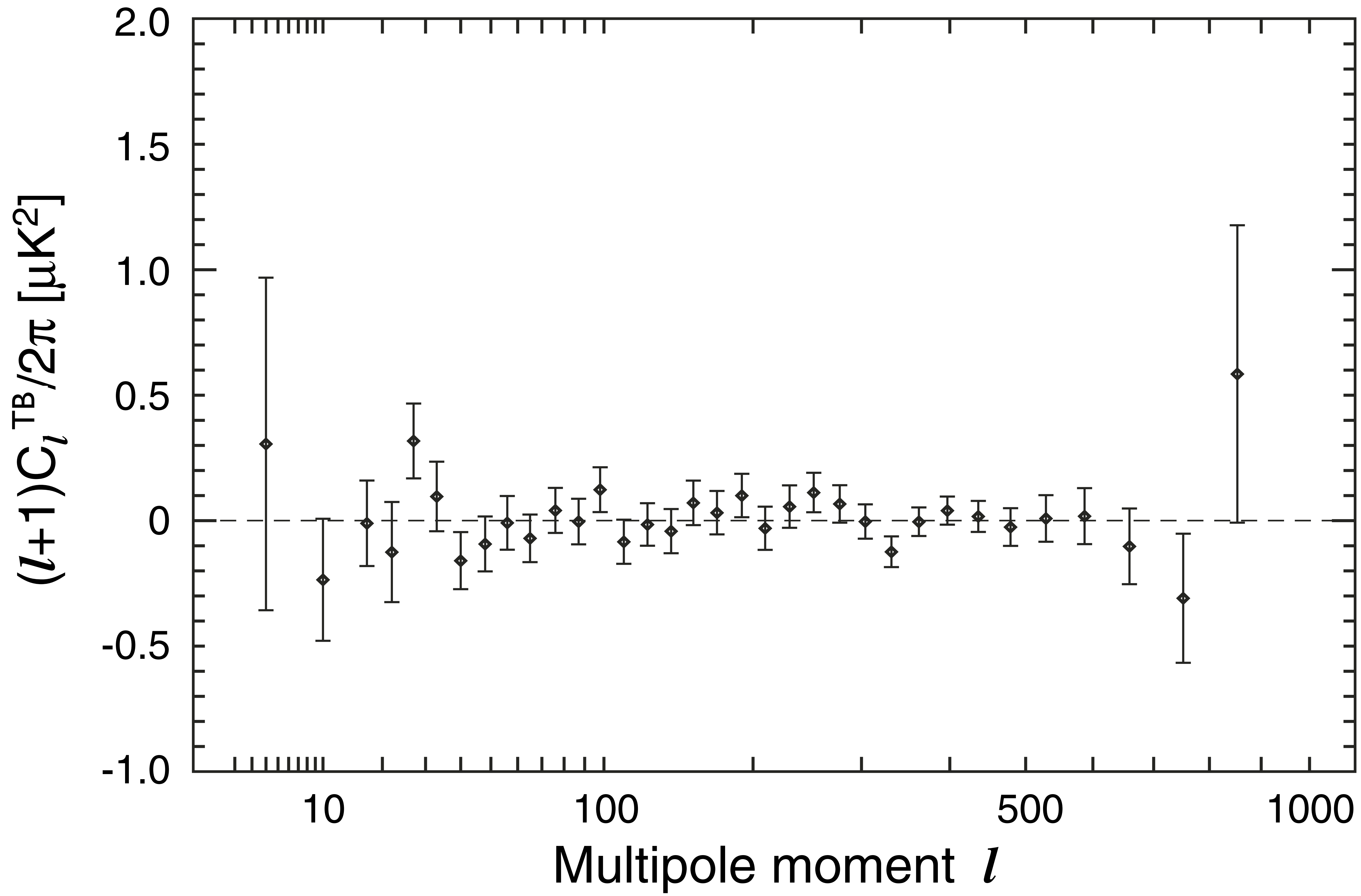
Dark Energy EOS: $w(z)=w_0+w'z/(1+z)$



- 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.

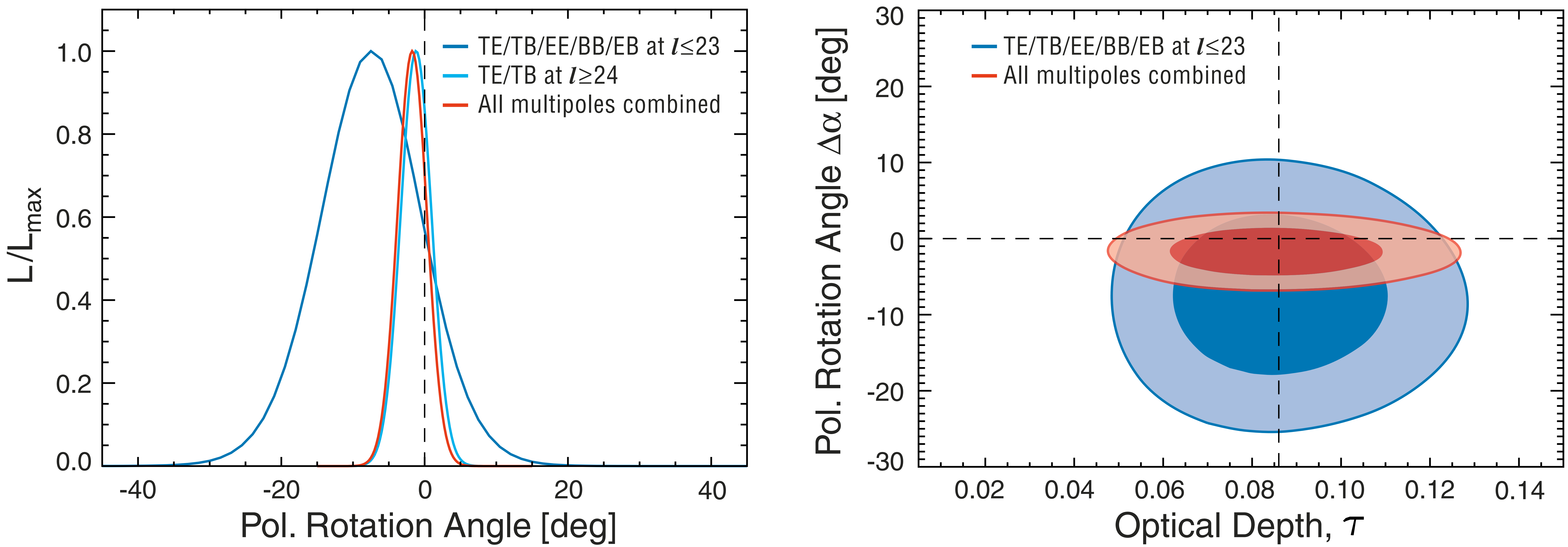
Lue, Wang & Kamionkowski (1999); Feng et al. (2005)

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?

Komatsu et al.



- **$\Delta\alpha$=(-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!