WMAP 5-Year Observations: Cosmological Interpretation

Eiichiro Komatsu
University of Texas at Austin

CITA, March 11, 2008

WMAP 5-Year Papers

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

WMAP 5-Year Science Team

- 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!**

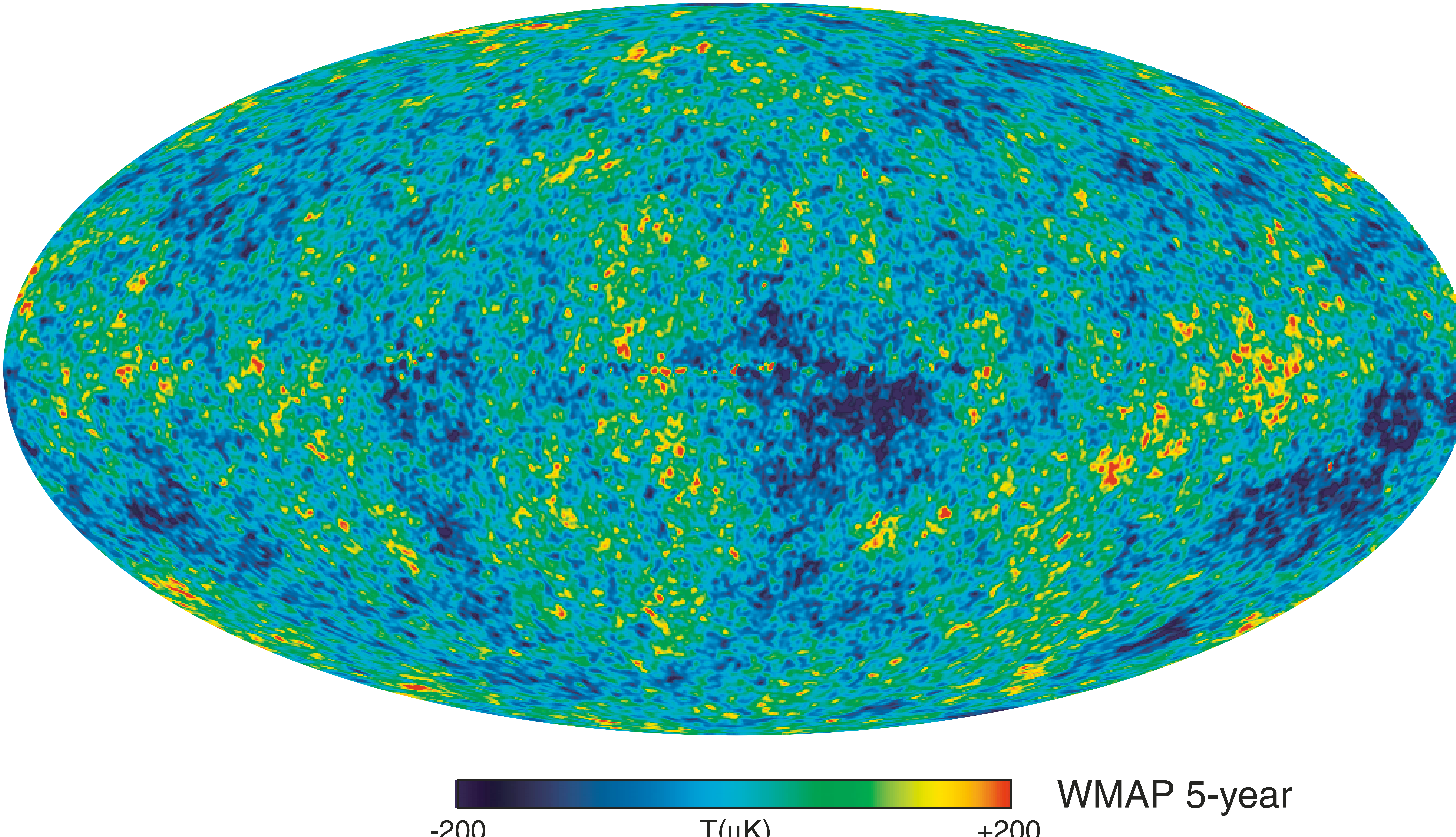
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

WMAP 5-Year Press Release On March 7, 2008

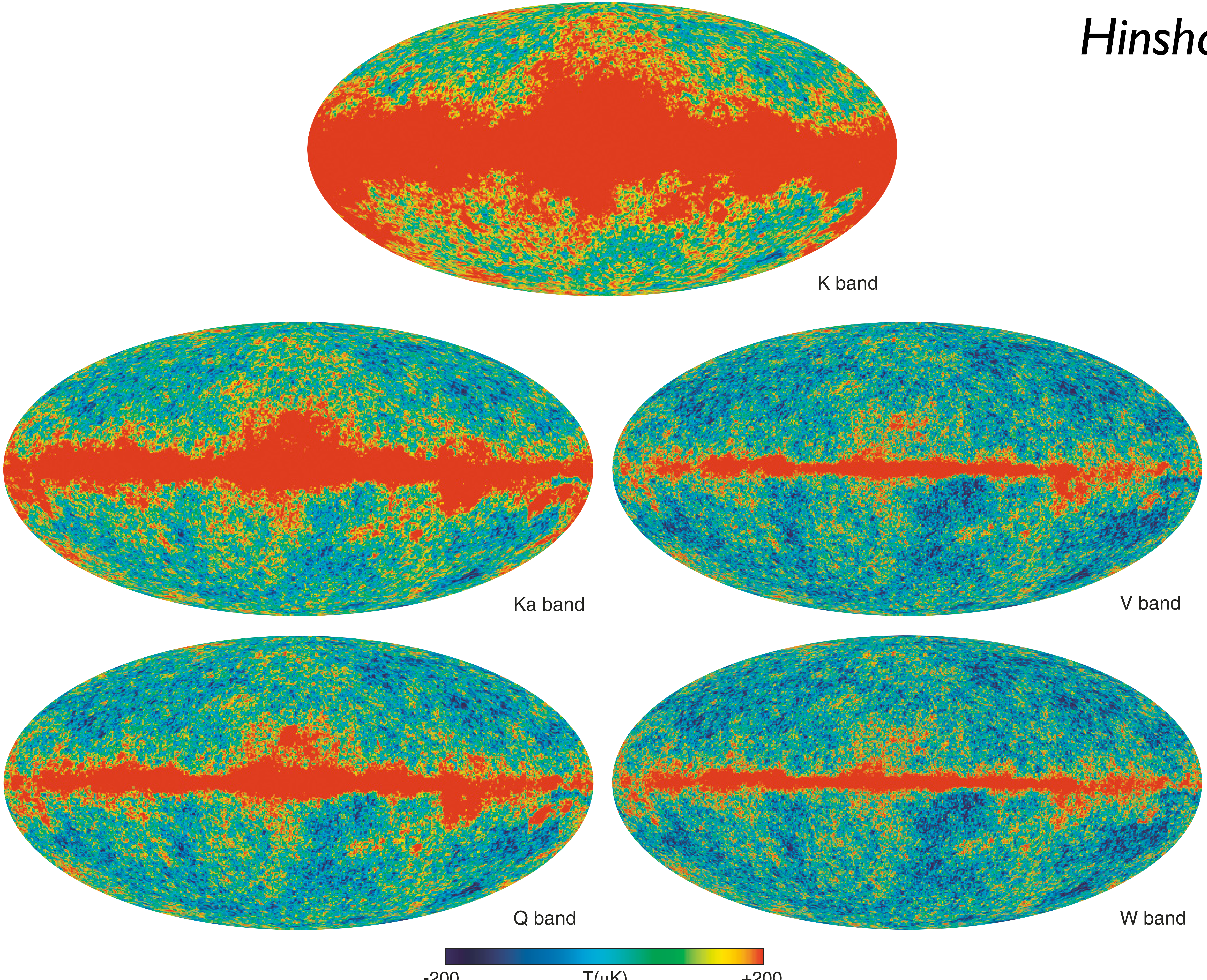
- Evidence for the cosmic neutrino background from the WMAP data alone
- Instantaneous reionization at $z_{reion}=6$ is excluded at the 3.5 sigma level
- The tightest constraints on inflation models to date

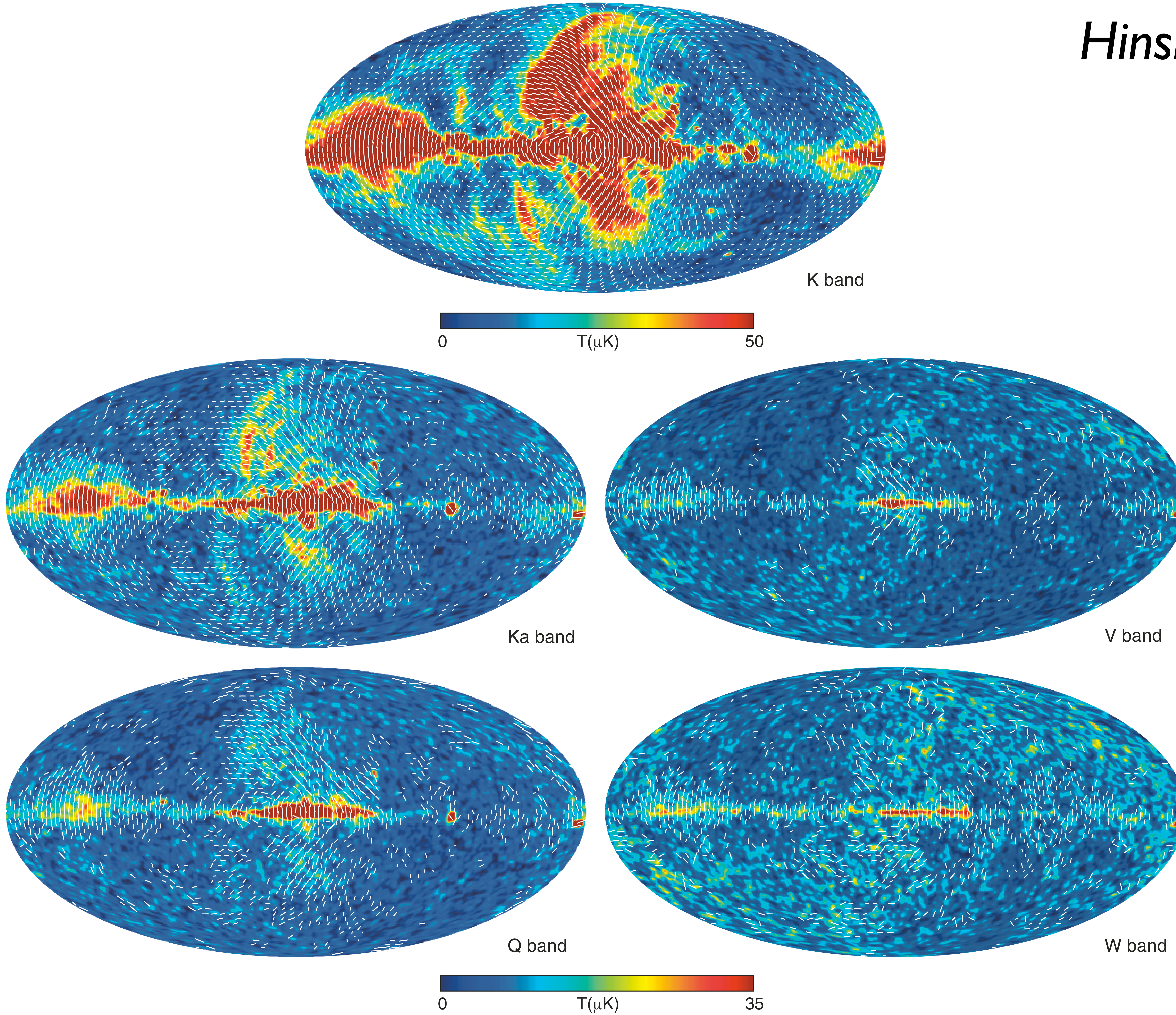
Hinshaw et al.

WMAP 5-Year Data



Hinshaw et al.




K band
0
T(μK)
50
Ka band
V band
Q band
W band
0
T(μK)
35

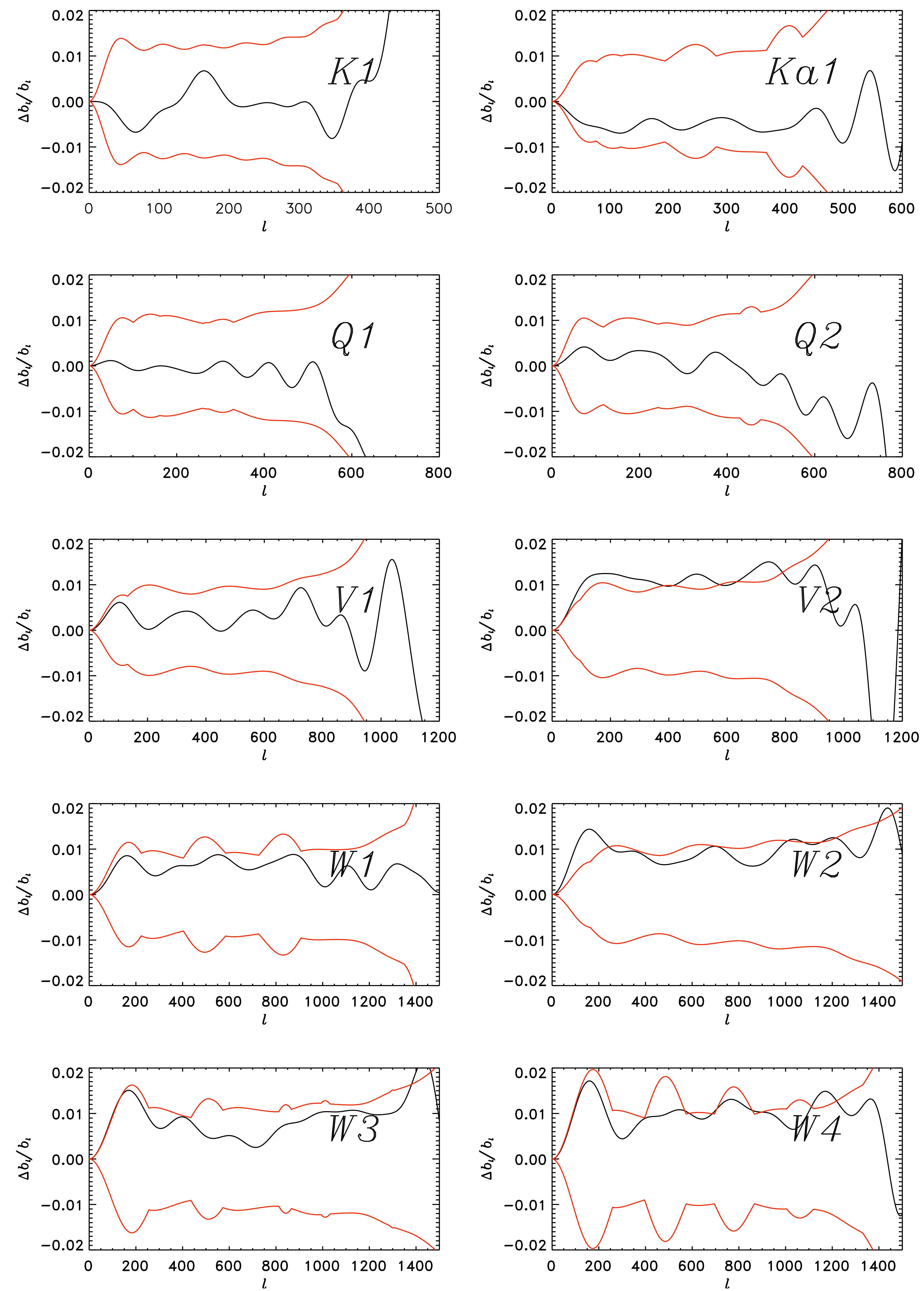
Improved Data/Analysis

- Improved Beam Model
    - 5 years of the Jupiter data, combined with the extensive physical optics modeling, reduced the beam uncertainty by a factor of 2 to 4.
- Improved Calibration
    - Improved algorithm for the gain calibration from the CMB dipole reduced the calibration error from 0.5% to 0.2%
- More Polarization Data Usable for Cosmology
    - We use the polarization data in Ka band. (We only used Q and V bands for the 3-year analysis.)

Hill et al.

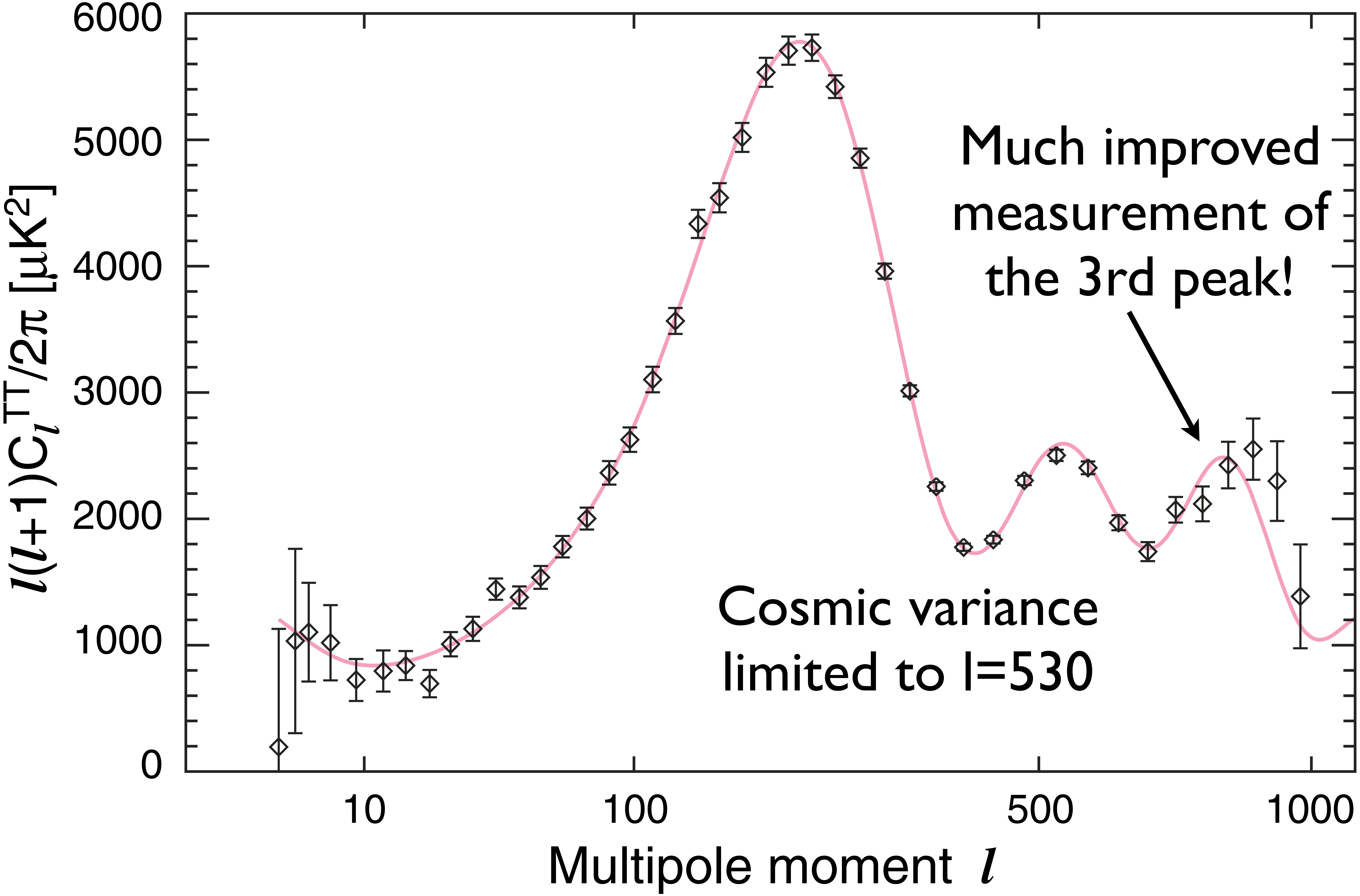
New Beam

- The difference between the 5-year beam and the 3-year beam (shown in black: **3yr minus 5yr beam**) is within ~1 sigma of the 3-year beam errors (shown in red)
- We use V and W bands for the temperature power spectrum, C_l
  - Power spectrum depends on the beam^2
  - **The 5-year C_l is ~2.5% larger than the 3-year C_l at l>200**



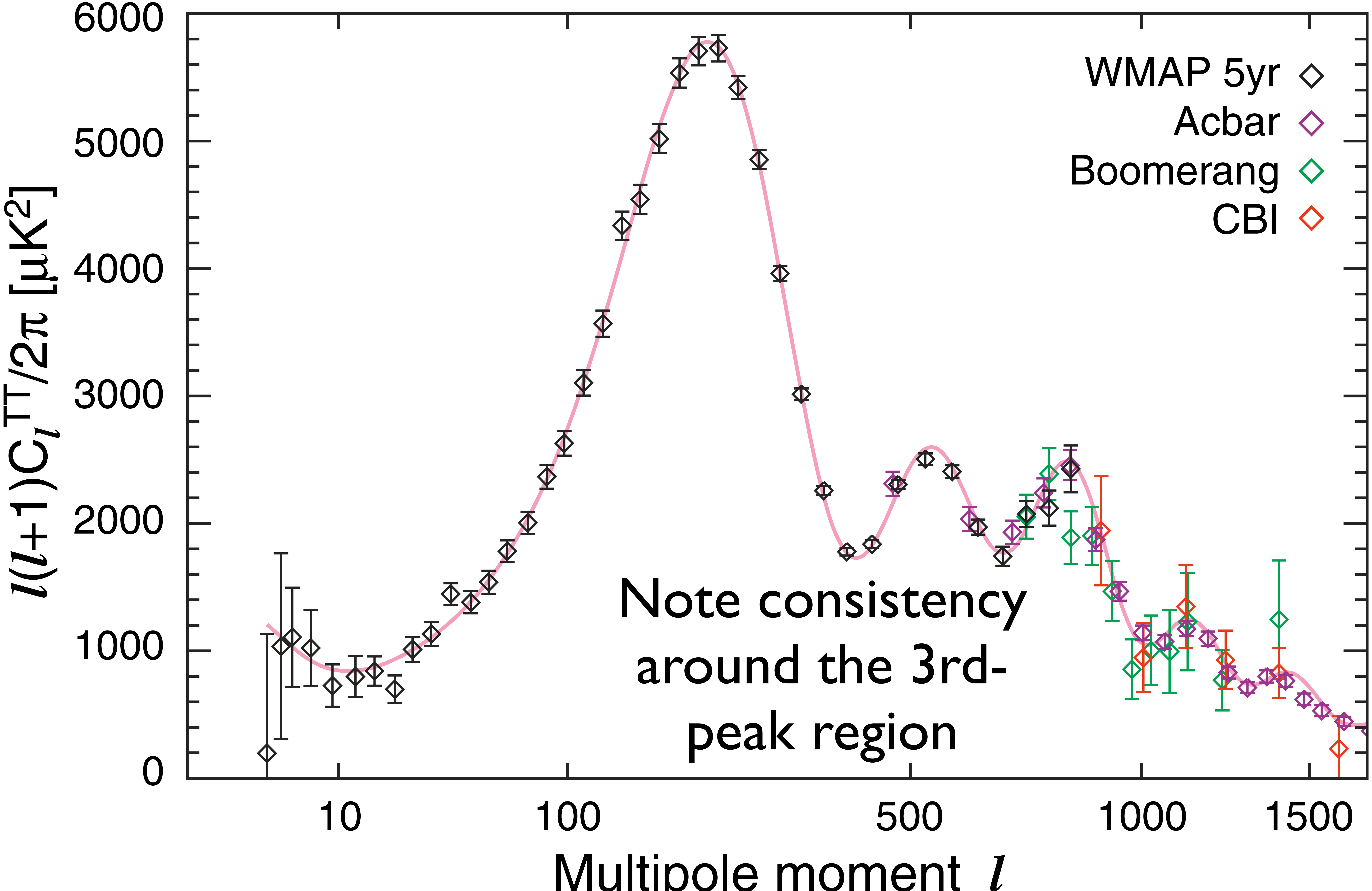
The 5-Year C_l

Nolta et al.



The 5-Year C_l

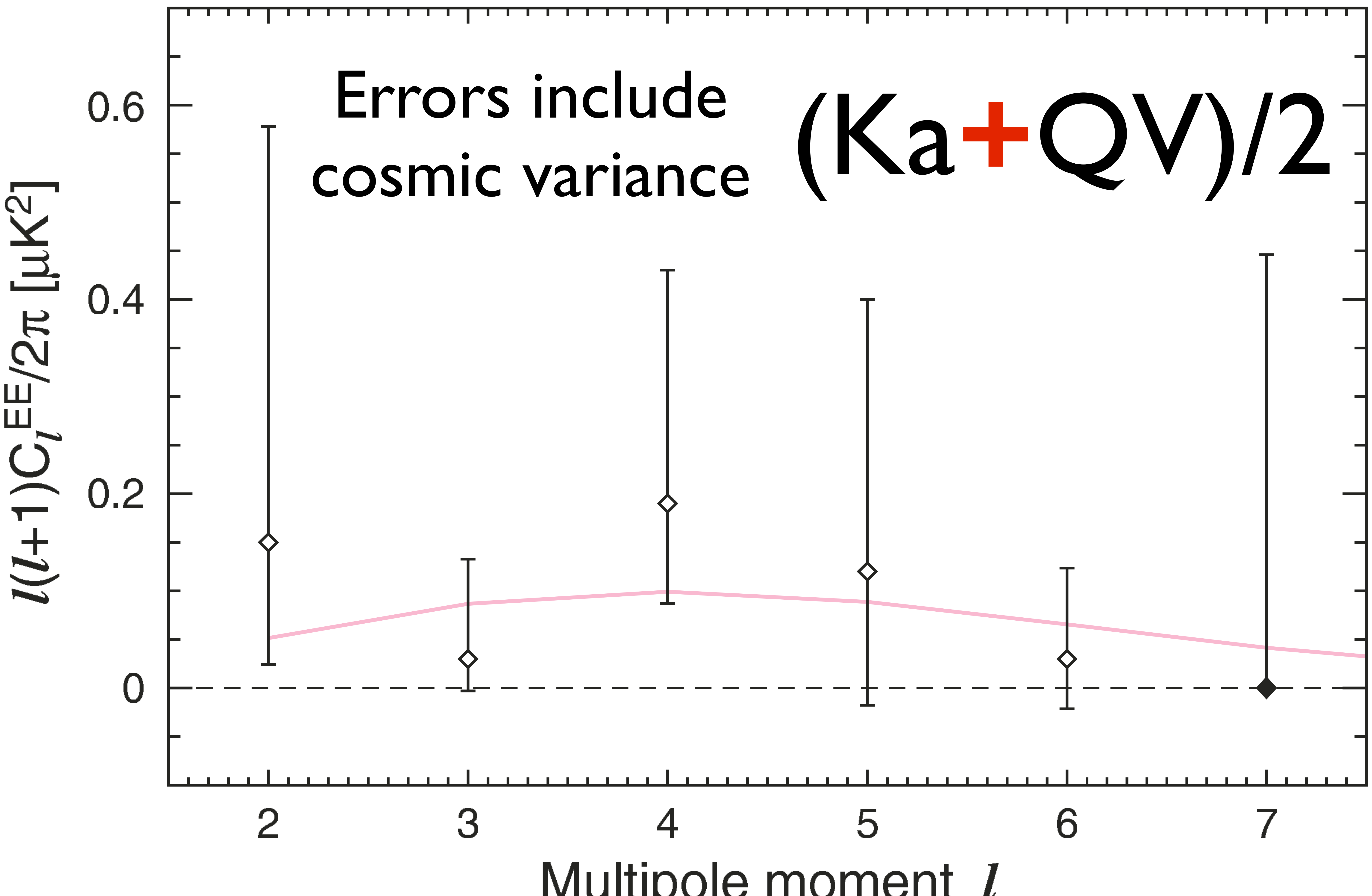
Nolta et al.



Note consistency around the 3rd-peak region

Nolta et al.

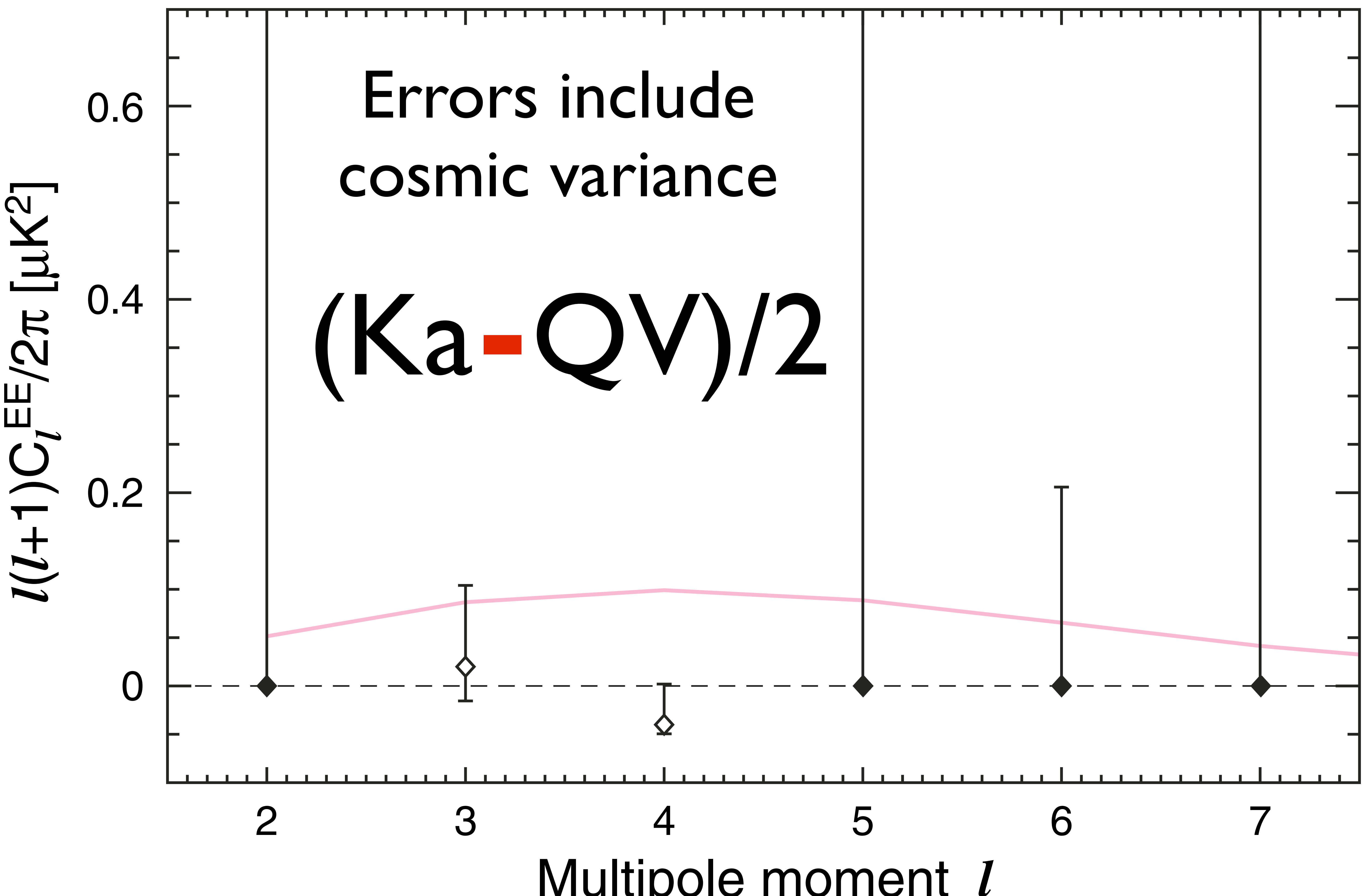
Adding Polarization in Ka: OK? Look at C_l^{EE}



Black Symbols are upper limits

Hinshaw et al.

Adding Polarization in Ka: Passed the Null Test

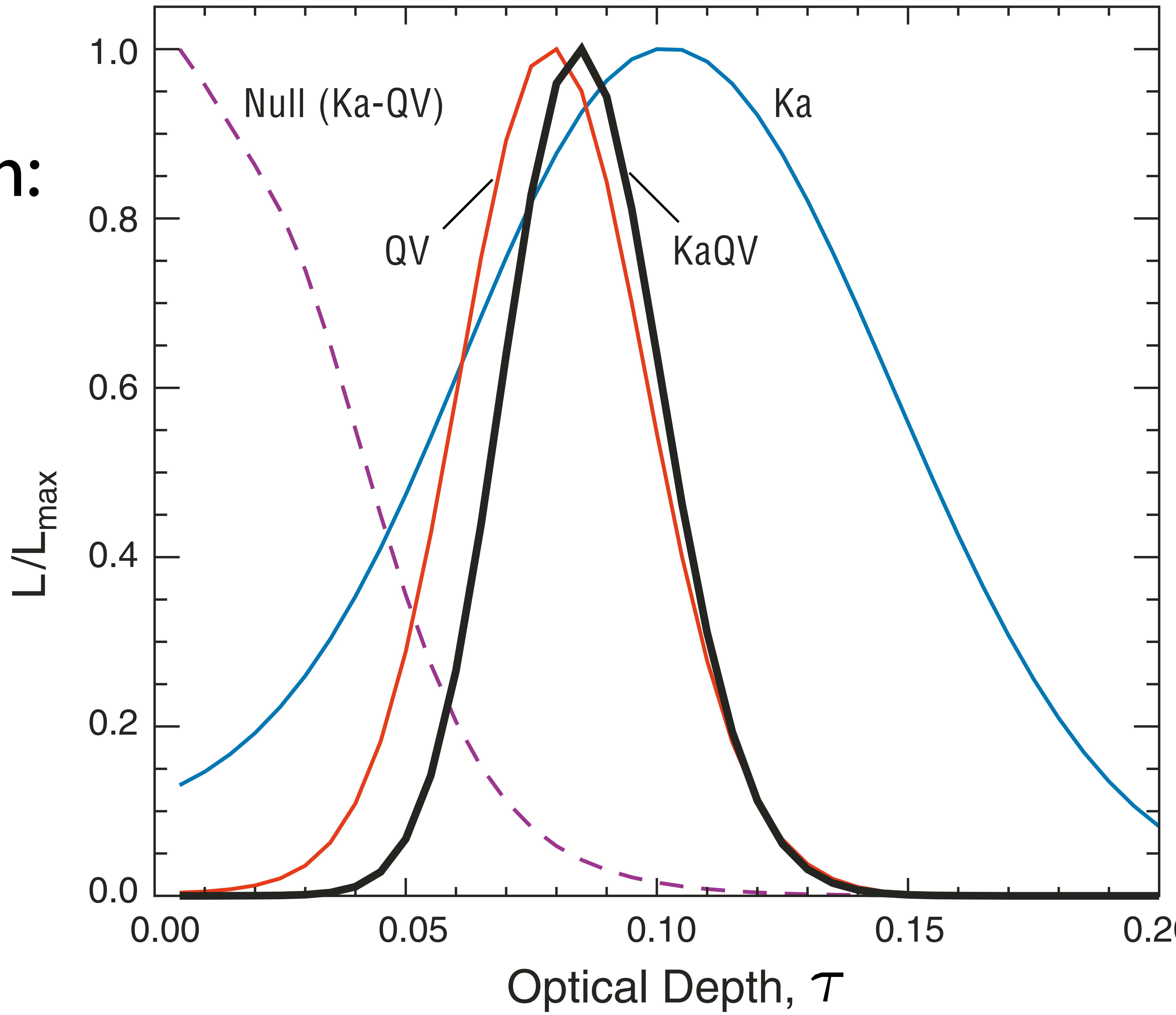


Black Symbols are upper limits

Hinshaw et al.

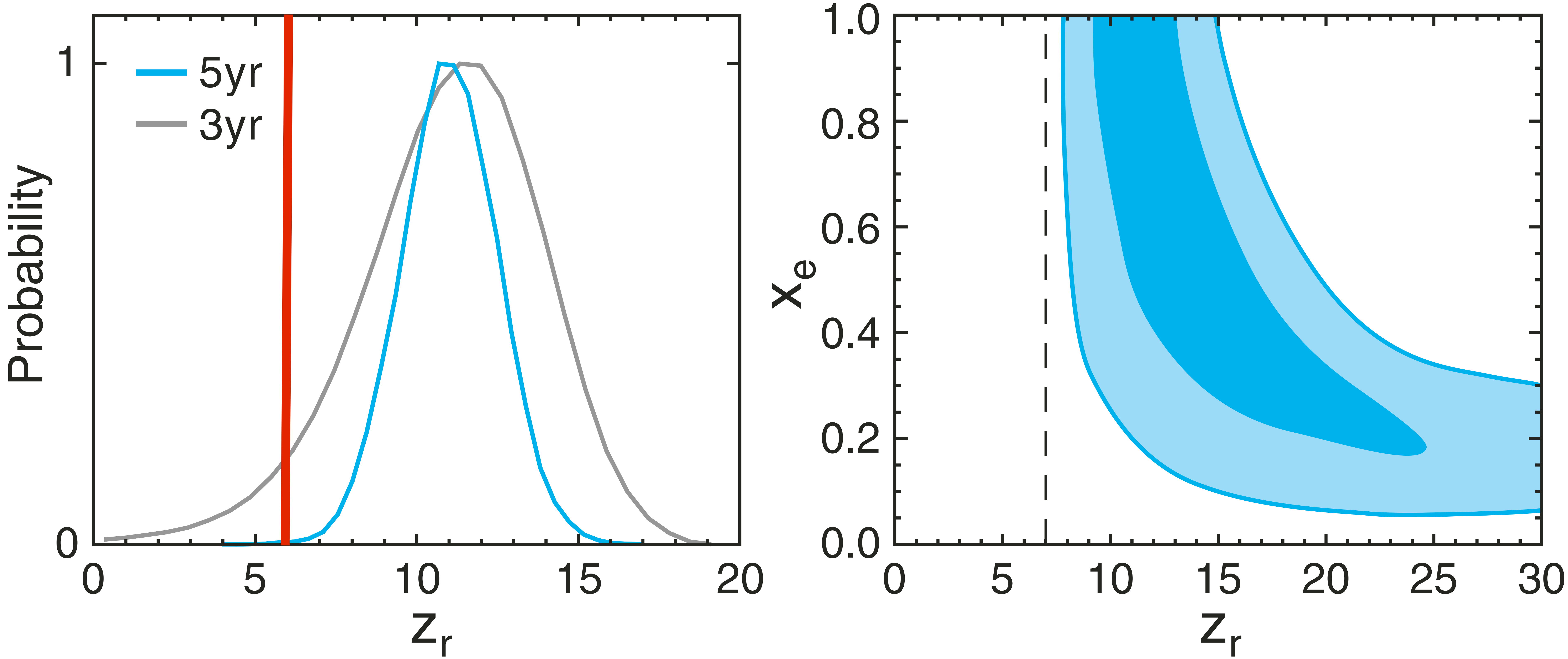
Adding Polarization in Ka: Passed the Null Test!!

- Optical Depth measured from the EE power spectrum:
- Tau(5yr)=0.087 +/- 0.017
- Tau(3yr)=0.089 +/- 0.030 (Page et al.; QV only)
- 3-sigma to 5-sigma!
- Tau form the null map (Ka-QV) is consistent with zero



z_{reion}=6 Excluded

Dunkley et al.



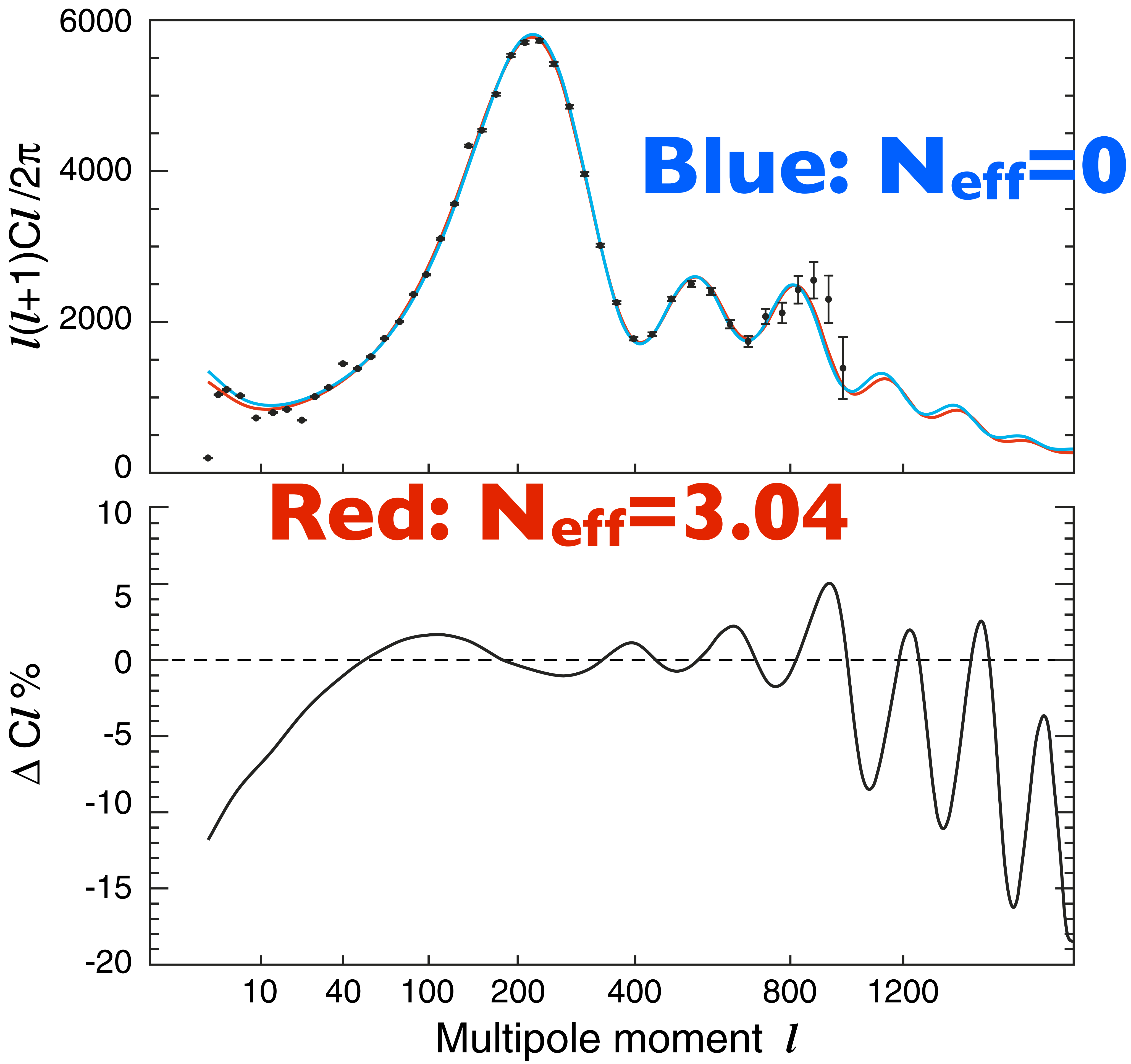
- Assuming instantaneous reionization from x_e=0 to x_e=1 at z_{reion}, we find **z_{reion}=11.0 +/- 1.4** (68 % CL).
- The reionization was not an instantaneous process at z~6. (The 3-sigma lower bound is z_{reion}>6.7.)

Cosmic Neutrino Background

- How do neutrinos affect CMB?
  - They change the radiation-to-matter ratio. The larger the number of neutrino species is, the later the matter-radiation equality, z_{equality}, becomes.
    - So, this effect is degenerate with the 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 in WMAP

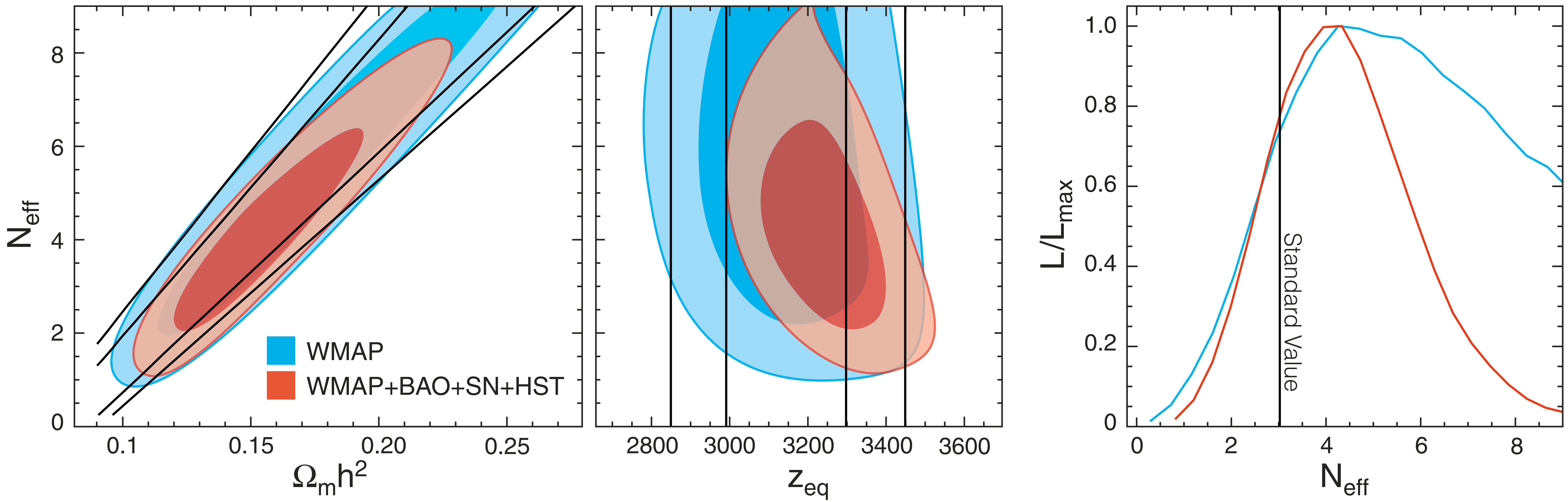


$\Delta\chi^2$=8.2 -> 99.5% CL

- 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.

It's not $z_{equality}$!



- The number of neutrino species is massively degenerate with $\Omega_m h^2$, which simply traces $z_{equality}$=constant.
- But, the contours close near N_{eff}~1, in contradiction to the prediction from $z_{equality}$=constant.

Komatsu et al.

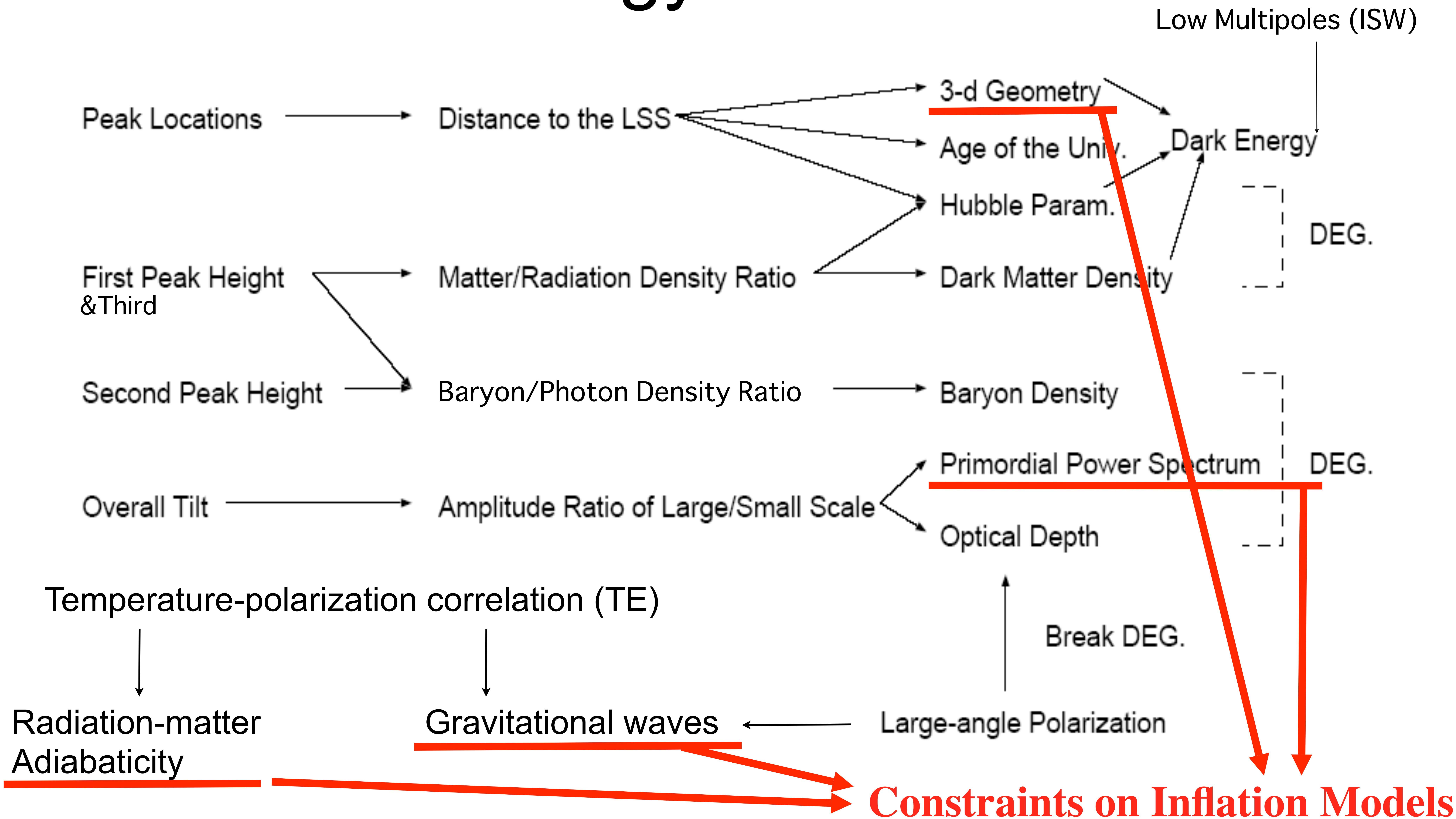
Cosmic/Laboratory Consistency

- 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

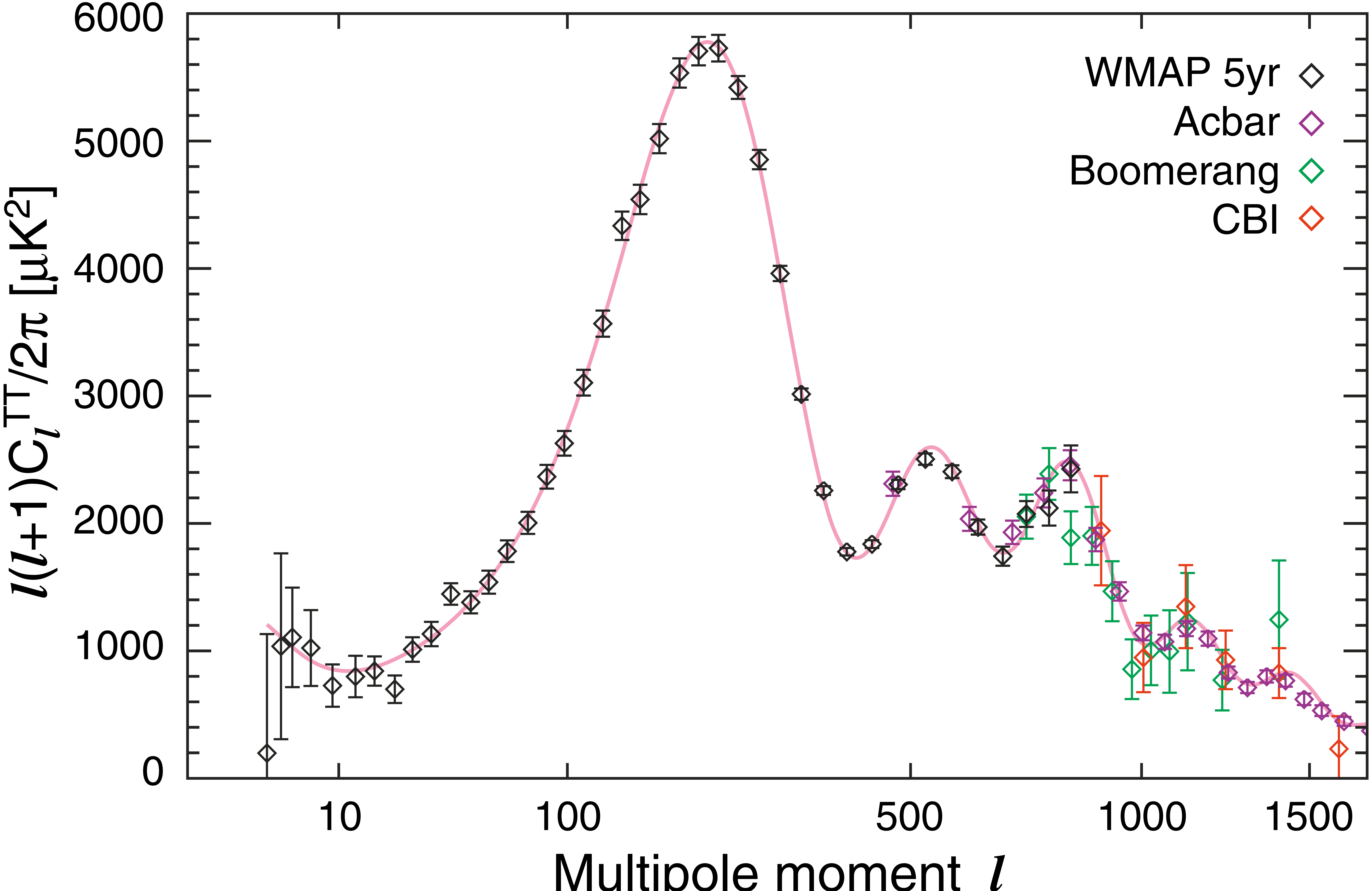
Testing Inflation

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

CMB to Cosmology to Inflation

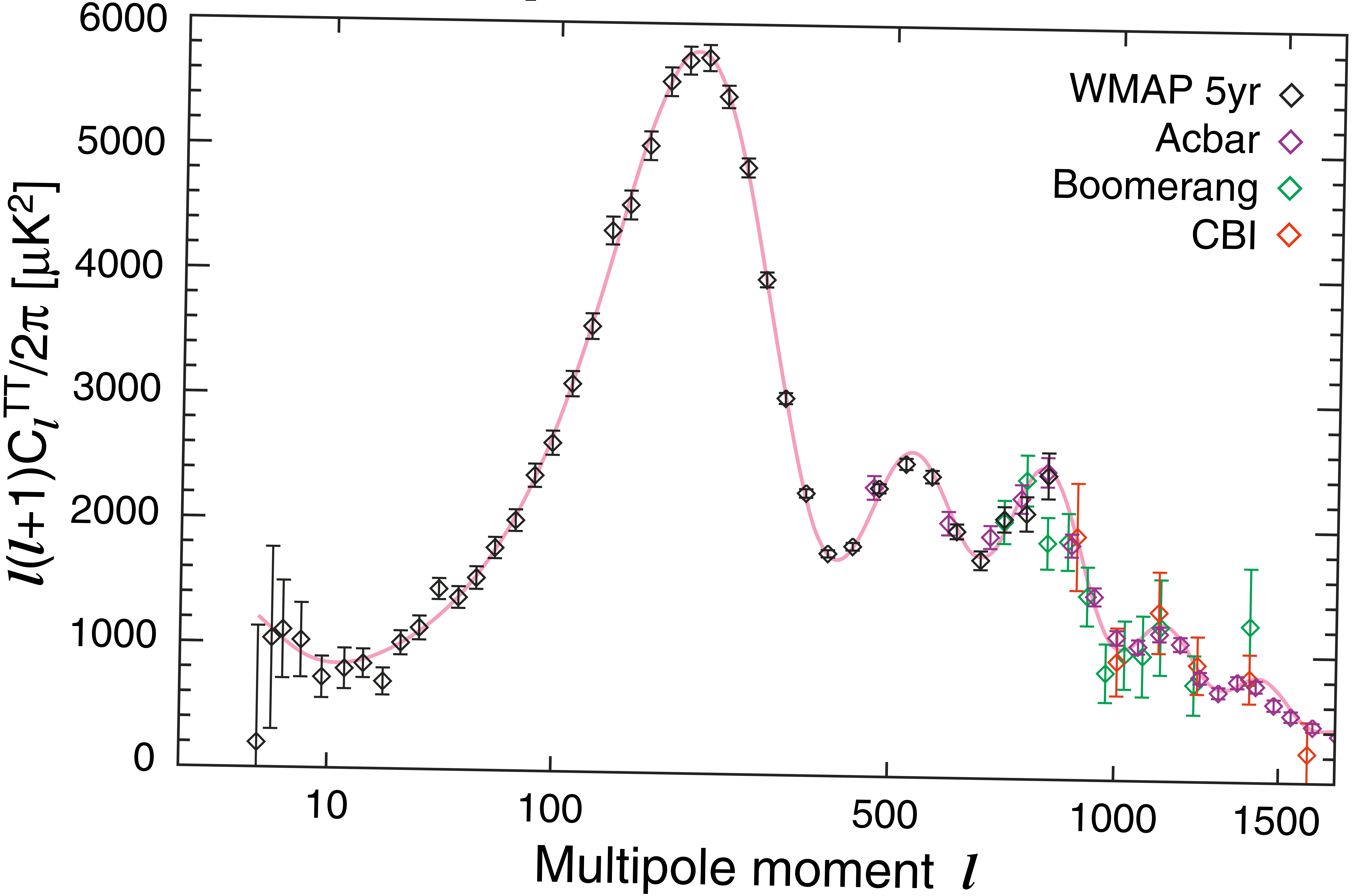


Tilting

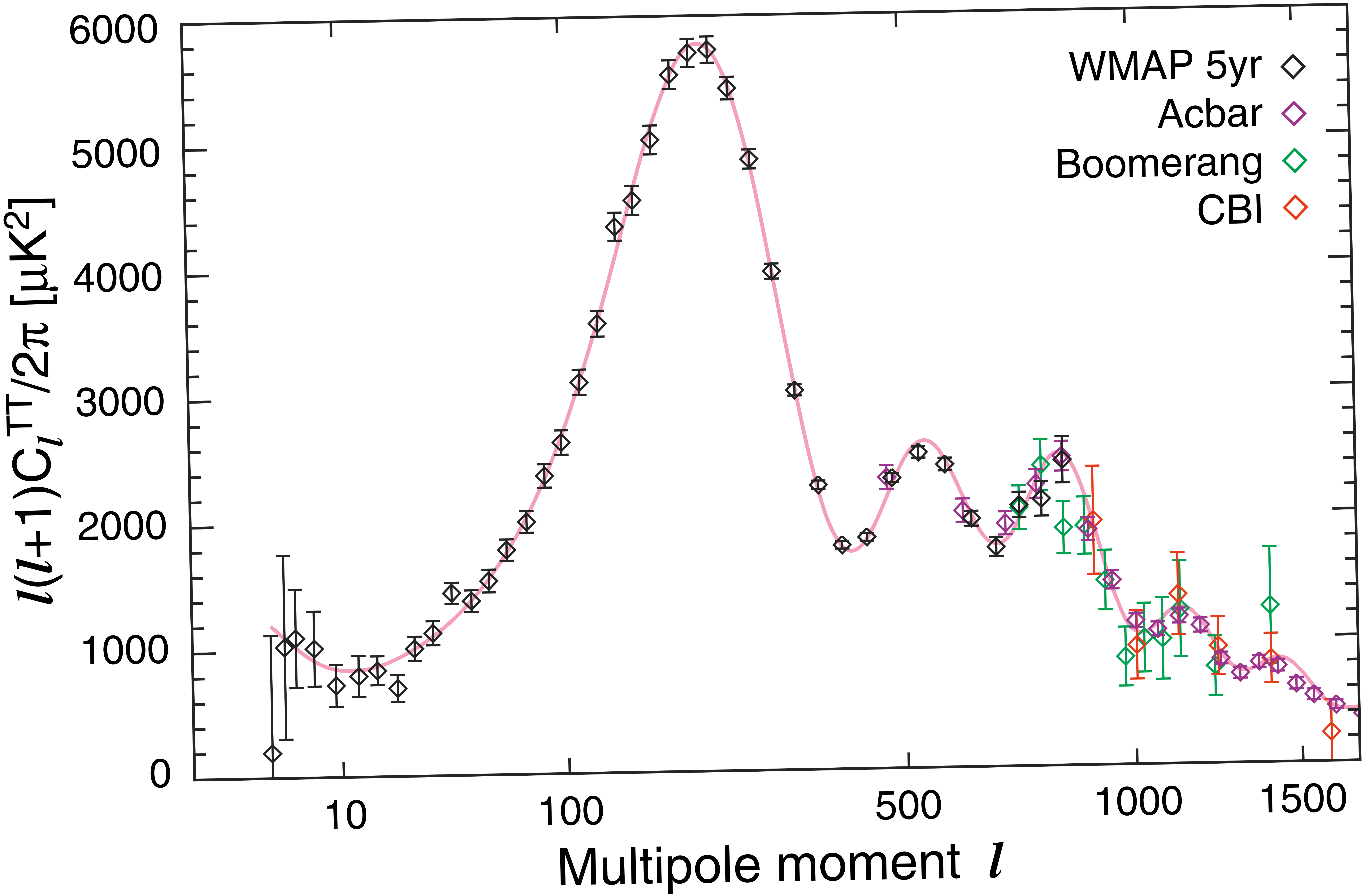


WMAP 5yr
Acbar
Boomerang
CBI
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
Multipole moment l
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500

“Red” Spectrum: $n_s < 1$

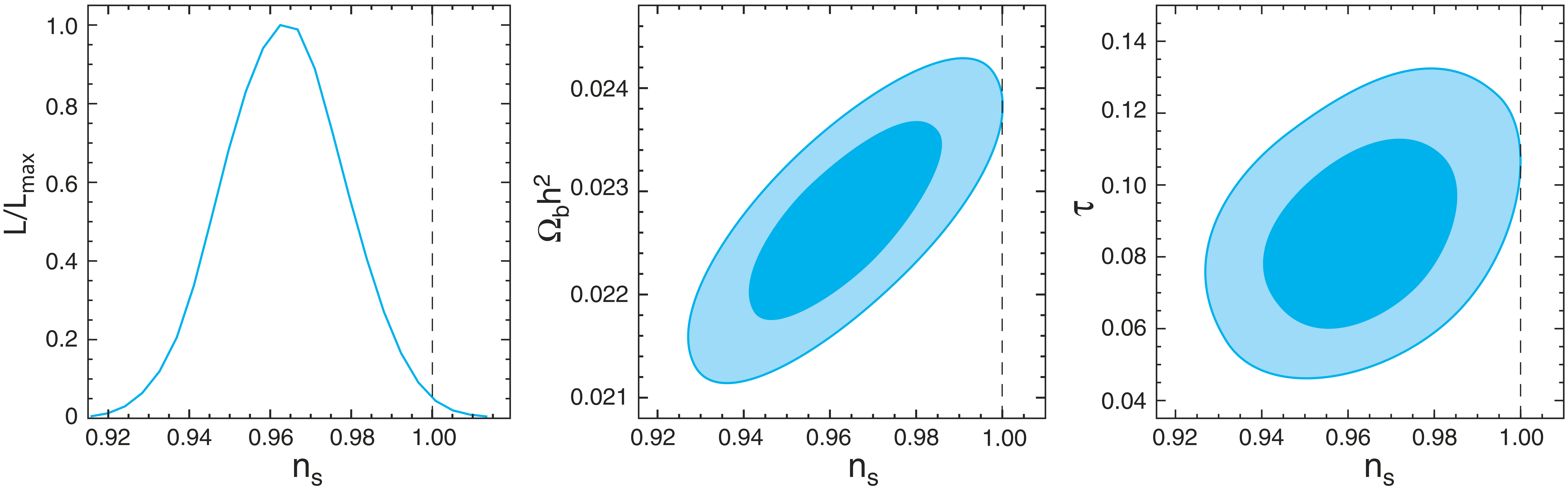


“Blue” Spectrum: $n_s > 1$



Tau: (Once) Important for n_s

Komatsu et al.



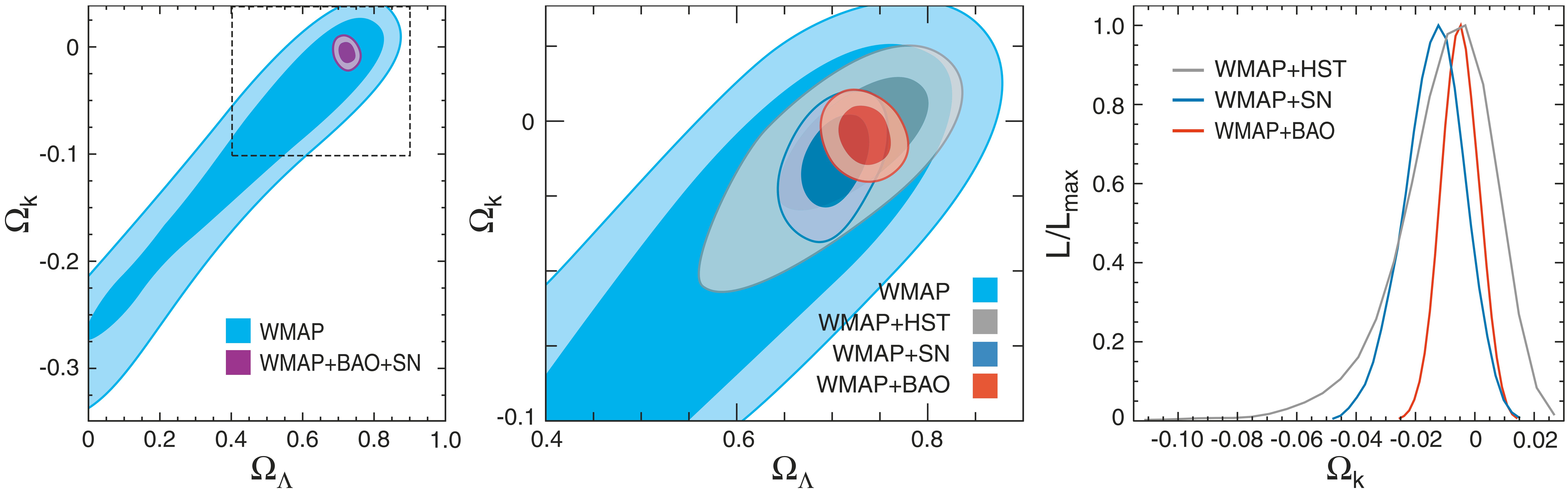
- With the 5-year determination of the optical depth (tau), the most dominant source of degeneracy is now $\Omega_b h^2$, rather than tau.
- WMAP-alone: n_s=0.963 (+0.014) (-0.015) (Dunkley et al.)
  - 2.5-sigma away from n_s=1

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 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

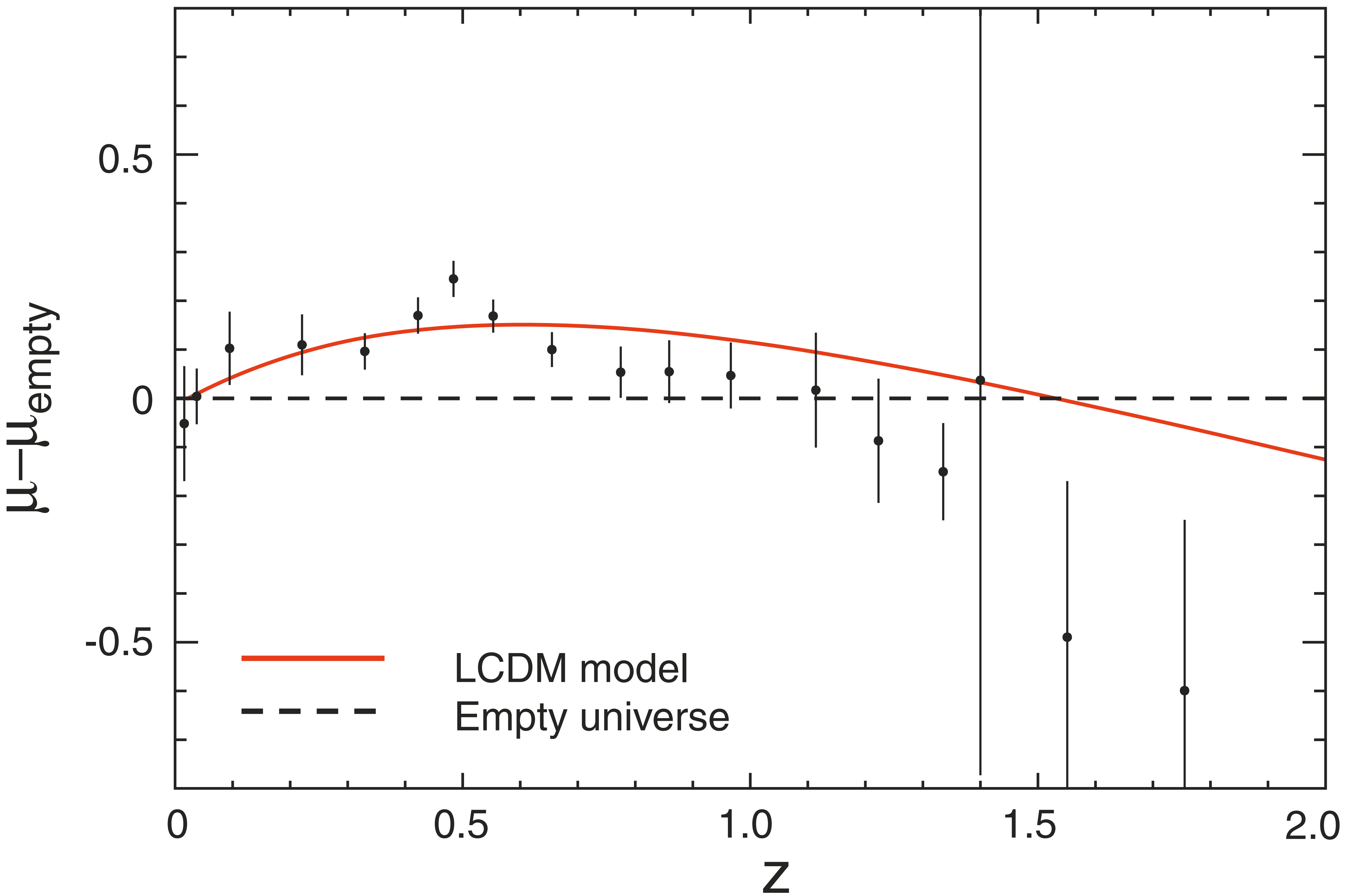
Komatsu et al.



- 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

Dunkley et al.

Type Ia Supernova (SN) Data

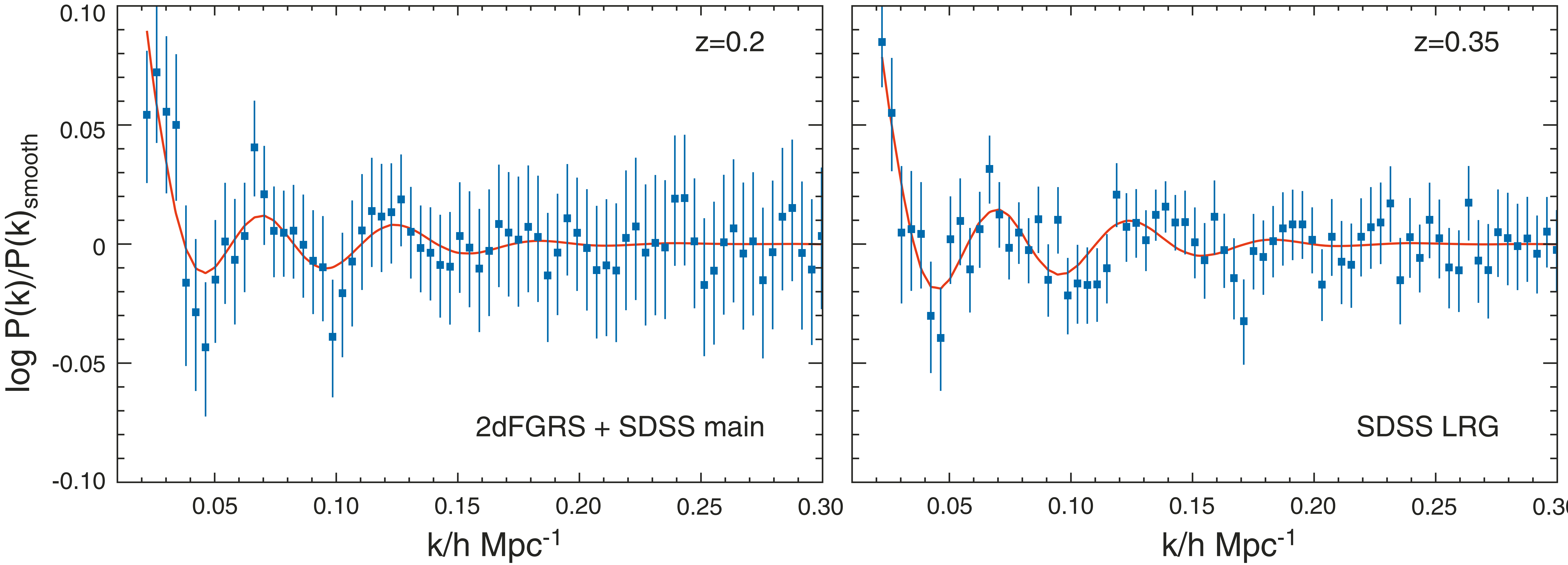


From these measurements, we get the **relative** luminosity distances between Type Ia SNe. Since we marginalize over the absolute magnitude, the current SN data are insensitive to the absolute distances.

- 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

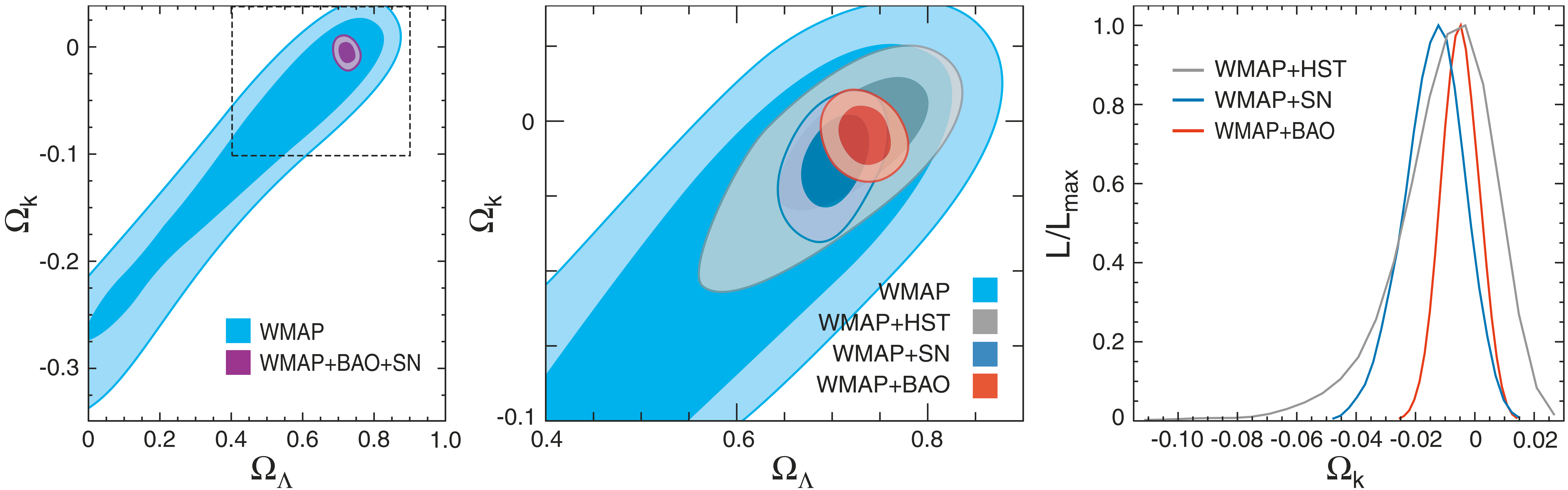
Dunkley et al.



- 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.

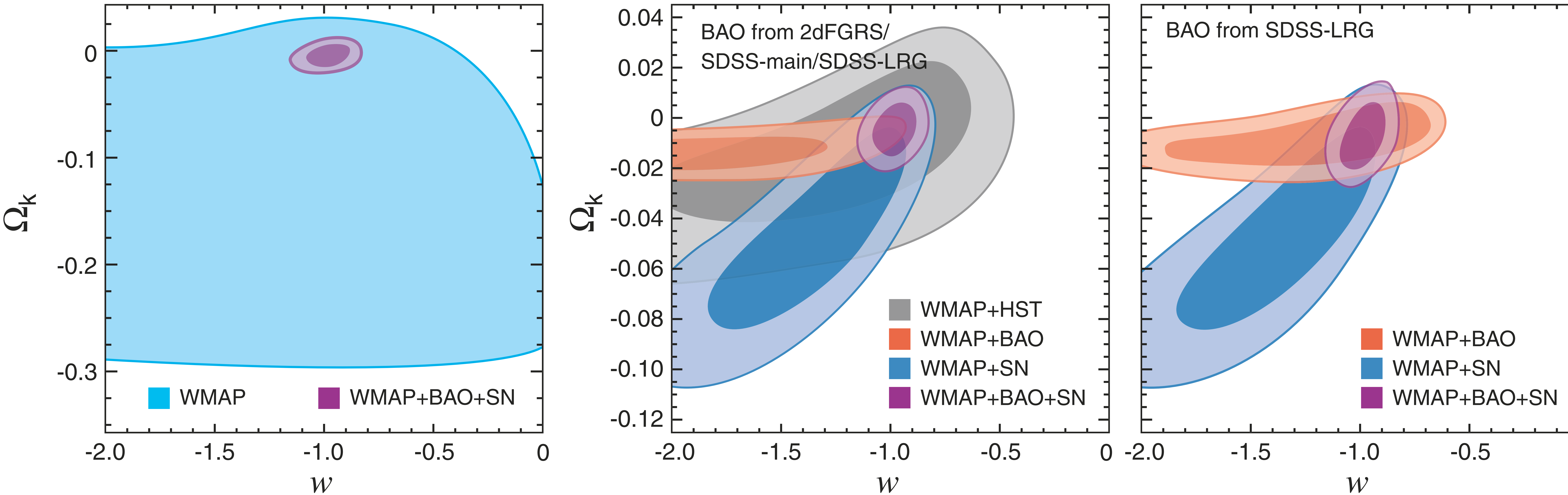
As a result..



- **$-0.0181 < \Omega_k < 0.0071$** (95% CL) for w=-1
- The constraint driven mostly by WMAP+BAO
- BAOs are more powerful than SNe in pinning down curvature, as they are **absolute** distance indicators.

What if w/=-1...

Komatsu et al.



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

Komatsu et al.

Fun Numbers to Quote...

- The curvature radius of the universe is given, by definition, 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 observable universe is pretty flat! (Fun to teach this in class)

Komatsu et al.

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

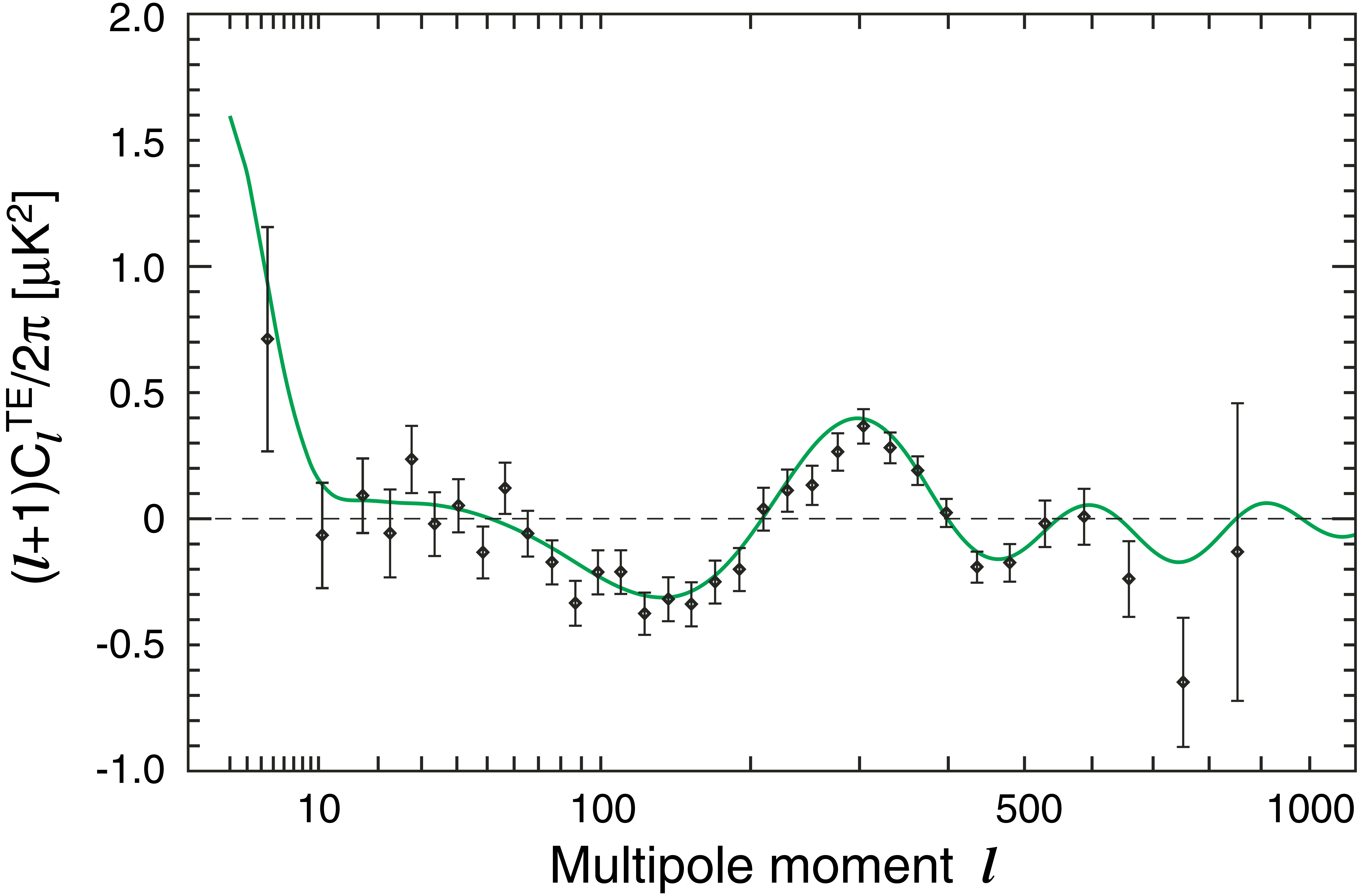
Komatsu et al.

Check List #2: 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.

Entropy and curvature perturbations

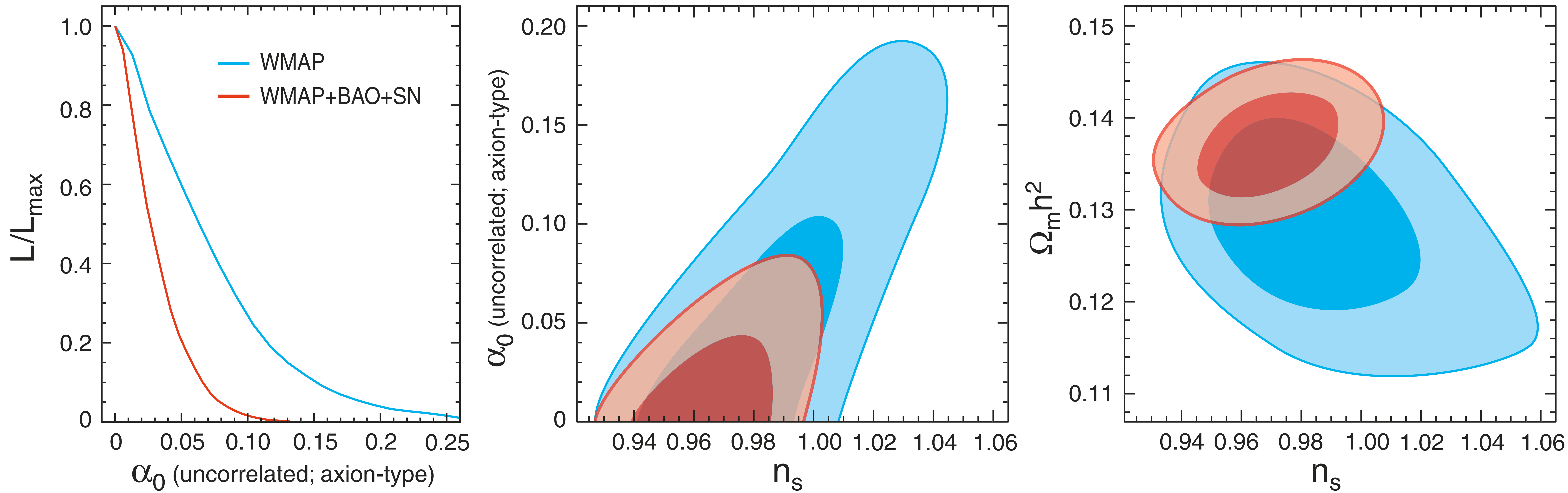
- Usually, we use the entropy perturbations and curvature perturbations when we talk about adiabaticity.
  - (Entropy Pert.) = $3\delta\rho_{radiation}/(4\rho_{radiation}) - \delta\rho_{matter}/\rho_{matter}$
  - (Curvature Pert.) = $\delta\rho_{matter}/(3\rho_{matter}) = \delta\rho_{radiation}/(4\rho_{radiation})$
- Let's take the ratio, square it, and call it α:
  - $\alpha = (\text{Entropy})^2/(\text{Curvature})^2 = 9\delta_{adi}^2$
  - This parameter, α, has often been used in the literature.

Two Scenarios

- To make the argument concrete, we take two concrete examples for entropy perturbations.
- (i) "***Axion Type***" Entropy perturbations and curvature perturbations are **uncorrelated**.
- (ii) "***Curvaton Type***" Entropy perturbations and curvature perturbations are **anti-correlated**. (or correlated, depending on the sign convention)
- In both scenarios, the entropy perturbation raises the temperature power spectrum at l<100
  - Therefore, *both contributions are degenerate with n_s.* How do we break the degeneracy? BAO&SN.

Axion Type

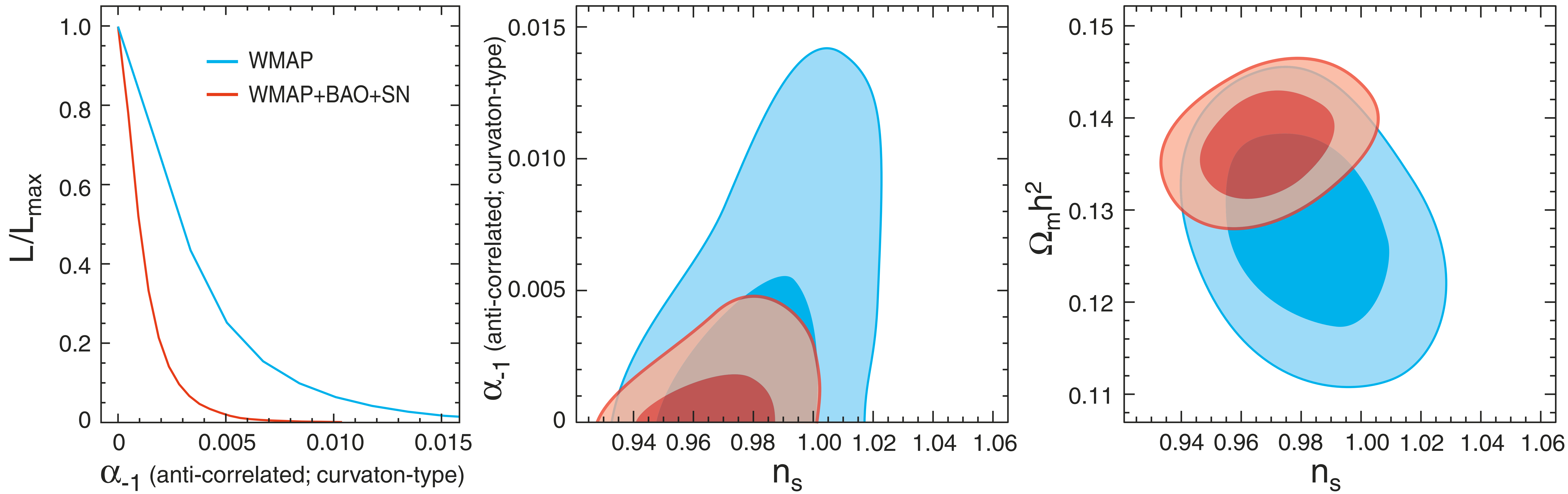
Komatsu et al.



- $\alpha_{axion} < 0.16$ [WMAP-only; 95% CL]
- $\alpha_{axion} < 0.067$ [WMAP+BAO+SN; 95% CL]
- CMB and axion-type dark matter are adiabatic to **8.6%**

Curvaton Type

Komatsu et al.



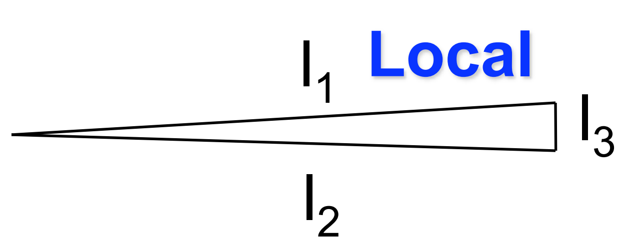
- $\alpha_{curvaton} < 0.011$ [WMAP-only; 95% CL]
- $\alpha_{curvaton} < 0.0037$ [WMAP+BAO+SN; 95% CL]
- CMB and axion-type dark matter are adiabatic to **2.0%**

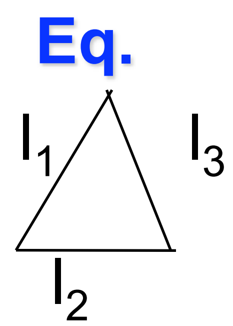
Check list #3: Gaussianity

- 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_{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**!

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 $\Omega_b h^2$

Dunkley et al.; Komatsu et al.

Running Index?

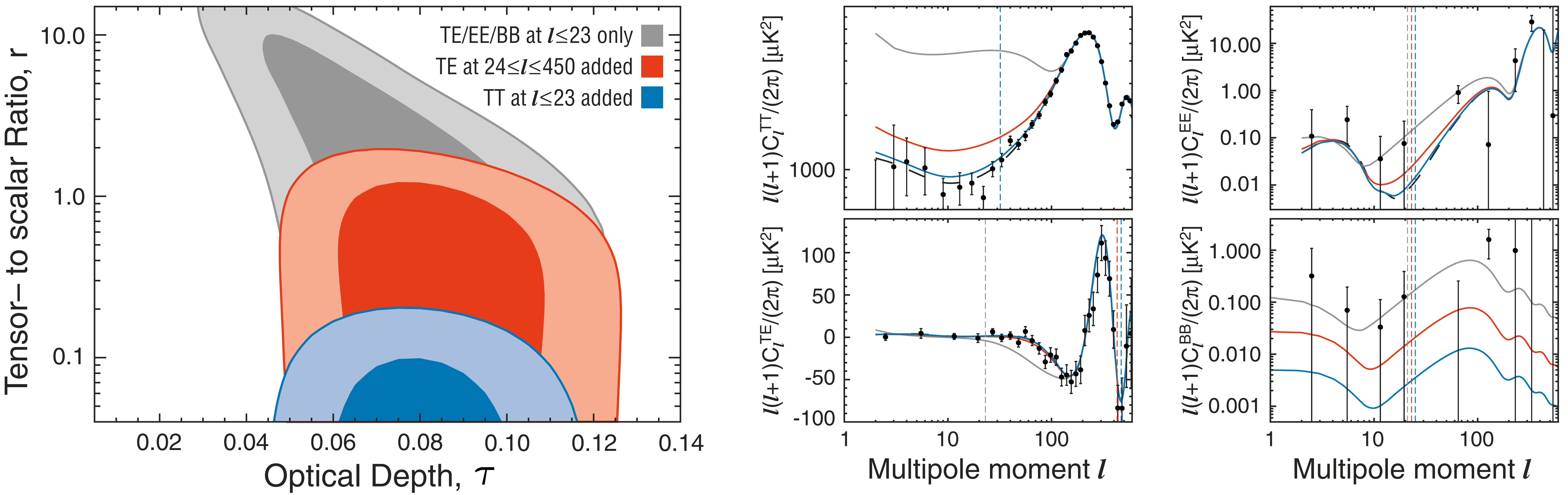
- No significant running index is observed.
  - WMAP-only: $dn_s/d\ln k$ = -0.037 +/- 0.028
  - WMAP+BAO+SN: $dn_s/d\ln k$ = -0.032 (+0.021) (-0.020)
- **A power-law spectrum is a good fit.**
- Note that $dn_s/d\ln k$ ~ O(0.001) is expected from simple inflation models (like $m^2\varphi^2$), but we are not there yet.

Check List #5: Gravitational Waves

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

Pedagogical Explanation

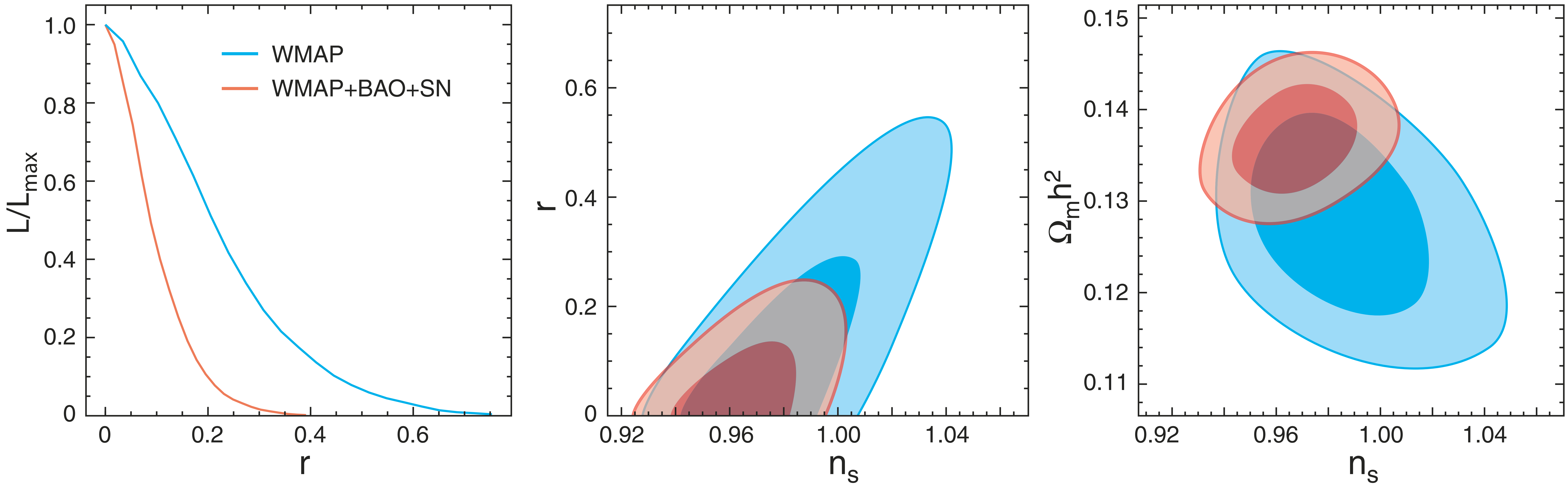
Komatsu et al.



- 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)

Komatsu et al.

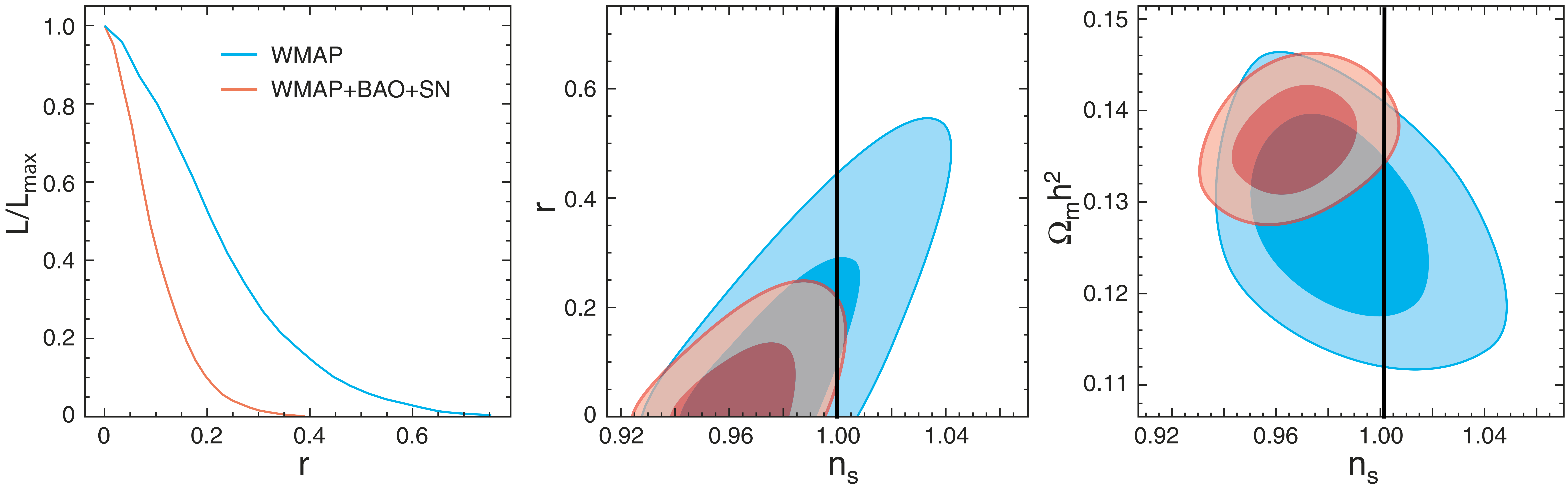
Real Life: Killer Degeneracy



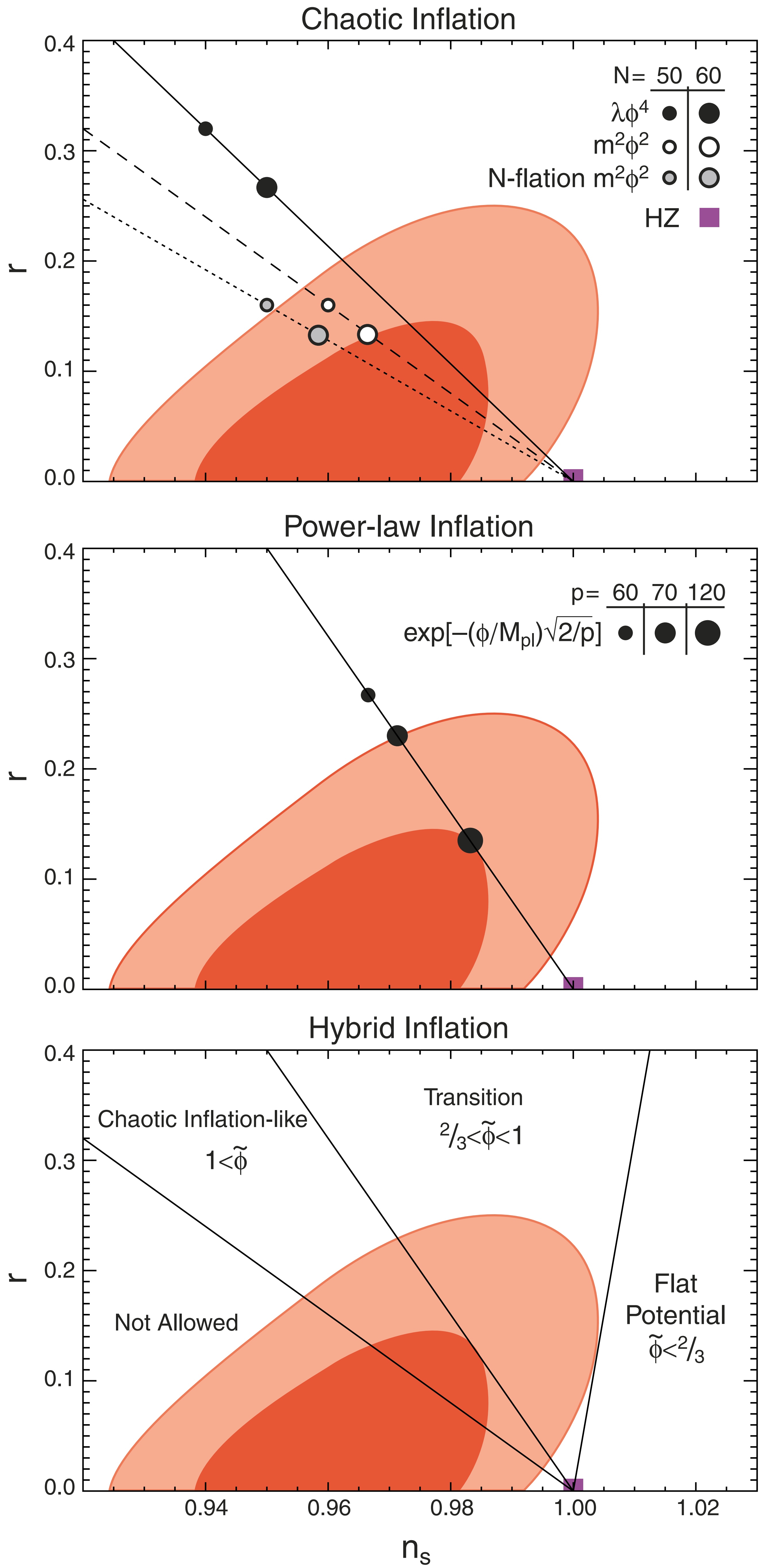
- Since the limit on r relies on the low-l temperature, it is strongly degenerate with n_s.
- The degeneracy can be broken partially by BAO&SN
  - r<0.43 (WMAP-only) -> **r<0.20** (WMAP+BAO+SN)

Komatsu et al.

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.**



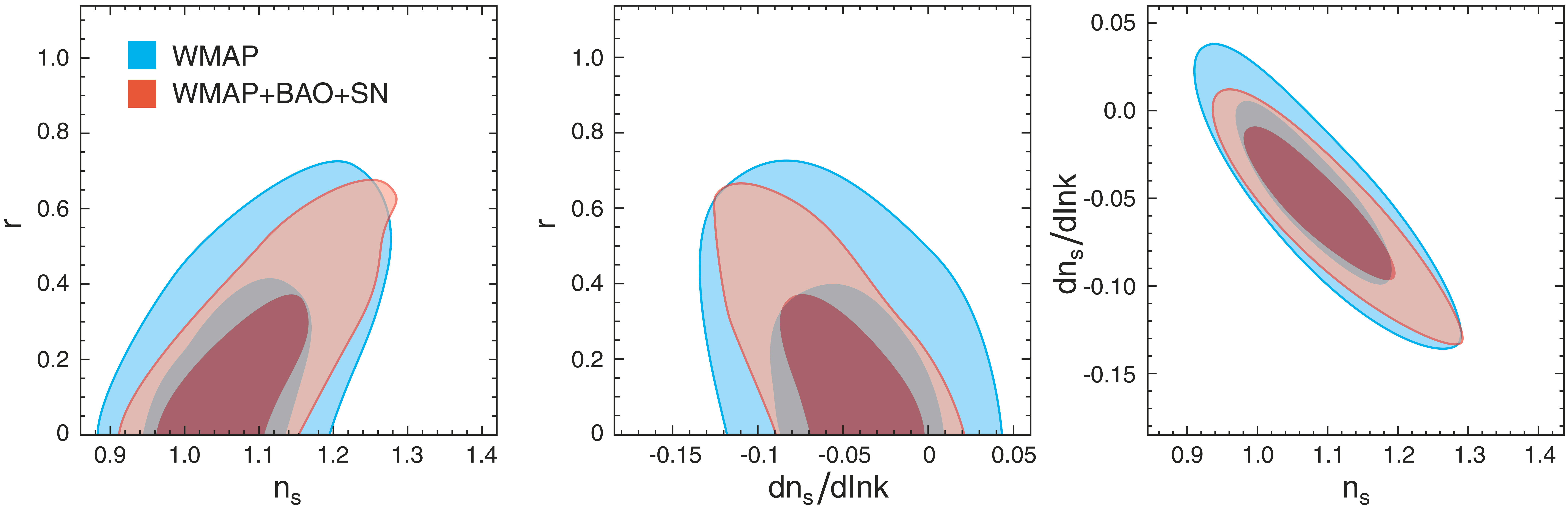
Komatsu et al.

Lowering a "Limbo Bar"

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

Komatsu et al.

How About Putting Everything (n_s, r, $dn_s/d\ln k$) In?



- Then of course, constraints are weakened... BAO&SN do not help much anymore.

Komatsu et al.

Grading Inflation

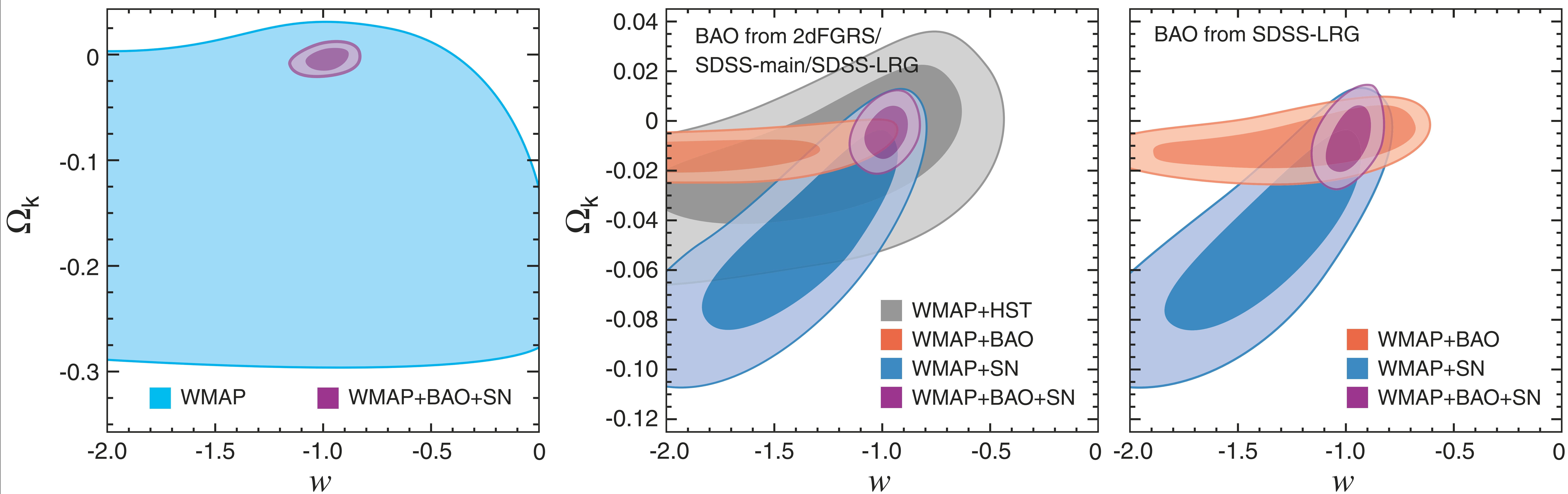
- Flatness: $-0.0175 < \Omega_k < 0.0085$ (not assuming w=-1!)
- Non-adiabaticity: <8.6% (axion DM); <2.0% (curvaton DM)
- Non-Gaussianity: -9 < Local < 111; -151 < Equilateral < 253
- Tilt (for r=0): n_s=0.960 (+0.014) (-0.013) [68% CL]
- Running (for r=0): $-0.0728 < dn_s/d\ln k < 0.0087$
- Gravitational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

What else in the interpretation paper...

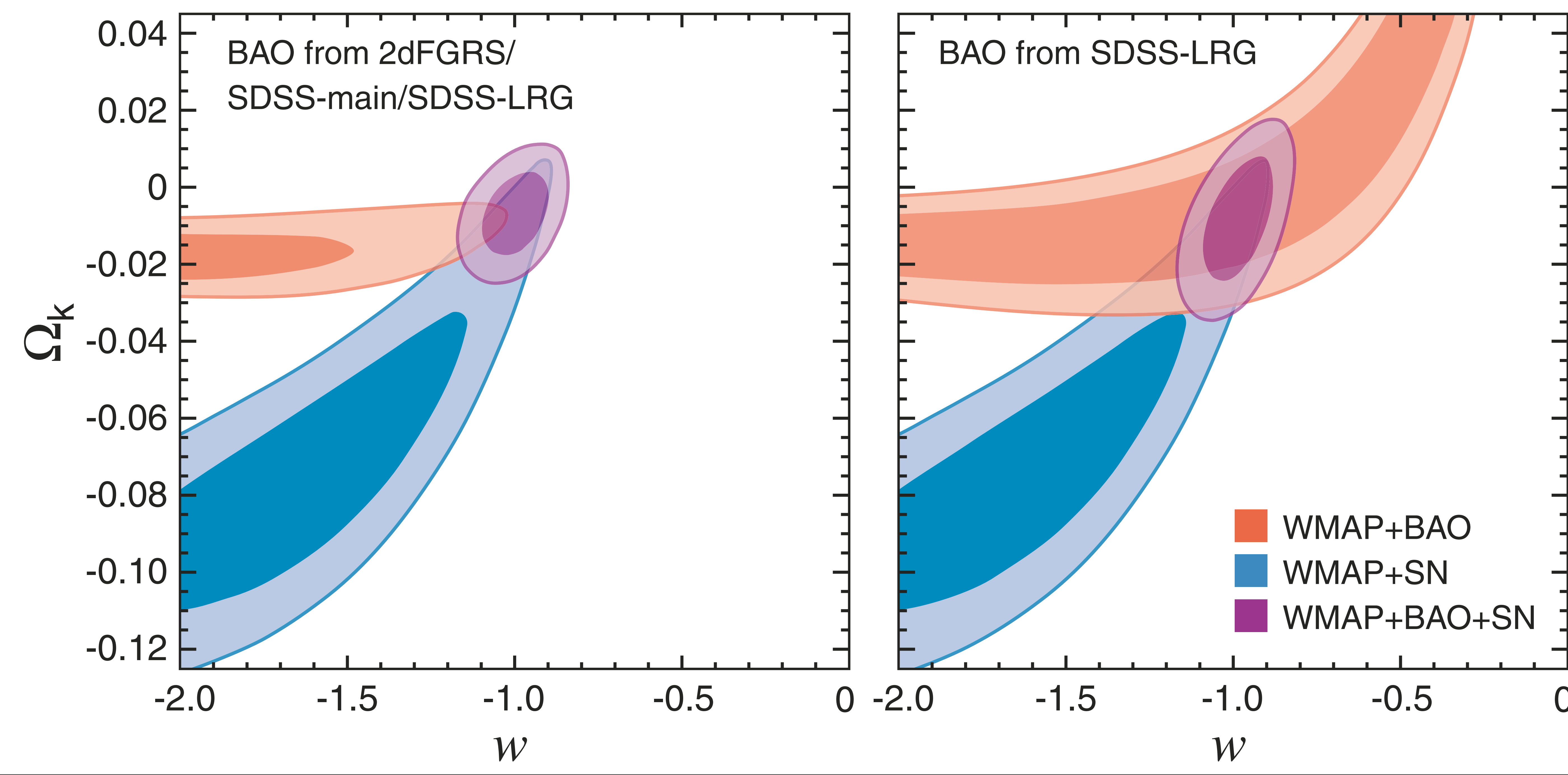
- Basically, we tried everything we could do (*in time before the release*) to find deviations from the simple 6-parameter ΛCDM.
- We failed to find any. A flat ΛCDM is annoying, but it is a good fit to the data!
- The interpretation paper is a journal on the pains-taking quest to look for new physics in the WMAP data. While we failed to find any, we report on quantitative, stringent limits on the deviations from the simple ΛCDM.

Dark Energy From Distance Information Alone

- We provide a set of "WMAP distance priors" for testing various dark energy models.
  - Redshift of decoupling, z_*=1090.04 (Err=0.93)
  - Acoustic scale, $l_A=\pi d_A(z_*)/r_s(z_*)$=302.10 (Err=0.86)
  - Shift parameter, $R=\mathrm{sqrt}(\Omega_m H_0^2) d_A(z_*)$=1.710 (Err=0.019)
  - Correlations between these three quantities are also provided.



- Top
  - Full WMAP Data
- Bottom
  - WMAP Distance Priors



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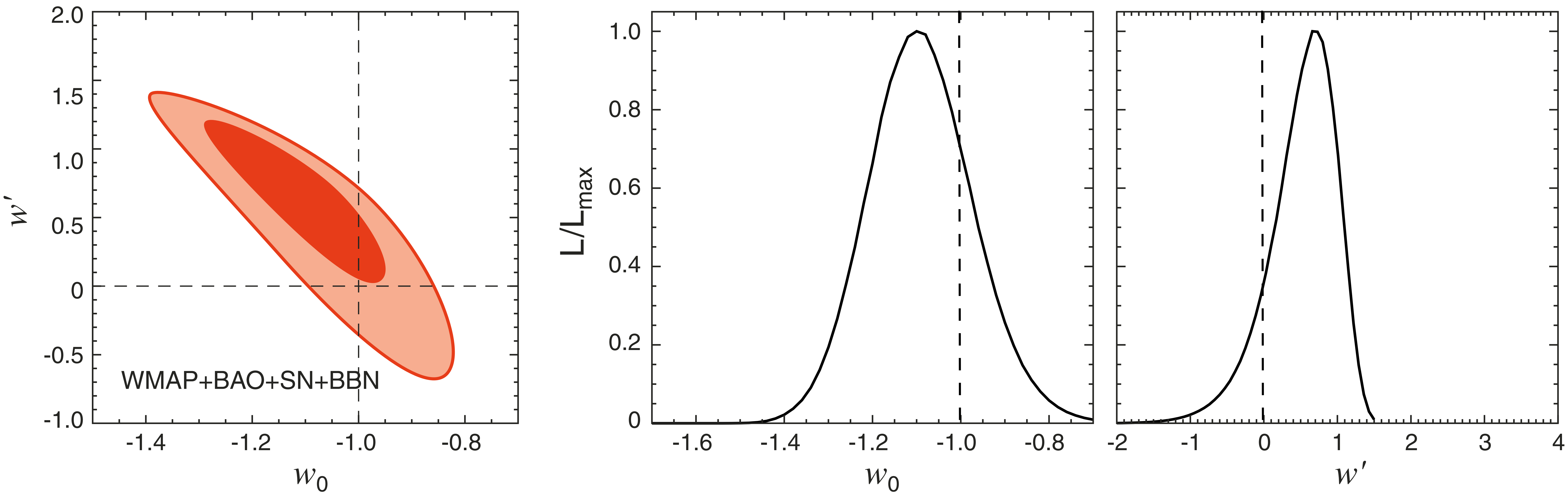
Application: $w(z)=w_0+w'z/(1+z)$



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

Probing Parity Violation

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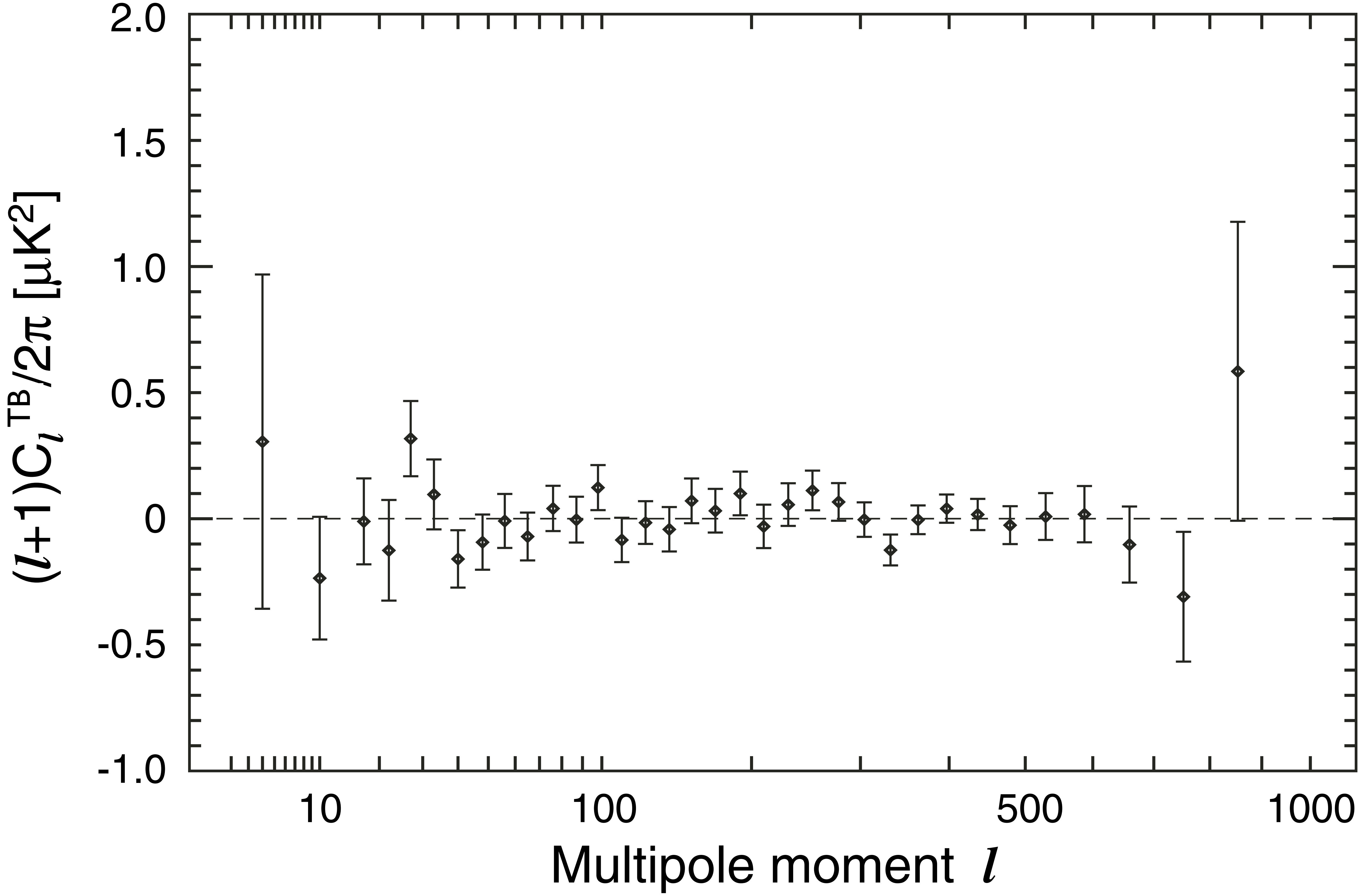

- Parity violating interactions that rotate the polarization angle of CMB can produce TB and EB correlations.

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

E -> B

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

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

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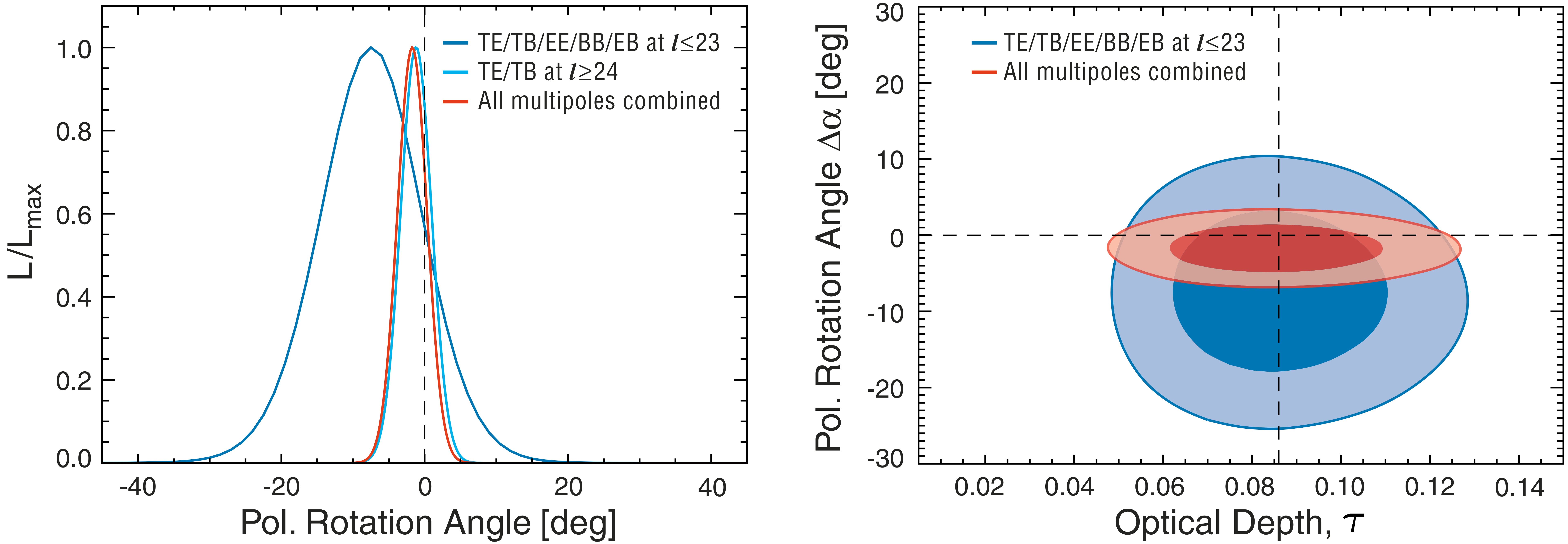

- **$\Delta\alpha$=(-1.7 +/- 2.1) degrees (68% CL)**
- Comparable to the astrophysical constraint from quasars and radio galaxies
  - $\Delta\alpha$=(-0.6 +/- 1.5) degrees (68% CL) (Carroll 1998)
- But, note the difference in path length!

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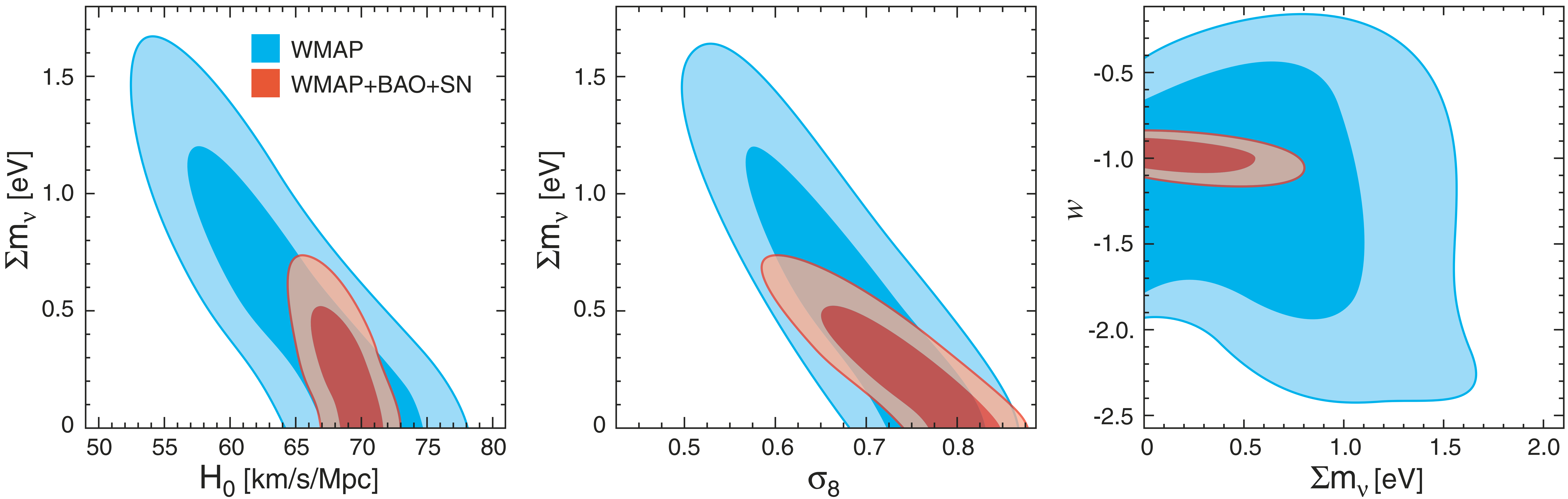
Neutrino Mass



- 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.

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After the quest in the dark forest...

TABLE 2
SUMMARY OF THE 95% CONFIDENCE LIMITS ON DEVIATIONS FROM THE SIMPLE (FLAT, GAUSSIAN, ADIABATIC, POWER-LAW) ΛCDM MODEL

Section	Name	Type	*WMAP* 5-year	*WMAP*+BAO+SN
§ 3.2	Gravitational Wave[a]	No Running Ind.	$r < 0.43^b$	$r < 0.20$
§ 3.1.3	Running Index	No Grav. Wave	$-0.090 < dn_s/d\ln k < 0.019^c$	$-0.0728 < dn_s/d\ln k < 0.0087$
§ 3.4	Curvature[d]		$-0.063 < \Omega_k < 0.017^e$	$-0.0175 < \Omega_k < 0.0085^f$
	Curvature Radius[g]	Positive Curv.	$R_{\rm curv} > 12\ h^{-1}$Gpc	$R_{\rm curv} > 23\ h^{-1}$Gpc
		Negative Curv.	$R_{\rm curv} > 23\ h^{-1}$Gpc	$R_{\rm curv} > 33\ h^{-1}$Gpc
§ 3.5	Gaussianity	Local	$-9 < f_{NL}^{\rm local} < 111^h$	N/A
		Equilateral	$-151 < f_{NL}^{\rm equil} < 253^i$	N/A
§ 3.6	Adiabaticity	Axion	$\alpha_0 < 0.16^j$	$\alpha_0 < 0.067^k$
		Curvaton	$\alpha_{-1} < 0.011^l$	$\alpha_{-1} < 0.0037^m$
§ 4	Parity Violation	Chern-Simons[n]	$-5.9^\circ < \Delta\alpha < 2.4^\circ$	N/A
§ 5	Dark Energy	Constant w^o	$-1.37 < 1 + w < 0.32^p$	$-0.11 < 1 + w < 0.14$
		Evolving $w(z)^q$	N/A	$-0.38 < 1 + w_0 < 0.14^r$
§ 6.1	Neutrino Mass[s]		$\sum m_\nu < 1.3$ eV^t	$\sum m_\nu < 0.61$ eV^u
§ 6.2	Neutrino Species		$N_{\rm eff} > 2.3^v$	$N_{\rm eff} = 4.4 \pm 1.5^w$ (68%)

- ...here is a report, captain...

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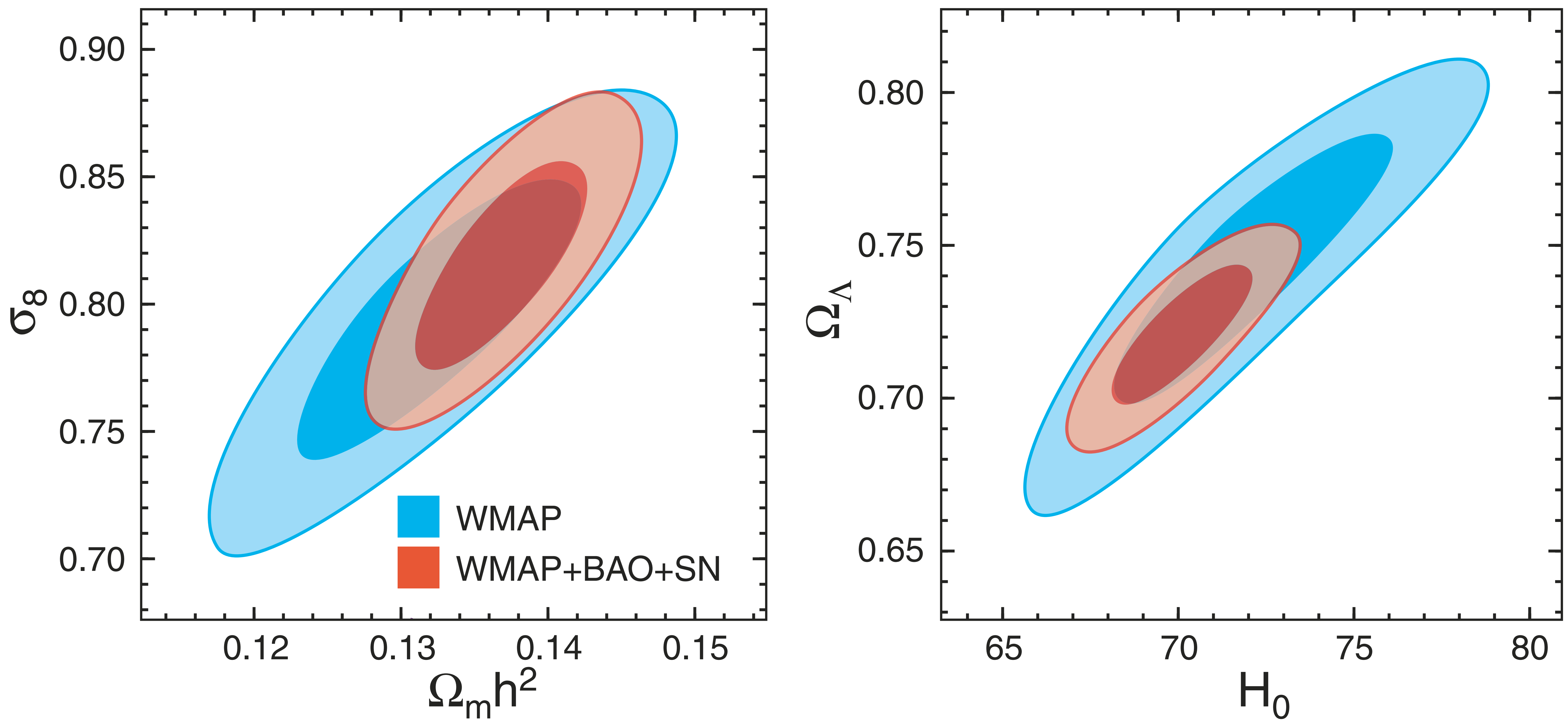
What About ΛCDM?



- BAO+SN are very powerful in reducing the uncertainty in several ΛCDM parameters.
- Any parameters related to $\Omega_m h^2$ & H_0 have improved significantly.

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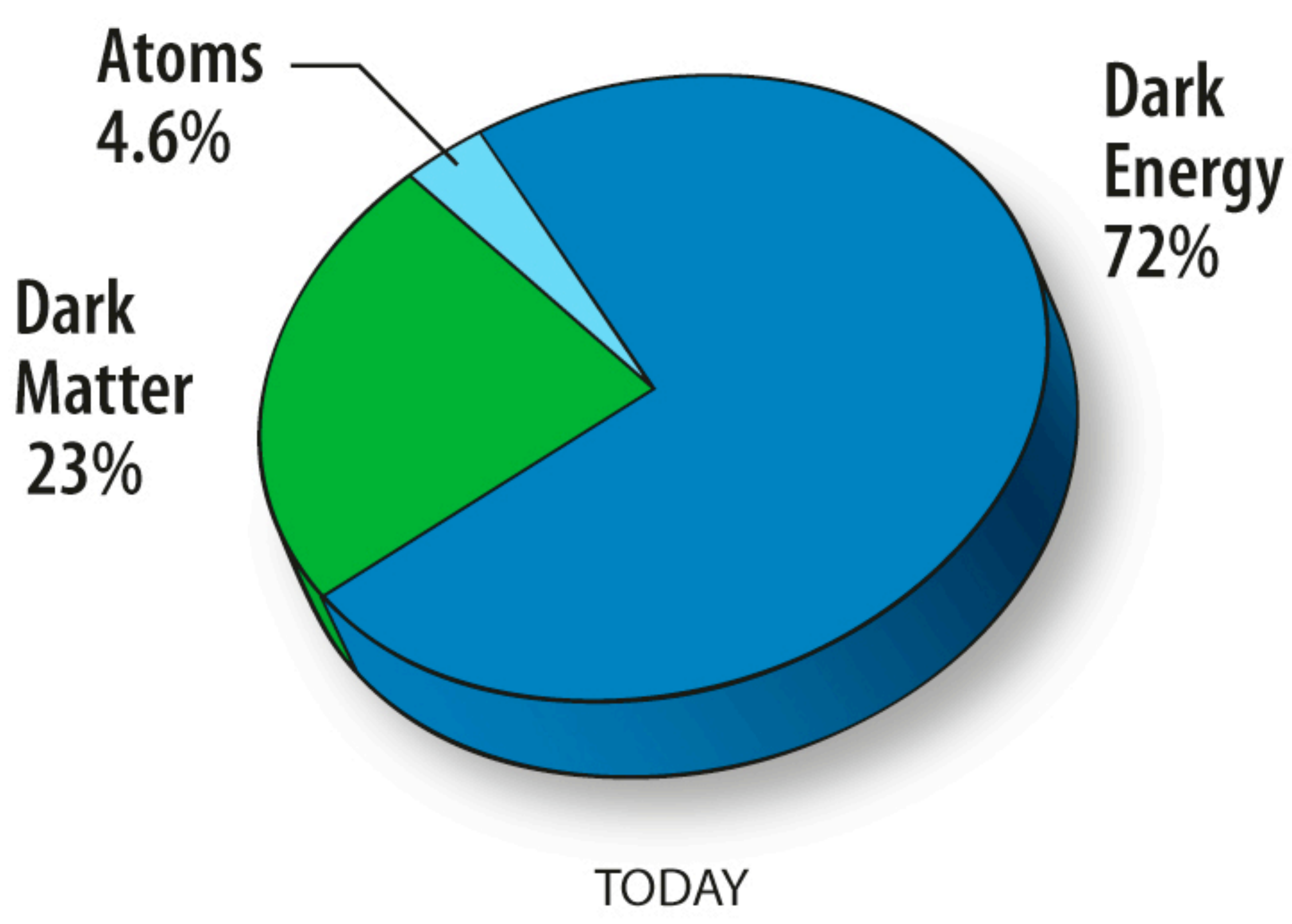
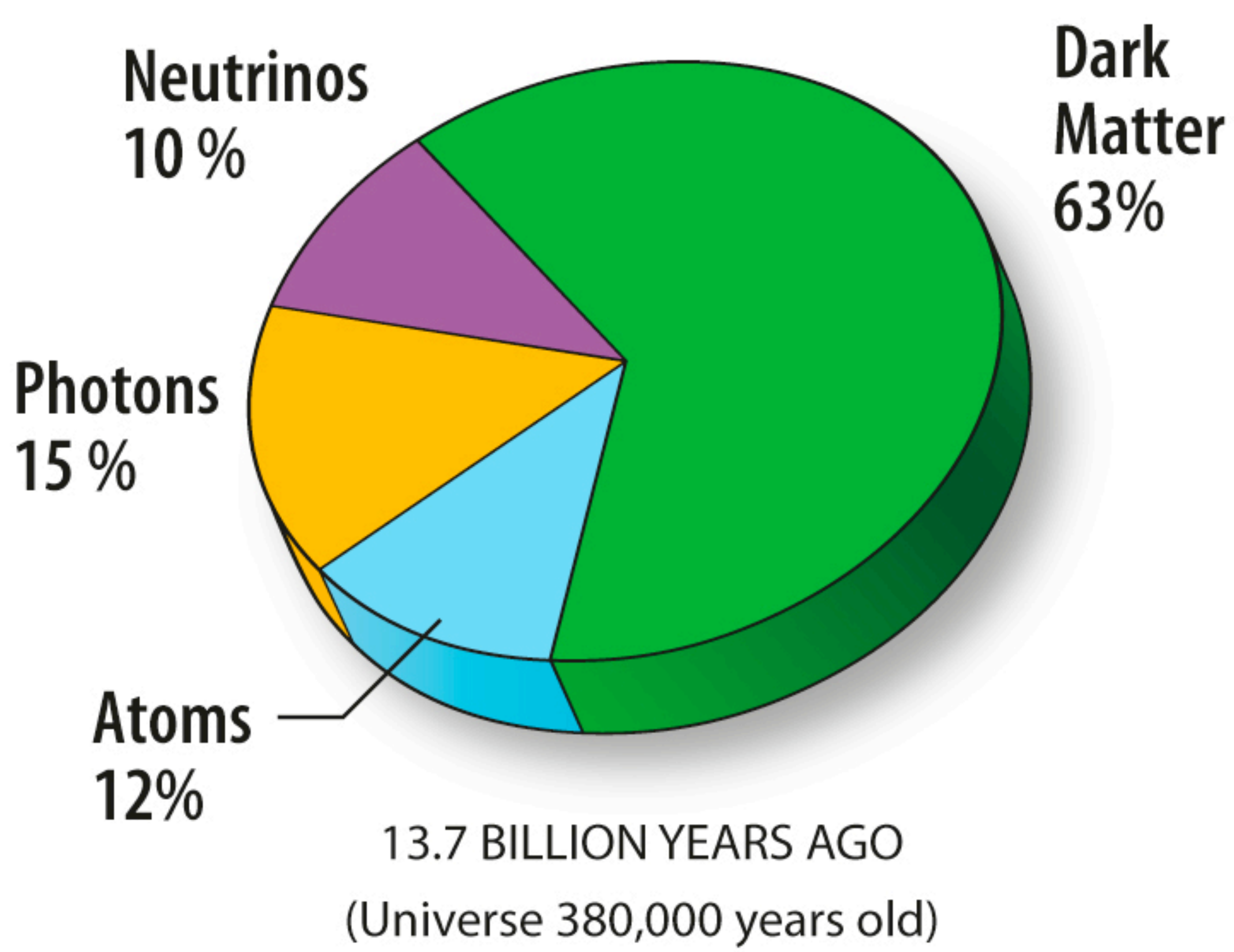
And, we ended up here again...

TABLE 1
SUMMARY OF THE COSMOLOGICAL PARAMETERS OF ΛCDM MODEL AND THE CORRESPONDING 68% INTERVALS

Class	Parameter	*WMAP* 5-year ML[a]	*WMAP*+BAO+SN ML	*WMAP* 5-year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.268	2.263	2.273 ± 0.062	2.265 ± 0.059
	$\Omega_c h^2$	0.1081	0.1136	0.1099 ± 0.0062	0.1143 ± 0.0034
	Ω_Λ	0.751	0.724	0.742 ± 0.030	0.721 ± 0.015
	n_s	0.961	0.961	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
	τ	0.089	0.080	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	2.41×10^{-9}	2.42×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	σ_8	0.787	0.811	0.796 ± 0.036	0.817 ± 0.026
	H_0	72.4 km/s/Mpc	70.3 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
	Ω_b	0.0432	0.0458	0.0441 ± 0.0030	0.0462 ± 0.0015
	Ω_c	0.206	0.230	0.214 ± 0.027	0.233 ± 0.013
	$\Omega_m h^2$	0.1308	0.1363	0.1326 ± 0.0063	0.1369 ± 0.0037
	$z_{\rm reion}{}^f$	11.2	10.5	11.0 ± 1.4	10.8 ± 1.4
	$t_0{}^g$	13.69 Gyr	13.72 Gyr	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr

- The latest cosmic pie chart that you should use in your cosmology class is...





WMAP 5-Year Press Release

- <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>Universe at the decoupling epoch</u>
  - The density of relativistic neutrinos is given by 3.04(7/8) $(4/11)^{4/3}$ ~ 0.69 times the photon density.

Summary

- Annoying ΛCDM still fits the WMAP data, as well as the other astrophysical data sets.
- We did everything we could do to find deviations, but failed.
- Significant improvements in limits on the deviations
  - Most notably, $r<0.2$ (95% CL), and $n_s>1$ is now disfavored regardless of r. This is new.
- 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.