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

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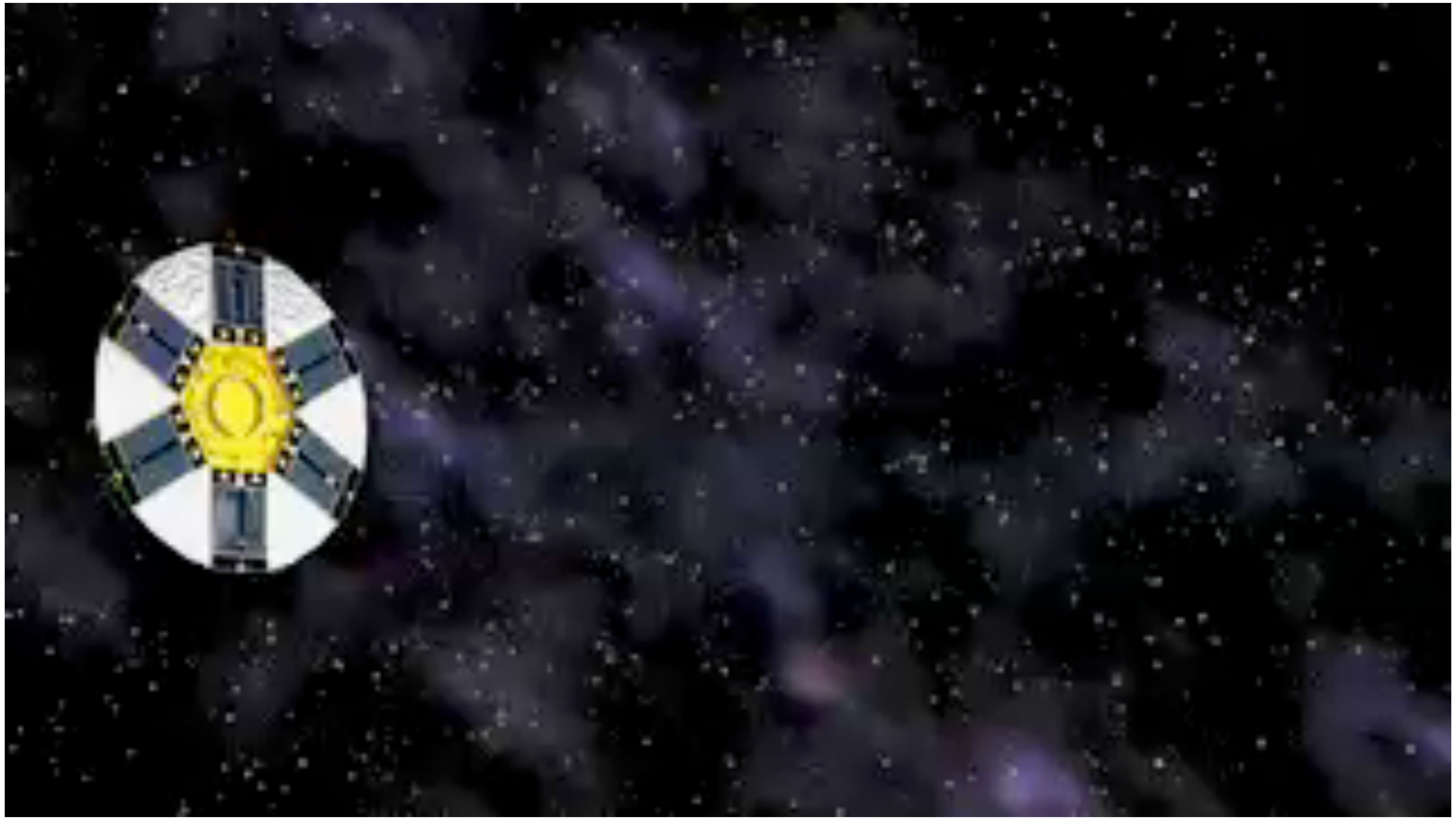
WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

February 2003:
The first-year data release

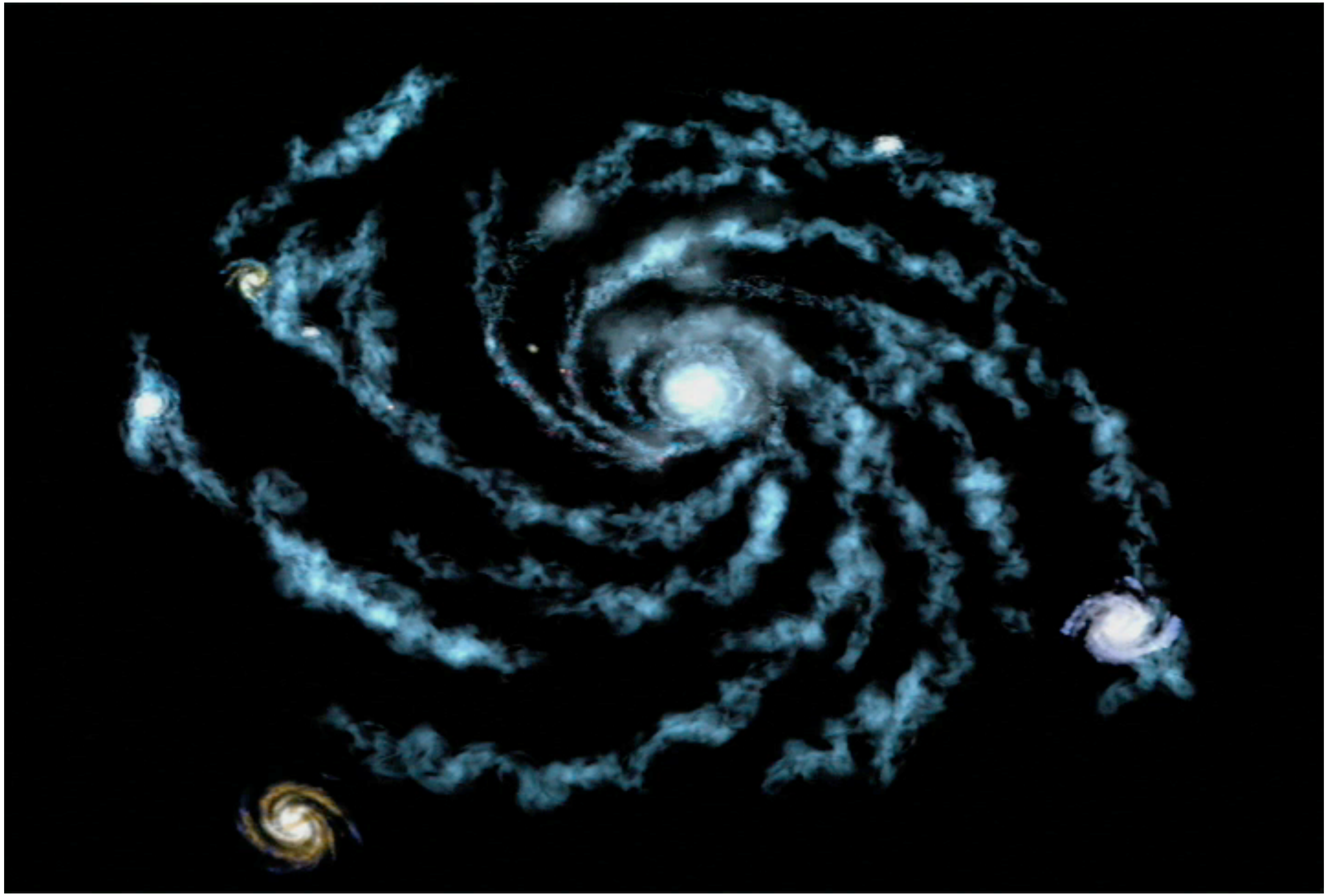
March 2006:
The three-year data release

**March 2008:
The five-year data release**



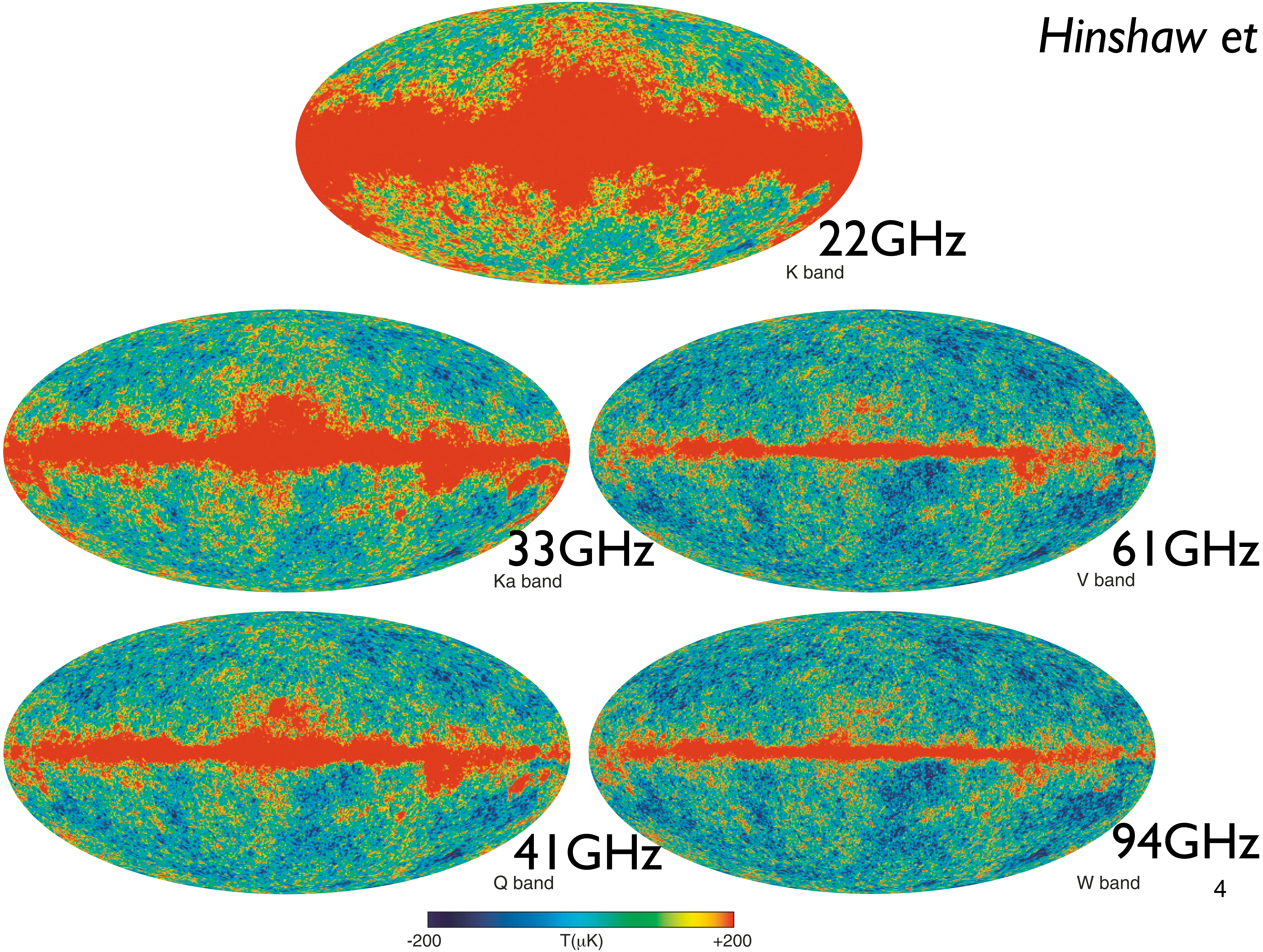
- L2 is a million miles from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them

WMAP Measures Microwaves From the Universe

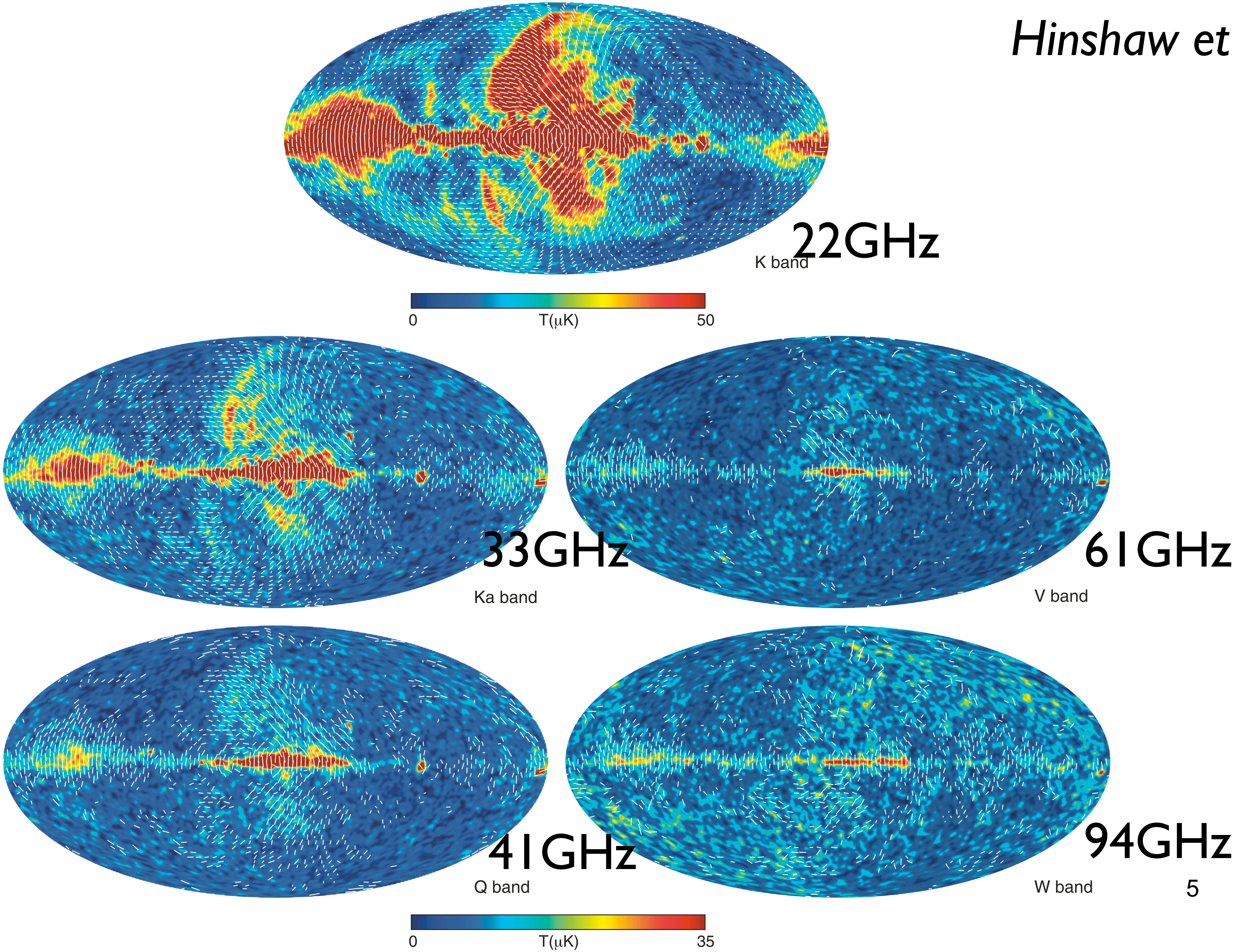


- The mean temperature of photons in the Universe today is 2.725 K
- WMAP is capable of measuring the temperature *contrast* down to better than **one part in millionth**

Hinshaw et al.

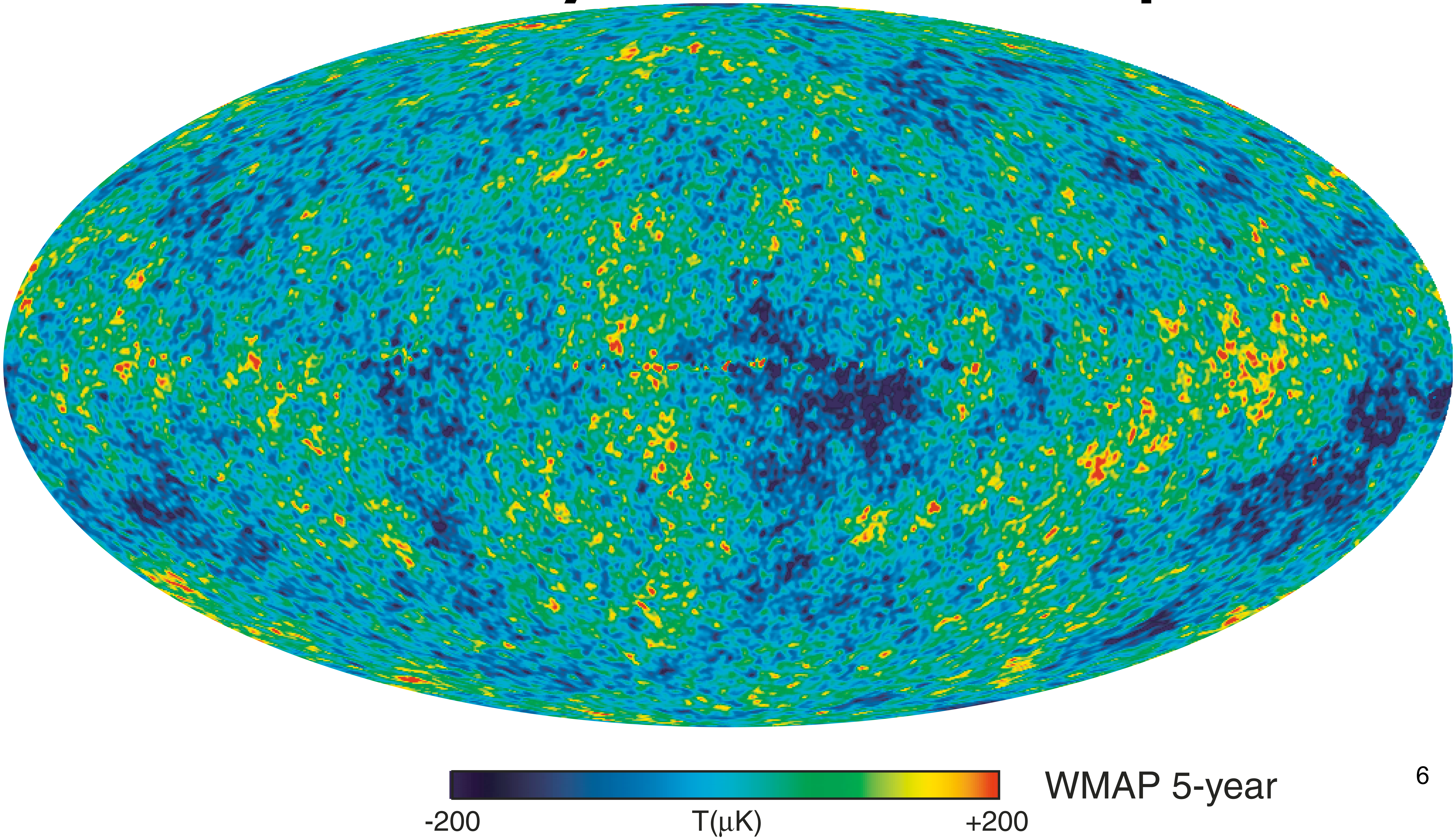


Hinshaw et al.



Hinshaw et al.

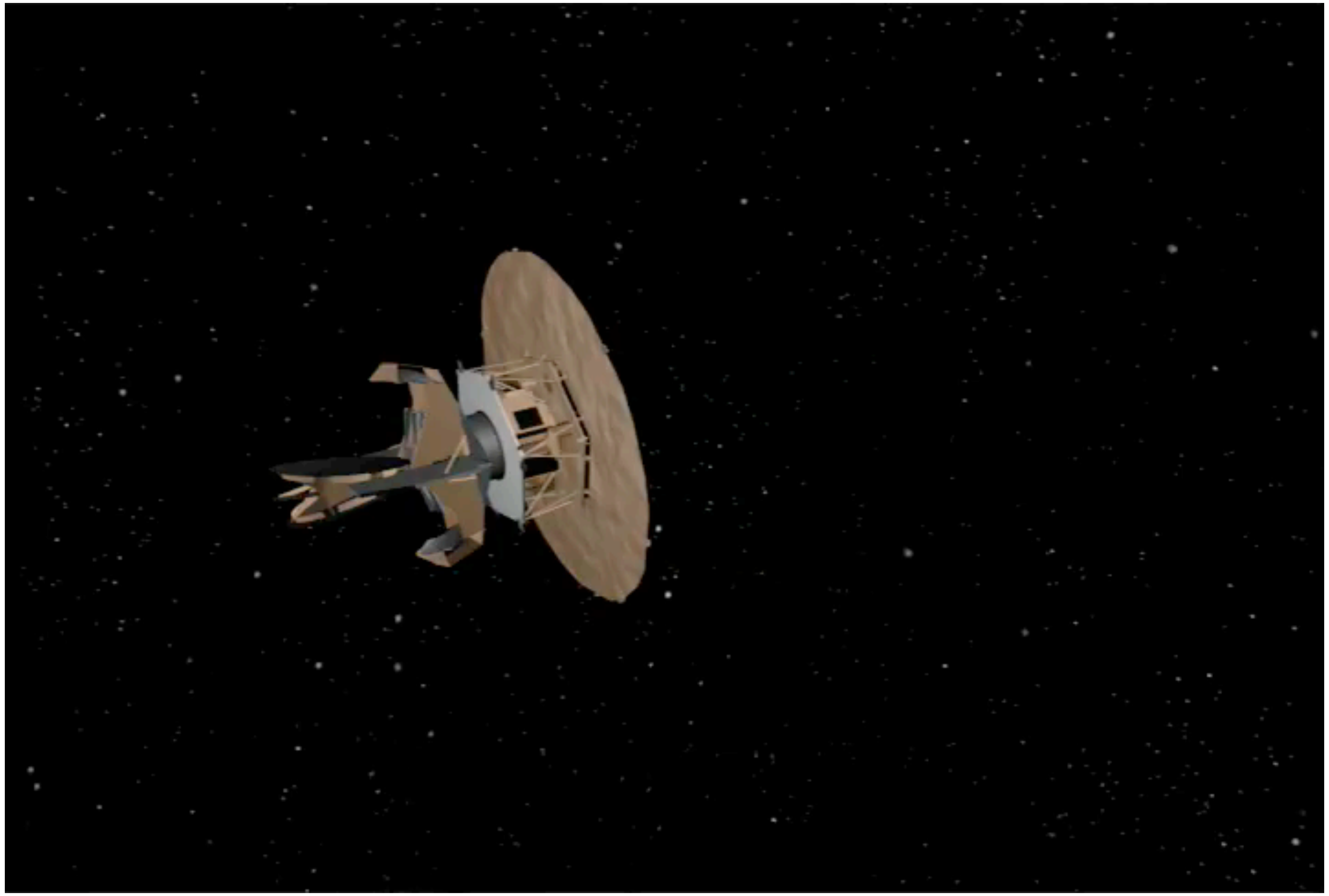
Galaxy-cleaned Map



WMAP 5-year

Journey Backwards in Time

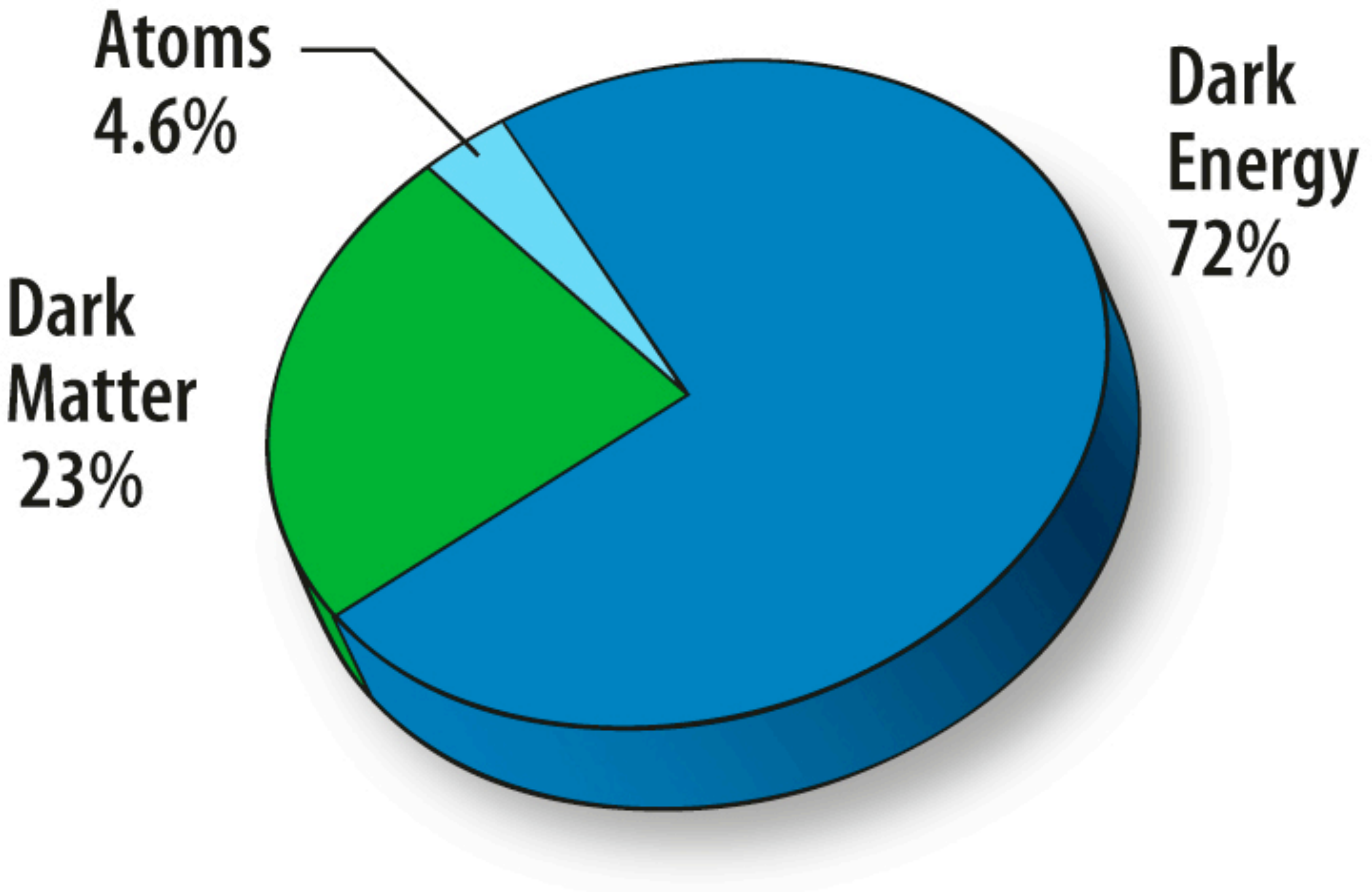
- The Cosmic Microwave Background (**CMB**) is ***the fossil light from the Big Bang***
- This is the oldest light that one can ever hope to measure
- CMB is a ***direct*** image of the Universe when the Universe was only 380,000 years old



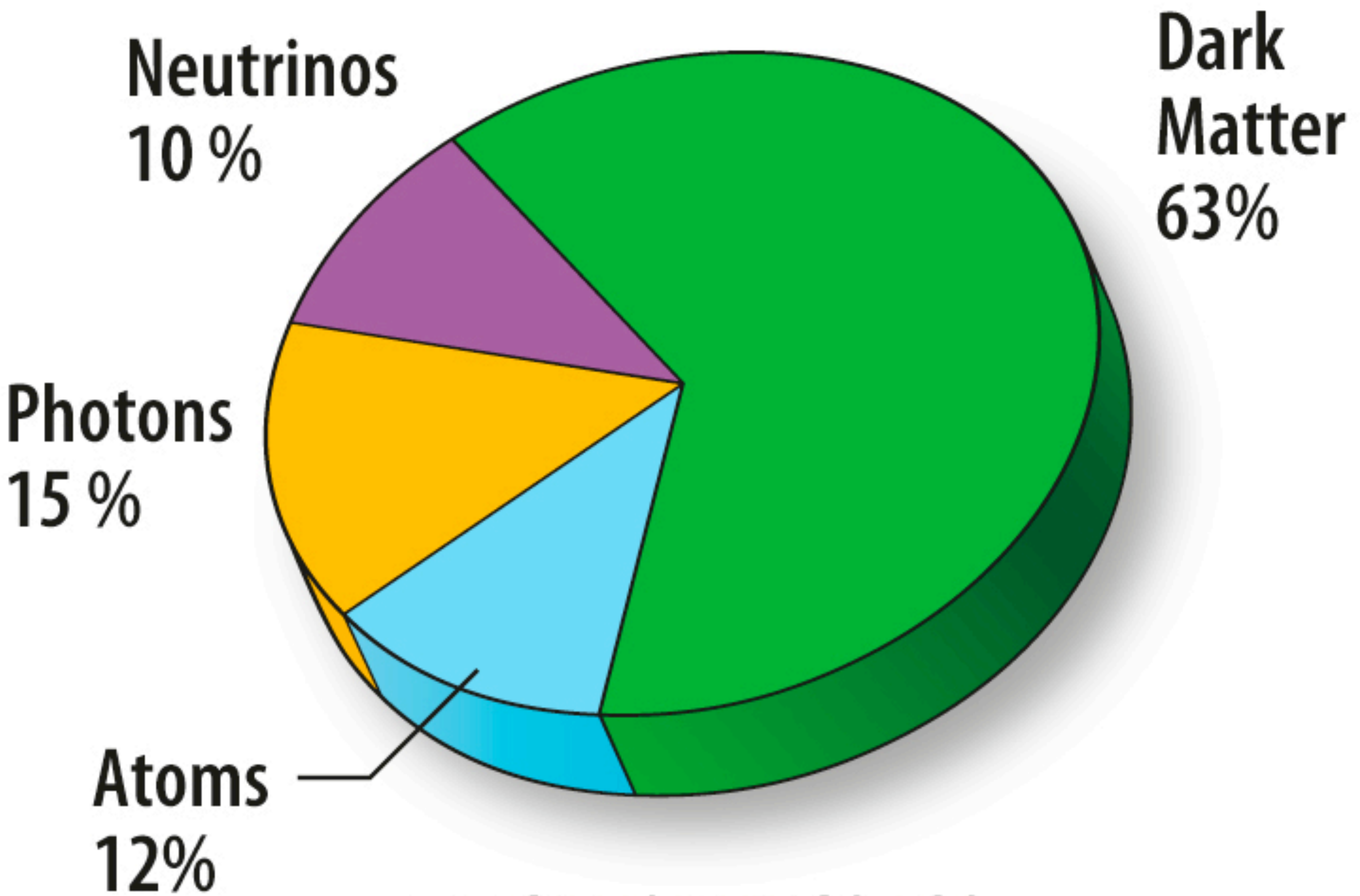
- CMB photons, after released from the cosmic plasma "soup," traveled for **13.7 billion years** to reach us.
- CMB collects information about the Universe as it travels through it.

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



TODAY



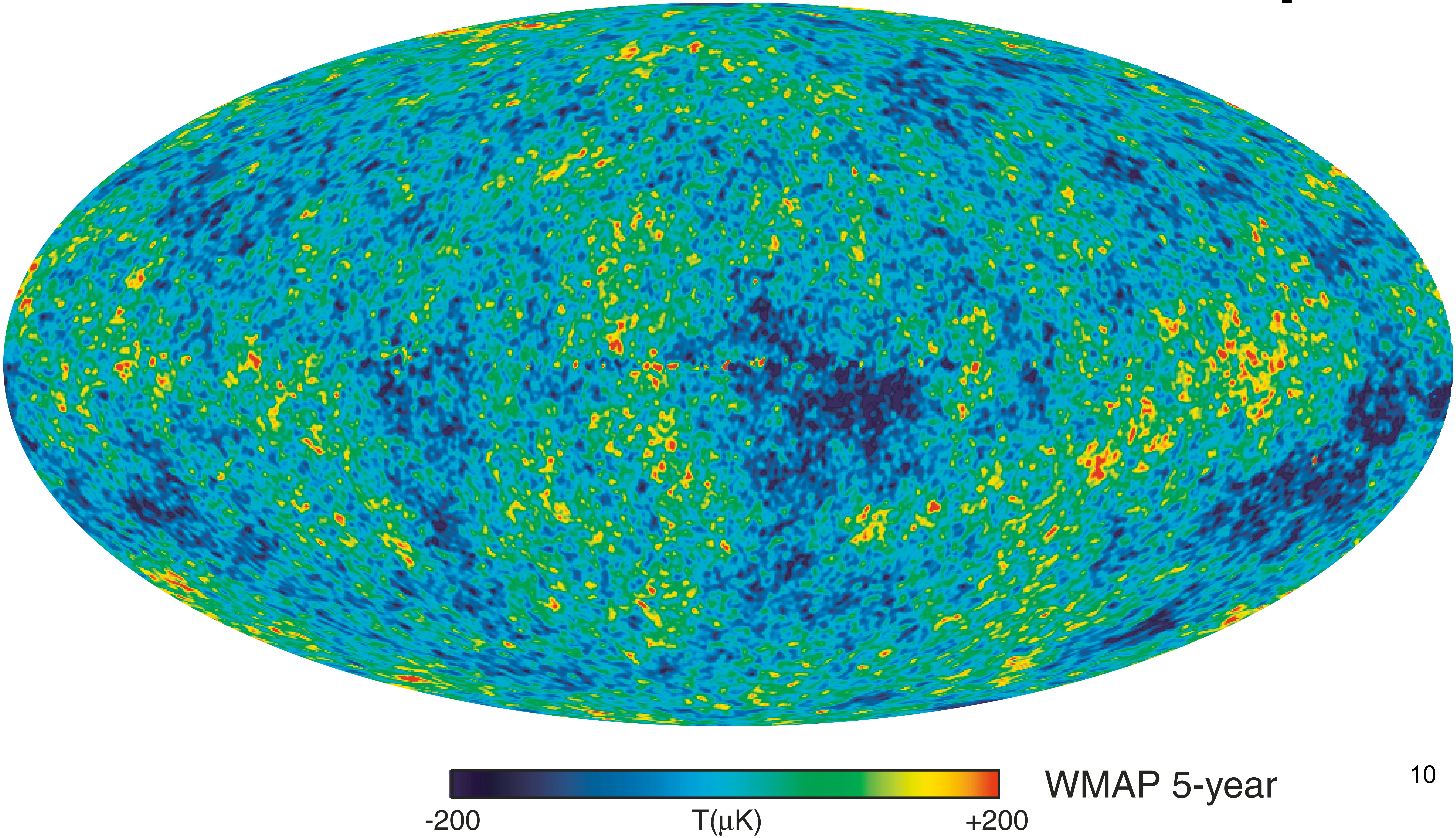
13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Komatsu et al.

~WMAP 5-Year~ Pie Chart Update!

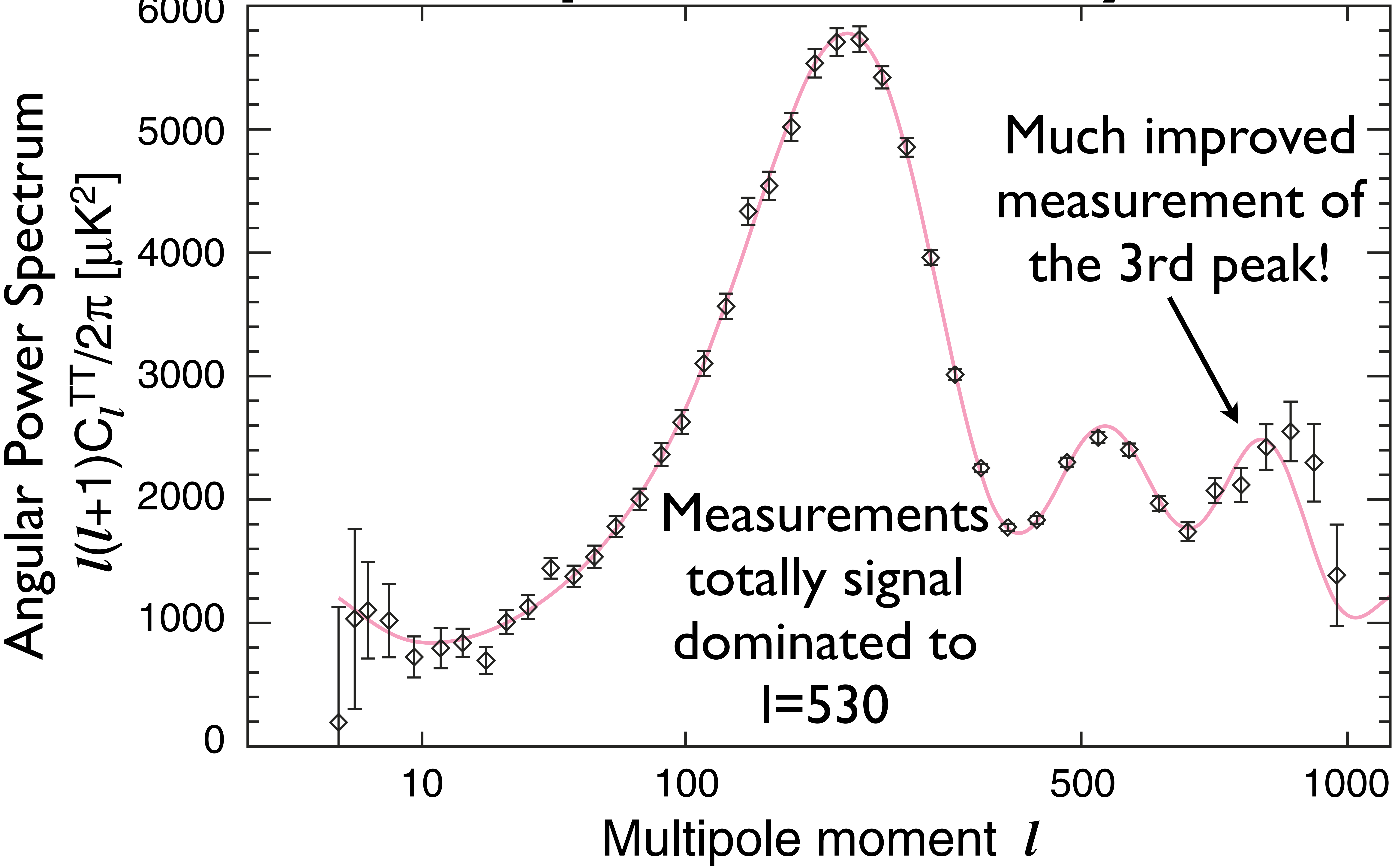
- Universe today
  - Age: **13.72 +/- 0.12** Gyr
  - Atoms: **4.56 +/- 0.15 %**
  - Dark Matter: **22.8 +/- 1.3%**
  - Vacuum Energy: **72.6 +/- 1.5%**
- When CMB was released 13.7 B yrs ago
  - A significant contribution from the *cosmic neutrino background*

How Did We Use This Map?



Nolta et al.

The Spectral Analysis

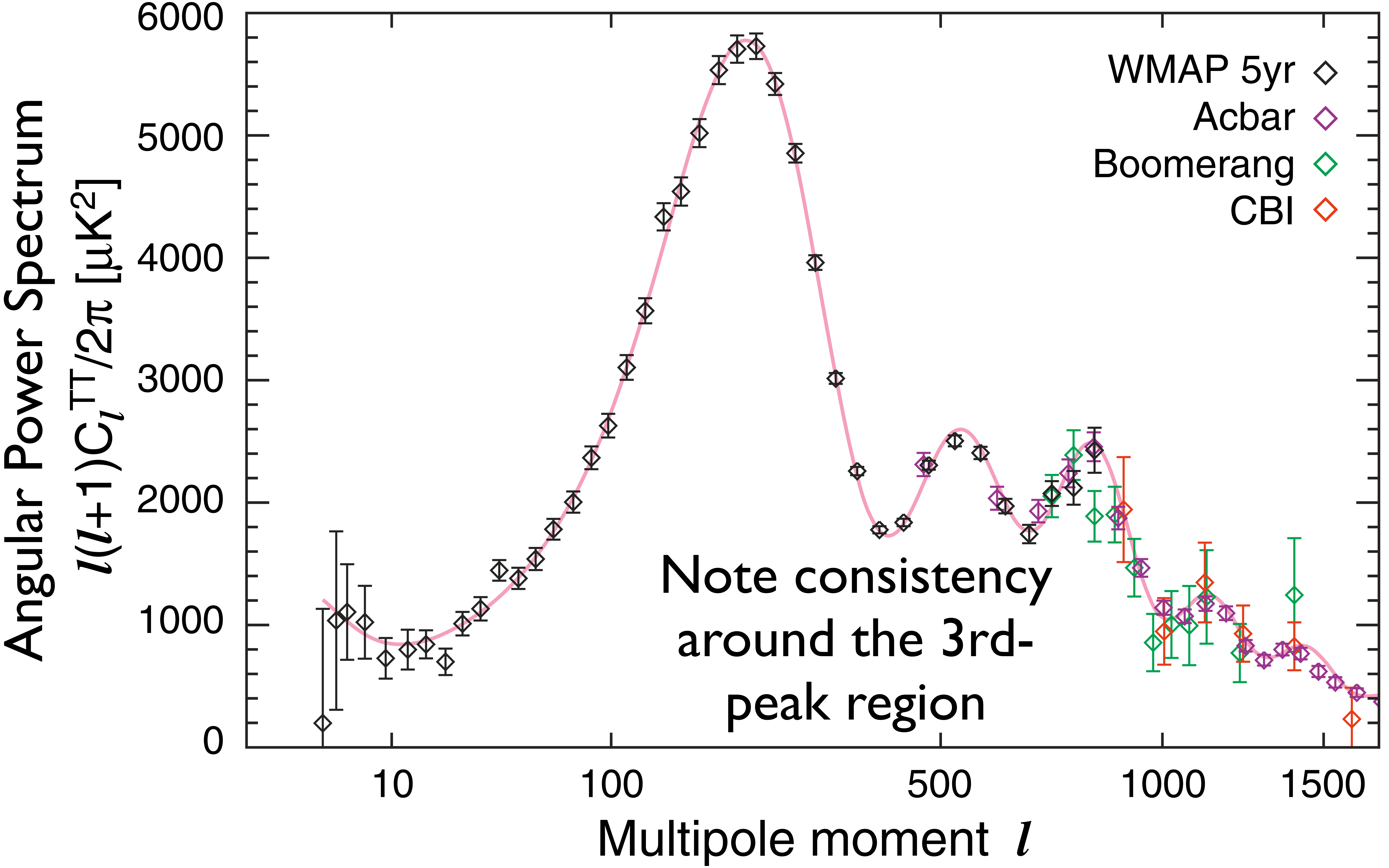


Much improved measurement of the 3rd peak!

Measurements totally signal dominated to l=530

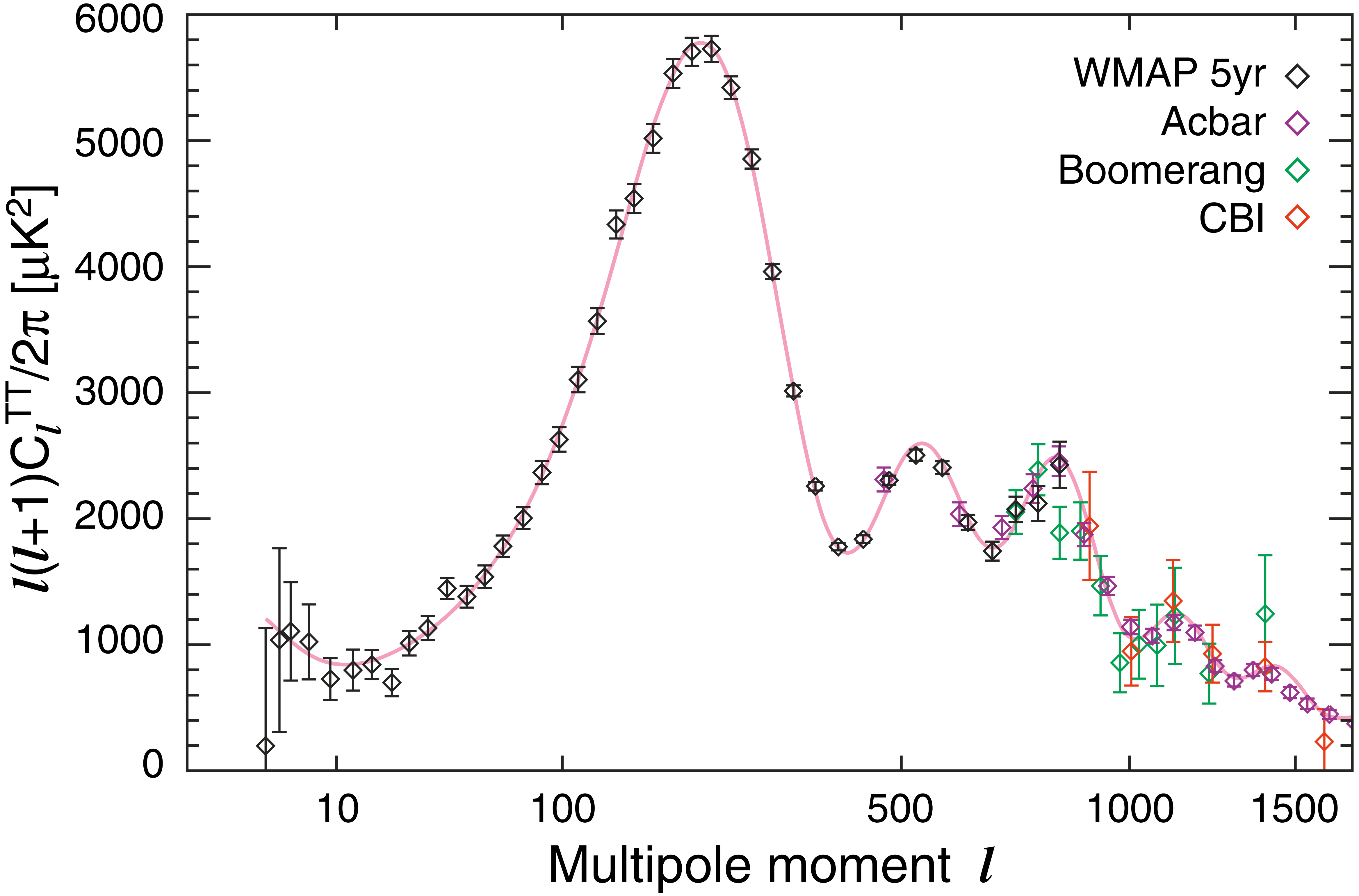
Nolta et al.

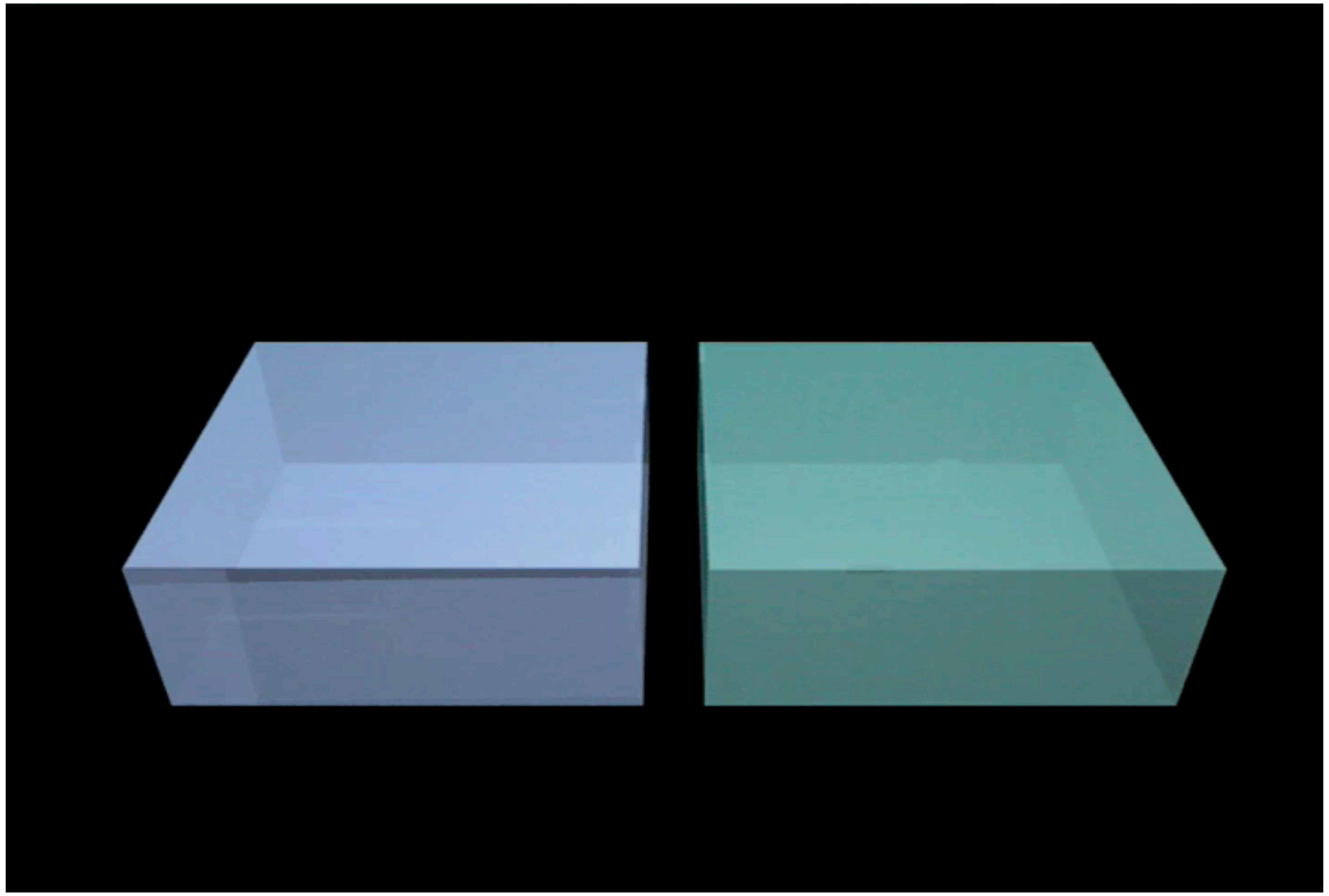
The Cosmic Sound Wave



Note consistency around the 3rd-peak region

The Cosmic Sound Wave



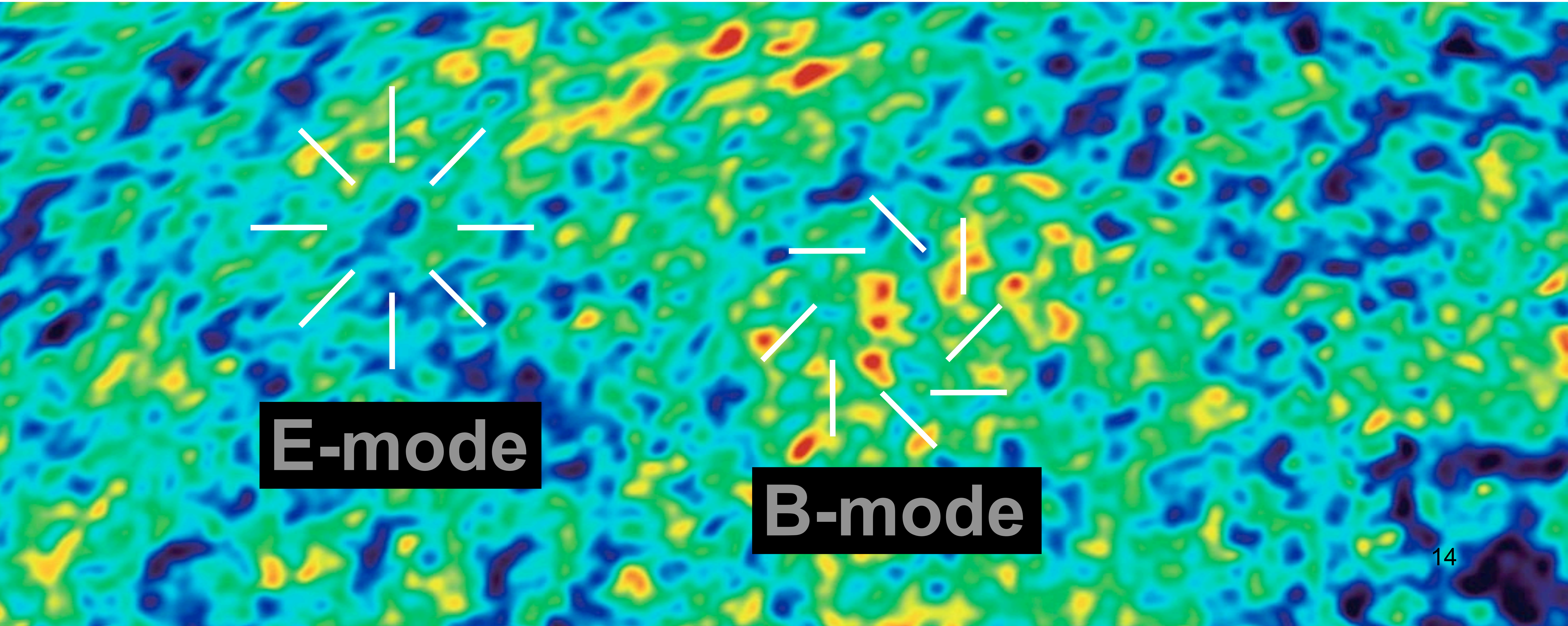


- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

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

How About Polarization?

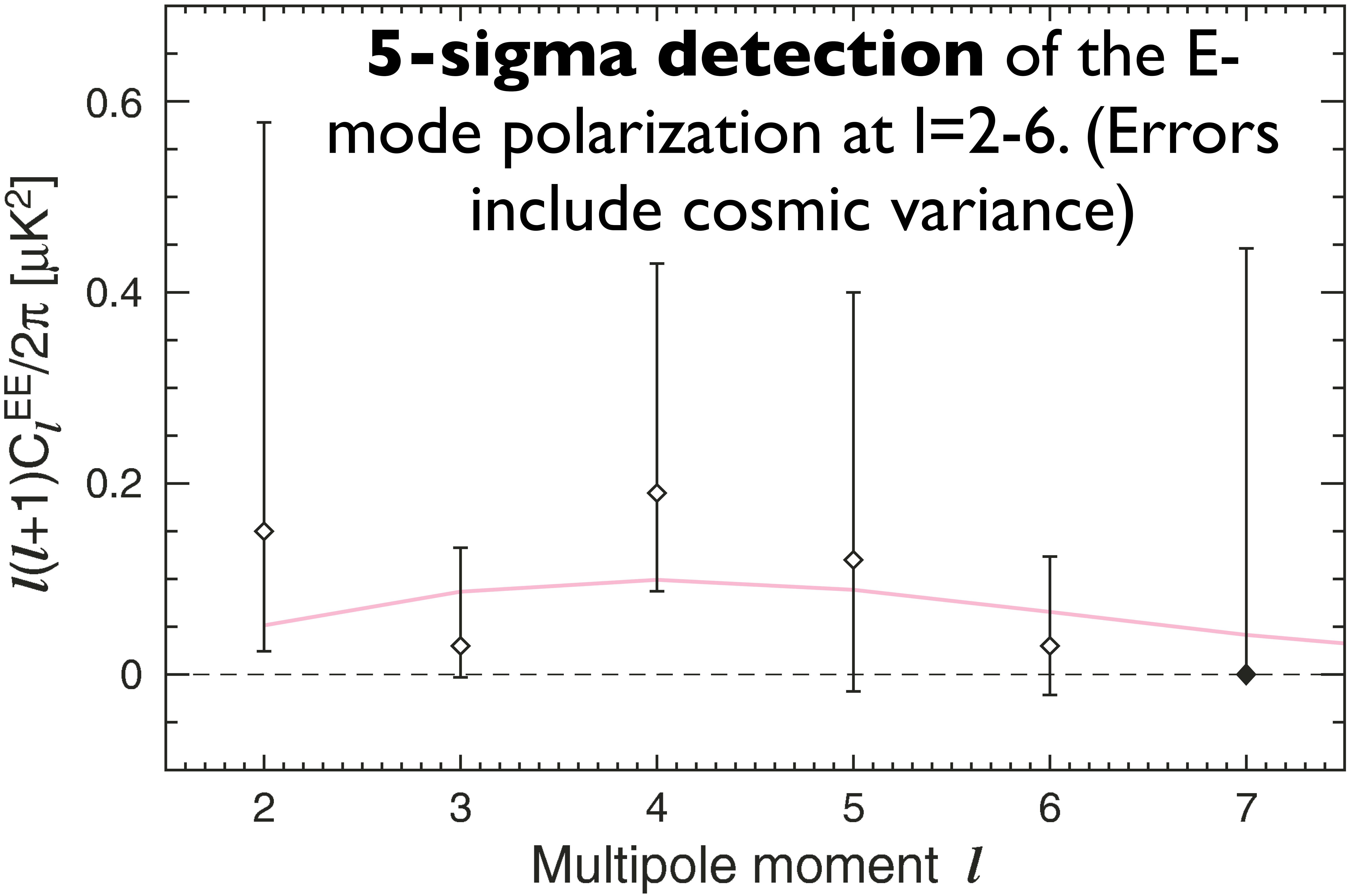
- Polarization is a rank-2 tensor field.
- One can decompose it into a divergence-like “E-mode” and a vorticity-like “B-mode”.



Nolta et al.

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

E-Mode Angular Power Spectrum

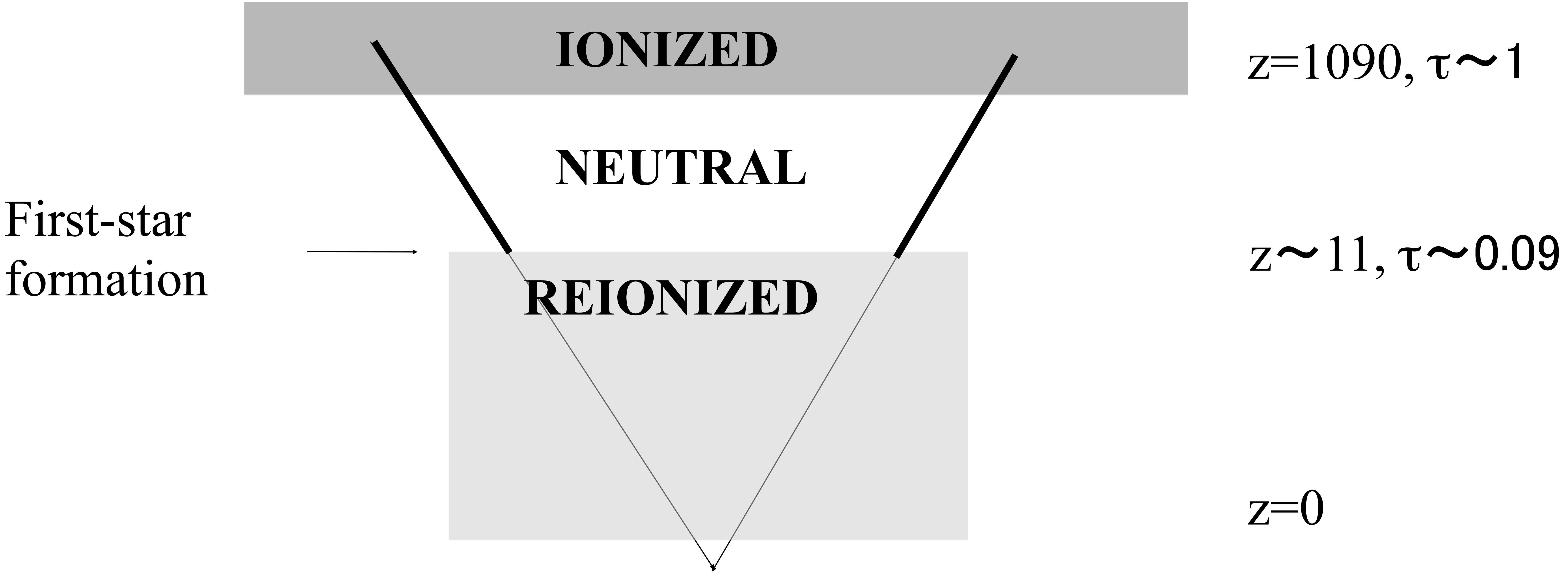


5-sigma detection of the E-mode polarization at l=2-6. (Errors include cosmic variance)

Black Symbols are upper limits

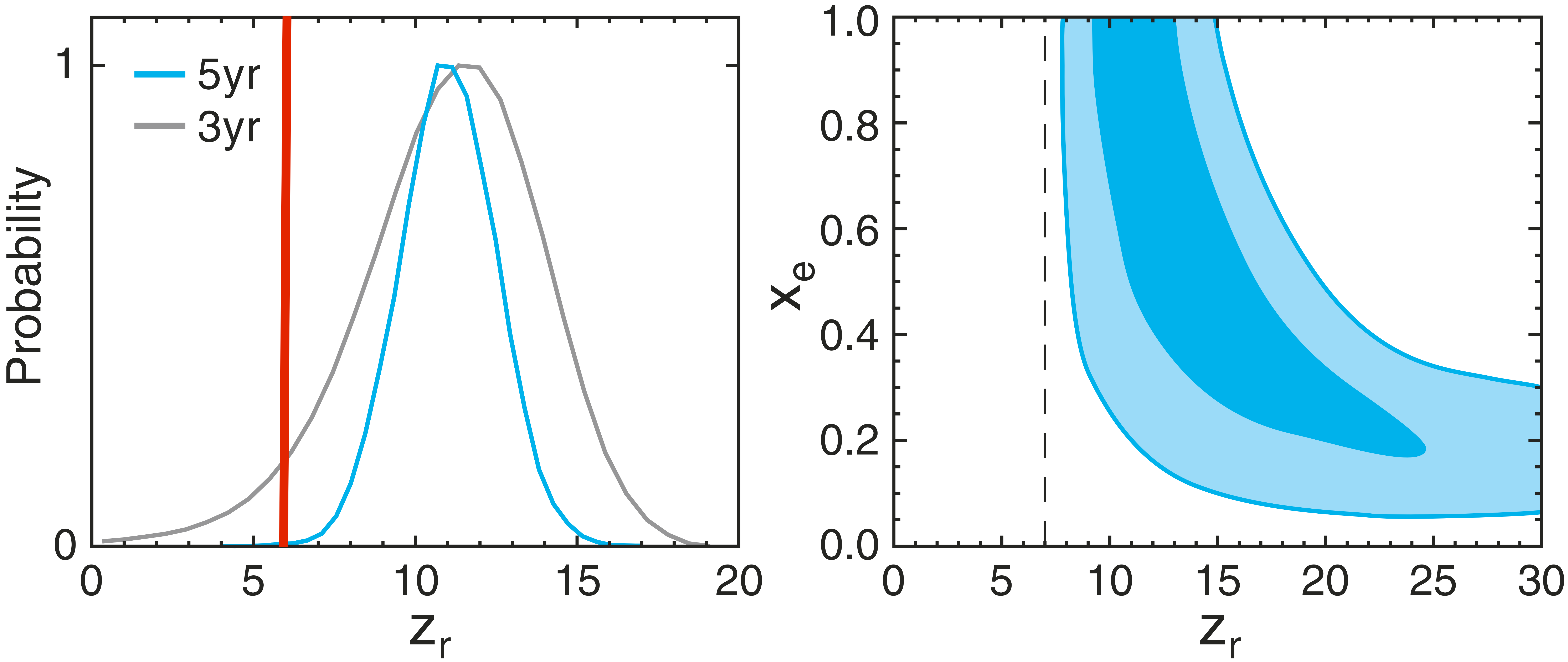
Polarization From Reionization

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



Z_{reion}=6 Is Excluded

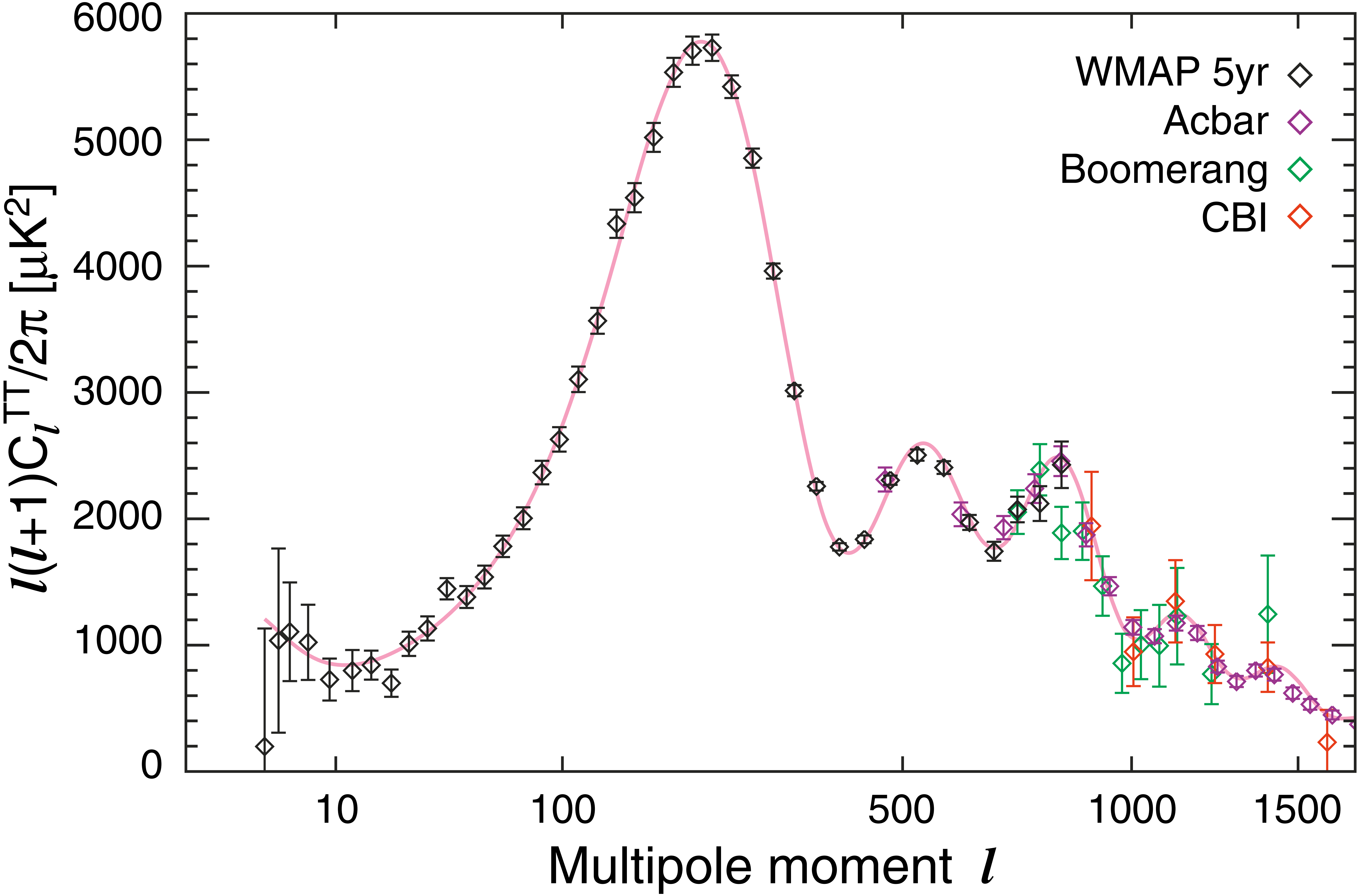
Dunkley et al.



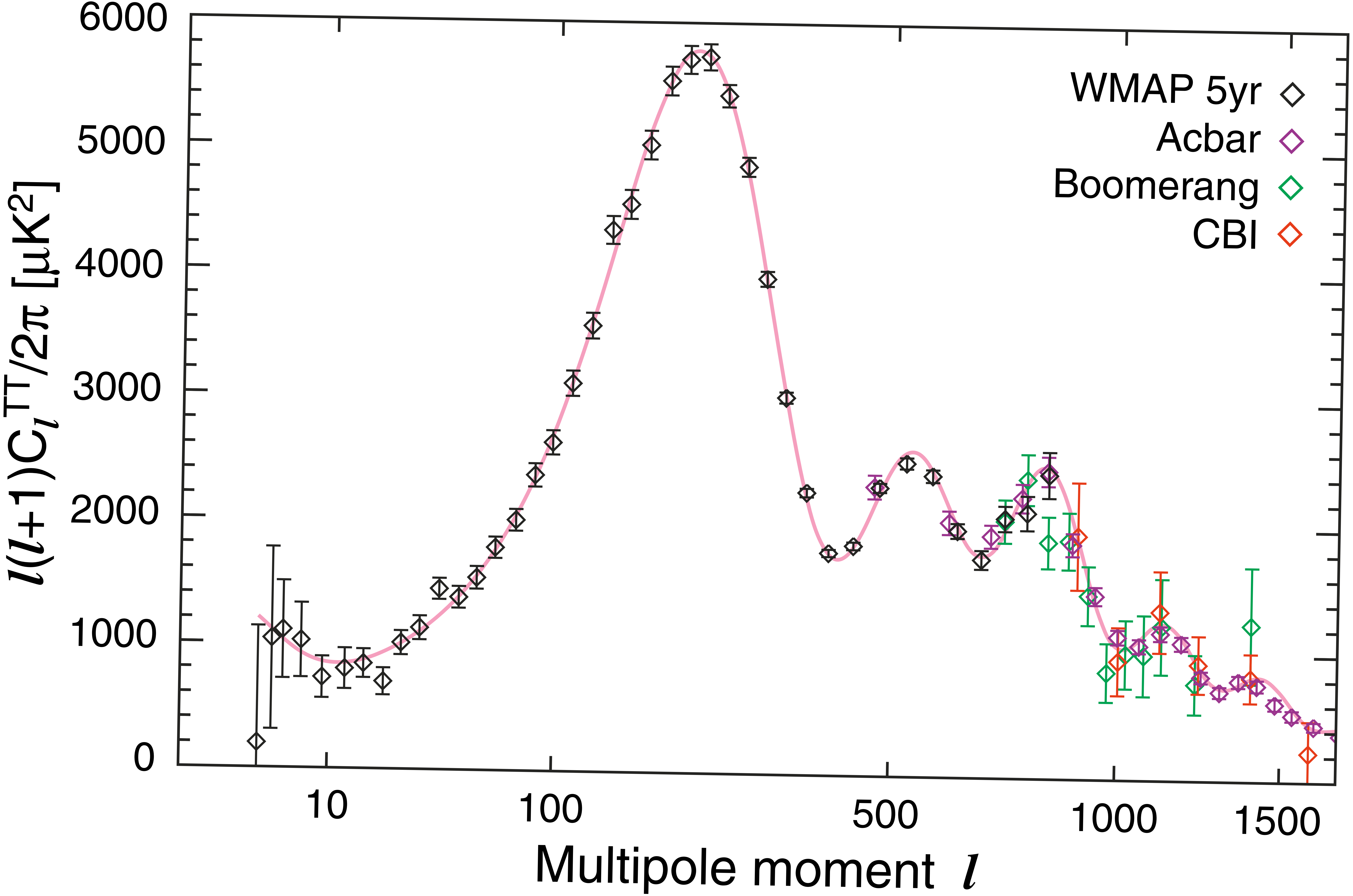
- Assuming an instantaneous reionization from x_e=0 to x_e=1 at z_{reion}, we find **z_{reion}=11.0 +/- 1.4** (68 % CL).

- The reionization was not an instantaneous process at z~6. (The 3-sigma lower bound is z_{reion}>6.7.)

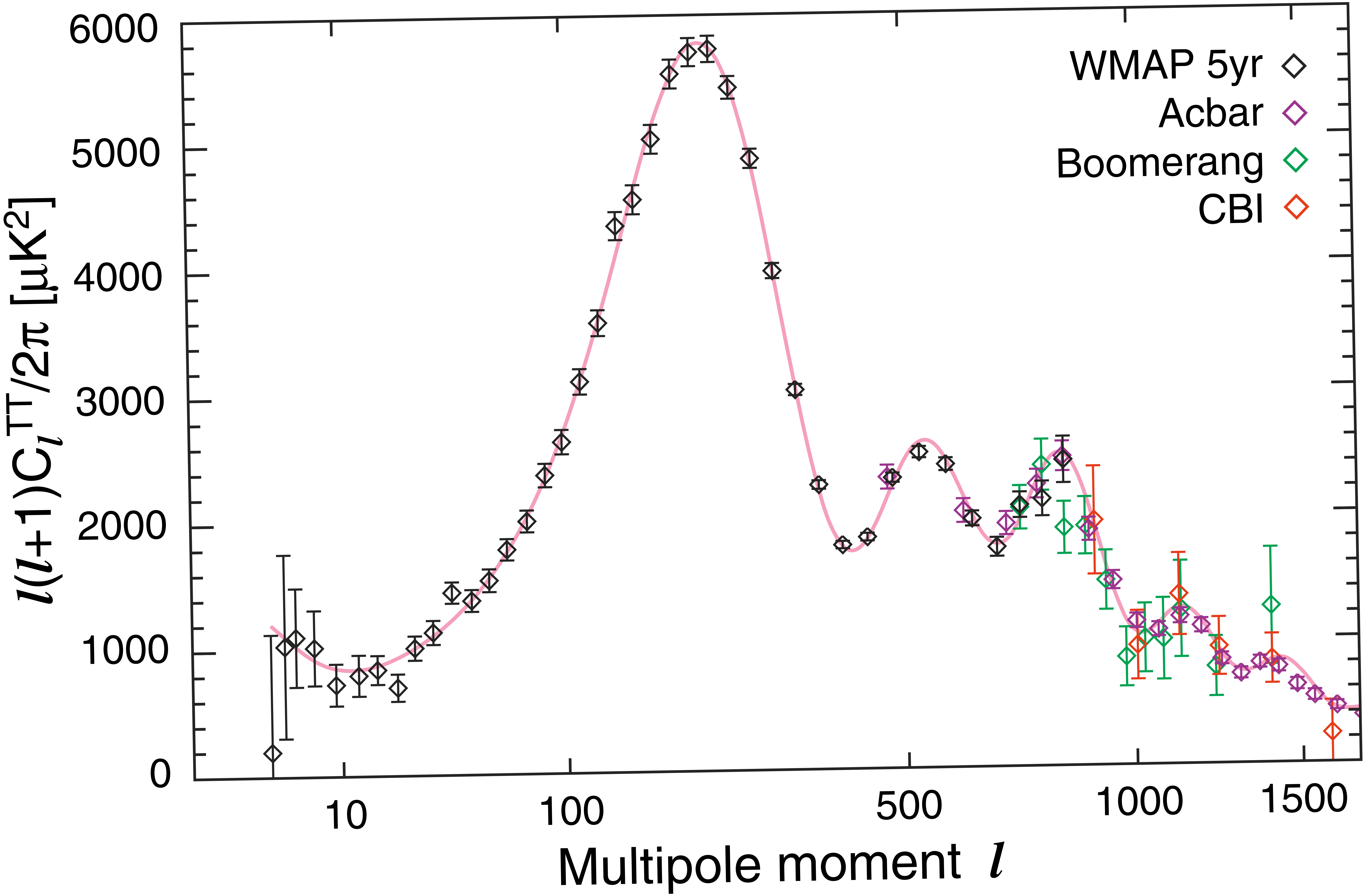
Tilting=Primordial Shape->Inflation



“Red” Spectrum: $n_s < 1$

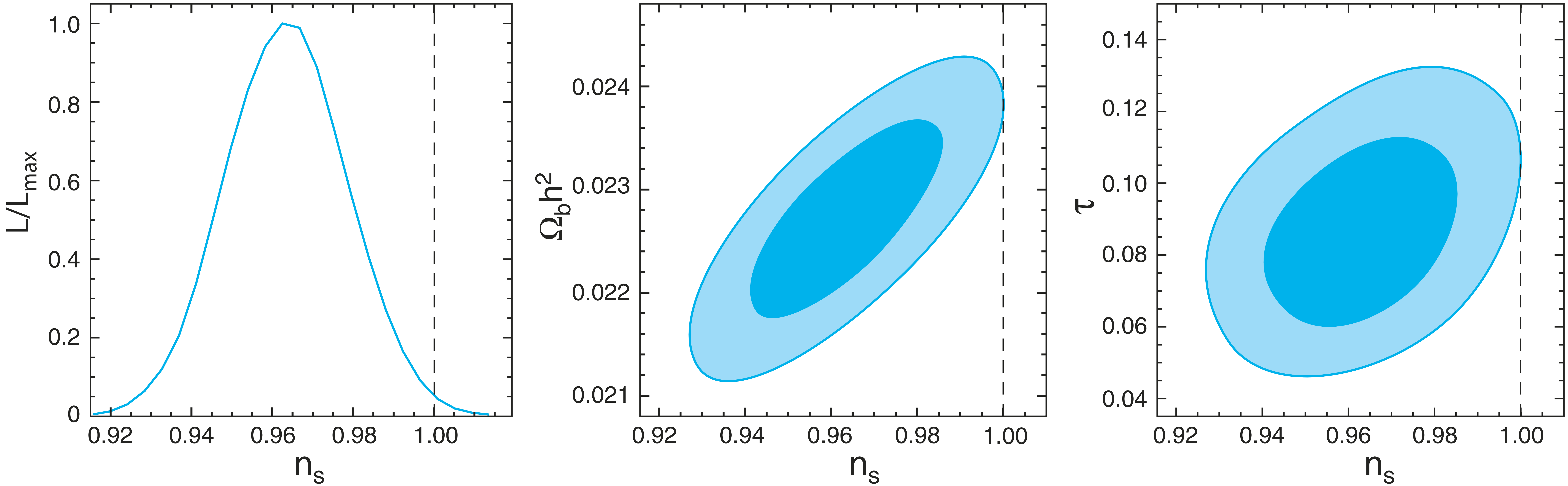


"Blue" Spectrum: $n_s > 1$



Is n_s different from ONE?

Komatsu et al.

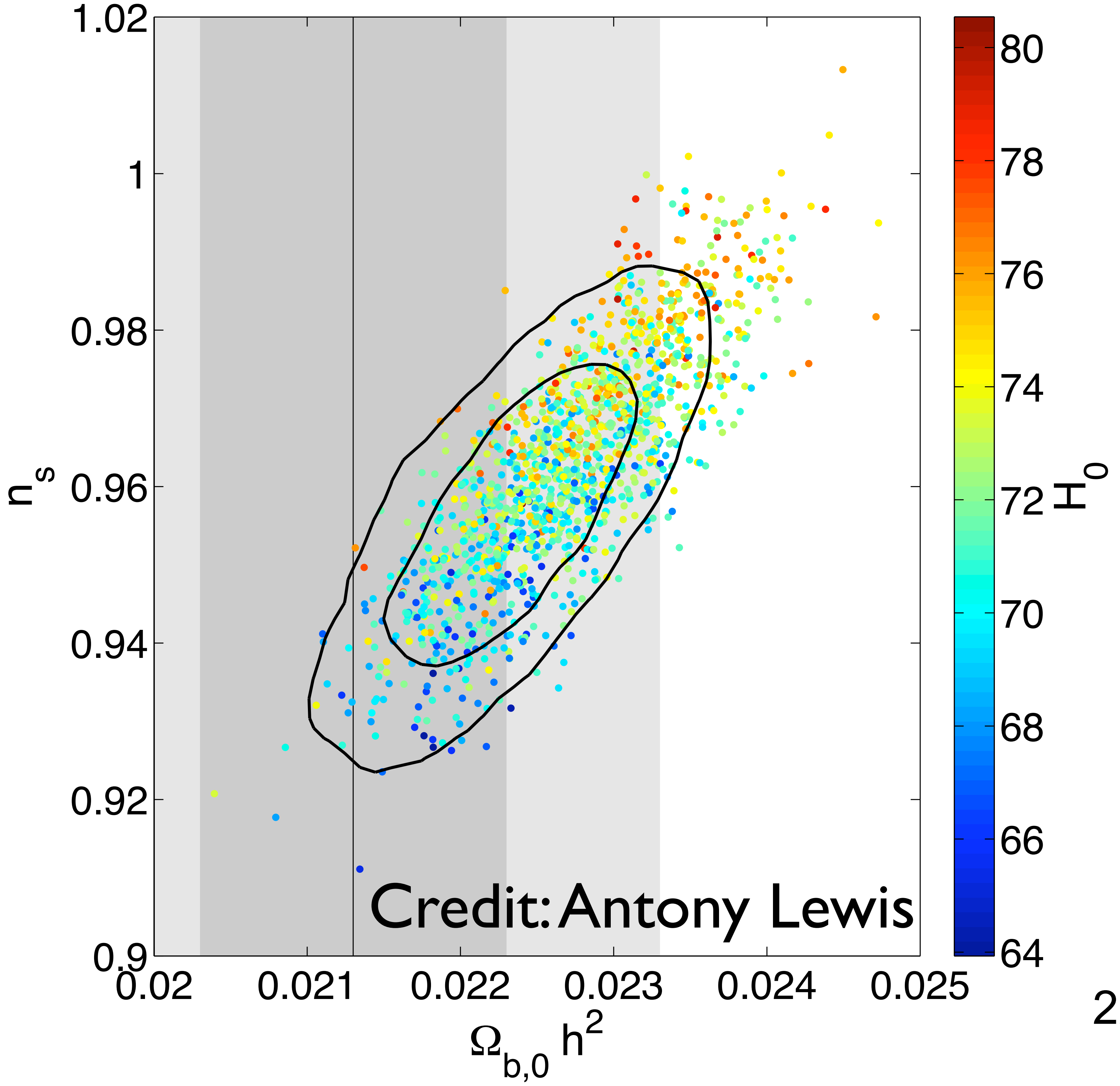


- WMAP-alone: **n_s=0.963** (+0.014) (-0.015) (Dunkley et al.)
    - 2.5-sigma away from n_s=1, "scale invariant spectrum"
- n_s is degenerate with $\Omega_b h^2$; thus, we can't really improve upon n_s further unless we improve upon $\Omega_b h^2$

Getting $\Omega_b h^2$ Elsewhere

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!
  - $\Omega_b h^2(\mathrm{DLA})=0.0213\pm0.0010$ from $\log(\mathrm{D/H})=-4.55\pm0.03$
  - $\Omega_b h^2(\mathrm{WMAP})=0.0227\pm0.0006$
- $\Omega_b h^2(\mathrm{DLA})$ is totally independent of n_s
  - *Degeneracy reduced!*
  - $n_s(\mathrm{DLA+WMAP})=0.956\pm0.013$
    - **3.4-sigma away from 1**
  - $n_s(\mathrm{WMAP})=0.963\ (+0.014)\ (-0.015)$



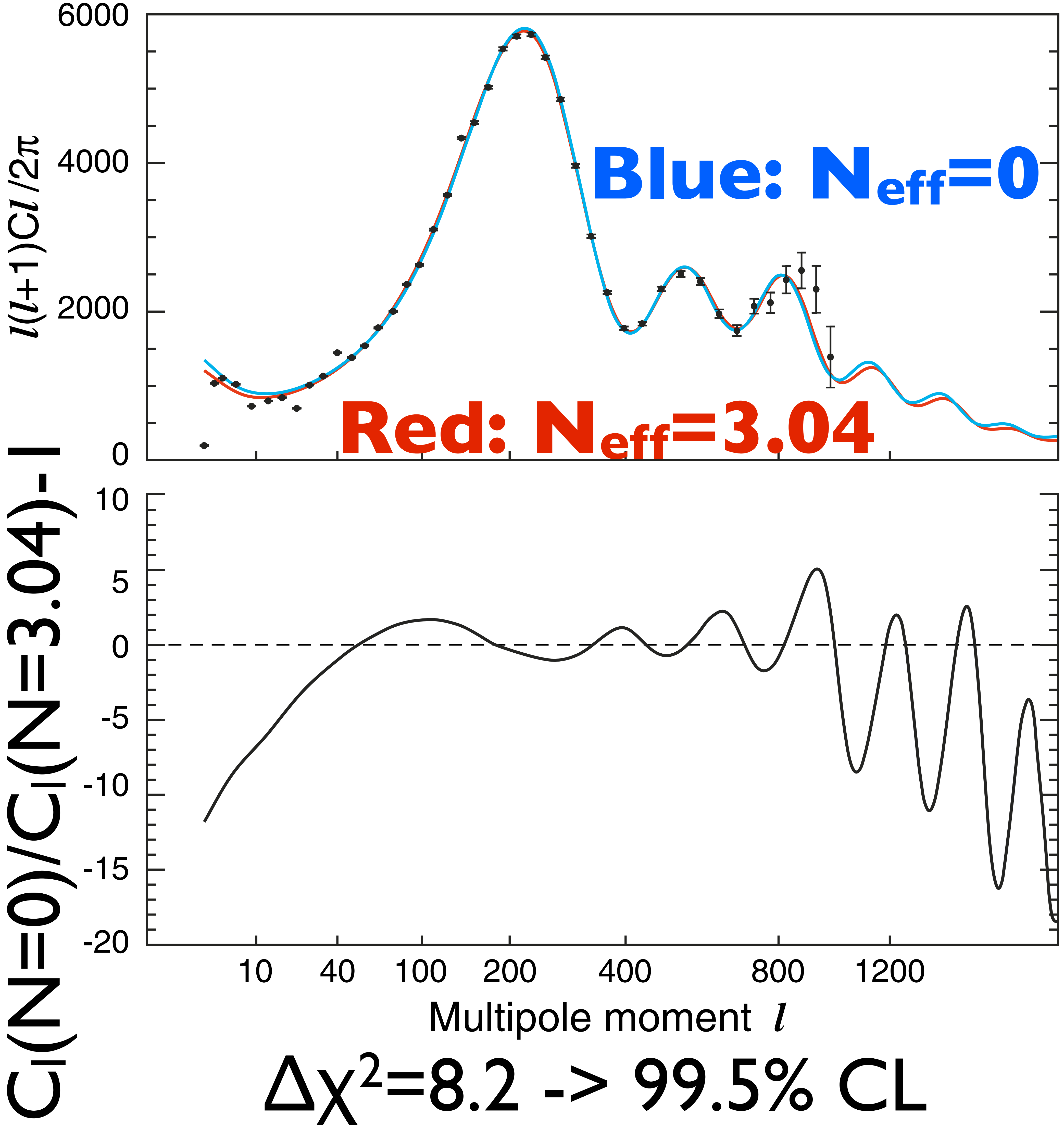
Credit: Antony Lewis

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

Dunkley et al.



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

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

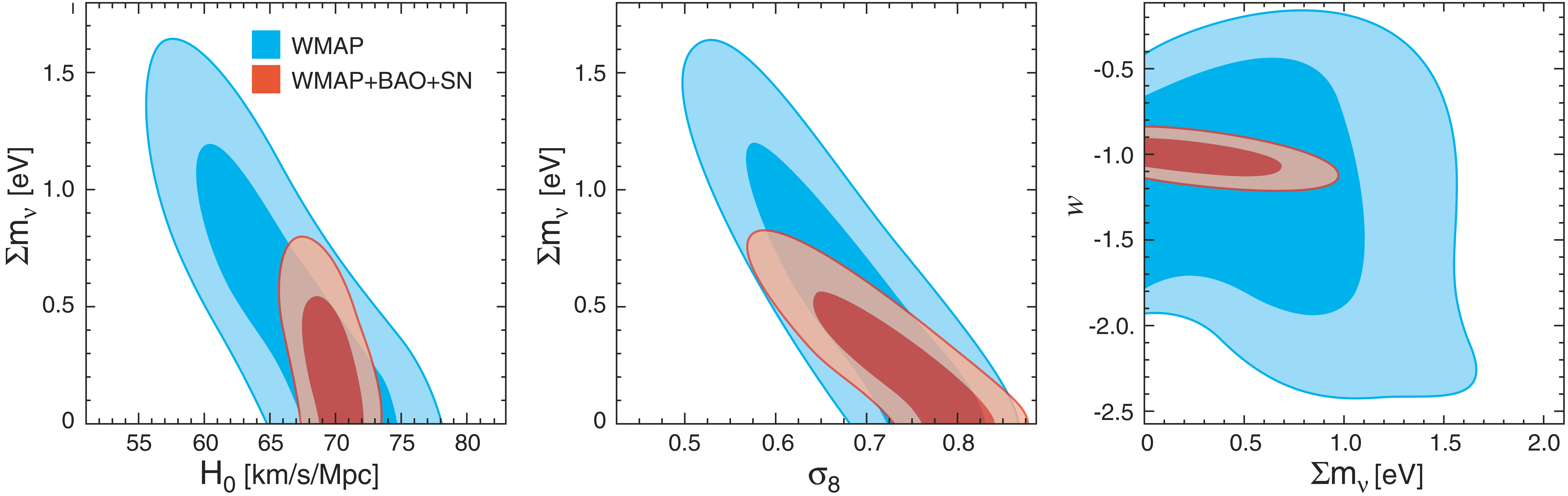
Komatsu et al.

Cosmic/Laboratory Consistency

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

Komatsu et al.

Neutrino Mass



- The local distance measurements (BAO) help determine the neutrino mass by giving H_0.
- **Sum(m_ν) < 0.67 eV** (95% CL) -- independent of the normalization of the large scale structure.

Testing Cosmic Inflation

~5 Tests~

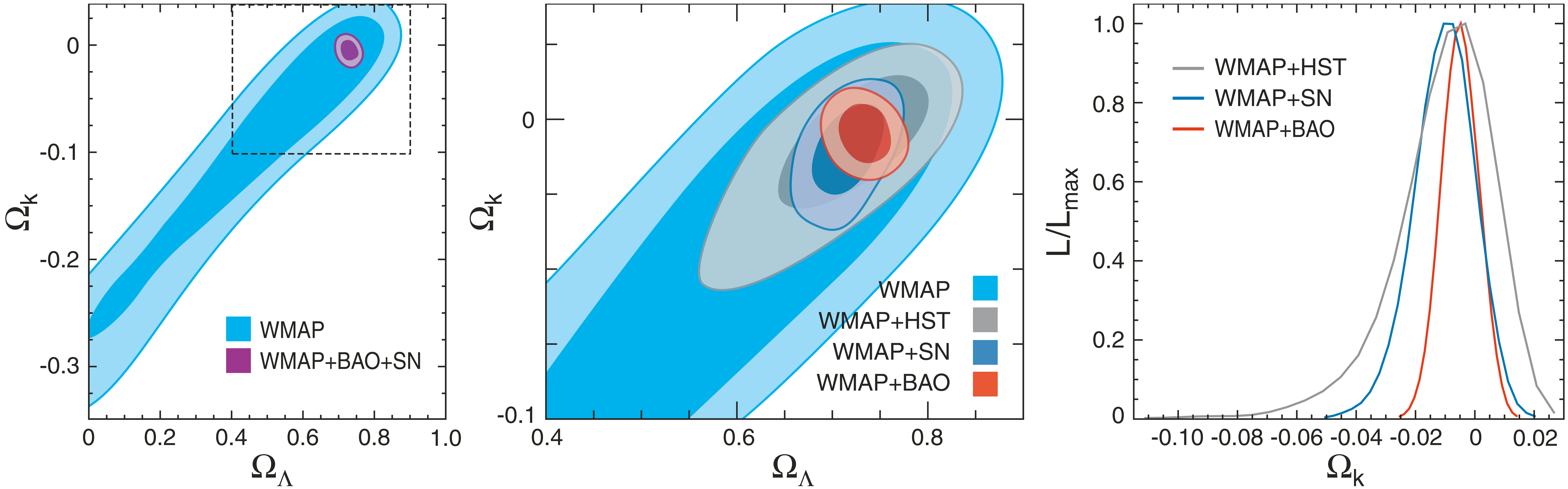
- Is the observable universe flat?
- Are the primordial fluctuations adiabatic?
- Are the primordial fluctuations nearly Gaussian?
- Is the power spectrum nearly scale invariant?
- Is the amplitude of gravitational waves reasonable?

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

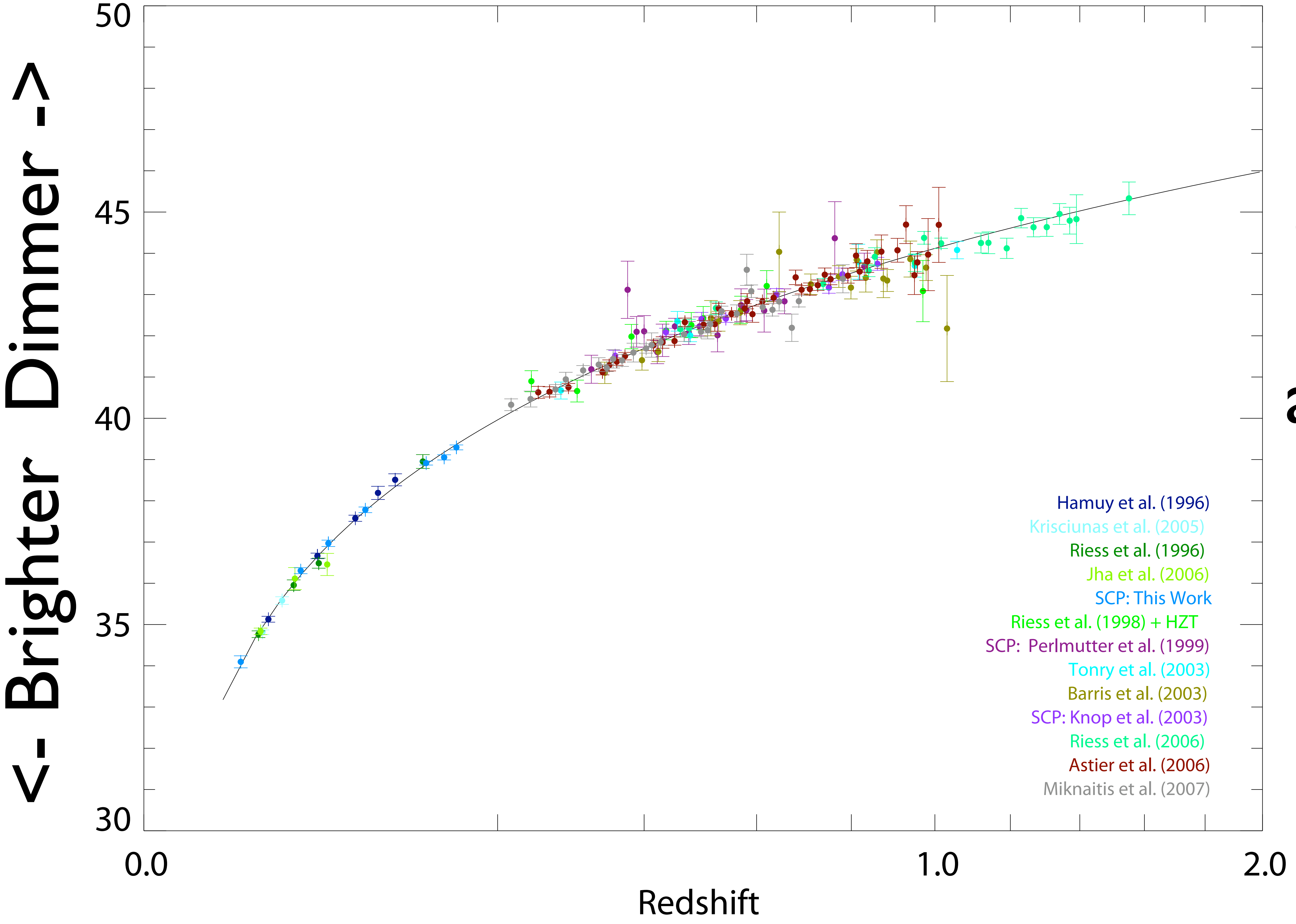
Komatsu et al.



- 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

Kowalski et al.

Type Ia Supernova (SN) Data

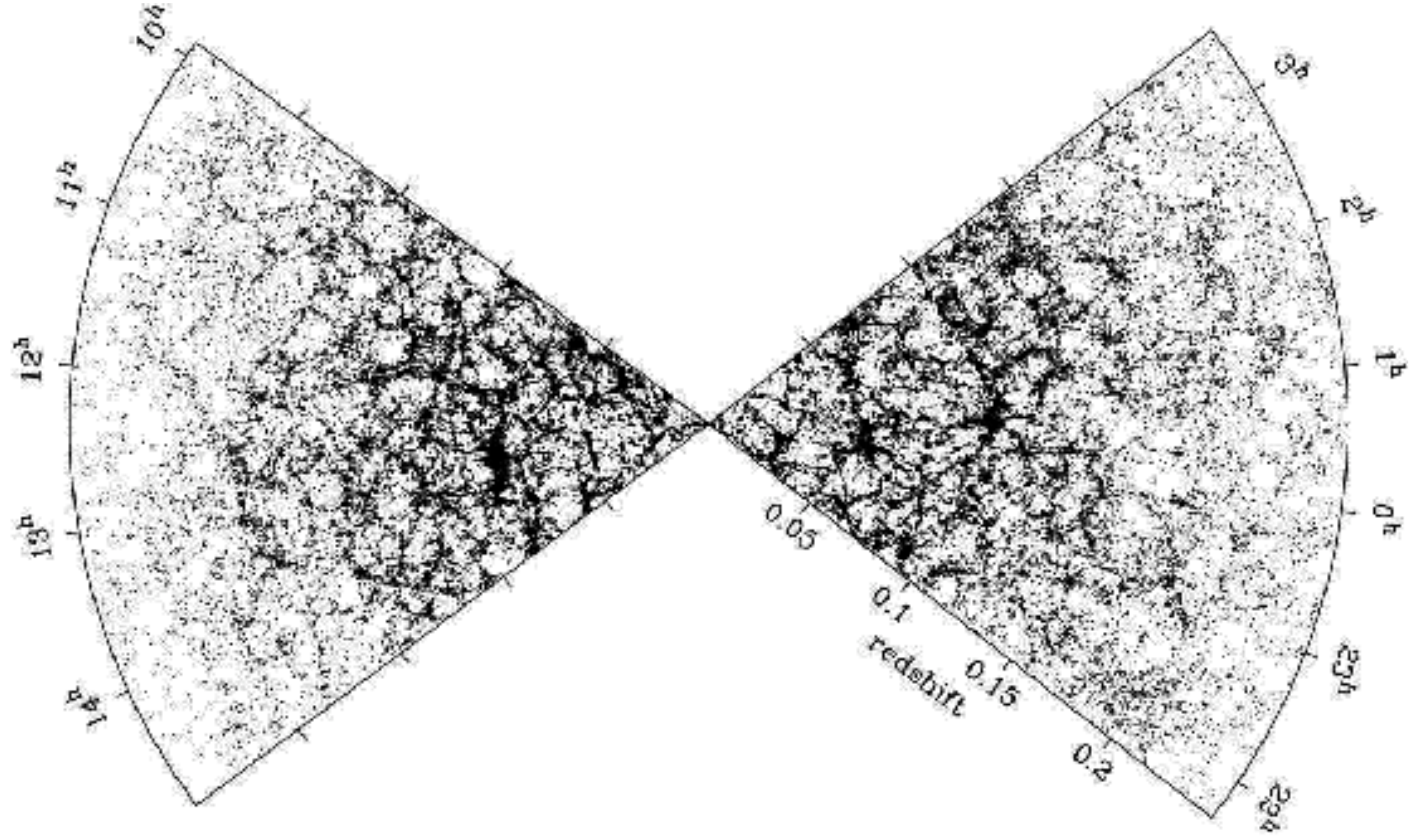

Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)

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.

- Latest “Union” supernova compilation (Kowalski et al.)

BAO in Galaxy Distribution

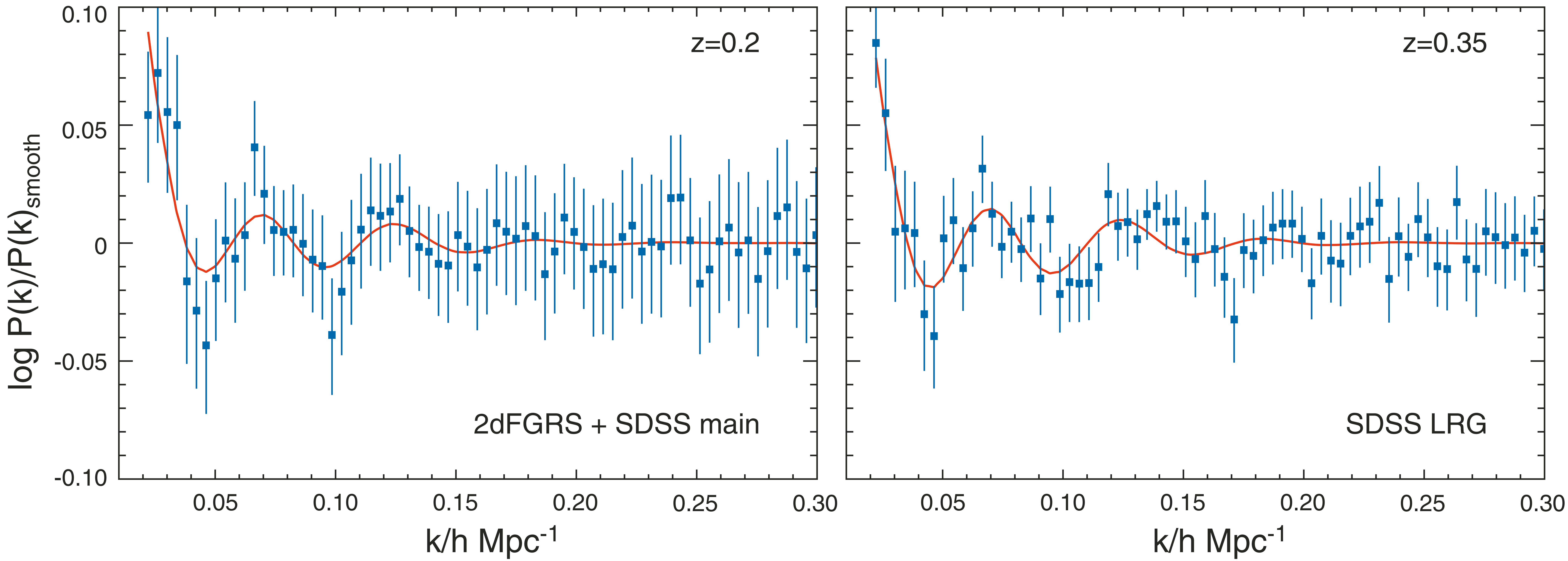
Tegmark et al.



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

BAO in Galaxy Distribution

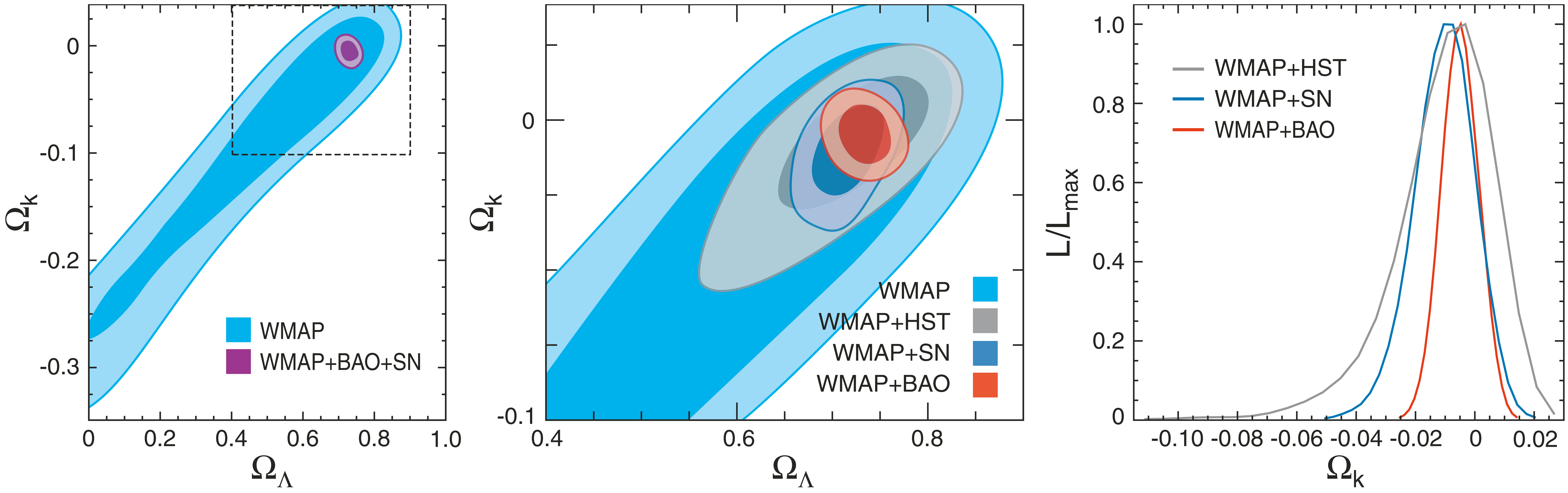
Dunkley et al.



- 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 ($\Omega_k<0$): $R>22h^{-1}$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.

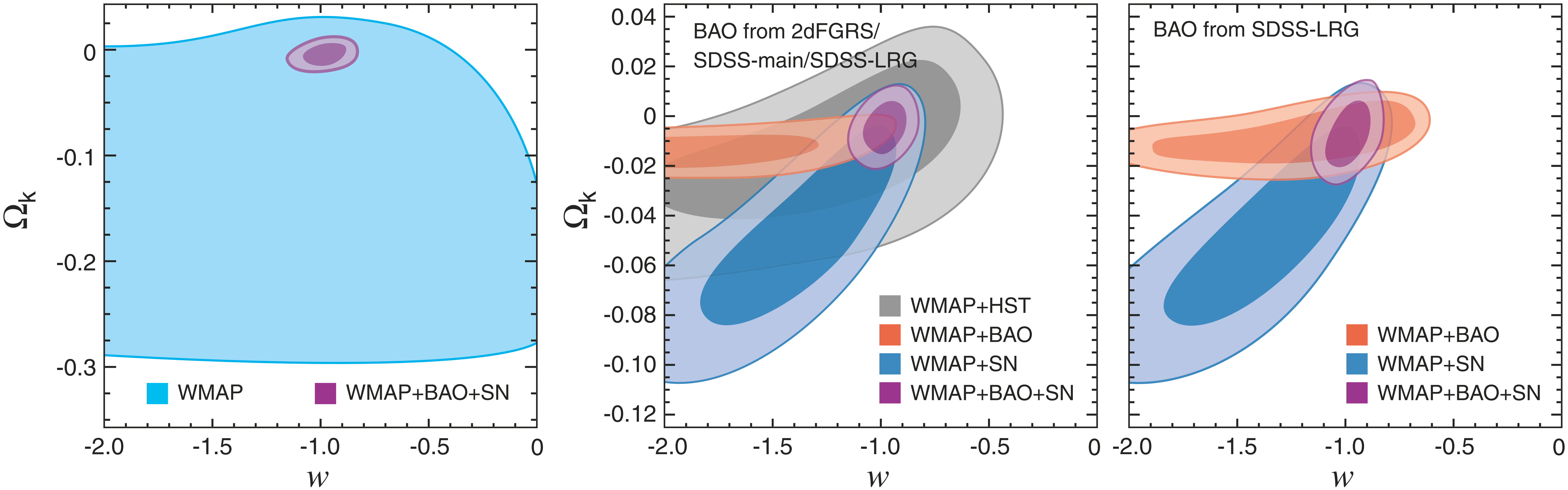
Komatsu et al.

How Long Did Inflation Last?

- The universe had expanded by $\mathbf{e^{Ntot}}$ during inflation.
    - Q. How long should inflation have lasted to explain the observed flatness of the universe?
    - A. $\mathbf{N_{total} > 36}$ + $\ln(T_{\rm reheating}/1\ \mathrm{TeV})$
    - A factor of 10 improvement in Ω_k will raise this lower limit by 1.2.
    - Lower if the reheating temperature was < 1 TeV
- This is the check list #1

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

Komatsu et al.



- WMAP+BAO -> Curvature; WMAP+SN -> w
- WMAP+BAO+SN -> Simultaneous limit
- **$-0.0179 < \Omega_k < 0.0081$** ; **$-0.14 < 1+w < 0.12$** (95% CL)

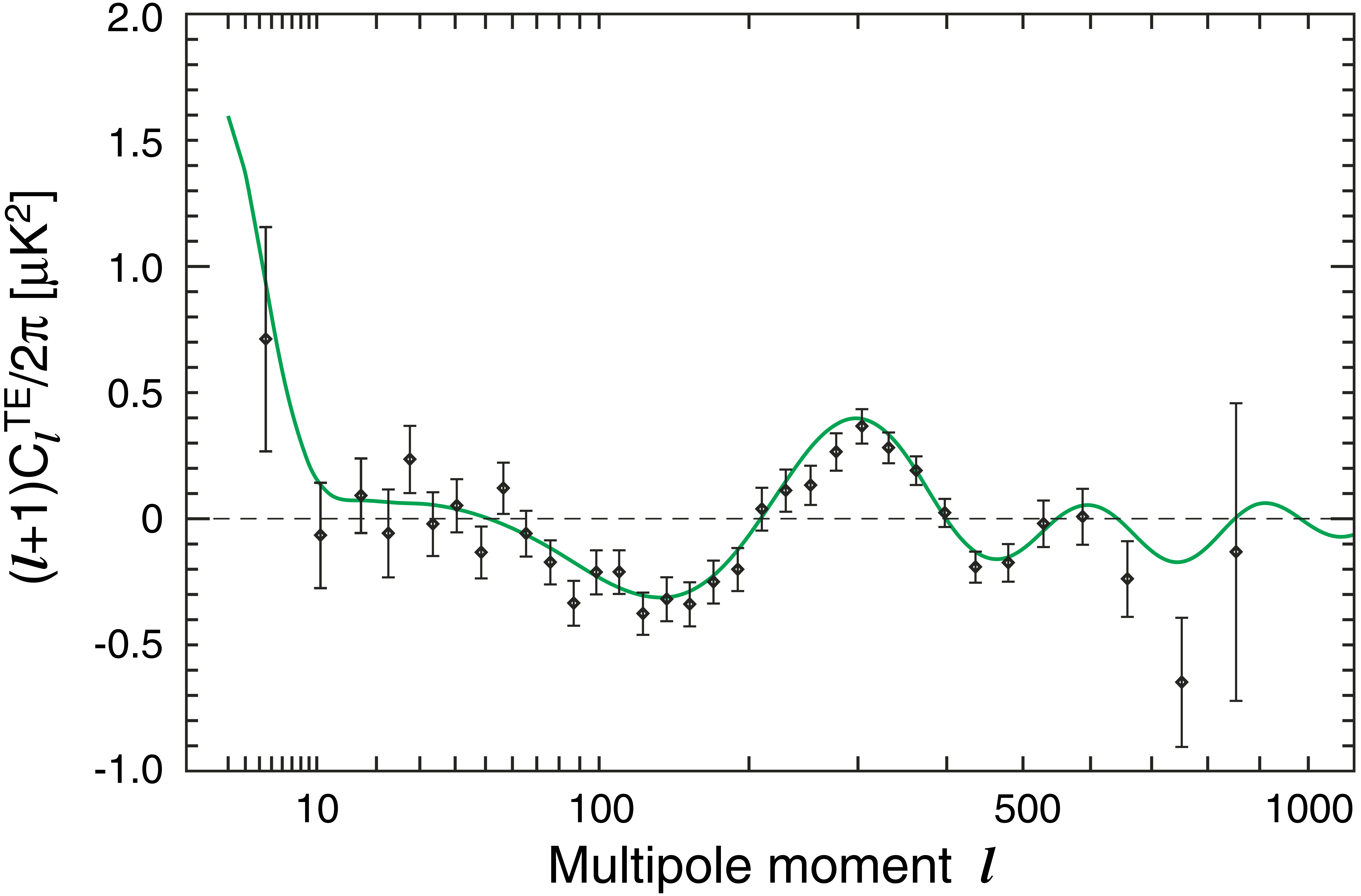
Komatsu et al.

Check List #2: Adiabaticity

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

Nolta et al.

WMAP 5-Year TE Power Spectrum



- The negative TE at l~100 is the distinctive signature of super-horizon adiabatic perturbations (Spergel & Zaldarriaga 1997)
- Non-adiabatic perturbations would fill in the trough, and shift the zeros.

Komatsu et al.

Axion Dark Matter?

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

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

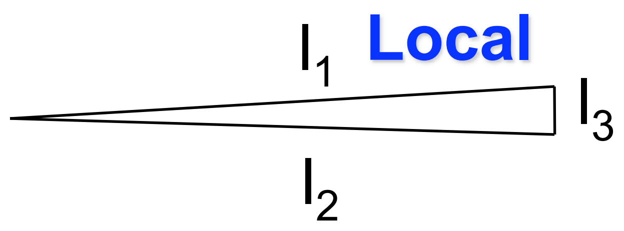
The non-adiabatic perturbations, combined with the expression for Ω_a, constrain $\Omega_a^{1/7}$.

Check list #3: Gaussianity

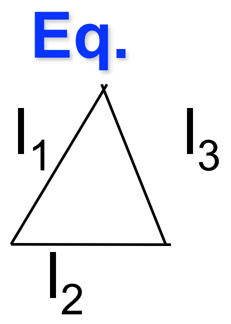
- In the simplest model of inflation, the distribution of primordial fluctuations is close to a Gaussian with random phases.
- The level of non-Gaussianity predicted by the simplest model is well below the current detection limit.
- A convincing detection of primordial non-Gaussianity will rule out most 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 $\mathbf{f_{NL}^{local}}$



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

Komatsu et al.

No Detection at >95%CL

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

- These numbers mean that the primordial curvature perturbations are Gaussian to **0.1% level**.
    - This result provides the strongest evidence for quantum origin of primordial fluctuations during inflation.

Dunkley et al.; Komatsu et al.

Check List #4: Scale Invariance

- For a power-law power spectrum (no $dn_s/d\ln k$):
  - WMAP-only: $n_s=0.963$ (+0.014) (-0.015)
  - WMAP+BAO+SN: $n_s=0.960 \pm 0.013$
    - **3.1 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)

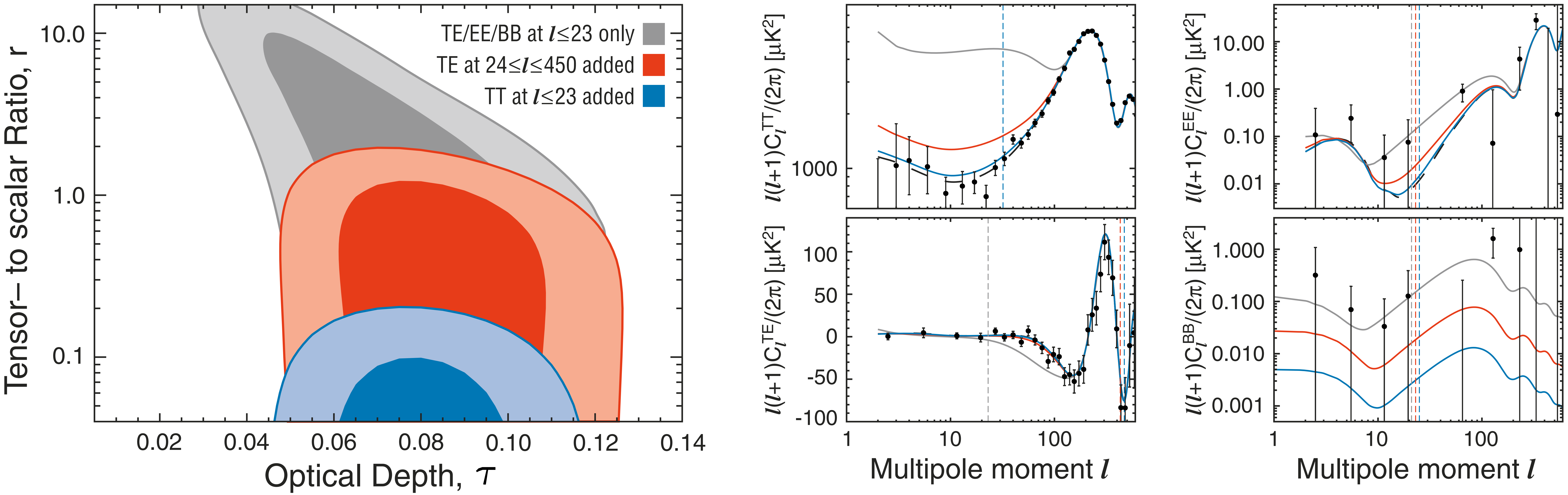
Check List #5: Gravitational Waves

- 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

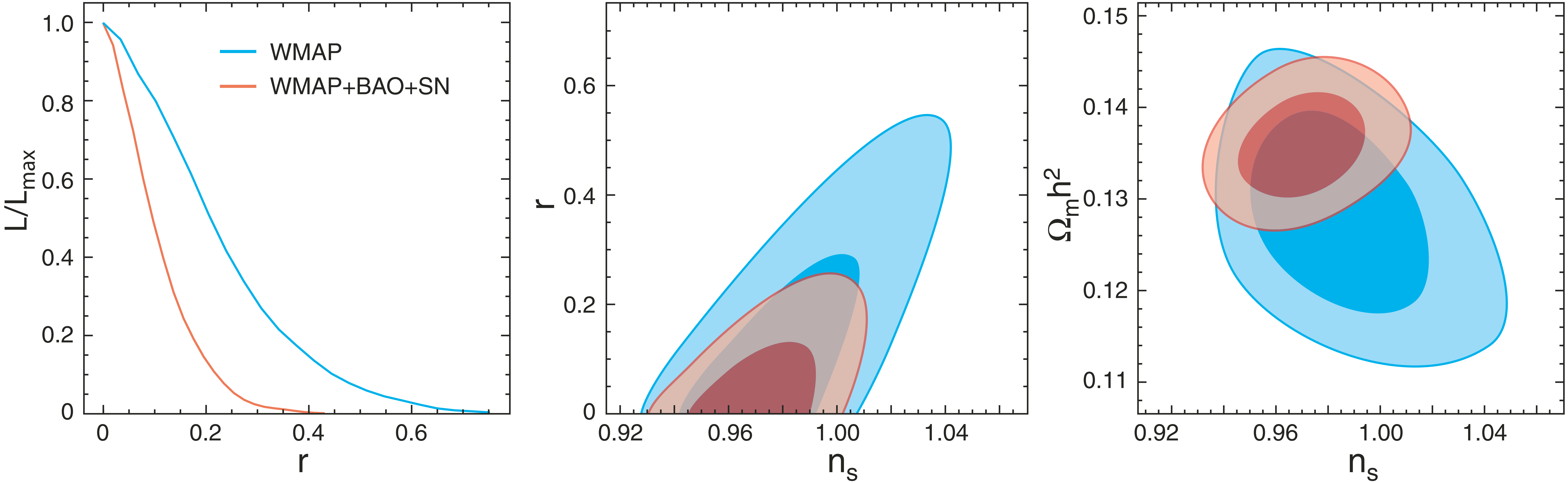
Komatsu et al.



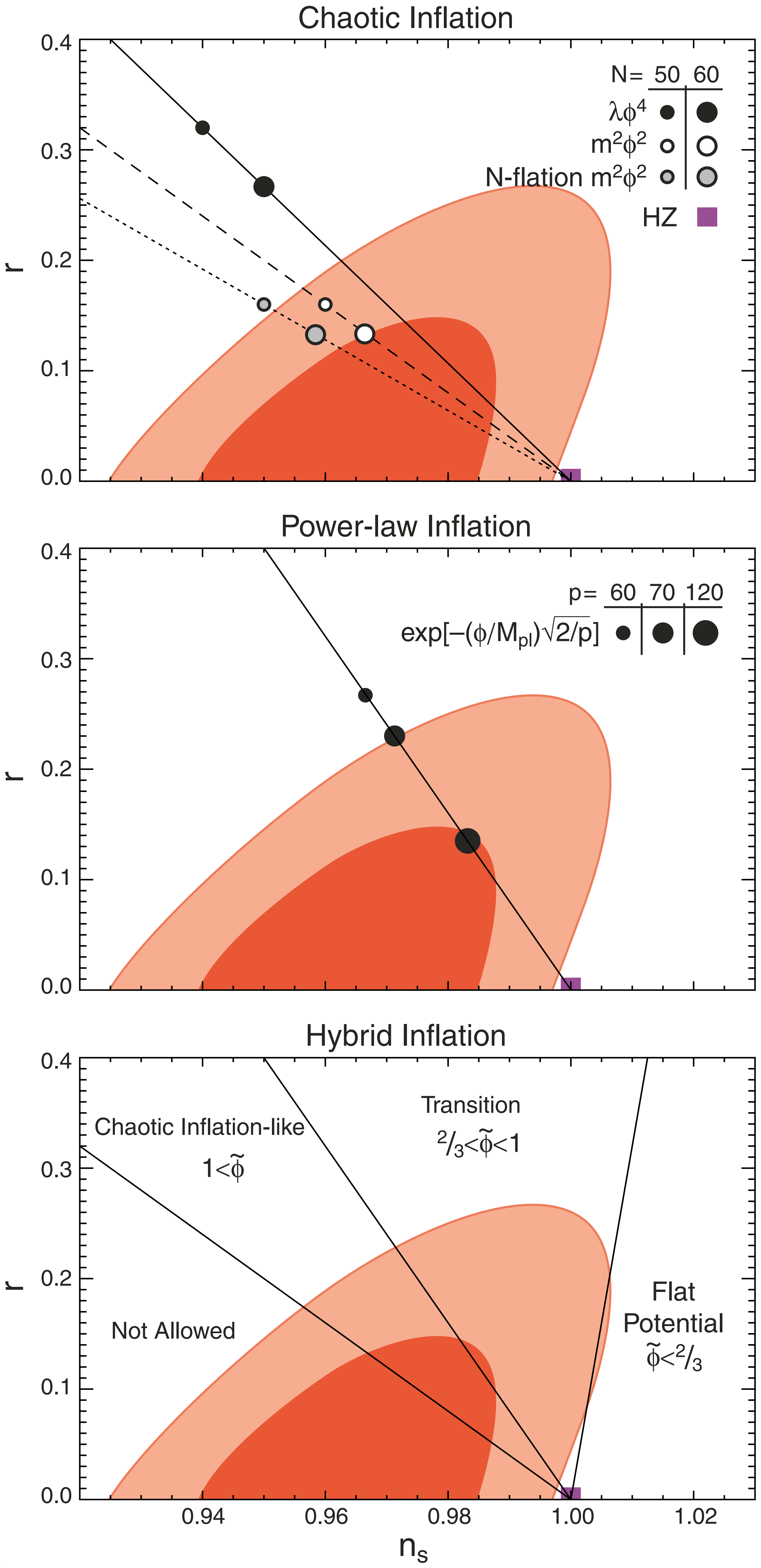
- If all the other parameters (n_s in particular) are fixed...
  - Low-l polarization gives r<20 (95% CL)
  - + high-l polarization gives r<2 (95% CL)
  - + low-l temperature gives r<0.2 (95% CL)

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) -> **$r<0.22$** (WMAP+BAO+SN)



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

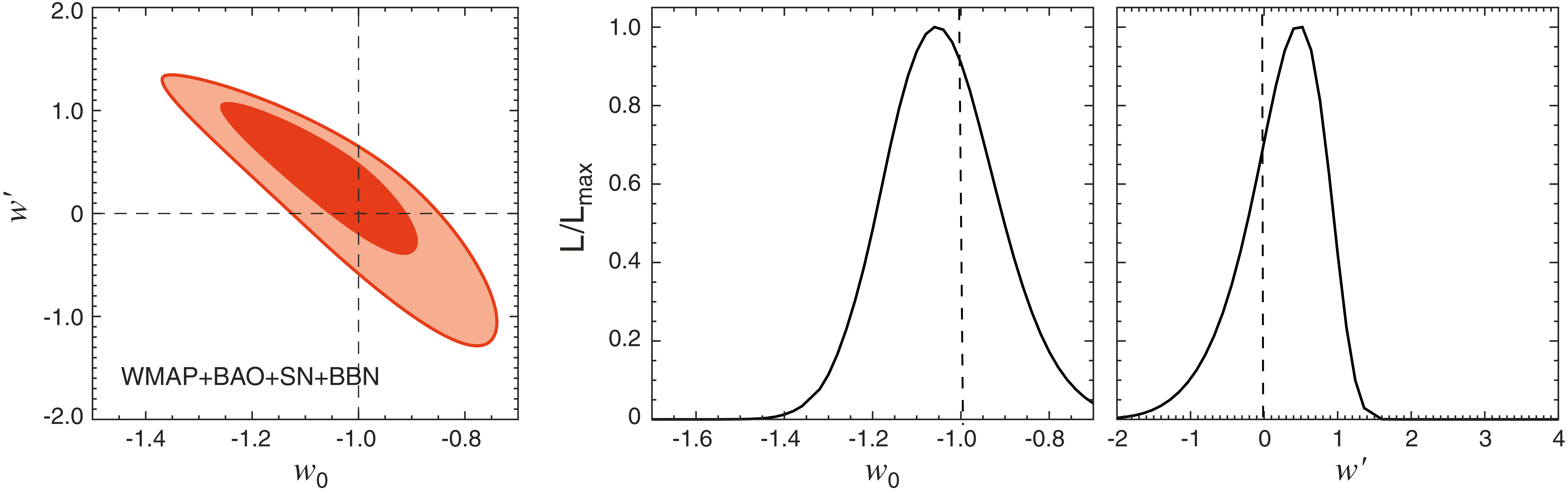
Komatsu et al.

Grading Inflation

- Flatness: $-0.0179 < \Omega_k < 0.0081$ (not assuming $w=-1$!)
- Non-adiabaticity: <8.9% (axion DM); <2.1% (curvaton DM)
- Non-Gaussianity: $-9 <$ Local < 111; $-151 <$ Equilateral < 253
- Tilt (for $r=0$): $n_s=0.960 \pm 0.013$ [68% CL]
- Gravitational waves: **$r < 0.22$**
  - $n_s=0.970 \pm 0.015$ [68% CL]
  - **$n_s>1$ disfavored at 95% CL regardless of r**

Komatsu et al.

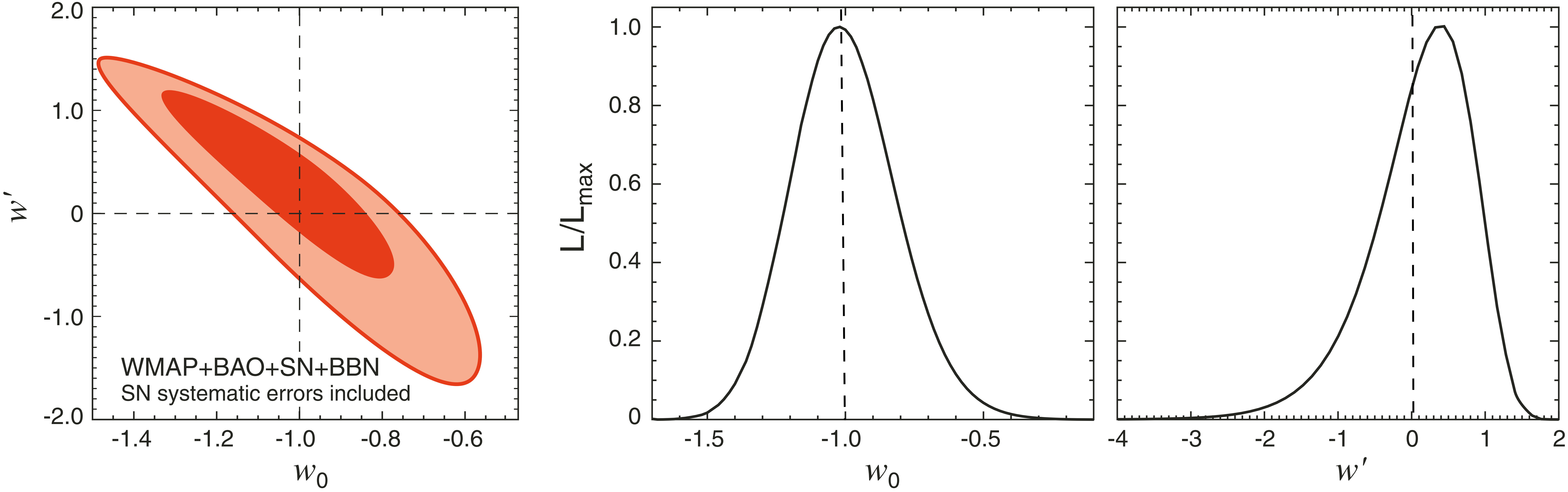
Dark Energy EOS: $w(z)=w_0+w'z/(1+z)$



- Dark energy is pretty consistent with cosmological constant: w_0=-1.04 +/- 0.13 & w'=0.24 +/- 0.55 (68%CL)

Komatsu et al.

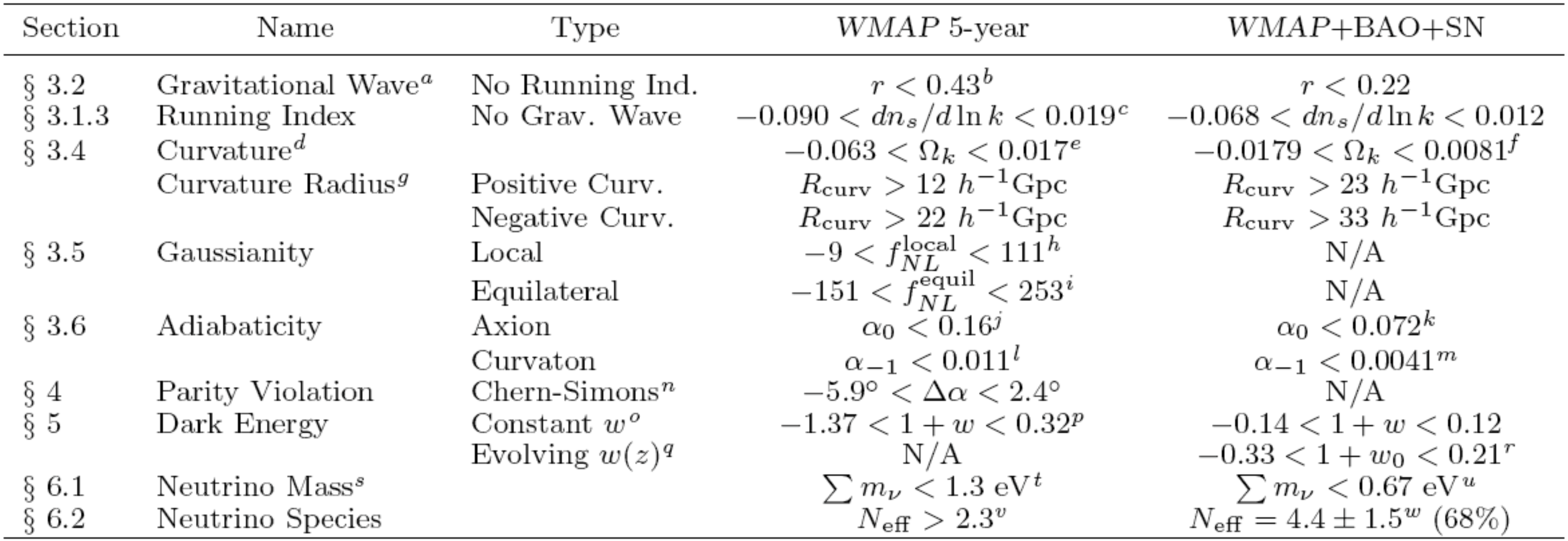
Dark Energy EOS: Including Sys. Err. in SN Ia



- Dark energy is pretty consistent with cosmological constant: w_0=-1.00 +/- 0.19 & w'=0.11 +/- 0.70 (68%CL)

Komatsu et al.

After the quest in the dark forest...

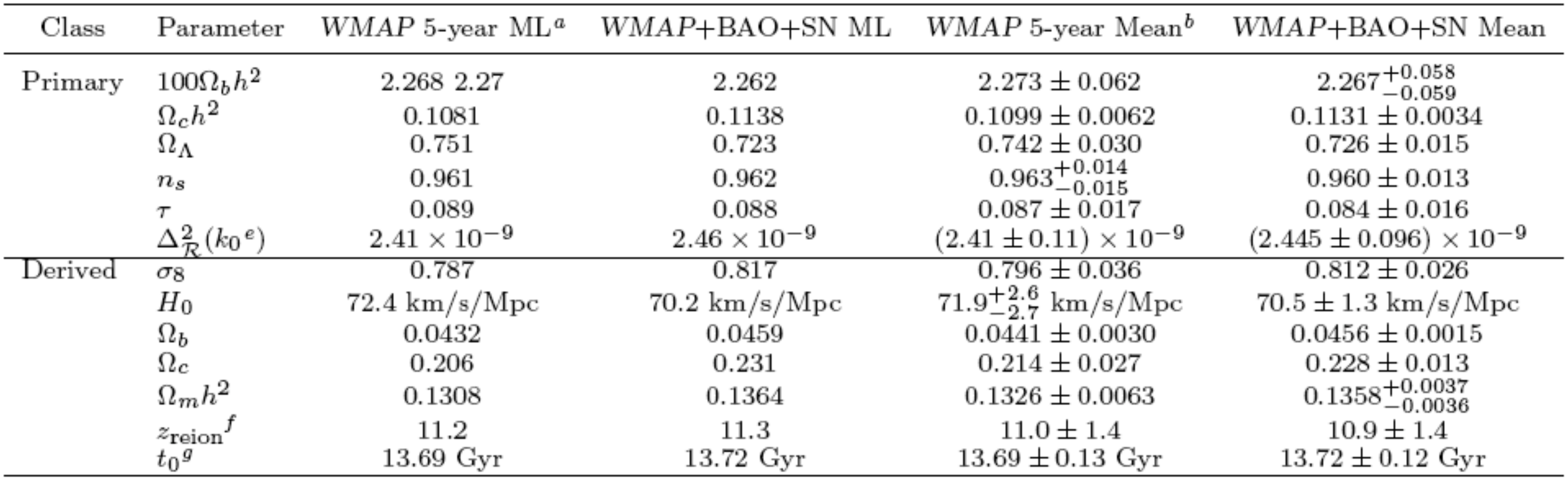


Section	Name	Type	*WMAP* 5-year	*WMAP*+BAO+SN
§ 3.2	Gravitational Wave[a]	No Running Ind.	$r < 0.43$[b]	$r < 0.22$
§ 3.1.3	Running Index	No Grav. Wave	$-0.090 < dn_s/d\ln k < 0.019$[c]	$-0.068 < dn_s/d\ln k < 0.012$
§ 3.4	Curvature[d]		$-0.063 < \Omega_k < 0.017$[e]	$-0.0179 < \Omega_k < 0.0081$[f]
	Curvature Radius[g]	Positive Curv.	$R_{\rm curv} > 12\ h^{-1}{\rm Gpc}$	$R_{\rm curv} > 23\ h^{-1}{\rm Gpc}$
		Negative Curv.	$R_{\rm curv} > 22\ h^{-1}{\rm Gpc}$	$R_{\rm curv} > 33\ h^{-1}{\rm Gpc}$
§ 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]	$\alpha_0 < 0.072$[k]
		Curvaton	$\alpha_{-1} < 0.011$[l]	$\alpha_{-1} < 0.0041$[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]	$-0.14 < 1+w < 0.12$
		Evolving $w(z)$[q]	N/A	$-0.33 < 1+w_0 < 0.21$[r]
§ 6.1	Neutrino Mass[s]		$\sum m_\nu < 1.3$ eV[t]	$\sum m_\nu < 0.67$ eV[u]
§ 6.2	Neutrino Species		$N_{\rm eff} > 2.3$[v]	$N_{\rm eff} = 4.4 \pm 1.5$[w] (68%)

- No significant deviation from the simplest, 6-parameter ΛCDM model has been found.

Komatsu et al.

And, we ended up here again...



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 2.27	2.262	2.273 ± 0.062	$2.267^{+0.058}_{-0.059}$
	$\Omega_c h^2$	0.1081	0.1138	0.1099 ± 0.0062	0.1131 ± 0.0034
	Ω_Λ	0.751	0.723	0.742 ± 0.030	0.726 ± 0.015
	n_s	0.961	0.962	$0.963^{+0.014}_{-0.015}$	0.960 ± 0.013
	τ	0.089	0.088	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	2.41×10^{-9}	2.46×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.445 \pm 0.096) \times 10^{-9}$
Derived	σ_8	0.787	0.817	0.796 ± 0.036	0.812 ± 0.026
	H_0	72.4 km/s/Mpc	70.2 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.5 ± 1.3 km/s/Mpc
	Ω_b	0.0432	0.0459	0.0441 ± 0.0030	0.0456 ± 0.0015
	Ω_c	0.206	0.231	0.214 ± 0.027	0.228 ± 0.013
	$\Omega_m h^2$	0.1308	0.1364	0.1326 ± 0.0063	$0.1358^{+0.0037}_{-0.0036}$
	$z_{\mathrm{reion}}{}^f$	11.2	11.3	11.0 ± 1.4	10.9 ± 1.4
	$t_0{}^g$	13.69 Gyr	13.72 Gyr	13.69 ± 0.13 Gyr	13.72 ± 0.12 Gyr

ΛCDM: Cosmologist’s Nightmare

Summary

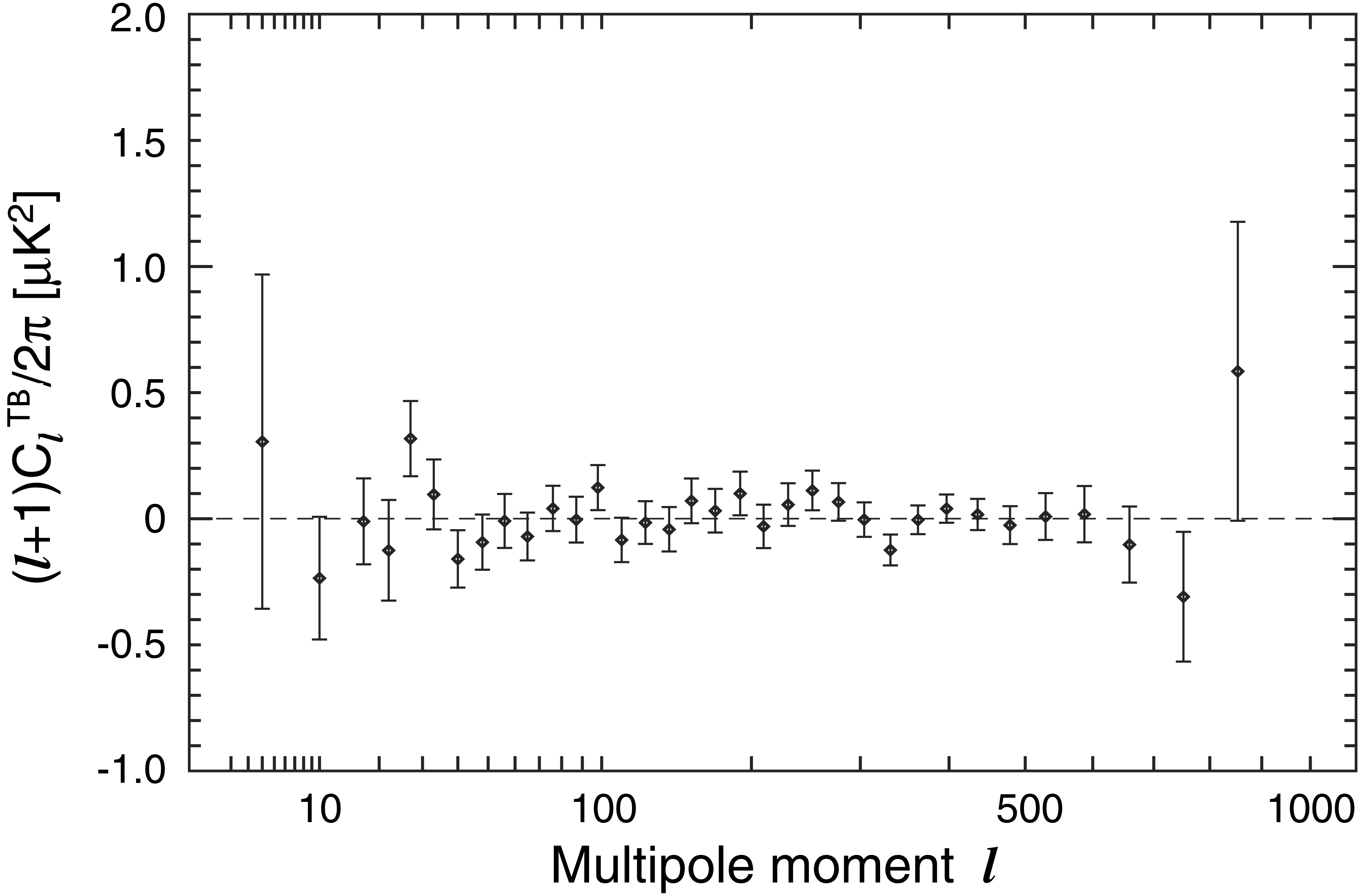
- A simple, yet *annoying* ΛCDM still fits the WMAP data, as well as the other astrophysical data sets.
- **We did everything we could do to find deviations from ΛCDM, but failed.**
  - Bad news... we still don't know what DE or DM is.
- Significant improvements in limits on the deviations
  - Most notably, $r<0.22$ (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!

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.

Probing Parity Violation

Nolta et al.



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

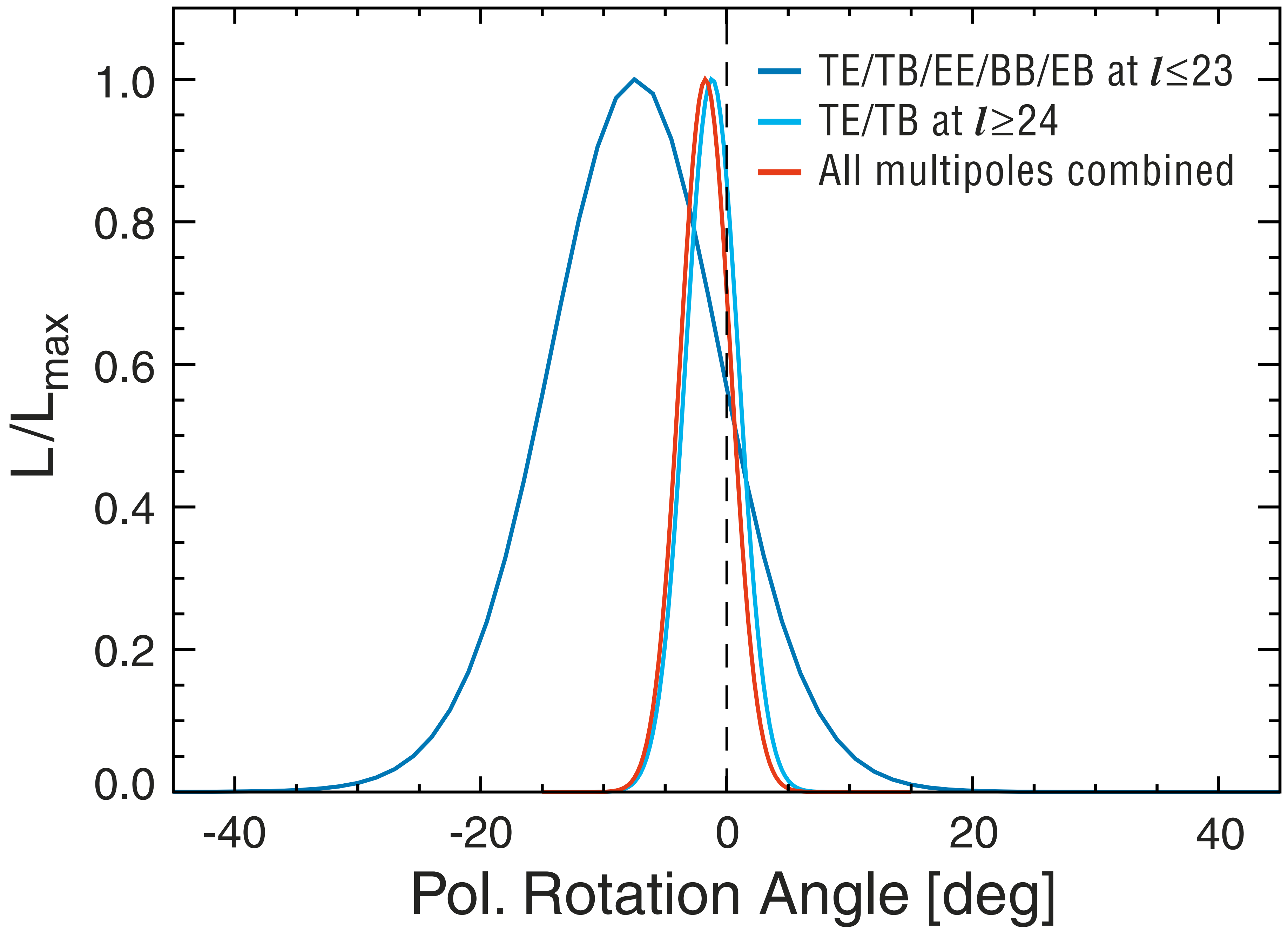
Lue, Wang & Kamionkowski (1999); Feng et al. (2005)

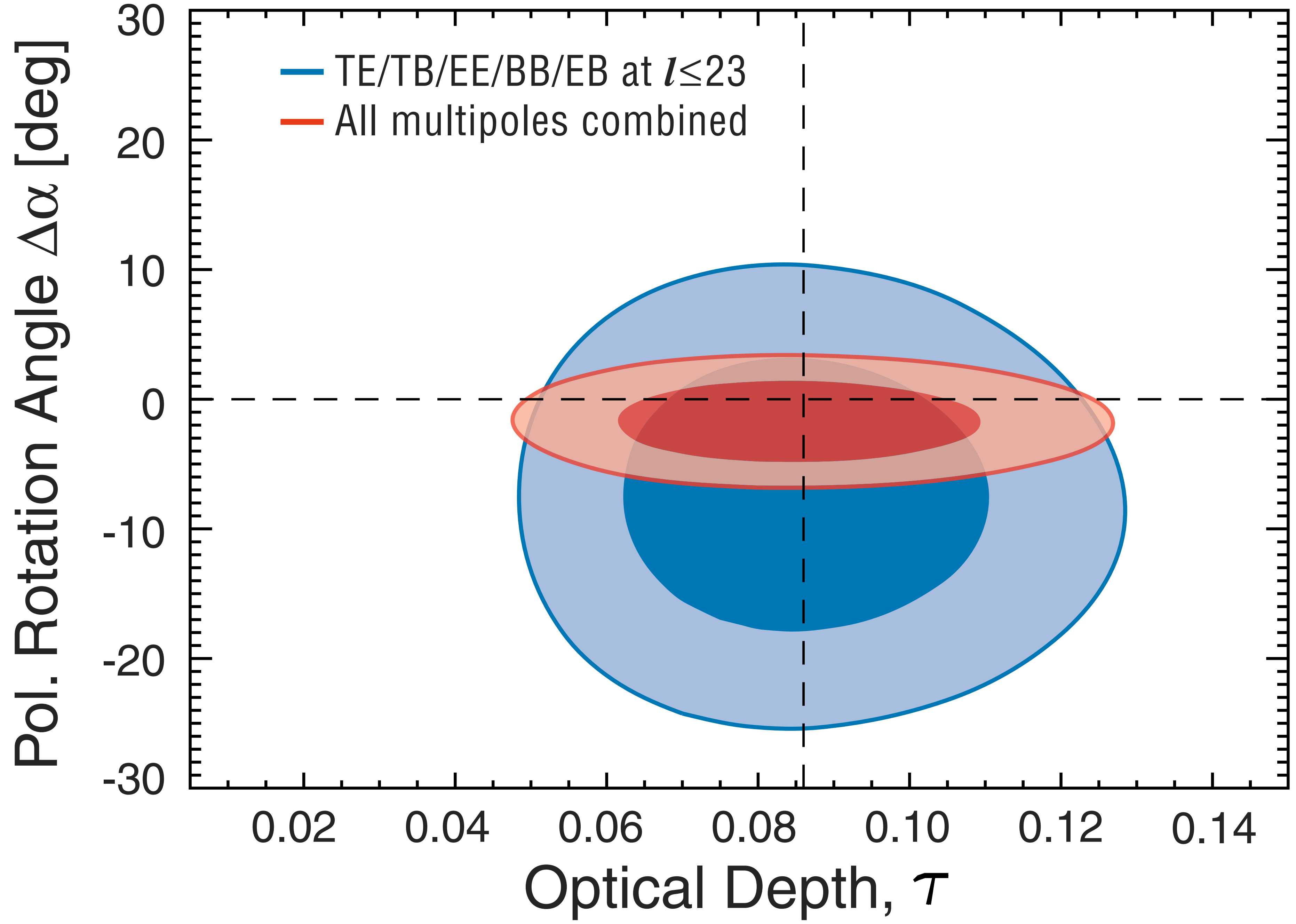
E -> B

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

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

Komatsu et al.

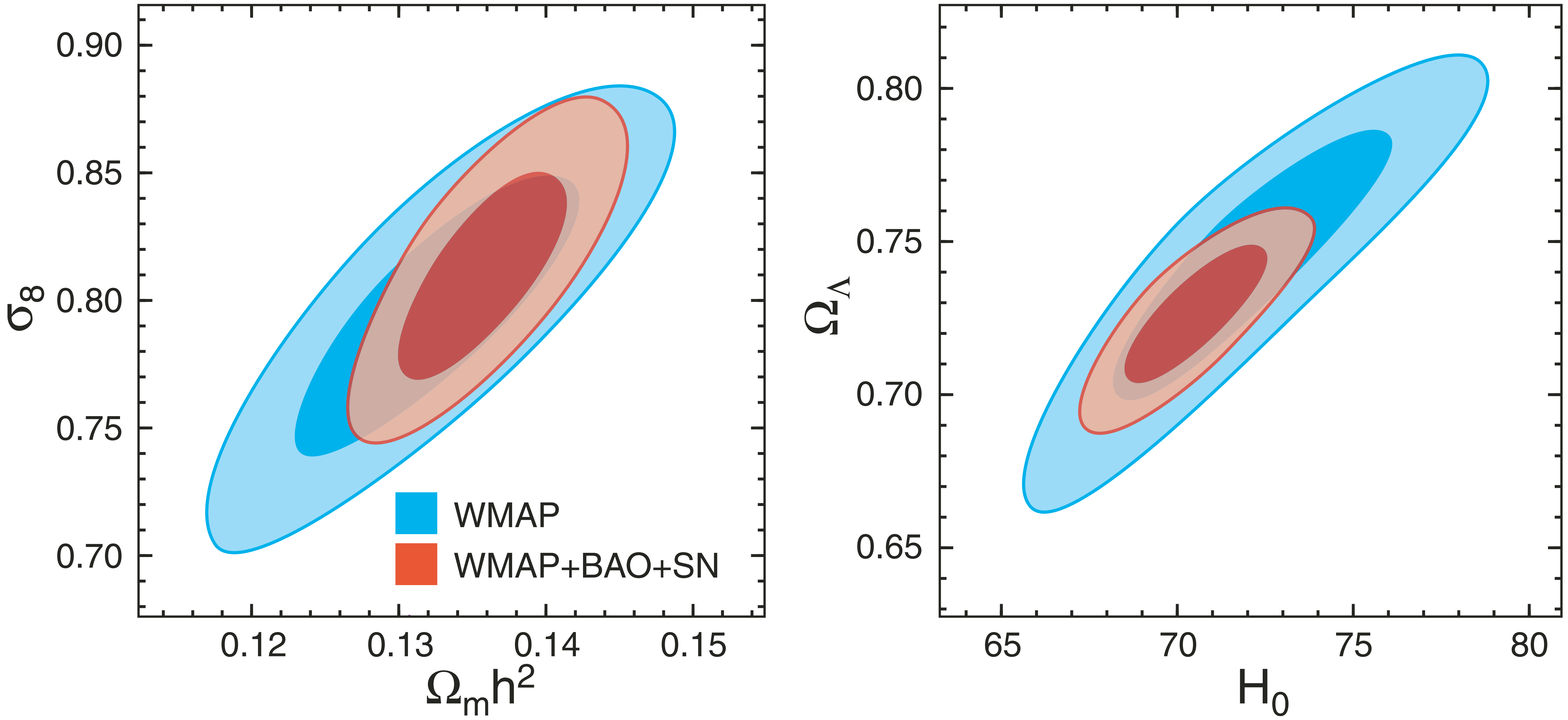




- **$\Delta\alpha$=(-1.7 +/- 2.1) degrees (68% CL)**
- Comparable to the astrophysical constraint from quasars and radio galaxies
    - $\Delta\alpha$=(-0.6 +/- 1.5) degrees (68% CL) (Carroll 1998)
- But, note the difference in path length!

Komatsu et al.

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.