



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

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CASPER Seminar, Baylor Univ., January 23, 2009

Texas Cosmology Center (TCC)

The University of Texas Austin

- The new Cosmology Center, founded in January 2009, at the University of Texas at Austin!

Research Unit, Texas Cosmology Center

Astronomy

Volker Bromm

Karl Gebhardt

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Paul Shapiro

Physics

Duane Dicus

Jacques Distler

Willy Fischler

Vadim Kaplunovsky

Sonia Paban

Steven Weinberg

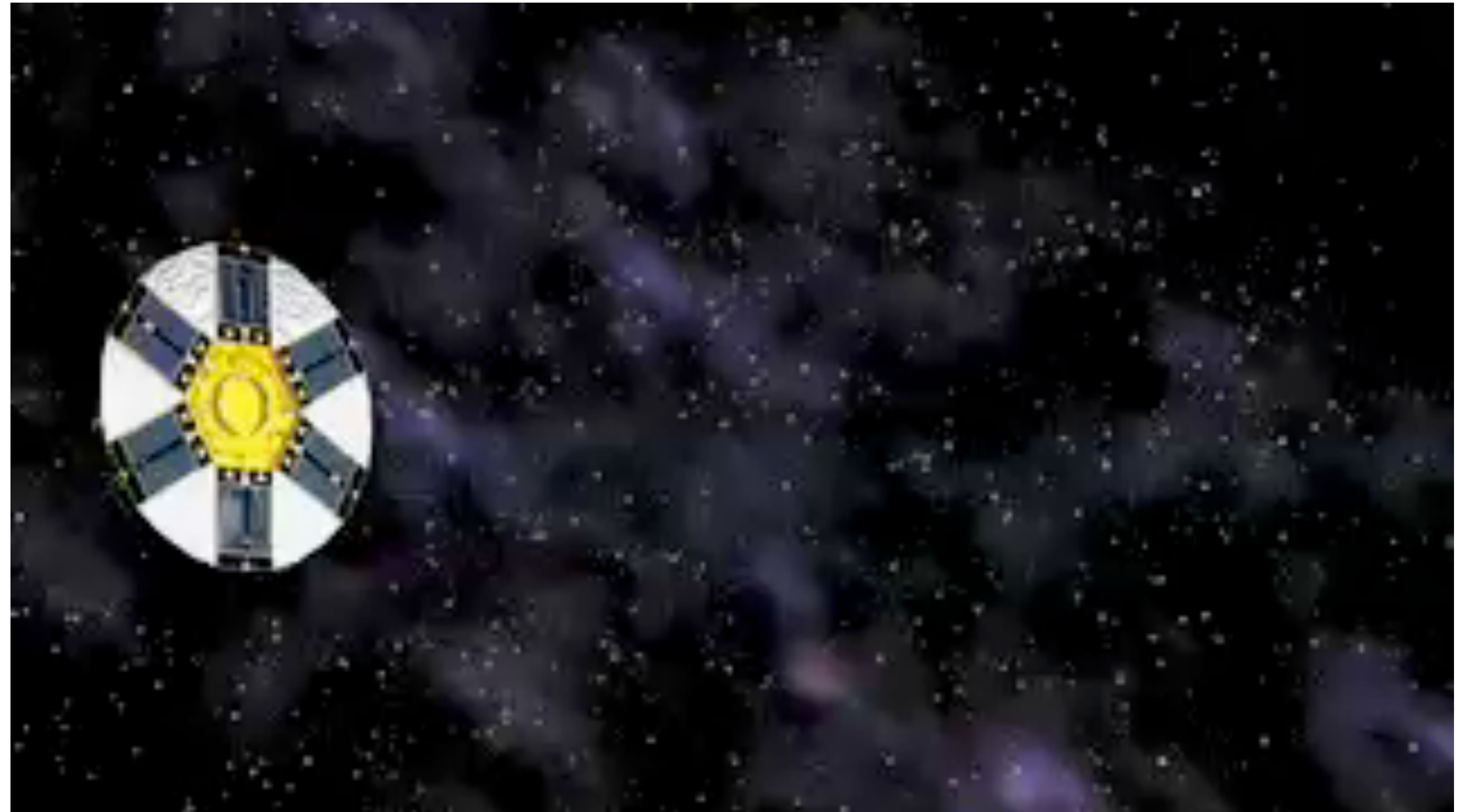
WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

February 2003:
The first-year data
release

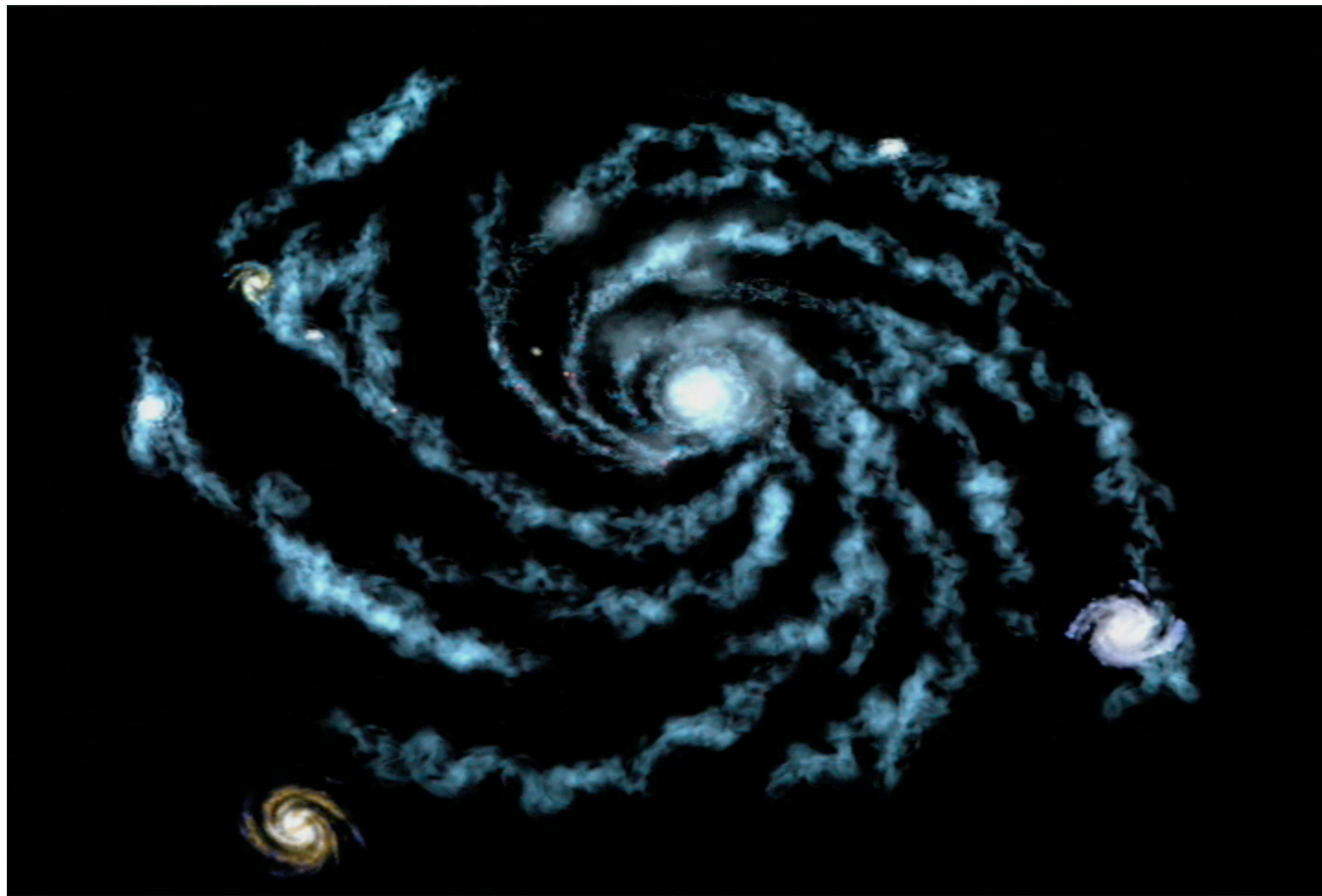
March 2006:
The three-year data
release

**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

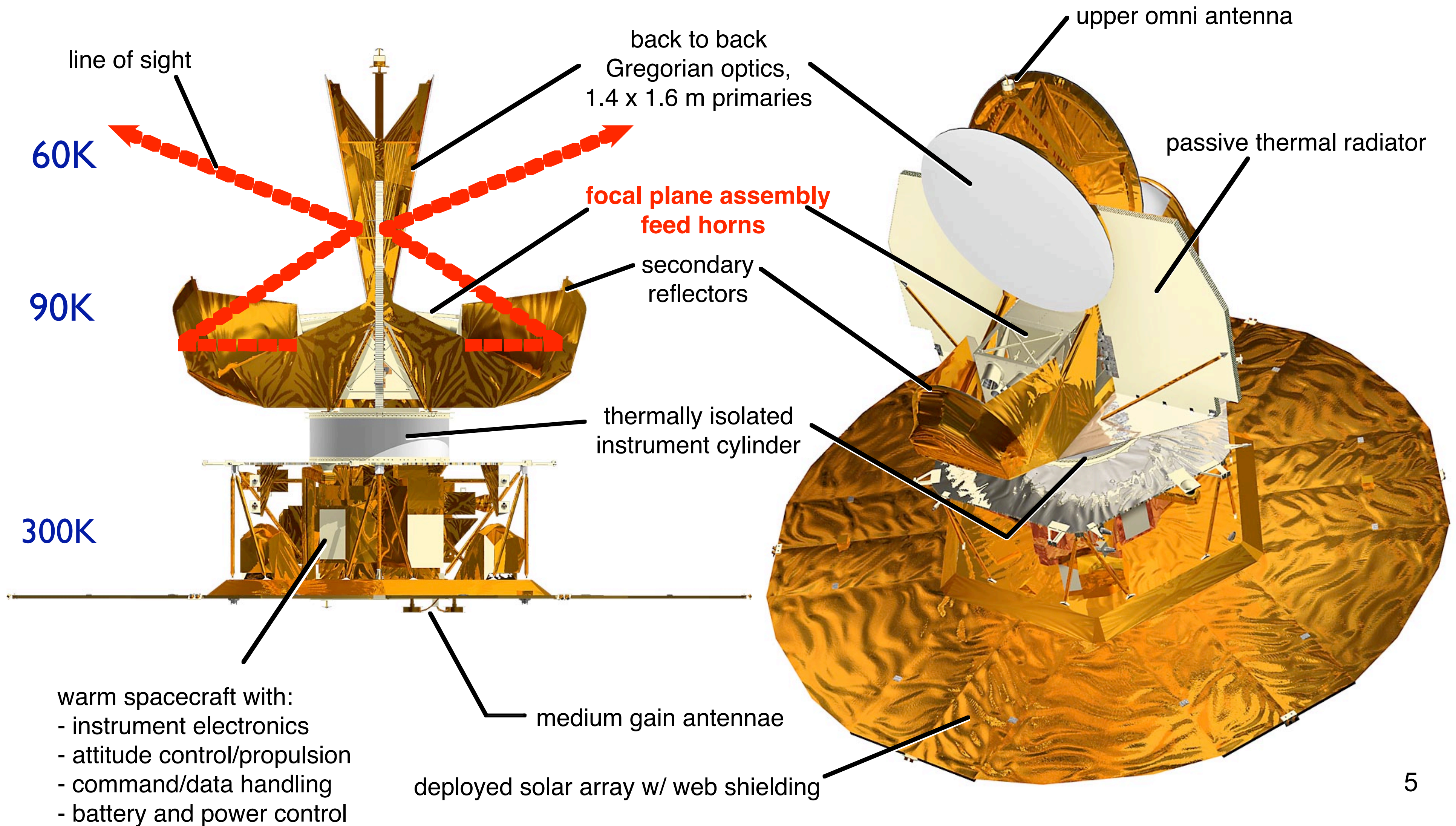
WMAP Measures Microwaves From the Universe



- 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**⁴

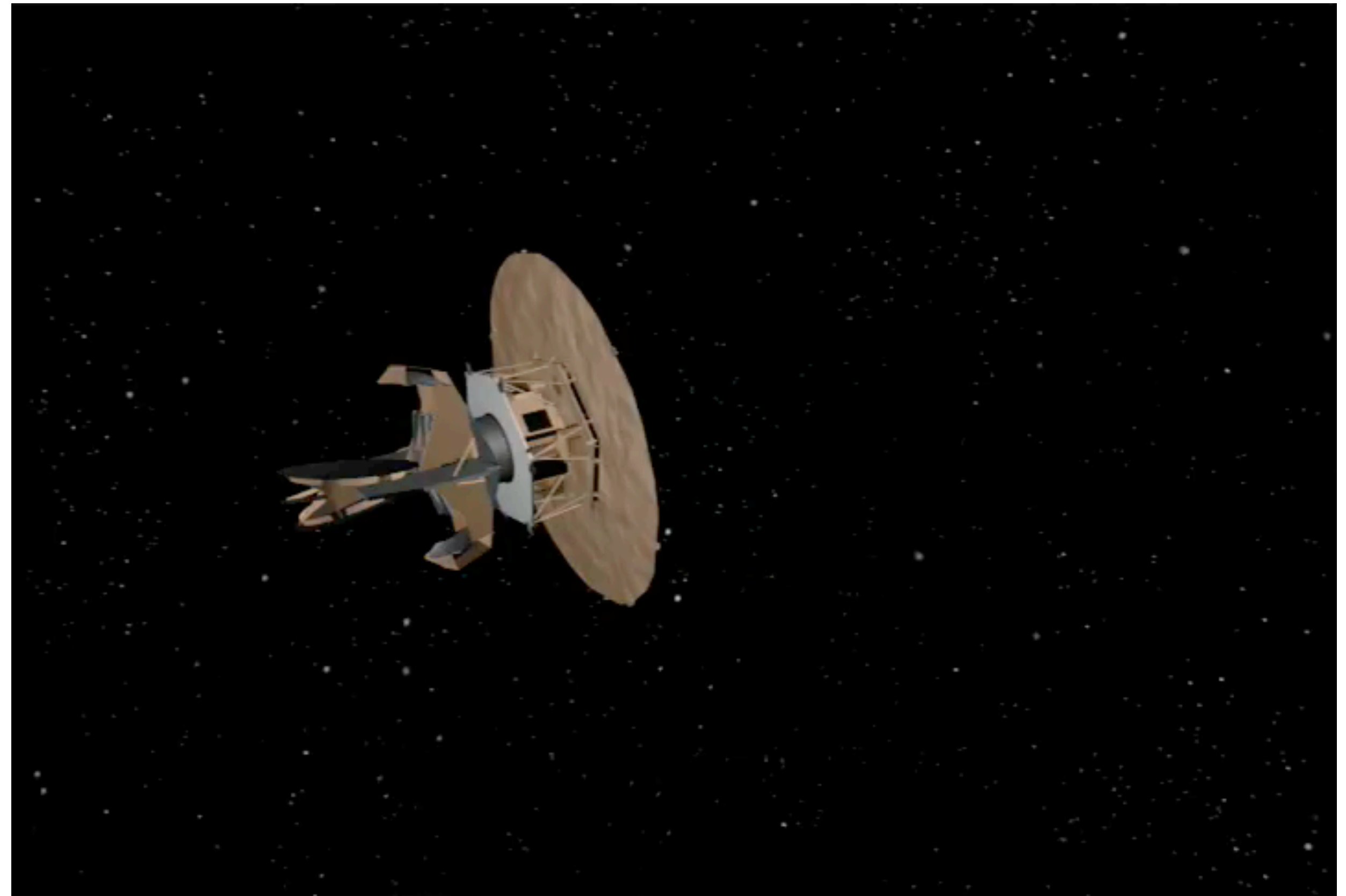
WMAP Spacecraft

Radiative Cooling: No Cryogenic System

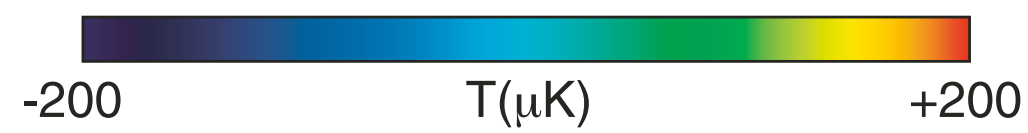
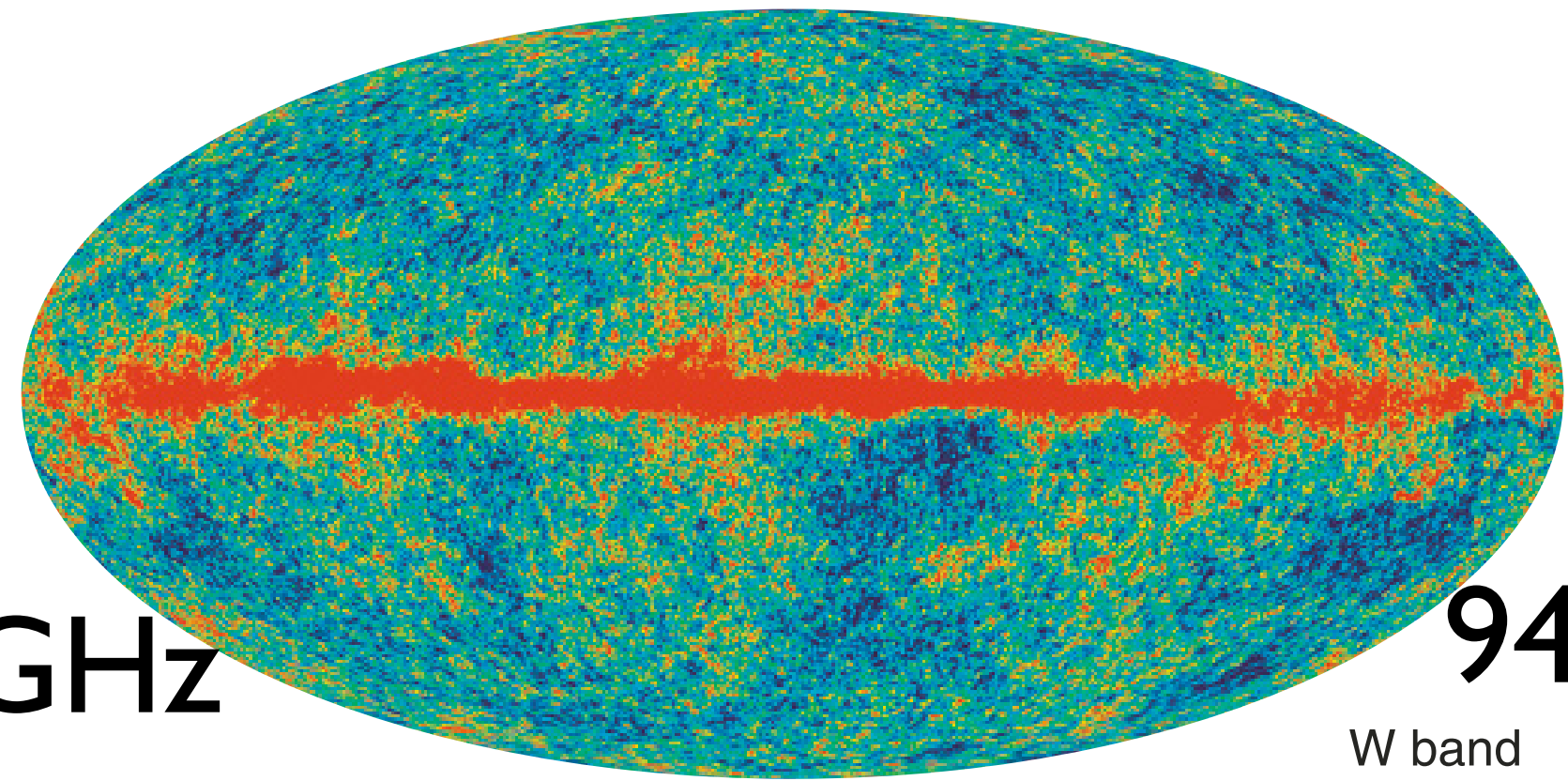
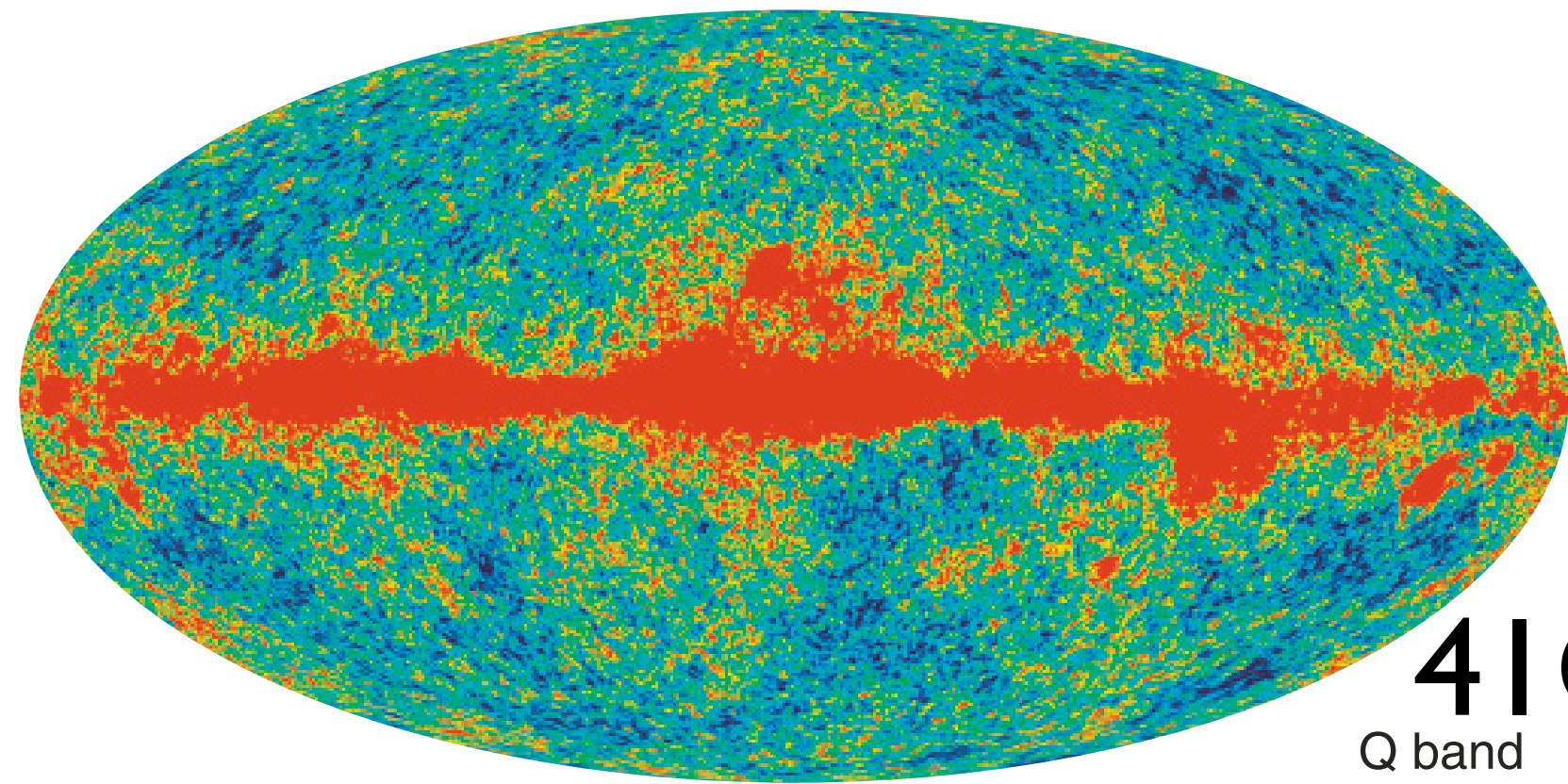
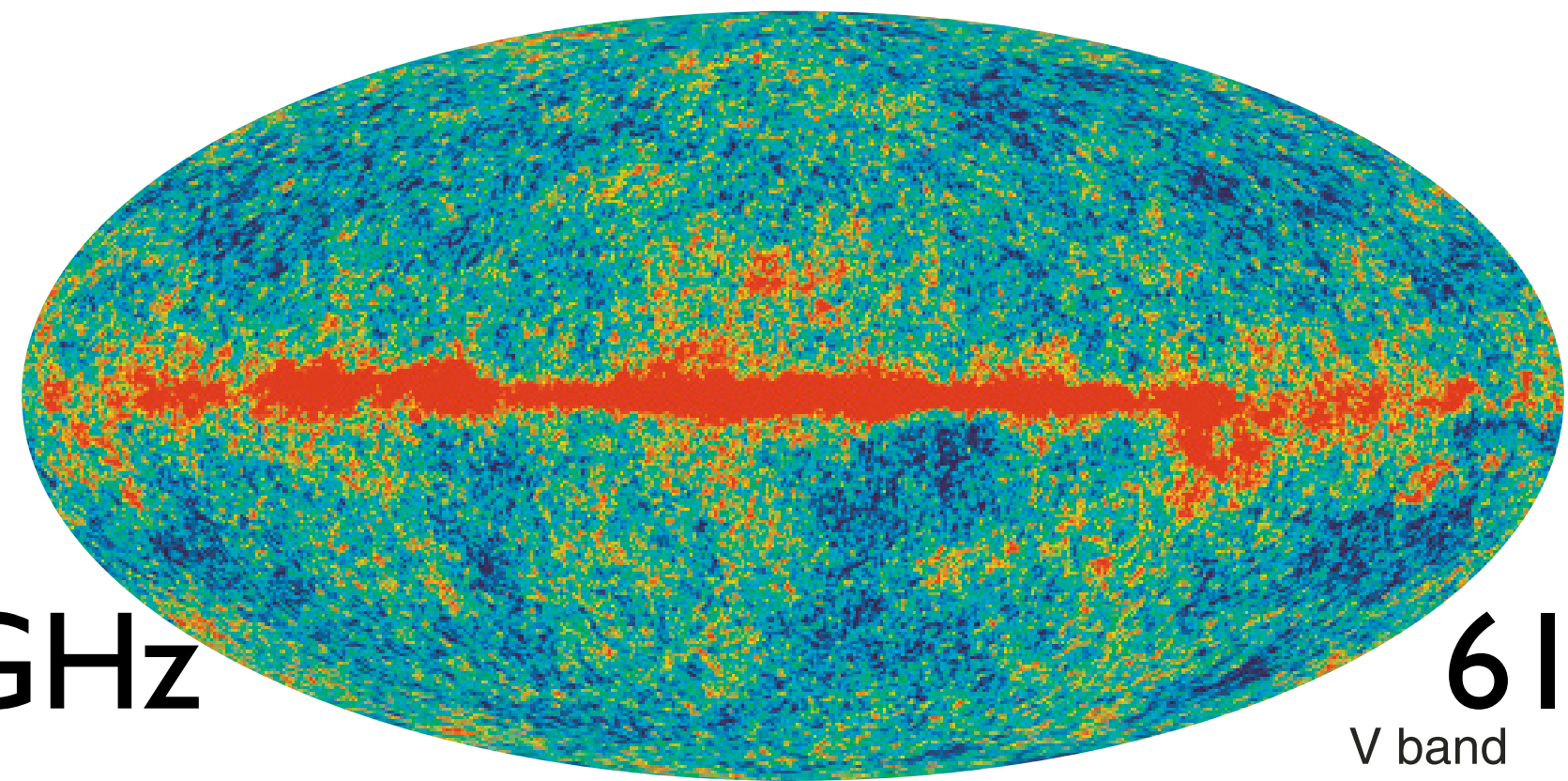
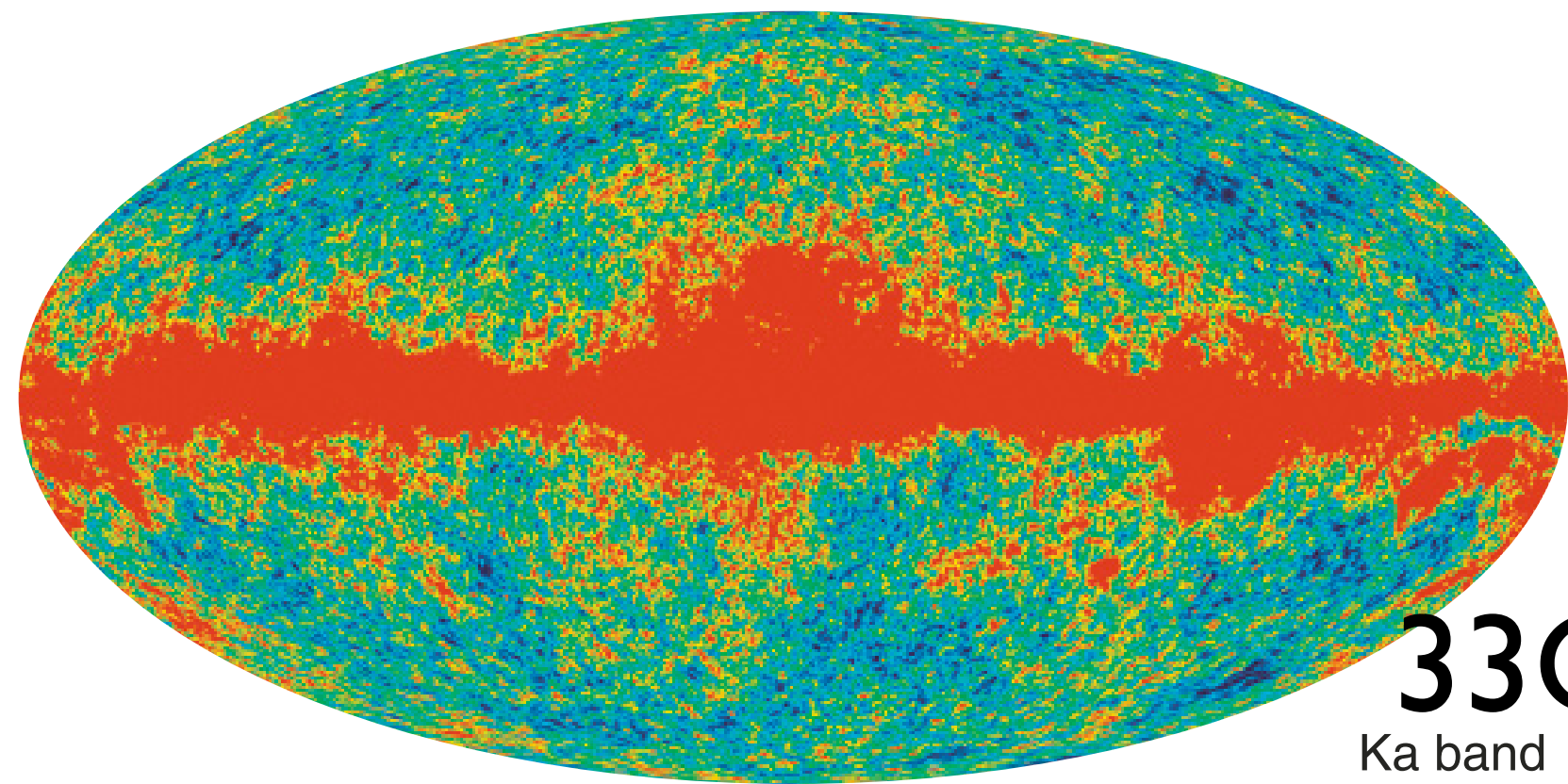
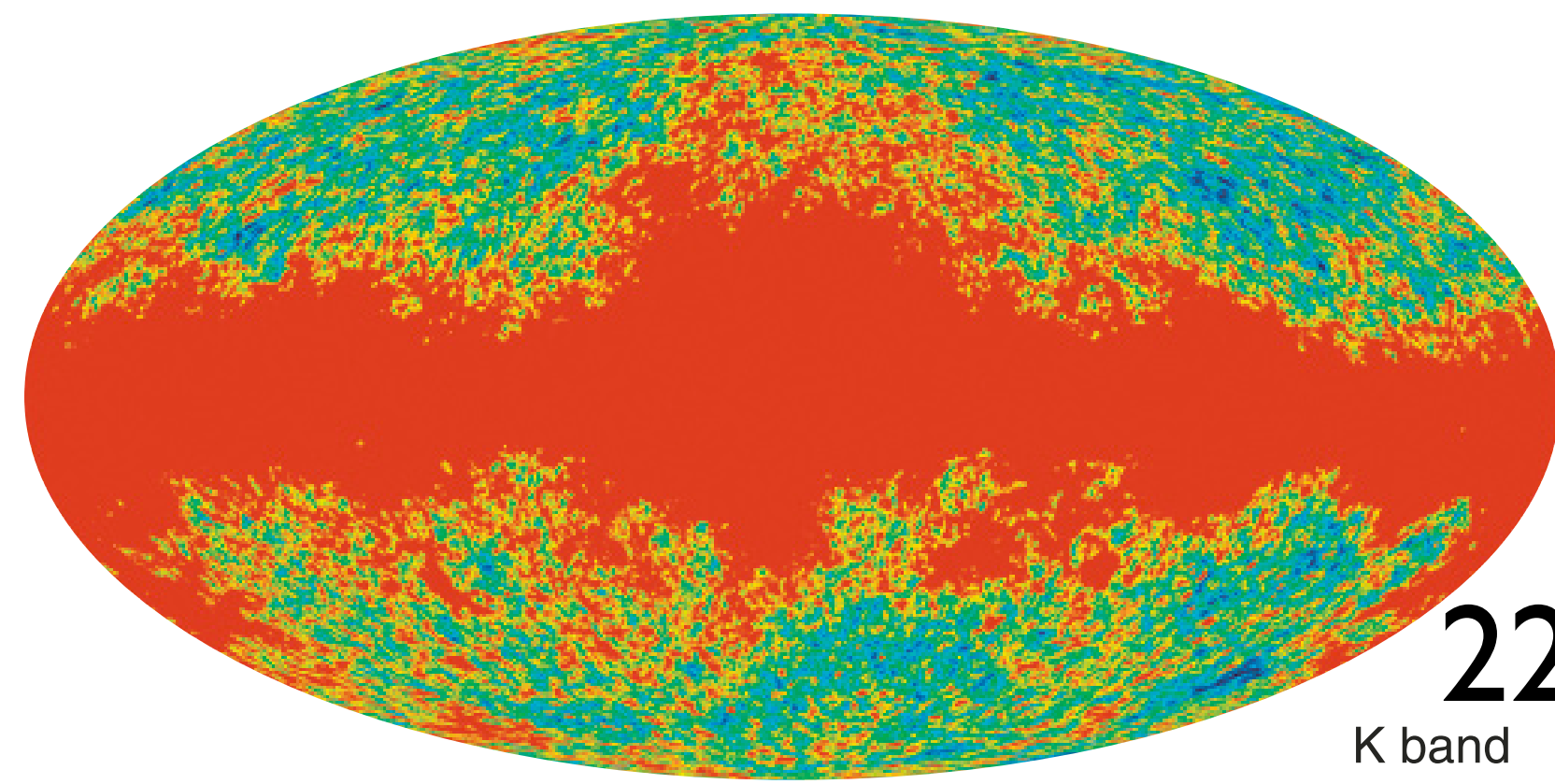


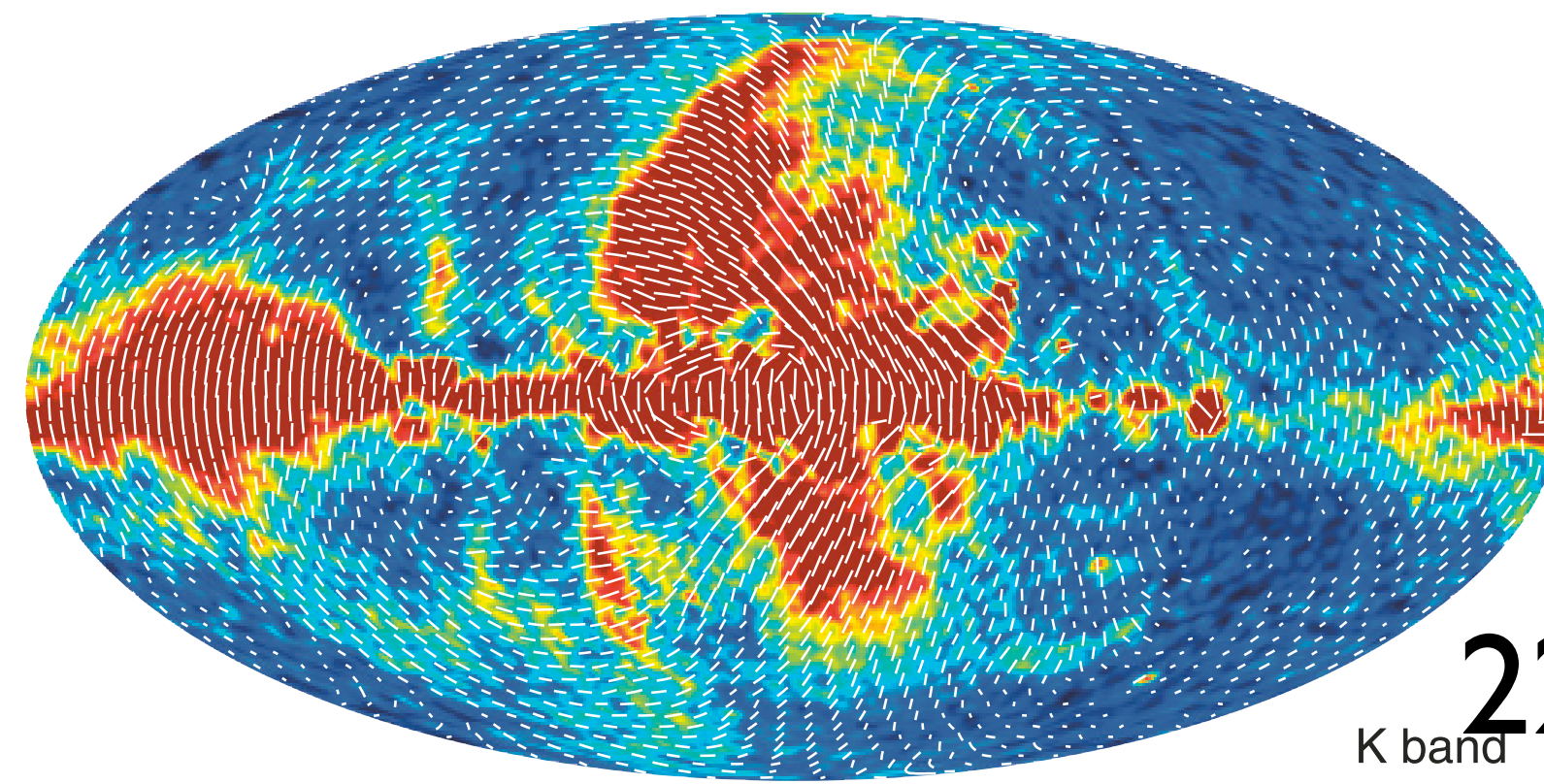
Journey Backwards in Time

- 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

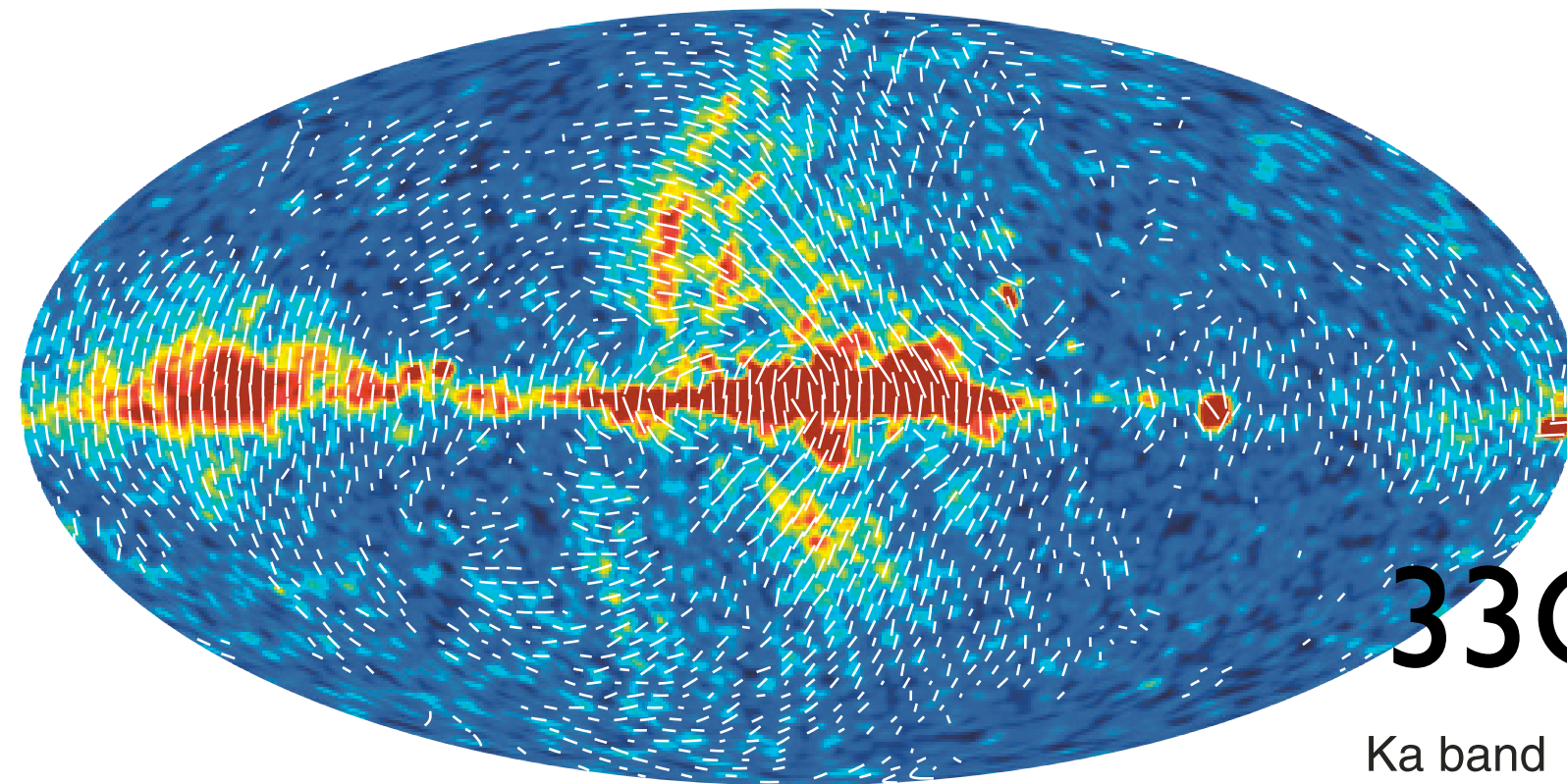
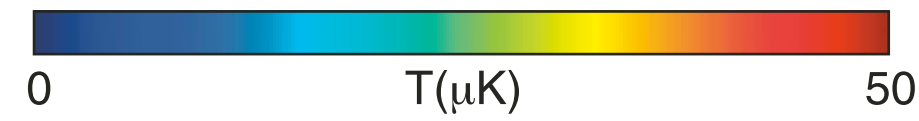


- CMB photons, after released from the cosmic plasma “soup,” traveled for **13.7 billion years** to reach us.
- CMB collects information about the Universe as it travels through it.

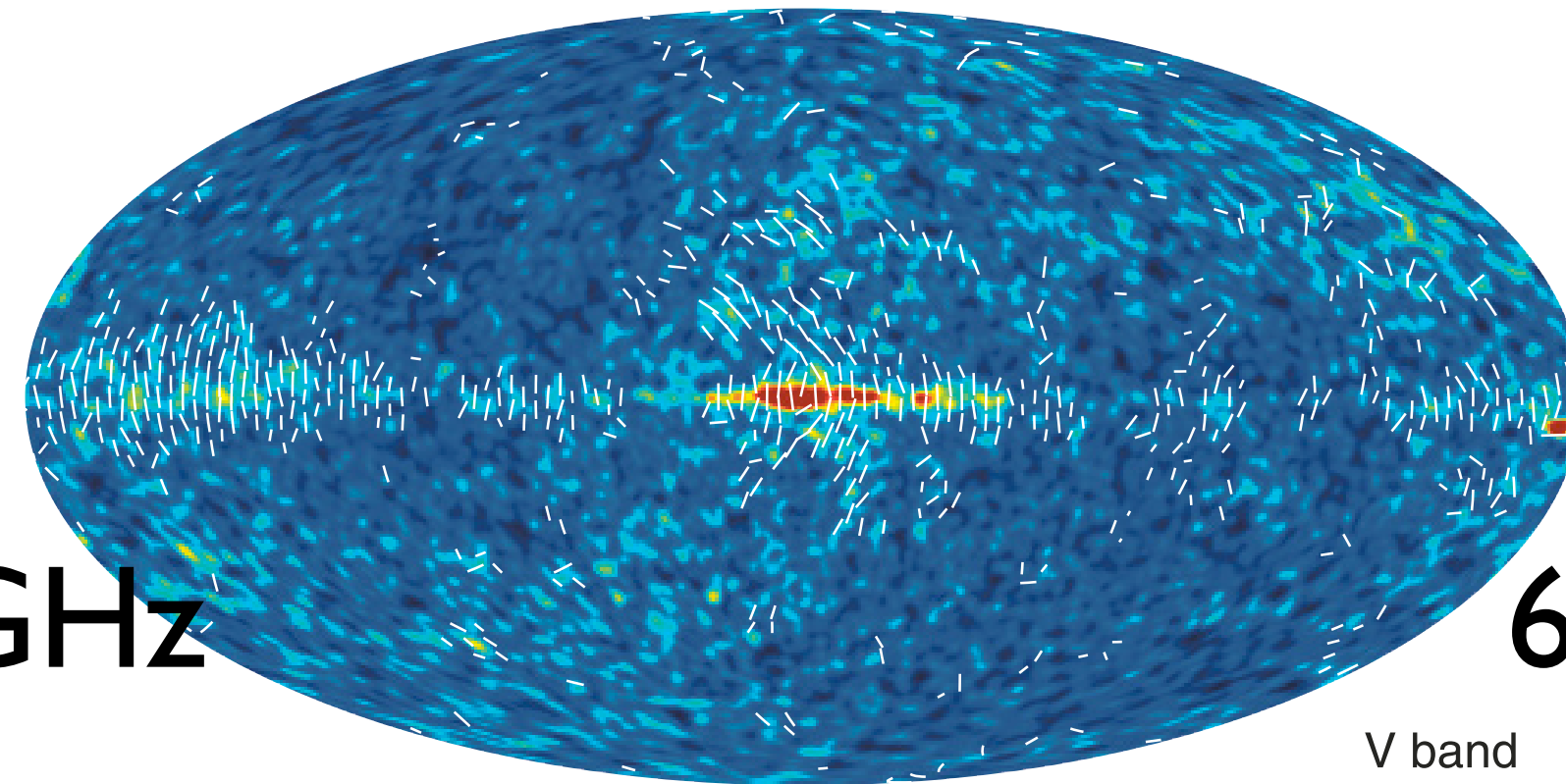




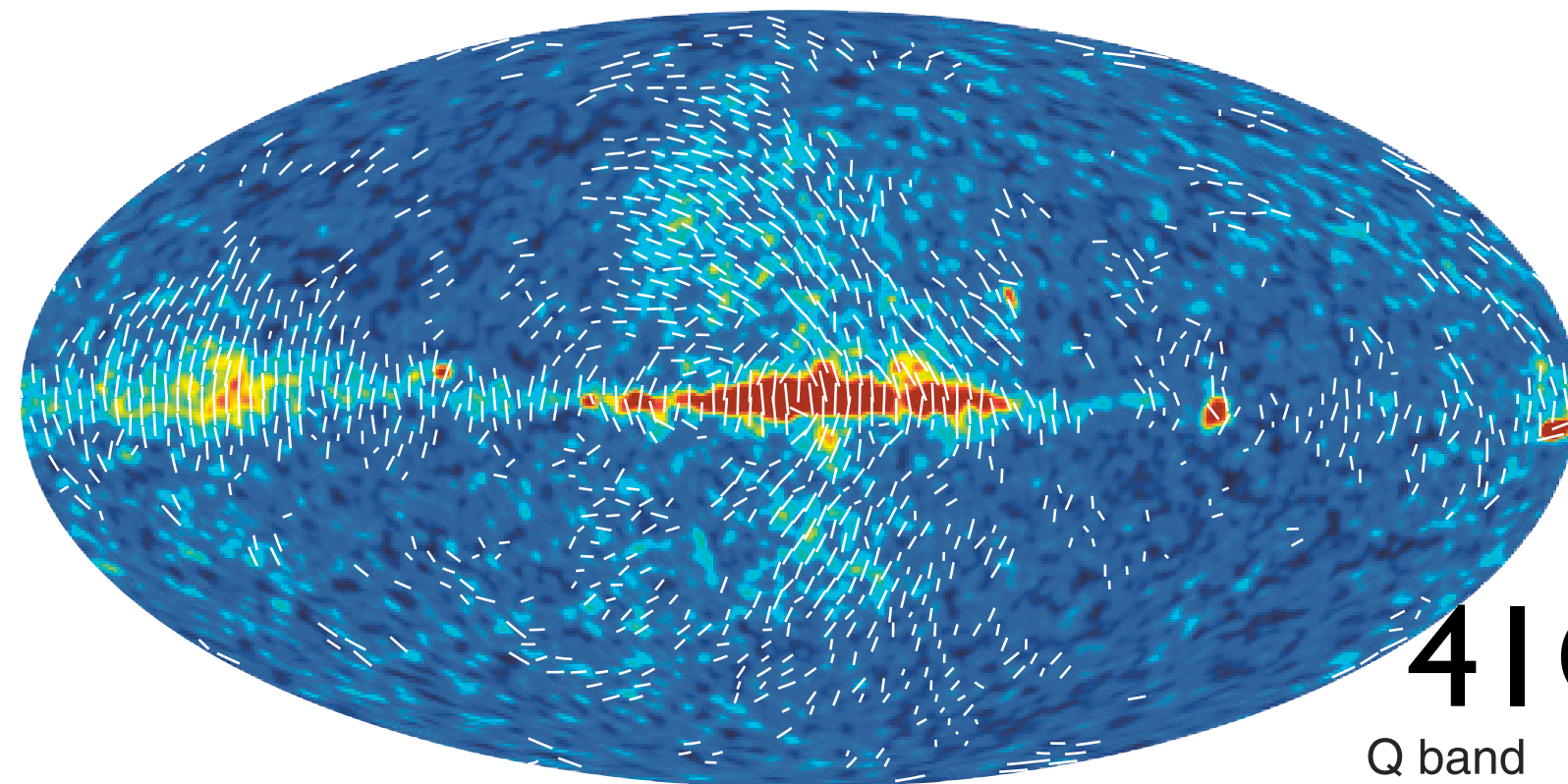
22GHz
K band



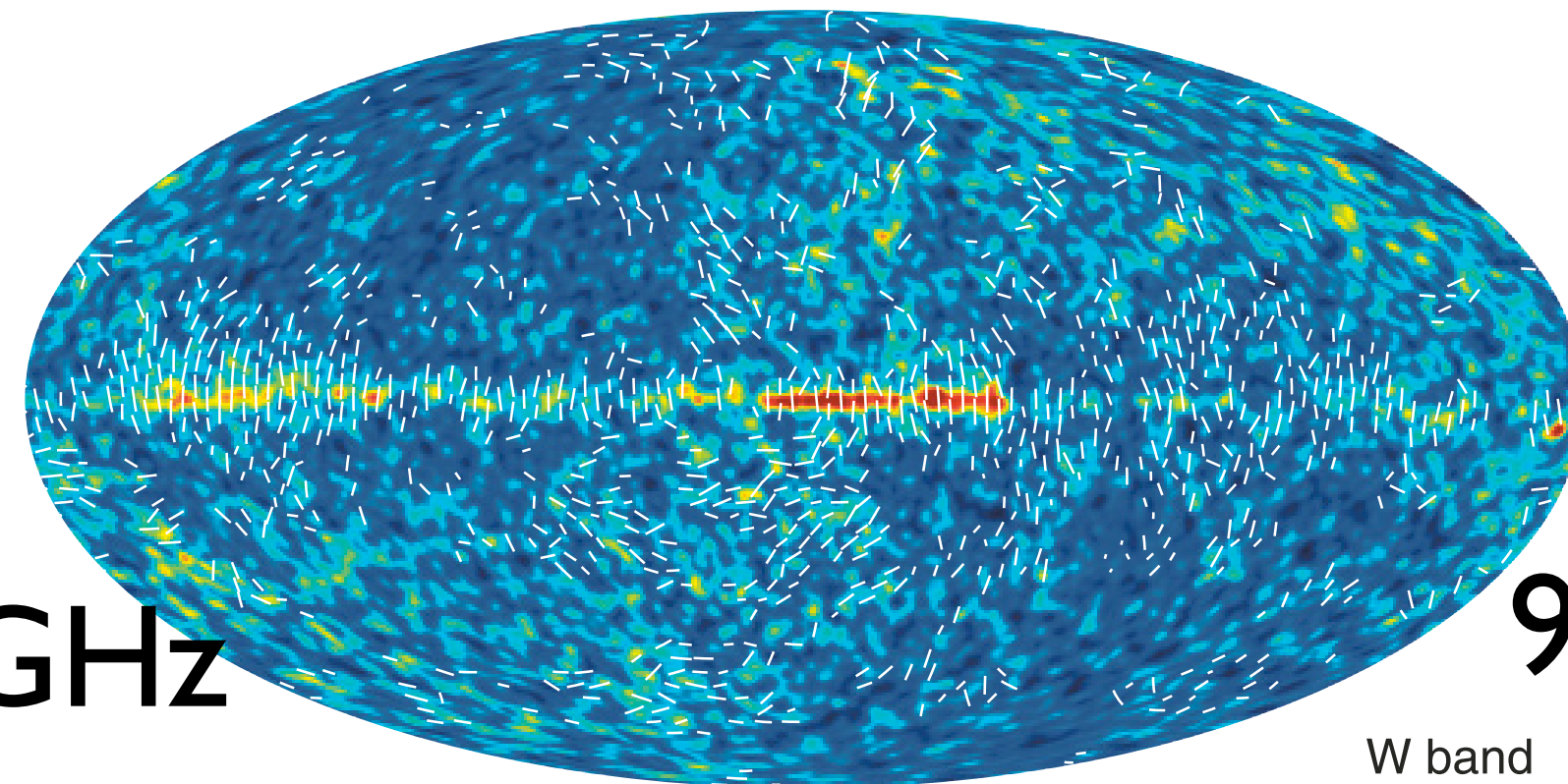
33GHz
Ka band



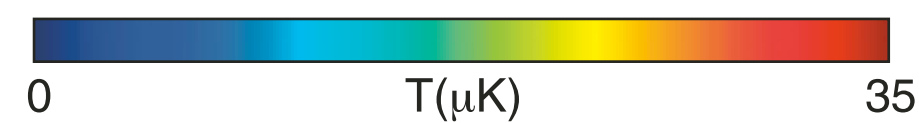
61GHz
V band



41GHz
Q band

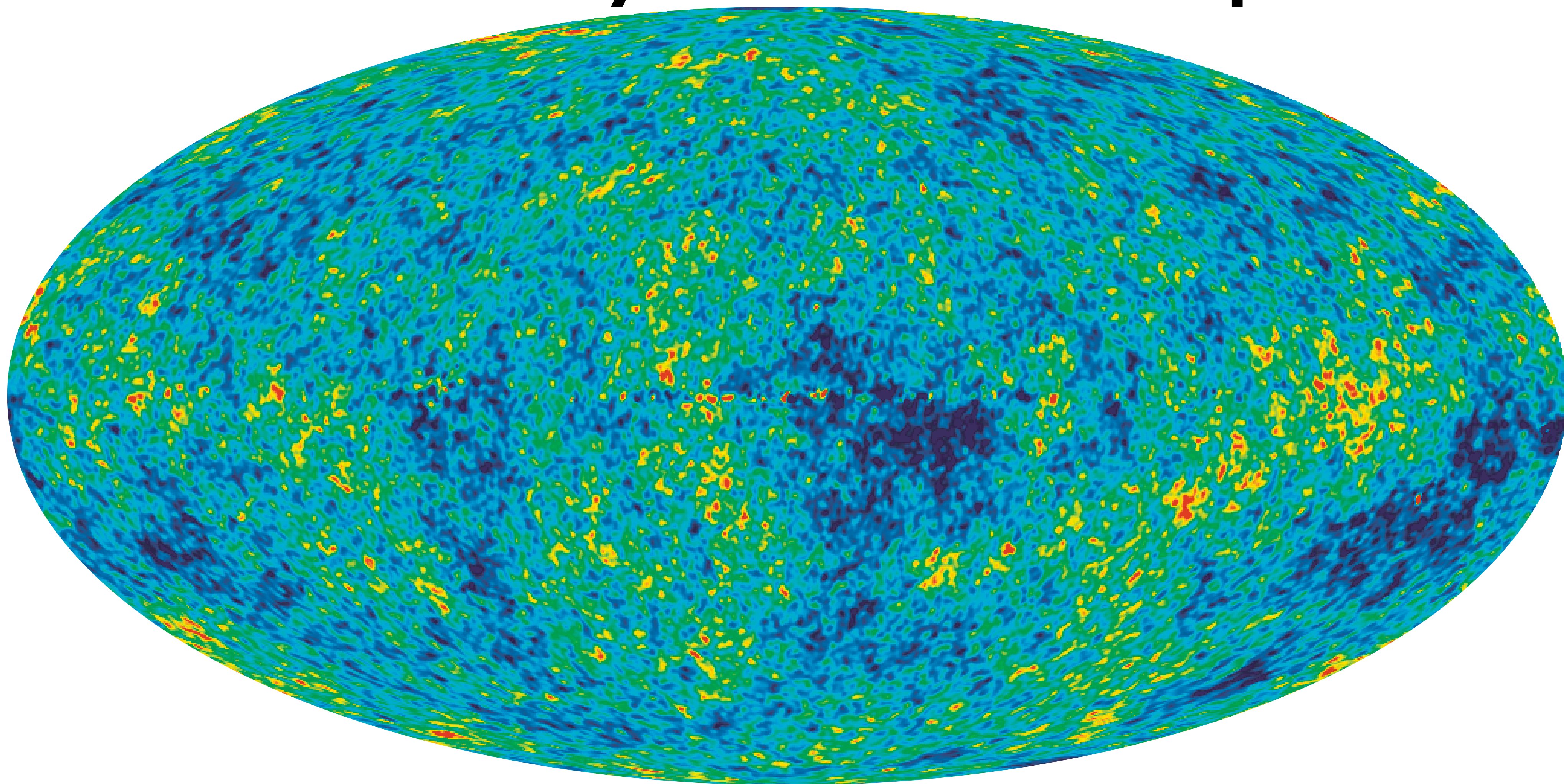


94GHz
W band



Galaxy-cleaned Map

Hinshaw et al.



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](#)

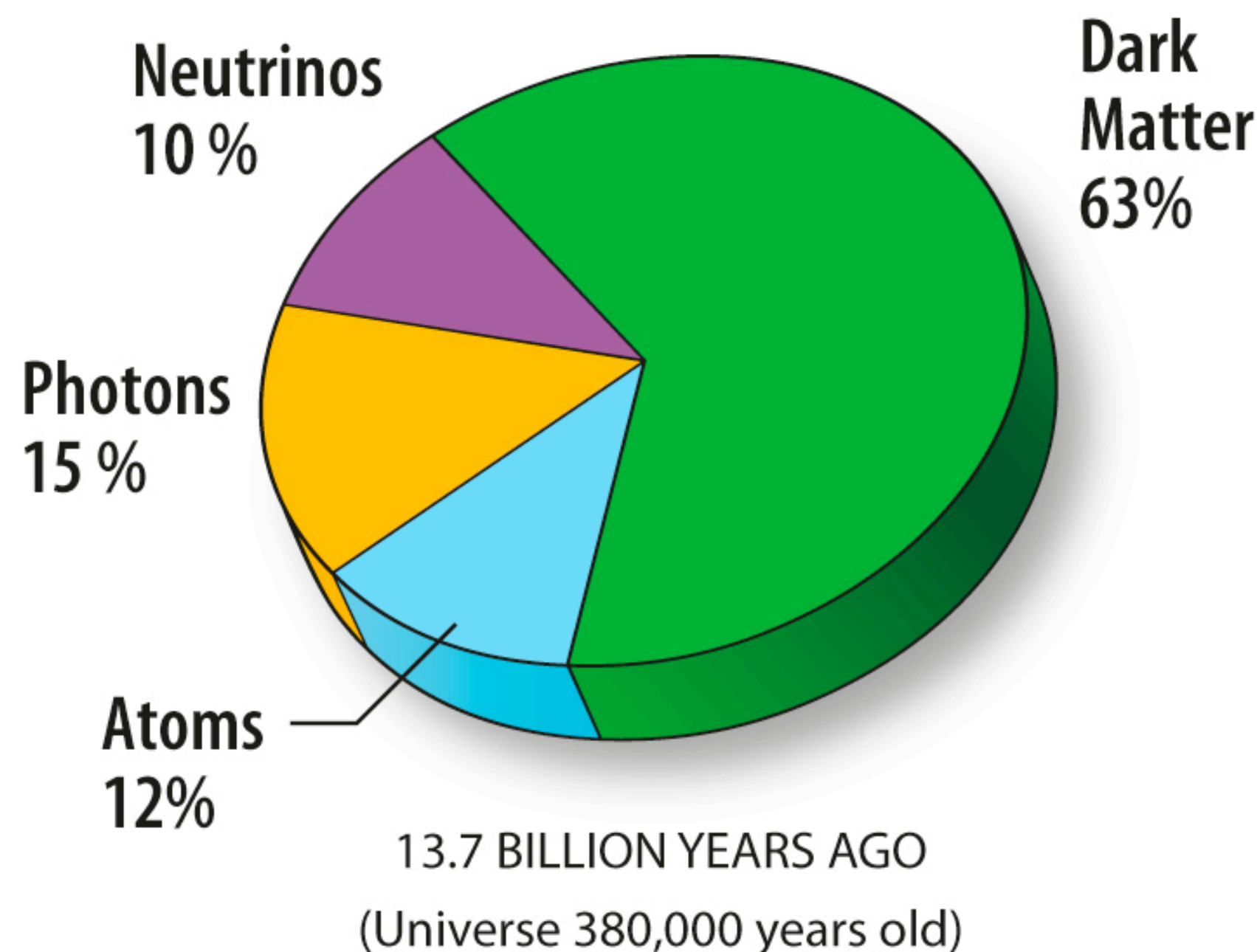
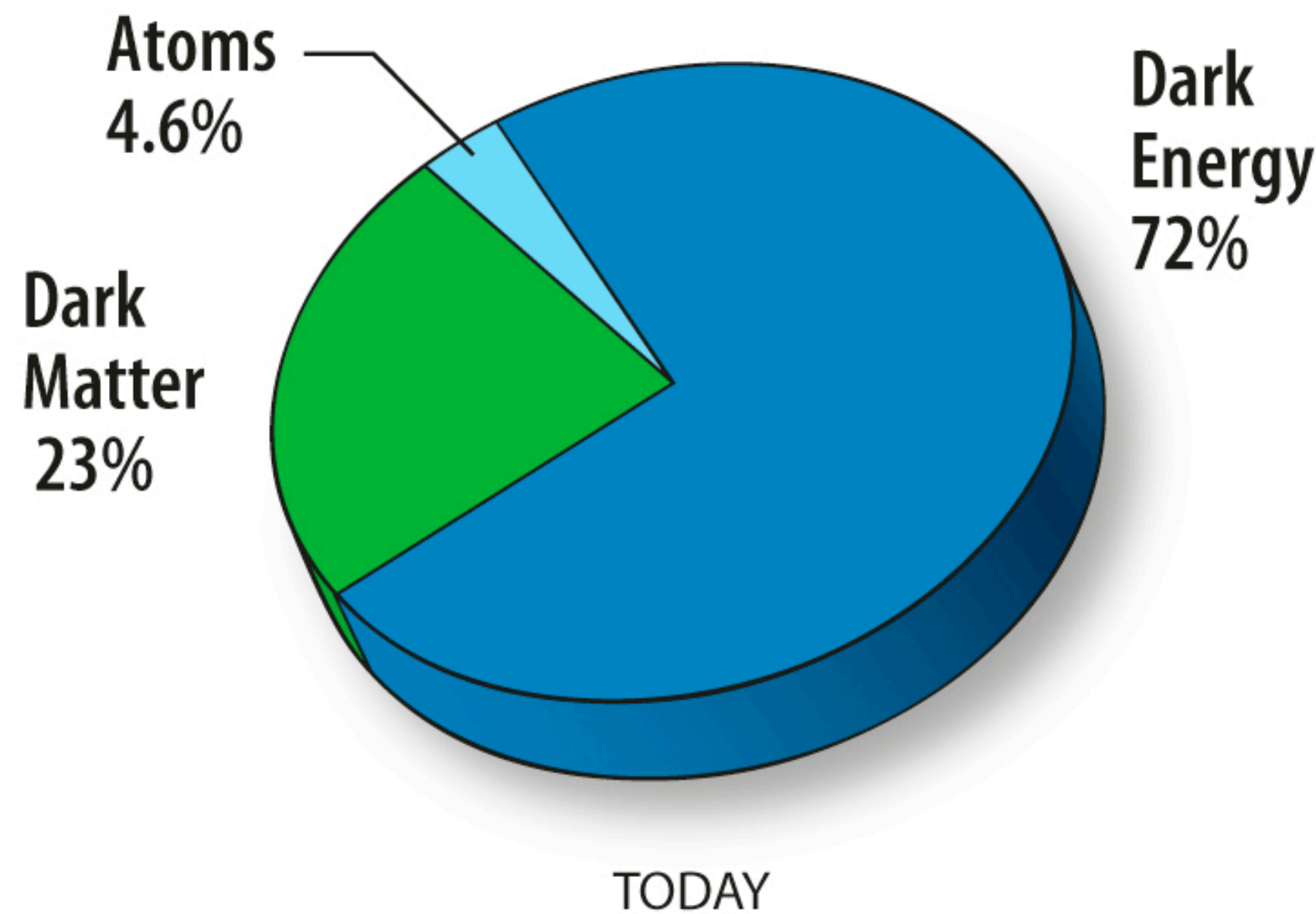
WMAP 5-Year Science Team

- 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!

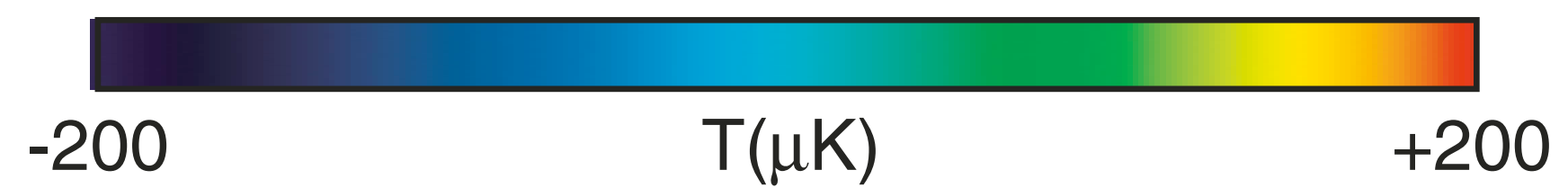
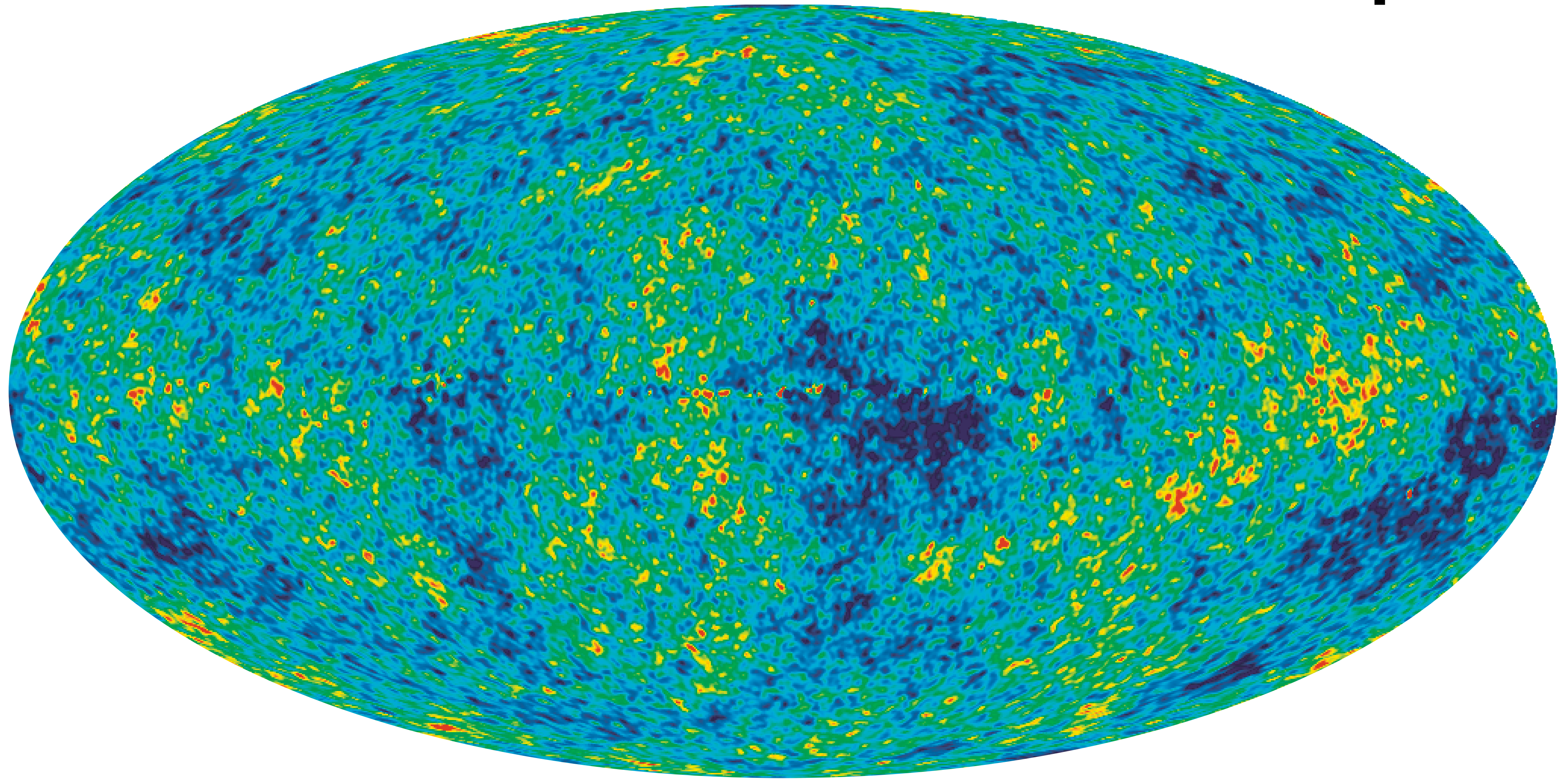
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

~WMAP 5-Year~ Pie Chart Update!



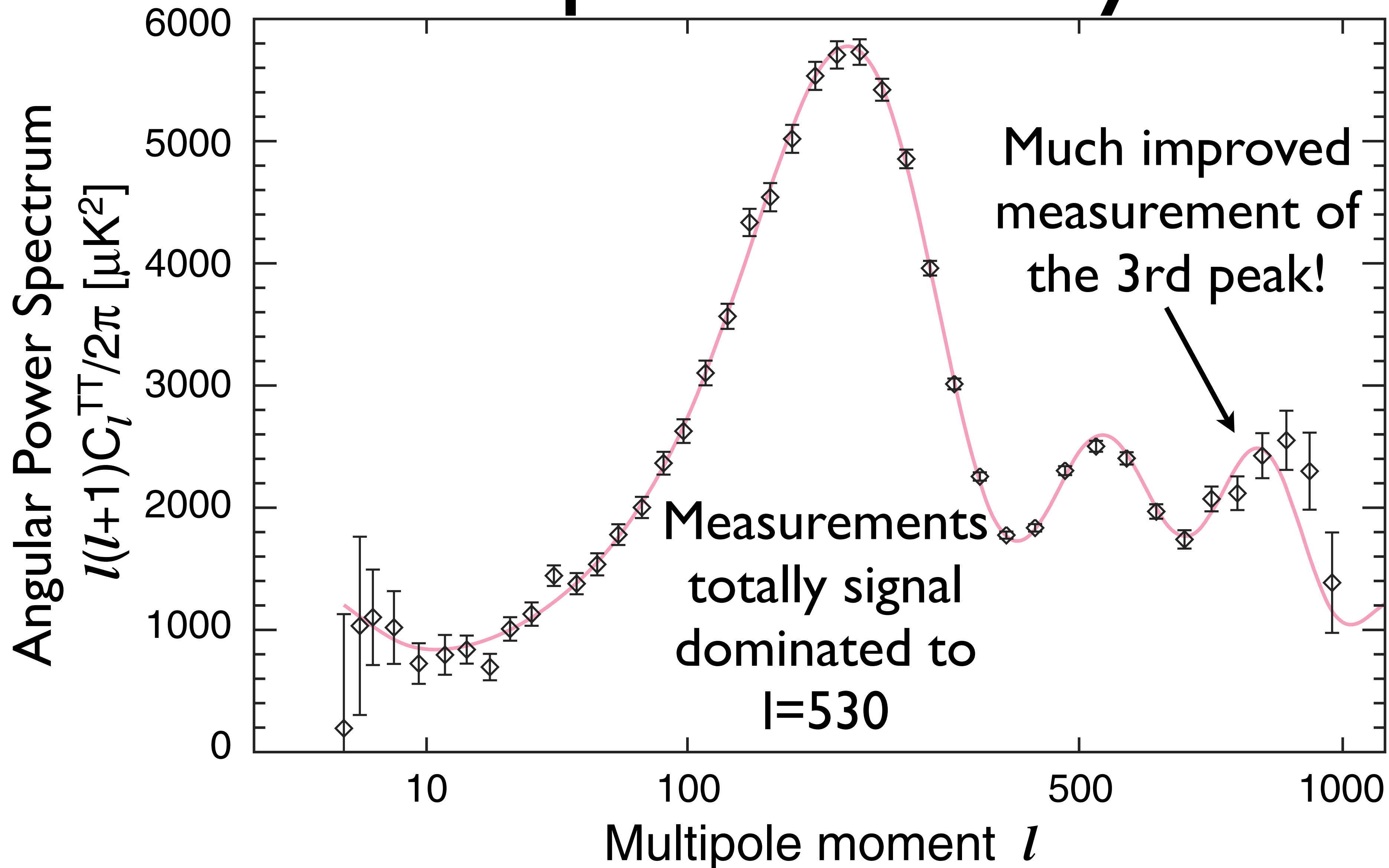
- Universe today
 - Age: **13.72 +/- 0.12 Gyr**
 - Atoms: **4.56 +/- 0.15 %**
 - Dark Matter: **22.8 +/- 1.3%**
 - Vacuum Energy: **72.6 +/- 1.5%**
- When CMB was released 13.7 B yrs ago
 - A significant contribution from the *cosmic neutrino background*

How Did We Use This Map?

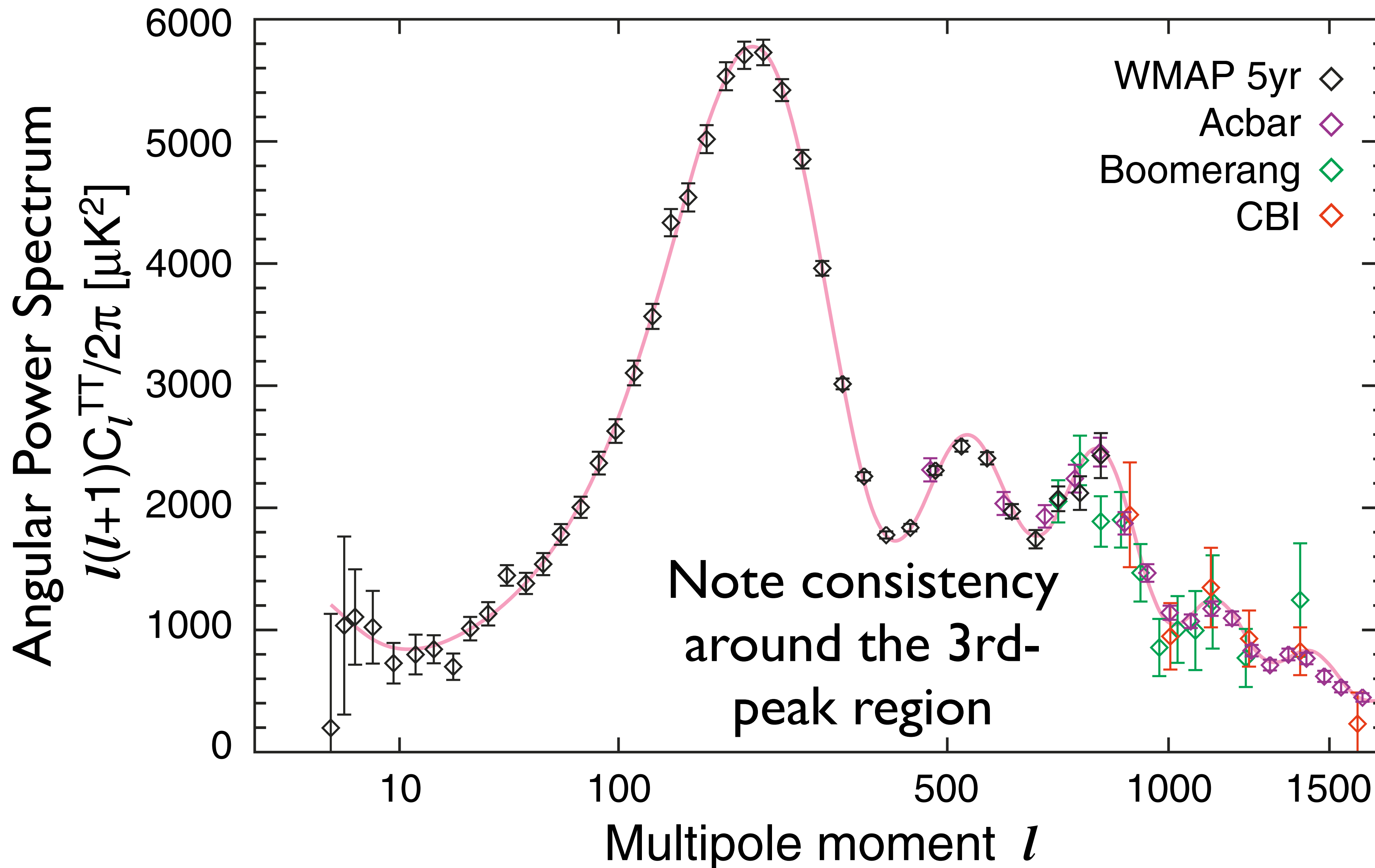


WMAP 5-year

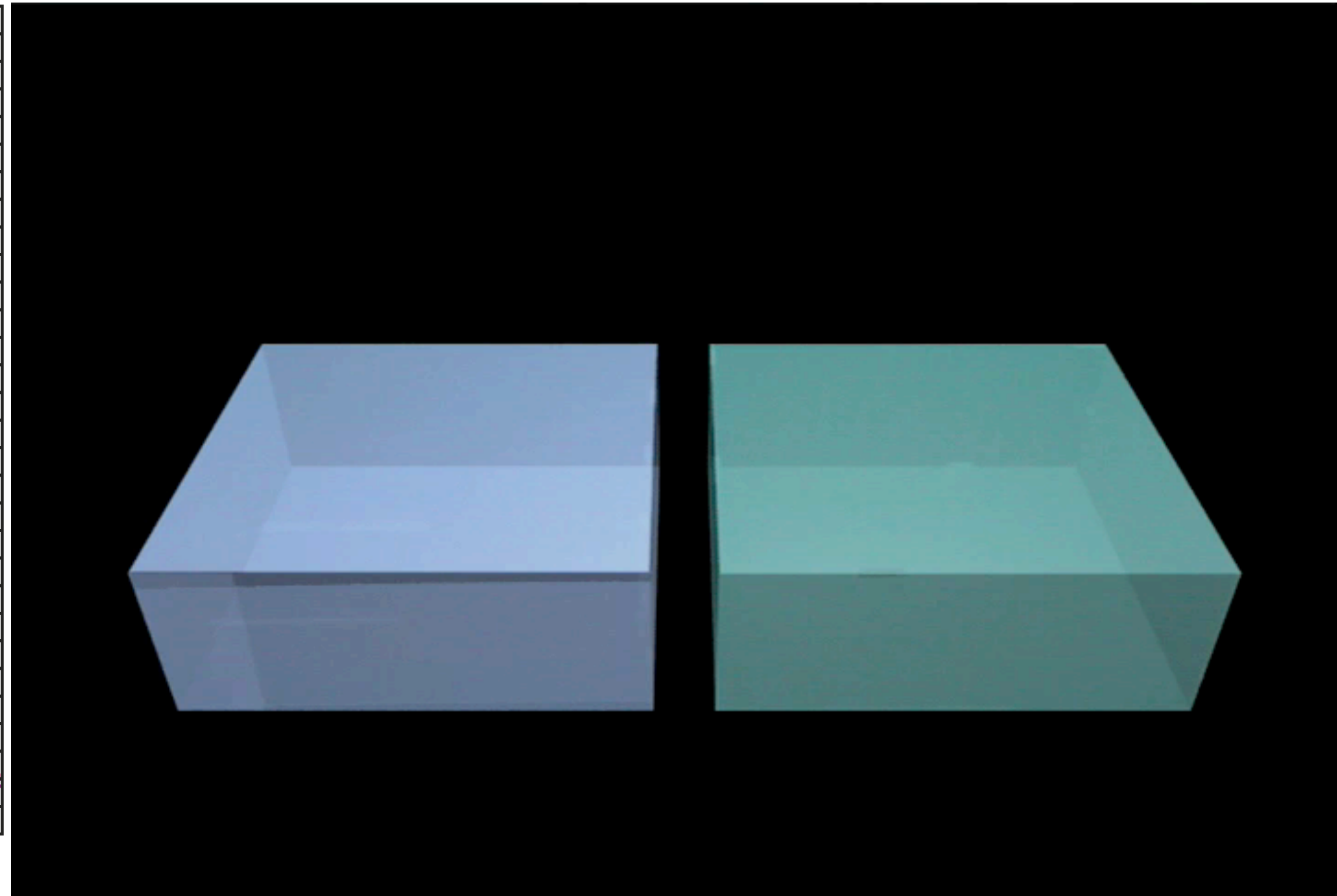
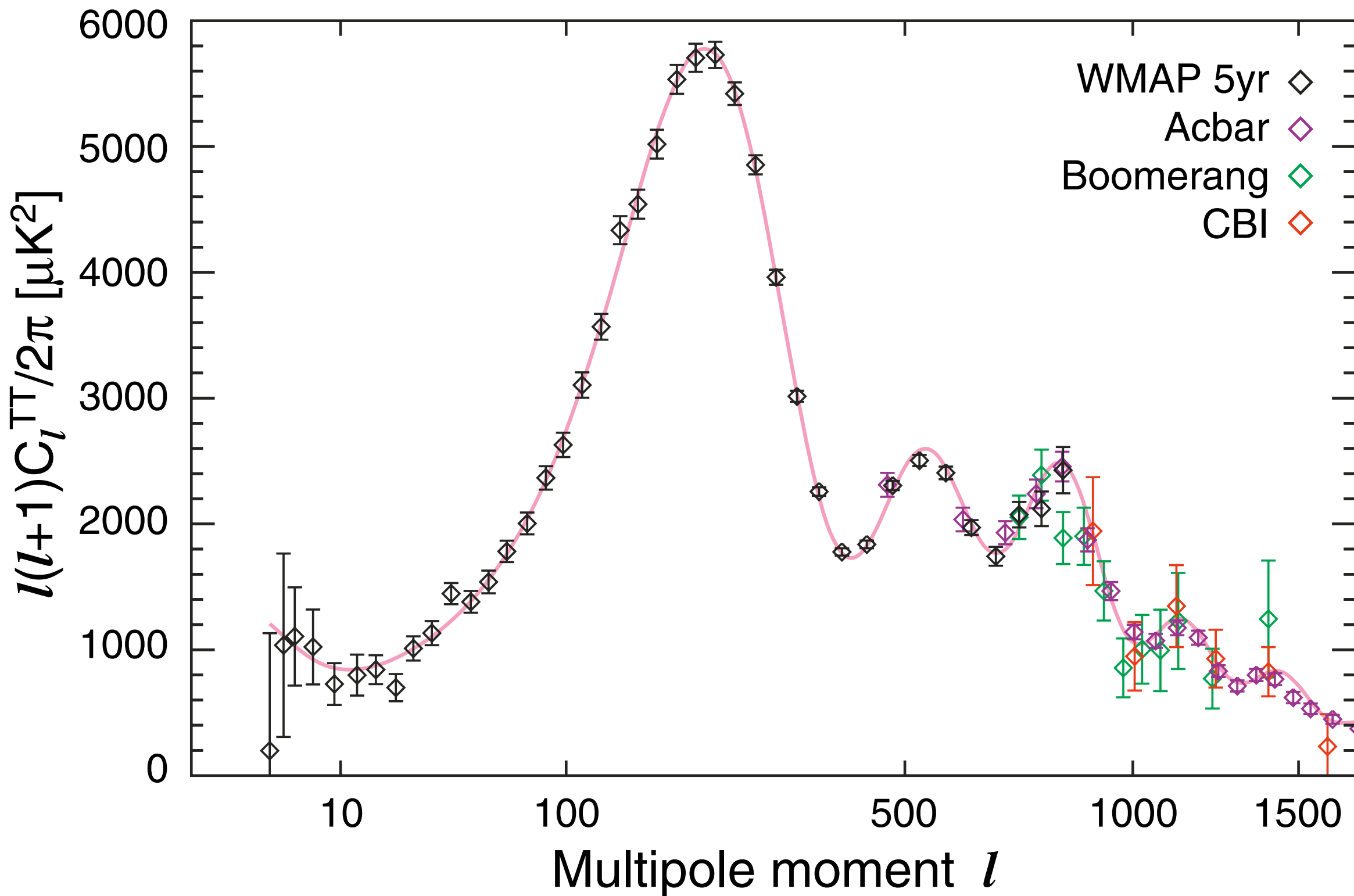
The Spectral Analysis



The Cosmic Sound Wave

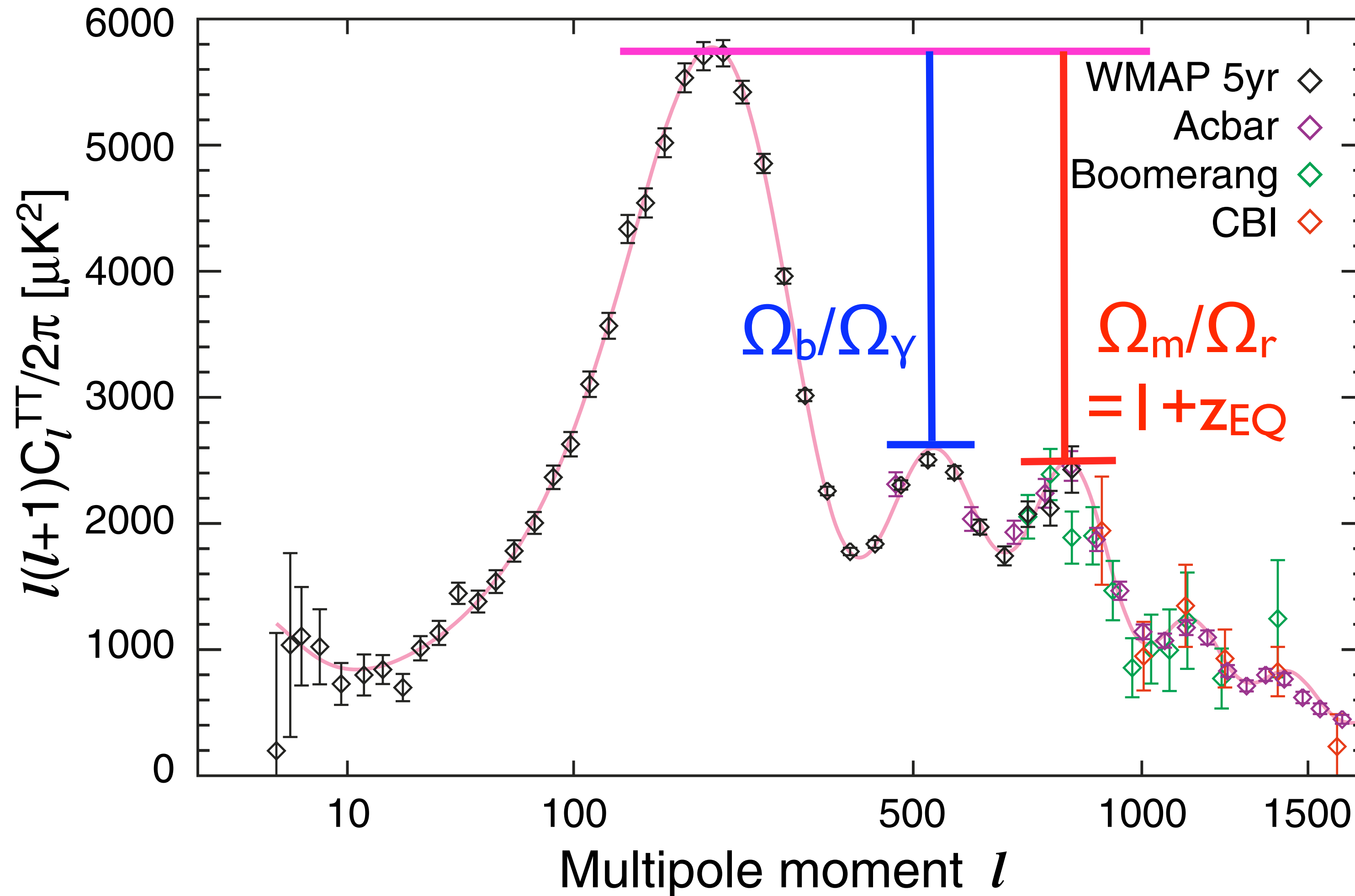


The Cosmic Sound Wave



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

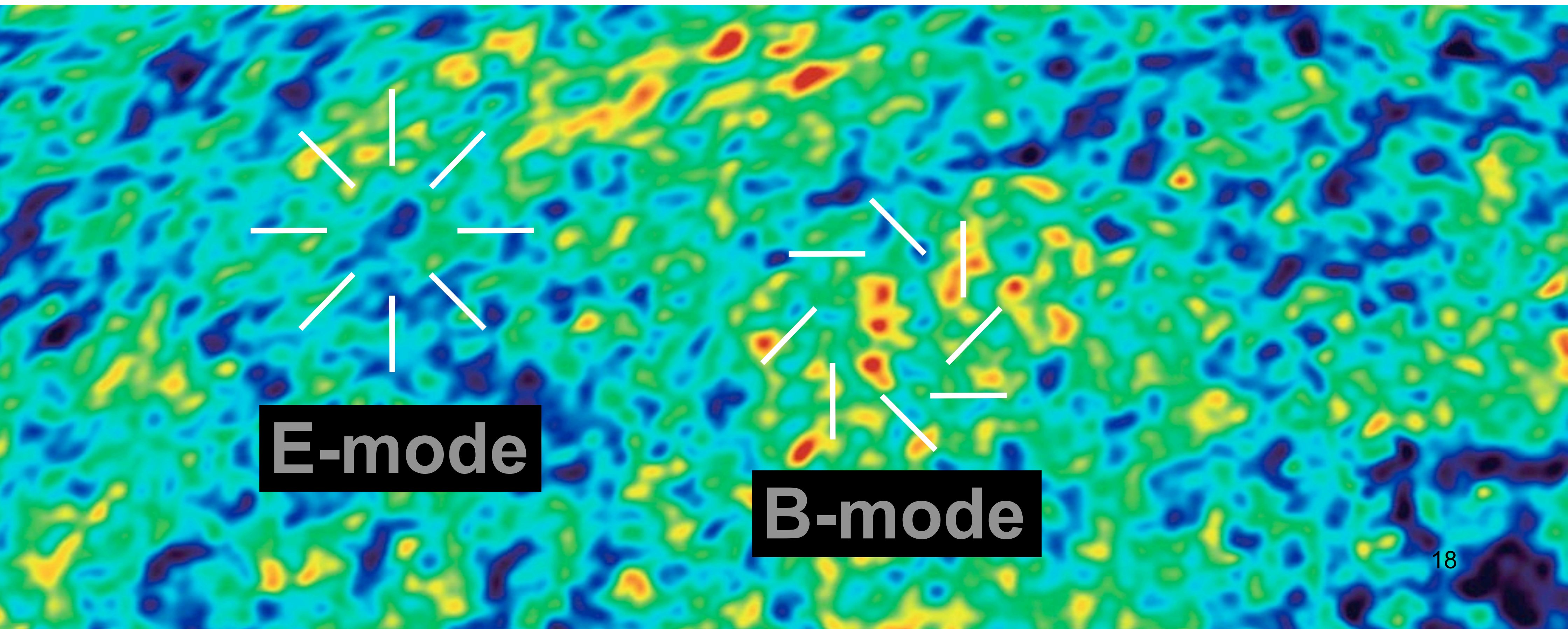
CMB to $\Omega_b h^2$ & $\Omega_m h^2$



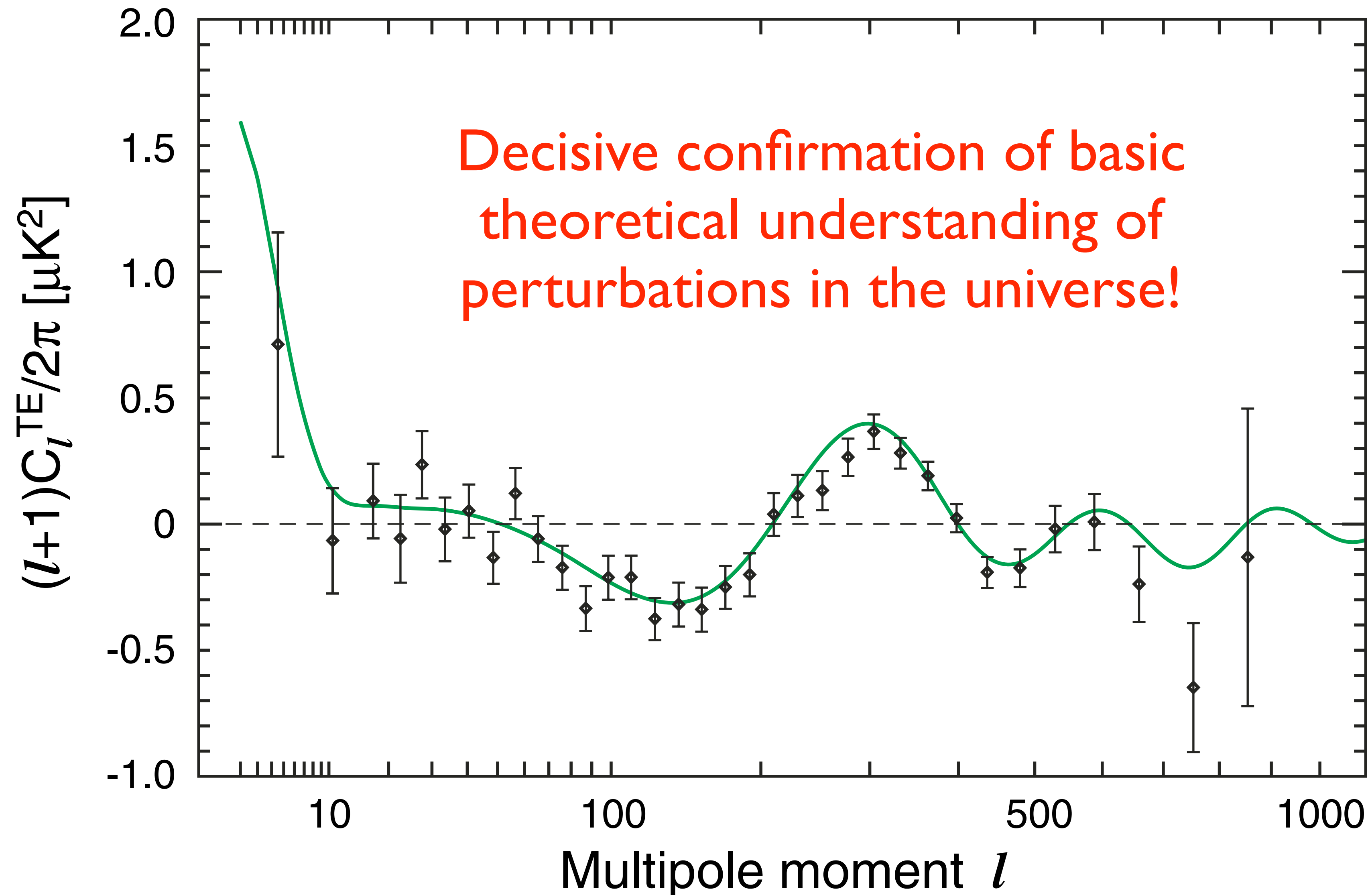
- l -to- 2 : baryon-to-photon; l -to- 3 : matter-to-radiation ratio
- $\Omega_\gamma = 2.47 \times 10^{-5} h^{-2}$ & $\Omega_r = \Omega_\gamma + \Omega_\nu = 1.69 \Omega_\gamma = 4.17 \times 10^{-5} h^{-2}$

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”.

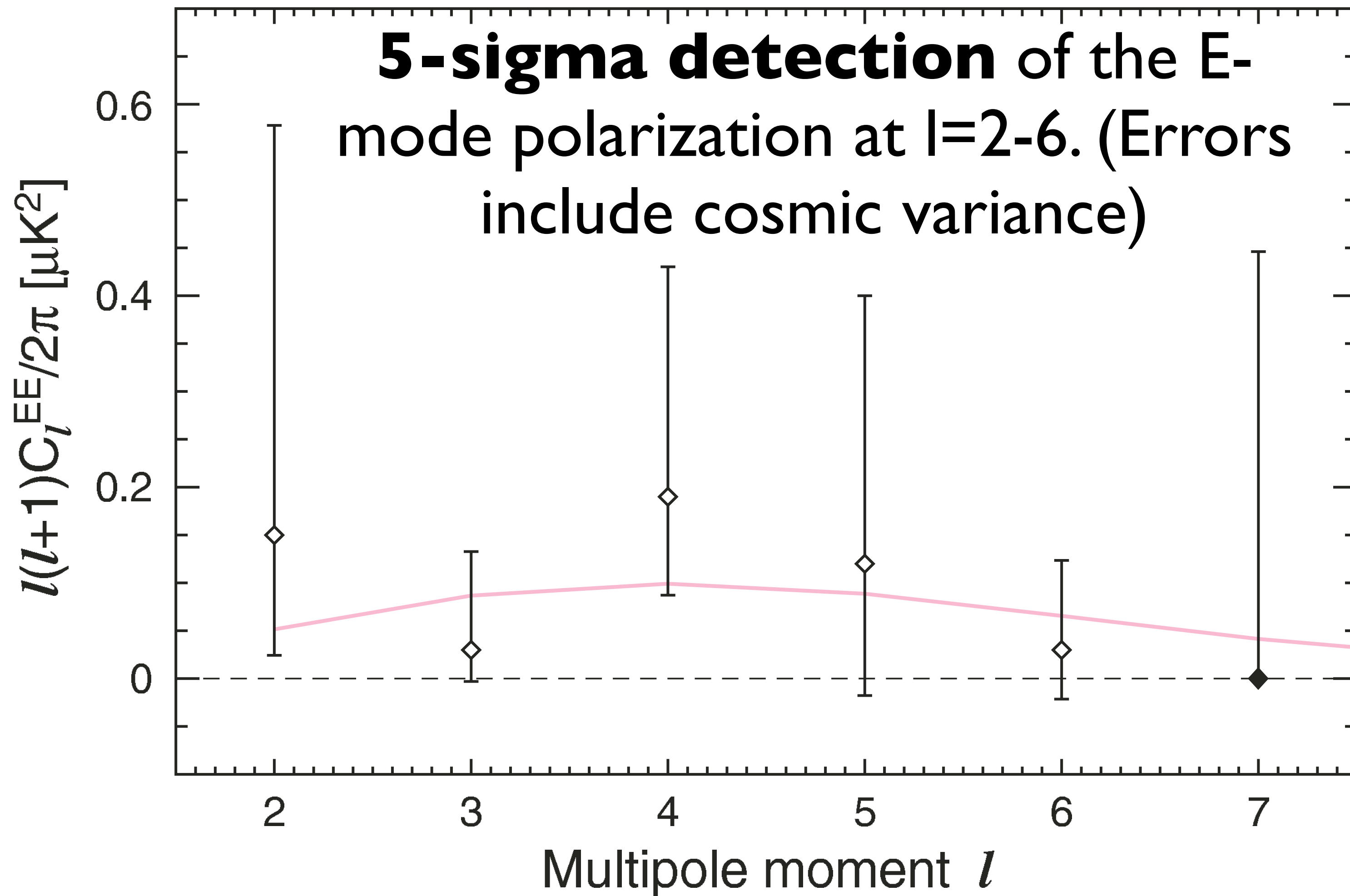


5-Year TxE Power Spectrum



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

E-Mode Angular Power Spectrum



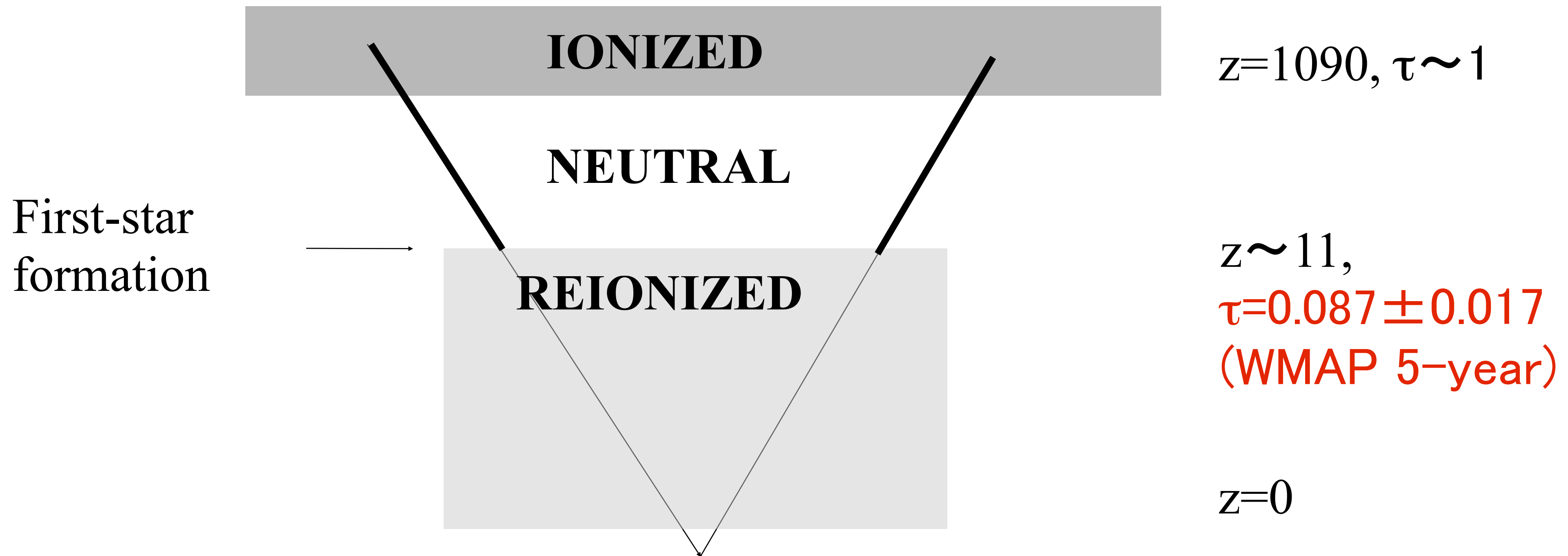
Black Symbols are upper limits

B-modes

- No detection of B-mode polarization yet.
- I will come back to this later.

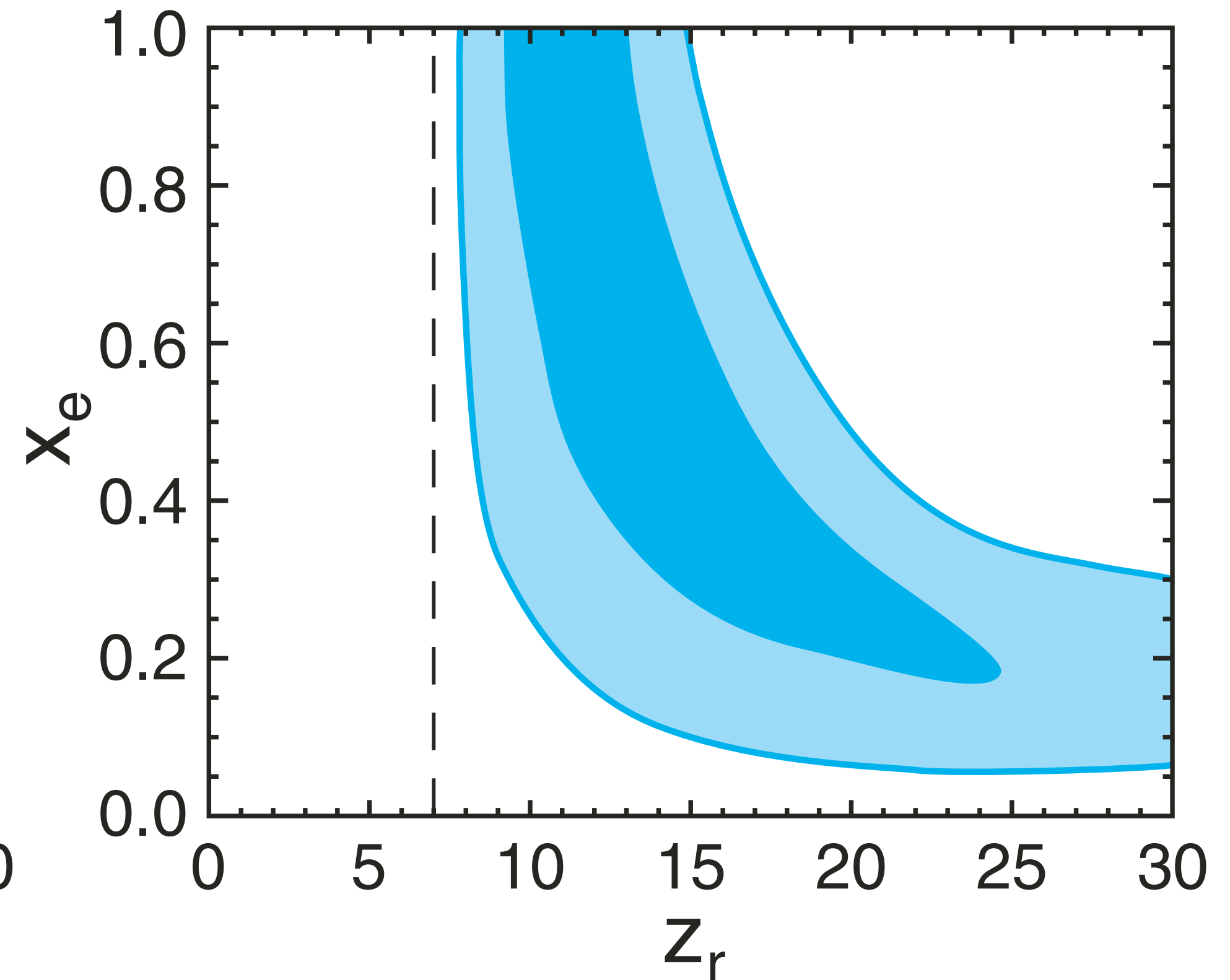
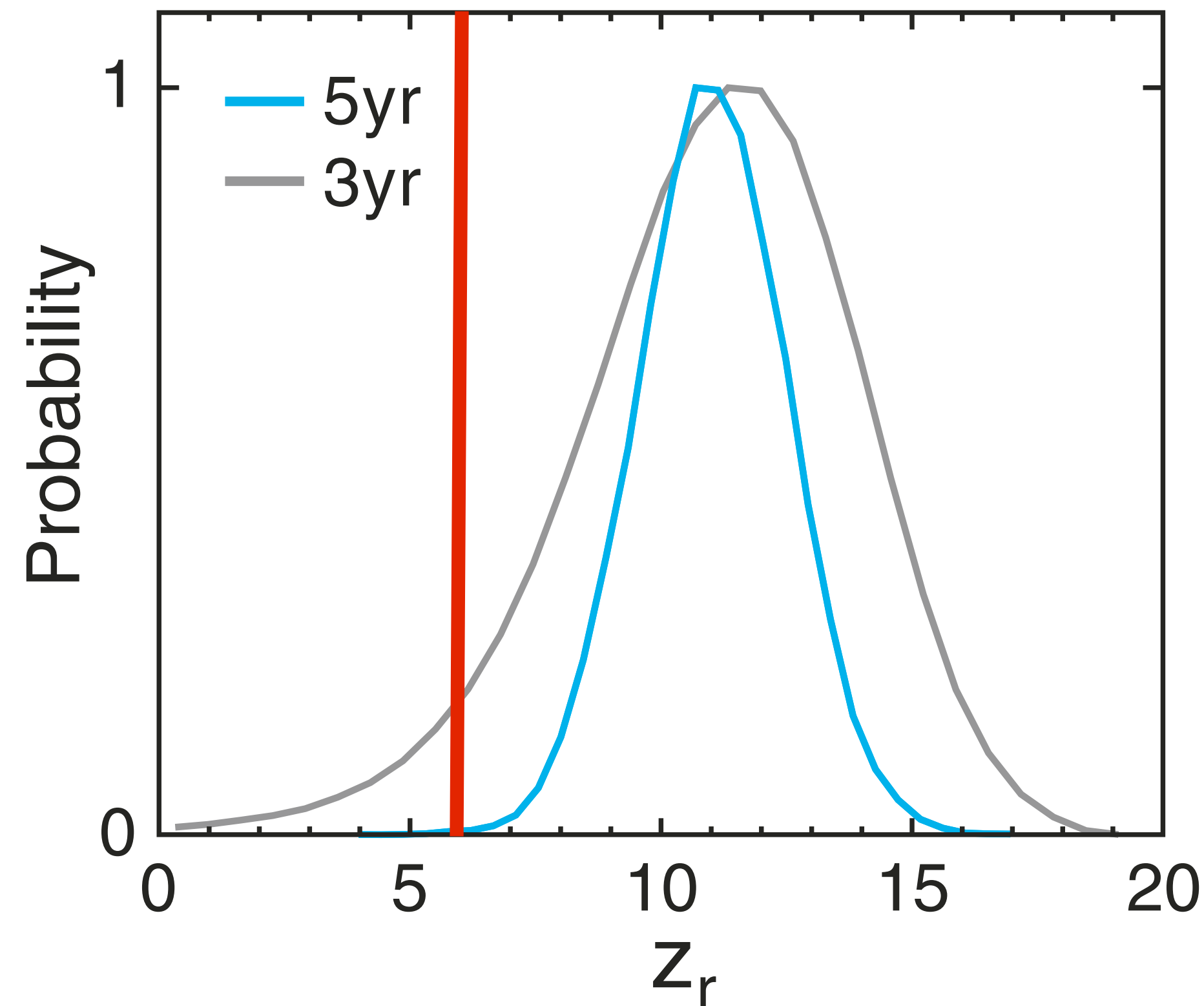
Polarization From Reionization

- 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.



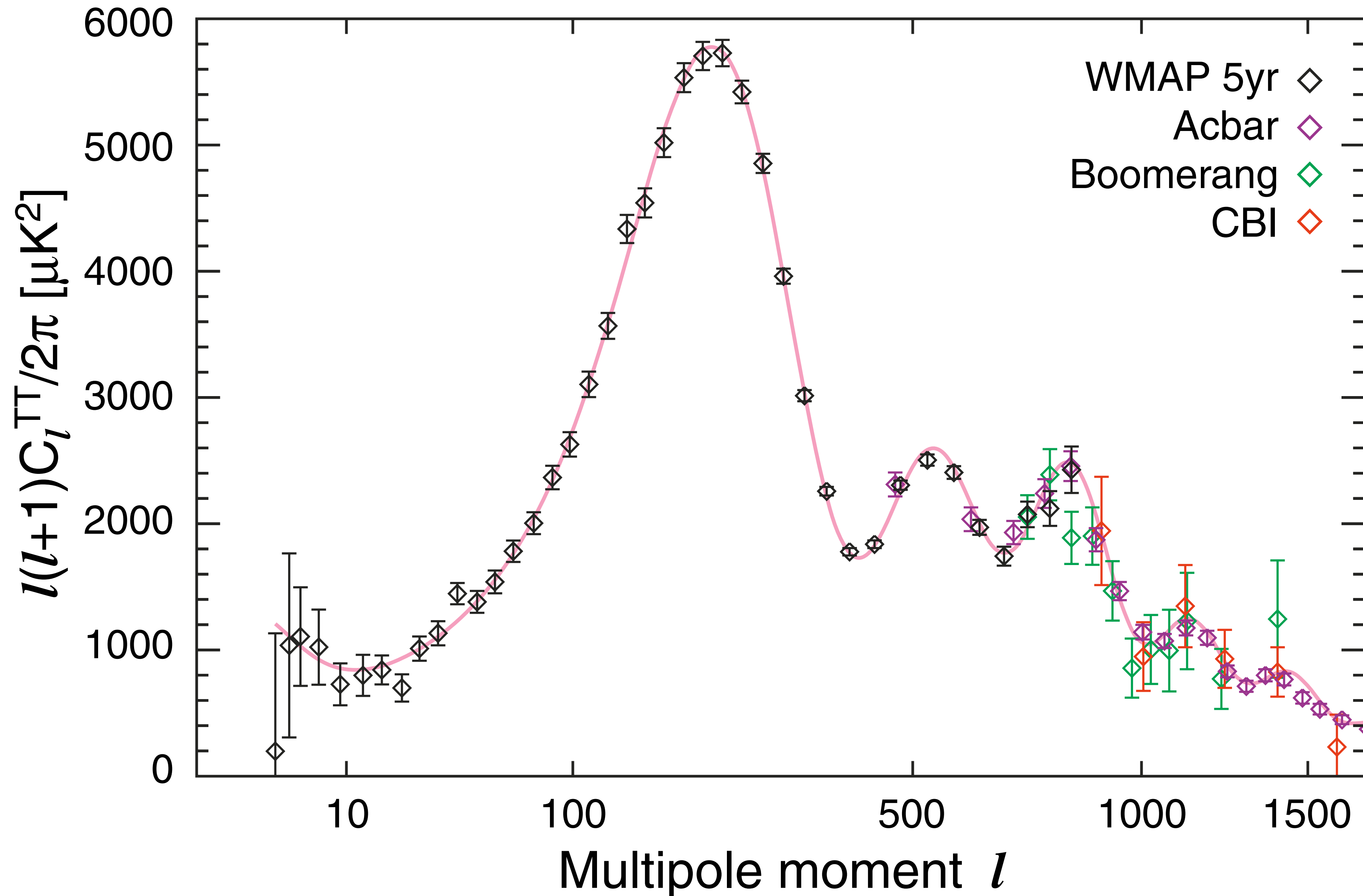
$z_{\text{reion}}=6$ Is Excluded

Dunkley et al.

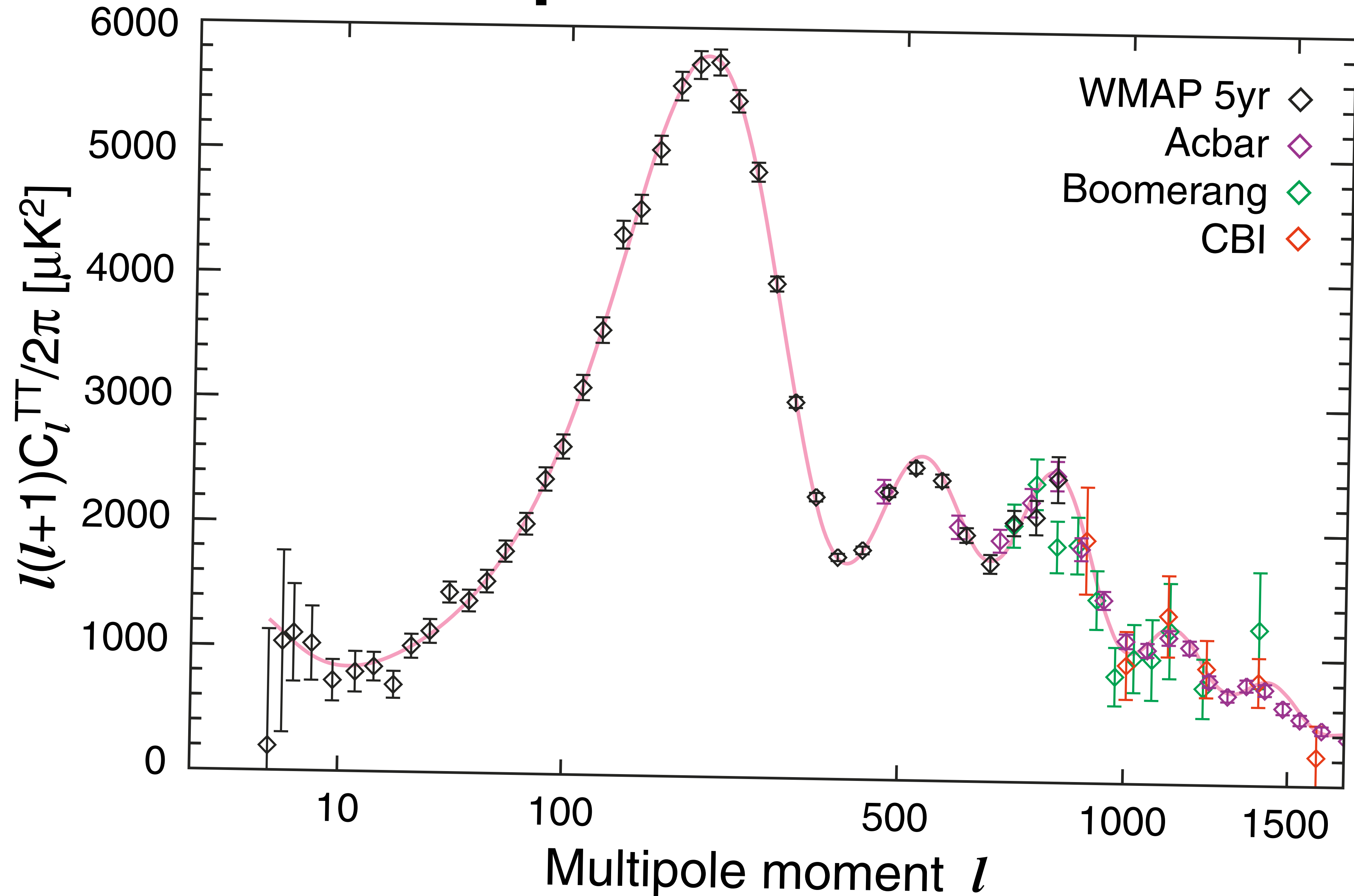


- Assuming an instantaneous reionization from $x_e=0$ to $x_e=1$ at z_{reion} , we find $z_{\text{reion}}=11.0 \pm 1.4$ (68 % CL).
- The reionization was not an instantaneous process at $z \sim 6$. (The 3-sigma lower bound is $z_{\text{reion}} > 6.7$.)

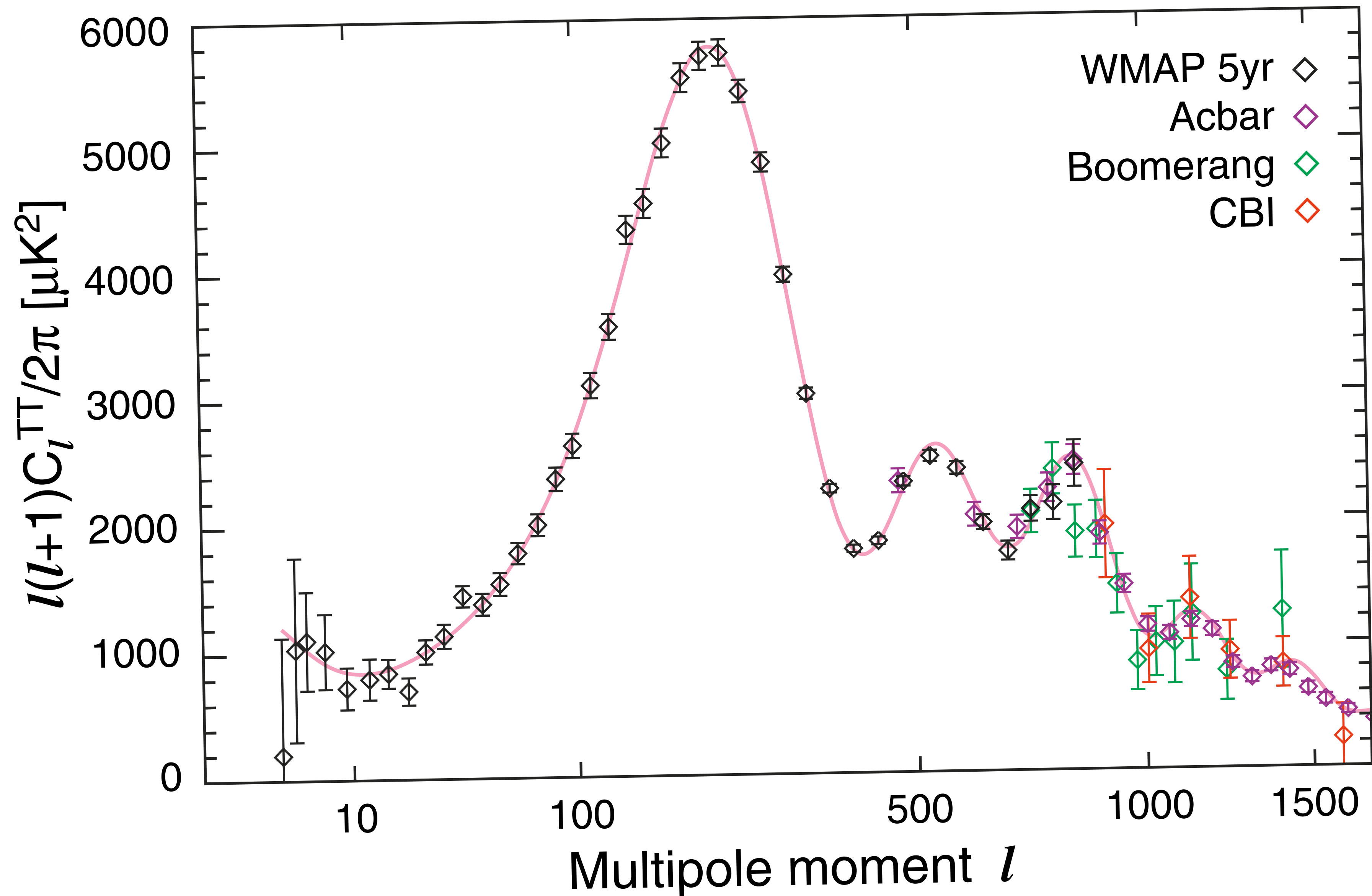
Tilting=Primordial Shape->Inflation



“Red” Spectrum: $n_s < 1$



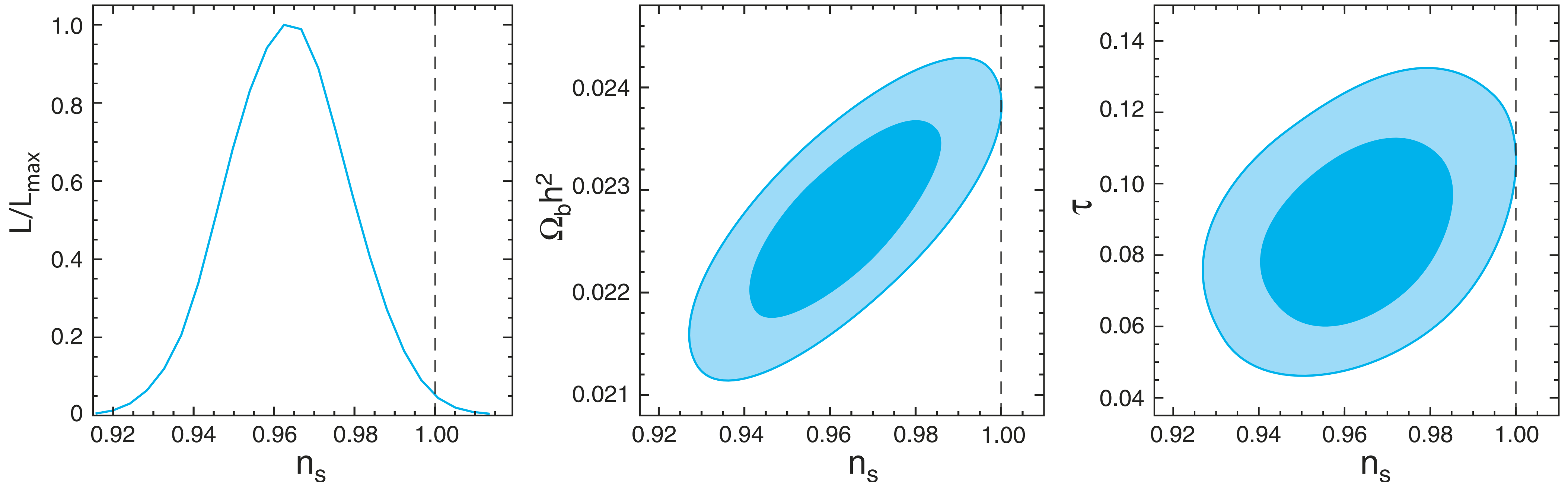
“Blue” Spectrum: $n_s > 1$



Expectations From 1970's: $n_s=1$

- Metric perturbations in g_{ij} (let's call that “curvature perturbations” Φ) is related to δ via
 - $k^2\Phi(k)=4\pi G\rho a^2\delta(k)$
- Variance of $\Phi(x)$ in position space is given by
 - $\langle\Phi^2(x)\rangle=\int\ln k \mathbf{k}^3|\Phi(\mathbf{k})|^2$
 - In order to avoid the situation in which curvature (geometry) diverges on small or large scales, a “scale-invariant spectrum” was proposed: $\mathbf{k}^3|\Phi(\mathbf{k})|^2 = \text{const.}$
 - This leads to the expectation: $\mathbf{P}(\mathbf{k})=|\delta(k)|^2=\mathbf{k} \ (n_s=1)$
 - *Harrison 1970; Zel'dovich 1972; Peebles&Yu 1970*

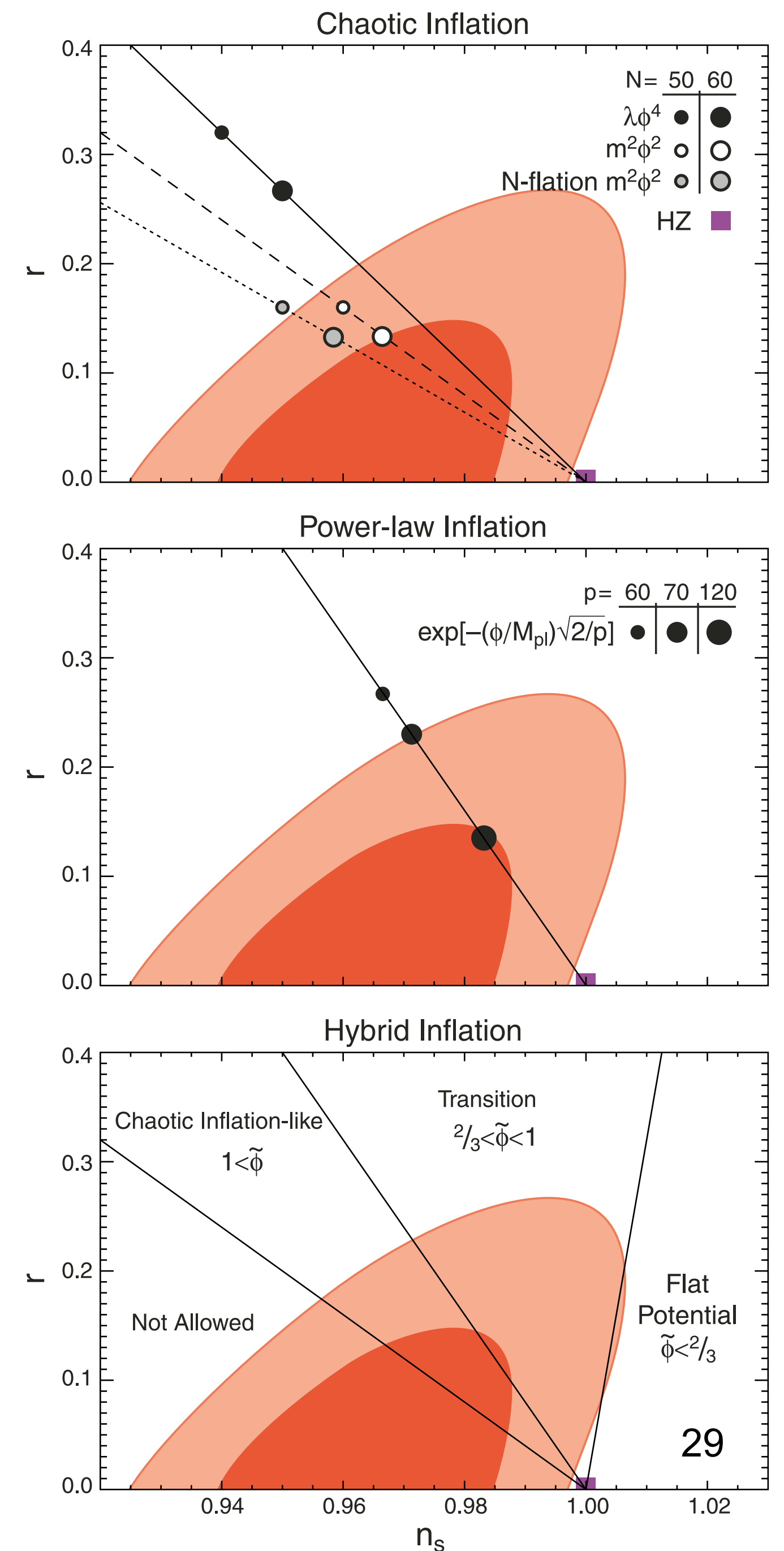
Is n_s different from ONE?



- 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 $\Omega_b h^2$

Deviation from $n_s=1$

- This was expected by many inflationary models
- In n_s - r plane (where r is called the “tensor-to-scalar ratio,” which is $P(k)$ of gravitational waves divided by $P(k)$ of density fluctuations) **many inflationary models are compatible with the current data**
- Many models have been excluded also

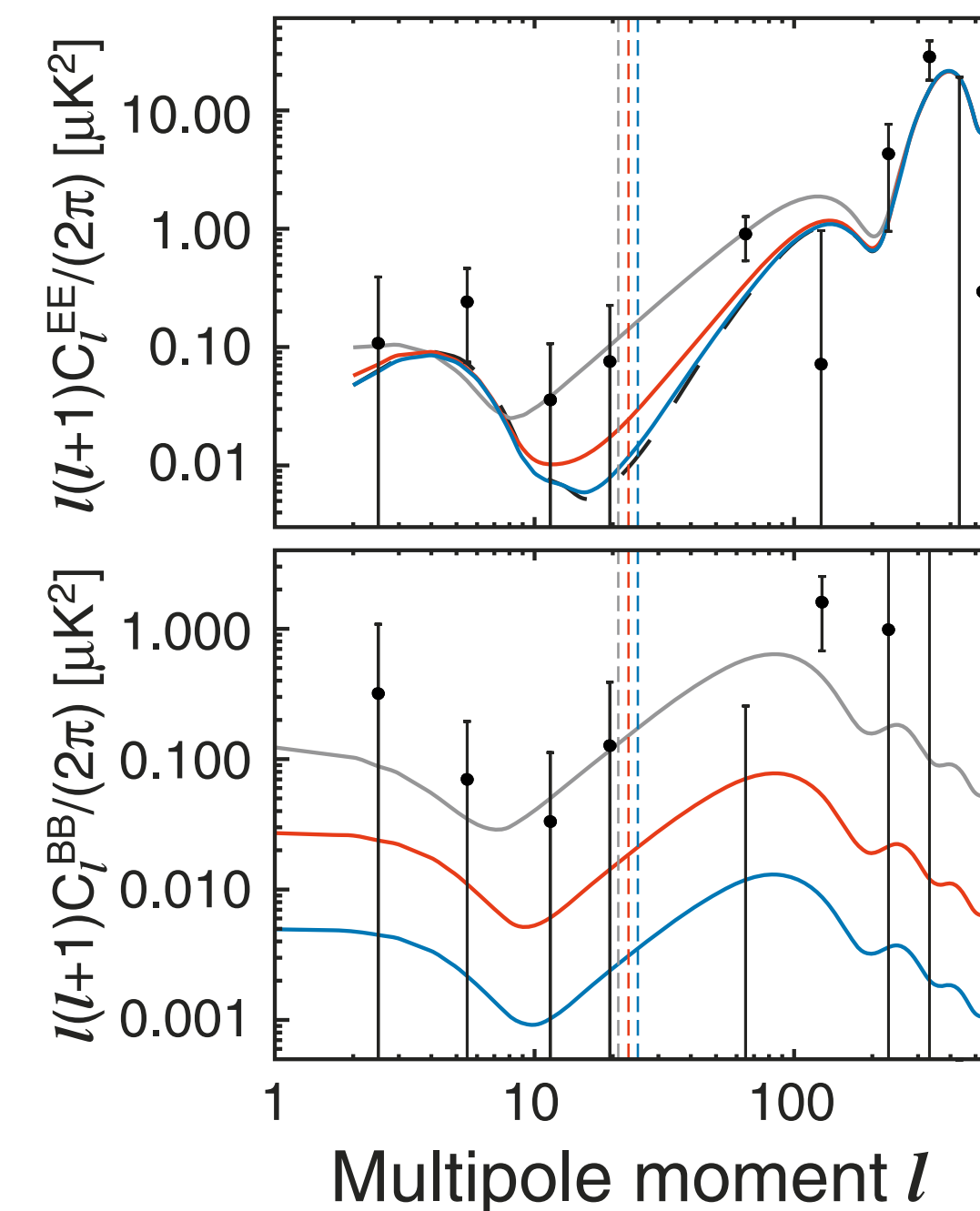
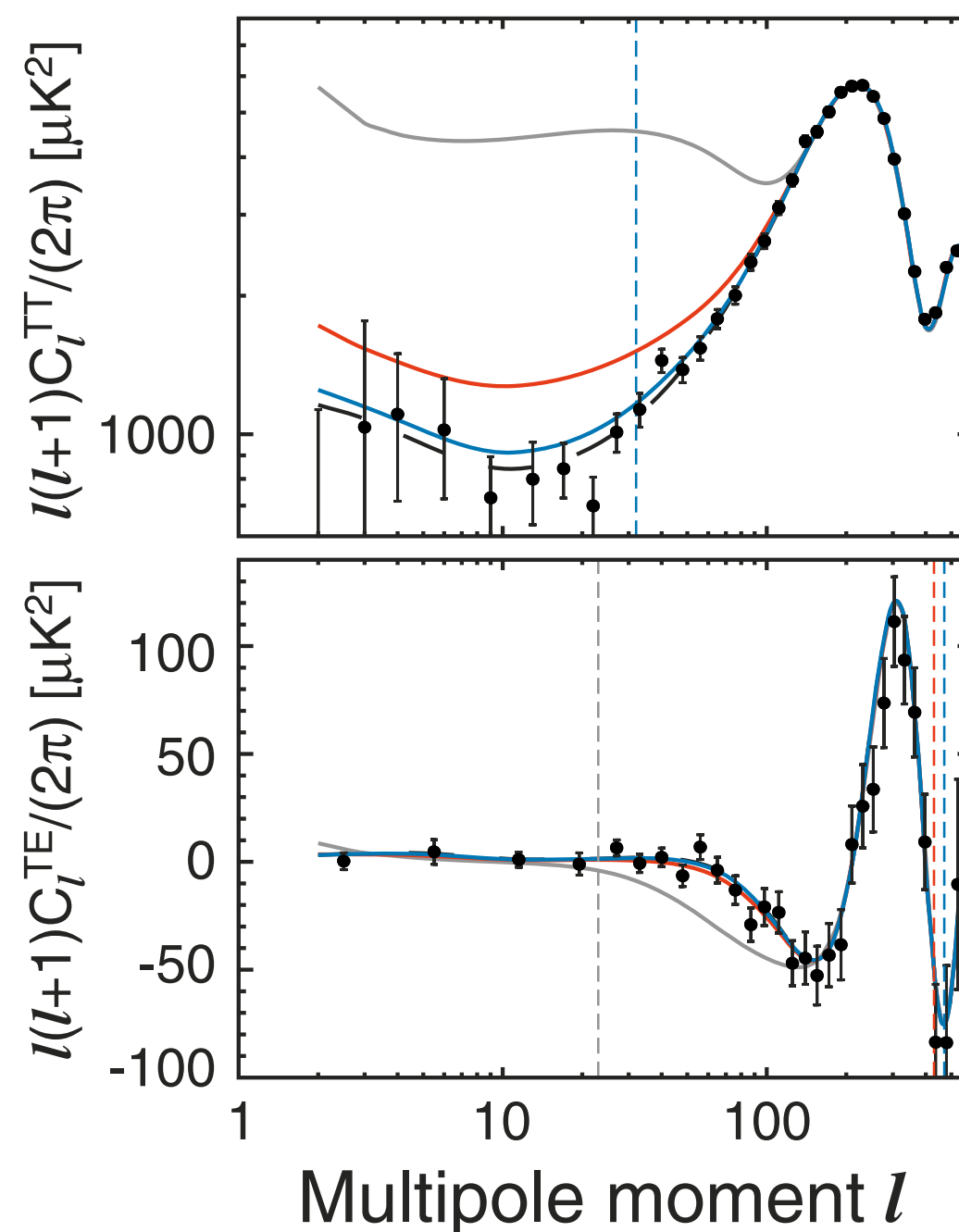
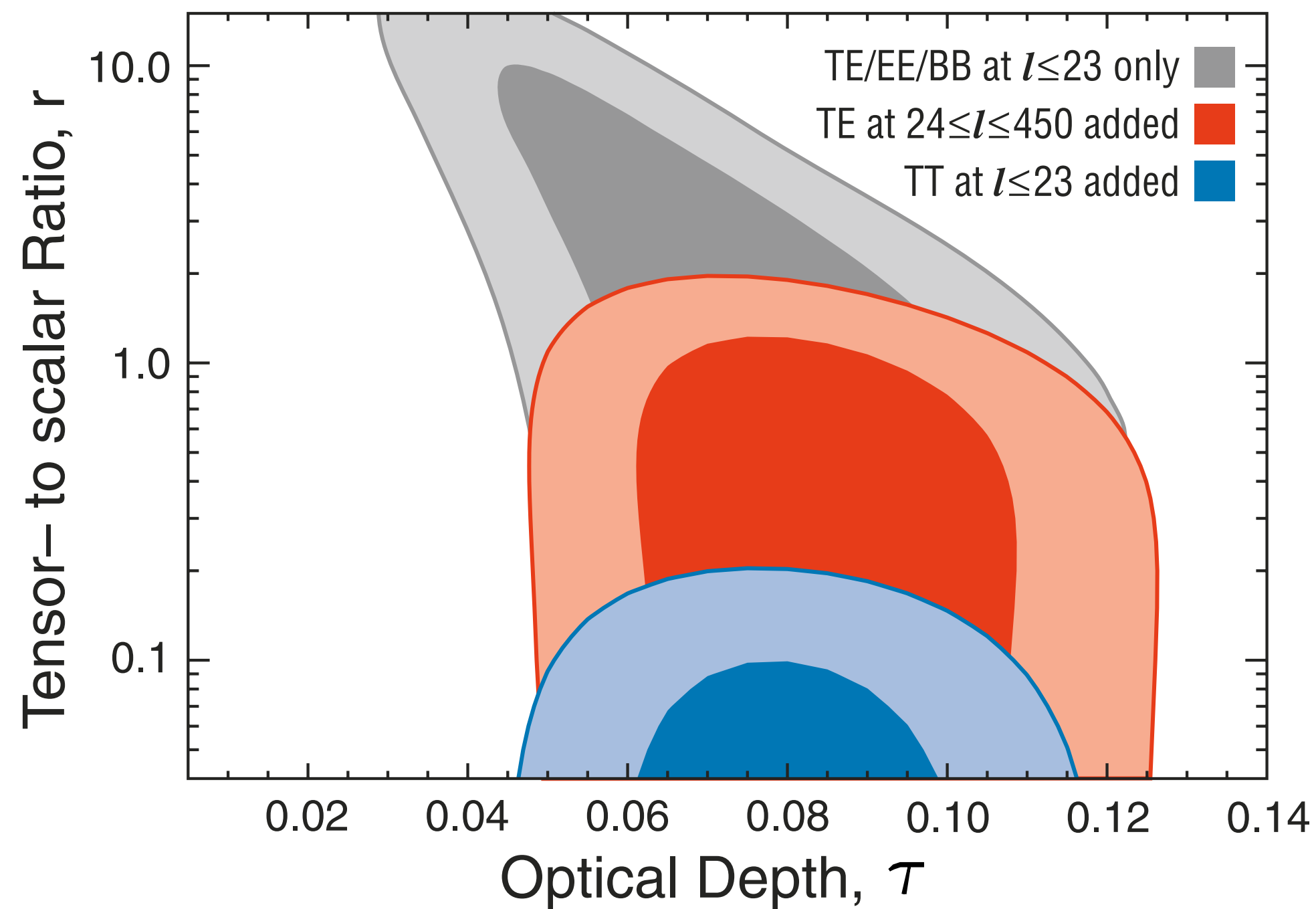


Searching for Primordial Gravitational Waves in CMB

- Not only do inflation models produce density fluctuations, but also primordial gravitational waves
- Some predict the observable amount ($r > 0.01$), some don't
- Current limit: **$r < 0.22$** (95%CL)
- Alternative scenarios (e.g., New Ekpyrotic) don't
- A powerful probe for testing inflation and testing specific models: next "Holy Grail" for CMBist

How GW Affects CMB

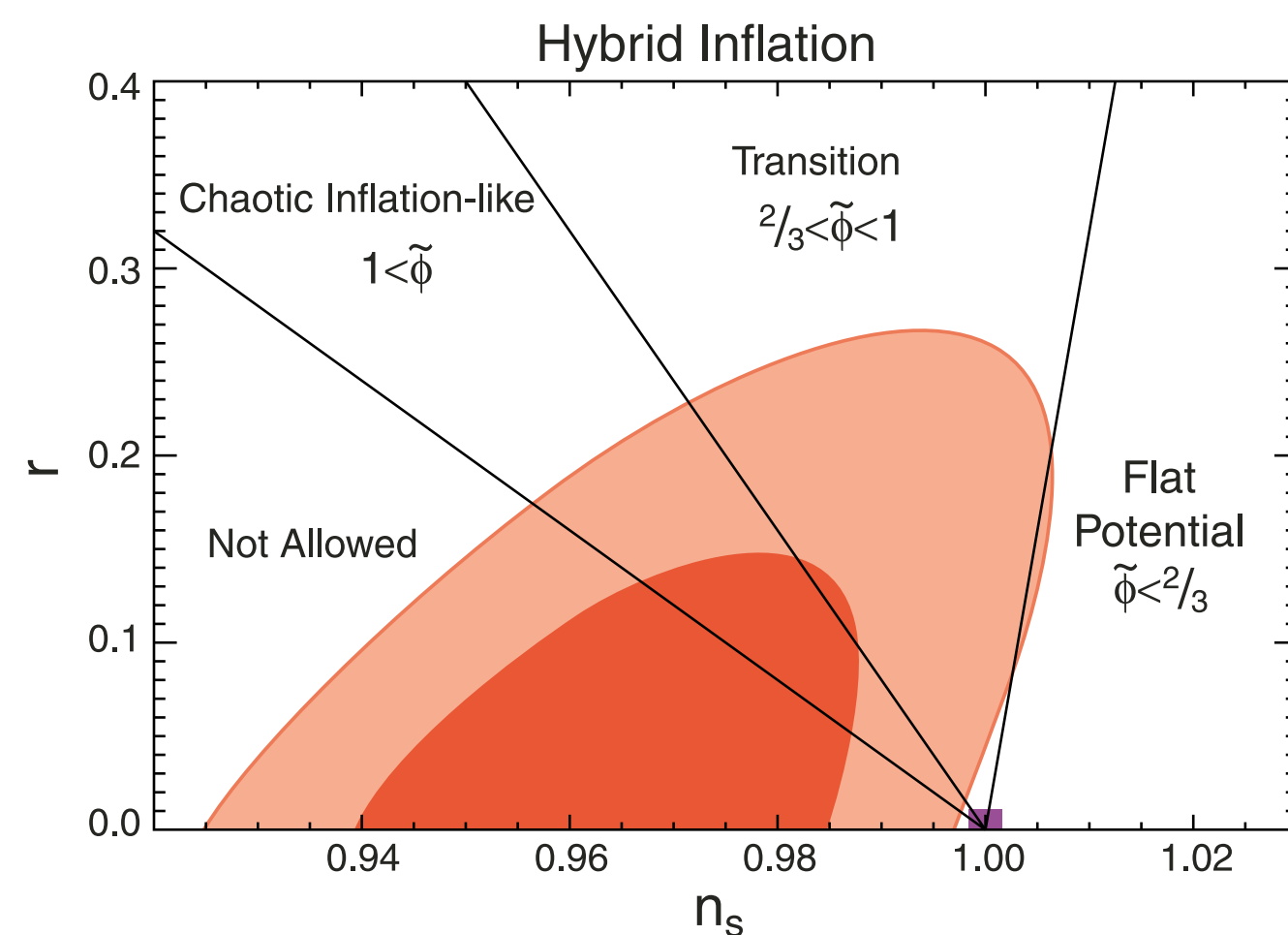
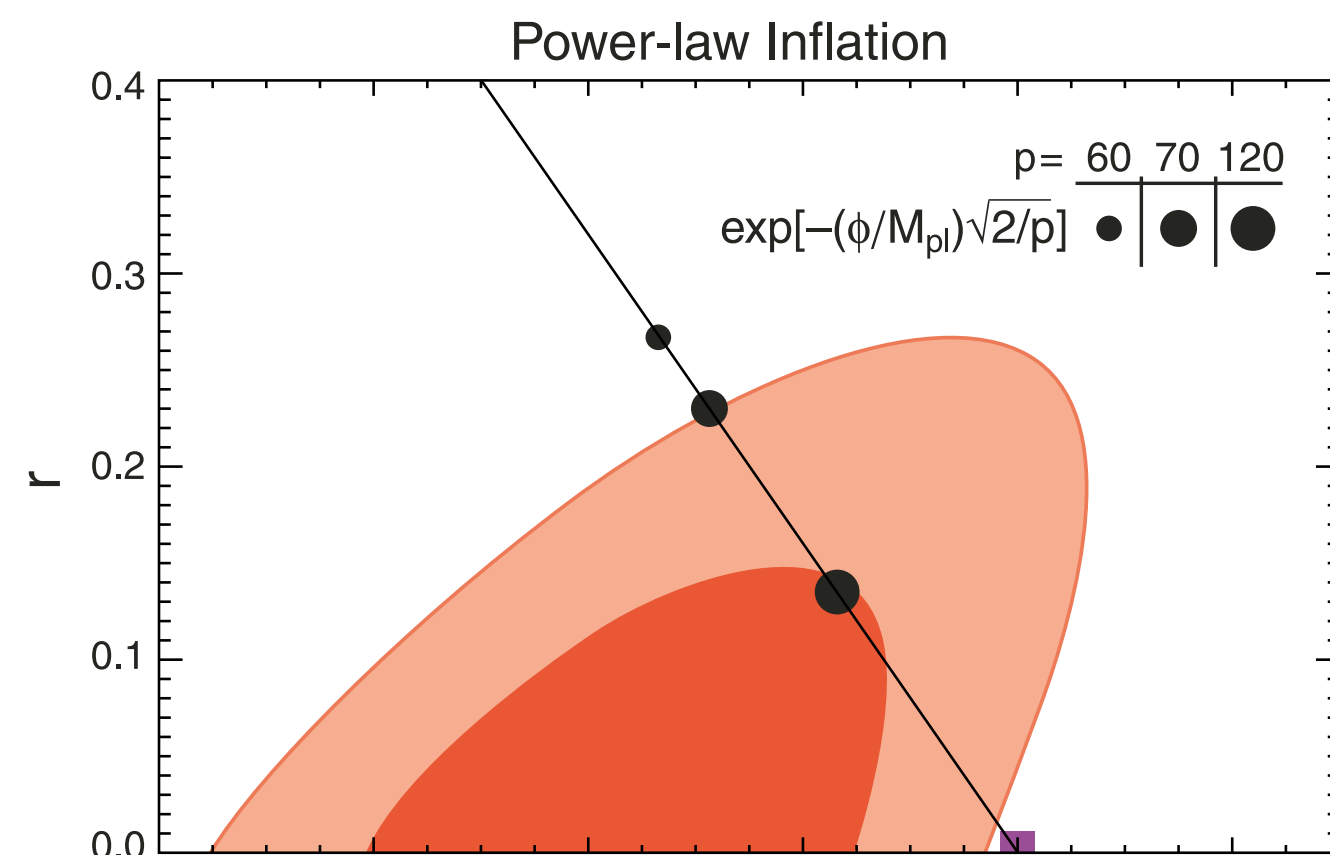
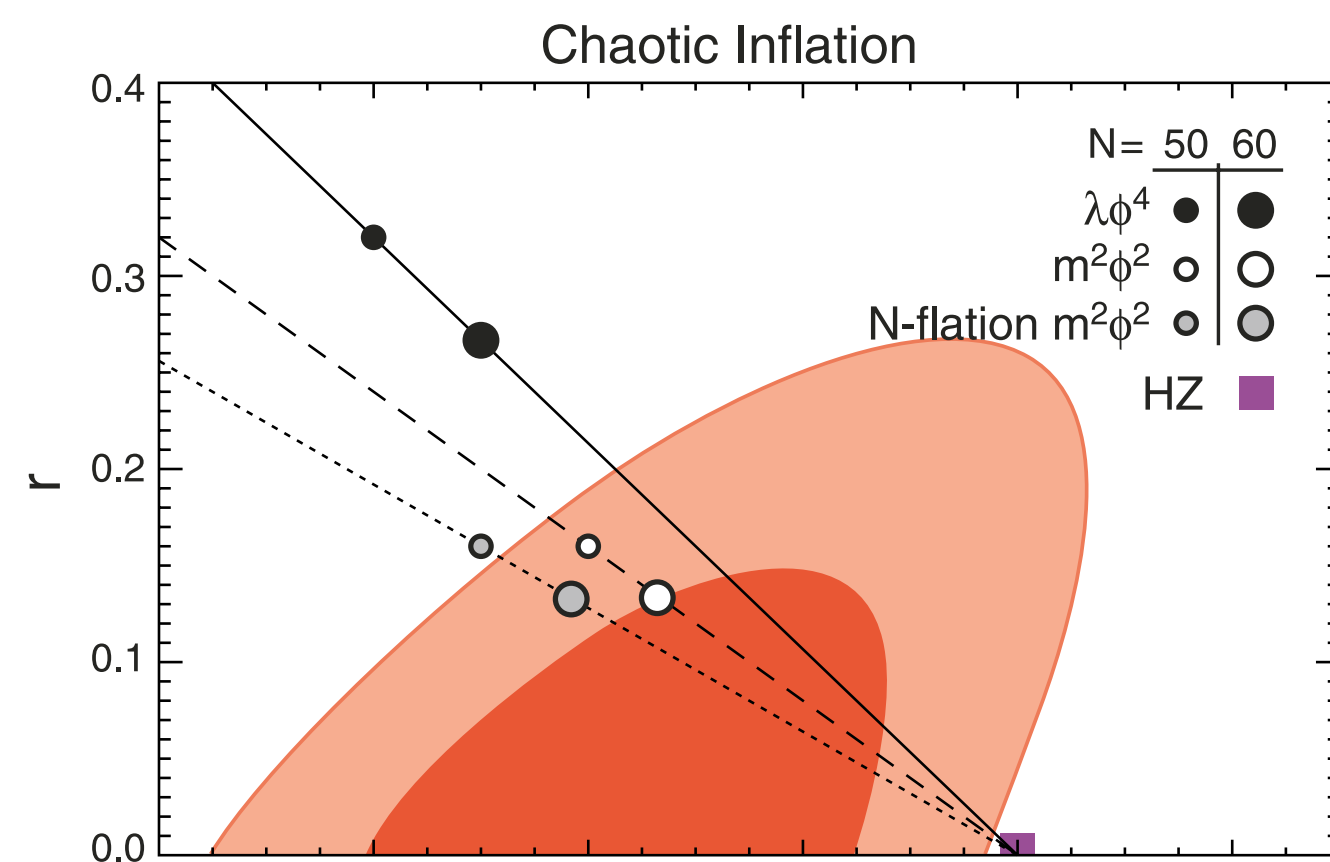
Komatsu et al.



- 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)

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

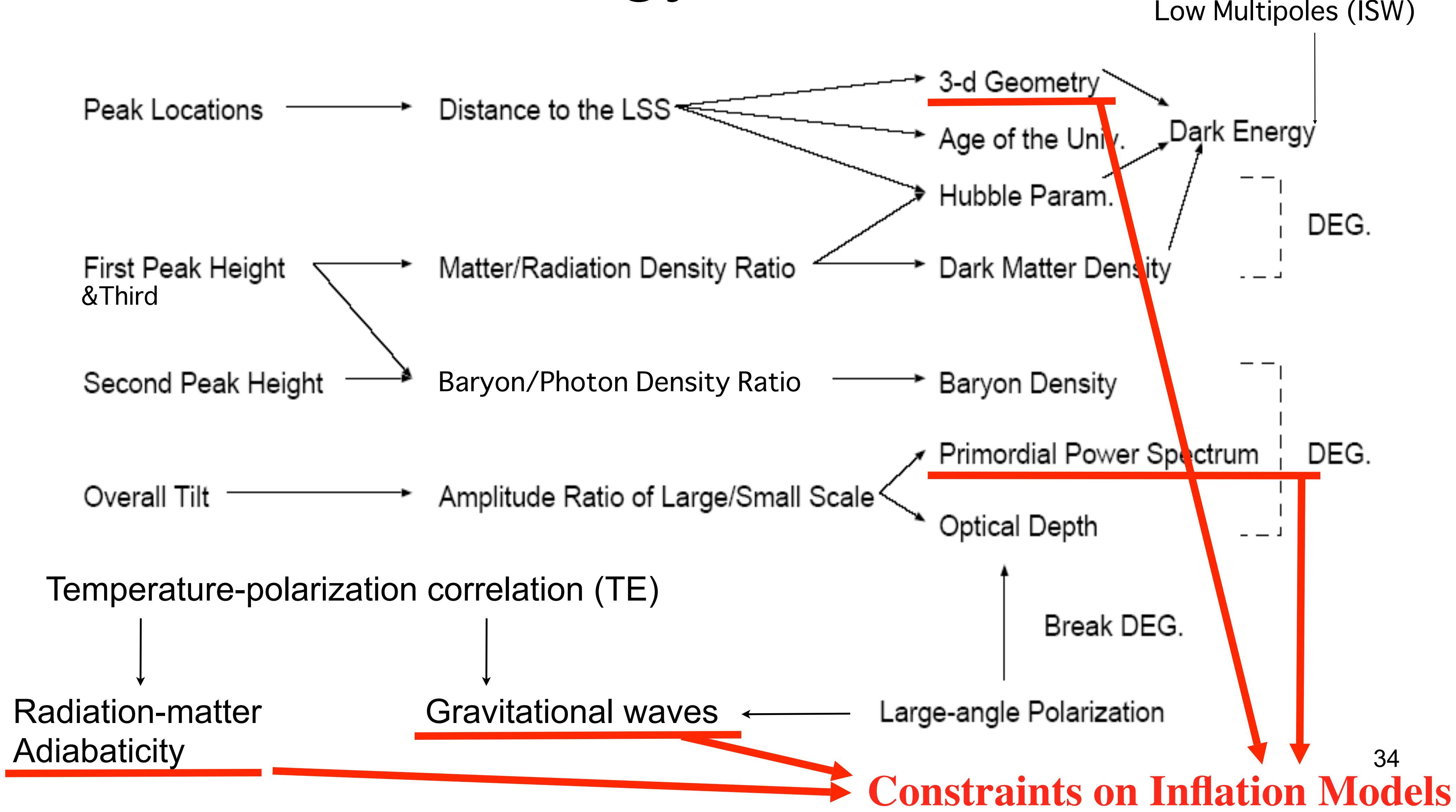


Testing Cosmic Inflation

~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?

CMB to Cosmology to Inflation

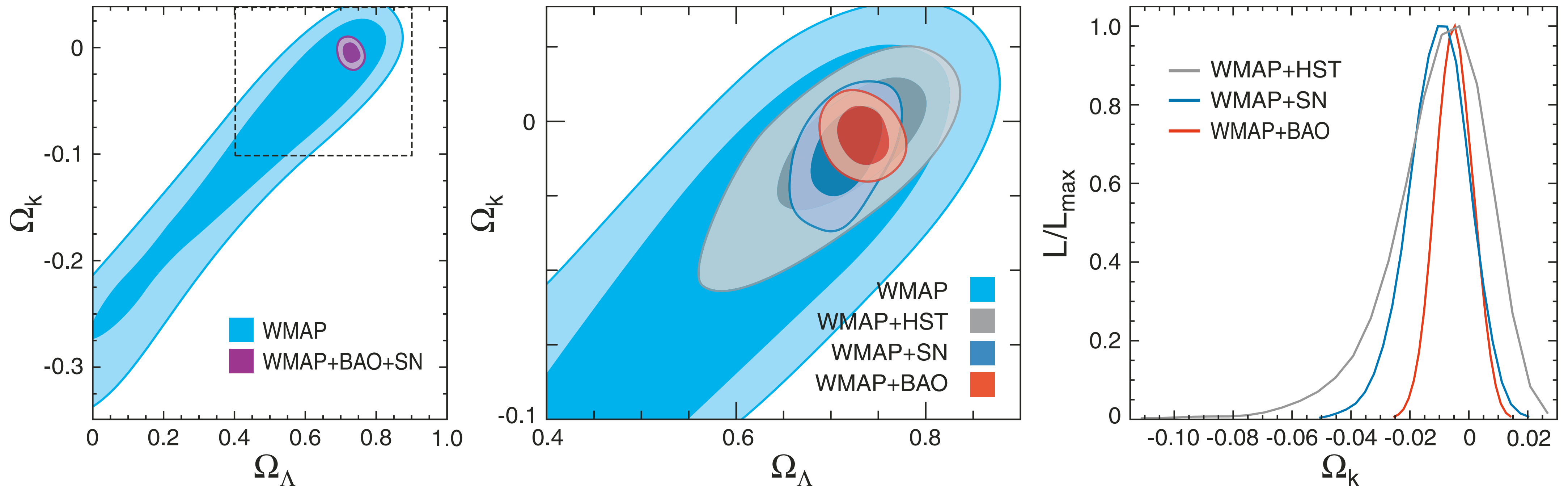


How Do We Test Inflation?

- 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

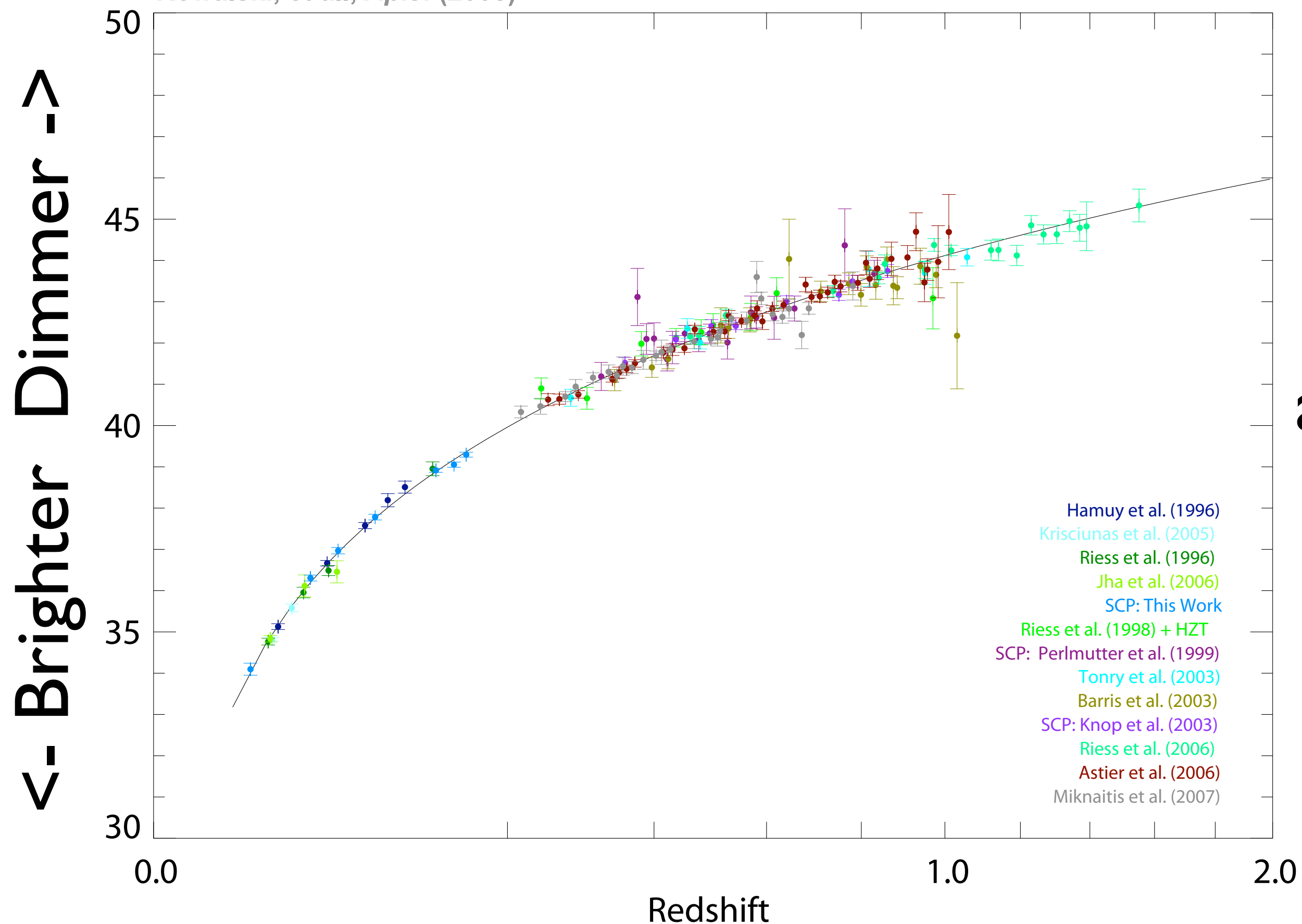
Komatsu et al.



- 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

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

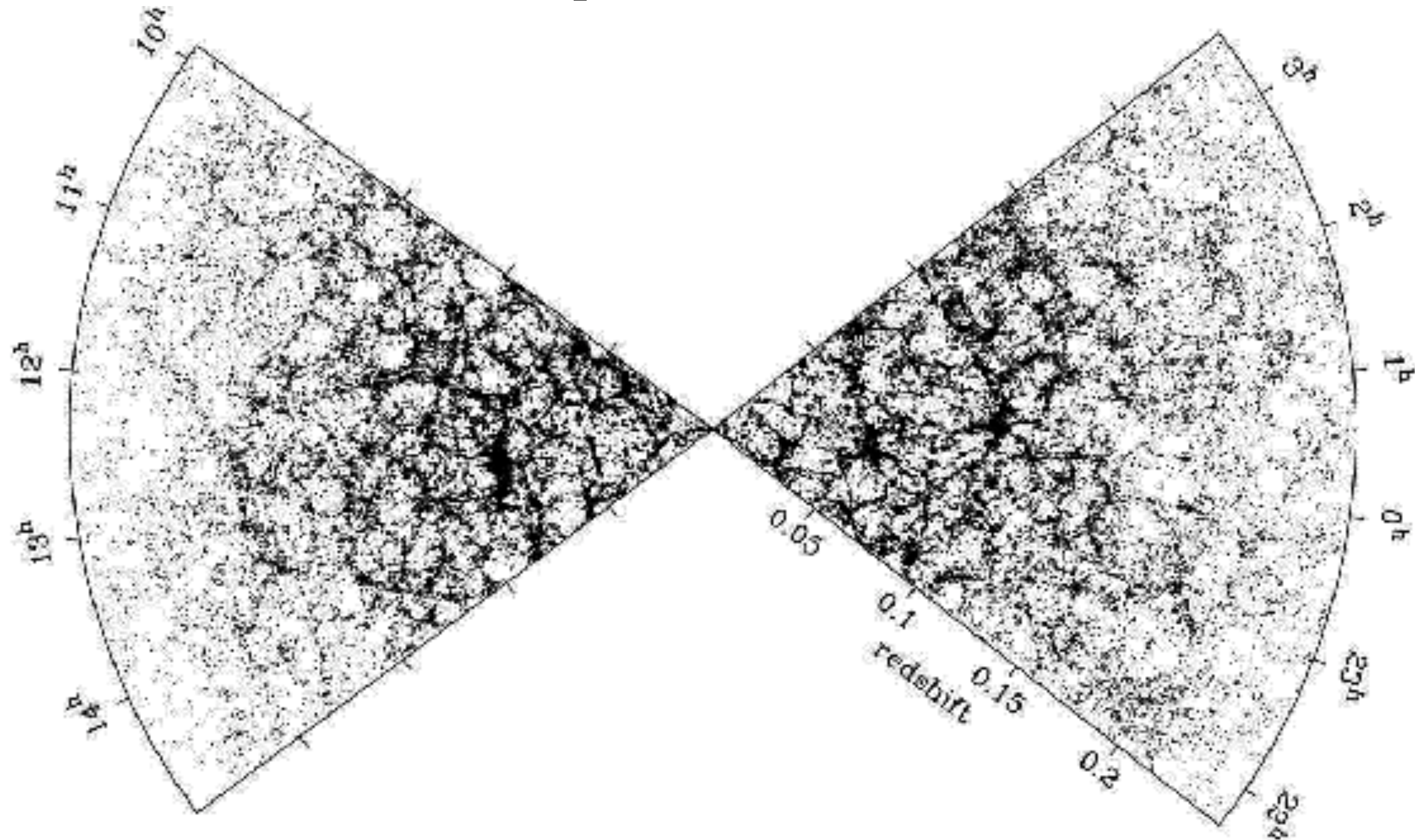


From these measurements, we get the **relative** luminosity distances between Type Ia SNe. Since we marginalize over the absolute magnitude, the current SN data are **not** sensitive to the absolute distances.

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

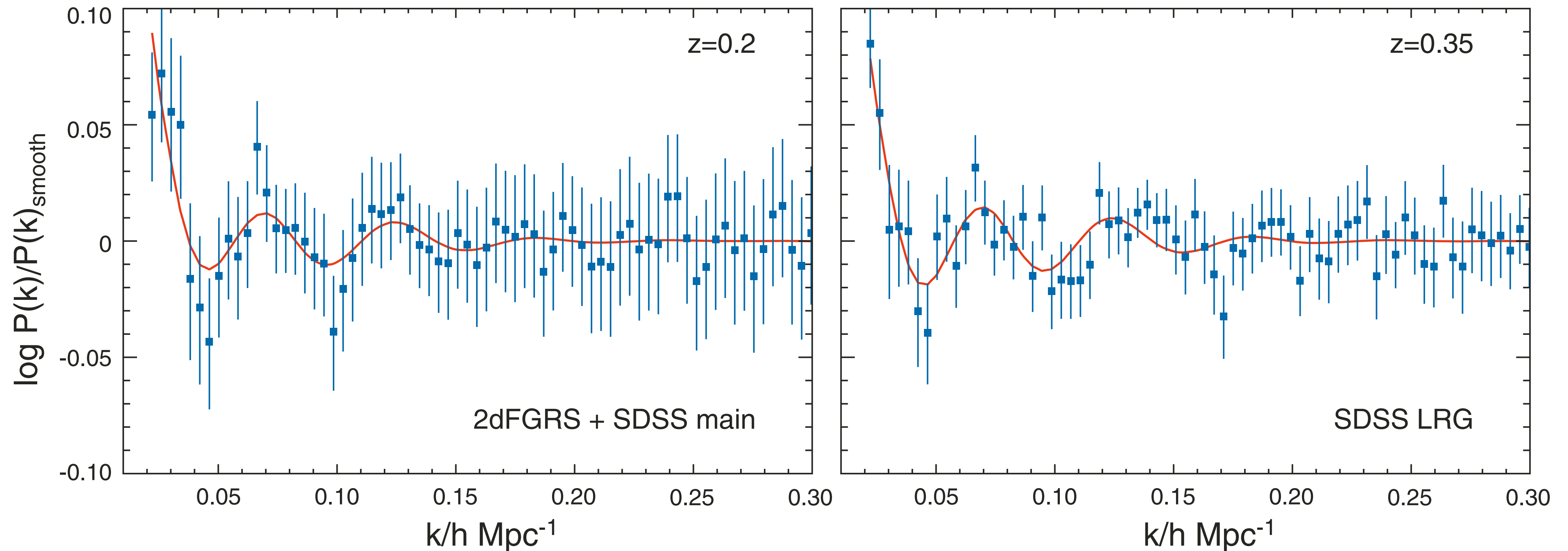
BAO in Galaxy Distribution

2dFGRS



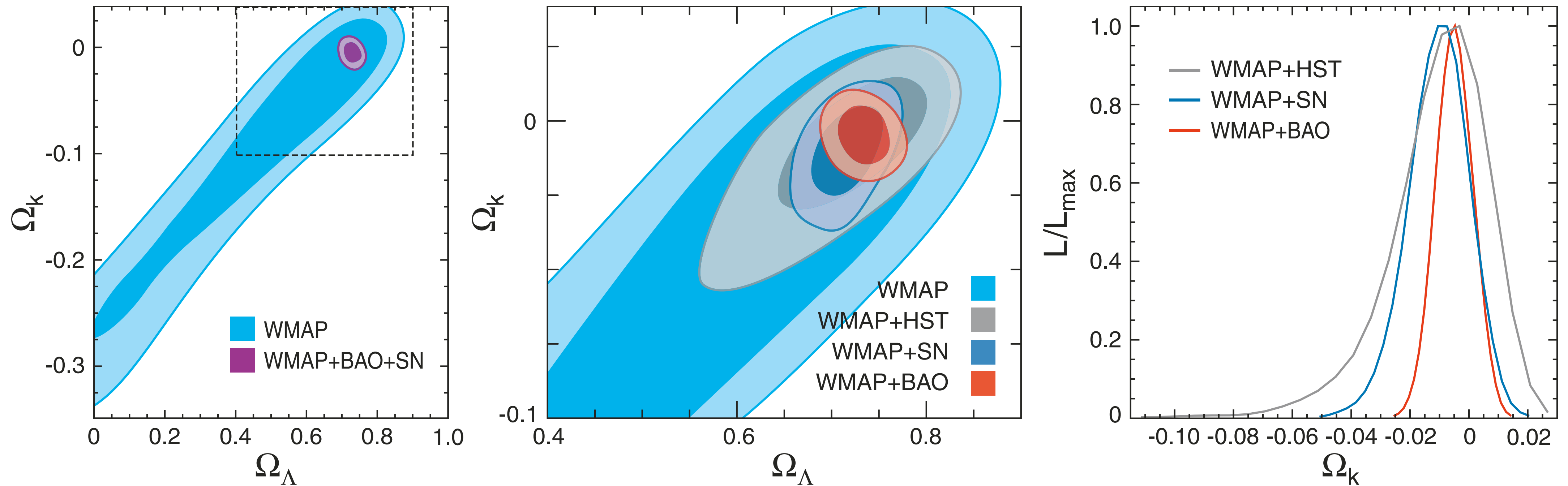
- The same acoustic oscillations should be hidden in this galaxy distribution...

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 ³⁹

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

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**

Getting the Most Out of Fluctuations, $\delta(\mathbf{x})$

- In Fourier space, $\delta(\mathbf{k}) = A(\mathbf{k})\exp(i\varphi_{\mathbf{k}})$
 - **Power:** $P(\mathbf{k}) = \langle |\delta(\mathbf{k})|^2 \rangle = A^2(\mathbf{k})$
 - **Phase:** $\varphi_{\mathbf{k}}$
- We can use the observed distribution of...
 - matter (e.g., galaxies, gas)
 - radiation (e.g., Cosmic Microwave Background)
- to learn about both $P(\mathbf{k})$ and $\varphi_{\mathbf{k}}$.

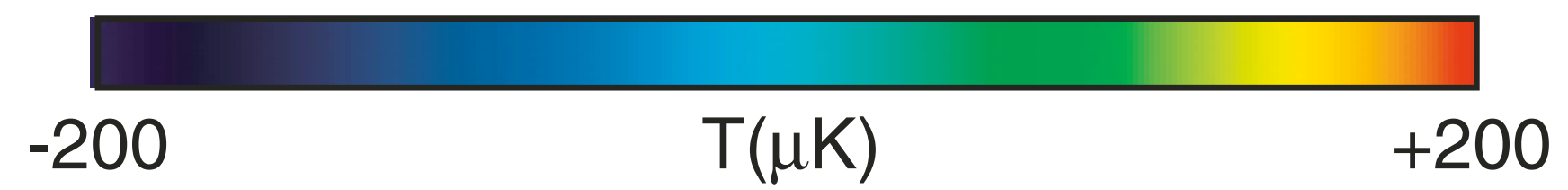
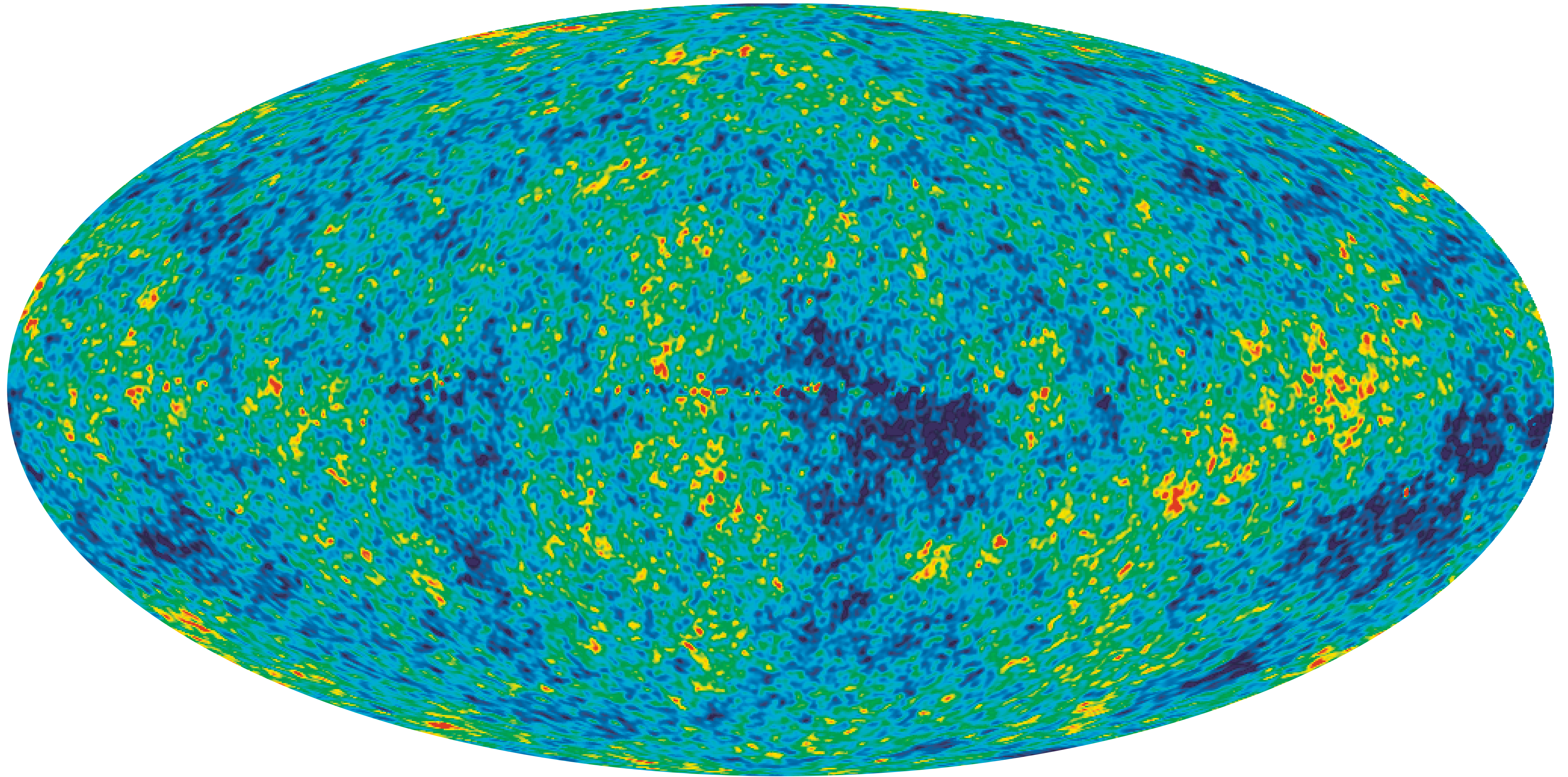
What About Phase, φ_k

- There were expectations also:
 - Random phases! (Peebles, ...)
- Collection of random, uncorrelated phases leads to the most famous probability distribution of δ :

Gaussian Distribution

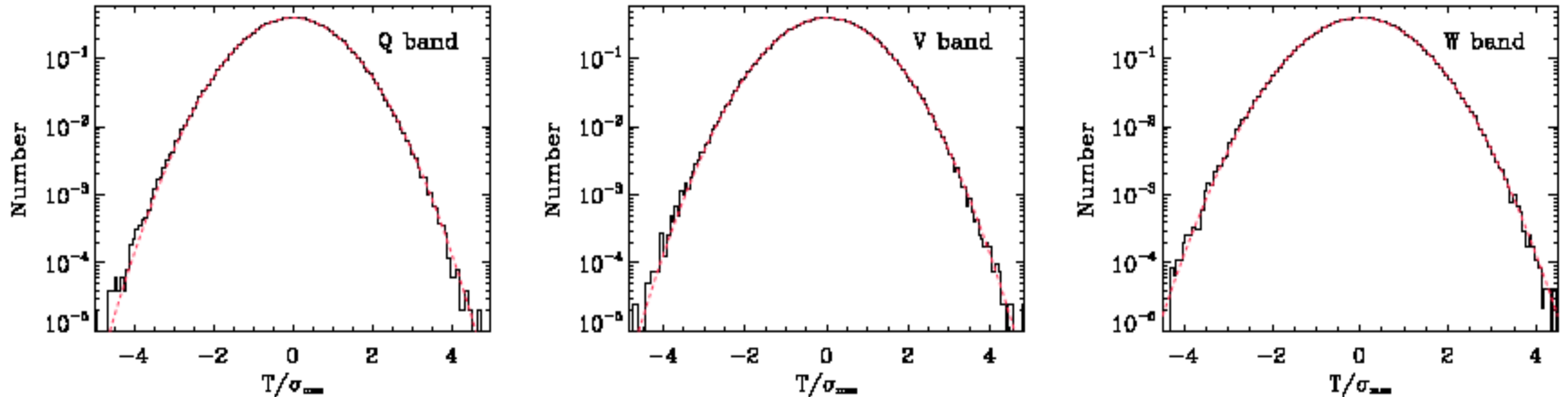
Gaussian?

WMAP5



WMAP 5-year

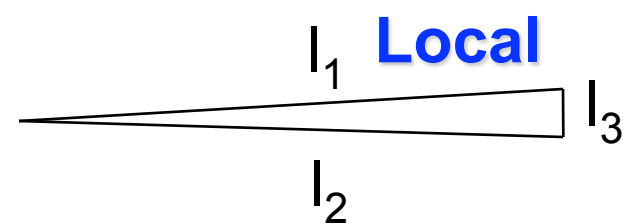
Take One-point Distribution Function



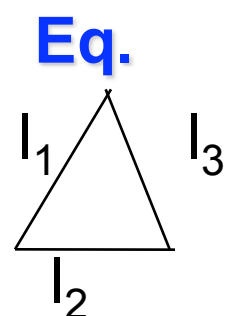
- The one-point distribution of WMAP map looks pretty Gaussian.
 - Left to right: Q (41GHz), V (61GHz), W (94GHz).
- Deviation from Gaussianity is small, if any.

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 $>95\%CL$

- $-9 < f_{NL}(\text{local}) < 111$ (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.

Grading Inflation

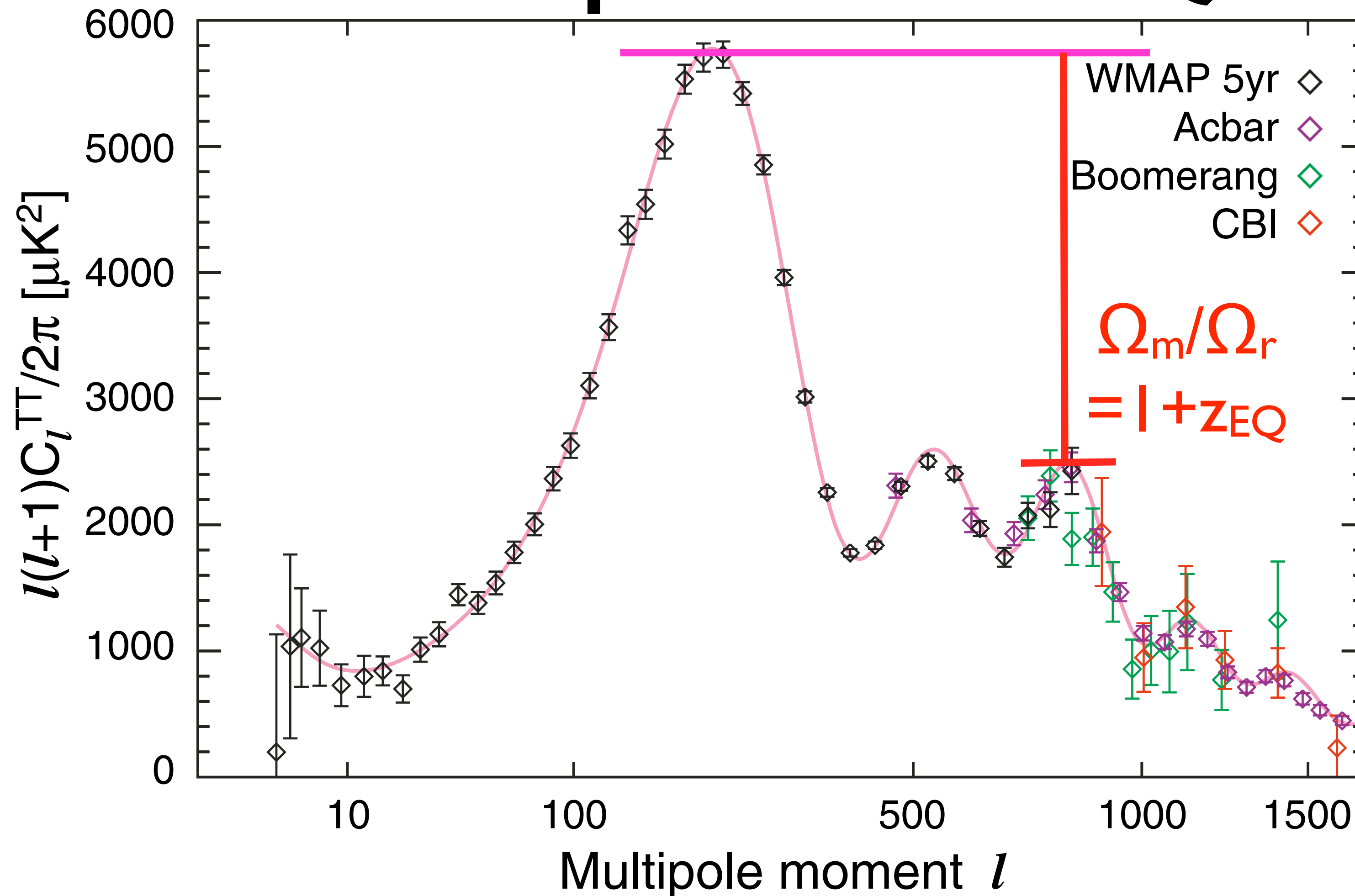
- **Flatness:** $-0.0179 < \Omega_k < 0.0081$ (not assuming $w=-1$!)
- **Non-adiabaticity:** $<8.9\%$ (axion DM); $<2.1\%$ (curvaton DM)
- **Non-Gaussianity:** $-9 < \text{Local} < 111$; $-151 < \text{Equilateral} < 253$
- **Tilt** (for $r=0$): $n_s = 0.960 \pm 0.013$ [68% CL]
- **Gravitational waves:**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

Effective Number of Neutrino Species, N_{eff}

- For relativistic neutrinos, the energy density is given by
 - $\rho_\nu = N_{\text{eff}} (7\pi^2/120) T_\nu^4$
 - where $N_{\text{eff}}=3.04$ for the standard model, and $T_\nu=(4/11)^{1/3}T_{\text{photon}}$
- Adding more relativistic neutrino species (or any other relativistic components) delays the epoch of the matter-radiation equality, as

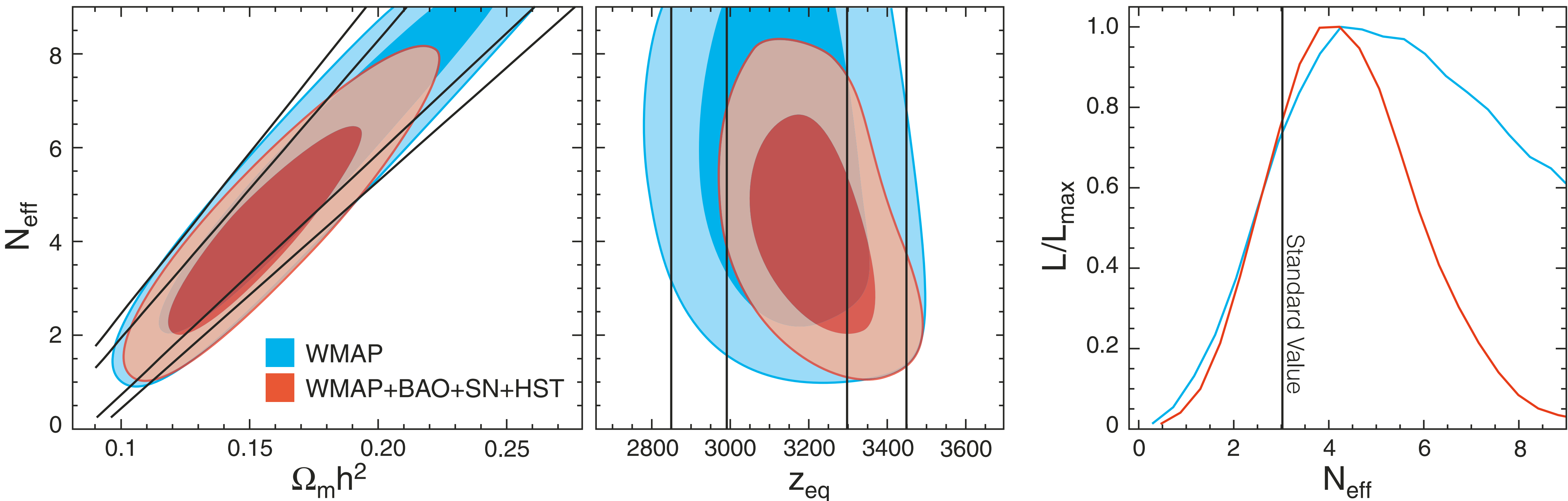
$$1+z_{\text{EQ}} = (\Omega_m h^2 / 2.47 \times 10^{-5}) / (1 + 0.227 N_{\text{eff}})$$

3rd-peak to z_{EQ}



- It is z_{EQ} that is observable from CMB.
- If we fix N_{eff} , we can determine $\Omega_m h^2$; otherwise...

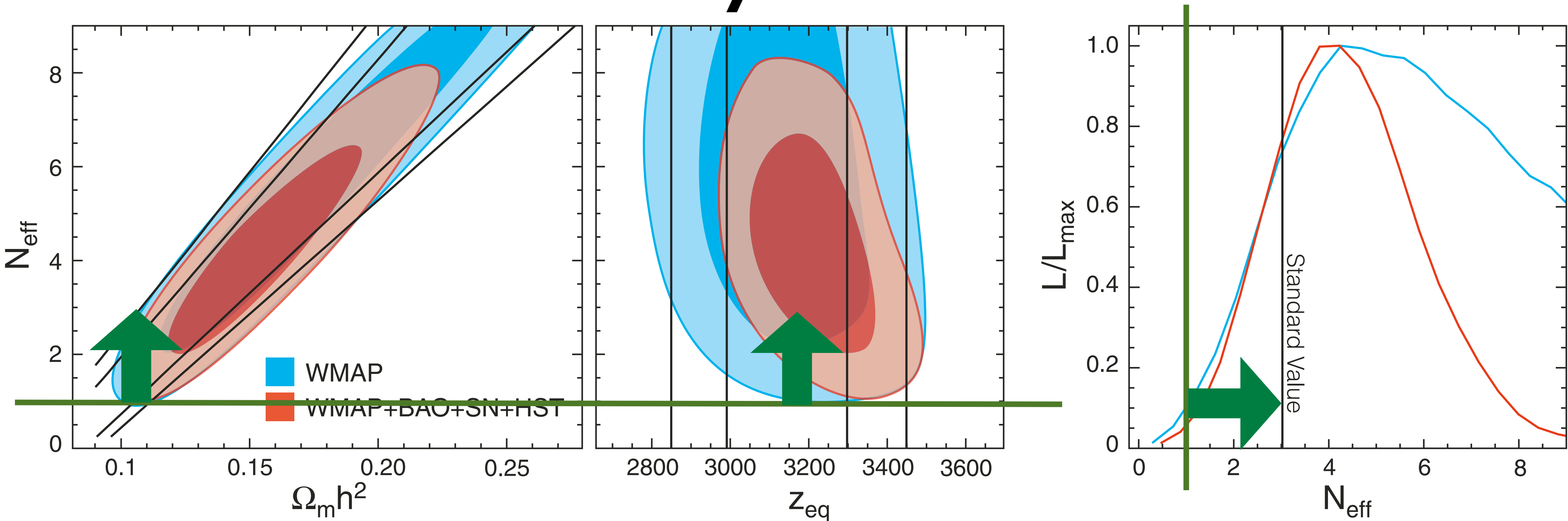
$N_{\text{eff}}-\Omega_m h^2$ Degeneracy



- N_{eff} and $\Omega_m h^2$ are totally degenerate!
- Adding information on $\Omega_m h^2$ from the distance measurements (BAO, SN, HST) breaks the degeneracy:

• **$N_{\text{eff}} = 4.4 \pm 1.5$ (68%CL)**

WMAP-only Lower Limit

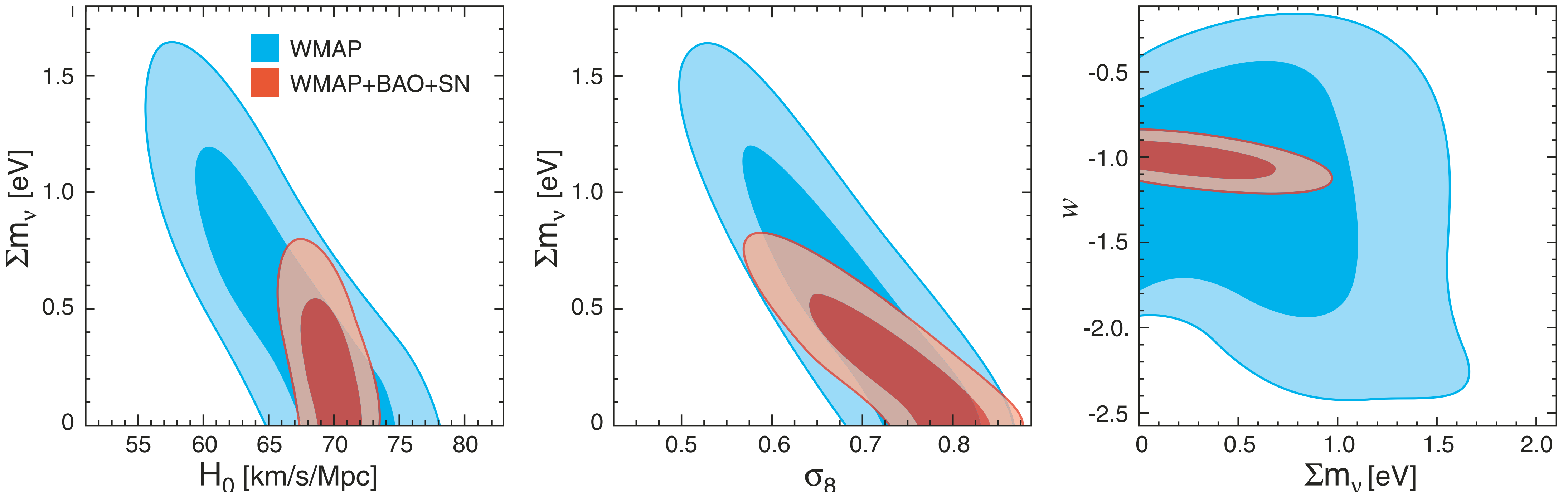


- N_{eff} and $\Omega_m h^2$ are totally degenerate - but, look.
- **WMAP-only lower limit is not $N_{\text{eff}}=0$**
- $N_{\text{eff}} > 2.3$ (95%CL) [Dunkley et al.]

Cosmic/Laboratory Consistency

- From WMAP($z=1090$)+BAO+SN
 - $N_{\text{eff}} = 4.4 \pm 1.5$
- From the Big Bang Nucleosynthesis ($z=10^9$)
 - $N_{\text{eff}} = 2.5 \pm 0.4$ (Gary Steigman)
- From the decay width of Z bosons measured in lab
 - $N_{\text{neutrino}} = 2.984 \pm 0.008$ (LEP)

Neutrino Mass



- The local distance measurements (BAO) help determine the neutrino mass by giving H_0 .
- **$\text{Sum}(m_\nu) < 0.67 \text{ eV}$** (95% CL) -- independent of the normalization of the large scale structure.

Summary

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
	$\Delta_{\mathcal{R}}^2 (k_0^e)$	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_{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

- Errorbars on the simplest, 6-parameter Λ CDM model are tightly constrained by WMAP-data only, and even more tightly (especially matter density and amplitude of fluctuations) by combining low-z distance measurements.

Summary

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.	$R_{\text{curv}} > 12 h^{-1} \text{Gpc}$	$R_{\text{curv}} > 23 h^{-1} \text{Gpc}$
		Negative Curv.	$R_{\text{curv}} > 22 h^{-1} \text{Gpc}$	$R_{\text{curv}} > 33 h^{-1} \text{Gpc}$
§ 3.5	Gaussianity	Local	$-9 < f_{NL}^{\text{local}} < 111^h$	N/A
		Equilateral	$-151 < f_{NL}^{\text{equil}} < 253^i$	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		$\sum m_\nu < 1.3 \text{ eV}^t$	$\sum m_\nu < 0.67 \text{ eV}^u$
§ 6.2	Neutrino Species		$N_{\text{eff}} > 2.3^v$	$N_{\text{eff}} = 4.4 \pm 1.5^w$ (68%)

- **We did everything we could do to find deviations from Λ CDM, but failed.**

- Well, we still don't know what DE or DM is.

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
 - More, maybe seeing a hint of it if $m^2\varphi^2$ is indeed the correct model?!