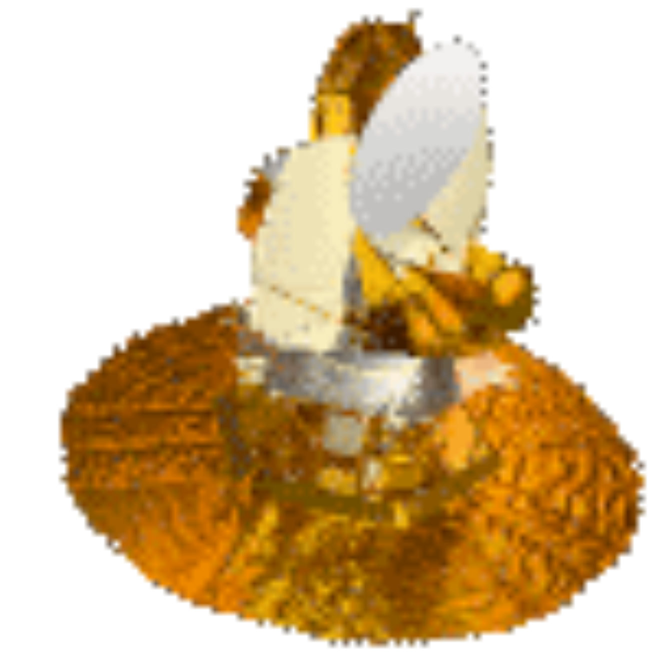


The 5-Year Wilkinson Microwave Anisotropy Probe (*WMAP*) Observations: Cosmological Interpretation

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)

Colloquium, University of Delaware, May 6, 2009

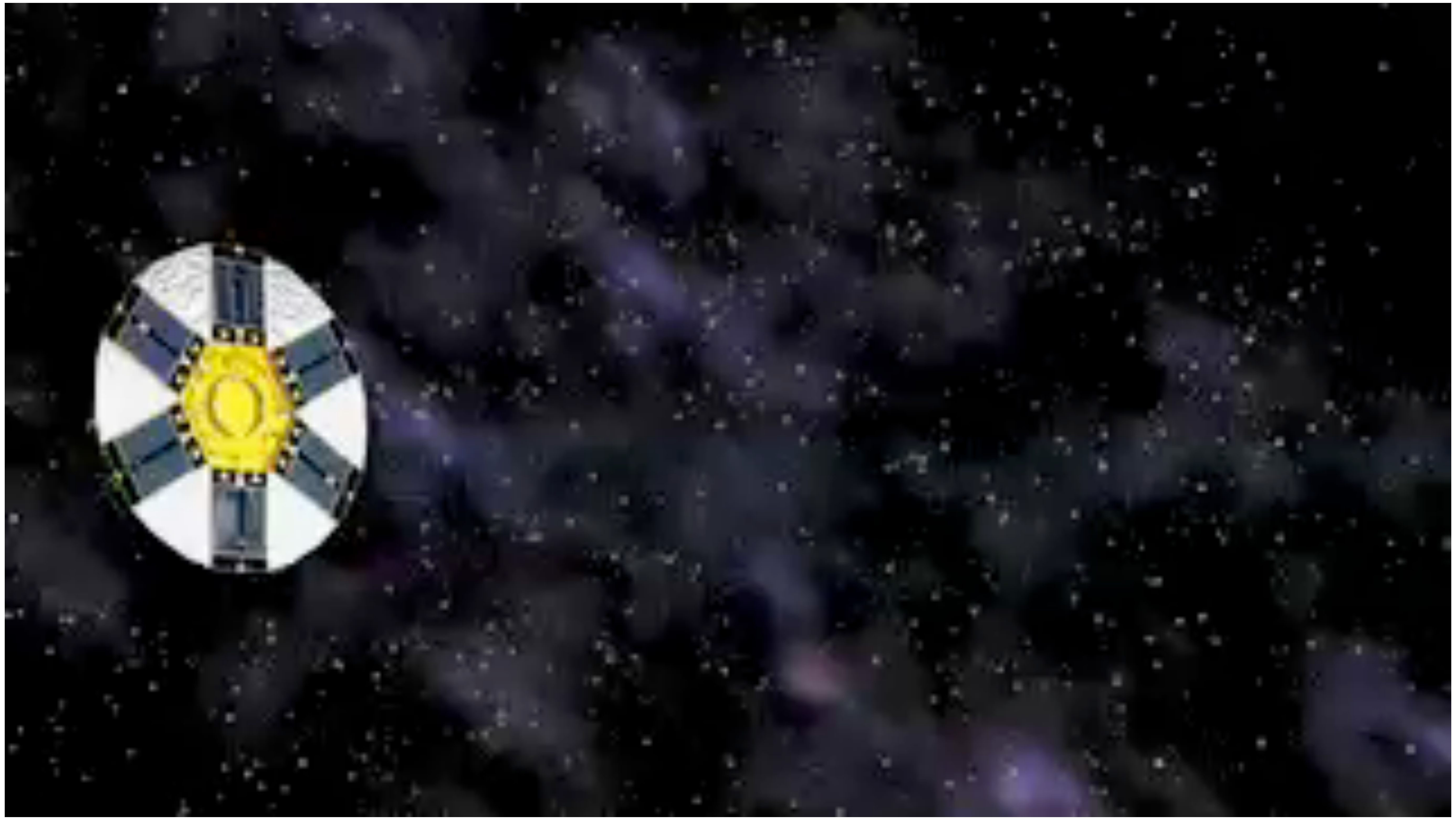
WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

February 2003:
The first-year data release

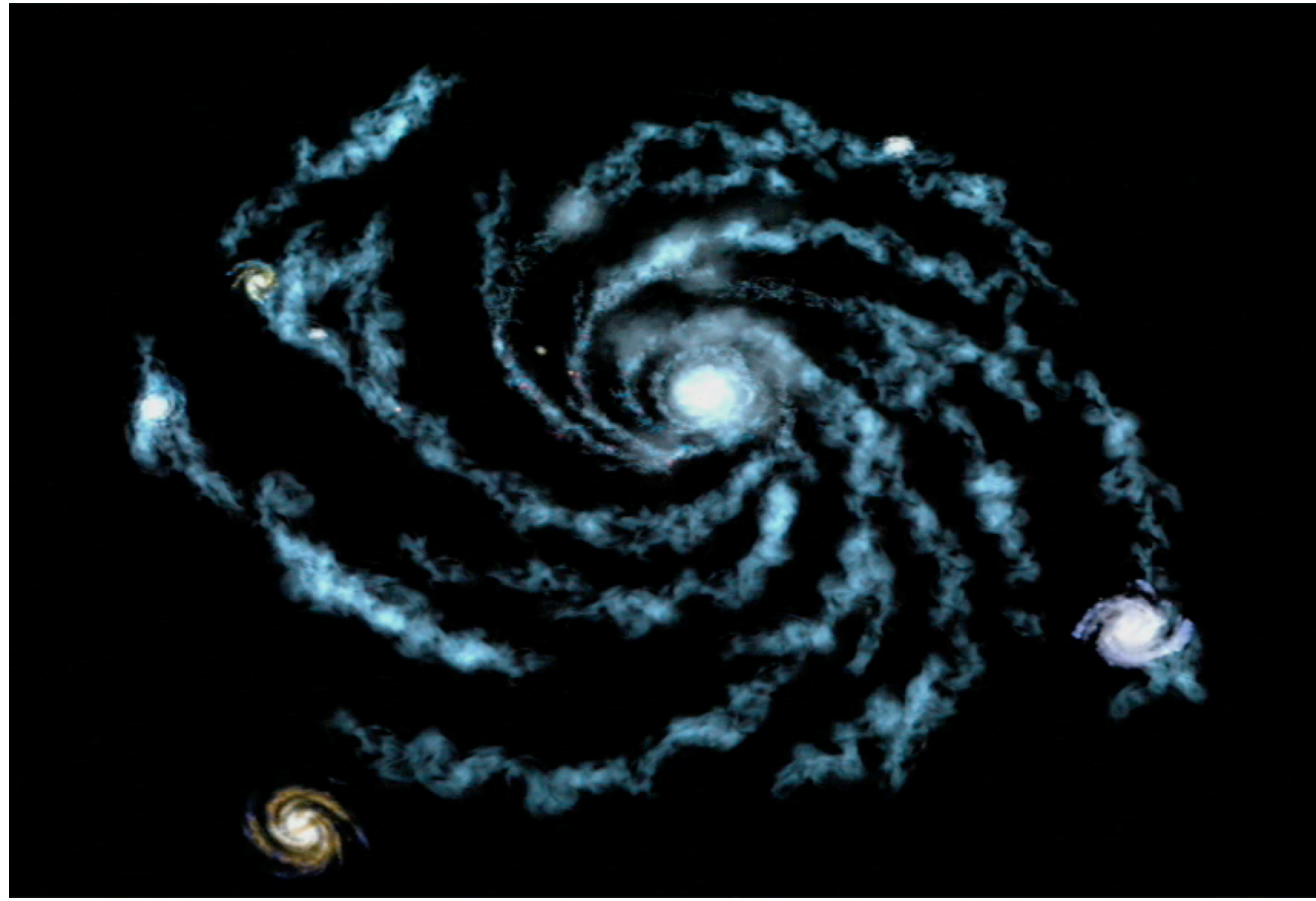
March 2006:
The three-year data release

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

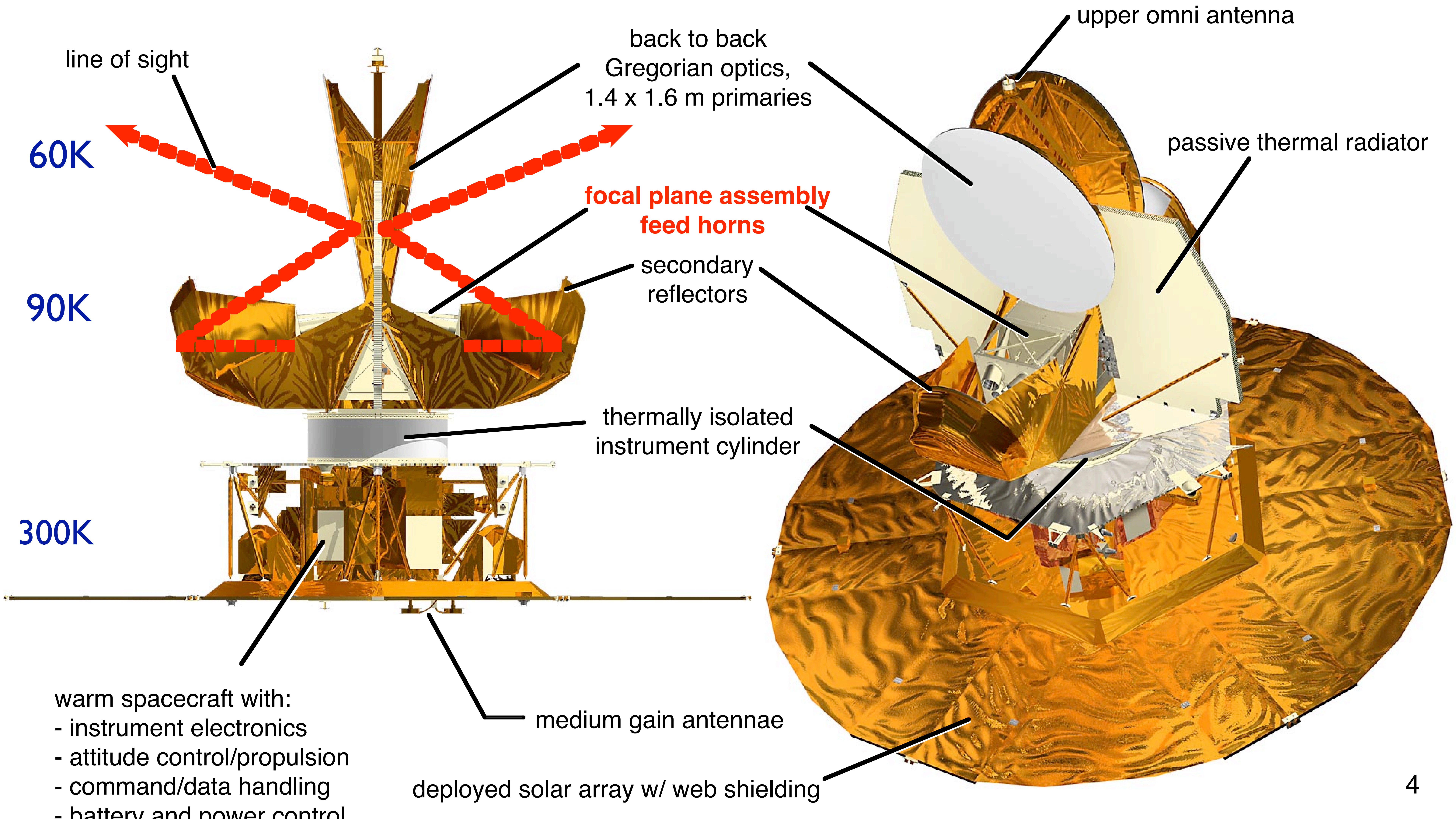
WMAP Measures Microwaves From the Universe



- 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**

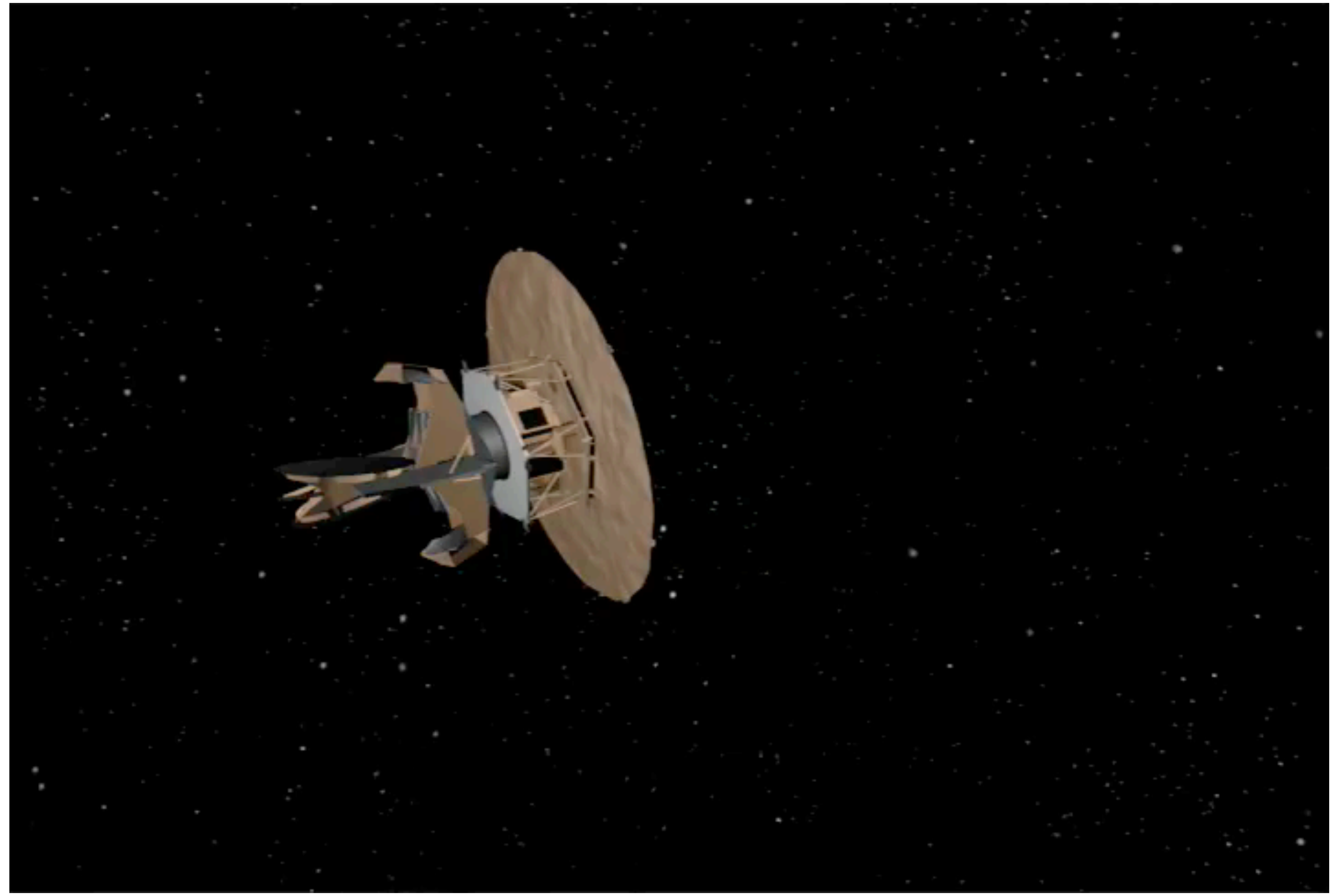
WMAP Spacecraft

Radiative Cooling: No Cryogenic System



Journey Backwards in Time

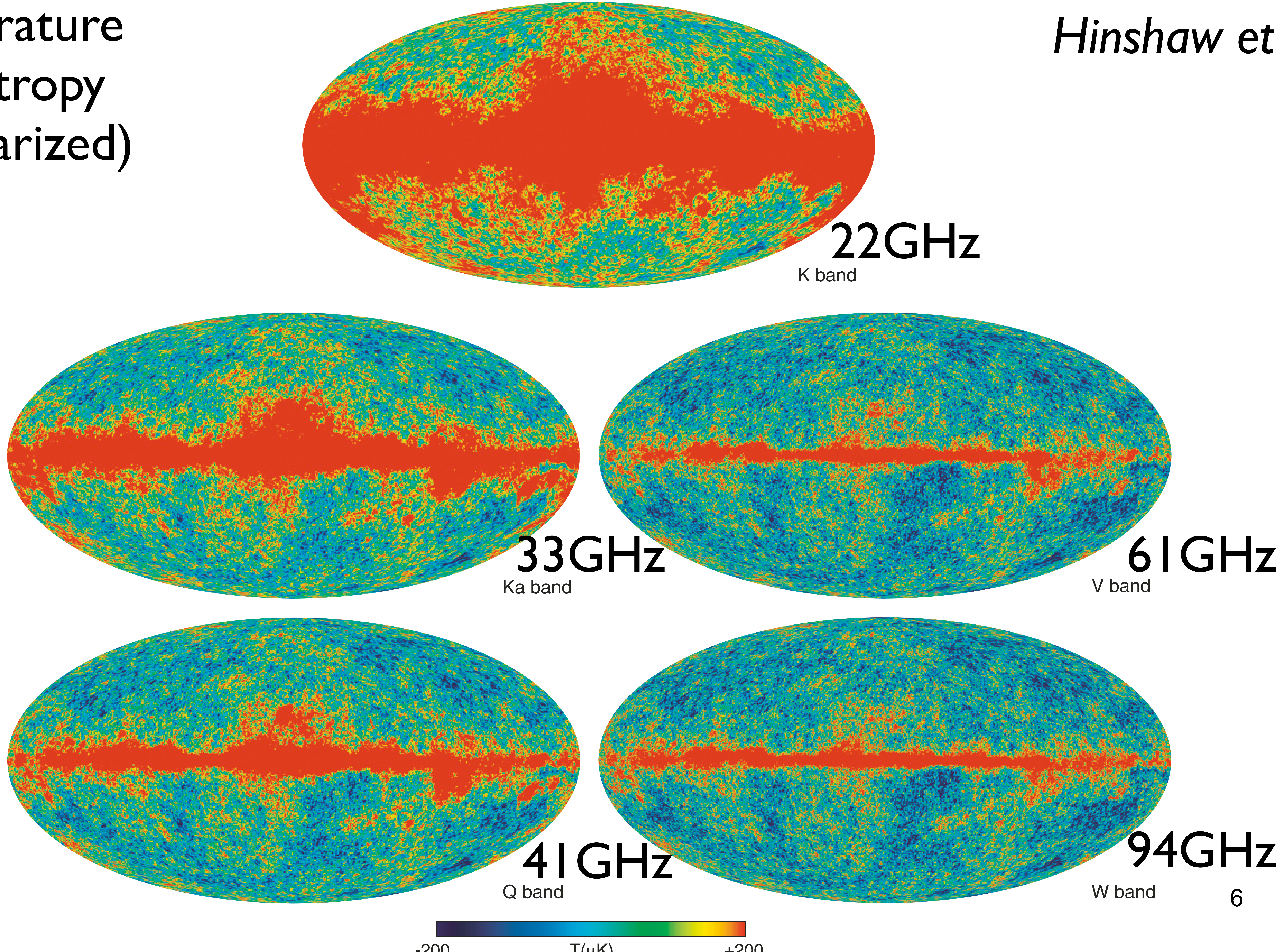
- The Cosmic Microwave Background (**CMB**) is ***the fossil light from the Big Bang***
- This is the oldest light that one can ever hope to measure
- CMB is a ***direct*** image of the Universe when the Universe was only 380,000 years old



- 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.

Temperature Anisotropy (Unpolarized)

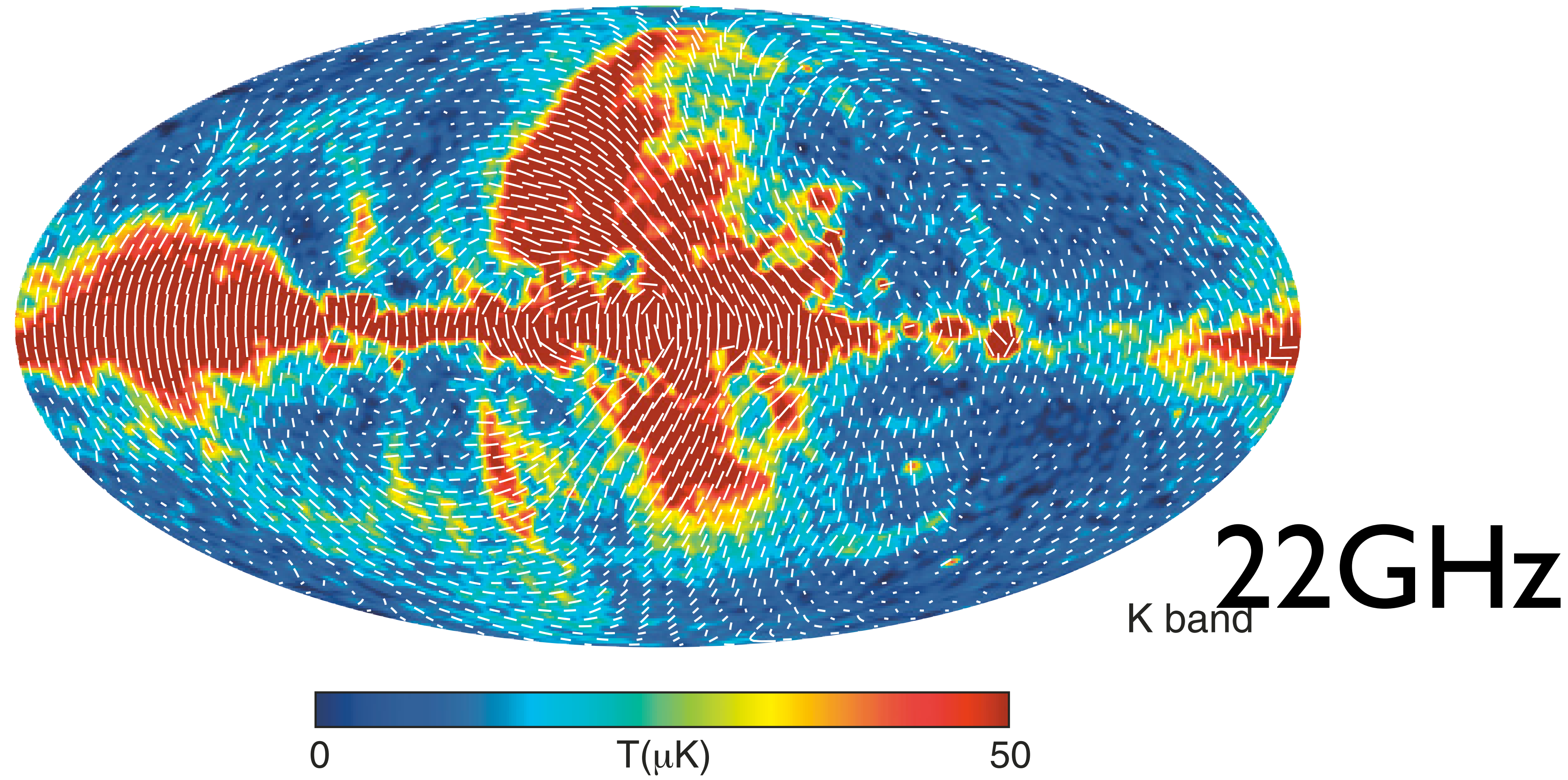
Hinshaw et al.

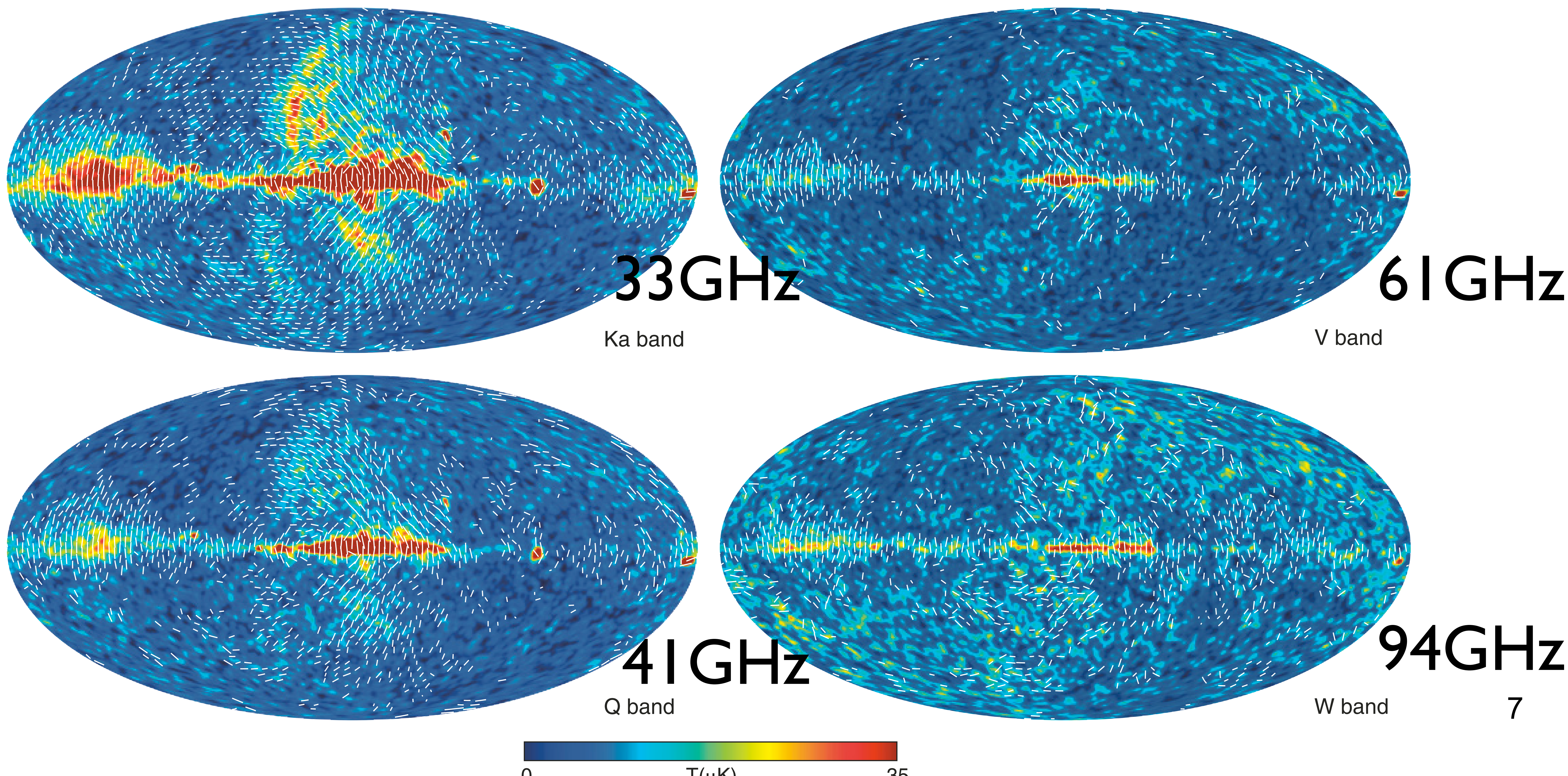


Polarization Anisotropy

Color:
Polarization Intensity
Line:
Polarization Direction

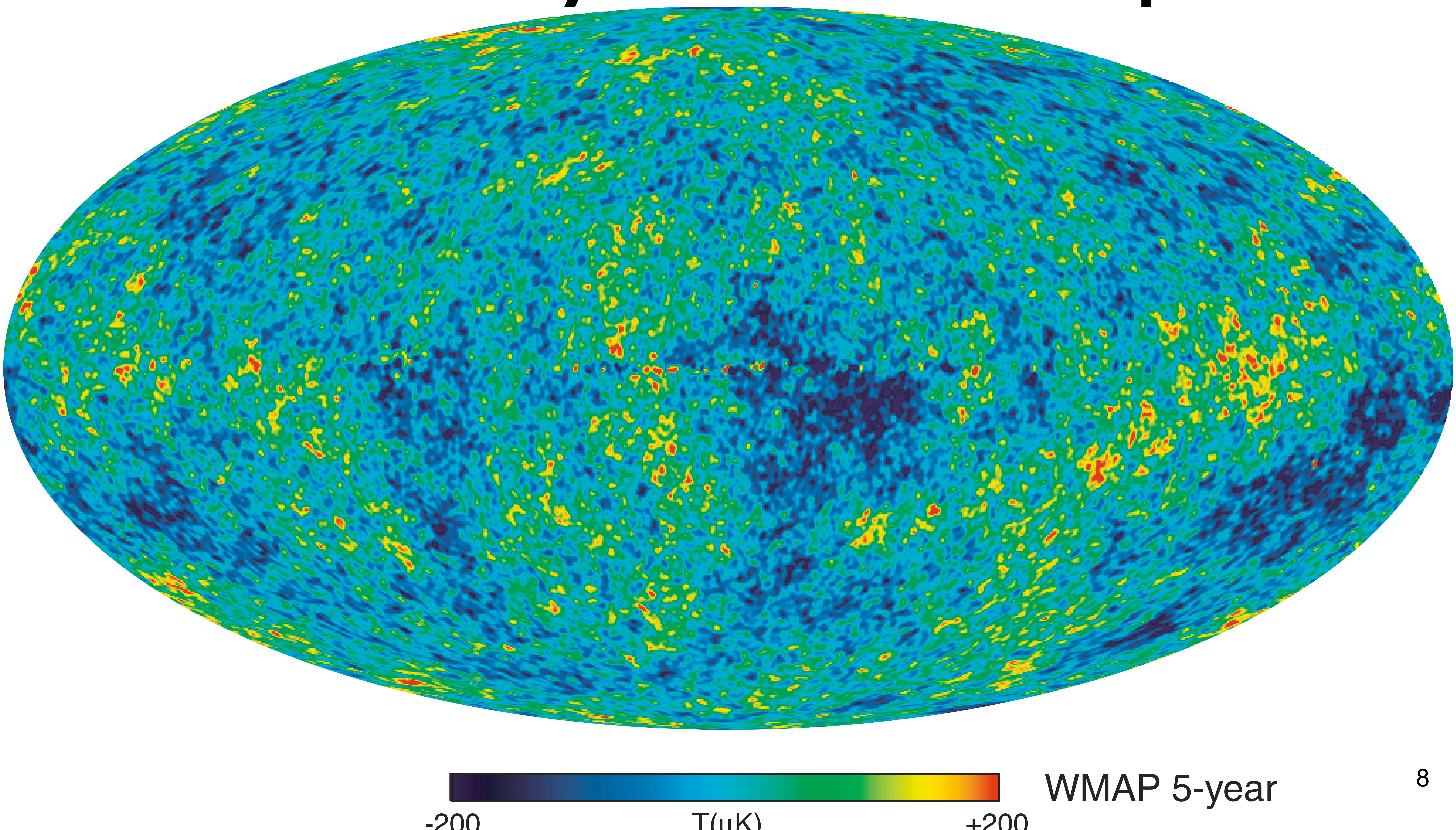
Hinshaw et al.





Hinshaw et al.

Galaxy-cleaned Map



WMAP 5-Year Papers

- **Hinshaw et al.**, "*Data Processing, Sky Maps, and Basic Results*" ApJS, 180, 225 (2009)
- **Hill et al.**, "*Beam Maps and Window Functions*" ApJS, 180, 246
- **Gold et al.**, "*Galactic Foreground Emission*" ApJS, 180, 265
- **Wright et al.**, "*Source Catalogue*" ApJS, 180, 283
- **Nolta et al.**, "*Angular Power Spectra*" ApJS, 180, 296
- **Dunkley et al.**, "*Likelihoods and Parameters from the WMAP data*" ApJS, 180, 306
- **Komatsu et al.**, "*Cosmological Interpretation*" ApJS, 180, 330

WMAP 5-Year Science Team

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

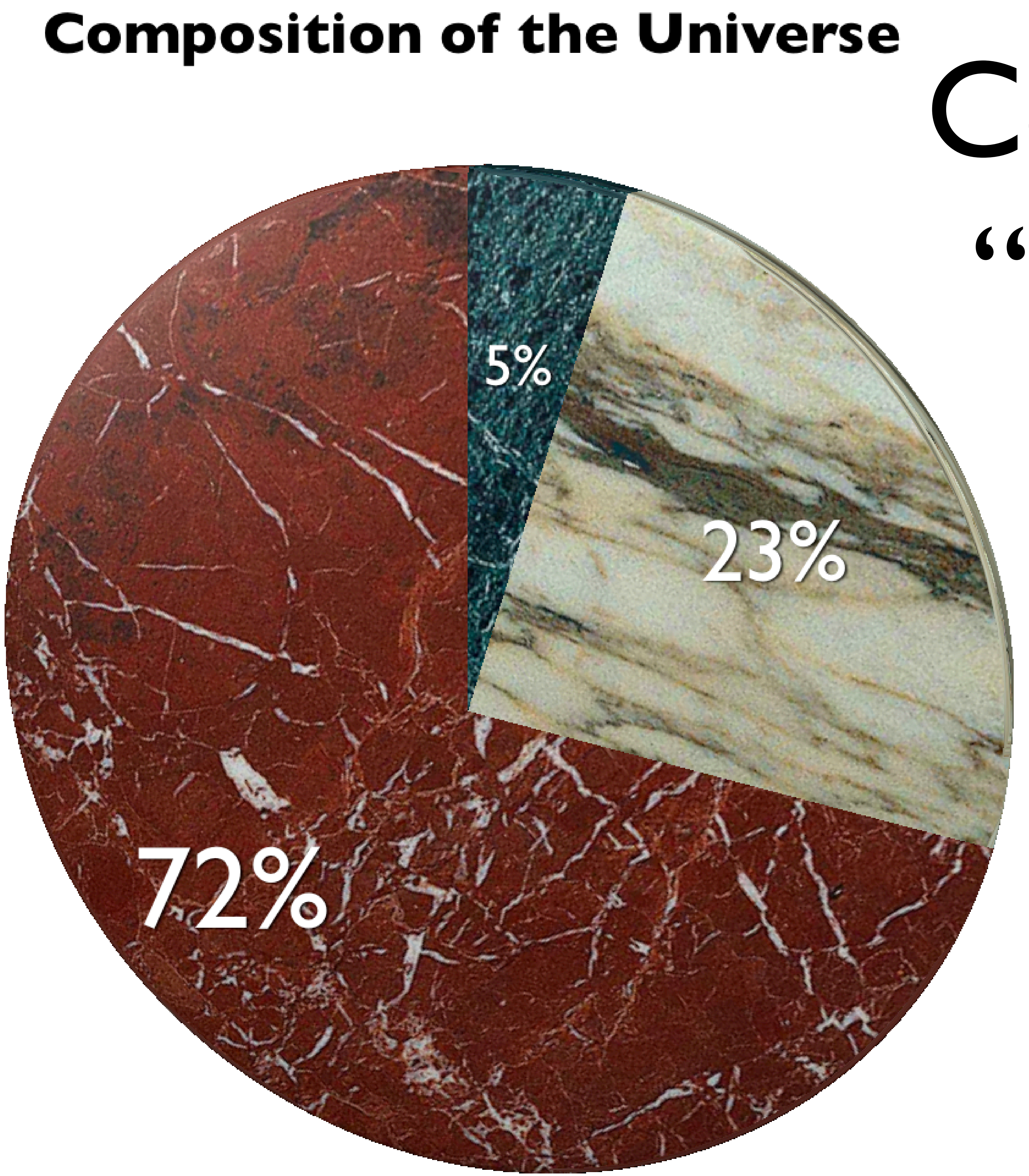
- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
- M. Limon
- N. Odegard
- G.S. Tucker

- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta

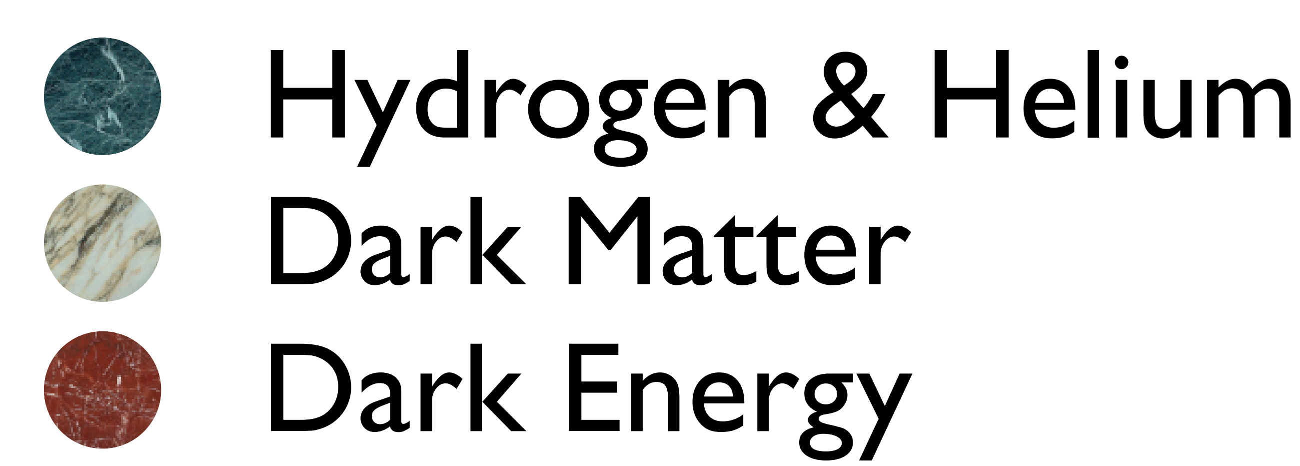
Special Thanks to **WMAP Graduates!**

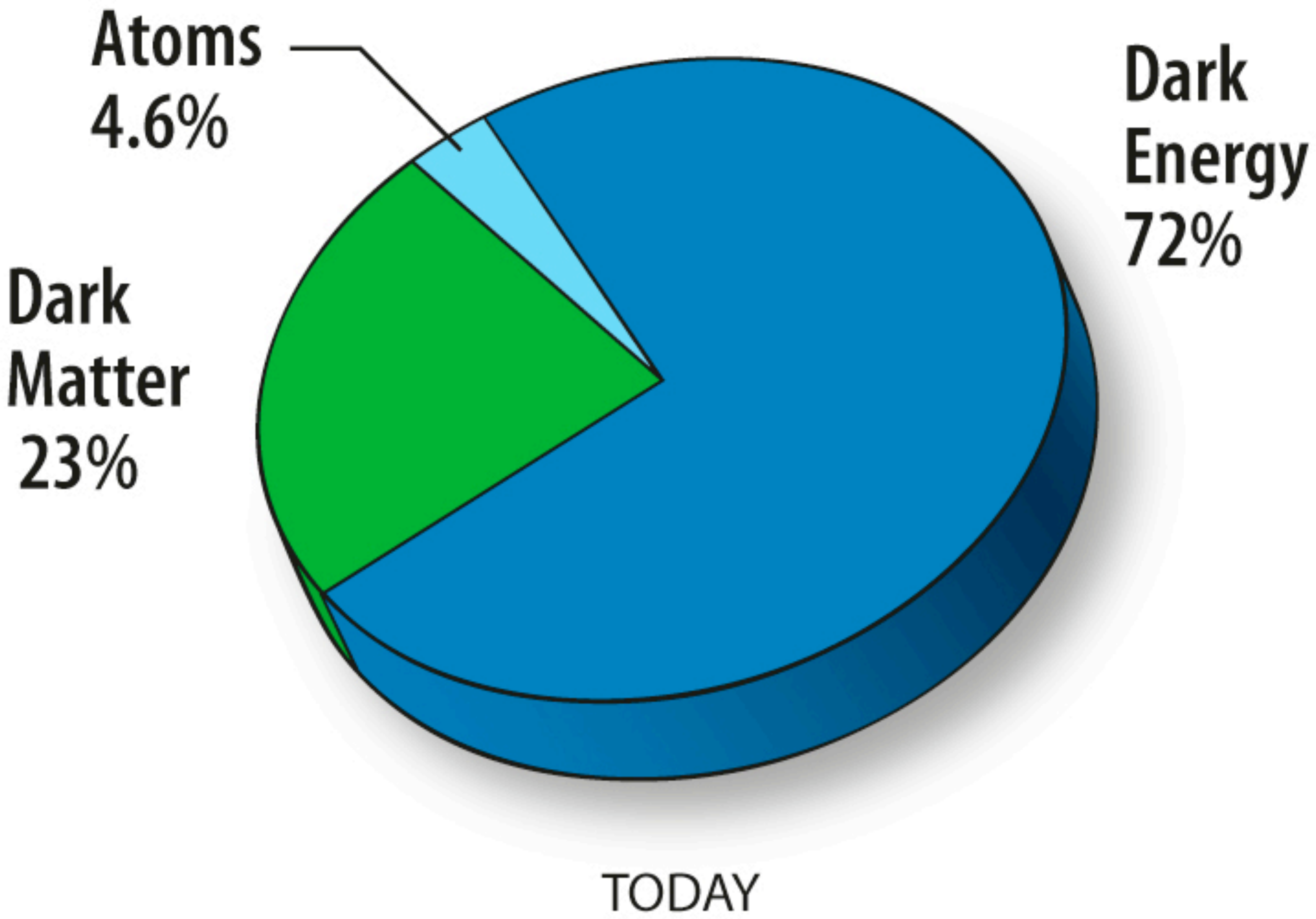
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

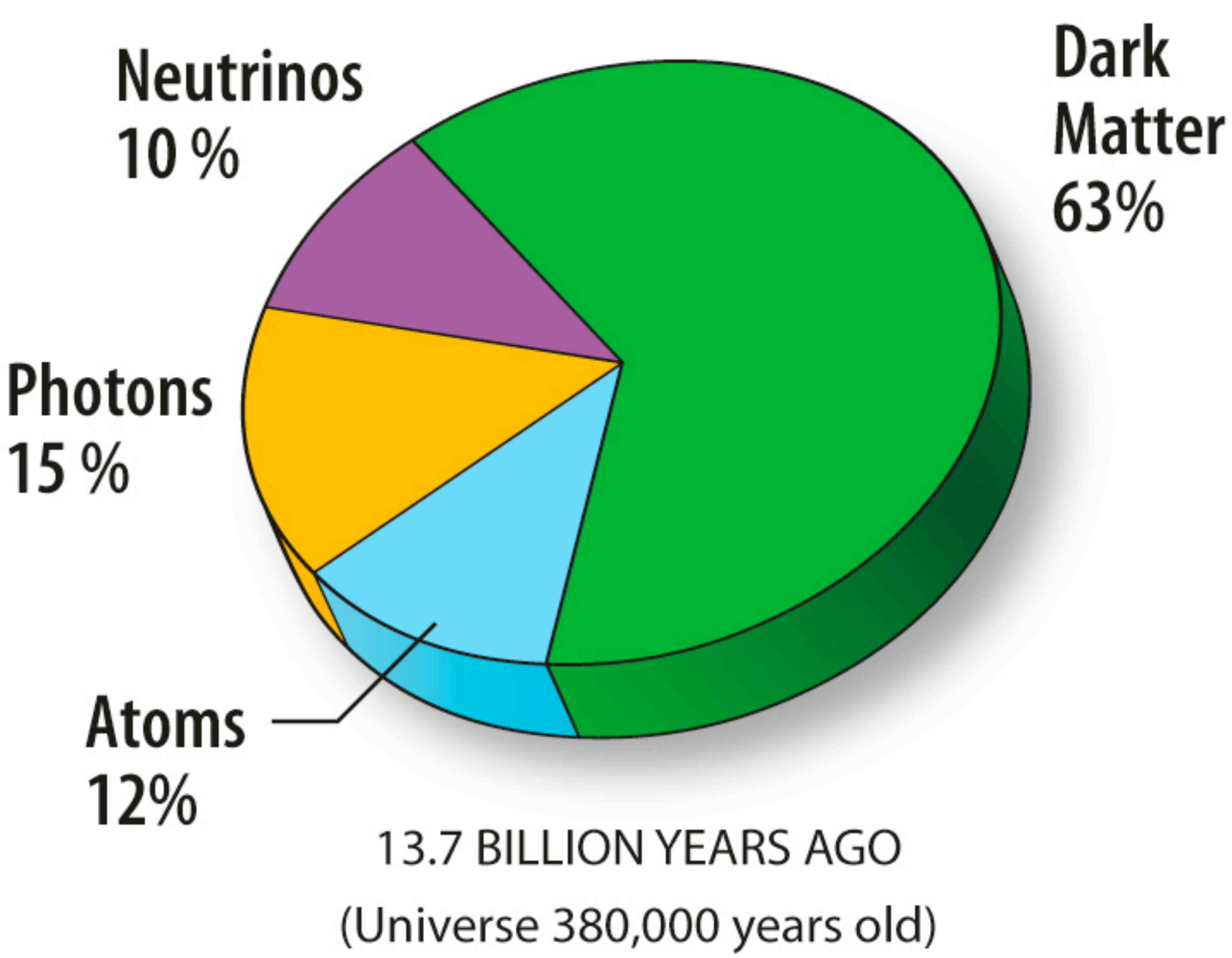
Cosmic Pie Chart
"ΛCDM" Model



- Cosmological observations (CMB, galaxies, supernovae) over the last decade told us that **we don't understand much of the Universe**.





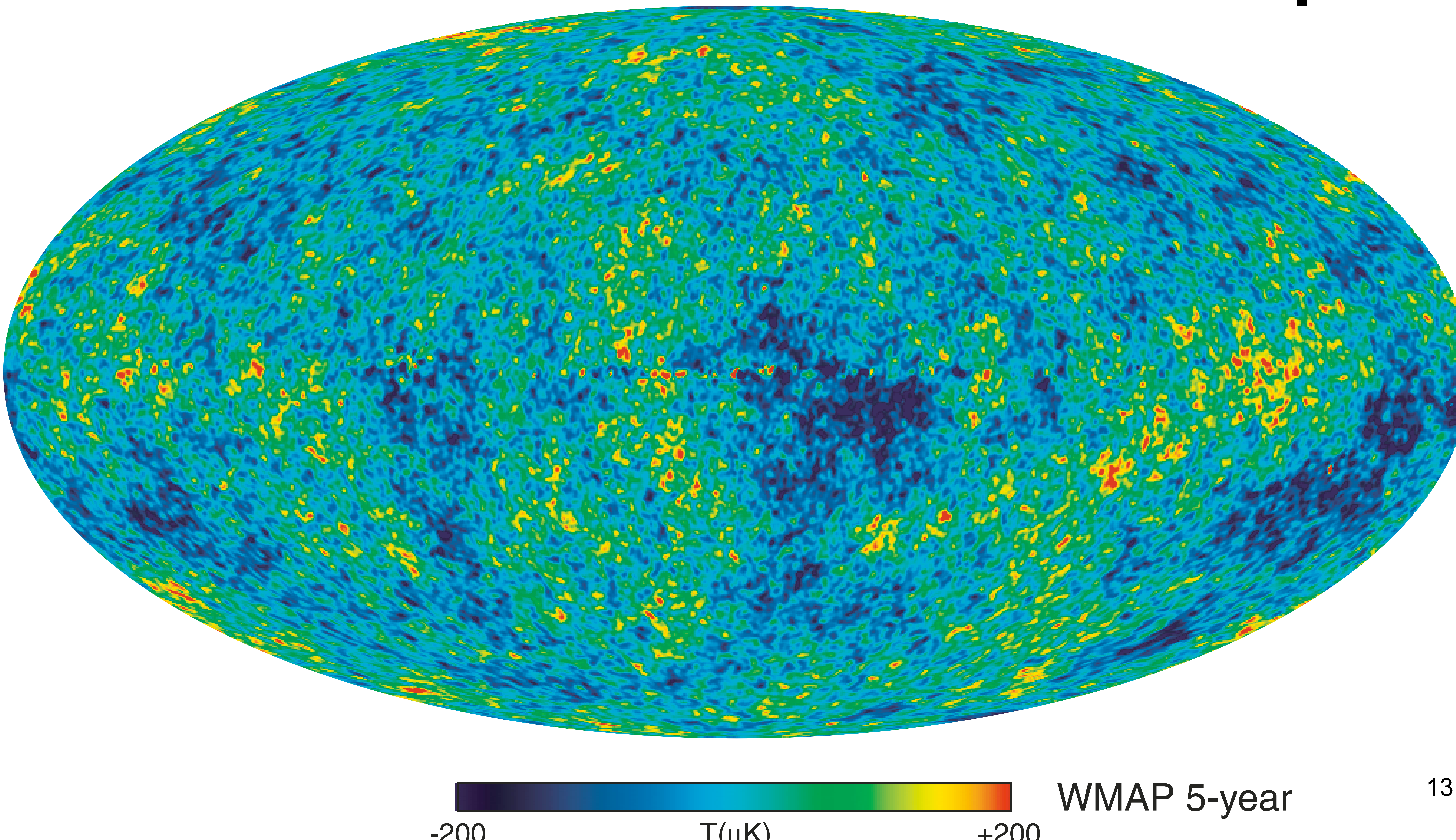


Komatsu et al.

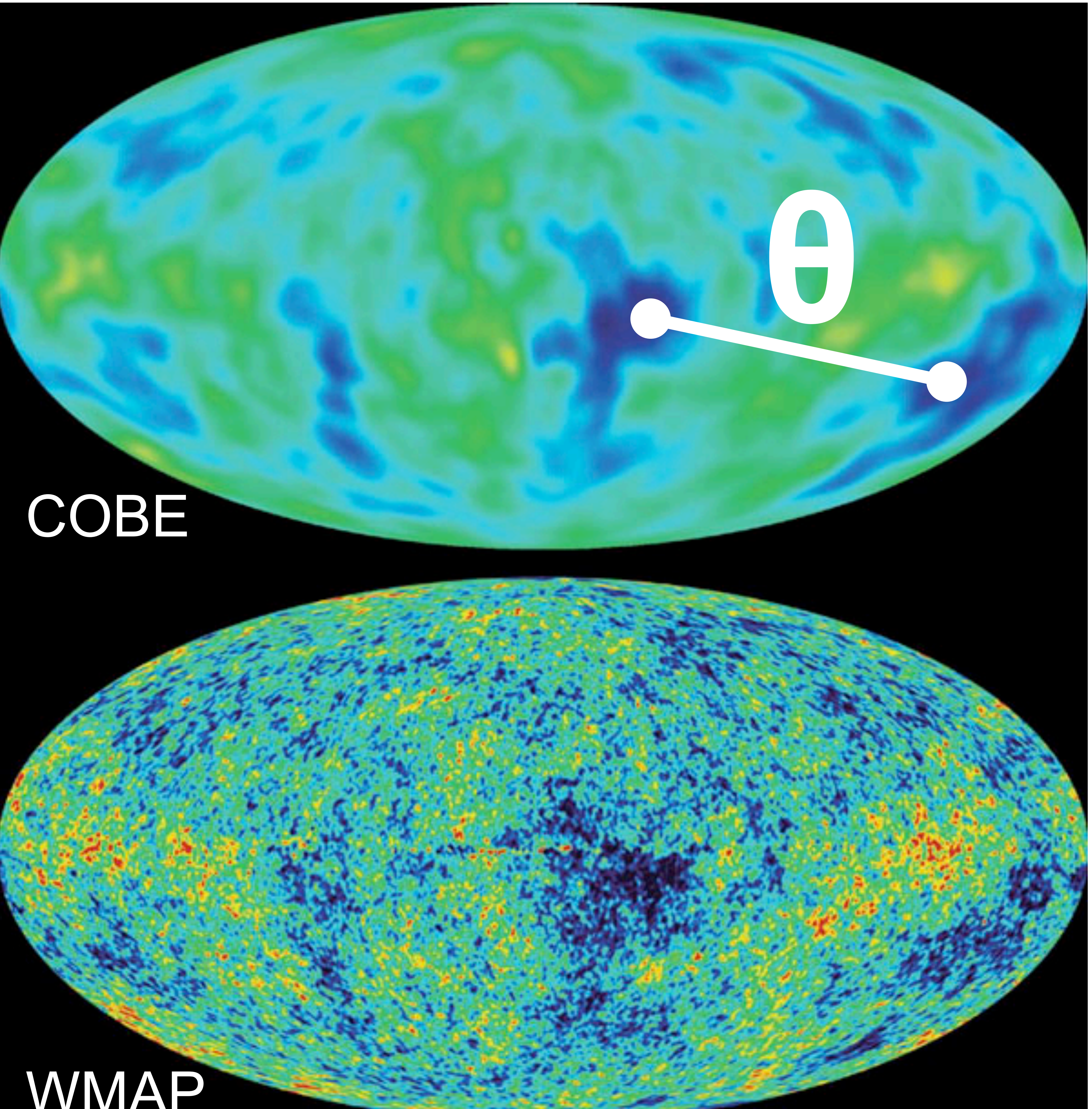
~WMAP 5-Year~ Pie Chart Update!

- 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?

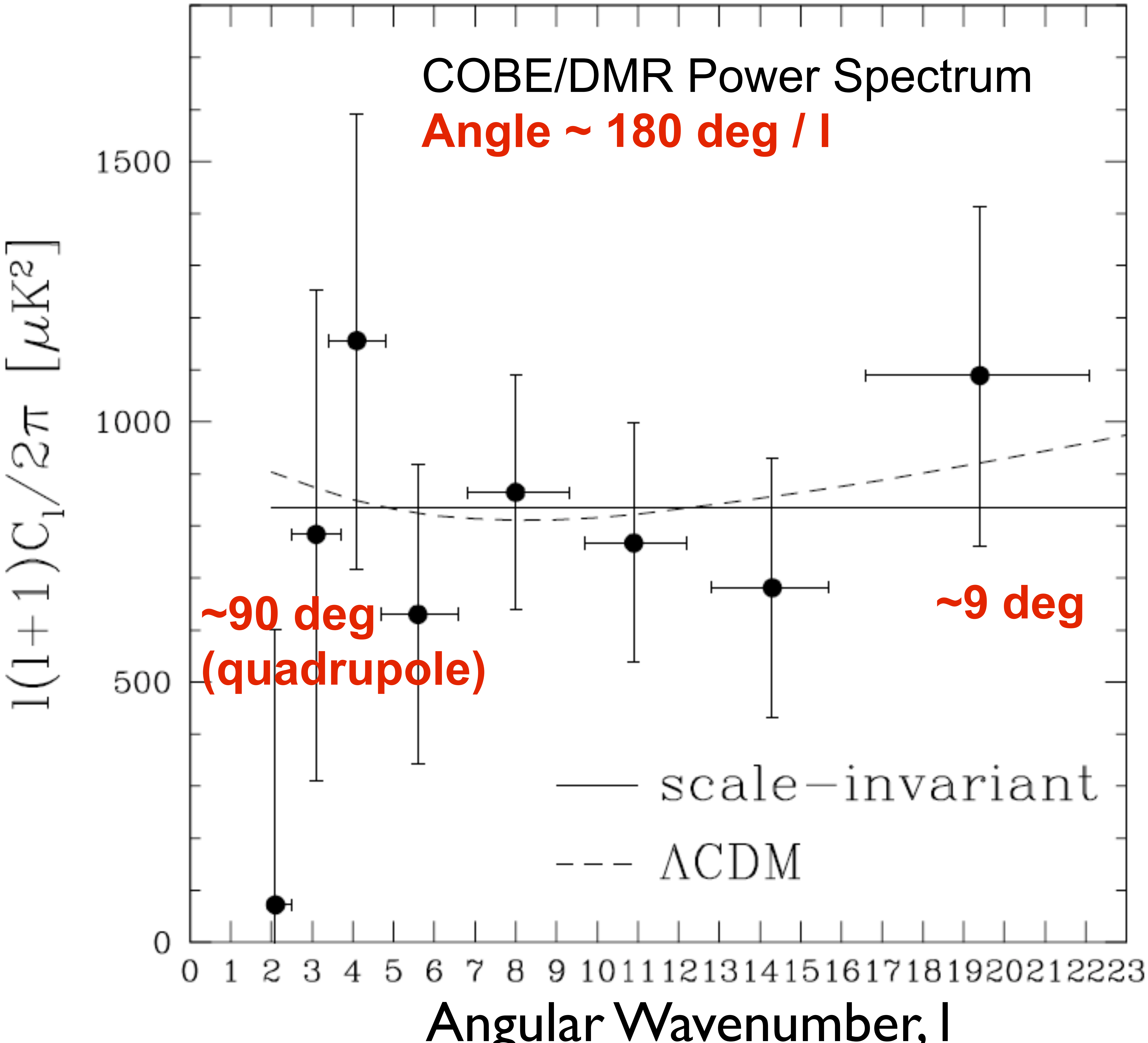


WMAP 5-year



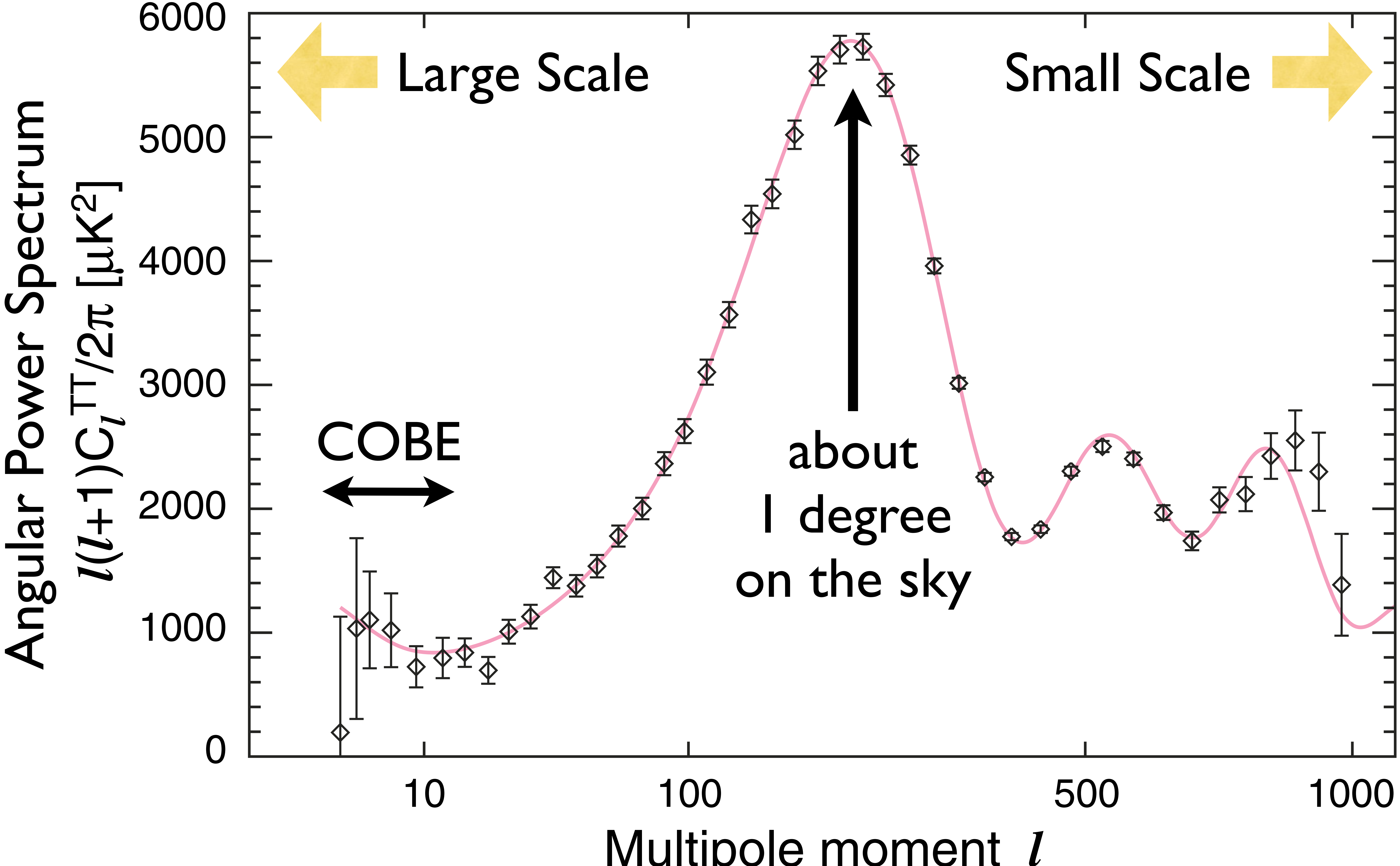
Analysis: 2-point Correlation

- $C(\theta)=(1/4\pi)\sum(2l+1)C_l P_l(\cos\theta)$
- "Power Spectrum," C_l
  - $l \sim 180$ degrees / θ



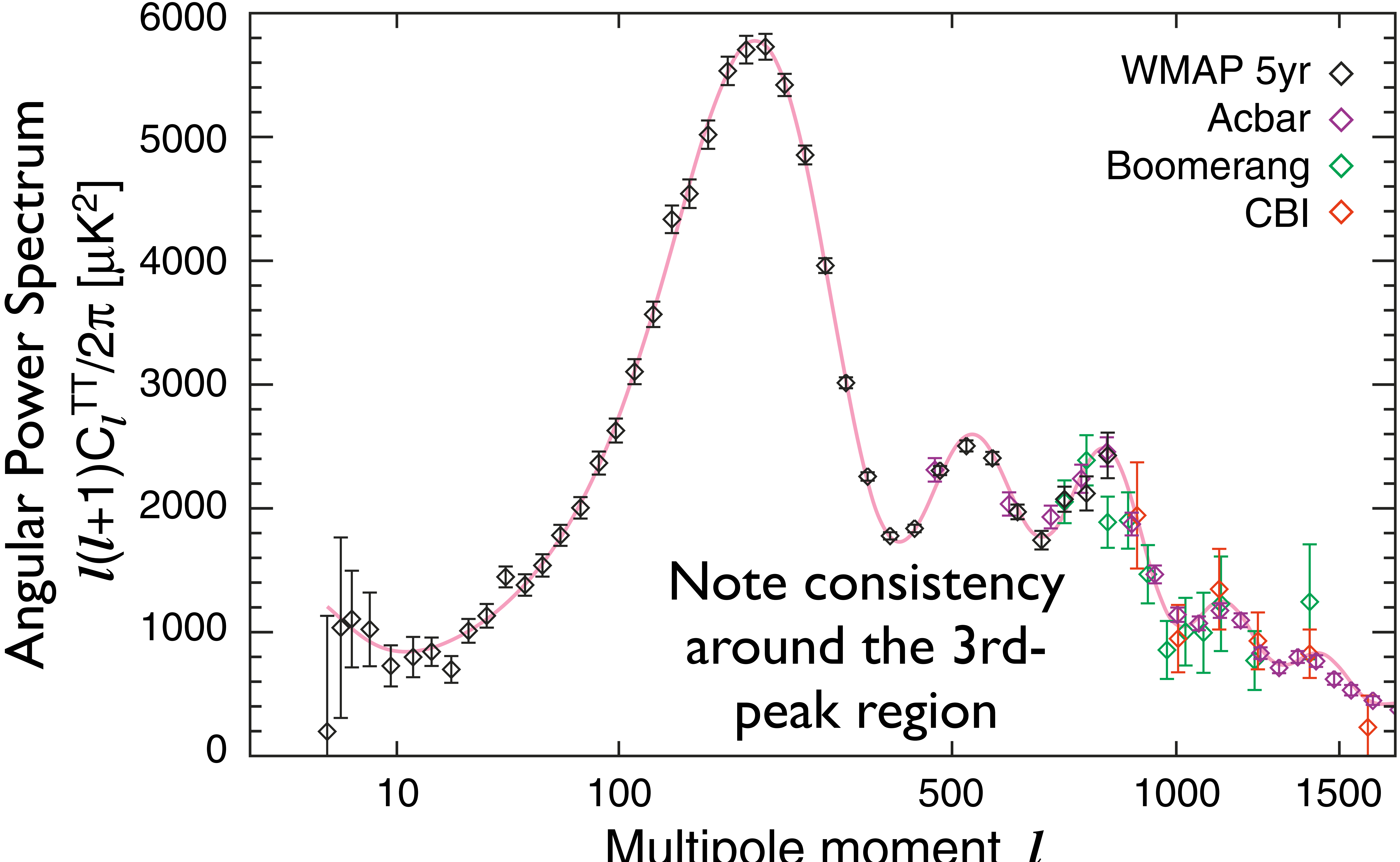
COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale−invariant
ΛCDM
l(l+1)C_l/2π [μK²]
0
500
1000
1500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Angular Wavenumber, l

WMAP Power Spectrum

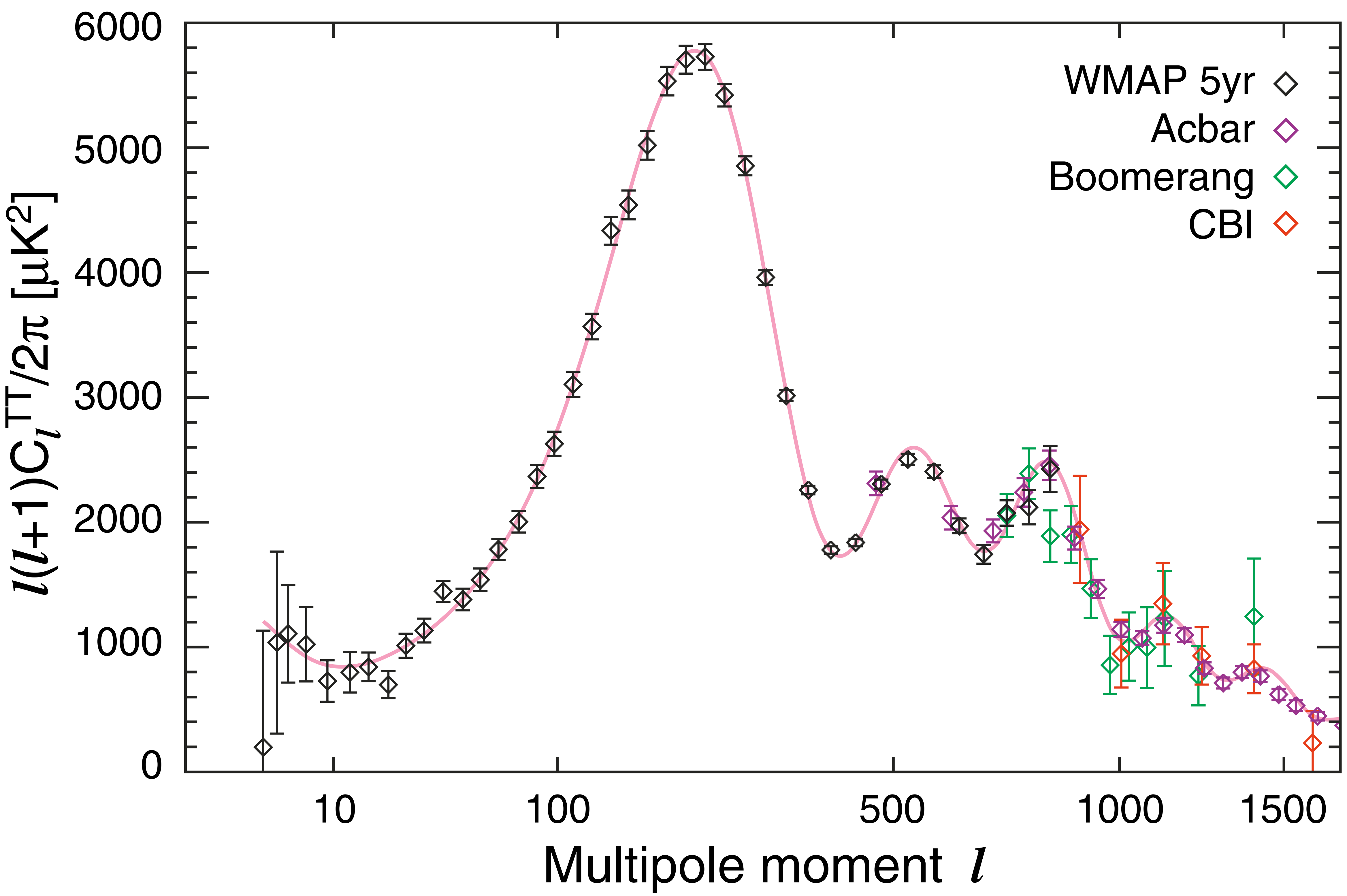


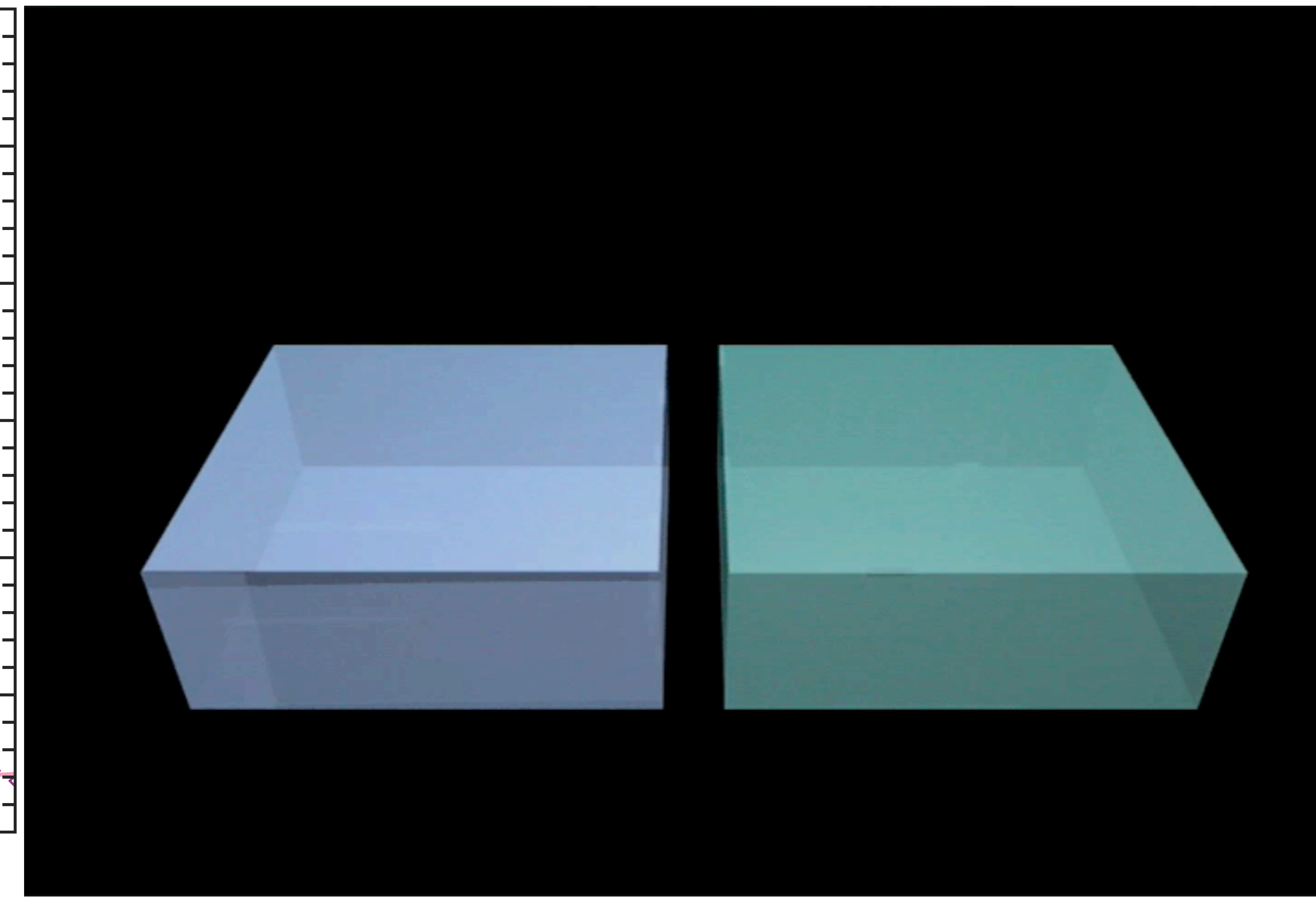
The Cosmic Sound Wave

Nolta et al.



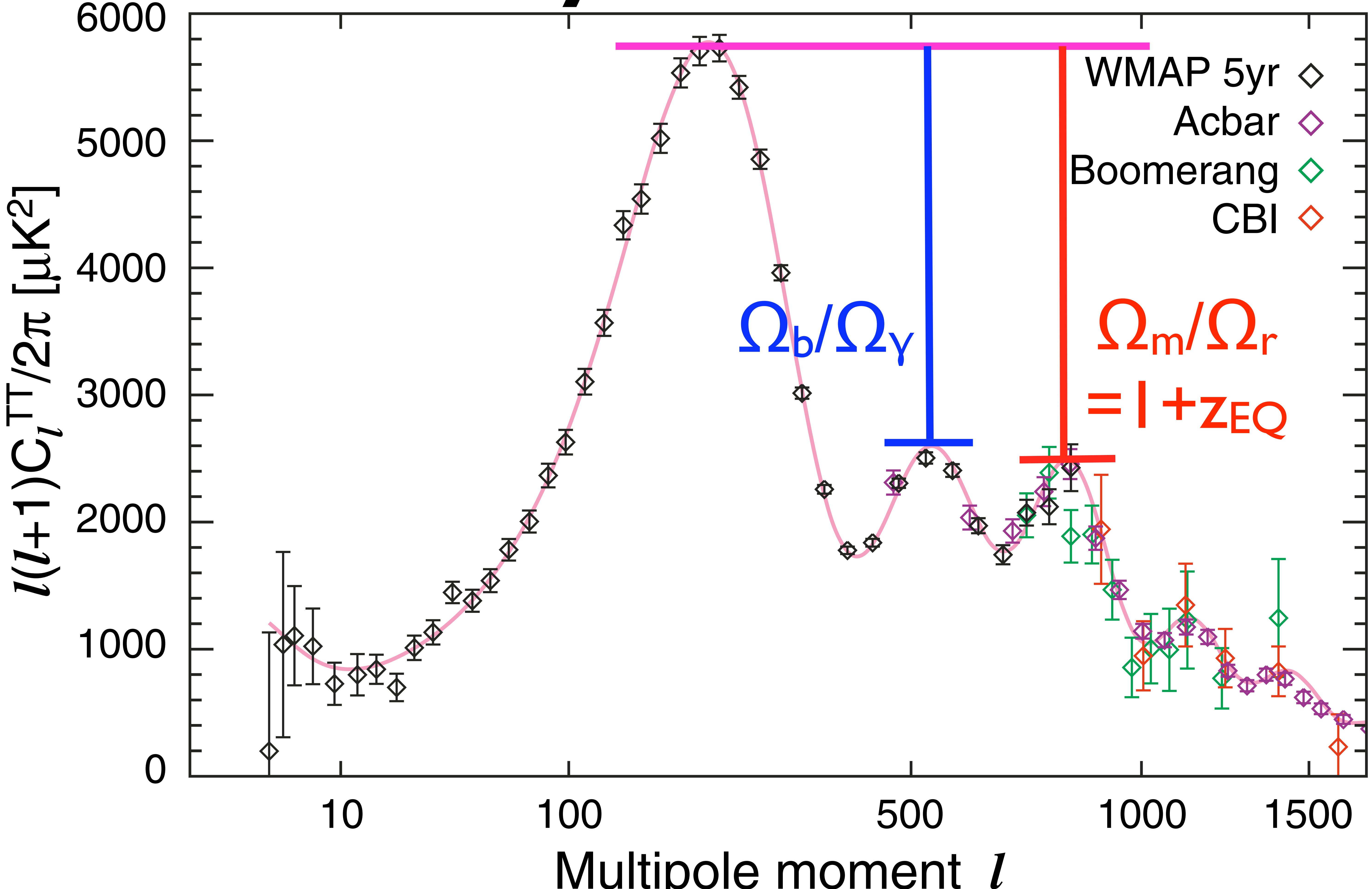
The Cosmic Sound Wave





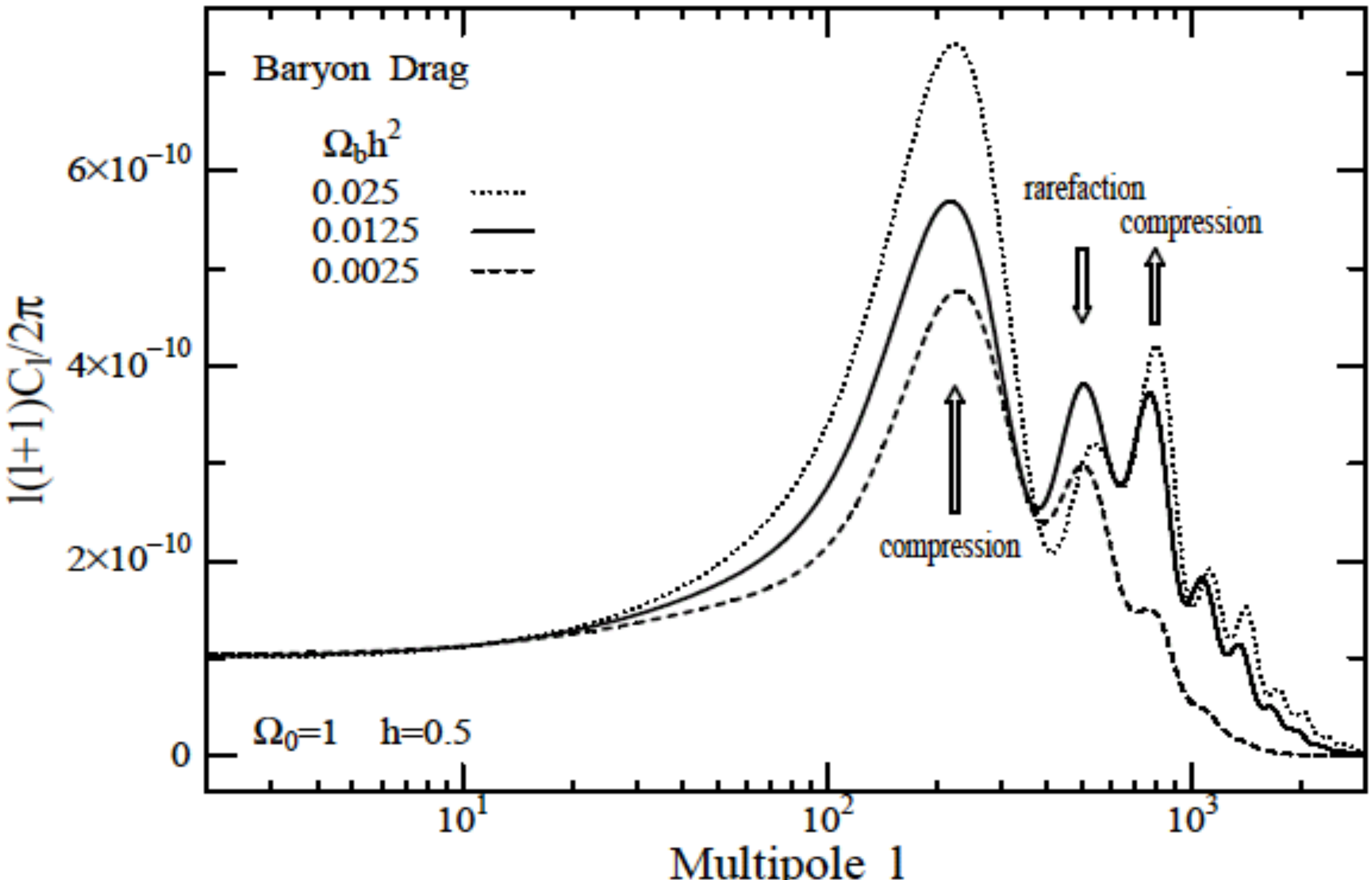
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

CMB to Baryon & Dark Matter

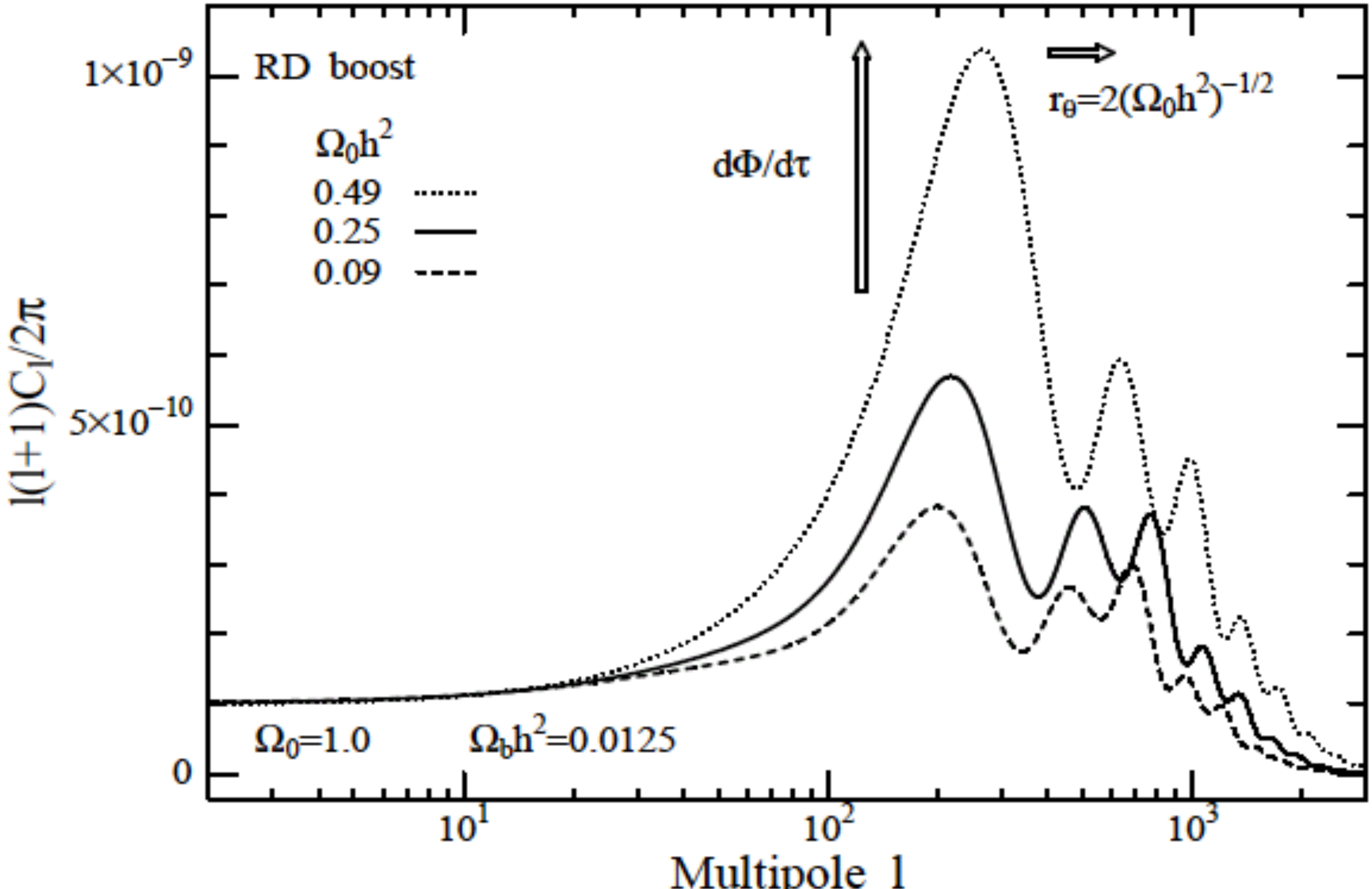


- 1-to-2: baryon-to-photon; 1-to-3: matter-to-radiation ratio
- $\Omega_\gamma=2.47\mathrm{x}10^{-5}h^{-2}$ & $\Omega_r=\Omega_\gamma+\Omega_\nu=1.69\Omega_\gamma=4.17\mathrm{x}10^{-5}h^{-2}$

Determining Baryon Density From C_l

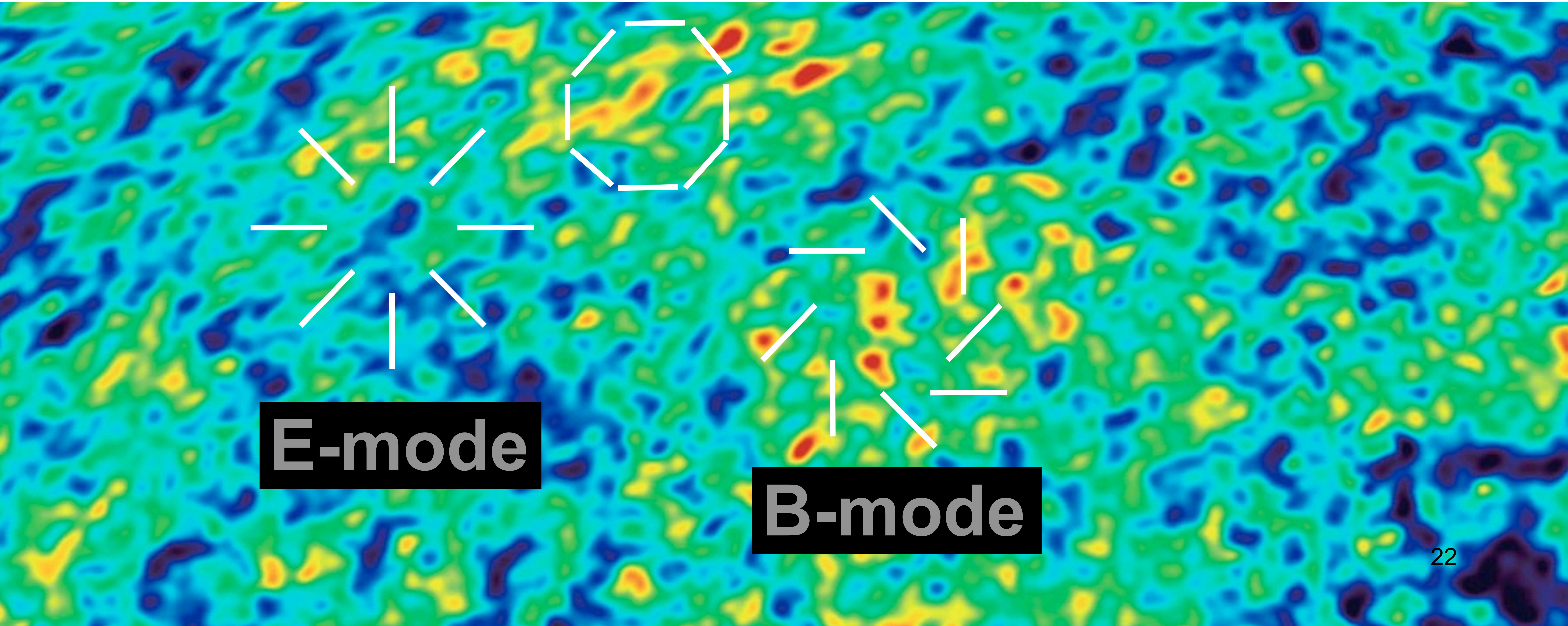


Determining Dark Matter Density From C_l



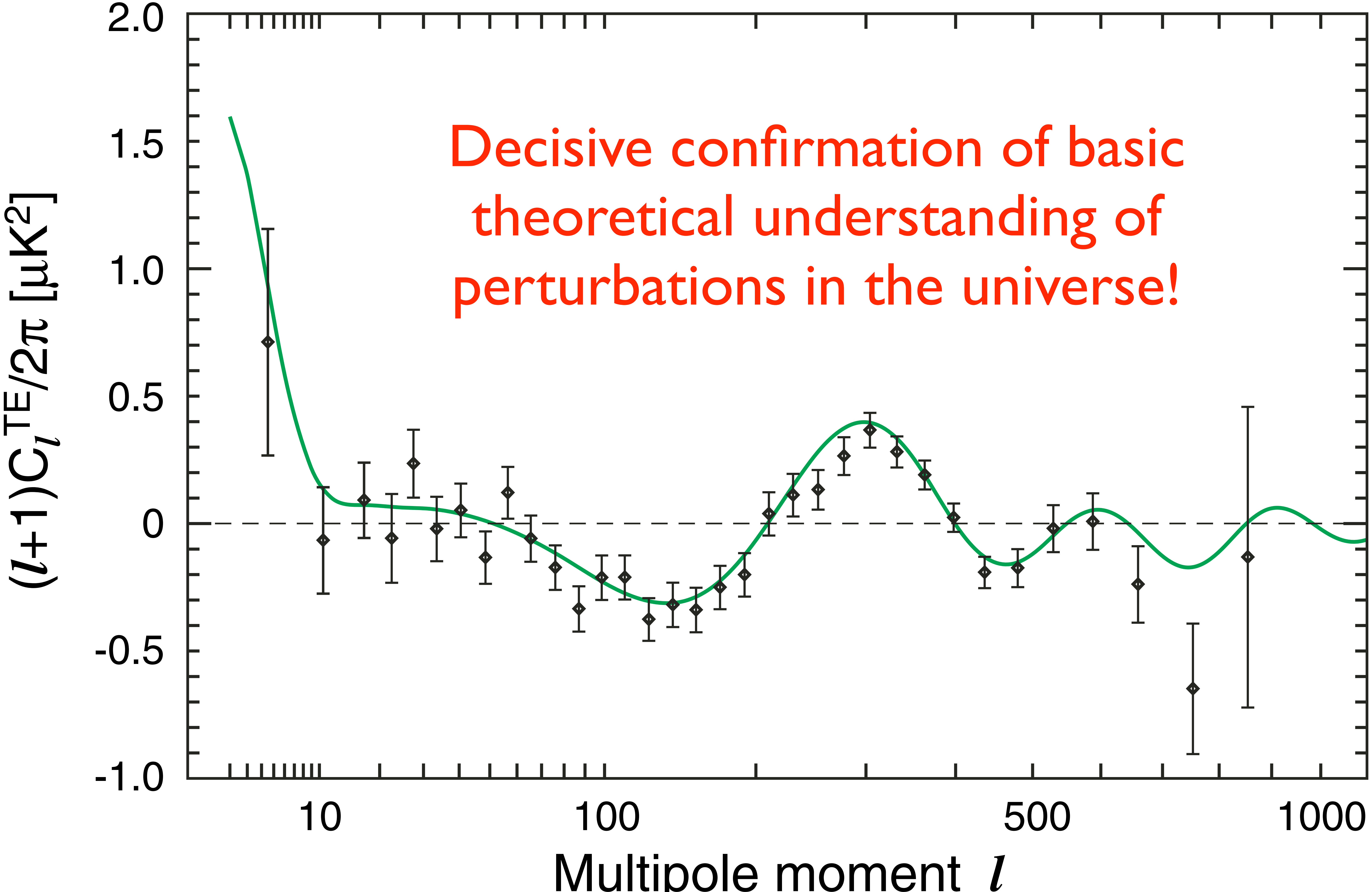
How About Polarization?

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



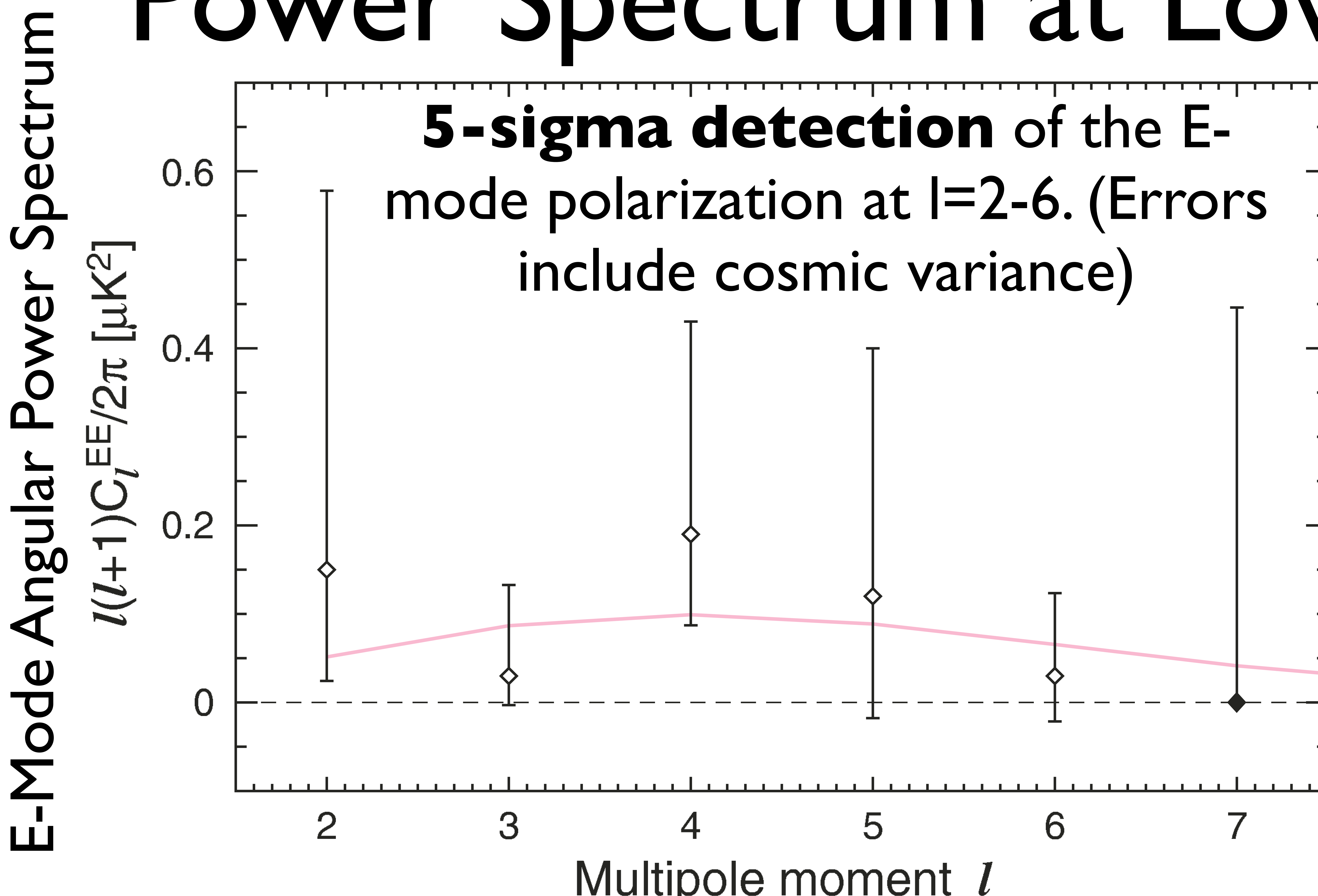
Nolta et al.

5-Year TxE Power Spectrum



Nolta et al.

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



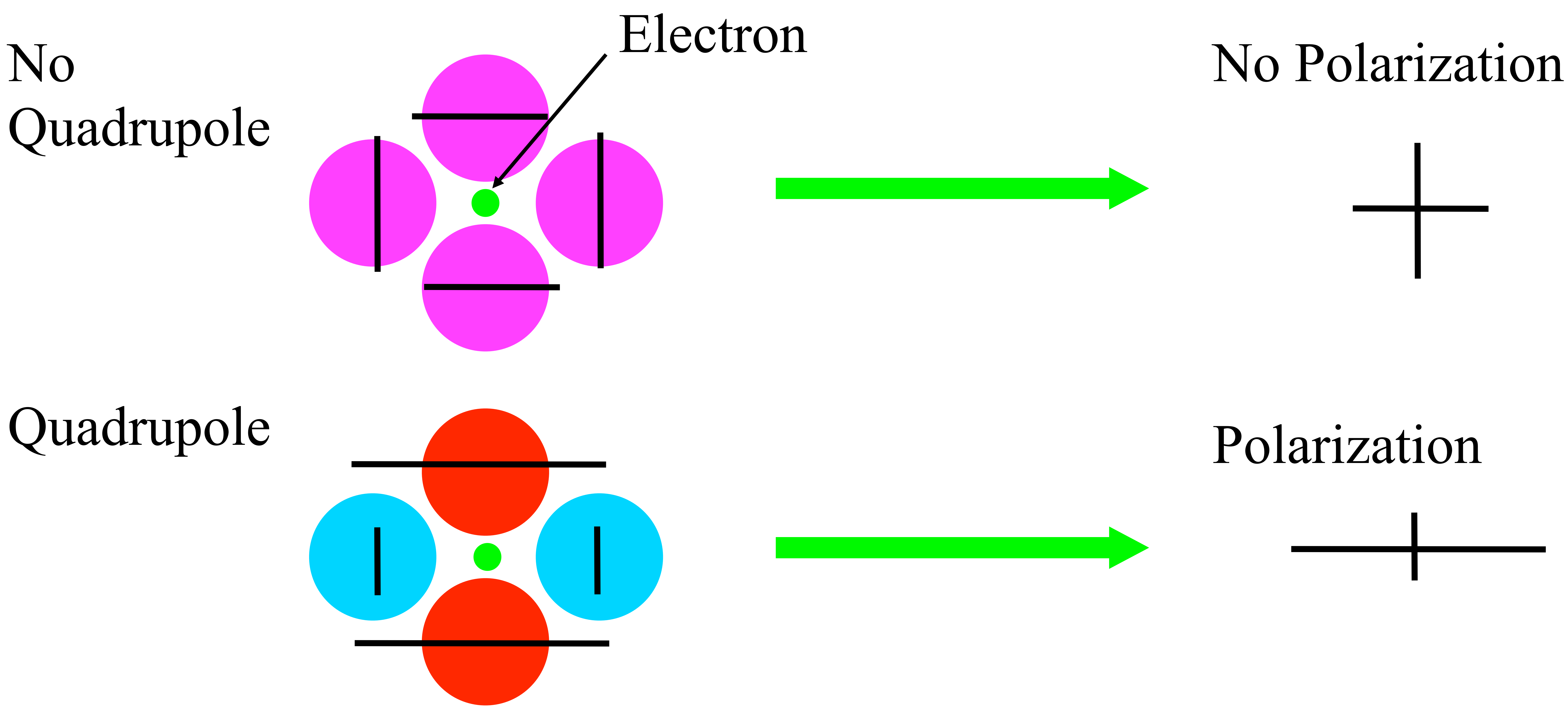
Black Symbols are upper limits

B-modes

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

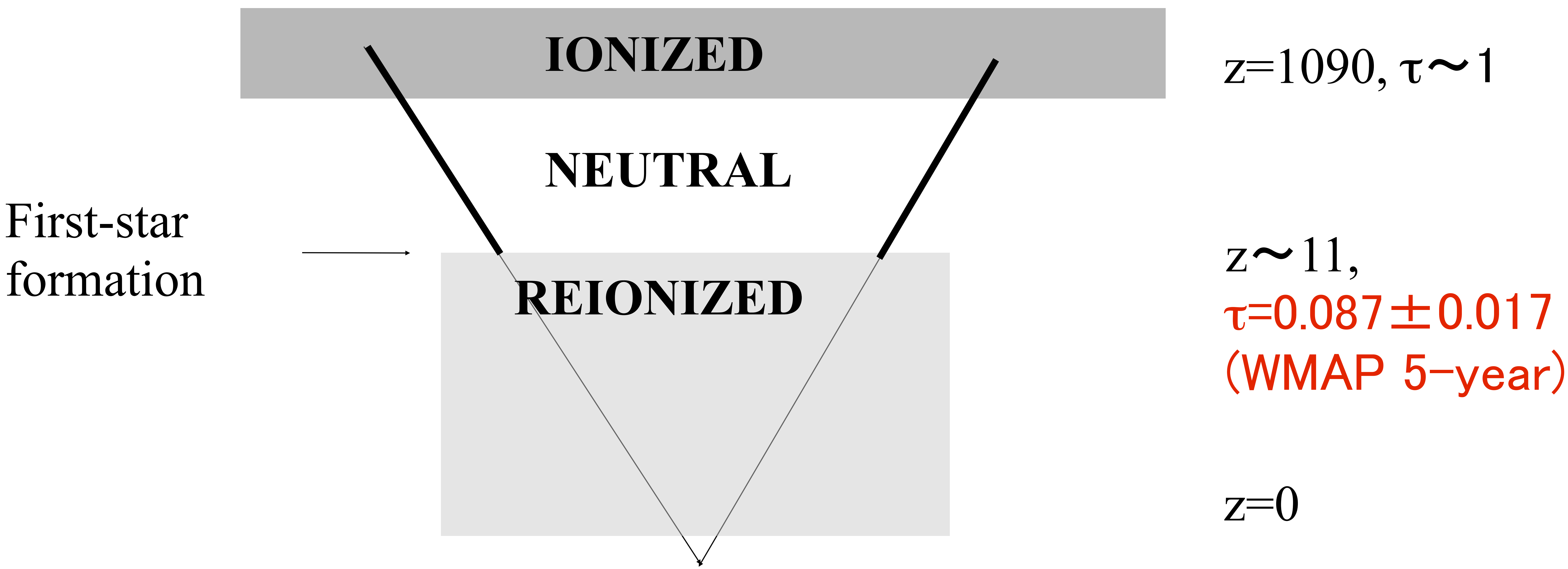
CMB Polarization

- Polarization is generated from an electron scattering, coupled with the quadrupolar radiation pattern around the electron.



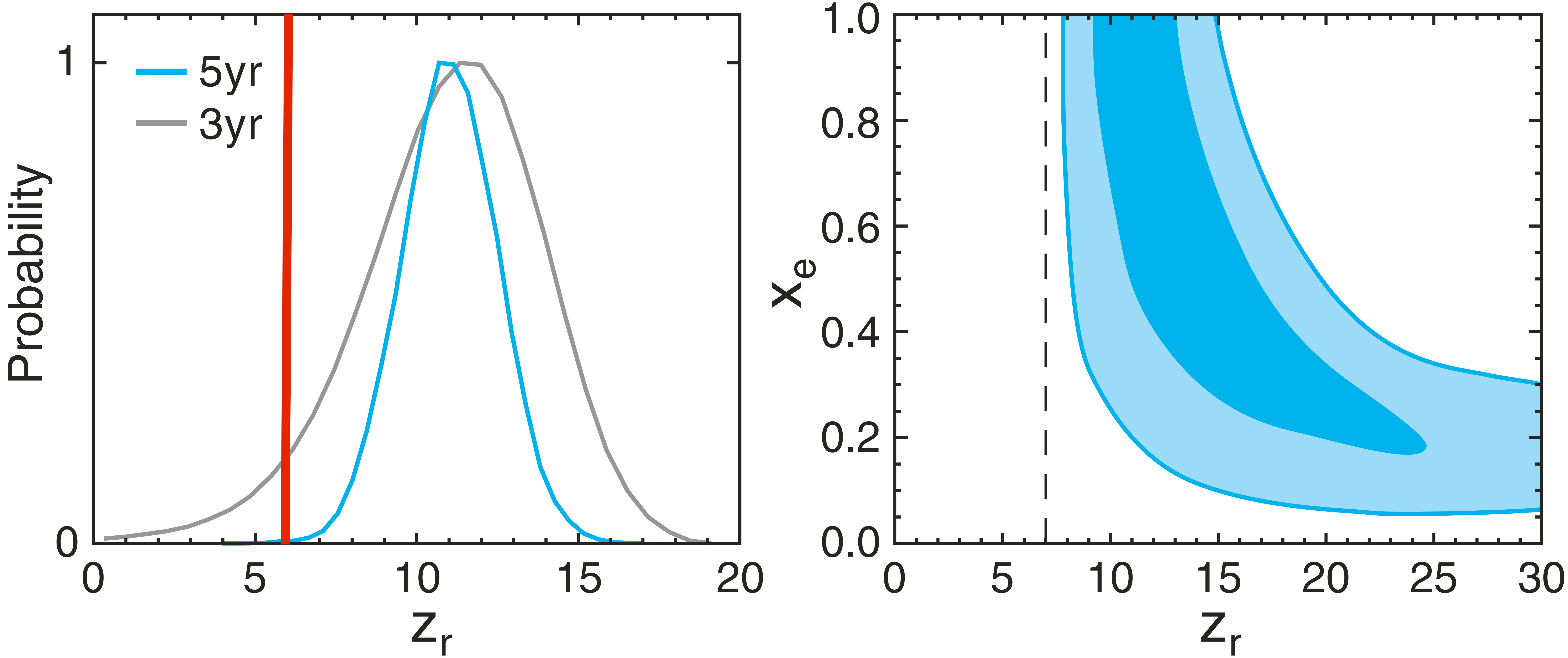
Polarization From Reionization

- 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.



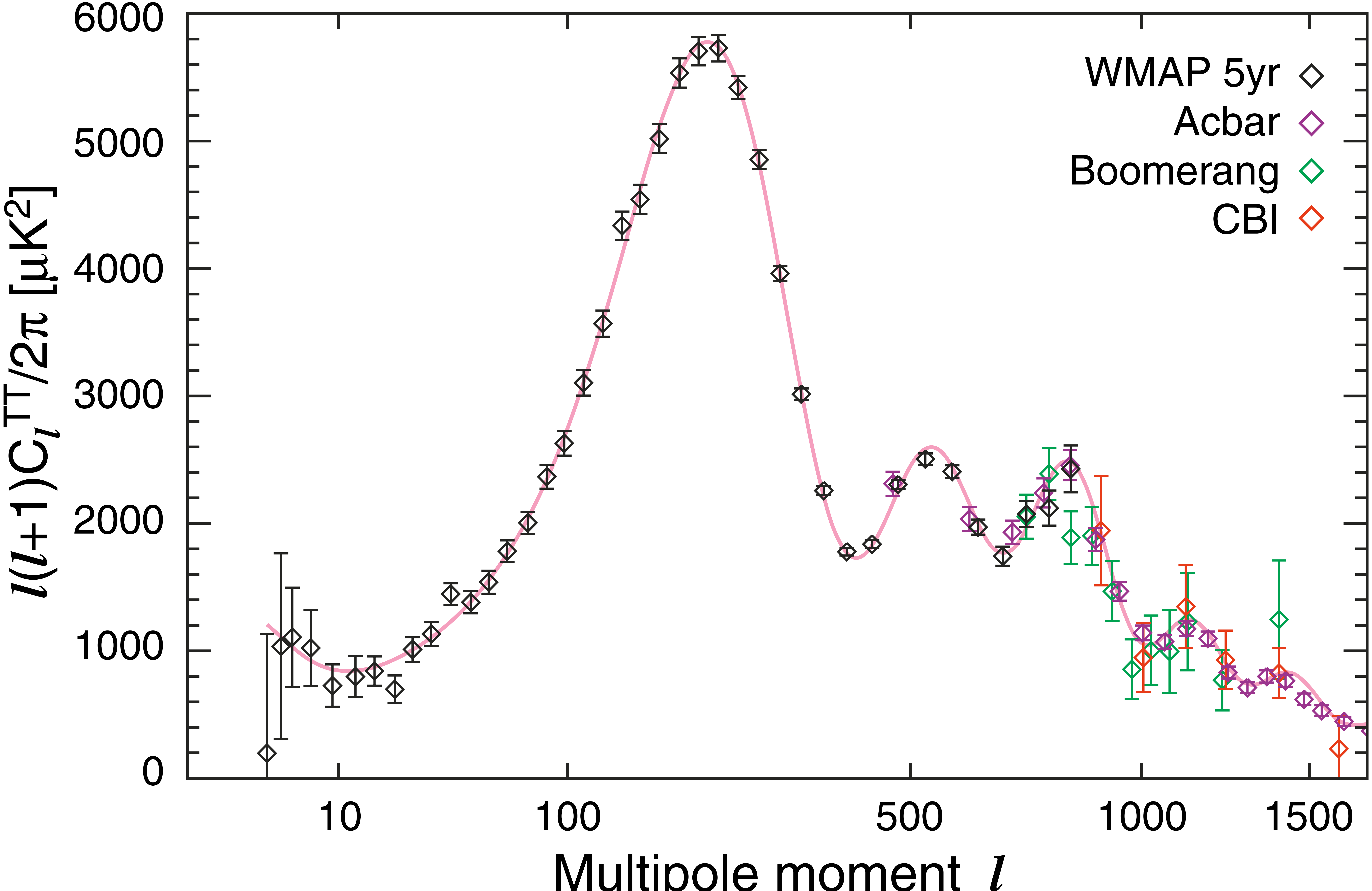
Z_{reion}=6 Is Excluded

Dunkley et al.

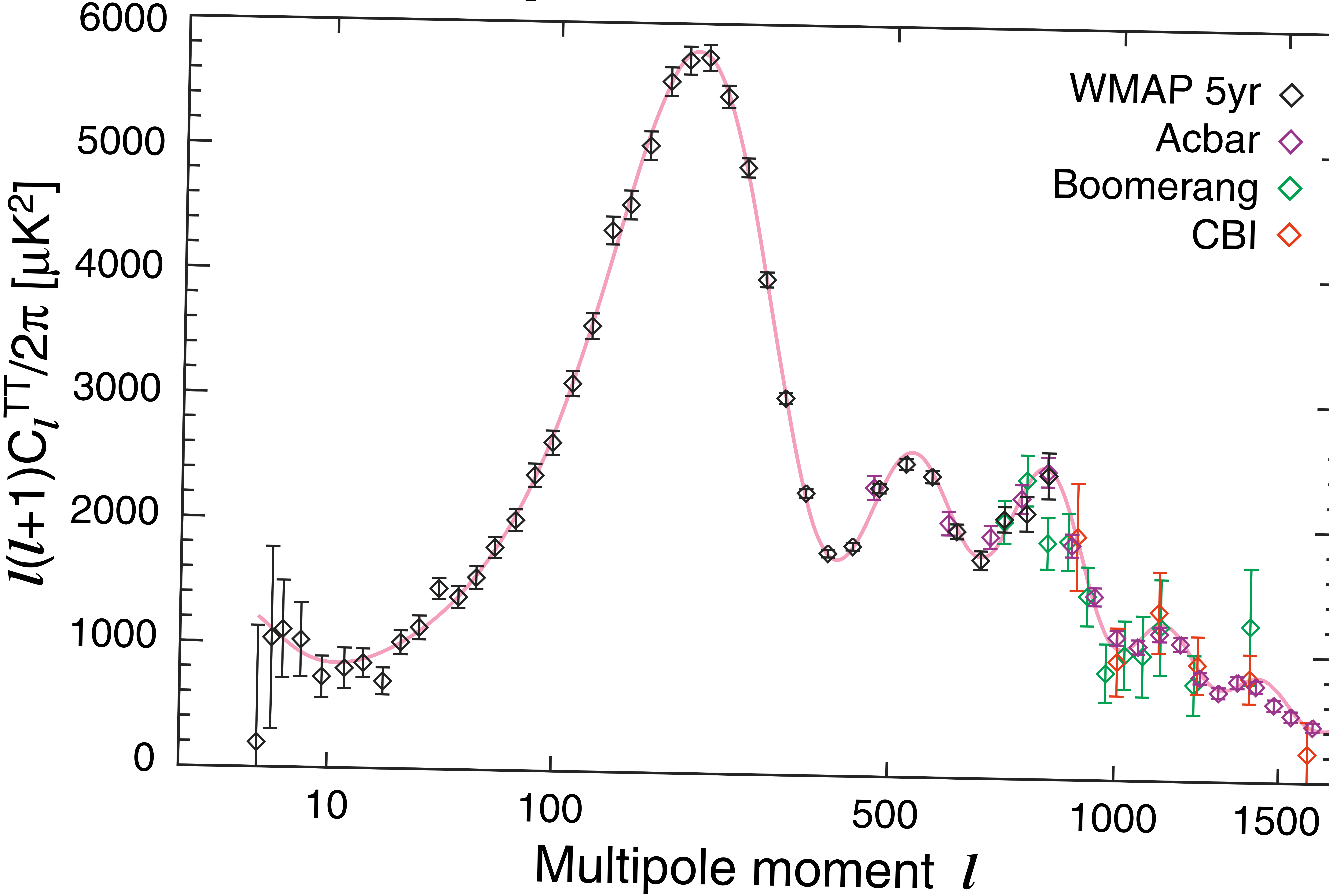


- Assuming an instantaneous reionization from x_e=0 to x_e=1 at z_{reion}, we find **z_{reion}=11.0 +/- 1.4** (68 % CL).
- The reionization was not an instantaneous process at z~6. (The 3-sigma lower bound is z_{reion}>6.7.)

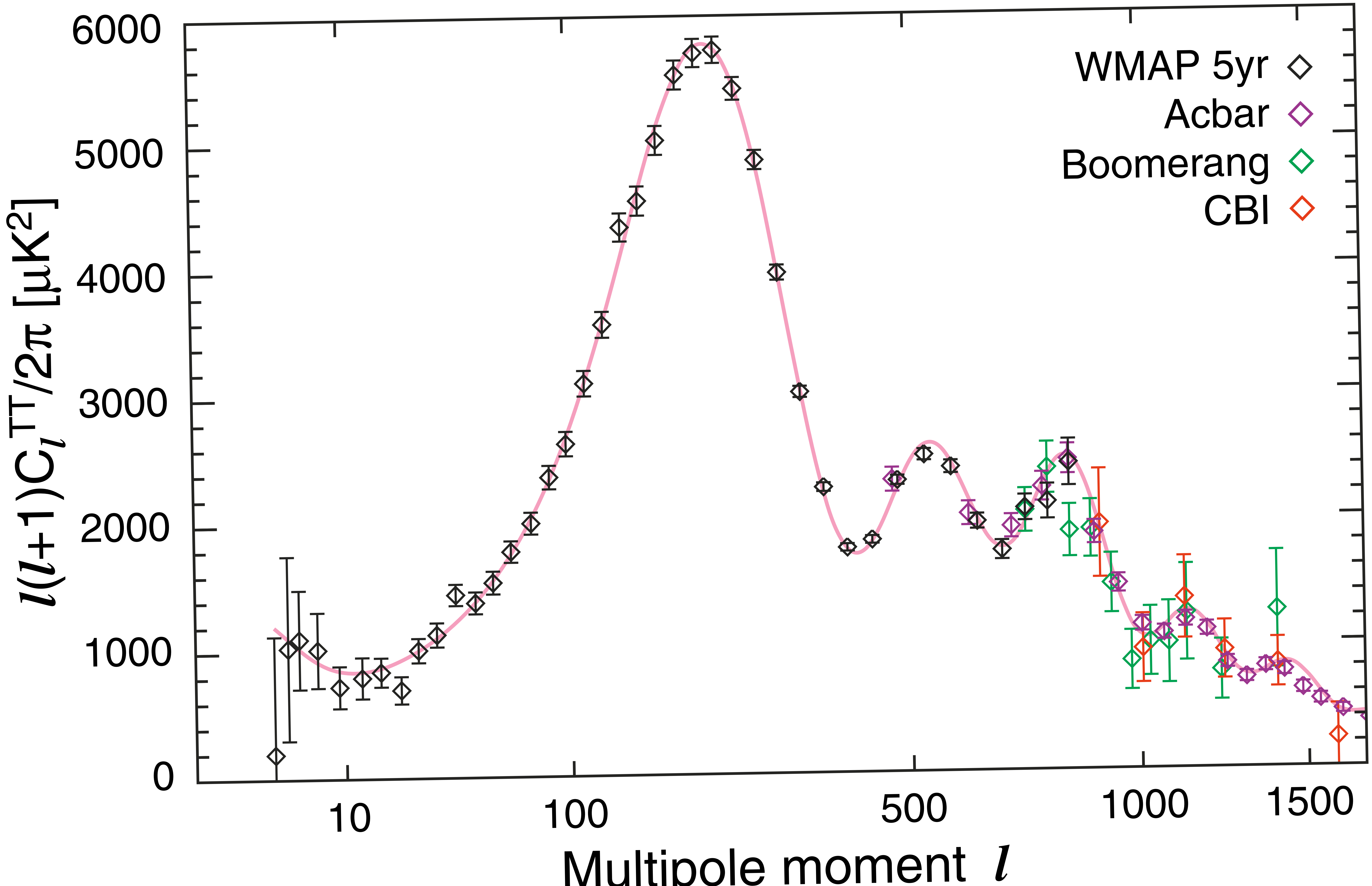
Tilting=Primordial Shape->Inflation



"Red" Spectrum: $n_s < 1$



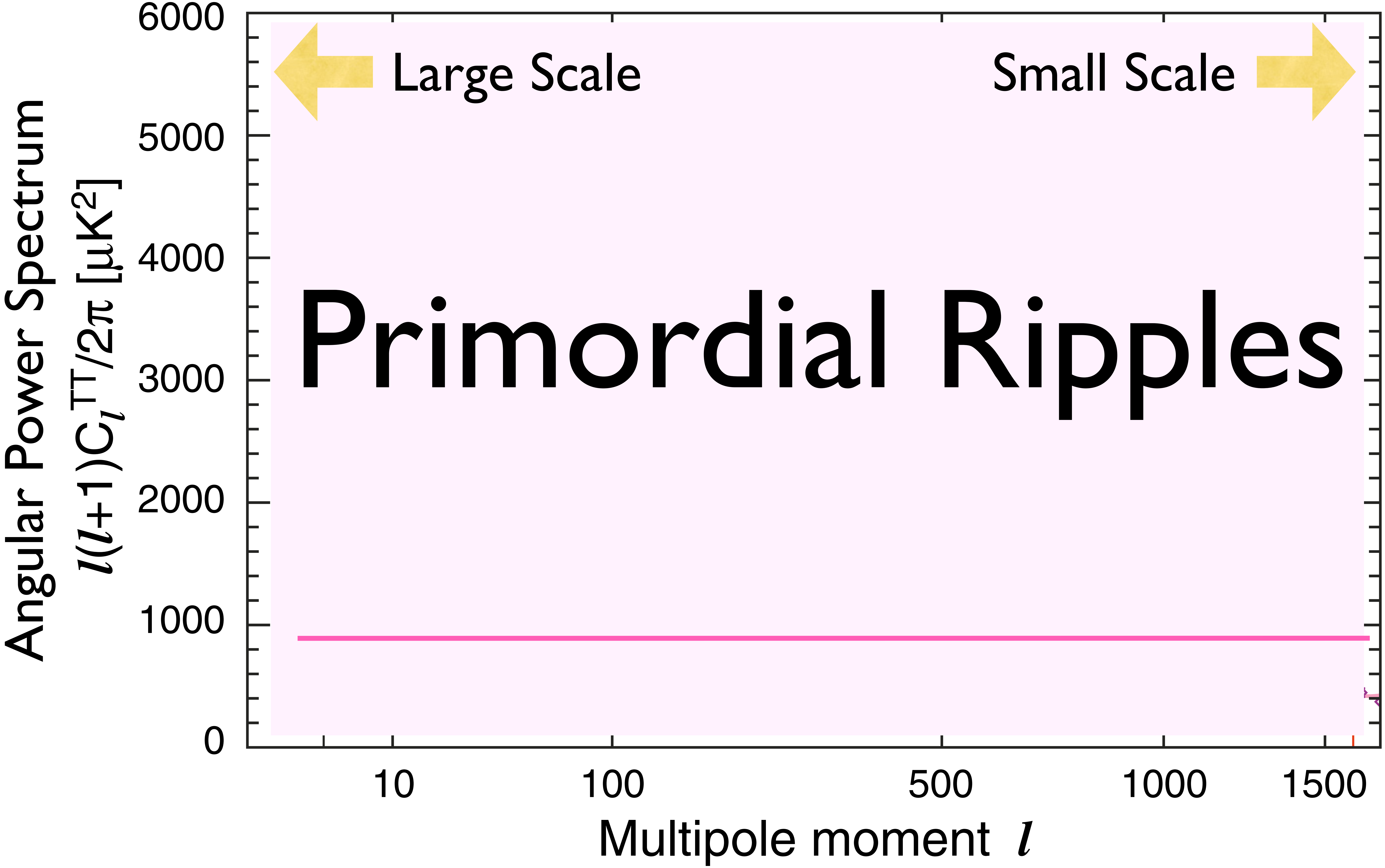
"Blue" Spectrum: $n_s > 1$



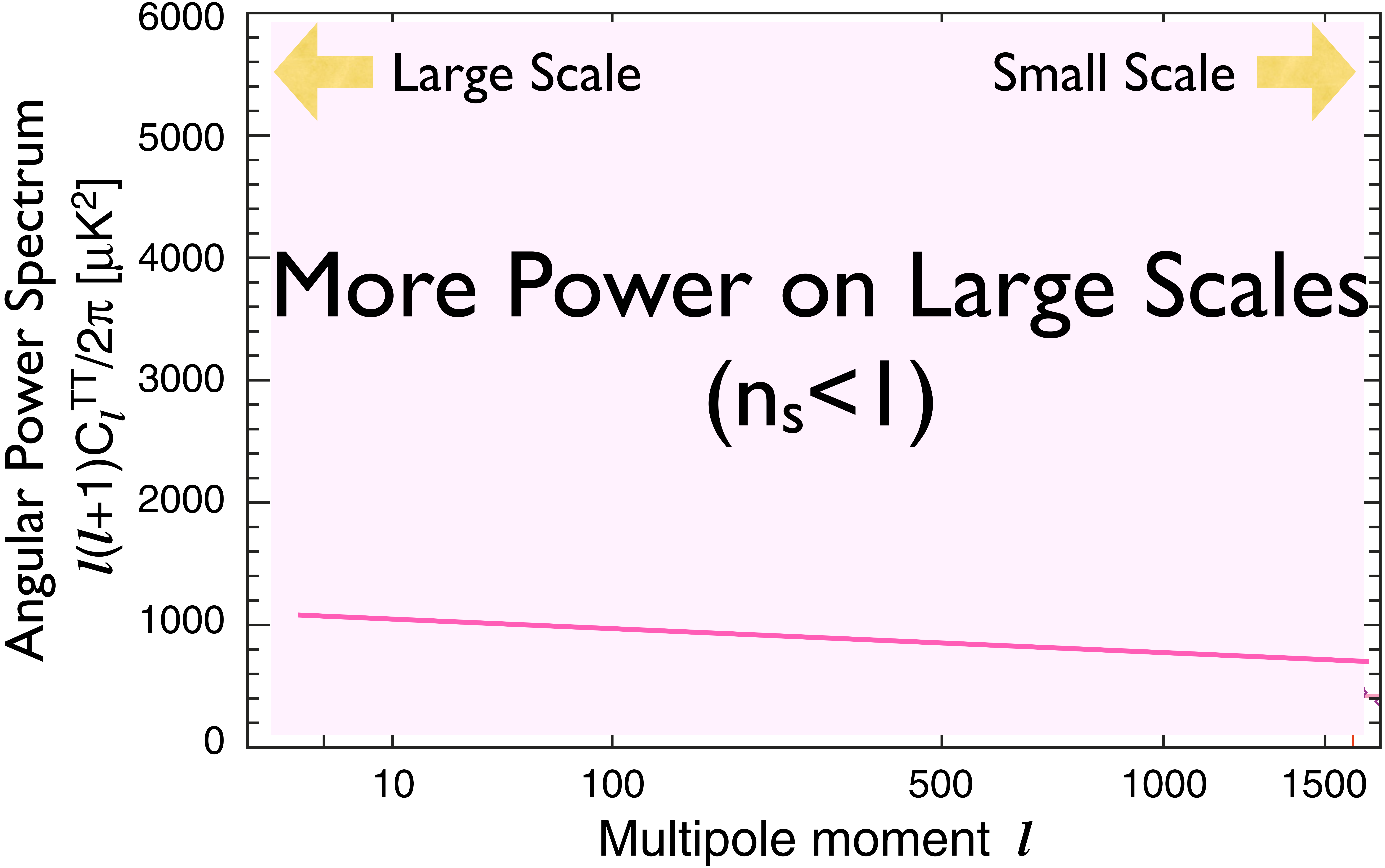
Expectations From 1970's: $n_s=1$

- 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
  - $<\Phi^2(x)>=\int \ln k\ \mathbf{k^3|\Phi(k)|^2}$
  - In order to avoid the situation in which curvature (geometry) diverges on small or large scales, a "scale-invariant spectrum" was proposed: $\mathbf{k^3|\Phi(k)|^2 = const.}$
  - This leads to the expectation: $\mathbf{P(k)}=|\delta(k)|^2\mathbf{=k^{ns}}$ $\mathbf{(n_s=1)}$
    - *Harrison 1970; Zel'dovich 1972; Peebles&Yu 1970*

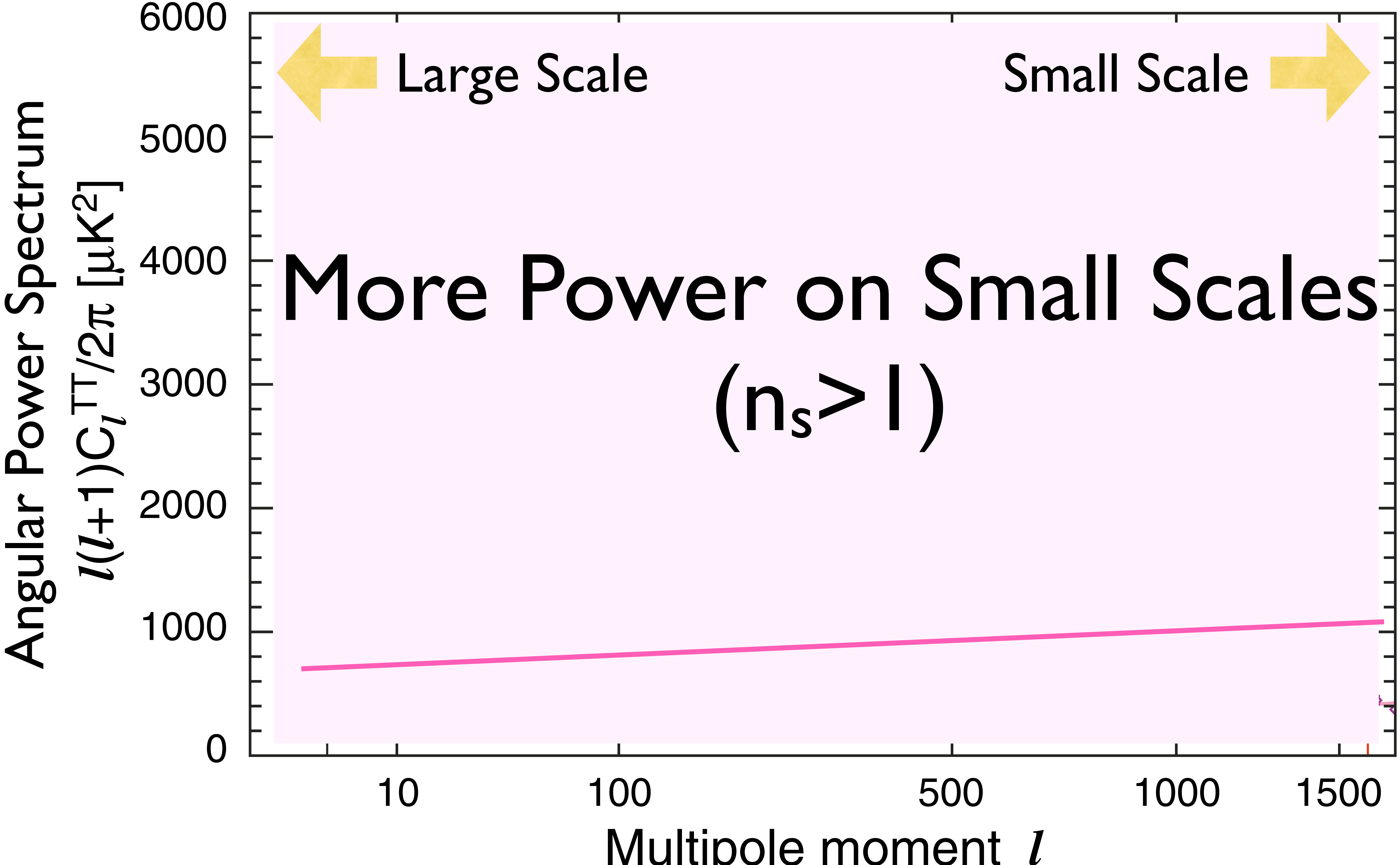
Getting rid of the Sound Waves



The Early Universe Could Have Done This Instead



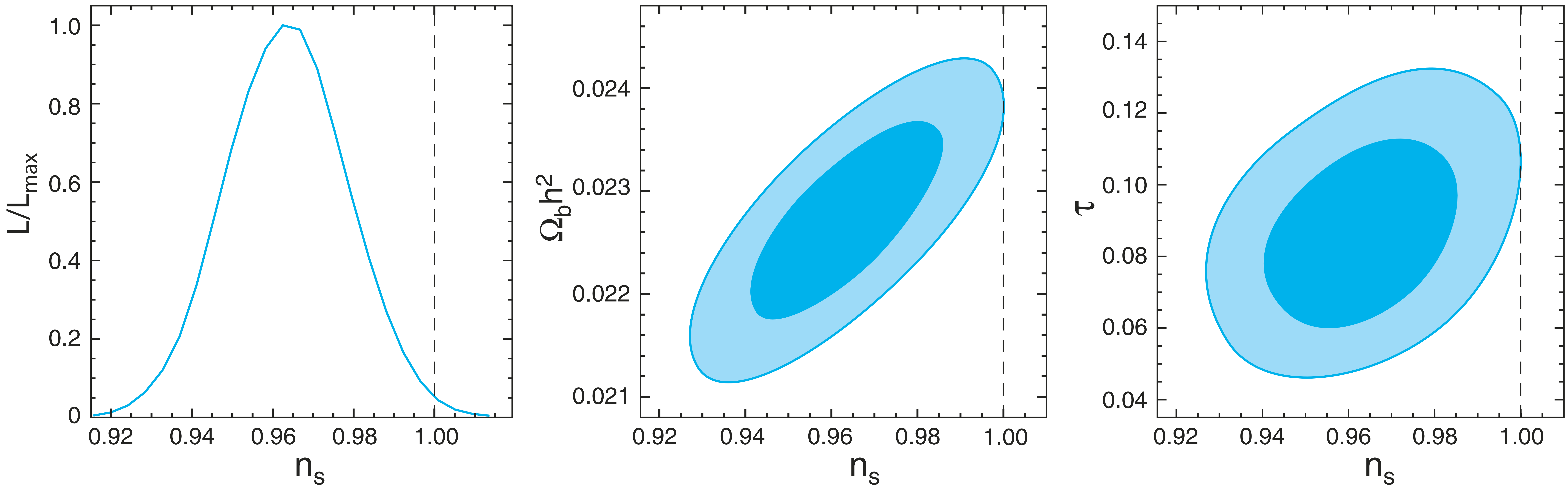
...or, This.



Large Scale
Small Scale
More Power on Small Scales
(n_s>1)
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Angular Power Spectrum
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
Multipole moment l

Is n_s different from ONE?

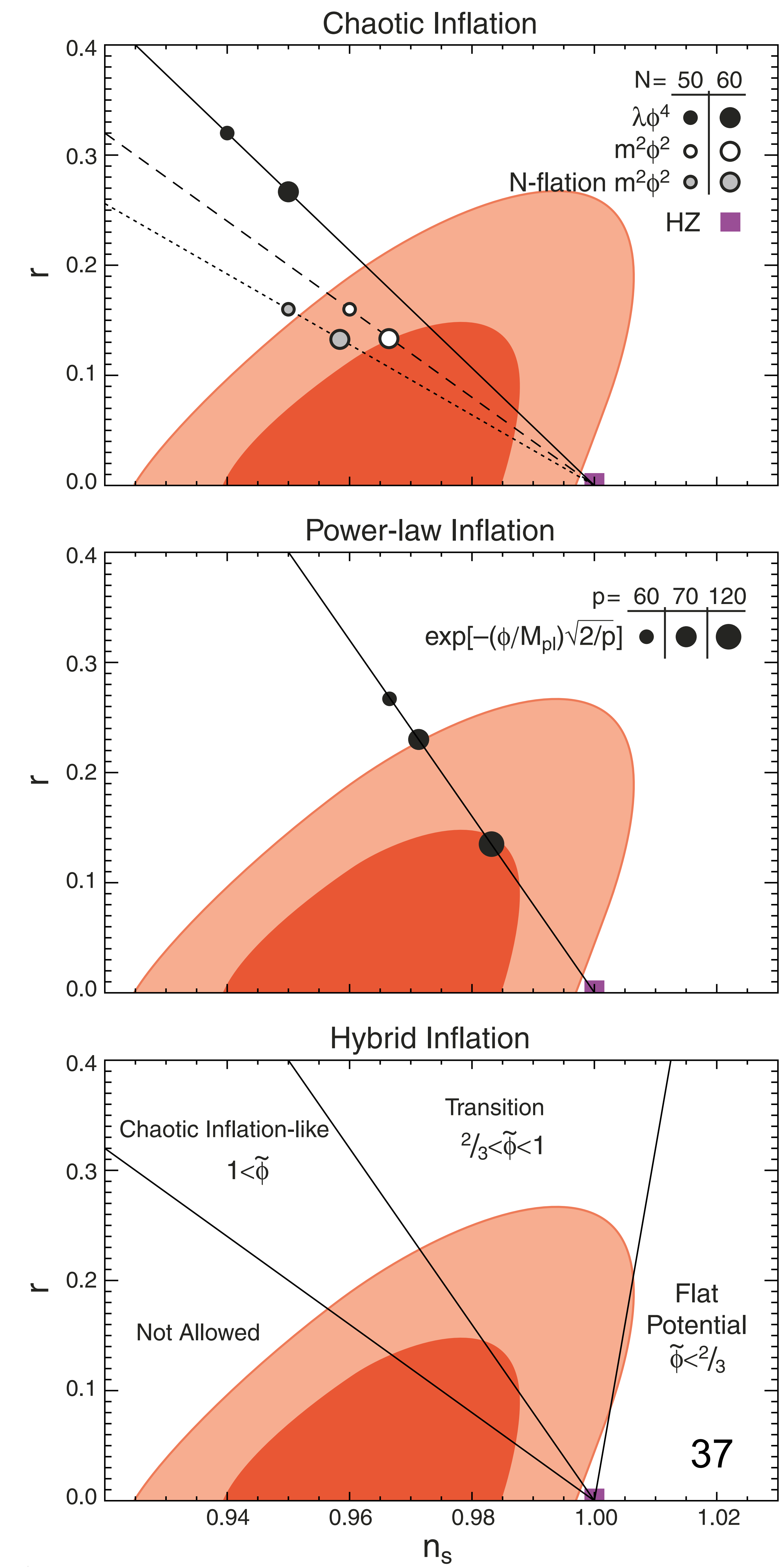
Komatsu et al.



- WMAP-alone: $\mathbf{n_s=0.963}$ (+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 $\Omega_b h^2$

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

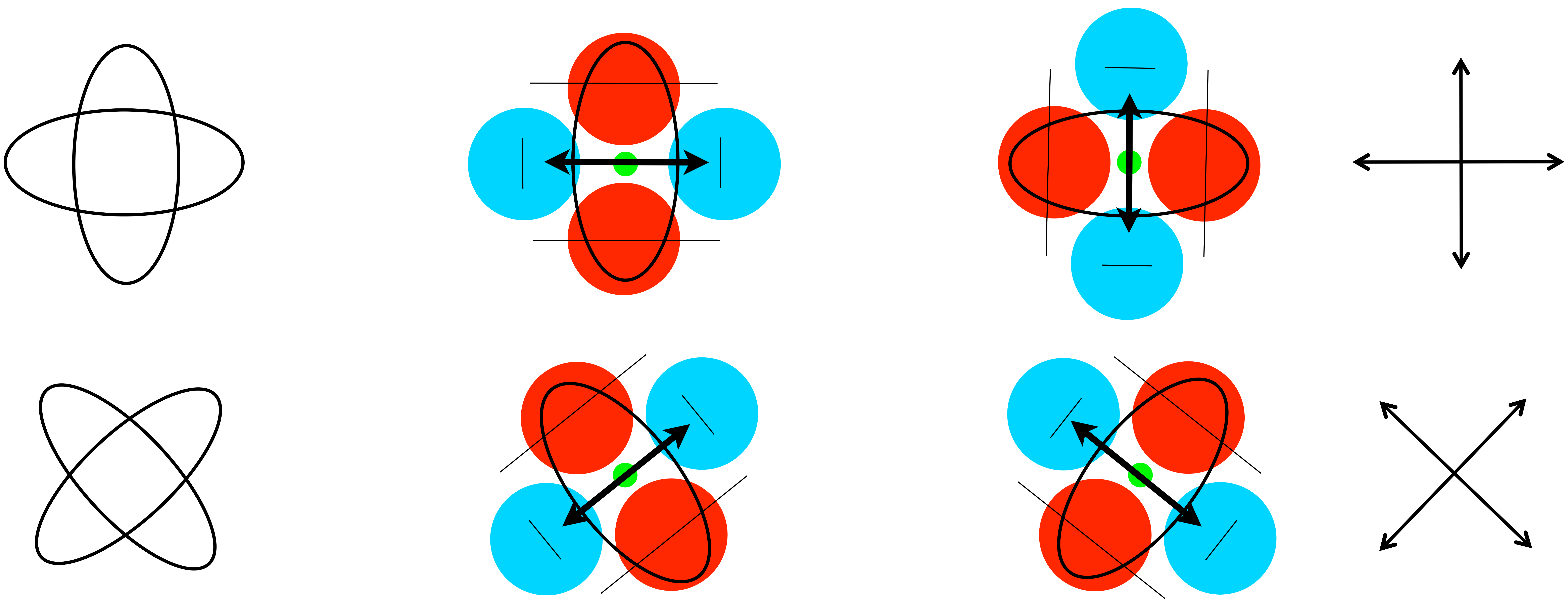


Searching for Primordial Gravitational Waves in CMB

- Not only do inflation models produce density fluctuations, but also primordial gravitational waves
- Some predict the observable amount (tensor-to-scalar ratio>0.01), some don't
  - Current limit: **tensor-to-scalar ratio <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

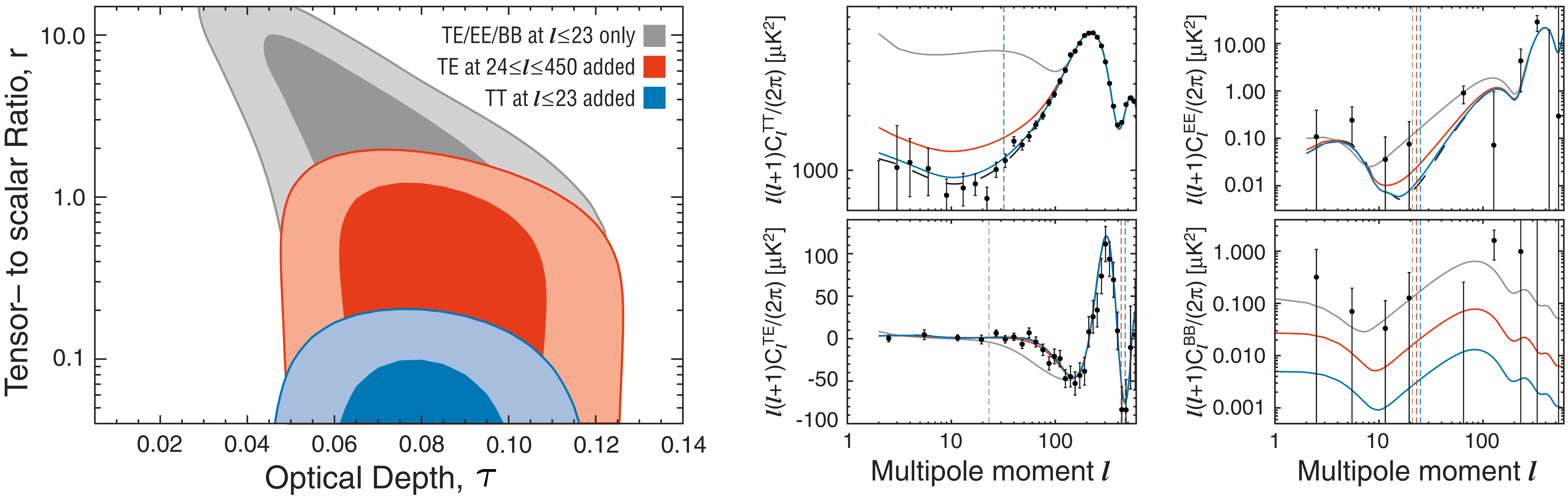
Gravitational Waves & Quadrupole

- As GW propagates in space, it stretches/contracts space.
  - –Stretch -> Redshift -> Lower temperature
  - –Contraction-> Blueshift -> Higher temperature

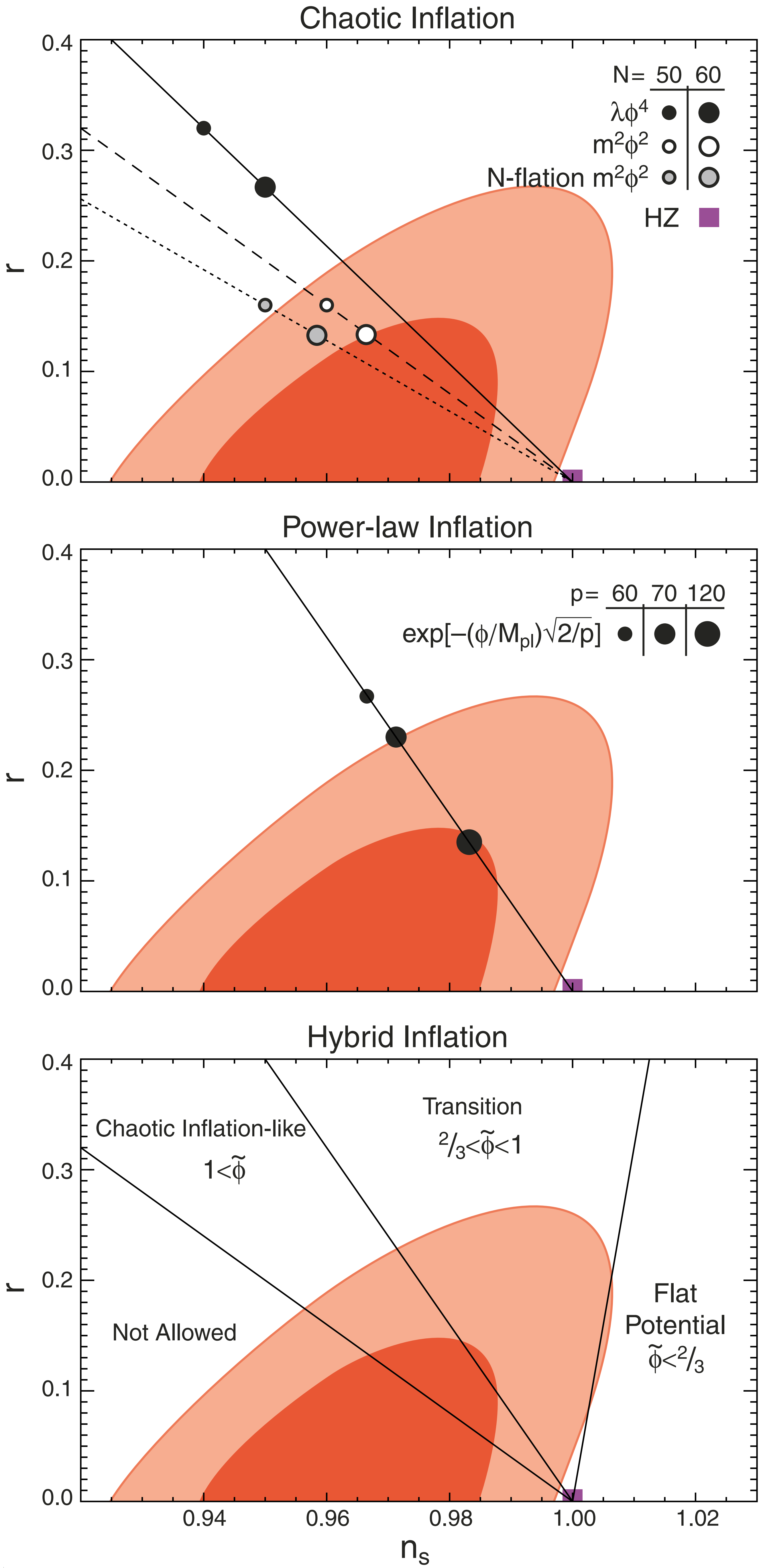


How GW Affects CMB

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)



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

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, $\delta(x)$

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

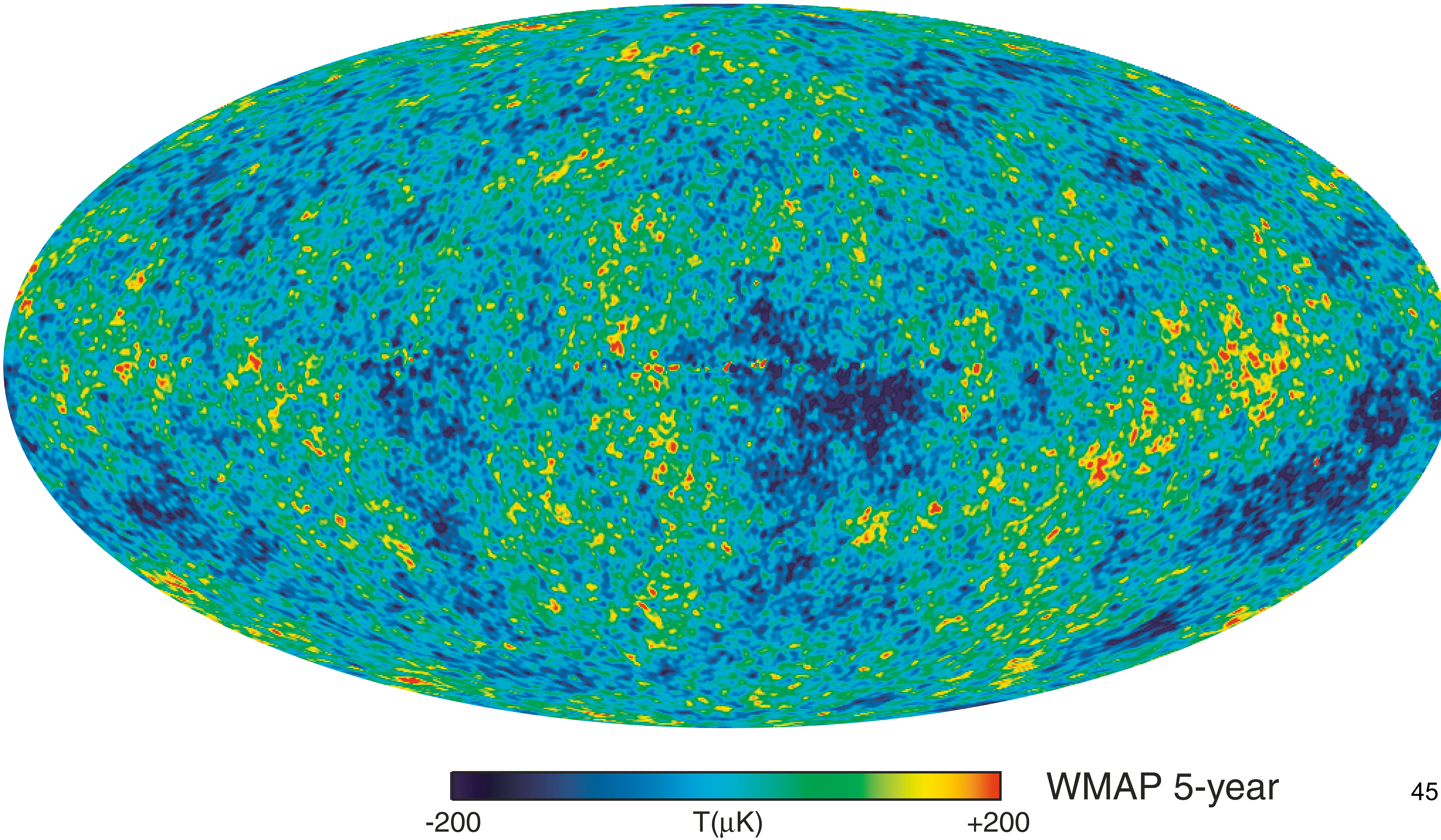
What About Phase, φ_k

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

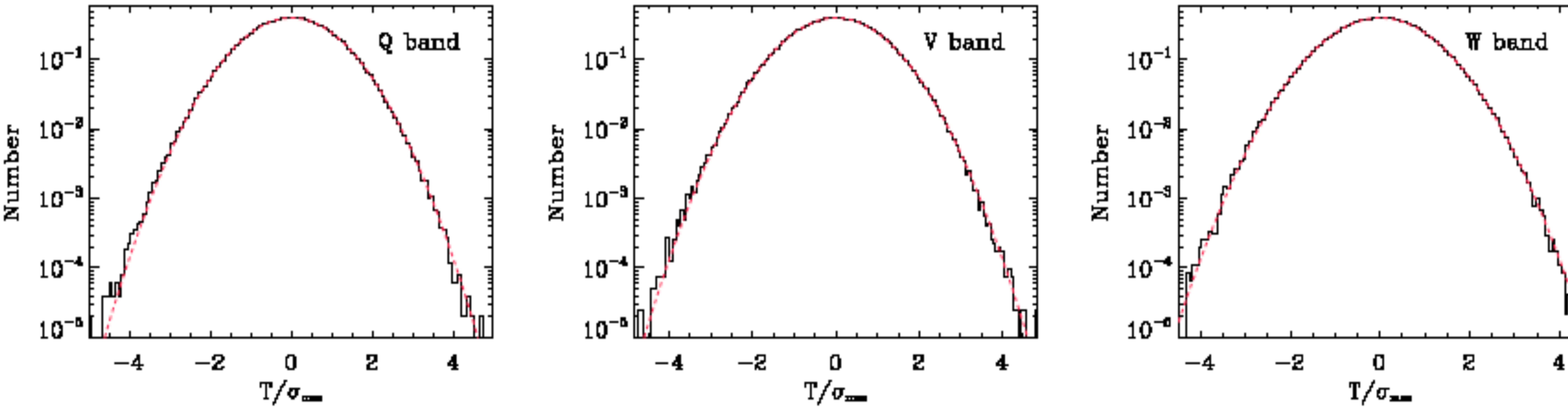
Gaussian Distribution

Gaussian?

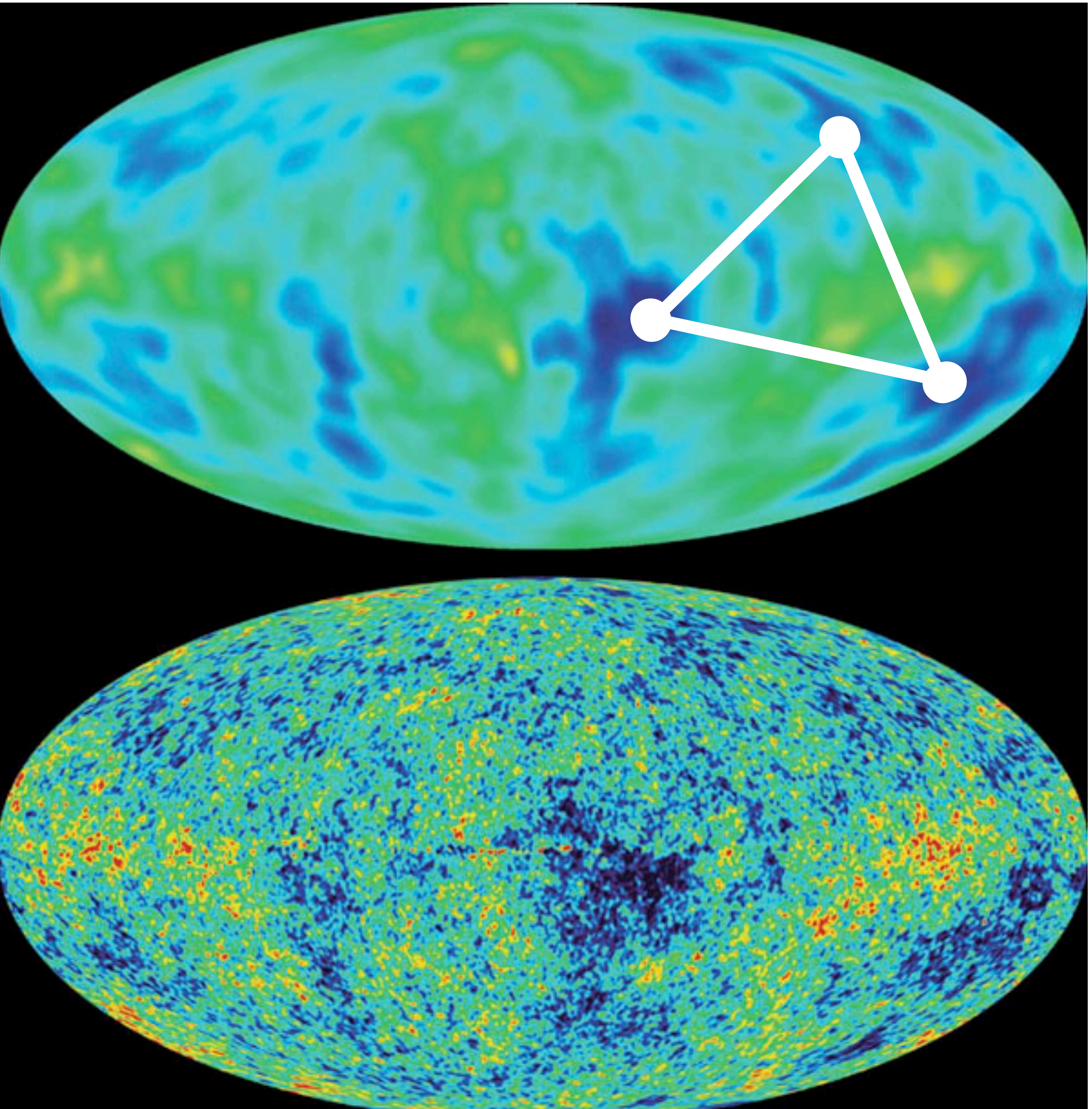
WMAP5



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.

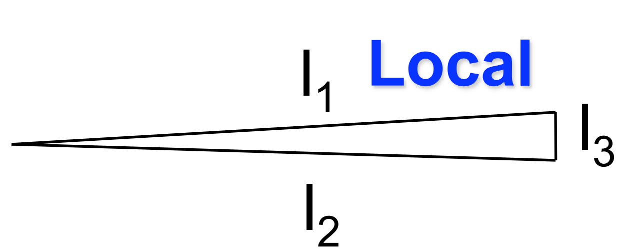


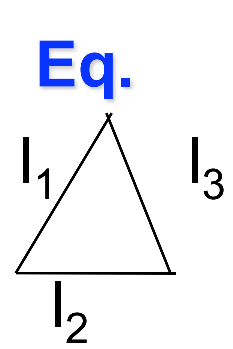
3-point Function

- Fourier Transform of the 3-point function is called the “bispectrum”
- Bispectrum＝$B(k_1,k_2,k_3)$

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}





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.

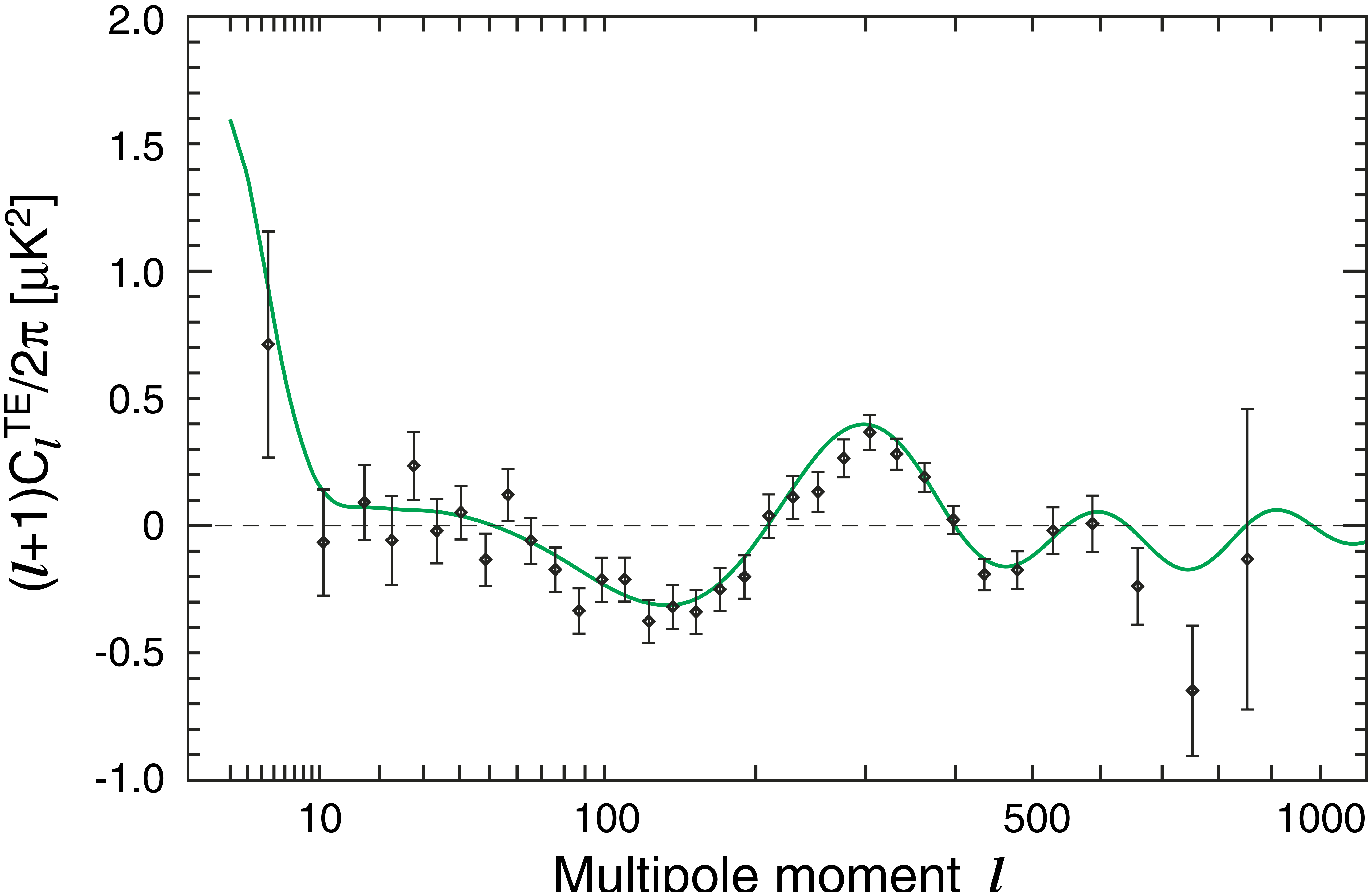
Komatsu et al.

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.

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 $\Omega_a^{1/7}$.

Komatsu et al.

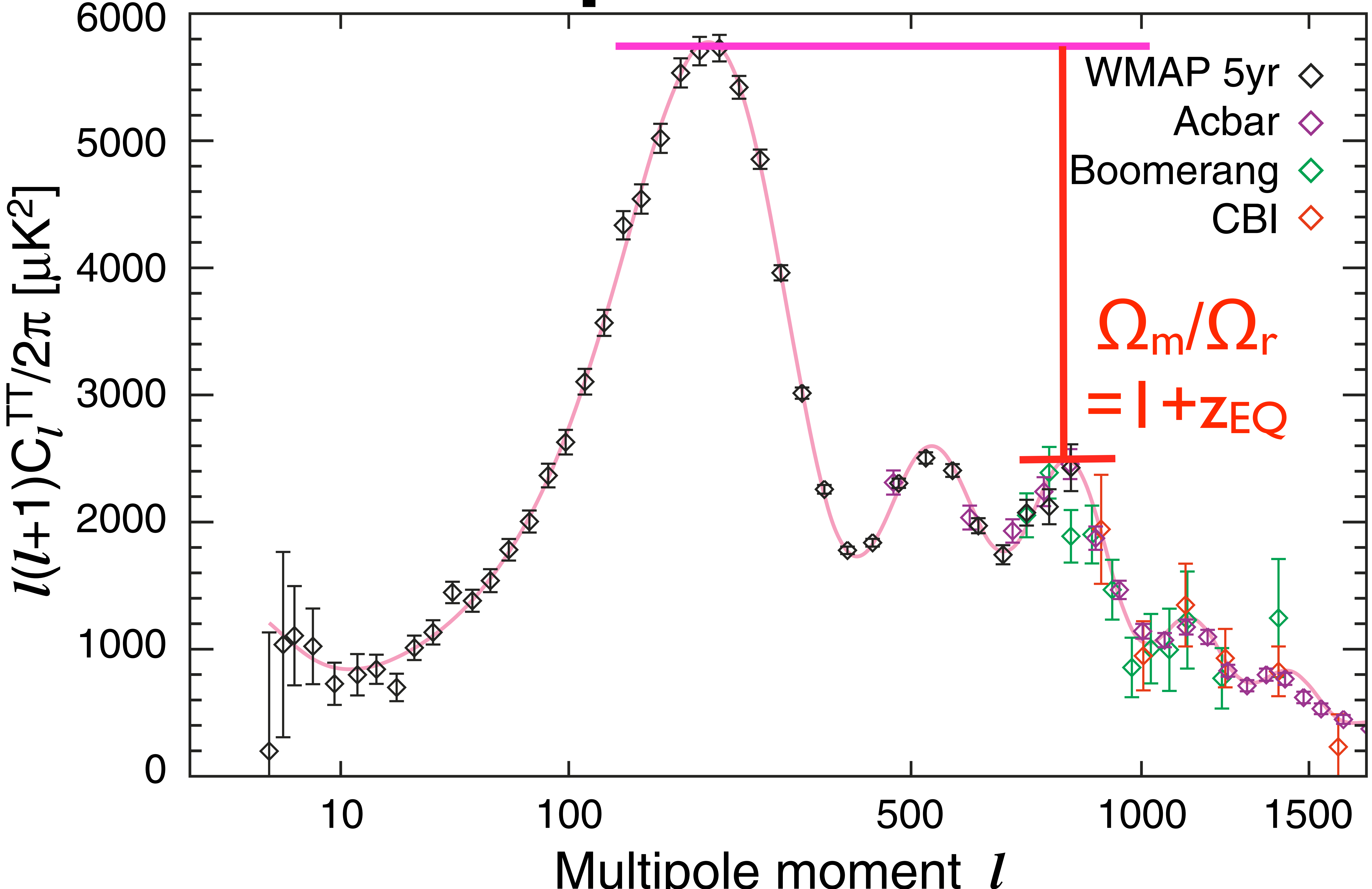
Grading Inflation

- 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: **tensor-to-scalar ratio < 0.22**

Effective Number of Neutrino Species, N_{eff}

- For relativistic neutrinos, the energy density is given by
  - $\rho_\nu = \mathbf{N_{eff}} (7\pi^2/120)\, T_\nu^4$
  - where N_{eff}=3.04 for the standard model, and $T_\nu=(4/11)^{1/3} T_{photon}$
- Adding more relativistic neutrino species (or any other relativistic components) delays the epoch of the matter-radiation equality, as
  - $\mathbf{1+z_{EQ} = (\Omega_m h^2/2.47\mathrm{x}10^{-5}) / (1+0.227N_{eff})}$

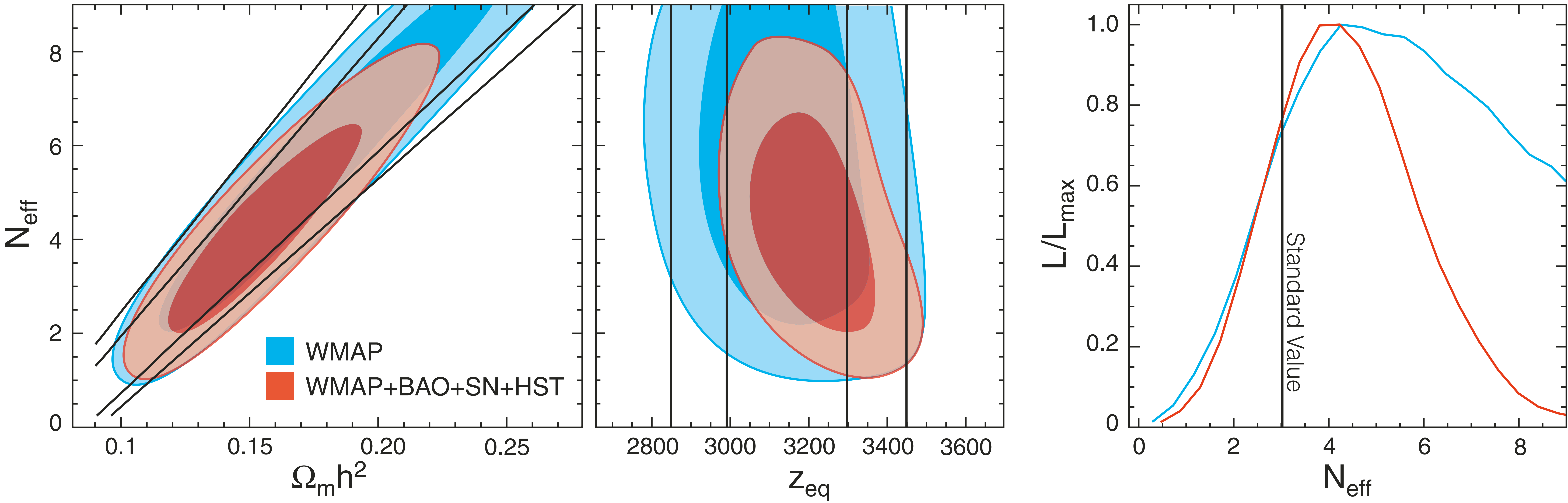
3rd-peak to z_{EQ}



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

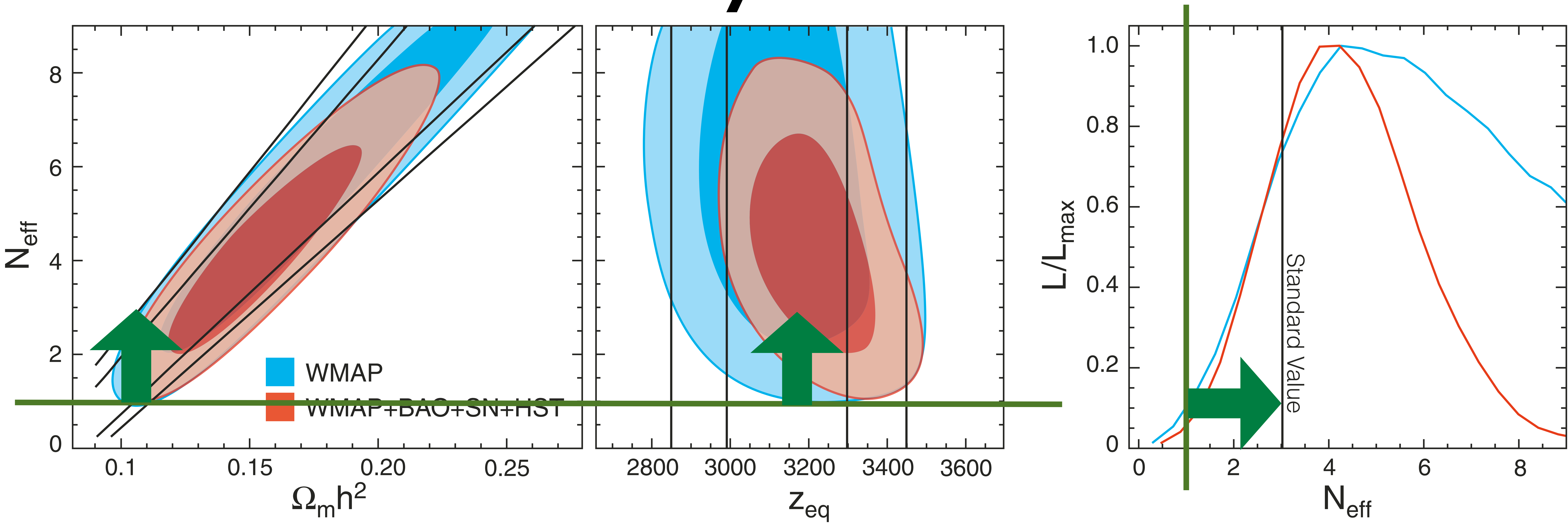
N_{eff}-$\Omega_m h^2$ Degeneracy

Komatsu et al.



- 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_{eff} = 4.4 ± 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_{eff}=0**
  - N_{eff}>2.3 (95%CL) [Dunkley et al.]

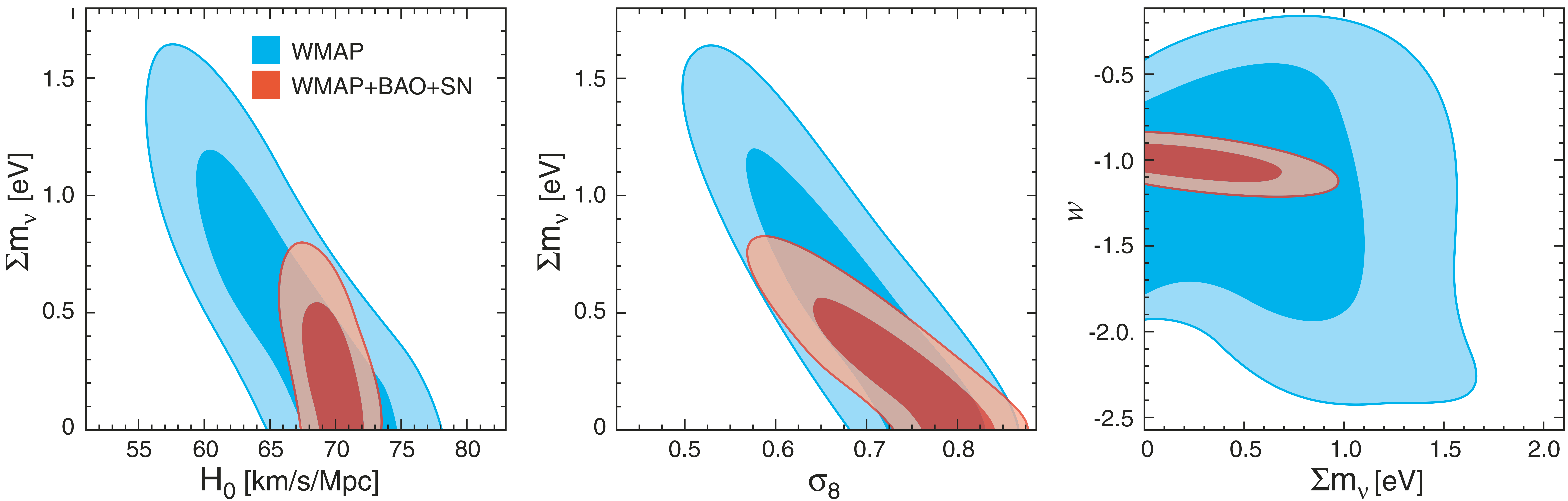
Komatsu et al.

Cosmic/Laboratory Consistency

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

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.

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
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	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	$0.1358^{+0.0037}_{-0.0036}$
	$z_{\rm reion}{}^f$	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 ΛCDM 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.	$R_{\rm curv} > 12\ h^{-1}$Gpc	$R_{\rm curv} > 23\ h^{-1}$Gpc
		Negative Curv.	$R_{\rm curv} > 22\ h^{-1}$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]	$\alpha_0 < 0.072$[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%)

- **We did everything we could do to find deviations from ΛCDM, 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_{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
    - More, maybe seeing a hint of it if $m^2\varphi^2$ is indeed the correct model?!