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

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)

Particle Physics Seminar, BNL, March 11, 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!
- www.tcc.utexas.edu

Research Unit, Texas Cosmology Center

Astronomy	***Physics***
Volker Bromm	Duane Dicus
Karl Gebhardt	Jacques Distler
Gary Hill	Willy Fischler
Eiichiro Komatsu(Director)	Vadim Kaplunovsky
Milos Milosavljevic	Sonia Paban
Paul Shapiro	Steven Weinberg

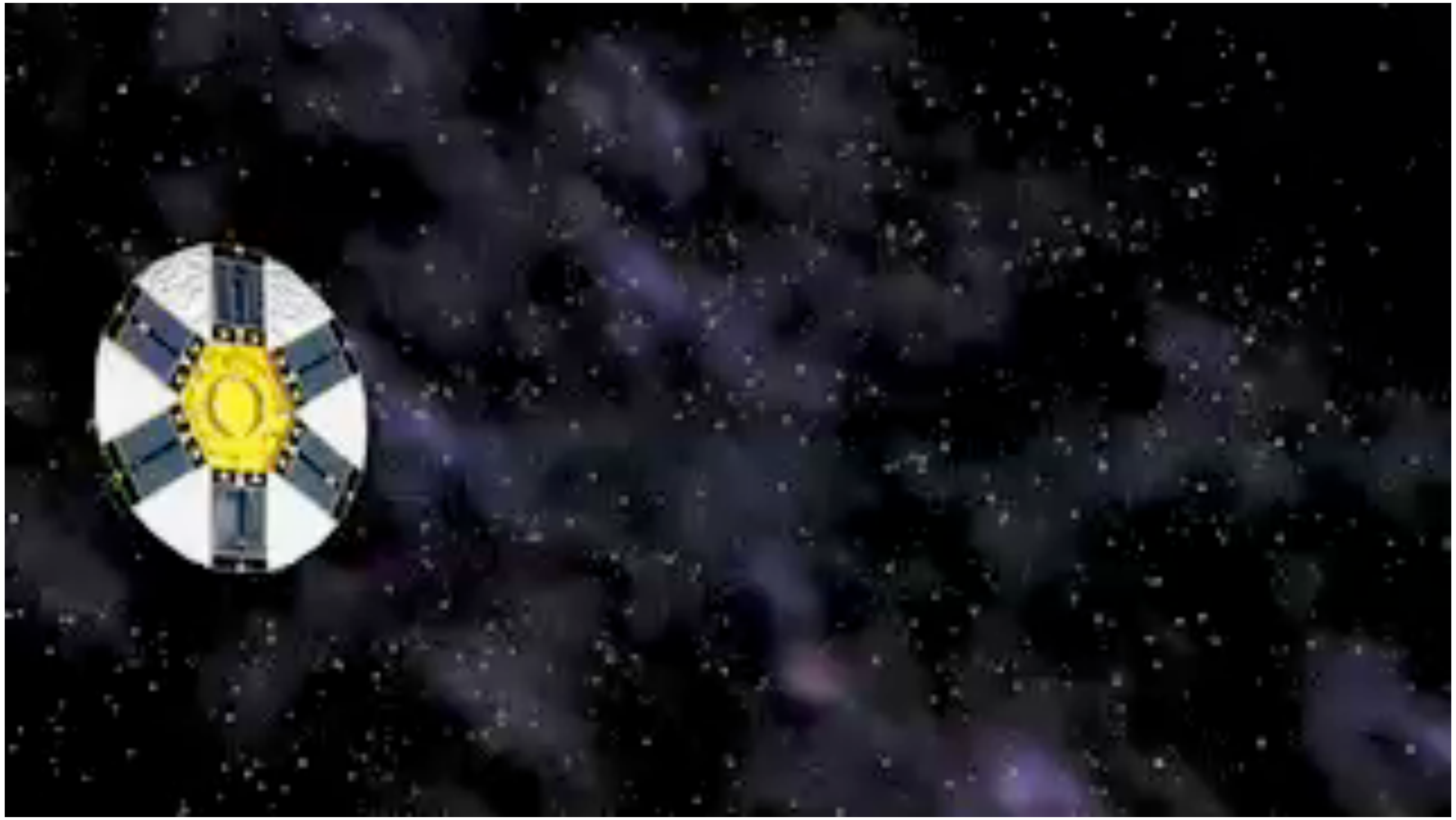
WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

February 2003:
The first-year data release

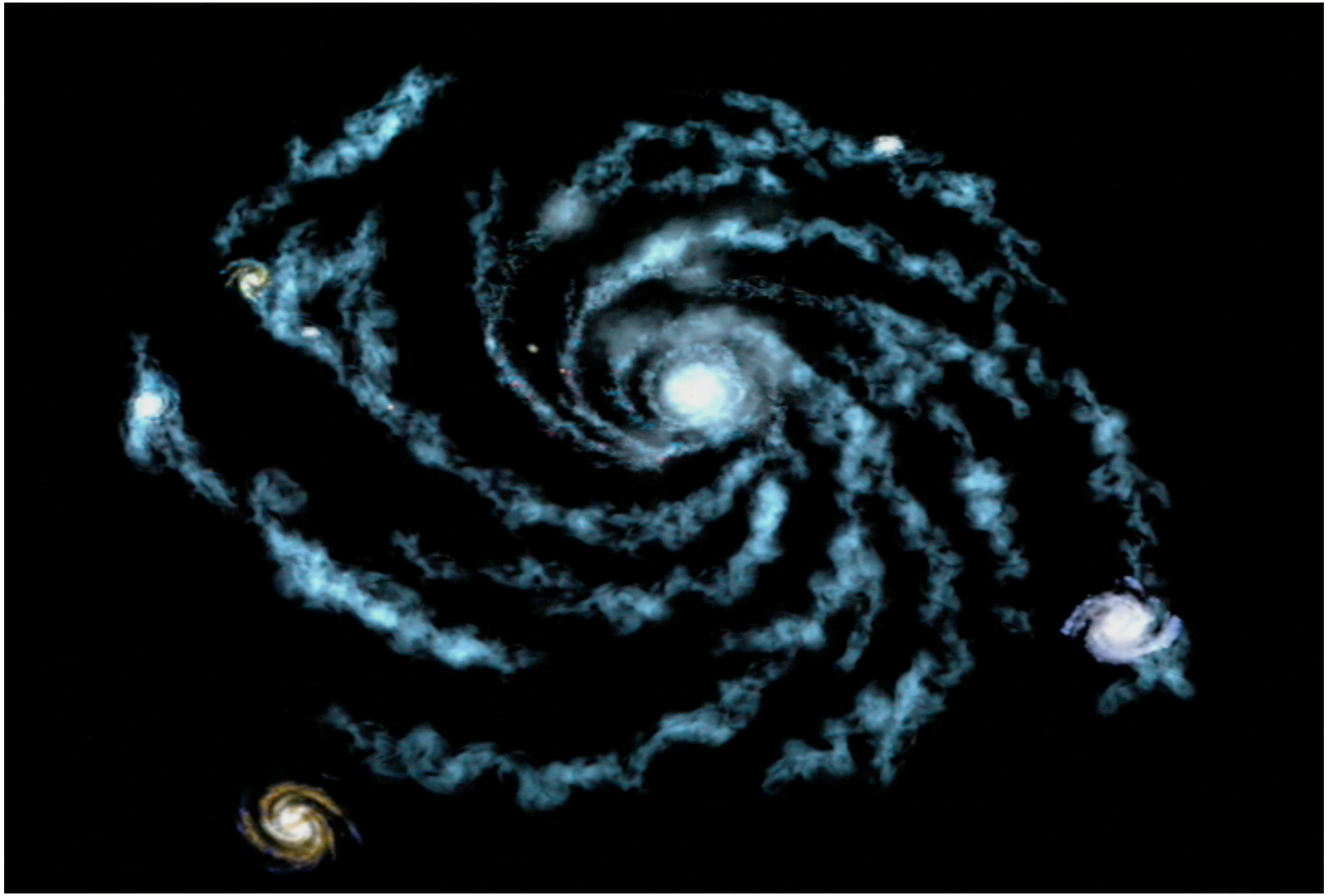
March 2006:
The three-year data release

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

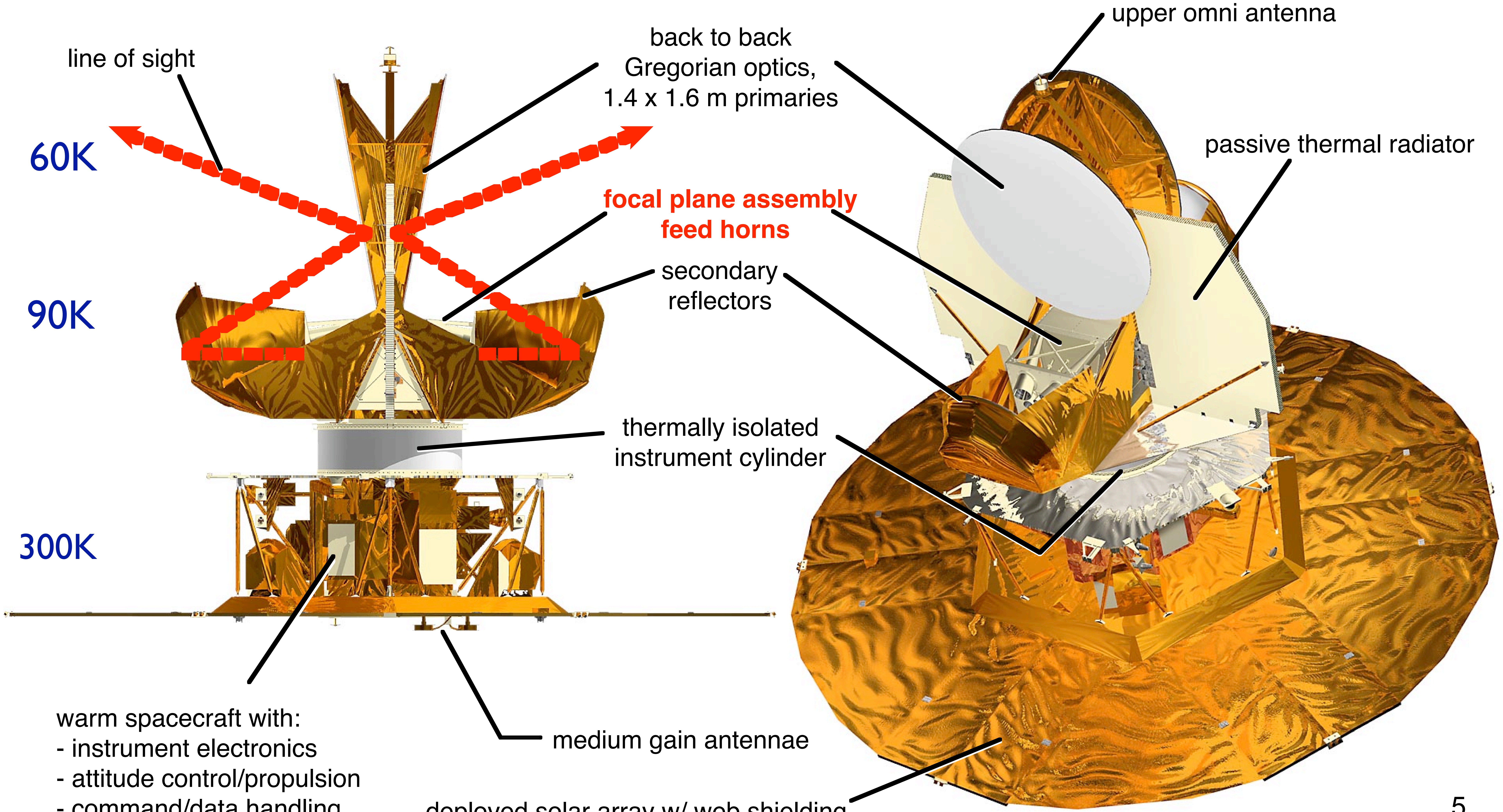
WMAP Measures Microwaves From the Universe



- 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**

WMAP Spacecraft

Radiative Cooling: No Cryogenic System



line of sight

60K

90K

300K

back to back
Gregorian optics,
1.4 x 1.6 m primaries

focal plane assembly
feed horns

secondary
reflectors

thermally isolated
instrument cylinder

upper omni antenna

passive thermal radiator

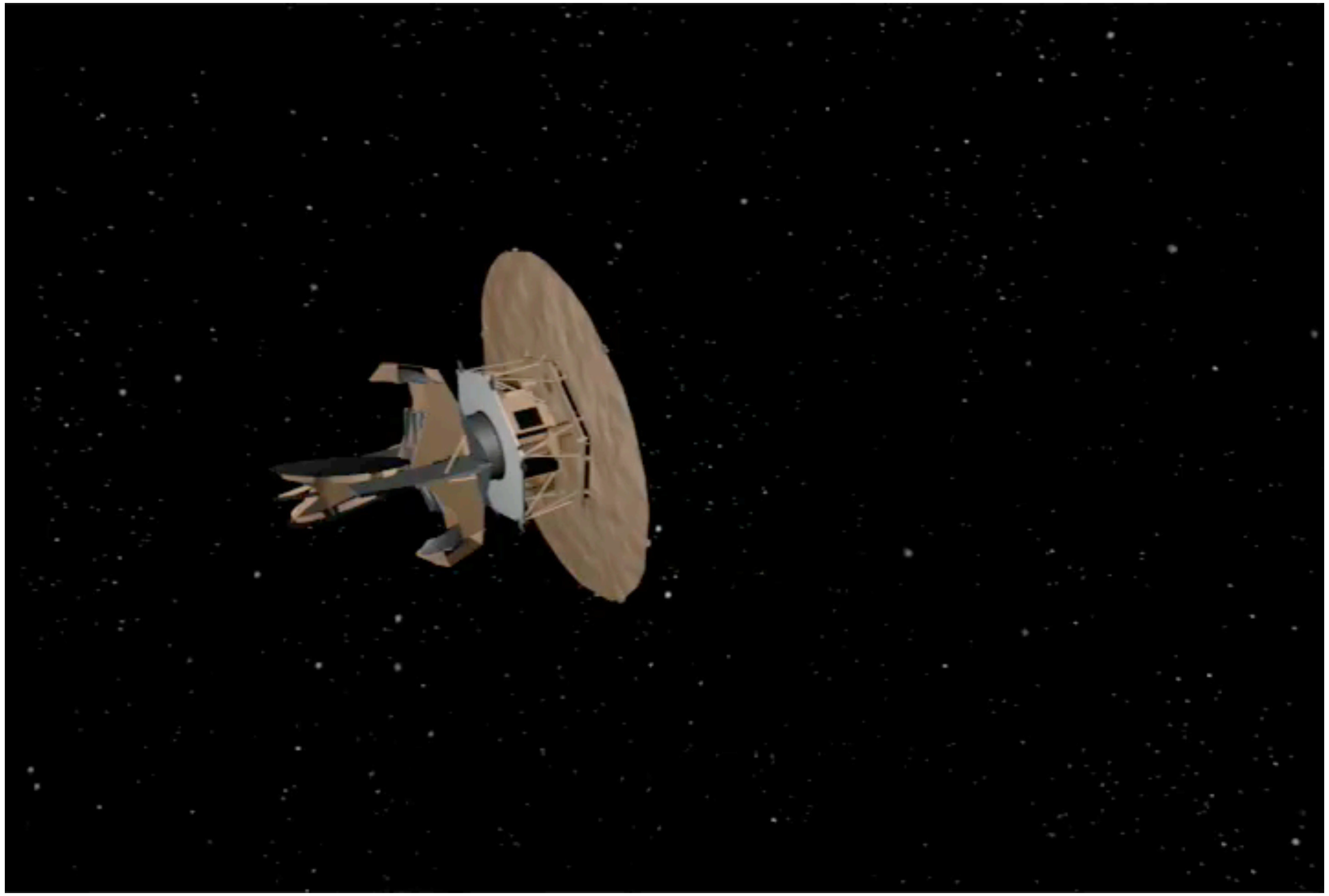
warm spacecraft with:
- instrument electronics
- attitude control/propulsion
- command/data handling
- battery and power control

medium gain antennae

deployed solar array w/ web shielding

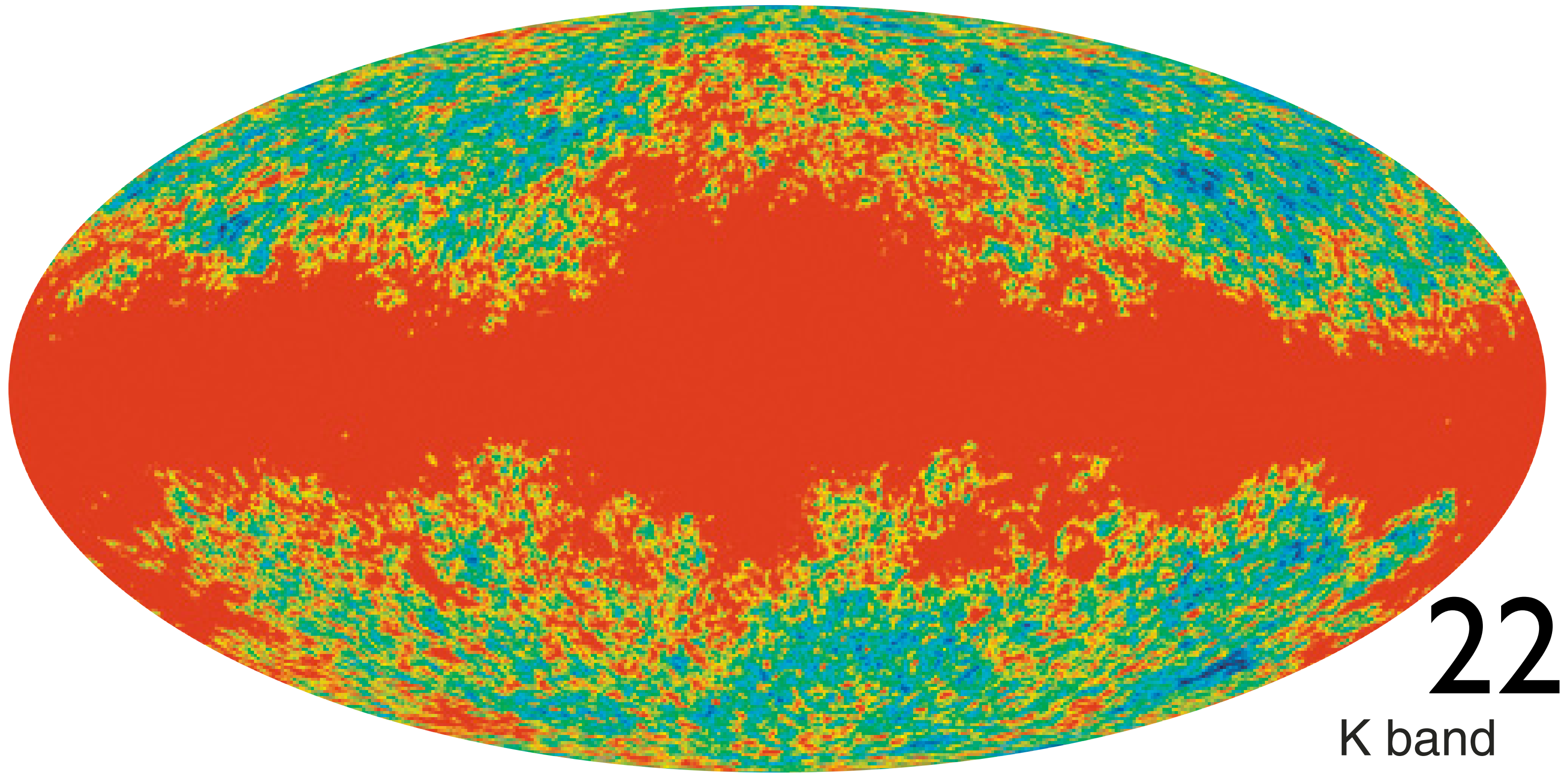
Journey Backwards in Time

- 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



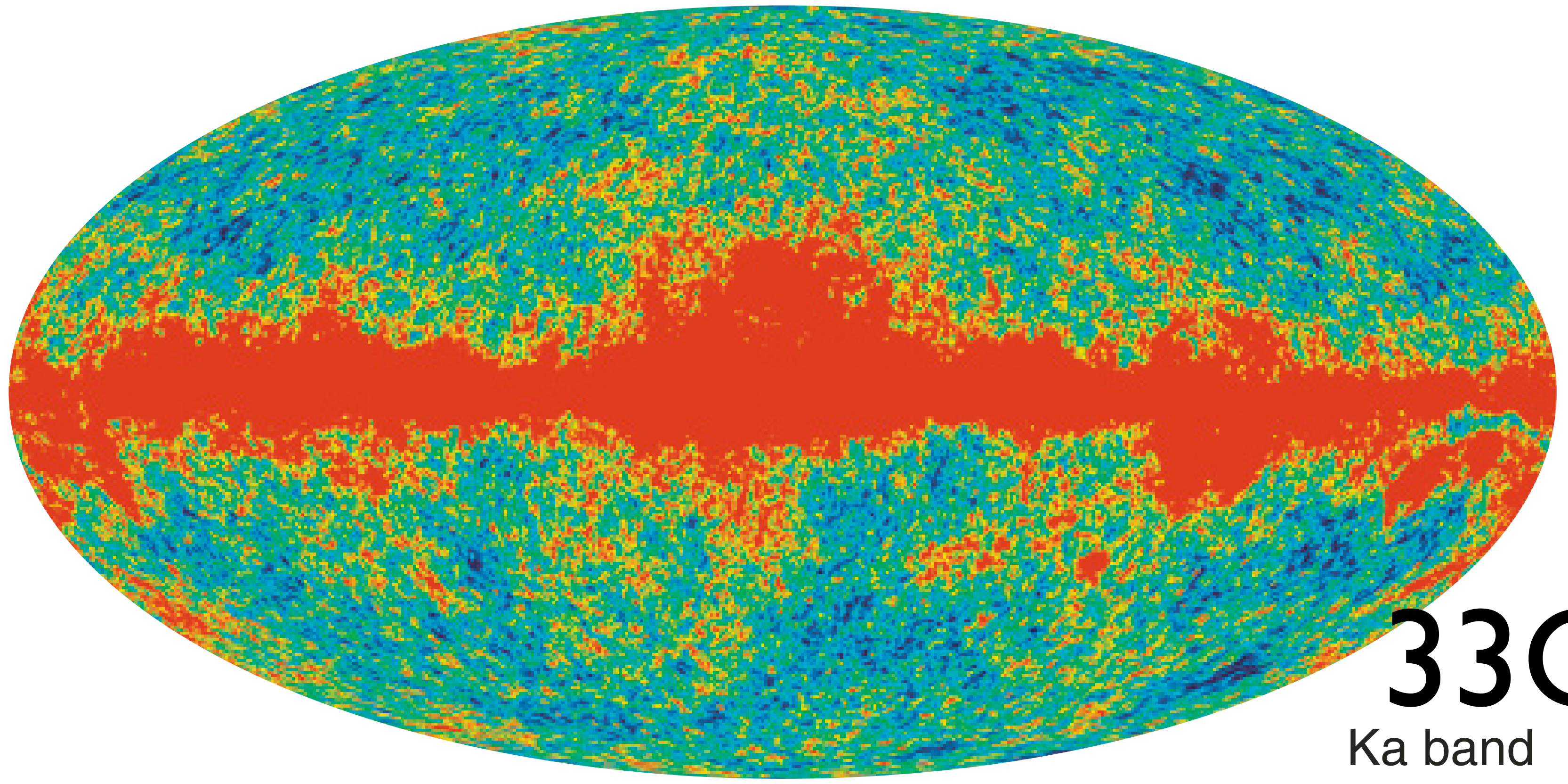
- CMB photons, after released from the cosmic plasma "soup," traveled for **13.7 billion years** to reach us.
- CMB collects information about the Universe as it travels through it.

Hinshaw et al.



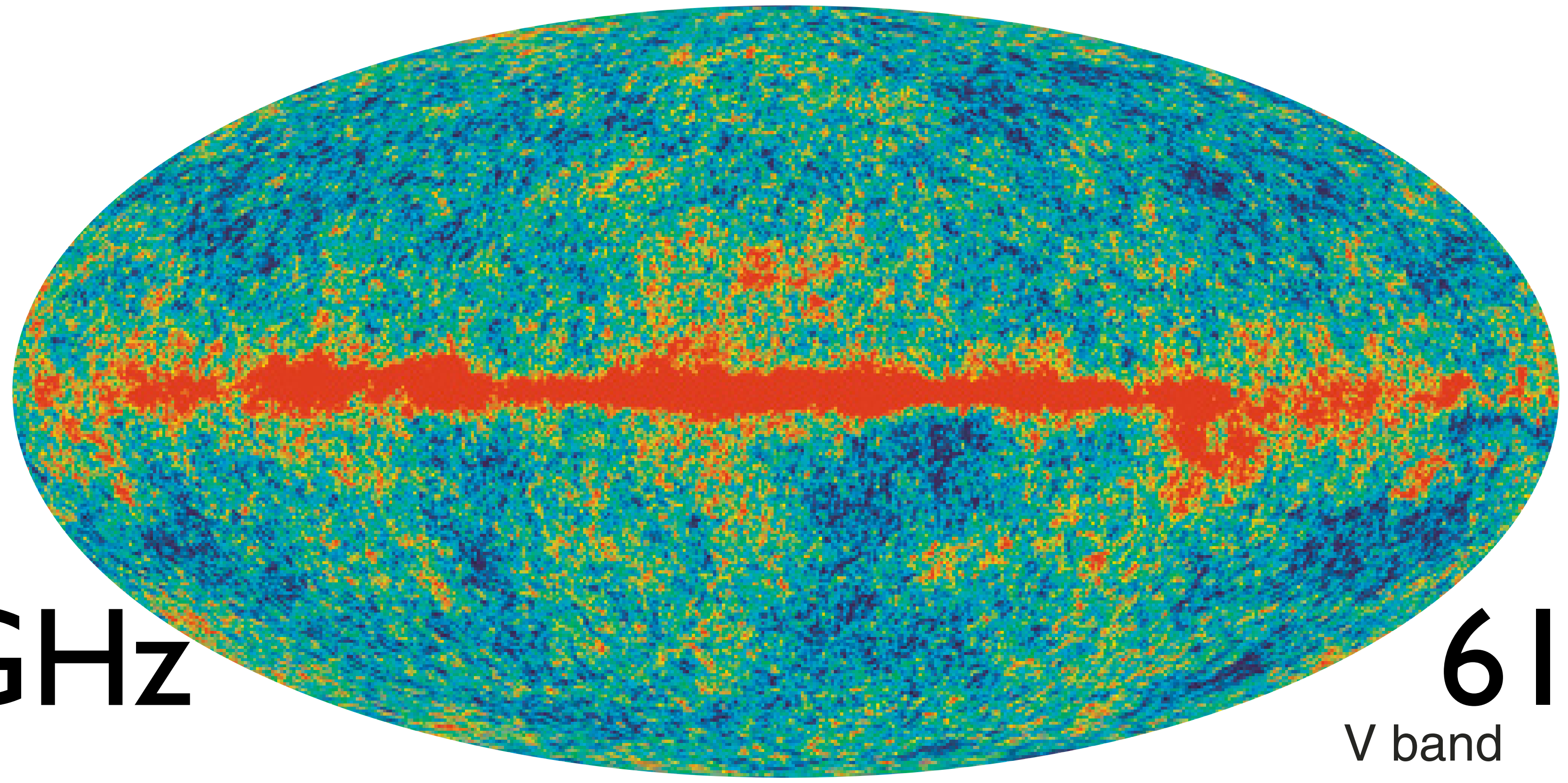
22GHz

K band



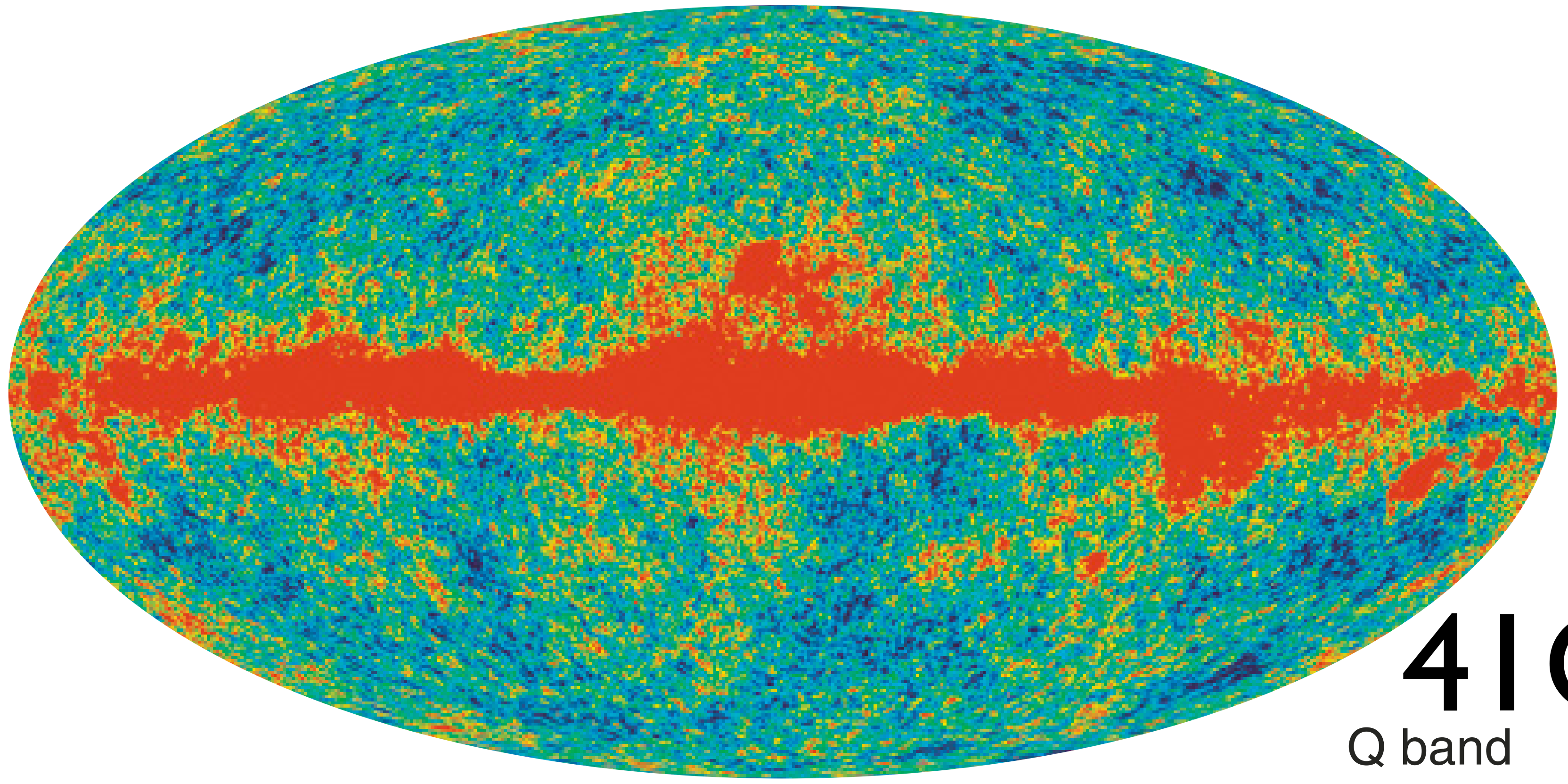
33GHz

Ka band



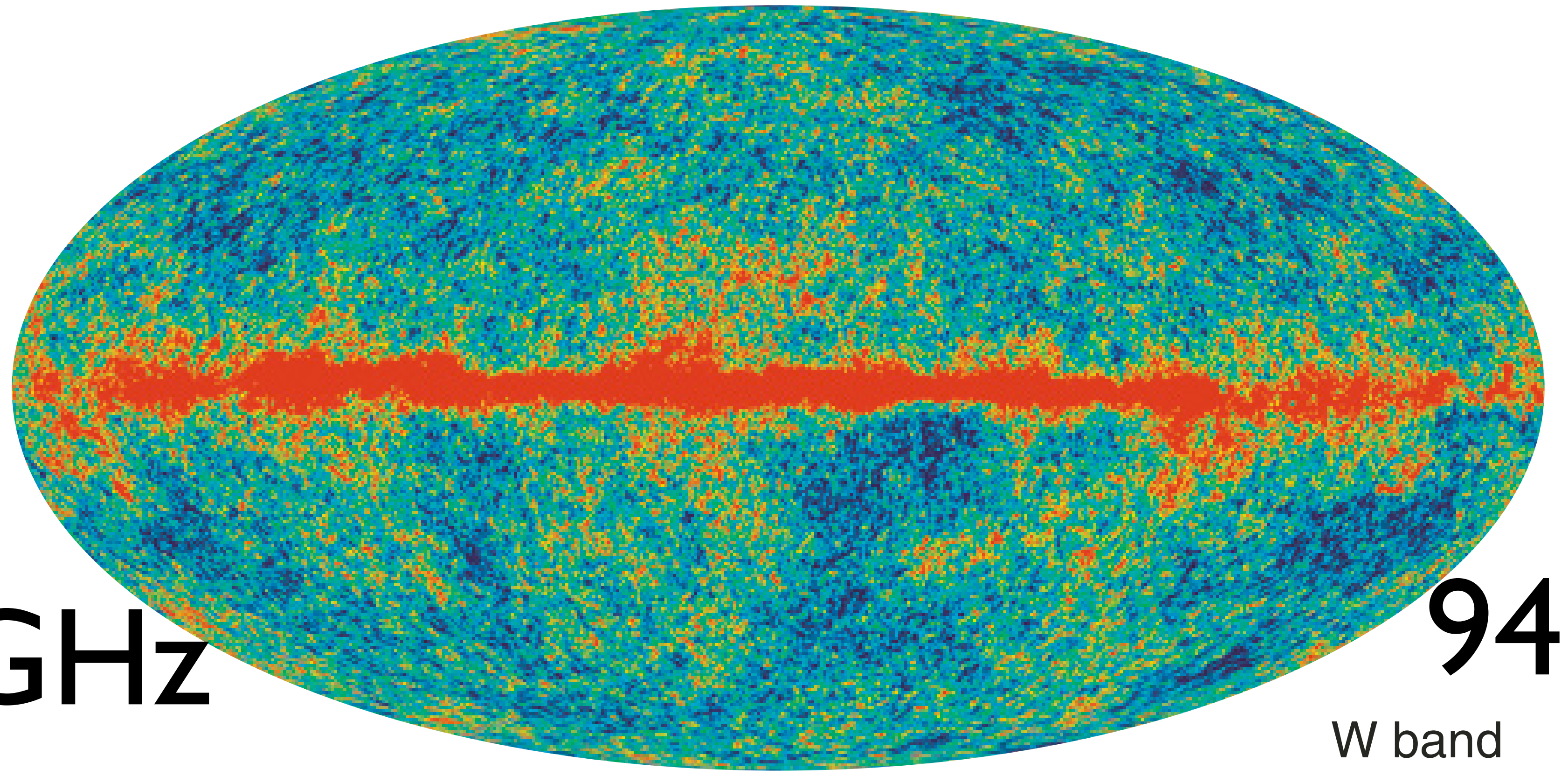
61GHz

V band



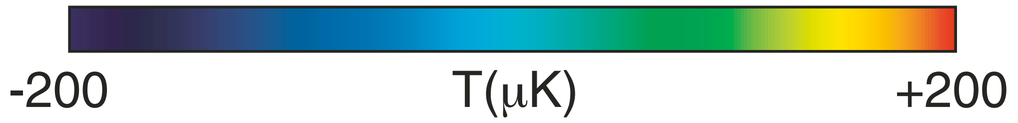
41GHz

Q band

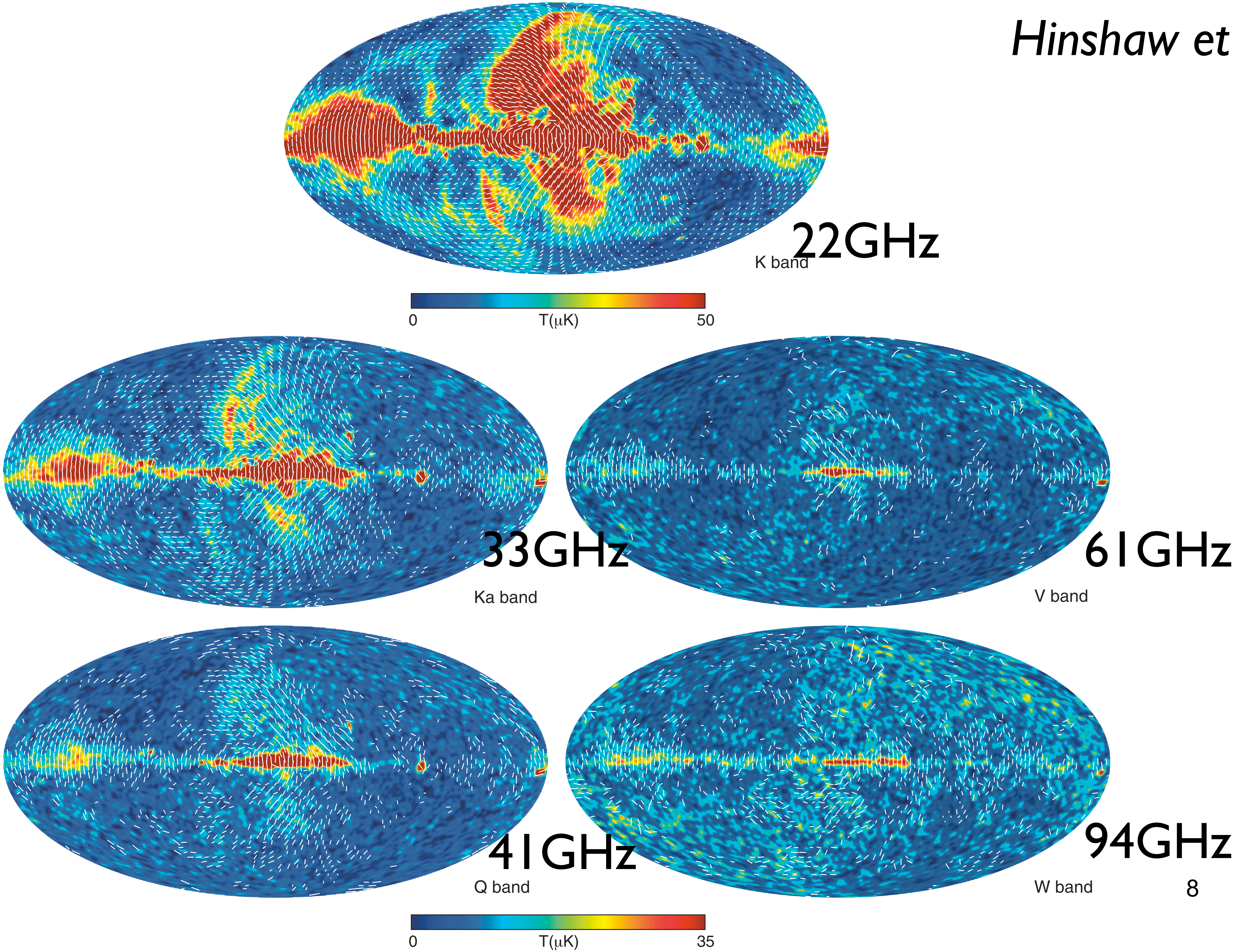


94GHz

W band

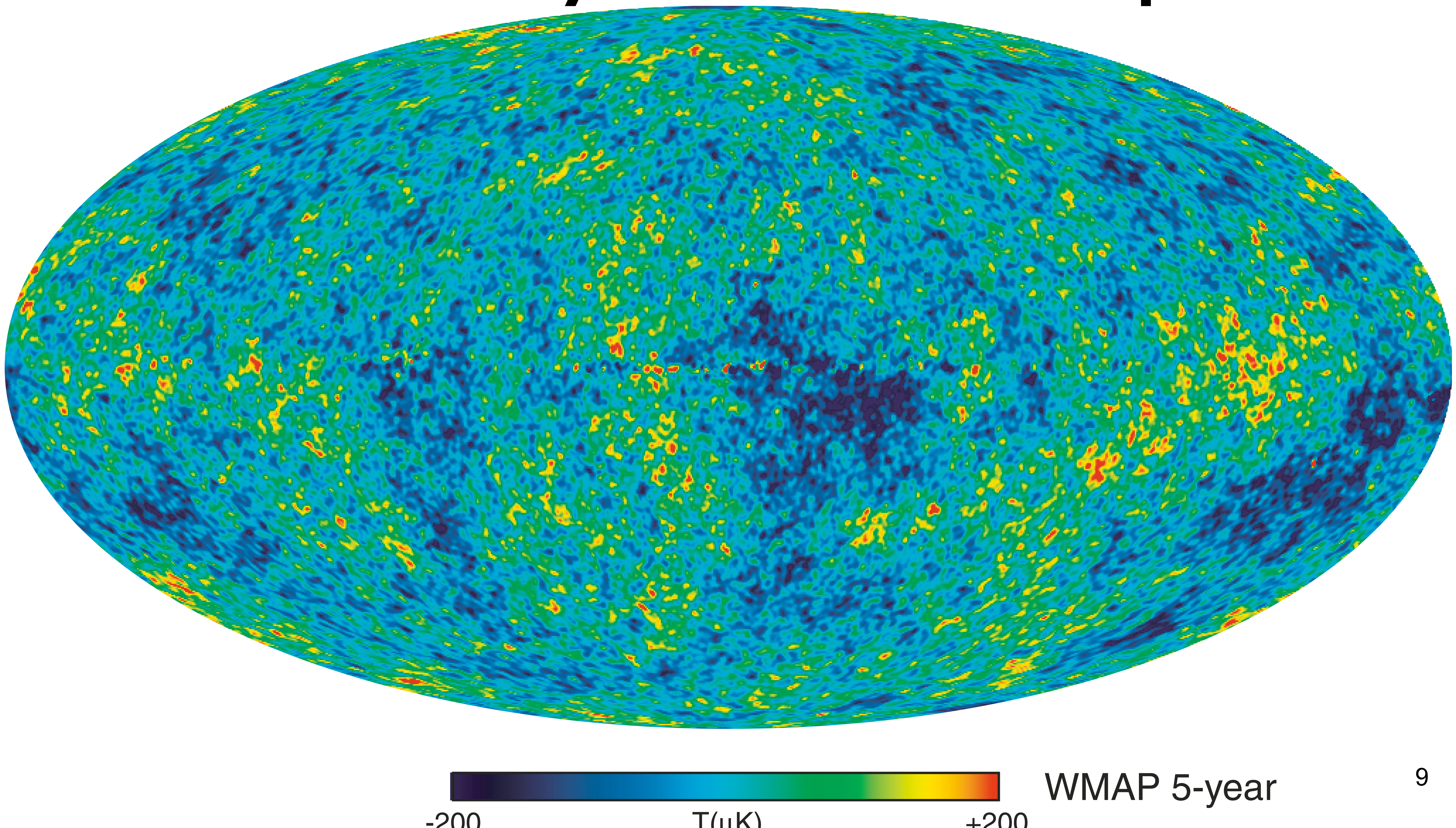


Hinshaw et al.



Hinshaw et al.

Galaxy-cleaned Map



WMAP 5-year

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

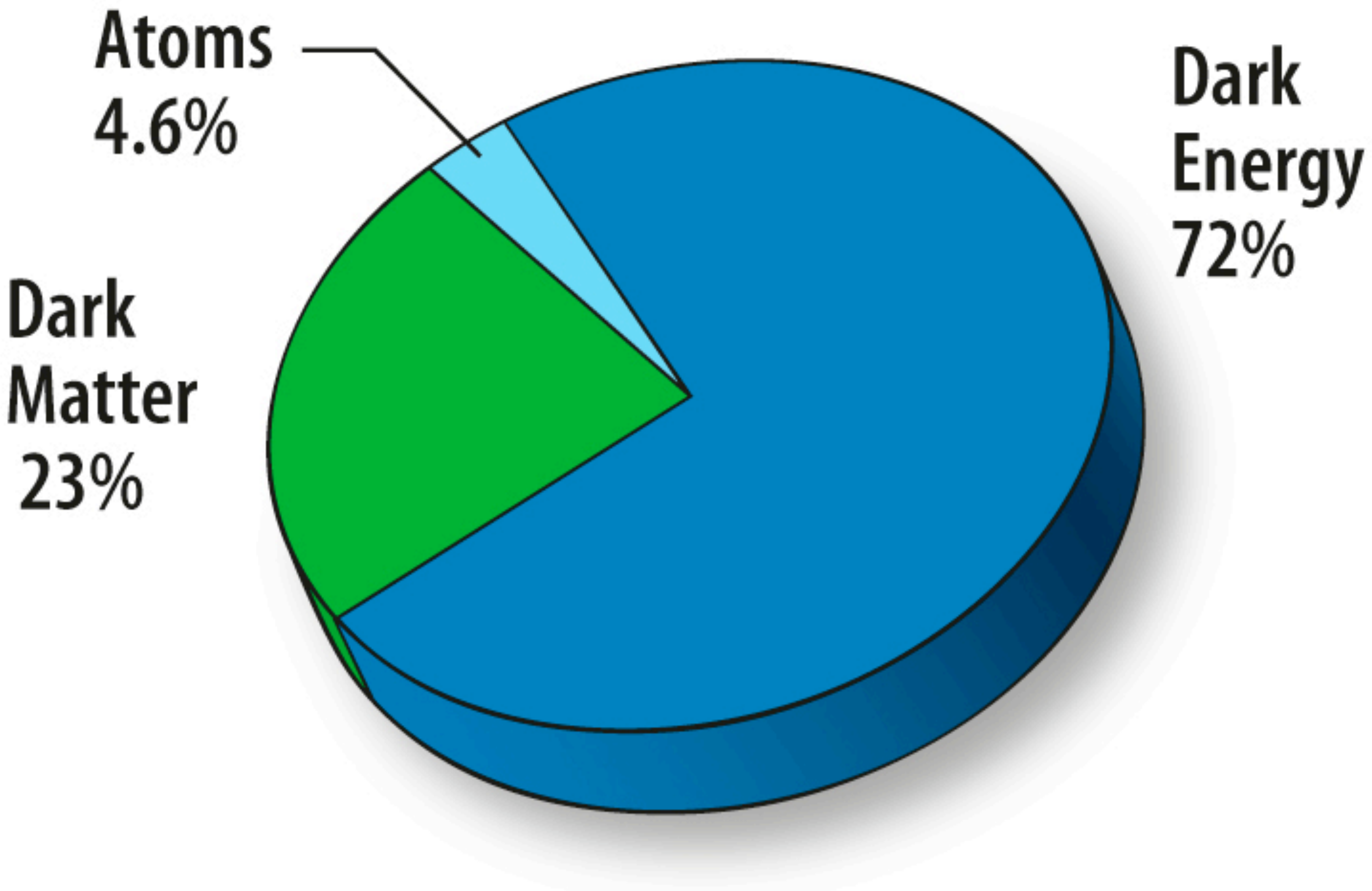
- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta

Special Thanks to **WMAP Graduates!**

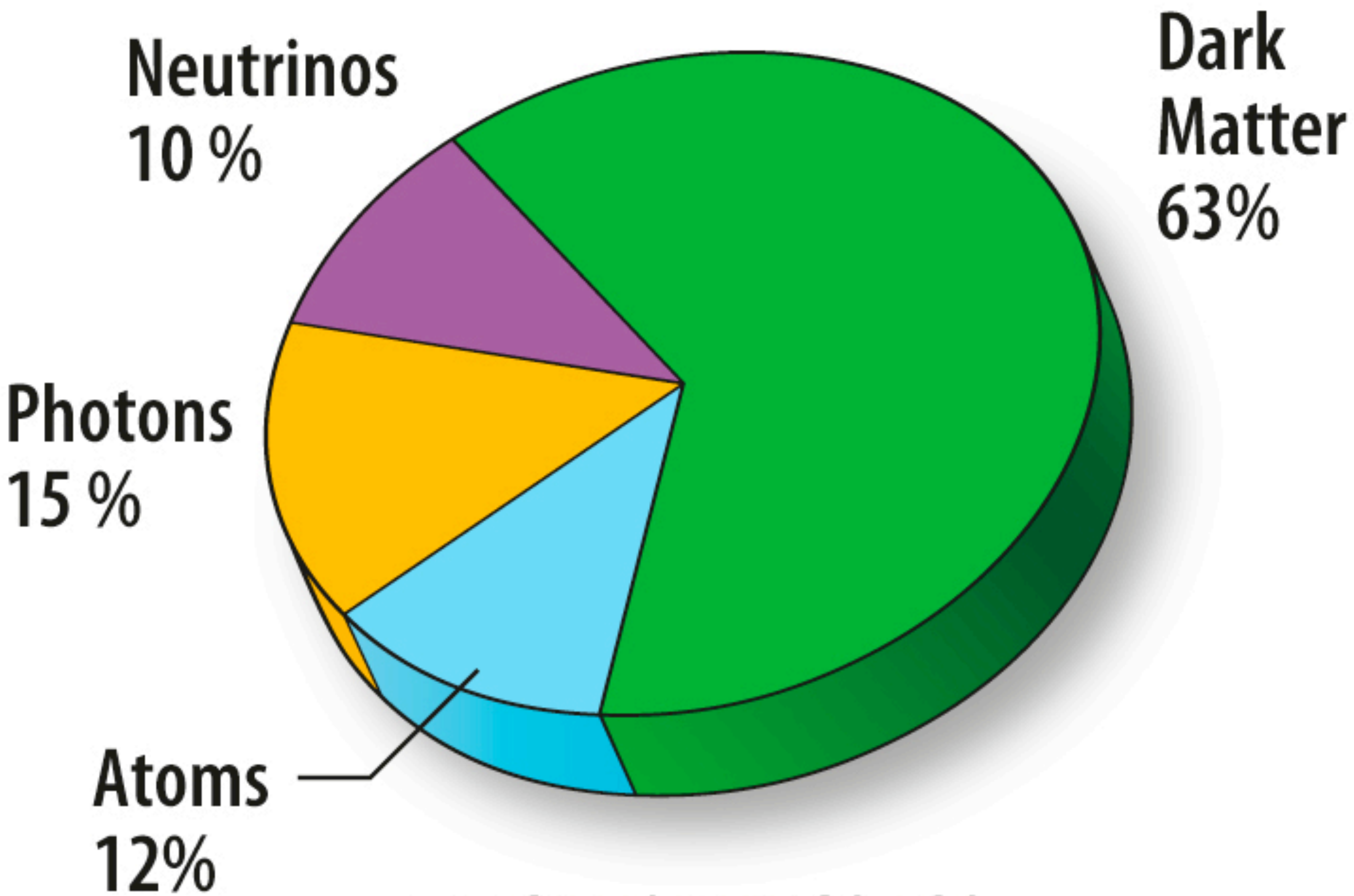
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

Komatsu et al.

~WMAP 5-Year~ Pie Chart Update!



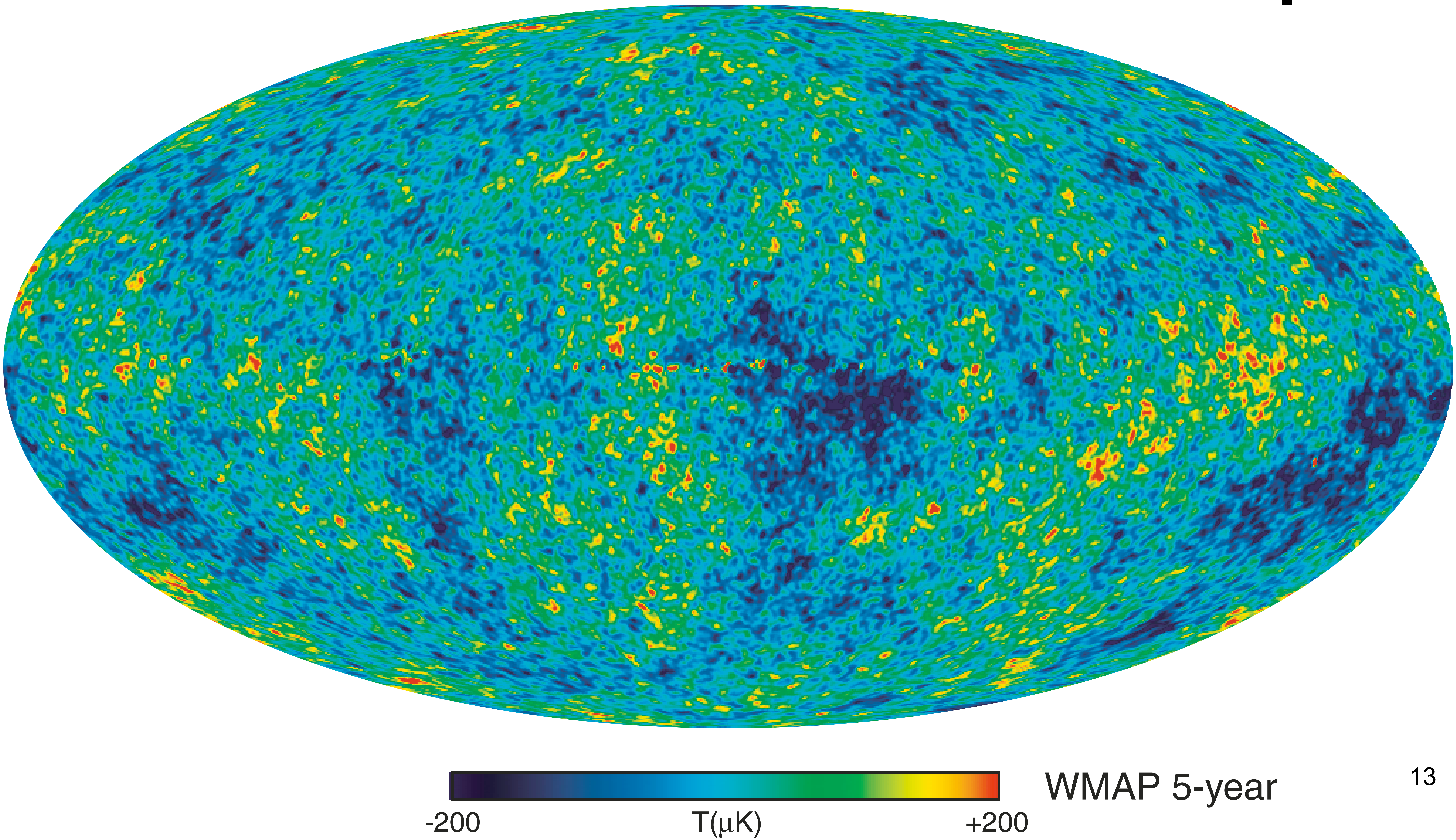
TODAY



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

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

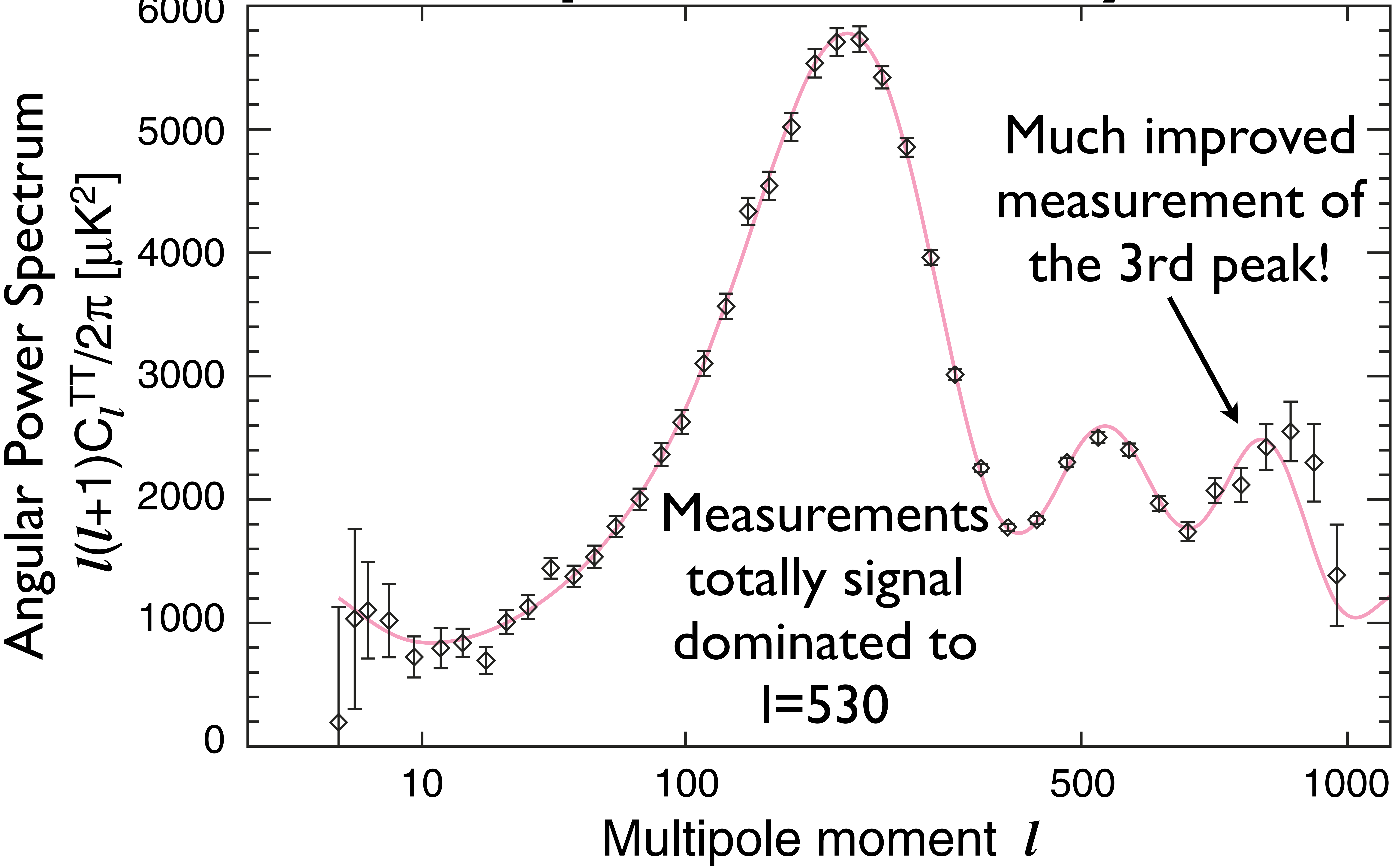
How Did We Use This Map?



WMAP 5-year

Nolta et al.

The Spectral Analysis

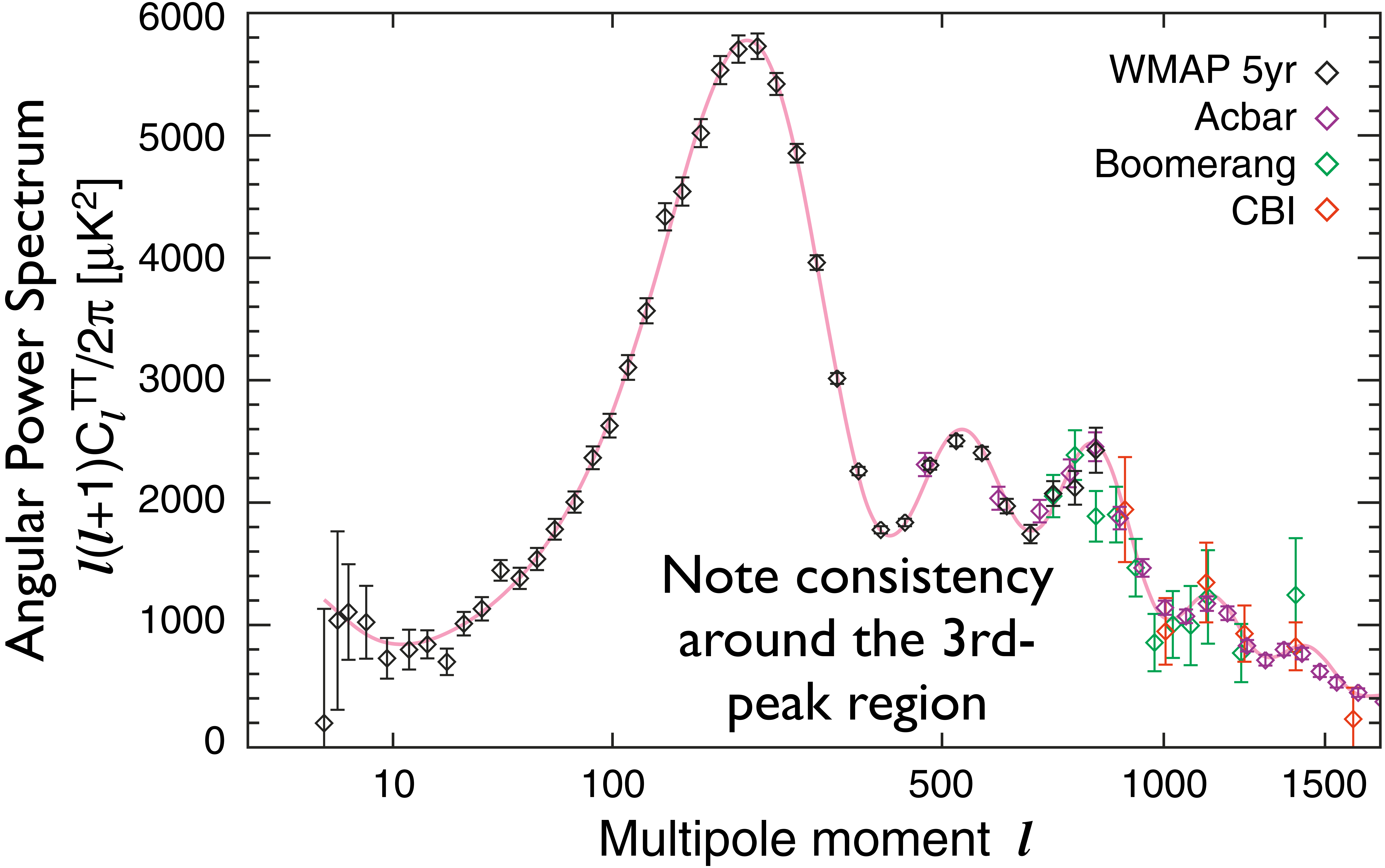


Much improved measurement of the 3rd peak!

Measurements totally signal dominated to l=530

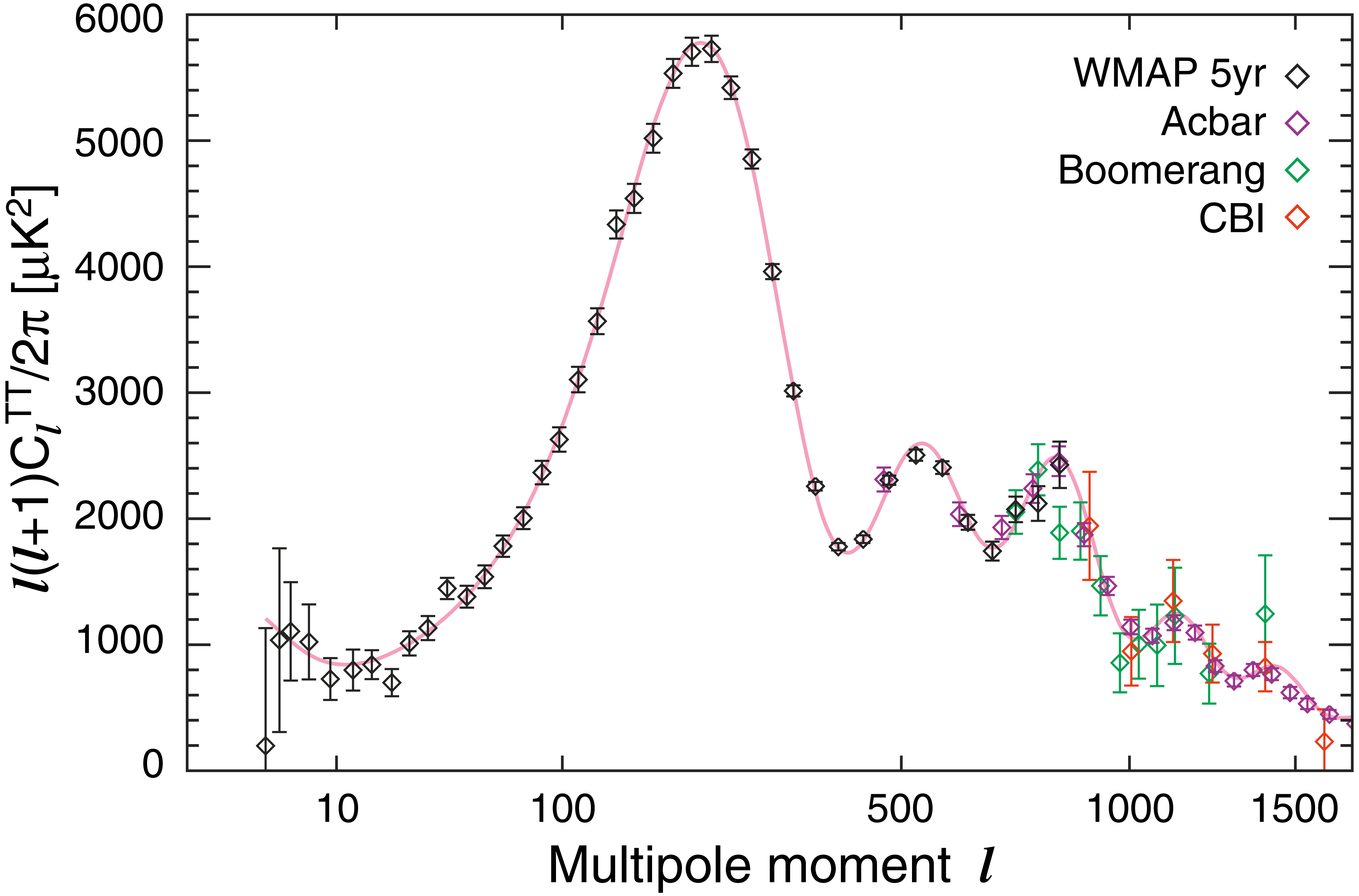
Nolta et al.

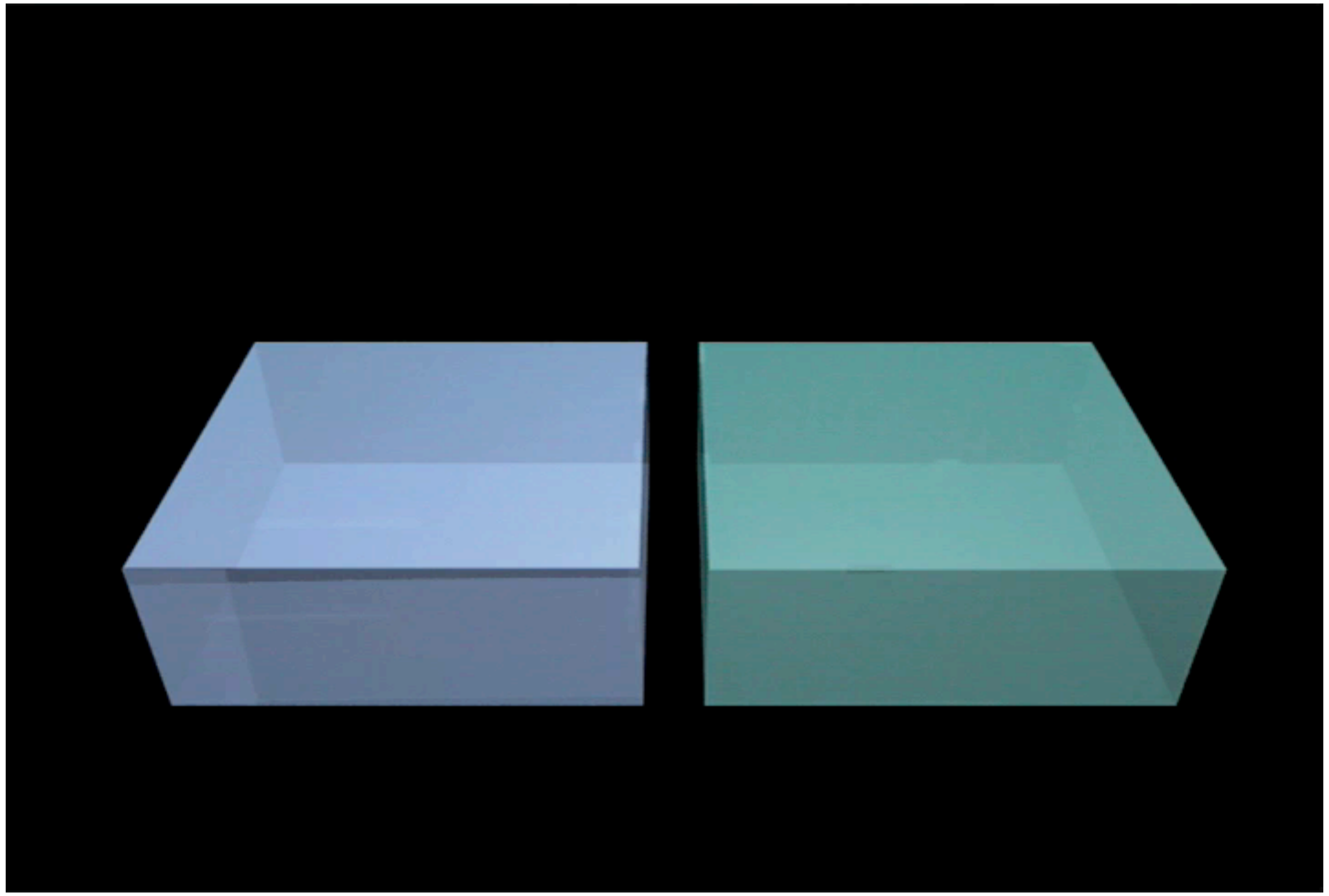
The Cosmic Sound Wave



Note consistency around the 3rd-peak region

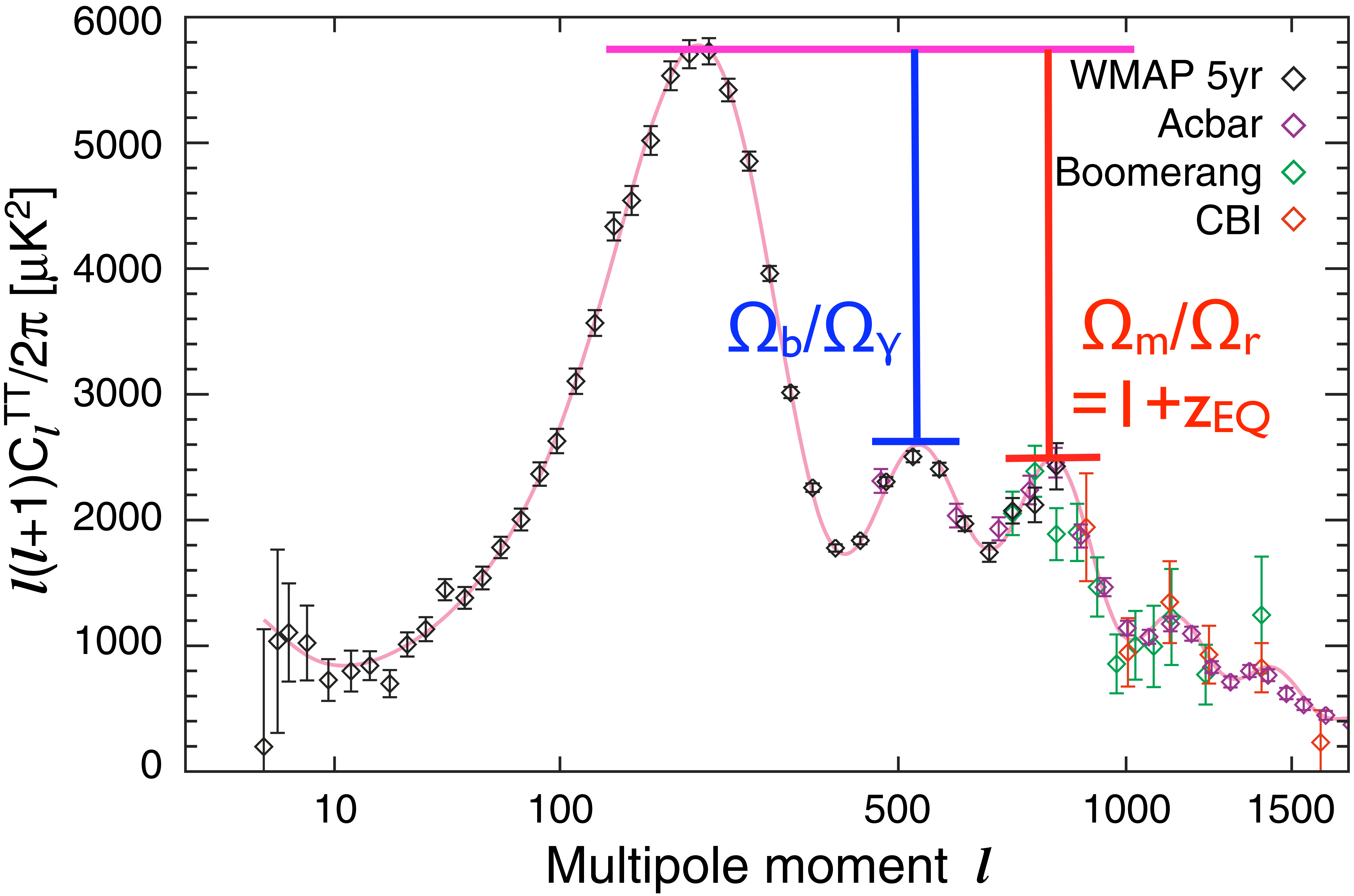
The Cosmic Sound Wave





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

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

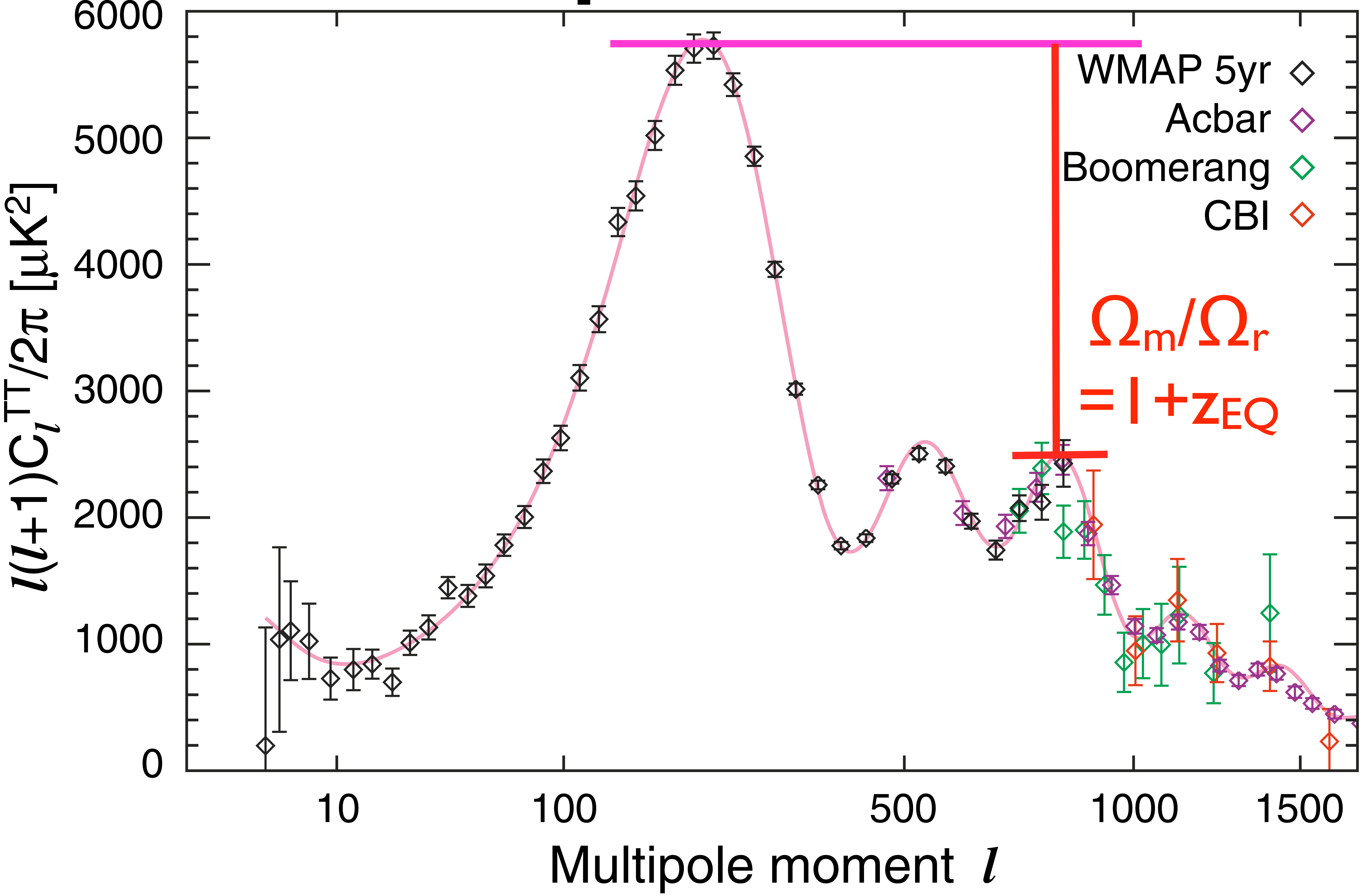


- 1-to-2: baryon-to-photon; 1-to-3: matter-to-radiation ratio
- $\Omega_\gamma=2.47\times10^{-5}h^{-2}$ & $\Omega_r=\Omega_\gamma+\Omega_\nu=1.69\Omega_\gamma=4.17\times10^{-5}h^{-2}$

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 $N_{\mathrm{eff}}=3.04$ for the standard model, and $T_\nu=(4/11)^{1/3}T_{\mathrm{photon}}$
- Adding more relativistic neutrino species (or any other relativistic components) delays the epoch of the matter-radiation equality, as
  - **$1+z_{EQ} = (\Omega_m h^2/2.47\mathrm{x}10^{-5}) / (1+0.227N_{\mathrm{eff}})$**

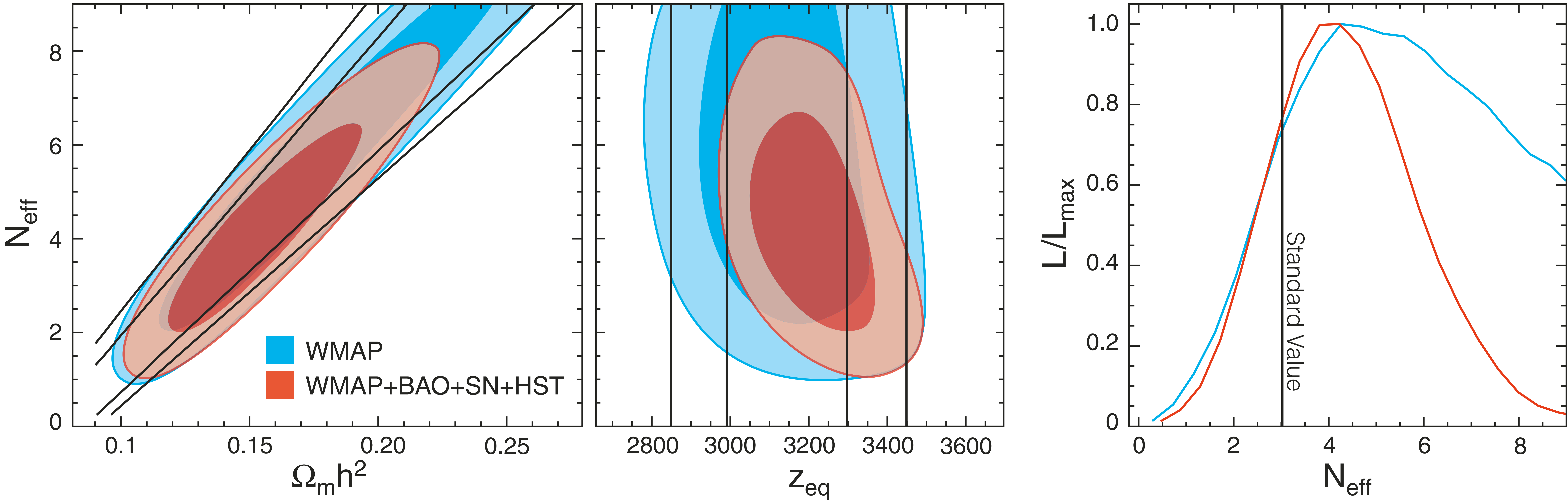
3rd-peak to z_{EQ}



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

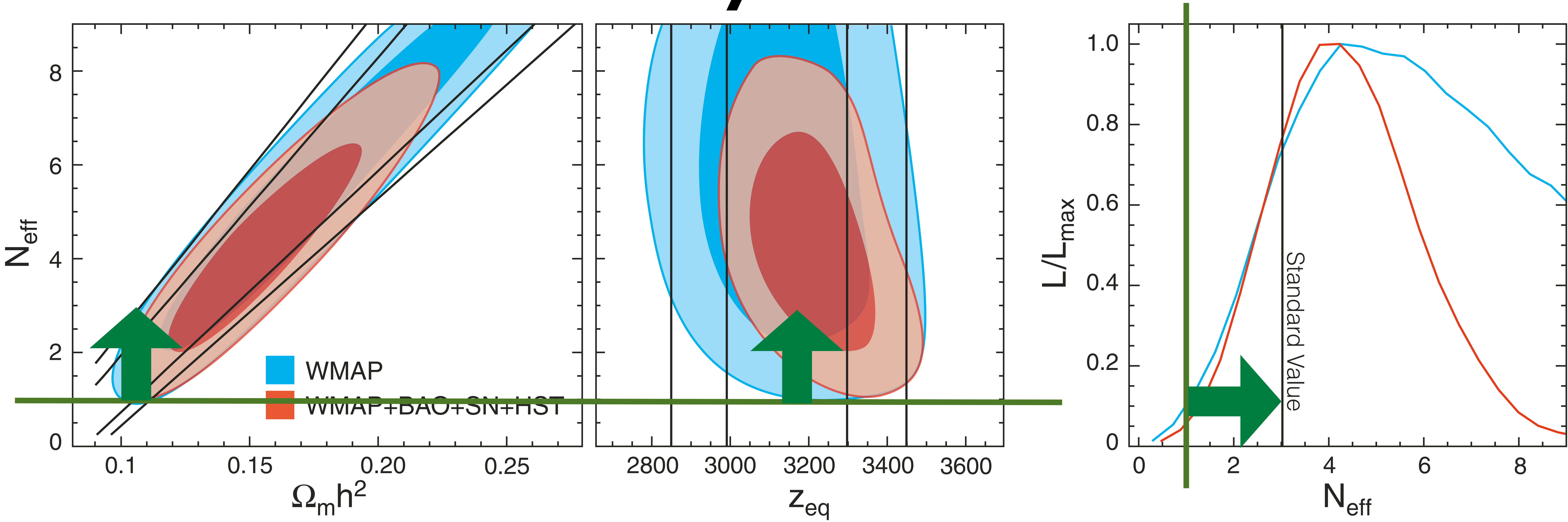
N_{eff}-$\Omega_m h^2$ Degeneracy

Komatsu et al.



- N_{eff} and $\Omega_m h^2$ are degenerate.
- Adding information on $\Omega_m h^2$ from the distance measurements (BAO, SN, HST) breaks the degeneracy:
  - **$N_{eff} = 4.4 \pm 1.5$ (68%CL)**

WMAP-only Lower Limit



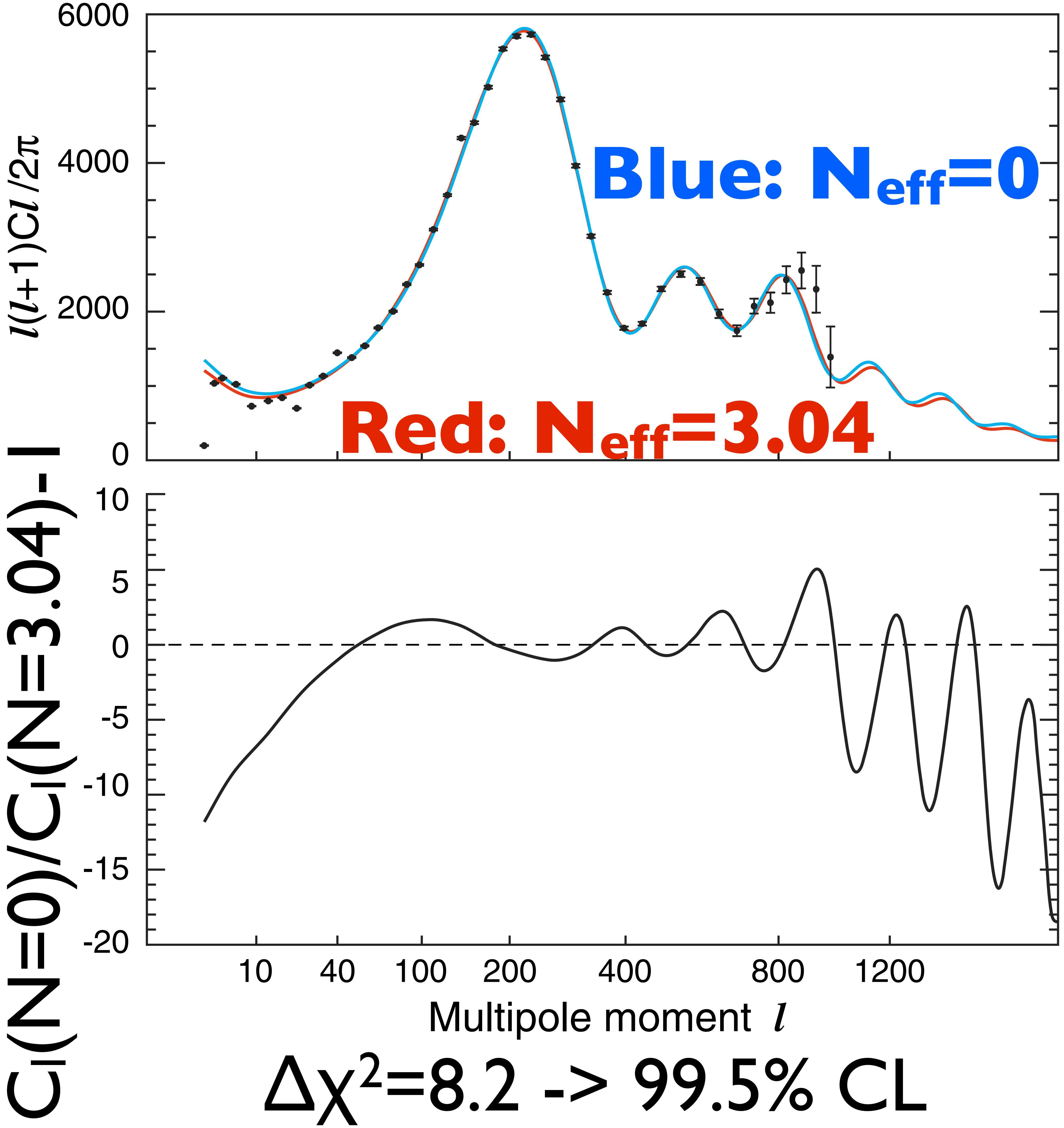
- N_{eff} and $\Omega_m h^2$ are degenerate - but, look.
- **WMAP-only lower limit is not N_{eff}=0**
  - N_{eff}>2.3 (95%CL) [Dunkley et al.]

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.

Dunkley et al.

CNB As Seen By WMAP



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

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

Komatsu et al.

Cosmic/Laboratory Consistency

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

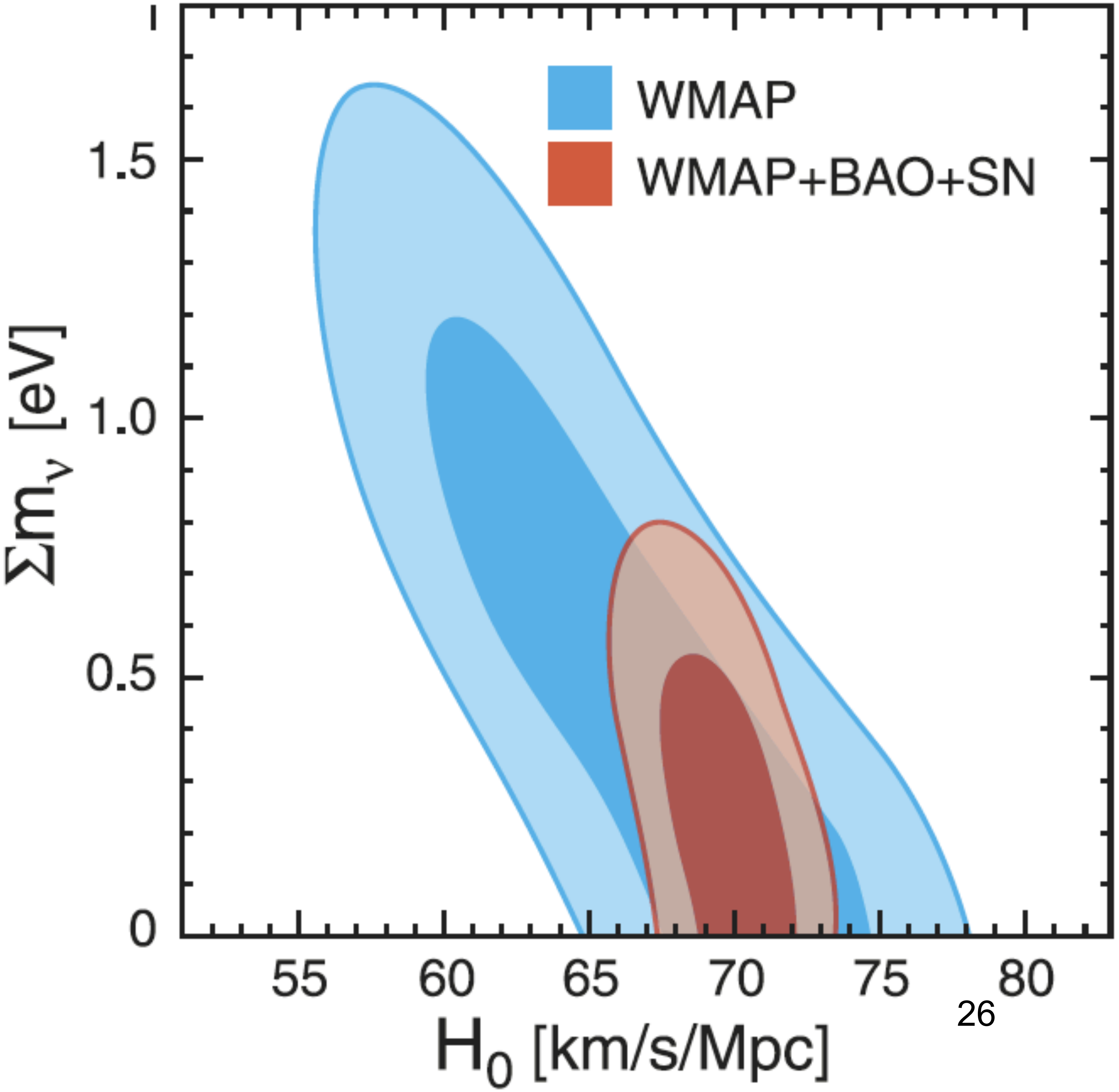
$\sum m_\nu$ from CMB alone

- There is a simple limit by which one can constrain $\sum m_\nu$ using the primary CMB from z=1090 alone (ignoring gravitational lensing of CMB by the intervening mass distribution)
- When all of neutrinos were lighter than ~0.6 eV, they were still relativistic at the time of photon decoupling at z=1090 (photon temperature 3000K=0.26eV).
  - $\langle E_\nu \rangle = 3.15(4/11)^{1/3} T_{\text{photon}} = 0.58$ eV
- Neutrino masses didn't matter if they were relativistic!
- For degenerate neurinos, $\sum m_\nu = 3.04\text{x}0.58 = 1.8$ eV
  - **If $\sum m_\nu \ll 1.8$eV, CMB alone cannot see it**

Komatsu et al.

CMB + H_0 Helps

- WMAP 5-year alone: $\sum m_\nu < 1.3$ eV (95%CL)
- WMAP+BAO+SN: **$\sum m_\nu < 0.67$ eV (95%CL)**
- Where did the improvement comes from? It's the present-day Hubble expansion rate, H_0



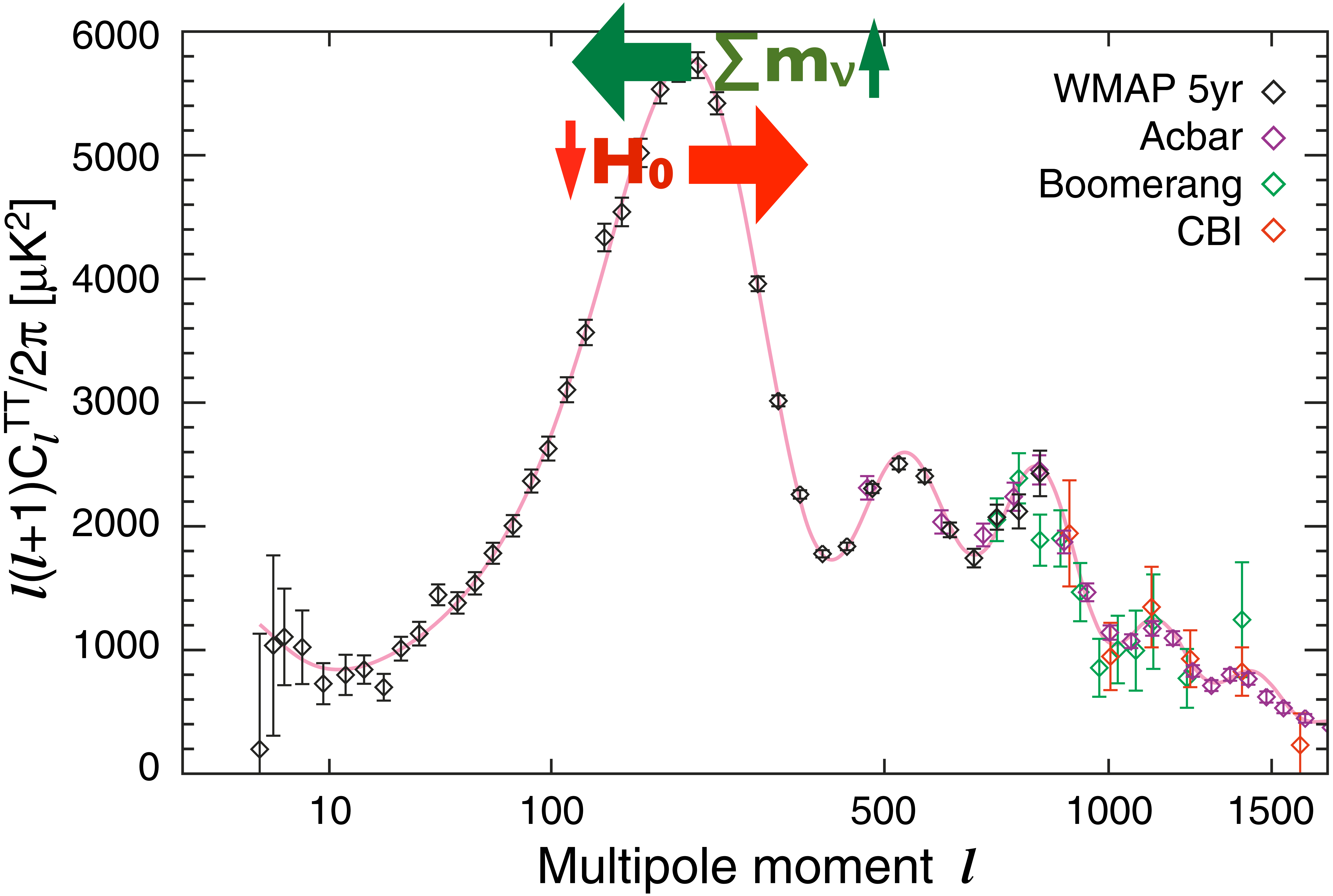
Neutrino Subtlety

- For $\sum m_\nu << 1.8\text{eV}$, neutrinos were relativistic at $z=1090$
- But, we know that $\sum m_\nu > 0.05\text{eV}$ from neutrino oscillation experiments
  - This means that **neutrinos are definitely non-relativistic today!**
- So, today's value of Ω_m is the sum of baryons, CDM, and neutrinos: $\Omega_m h^2 = (\Omega_b + \Omega_c)h^2 + 0.0106(\sum m_\nu/1\text{eV})$

Matter-Radiation Equality

- However, since neutrinos were relativistic before $z=1090$, the matter-radiation equality is determined by:
  - $1+z_{EQ} = (\Omega_b+\Omega_c)h^2 / 4.17\times10^{-5}$ (observable by CMB)
- Now, recall $\Omega_m h^2 = (\Omega_b+\Omega_c)h^2 + 0.0106(\sum m_\nu/1\,\mathrm{eV})$
  - For a given $\Omega_m h^2$ constrained by BAO+SN, adding $\sum m_\nu$ makes $(\Omega_b+\Omega_c)h^2$ smaller -> smaller z_{EQ} -> **Radiation Era lasts longer**
- **This effect shifts the first peak to a lower multipole**

$\sum m_\nu$: Shifting the Peak To Low-l

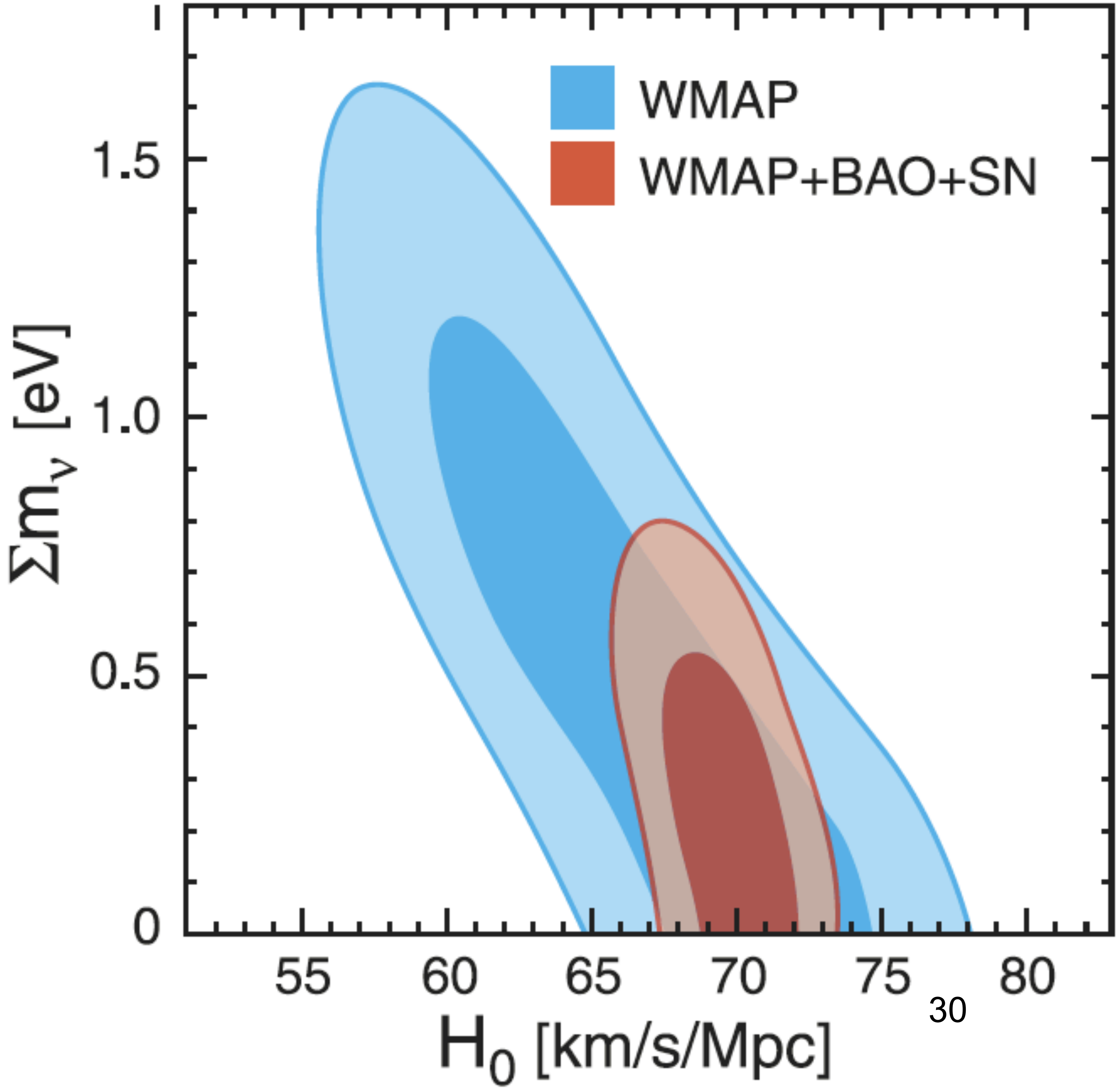


- But, lowering H_0 shifts the peak in the opposite direction. So...

Ichikawa, Fukugita & Kawasaki (2005)

Shift of Peak Absorbed by H_0

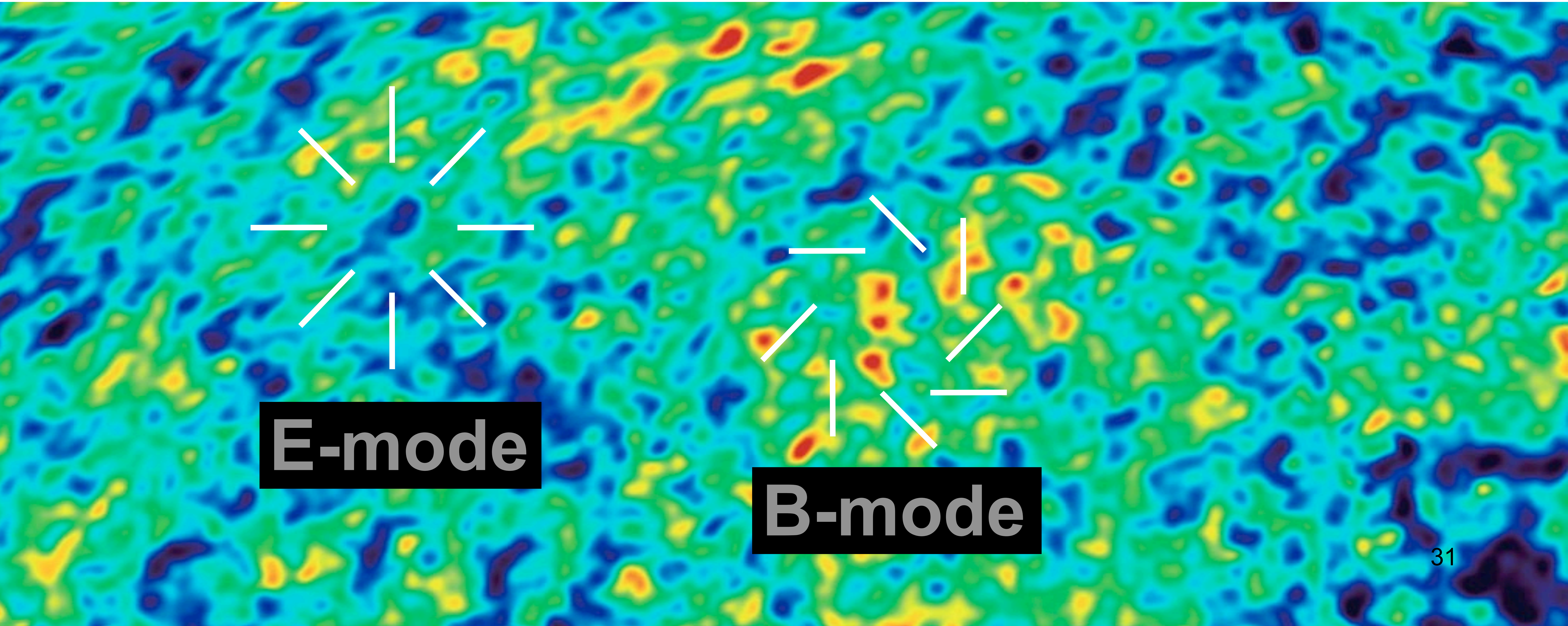
- Here is a catch:
  - **Shift of the first peak to a lower multipole can be canceled by lowering H_0!**
- Same thing happens to curvature of the universe: making the universe positively curved shifts the first peak to a lower multipole, but this effect can be canceld by lowering H_0.
  - So, 30% positively curved univese is consistent with the WMAP data, IF H_0=30km/s/Mpc



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

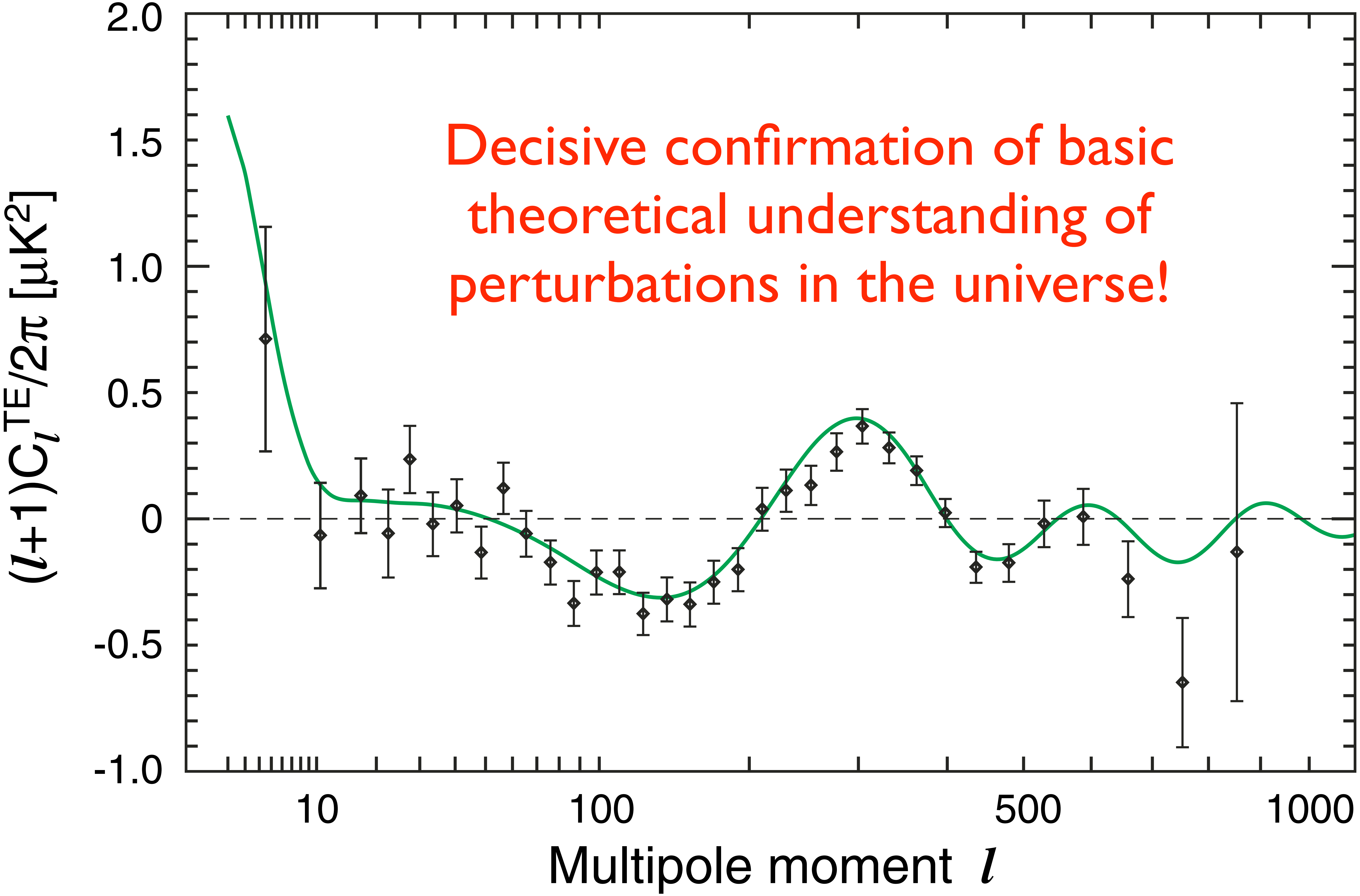
How About Polarization?

- 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 TxE Power Spectrum

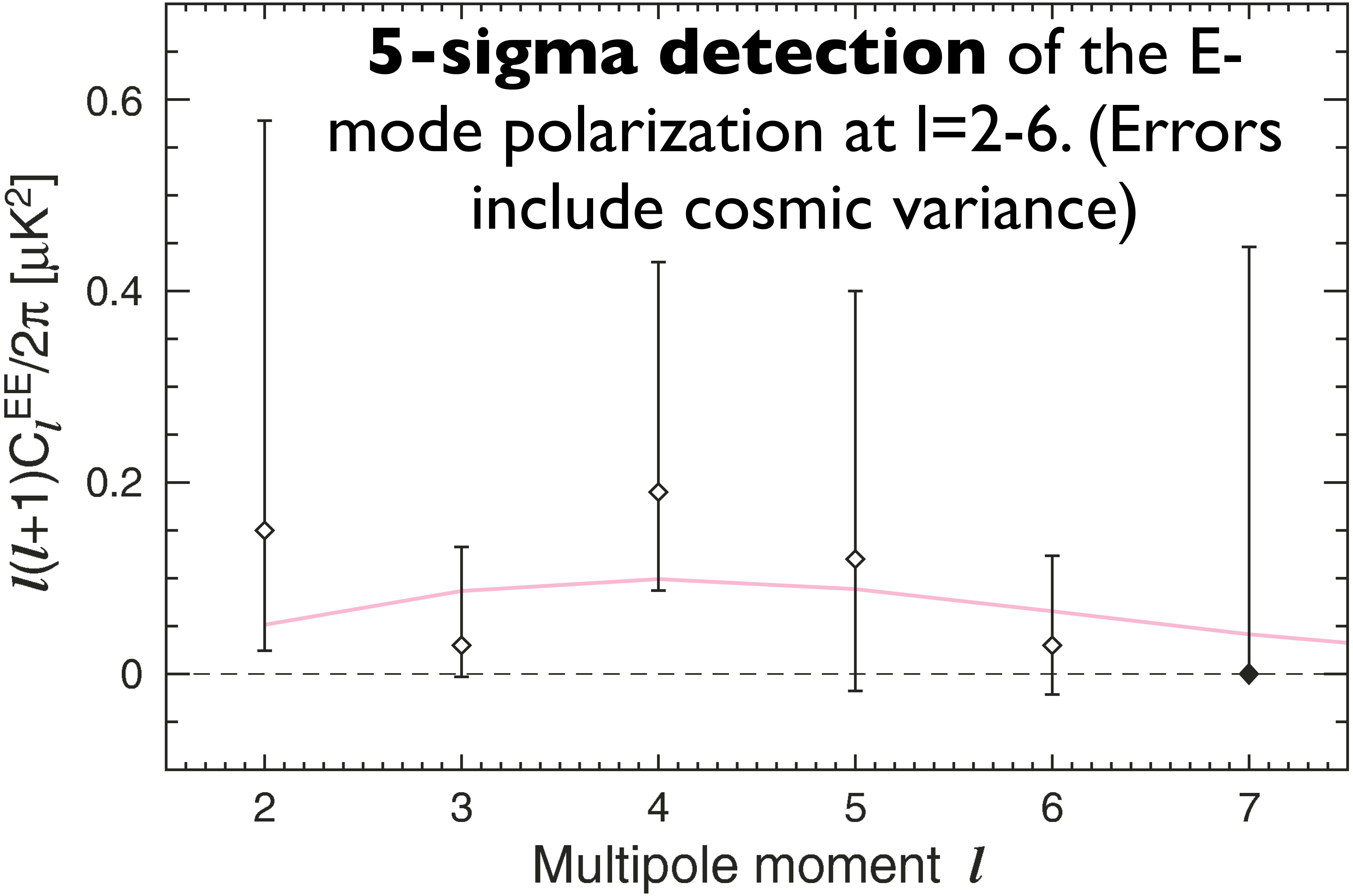


Decisive confirmation of basic theoretical understanding of perturbations in the universe!

Nolta et al.

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

E-Mode Angular Power Spectrum

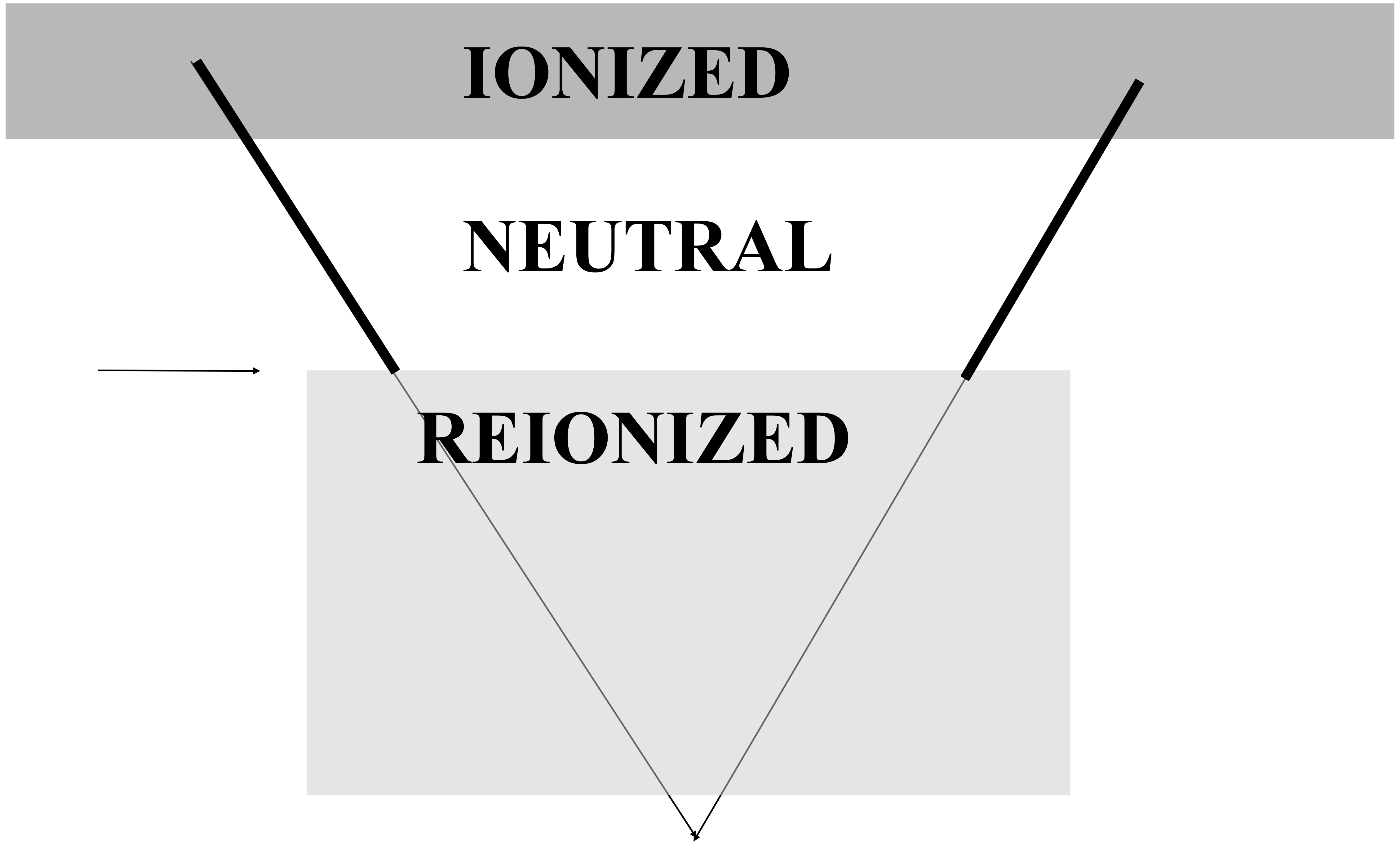


5-sigma detection of the E-mode polarization at l=2-6. (Errors include cosmic variance)

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.



First-star formation

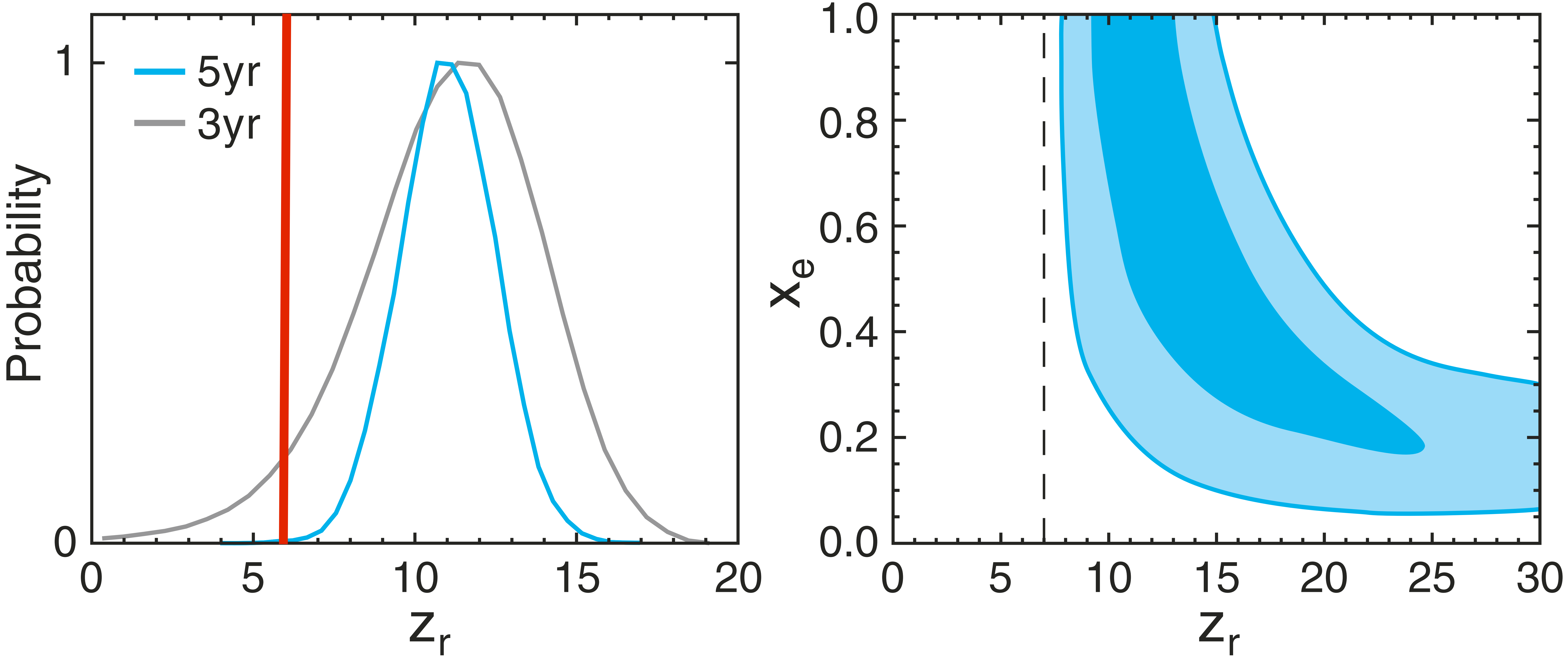
z=1090, τ∼1

z∼11,
τ=0.087±0.017
(WMAP 5-year)

z=0

Z_{reion}=6 Is Excluded

Dunkley et al.

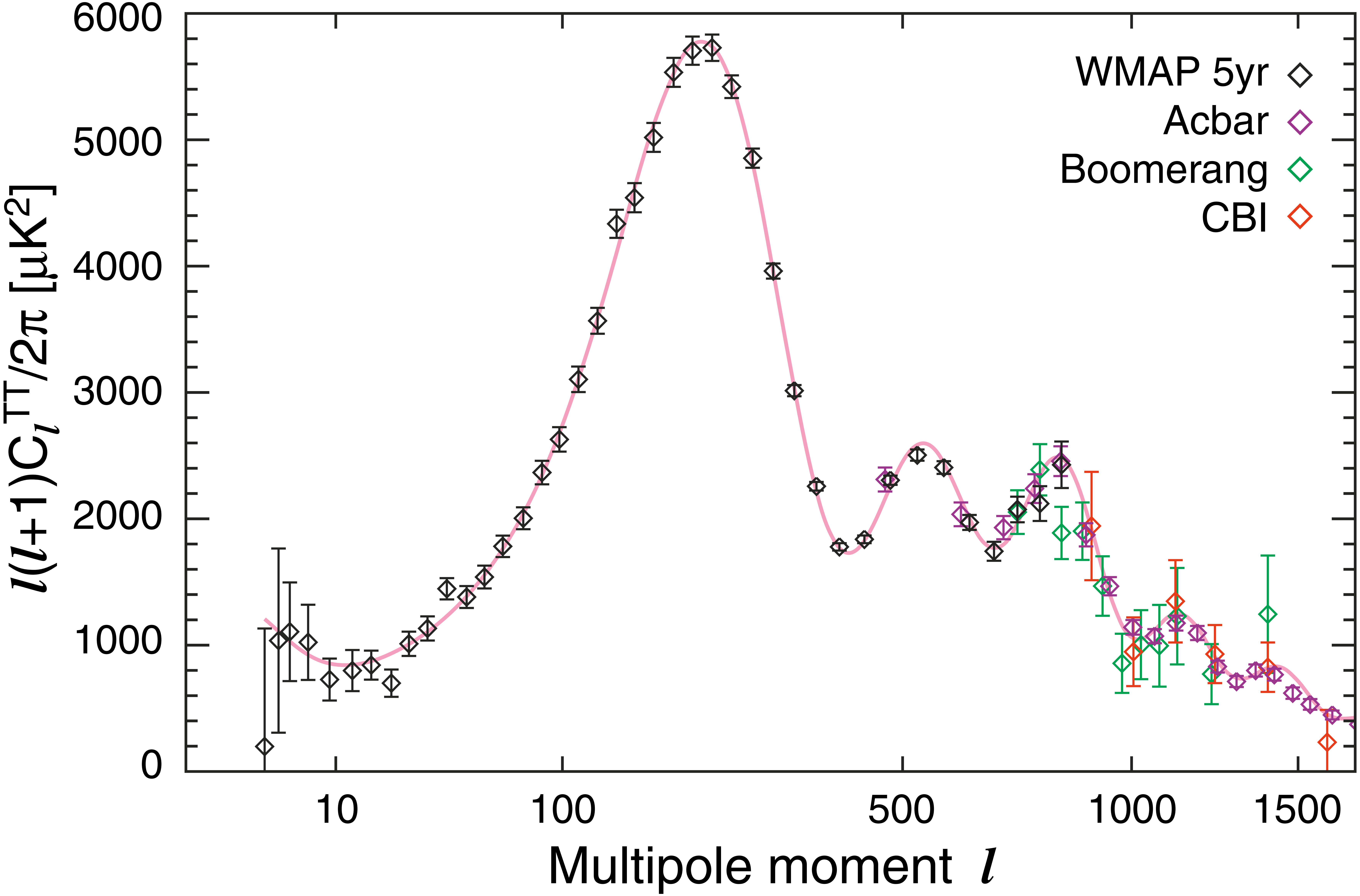


- Assuming an instantaneous reionization from x_e=0 to x_e=1 at z_{reion}, we find **z_{reion}=11.0 +/- 1.4** (68 % CL).
- The reionization was not an instantaneous process at z~6. (The 3-sigma lower bound is z_{reion}>6.7.)

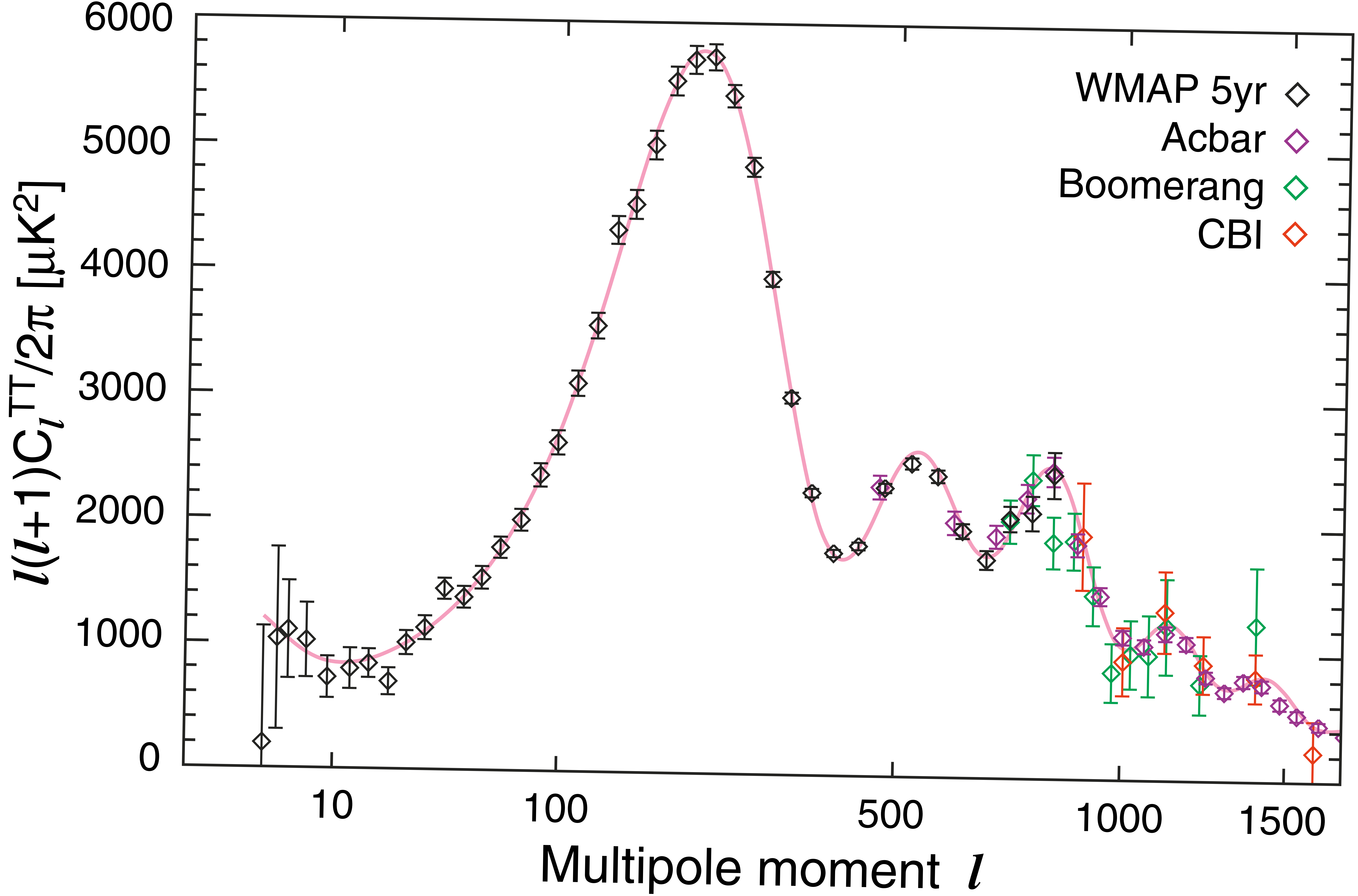
B-modes

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

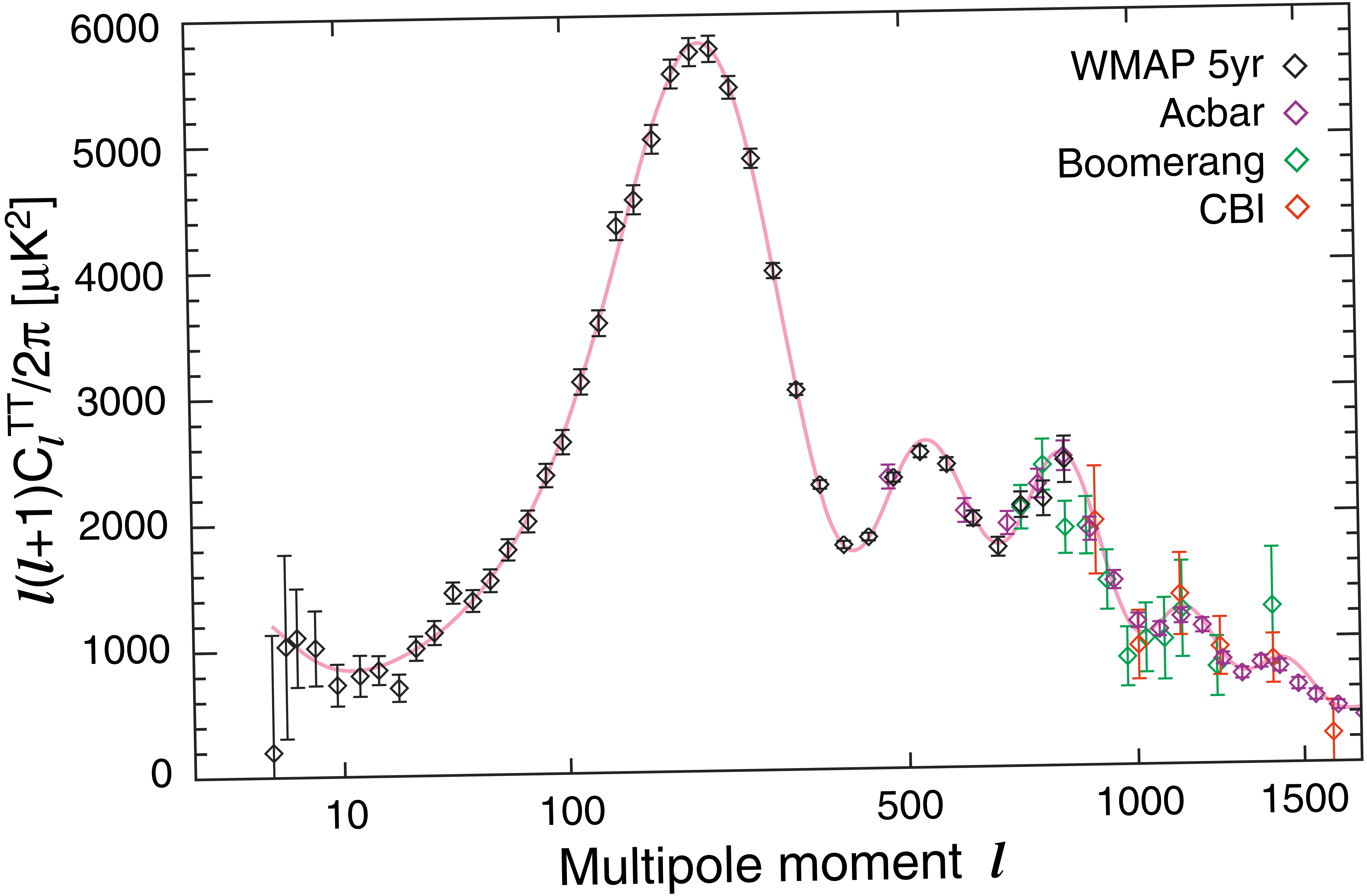
Tilting=Primordial Shape->Inflation



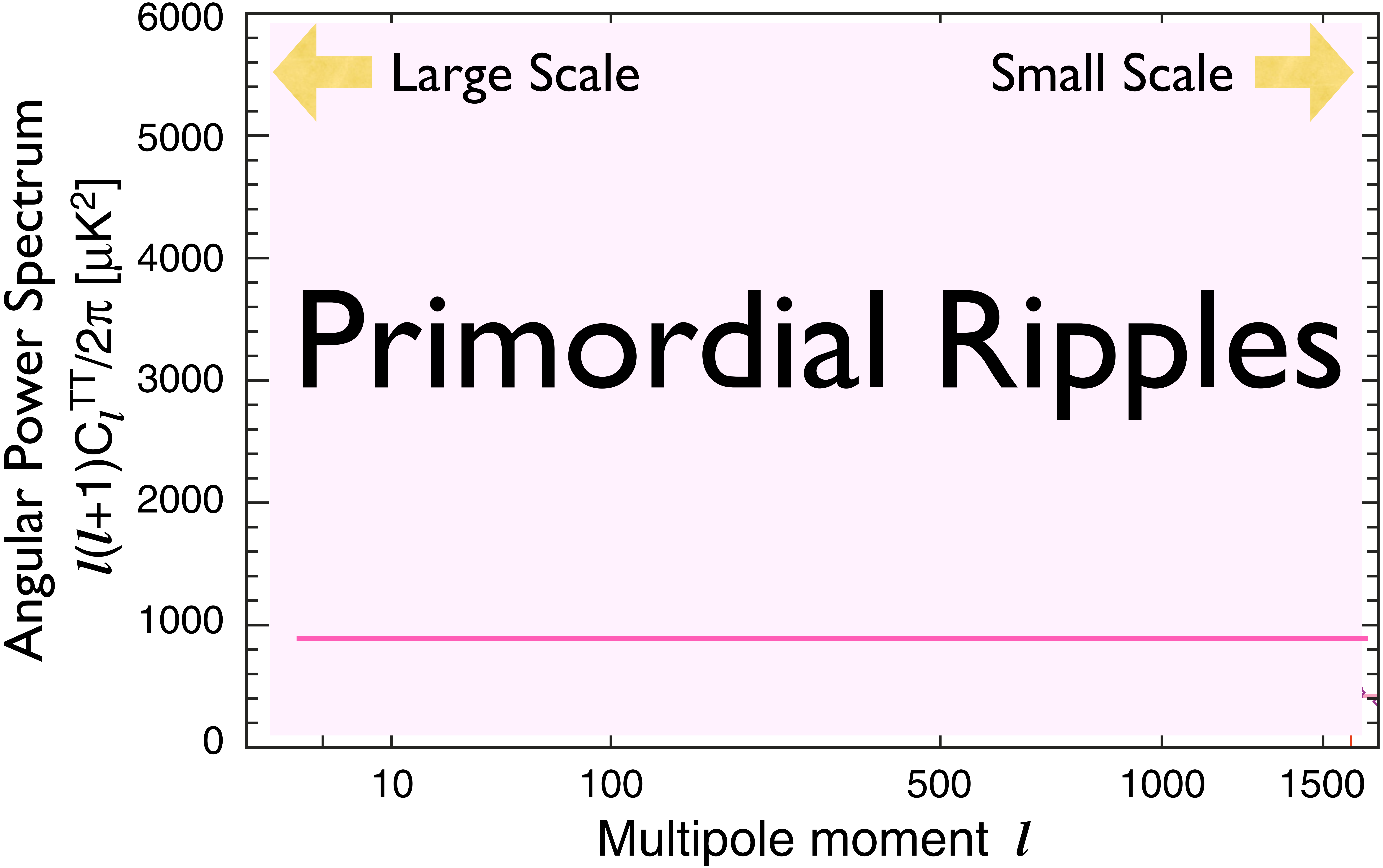
“Red” Spectrum: $n_s < 1$



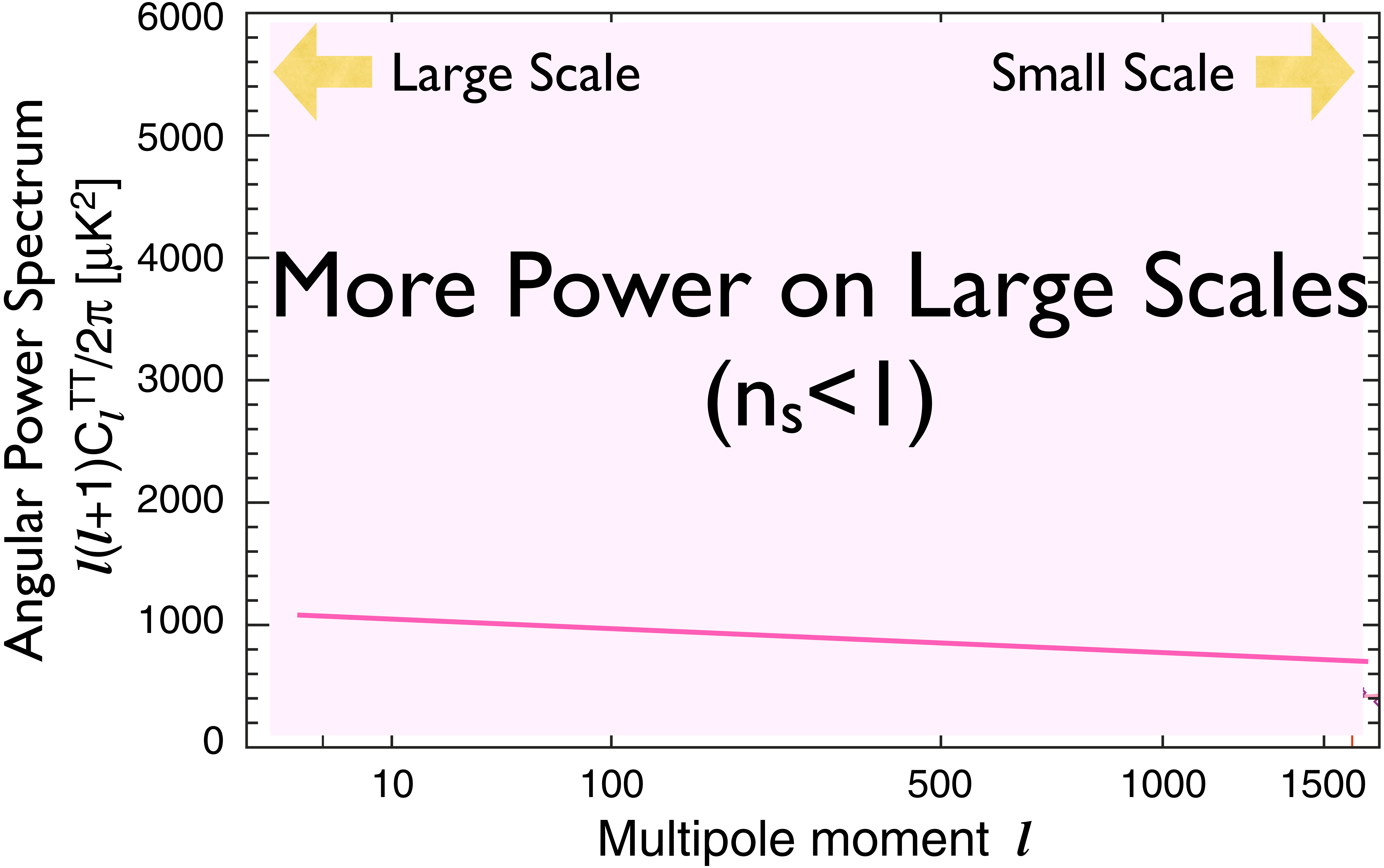
"Blue" Spectrum: $n_s > 1$



Getting rid of the Sound Waves

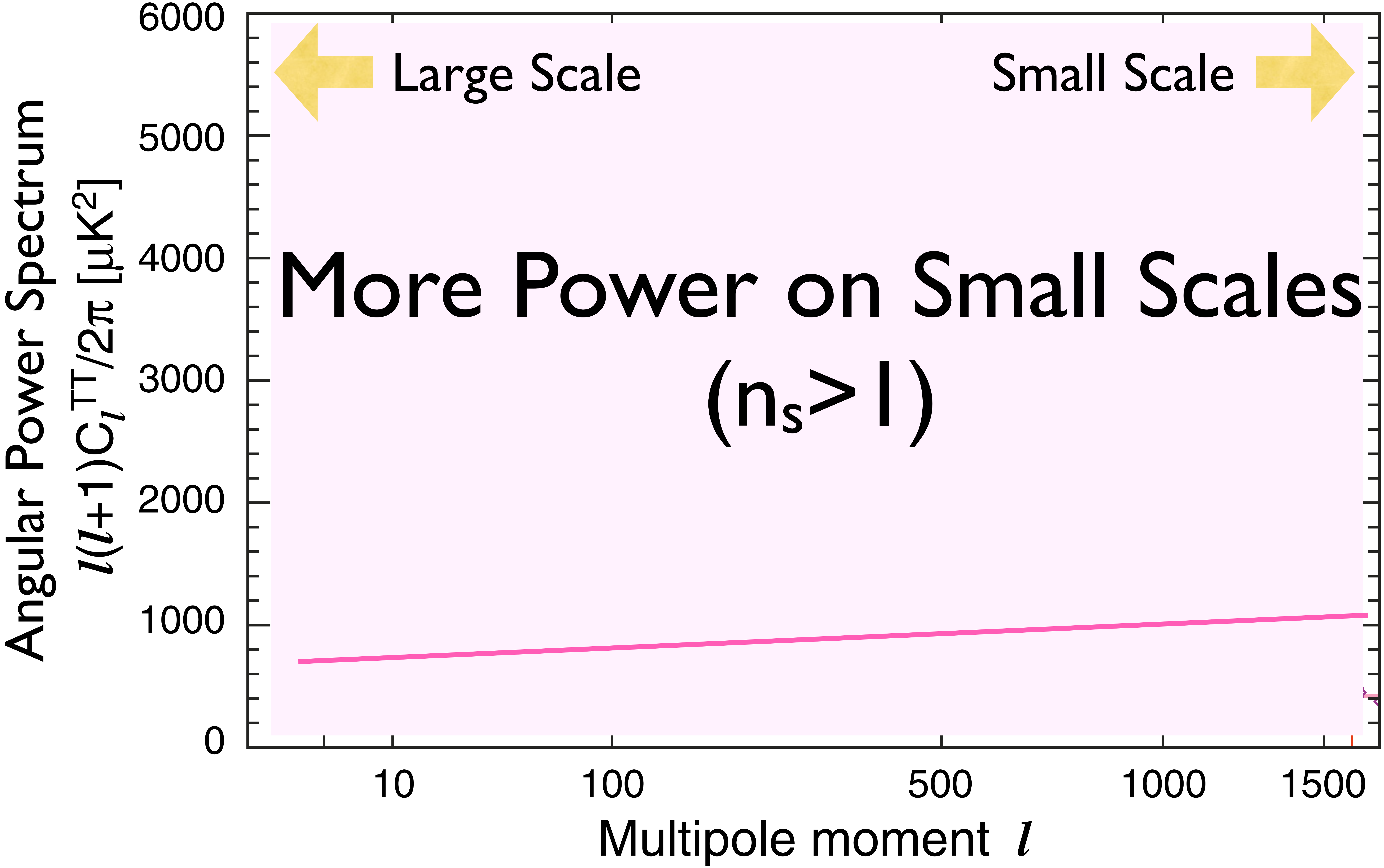


The Early Universe Could Have Done This Instead



More Power on Large Scales ($n_s<1$)

…or, This.



More Power on Small Scales

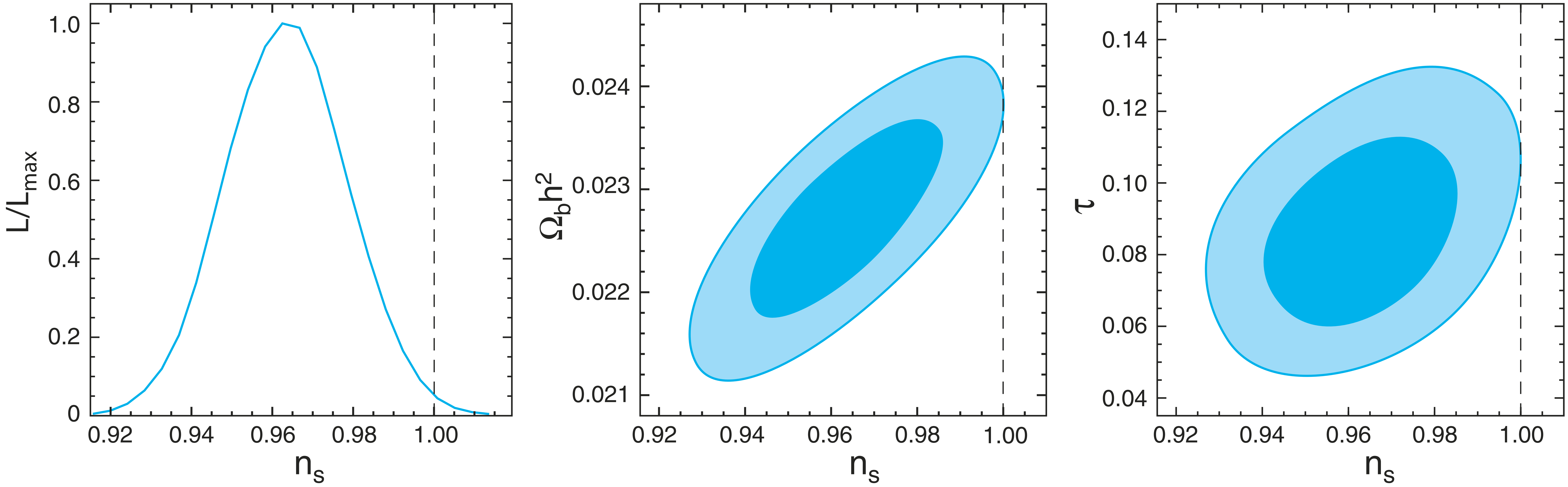
($n_s > 1$)

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*

Is n_s different from ONE?

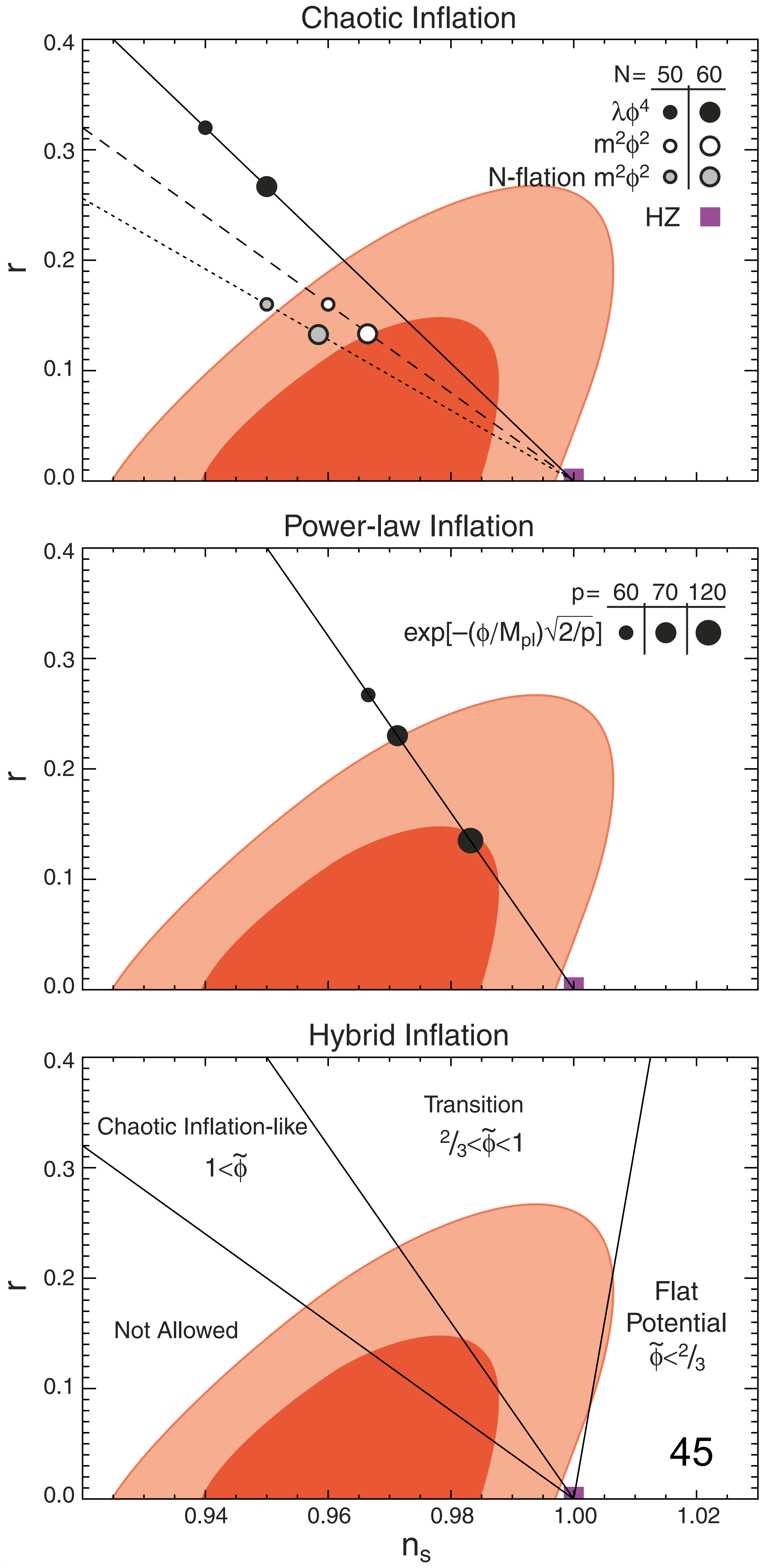
Komatsu et al.



- 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 $\Omega_b h^2$

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

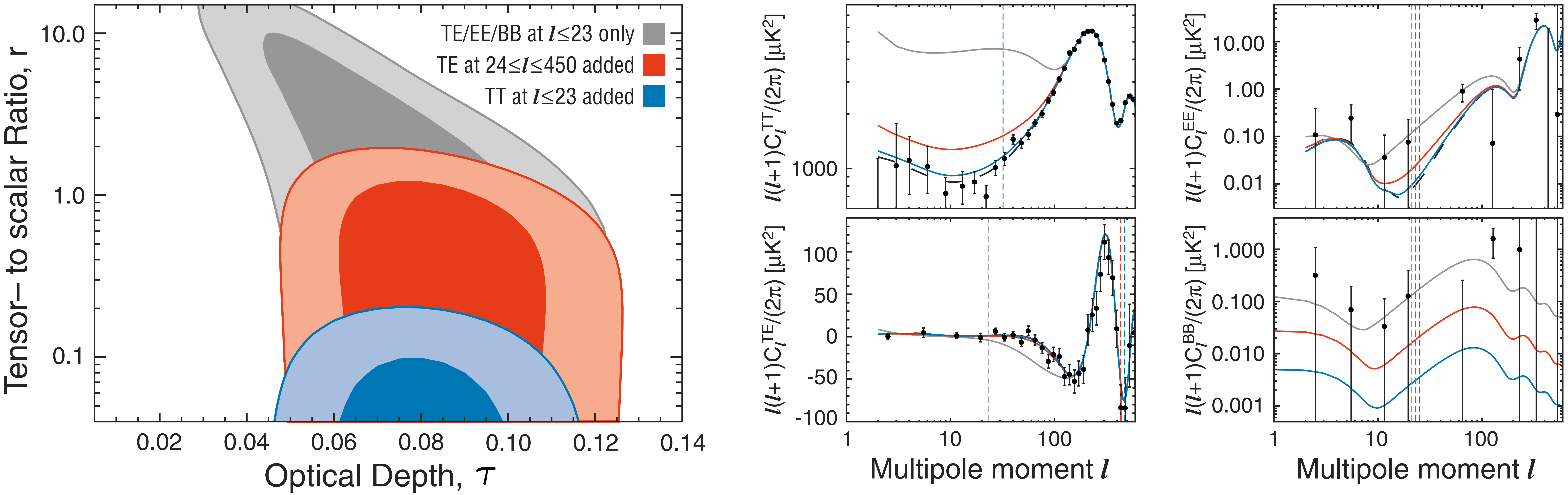


Searching for Primordial Gravitational Waves in CMB

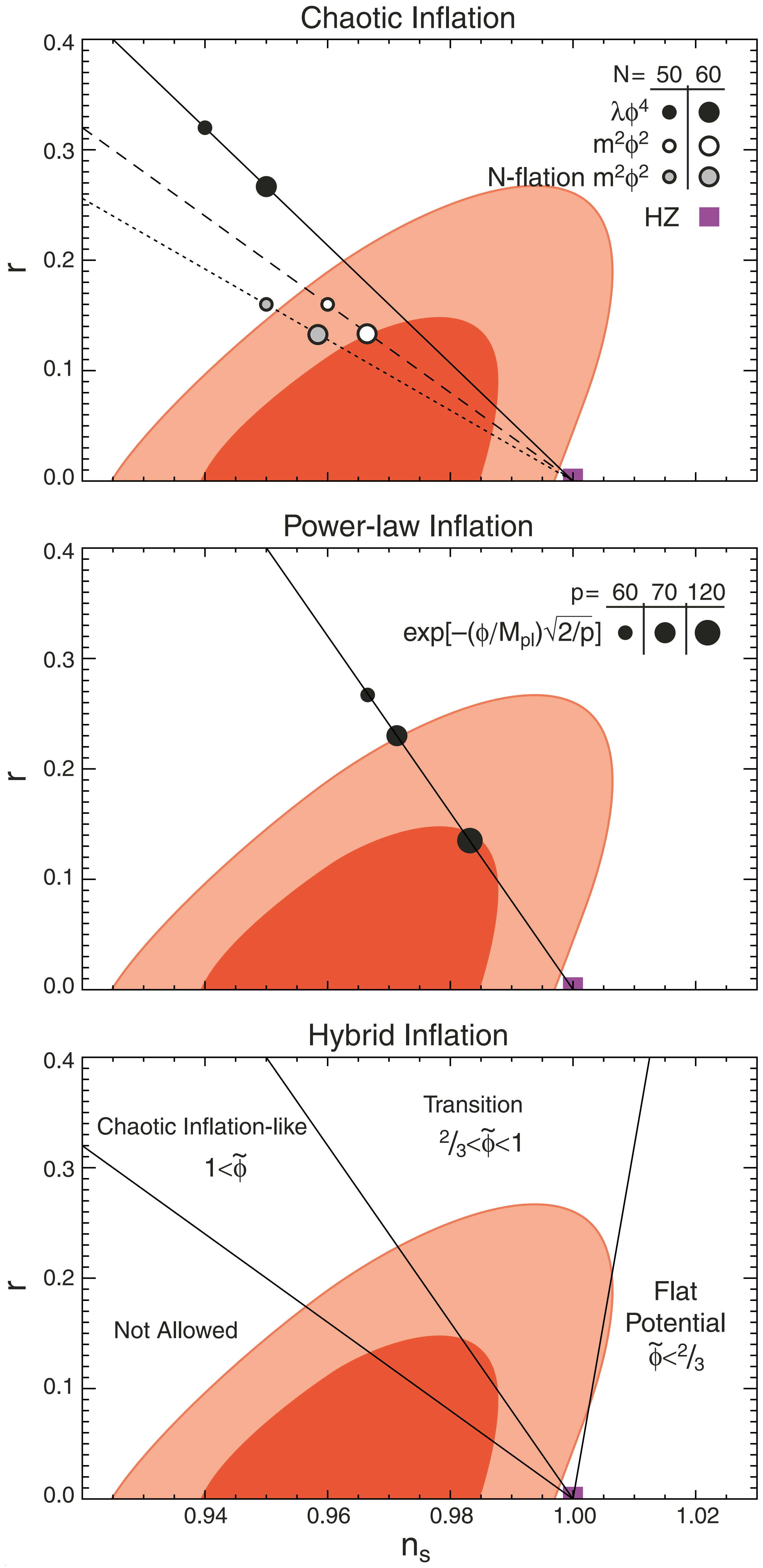
- Not only do inflation models produce density fluctuations, but also primordial gravitational waves
- Some predict the observable amount (r>0.01), some don’t
  - Current limit: **r<0.22** (95%CL)
- Alternative scenarios (e.g., New Ekpyrotic) don’t
- A powerful probe for testing inflation and testing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



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.

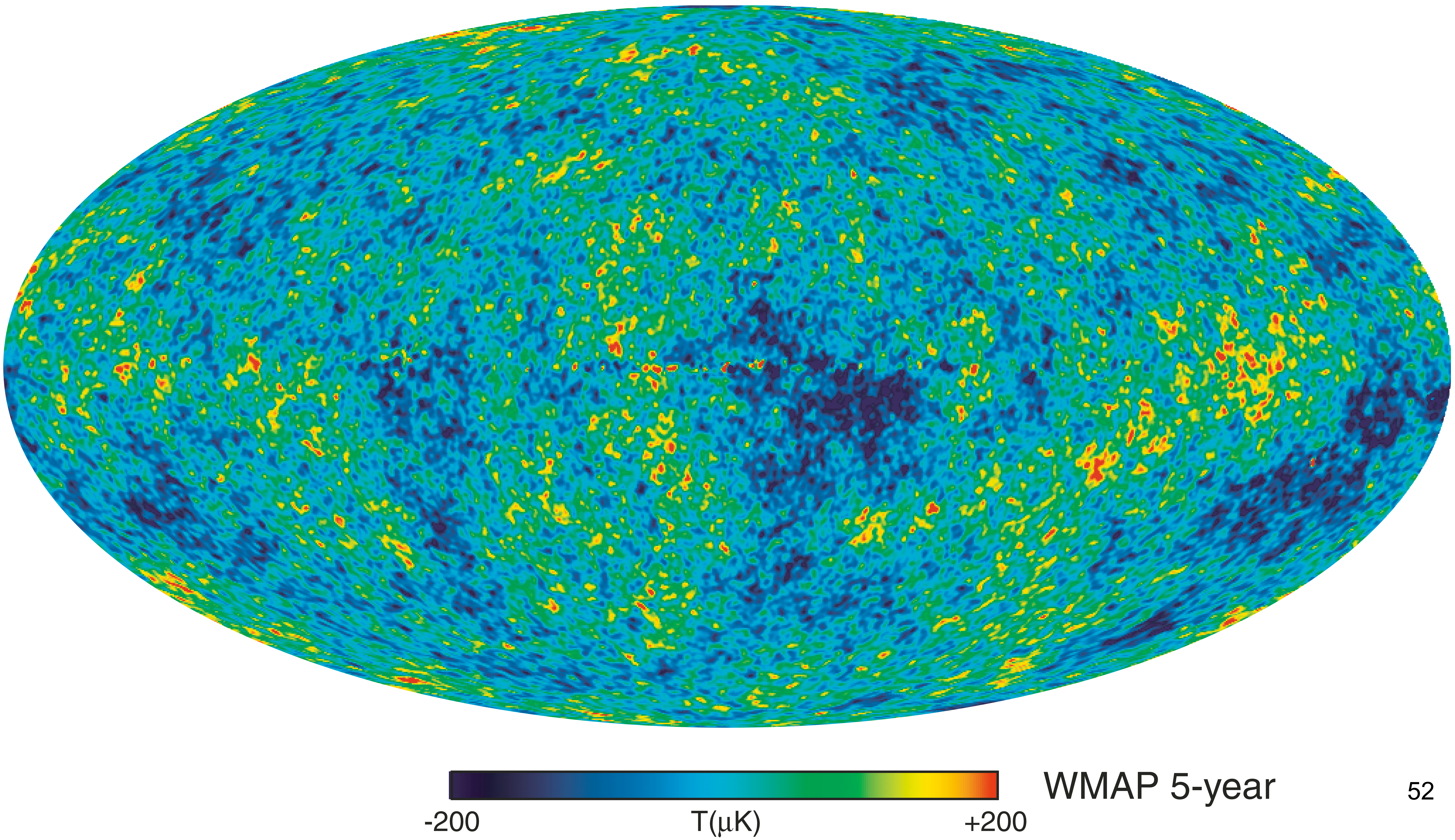
What About Phase, φ_k

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

Gaussian Distribution

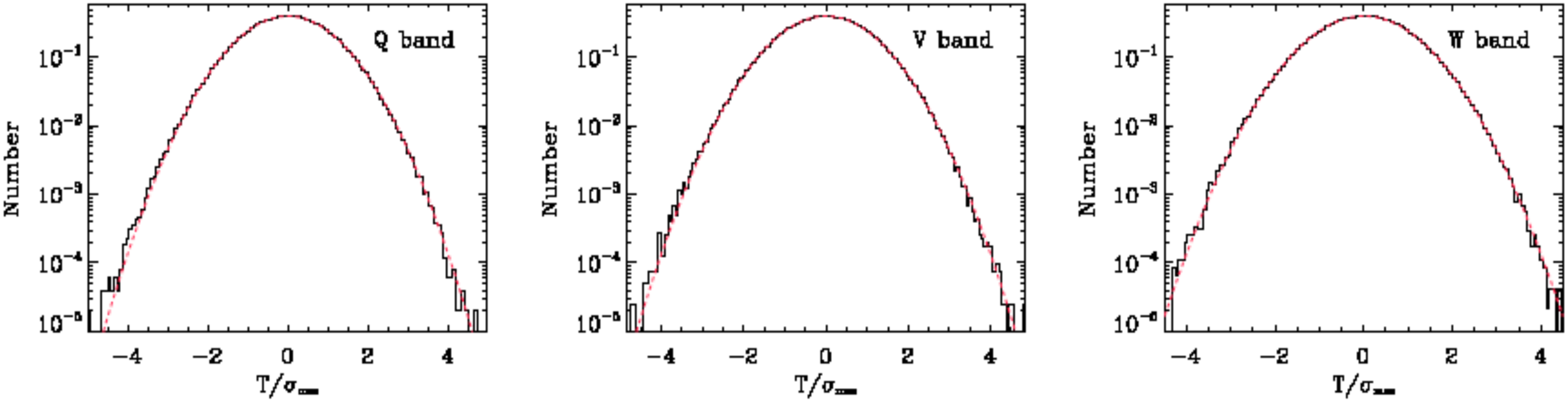
Gaussian?

WMAP5



Spergel et al. (2008)

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.

Inflation Likes This Result

- According to inflation (Guth & Yi; Hawking; Starobinsky; Bardeen, Steinhardt & Turner), CMB anisotropy was created from **quantum fluctuations of a scalar field in Bunch-Davies vacuum** during inflation
- Successful inflation (with the expansion factor more than e^{60}) *demands* the scalar field be almost interaction-free
- The wave function of free fields in the ground state is a Gaussian!

But, Not Exactly Gaussian

- Of course, there are always corrections to the simplest statement like this
- For one, inflaton field **does** have interactions. They are simply weak – of order the so-called slow-roll parameters, ε and η, which are O(0.01)

Simplified Treatment

- Let's try to capture field interactions, or whatever non-linearities that might have been there during inflation, by the following simple, order-of-magnitude form (*Komatsu & Spergel 2001*):
  - $\mathbf{\Phi(x) = \Phi_{gaussian}(x) + f_{NL}[\Phi_{gaussian}(x)]^2}$
  - One finds $f_{NL}=O(0.01)$ from inflation (*Maldacena 2003*; *Acquaviva et al. 2003*)

Earlier work on this form:
Salopek&Bond (1990); Gangui et al. (1994); Verde et al. (2000); Wang&Kamionkowski (2000)

- **This is a powerful prediction of inflation**

Why Study Non-Gaussianity?

- Because a detection of f_{NL} has a best chance of **ruling out the largest class of inflation models**.
- Namely, it will rule out inflation models based upon
  - a single scalar field <u>with</u>
  - the canonical kinetic term <u>that</u>
  - rolled down a smooth scalar potential slowly, <u>and</u>
  - was initially in the Bunch-Davies vacuum.
- ***Detection of non-Gaussianity would be a major breakthrough in cosmology.***

Tool: Bispectrum

- **Bispectrum = Fourier Trans. of 3-pt Function**
- **The bispectrum vanishes** for Gaussian fluctuations with random phases.
- Any non-zero detection of the bispectrum indicates the presence of (some kind of) non-Gaussianity.
- A sensitive tool for finding non-Gaussianity.

Komatsu et al.

No Detection at >95%CL

- $-9 < f_{NL} < 111$ (95% CL)
- $f_{NL} = 51 \pm 30$ (68% CL)
- Latest reanalysis: $f_{NL} = 38 \pm 20$ (68% CL) [Smith et al.]
- 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.

Summary

- The WMAP 5-year data indicate that the simplest cosmological model that fits that the data has 6 parameters: the amplitude of fluctuations, baryon density, dark matter density, dark energy density, the optical depth, and $\mathbf{n_s}$.
- Other parameters are consistent with the standard values: $N_\nu=4.4\pm1.5$, $\sum m_\nu<0.67$eV, ...
- No detection of gravitational waves ($r<0.22$) or non-Gaussianity ($f_{NL}=38\pm20$) ***yet***
- I didn't have time to talk about it, but the spatial geometry of the universe is flat to 1%, and the dark energy is consistent with C.C. to 10%.

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}~40, we will see it at ~2.5 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?!