The 5-Year Wilkinson Microwave Anisotropy Probe (*WMAP*) Observations: Implications for Neutrinos

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Neutrino Frontiers, October 23, 2008

WMAP 5-Year Papers

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

WMAP 5-Year Science Team

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Special Thanks to **WMAP Graduates!**

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

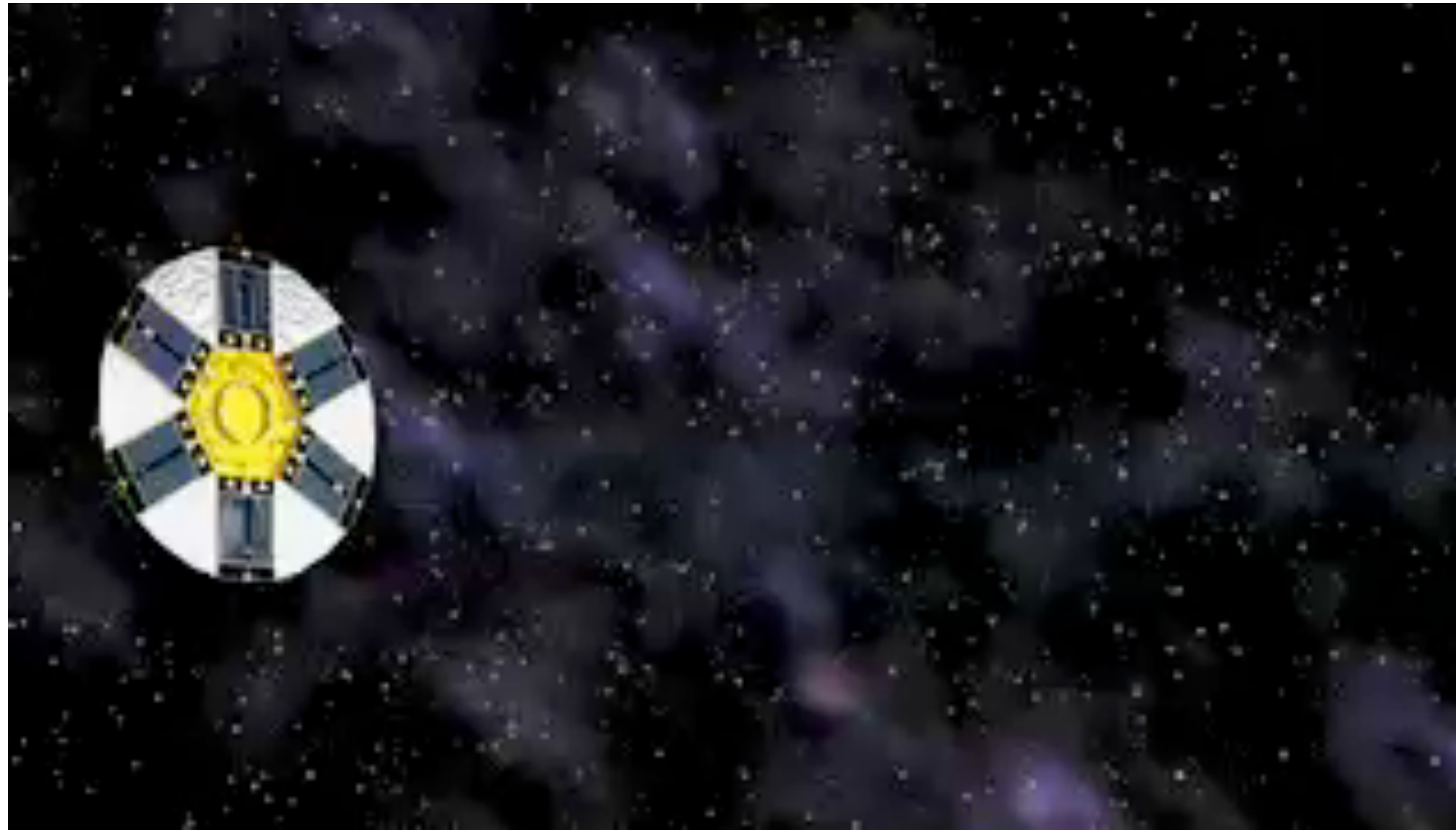
WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

February 2003:
The first-year data release

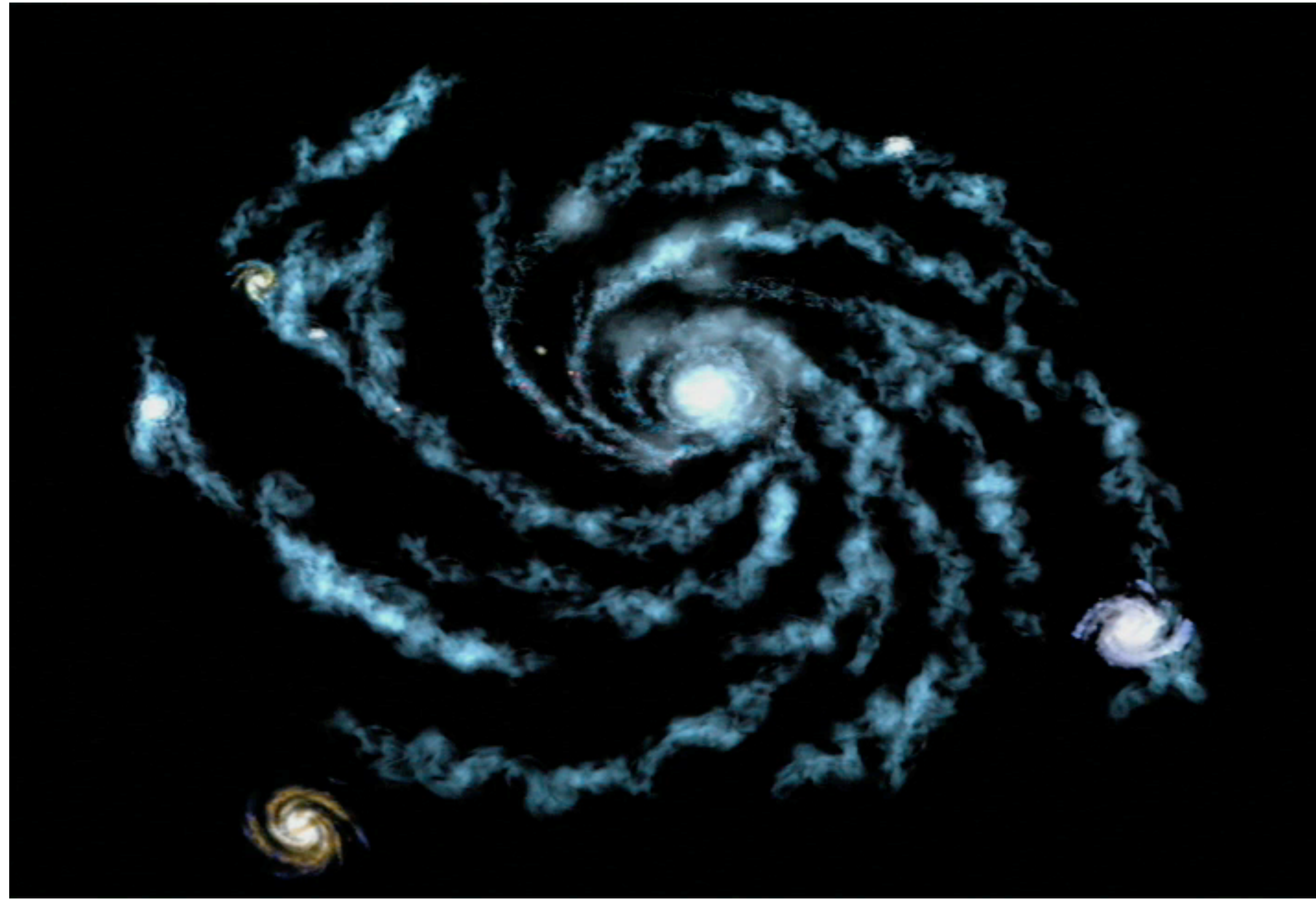
March 2006:
The three-year data release

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

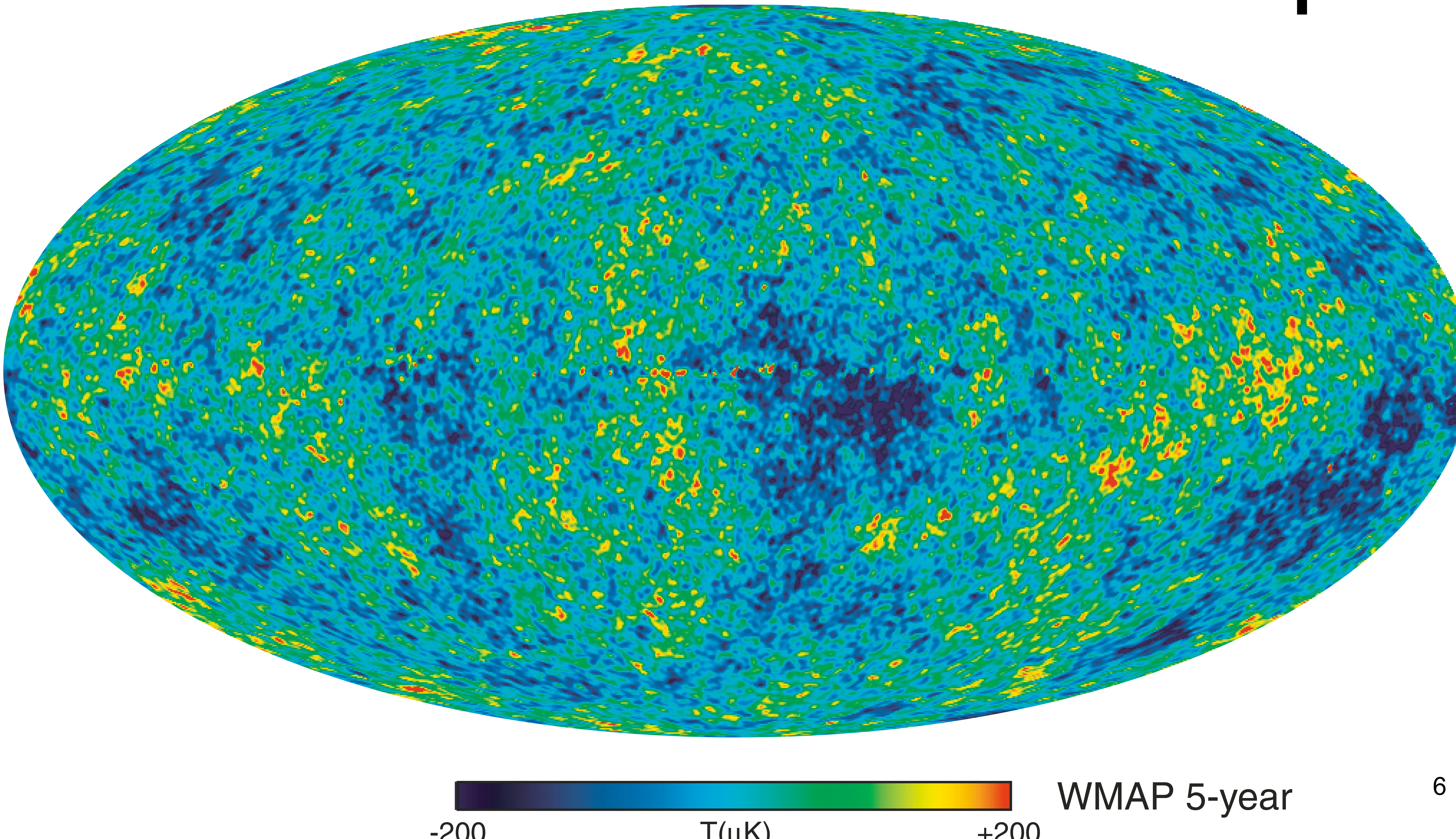
WMAP Measures Microwaves From the Universe



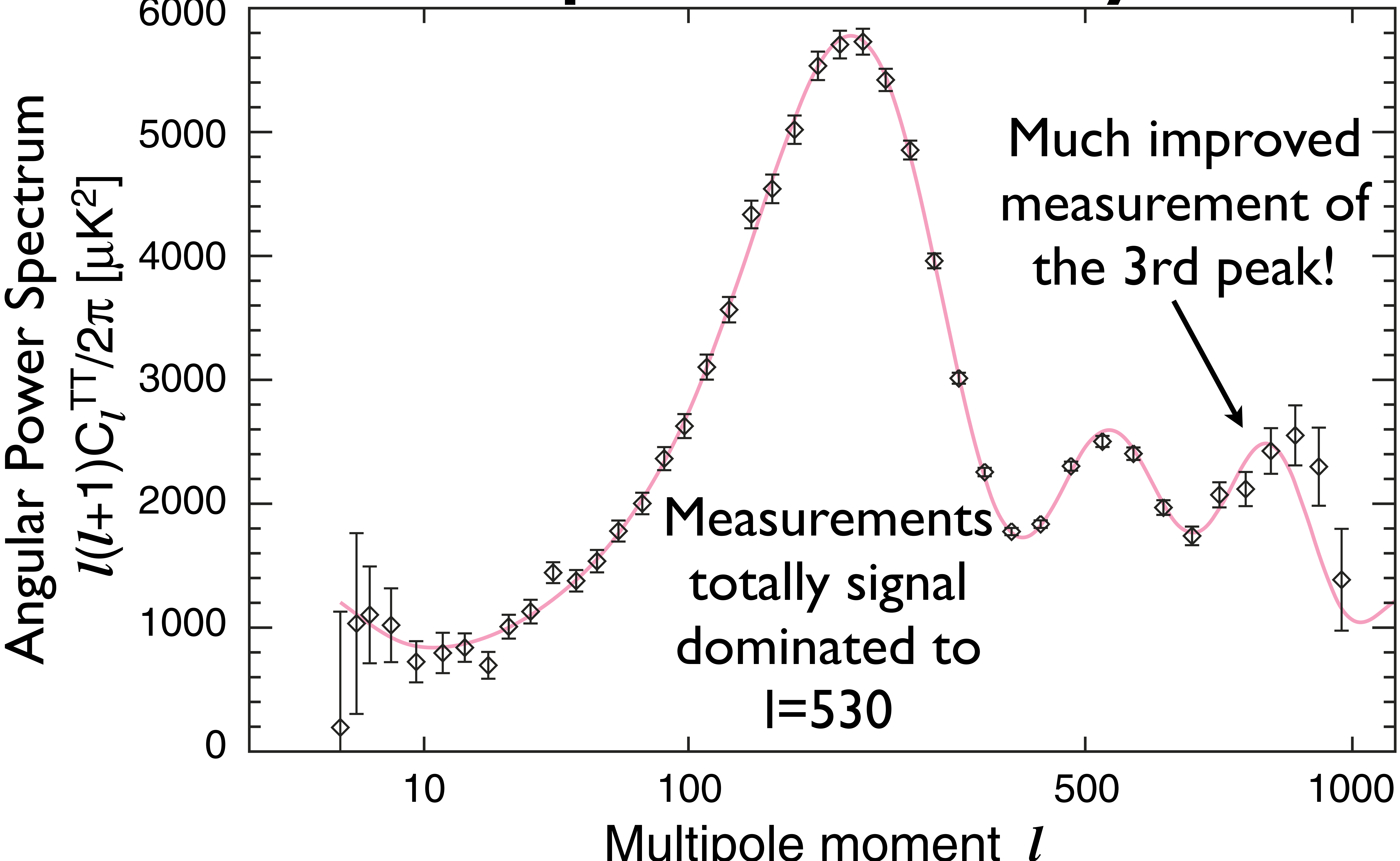
- The mean temperature of photons in the Universe today is 2.725 K
- WMAP is capable of measuring the temperature *contrast* down to better than **one part in millionth**

Hinshaw et al.

How Did We Use This Map?

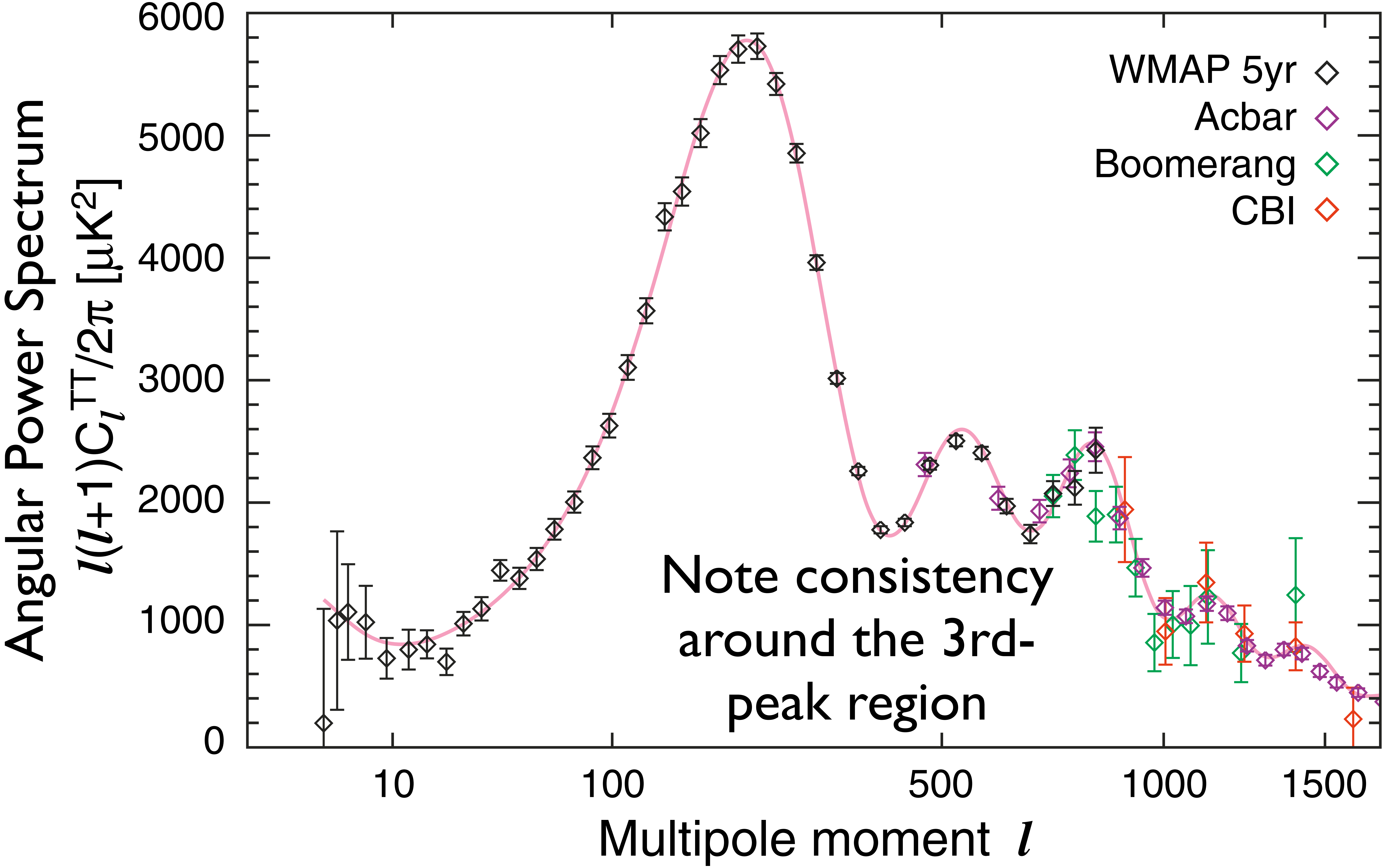


The Spectral Analysis

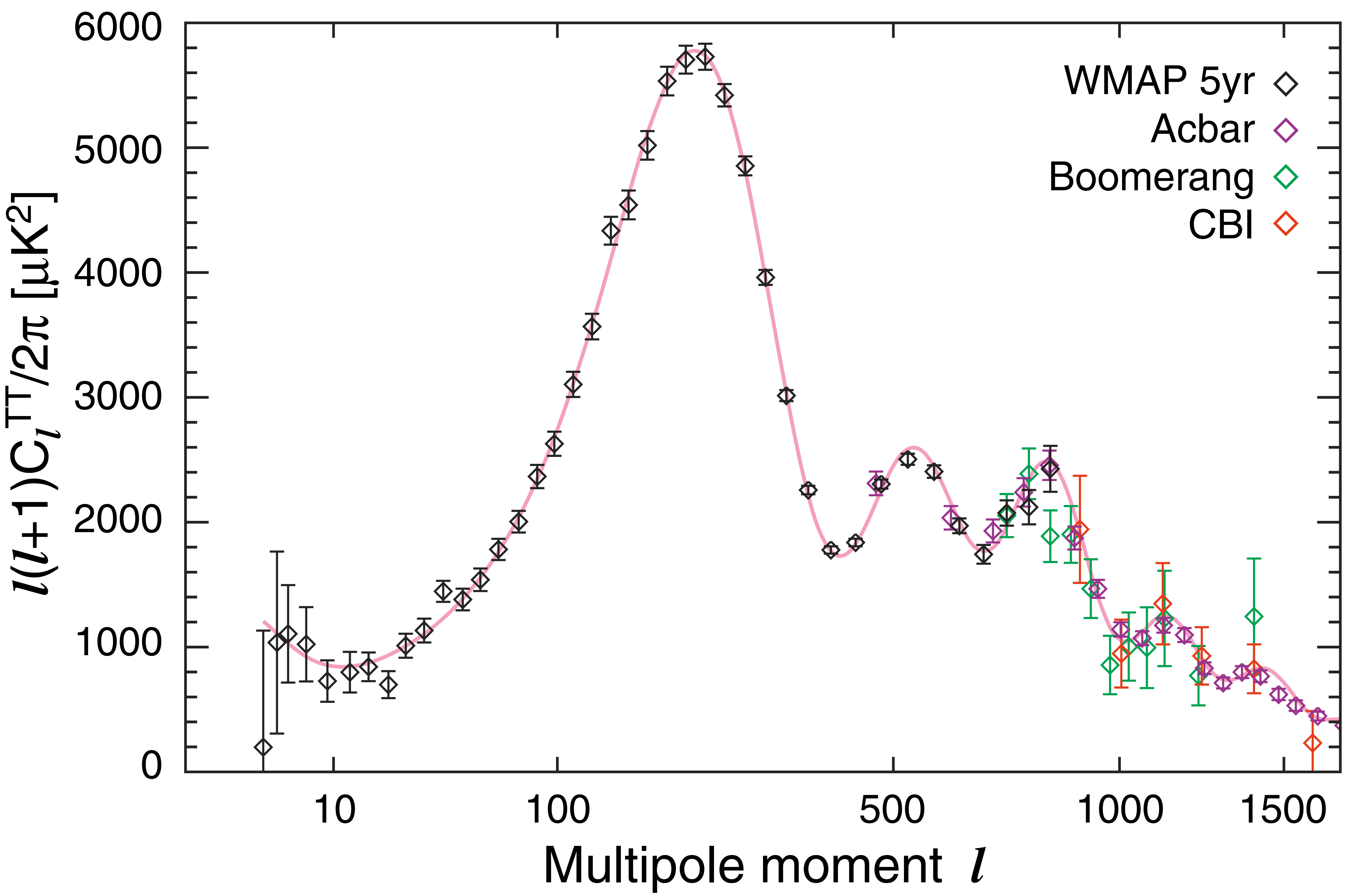


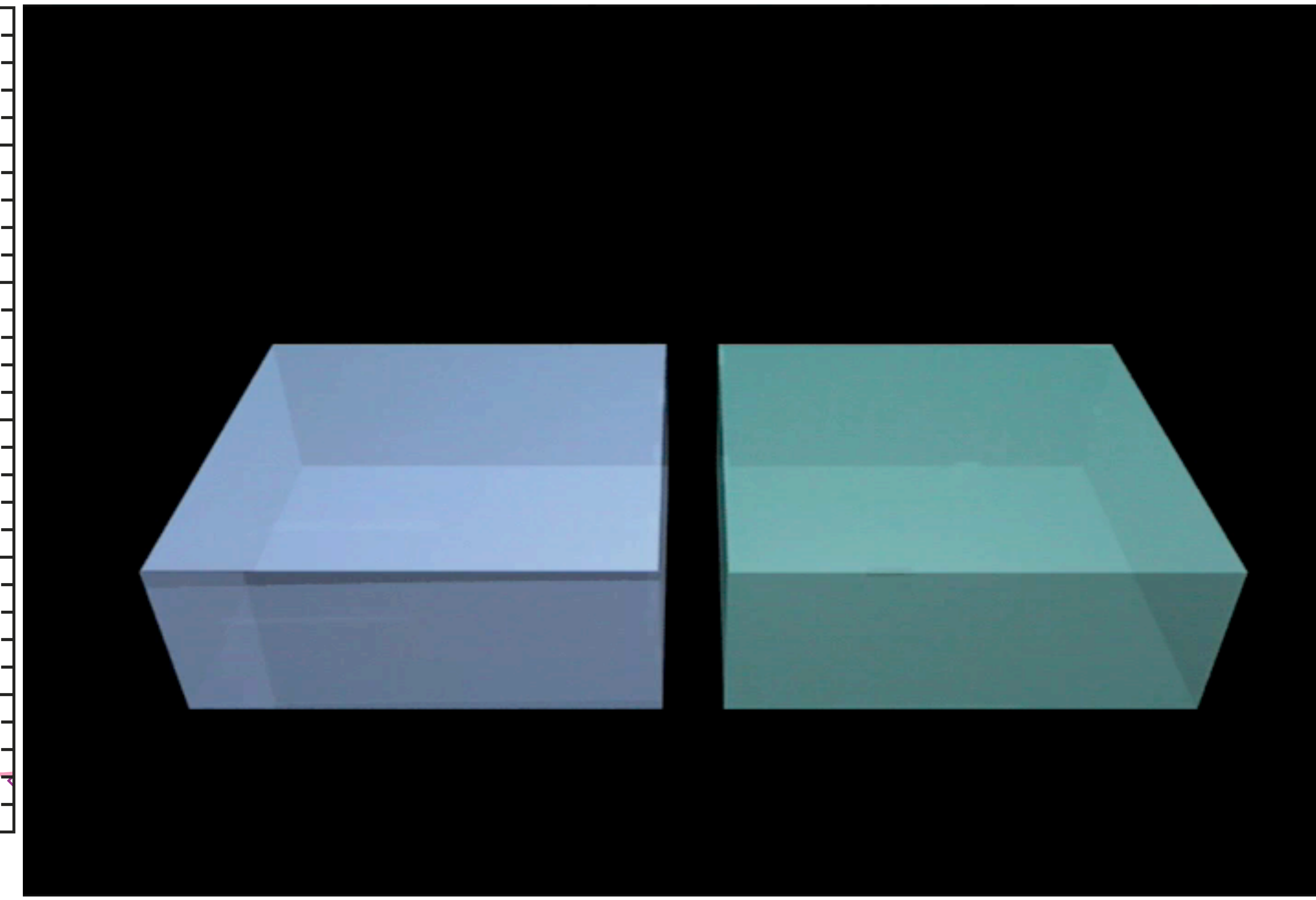
Nolta et al.

The Cosmic Sound Wave



The Cosmic Sound Wave

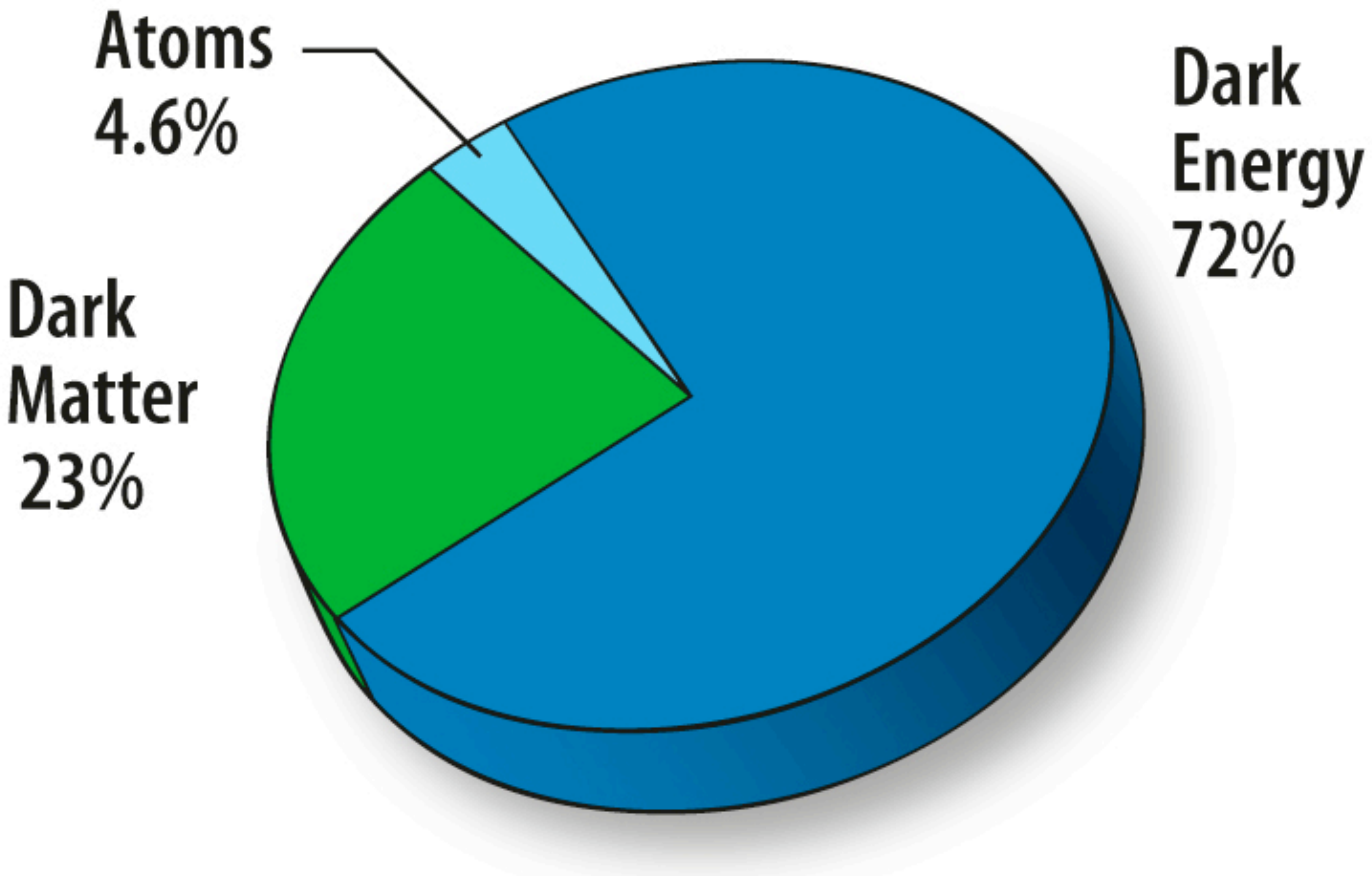




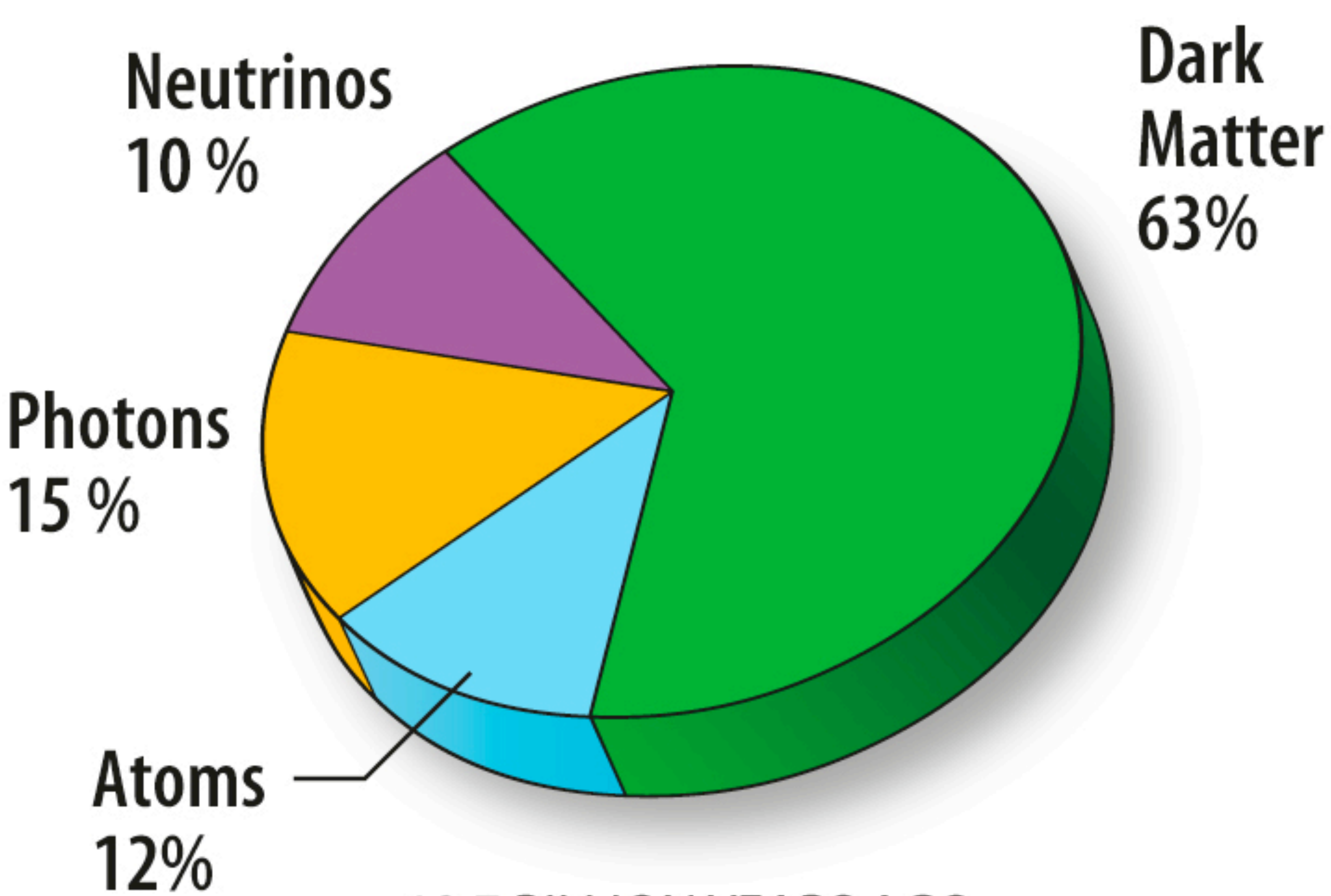
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

Komatsu et al.

~WMAP 5-Year~ Pie Chart Update!



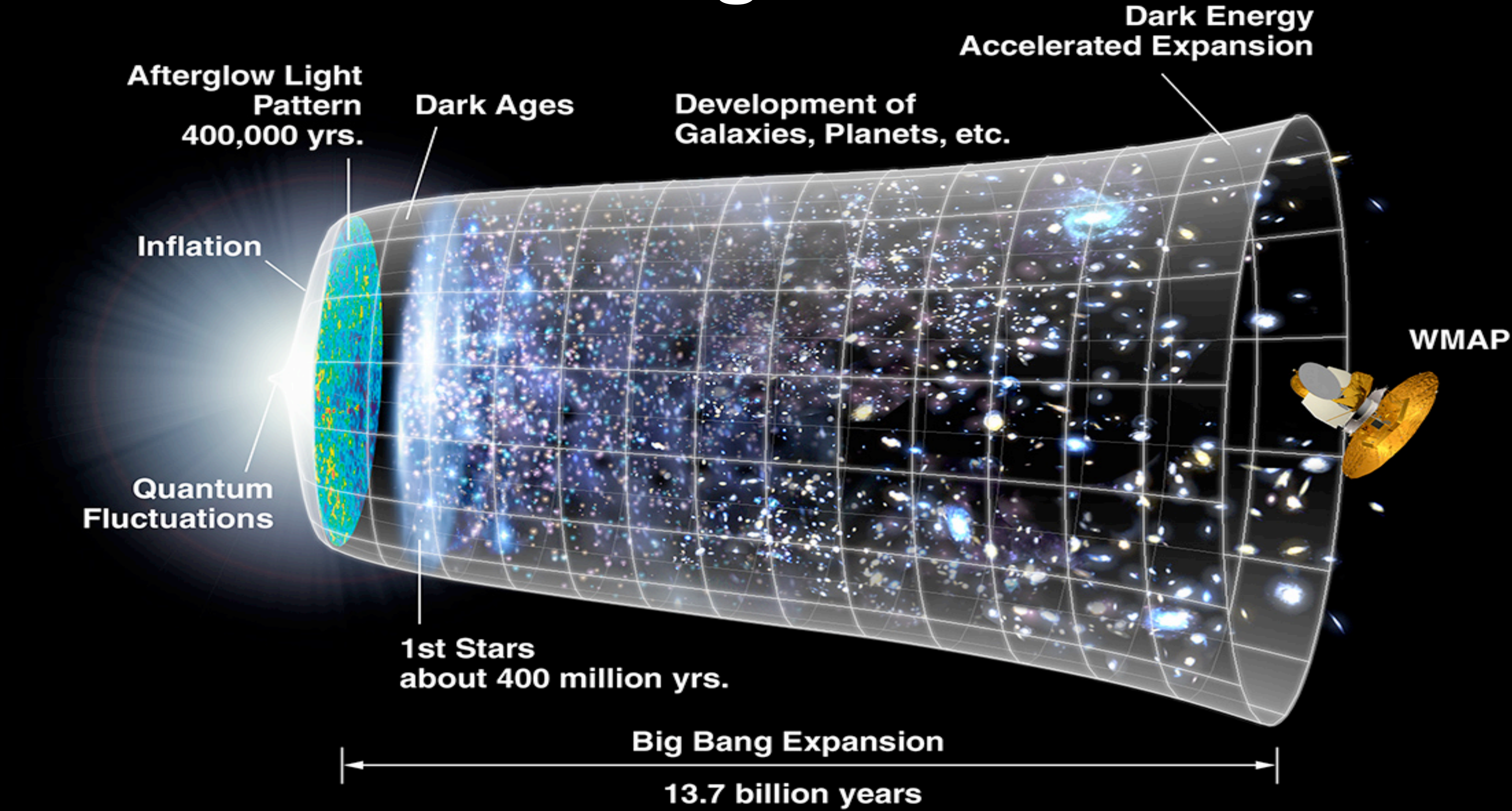
TODAY



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

- 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*

Seeing Neutrinos in Cosmic Microwave Background



NASA/WMAP Science Team

Neutrino Properties in Question

- Total Neutrino Mass, $\boldsymbol{\sum m_\nu}$
  - Section 6.1 of the interpretation paper
- Effective Number of Neutrino Species, $\boldsymbol{N_{eff}}$
  - Section 6.2

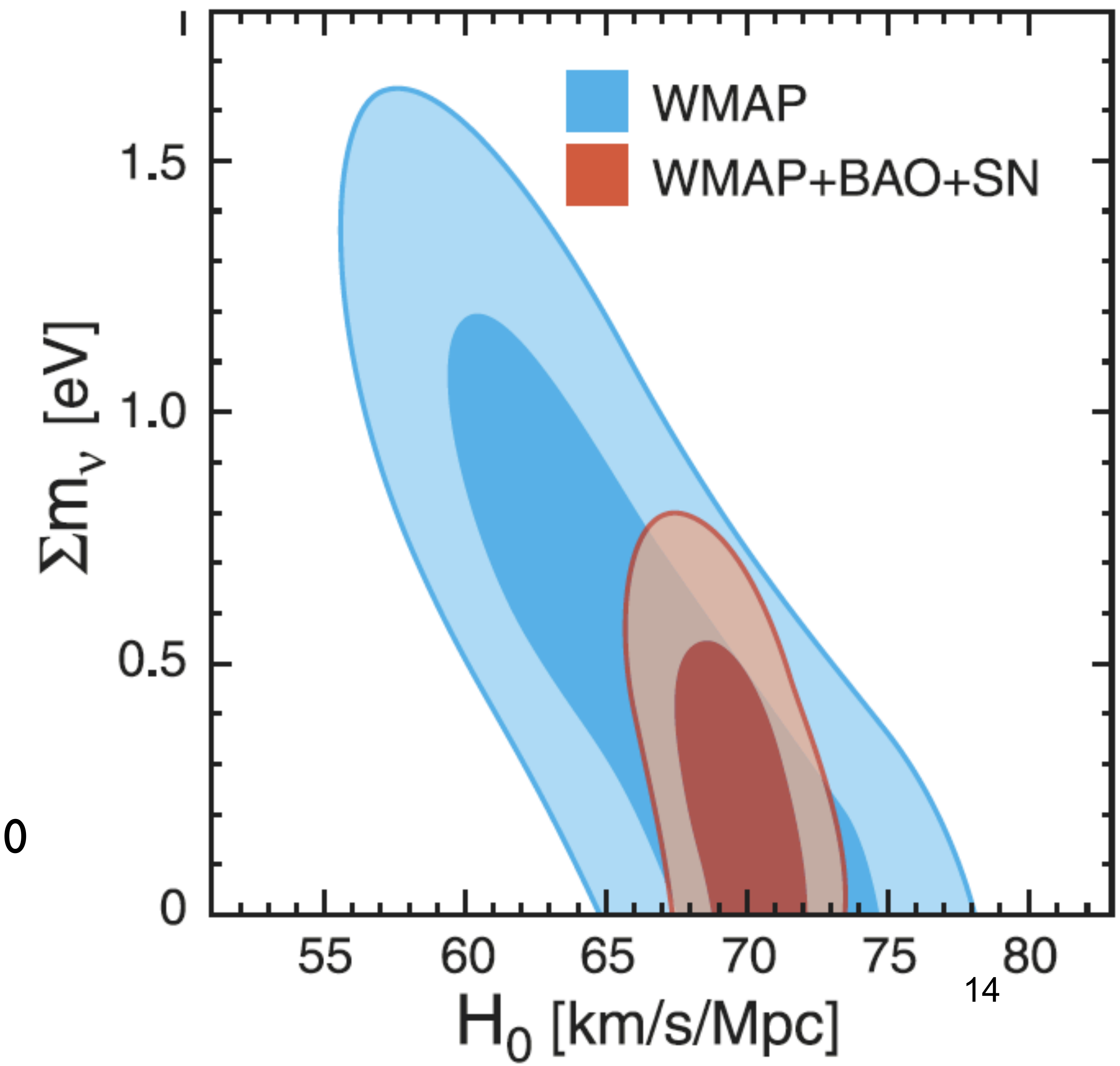
$\sum m_\nu$ from CMB alone

- 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).
    - $\langle E_\nu \rangle = 3.15(4/11)^{1/3} T_{photon} = 0.58$ eV
- Neutrino masses didn't matter if they were relativistic!
- For degenerate neurinos, $\sum m_\nu = 3.04 \times 0.58 = 1.8$ eV
    - **If $\sum m_\nu \ll 1.8$eV, CMB alone cannot see it**

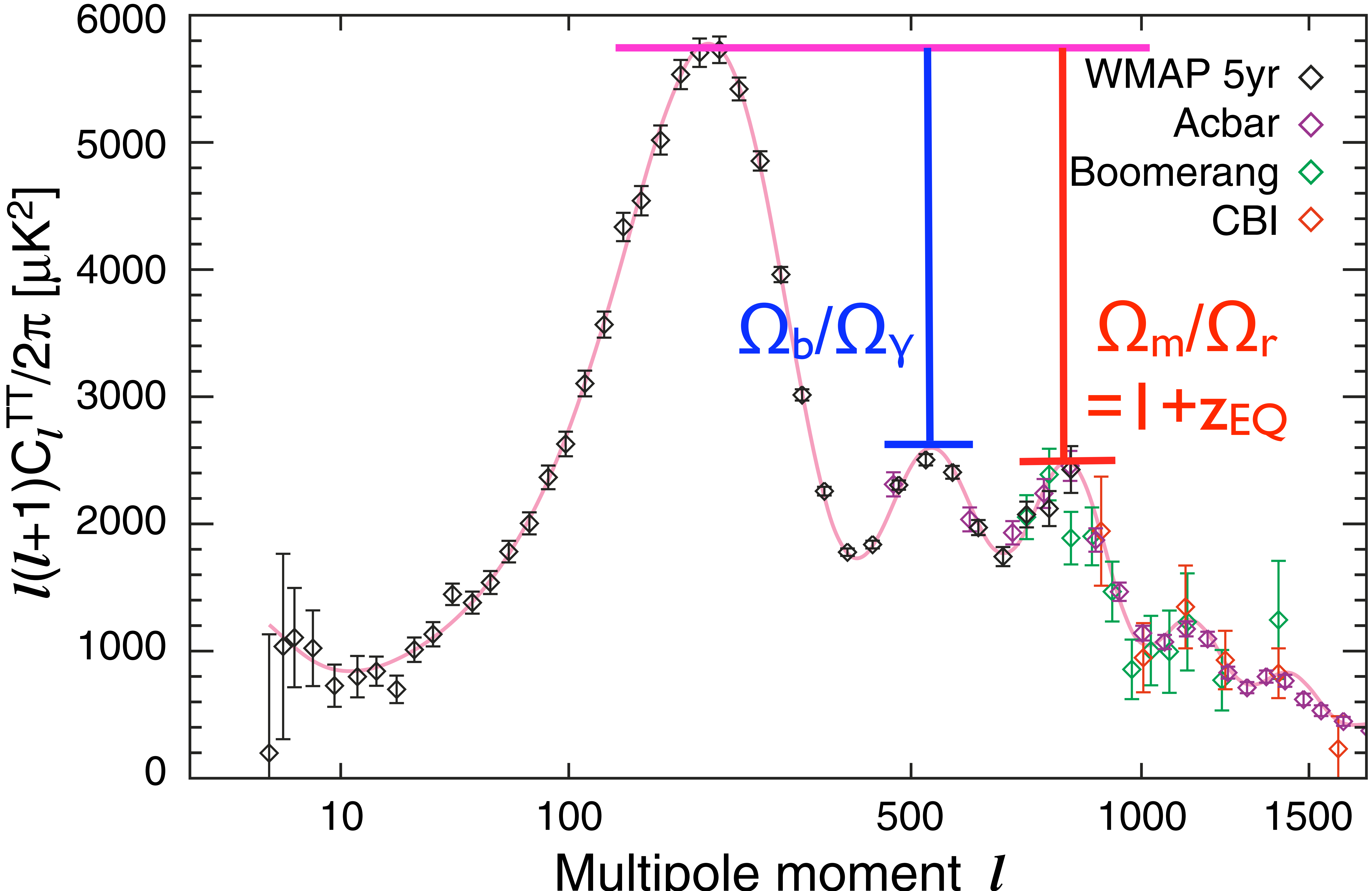
Komatsu et al.

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



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



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

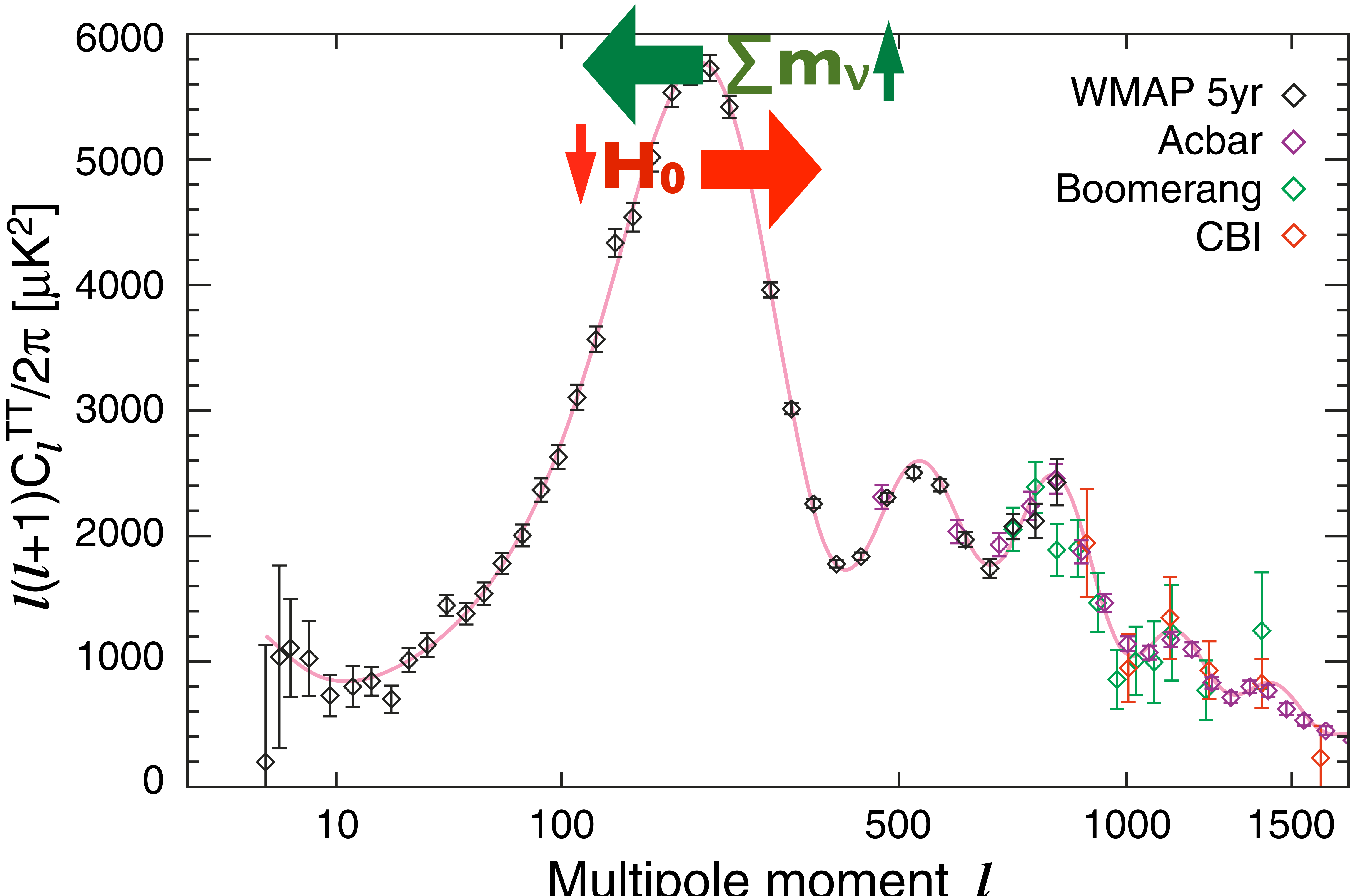
Neutrino Subtlety

- For $\sum m_\nu << 1.8$eV, neutrinos were relativistic at $z=1090$
- But, we know that $\sum m_\nu > 0.05$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

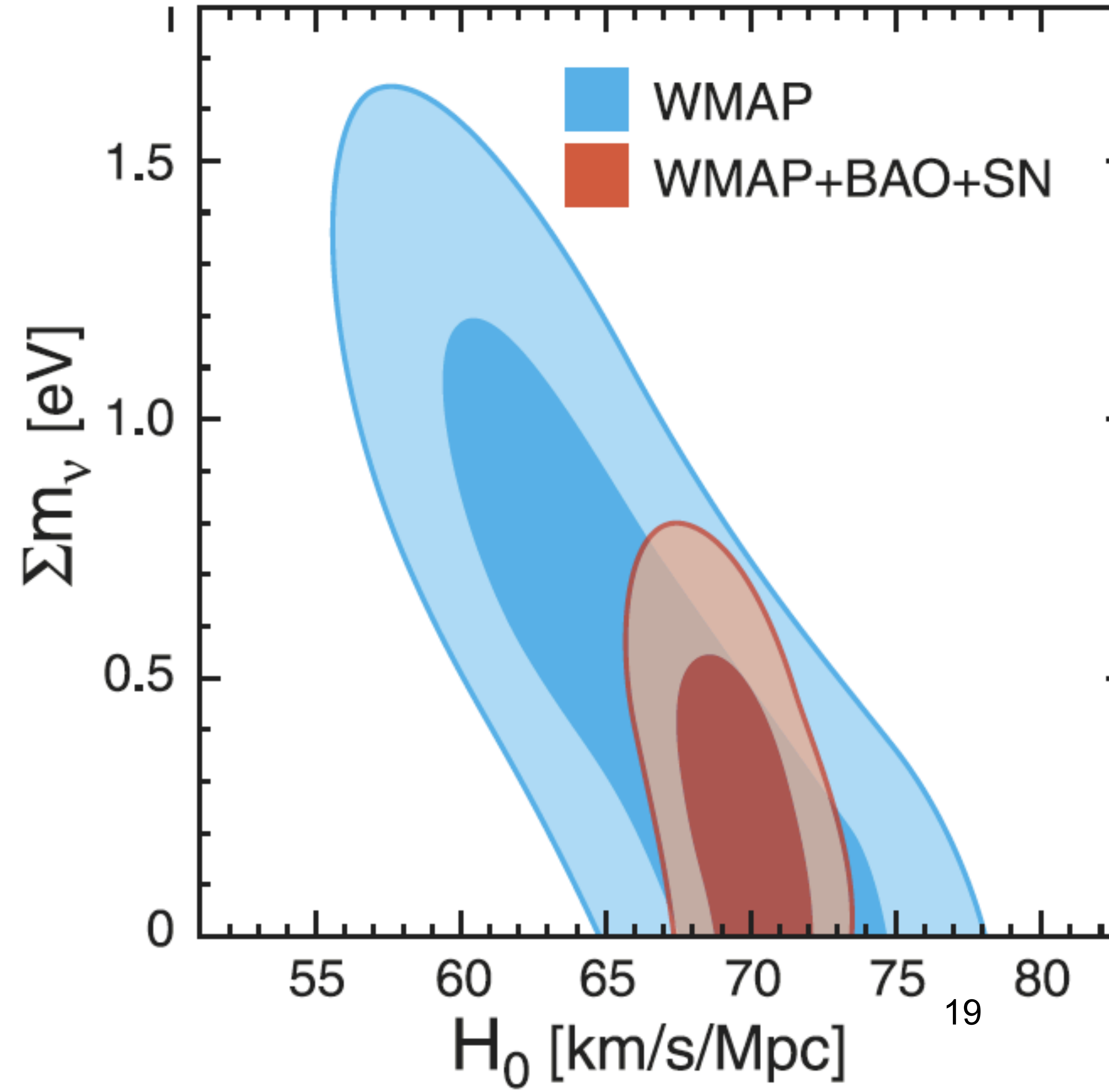


- But, lowering H_0 shifts the peak in the opposite direction. So...

Ichikawa, Fukugita & Kawasaki (2005)

Shift of Peak Absorbed by H_0

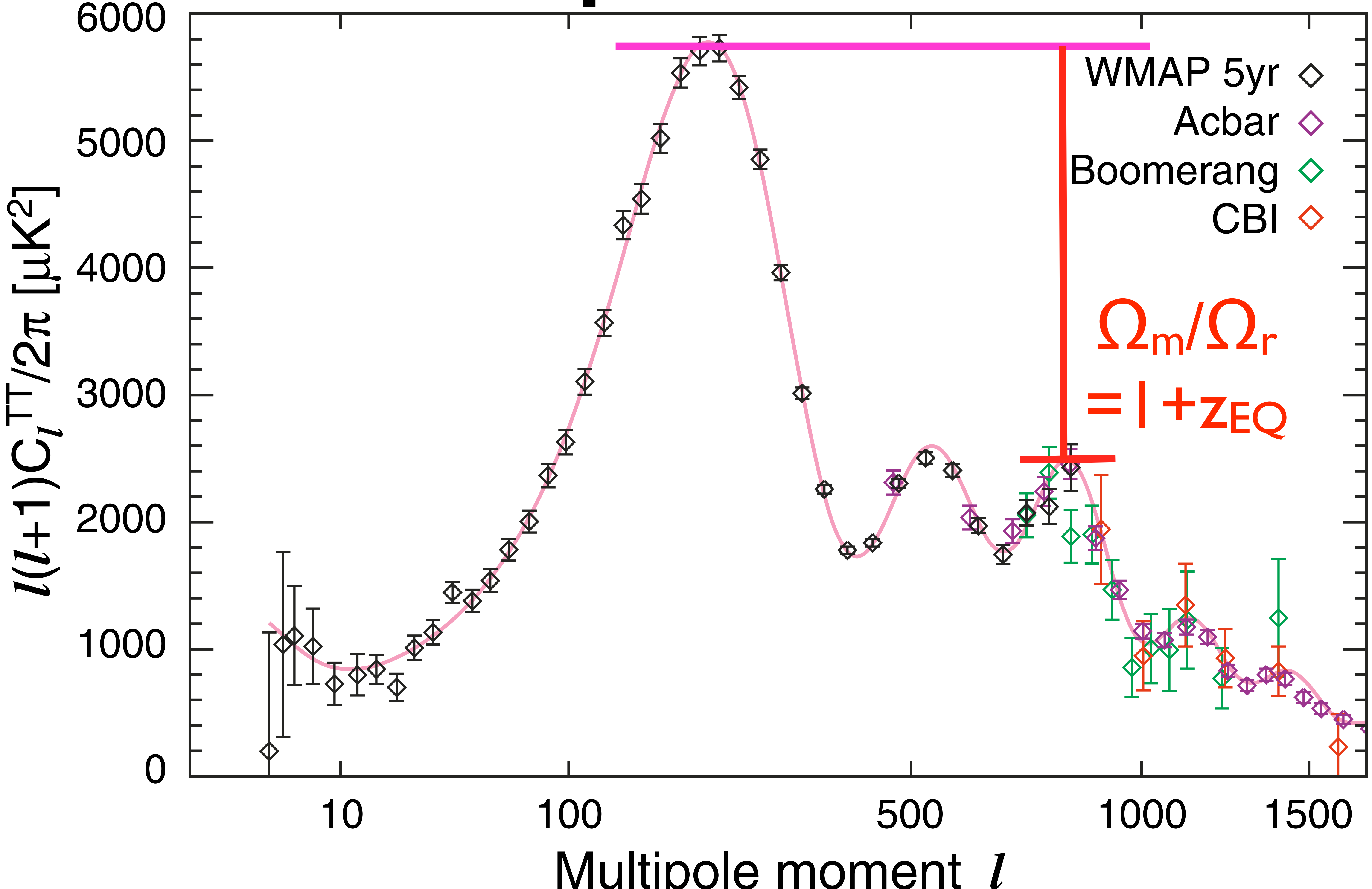
- Here is a catch:
  - **Shift of the first peak to a lower multipole can be canceled by lowering H_0!**
- Same thing happens to curvature of the universe: making the universe positively curved shifts the first peak to a lower multipole, but this effect can be canceld by lowering H_0.
  - So, 30% positively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



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
  - $\mathbf{1+z_{EQ} = (\Omega_m h^2/2.47\times10^{-5}) / (1+0.227N_{eff})}$

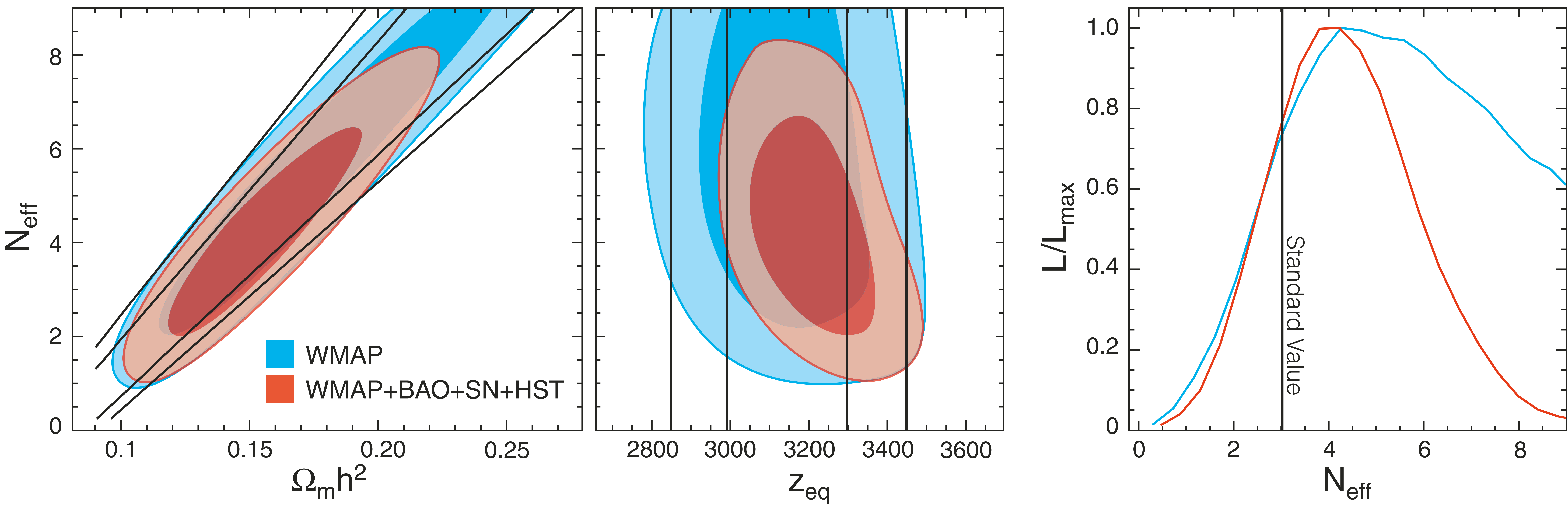
3rd-peak to z_{EQ}



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

Komatsu et al.

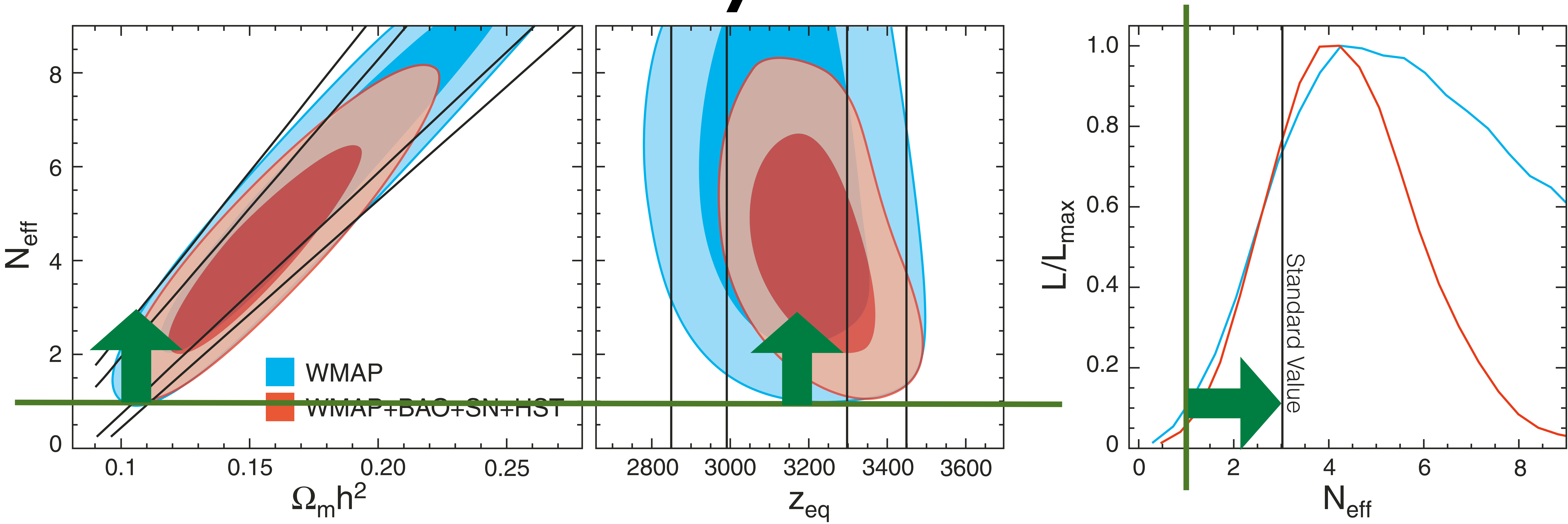
N_{eff}-$\Omega_m h^2$ Degeneracy



- 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_{eff} = 4.4 ± 1.5 (68%CL)**

WMAP-only Lower Limit



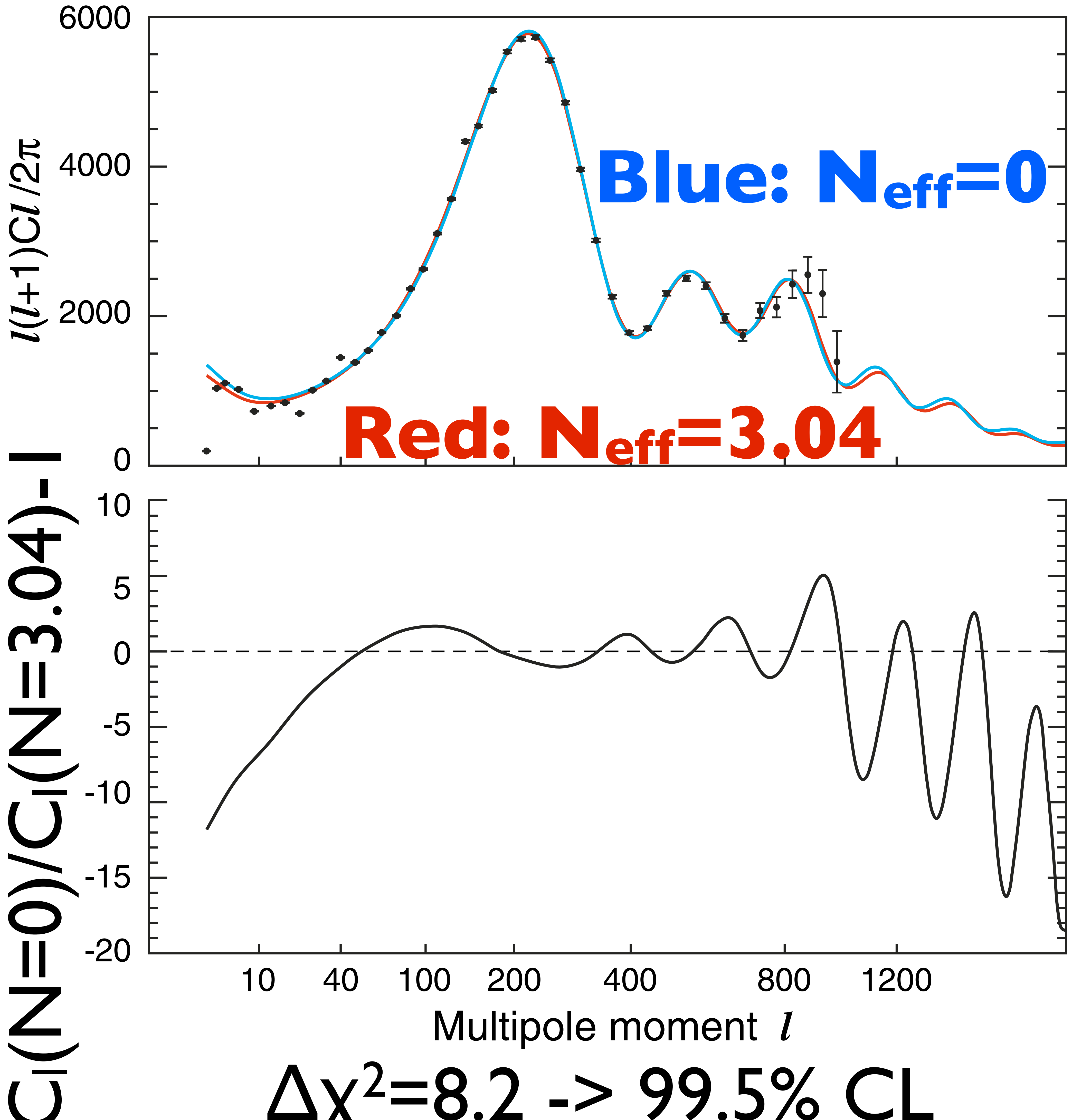
- N_{eff} and $\Omega_m h^2$ are totally degenerate - but, look.
- **WMAP-only lower limit is not N_{eff}=0**
  - N_{eff}>2.3 (95%CL) [Dunkley et al.]

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* $\Omega_m h^2$
- 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
  - $N_{eff} = 4.4 \pm 1.5$
- 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)

WMAP Amplitude Prior

- WMAP measures the amplitude of curvature perturbations at z~1090. Let's call that R_k. The relation to the density fluctuation is

$$\delta_{m,\mathbf{k}}(z) = \frac{2k^3}{5H_0^2\Omega_m}\mathcal{R}_{\mathbf{k}}T(k)D(k,z)$$

- Variance of R_k has been constrained as:

AMPLITUDE OF CURVATURE PERTURBATIONS, $\mathcal{R}$, MEASURED BY *WMAP* AT $k_{WMAP} = 0.02\ \mathrm{Mpc}^{-1}$

Model	$10^9 \times \Delta^2_{\mathcal{R}}(k_{WMAP})$
$\Omega_k = 0$ and $w = -1$	2.211 ± 0.083
$\Omega_k \neq 0$ and $w = -1$	2.212 ± 0.084
$\Omega_k = 0$ and $w \neq -1$	2.208 ± 0.087
$\Omega_k \neq 0$ and $w \neq -1$	2.210 ± 0.084
$\Omega_k = 0$, $w = -1$ and $m_\nu > 0$	2.212 ± 0.083
$\Omega_k = 0$, $w \neq -1$ and $m_\nu > 0$	2.218 ± 0.085
WMAP Normalization Prior	2.21 ± 0.09

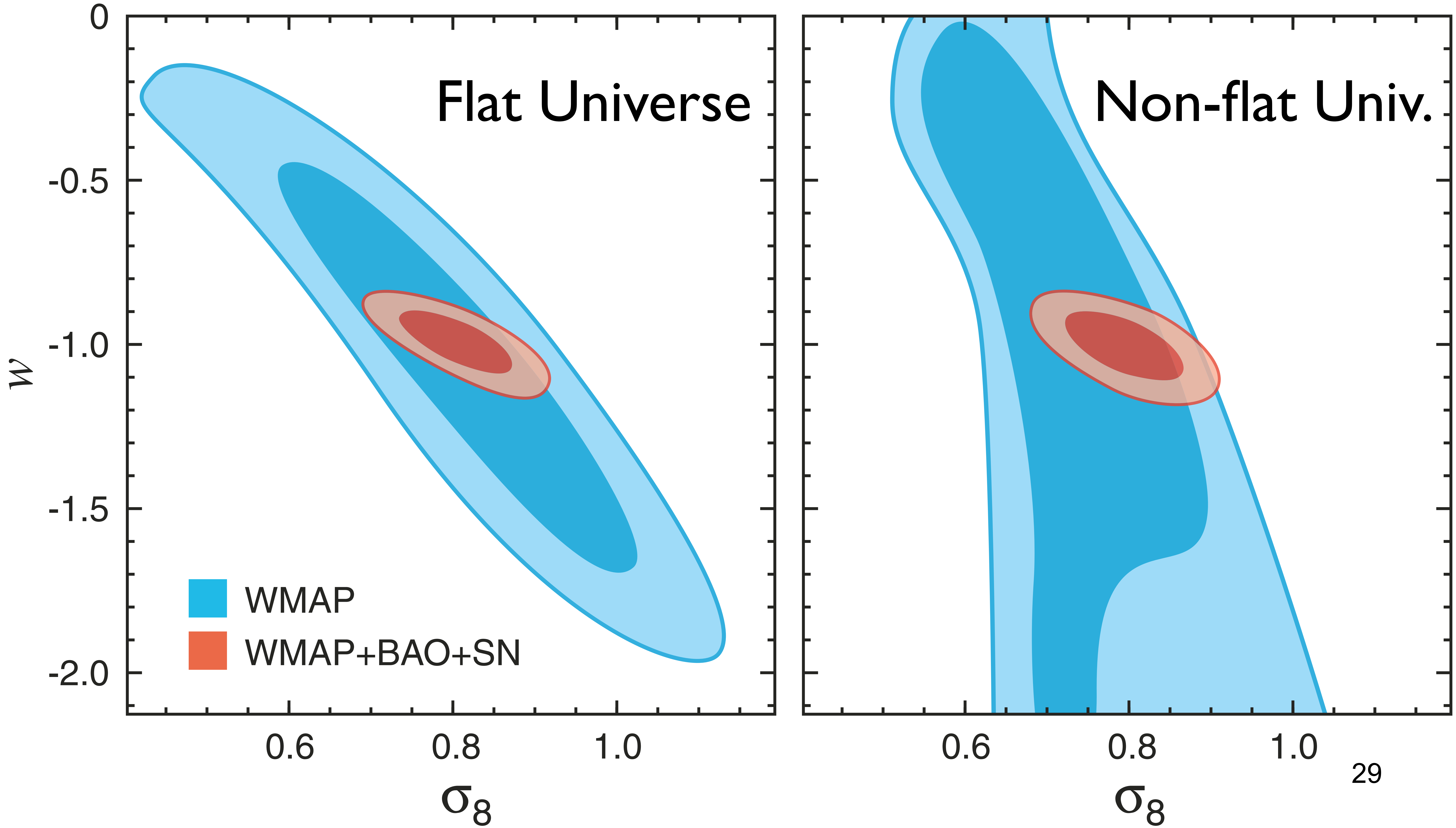
Then Solve This Diff. Equation...

Ignoring the mass of neutrinos and modifications to gravity, one can obtain the growth rate by solving the following differential equation (Wang & Steinhardt 1998; Linder & Jenkins 2003): **g(z)=(1+z)D(z)**

$$\frac{d^2 g}{d\ln a^2} + \left[\frac{5}{2} + \frac{1}{2}\left(\Omega_k(a) - 3w_{\rm eff}(a)\Omega_{de}(a)\right)\right]\frac{dg}{d\ln a} + \left[2\Omega_k(a) + \frac{3}{2}(1 - w_{\rm eff}(a))\Omega_{de}(a)\right] g(a) = 0, \qquad (76)$$

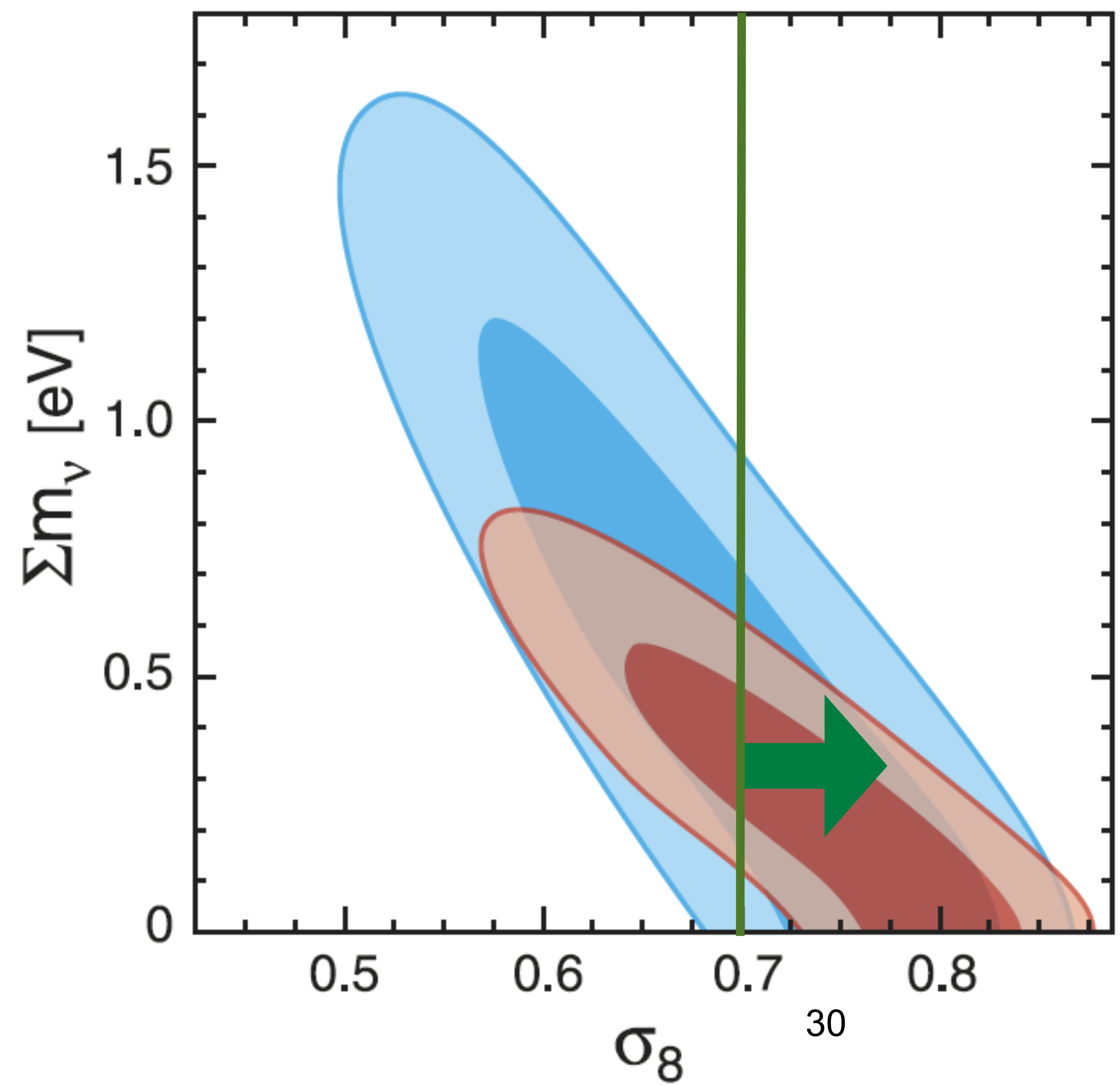
- If you need a code for doing this, search for "**Cosmology Routine Library**" on Google

Degeneracy Between Amplitude at z=0 (σ_8) and w



Degeneracy Between σ_8 and $\sum m_\nu$

- Reliable and accurate measurements of the amplitude of fluctuations at lower redshifts will improve upon the limit on $\sum m_\nu$ significantly.
- In fact, what's required is the lower limit on σ_8.
- Even a modest lower limit like $\sigma_8 > 0.7$ would lead to a significant improvement.



Summary

- WMAP 5-year's improved definition of the 3rd peak helped us constrain the properties of neutrinos, such as masses and species.
  - In particular, we could place a lower bound on N_{eff} using the WMAP data alone - confirmation of the existence of the Cosmic Neutrino Background
- With WMAP, combined with the external distance measurements (still excluding the external amplitude data), we have obtained:
  - $\sum m_\nu < 0.67$eV (95%CL); $N_{eff}=4.4\pm1.5$ (65%CL)
- Future direction: find a good lower bound on σ_8 from galaxies, clusters, lensing, Lyman-α, etc.