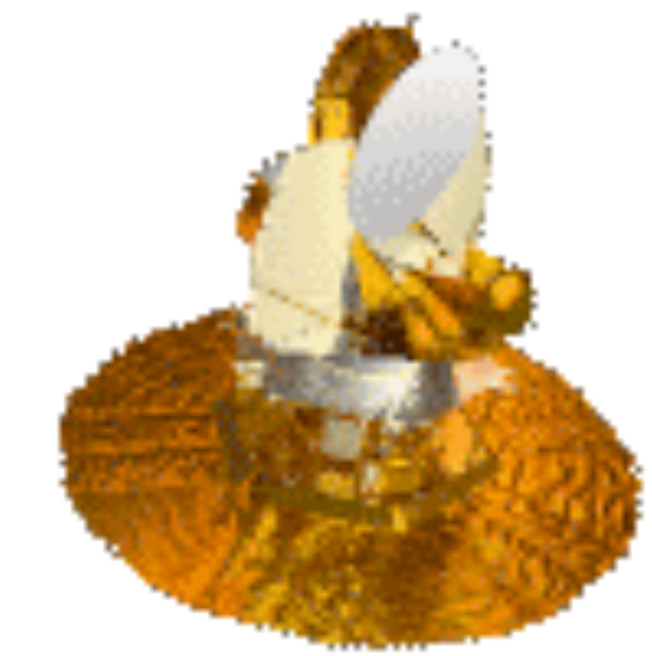


WMAP 9-Year Results and Cosmological Implications: **The Final Results**

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)

17th Paris Cosmology Colloquium 2013

Observatoire de Paris, July 24, 2013

used to be

WMAP at Lagrange 2 (L2) Point

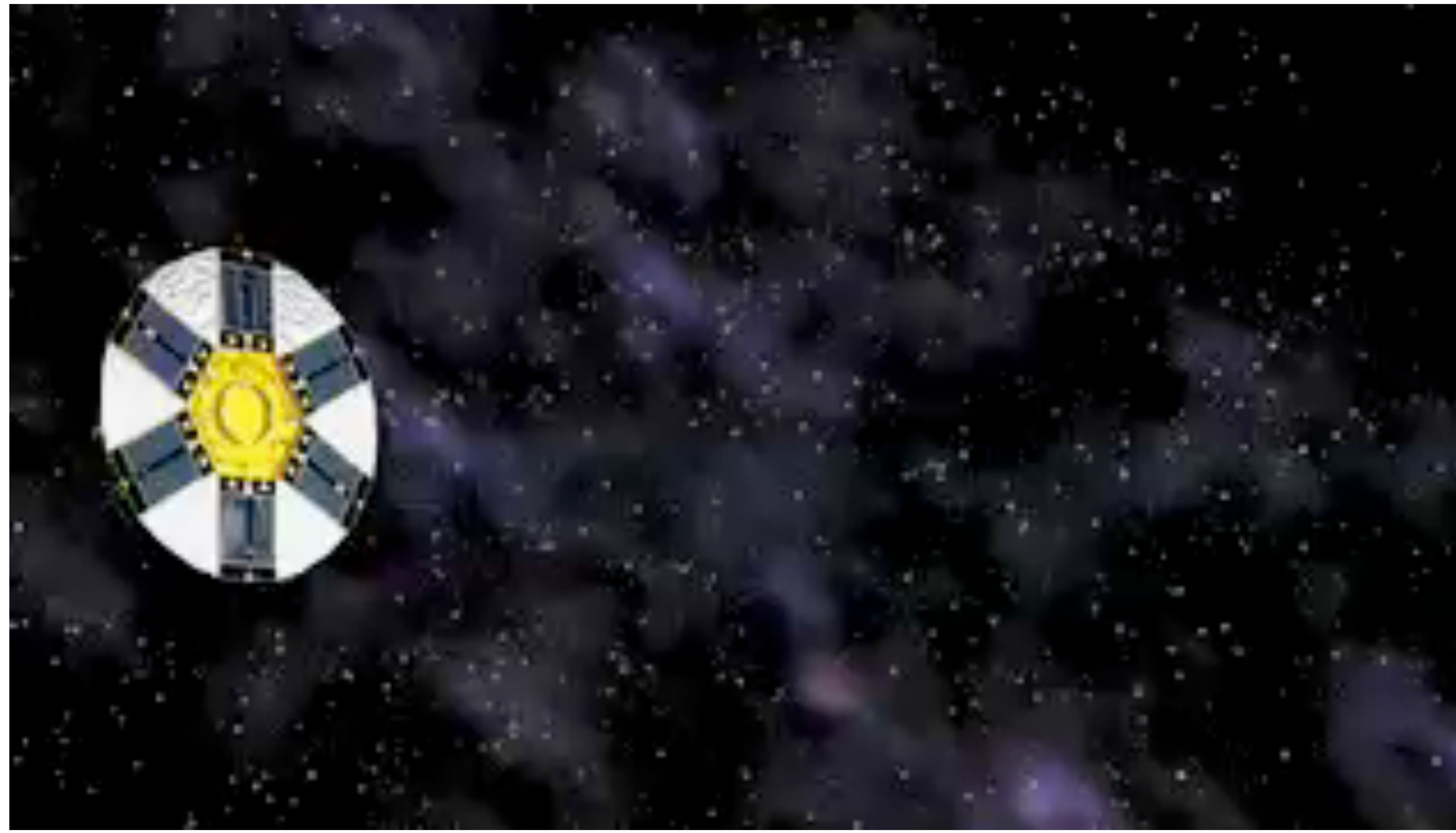
June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

March 2008:
The five-year data release

January 2010:
The seven-year data release



September 8, 2010:
WMAP left L2

December 21, 2012:
The final, nine-year data release

WMAP 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
- K.M. Smith
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

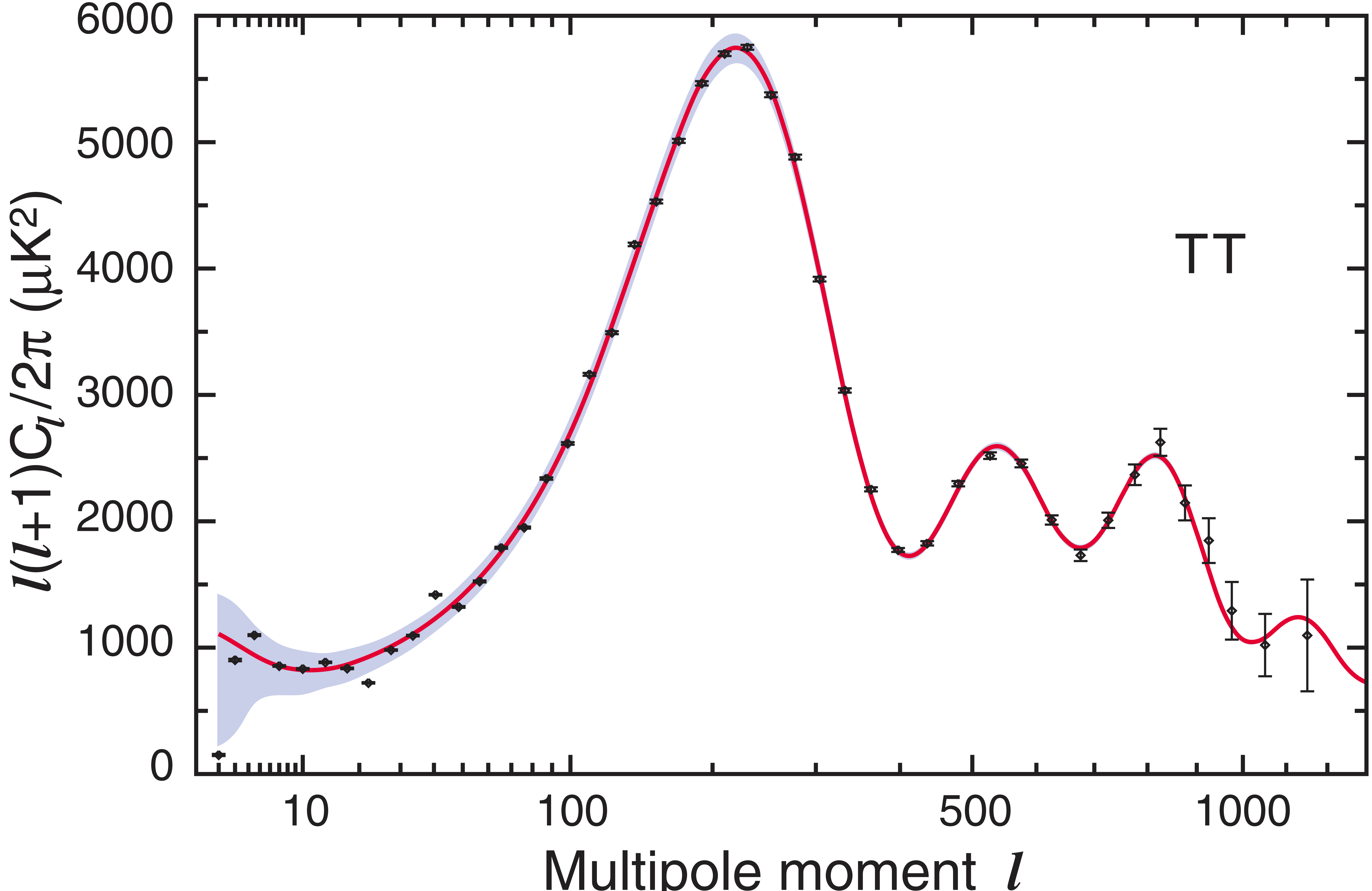
WMAP 9-Year Papers

- **Bennett et al.**, "*Final Maps and Results*," accepted for publication in ApJS, arXiv:1212.5225
- **Hinshaw et al.**, "*Cosmological Parameter Results*," accepted for publication in ApJS, arXiv:1212.5226

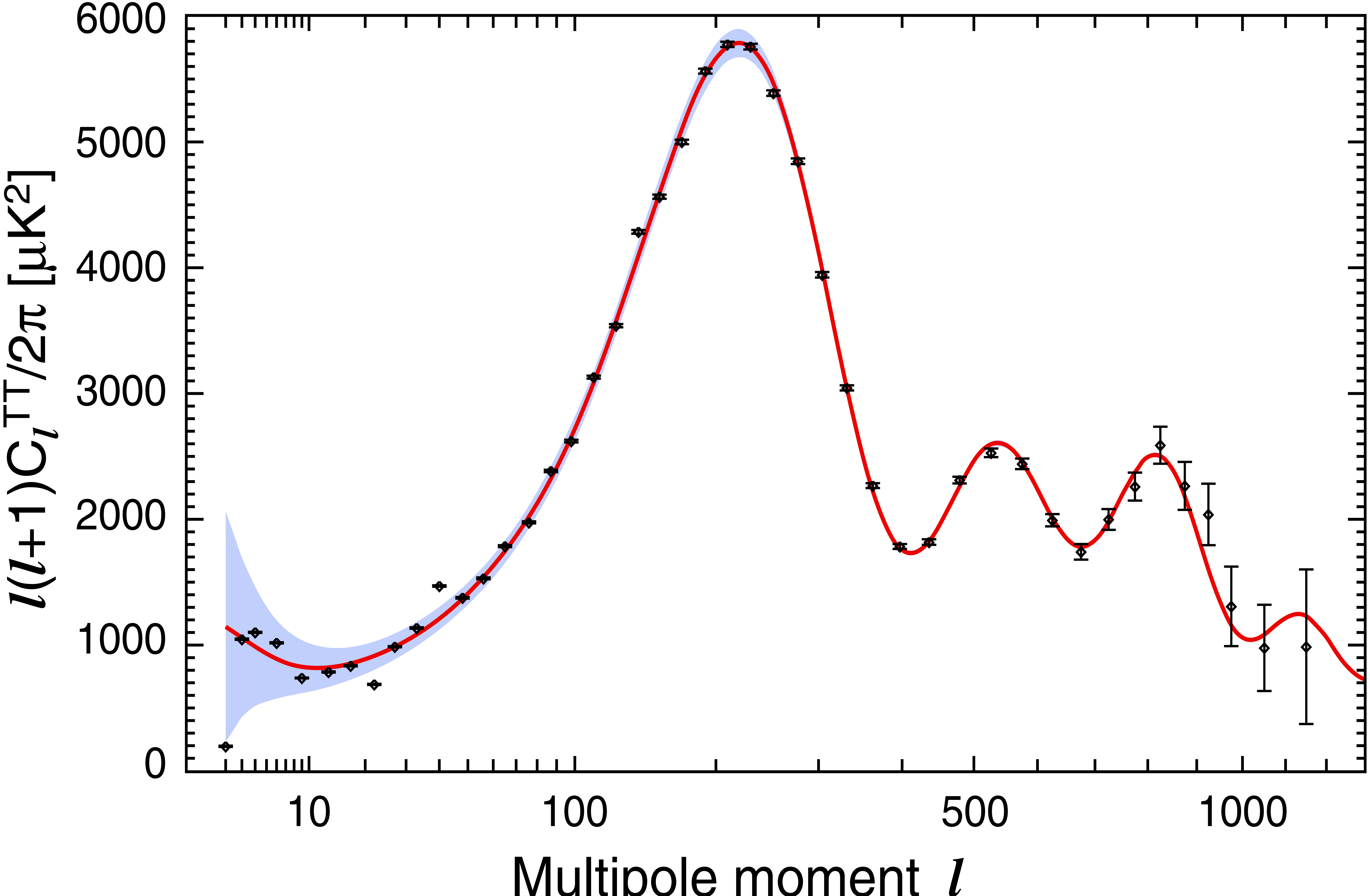
9-year Science Highlights

- The effective number of relativistic species is consistent with three
- The joint constraint on the helium abundance and the number of relativistic species from CMB strongly supports Big Bang nucleosynthesis
- Single-field slow-roll inflation continues to be supported by the data, with much restricted range of the parameter space

9-year temperature C_l

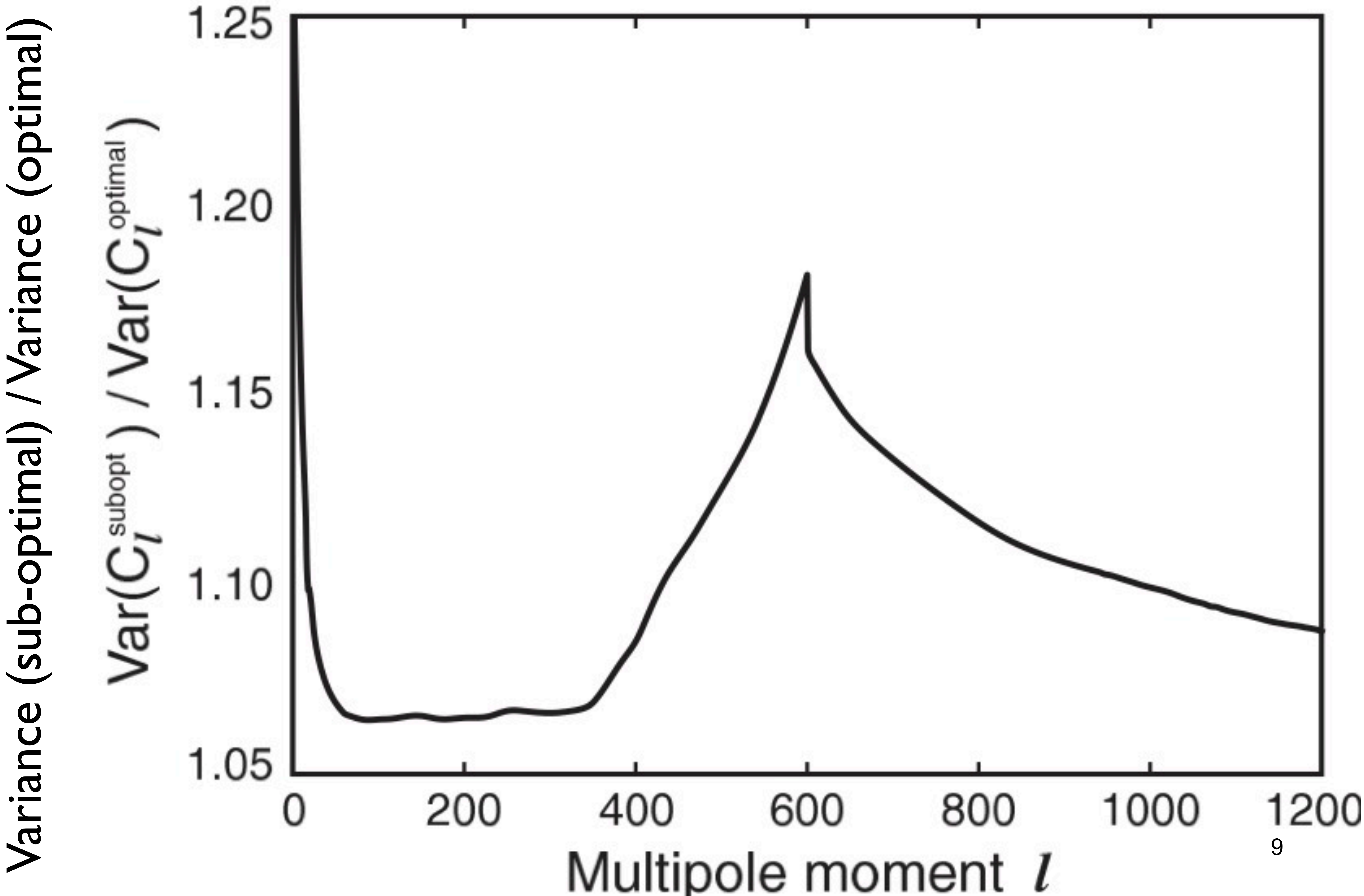


7-year temperature C_l



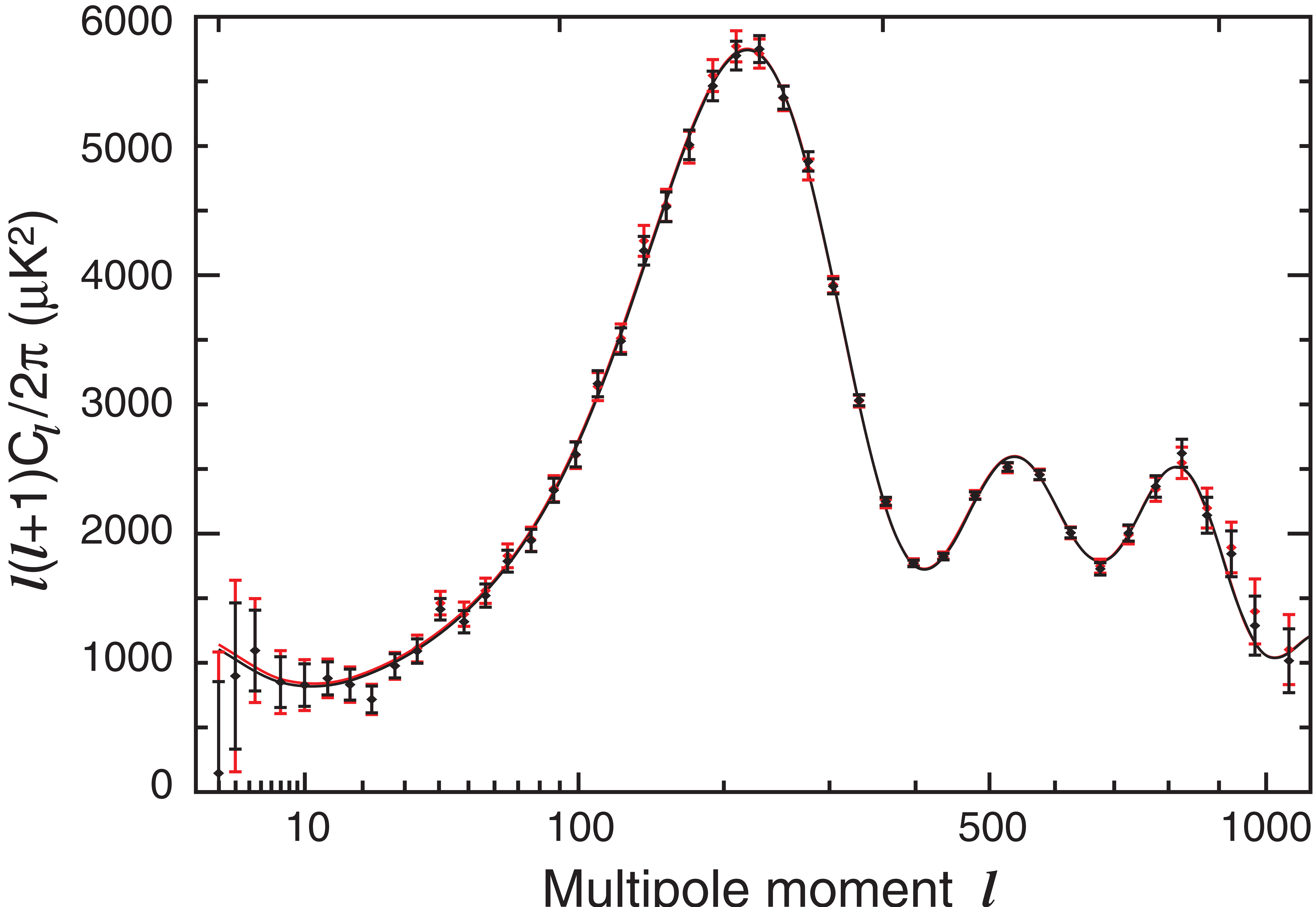
What changed?

- An improved analysis! The error bar decreased by more than expected for the number of years (9 vs 7). Why?
- We now use the optimal (minimum variance) estimator of the angular power spectrum.
  - Previously, we estimated C_l for low-l (l<600) and high-l (l>600) separately. No weighting for low-l and inverse-noise-weighting for high-l.
  - This results in a sub-optimal estimator near l~600.
  - We now use the optimal $(S+N)^{-1}$ weighting.



Variance (sub-optimal) / Variance (optimal)
Var(C_l^{subopt}) / Var($C_l^{optimal}$)
1.25
1.20
1.15
1.10
1.05
0
200
400
600
800
1000
1200
Multipole moment l

9-year (sub-optimal) vs 9-year (optimal)

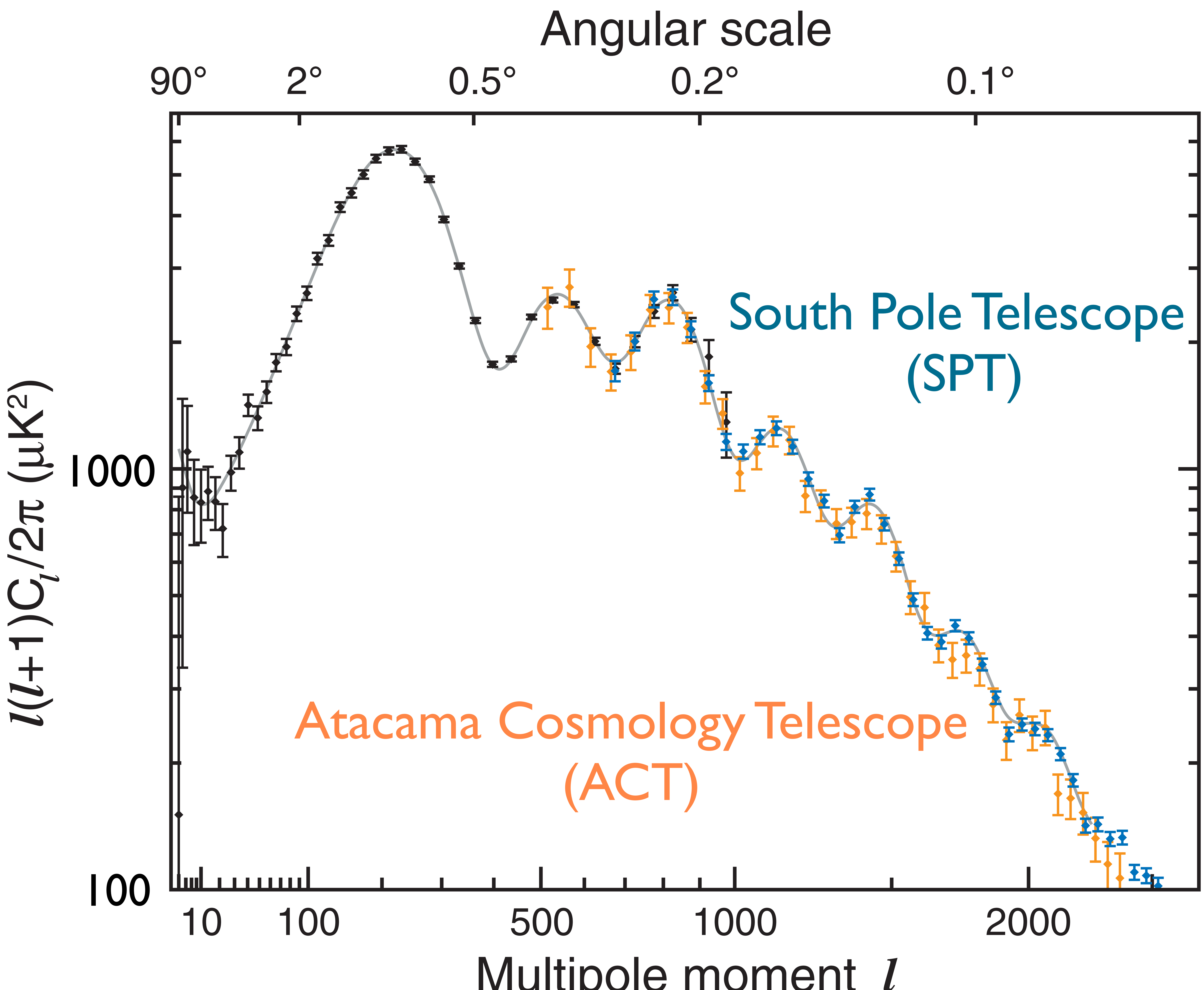


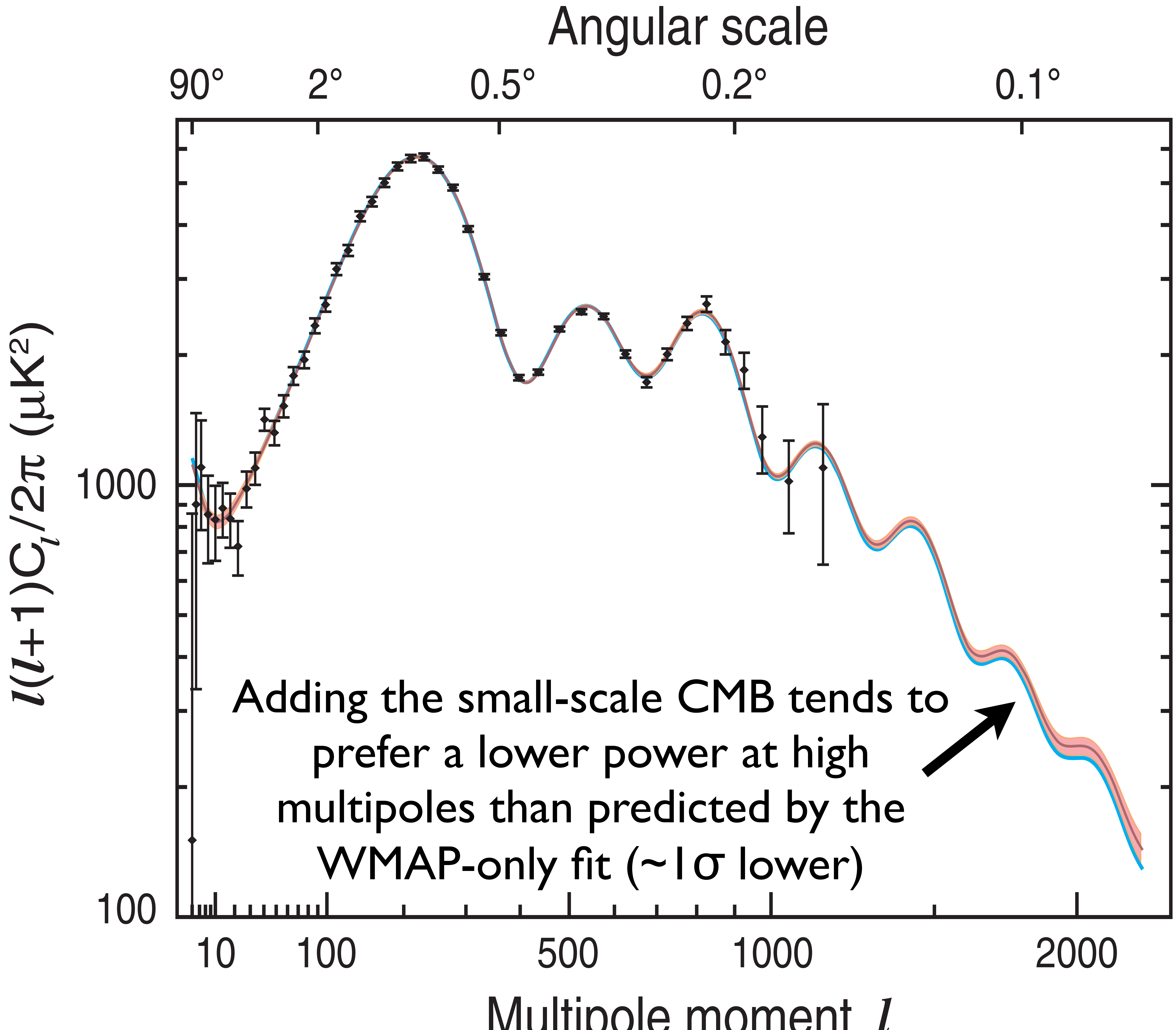
Parameter	Nine-year	Seven-year
Fit parameters		
$\Omega_b h^2$	0.02264 ± 0.00050	$0.02249^{+0.00056}_{-0.00057}$
$\Omega_c h^2$	0.1138 ± 0.0045	0.1120 ± 0.0056
Ω_Λ	0.721 ± 0.025	$0.727^{+0.030}_{-0.029}$
$10^9 \Delta^2_{\mathcal{R}}$	2.41 ± 0.10	2.43 ± 0.11
n_s	0.972 ± 0.013	0.967 ± 0.014
τ	0.089 ± 0.014	0.088 ± 0.015
Derived parameters		
t_0 (Gyr)	13.74 ± 0.11	13.77 ± 0.13
H_0 (km/s/Mpc)	70.0 ± 2.2	70.4 ± 2.5
σ_8	0.821 ± 0.023	$0.811^{+0.030}_{-0.031}$
Ω_b	0.0463 ± 0.0024	0.0455 ± 0.0028
Ω_c	0.233 ± 0.023	0.228 ± 0.027
$z_{\rm reion}$	10.6 ± 1.1	10.6 ± 1.2

Adding the small-scale CMB data

- Atacama Cosmology Telescope (ACT)
  - a 6-m telescope in Chile, led by Lyman Page (Princeton)
  - C_l from Das et al. (2011)
- South Pole Telescope (SPT)
  - a 10-m telescope in South Pole, led by John Carlstrom (Chicago)
  - C_l from Keisler et al. (2011); Reichardt et al. (2012)

These data are not latest [Story et al. for SPT; Sievers et al. for ACT]


Angular scale
90°
2°
0.5°
0.2°
0.1°
South Pole Telescope
(SPT)
Atacama Cosmology Telescope
(ACT)
l(l+1)C_l/2π (μK²)
1000
100
10
100
500
1000
2000
Multipole moment l


Angular scale
90°
2°
0.5°
0.2°
0.1°
l(l+1)C_l/2π (μK²)
1000
100
10
100
500
1000
2000
Multipole moment l
Adding the small-scale CMB tends to prefer a lower power at high multipoles than predicted by the WMAP-only fit (~1σ lower)

The number of "neutrino" species

total radiation density: $\rho_r \equiv \rho_\gamma + \rho_\nu + \rho_{\rm er}$

photon density: $\rho_\gamma = \frac{\pi^2}{15} T_\gamma^4$

neutrino density: $\rho_\nu = \frac{7}{8}\frac{\pi^2}{15} N_\nu T_\nu^4$ where $T_\nu = (4/11)^{1/3}\, T_\gamma$, $N_\nu = 3.04$

neutrino+extra species: $\rho_\nu + \rho_{\rm er} \equiv \dfrac{7\pi^2}{120} N_{\rm eff}\, T_\nu^4$

$$\rho_r = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \simeq \rho_\gamma (1 + 0.2271 N_{\rm eff})$$

What the extra radiation species does

- Extra energy density increases the expansion rate at the decoupling epoch.
  - Smaller sound horizon: peak shifts to the high l
  - Large damping-scale-to-sound-horizon ratio, causing more Silk damping at high l
- Massless free-streaming particles have anisotropic stress, affecting modes which entered the horizon during radiation era.

“Neutrinos” have anisotropic stress

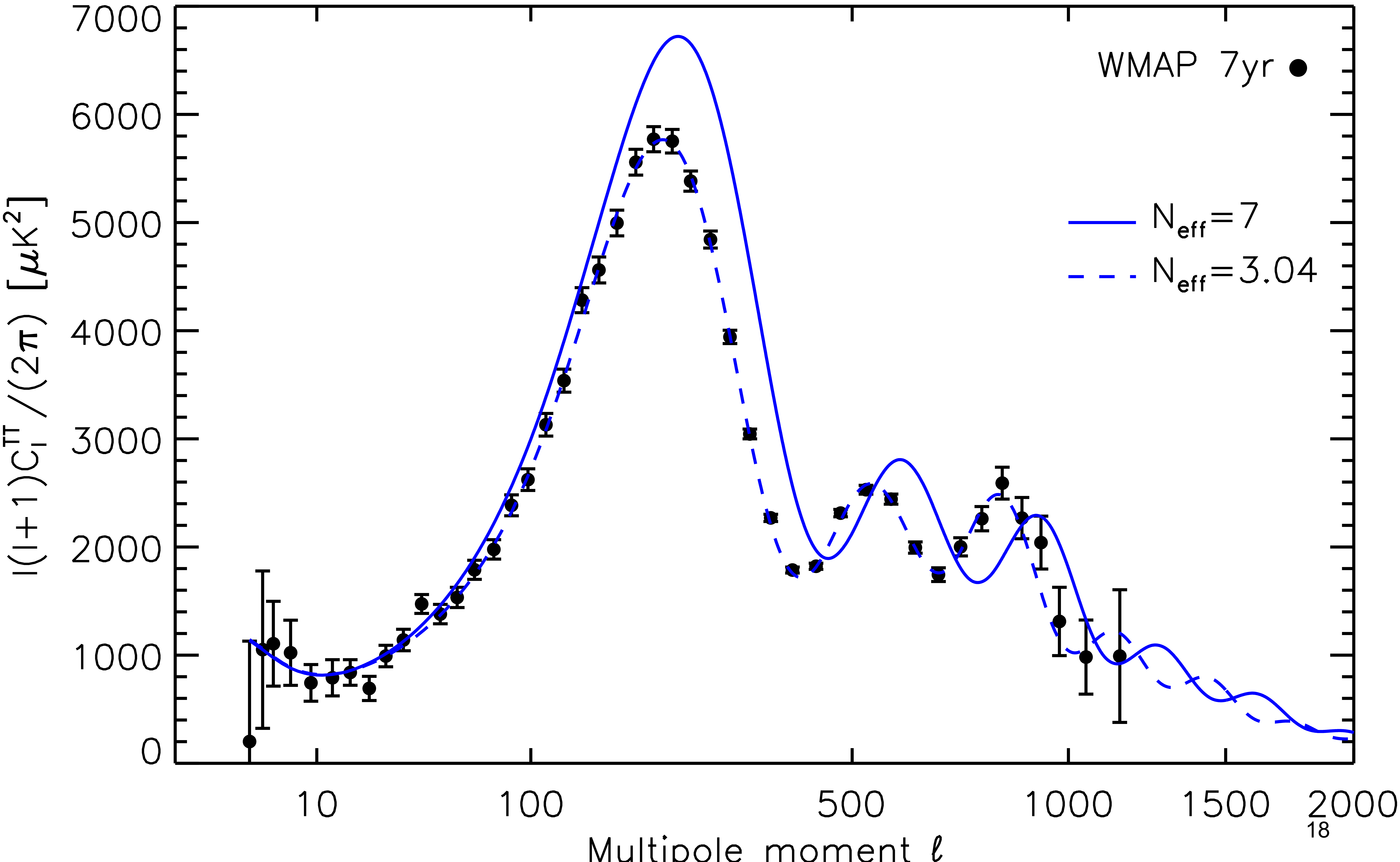
$$\pi_{ij} \equiv \int \frac{d^3p}{(2\pi)^3}\, p \left(\hat{p}_i \hat{p}_j - \frac{1}{3}\delta_{ij} \right) f(\mathbf{x}, \mathbf{p}, t)$$

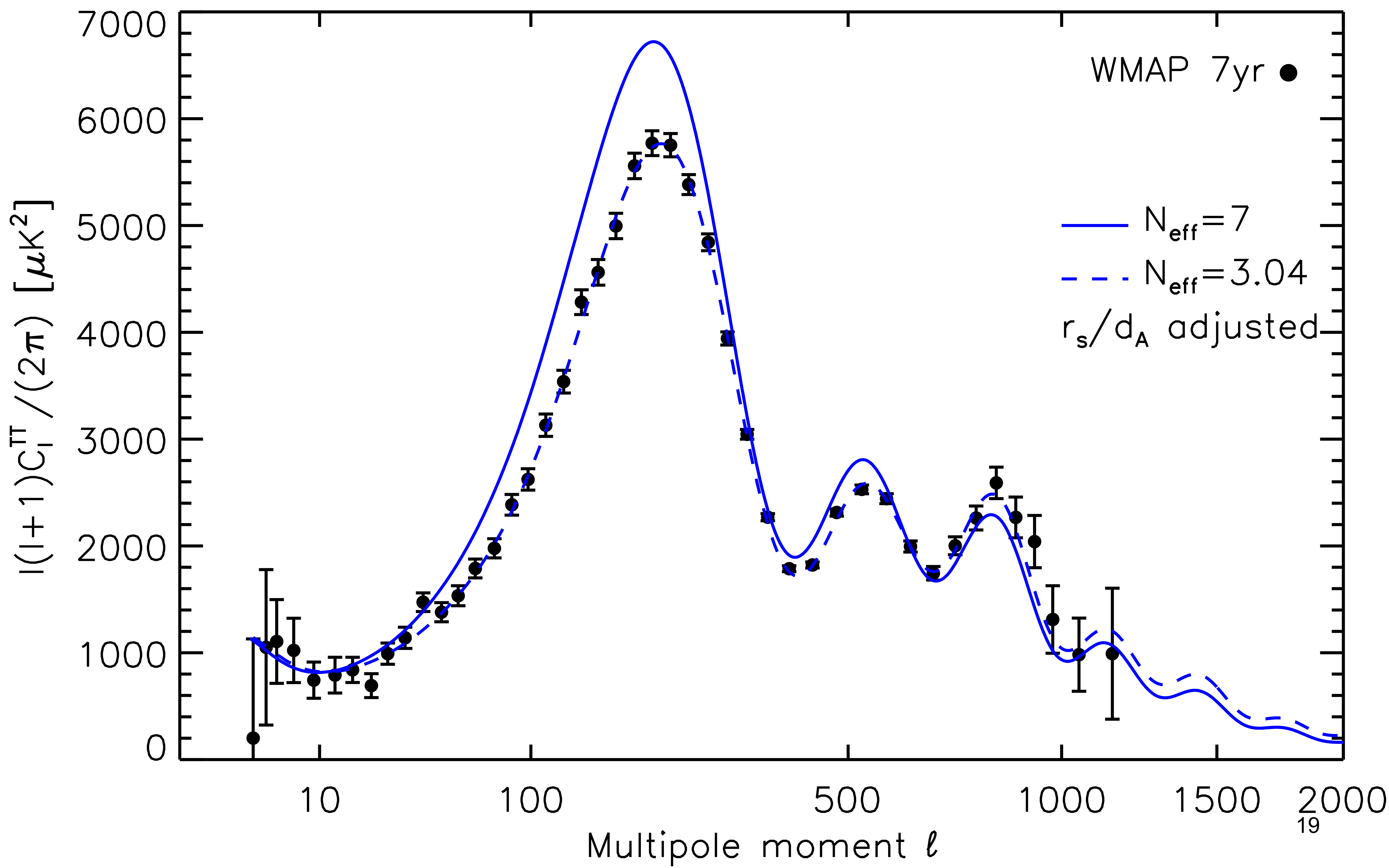
- This changes metric perturbations as

$$k^2 \left(\Phi_H + \Phi_A \right) = -8\pi G \bar{a}^2 \bar{p} \pi$$

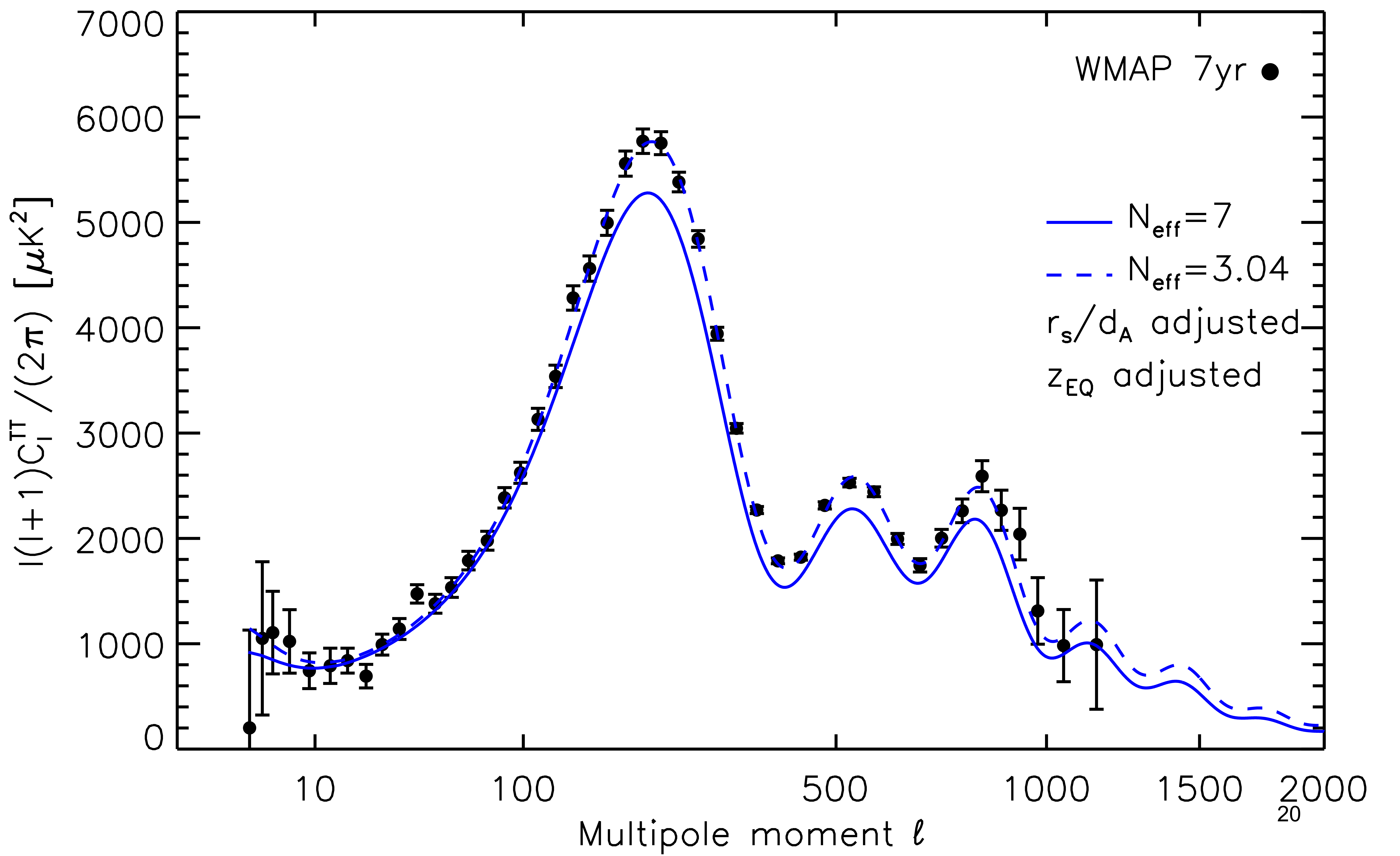
tr(i-j)   0-0

- This changes the early Integrated-Sachs-Wolfe effect (ISW)

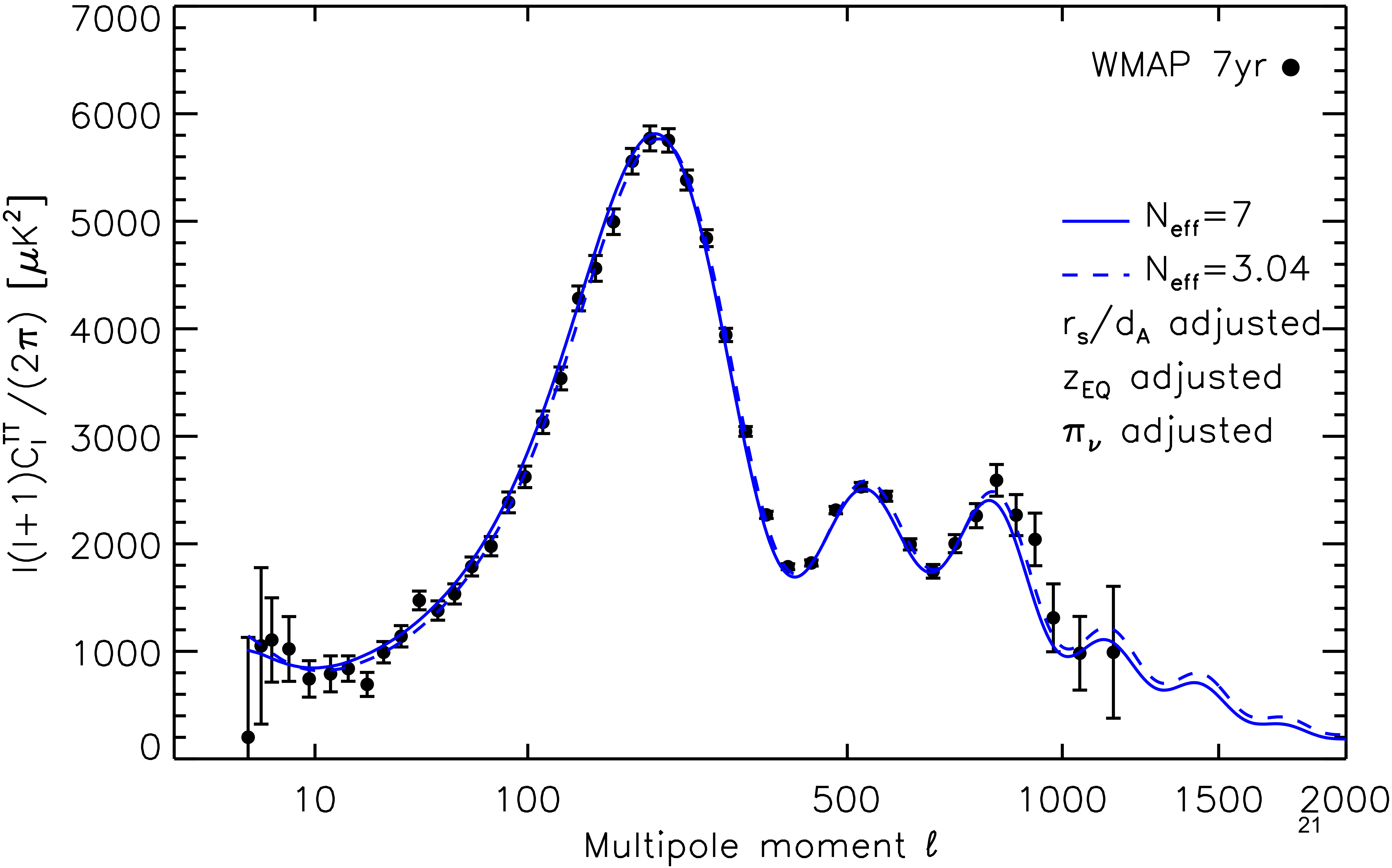

WMAP 7yr
N_eff=7
N_eff=3.04
l(l+1)C_l^TT/(2π) [μK²]
Multipole moment ℓ
0
1000
2000
3000
4000
5000
6000
7000
10
100
500
1000
1500
2000



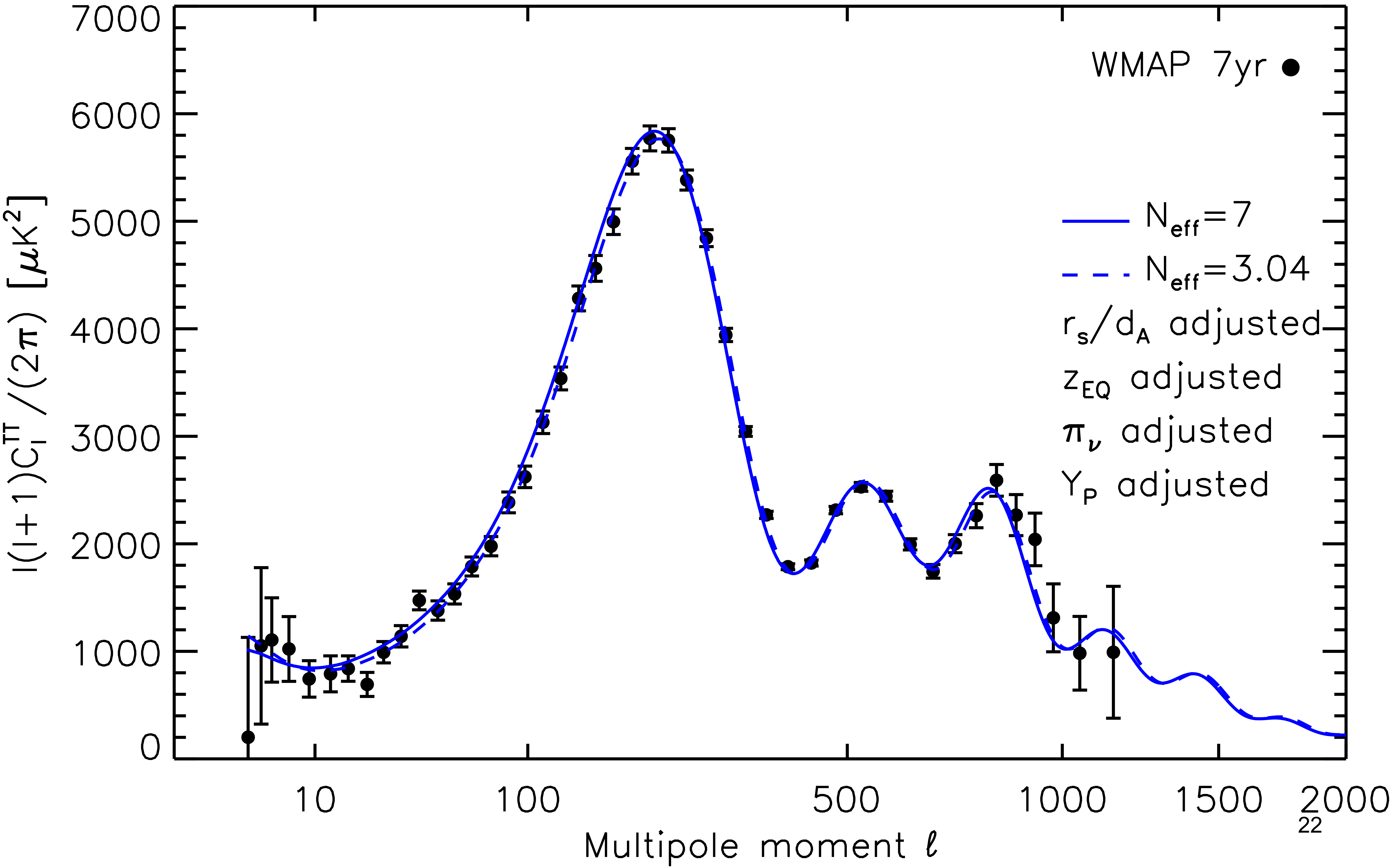
WMAP 7yr
$N_{eff}=7$
$N_{eff}=3.04$
r_s/d_A adjusted
$l(l+1)C_l^{TT}/(2\pi)$ [μK^2]
Multipole moment ℓ
0
1000
2000
3000
4000
5000
6000
7000
10
100
500
1000
1500
2000



WMAP 7yr
$N_{eff}=7$
$N_{eff}=3.04$
r_s/d_A adjusted
z_{EQ} adjusted
$l(l+1)C_l^{TT}/(2\pi)$ [μK^2]
Multipole moment ℓ



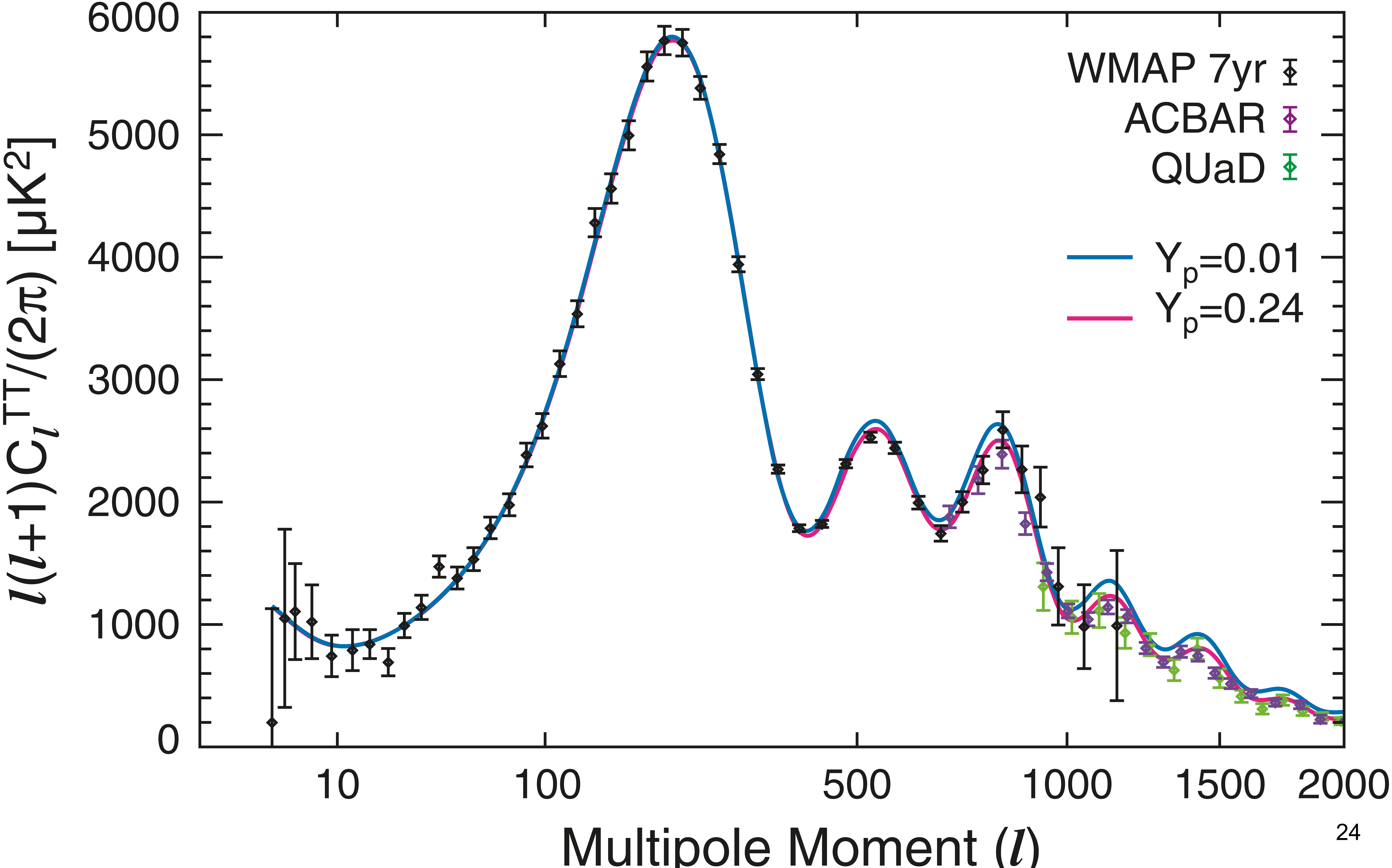
WMAP 7yr
$N_{eff}=7$
$N_{eff}=3.04$
r_s/d_A adjusted
z_{EQ} adjusted
π_ν adjusted
$l(l+1)C_l^{TT}/(2\pi)$ [μK^2]
Multipole moment ℓ
0
1000
2000
3000
4000
5000
6000
7000
10
100
500
1000
1500
2000



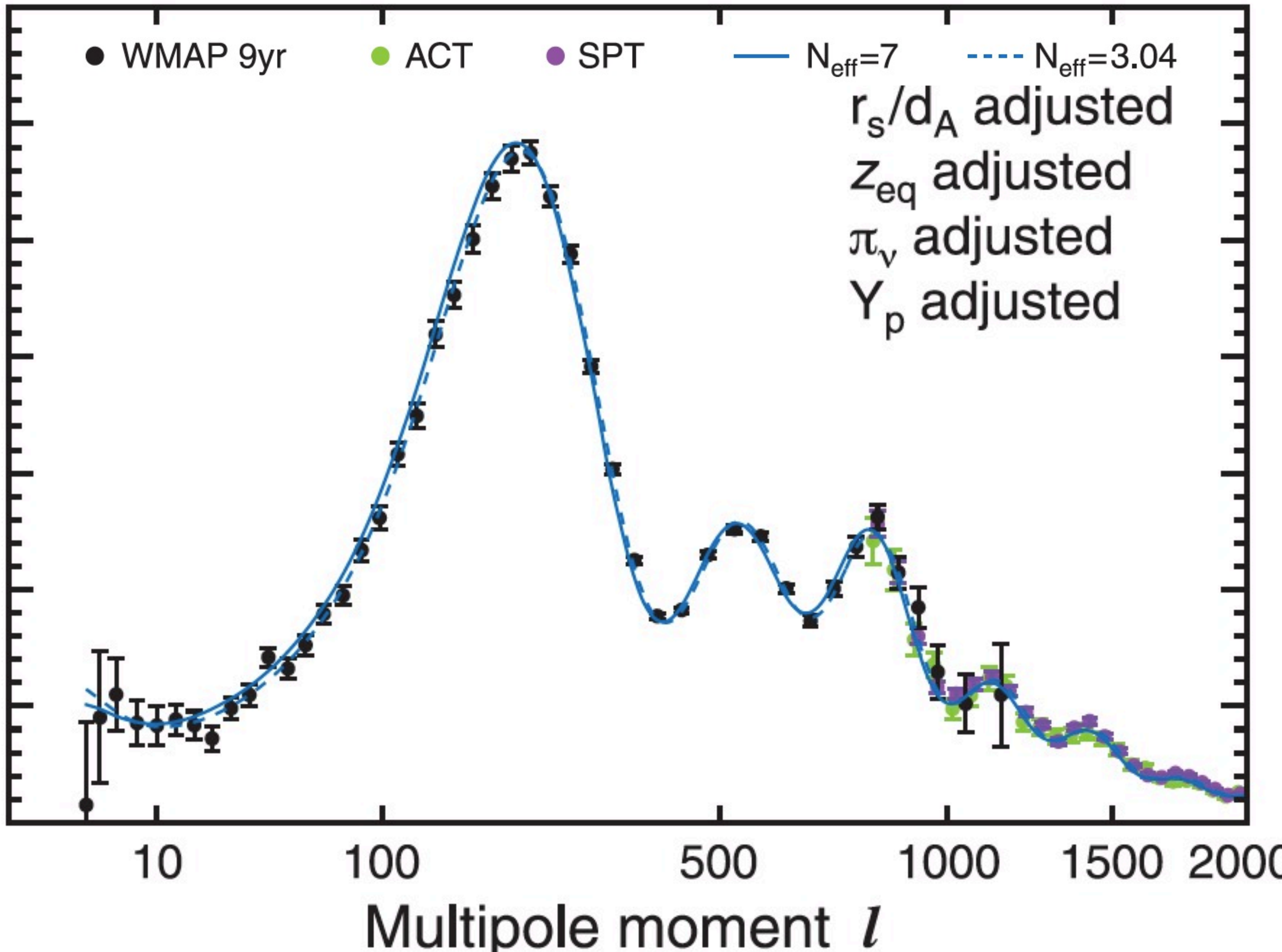
WMAP 7yr
$N_{eff}=7$
$N_{eff}=3.04$
r_s/d_A adjusted
z_{EQ} adjusted
π_ν adjusted
Y_P adjusted
$l(l+1)C_l^{TT}/(2\pi)$ $[\mu K^2]$
Multipole moment ℓ
0
1000
2000
3000
4000
5000
6000
7000
10
100
500
1000
1500
2000

Effect of helium on C_l^{TT}

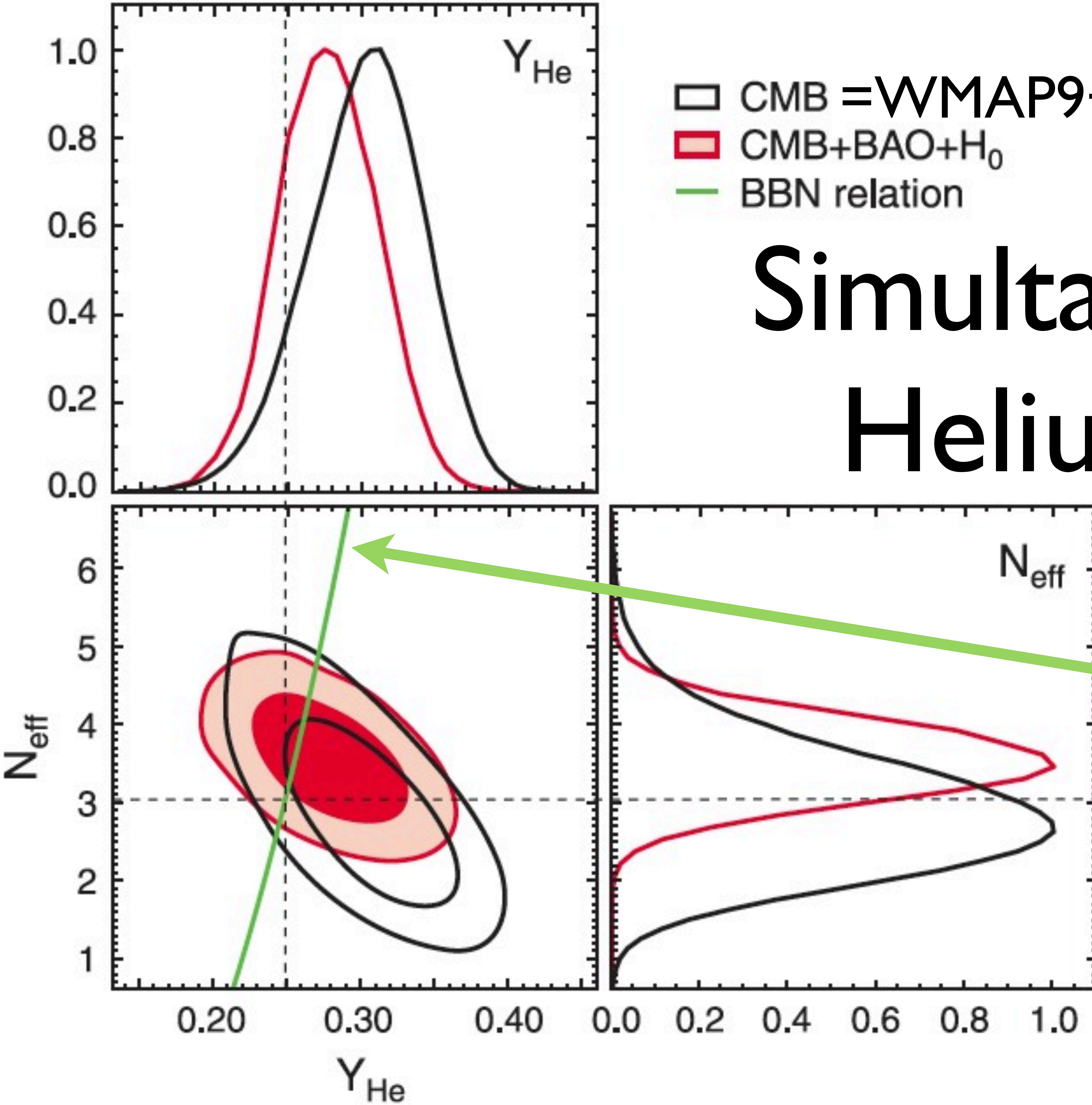
- We measure the baryon number density, n_b, from the 1st-to-2nd peak ratio.
- For a given n_b, we can calculate the number density of electrons: $n_e=(1-Y_p/2)n_b$.
- As helium recombined at z~1800, there were even fewer electrons at the decoupling epoch (z=1090): $n_e=(1-Y_p)n_b$.
- **More helium** = Fewer electrons = Longer photon mean free path $1/(\sigma_T n_e)$ = **Enhanced Silk damping**



WMAP 7yr
ACBAR
QUaD
Y_p=0.01
Y_p=0.24
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
2000
l(l+1)C_l^TT/(2π) [μK^2]
Multipole Moment (l)


WMAP 9yr
ACT
SPT
N_eff=7
N_eff=3.04
r_s/d_A adjusted
z_eq adjusted
π_ν adjusted
Y_p adjusted
10
100
500
1000
1500
2000
Multipole moment l

Simultaneous Fit to Helium and N_{eff}



Results consistent with the BBN prediction

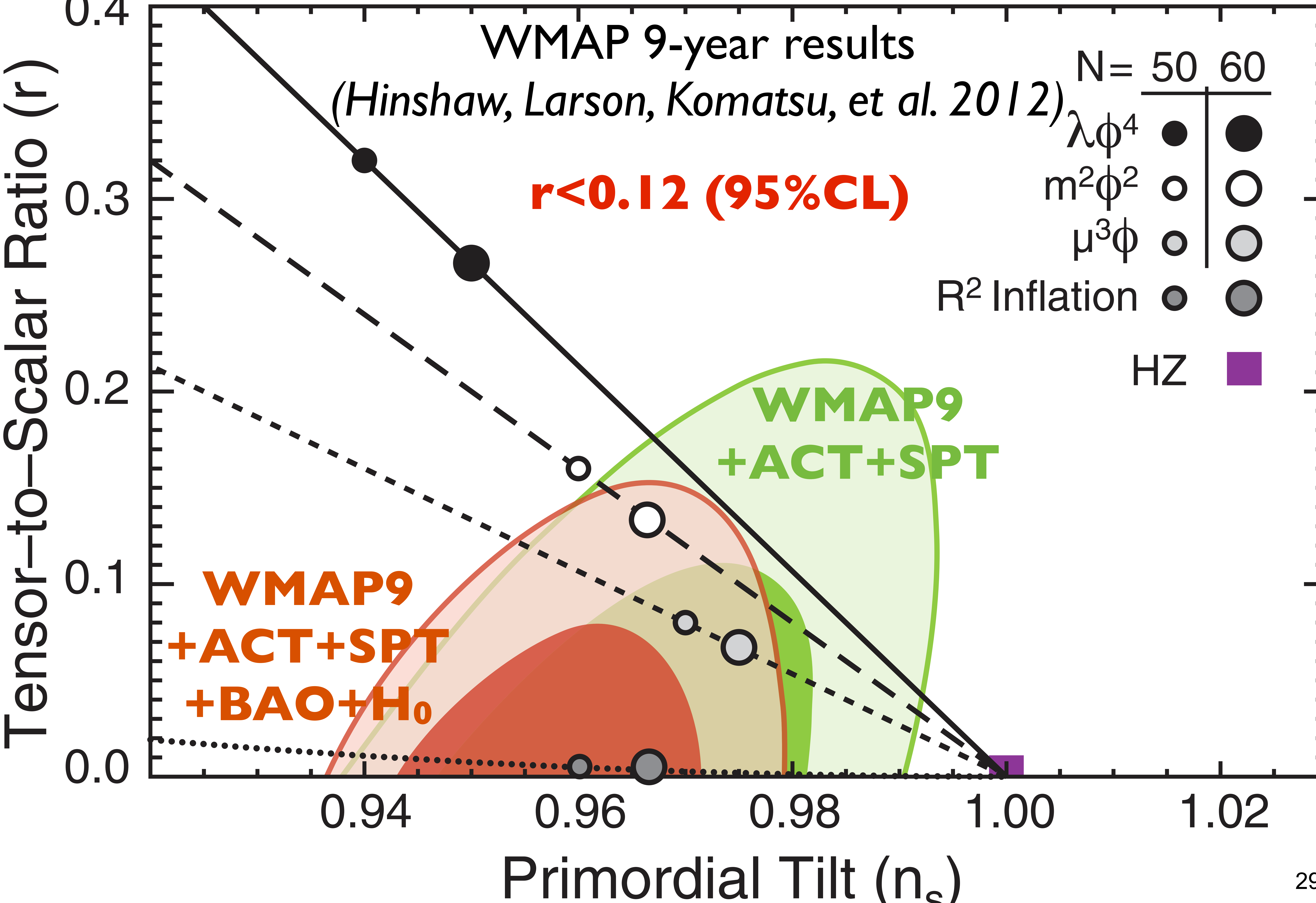
Implications for Inflation

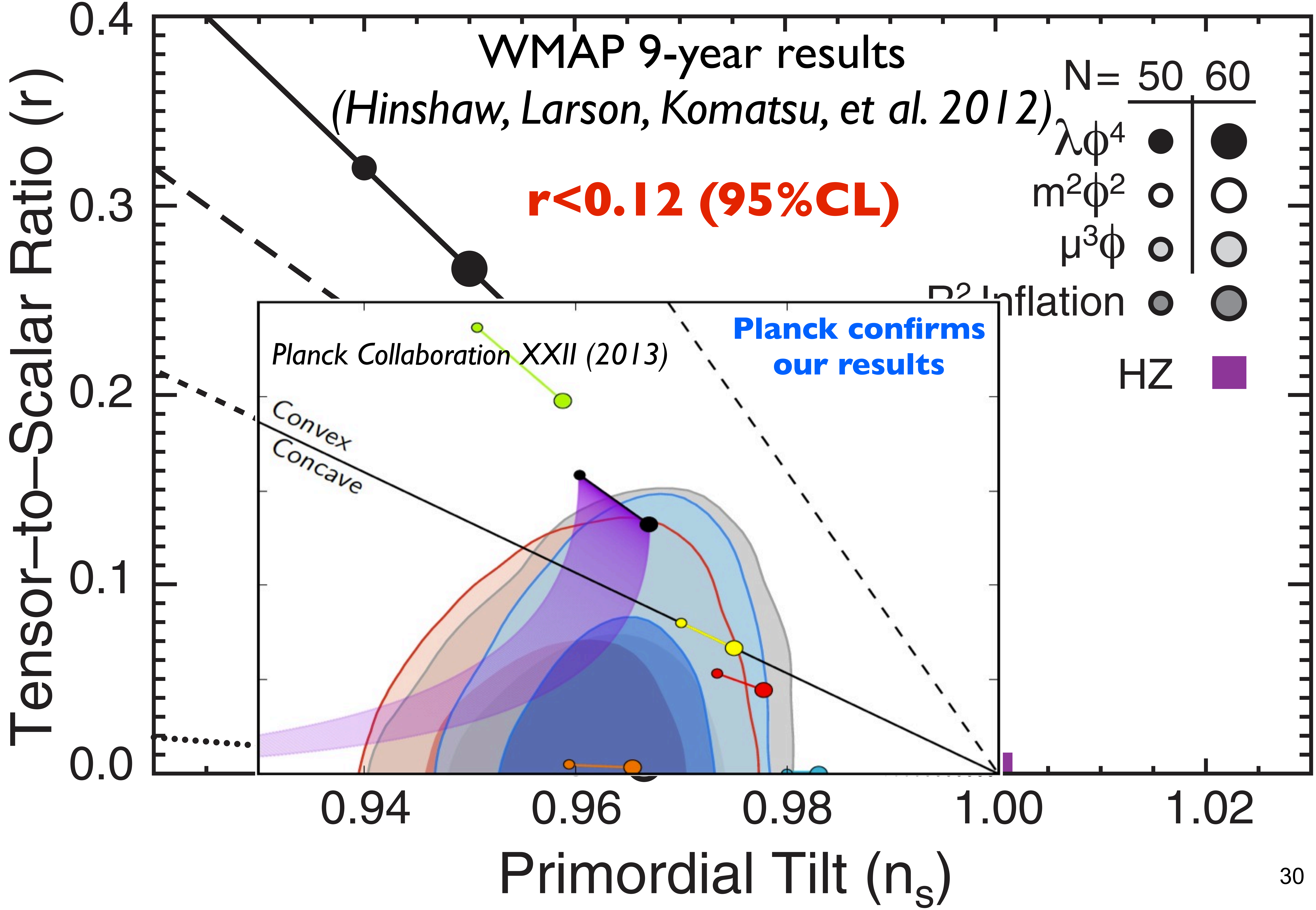
- Two-point function analysis: the tensor-to-scalar ratio, r, and the primordial spectral tilt, n_s
- Three-point function analysis: are fluctuations consistent with Gaussian?

Assuming no tensor modes

- WMAP9 only: $\mathbf{n_s = 0.972 \pm 0.013}$
- WMAP9+CMB: $n_s = 0.965 \pm 0.010$
- WMAP9+CMB+BAO: $n_s = 0.958 \pm 0.008$
- WMAP9+CMB+BAO+H_0: $\mathbf{n_s = 0.961 \pm 0.008}$

- *Confirmed by Planck+WMAP9pol:* $n_s = 0.960 \pm 0.007$


WMAP 9-year results
(Hinshaw, Larson, Komatsu, et al. 2012)
r<0.12 (95%CL)
N= 50 60
λφ4
m2φ2
μ3φ
R2 Inflation
HZ
WMAP9
+ACT+SPT
WMAP9
+ACT+SPT
+BAO+H0
Tensor-to-Scalar Ratio (r)
Primordial Tilt (ns)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02


WMAP 9-year results
(Hinshaw, Larson, Komatsu, et al. 2012)
r<0.12 (95%CL)
N= 50 60
λφ4
m2φ2
μ3φ
R2 Inflation
HZ
Planck Collaboration XXII (2013)
Planck confirms our results
Convex
Concave
Tensor-to-Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (ns)

Congratulations, Slava and Alexei!

GRUBER FOUNDATION

July 11, 2013

COSMOLOGY

2013 Gruber Cosmology Prize Citation

The Gruber Foundation proudly presents the 2013 Cosmology Prize to Viatcheslav Mukhanov and Alexei Starobinsky for their profound contribution to inflationary cosmology and the theory of inflationary perturbations of the metric. These developments changed our views on the origin of our universe and on the mechanism of formation of its structure.

Viatcheslav Mukhanov

Alexei Starobinsky

n_s~0.96 [Mukhanov & Chibisov 1981], now observed;
and the R^2 inflation [Starobinsky 1980], continues to fit the data rather well

R^2 Inflation [Starobinsky 1980]

$$I = \frac{1}{2}\int d^4x\sqrt{-g}\,(R + \alpha R^2)$$

- This theory is conformally equivalent to a theory with a canonically normalized scalar field with a potential given by

$$V(\Psi) = \frac{1}{8\alpha}\left(1 - e^{-\sqrt{2/3}\Psi}\right)^2$$

where [very flat potential for large Ψ –> smaller r]

$$\Psi = \sqrt{3/2}\,\ln(1 + 2\alpha R)$$

$\xi\varphi^2 R$ [Futamase & Maeda1989]

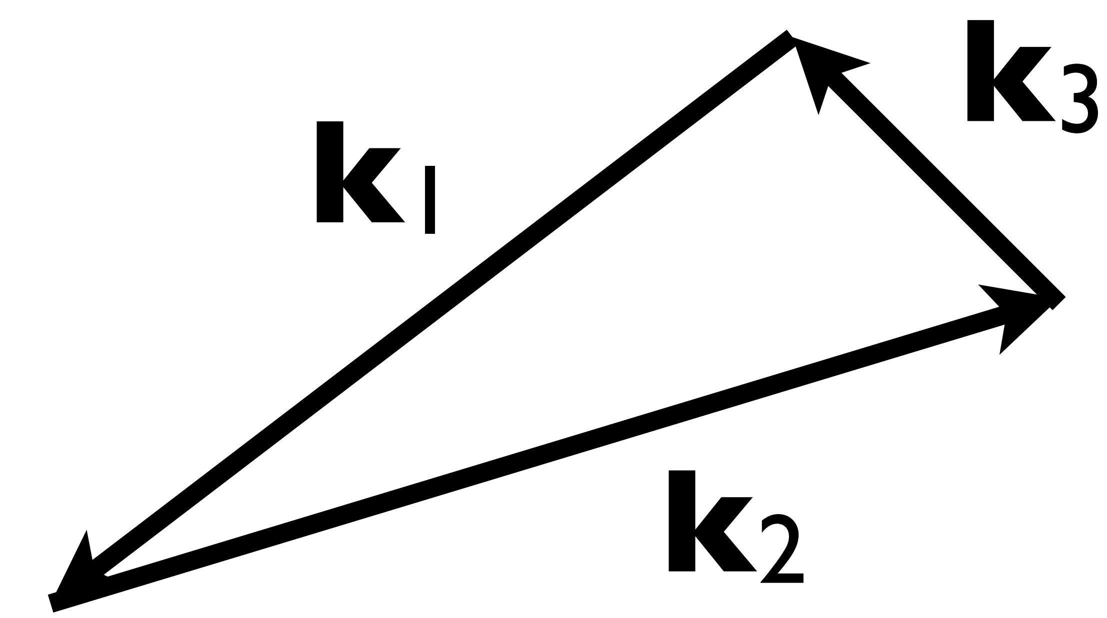
$$I = \frac{1}{2}\int d^4x\sqrt{-g}\left(1+\xi\phi^2\right)R$$

- The predictions of this model for the tilt and tensor-to-scalar ratio are identical to R^2 inflation! Komatsu & Futamase (1999) showed:

$$r = \frac{12}{N^2}\frac{1+6\xi}{6\xi} \sim 0.005$$

- So, the tensor-to-scalar ratio is tiny.

Bispectrum

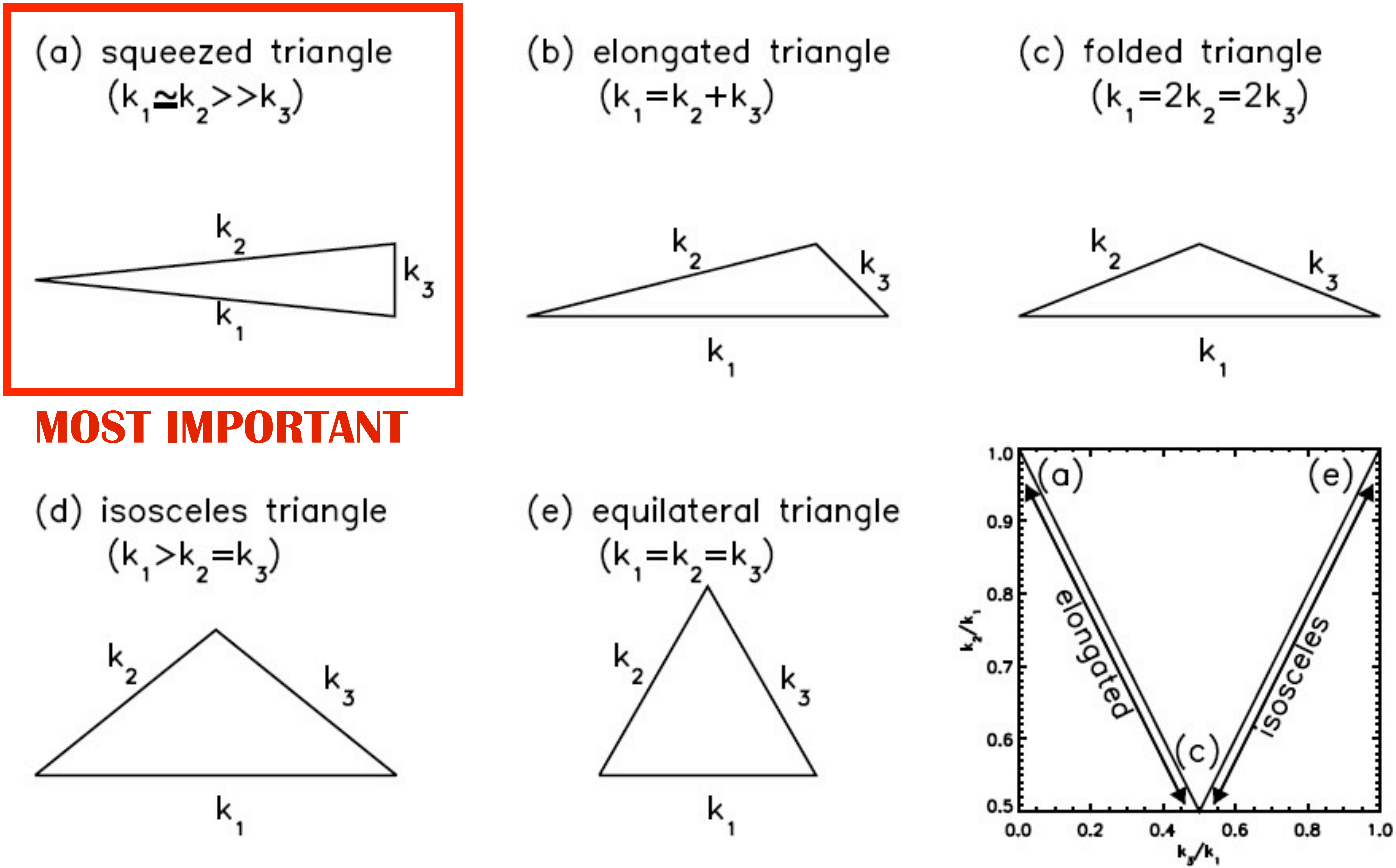


- Three-point function!
- $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$
  $= \langle \zeta_{\mathbf{k}1}\zeta_{\mathbf{k}2}\zeta_{\mathbf{k}3} \rangle = (\text{amplitude}) \times (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)F(k_1,k_2,k_3)$

model-dependent function

Primordial fluctuation

"f_{NL}"


(a) squeezed triangle
(k1≃k2>>k3)
MOST IMPORTANT
(b) elongated triangle
(k1=k2+k3)
(c) folded triangle
(k1=2k2=2k3)
(d) isosceles triangle
(k1>k2=k3)
(e) equilateral triangle
(k1=k2=k3)
k1
k2
k3
elongated
isosceles
k2/k1
k3/k1
0.0
0.2
0.4
0.6
0.8
1.0
0.5
0.6
0.7
0.8
0.9
1.0

Probing Inflation (3-point Function)

- Inflation models predict that primordial fluctuations are very close to Gaussian.
  - In fact, ALL SINGLE-FIELD models predict a particular form of 3-point function to have the amplitude of $f_{NL}=0.02$.
  - Detection of $f_{NL}>1$ would rule out ALL single-field models!
- No detection of 3-point functions of primordial curvature perturbations. The 68% CL limit is:
  - **$f_{NL} = 37 \pm 20$ (1σ)**
  - The WMAP data are consistent with the prediction of **simple single-field inflation** models: $1-n_s \approx r \approx f_{NL}$

PHYSICAL REVIEW D, VOLUME 63, 063002 *Komatsu&Spergel (2001)*

Acoustic signatures in the primary microwave background bispectrum

Eiichiro Komatsu* and David N. Spergel†
Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544
(Received 25 October 2000; published 13 February 2001)

If the primordial fluctuations are non-Gaussian, then this non-Gaussianity will be apparent in the cosmic microwave background (CMB) sky. With their sensitive all-sky observation, MAP and Planck satellites should be able to detect weak non-Gaussianity in the CMB sky. On a large angular scale, there is a simple relationship between the CMB temperature and the primordial curvature perturbation: $\Delta T/T = -\Phi/3$. On smaller scales, however, the radiation transfer function becomes more complex. In this paper, we present the angular bispectrum of the primary CMB anisotropy that uses the full transfer function. We find that the bispectrum has a series of acoustic peaks that change a sign and a period of acoustic oscillations is twice as long as that of the angular power spectrum. Using a single non-linear coupling parameter to characterize the amplitude of the bispectrum, we estimate the expected signal-to-noise ratio for COBE, MAP, and Planck experiments. In order to detect the primary CMB bispectrum by each experiment, we find that the coupling parameter should be larger than 600, 20, and 5 for COBE, MAP, and Planck experiments, respectively. Even for the ideal noise-free and infinitesimal thin-beam experiment, the parameter should be larger than 3. We have included effects from the cosmic variance, detector noise, and foreground sources in the signal-to-noise estimation. Since the simple inflationary scenarios predict that the parameter is an order of 0.01, the detection of the primary bispectrum by any kind of experiments should be problematic for those scenarios. We compare the sensitivity of the primary bispectrum to the primary skewness and conclude that, when we can compute the predicted form of the bispectrum, it becomes a "matched filter" for detecting the non-Gaussianity in the data and a much more powerful tool than the skewness. For example, we need the coupling parameter of larger than 800, 80, 70, and 60 for each relevant experiment in order to detect the primary skewness. We also show that MAP and Planck can separate the primary bispectrum from various secondary bispectra on the basis of the shape difference. The primary CMB bispectrum is a test of the inflationary scenario and also a probe of the non-linear physics in the very early universe.

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Acoustic signatures in the primary microwave background bispectrum

Eiichiro Komatsu* and David N. Spergel†
Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544
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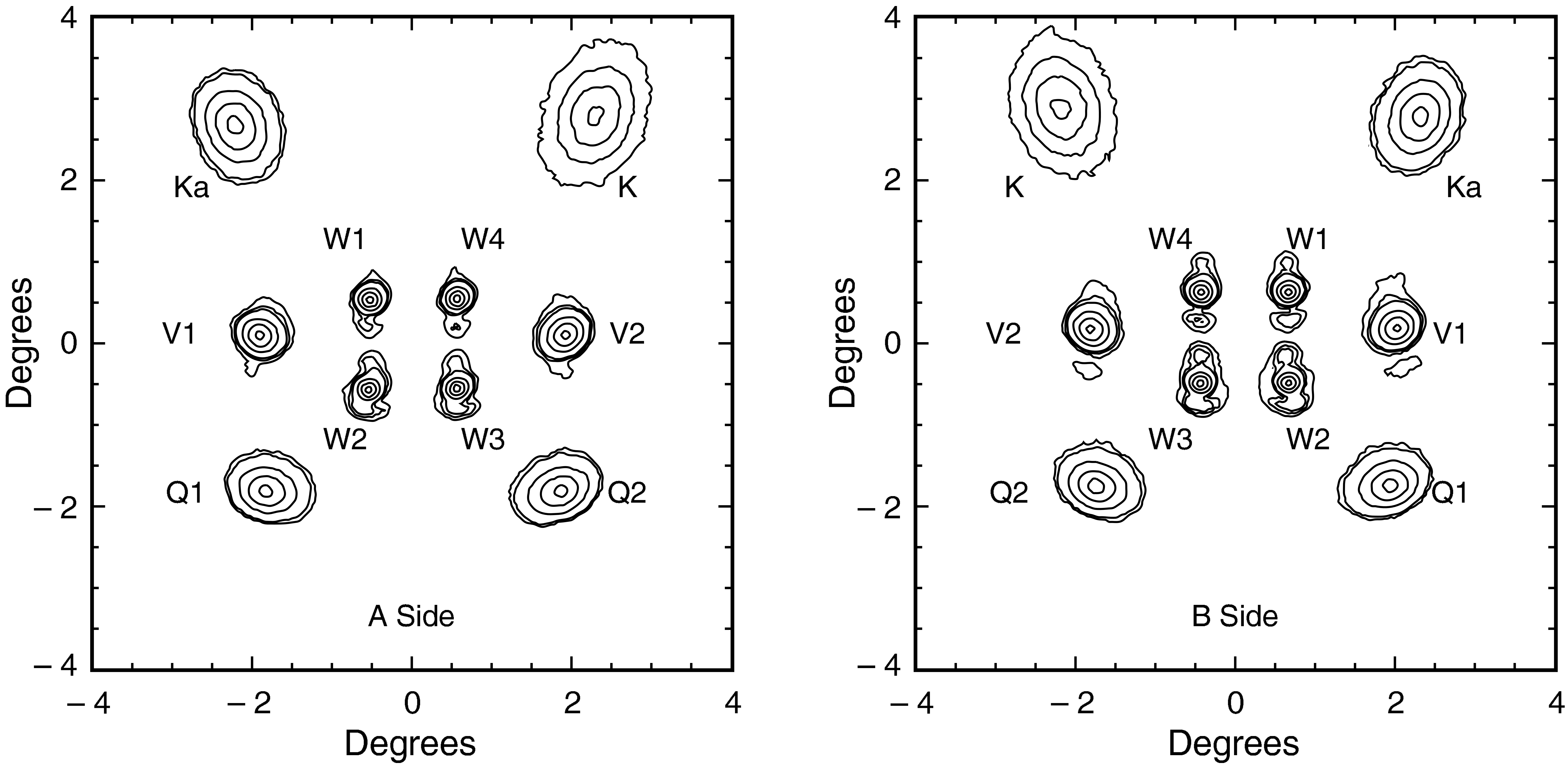
If the primordial fluctuations are non-Gaussian, then this non-Gaussianity will be apparent in the cosmic microwave background (CMB) sky. With their sensitive all-sky observation, MAP and Planck satellites should be able to detect weak non-Gaussianity in the CMB sky. On a large angular scale, there is a simple relationship between the CMB temperature and the primordial curvature perturbation: $\Delta T/T = -\Phi/3$. On smaller scales, however, the radiation transfer function becomes more complex. In this paper, we present the angular bispectrum of the primary CMB anisotropy that uses the full transfer function. We find that the bispectrum has a

Planck Result: $f_{NL} = 2.7 \pm 5.8$ (68%CL)

to detect the primary CMB bispectrum by each experiment, we find that the coupling parameter should be larger than 600, 20, and 5 for COBE, MAP, and Planck experiments, respectively. Even for the ideal noise-free and infinitesimal thin-beam experiment, the parameter should be larger than 3. We have included effects from the cosmic variance, detector noise, and foreground sources in the signal-to-noise estimation. Since the simple inflationary scenarios predict that the parameter is an order of 0.01, the detection of the primary bispectrum by any kind of experiments should be problematic for those scenarios. We compare the sensitivity of the primary bispectrum to the primary skewness and conclude that, when we can compute the predicted form of the bispectrum, it becomes a "matched filter" for detecting the non-Gaussianity in the data and a much more powerful tool than the skewness. For example, we need the coupling parameter of larger than 800, 80, 70, and 60 for each relevant experiment in order to detect the primary skewness. We also show that MAP and Planck can separate the primary bispectrum from various secondary bispectra on the basis of the shape difference. The primary CMB bispectrum is a test of the inflationary scenario and also a probe of the non-linear physics in the very early universe.

Statistical Anisotropy

- Is the power spectrum anisotropic?
  - $P(\mathbf{k}) = P(|\mathbf{k}|)[1+g^*(\cos\theta)^2]$
- This makes shapes of temperature spots anisotropic on the sky.
- Statistically significant detection of g^*
  - Is this cosmological?
  - The answer is no: the same (identical!) effect can be caused by **ellipticity of beams**



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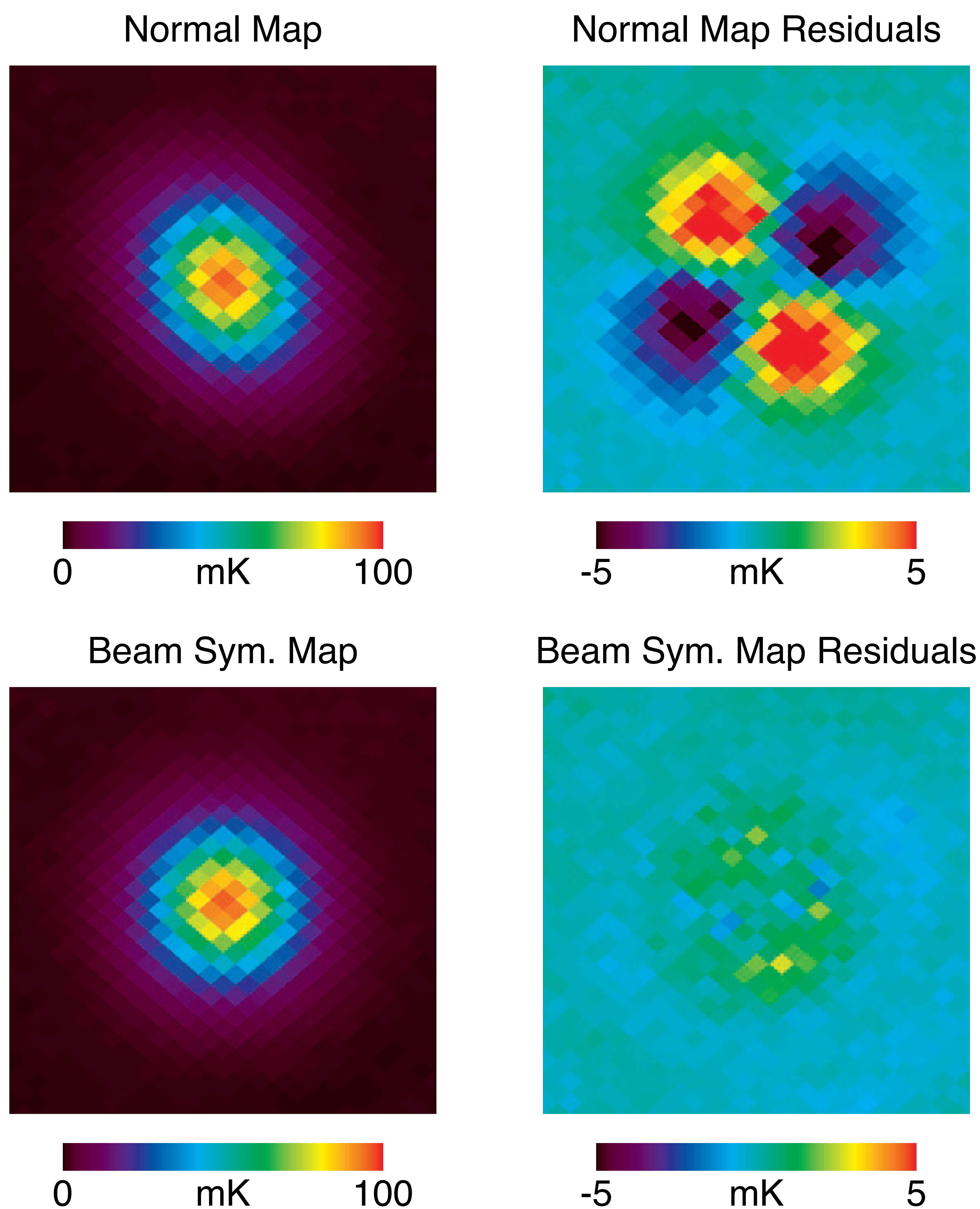
This is coupled with the scan pattern

- WMAP scans the ecliptic poles many more times and from different orientations.
  - Thus, the averaged beam is nearly circular in the poles.
- The ecliptic plane is scanned less frequently and from limited orientations.
  - Thus, the averaged beam is more elliptical in the plane.
- This is exactly what the anisotropic power spectrum gives.

Creating a map with a circular beam

- We create a map in which the elliptical beam shape is deconvolved. The resulting map has an effective circular beam.
- This map is not used for cosmology, but used for the analysis of foregrounds and statistical anisotropy.



- A deconvolved image of a supernova remnant “Tau A” at 23 GHz
- Deconvolved image is more circular, as expected
- **Deconvolved map does not show the anisotropic power spectrum anymore!**

Summary

- The minimal, 6-parameter ΛCDM model continues to describe all the data we have
    - No significant deviation from the minimal model
- Rather stringent constraints on inflation models
- Strong support for Big Bang nucleosynthesis with the standard effective number of neutrino species
- Anisotropic power spectrum is due to elliptical beams

"These results ... complete the *WMAP* Team's formal analysis and interpretation of the *WMAP* data." (Hinshaw et al. 2012)