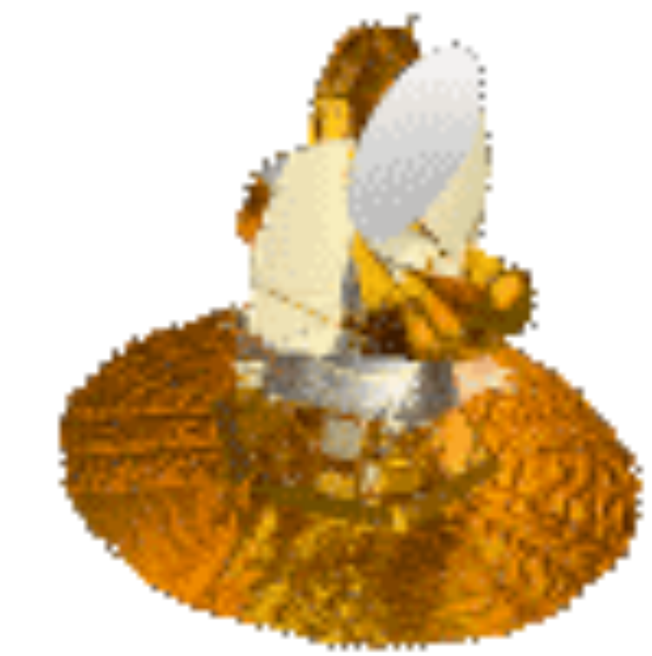


Critical Tests of Theory of the Early Universe Using the Cosmic Microwave Background

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
Colloquium, IAP, November 9, 2012

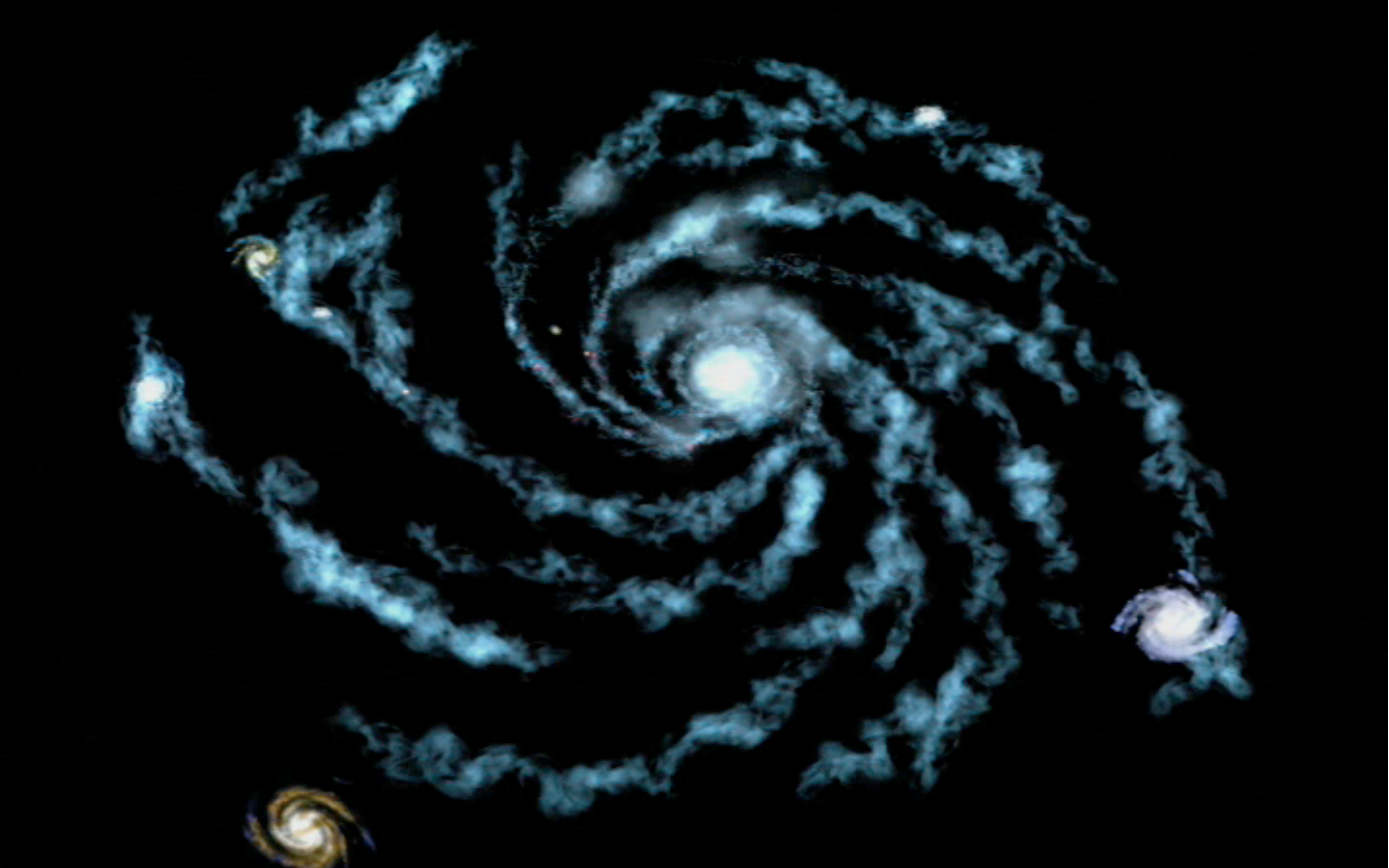
The Breakthrough

- Now we can **observe** the physical condition of the Universe when it was very young.

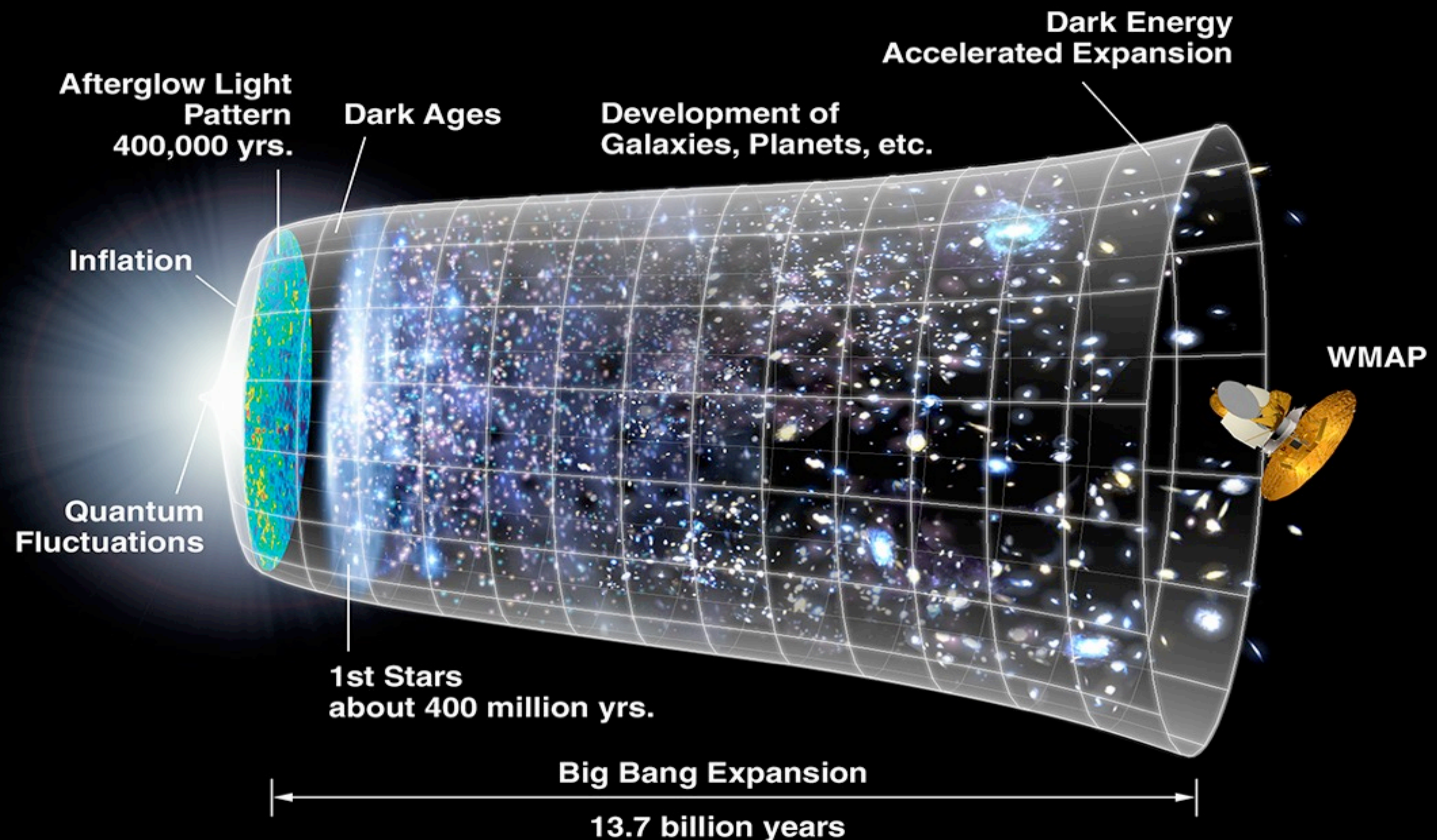
Cosmic Microwave Background (CMB)

- Fossil light of the Big Bang!

From "Cosmic Voyage"



CMB: The Farthest and Oldest Light That We Can Ever Hope To Observe Directly



- When the Universe was 3000K (~380,000 years after the Big Bang), electrons and protons were combined to form neutral hydrogen.

NASA/WMAP Science Team

used to be

WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

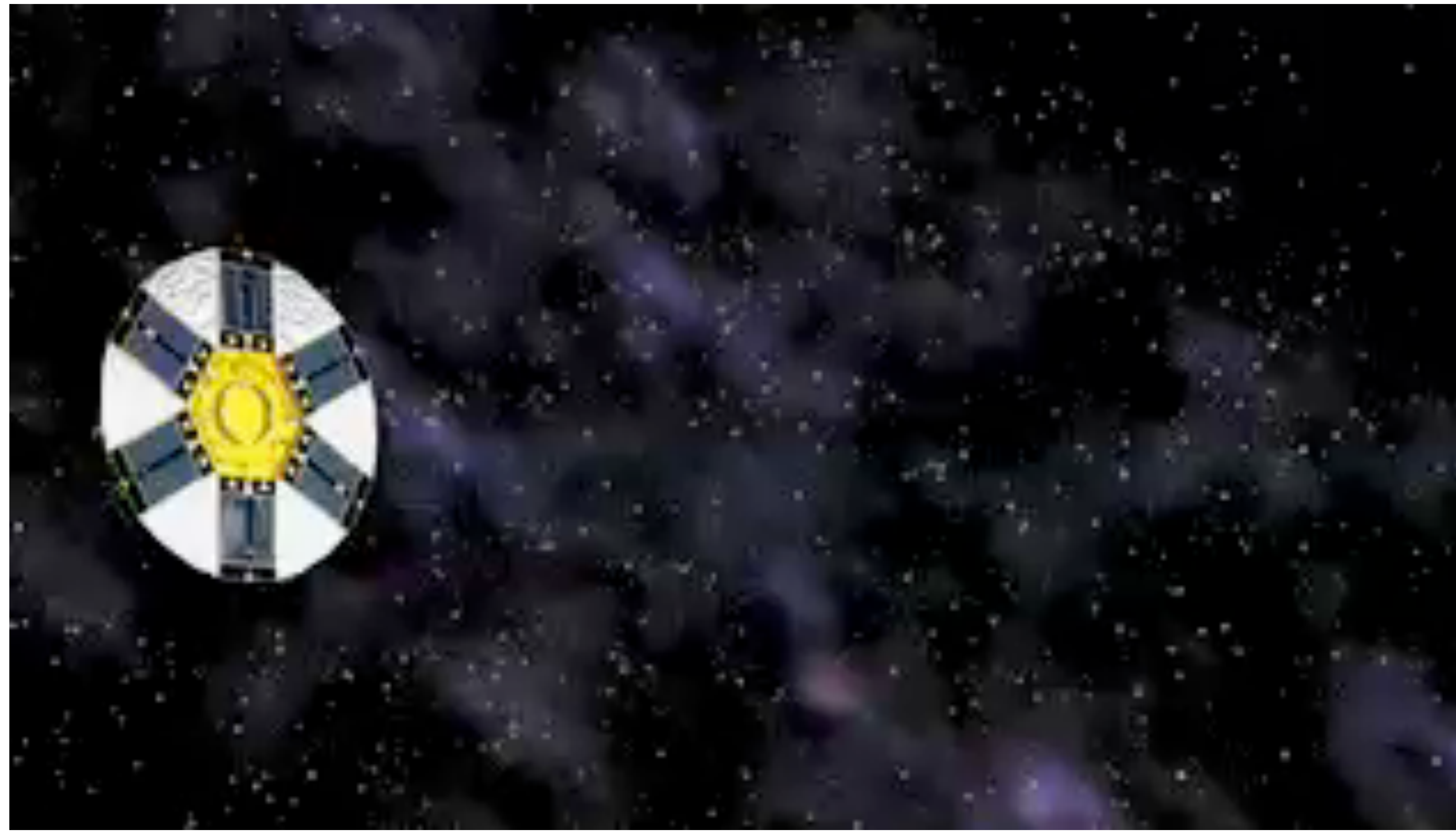
February 2003:
The first-year data release

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



- L2 is 1.6 million kilometers from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them

used to be

WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

February 2003:
The first-year data releas

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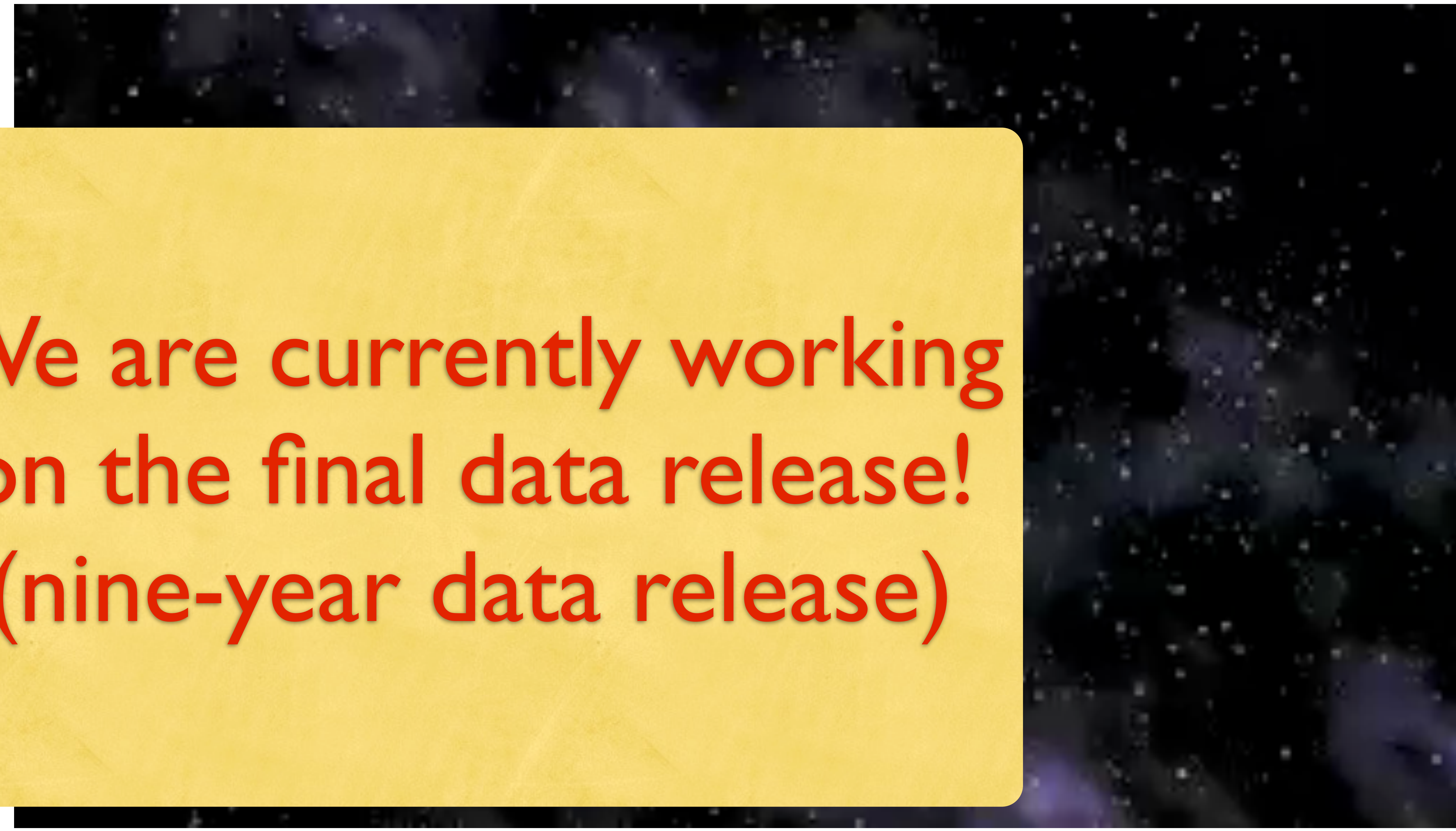
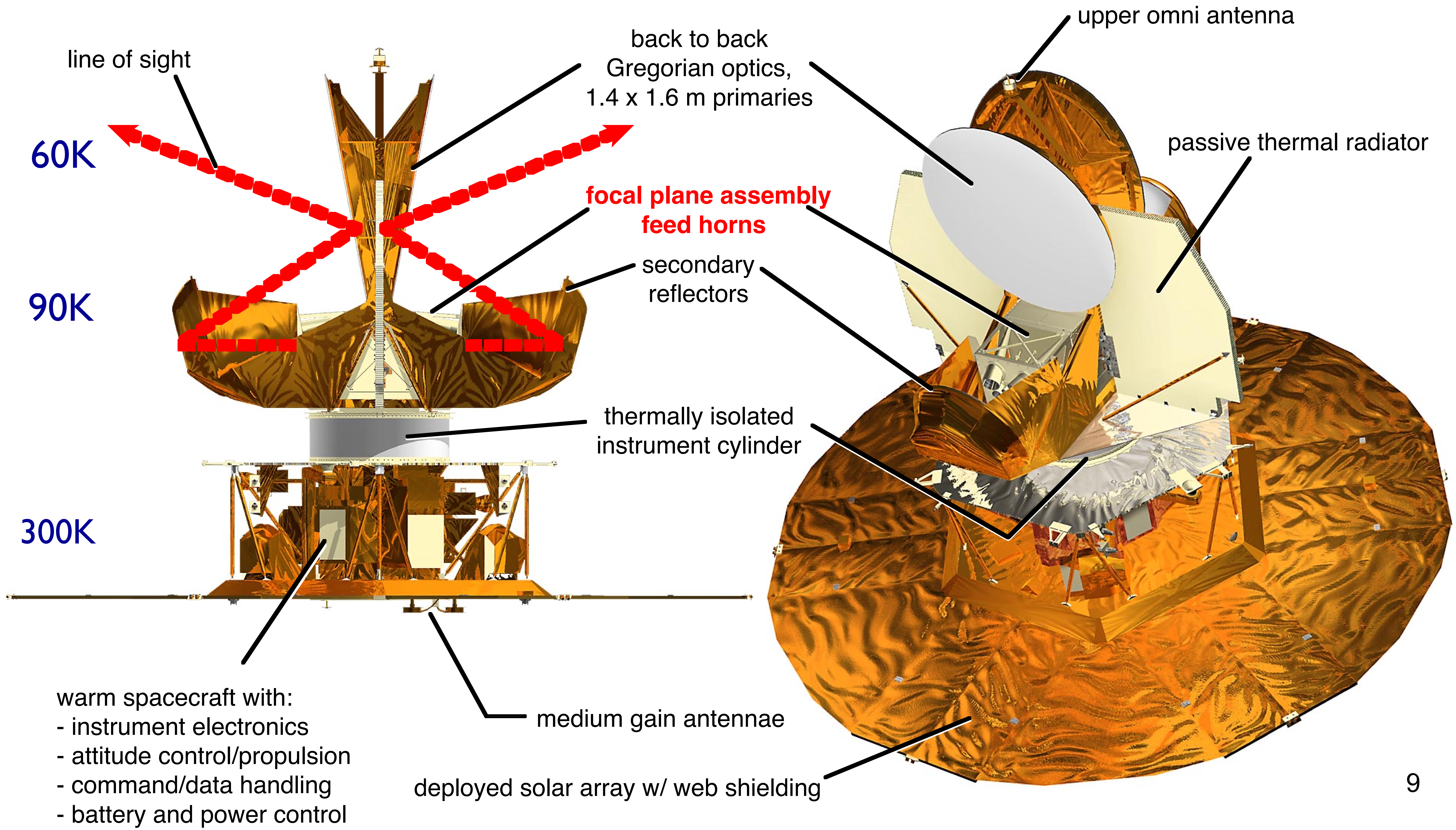


We are currently working on the final data release!
(nine-year data release)

- L2 is 1.6 million kilometers from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them

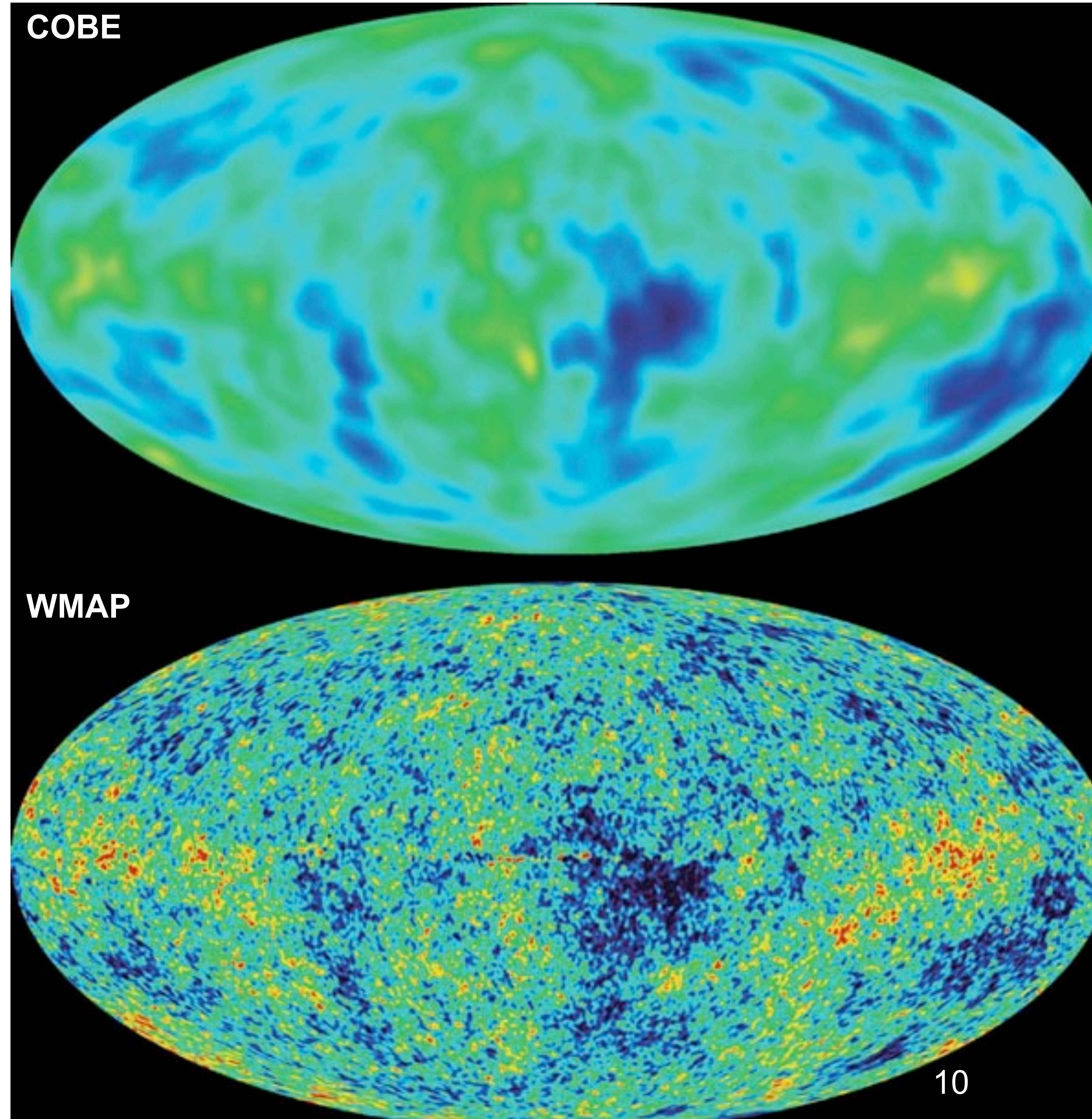
WMAP Spacecraft

Radiative Cooling: No Cryogenic System



COBE to WMAP (x35 better resolution)

COBE
1989



WMAP
2001

WMAP 7-Year Science Team

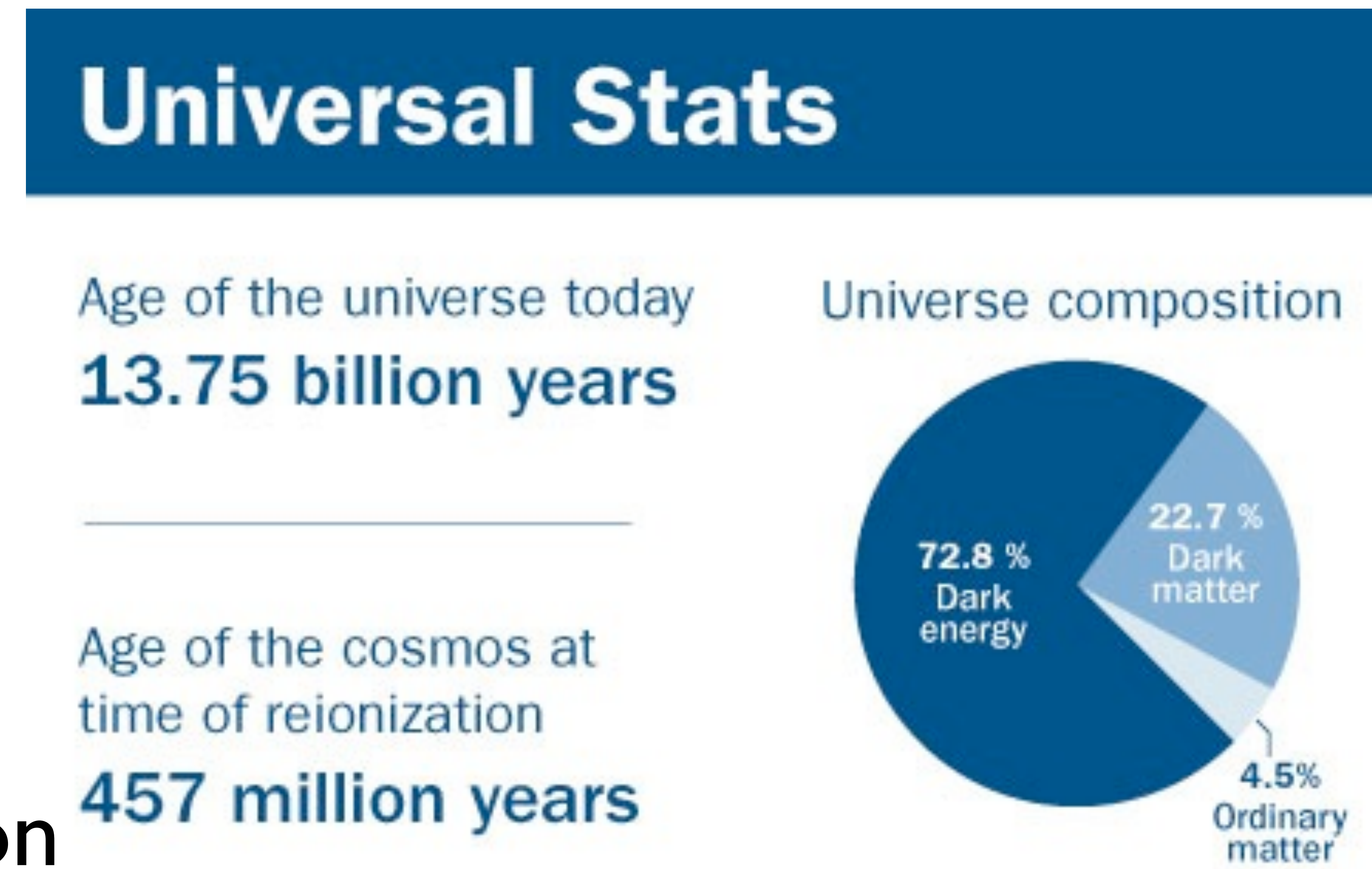
- C.L. Bennett
- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright
- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
- M. Limon
- N. Odegard
- G.S. Tucker
- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta
- K.M. Smith
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

WMAP 7-Year Papers

- **Jarosik et al.**, "*Sky Maps, Systematic Errors, and Basic Results*" Astrophysical Journal Supplement Series (ApJS), 192, 14 (2011)
- **Gold et al.**, "*Galactic Foreground Emission*" ApJS, 192, 15 (2011)
- **Weiland et al.**, "*Planets and Celestial Calibration Sources*" ApJS, 192, 19 (2011)
- **Bennett et al.**, "*Are There CMB Anomalies?*" ApJS, 192, 17 (2011)
- **Larson et al.**, "*Power Spectra and WMAP-Derived Parameters*" ApJS, 192, 16 (2011)
- **Komatsu et al.**, "*Cosmological Interpretation*" ApJS, 192, 18 (2011)

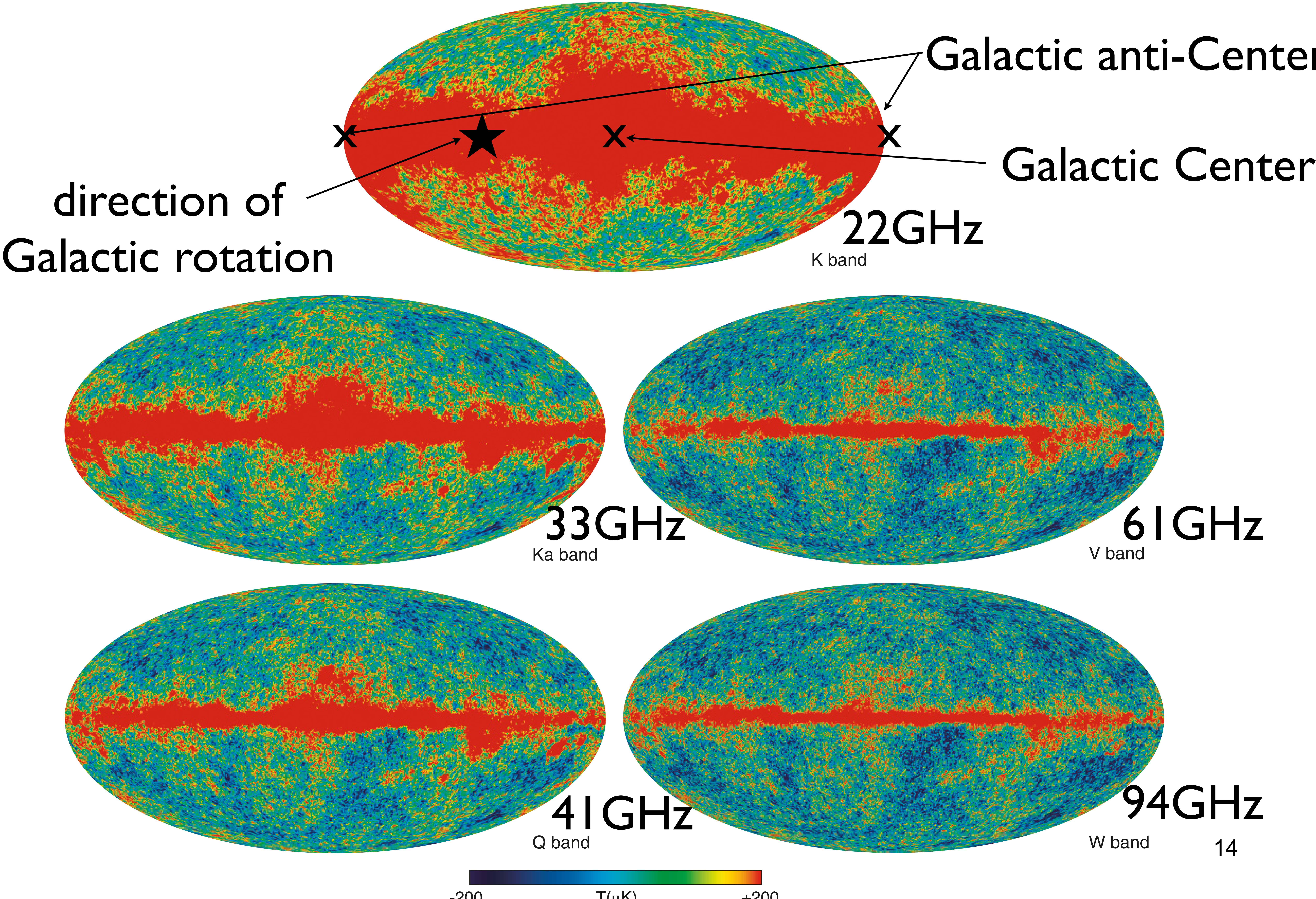
Cosmic Pie Chart: 7-year

- **Standard Model**
  - H&He = **4.58**% (±0.16%)
  - Dark Matter = **22.9**% (±1.5%)
  - Dark Energy = **72.5**% (±1.6%)
  - H_0=70.2±1.4 km/s/Mpc
  - Age of the Universe = 13.76 billion years (±0.11 billion years)



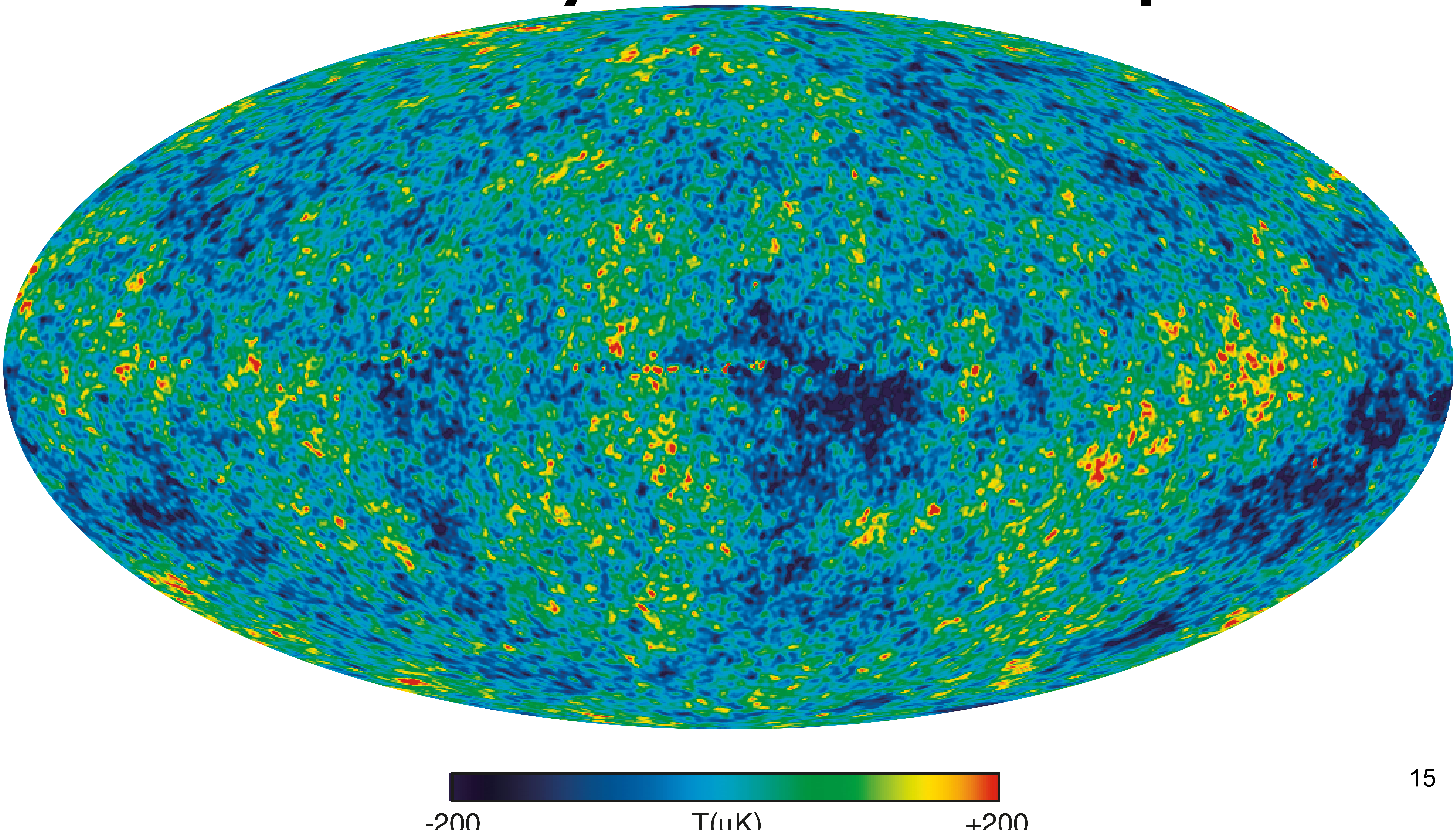
"ScienceNews" article on the WMAP 7-year results

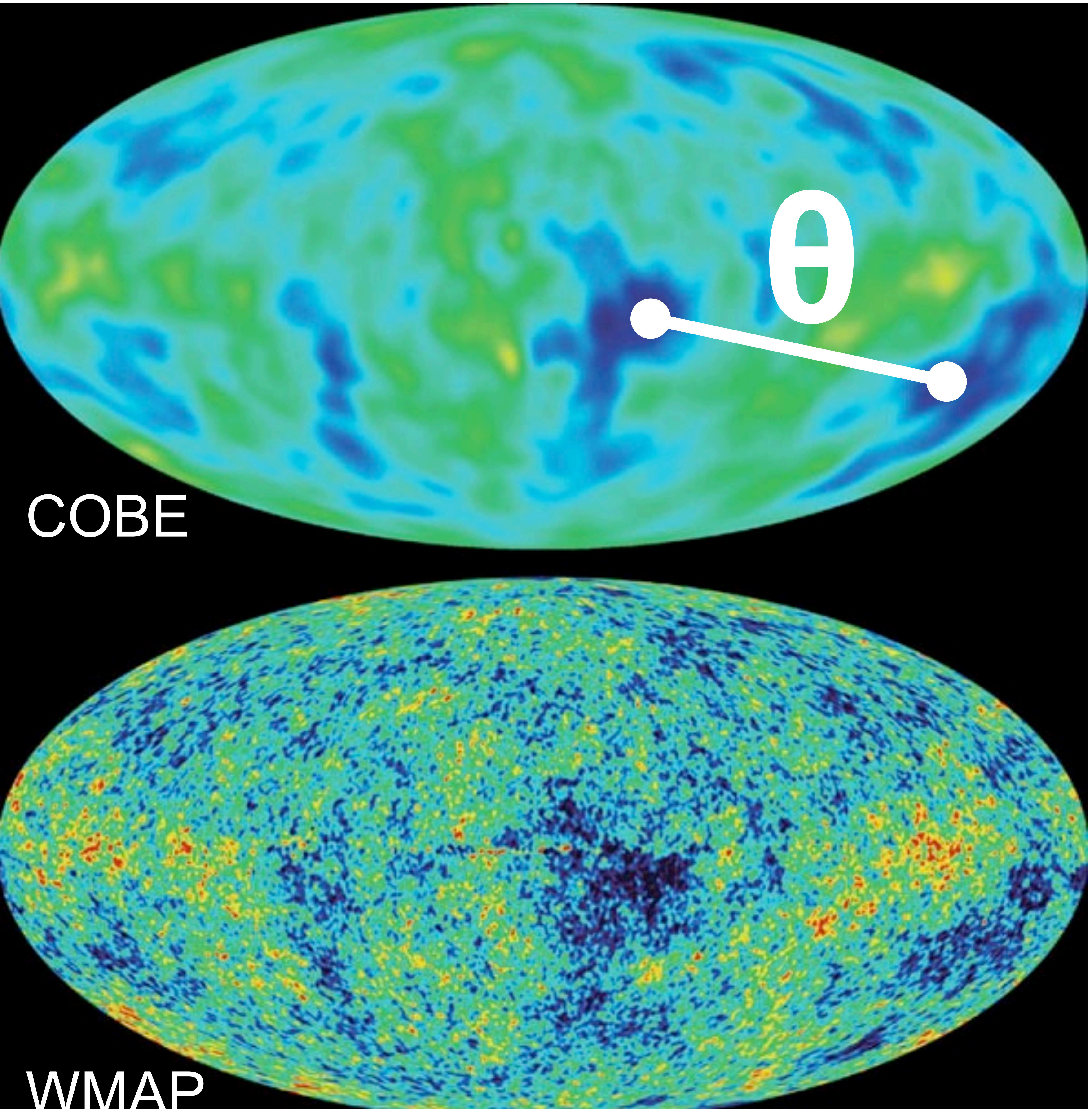
How did we obtain these numbers?



Galactic anti-Center
Galactic Center
direction of
Galactic rotation
22GHz
K band
33GHz
Ka band
61GHz
V band
41GHz
Q band
94GHz
W band
-200
T(μK)
+200

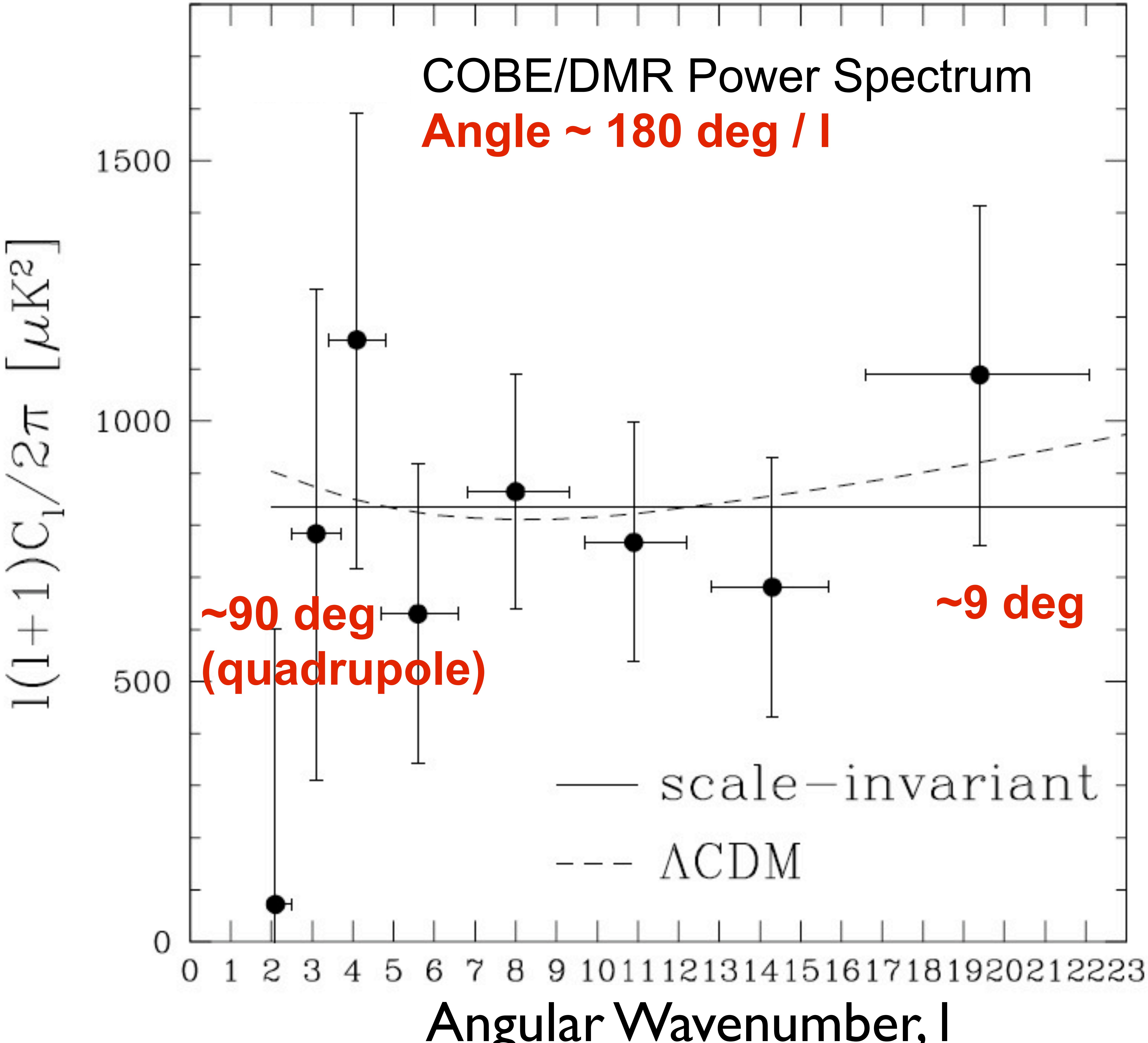
Galaxy-cleaned Map

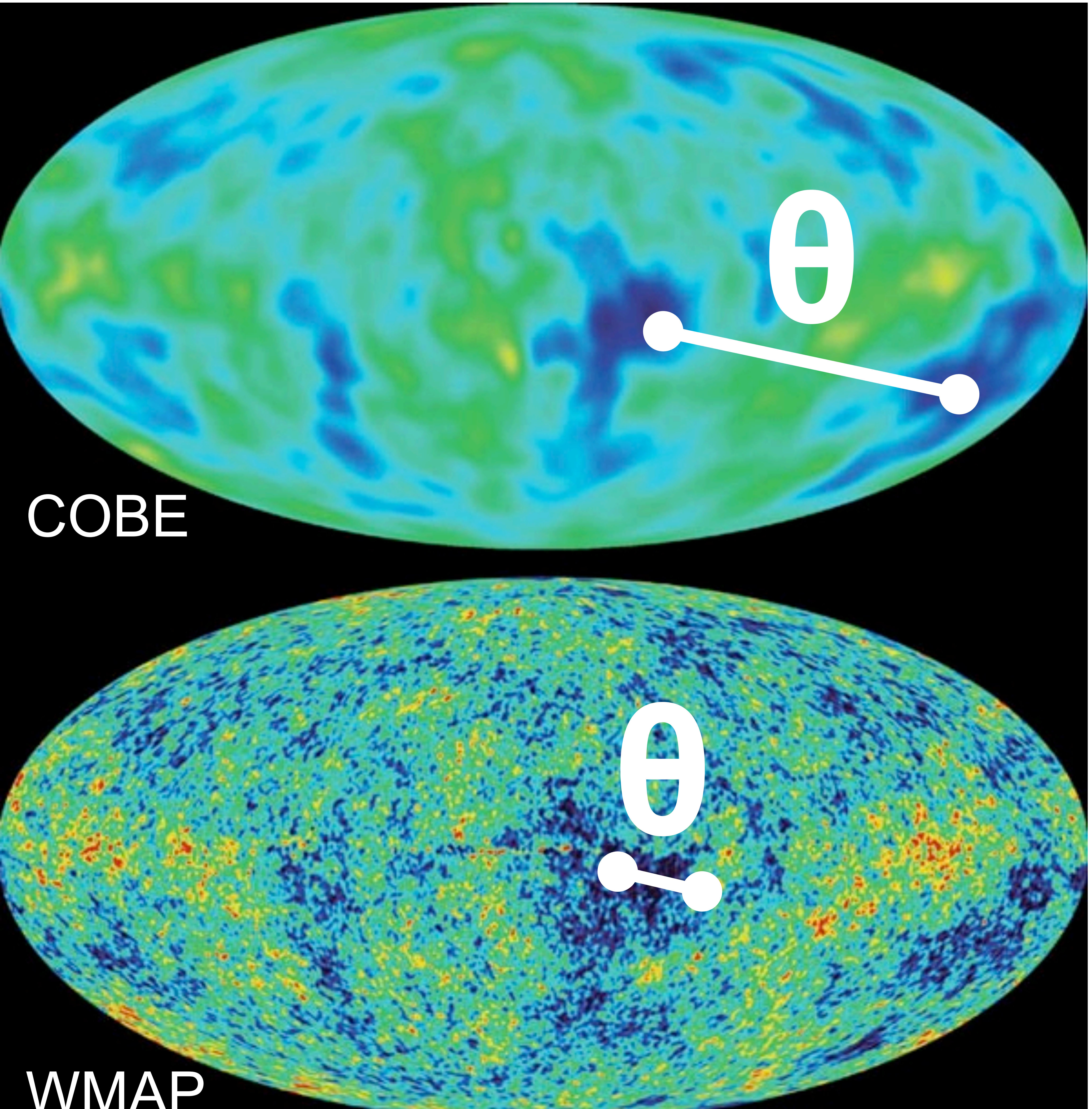




Analysis: 2-point Correlation

- $C(\theta)=(1/4\pi)\sum(2l+1)C_l P_l(\cos\theta)$
- How are temperatures on two points on the sky, separated by θ, are correlated?
- **"Power Spectrum," C_l**
  - How much fluctuation power do we have at a given angular scale?
  - **$l \sim 180$ degrees / θ**

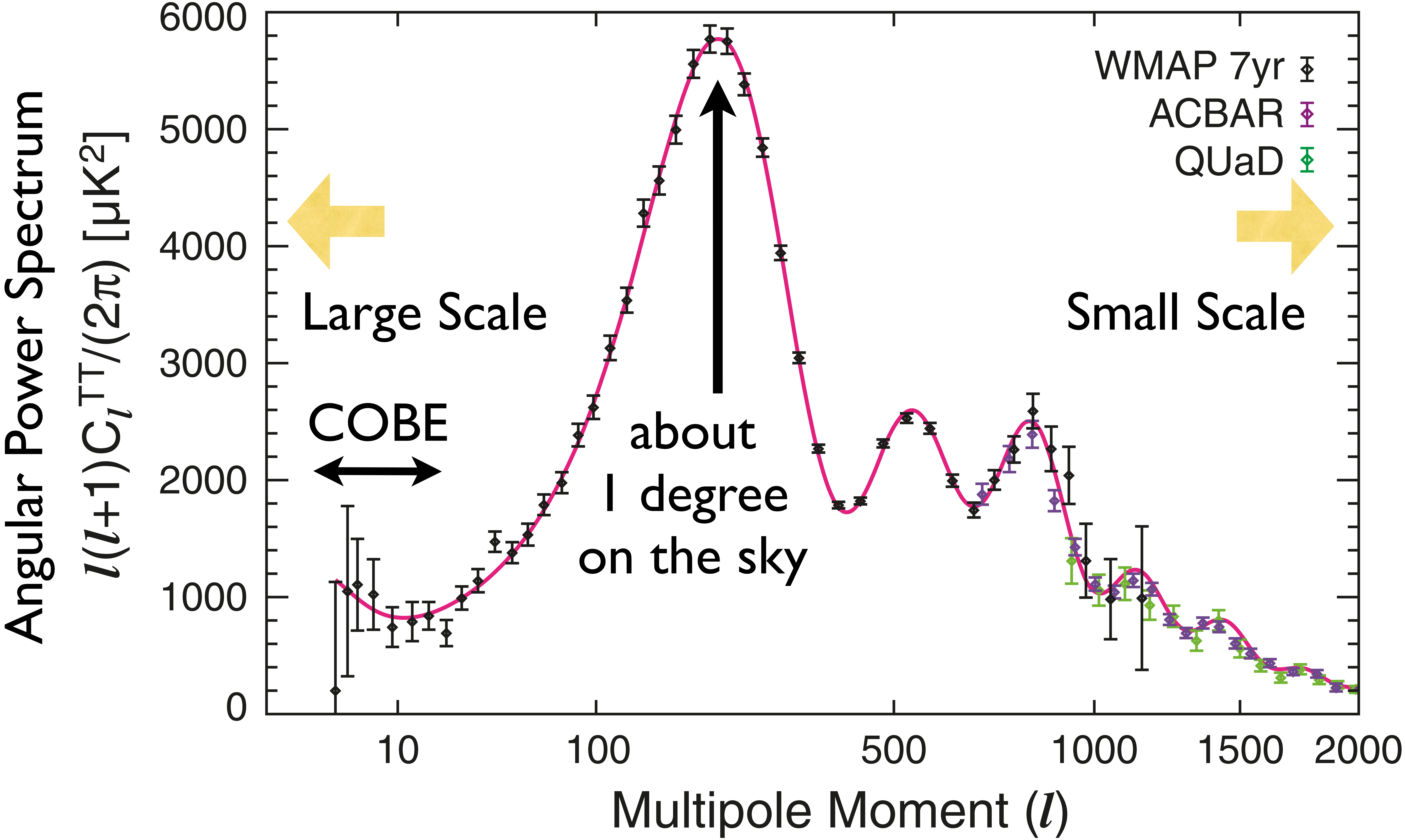

COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale-invariant
ΛCDM
l(l+1)C_l/2π [μK²]
0
500
1000
1500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Angular Wavenumber, l



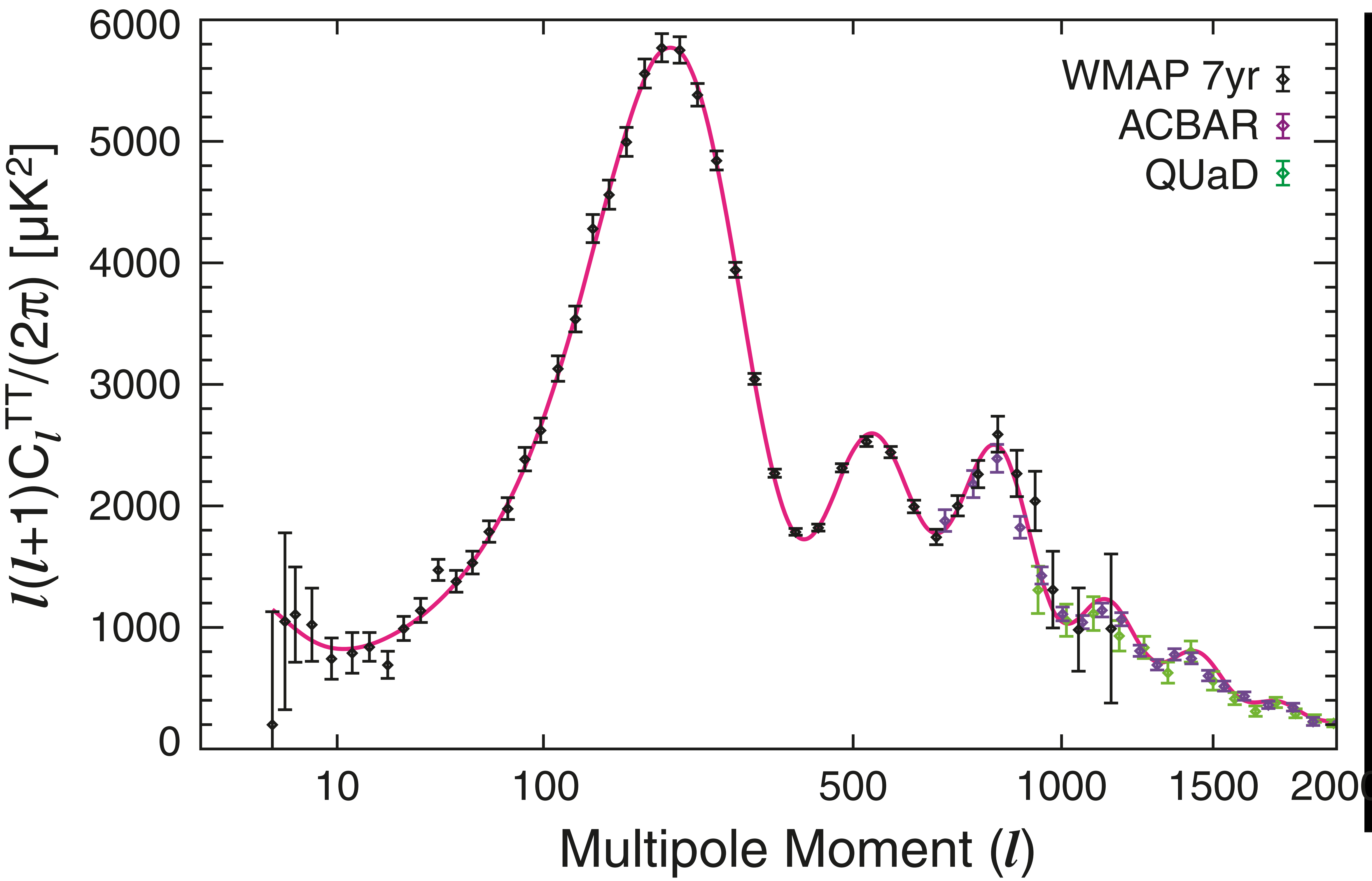
COBE To WMAP

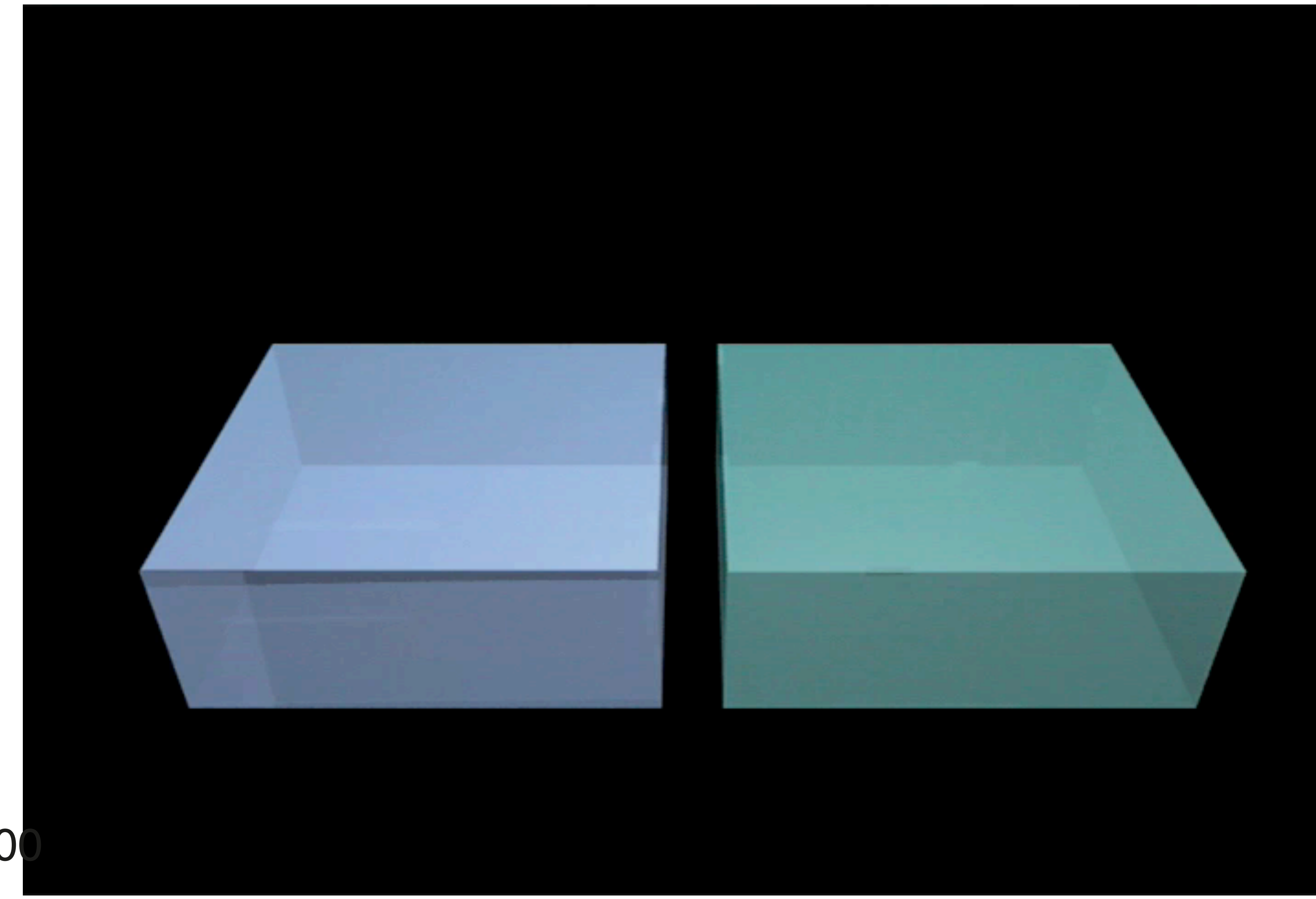
- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

WMAP Power Spectrum



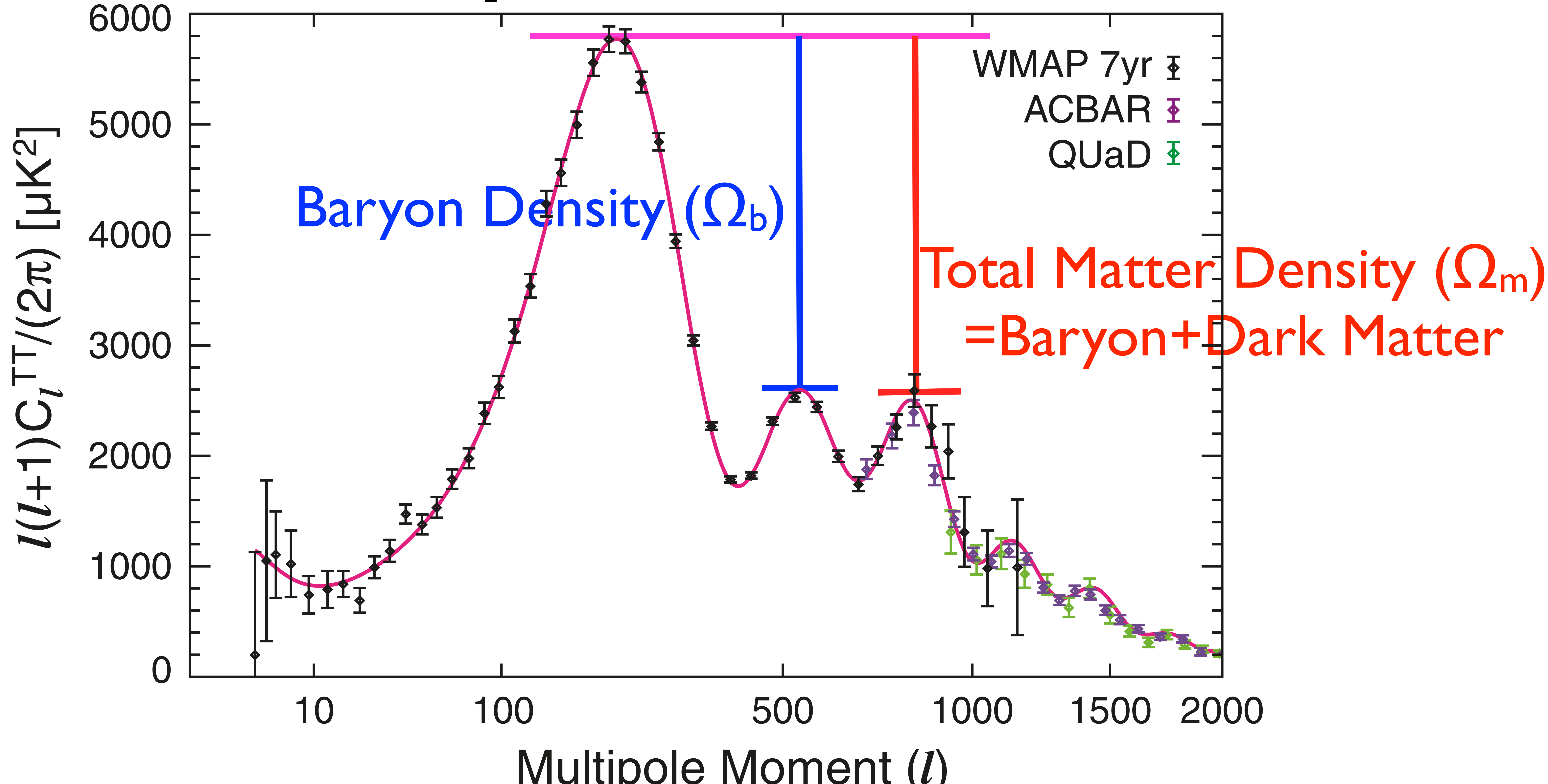
The Cosmic Sound Wave





- *"The Universe as a Miso soup"*
  - *Main Ingredients: protons, helium nuclei, electrons, photons*
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

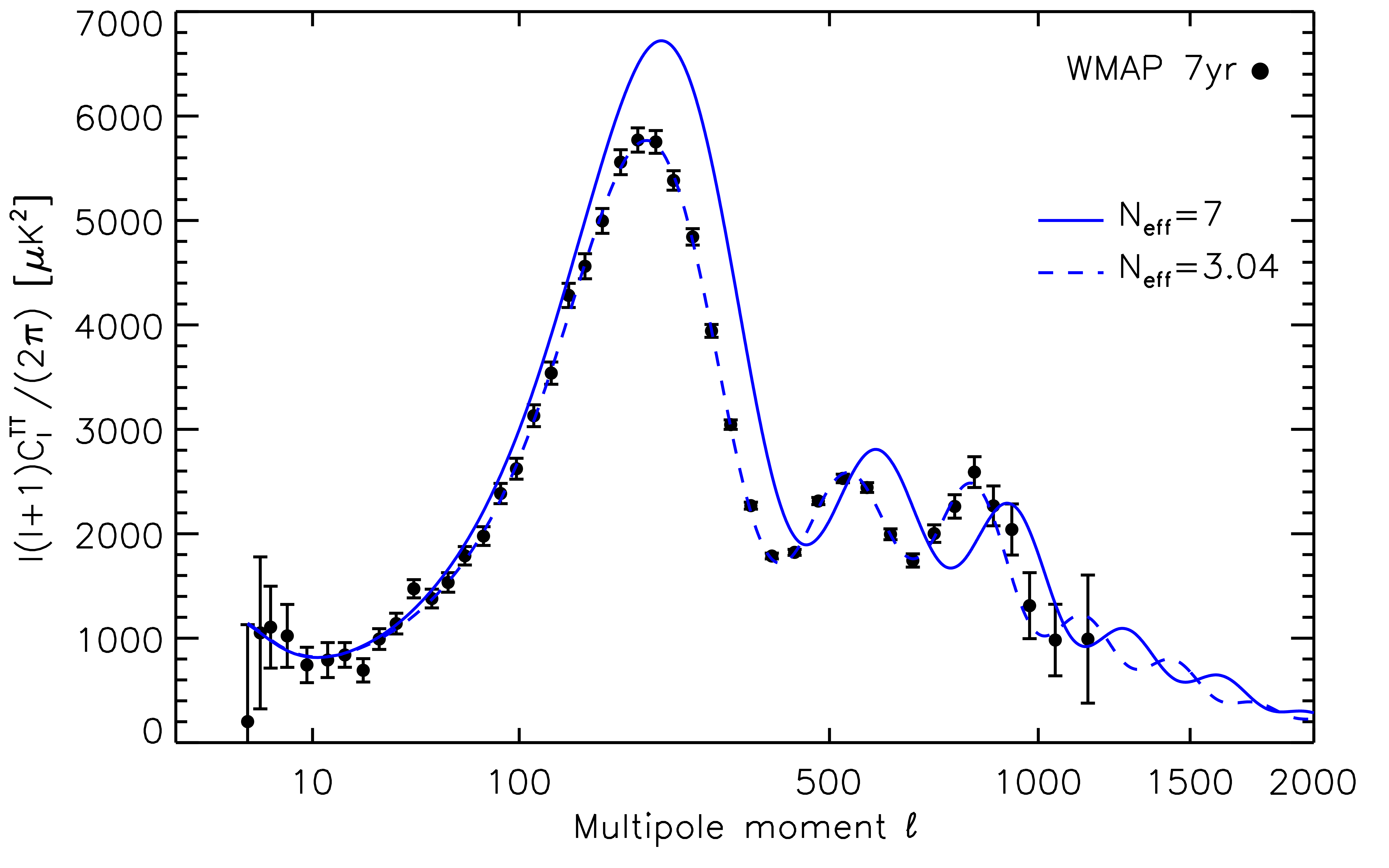
CMB to Baryon & Dark Matter



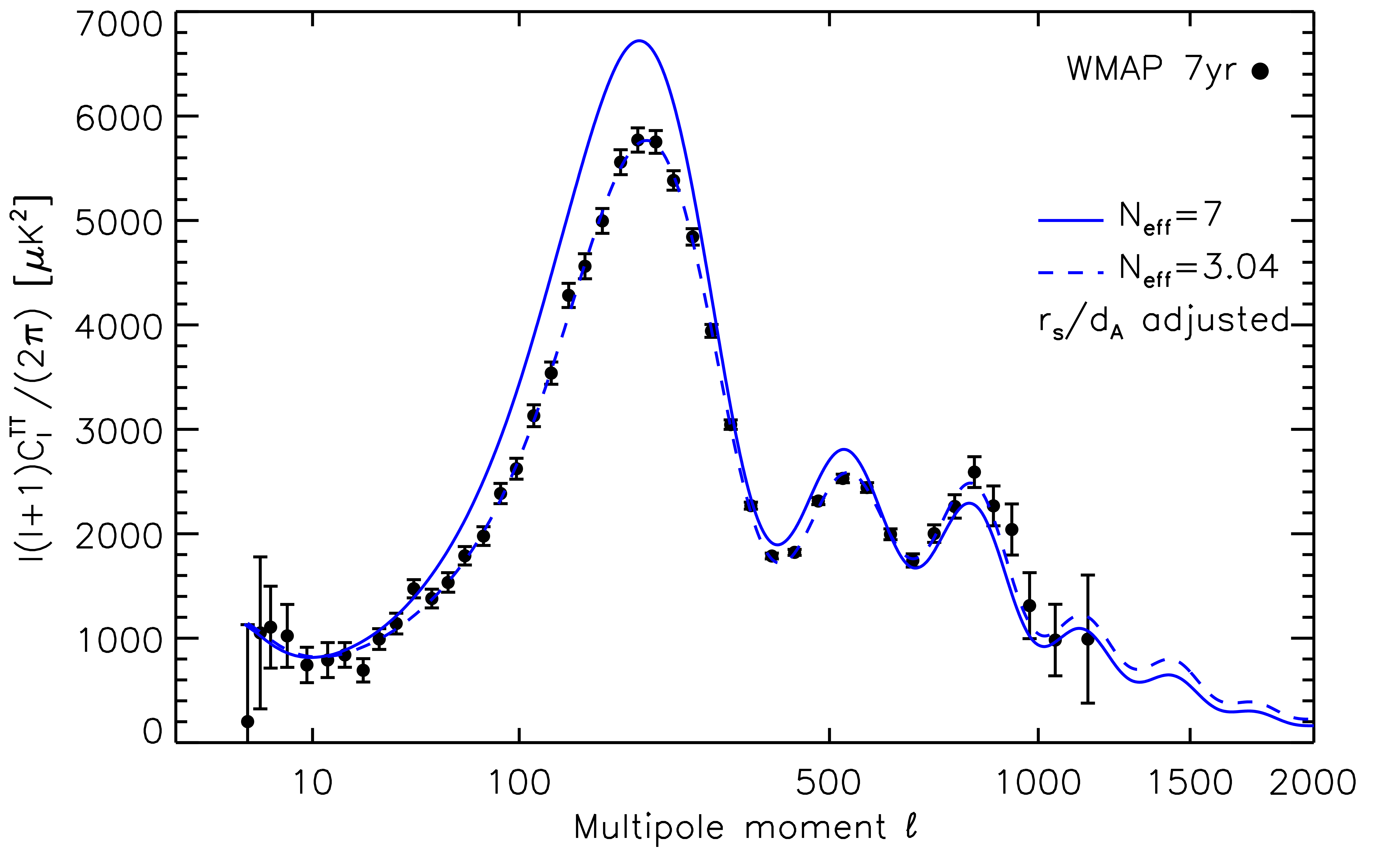
- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio (z_{EQ}: equality redshift)

3rd-peak "Spectroscopy"

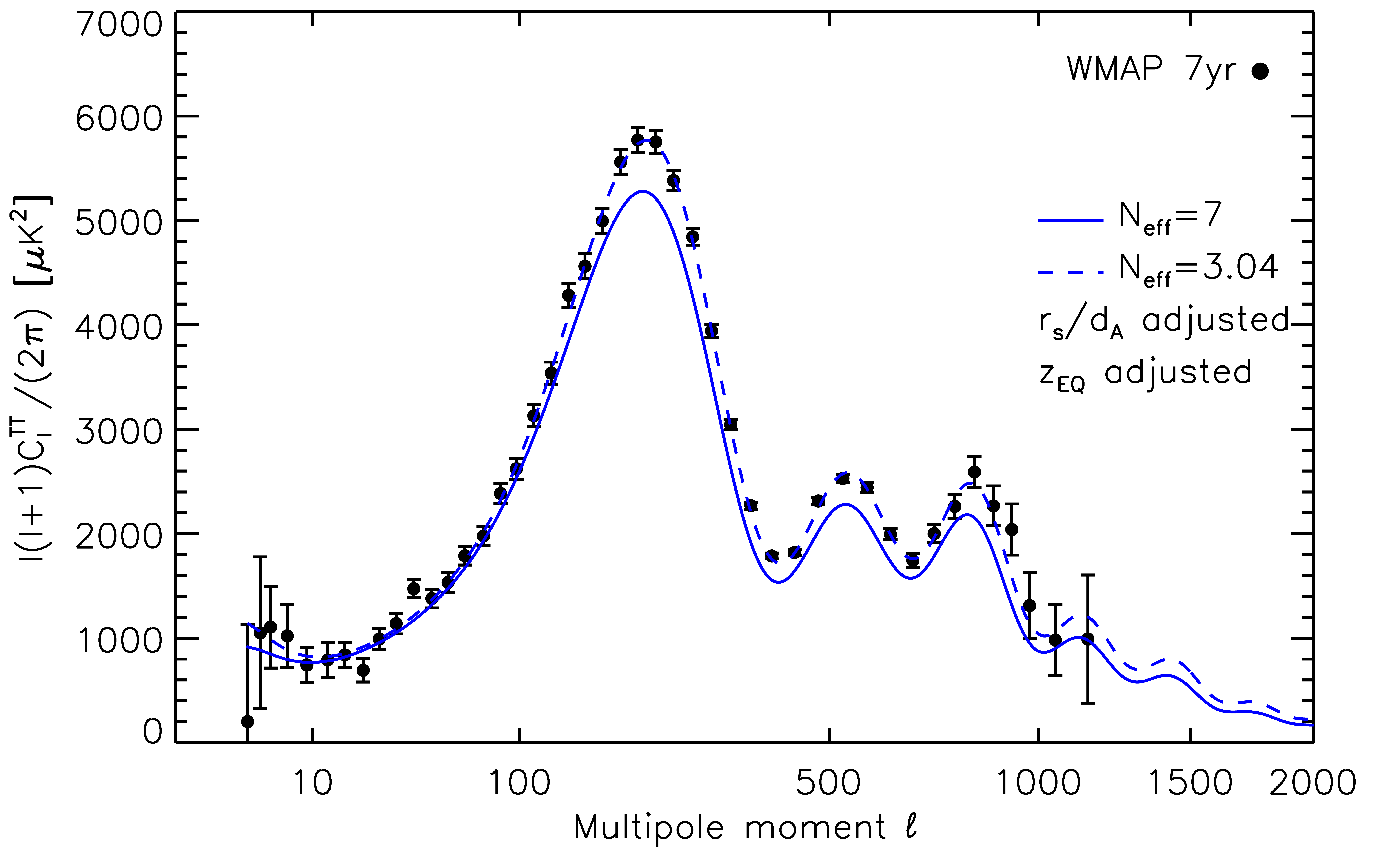
- Total Matter = Baryons (H&He) + Dark Matter
- Total Radiation = Photons + Neutrinos (+new radiation)
  - Neutrino temperature = $(4/11)^{1/3}$ Photon temperature
- So, for a given assumed value of the number of neutrino species (or the number of new radiation species, i.e., zero), we can measure the dark matter density.
- Or, we can get the dark matter density from elsewhere, and determine the number of radiation species!



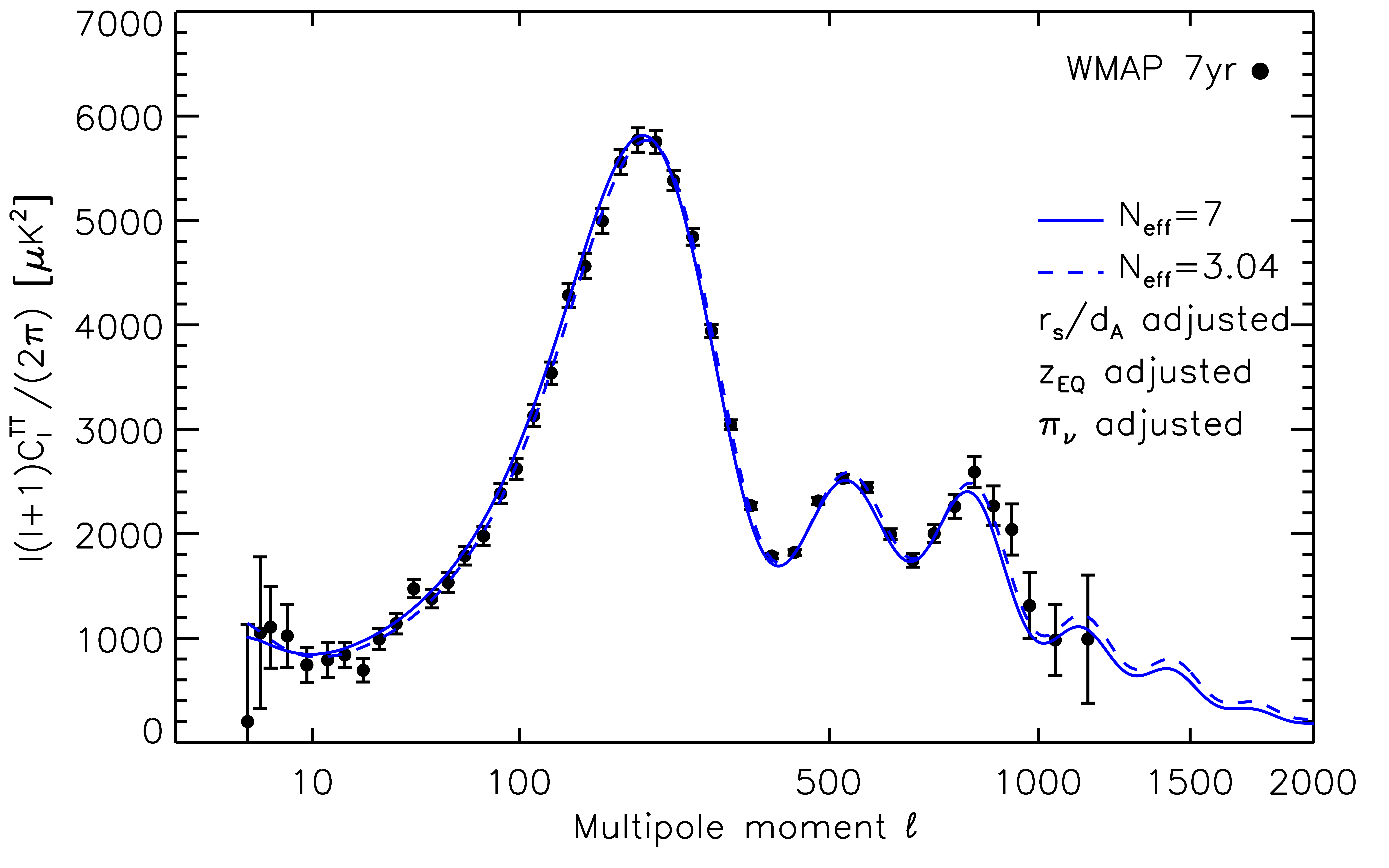
7000
6000
5000
4000
3000
2000
1000
0
l(l+1)C_l^TT/(2π) [μK^2]
WMAP 7yr
N_eff=7
N_eff=3.04
10
100
500
1000
1500
2000
Multipole moment ℓ



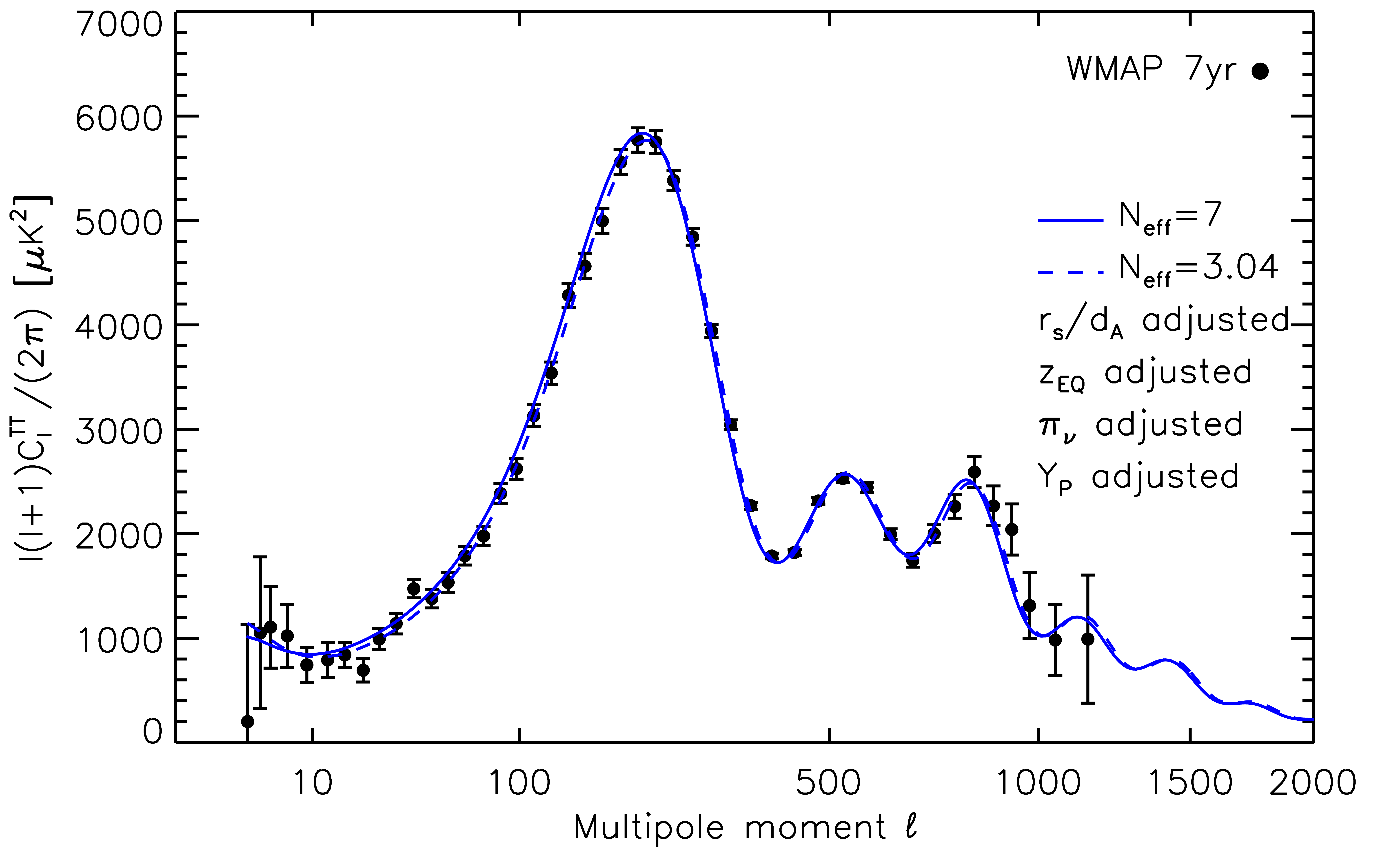
WMAP 7yr
$N_{eff}=7$
$N_{eff}=3.04$
r_s/d_A adjusted
$l(l+1)C_l^{TT}/(2\pi)$ [μK^2]
Multipole moment ℓ
0
1000
2000
3000
4000
5000
6000
7000
10
100
500
1000
1500
2000



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

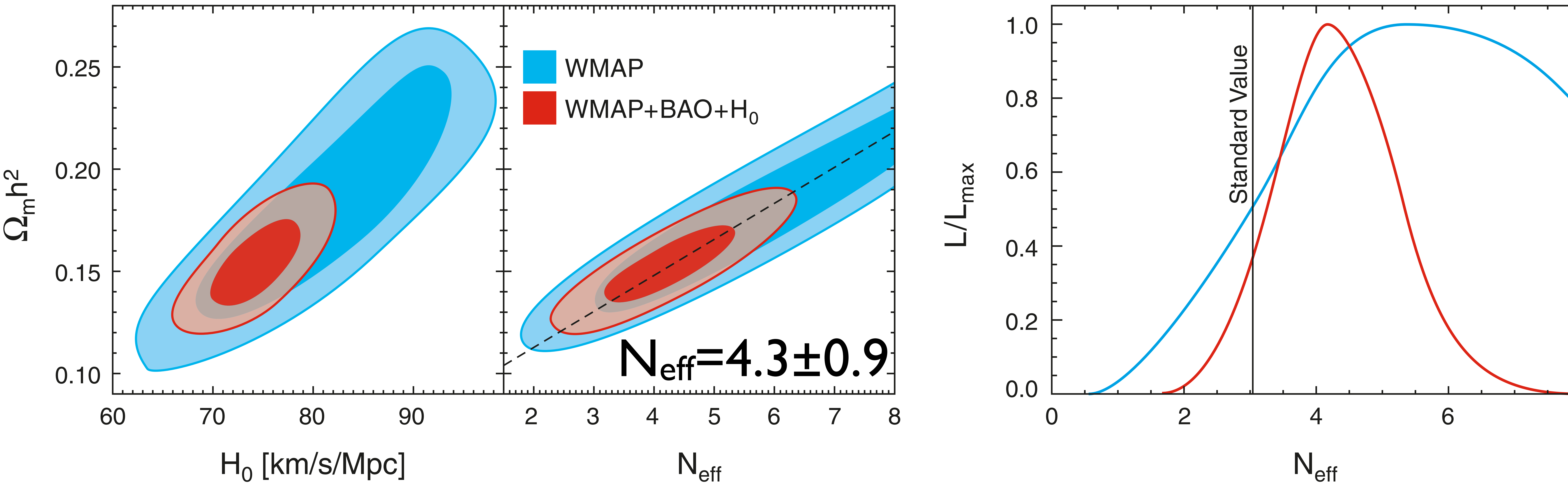


WMAP 7yr
N_eff=7
N_eff=3.04
r_s/d_A adjusted
z_EQ adjusted
π_ν adjusted
l(l+1)C_l^TT/(2π) [μK^2]
Multipole moment ℓ
0
1000
2000
3000
4000
5000
6000
7000
10
100
500
1000
1500
2000



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

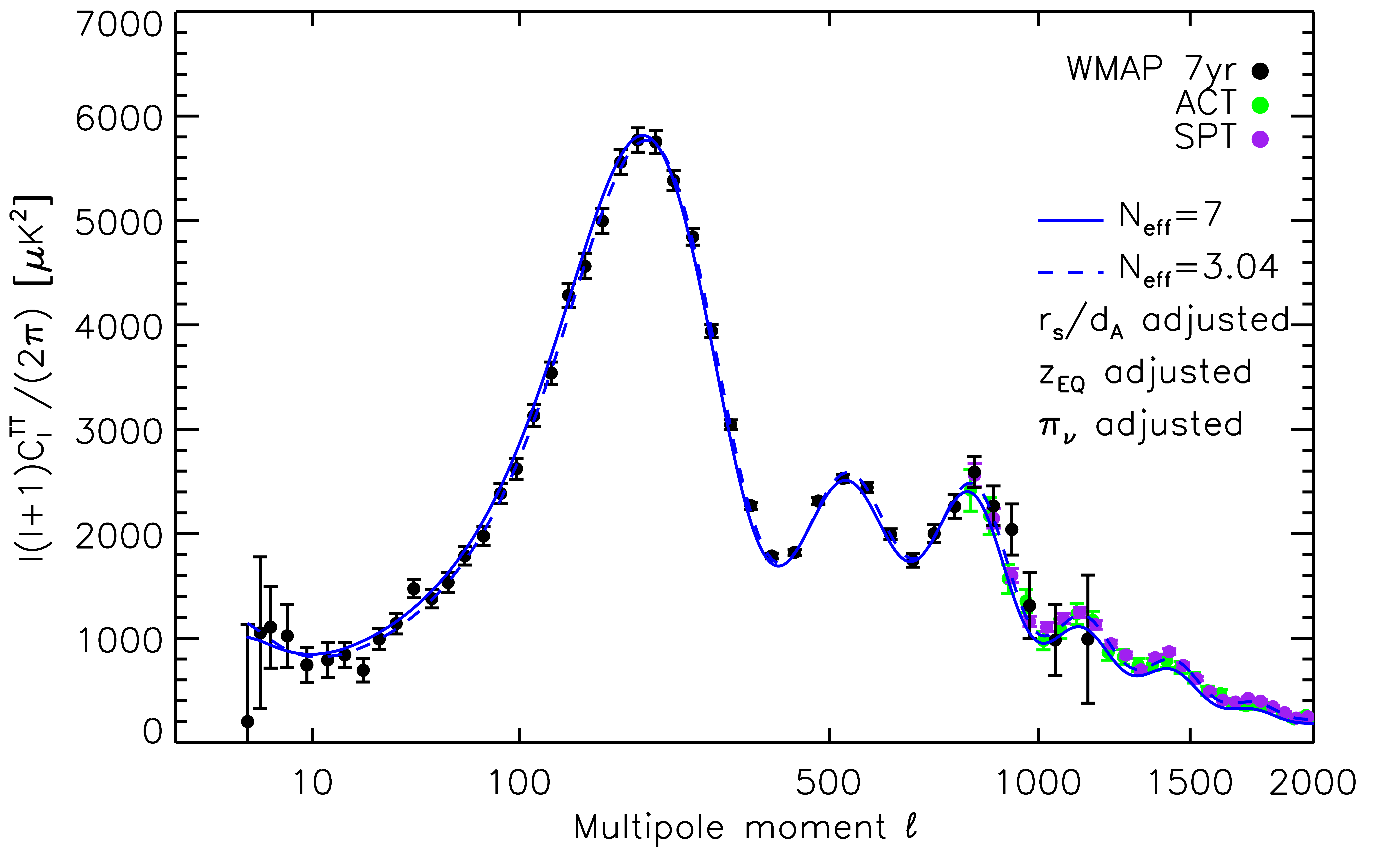
"3rd peak spectroscopy": Number of Relativistic Species



from external data

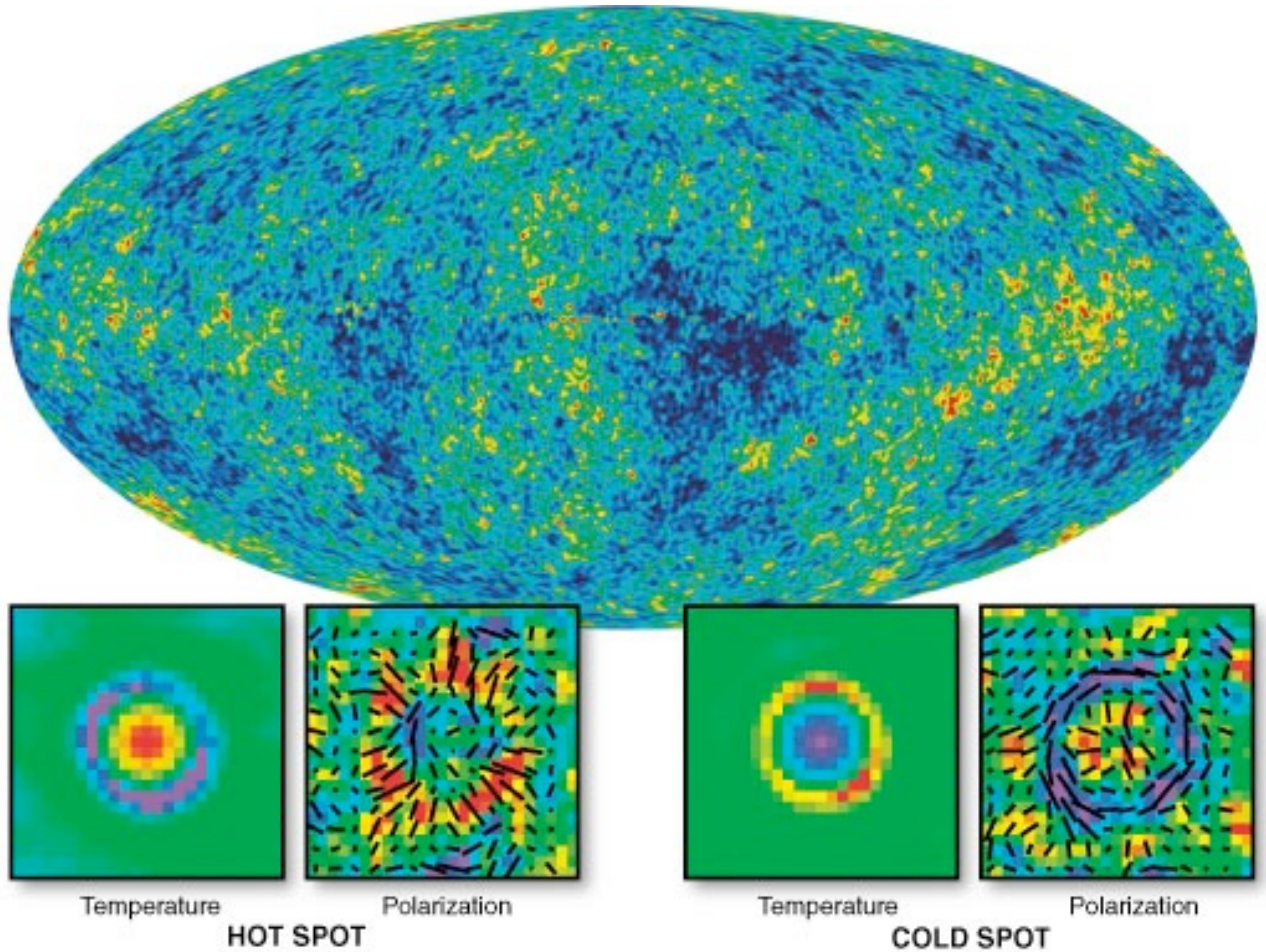
$$N_{\rm eff} = 3.04 + 7.44\left(\frac{\Omega_m h^2}{0.1308}\frac{3139}{1+z_{\rm eq}} - 1\right)$$

from 3rd peak



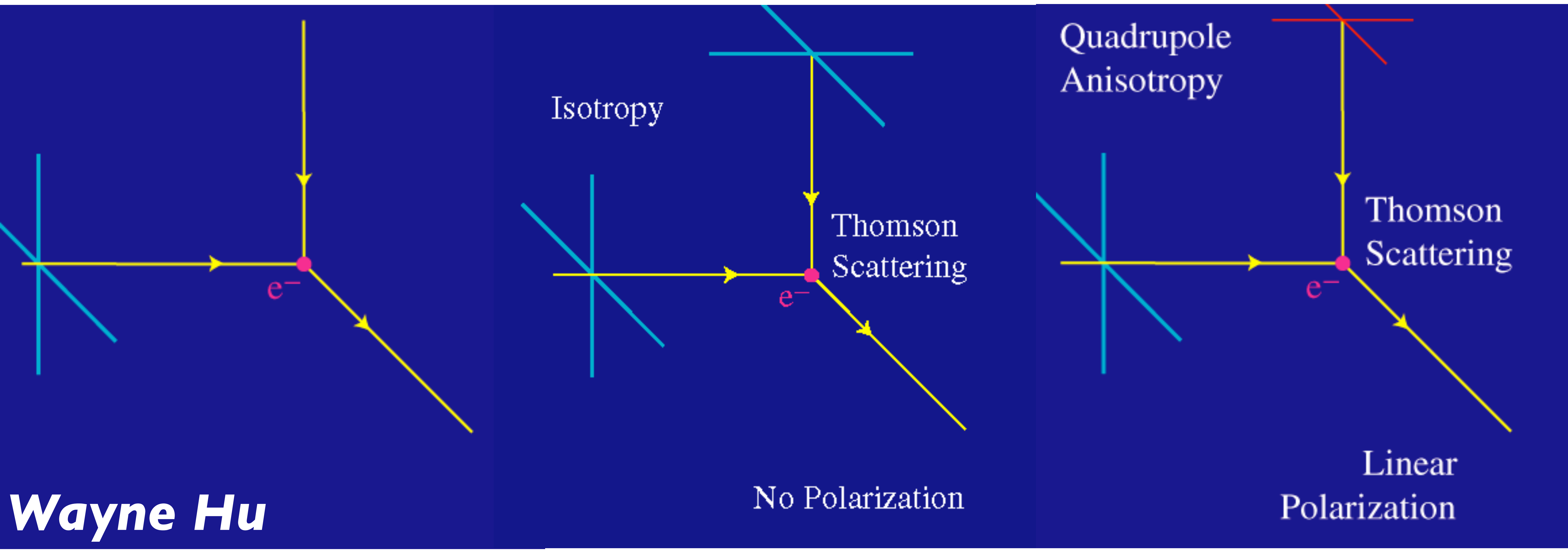
7000
6000
5000
4000
3000
2000
1000
0
l(l+1)C$_l^{TT}$/(2π) [μK^2]
10
100
500
1000
1500
2000
Multipole moment ℓ
WMAP 7yr
ACT
SPT
N$_{eff}$=7
N$_{eff}$=3.04
r$_s$/d$_A$ adjusted
z$_{EQ}$ adjusted
π$_ν$ adjusted

CMB Polarization



- *CMB is (very weakly) polarized!*

Physics of CMB Polarization

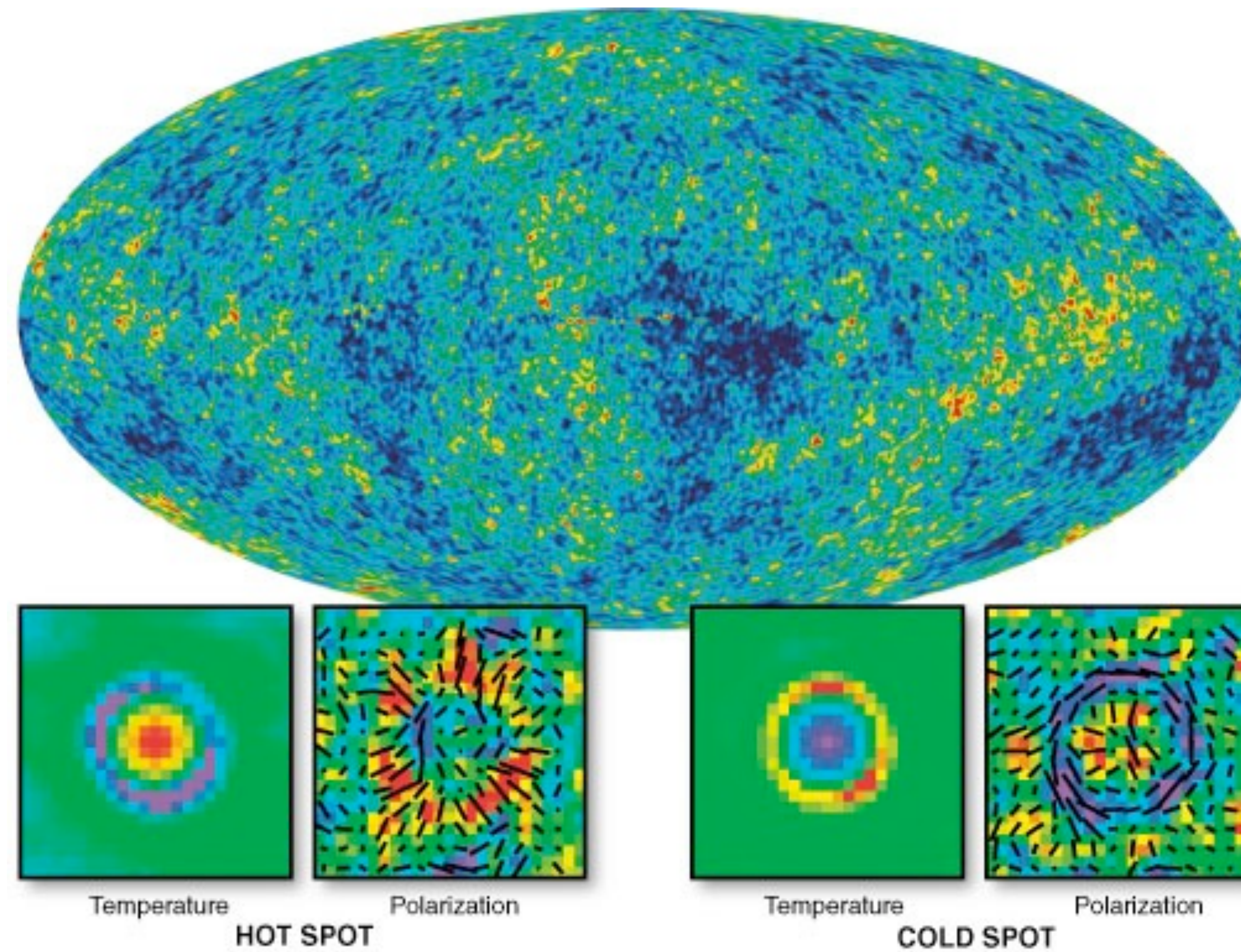


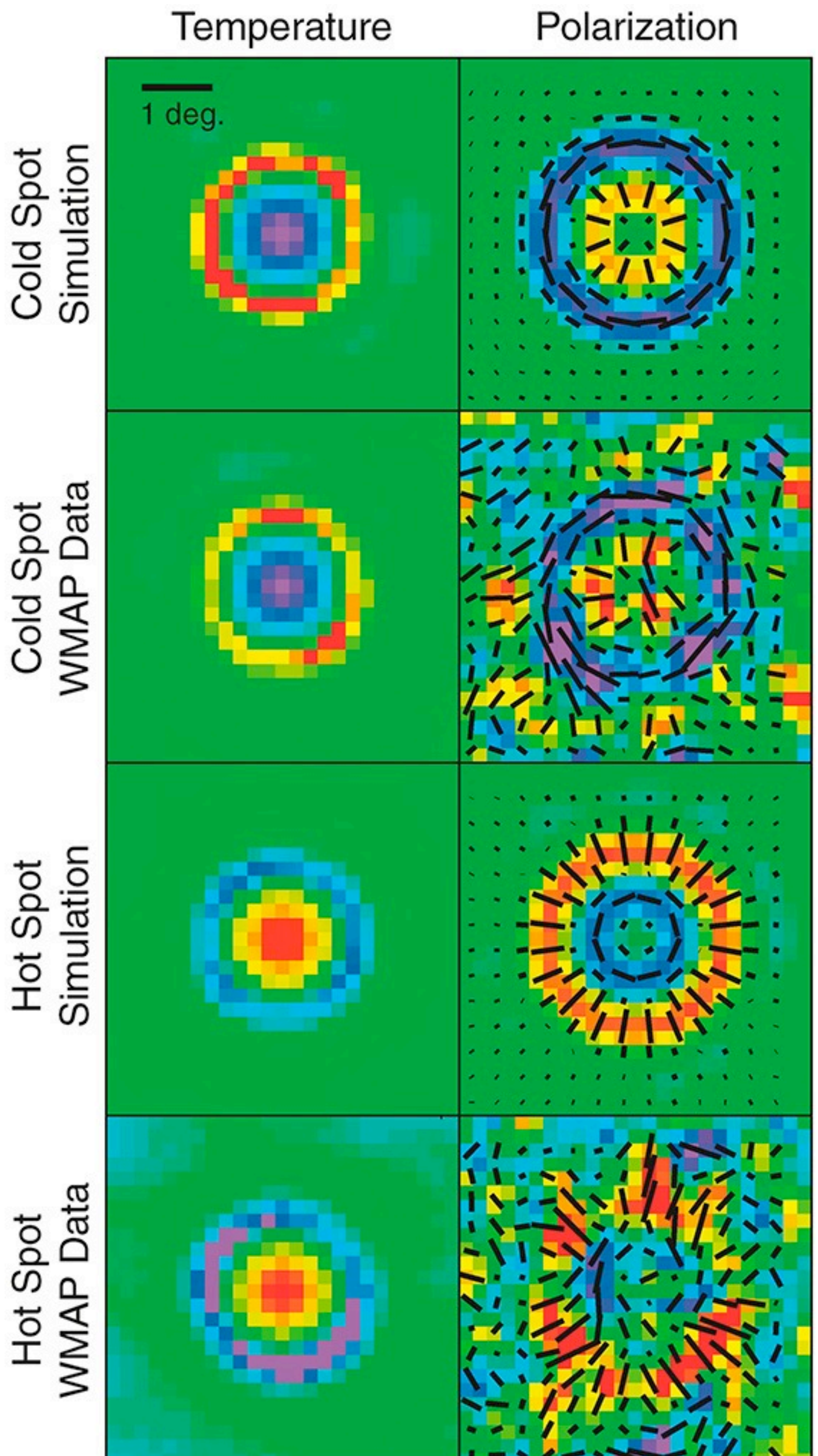
- CMB Polarization is created by a local temperature **quadrupole** anisotropy.

Stacking Analysis

- Stack polarization images around temperature hot and cold spots.

- Outside of the Galaxy mask (not shown), there are **12387 hot spots** and **12628 cold spots**.

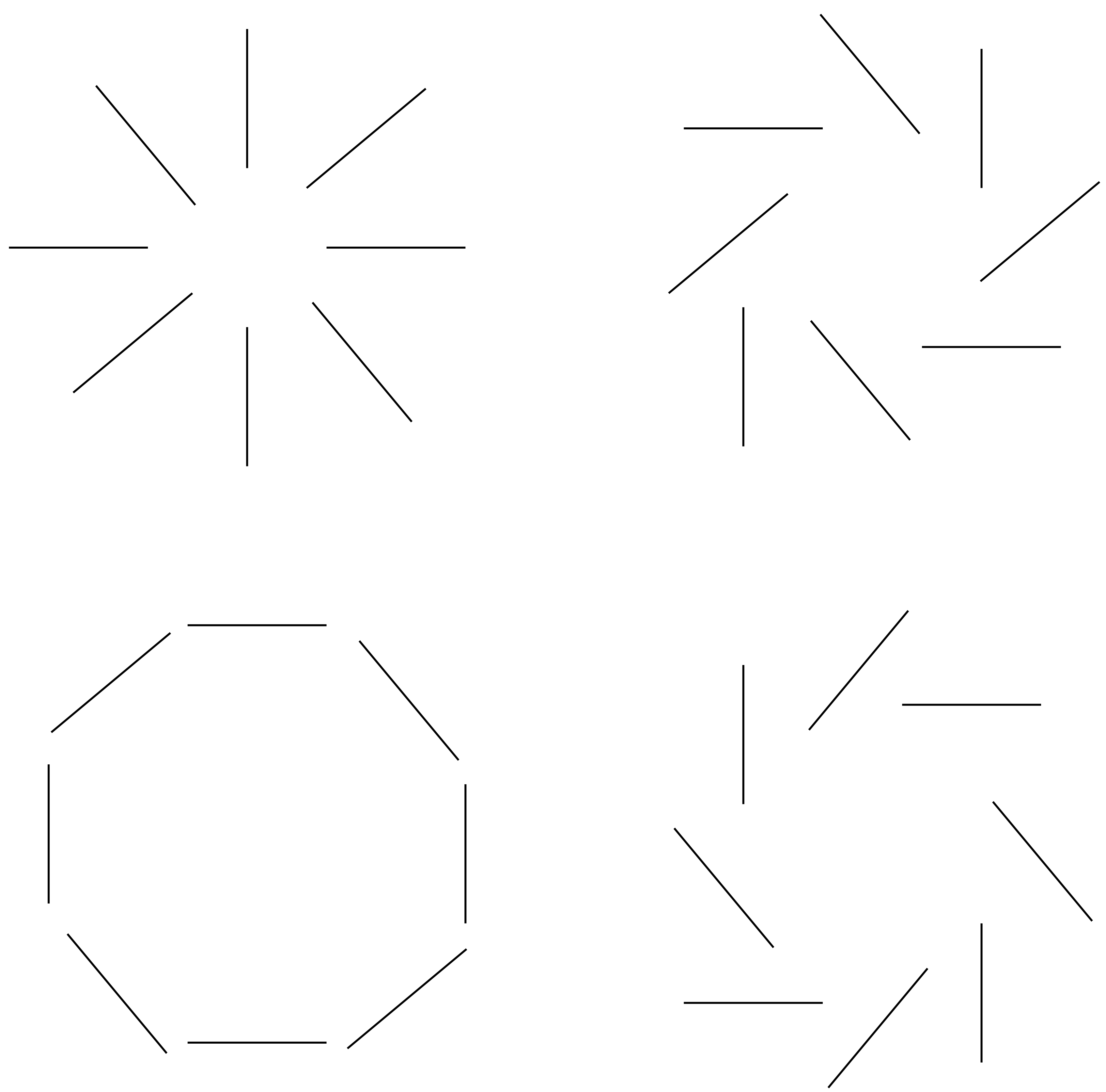




Radial and Tangential Polarization Patterns around Temp. Spots

- All hot and cold spots are stacked
- "Compression phase" at θ=1.2 deg and "slow-down phase" at θ=0.6 deg are predicted to be there and we observe them!
  - The overall significance level: 8σ

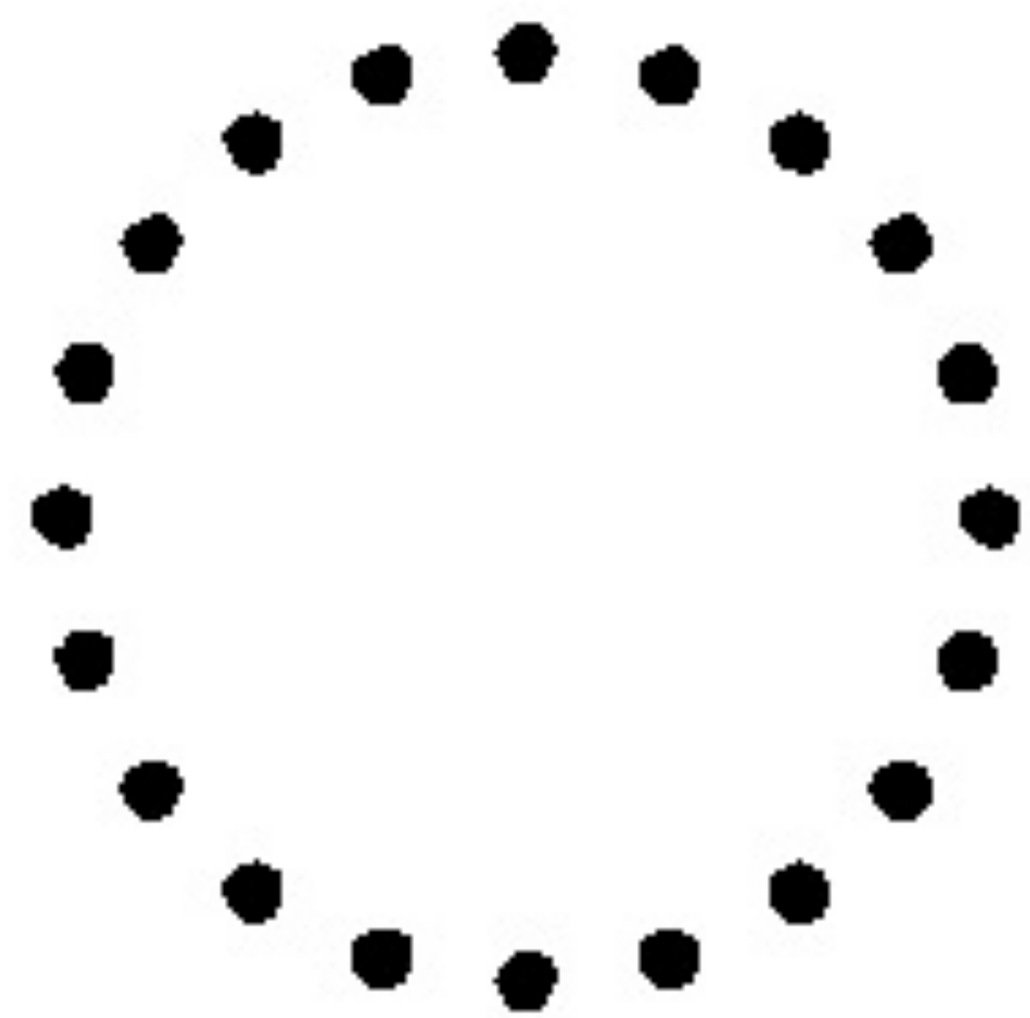
E-mode and B-mode



E mode B mode

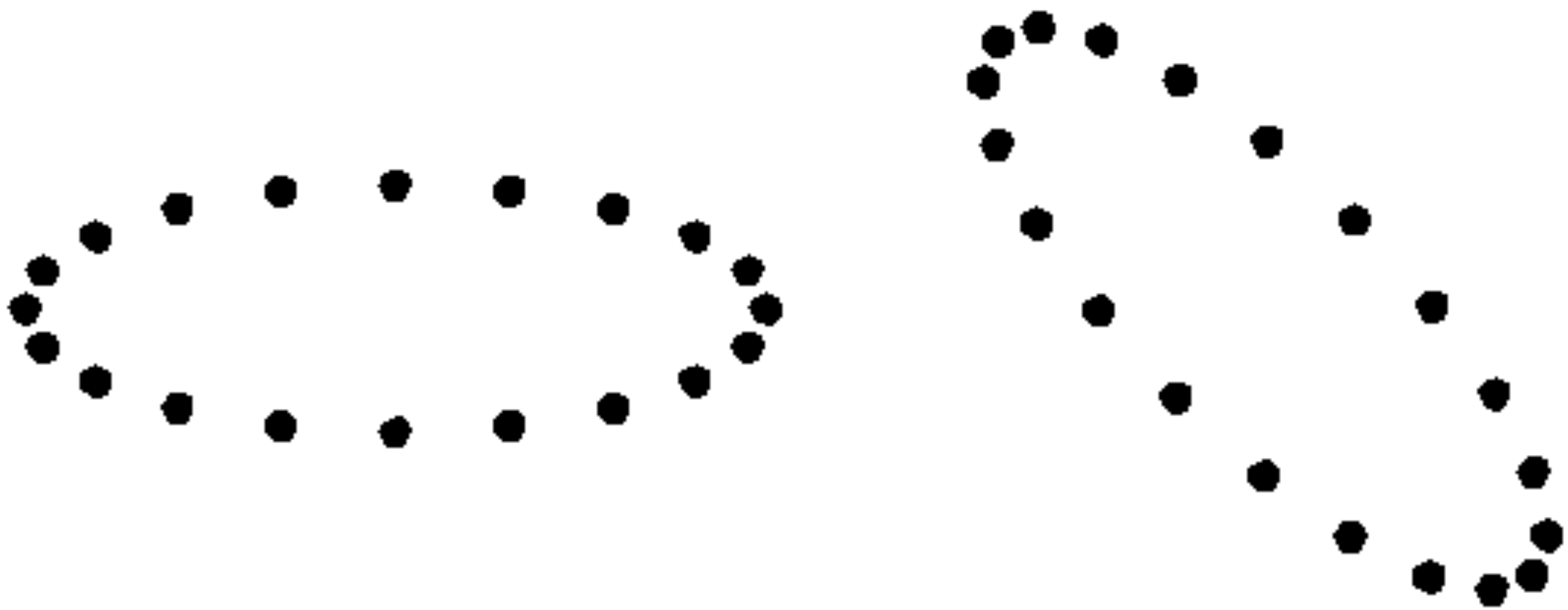
- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

Gravitational waves are coming toward you... What do you do?



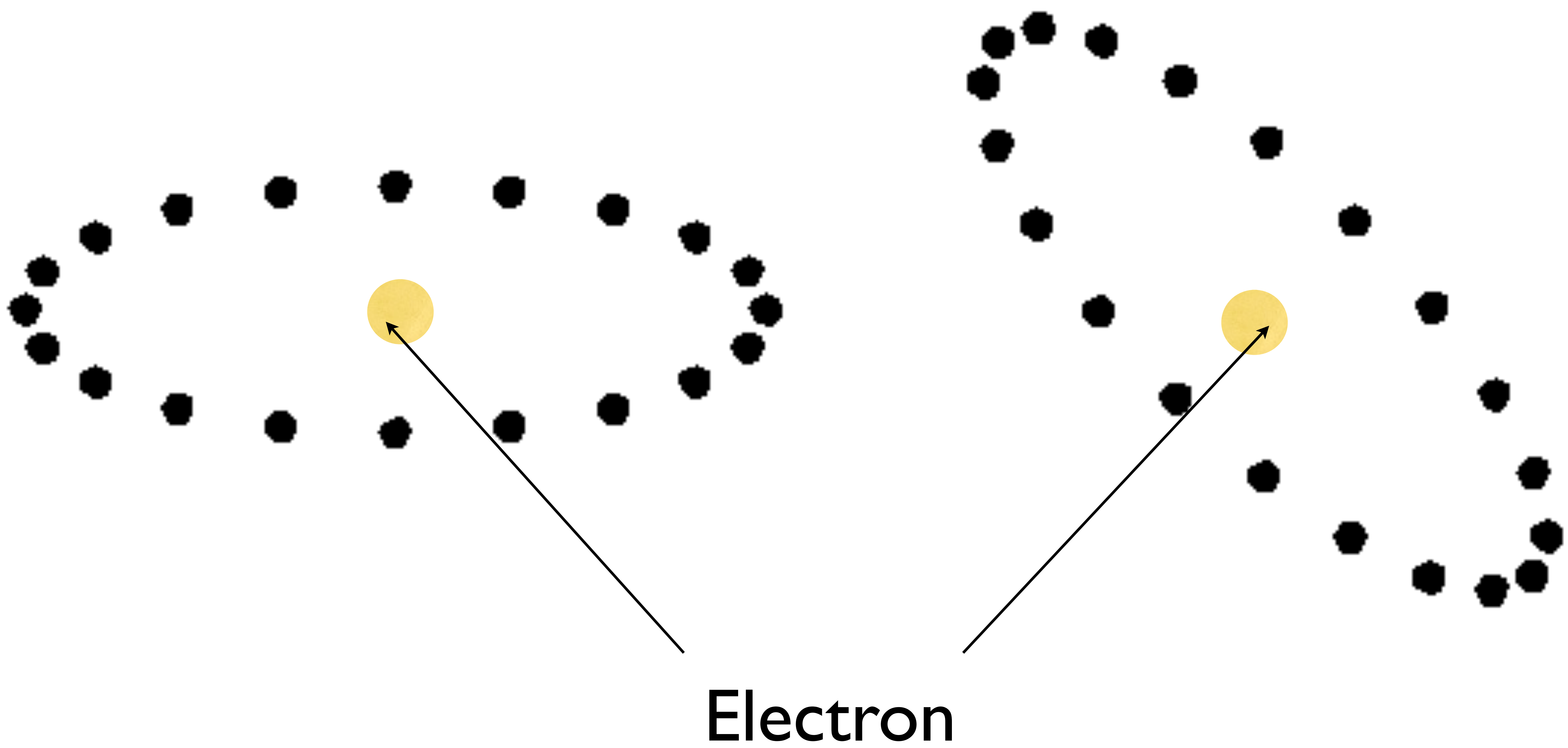
- Gravitational waves stretch space, causing particles to move.

Two Polarization States of GW

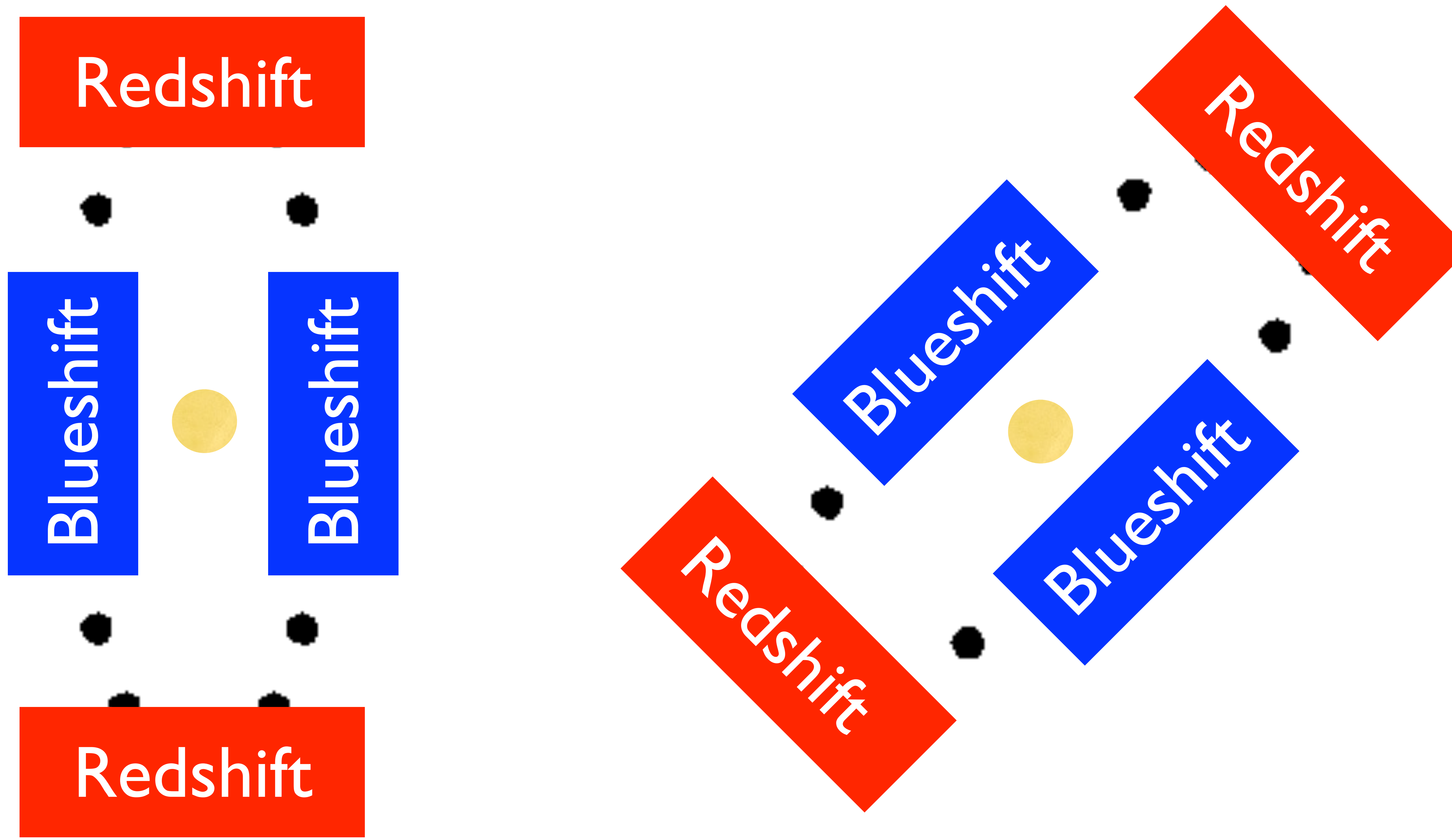


- This is great - this will automatically generate quadrupolar anisotropy around electrons!

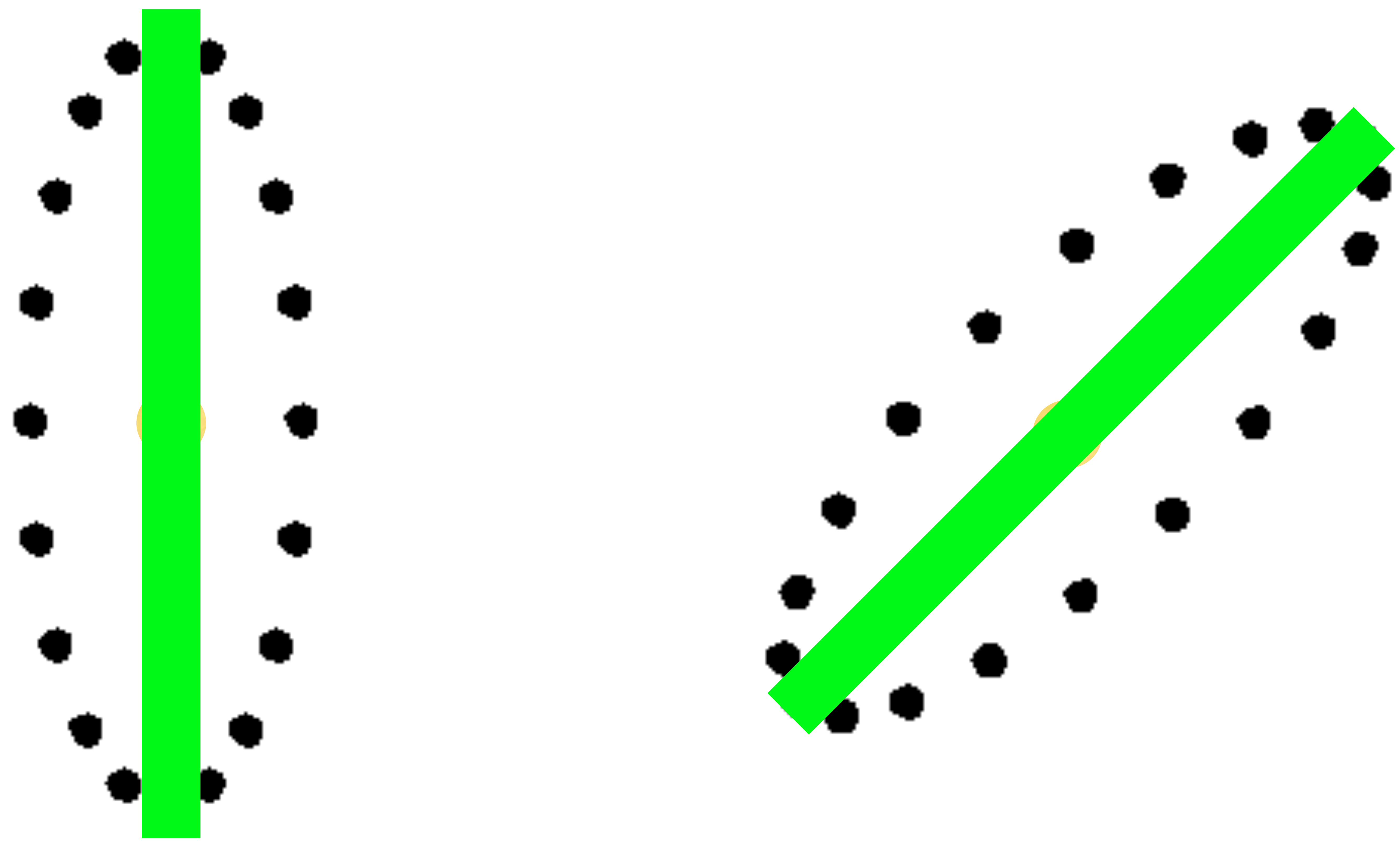
From GW to CMB Polarization



From GW to CMB Polarization



From GW to CMB Polarization



Gravitational waves can produce **both** E- and B-mode polarization

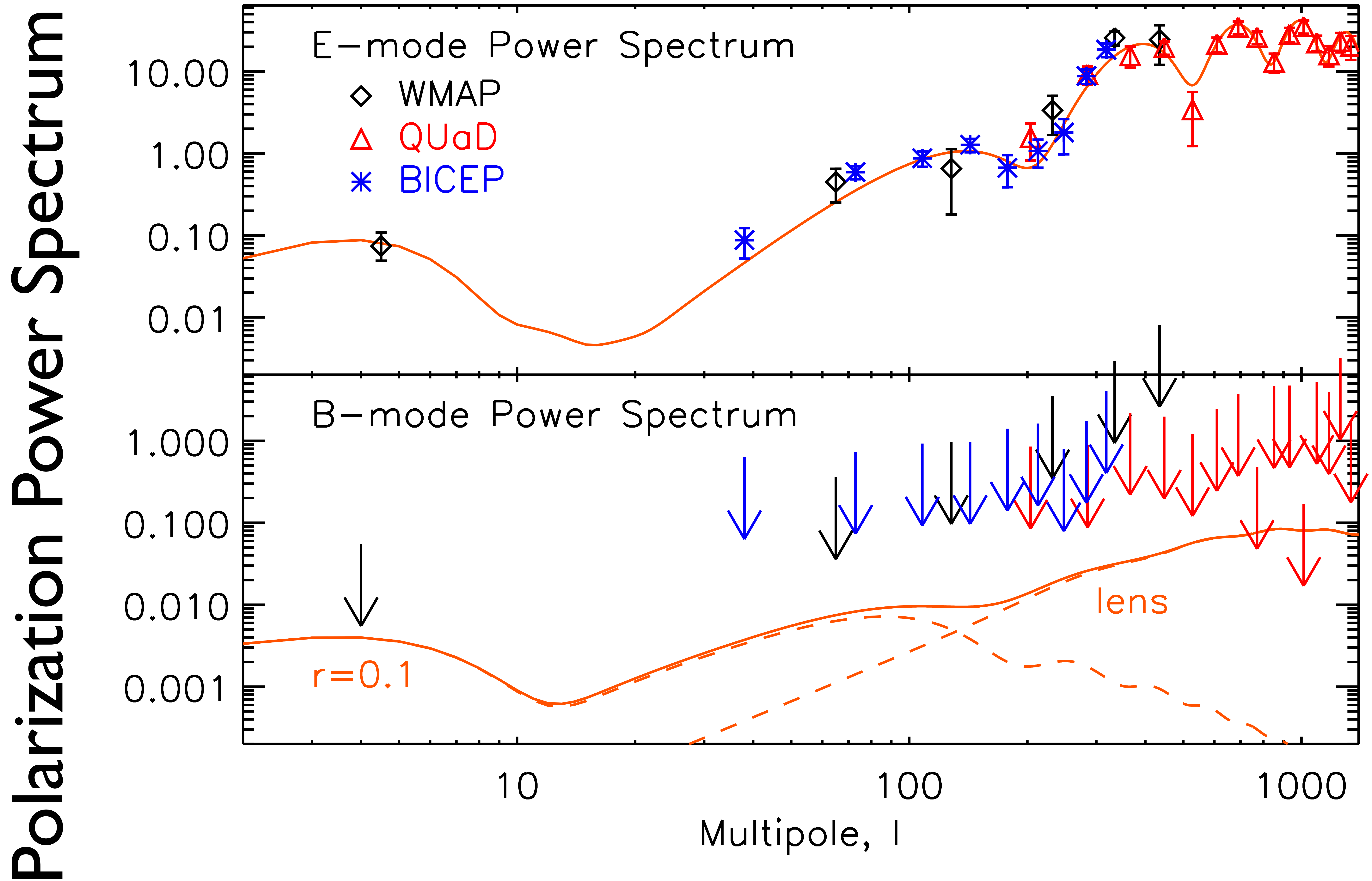
"Tensor-to-scalar Ratio," r

r = [Power in Gravitational Waves]

/ [Power in Gravitational Potential]

Theory of "Cosmic Inflation" predicts r <~ 1

– I will come back to this in a moment

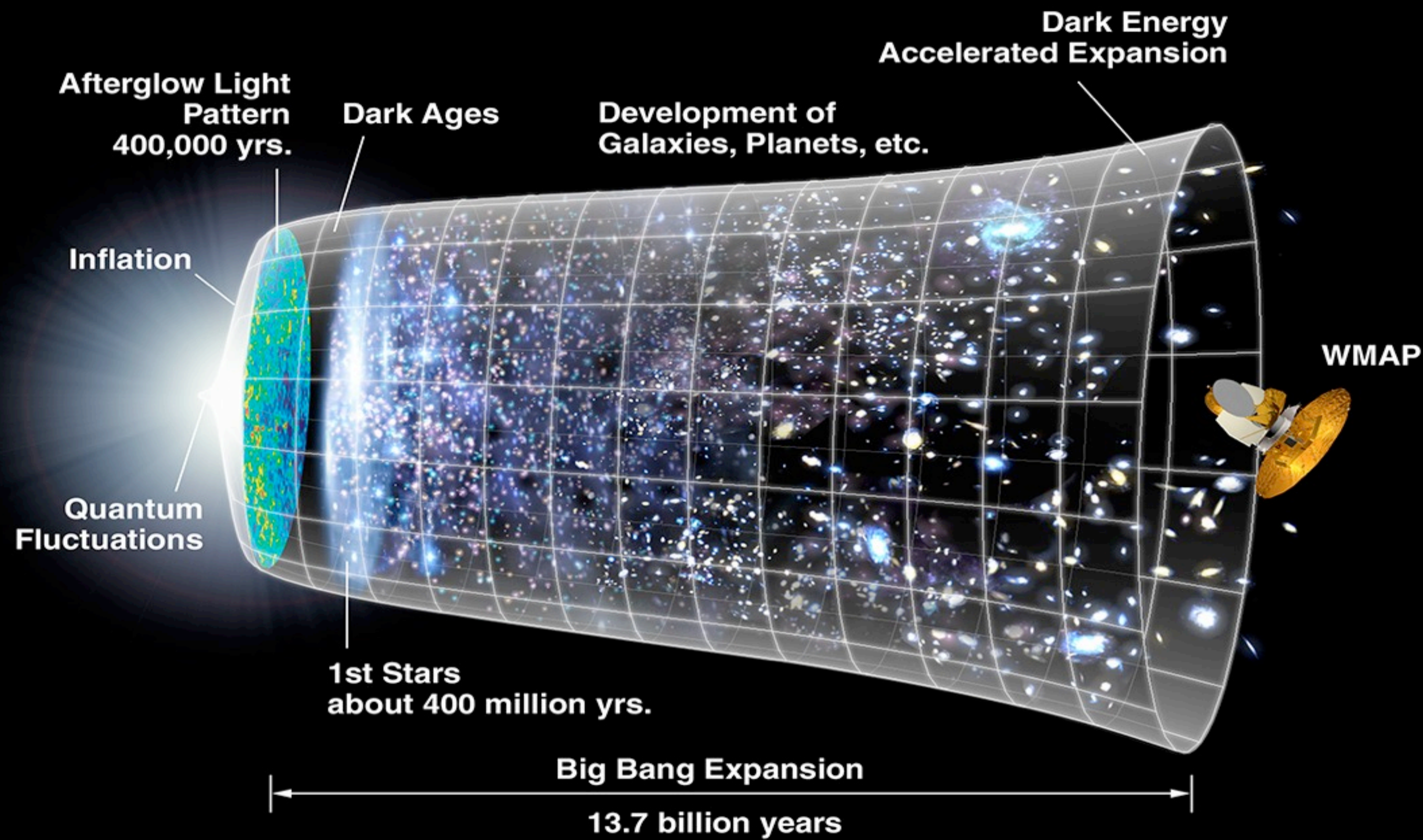


- No detection of B-mode polarization yet.
  B-mode is the next holy grail!

Theory of the Very Early Universe

- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  (Guth 1981; Linde 1982; Albrecht & Steinhardt 1982; Starobinsky 1980)
  - The expansion of our Universe ***accelerated*** in a tiny fraction of a second after its birth.
  - Just like Dark Energy accelerating today's expansion: the acceleration also happened at very, very early times!
- **Inflation stretches "*micro to macro*"**
  - In a tiny fraction of a second, the size of an atomic nucleus (~10^{-15}m) would be stretched to 1 A.U. (~10^{11}m), at least.

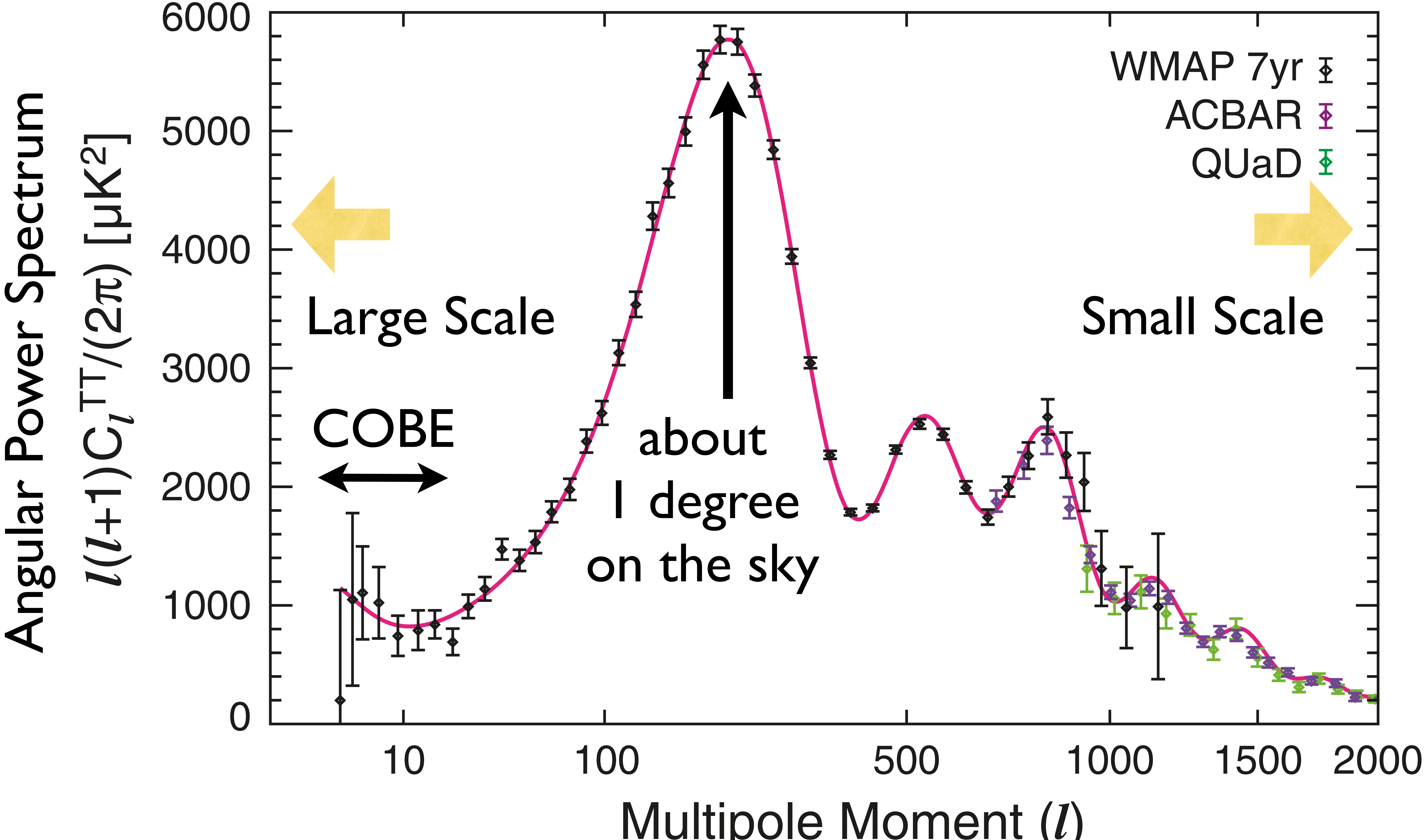
Cosmic Inflation = Very Early Dark Energy



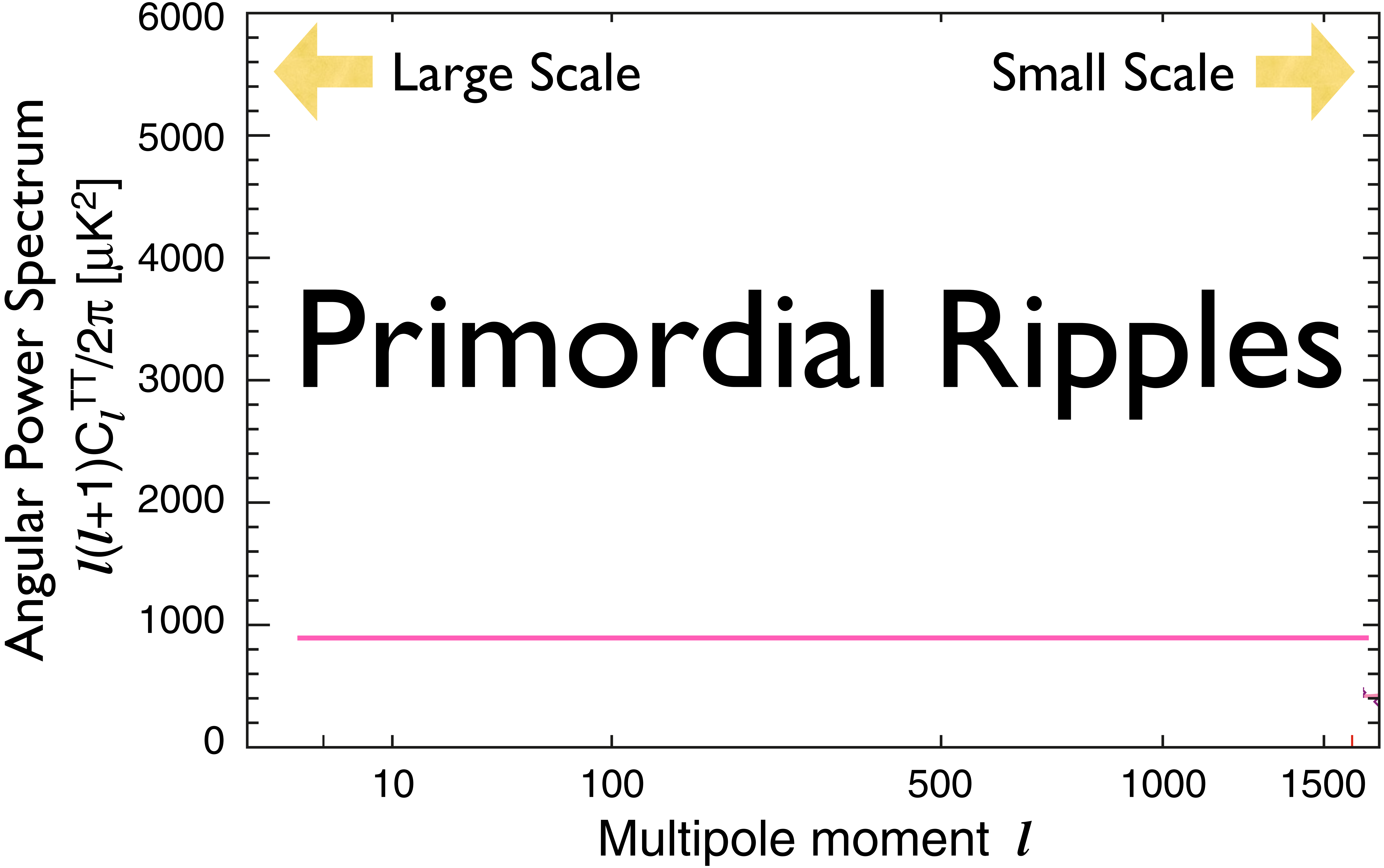
Origin of Fluctuations

- OK, back to the cosmic hot soup.
- The sound waves were created when we perturbed it.
- "We"? **Who?**
- Who actually perturbed the cosmic soup?
- **Who generated the original (seed) ripples?**

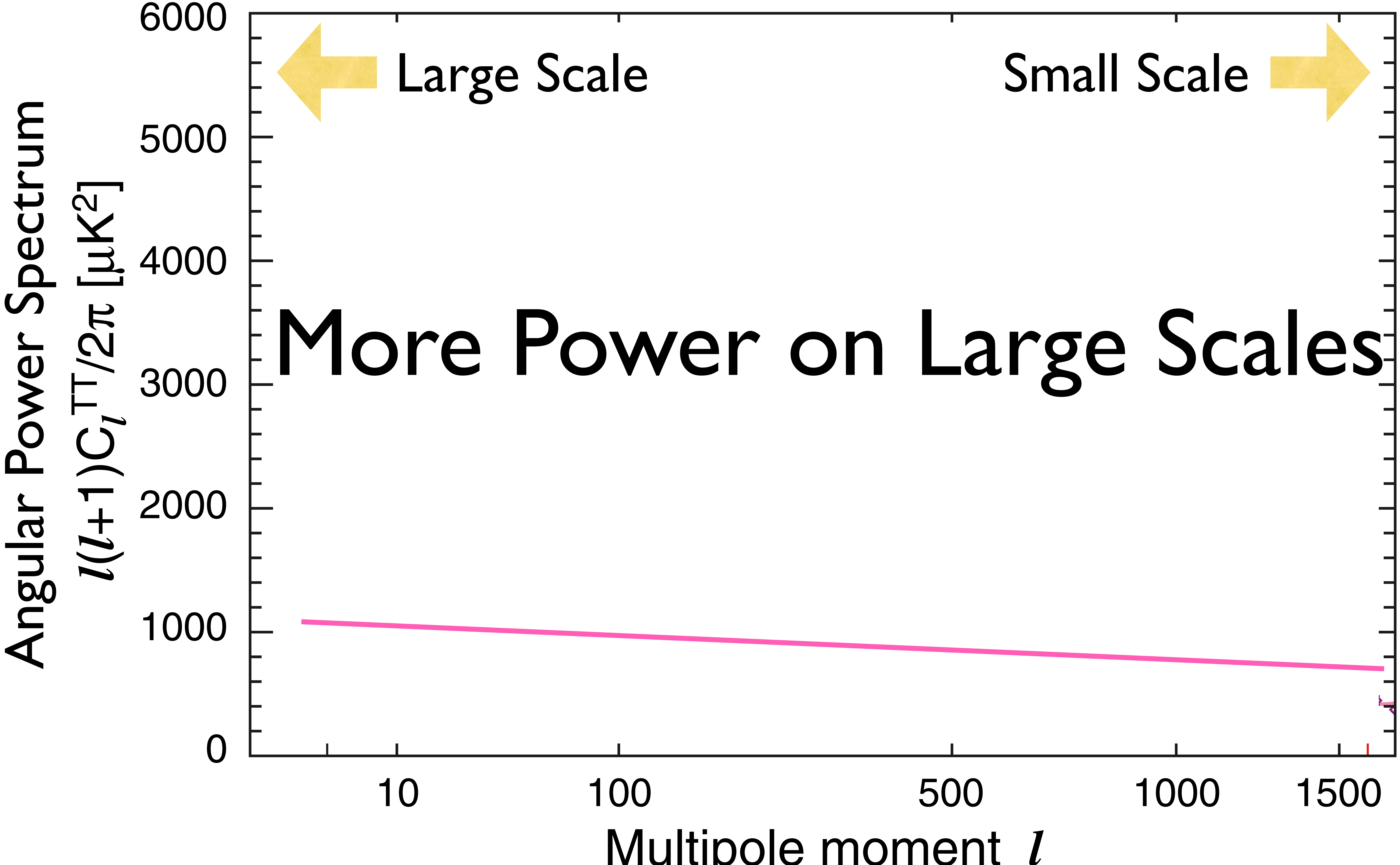
WMAP Power Spectrum



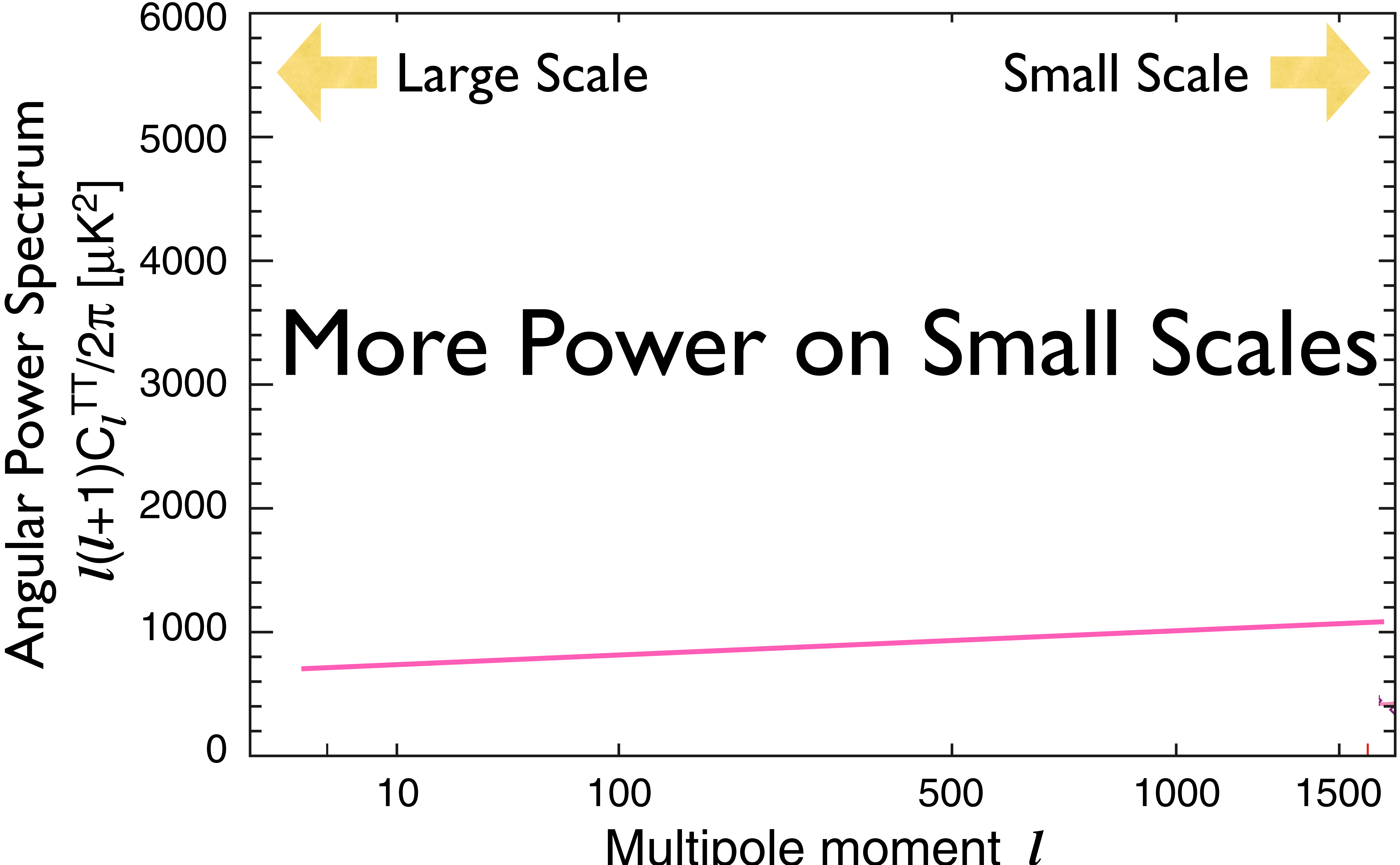
Getting rid of the Sound Waves



The Early Universe Could Have Done This Instead

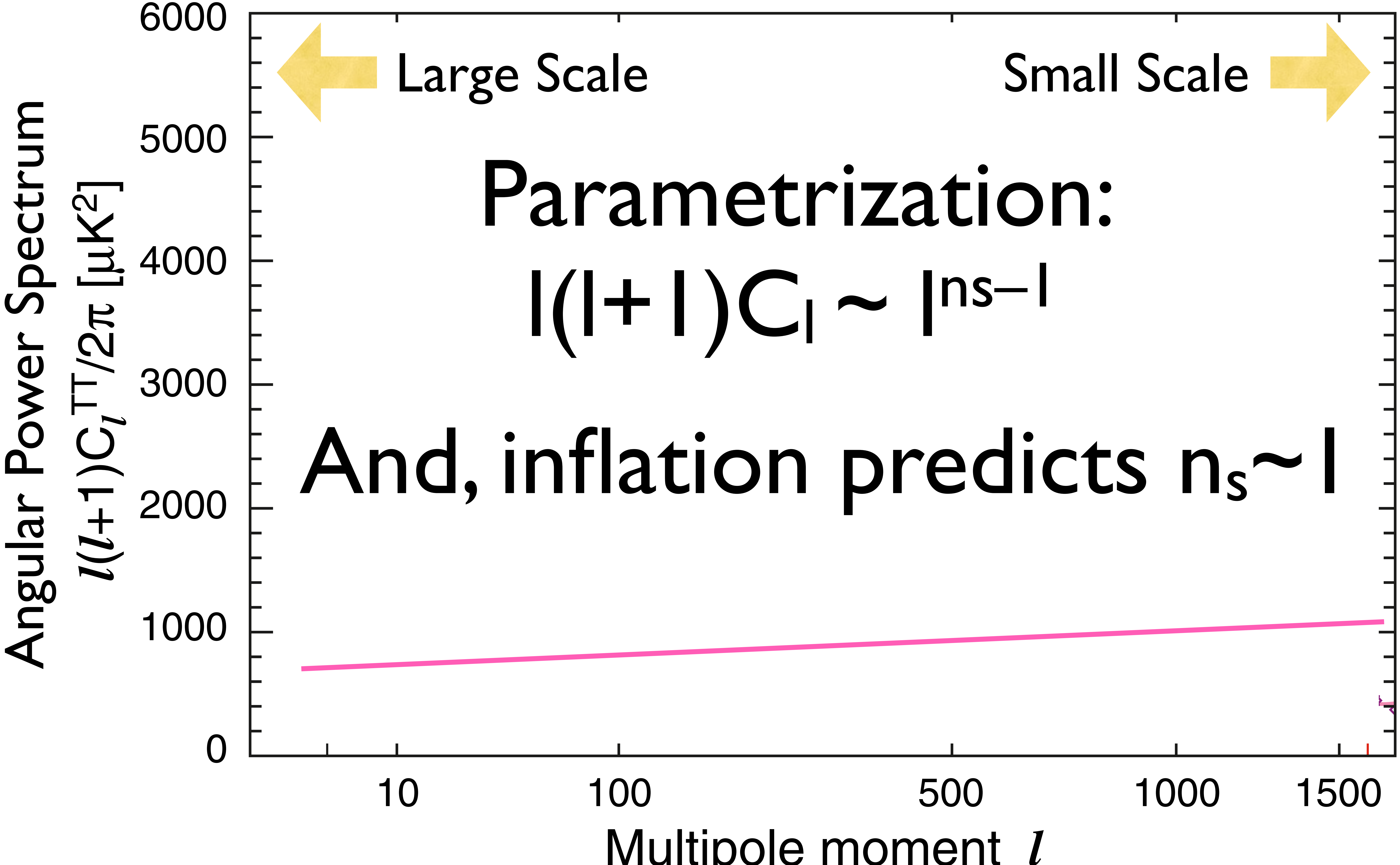


...or, This.



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

...or, This.



Large Scale
Small Scale
Parametrization:
$l(l+1)C_l \sim l^{ns-1}$
And, inflation predicts $n_s \sim 1$
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Angular Power Spectrum
$l(l+1)C_l^{TT}/2\pi$ [μK²]
Multipole moment l

Theory Says...

- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  - The expansion of our Universe ***accelerated*** in a tiny fraction of a second after its birth.
  - the primordial ripples were created by ***quantum fluctuations*** during inflation, and
  - how the power is distributed over the scales is determined by the **expansion history during cosmic inflation**.
- Measurement of n_s gives us **this** remarkable information!

Mukhanov & Chibisov (1981); Guth & Pi (1982); Starobinsky (1982); Hawking (1982); Bardeen, Turner & Steinhardt (1983)

(Scalar) Quantum Fluctuations

$\delta\varphi$ = (Expansion Rate)/(2π) [in natural units]

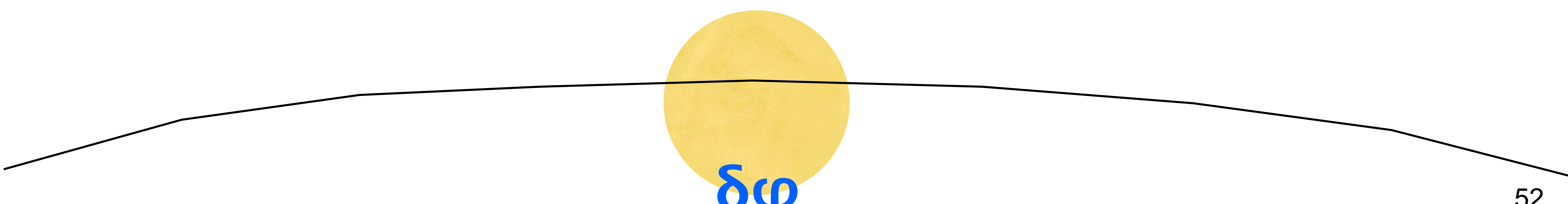
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like 10^{-36} second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~10^{12}GeV)
  - *Quantum fluctuations were important during inflation!*

Stretching Micro to Macro

Macroscopic size at which gravity becomes important

Quantum fluctuations on microscopic scales

INFLATION!



Quantum fluctuations cease to be quantum, and become observable!

Inflation Offers a Magnifier for Microscopic World

- Using the *power spectrum of primordial fluctuations* imprinted in CMB, we can observe the quantum phenomena at the ultra high-energy scales that would never be reached by the particle accelerator.

- Measured value: $n_s = 0.968 \pm 0.012$ (68%CL)

Starobinsky (1979)

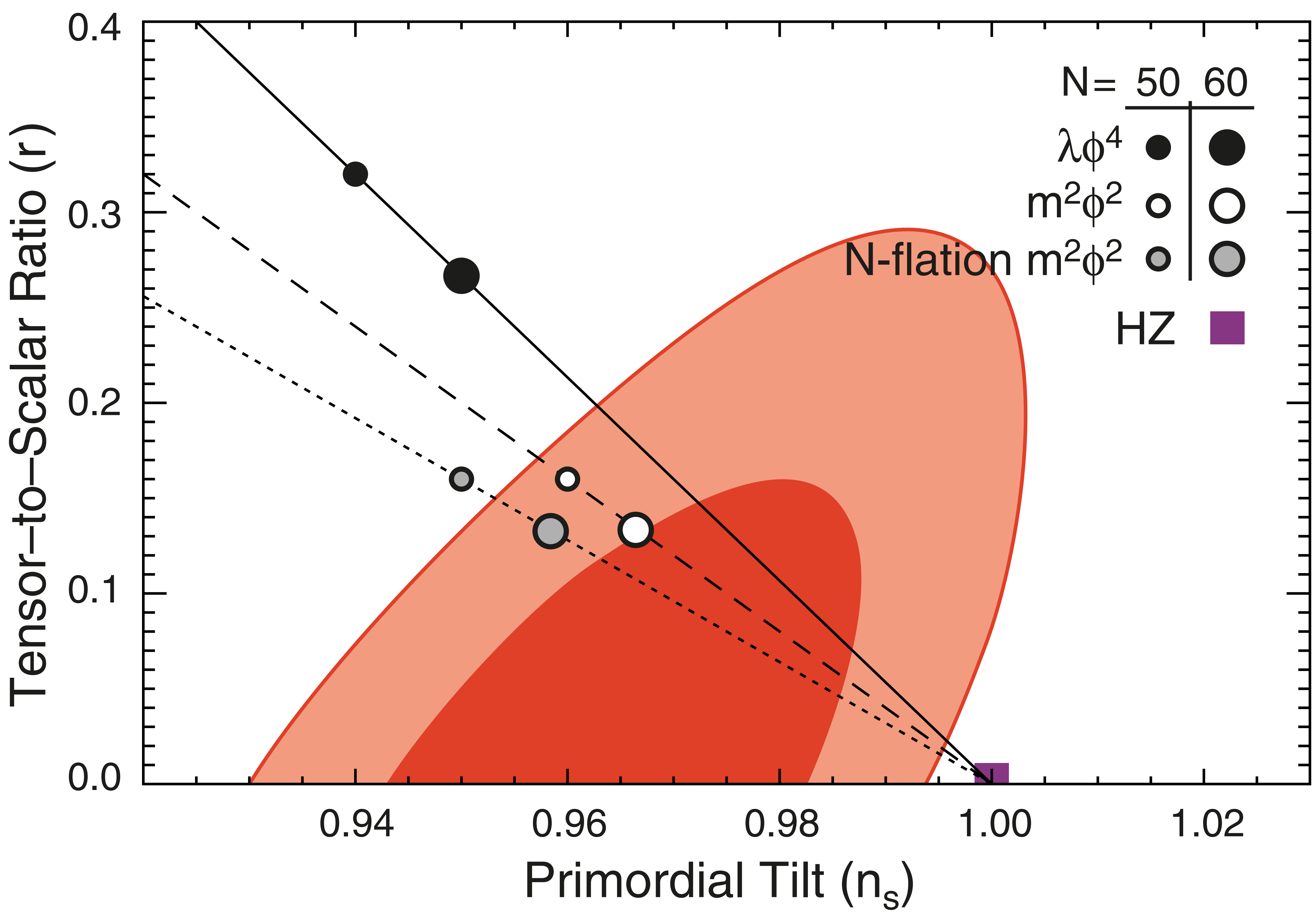
(Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

h = (Expansion Rate)/($2^{1/2}\pi M_{planck}$) [in natural units]

[h = "strain"]

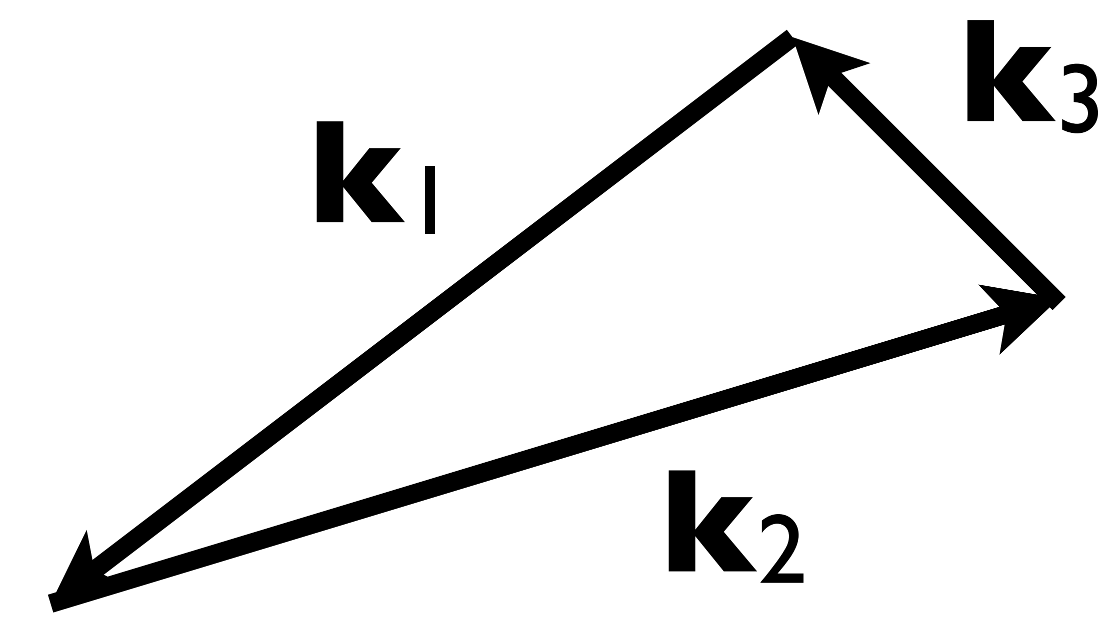
- Quantum fluctuations also generate ripples in space-time, i.e., gravitational waves, by the same mechanism.
- Primordial gravitational waves generate temperature anisotropy in CMB, as well as polarization in CMB with a distinct pattern called "**B-mode polarization**."

Probing Inflation (2-point Function)



- Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.
  - $r < 0.24$ (95%CL)

Bispectrum

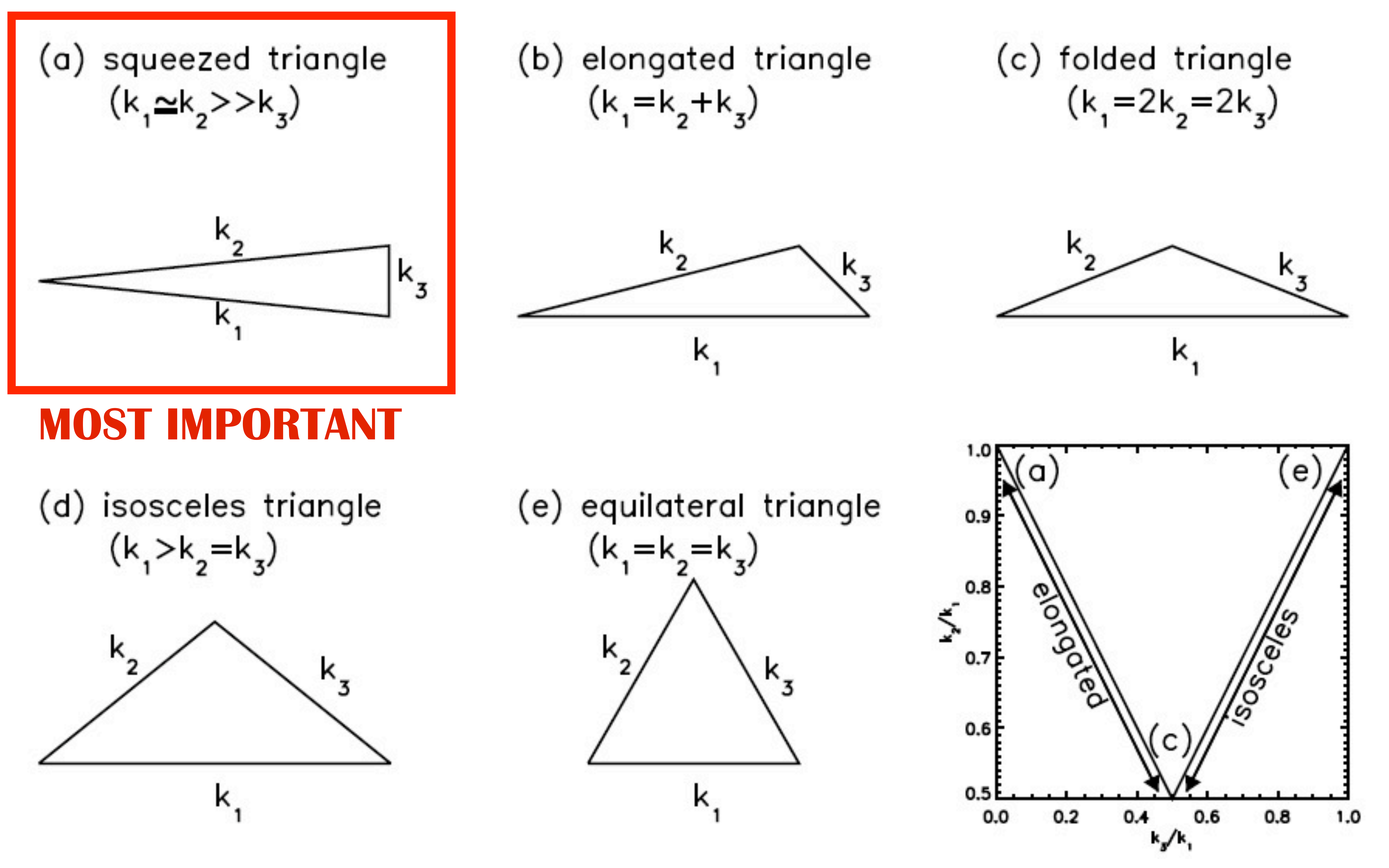


- Three-point function!
- $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$
  $= \langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle = (\text{amplitude}) \times (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)F(k_1,k_2,k_3)$

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:
  - **$f_{NL} = 32 \pm 21$ (1σ)**
  - The WMAP data are consistent with the prediction of **simple single-field inflation** models: $1-n_s \approx r \approx f_{NL}$

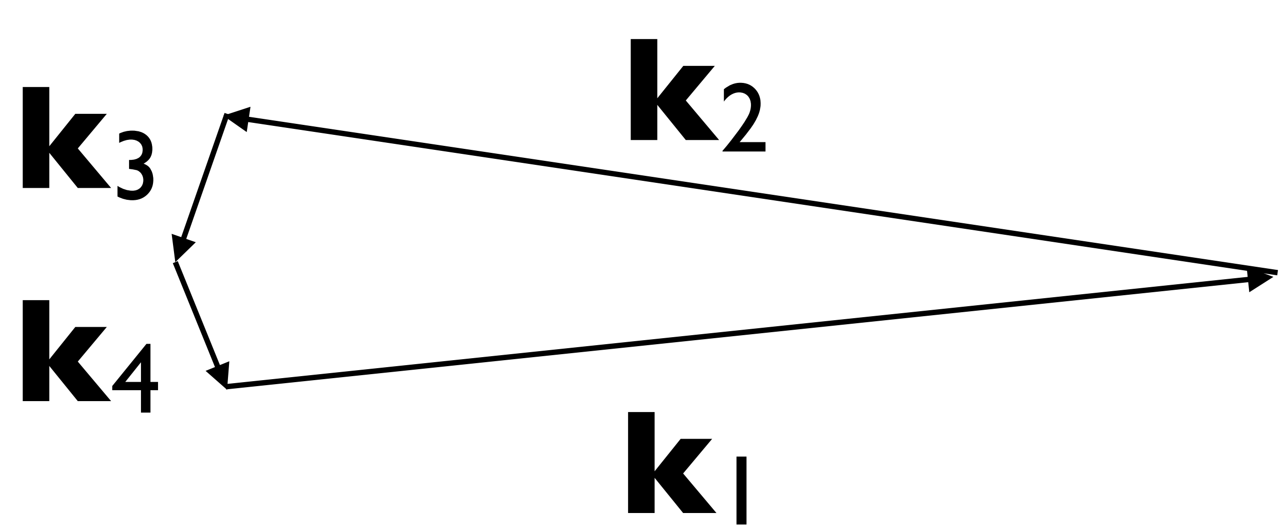
Summary

- CMB is the fossil light of the Big Bang.
- We could determine the age, composition, expansion rate, etc., from CMB.
- We could even push the boundary farther back in time, probing the origin of fluctuations in the very early Universe: inflationary epoch at ultra-high energies.
- Next Big Thing: **Primordial gravitational waves**.
- The 3-point function: **Powerful test of inflation**.

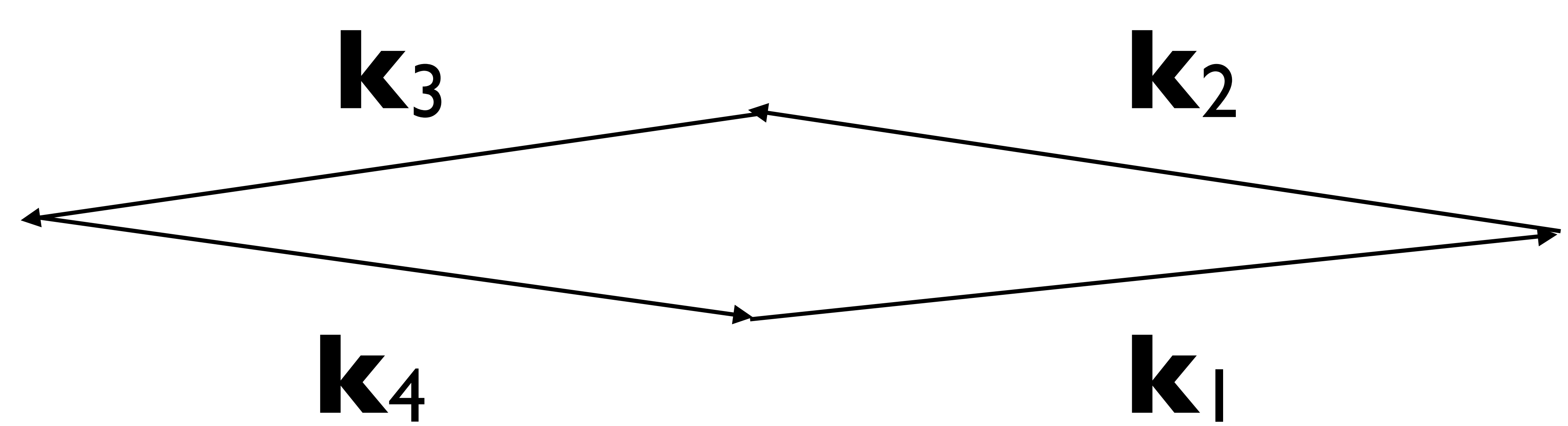
Trispectrum

- $T_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)=(2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\mathbf{k}_4)$
  $\{g_{NL}[(54/25)P_\zeta(k_1)P_\zeta(k_2)P_\zeta(k_3)+\text{cyc.}]$
  $+\tau_{NL}[P_\zeta(k_1)P_\zeta(k_2)(P_\zeta(|\mathbf{k}_1+\mathbf{k}_3|)+P_\zeta(|\mathbf{k}_1+\mathbf{k}_4|))+\text{cyc.}]\}$

The local form consistency relation,
$\tau_{NL}=(6/5)(f_{NL})^2$, may not be respected –
additional test of multi-field inflation!

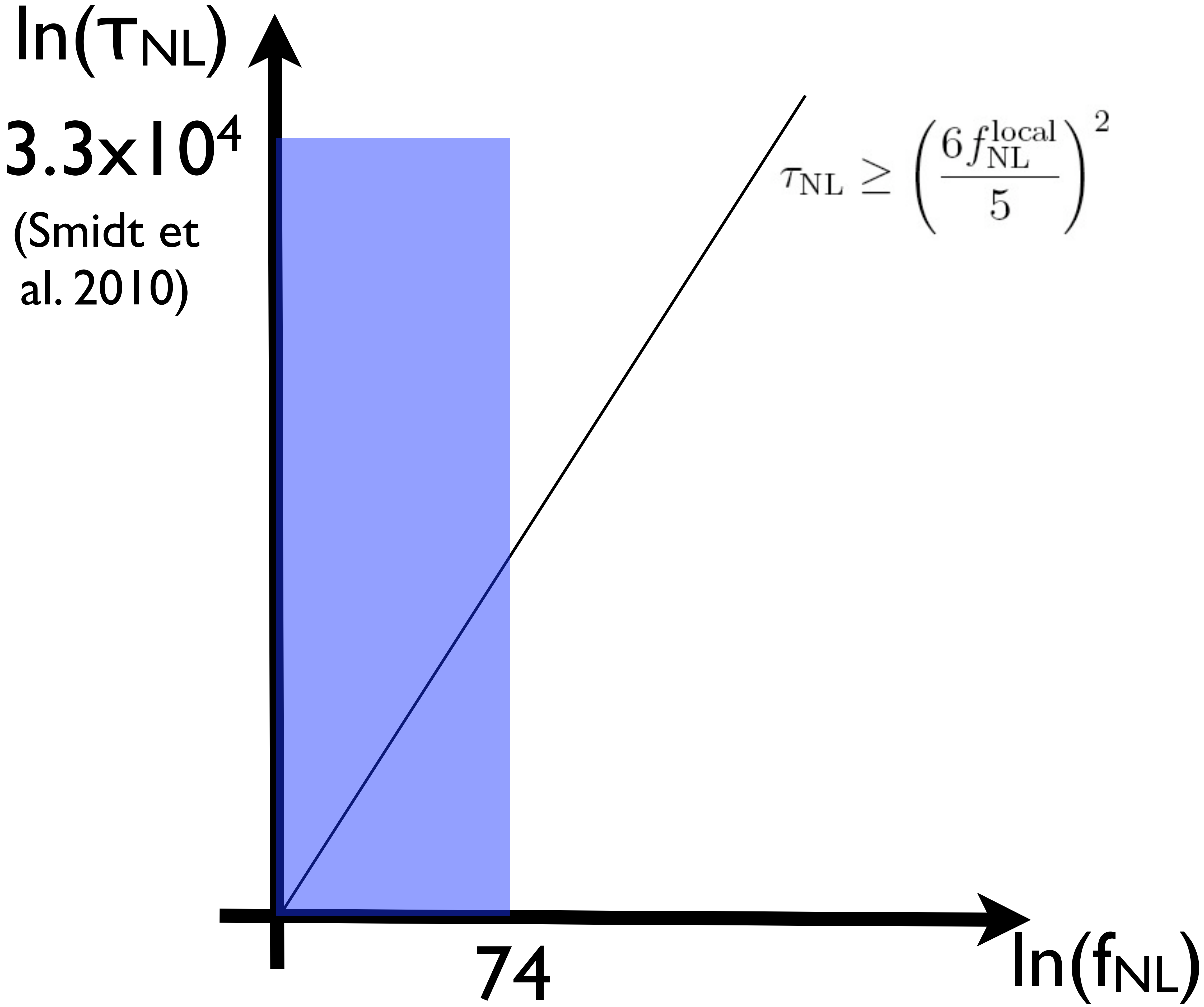


g_{NL}



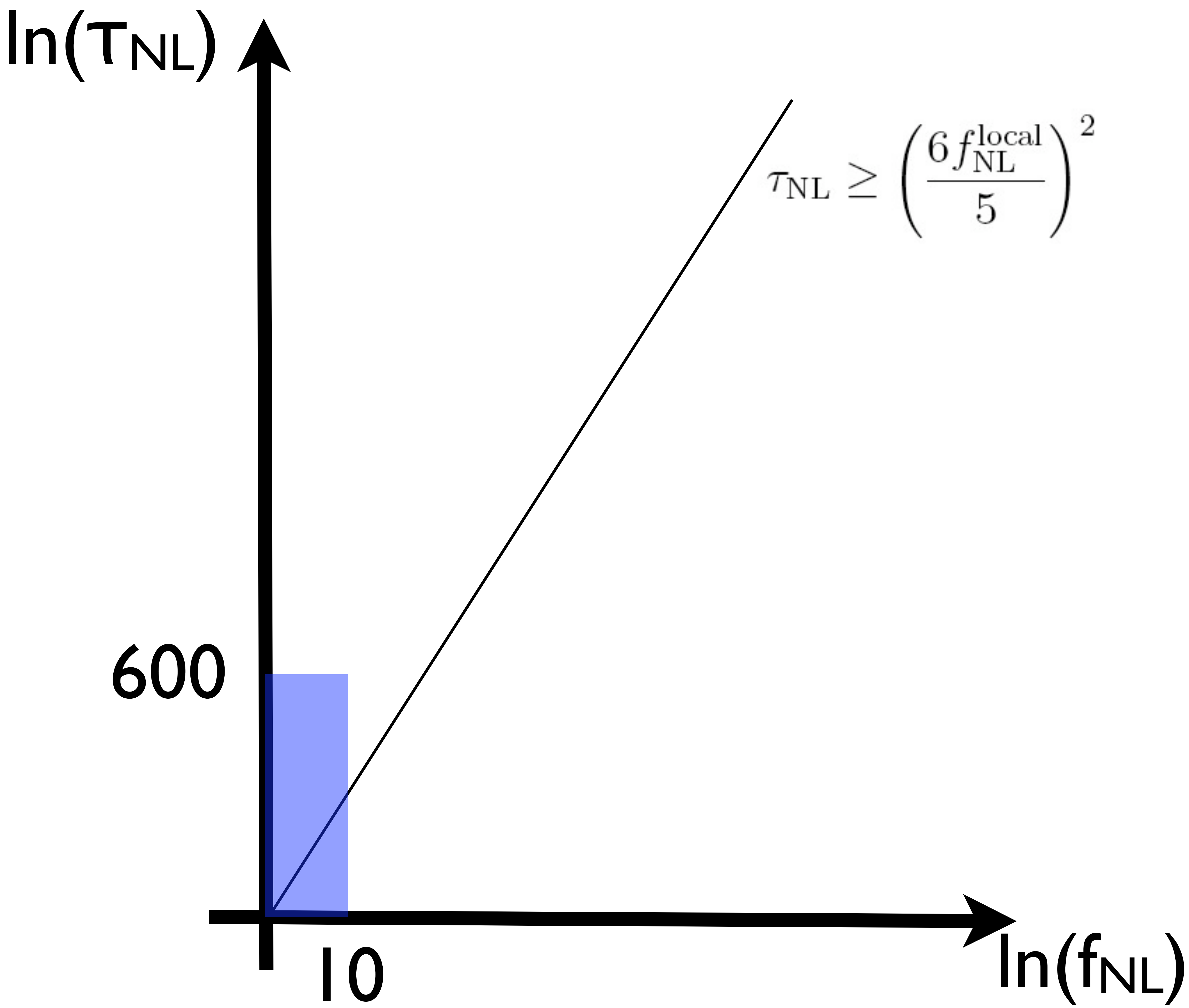
τ_{NL}

The diagram that you should take away from this talk.



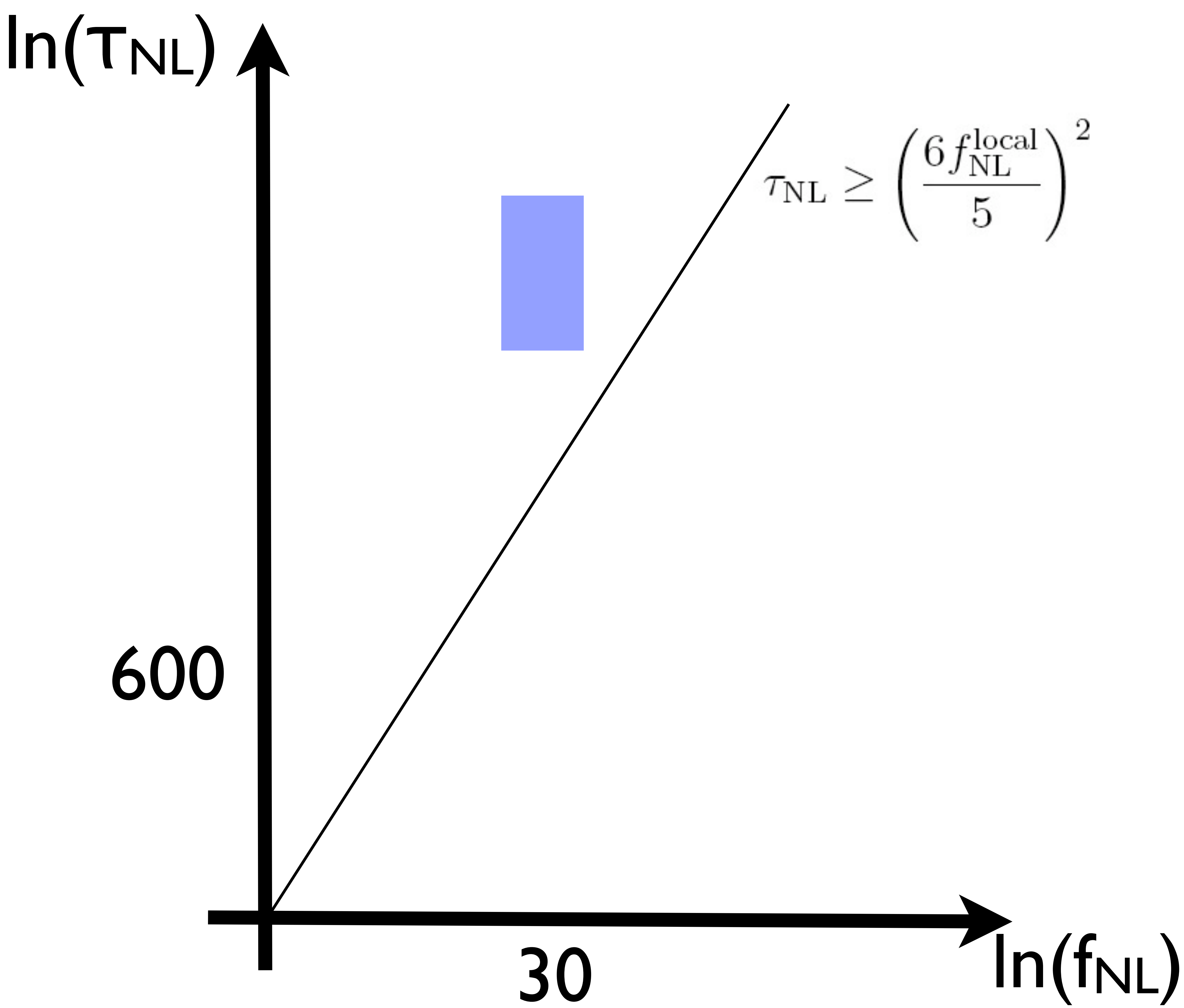
- The current limits from WMAP 7-year are consistent with single-field or multi-field models.
- So, let's play around with the future.

Case A: Single-field Happiness



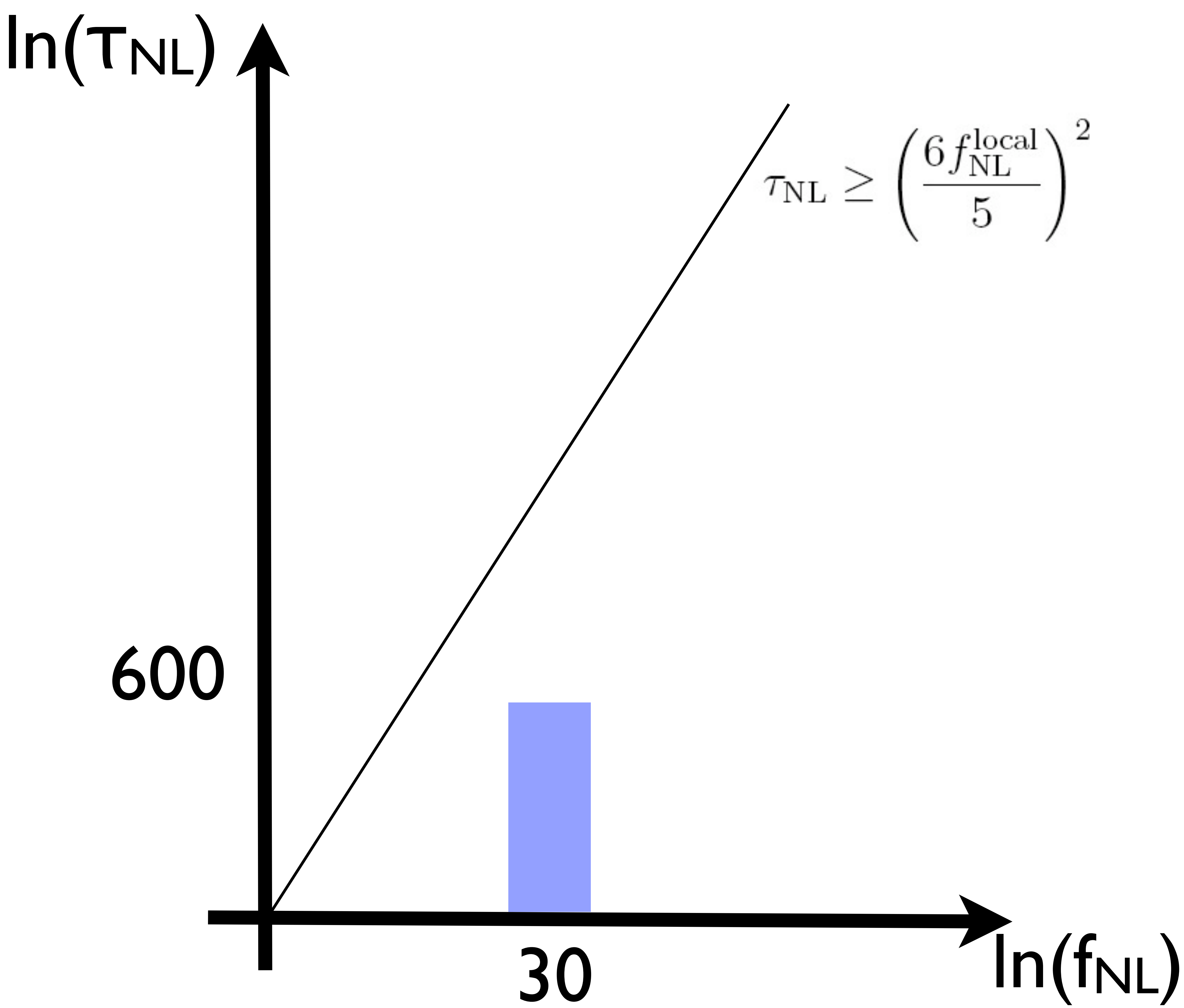
- No detection of anything after Planck. Single-field survived the test (for the moment: the future galaxy surveys can improve the limits by a factor of ten).

Case B: Multi-field Happiness



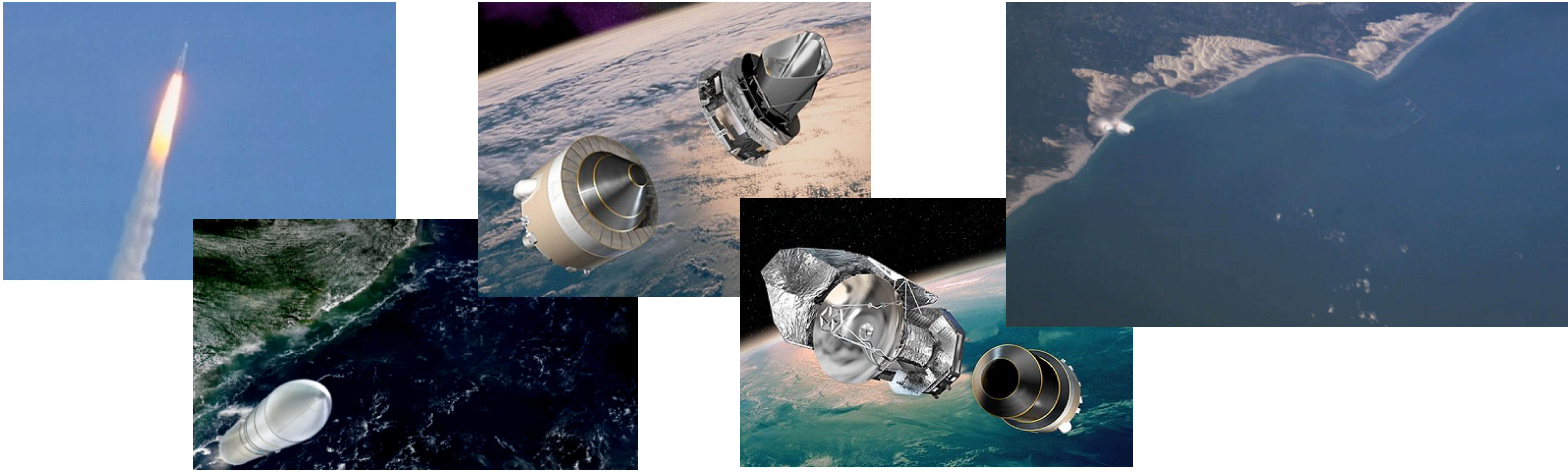
- f_{NL} is detected. Single-field is dead.
- But, τ_{NL} is also detected, in accordance with the Suyama-Yamaguchi inequality, as expected from most (if not all - left unproven) of multi-field models.

Case C: Madness



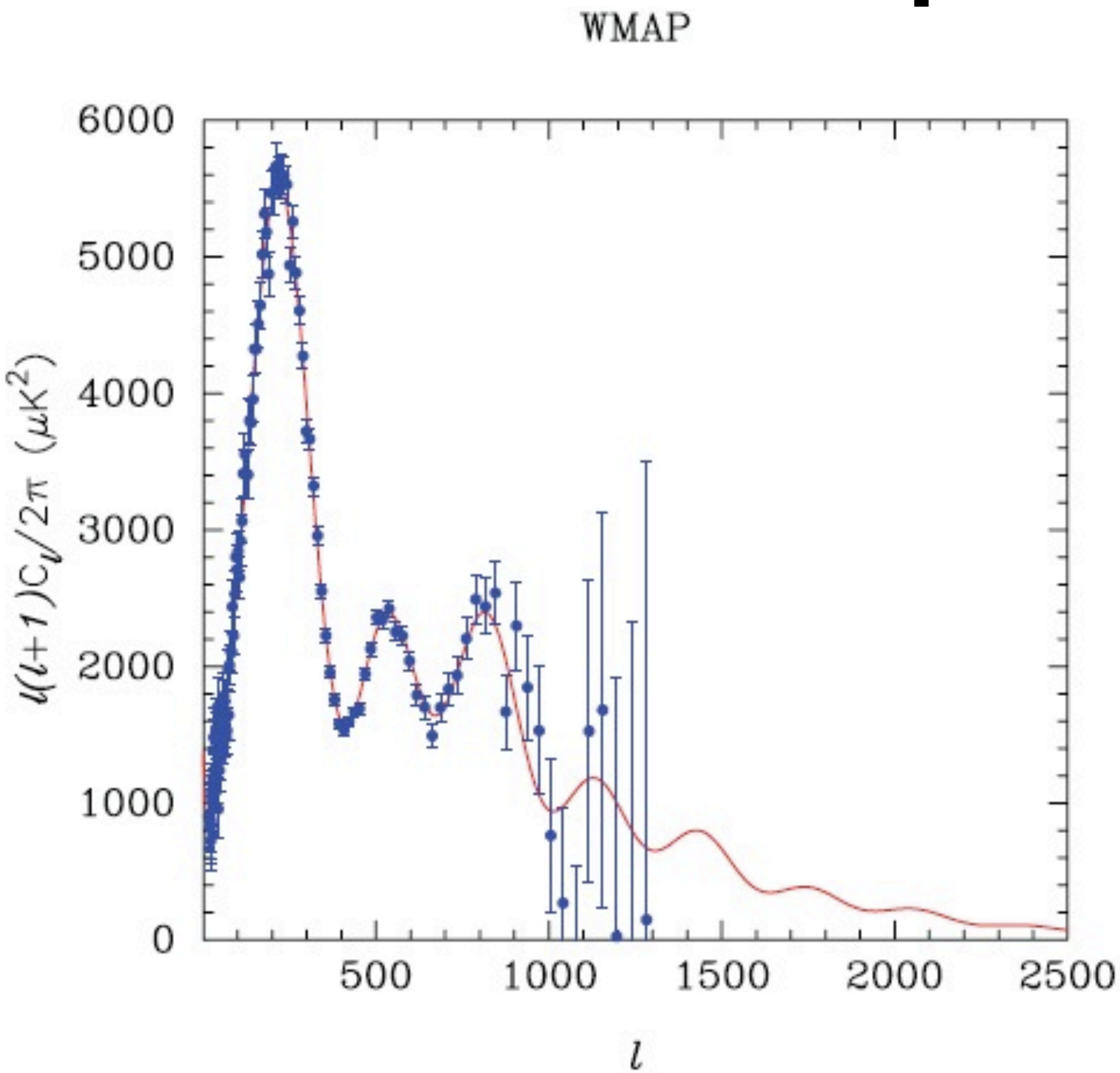
- f_{NL} is detected. Single-field is dead.
- But, τ_{NL} is **not** detected, inconsistent with the Suyama-Yamaguchi inequality.
- (With the caveat that this may not be completely general) BOTH the single-field and multi-field are gone.

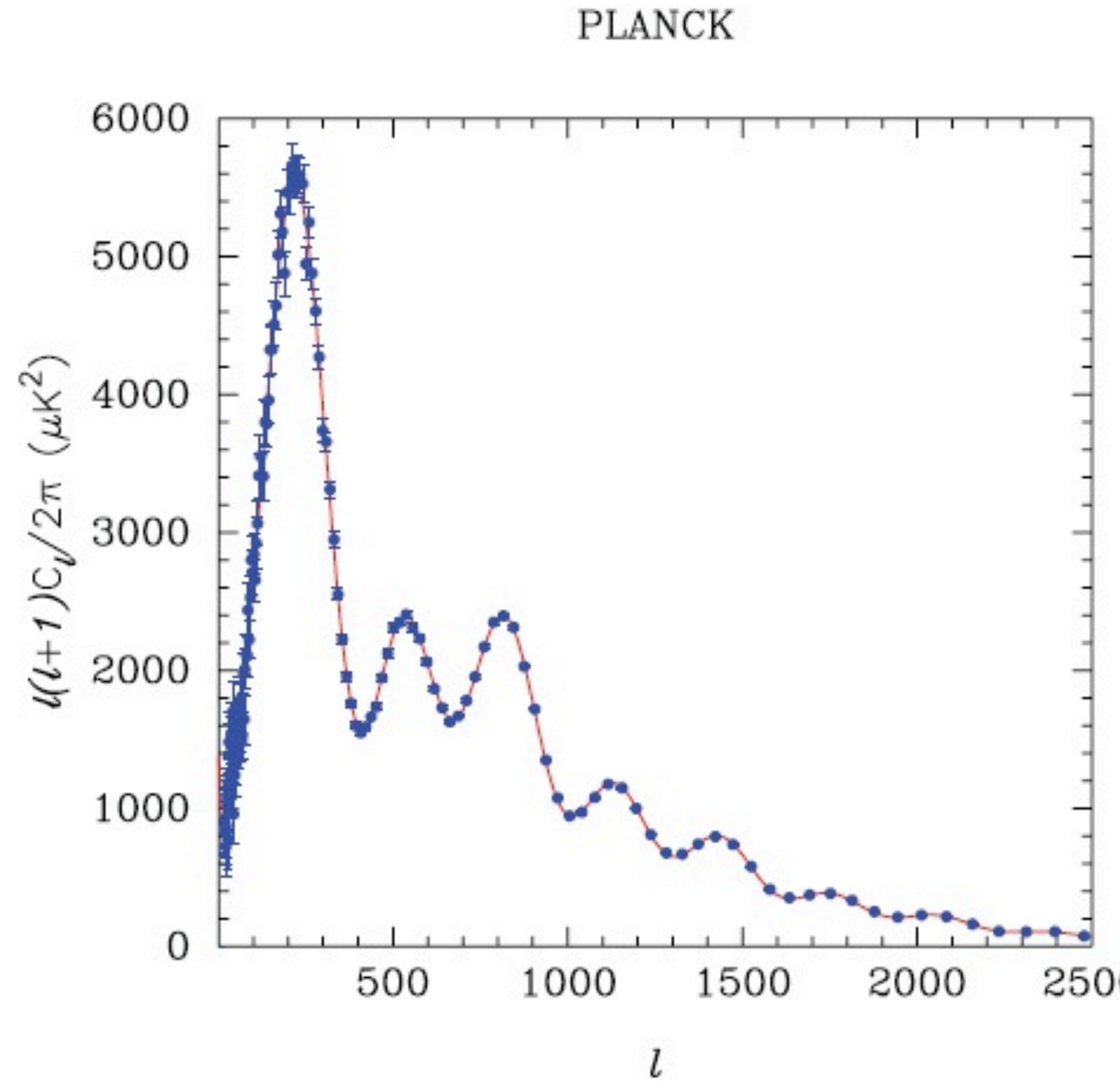
Planck Launched!



- The Planck satellite was successfully launched from French Guiana on May 14, 2009.
- Separation from the Herschell satellite was also successful.
- Planck has mapped the full sky already - results expected to be released in December, 2012.

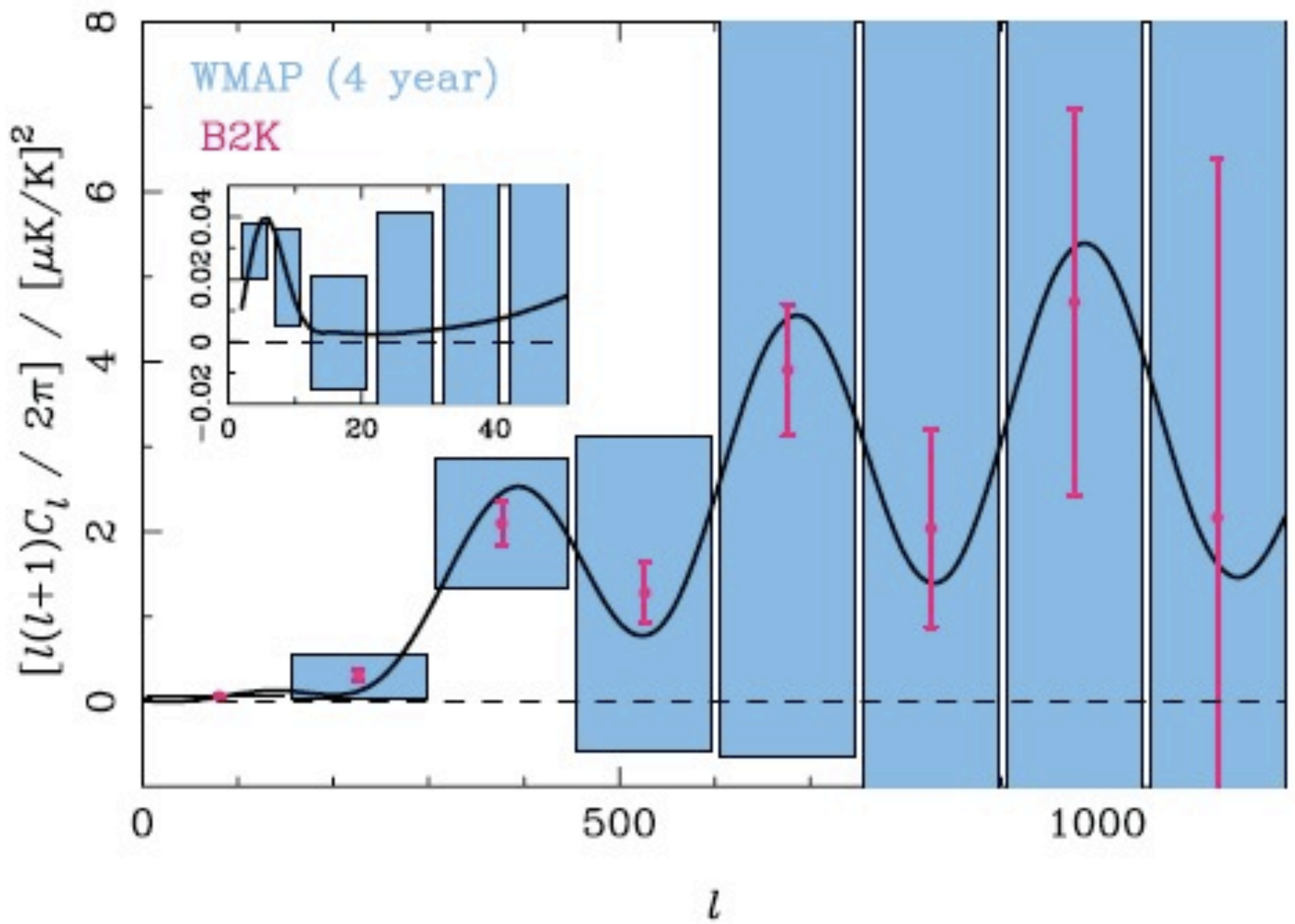
Planck: Expected $C_l^{Temperature}$

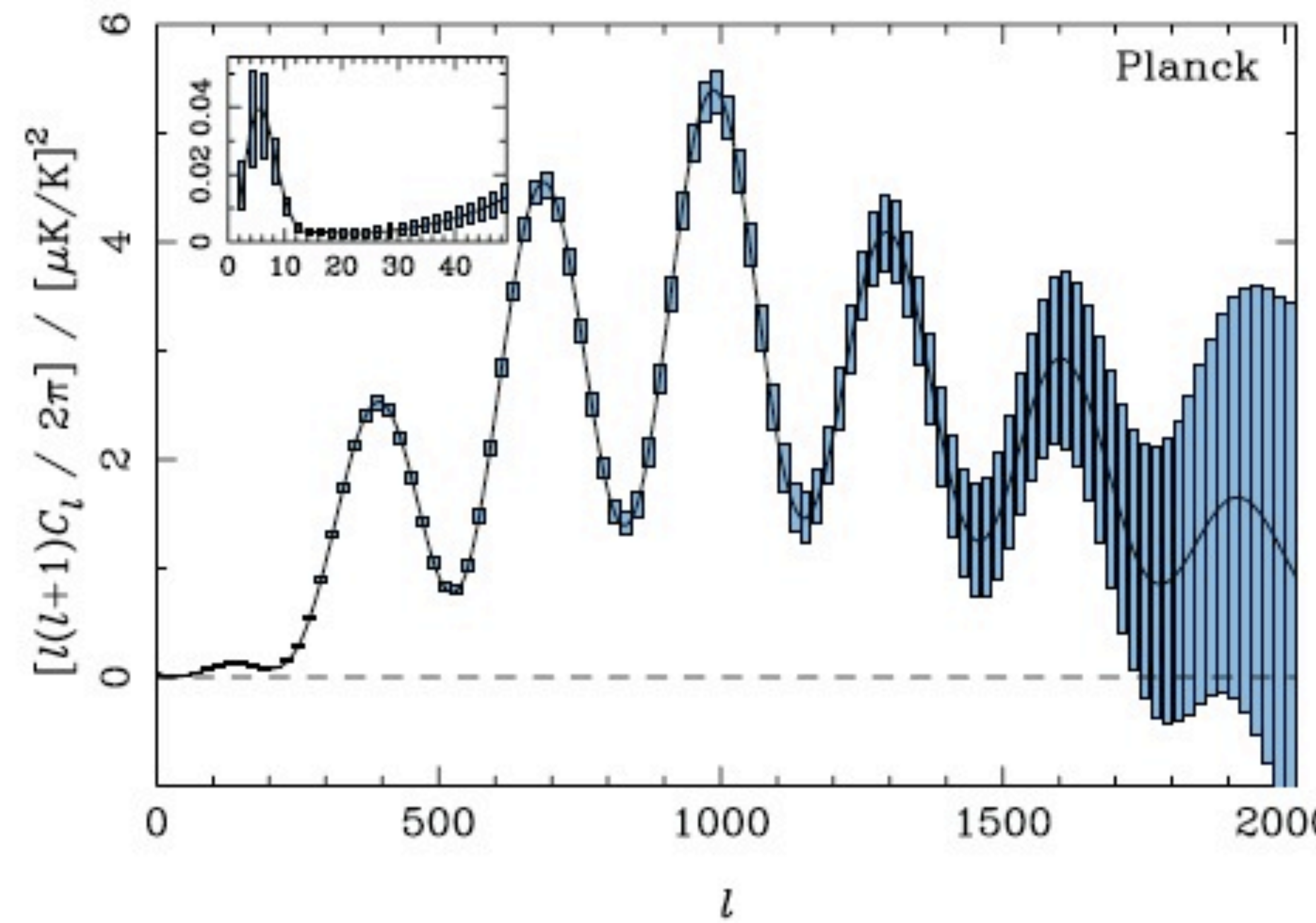


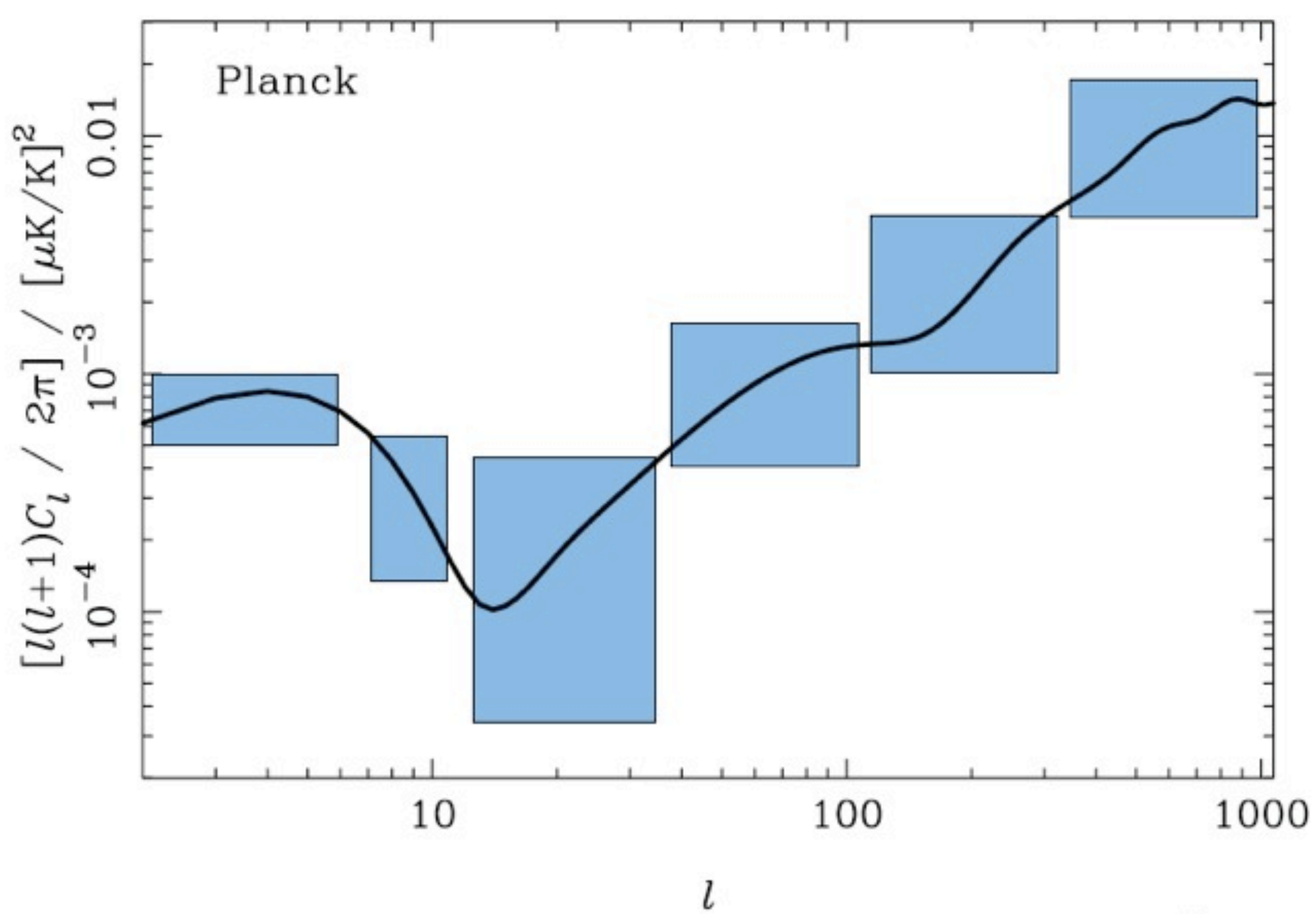


- WMAP: l~1000 => Planck: l~3000

Planck: Expected $C_l^{Polarization}$







- (Above) E-modes
- (Left) B-modes (r=0.3)