The **7**-Year *WMAP* Observations: Cosmological Interpretation

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)
Physics Colloquium, Florida State University, September 30, 2010

Cosmology: The Questions

- How much do we understand our Universe?
  - How old is it?
  - How big is it?
  - What shape does it take?
  - What is it made of?
  - How did it begin?

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"

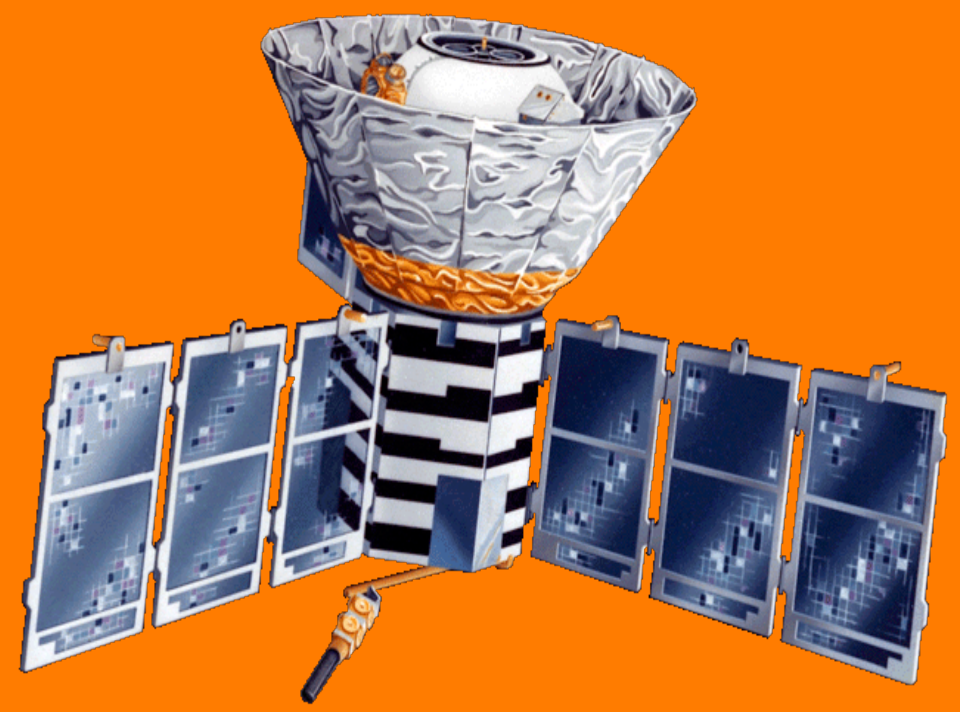
Night Sky in Optical (~0.5μm)

Night Sky in Microwave (~1mm)

courtesy University of Arizona

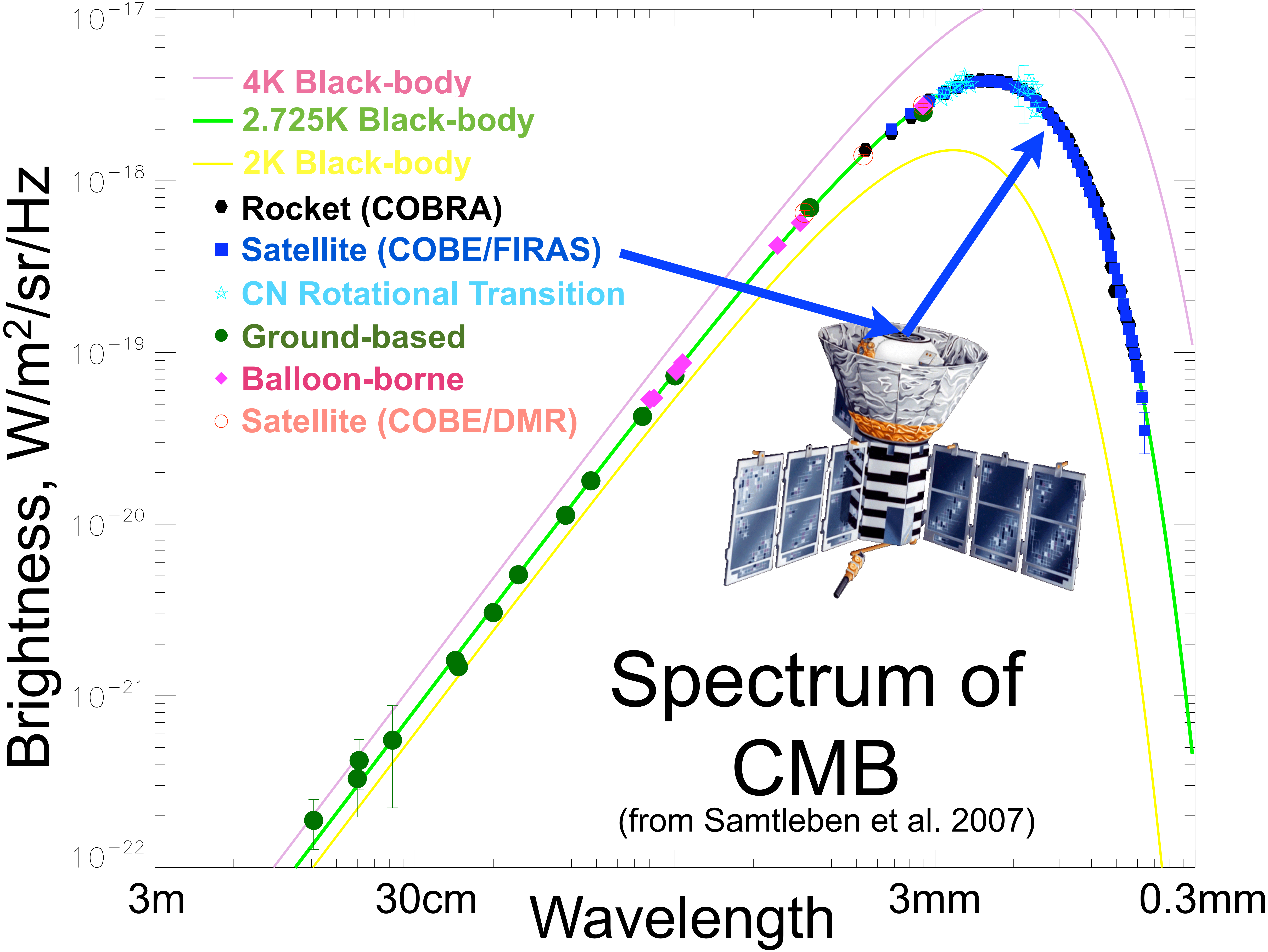
Night Sky in Microwave (~1mm)

T_{today}=2.725K



COBE Satellite, 1989-1993

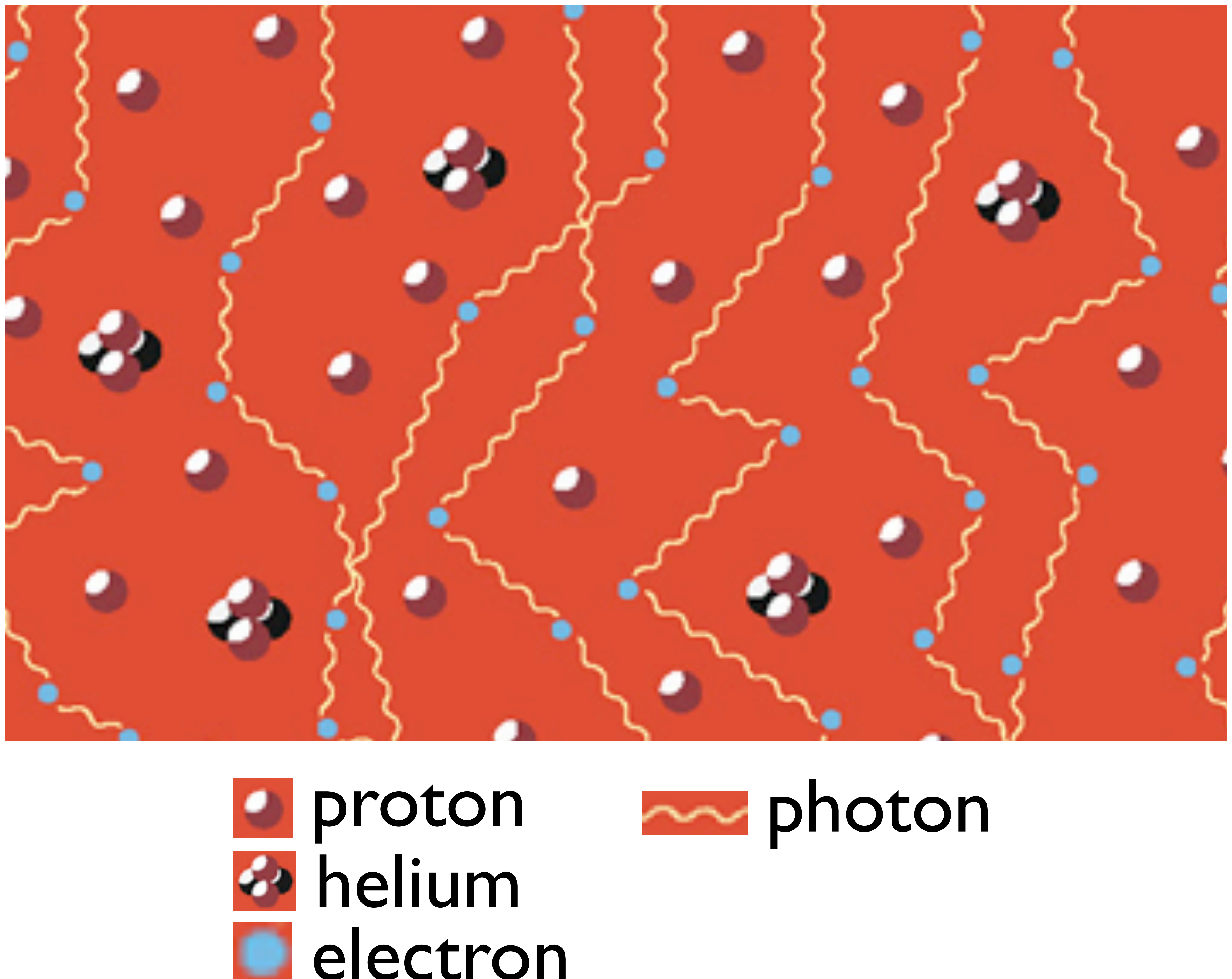
courtesy University of Arizona


4K Black-body
2.725K Black-body
2K Black-body
Rocket (COBRA)
Satellite (COBE/FIRAS)
CN Rotational Transition
Ground-based
Balloon-borne
Satellite (COBE/DMR)
Spectrum of CMB
(from Samtleben et al. 2007)
Brightness, W/m²/sr/Hz
10−17
10−18
10−19
10−20
10−21
10−22
3m
30cm
3mm
0.3mm
Wavelength

How was CMB created?

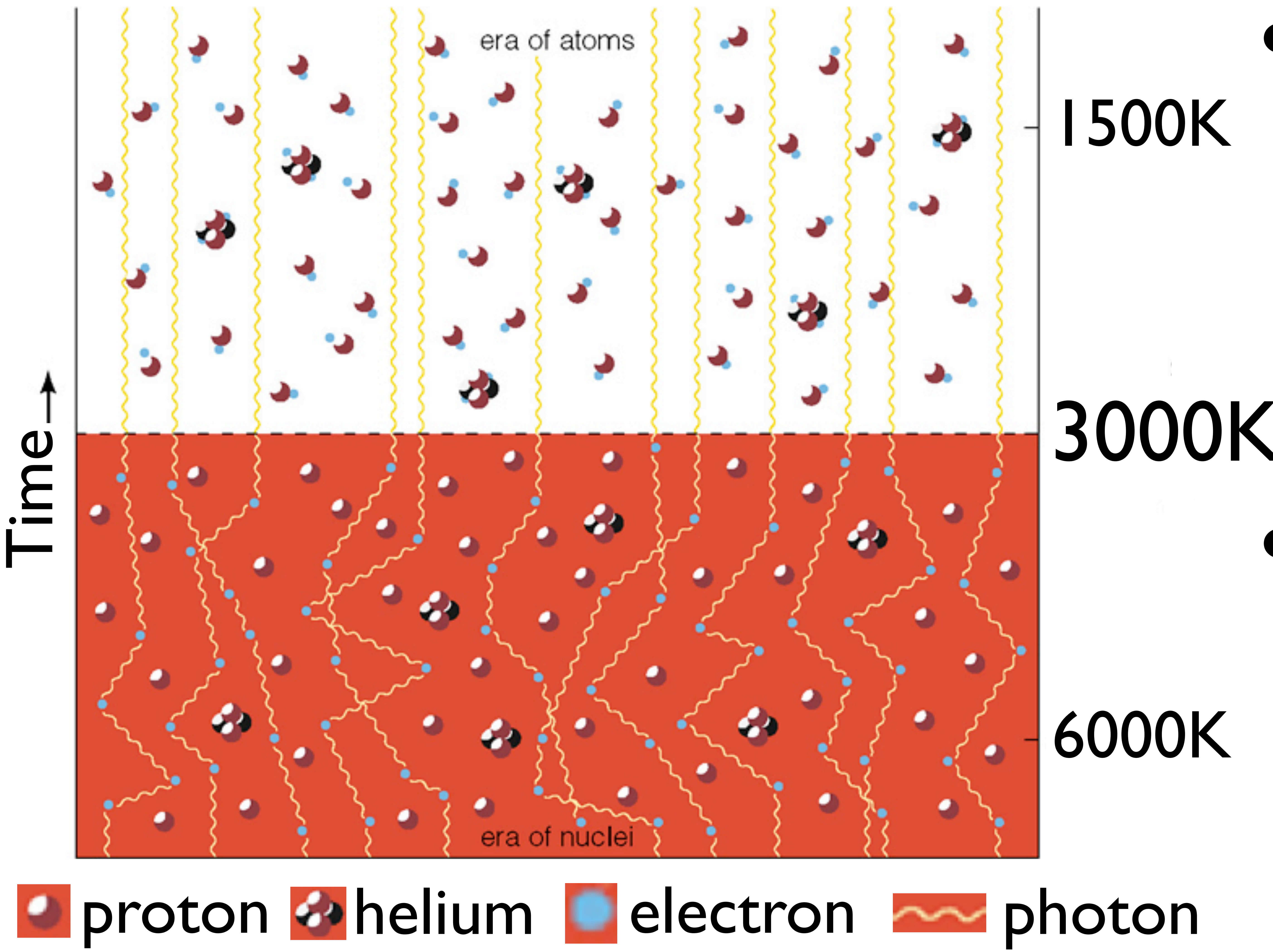
- When the Universe was hot, it was a hot soup made of:
  - Protons, electrons, and helium nuclei
  - Photons and neutrinos
  - Dark matter

Universe as a hot soup

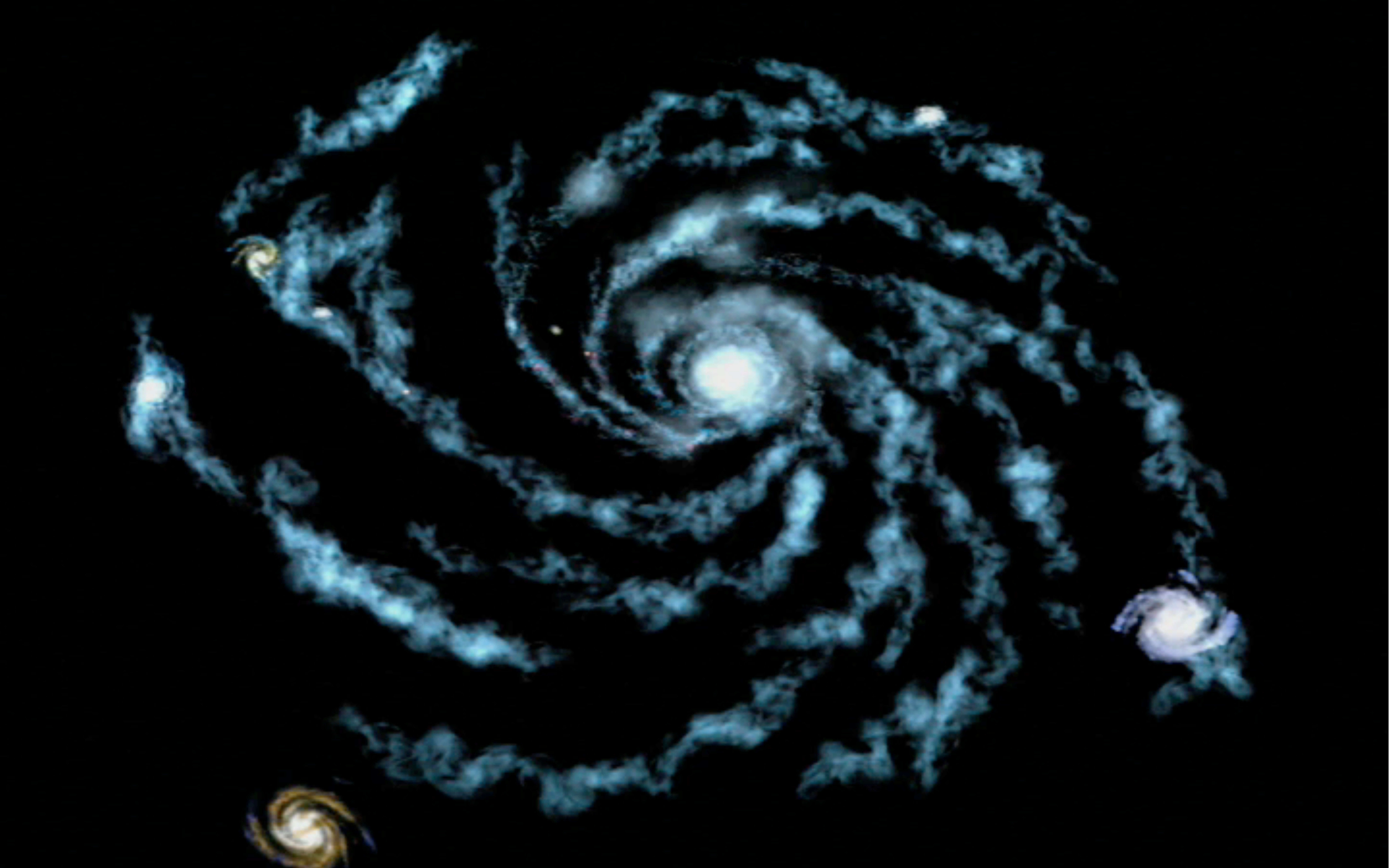


- Free electrons can scatter photons efficiently.
- Photons cannot go very far.

Recombination and Decoupling

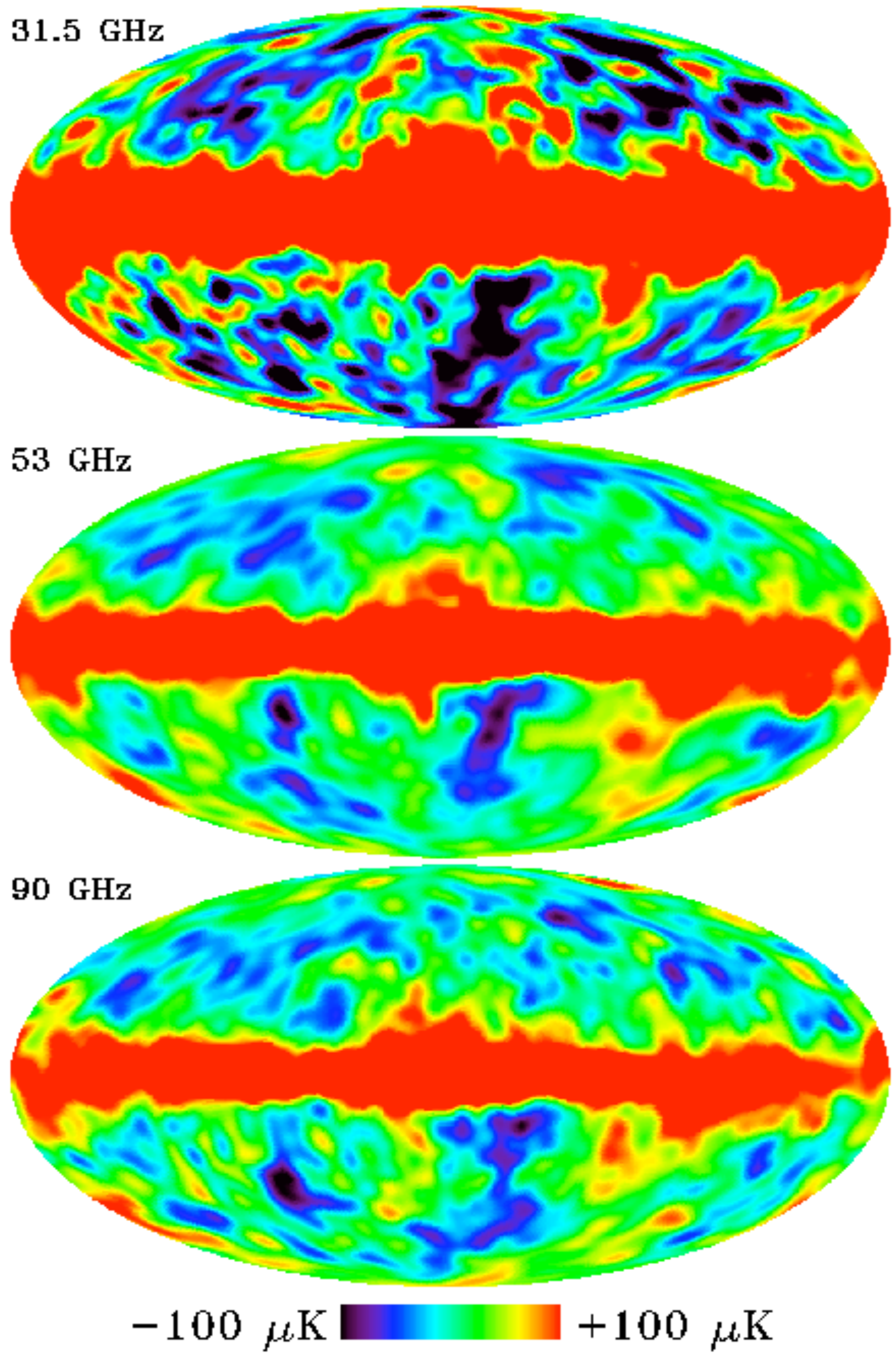


- [***recombination***] When the temperature falls below 3000 K, almost all electrons are captured by protons and helium nuclei.
- [***decoupling***] Photons are no longer scattered. I.e., photons and electrons are no longer coupled.



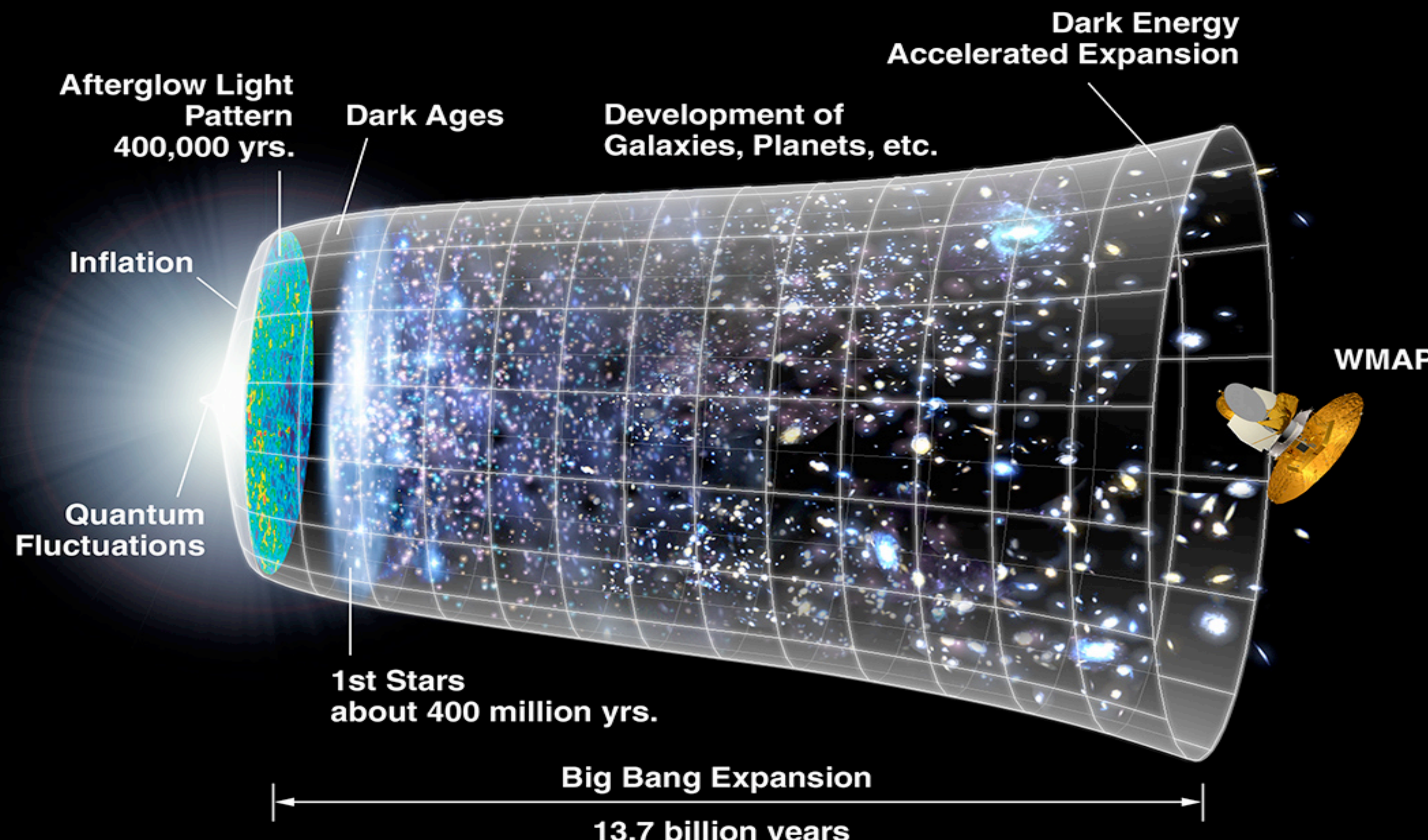
Smoot et al. (1992)

COBE/DMR, 1992



- **Isotropic?**
- **CMB is anisotropic! (at the 1/100,000 level)**

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

WMAP at Lagrange 2 (L2) Point

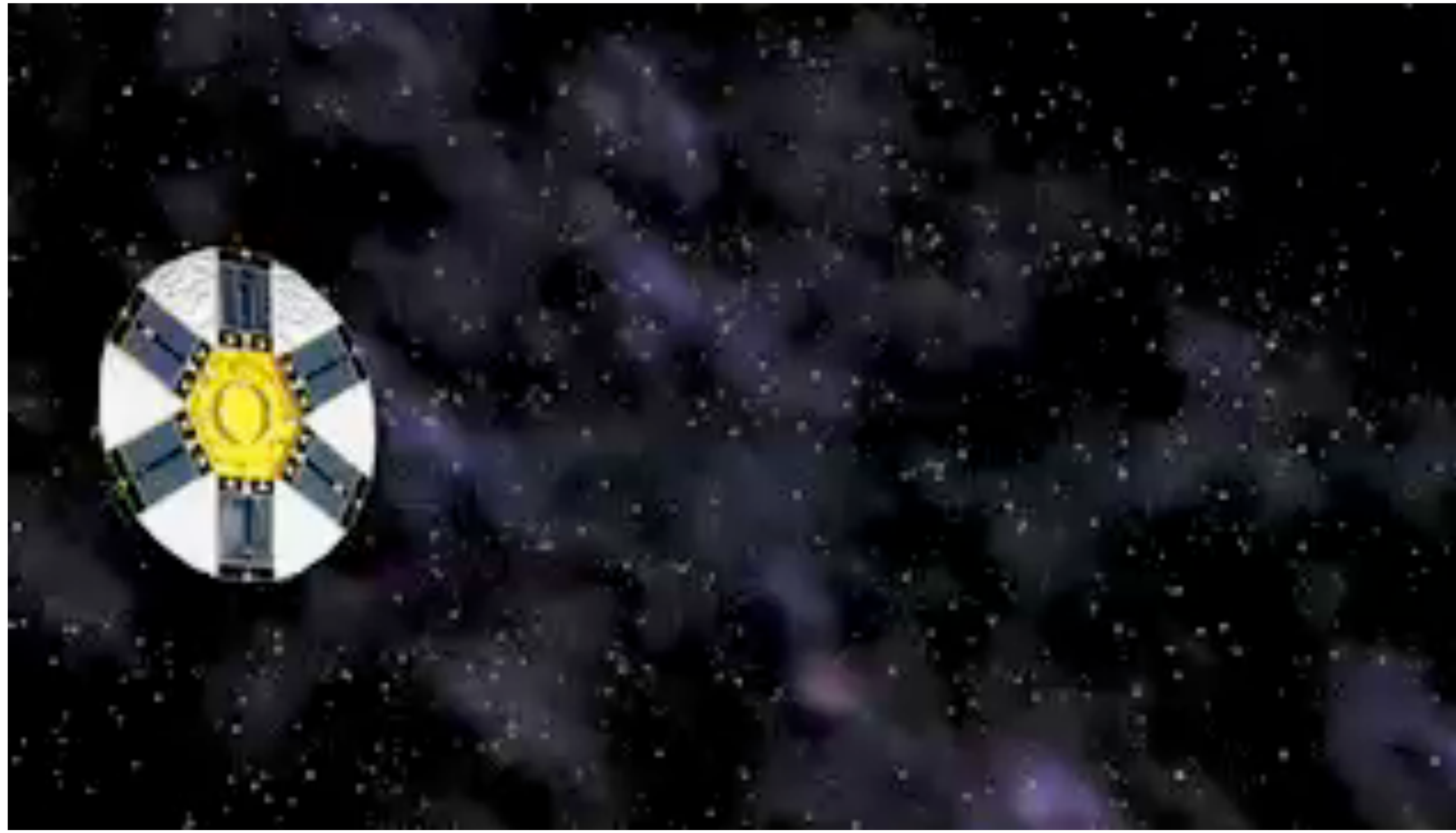
June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

March 2008:
The five-year data release

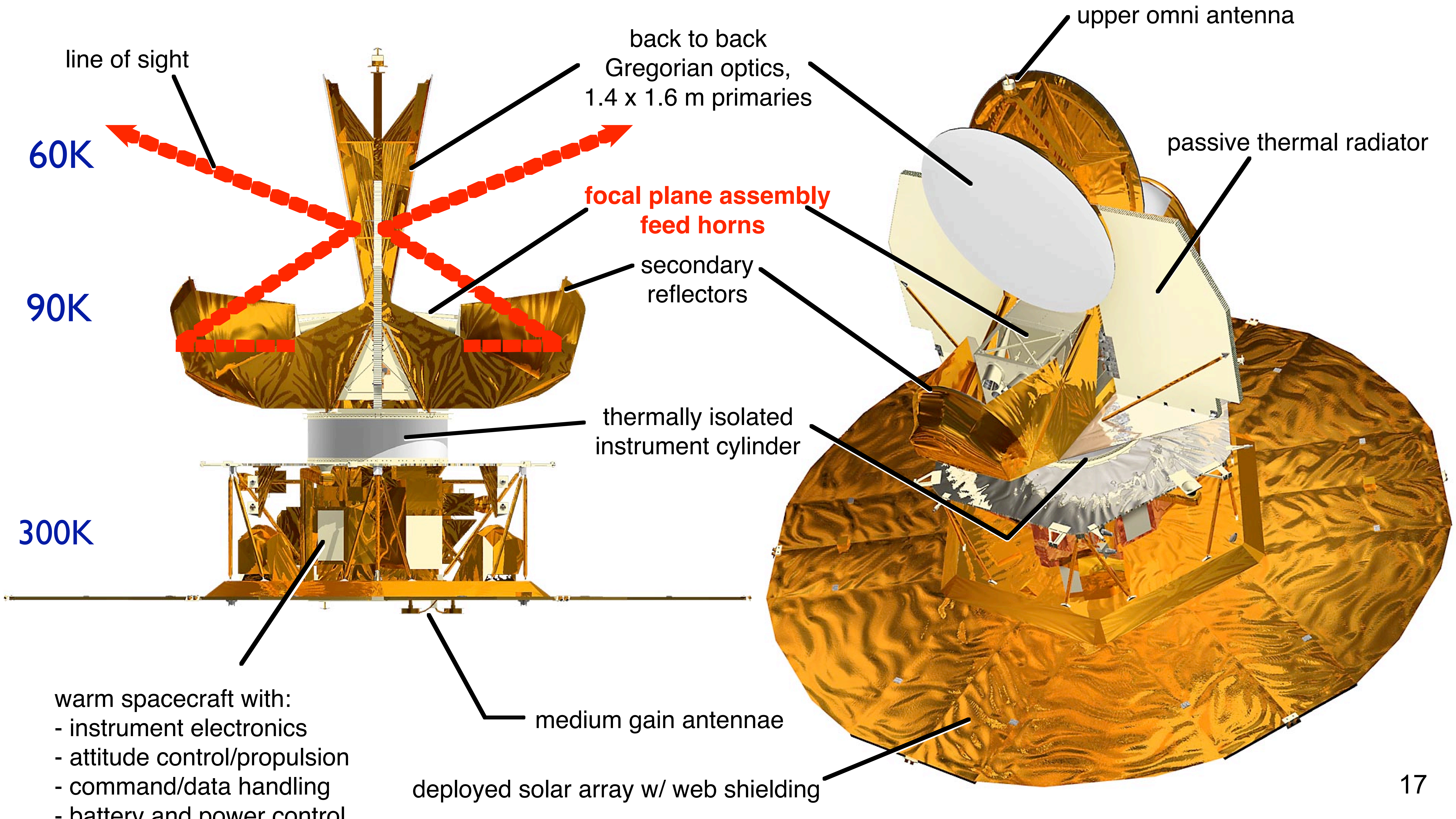
January 2010:
The seven-year data release



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

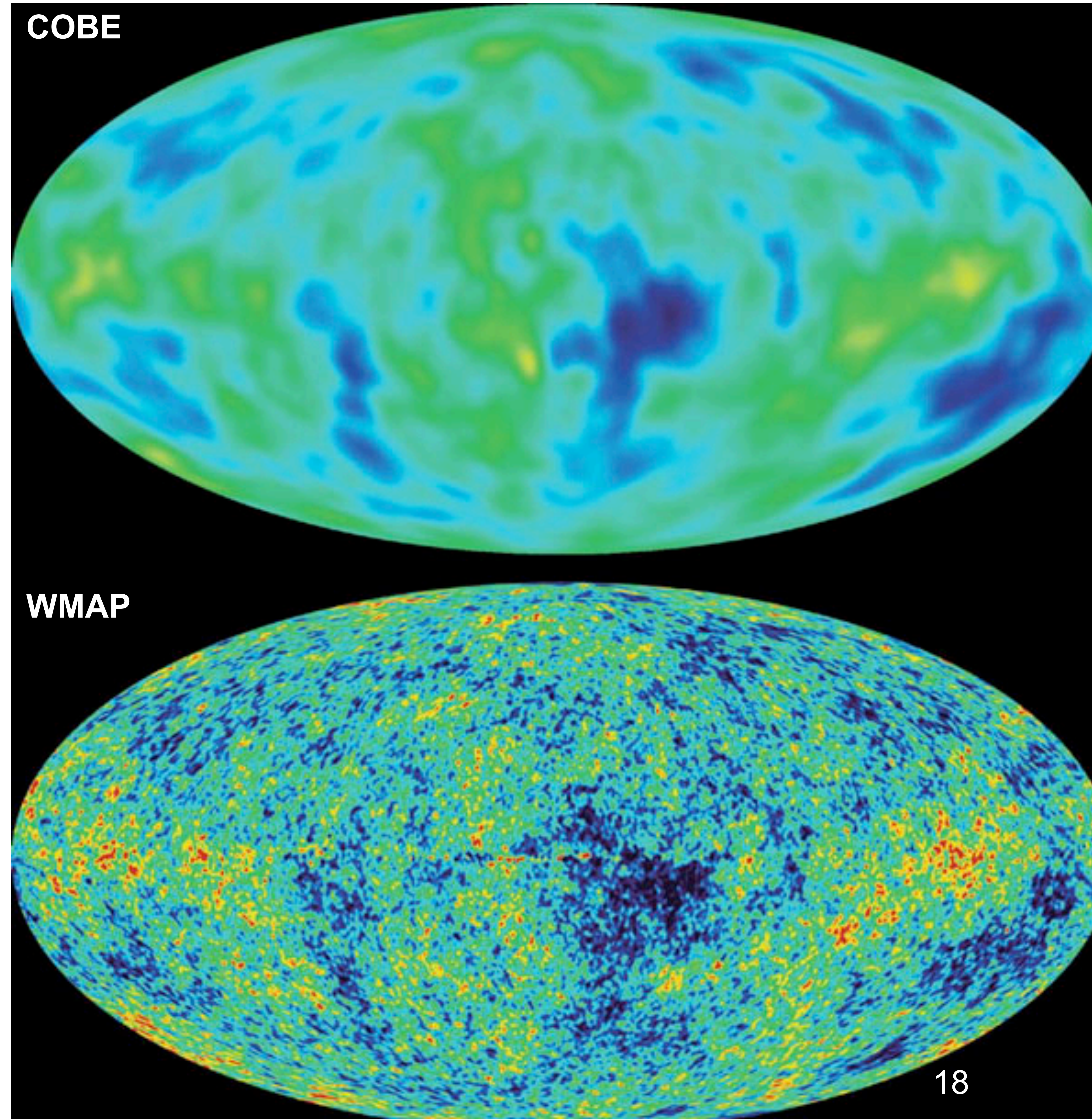
WMAP Spacecraft

Radiative Cooling: No Cryogenic System

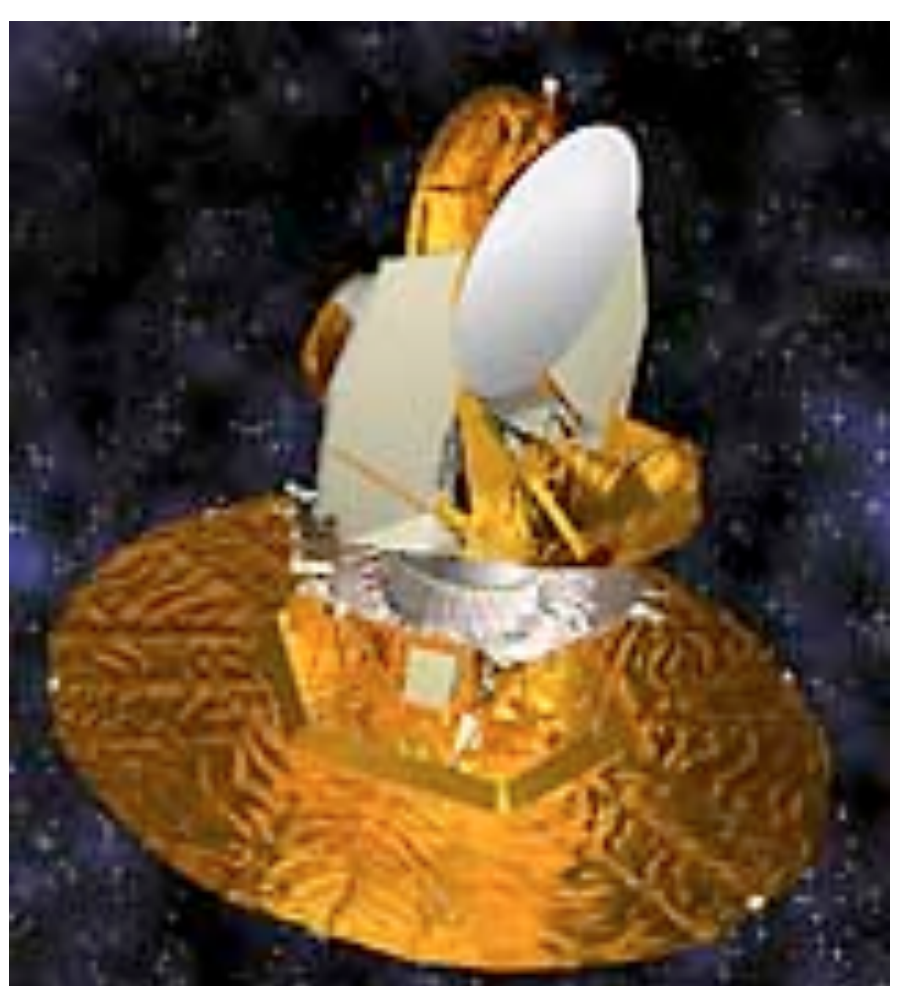


COBE to WMAP (x35 better resolution)

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

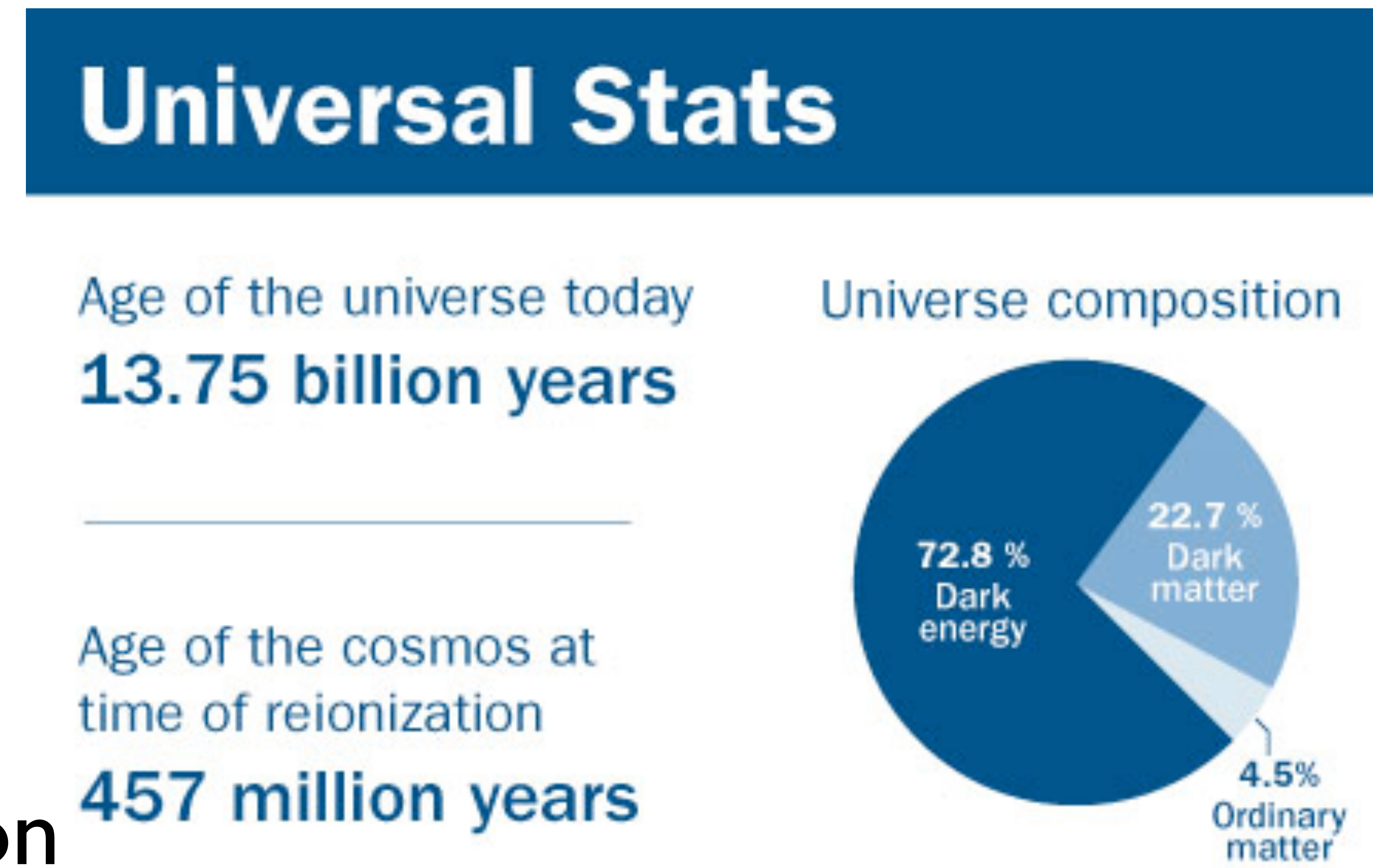
- K.M. Smith
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde

WMAP 7-Year Papers

- **Jarosik et al.**, "*Sky Maps, Systematic Errors, and Basic Results*" arXiv:1001.4744
- **Gold et al.**, "*Galactic Foreground Emission*" arXiv:1001.4555
- **Weiland et al.**, "*Planets and Celestial Calibration Sources*" arXiv:1001.4731
- **Bennett et al.**, "*Are There CMB Anomalies?*" arXiv:1001.4758
- **Larson et al.**, "*Power Spectra and WMAP-Derived Parameters*" arXiv:1001.4635
- **Komatsu et al**., "*Cosmological Interpretation*" arXiv:1001.4538

Cosmology Update: 7-year

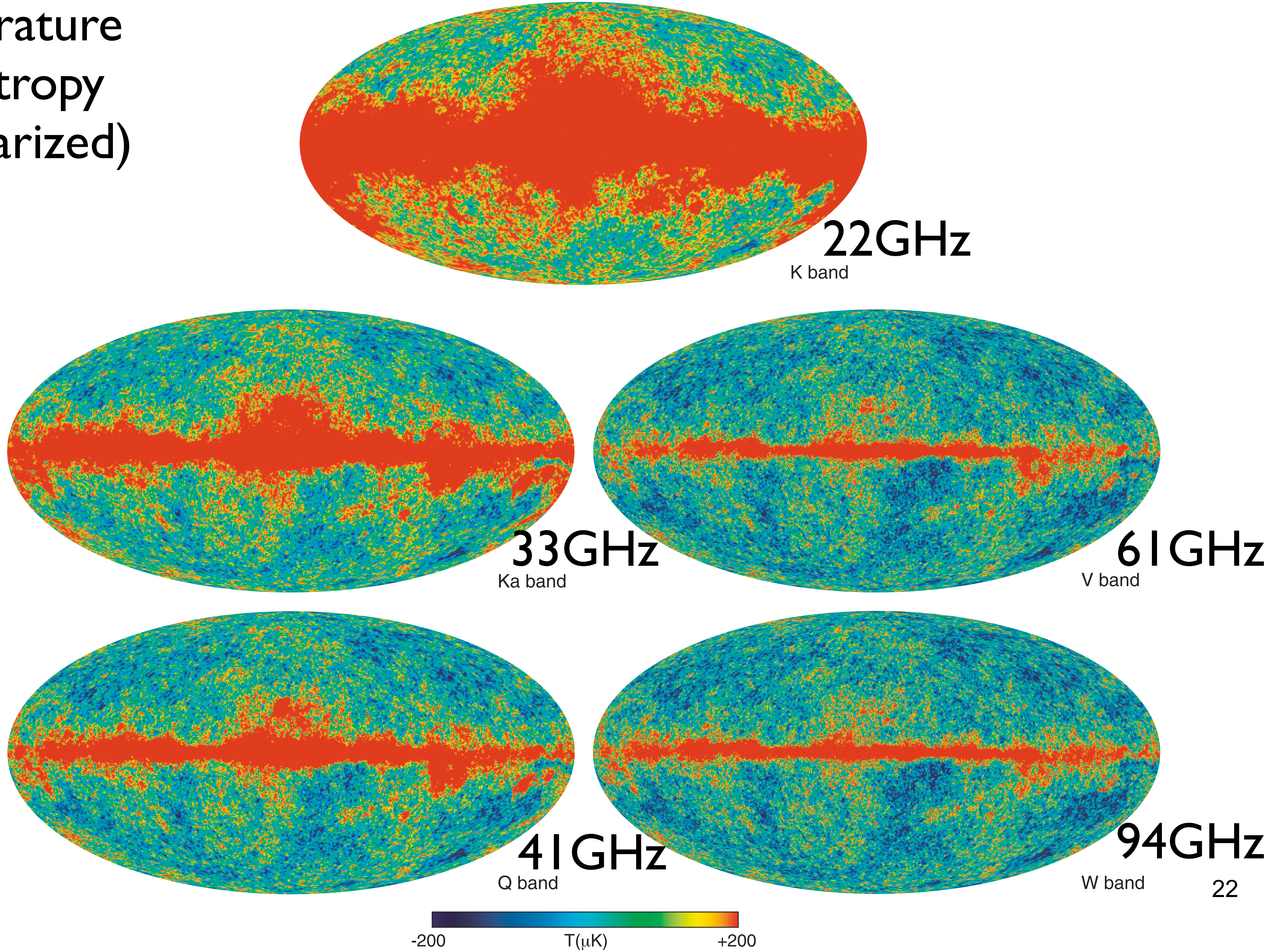
- **Standard Model**
  - H&He = **4.58**% (±0.16%)
  - Dark Matter = **22.9**% (±1.5%)
  - Dark Energy = **72.5**% (±1.6%)
  - H_0=70.2±1.4 km/s/Mpc
  - Age of the Universe = 13.76 billion years (±0.11 billion years)



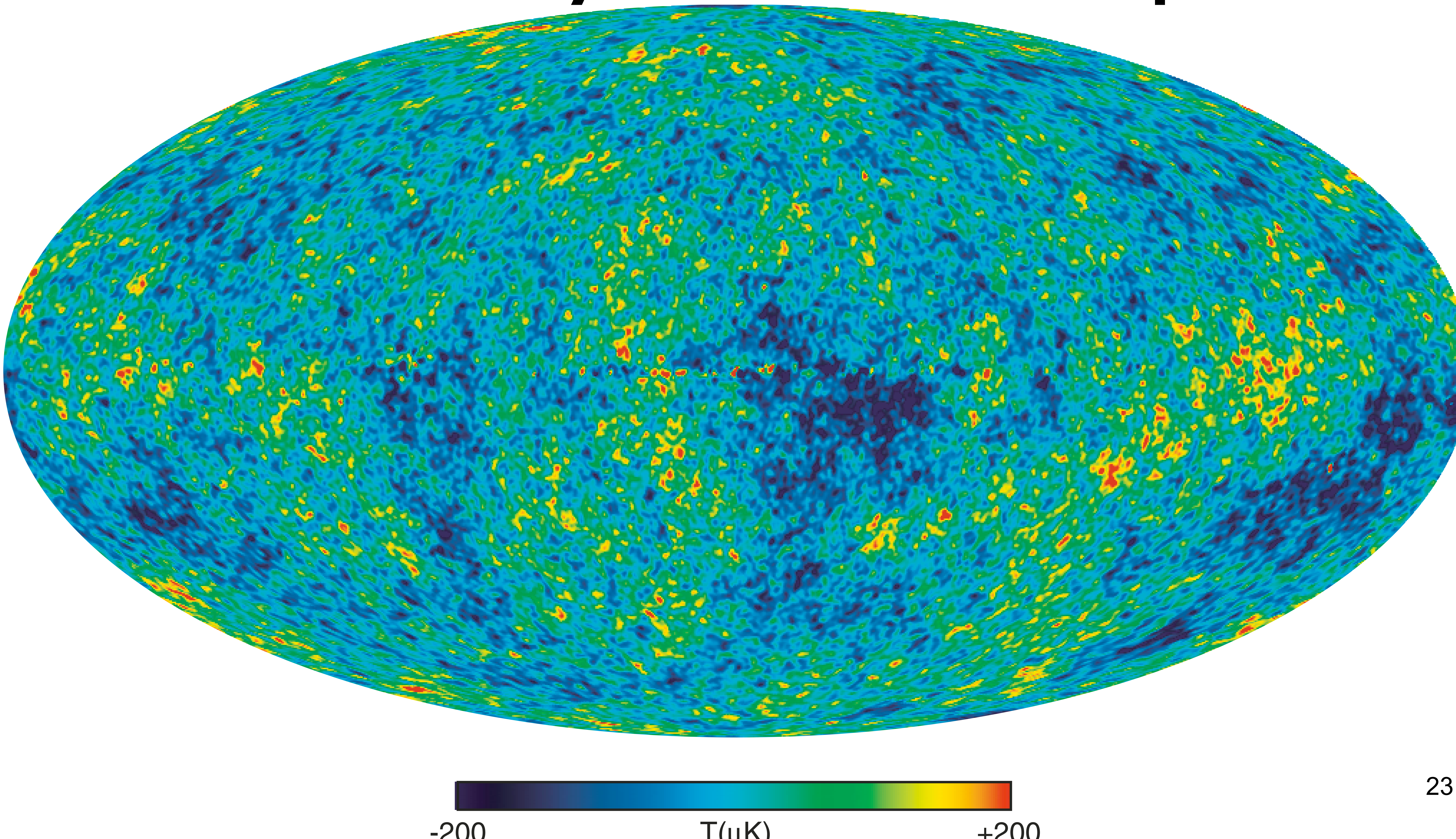
"ScienceNews" article on the WMAP 7-year results

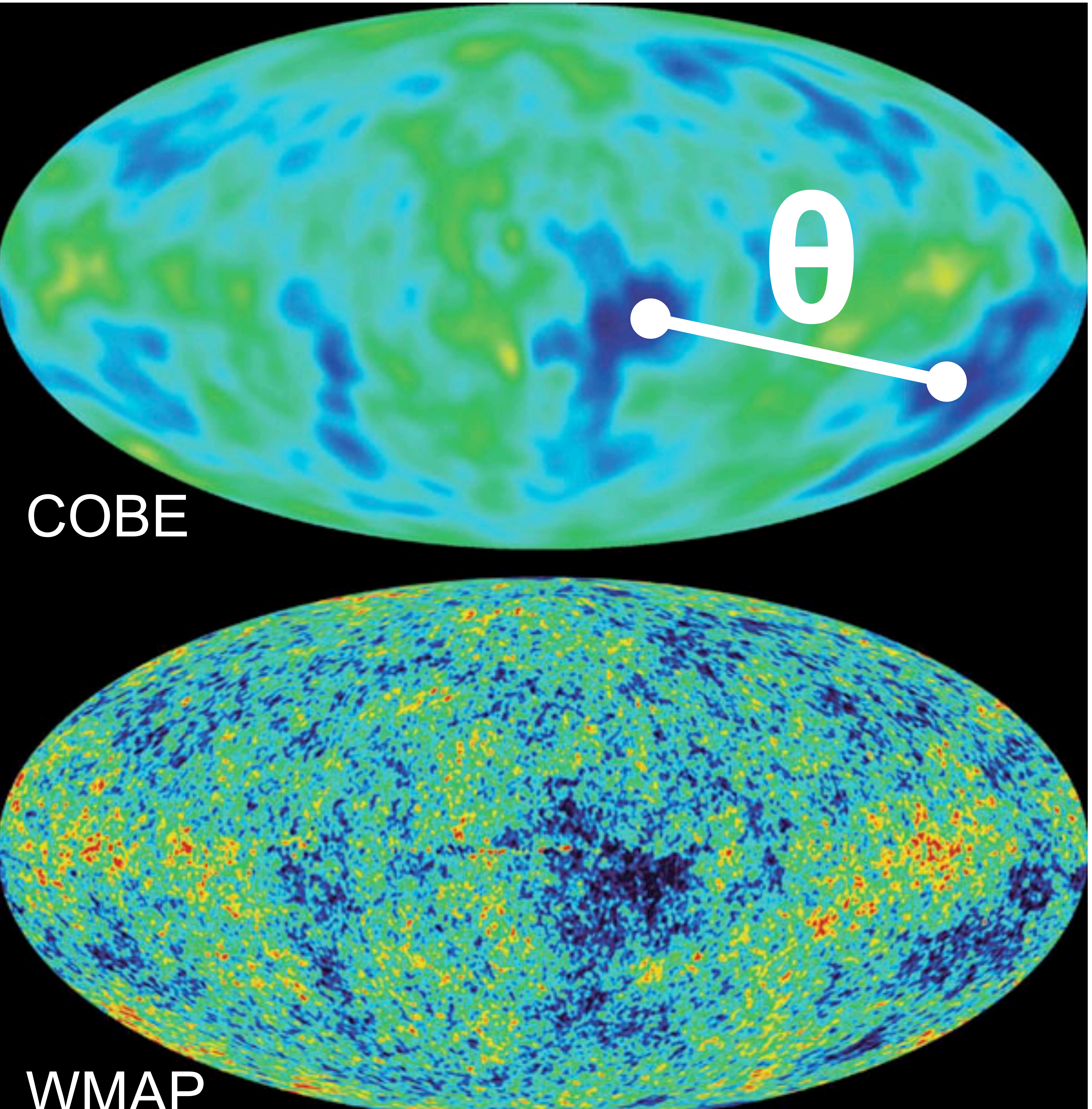
How did we obtain these numbers?

Temperature Anisotropy (Unpolarized)



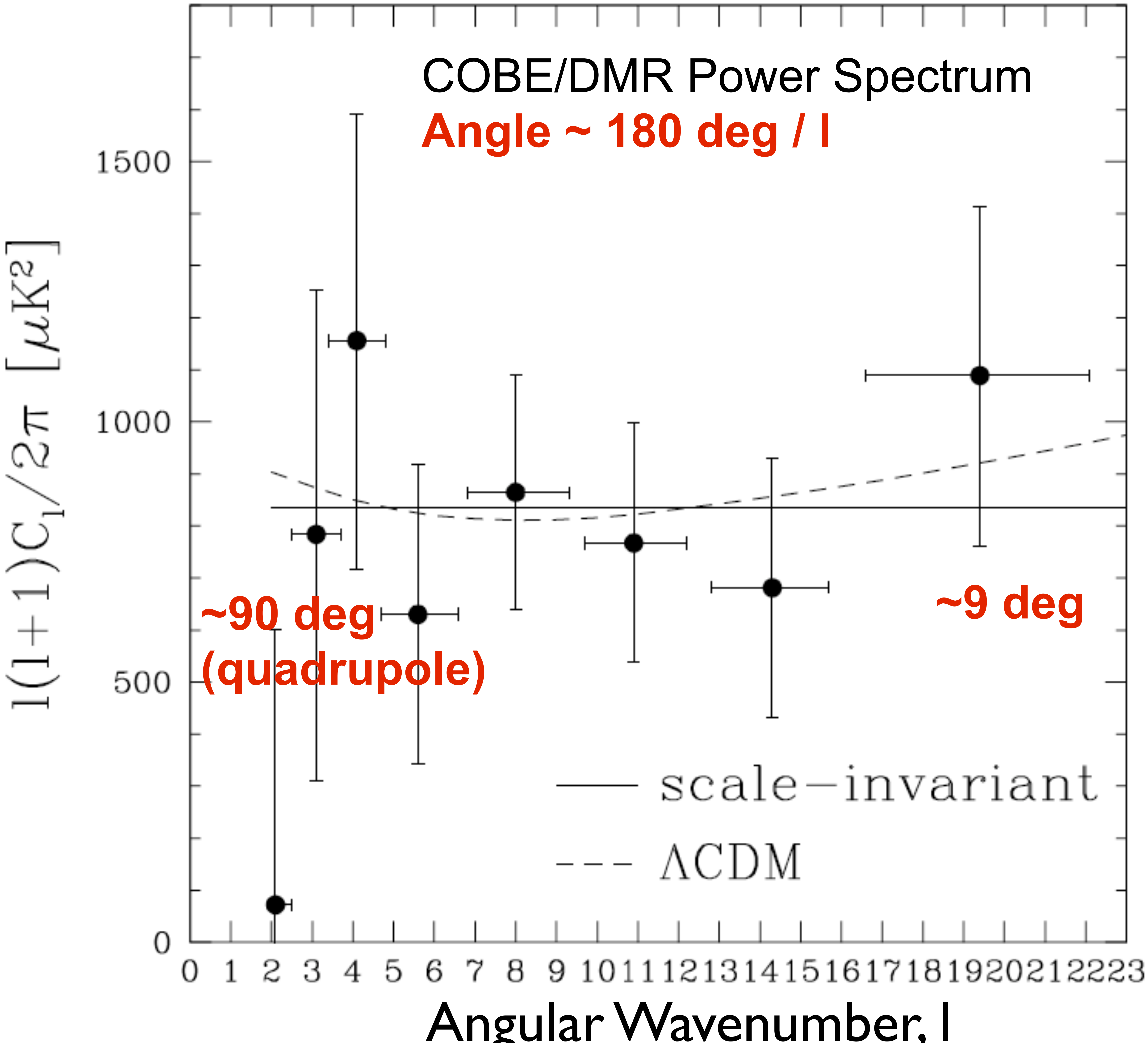
Galaxy-cleaned Map

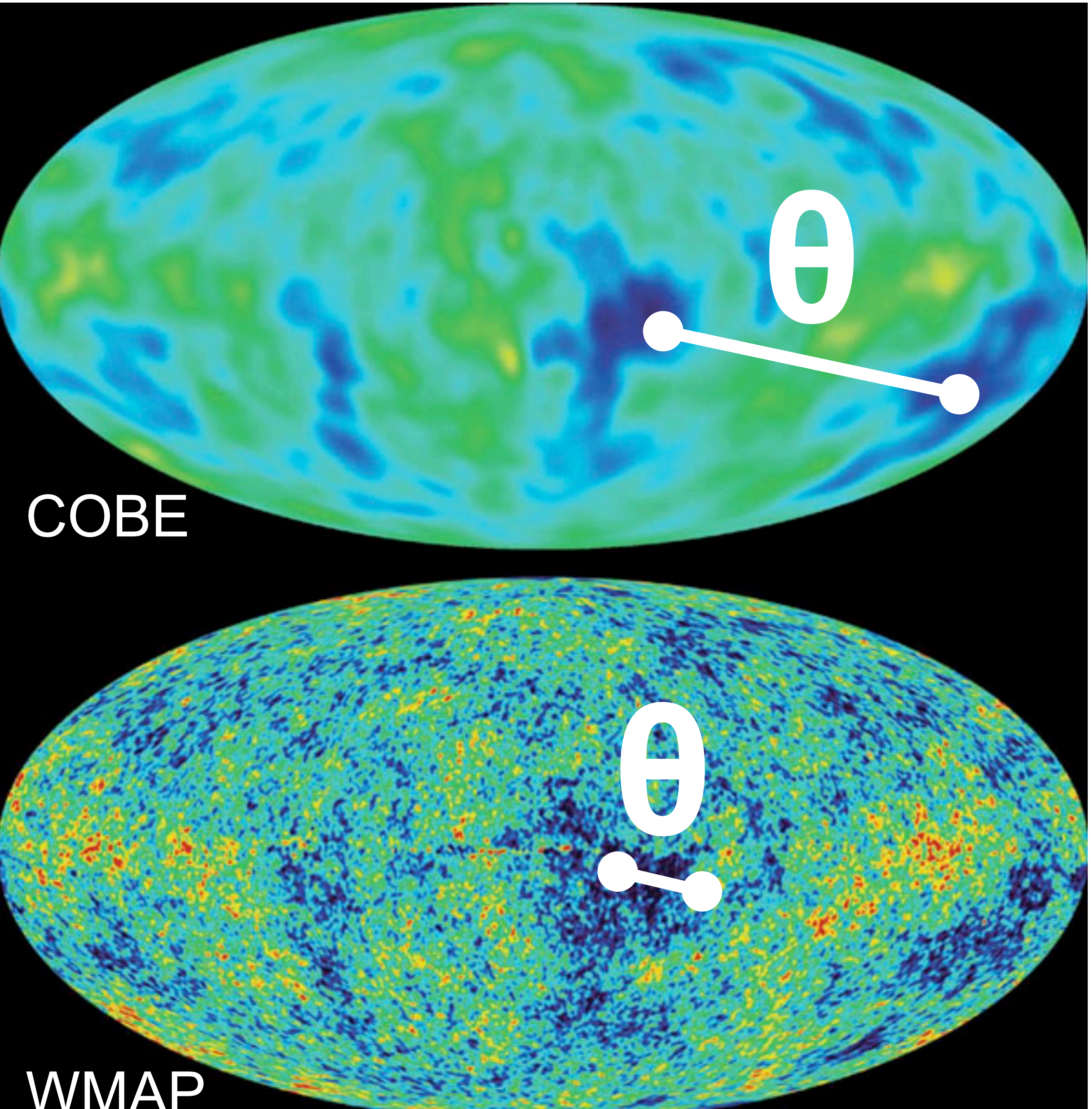




Analysis: 2-point Correlation

- $C(\theta)=(1/4\pi)\sum(2l+1)C_l P_l(\cos\theta)$
- 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**

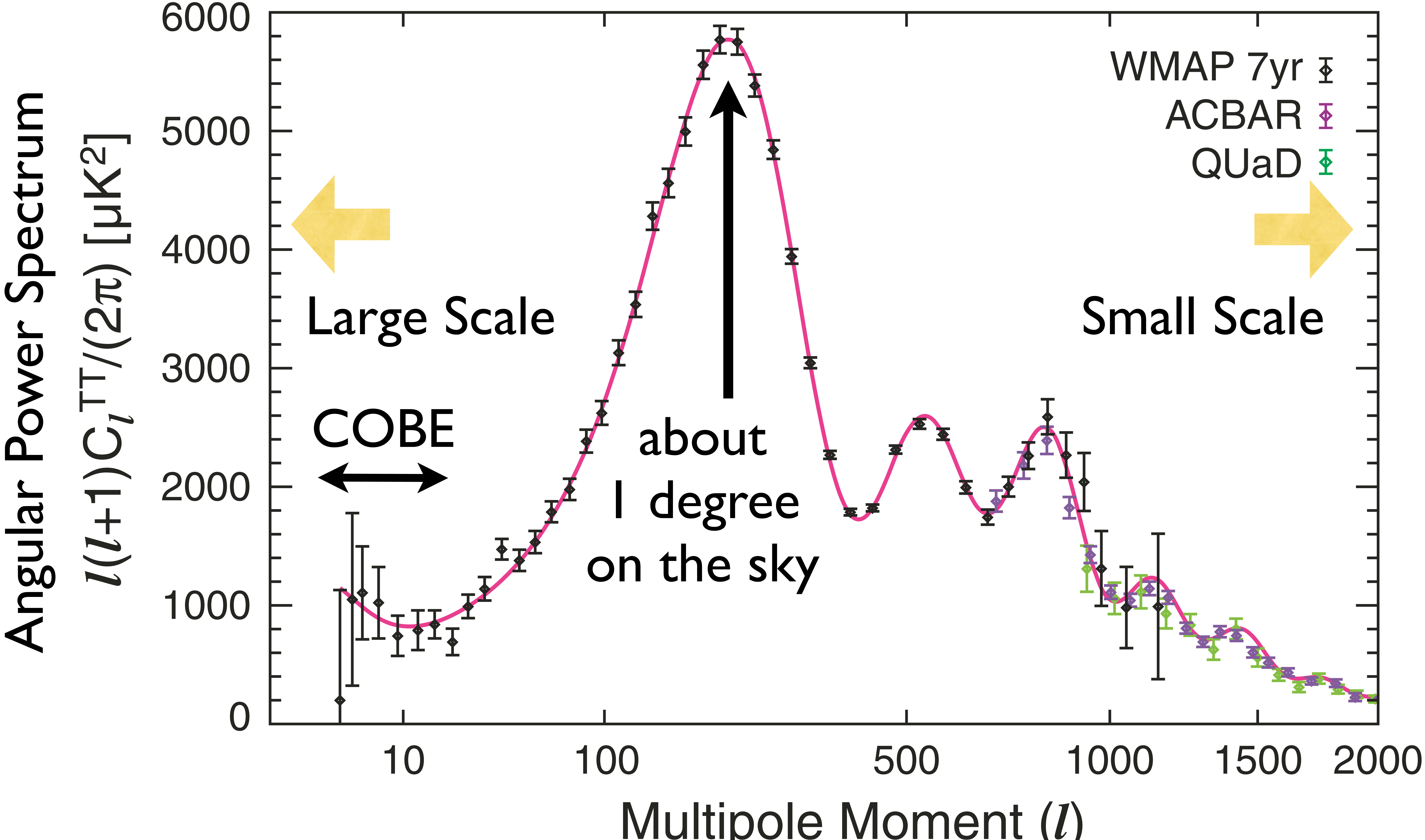

COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale−invariant
ΛCDM
l(l+1)C_l/2π [μK²]
0
500
1000
1500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Angular Wavenumber, l



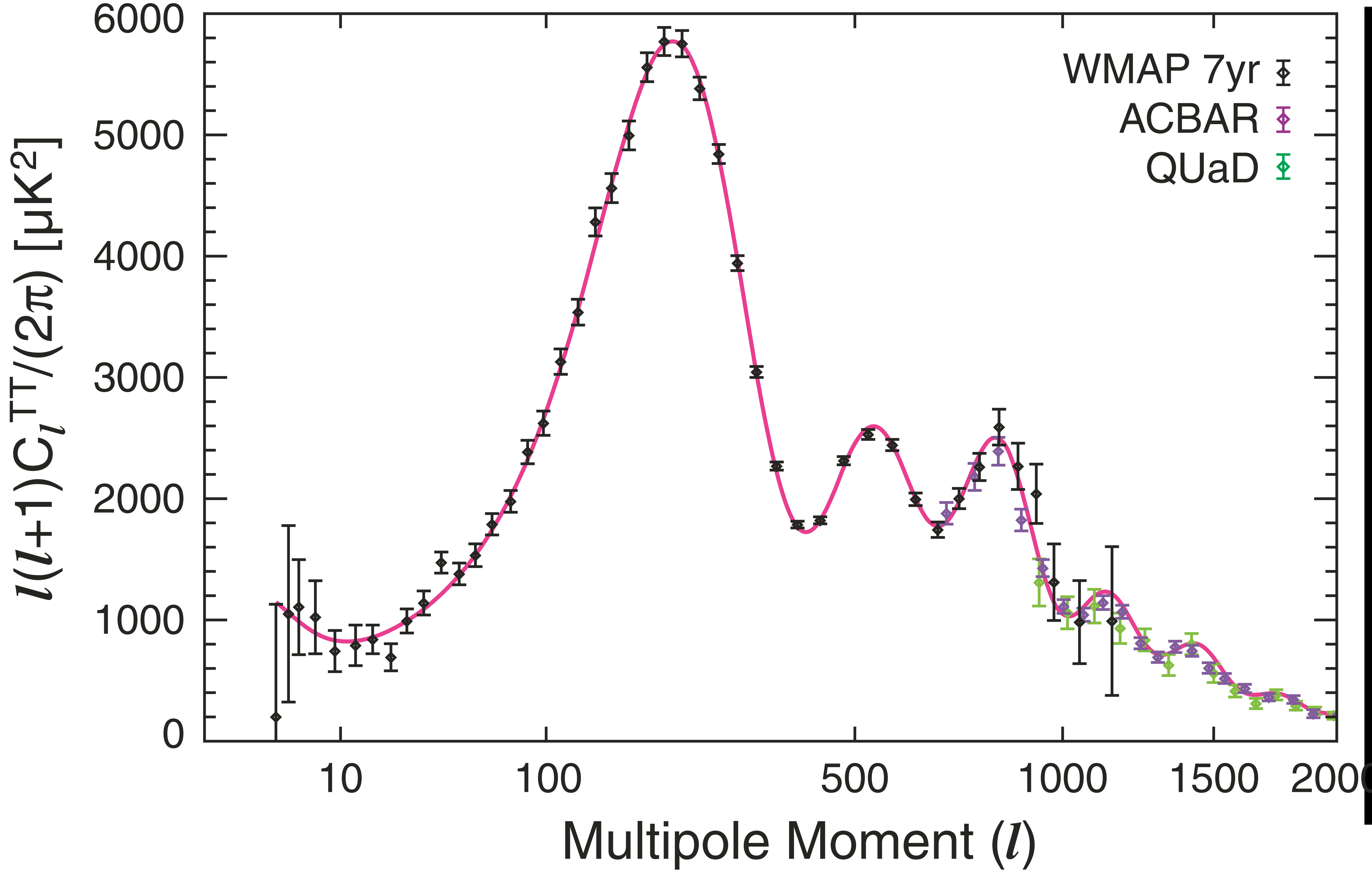
COBE To WMAP

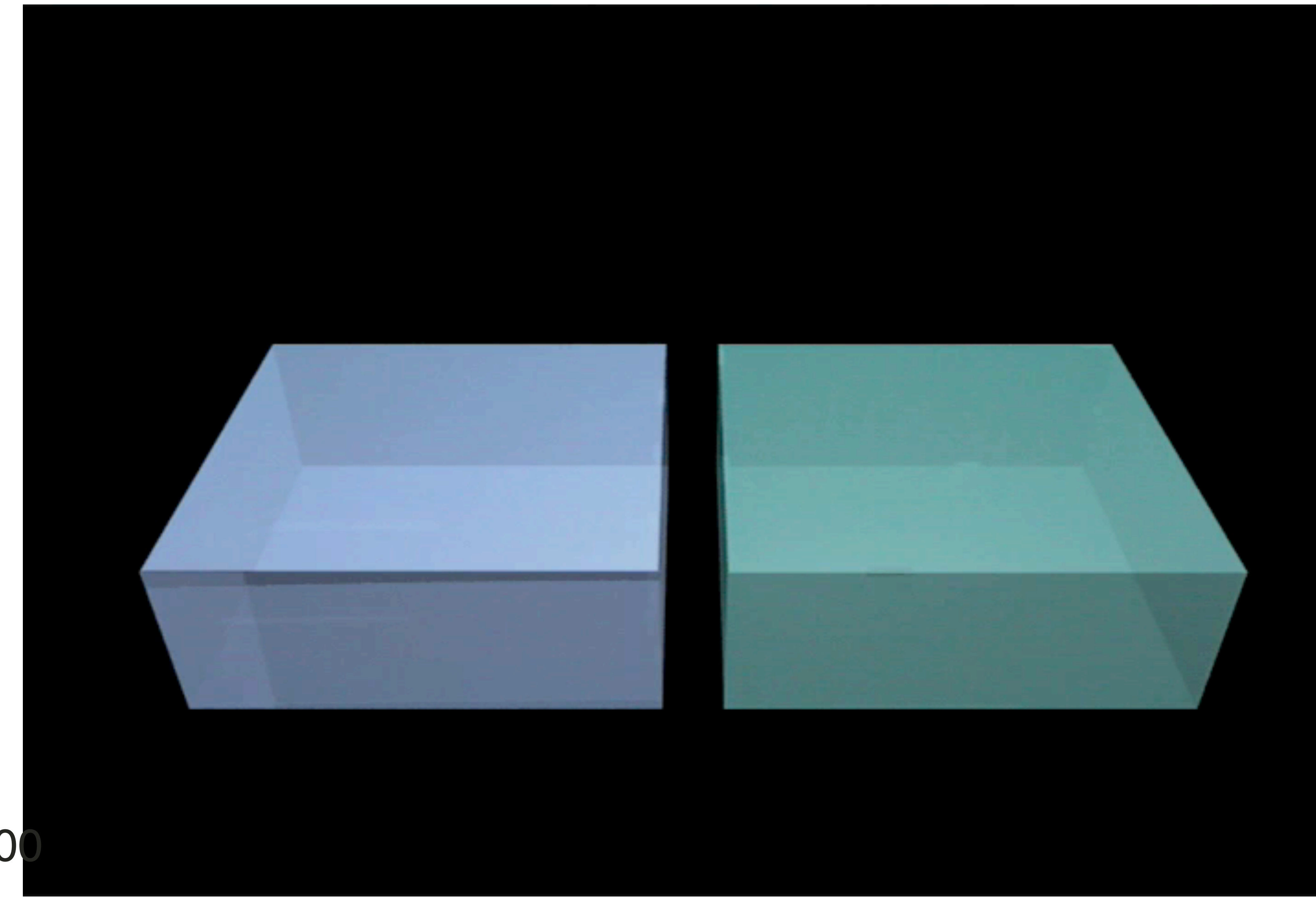
- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

WMAP Power Spectrum



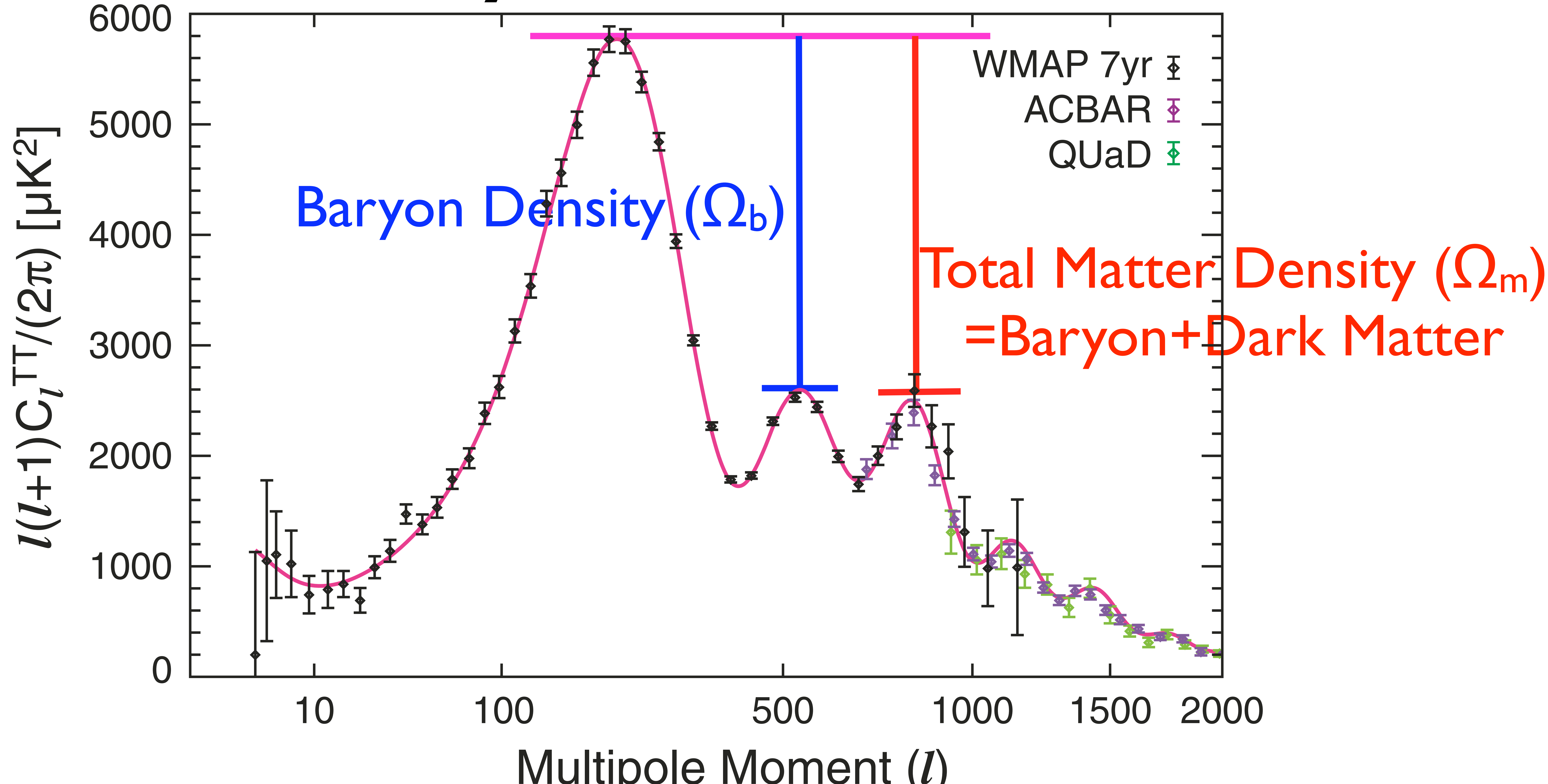
The Cosmic Sound Wave





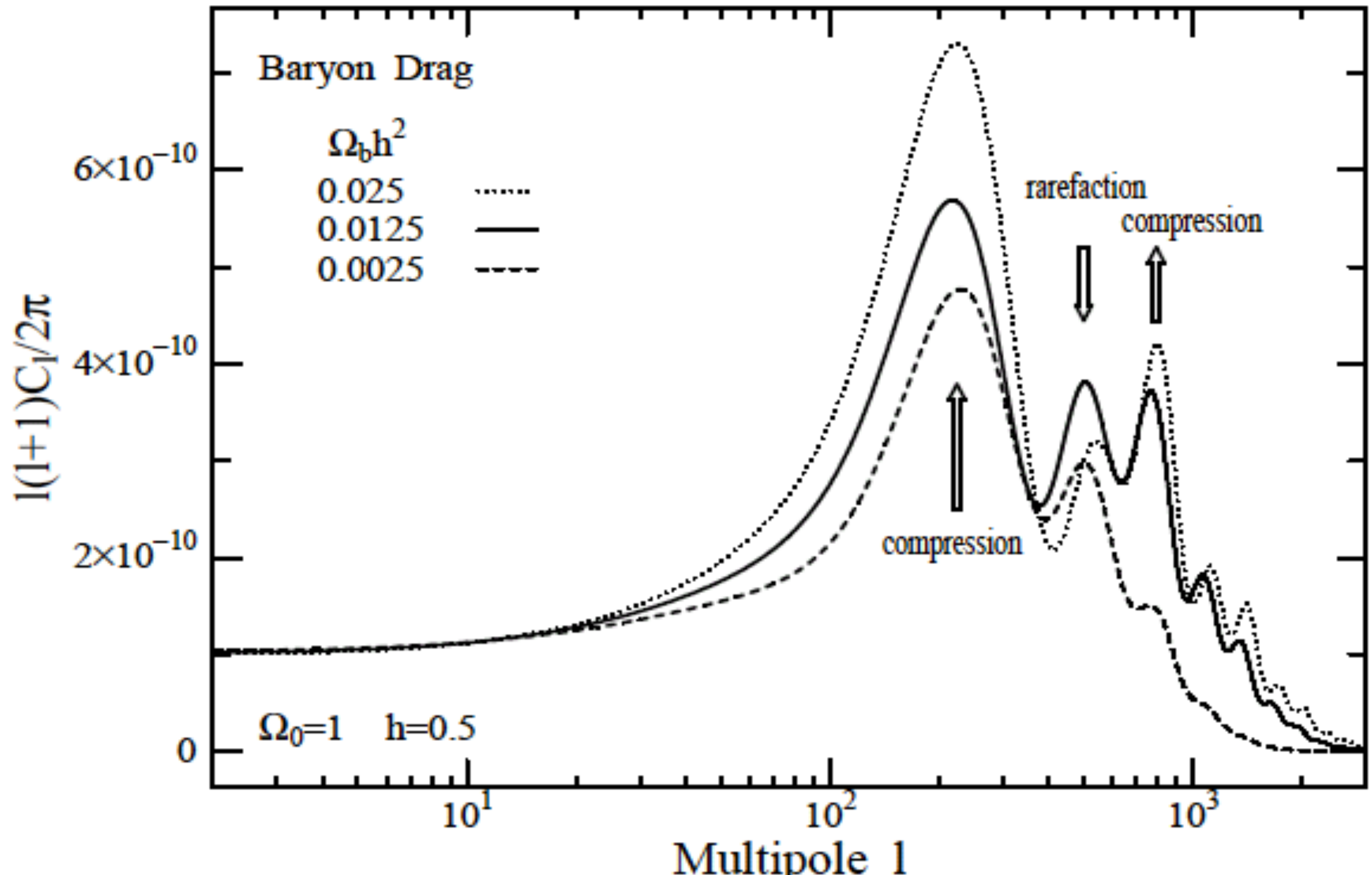
- *"The Universe as a Miso soup"*
  - *Main Ingredients: protons, helium nuclei, electrons, photons*
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

CMB to Baryon & Dark Matter

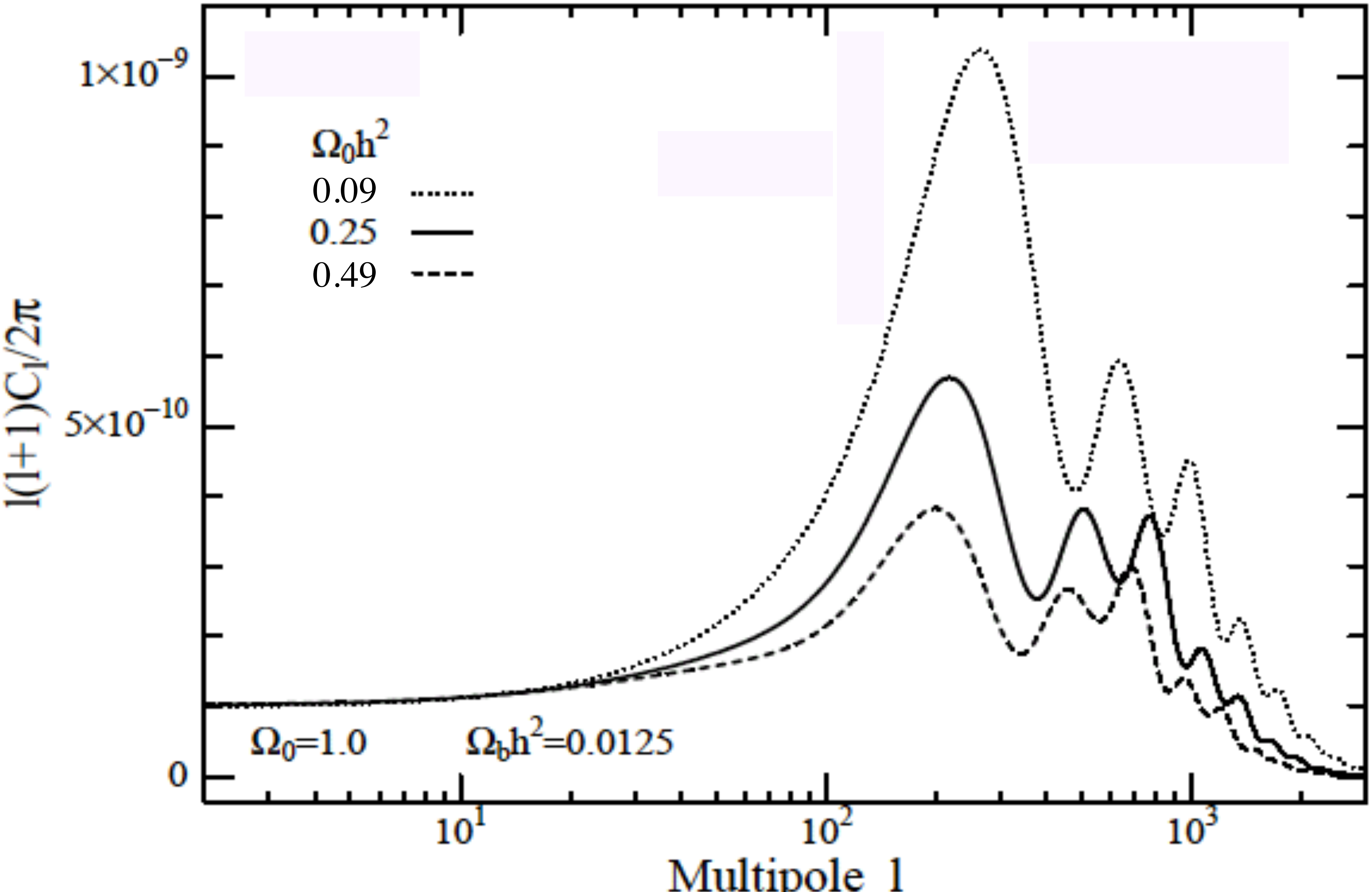


- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio (z_{EQ}: equality redshift)

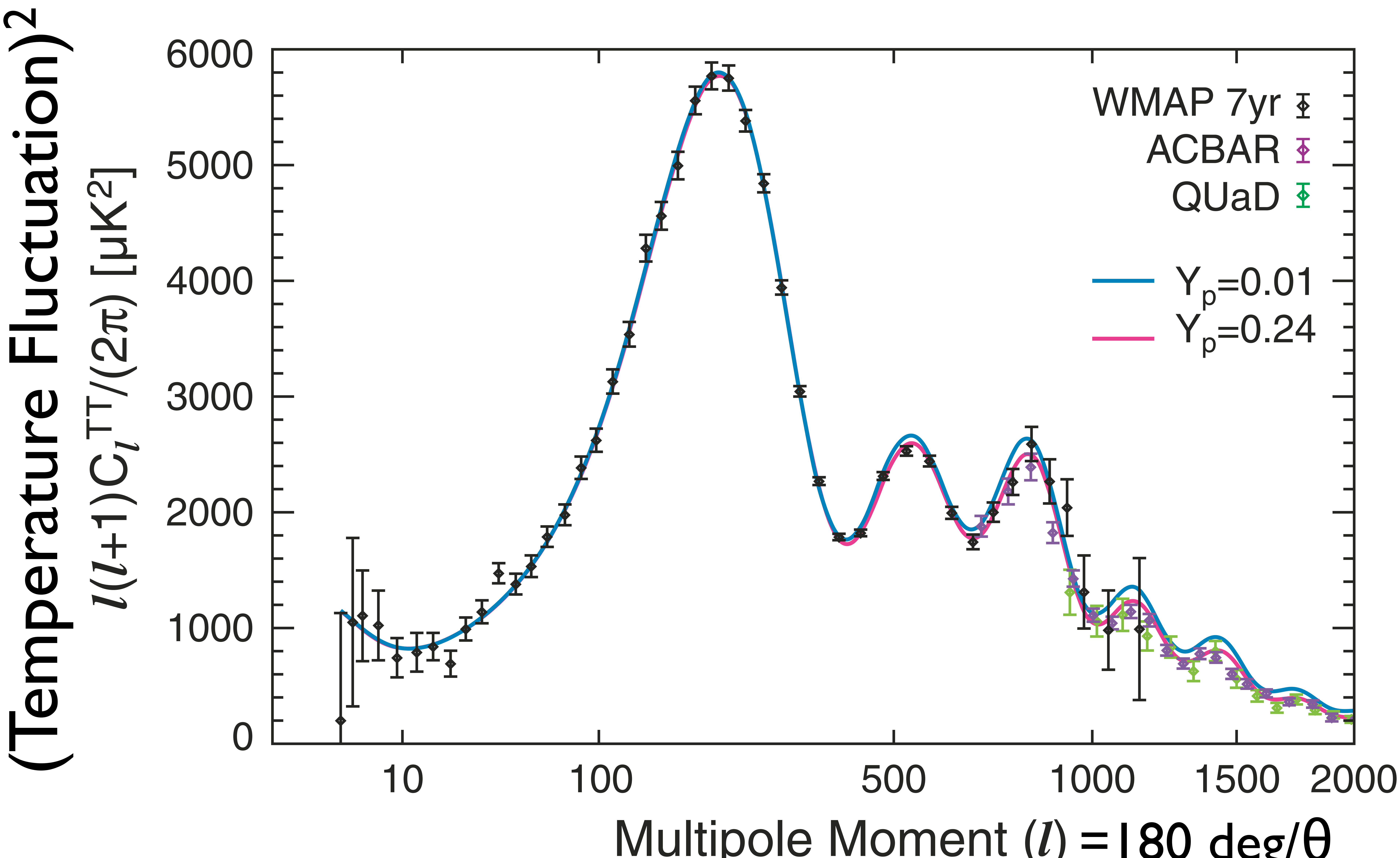
Determining Baryon Density From C_l



Determining Dark Matter Density From C_l



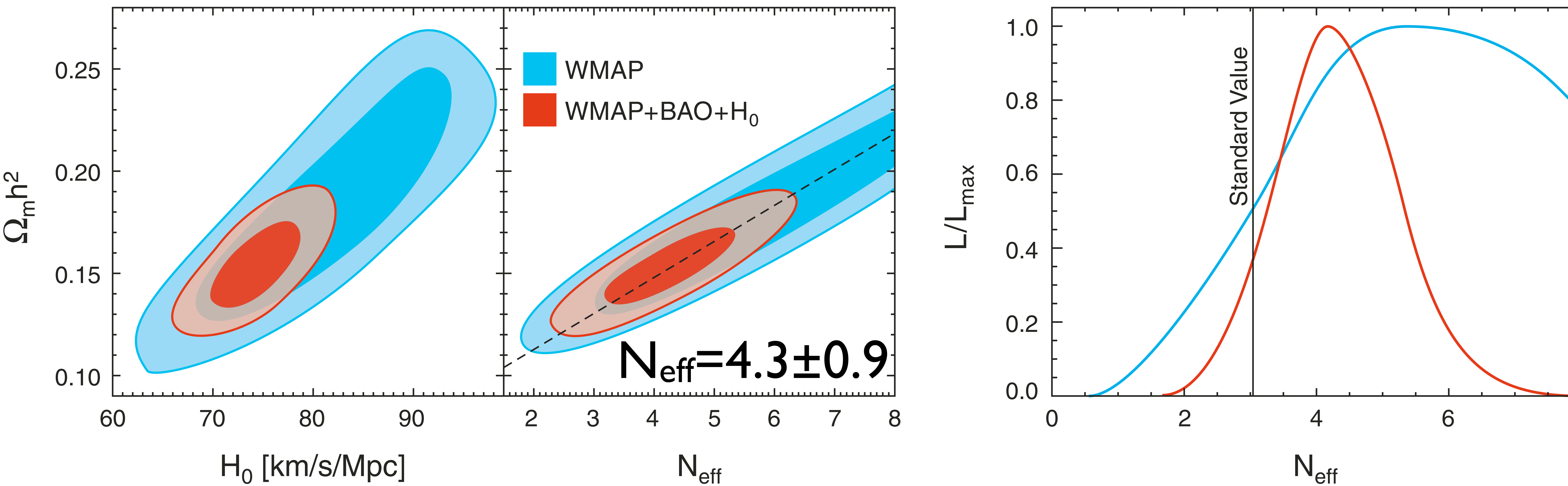
Detection of Primordial Helium



Effect of helium on C_l^{TT}

- We measure the baryon number density, n_b, from the 1st-to-2nd peak ratio.
- As helium recombined at z~1800, there were 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 damping**
- **Y_p = 0.33 ± 0.08** (68%CL)
  - Consistent with the standard value from the Big Bang nucleosynthesis theory: Y_P=0.24.

Another "3rd peak science": Number of Relativistic Species

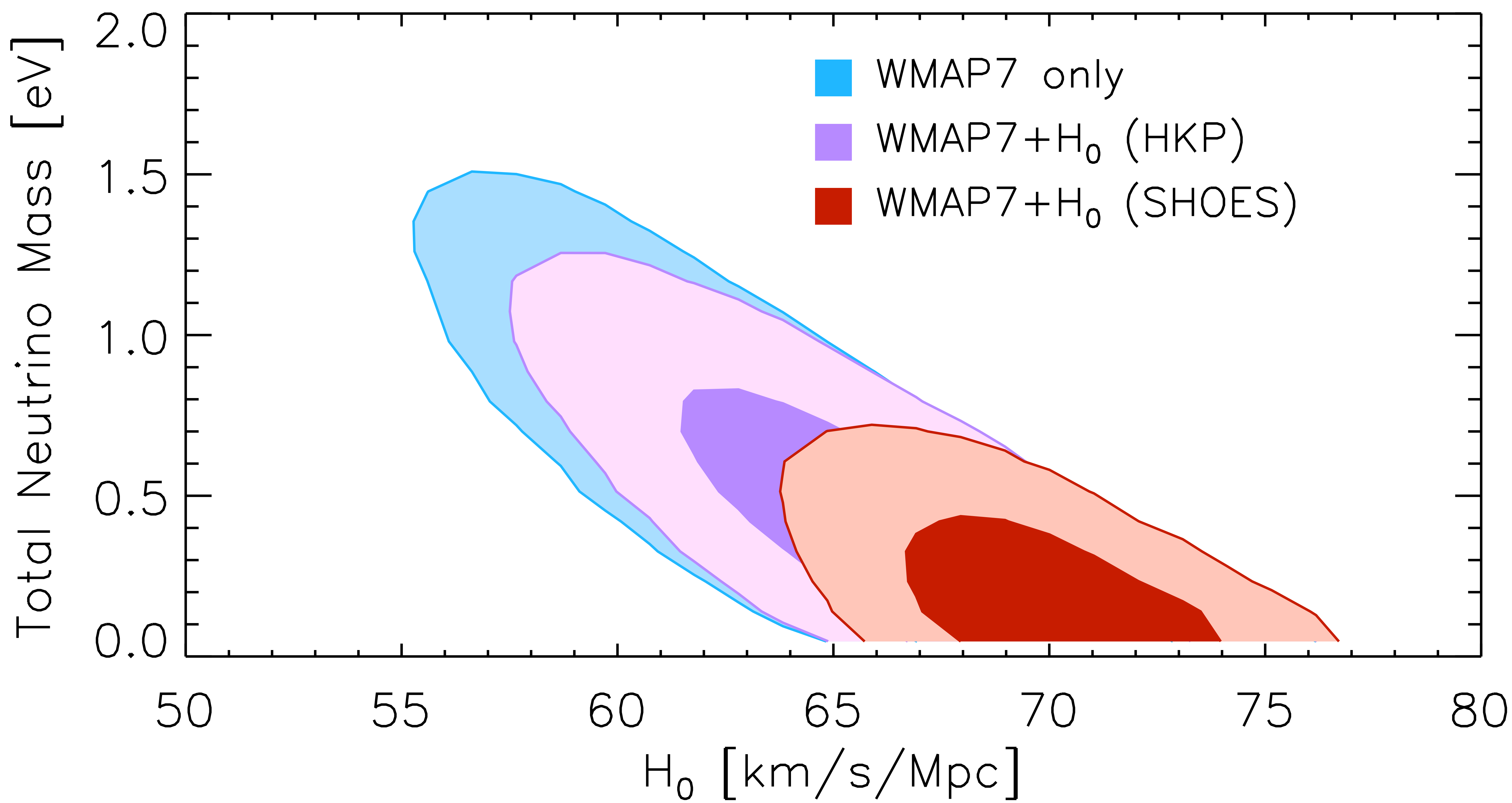


from external data

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

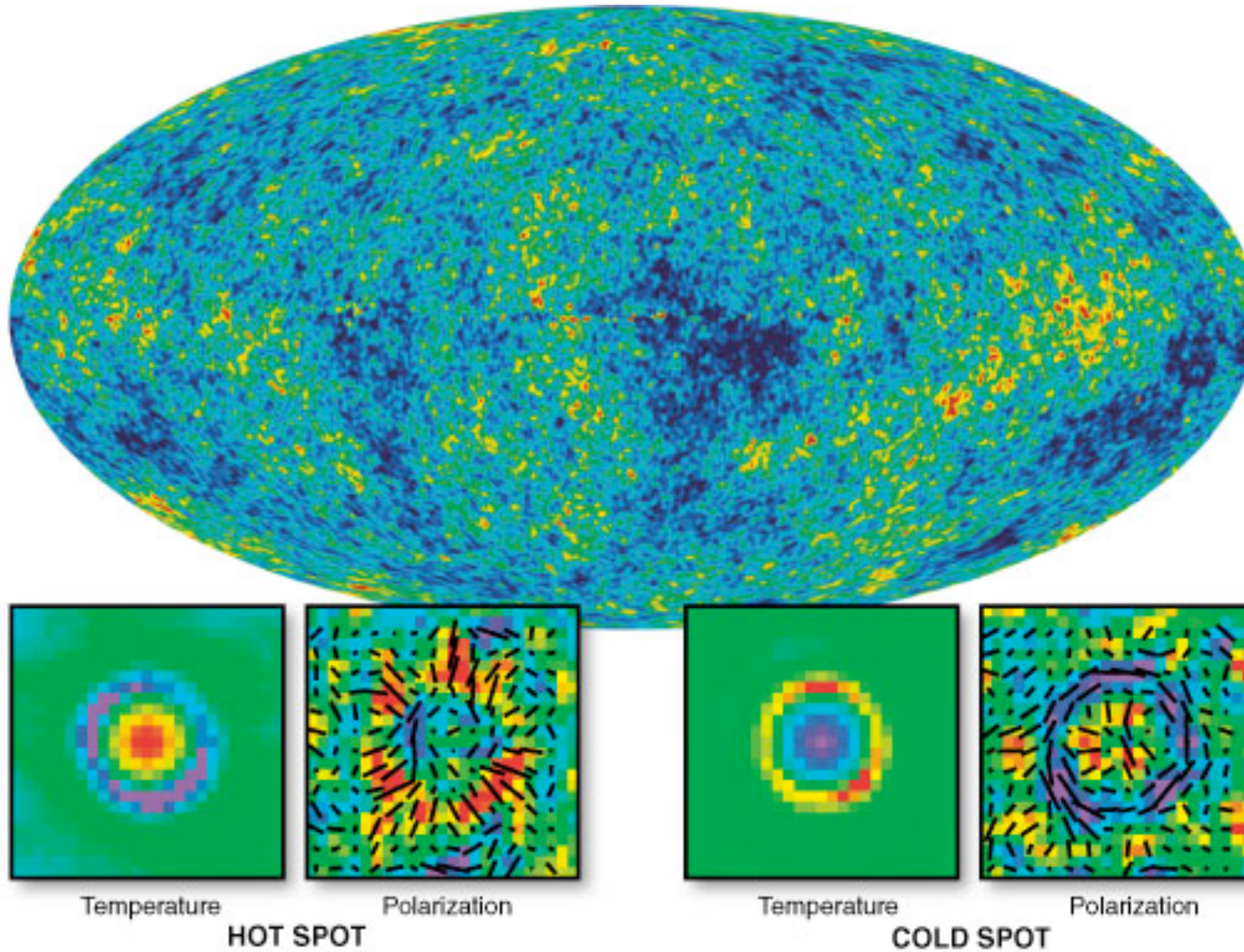
from 3rd peak

And, the mass of neutrinos



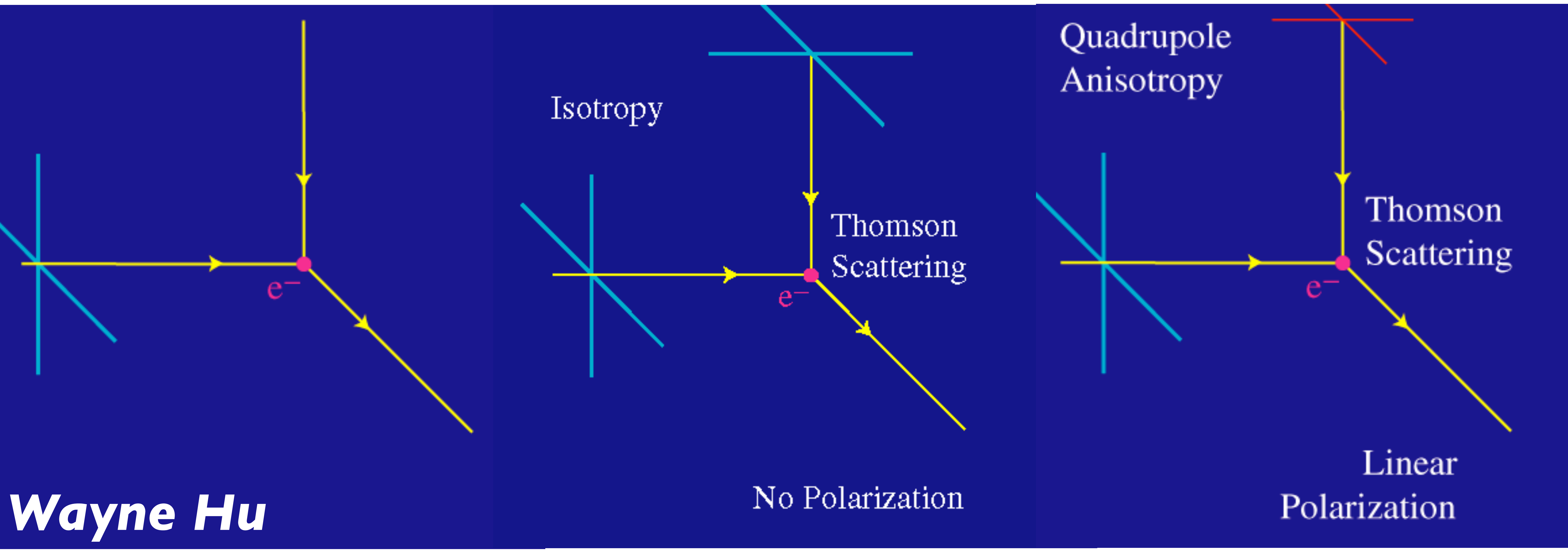
- WMAP data combined with the local measurement of the expansion rate (H_0), we get $\sum m_\nu < 0.6$ eV (95%CL)

CMB Polarization



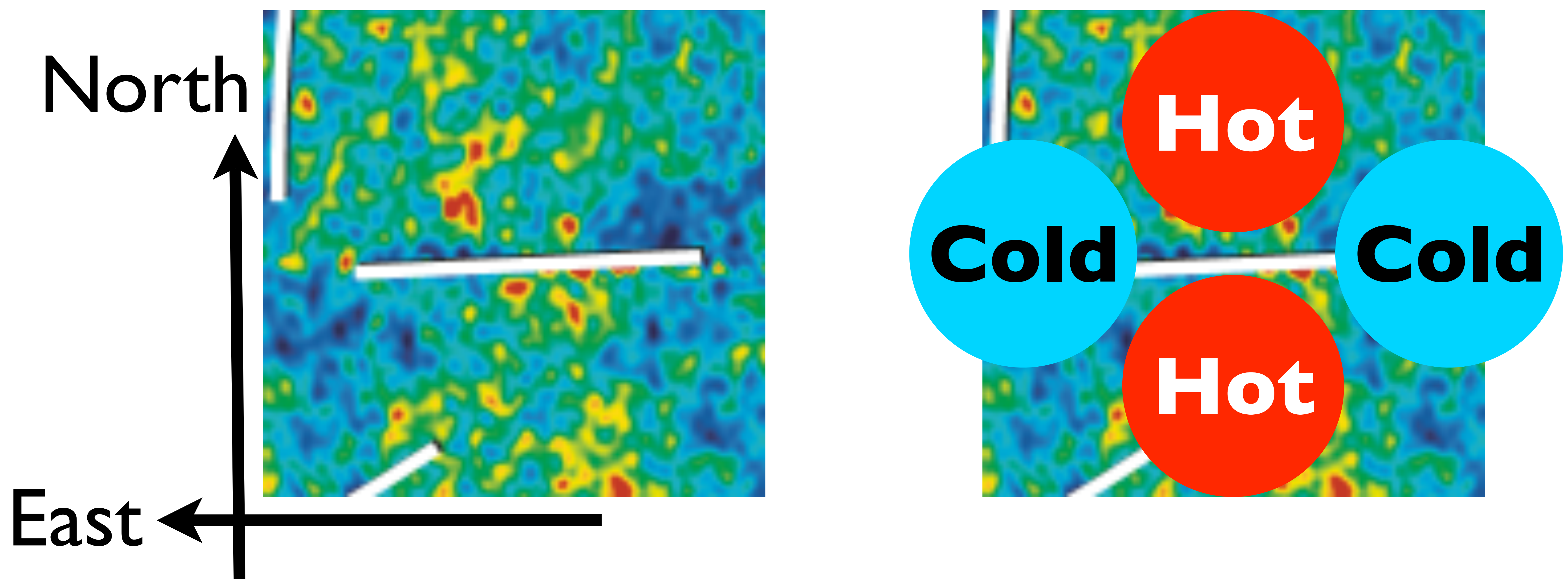
- *CMB is (very weakly) polarized!*

Physics of CMB Polarization



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

Principle



- **Polarization direction is parallel to "hot."**

CMB Polarization on Large Angular Scales (>2 deg)

Matter Density

Potential

$\Delta T/T$ = (Newton's Gravitation Potential)/3

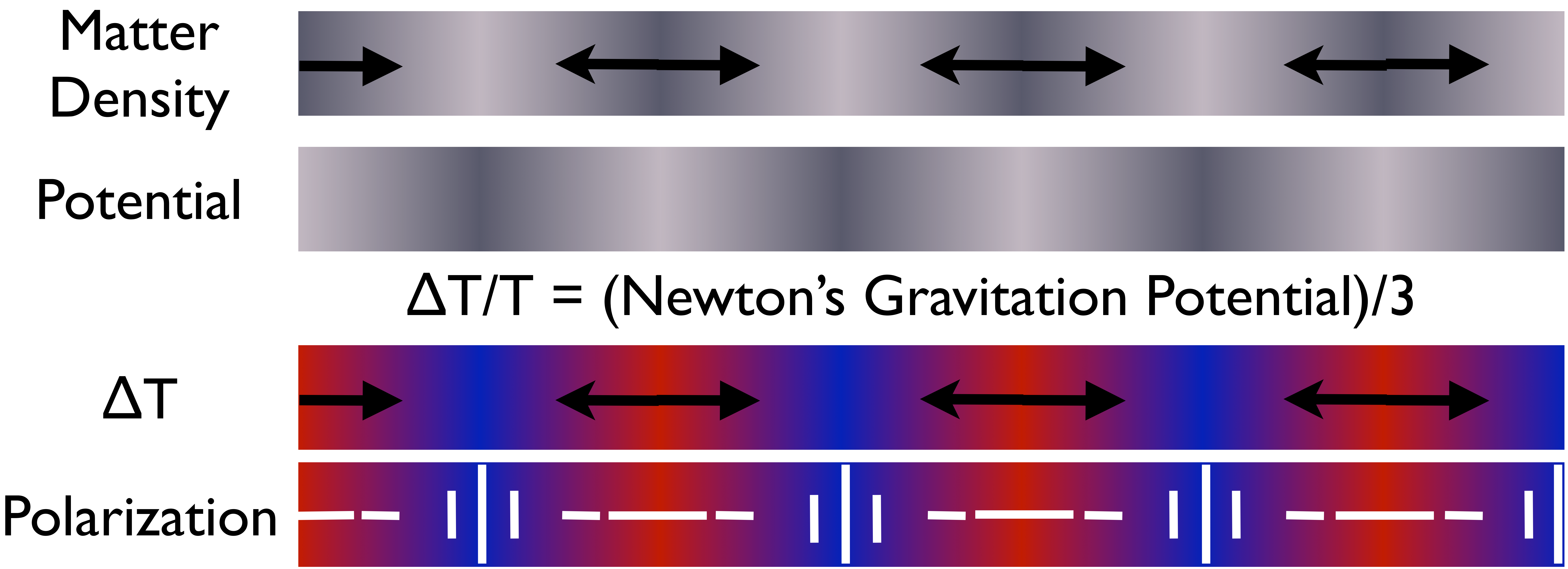
ΔT

Polarization

- How does the photon-baryon plasma move?

CMB Polarization Tells Us How Plasma Moves at z=1090

Zaldarriaga & Harari (1995)



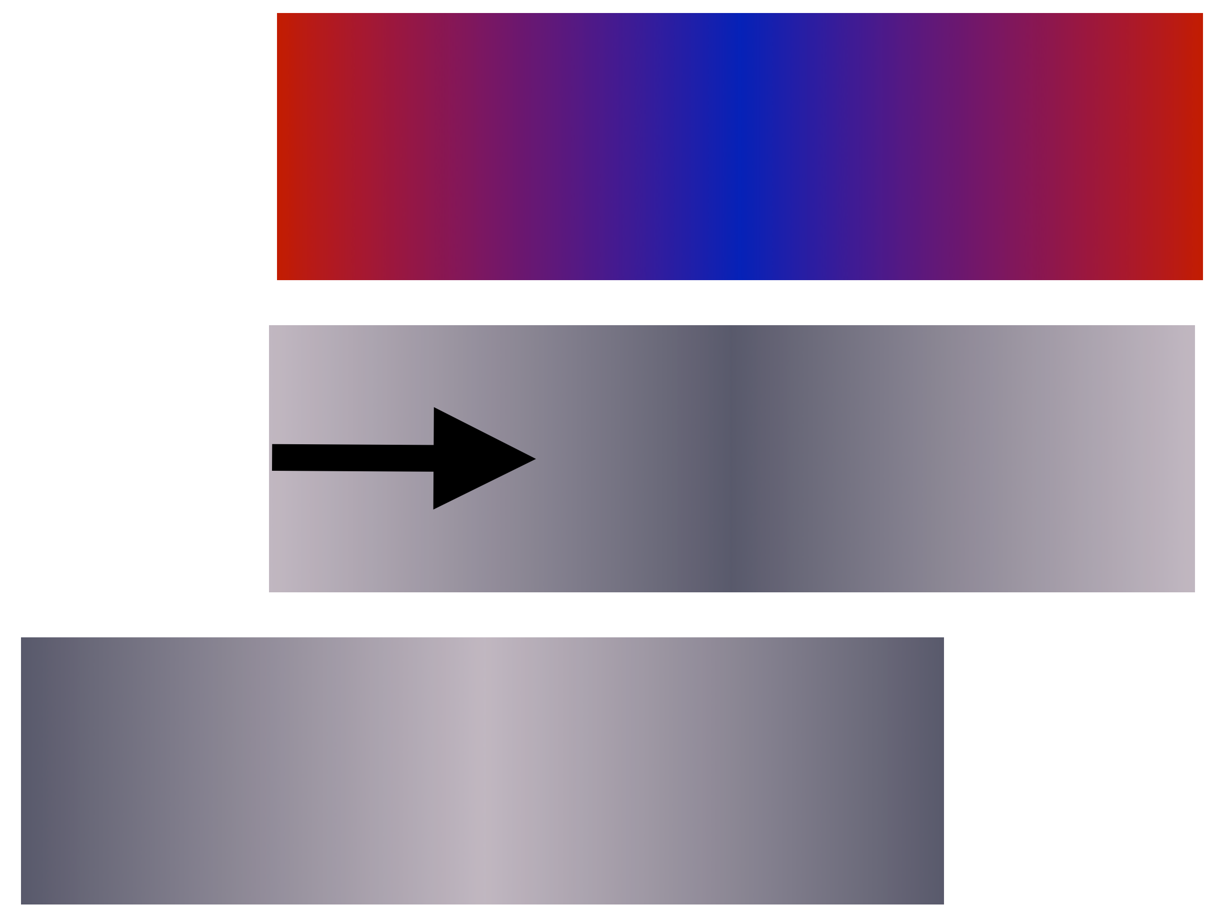
- Plasma **falling into** the gravitational potential well = **Radial** polarization pattern

Quadrupole From Velocity Gradient (Large Scale)

ΔT — Sachs-Wolfe: $\Delta T/T = \Phi/3$

Potential Φ — Stuff flowing *in*

Acceleration $a = -\partial\Phi$



$a > 0 \quad = 0$

Velocity — Velocity gradient

Velocity in the rest frame of electron — e^- e^- — The left electron sees colder photons along the plane wave

Polarization — Radial — None

Quadrupole From Velocity Gradient (Small Scale)

ΔT — Compression increases temperature

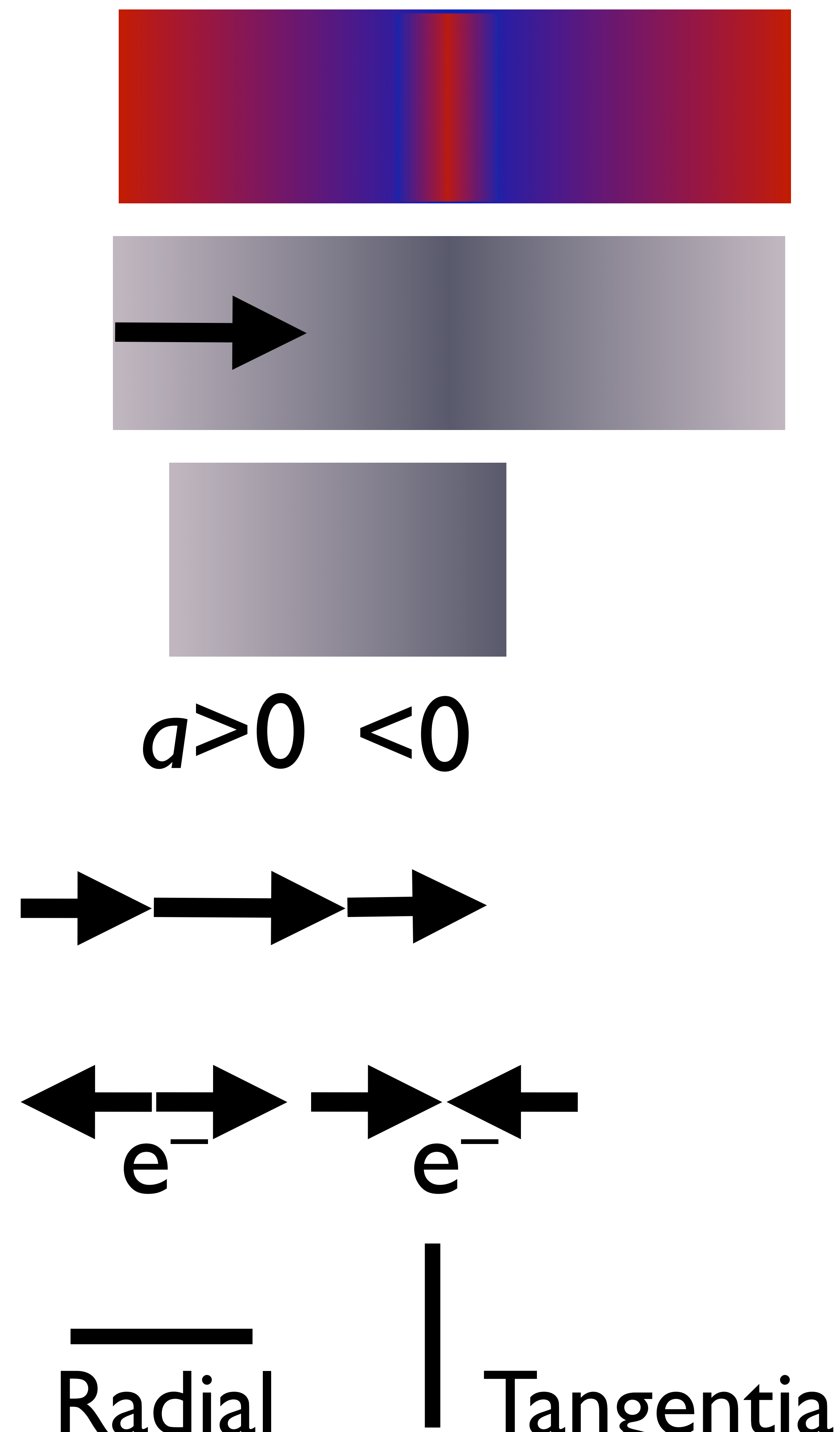
Potential Φ — Stuff flowing *in*

Acceleration $a = -\partial\Phi - \partial P$ — Pressure gradient slows down the flow

Velocity — Velocity gradient

Velocity in the rest frame of electron

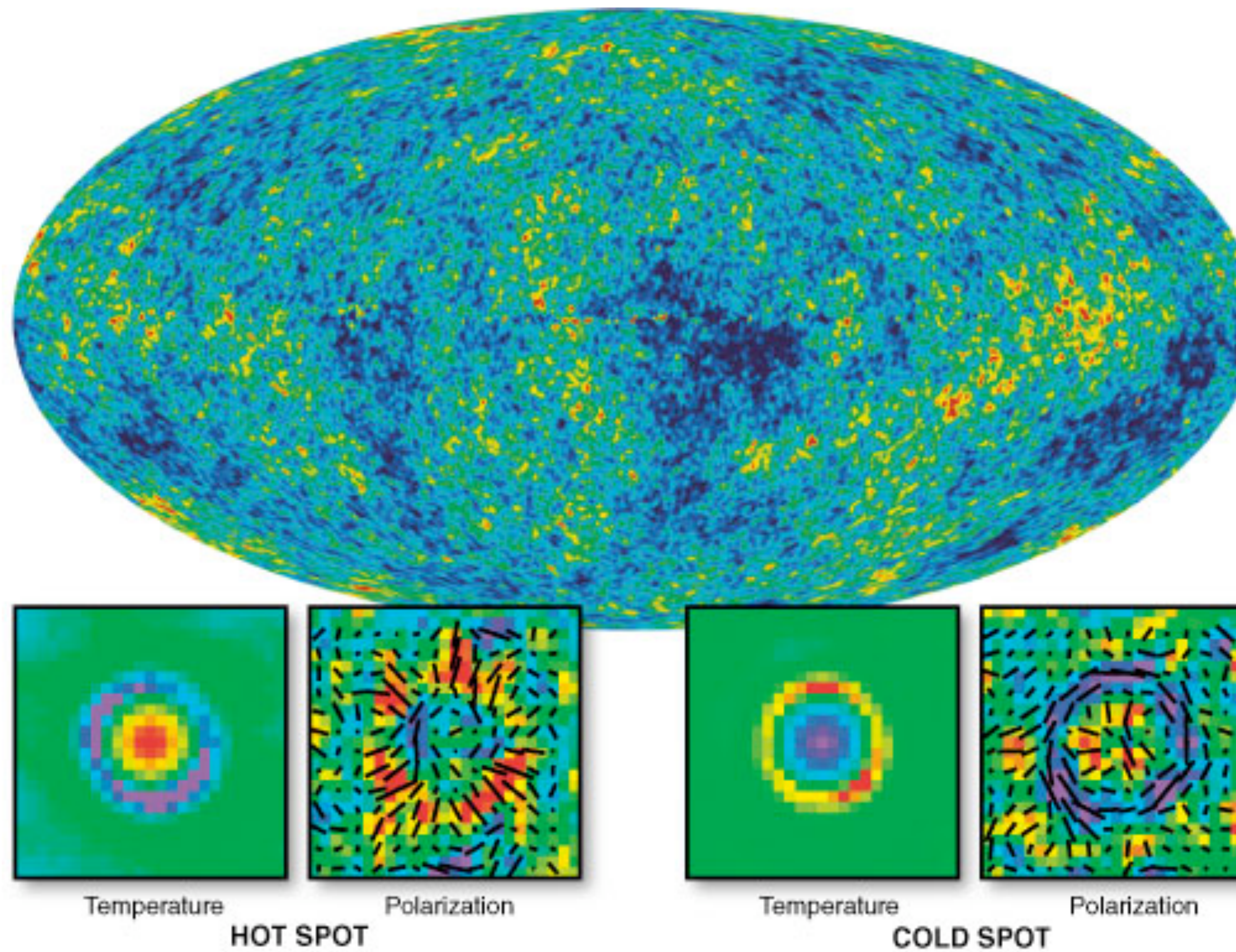
Polarization

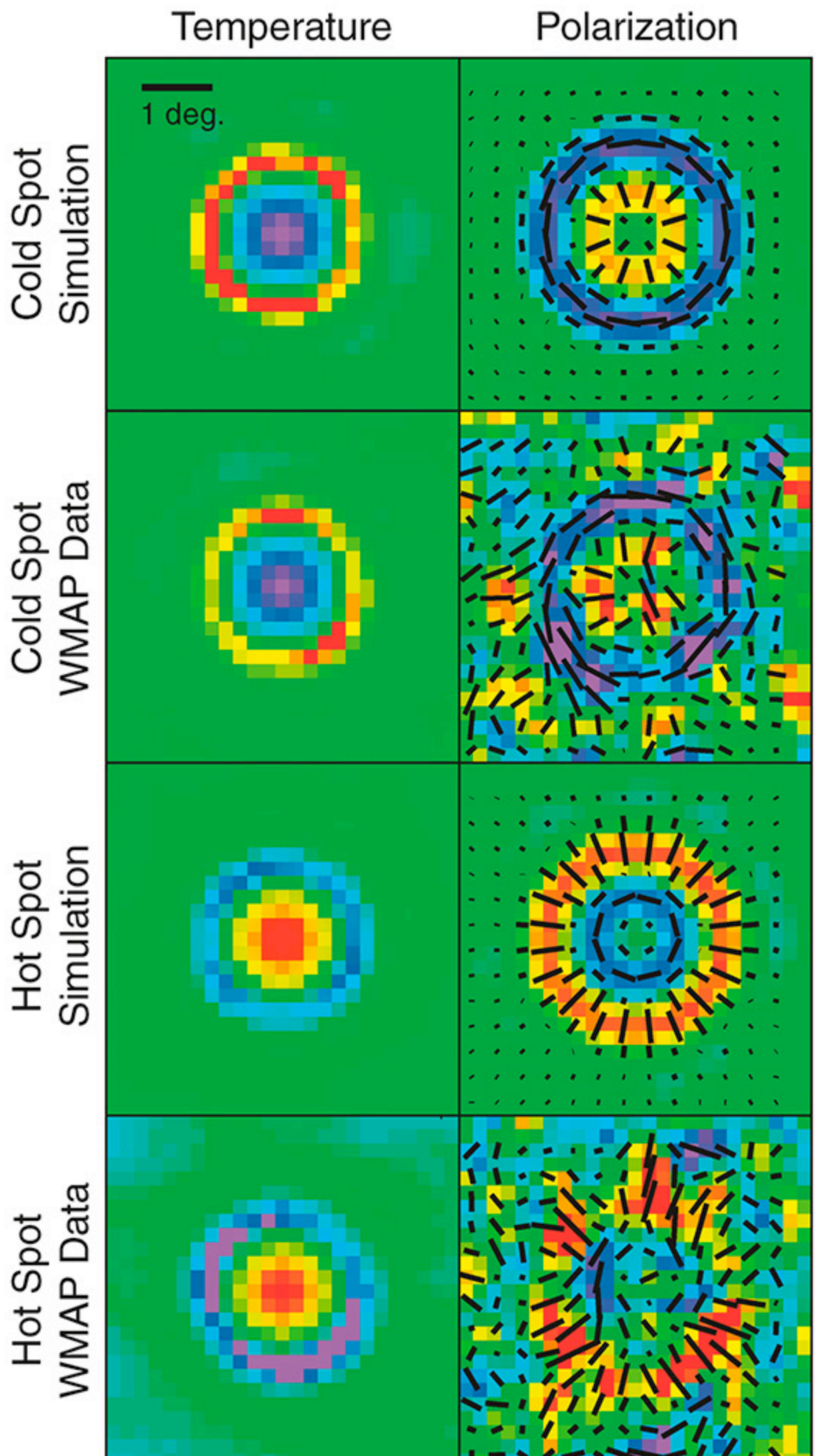


Stacking Analysis

- 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**.

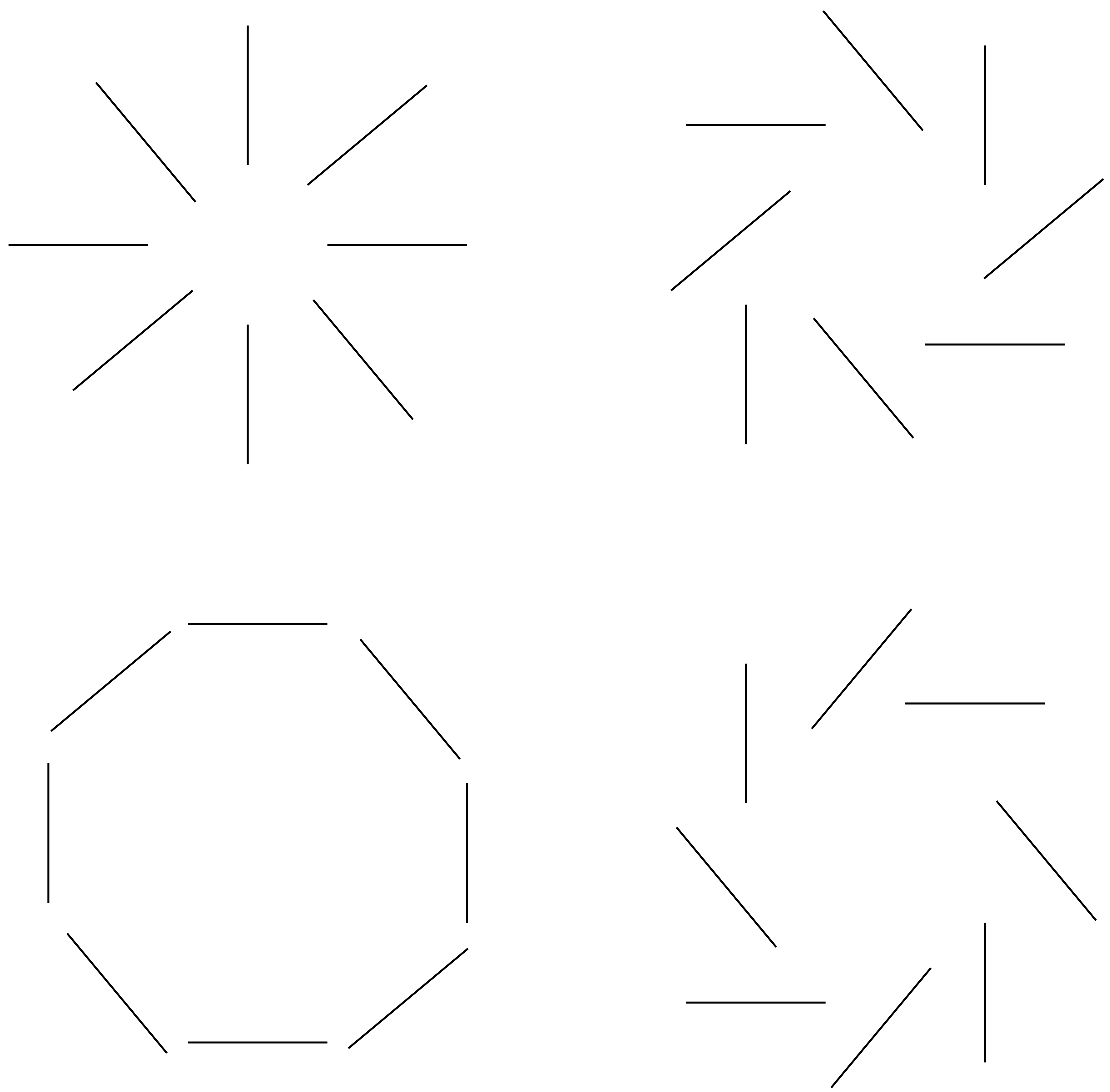




Two-dimensional View

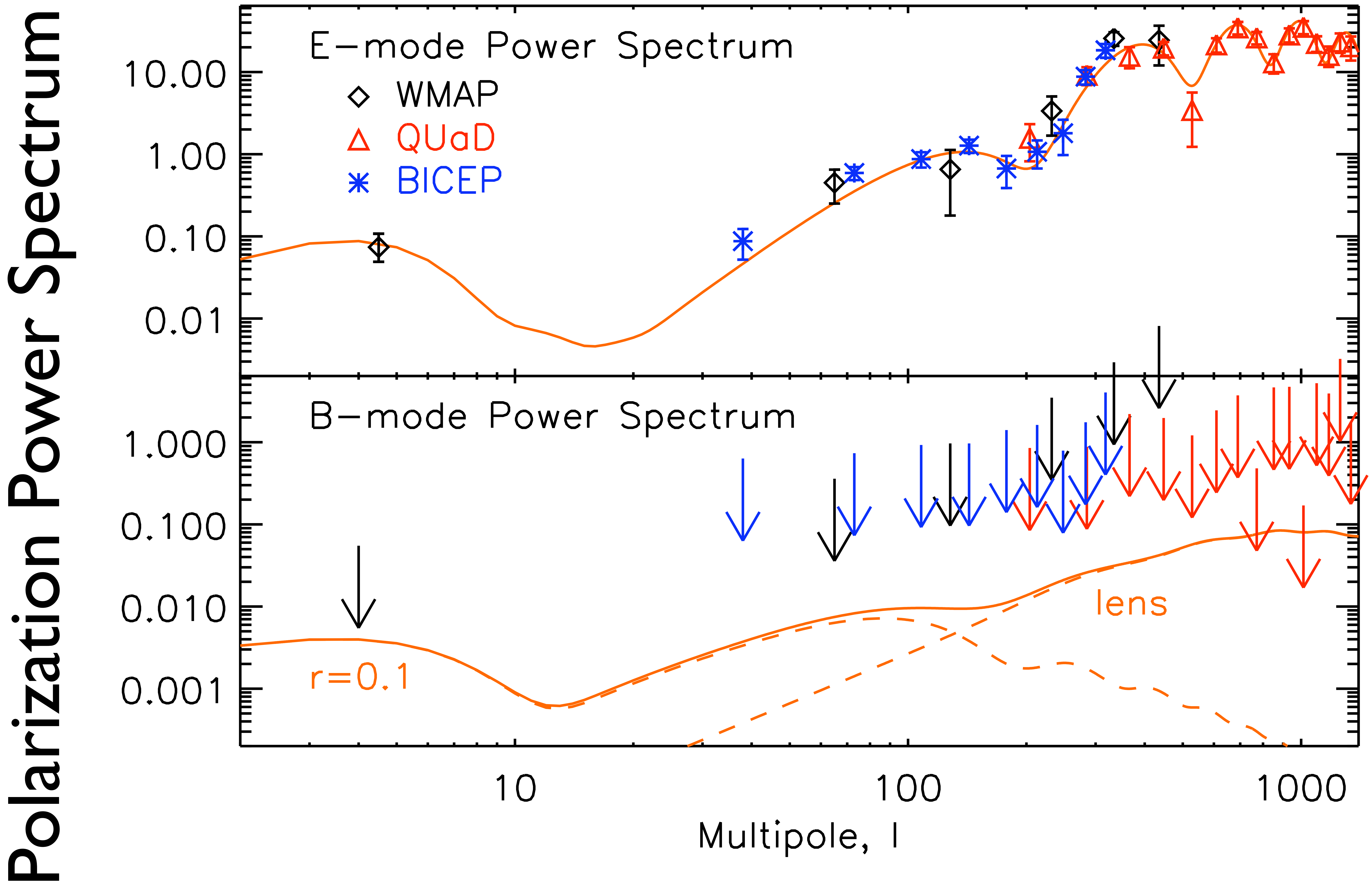
- All hot and cold spots are stacked (the threshold peak height, $\Delta T/\sigma$, is zero)
- "Compression phase" at θ=1.2 deg and "slow-down phase" at θ=0.6 deg are predicted to be there and we observe them!
  - The overall significance level: 8σ

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!

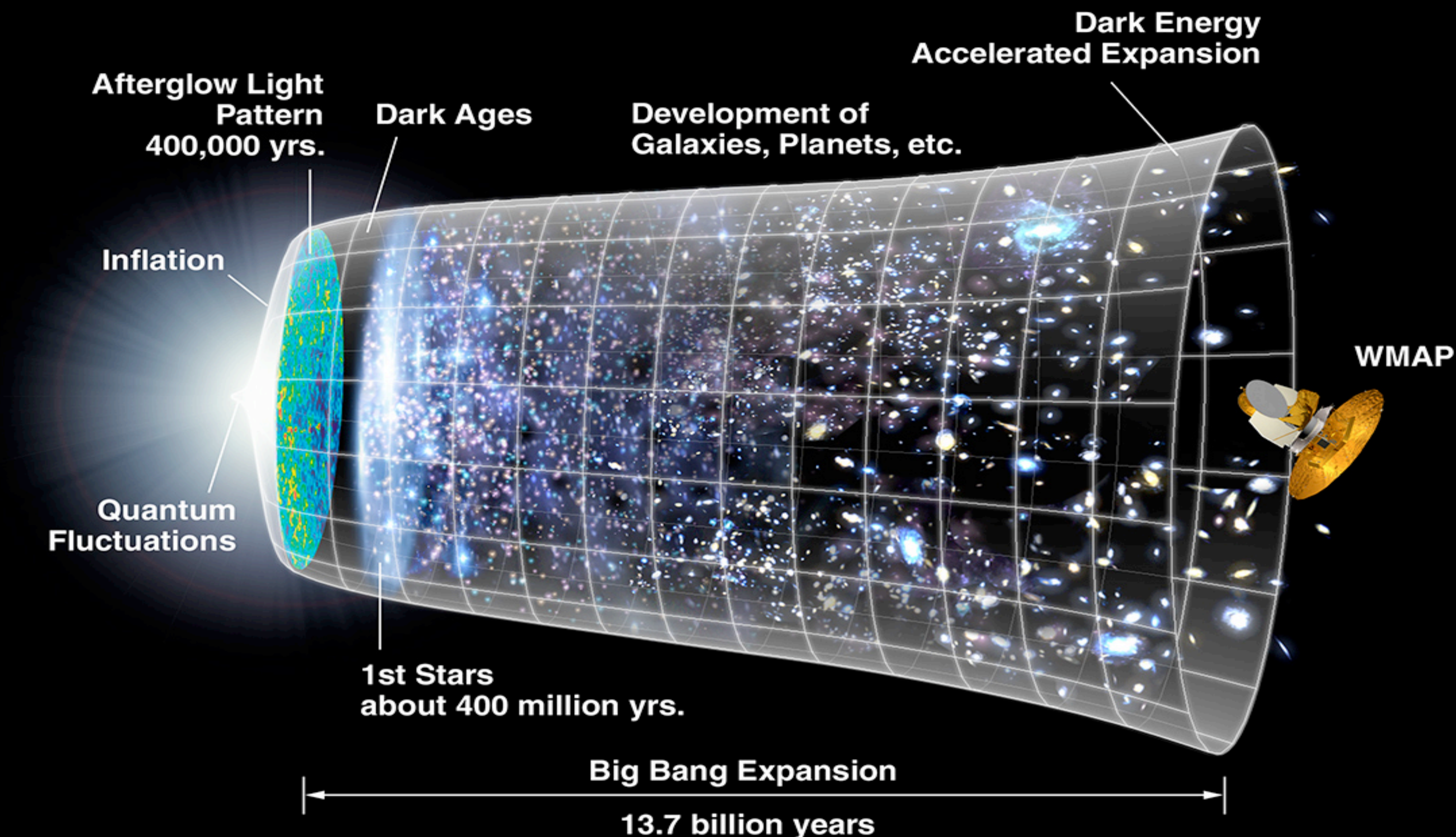


- No detection of B-mode polarization yet. **B-mode is the next holy grail!**

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



NASA/WMAP Science Team

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**.
- Detailed observations give us **this** remarkable information!

Quantum Fluctuations

- You may borrow a lot of **energy** from vacuum if you promise to return it to the vacuum immediately.
- The amount of **energy** you can borrow is inversely proportional to the time for which you borrow the **energy** from the vacuum.
- Just (a version of) Heisenberg's Uncertainty Principle, the foundation of Quantum Mechanics.

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]

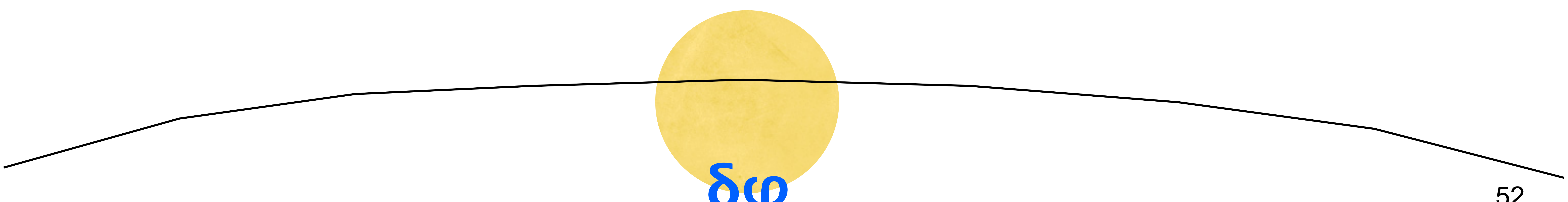
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like 10^{-36} second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~10^{12}GeV)
  - *Quantum fluctuations were important during inflation!*

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.

Starobinsky (1979)

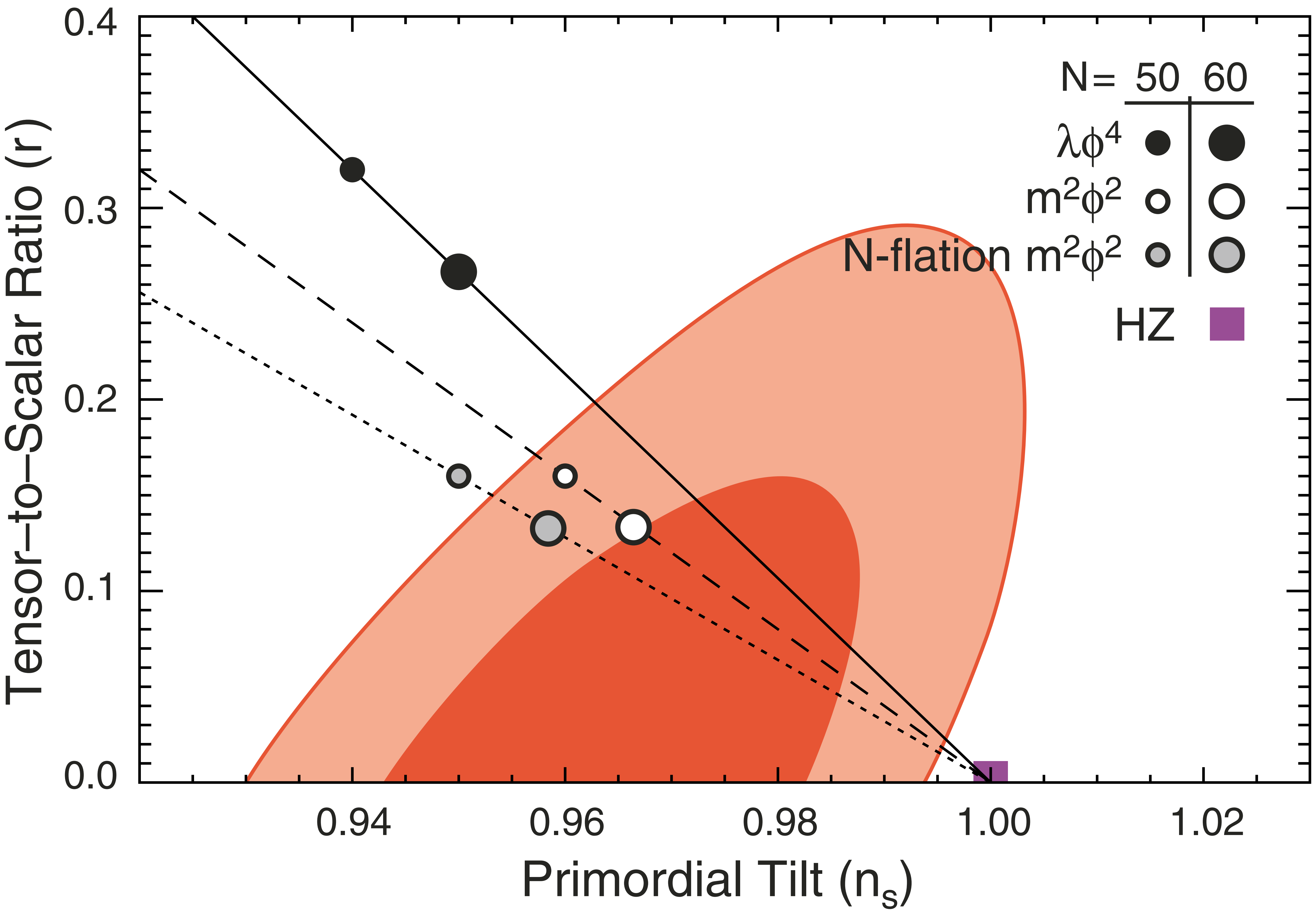
(Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

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.
  - Not so different from the 5-year limit.
  - $r < 0.24$ (95%CL)

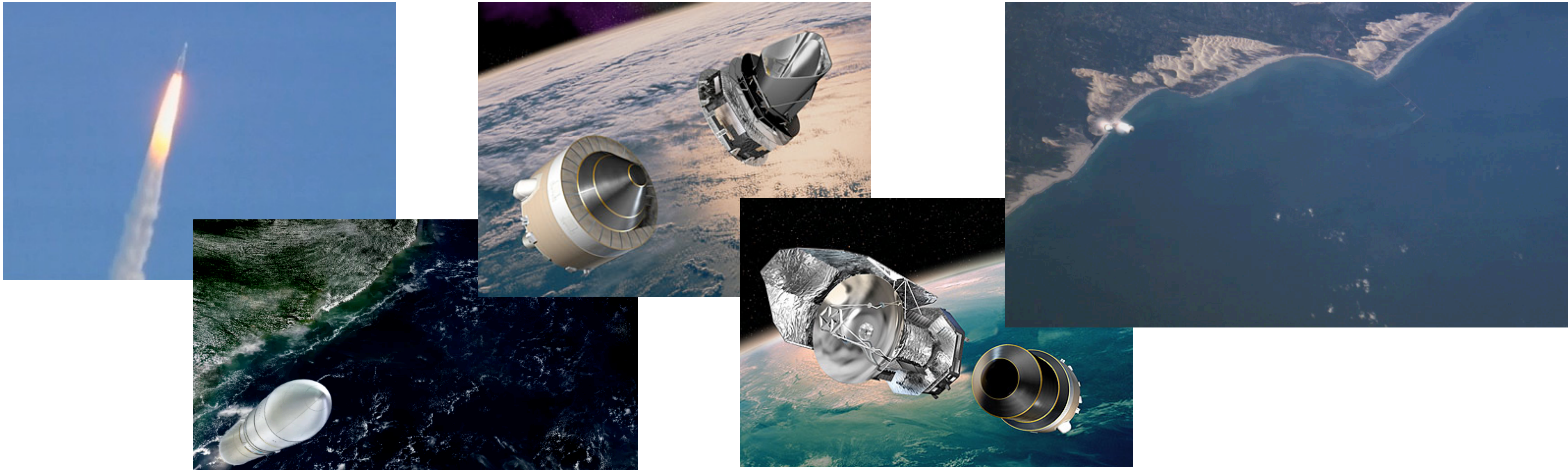
Probing Inflation (3-point Function)

- 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 95% CL limits are:
  - $-10 < f_{NL} < 74$
  - The WMAP data are consistent with the prediction of **simple single-field inflation** models: $1-n_s \approx r \approx f_{NL}$

Summary

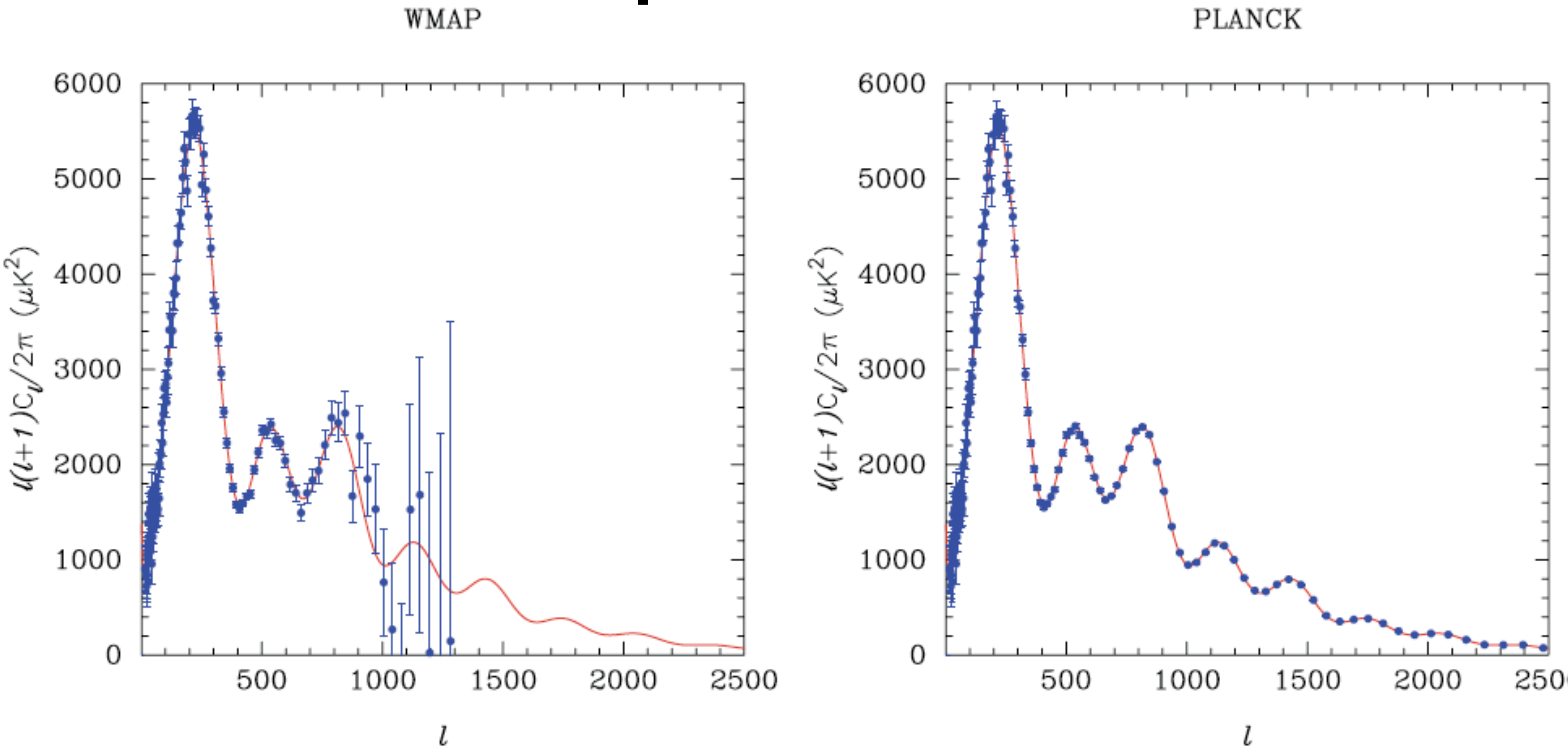
- CMB is the fossil light of the Big Bang.
- We could determine the age, composition, expansion rate, etc., from CMB.
- We could even push the boundary farther back in time, probing the origin of fluctuations in the very early Universe: inflationary epoch at ultra-high energies.
- Next Big Thing: **Primordial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

Planck Launched!



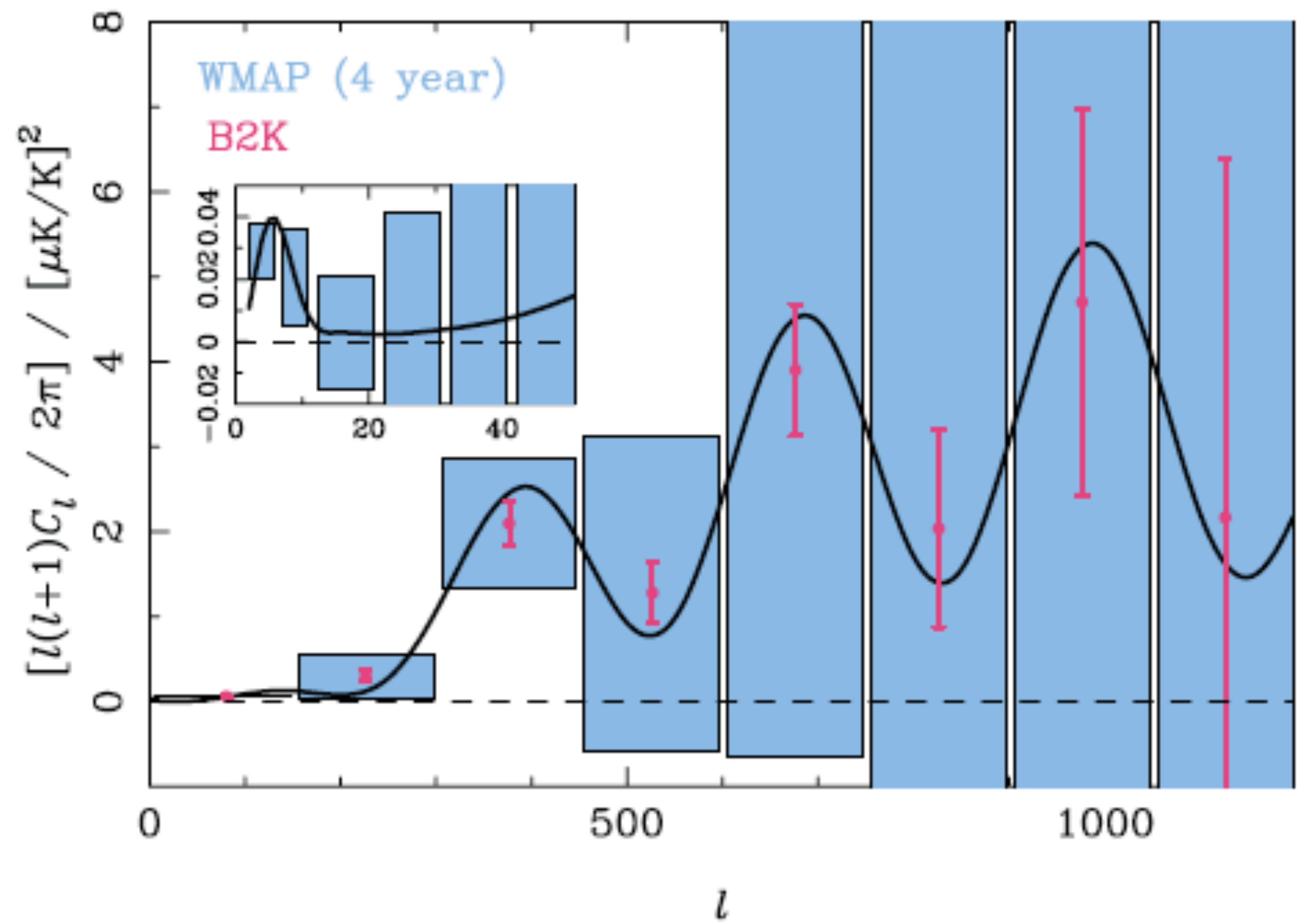
- The Planck satellite was successfully launched from French Guiana on May 14.
- Separation from the Herschell satellite was also successful.
- Planck has mapped the full sky already - results expected to be released in December, 2012.

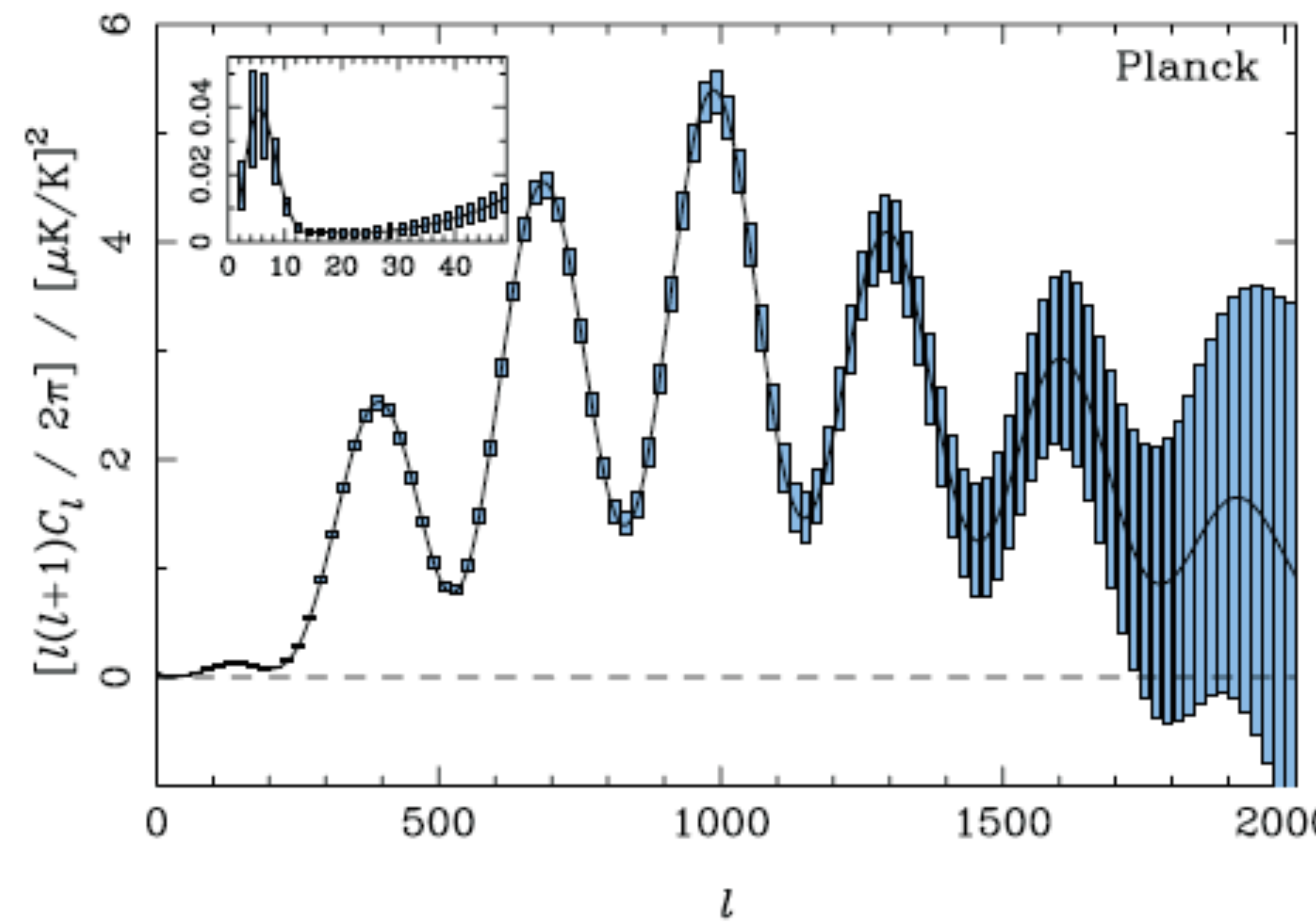
Planck: Expected $C_l^{Temperature}$

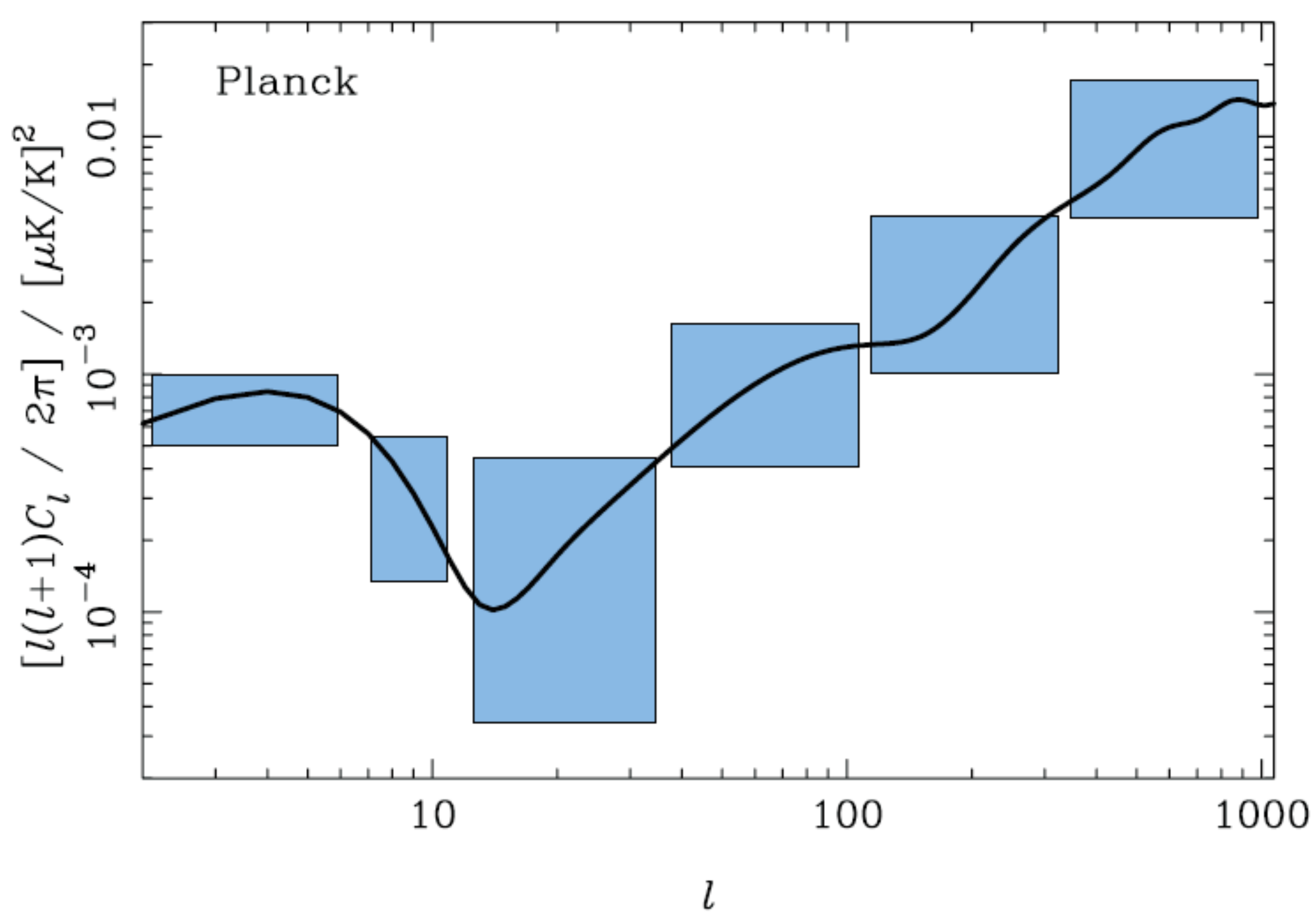


- WMAP: l~1000 => Planck: l~3000

Planck: Expected $C_l^{Polarization}$







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