

# The 7-Year WMAP Observations: Cosmological Interpretation

**Eiichiro Komatsu** (Texas Cosmology Center, UT Austin)  
Colloquium, Max Planck Institute for Physics, July 20, 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 ( $\sim 0.5\mu\text{m}$ )



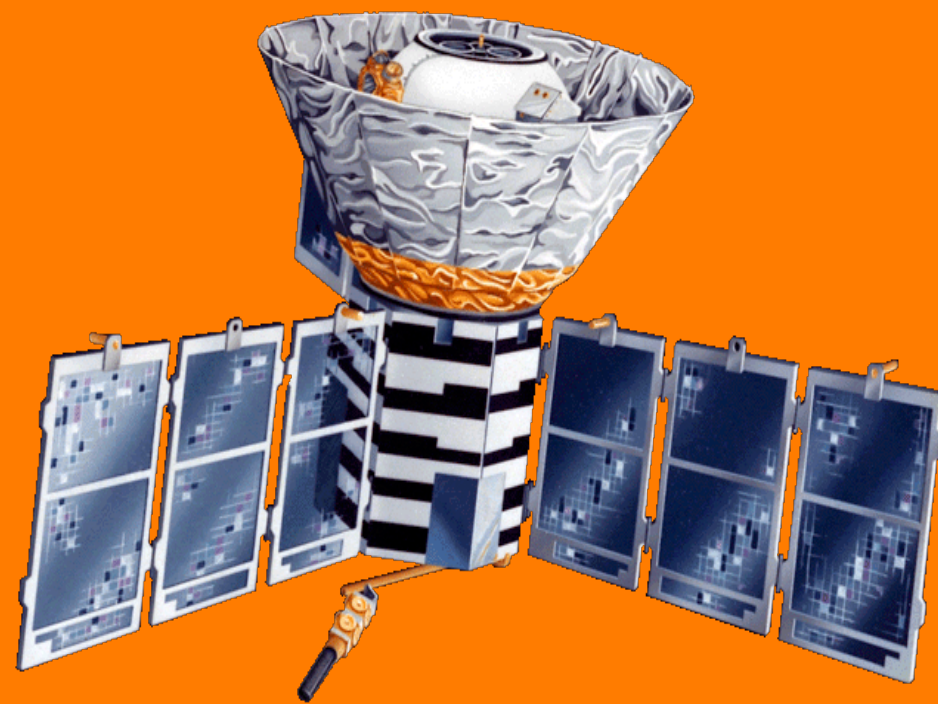


# Night Sky in Microwave (~1mm)

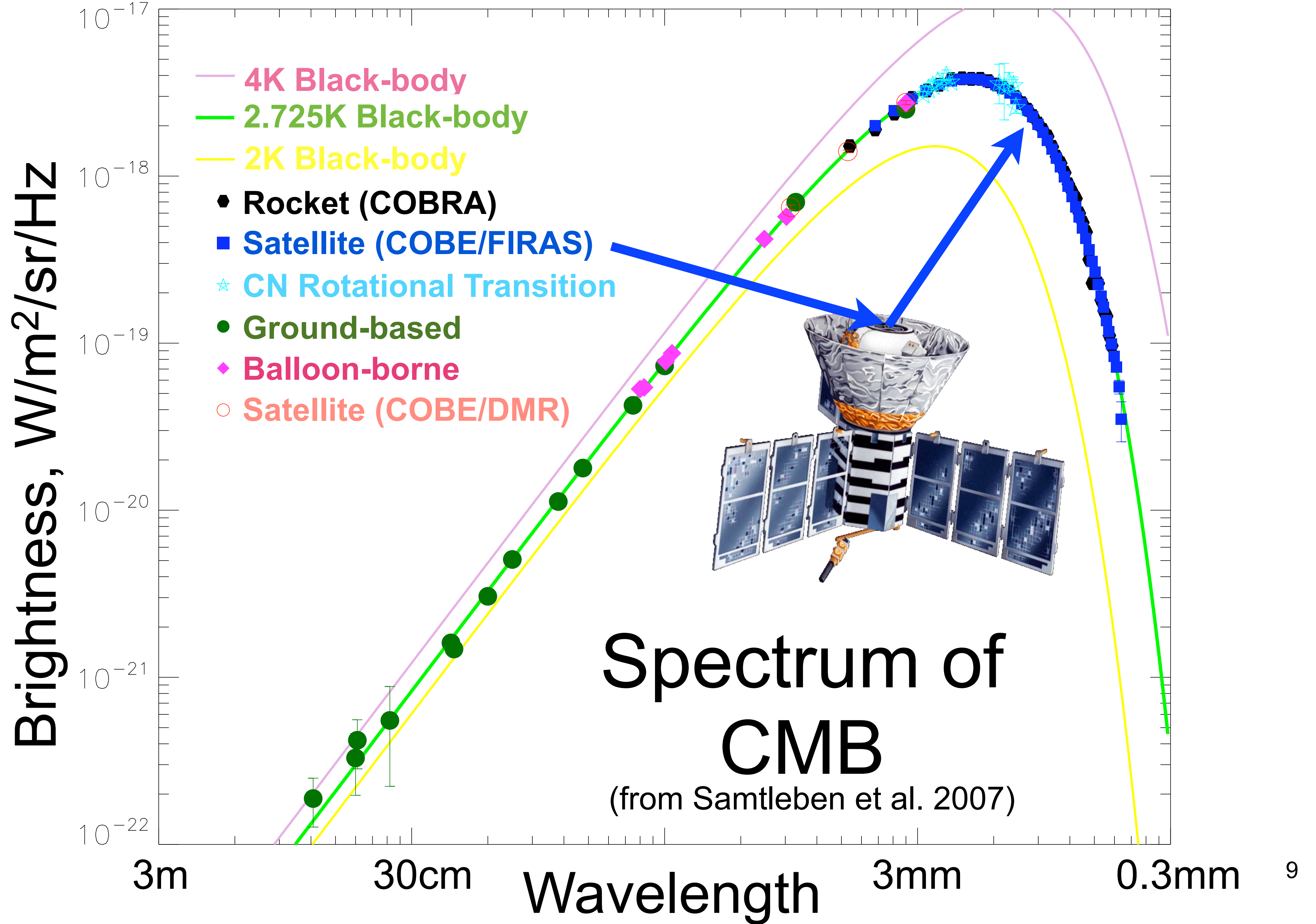


# Night Sky in Microwave ( $\sim 1\text{mm}$ )

$T_{\text{today}} = 2.725\text{K}$



***COBE Satellite, 1989-1993***

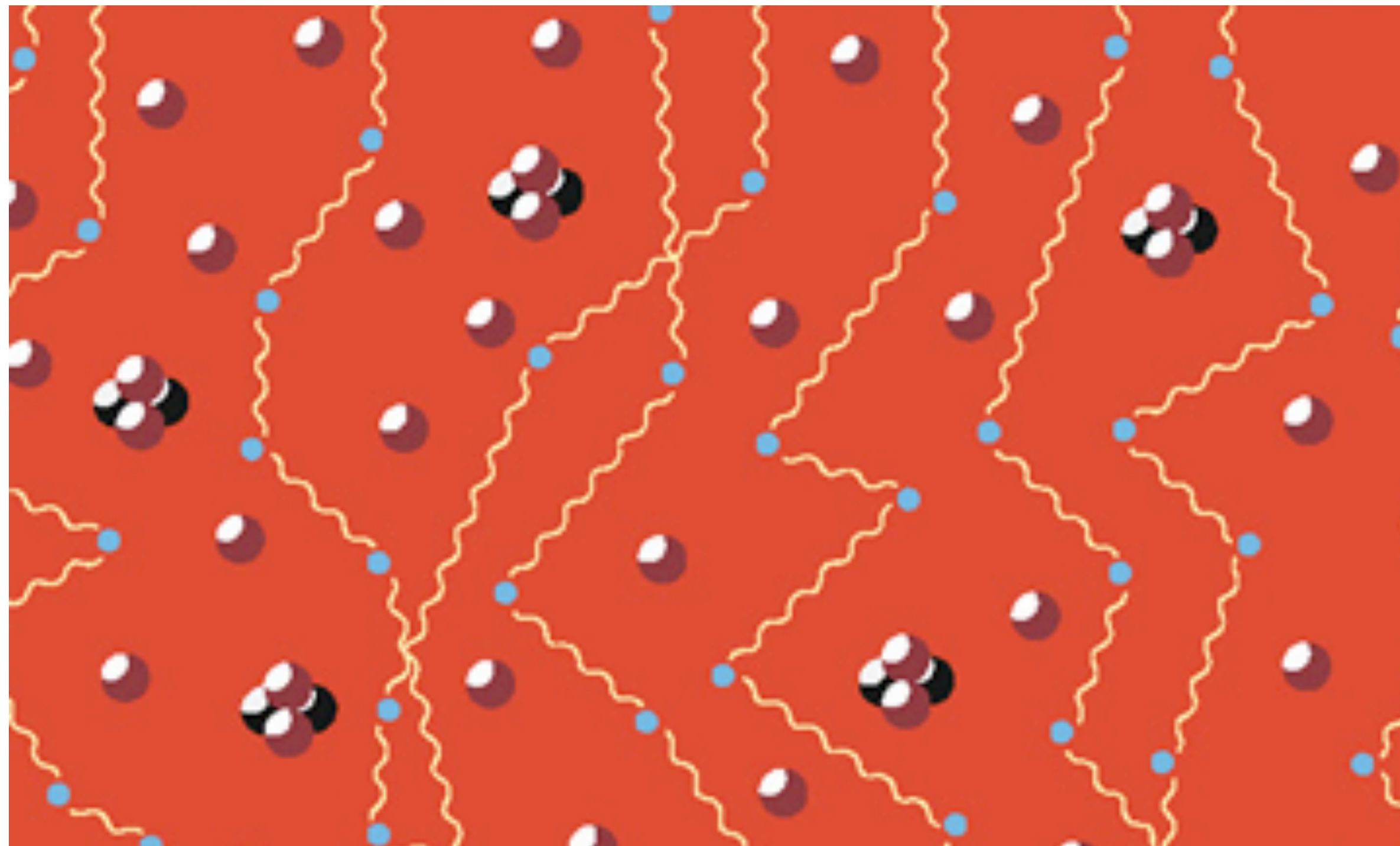


# How was CMB created?

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

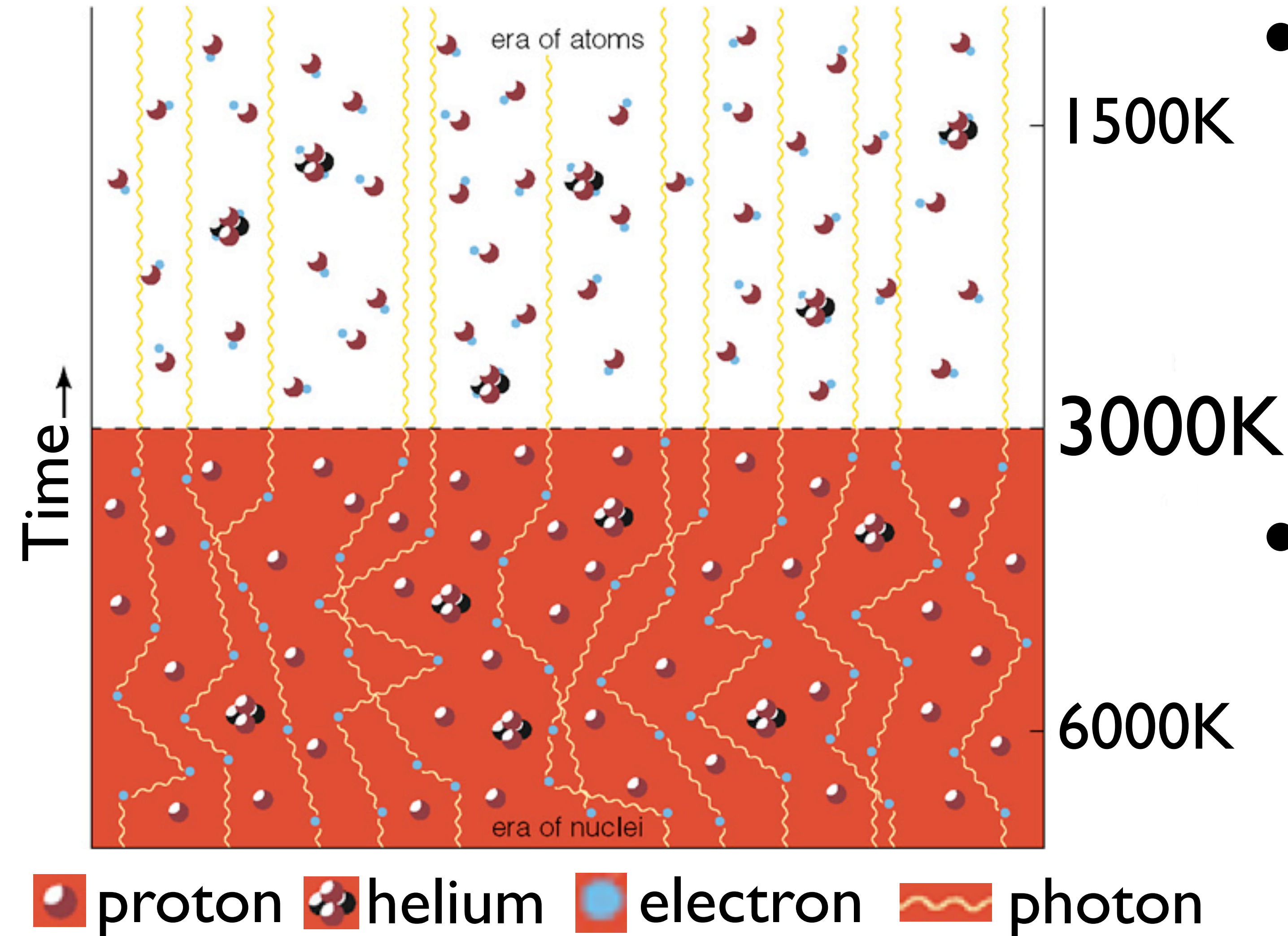


# Universe as a hot soup



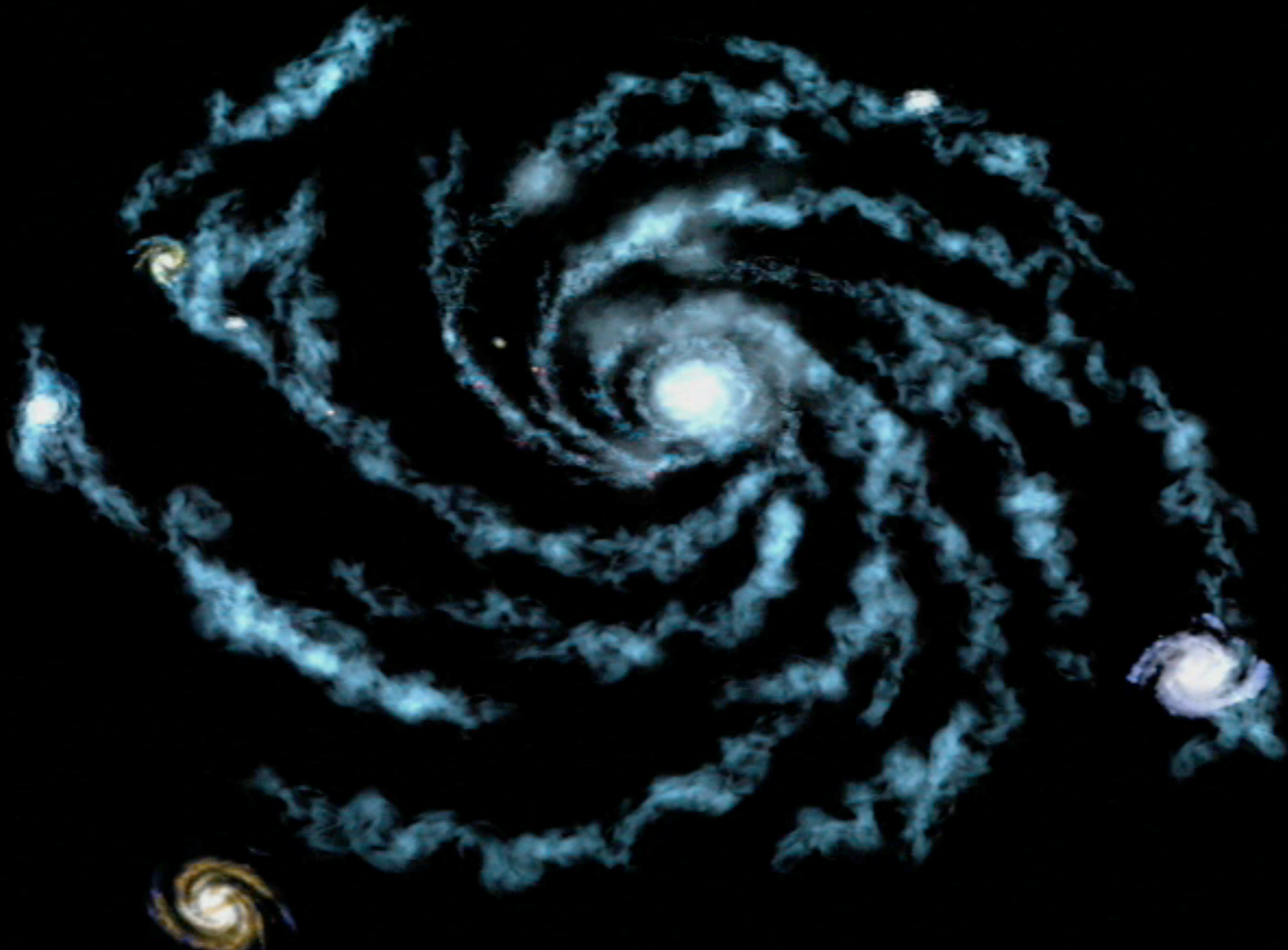
- Free electrons can scatter photons efficiently.
- Photons cannot go very far.

# 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.

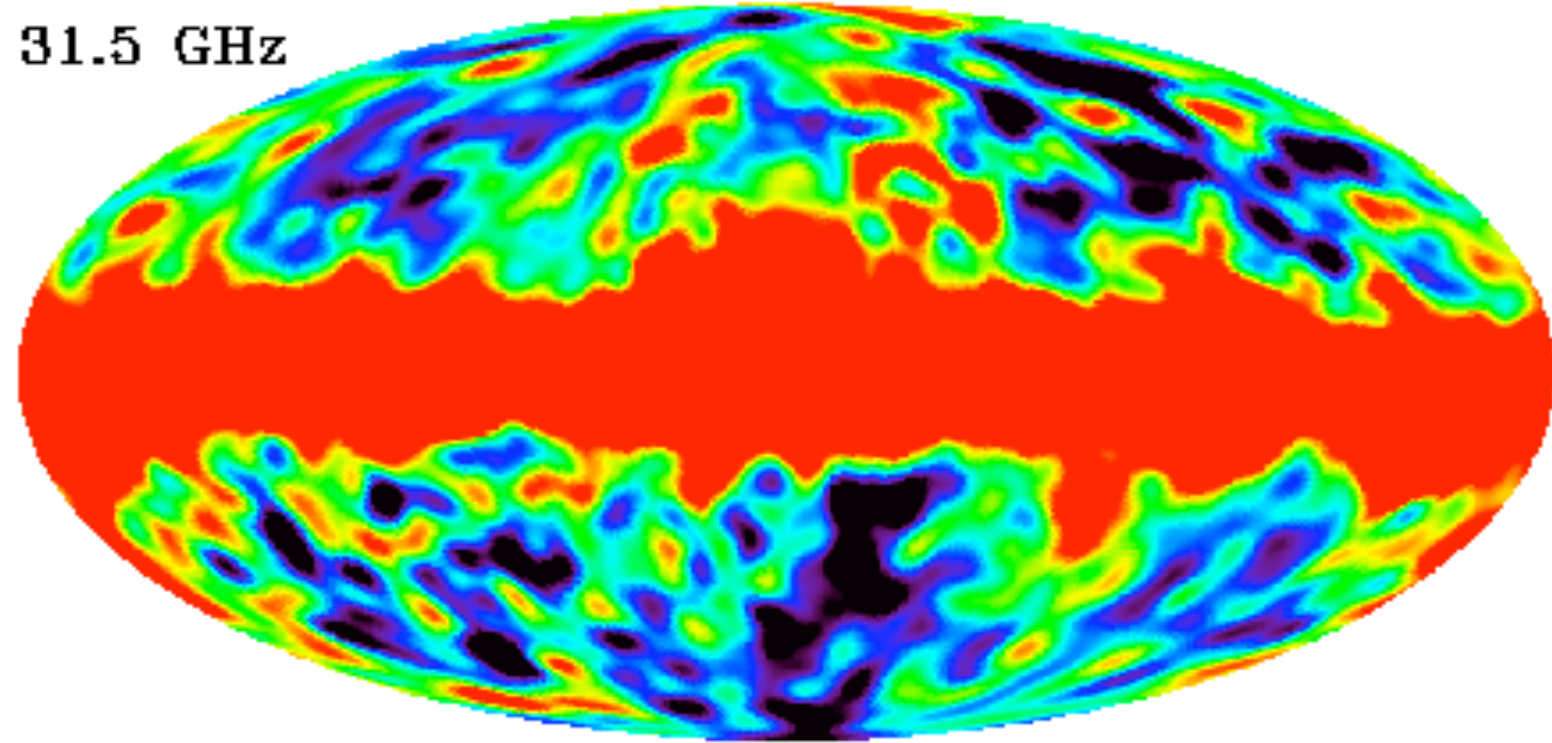




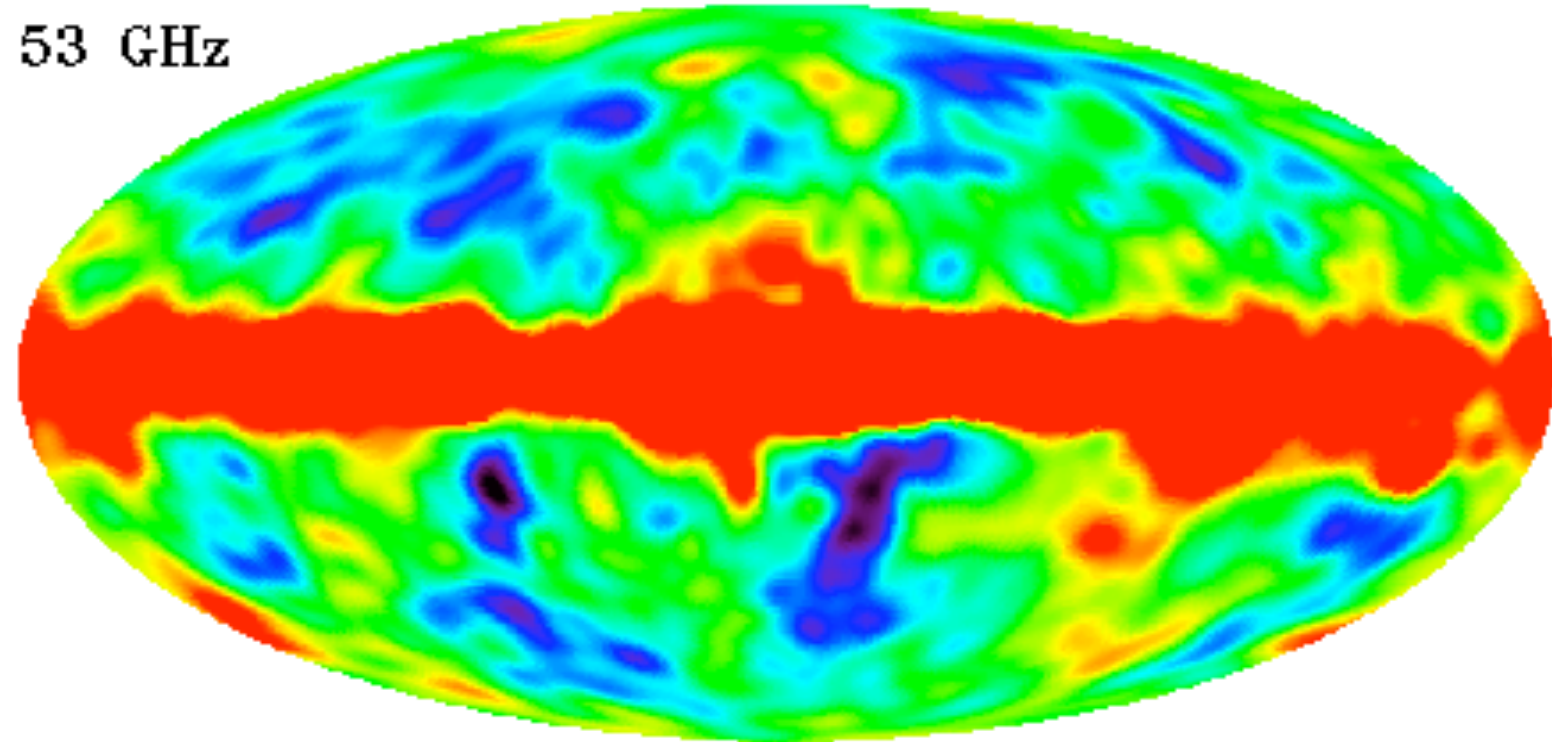


# COBE/DMR, 1992

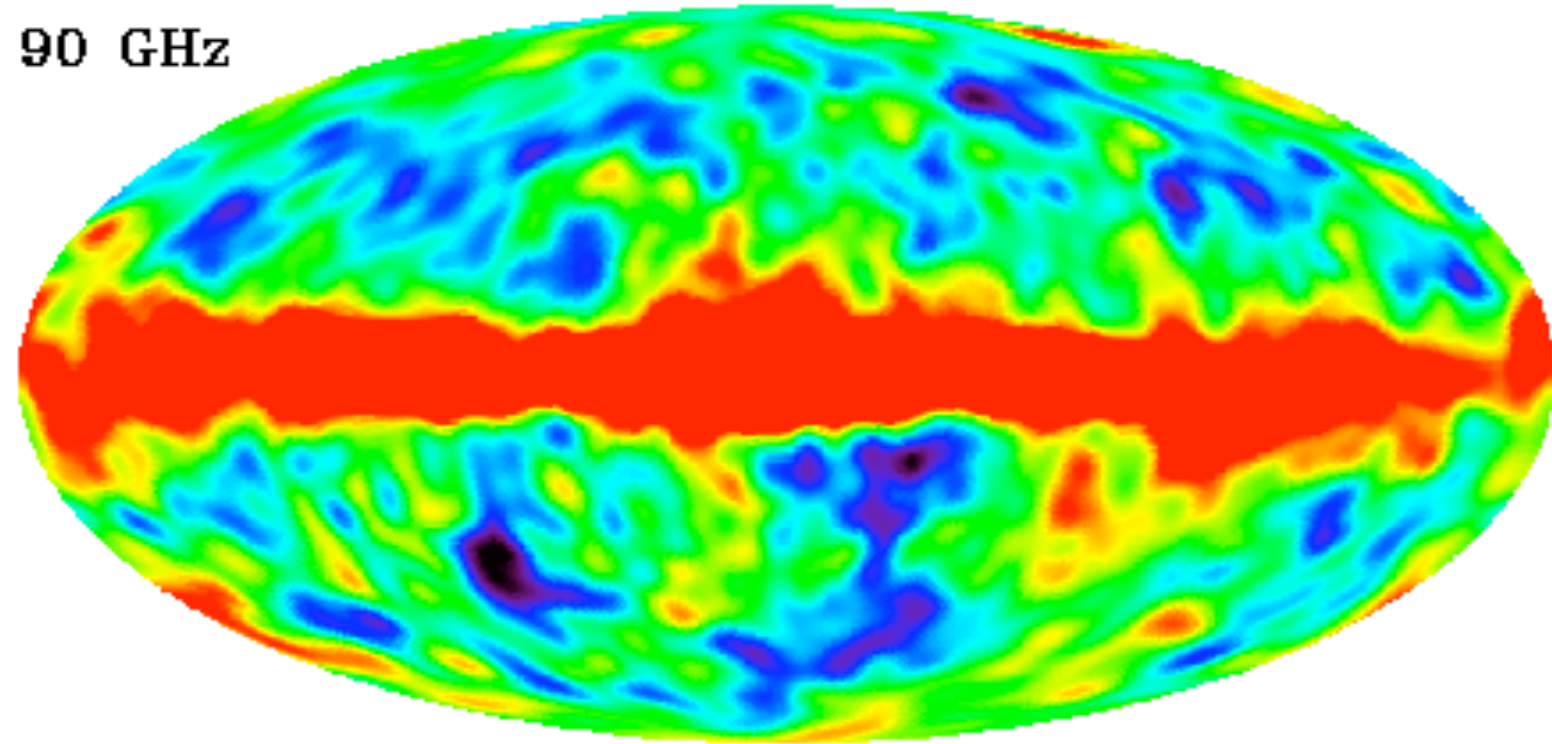
31.5 GHz



53 GHz



90 GHz



-100 μK  +100 μK

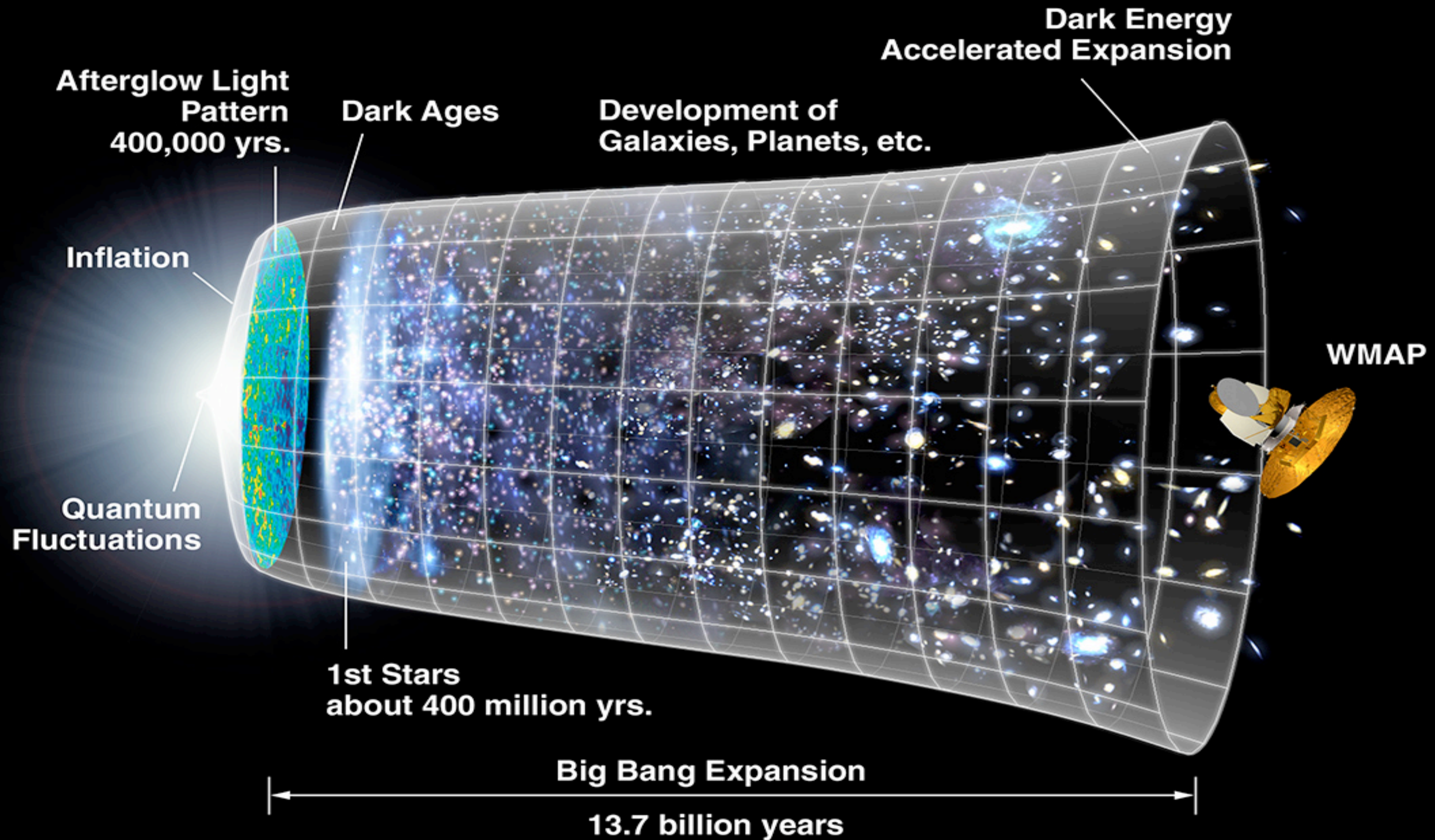


• **Isotropic?**

• **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.



# WMAP at Lagrange 2 (L2) Point

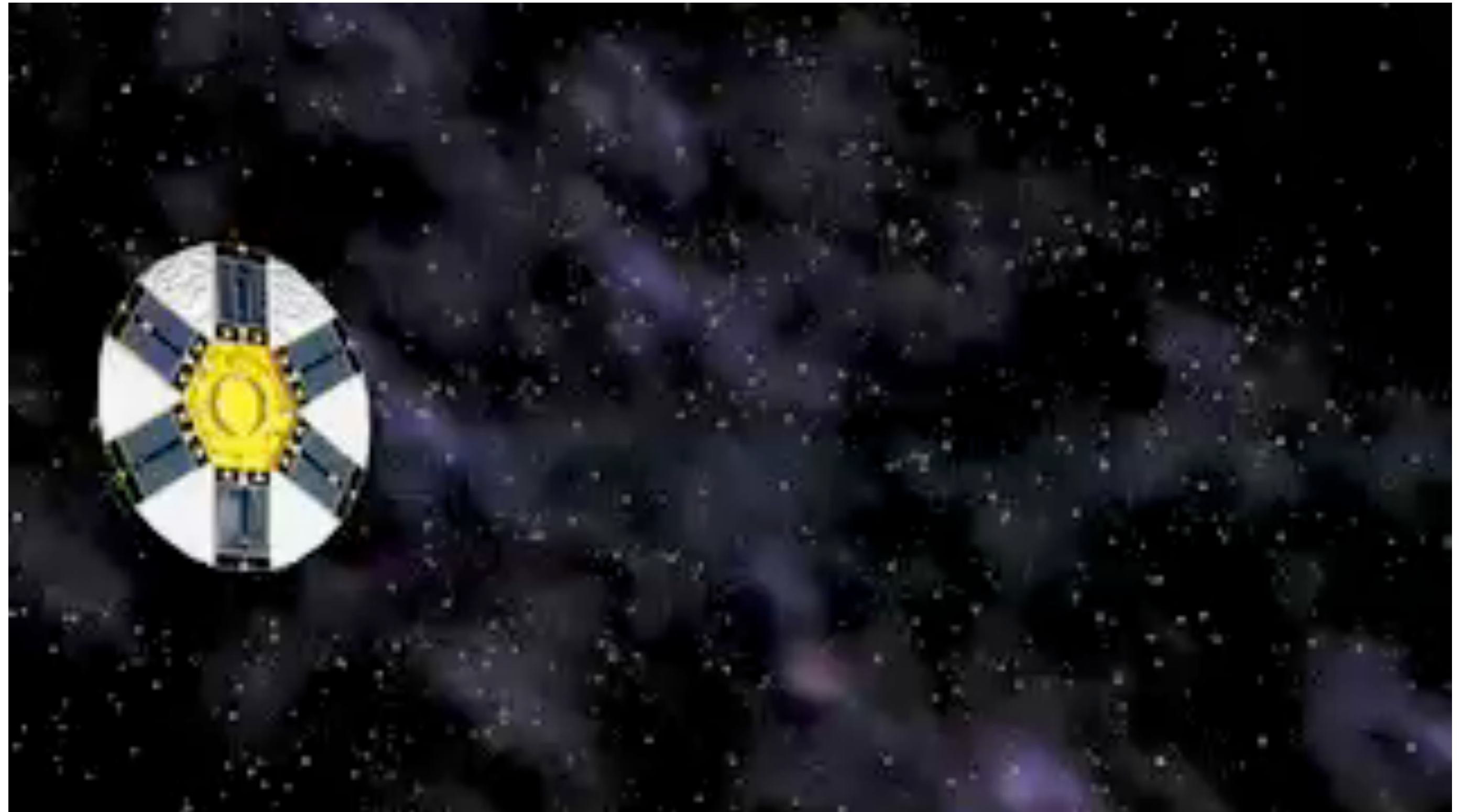
June 2001:  
WMAP launched!

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**

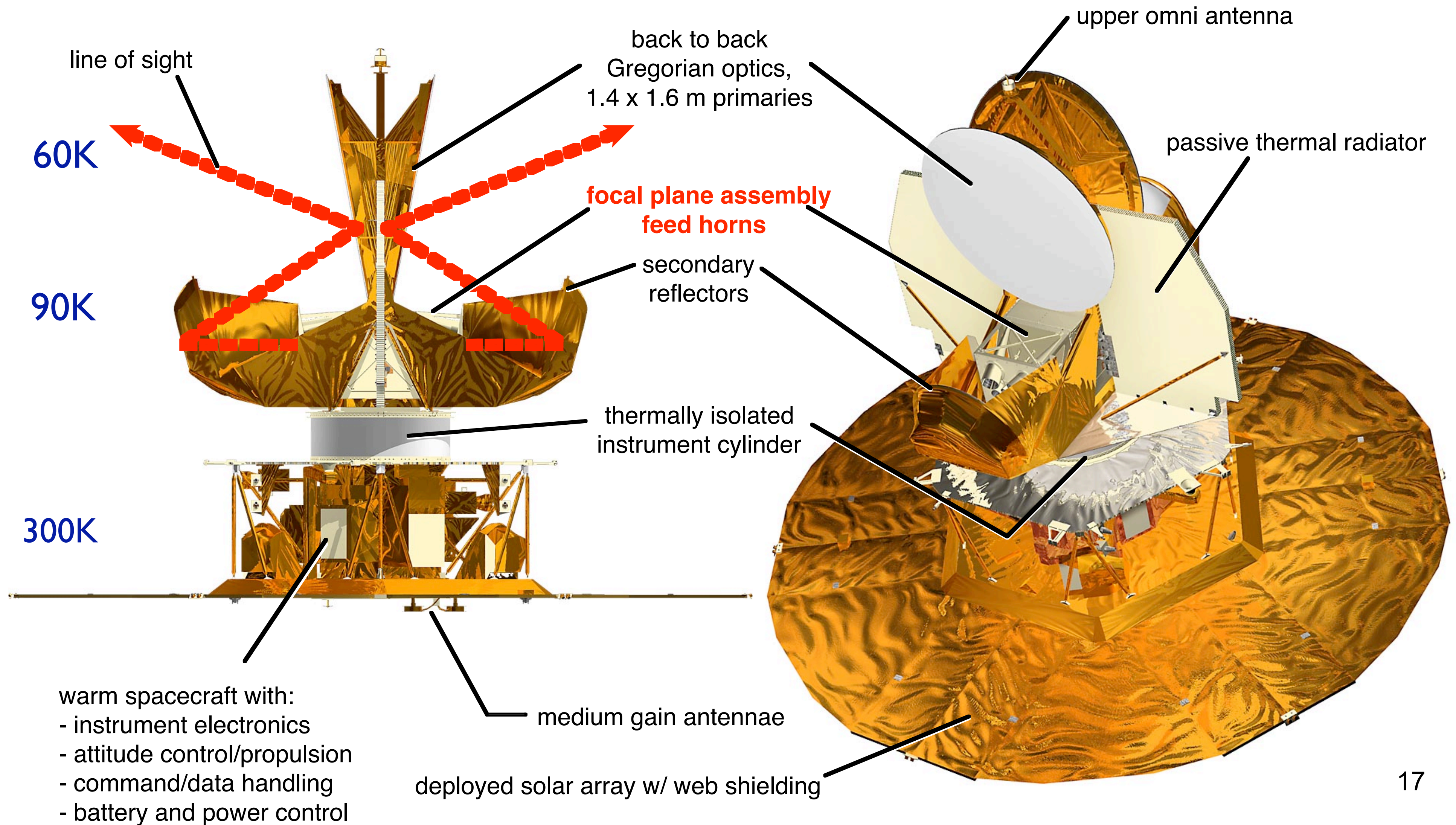


- L2 is a million miles from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them



# WMAP Spacecraft

## Radiative Cooling: No Cryogenic System

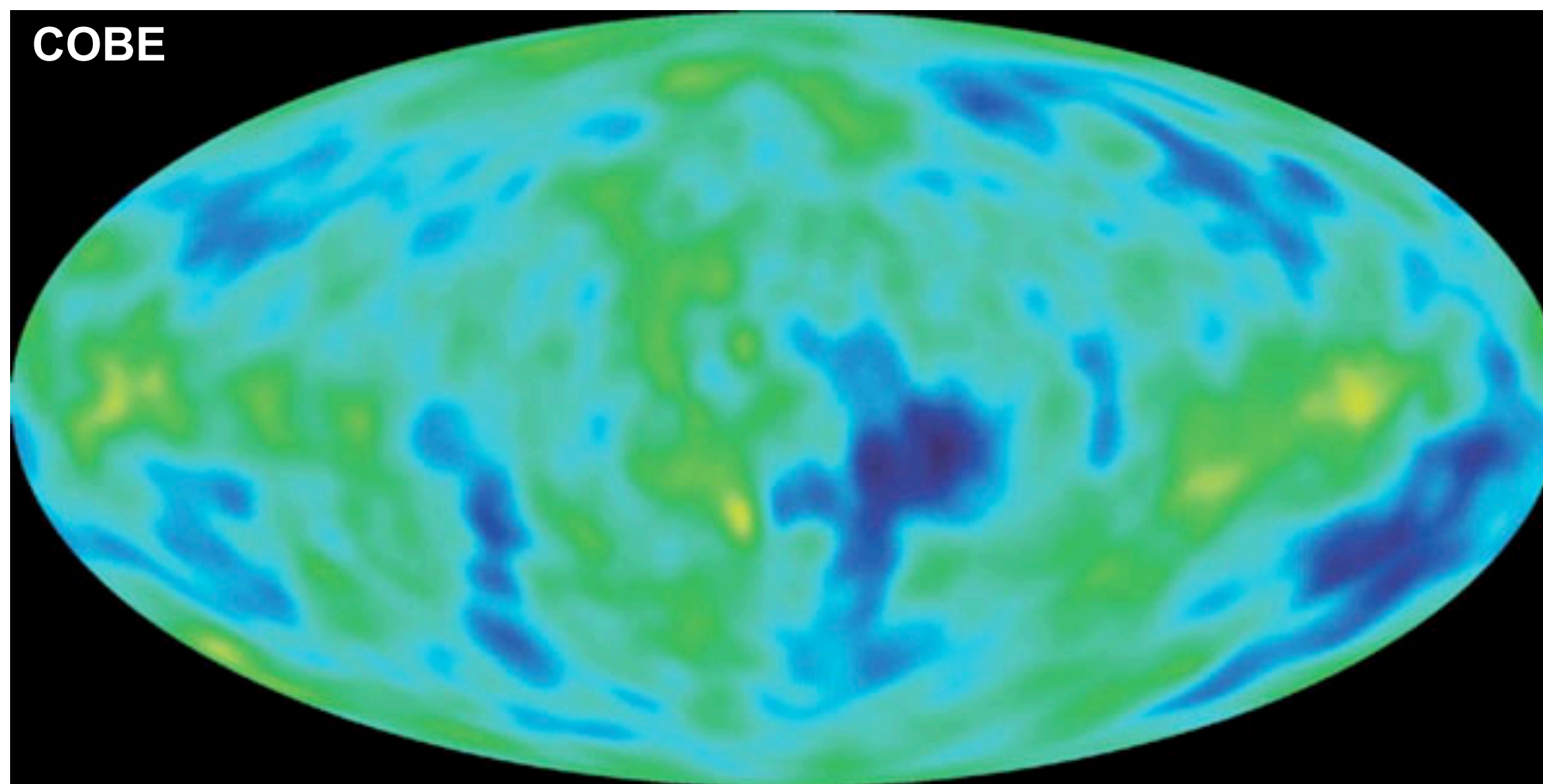




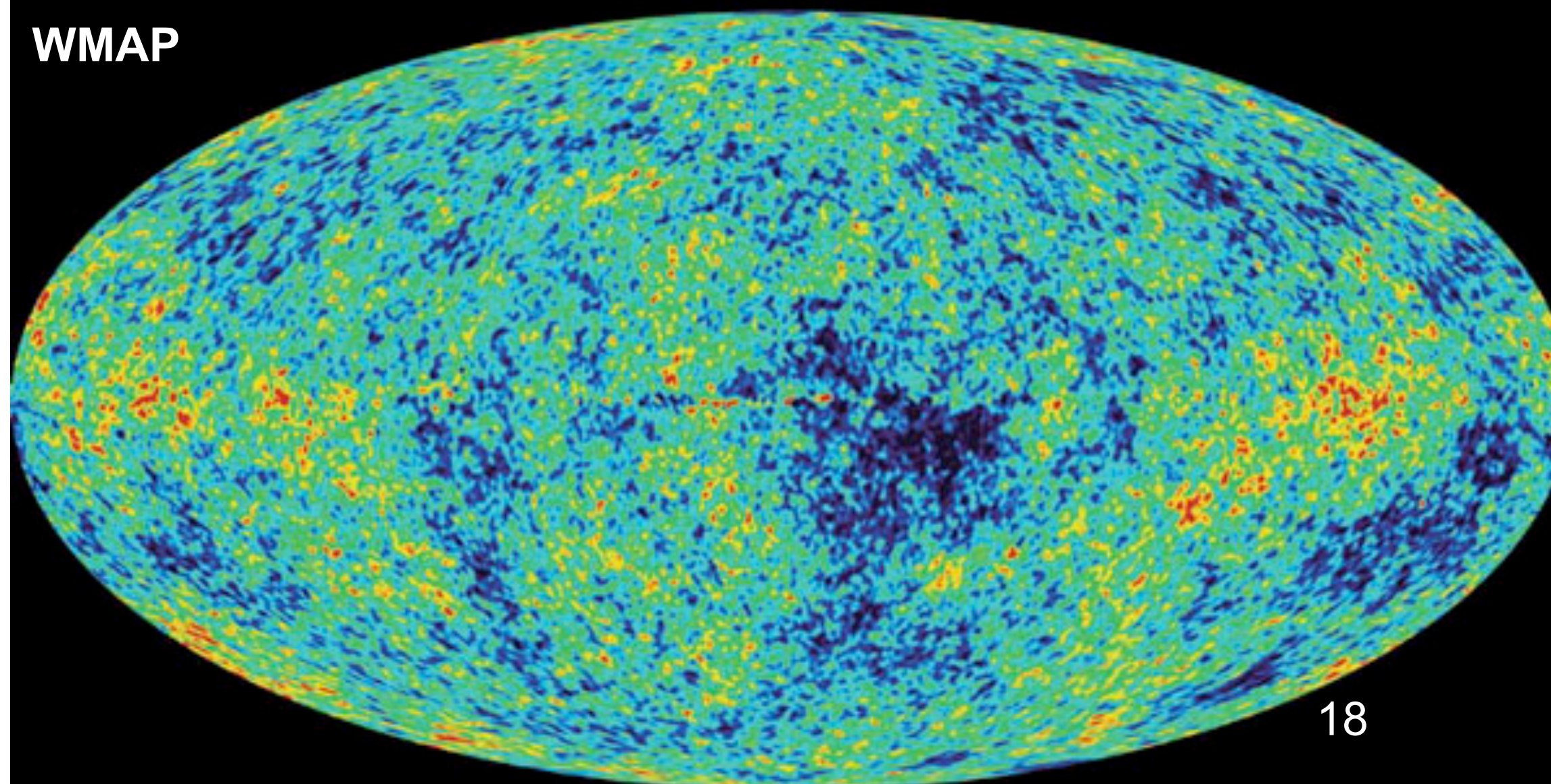
# COBE to WMAP (x35 better resolution)



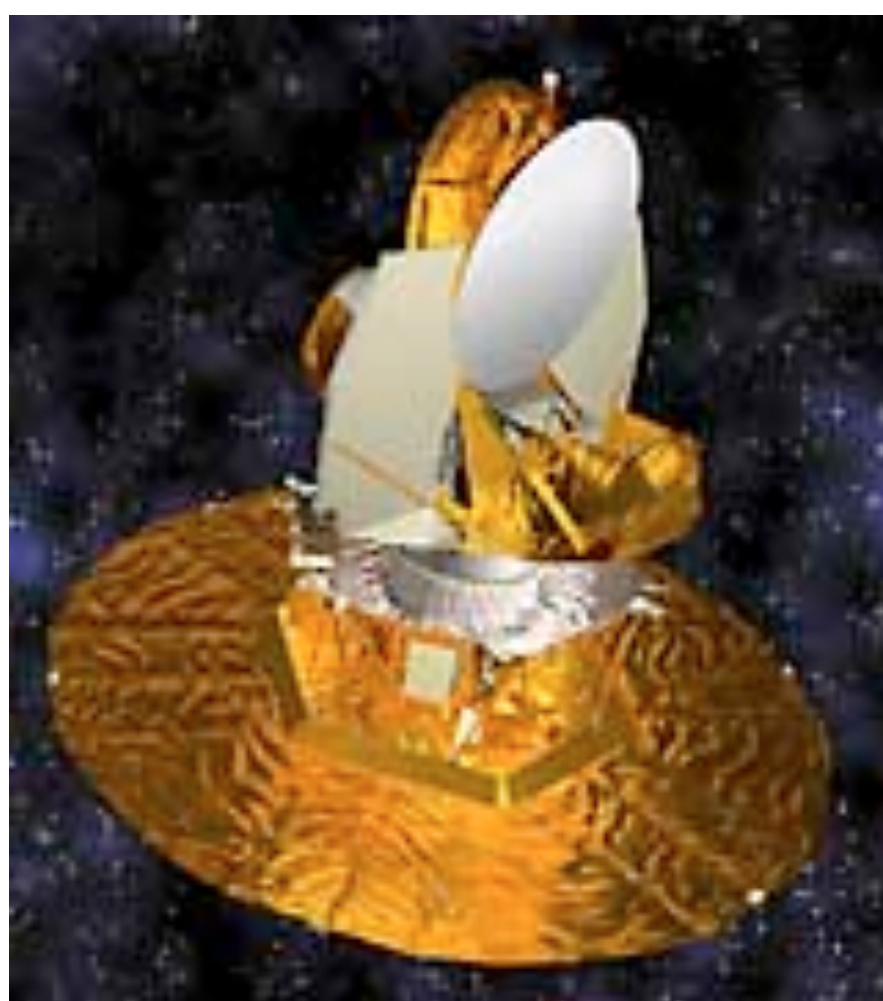
COBE  
1989



WMAP



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.olta
- 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

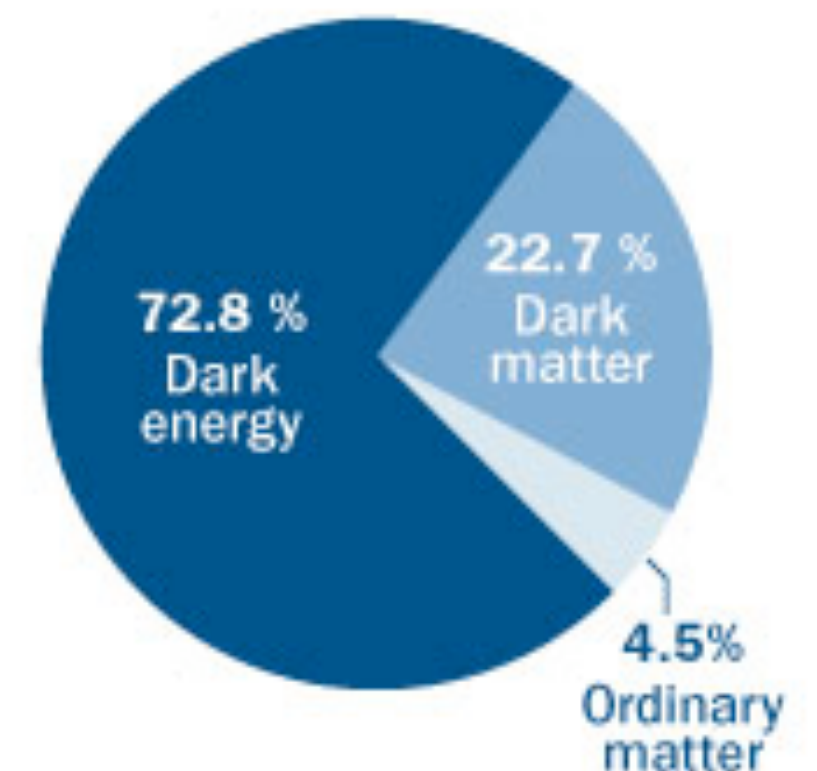
- H&He = 4.56% ( $\pm 0.16\%$ )
- Dark Matter = 22.7% ( $\pm 1.6\%$ )
- Dark Energy = 72.8% ( $\pm 1.6\%$ )
- $H_0 = 70.4 \pm 1.4$  km/s/Mpc
- Age of the Universe = 13.75 billion years ( $\pm 0.11$  billion years)

## Universal Stats

Age of the universe today  
**13.75 billion years**

Age of the cosmos at  
time of reionization  
**457 million years**

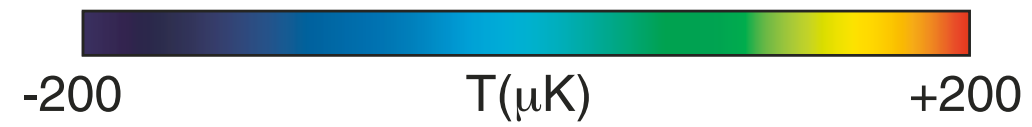
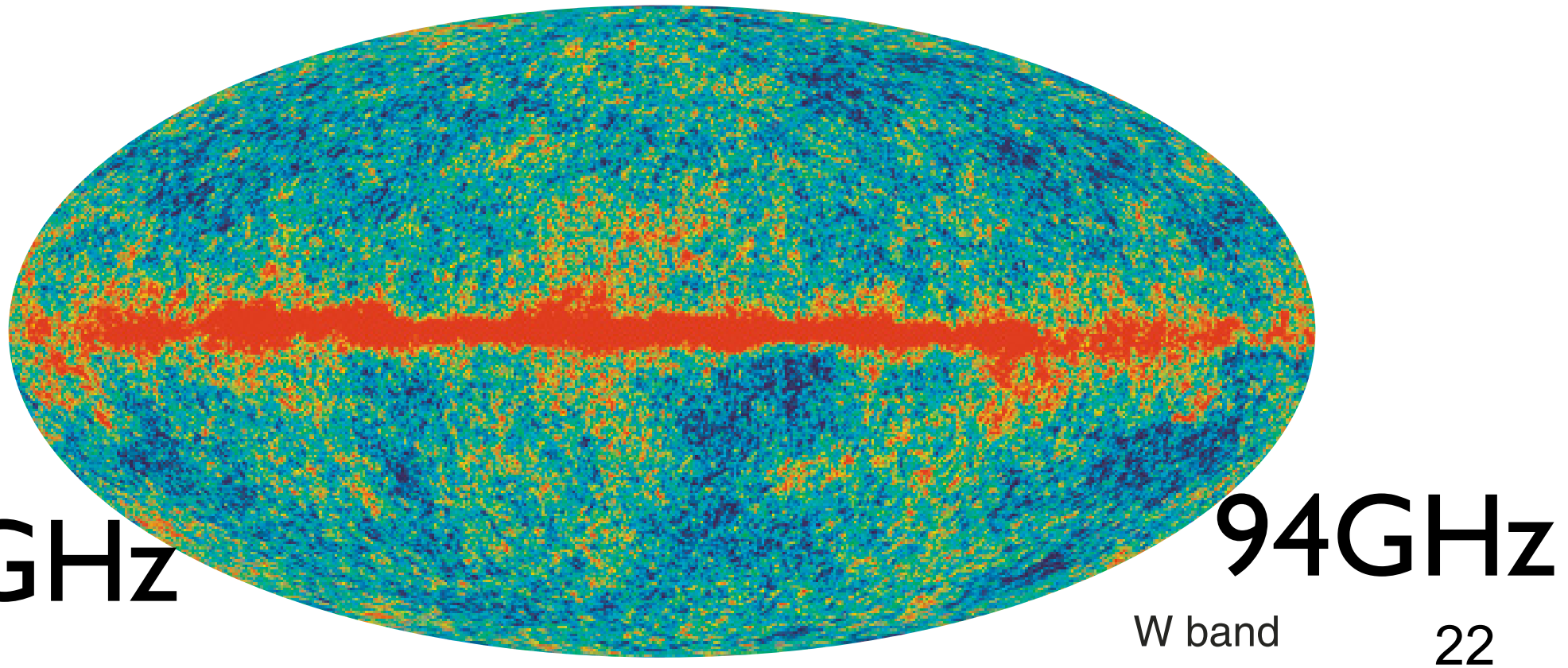
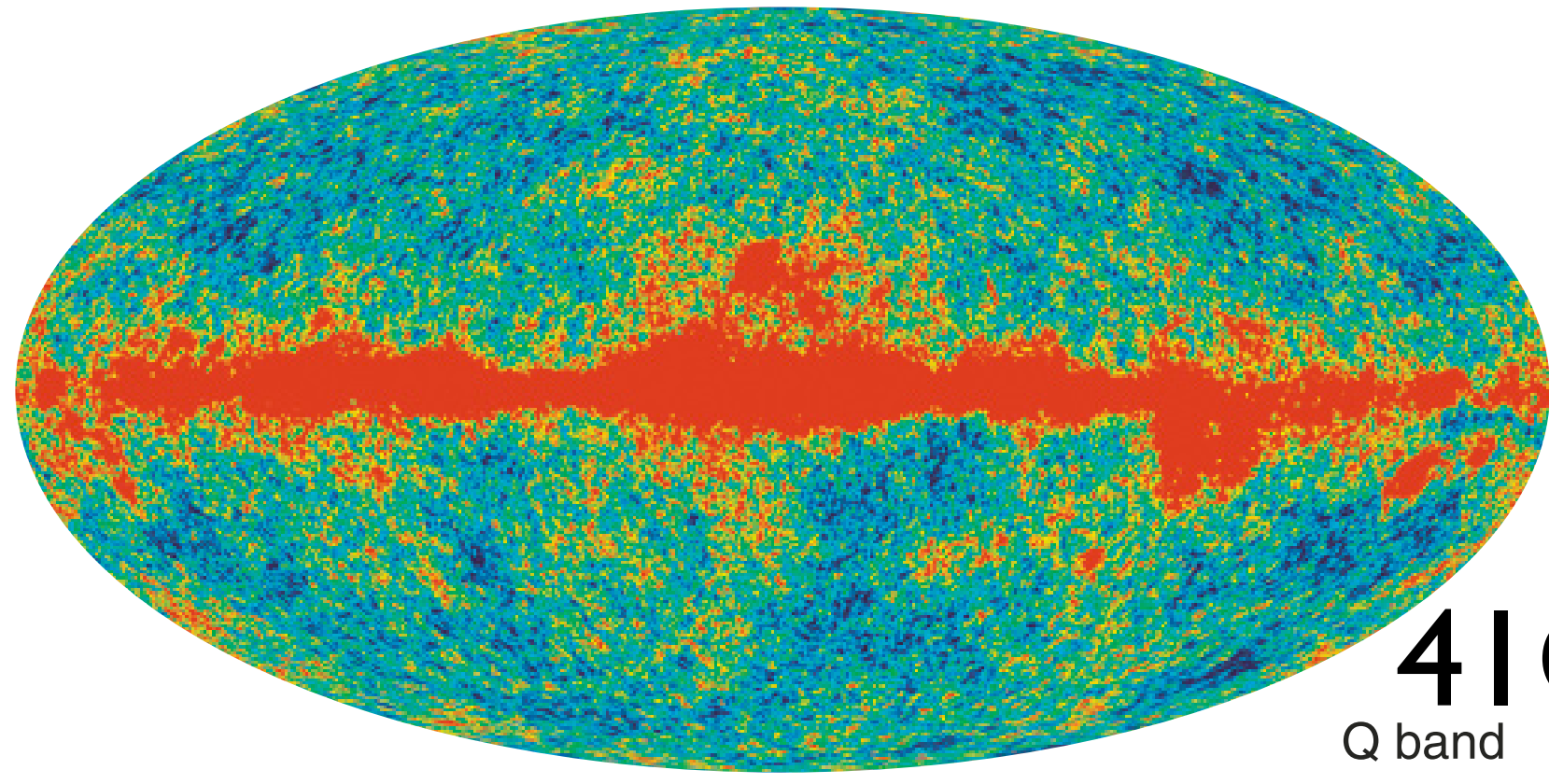
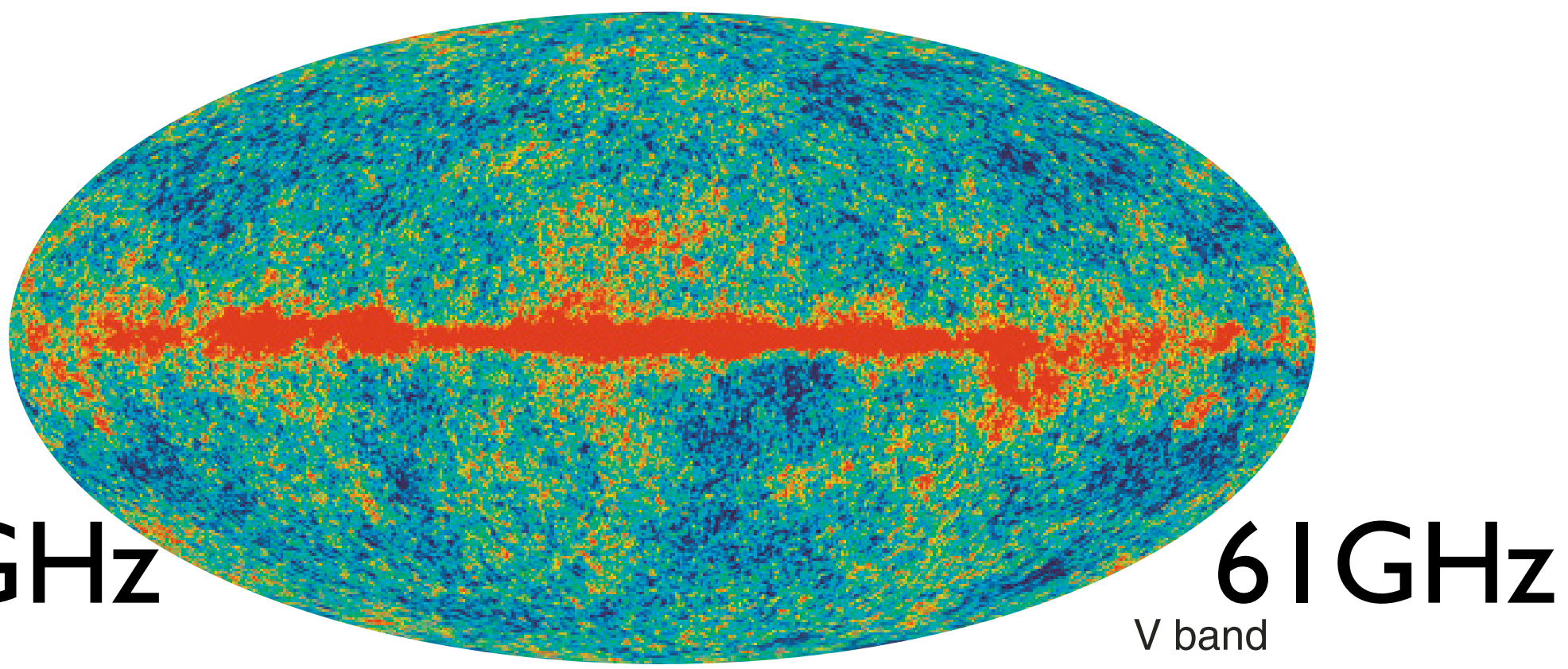
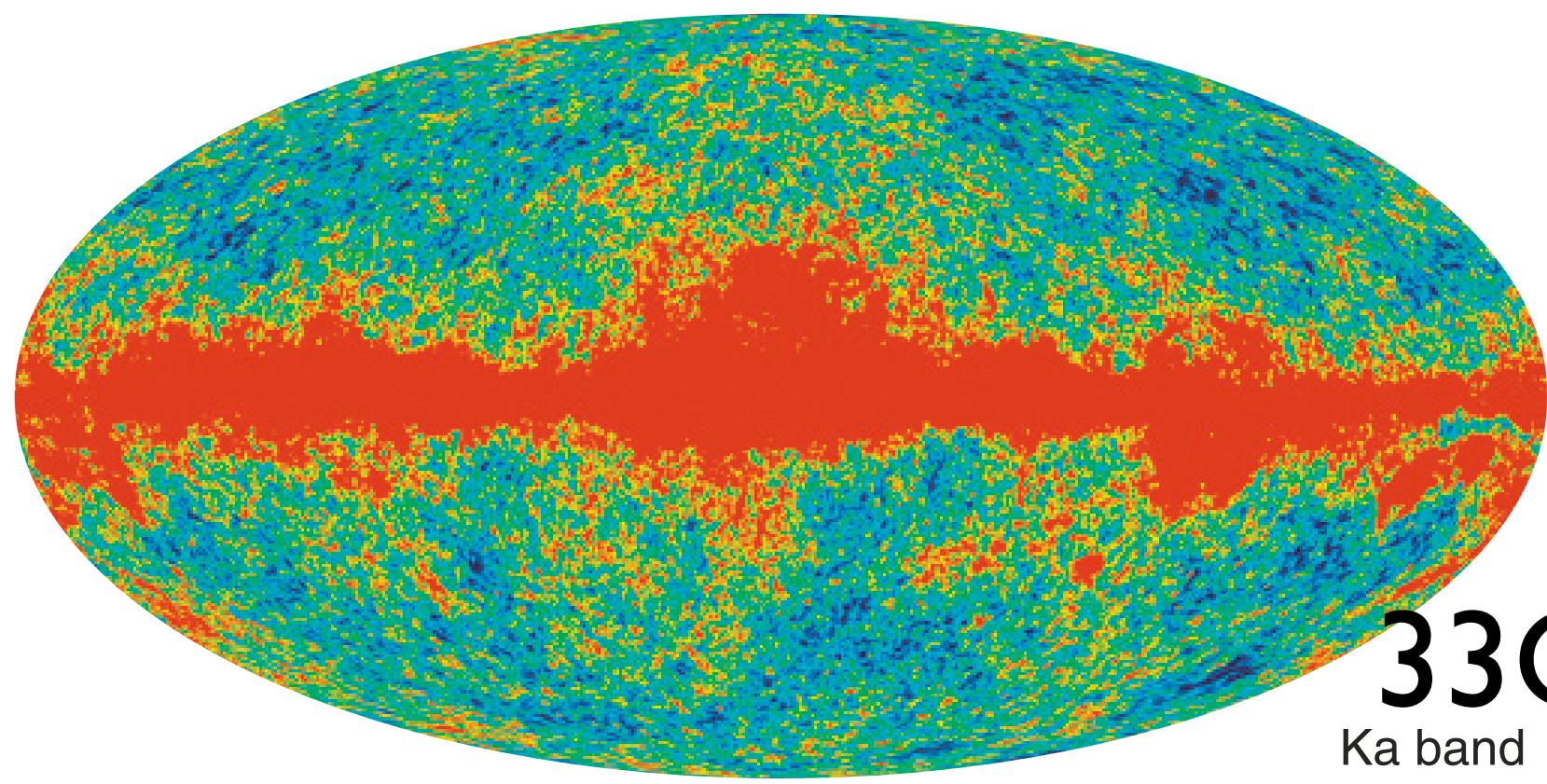
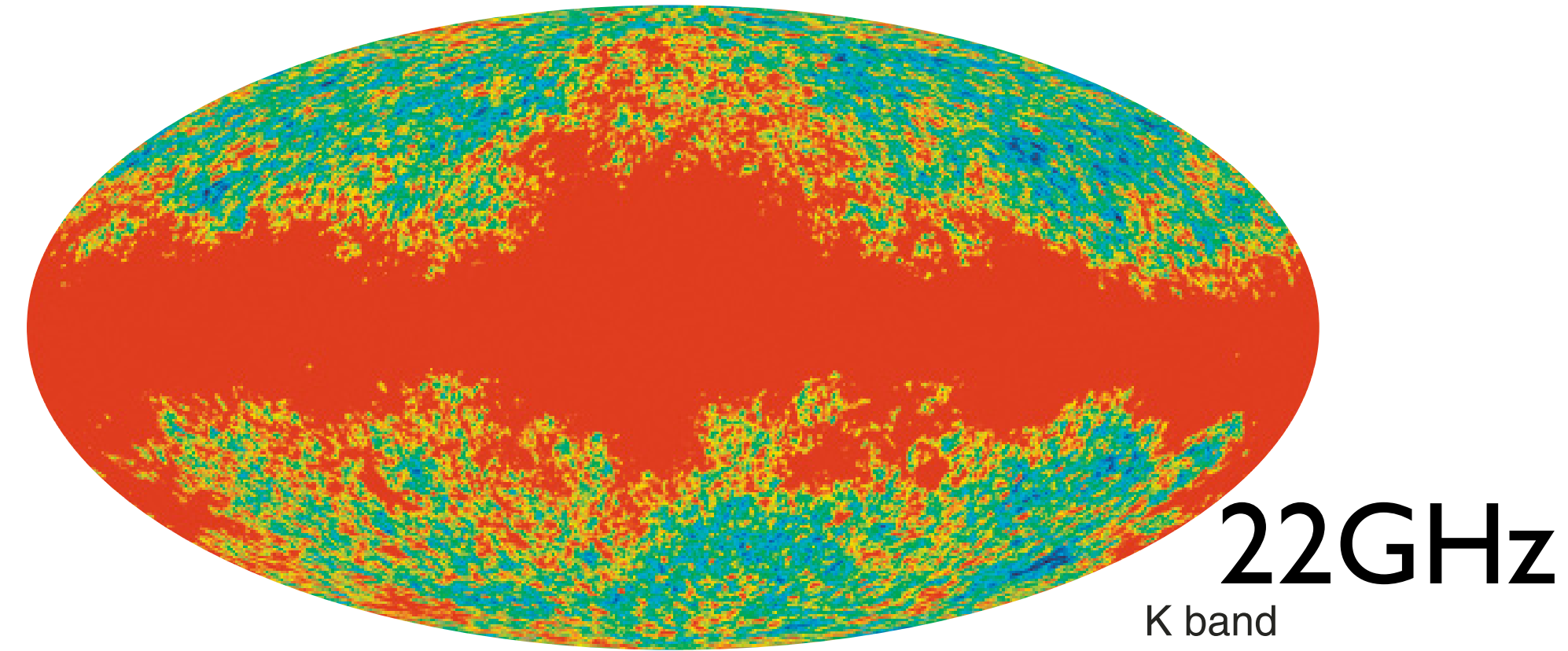
Universe composition



*“ScienceNews” article on  
the WMAP 7-year results*

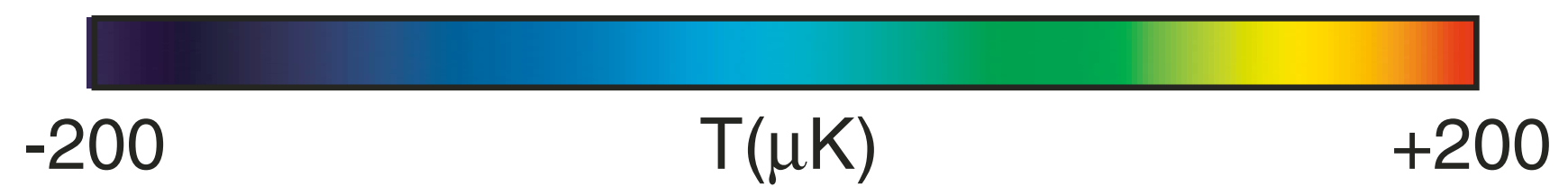
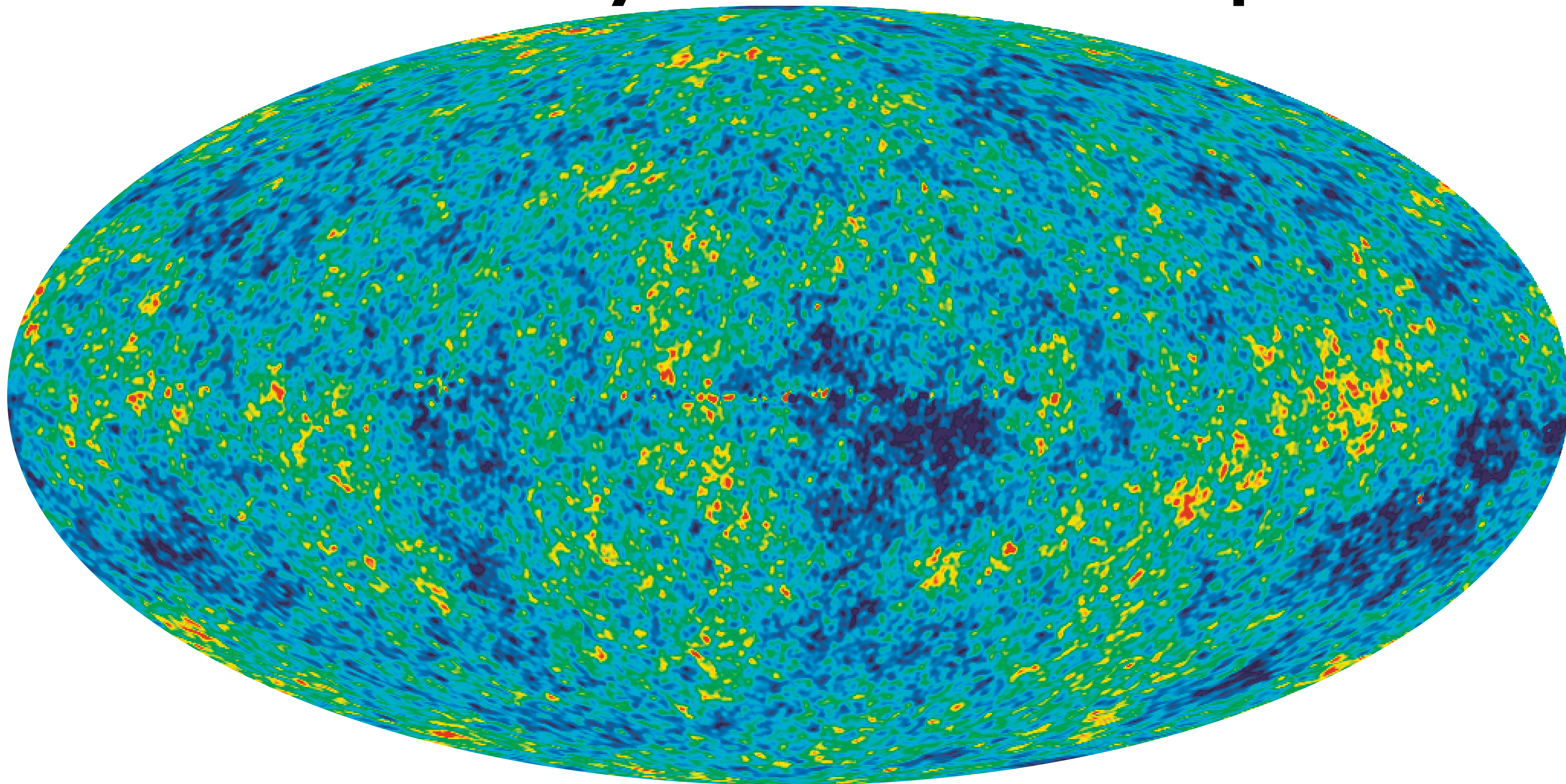
***How did we obtain these numbers?***

# Temperature Anisotropy (Unpolarized)





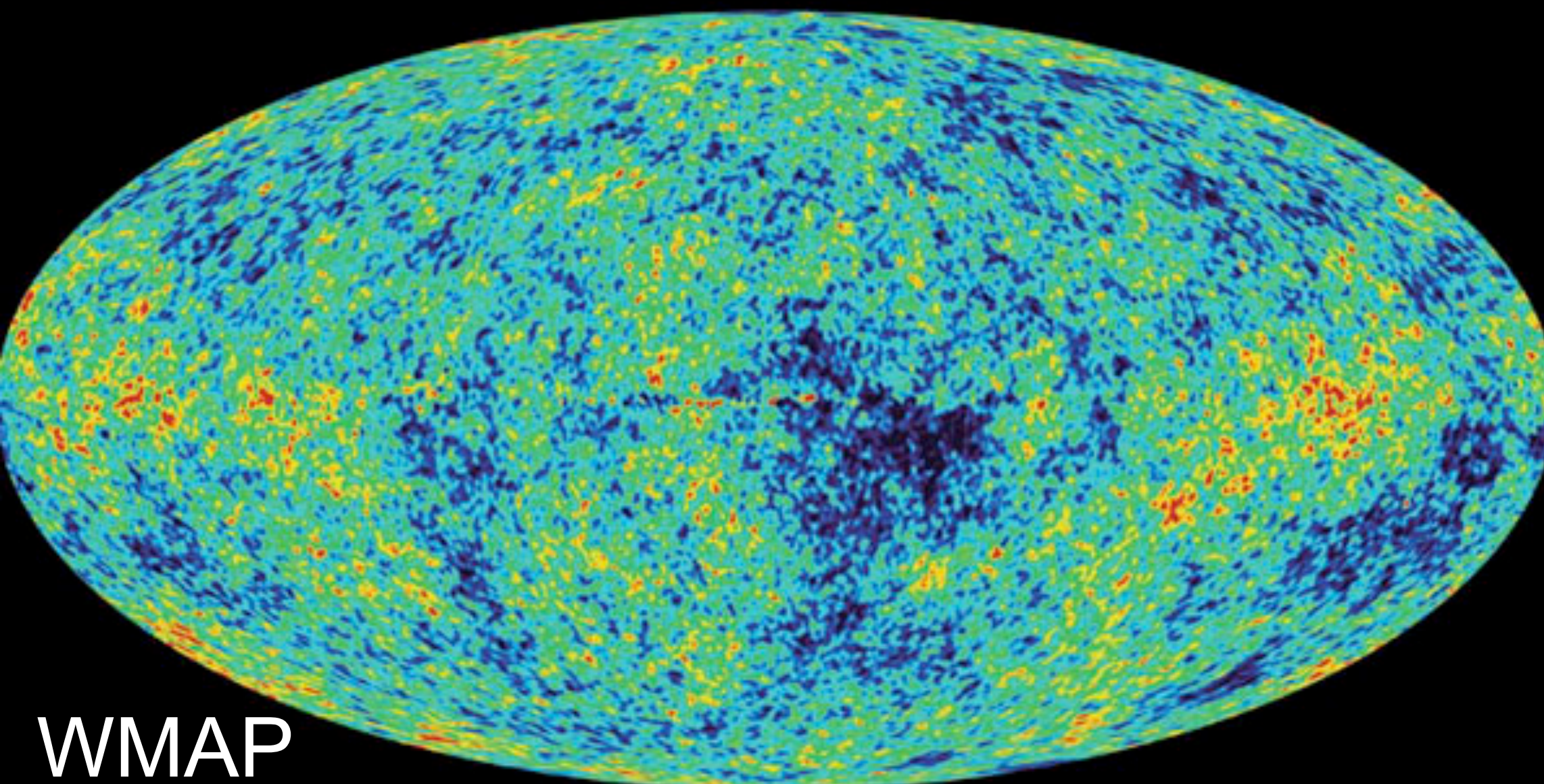
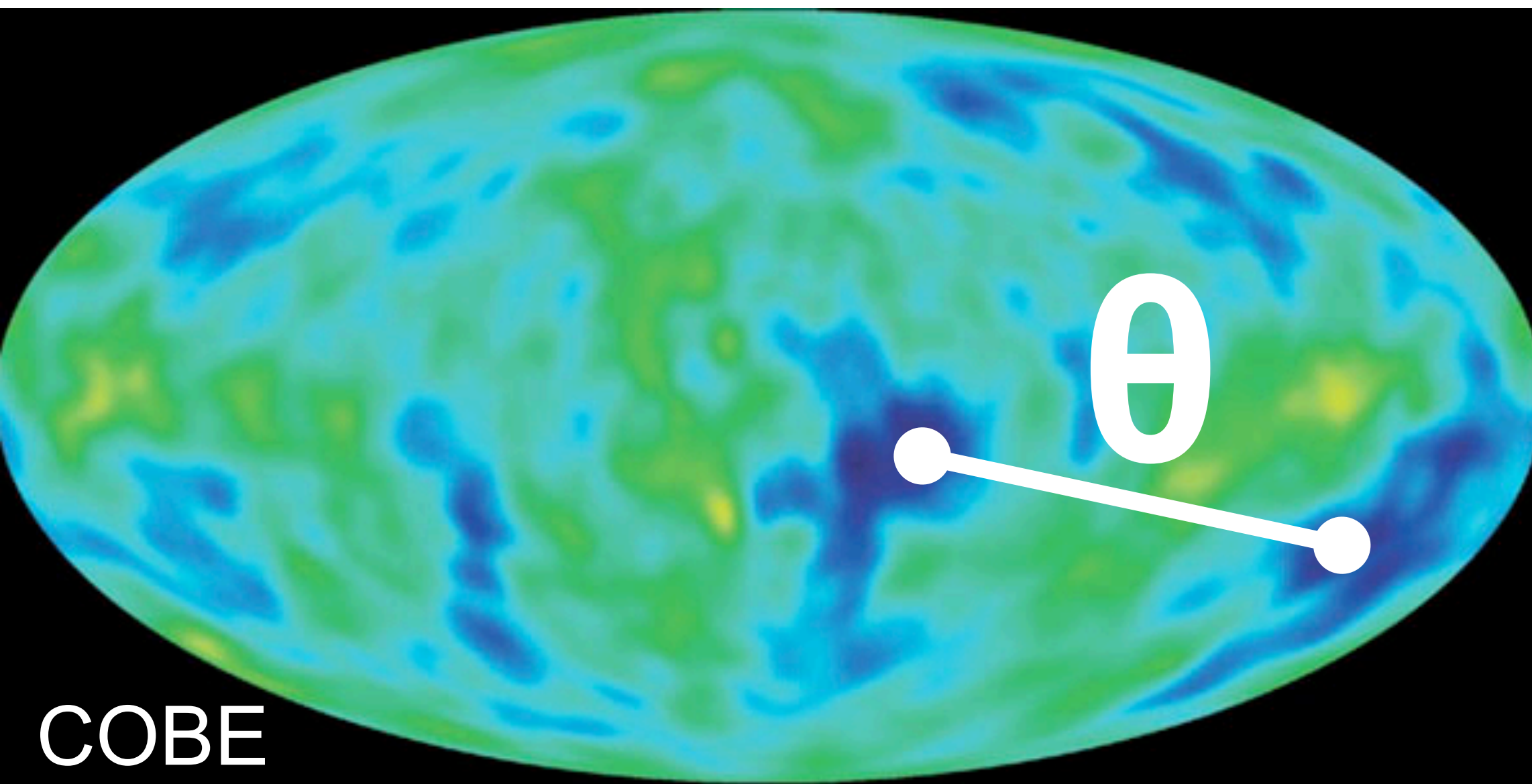
# Galaxy-cleaned Map



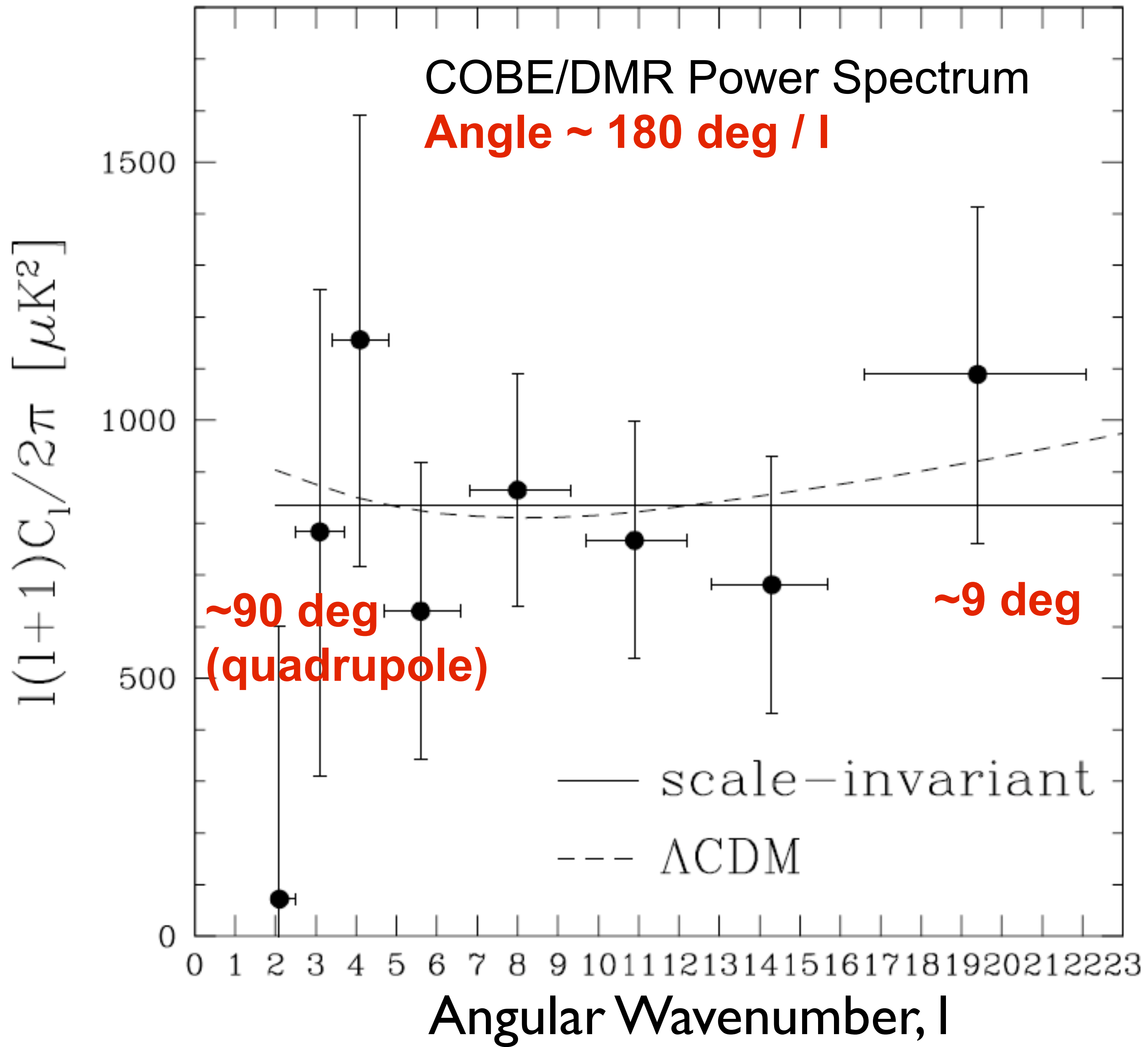


# Analysis: 2-point Correlation

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

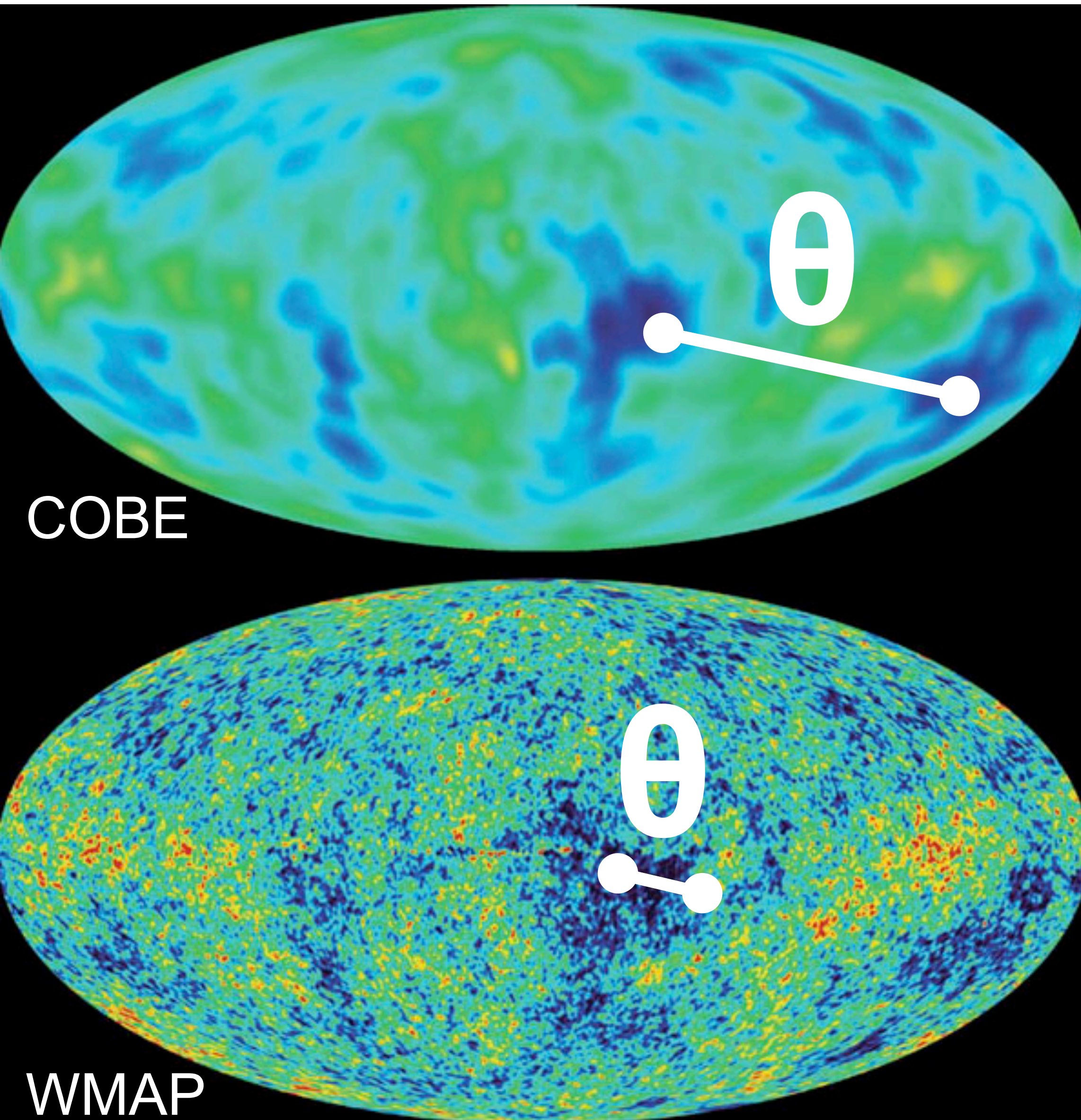








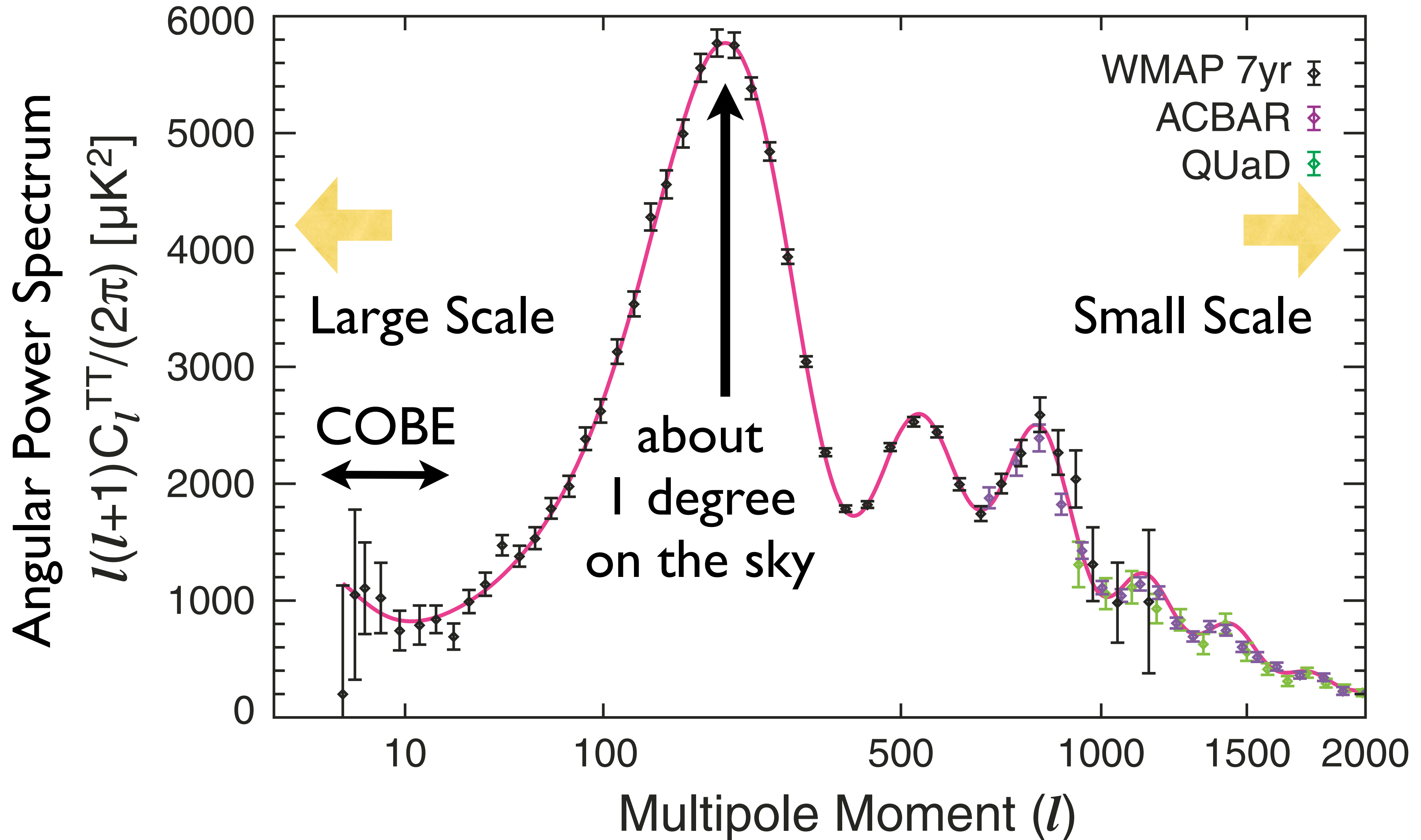
# COBE To WMAP



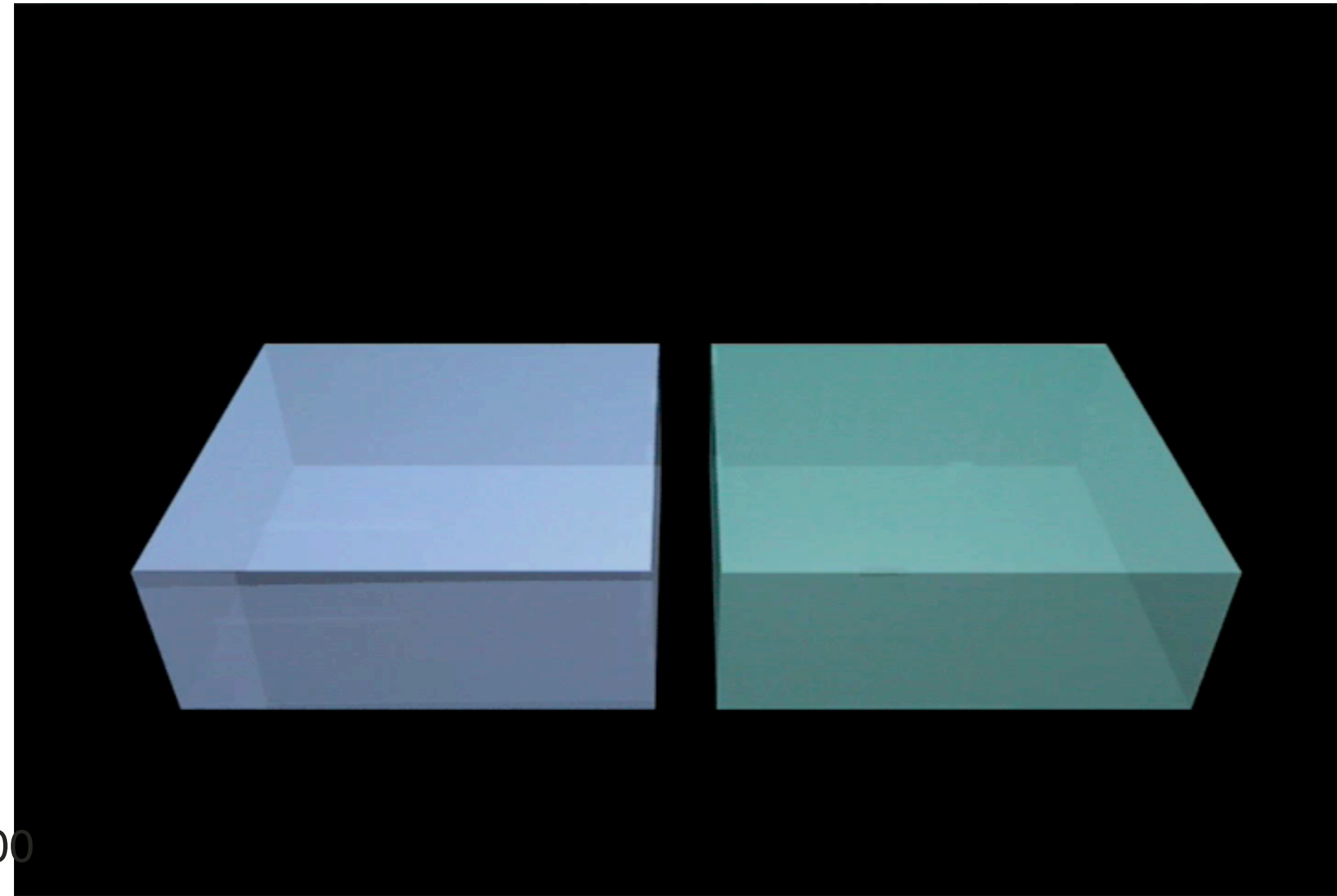
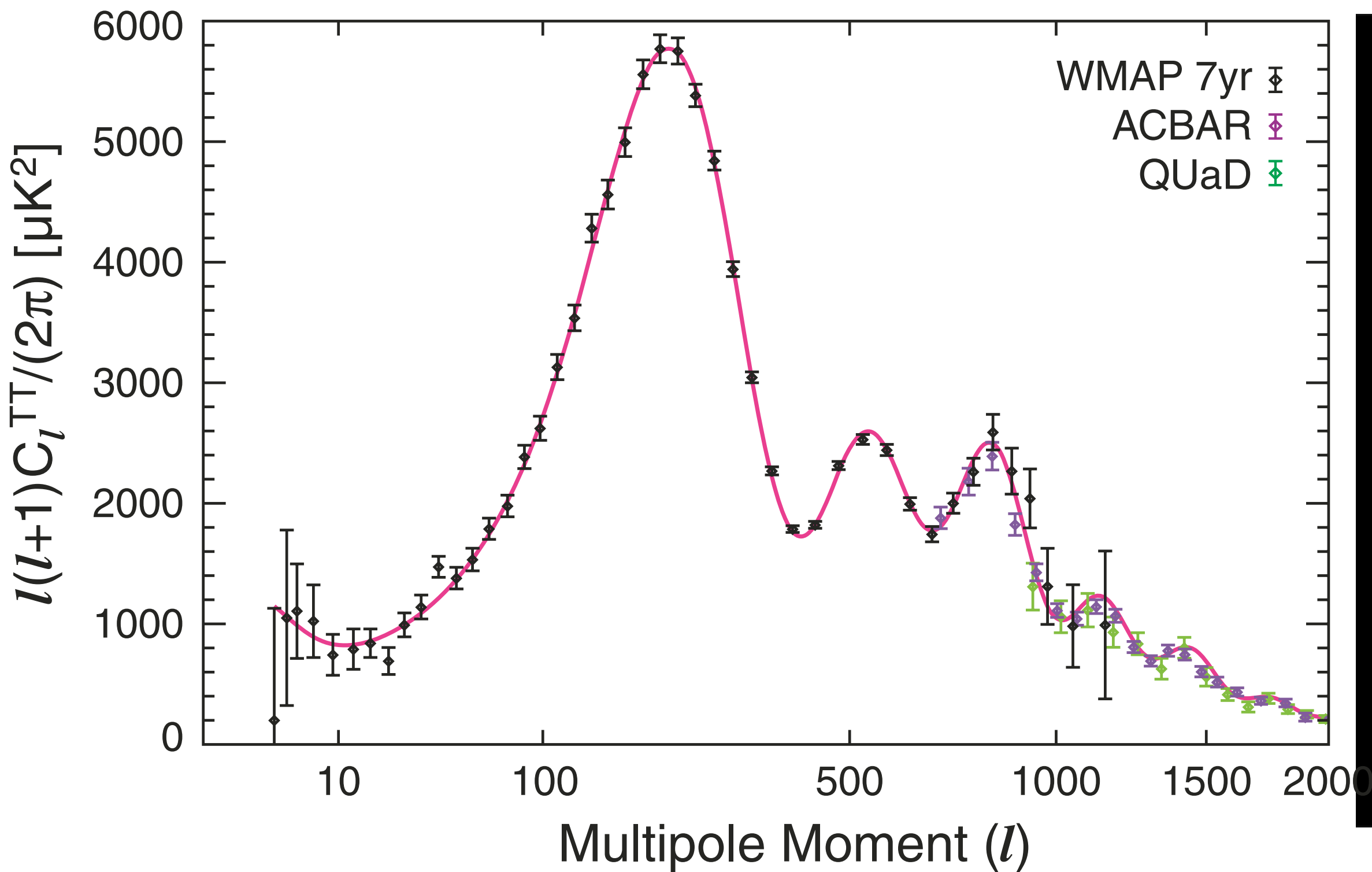
- COBE is unable to resolve the structures below  $\sim 7$  degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?



# WMAP Power Spectrum



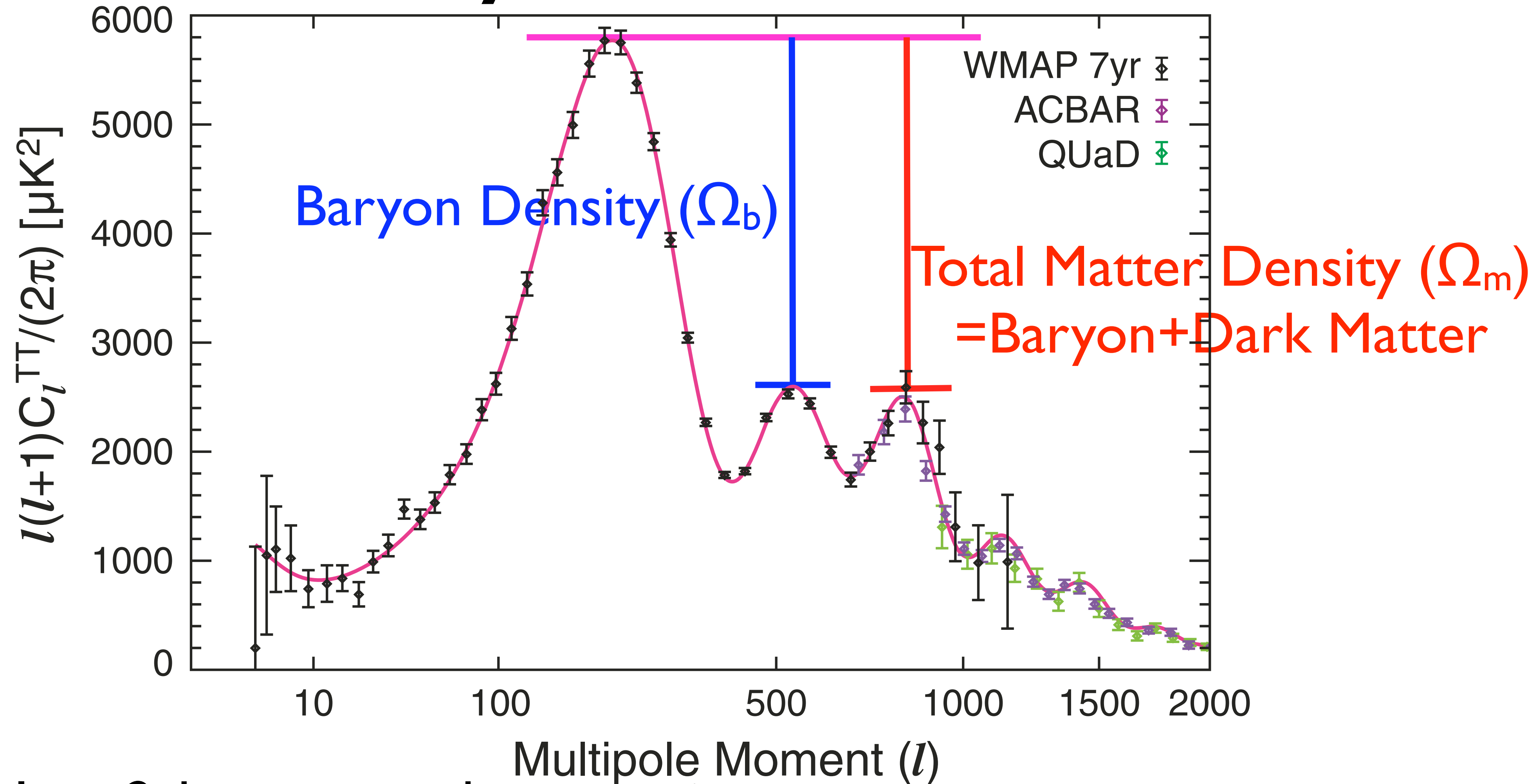
# The Cosmic Sound Wave



- “*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.

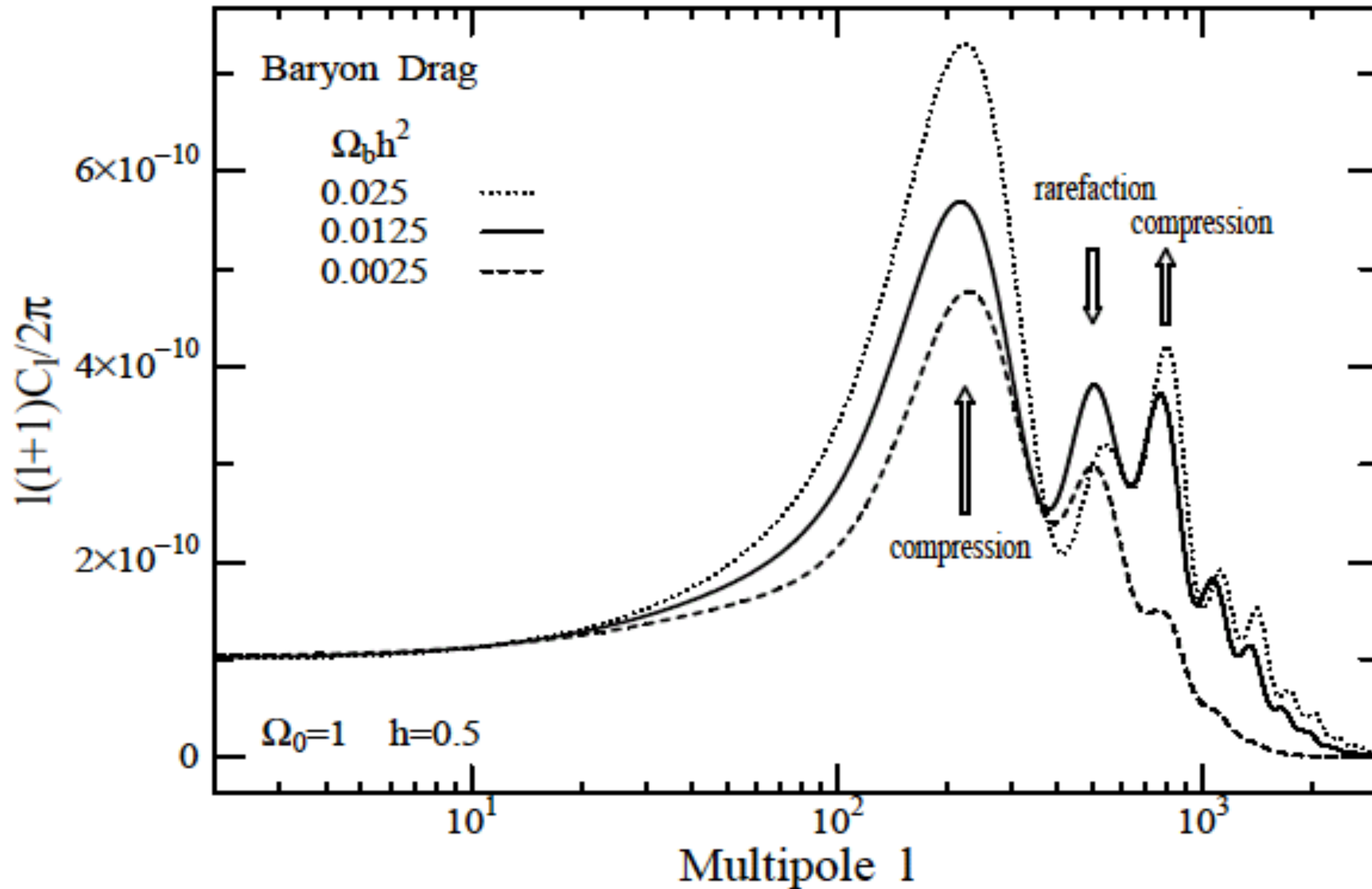


# CMB to Baryon & Dark Matter

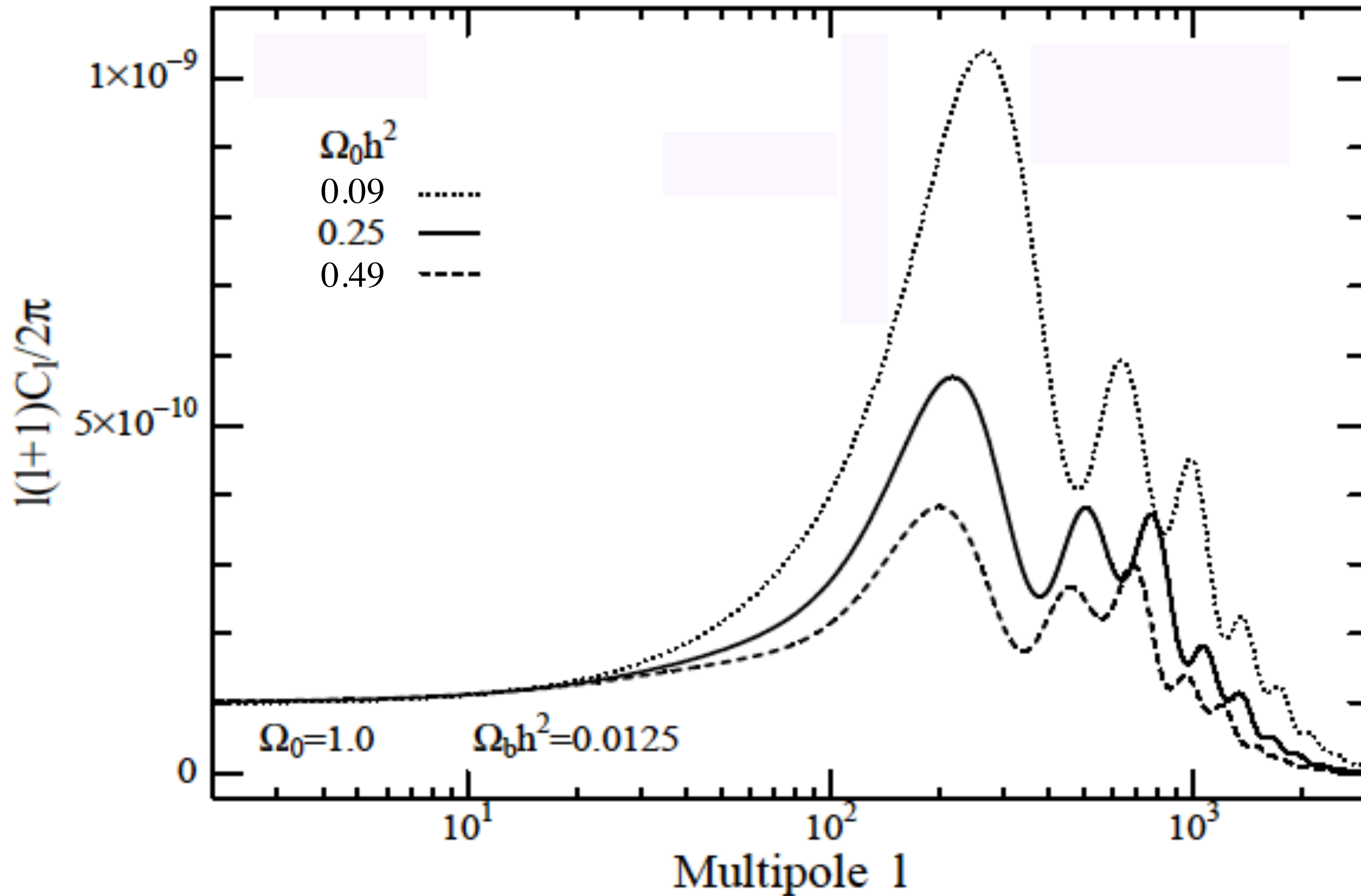


- $l$ -to-2: baryon-to-photon ratio
- $l$ -to-3: matter-to-radiation ratio ( $z_{\text{EQ}}$ : equality redshift)

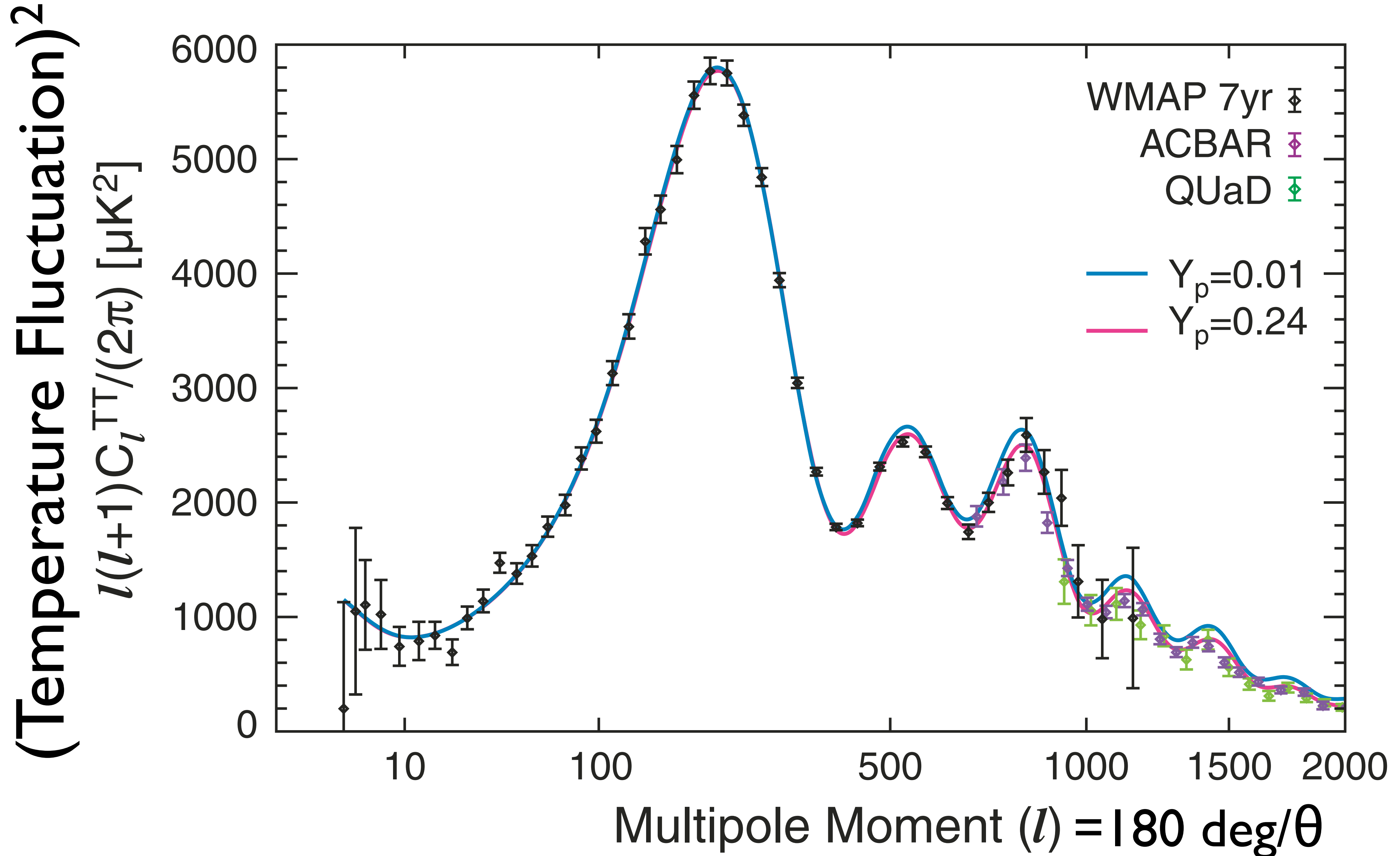
# Determining Baryon Density From $C_l$



# Determining Dark Matter Density From $C_l$



# Detection of Primordial Helium

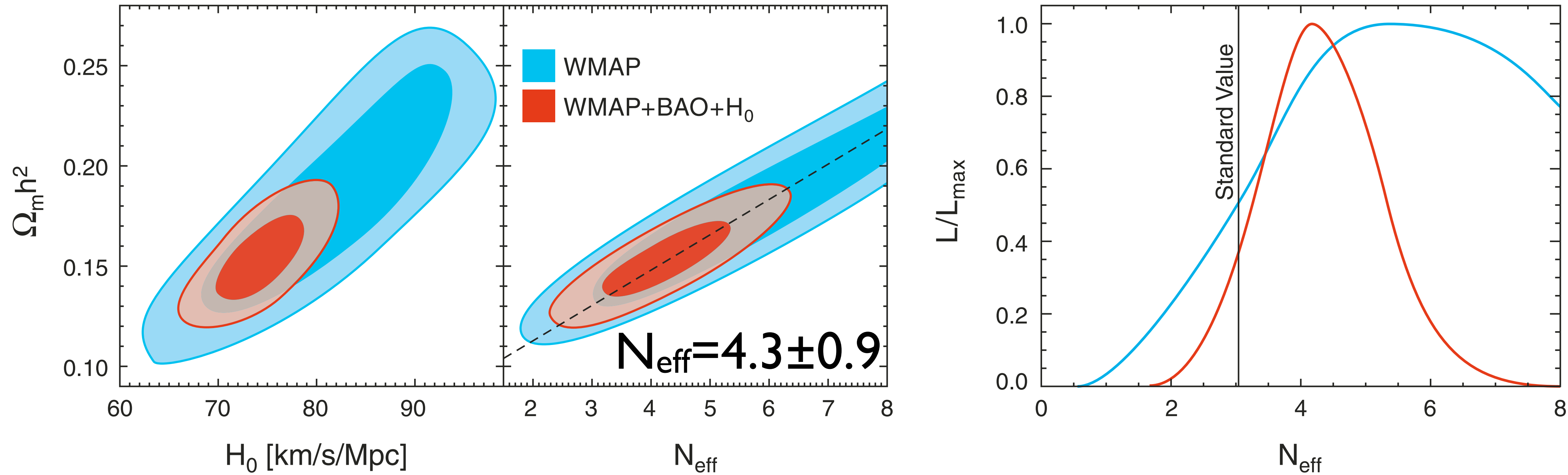


# Effect of helium on $C_l^{TT}$

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



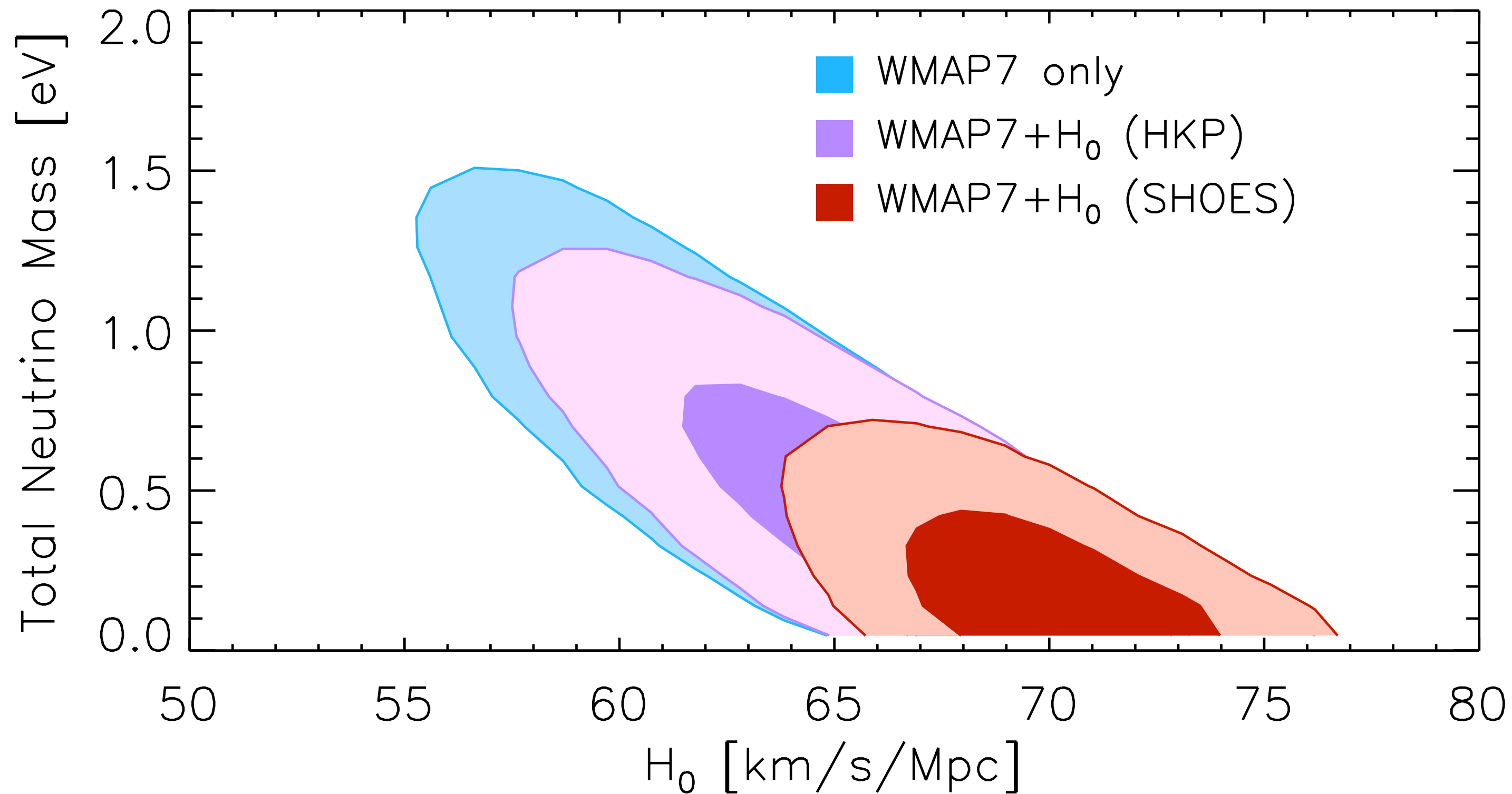
# Another “3rd peak science”: Number of Relativistic Species



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

← from external data
← from 3rd peak

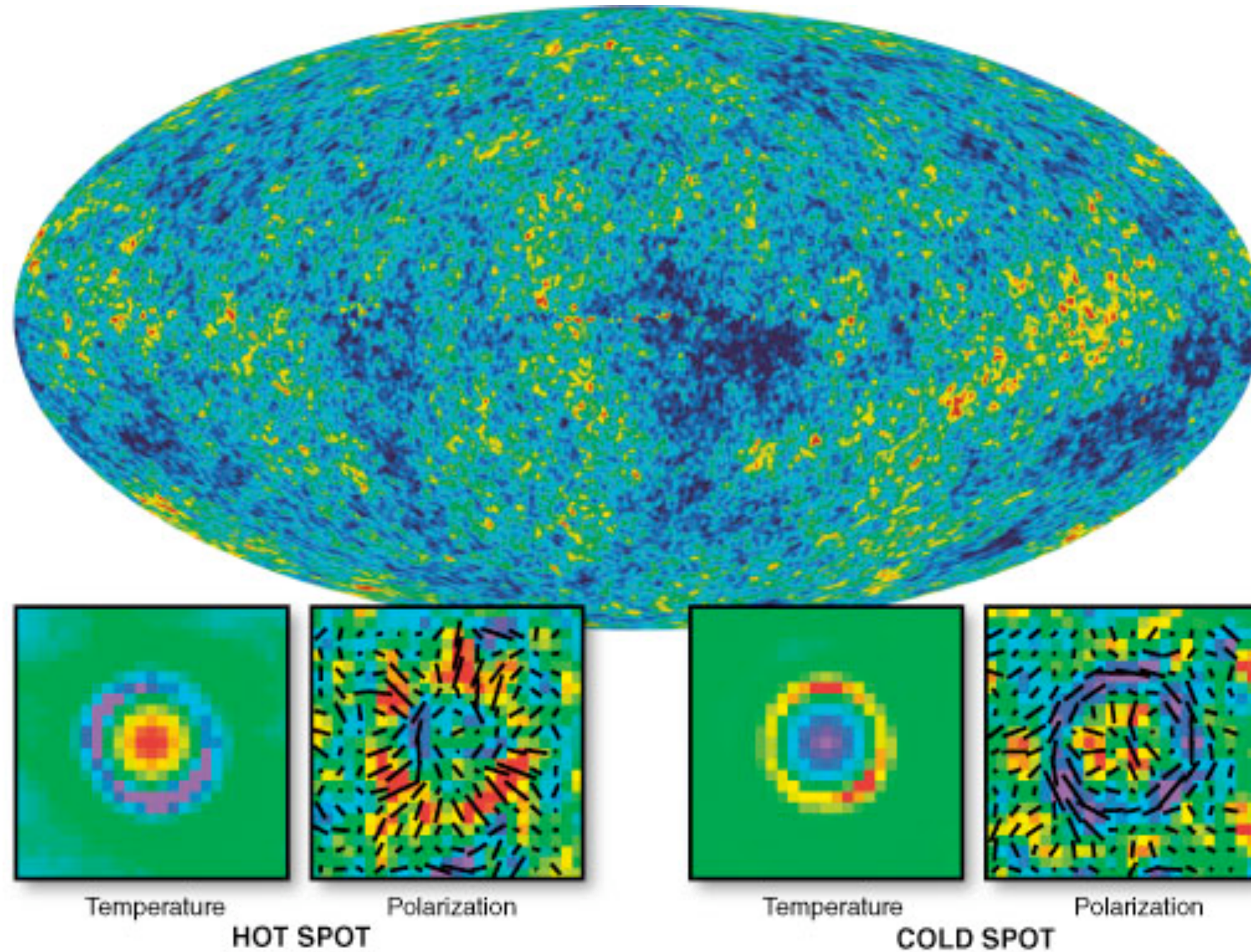
# And, the mass of neutrinos



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



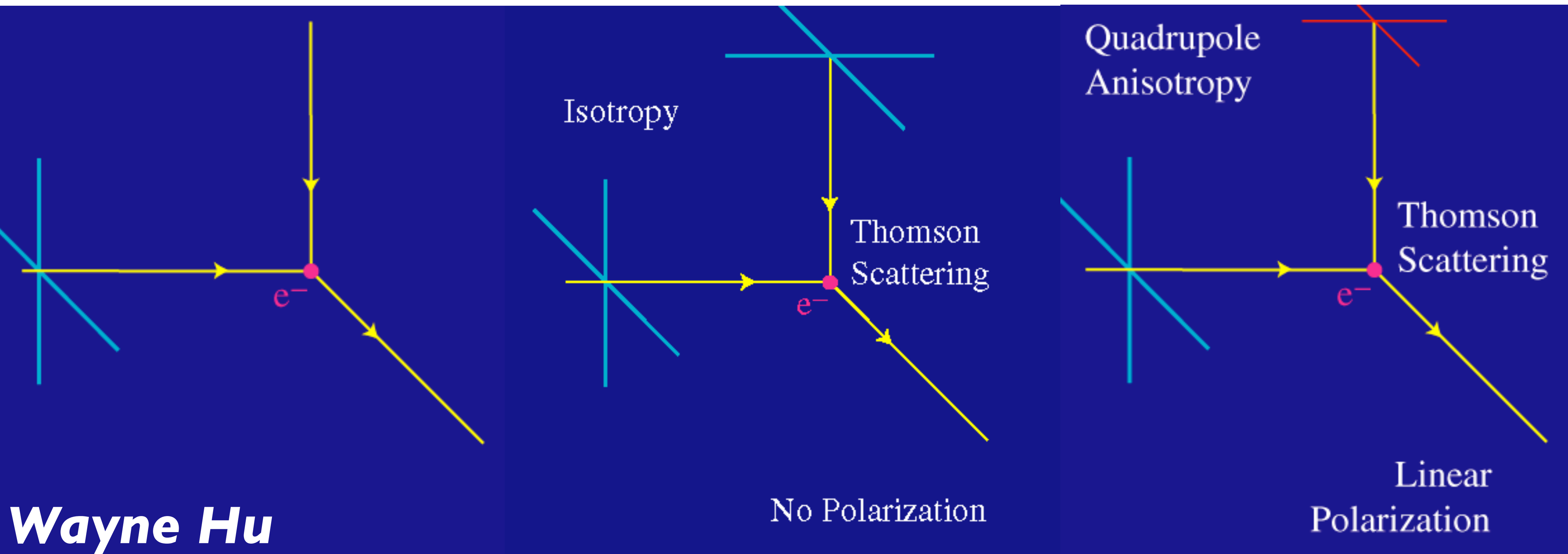
# CMB Polarization



- *CMB is (very weakly) polarized!*

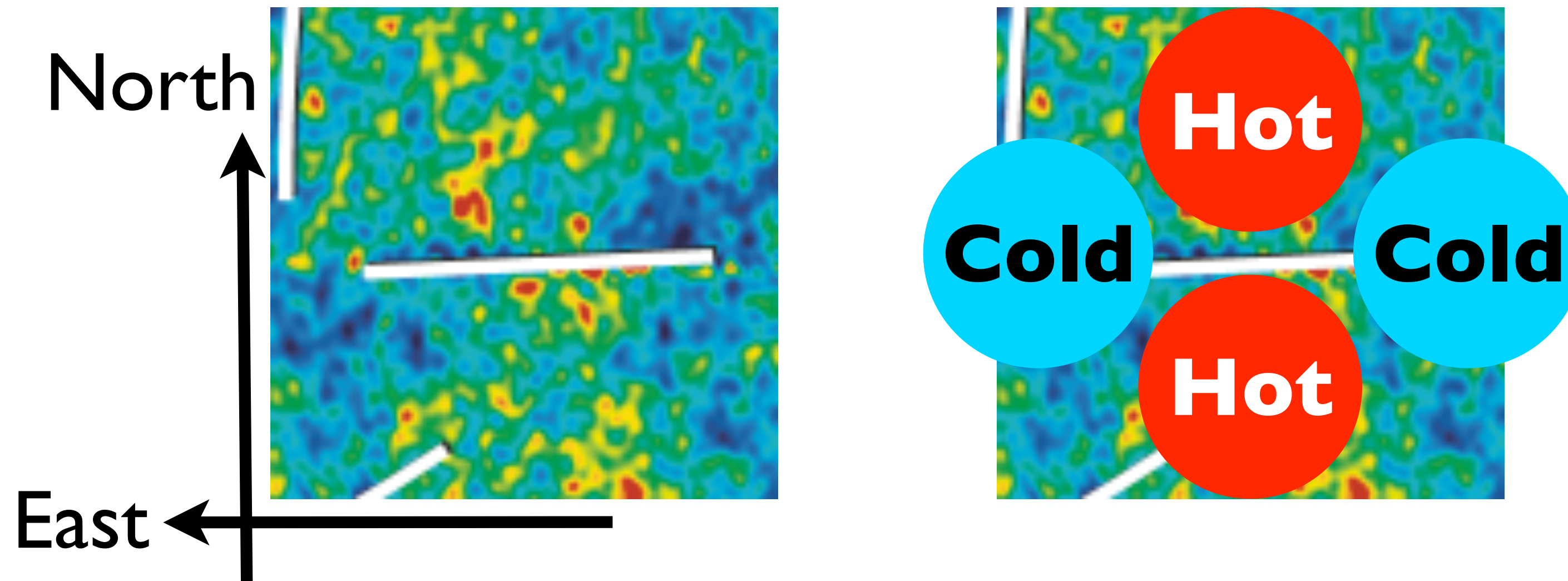


# Physics of CMB Polarization



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

# Principle



- **Polarization direction is parallel to “hot.”**
- This is the so-called “E-mode” polarization.

# CMB Polarization on Large Angular Scales ( $>2$ deg)

Matter Density



Potential

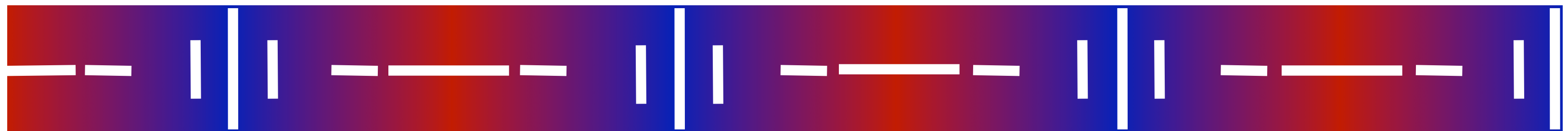


$$\Delta T/T = (\text{Newton's Gravitation Potential})/3$$

$\Delta T$



Polarization

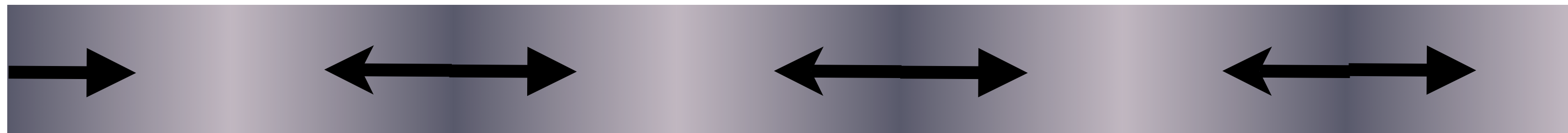


- How does the photon-baryon plasma move?

# CMB Polarization Tells Us How Plasma Moves at $z=1090$

*Zaldarriaga & Harari (1995)*

Matter Density

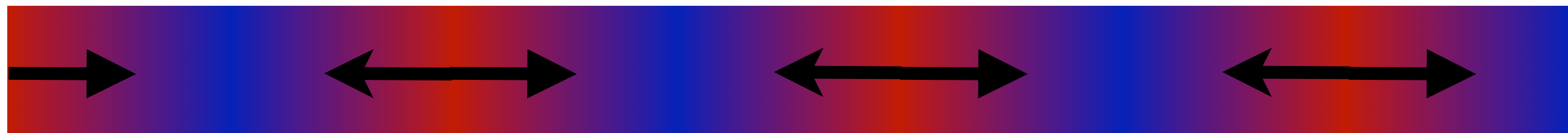


Potential

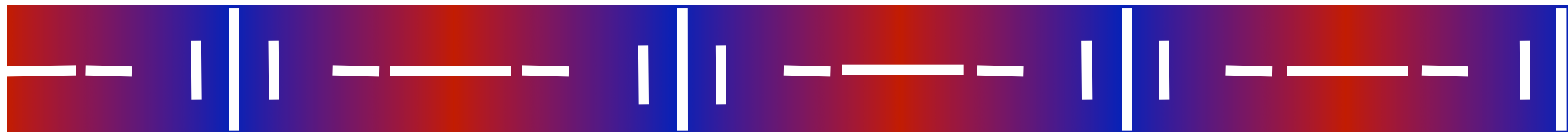


$$\Delta T/T = (\text{Newton's Gravitation Potential})/3$$

$\Delta T$



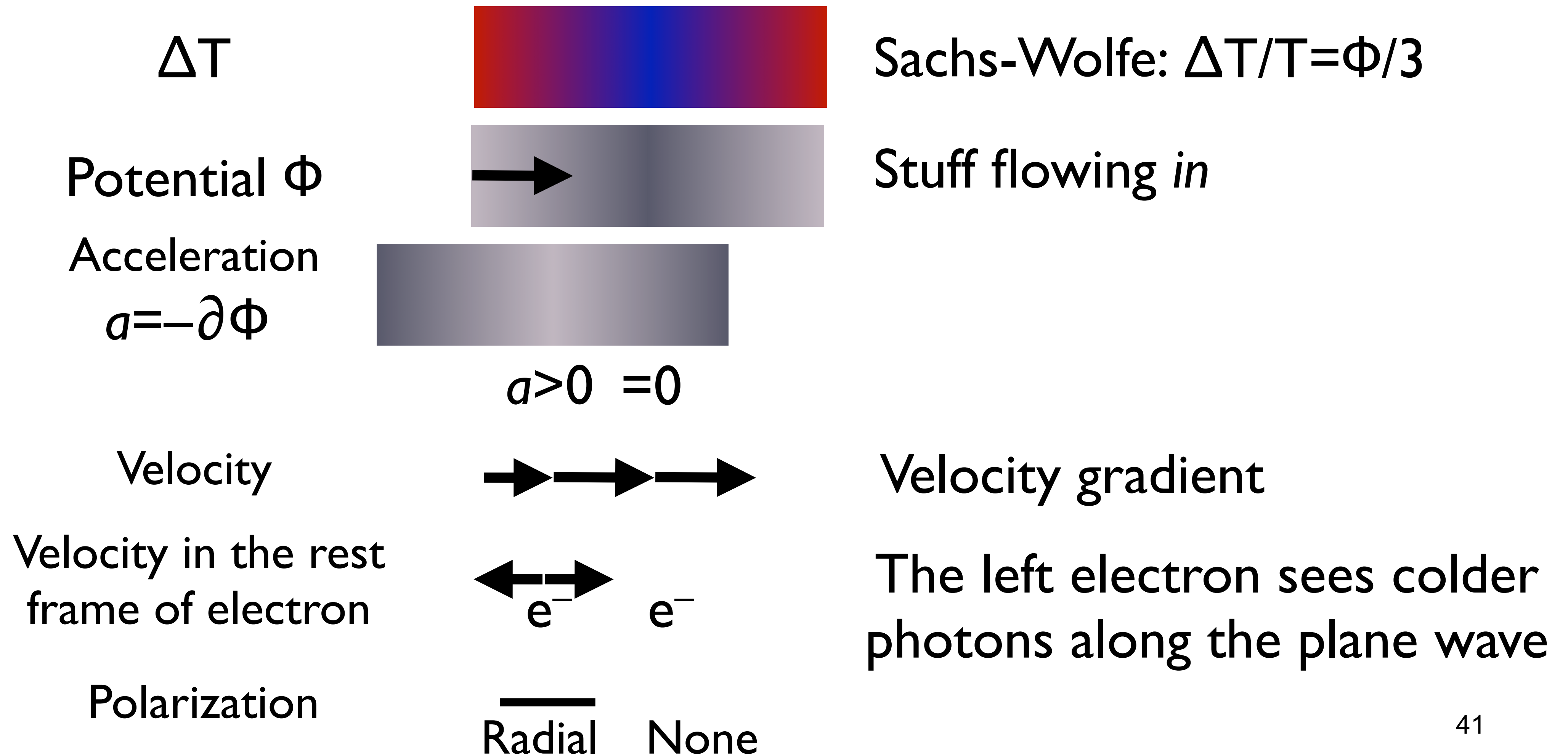
Polarization



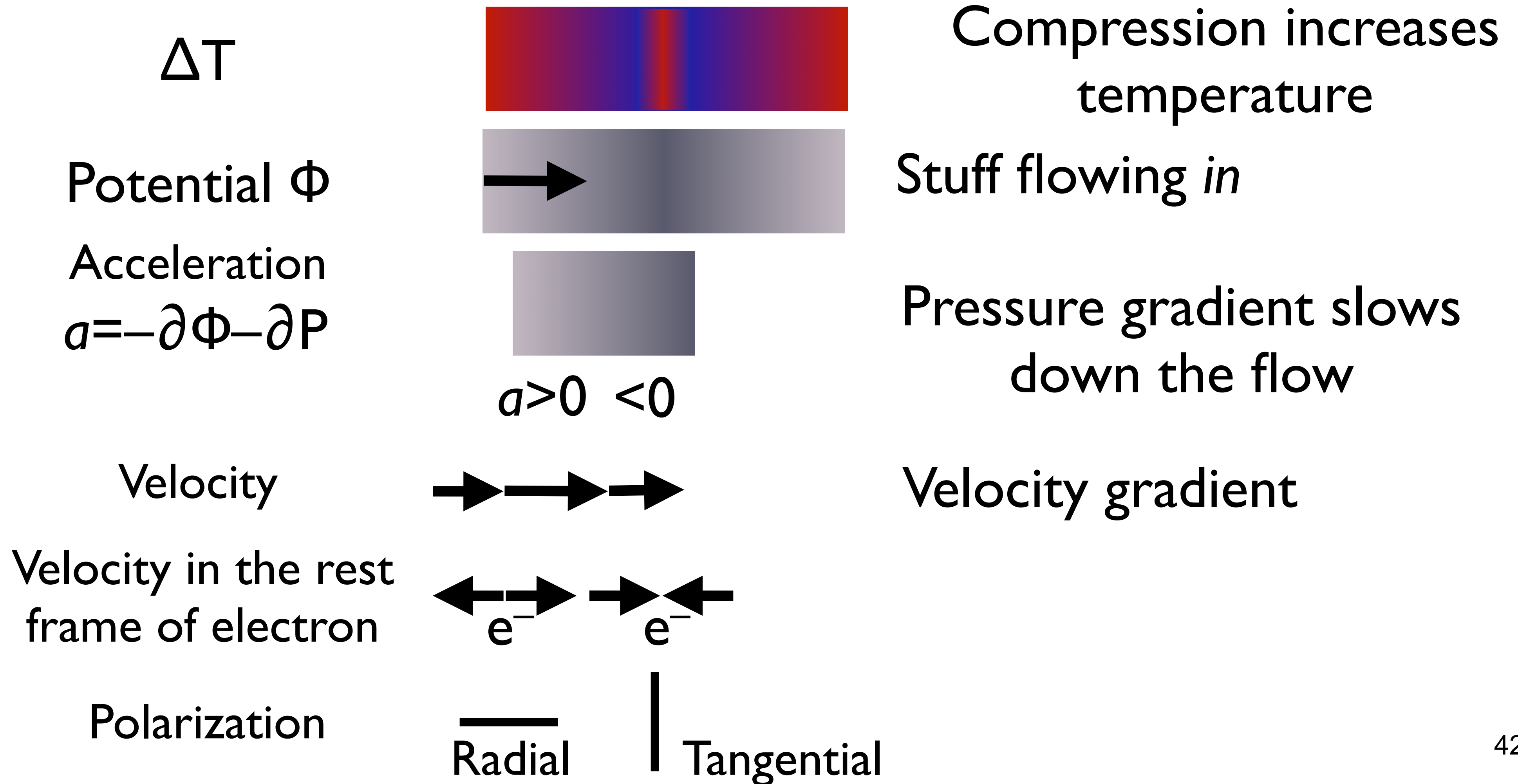
- Plasma **falling into** the gravitational potential well = **Radial** polarization pattern



# Quadrupole From Velocity Gradient (Large Scale)



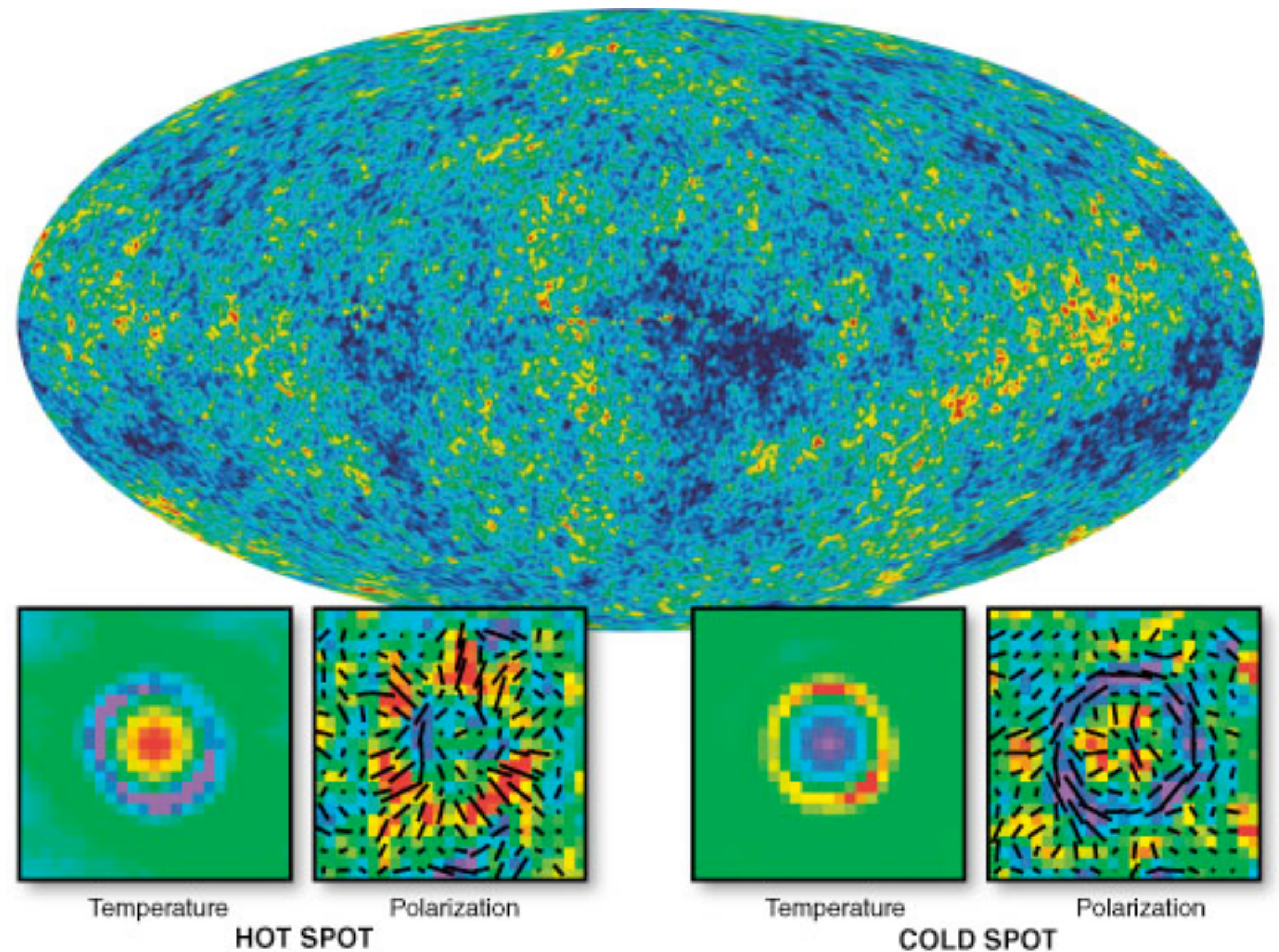
# Quadrupole From Velocity Gradient (Small Scale)





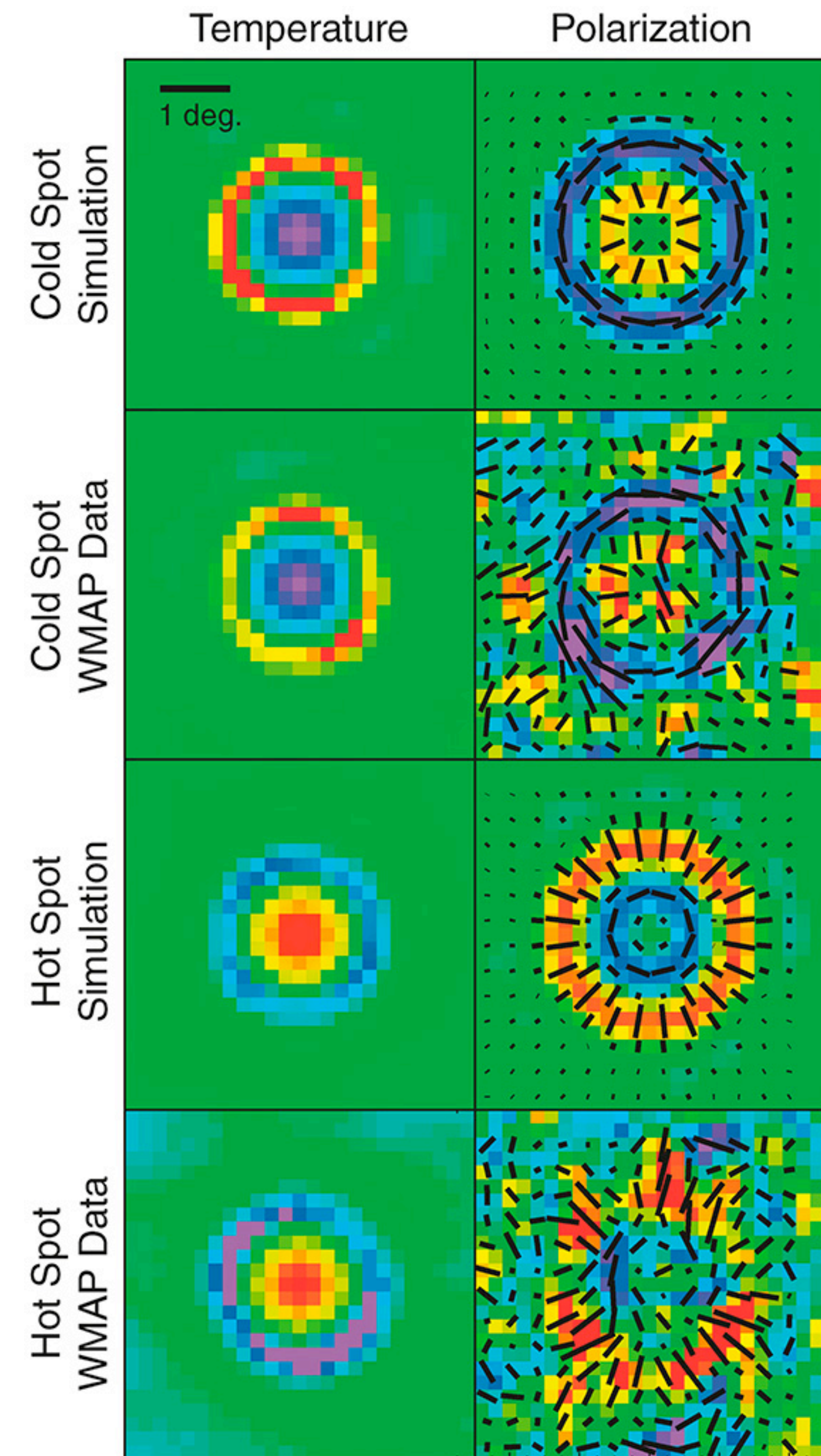
# Stacking Analysis

- 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**.



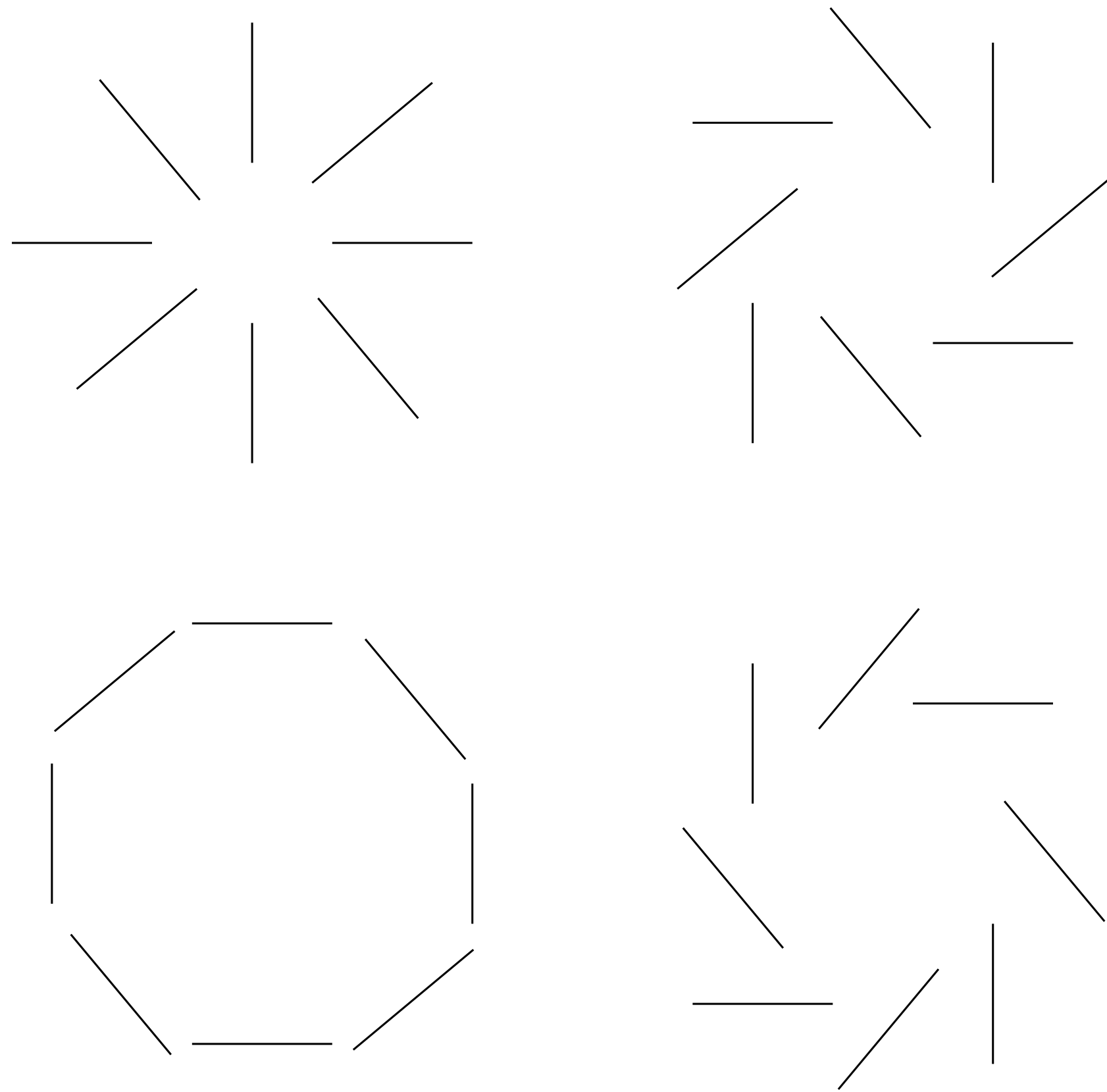


# Two-dimensional View



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

# 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!



# E-mode

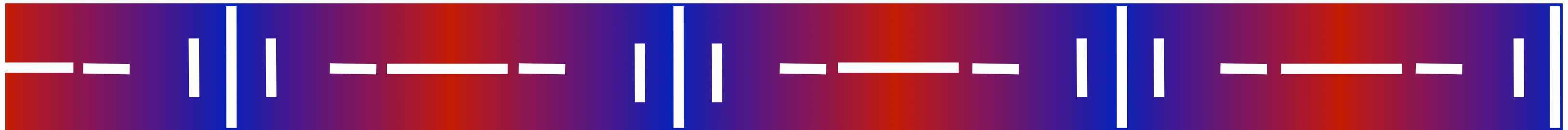
Potential



$$\Phi(\mathbf{k}, \mathbf{x}) = \cos(\mathbf{kx})$$

→  
Direction of a plane wave

Polarization  
Direction



- **E-mode**: the polarization directions are either parallel or tangential to the direction of the plane wave perturbation.

# B-mode

G.W.



$$h(\mathbf{k}, \mathbf{x}) = \cos(\mathbf{kx})$$

→  
Direction of a plane wave

Polarization  
Direction

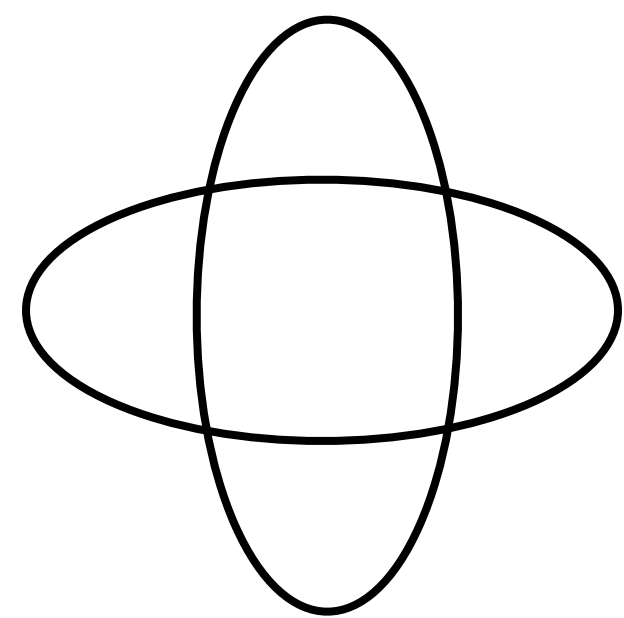


- **B-mode**: the polarization directions are tilted by 45 degrees relative to the direction of the plane wave perturbation.

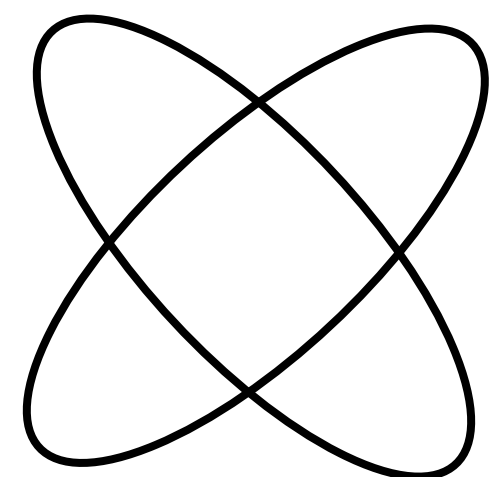
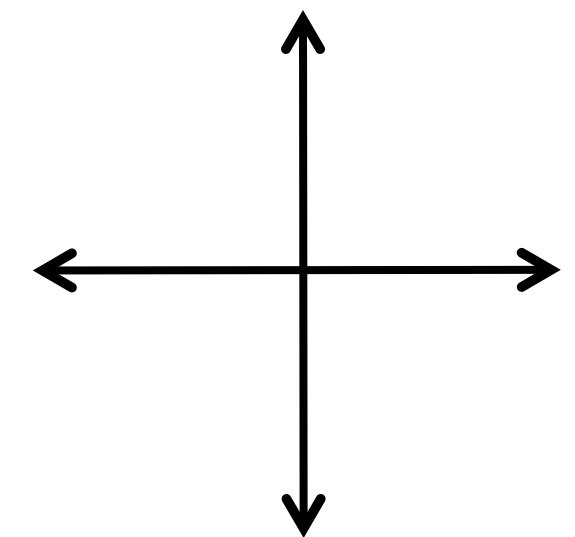
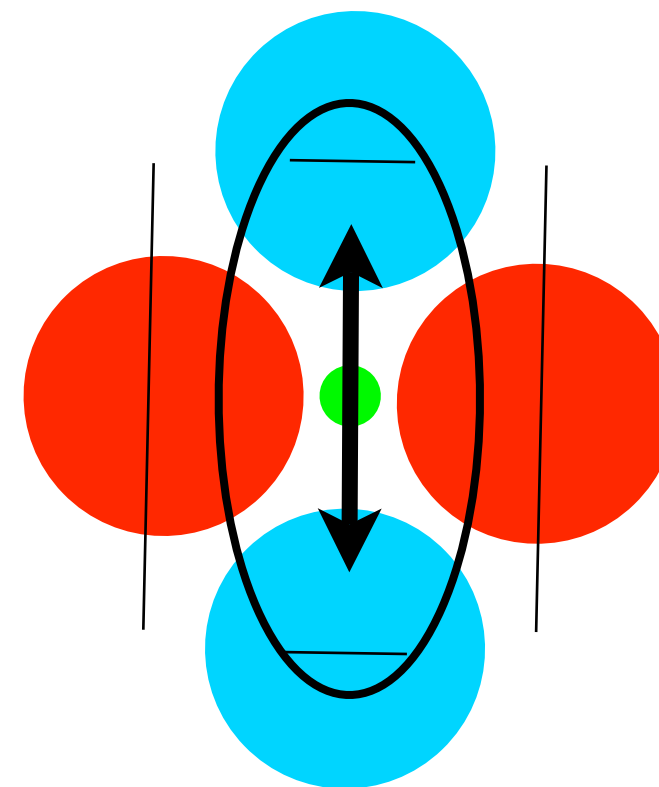
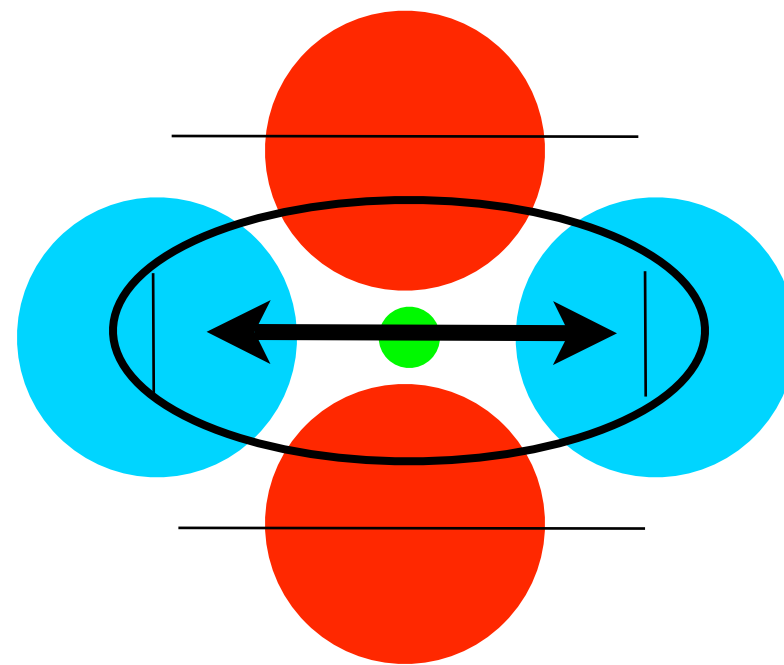


# Gravitational Waves and Quadrupole

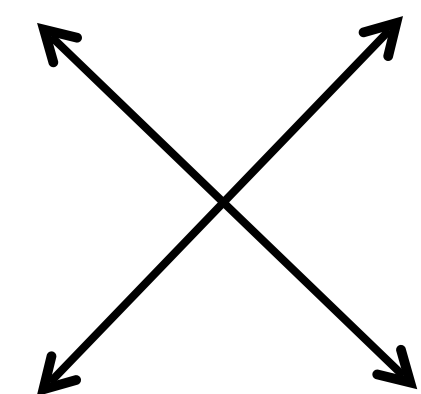
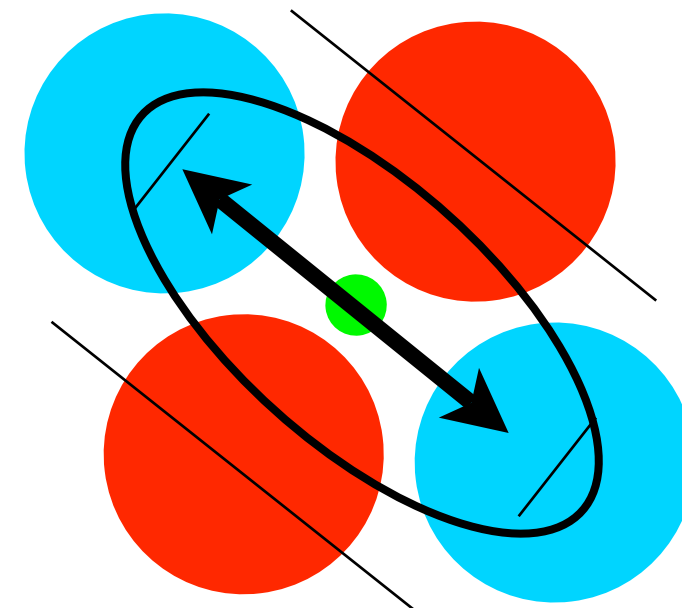
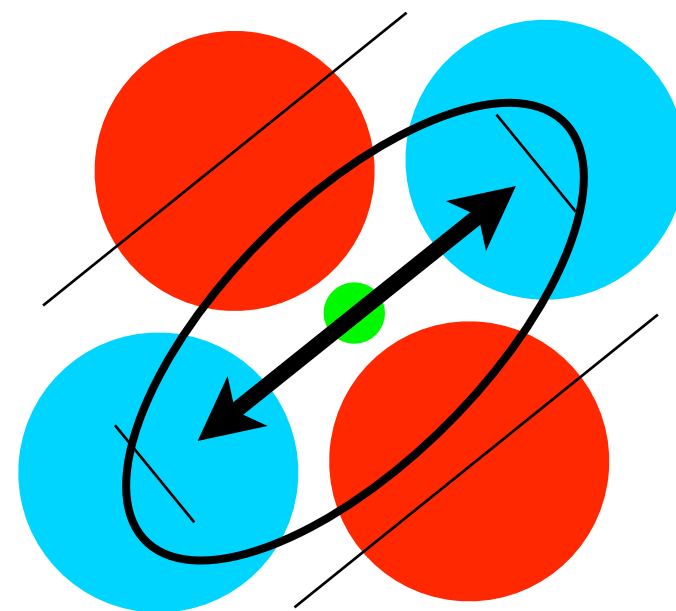
- Gravitational waves stretch space with a quadrupole pattern.



“+ mode”



“X mode”



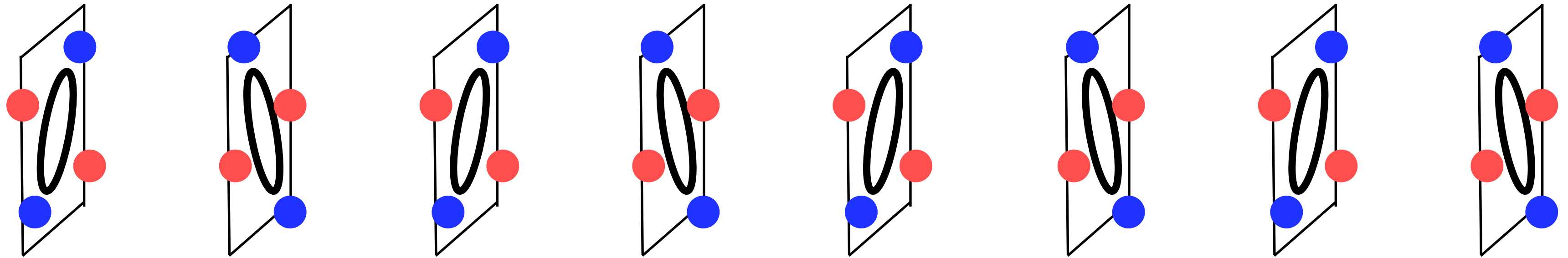
# Quadrupole from G.W.

$$h(\mathbf{k}, \mathbf{x}) = \cos(\mathbf{kx})$$

Direction of the plane wave of G.W.



$h_x$



temperature



polarization



**B-mode**

- B-mode polarization generated by  $h_x$



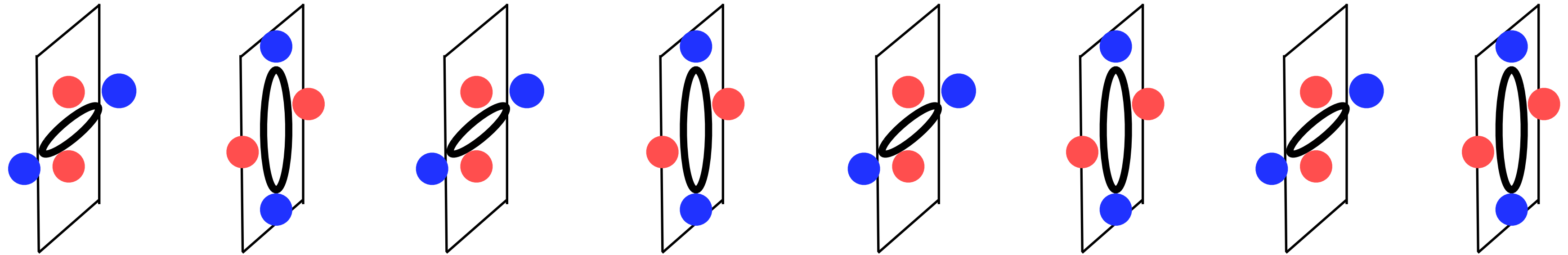
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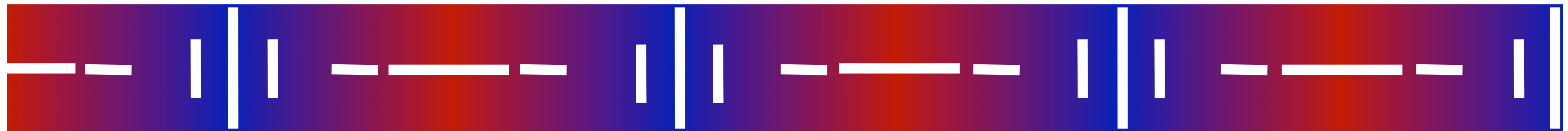
$h_+$



temperature



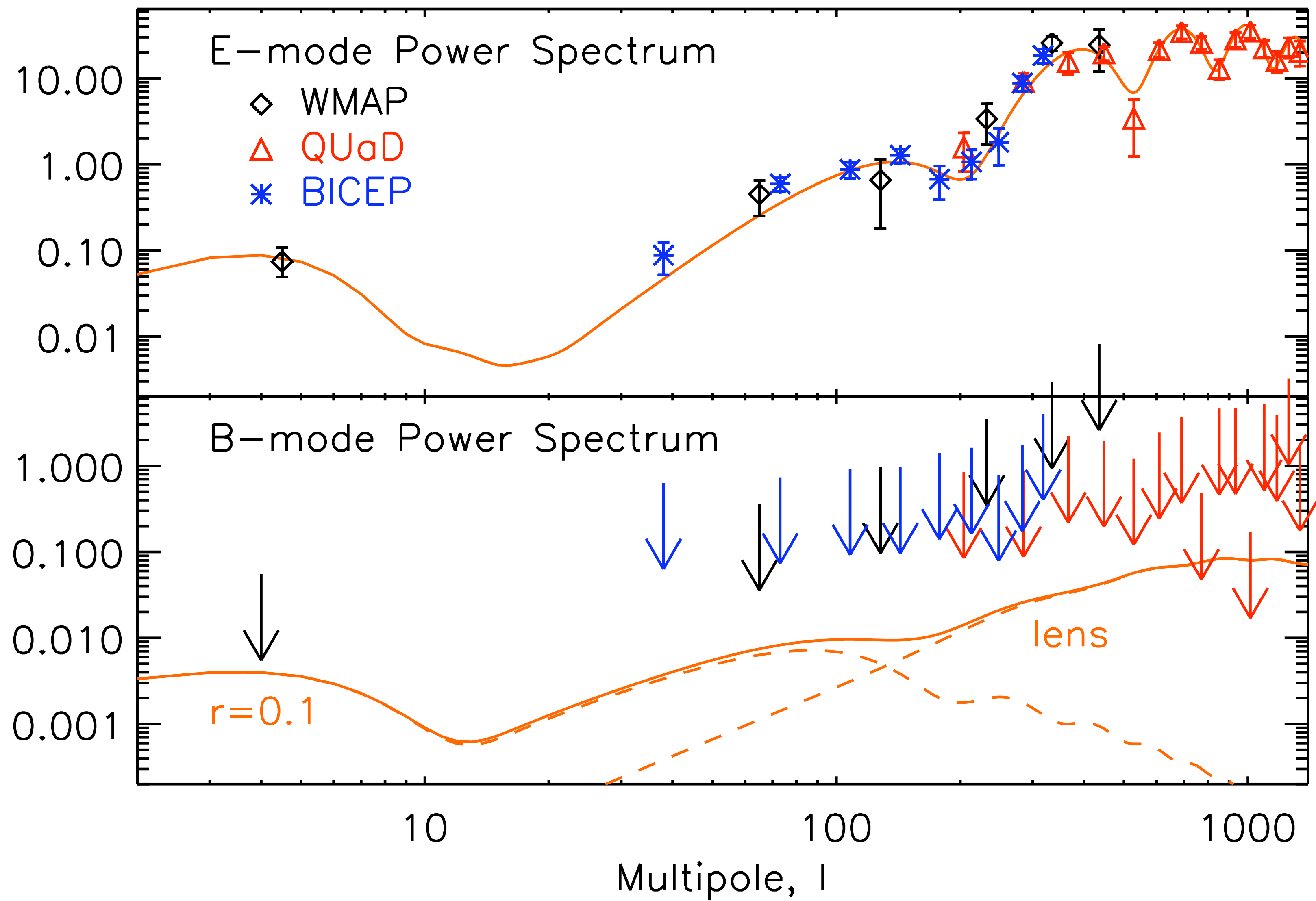
polarization



E-mode

- E-mode polarization generated by  $h_+$

# Polarization Power Spectrum



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

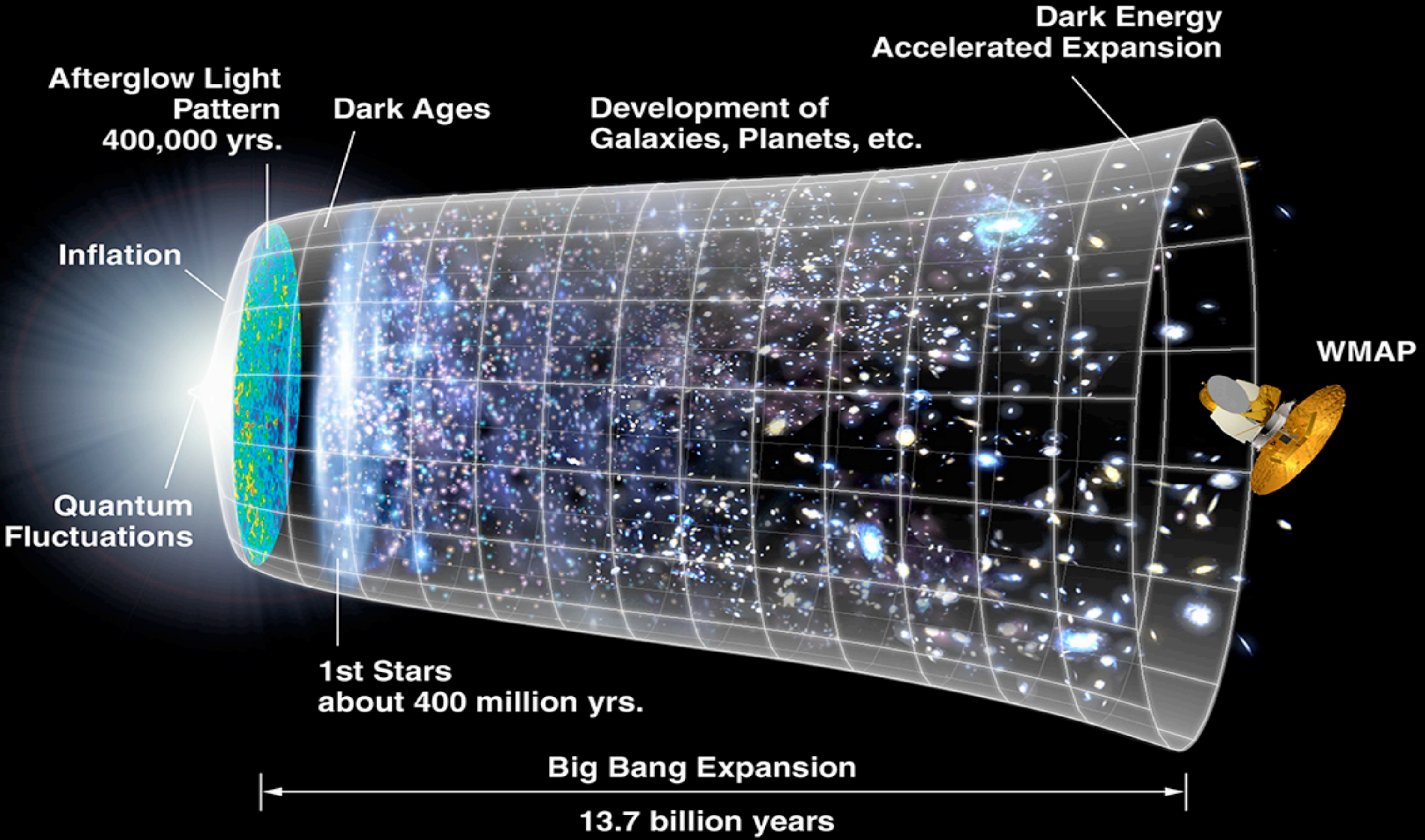


# Theory of the Very Early Universe

- 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 ( $\sim 10^{-15}\text{m}$ ) would be stretched to 1 A.U. ( $\sim 10^{11}\text{m}$ ), at least.



# Cosmic Inflation = Very Early Dark Energy





# 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.
- This is the so-called Heisenberg's Uncertainty Principle, which is the foundation of Quantum Mechanics.



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

# (Scalar) Quantum Fluctuations

$$\delta\varphi = (\text{Expansion Rate})/(2\pi) \text{ [in natural units]}$$

- 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)  $\sim 1/(\text{Time})$ 
    - which is a big number! ( $\sim 10^{12}\text{GeV}$ )
- *Quantum fluctuations were important during inflation!*

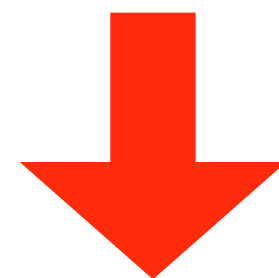
# Stretching Micro to Macro

Macroscopic size at which gravity becomes important

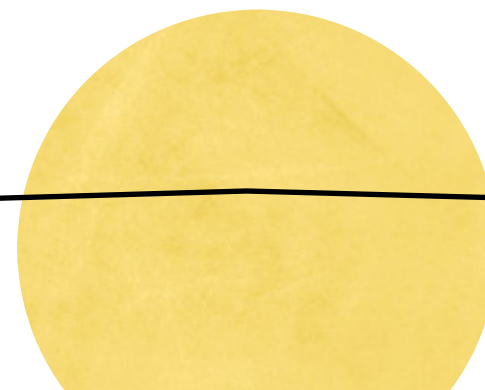


$\delta\varphi$

Quantum fluctuations on microscopic scales



**INFLATION!**



$\delta\varphi$

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.

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

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

[h = “strain”]

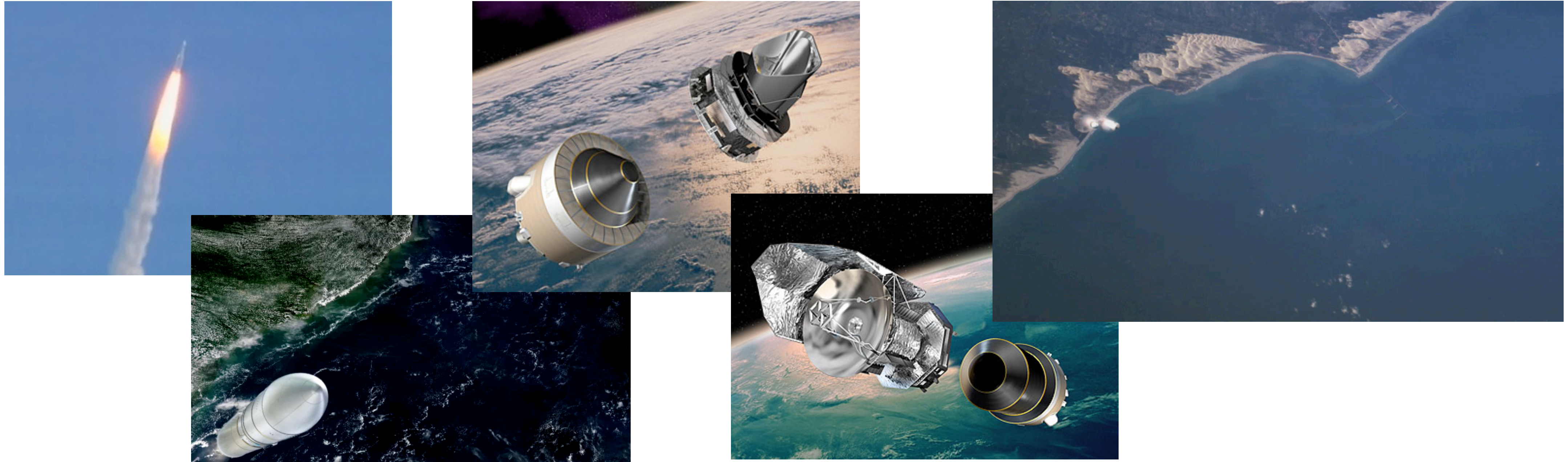
- Quantum fluctuations also generate ripples in space-time, i.e., gravitational waves, by the same mechanism.
- Primordial gravitational waves generate temperature anisotropy in CMB, as well as polarization in CMB with a distinct pattern called “**B-mode polarization.**”



# 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.**

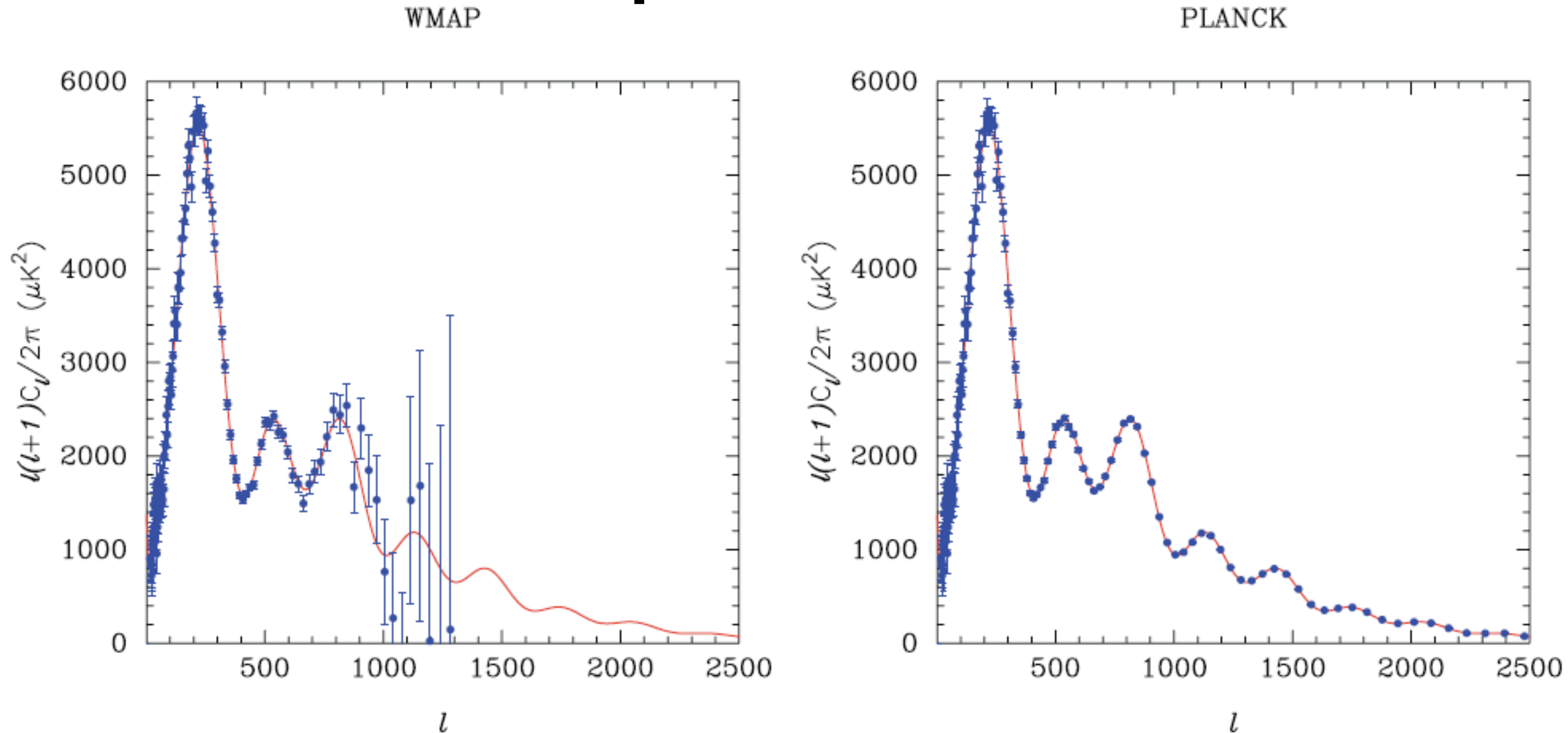
# Planck Launched!



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

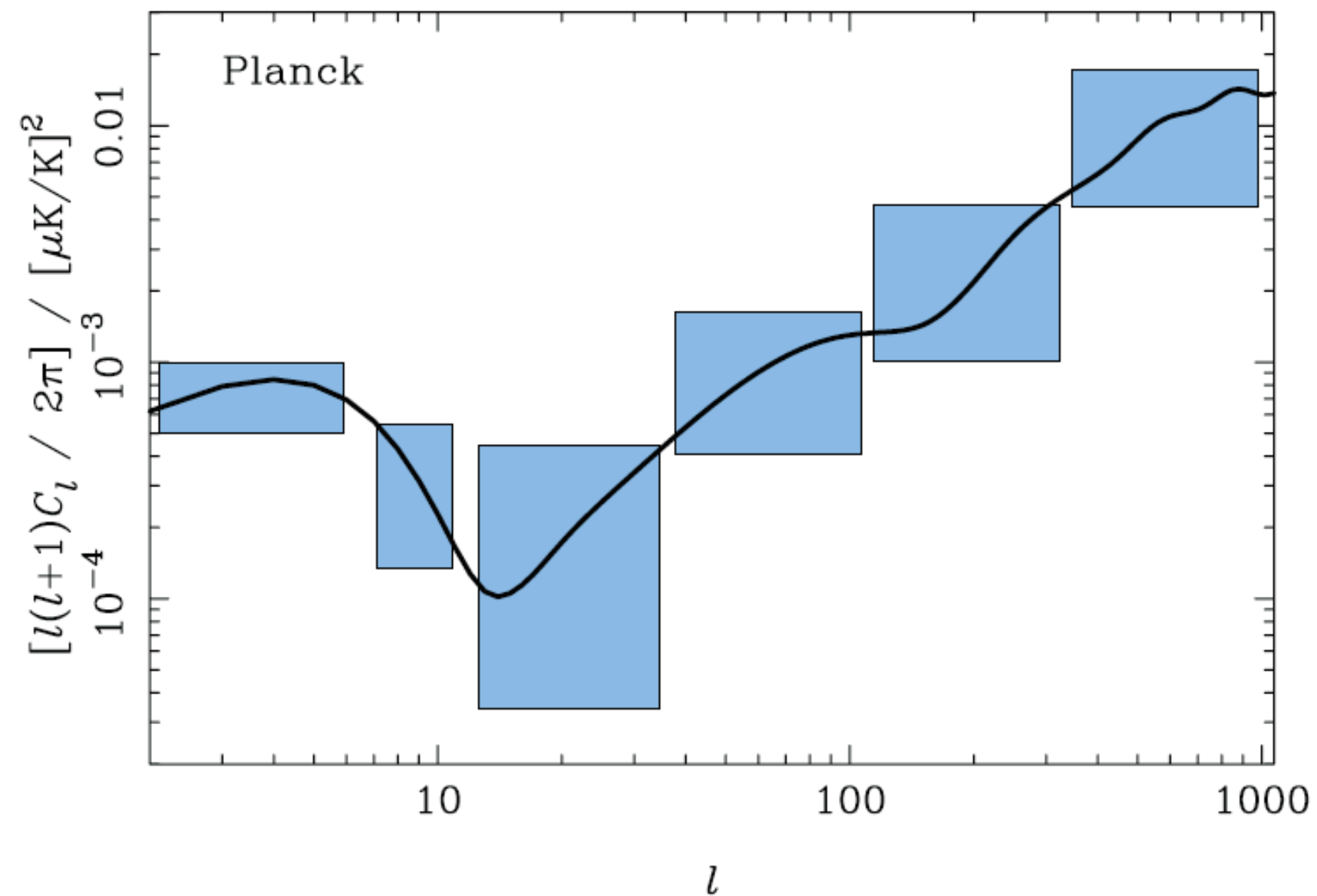
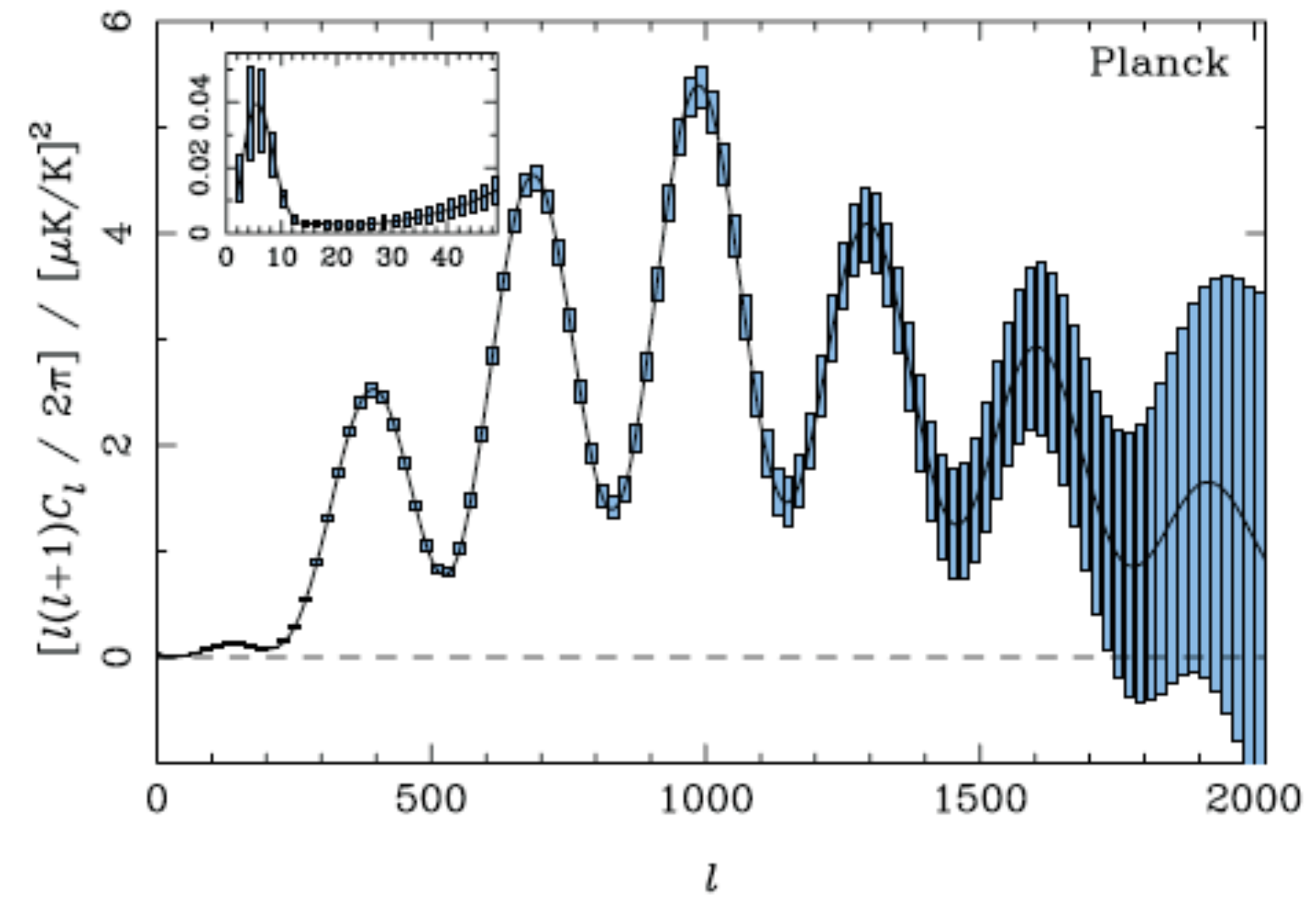
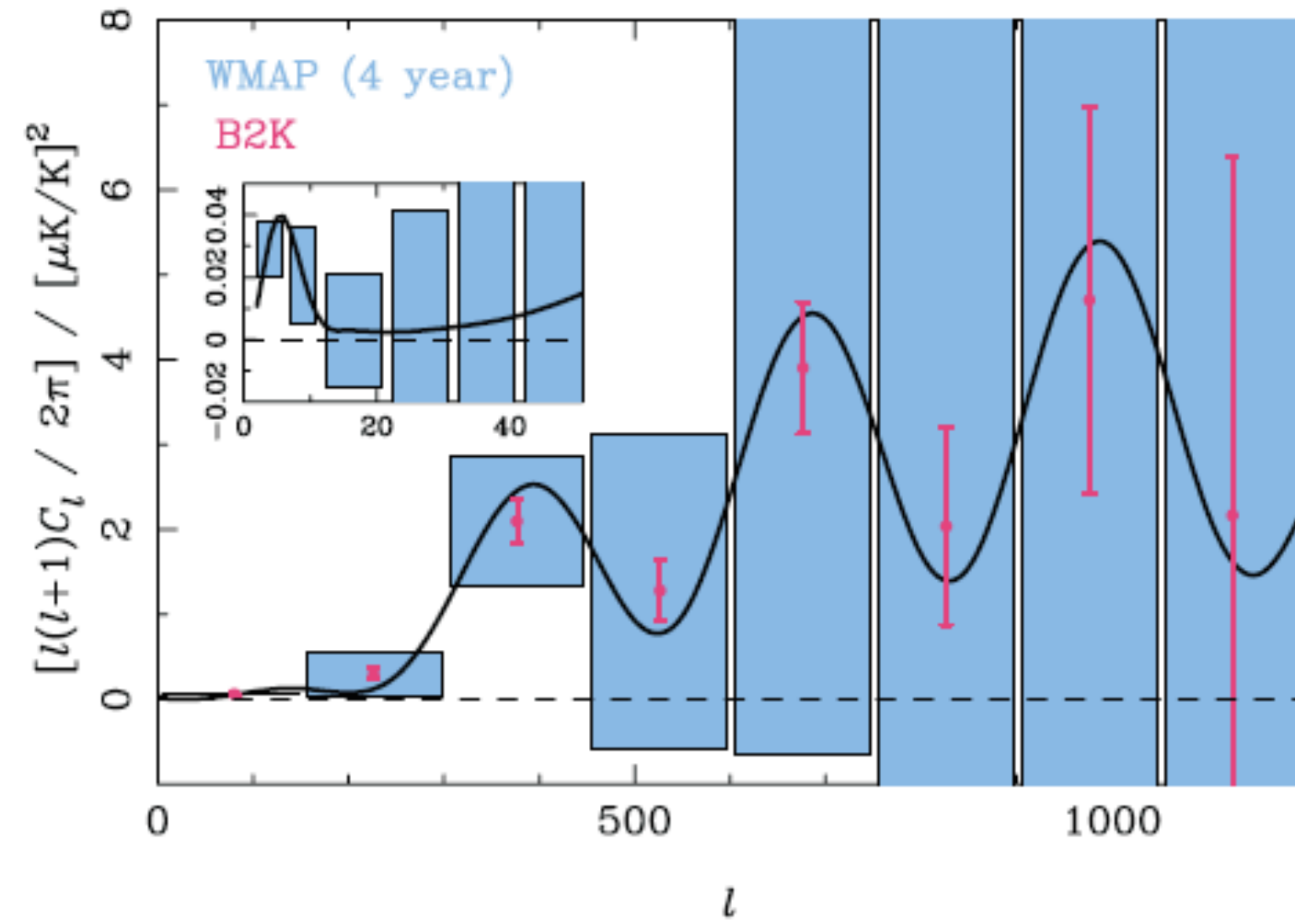


# Planck: Expected $C_l$ Temperature



- WMAP:  $l \sim 1000 \Rightarrow$  Planck:  $l \sim 3000$

# Planck: Expected $C_l$ Polarization



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