# Cosmic Microwave Background

Eiichiro Komatsu

Guest Lecture, University of Copenhagen, May 19, 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)

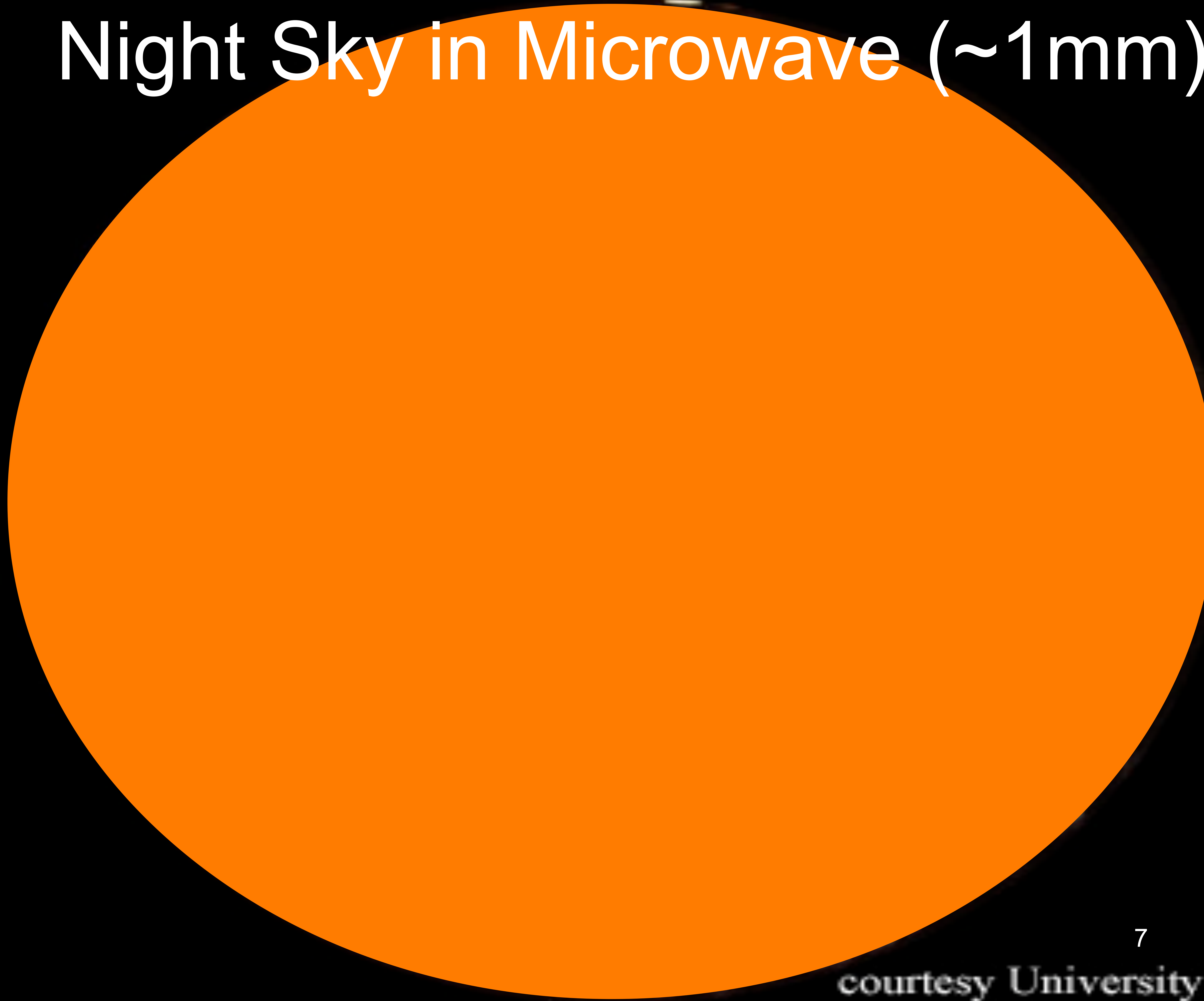
- Fossil light of the Big Bang!

*From "Cosmic Voyage"*

# Night Sky in Optical (~0.5μm)


courtesy University of Arizona

# Night Sky in Microwave (~1mm)



courtesy University of Arizona

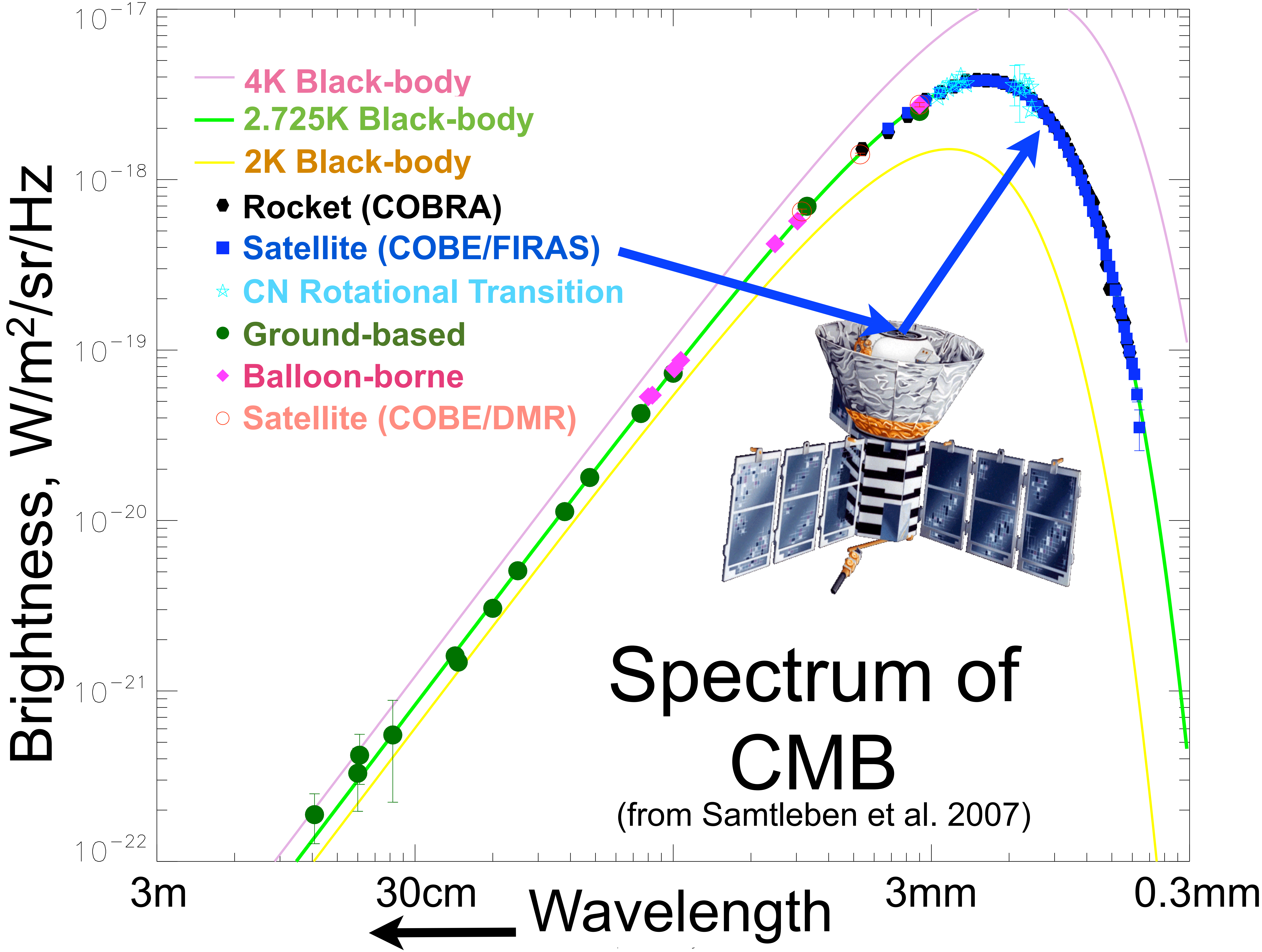
# Night Sky in Microwave (~1mm)

$$T_{today} = 2.725K$$

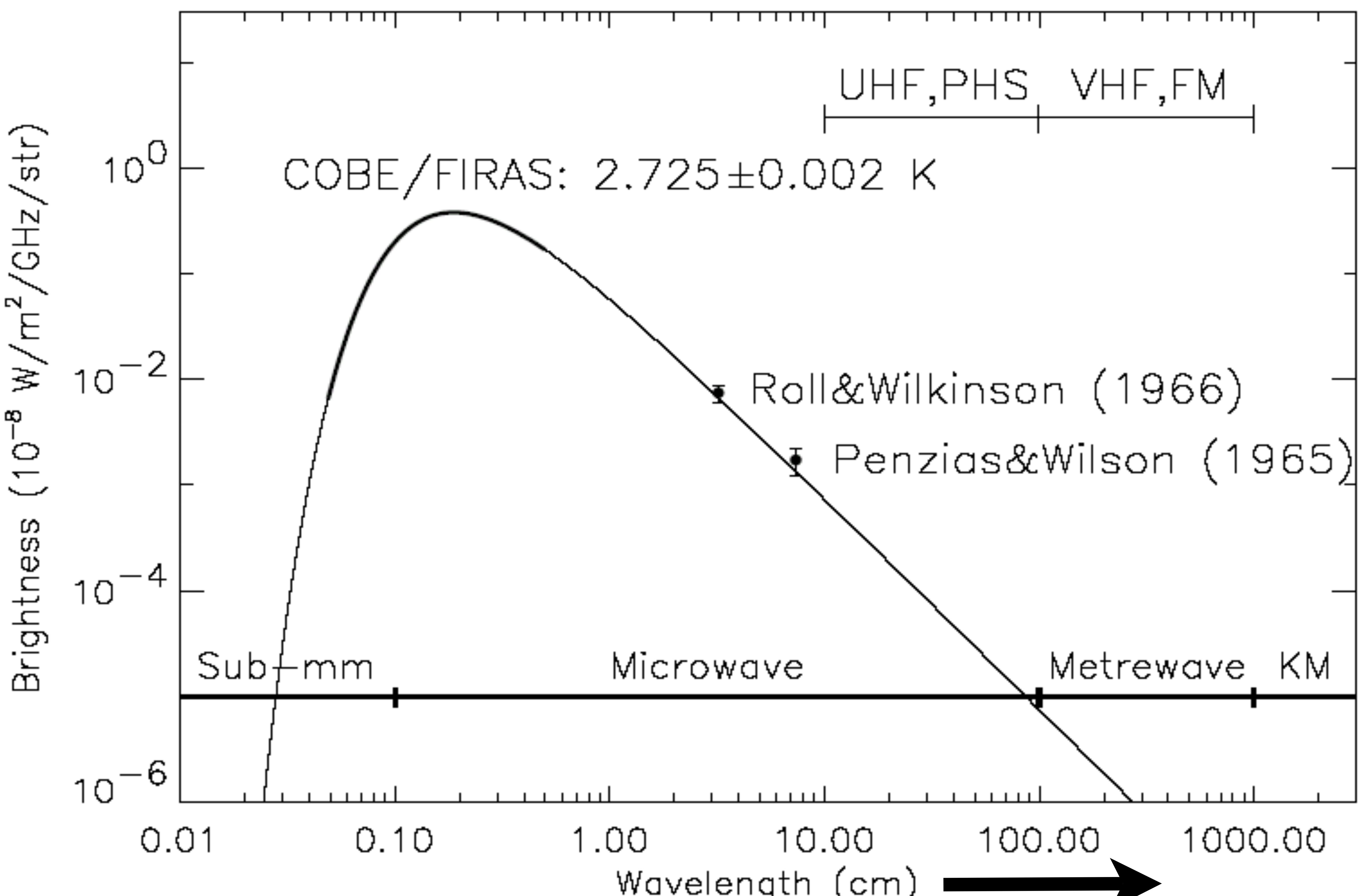
***COBE Satellite, 1989-1993***

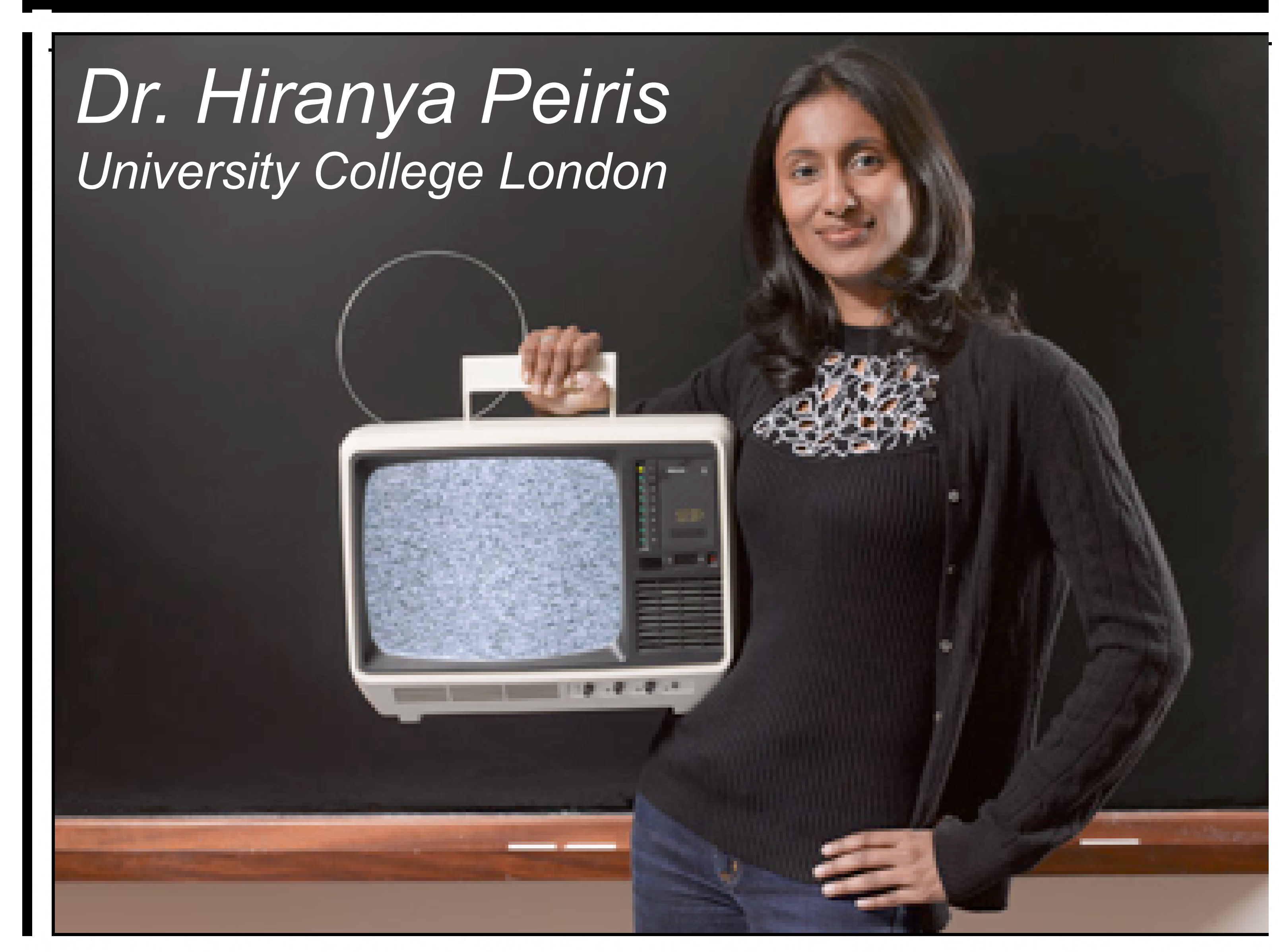


courtesy University of Arizona


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)
Brightness, W/m²/sr/Hz
$10^{-17}$
$10^{-18}$
$10^{-19}$
$10^{-20}$
$10^{-21}$
$10^{-22}$
3m
30cm
3mm
0.3mm
Wavelength
Spectrum of CMB
(from Samtleben et al. 2007)

- The spectrum of CMB has a peak at 1.1mm.
- Let's compare it with…
  - Microwave oven: 12cm
  - Cellular phone: 20cm
  - UHF Television: 39-64cm
  - FM radio: 3m
  - AM radio: 300m




You can "see" CMB by TV (not by a cable TV of course!).

Perhaps you can "hear" CMB by a cell phone?

# Arno Penzias & Robert Wilson, 1965

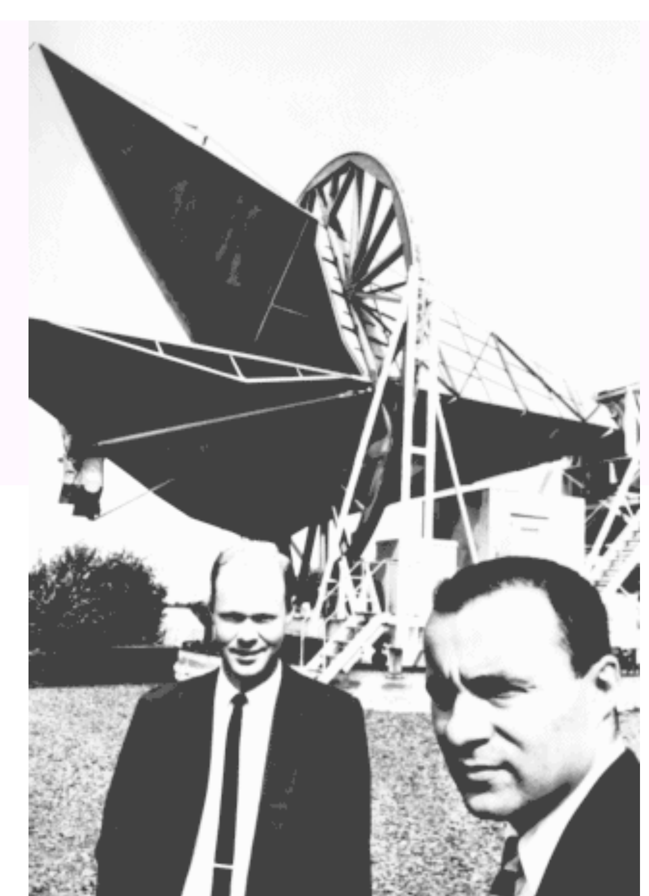
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

- **Isotropic**

A. A. PENZIAS
R. W. WILSON

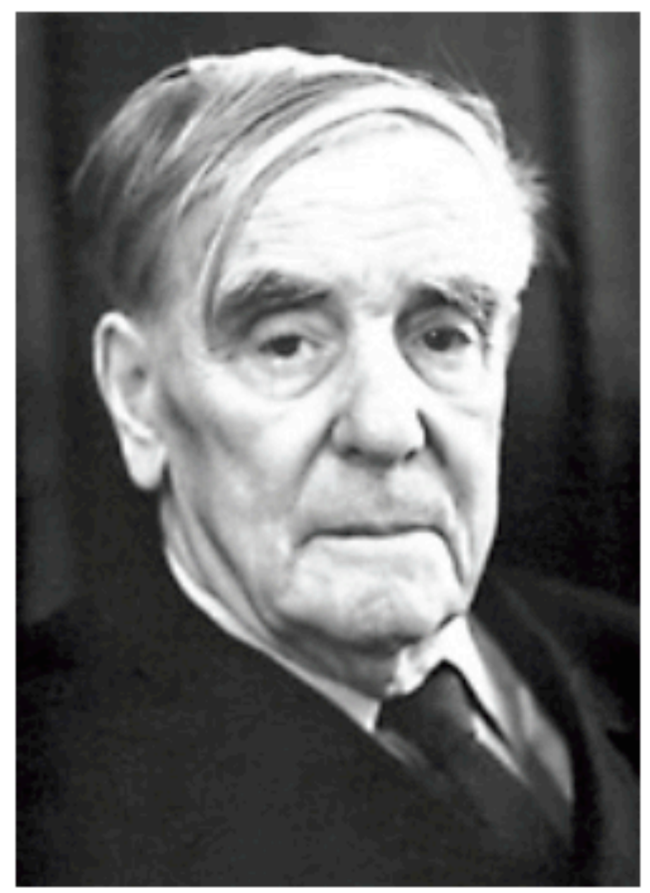
May 13, 1965
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY



# The Nobel Prize in Physics 1978

"for his basic inventions and discoveries in the area of low-temperature physics"

**"For their discovery of cosmic microwave background radition"**



**Pyotr Leonidovich Kapitsa**

1/2 of the prize

USSR

Academy of Sciences
Moscow, USSR

b. 1894
d. 1984

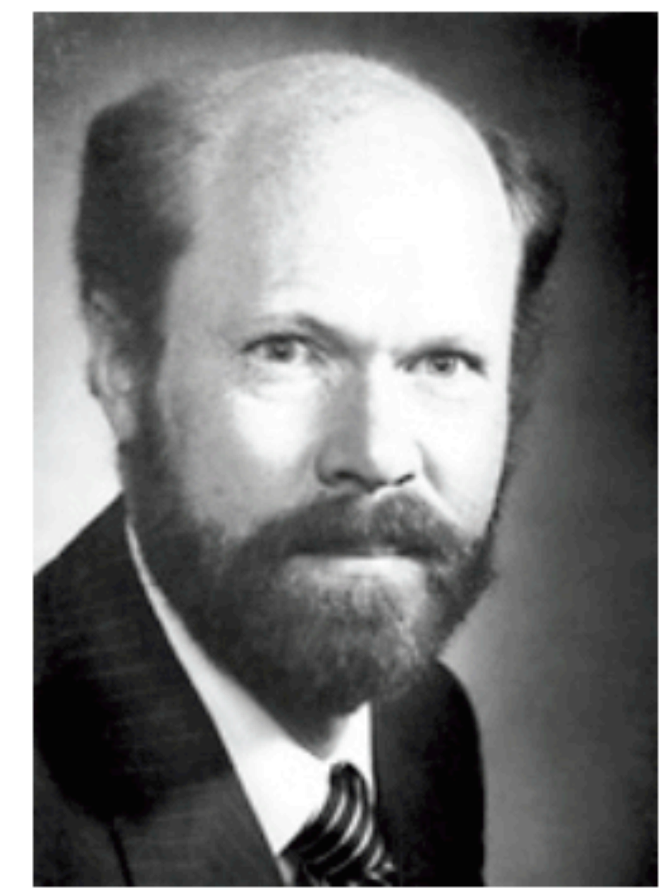
**Arno Allan Penzias**

1/4 of the prize

USA

Bell Laboratories
Holmdel, NJ, USA

b. 1933
(in Munich, Germany)



**Robert Woodrow Wilson**

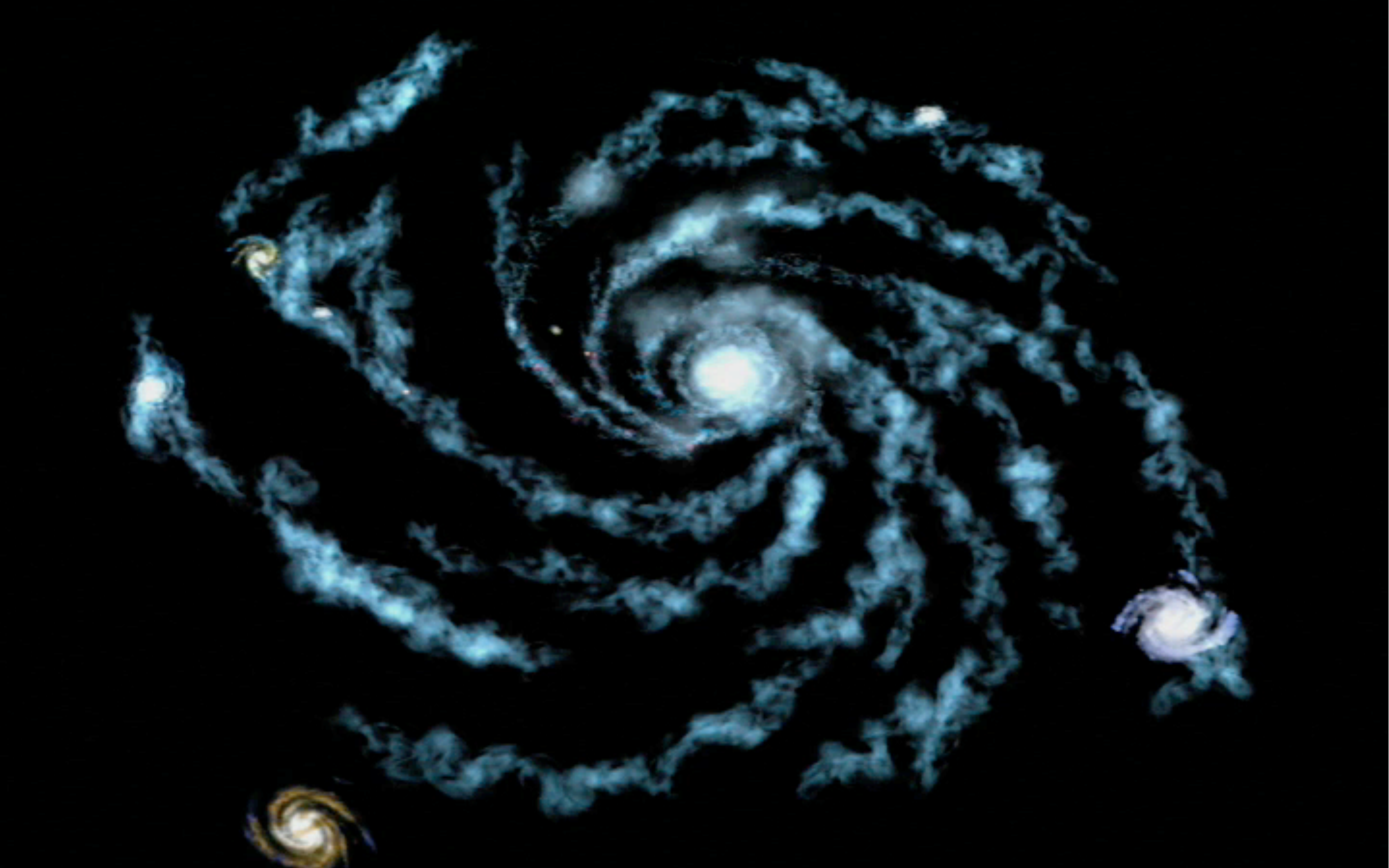
1/4 of the prize

USA

Bell Laboratories
Holmdel, NJ, USA

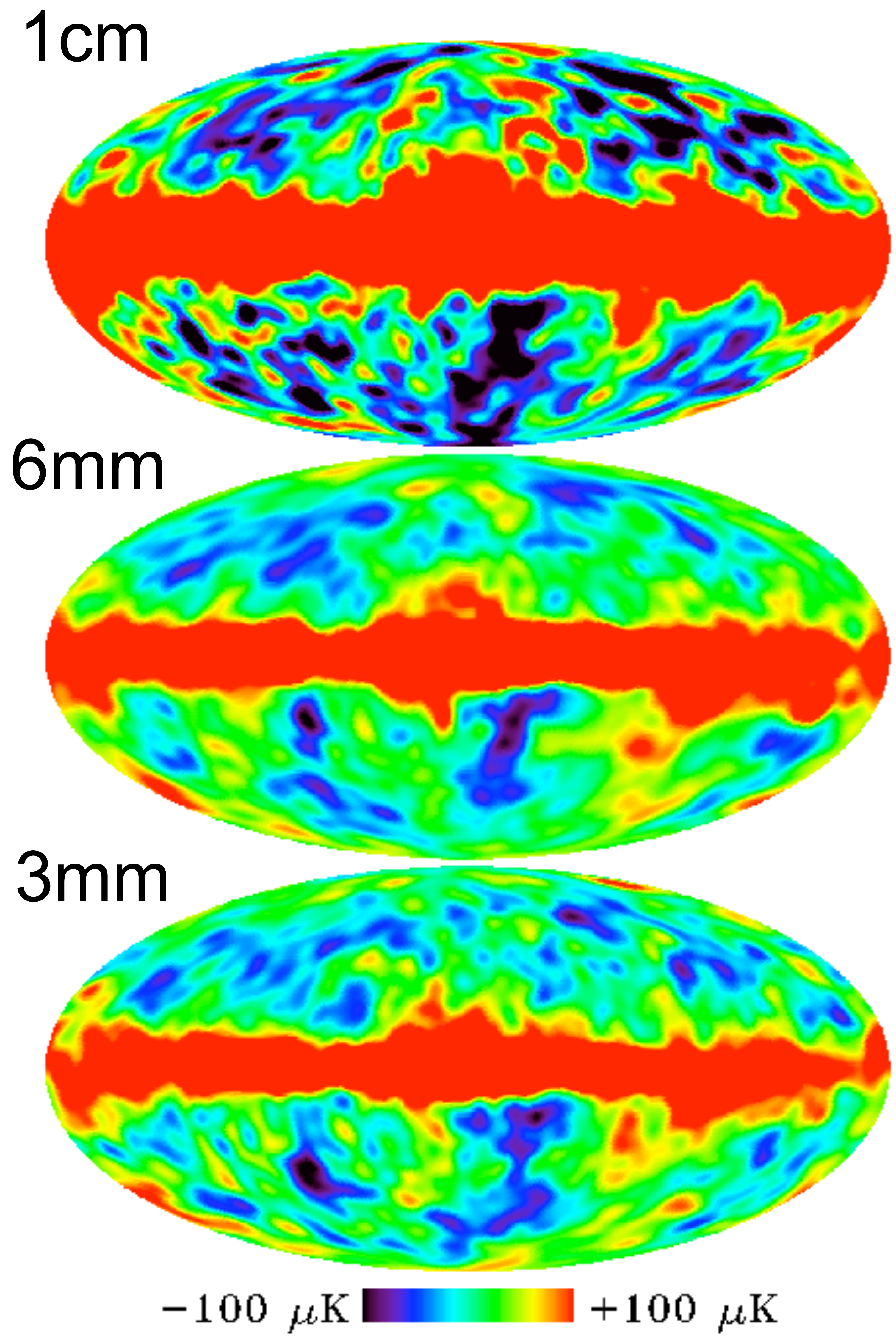
b. 1936

Titles, data and places given above refer to the time of the award.



*Smoot et al. (1992)*

# COBE/DMR, 1992




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

# The Nobel Prize in Physics 2006

**"For their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"**

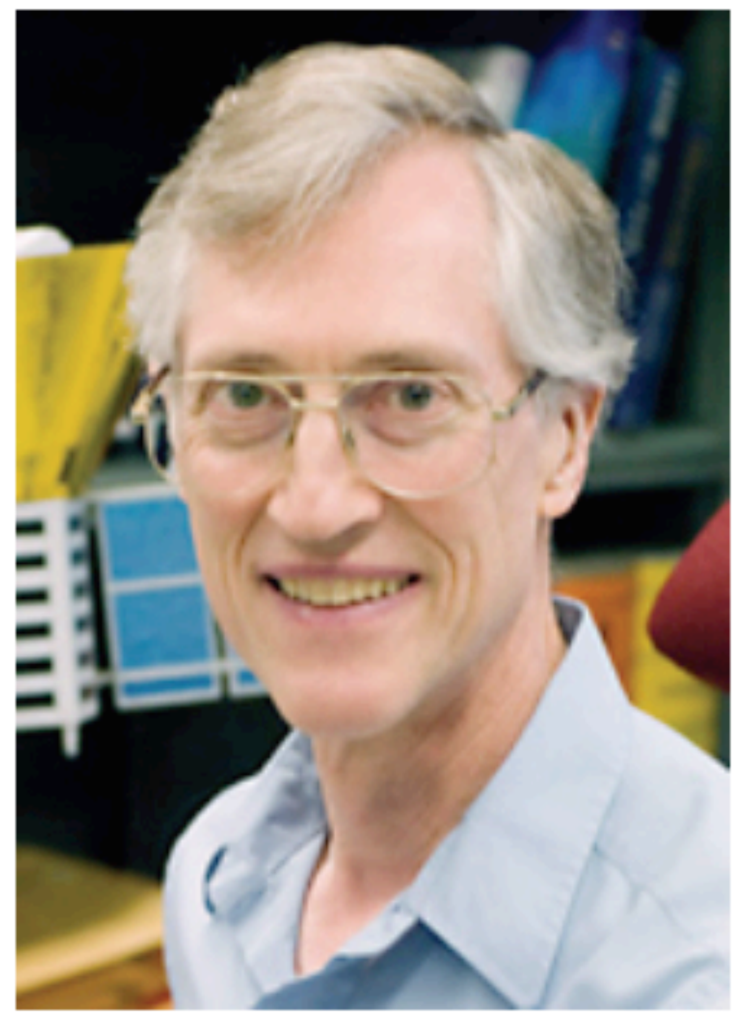


Photo: NASA

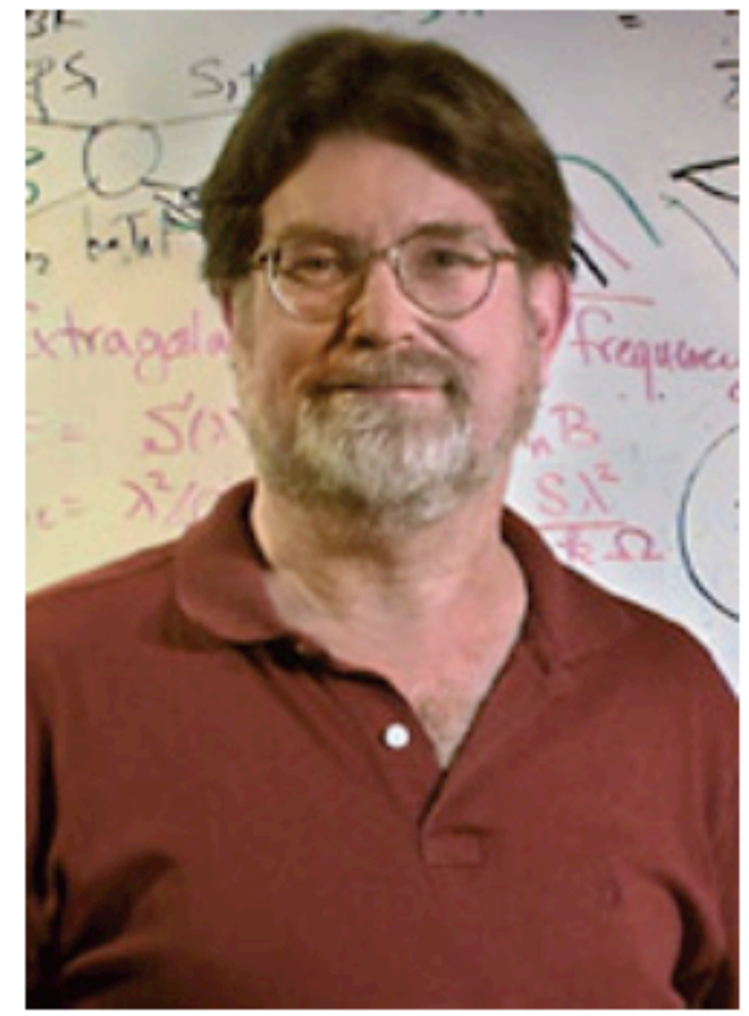


Photo: R. Kaltschmidt/LBNL

**John C. Mather**

1/2 of the prize

USA

NASA Goddard Space
Flight Center
Greenbelt, MD, USA

b. 1946

**George F. Smoot**

1/2 of the prize

USA

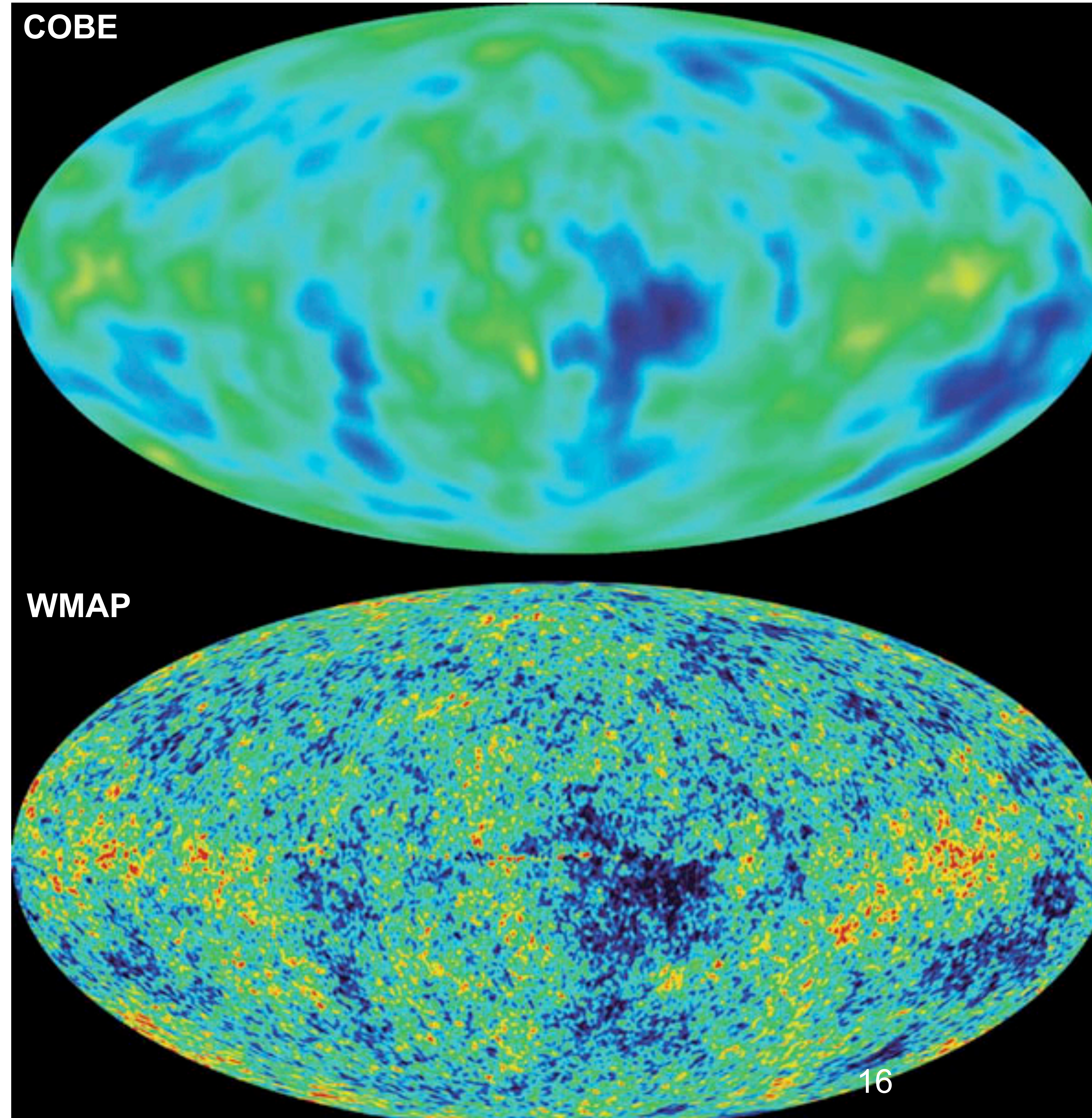
University of California
Berkeley, CA, USA

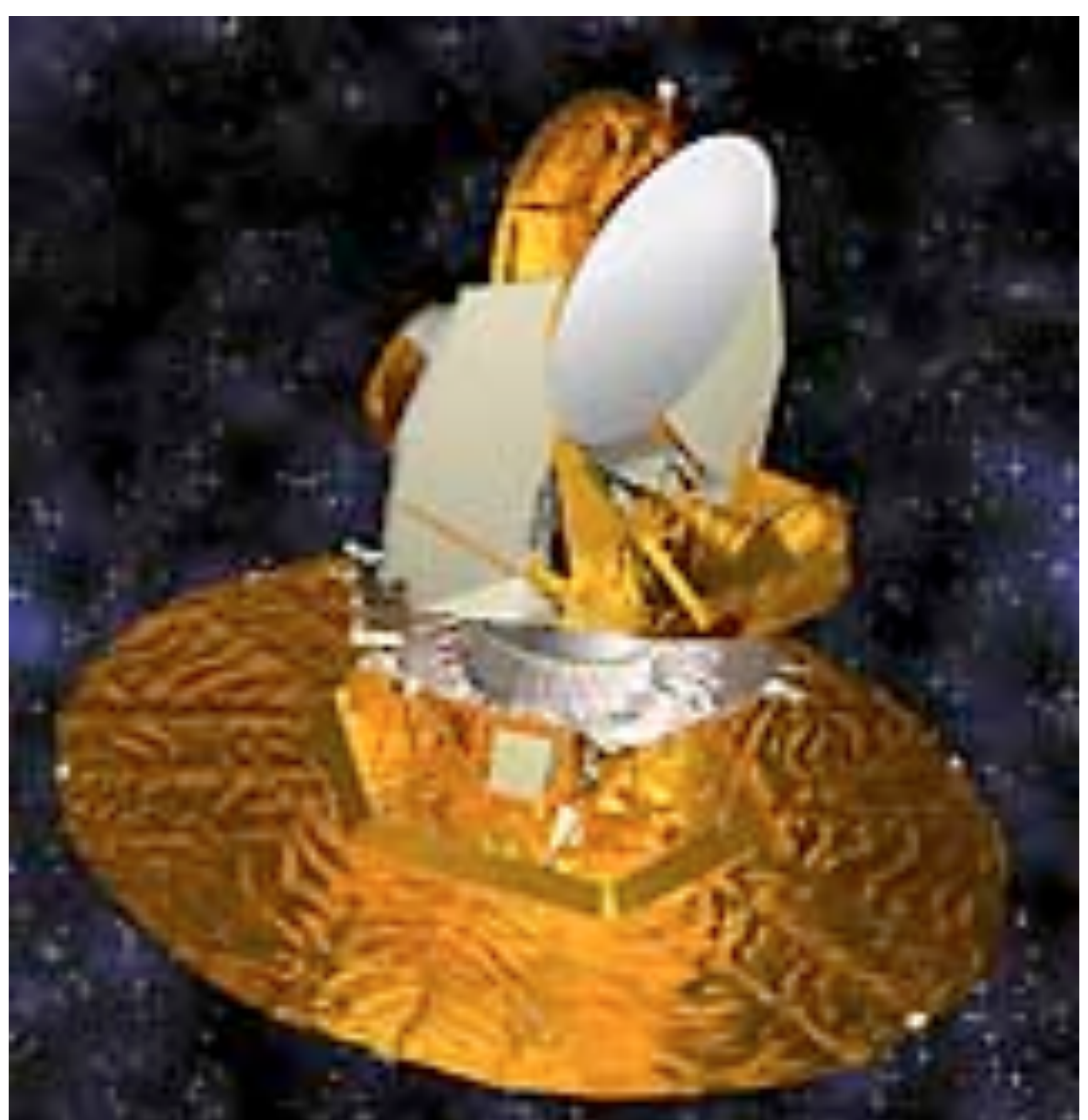
b. 1945

Titles, data and places given above refer to the time of the award.

# COBE to WMAP (x35 better resolution)

COBE
1989

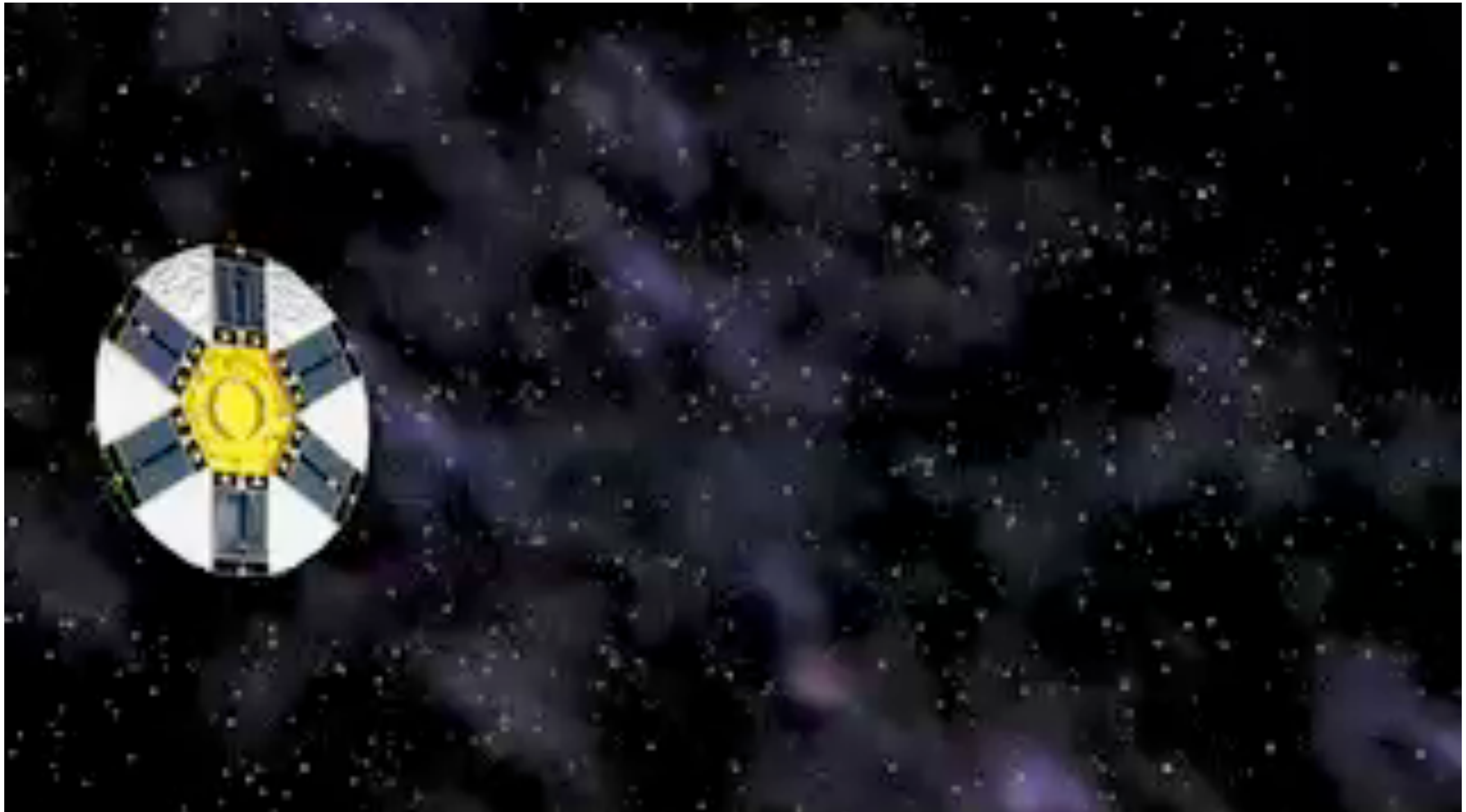


WMAP
2001

*Wilkinson Microwave Anisotropy Probe*

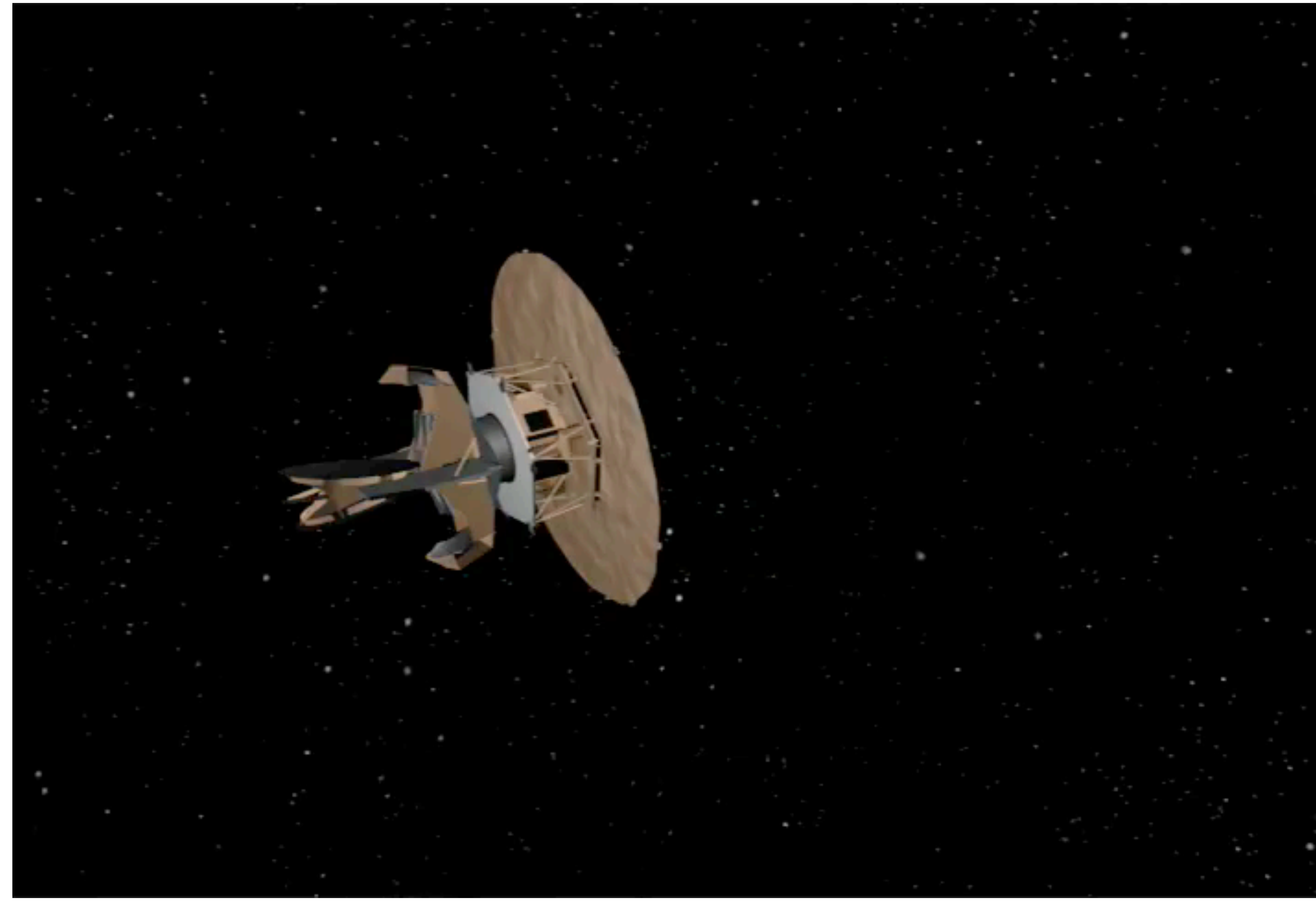
# WMAP at Lagrange 2 (L2) Point



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

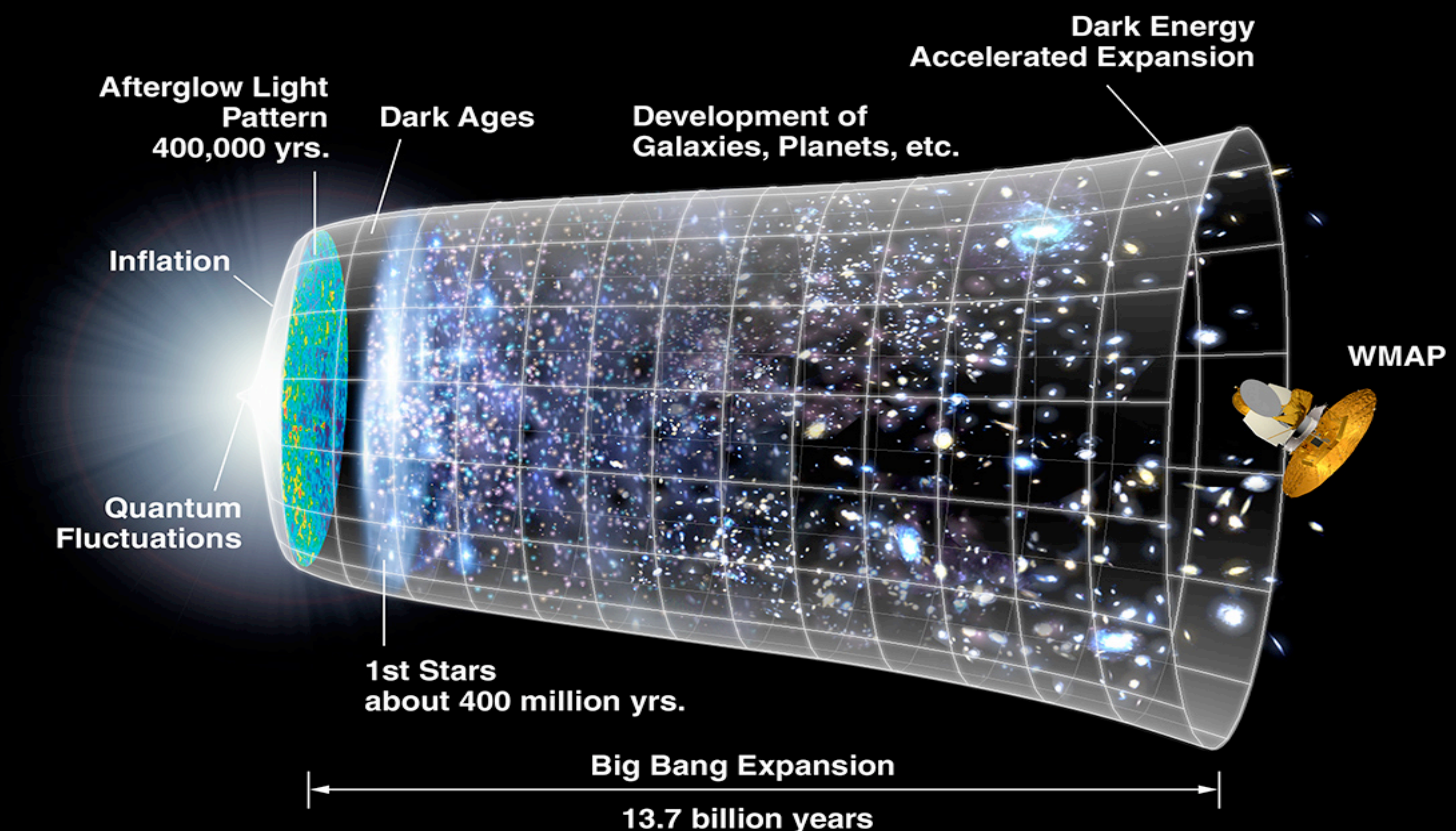
# Journey Backwards in Time

- The Cosmic Microwave Background (**CMB**) is ***the fossil light from the Big Bang***
- This is the oldest light that one can ever hope to measure
- CMB is a ***direct*** image of the Universe when the Universe was only 380,000 years old



- CMB photons, after released from the cosmic plasma "soup," traveled for **13.7 billion years** to reach us.
- CMB collects information about the Universe as it travels through it.

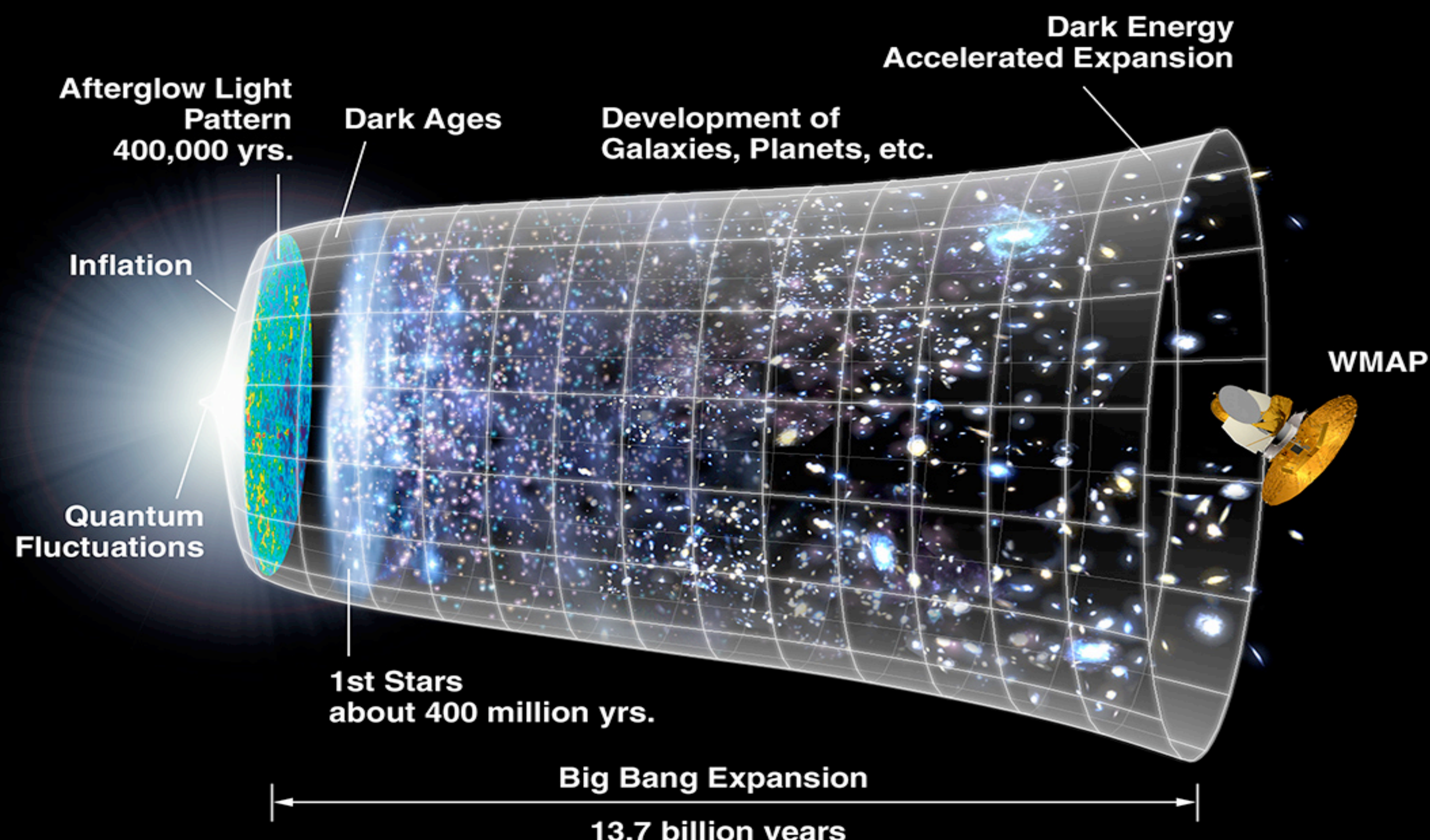
# CMB: A Messenger From the Early Universe...






NASA/WMAP Science Team

# CMB: The Most Distant Light




- CMB was emitted when the Universe was only 380,000 years old.
- WMAP has measured the distance to this epoch very precisely.
- From (time)=(distance)/c we obtained 13.7±0.1 billion years.

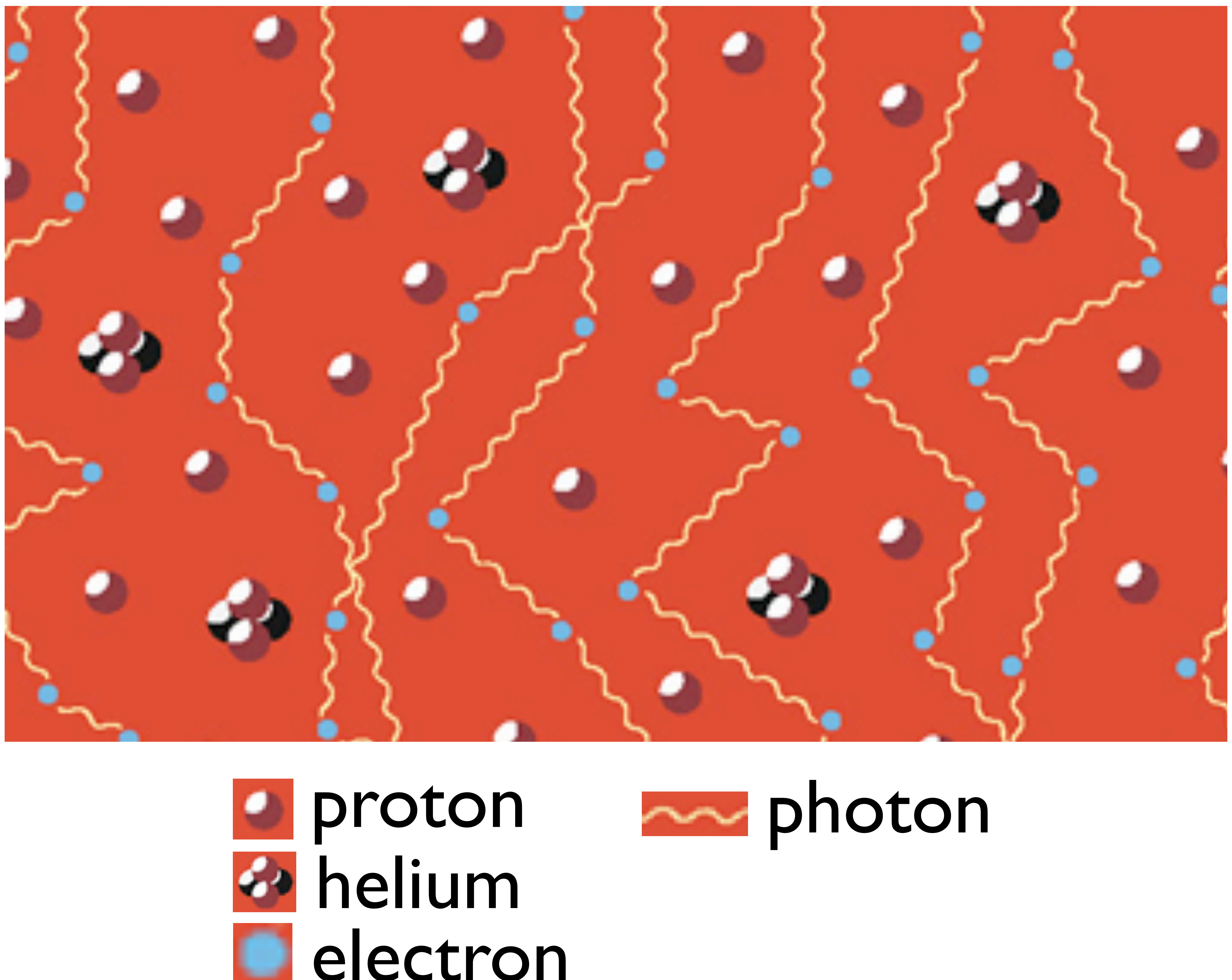


NASA/WMAP Science Team

# How was CMB created?

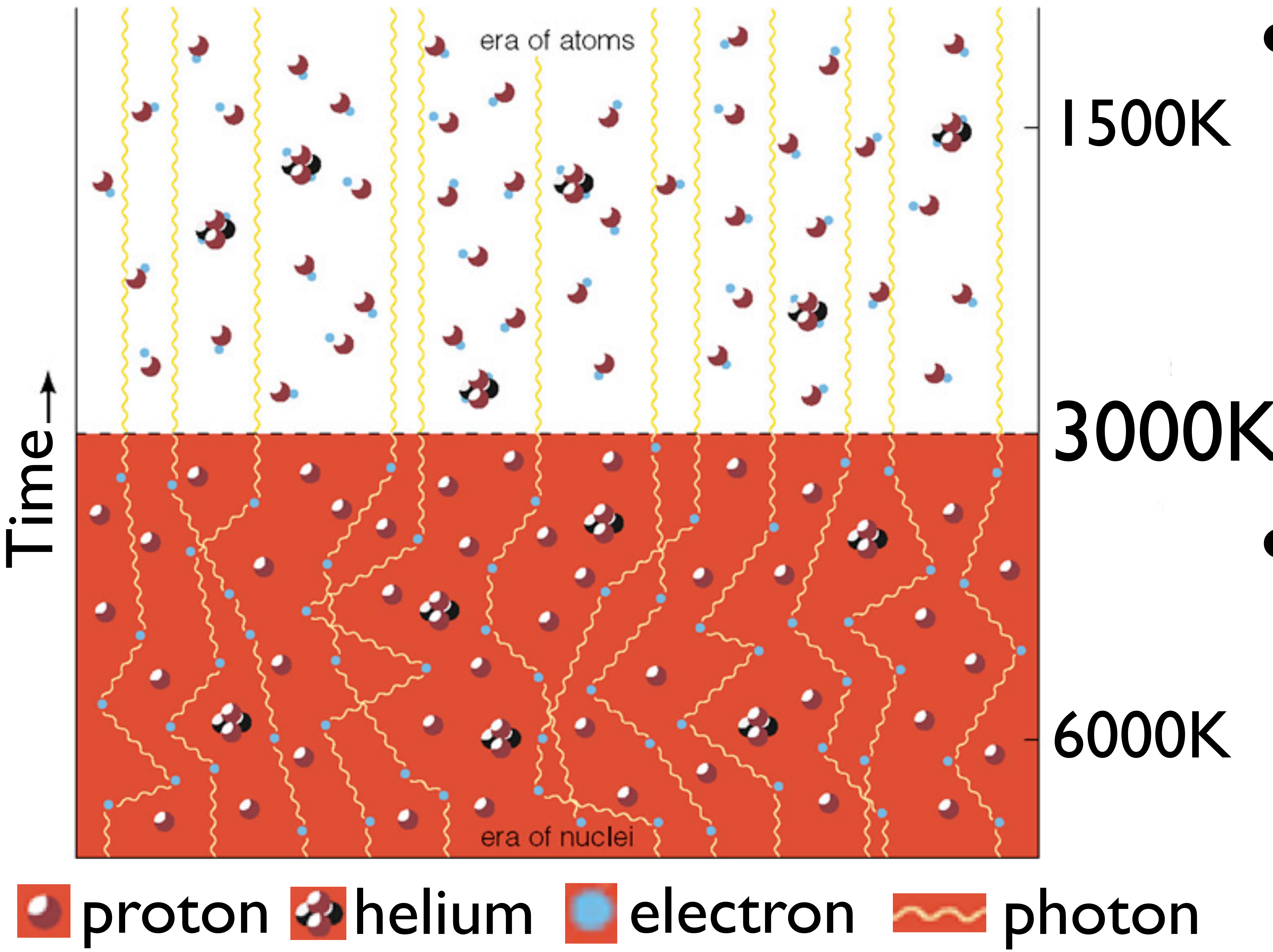
- When the Universe was hot... can you imagine?
  - The Universe was a hot soup made of:
    - Protons, electrons, and helium nuclei
    - Photons and neutrinos
    - Dark matter

# Universe as a hot soup

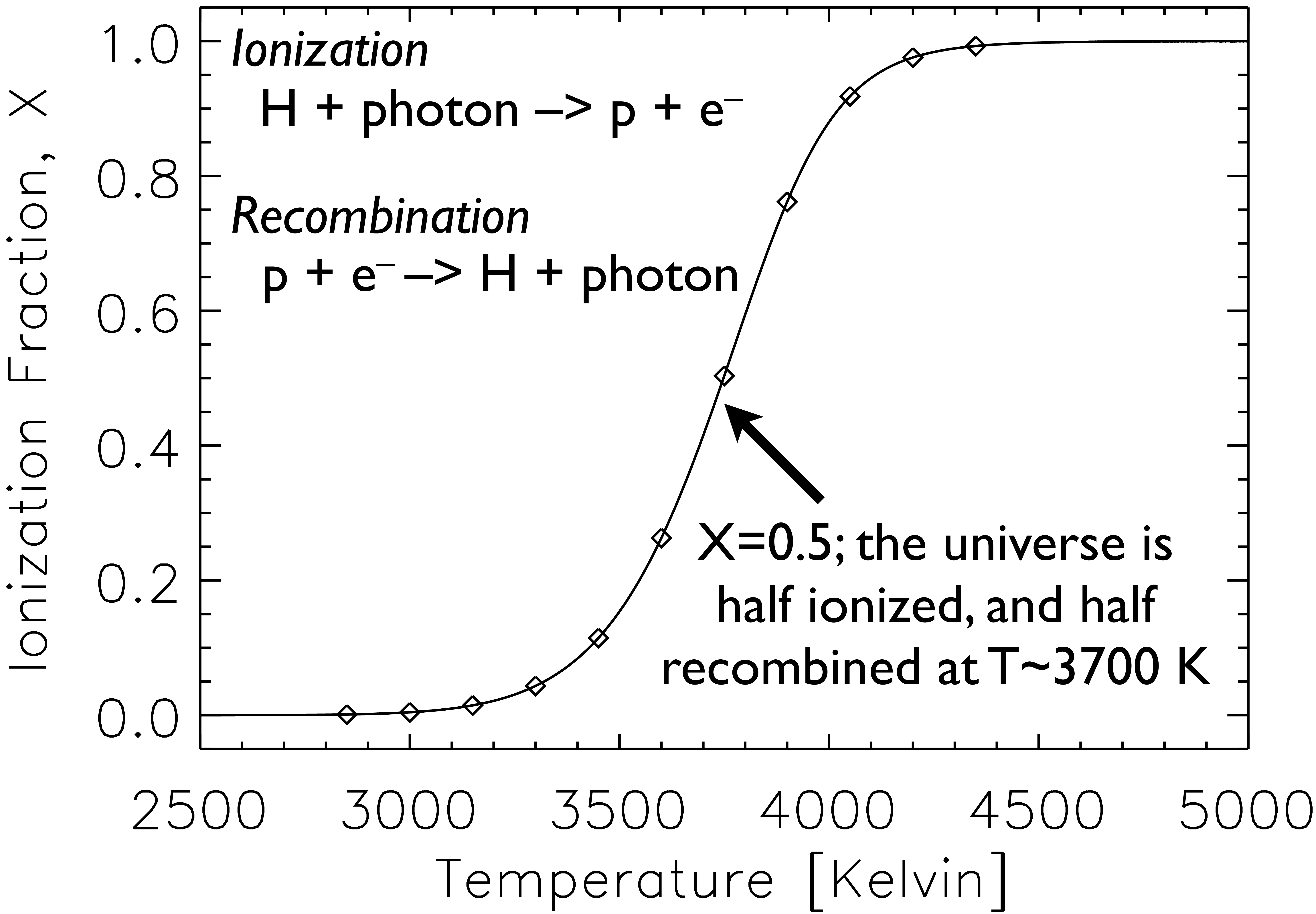



- Free electrons can scatter photons efficiently.
- Photons cannot go very far.

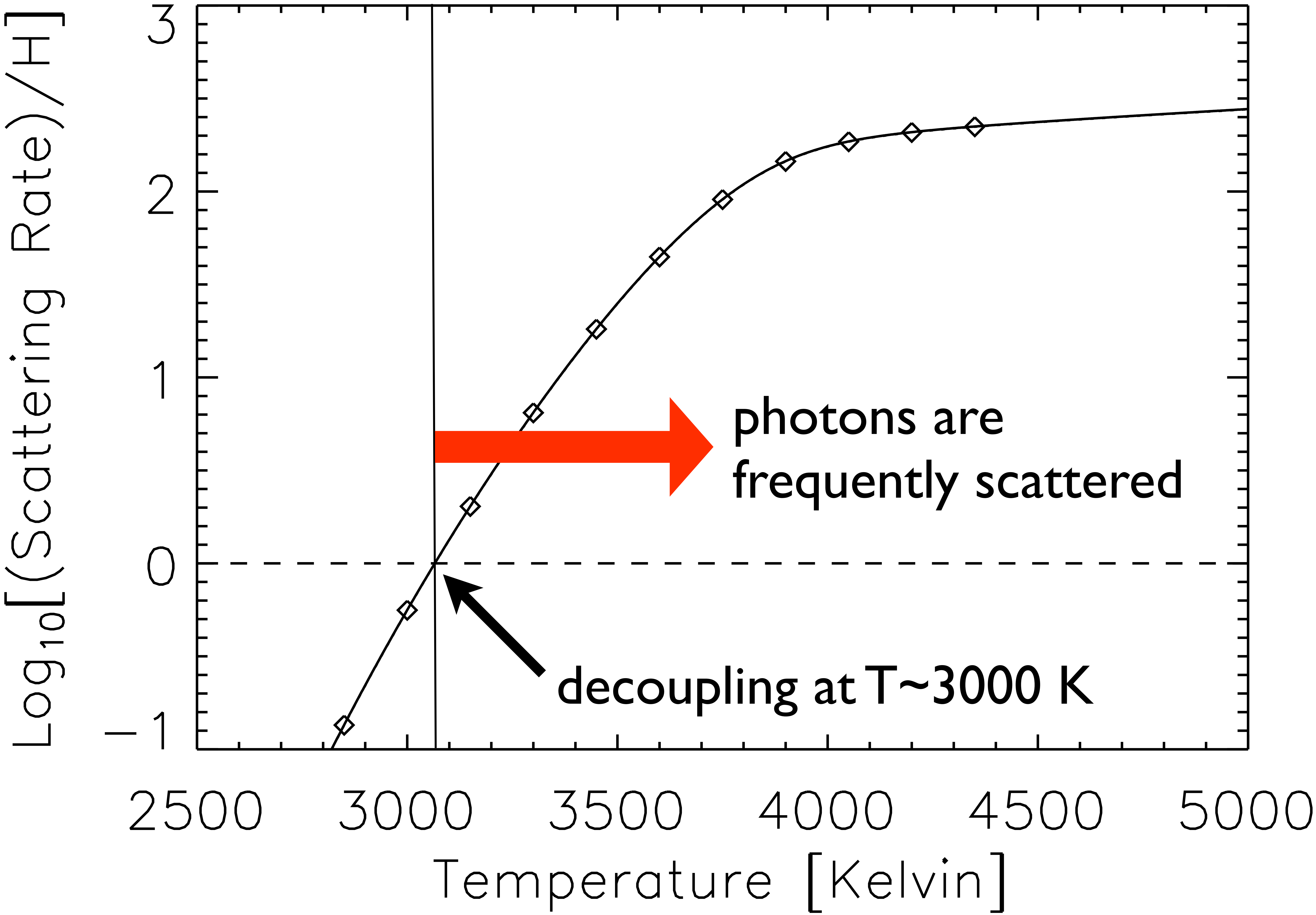
# Recombination and Decoupling




- [***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.

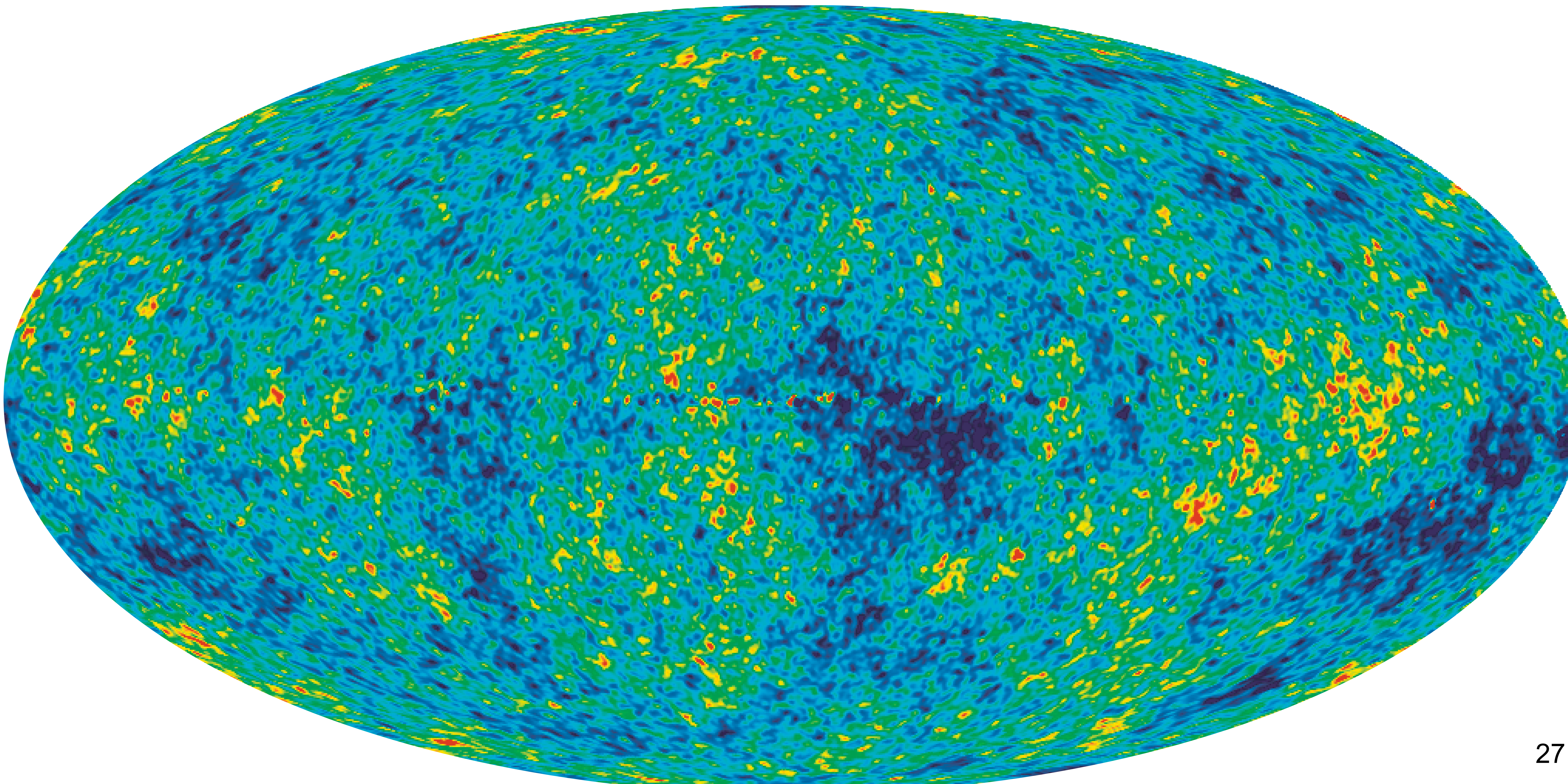


Ionization
H + photon –> p + e⁻
Recombination
p + e⁻ –> H + photon
X=0.5; the universe is
half ionized, and half
recombined at T~3700 K
1.0
0.8
0.6
0.4
0.2
0.0
2500
3000
3500
4000
4500
5000
Ionization Fraction, X
Temperature [Kelvin]

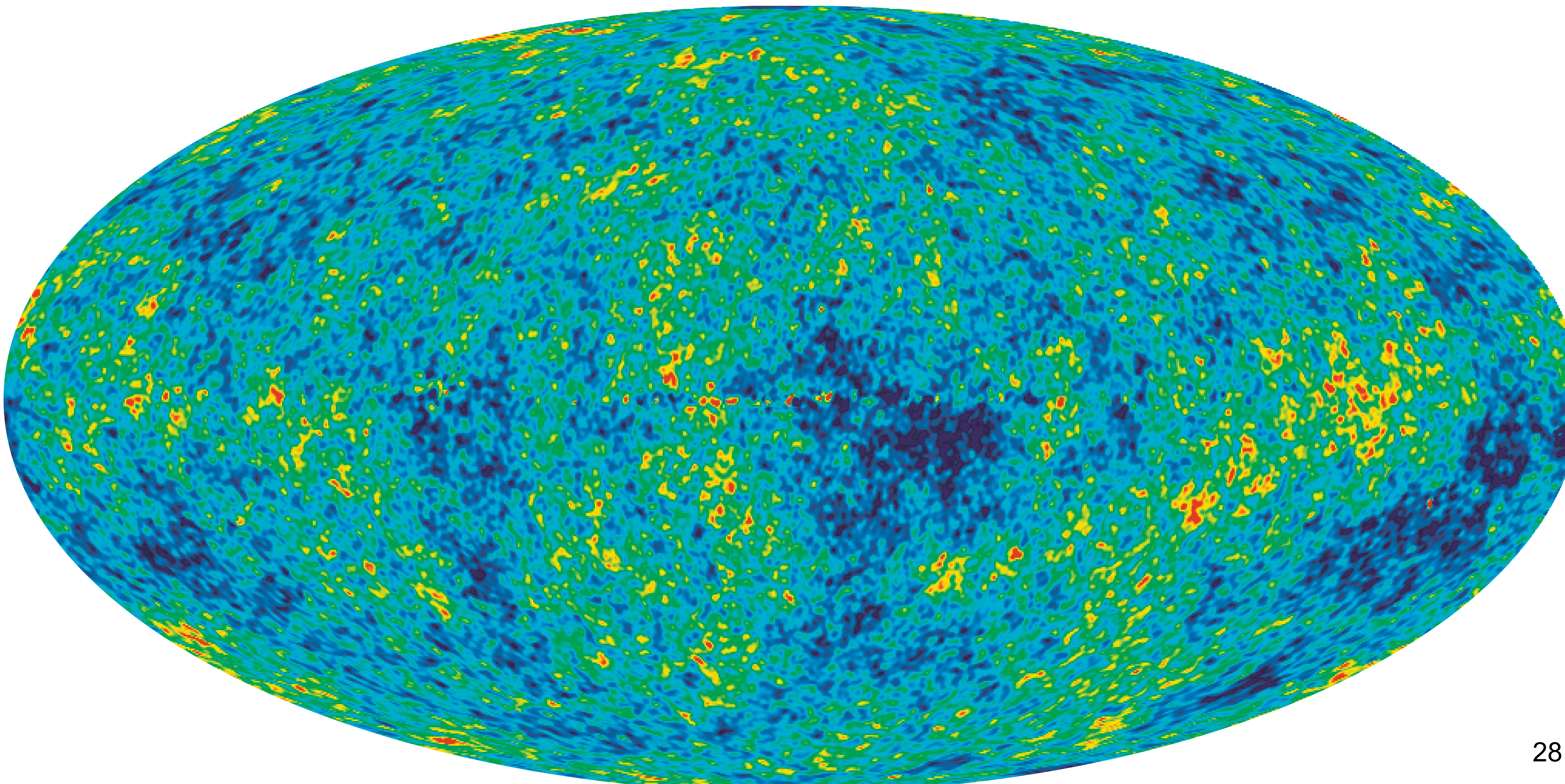


Log10[(Scattering Rate)/H]
3
2
1
0
−1
2500
3000
3500
4000
4500
5000
Temperature [Kelvin]
photons are
frequently scattered
decoupling at T~3000 K

# A direct image of the Universe when it was 3000 K.



# How were these ripples created?

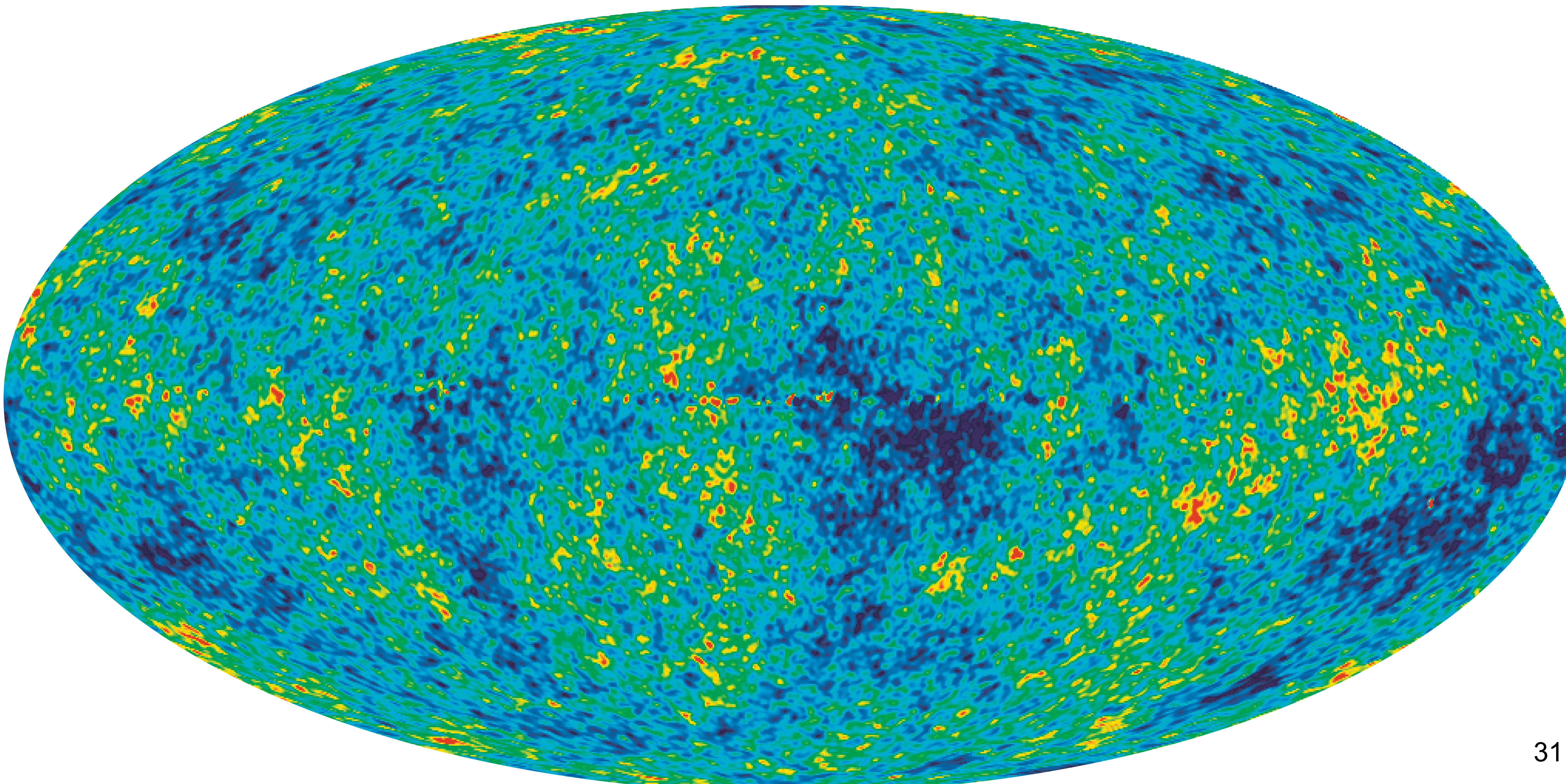


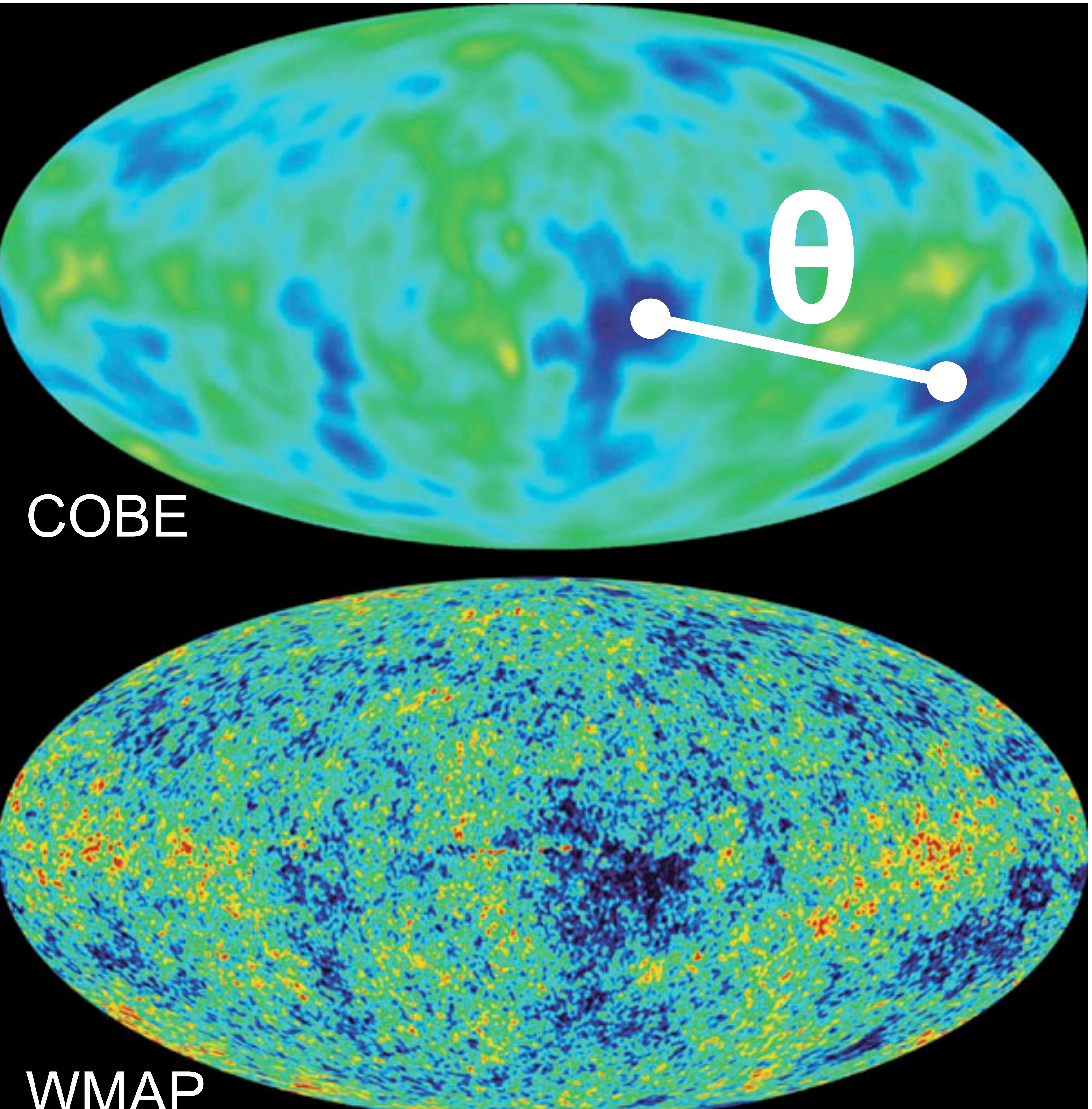
# Have you dropped potatoes in a soup?

- What would happen if you “perturb” the soup?

# The Cosmic Sound Wave

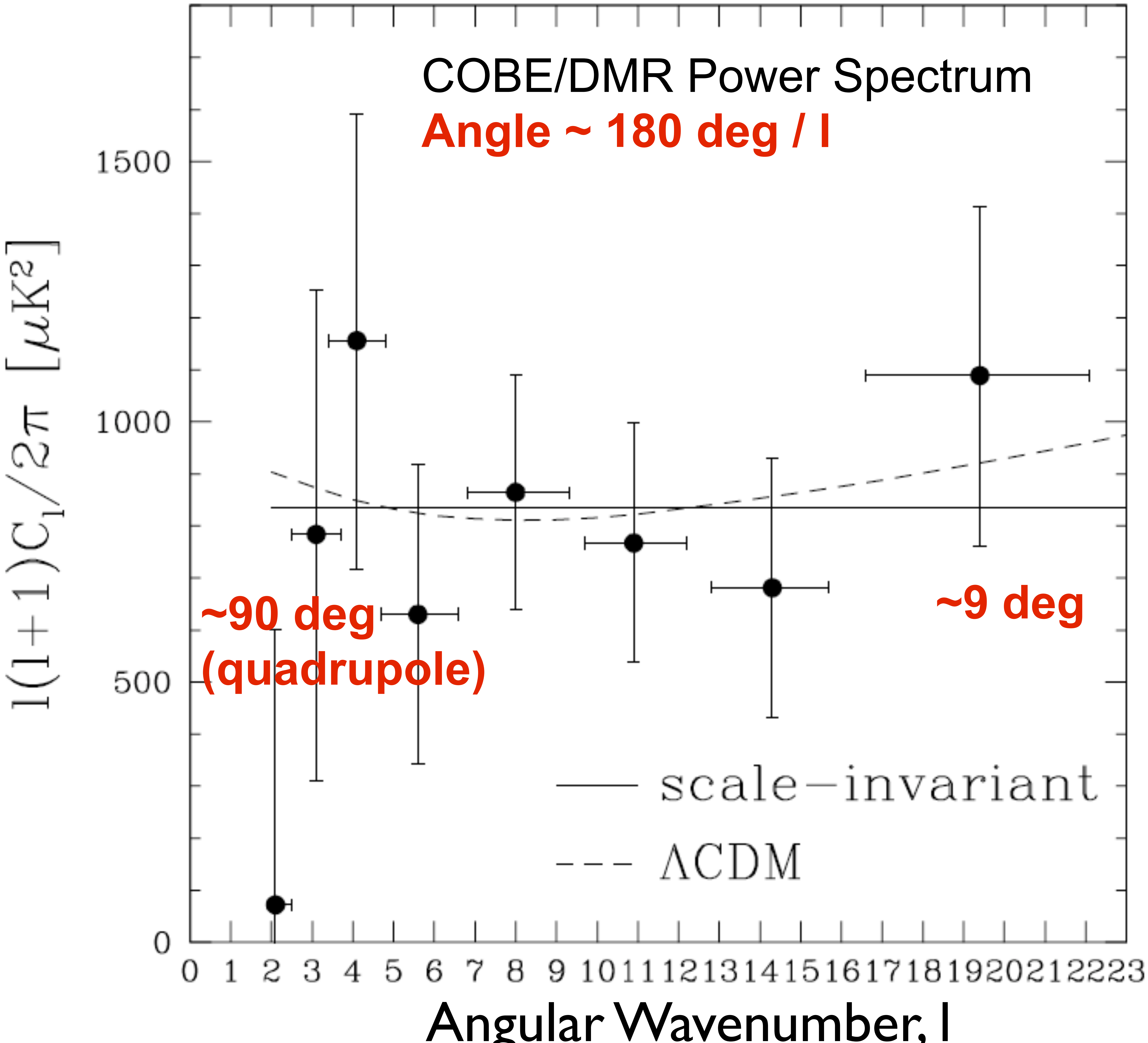
# Can You See the Sound Wave?



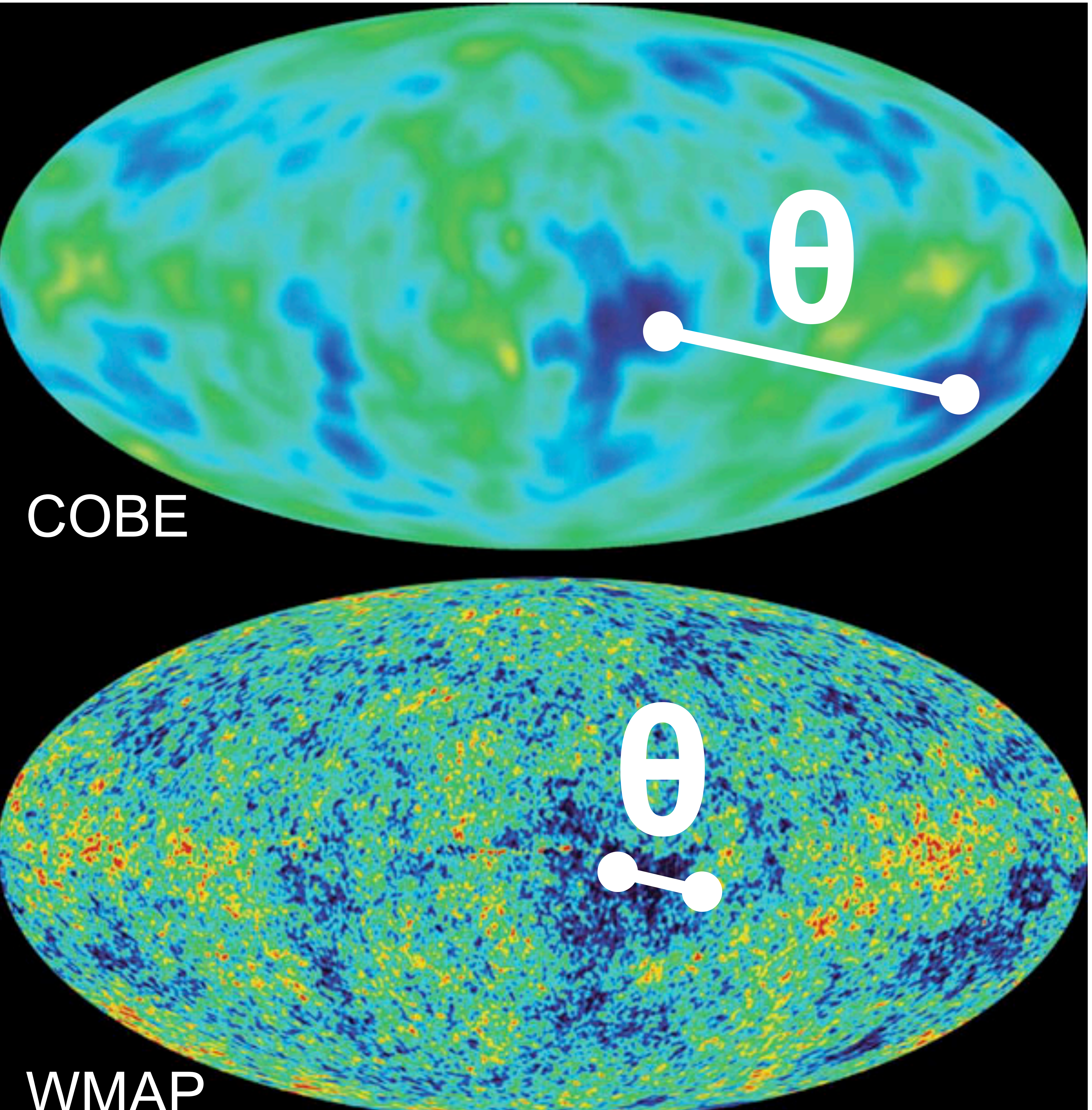



# Analysis: 2-point Correlation

- $C(\theta)=(1/4\pi)\sum(2l+1)C_l P_l(\cos\theta)$
- 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?
  - **$l$~180 degrees / θ**



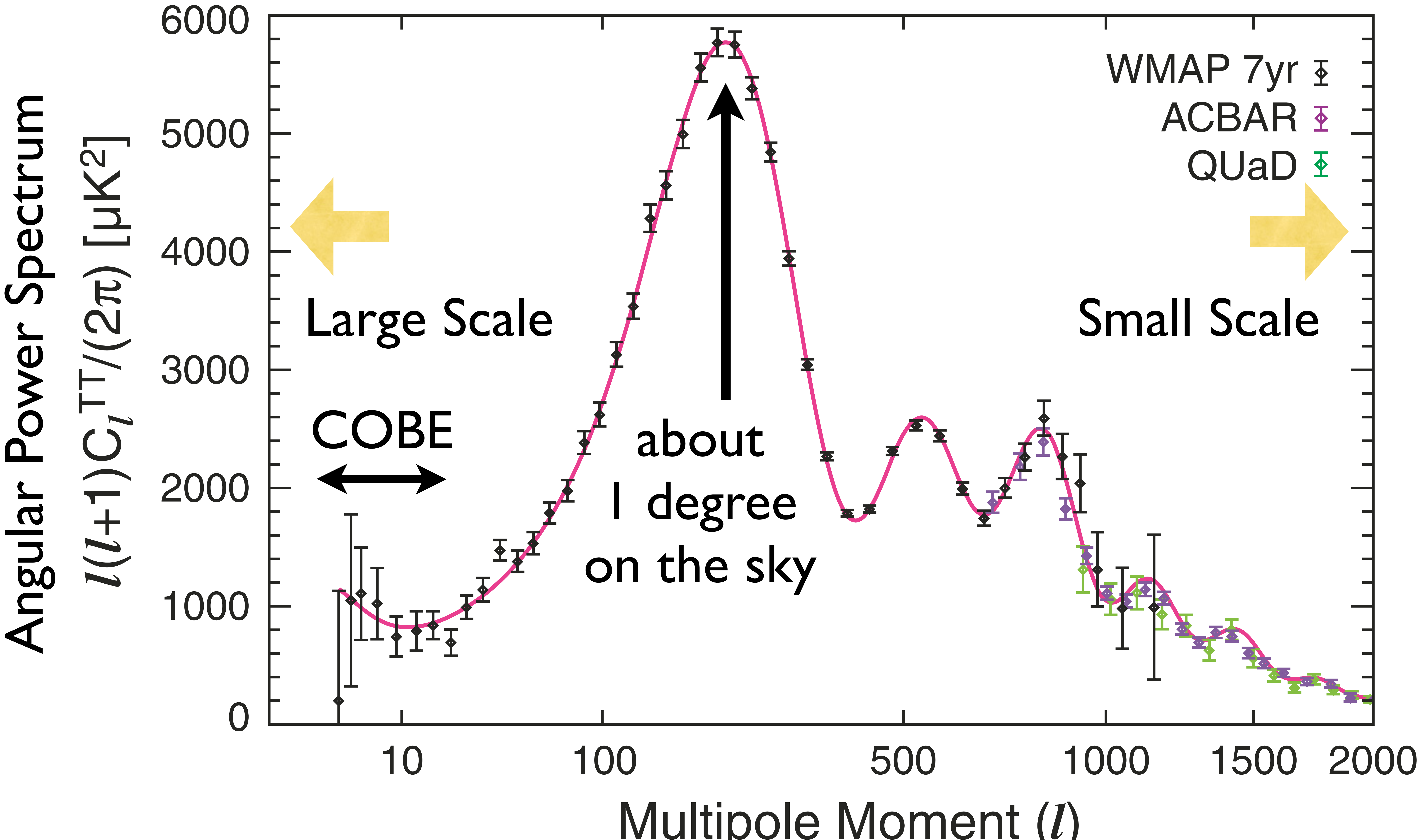
COBE/DMR Power Spectrum
Angle ~ 180 deg / l
~90 deg
(quadrupole)
~9 deg
scale−invariant
ΛCDM
l(l+1)C_l/2π [μK²]
0
500
1000
1500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Angular Wavenumber, l



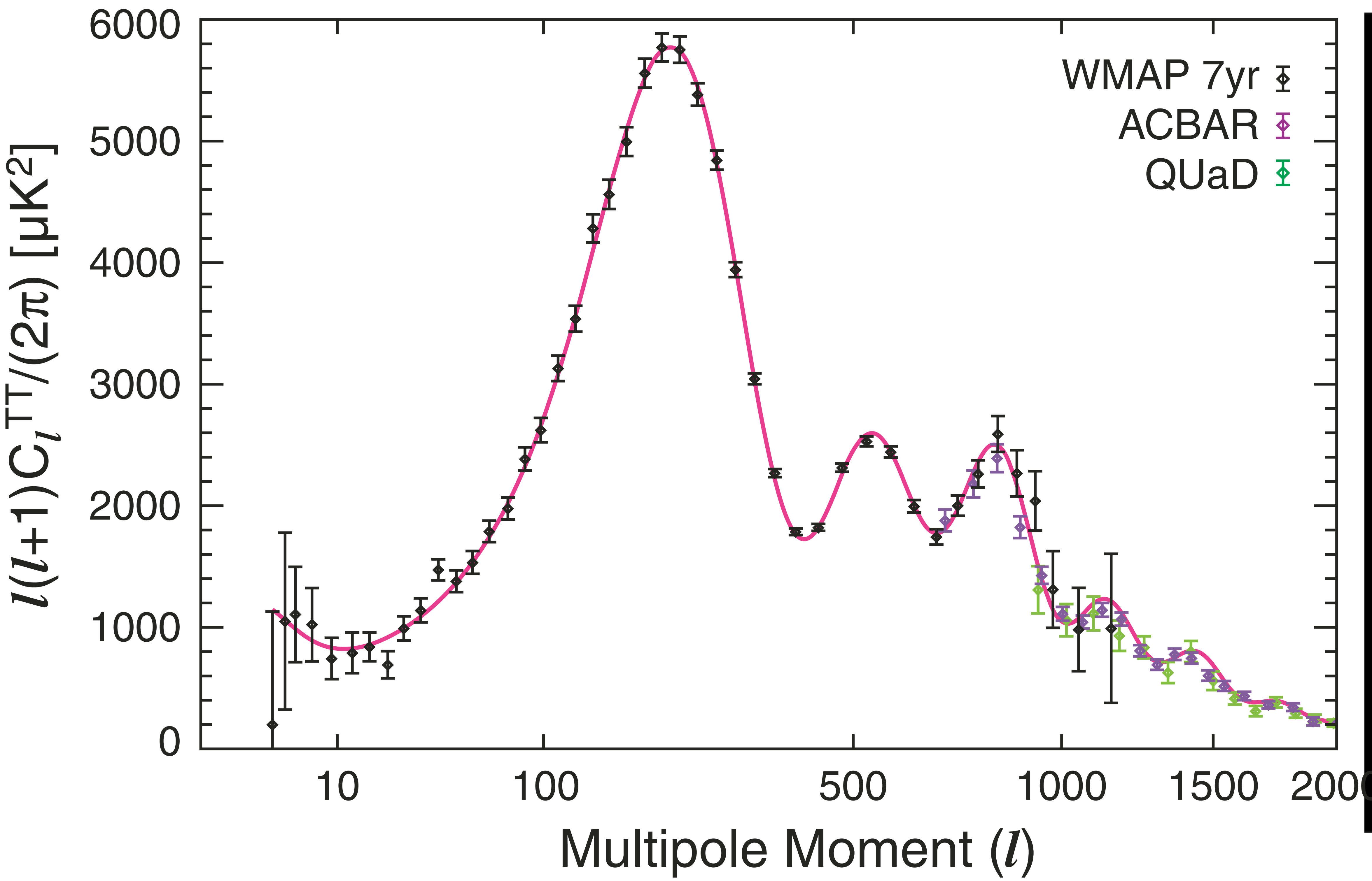

# COBE To WMAP

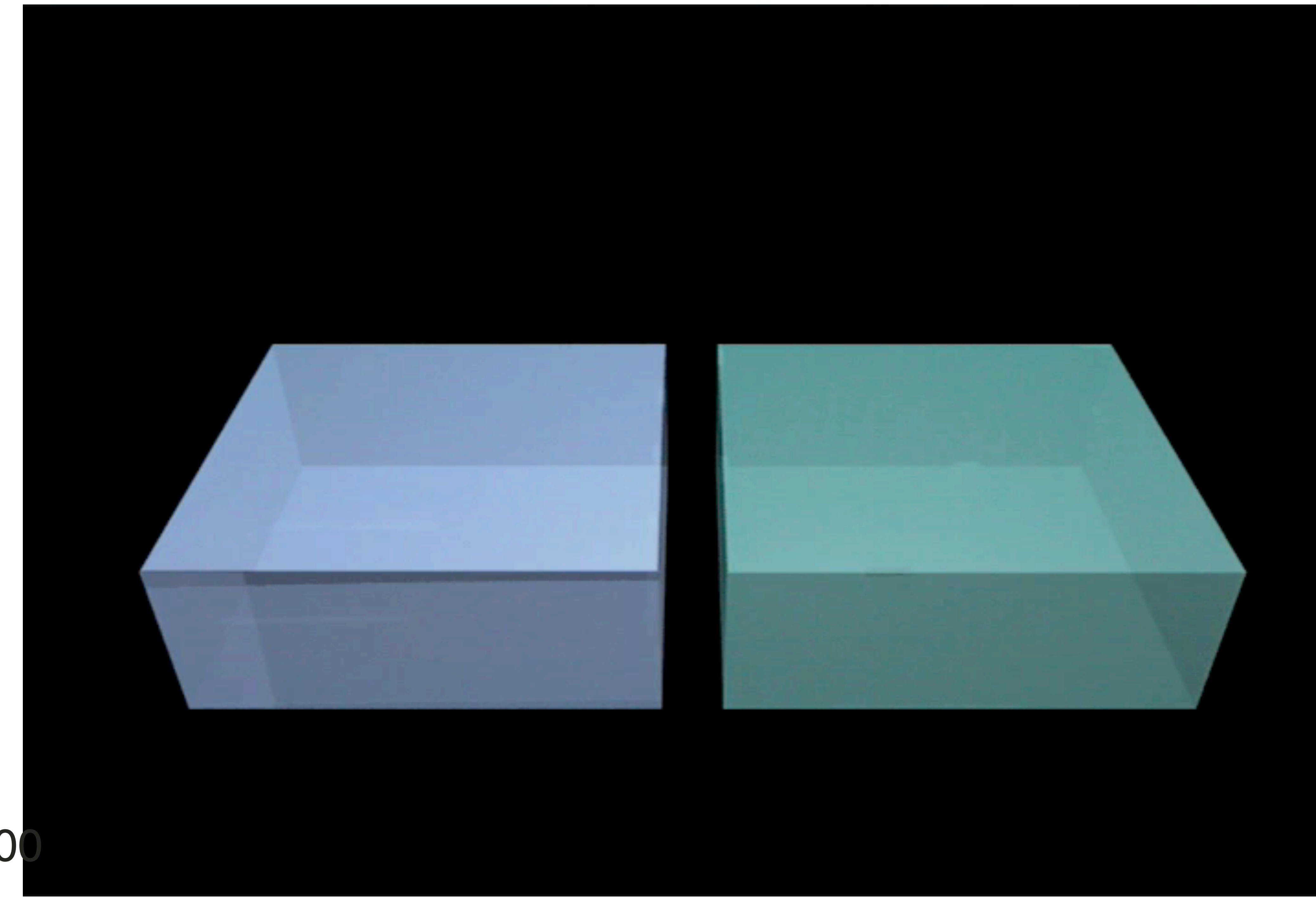
- COBE is unable to resolve the structures below ~7 degrees
- WMAP's resolving power is 35 times better than COBE.
- What did WMAP see?

# WMAP Power Spectrum



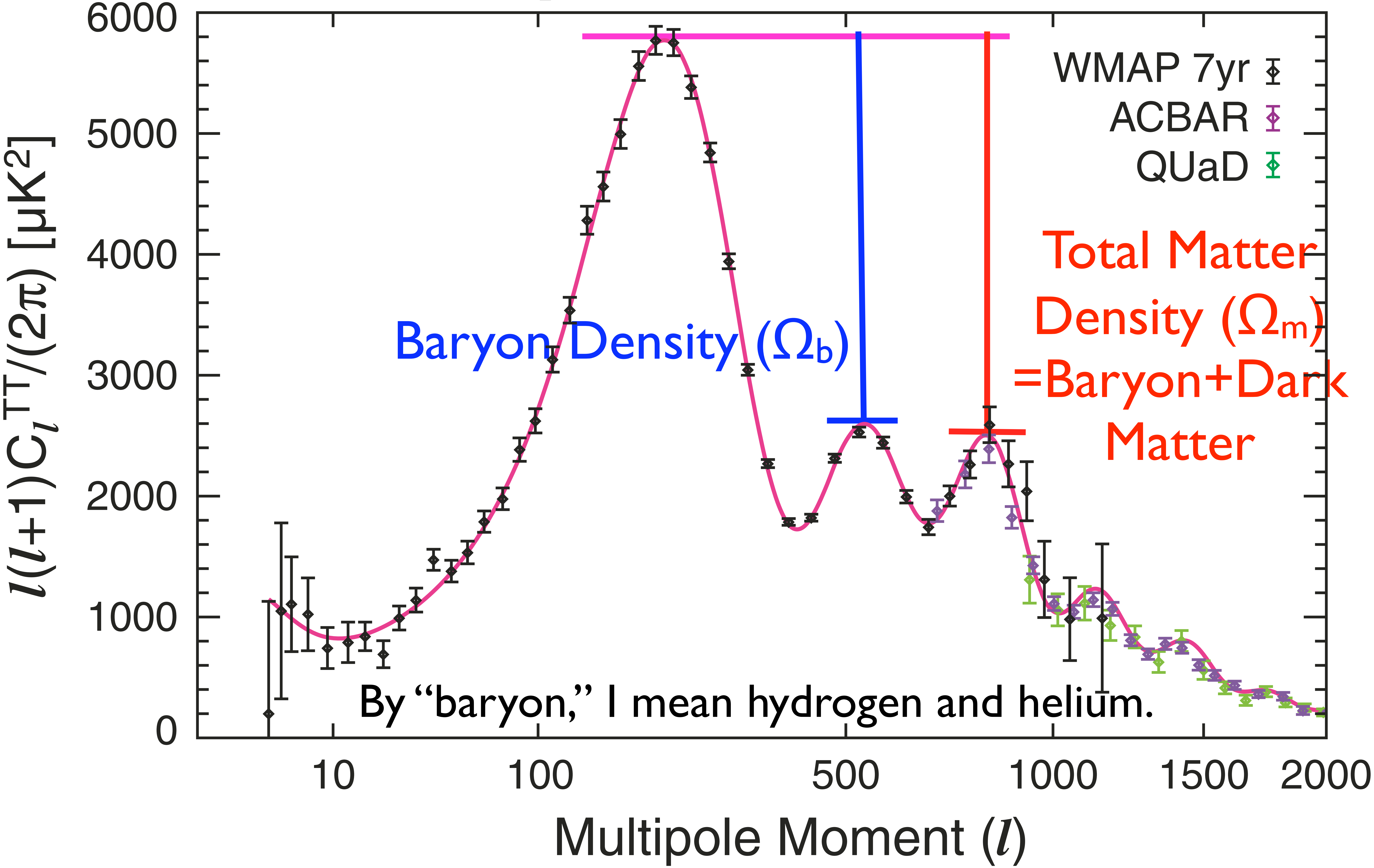
# The Cosmic Sound Wave



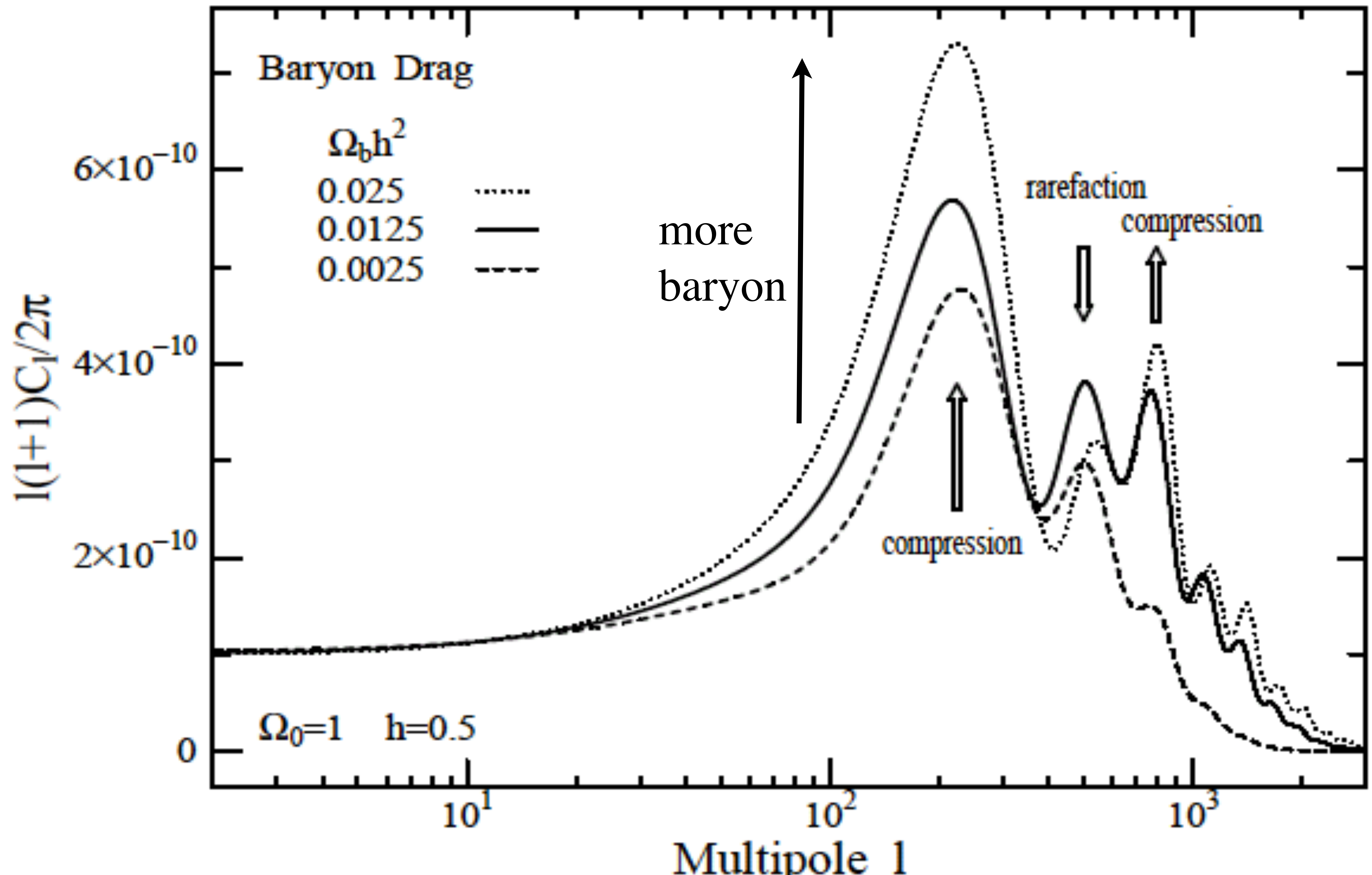



- *"The Universe as a potato soup"*
  - *Main Ingredients: protons, helium nuclei, electrons, photons*
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

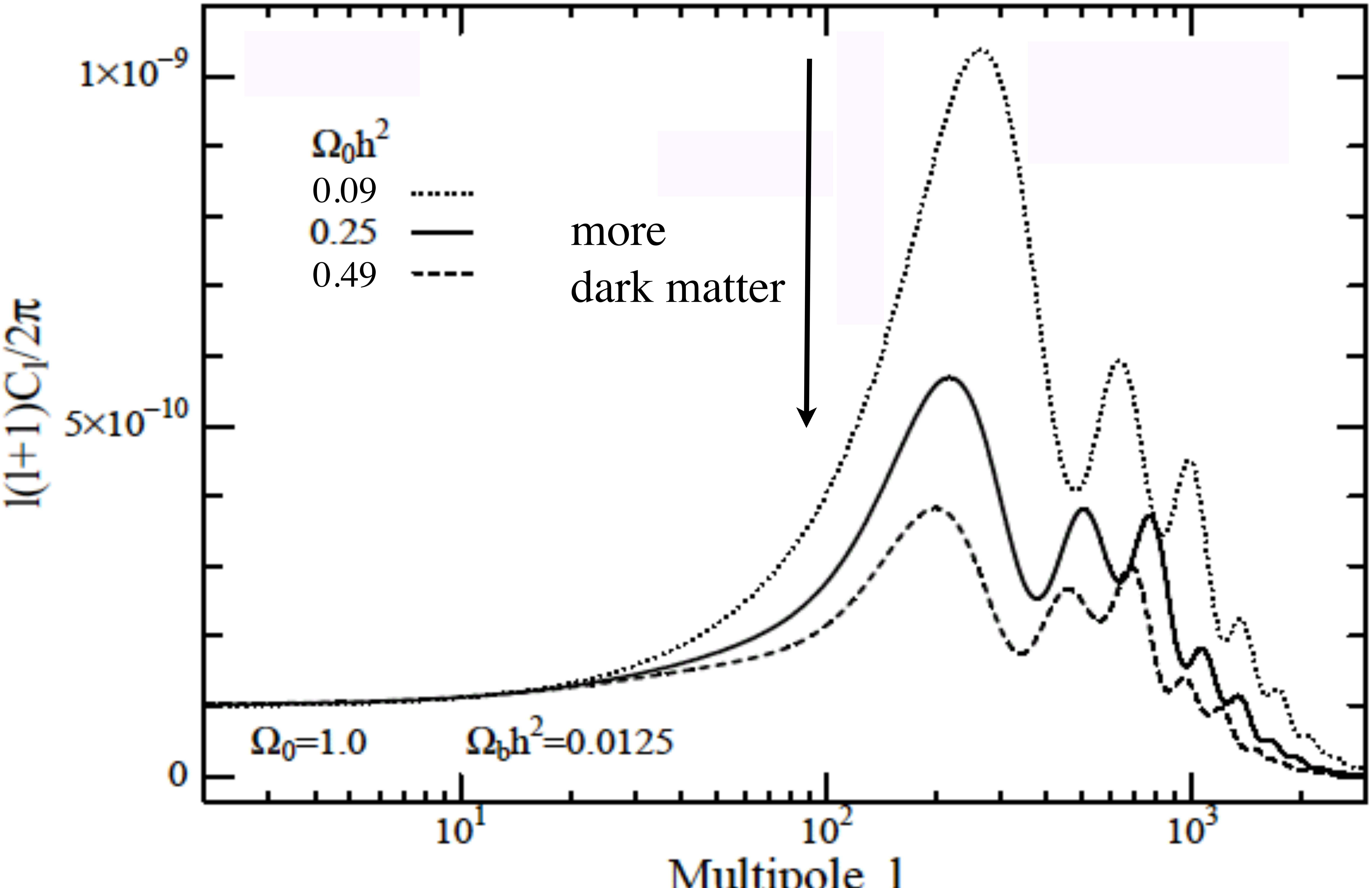
# CMB to Baryon & Dark Matter



# Determining Baryon Density From $C_l$

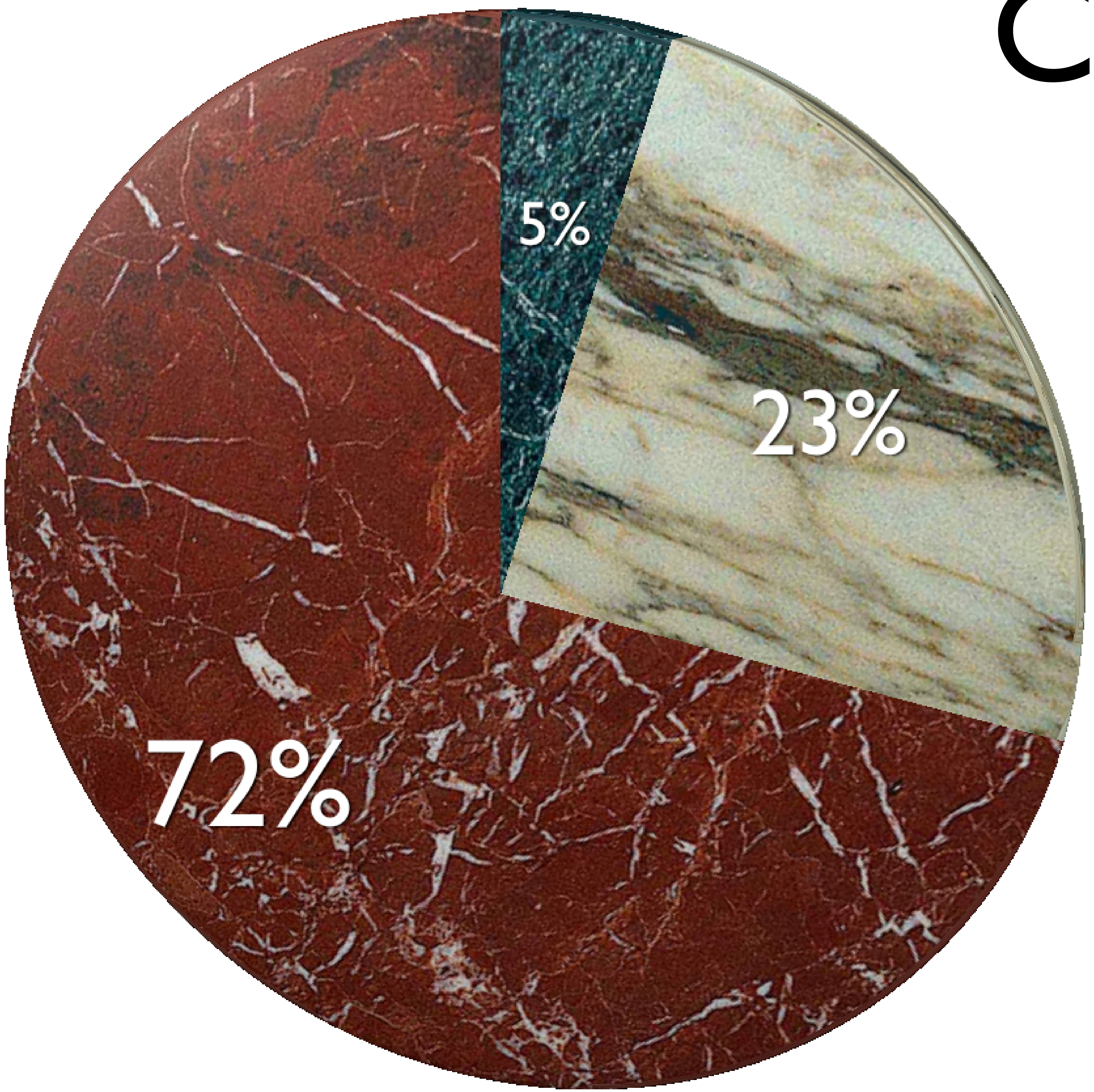


# Determining Dark Matter Density From $C_l$



## Composition of the Universe

# Cosmic Pie Chart




- Cosmological observations (CMB, galaxies, supernovae) over the last decade told us that **we don't understand much of the Universe**.

Hydrogen & Helium
Dark Matter
Dark Energy

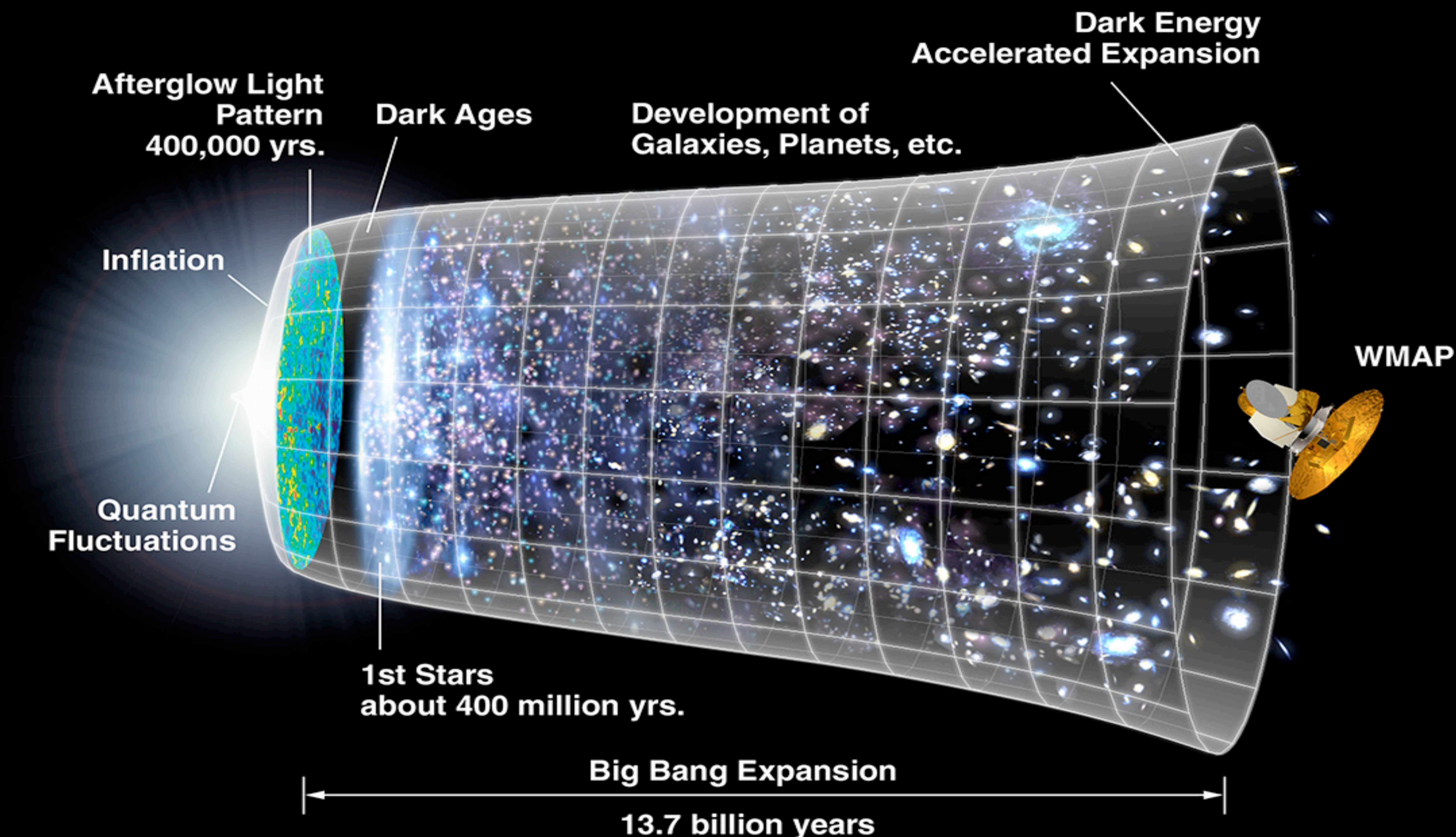
# Going Farther Back in Time!

- 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?**

# Again, Theory:

- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  - The expansion of our Universe ***accelerated*** when it was born.
  - 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 ($\sim 10^{-15}$m) would be stretched to 1 Astronomical Unit ($\sim 10^{11}$m), at least.

# Cosmic Inflation = Very Early Dark Energy






NASA/WMAP Science Team

# Again, Theory:

- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  - The expansion of our Universe ***accelerated*** when it was born,
  - the primordial ripples were created by ***quantum fluctuations*** during inflation.
- Detailed observations give us this remarkable information!

# Quantum Fluctuations?

- You may borrow a lot of money if you promise to return it immediately.
- The amount of money you can borrow is inversely proportional to the time for which you borrow the money.

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

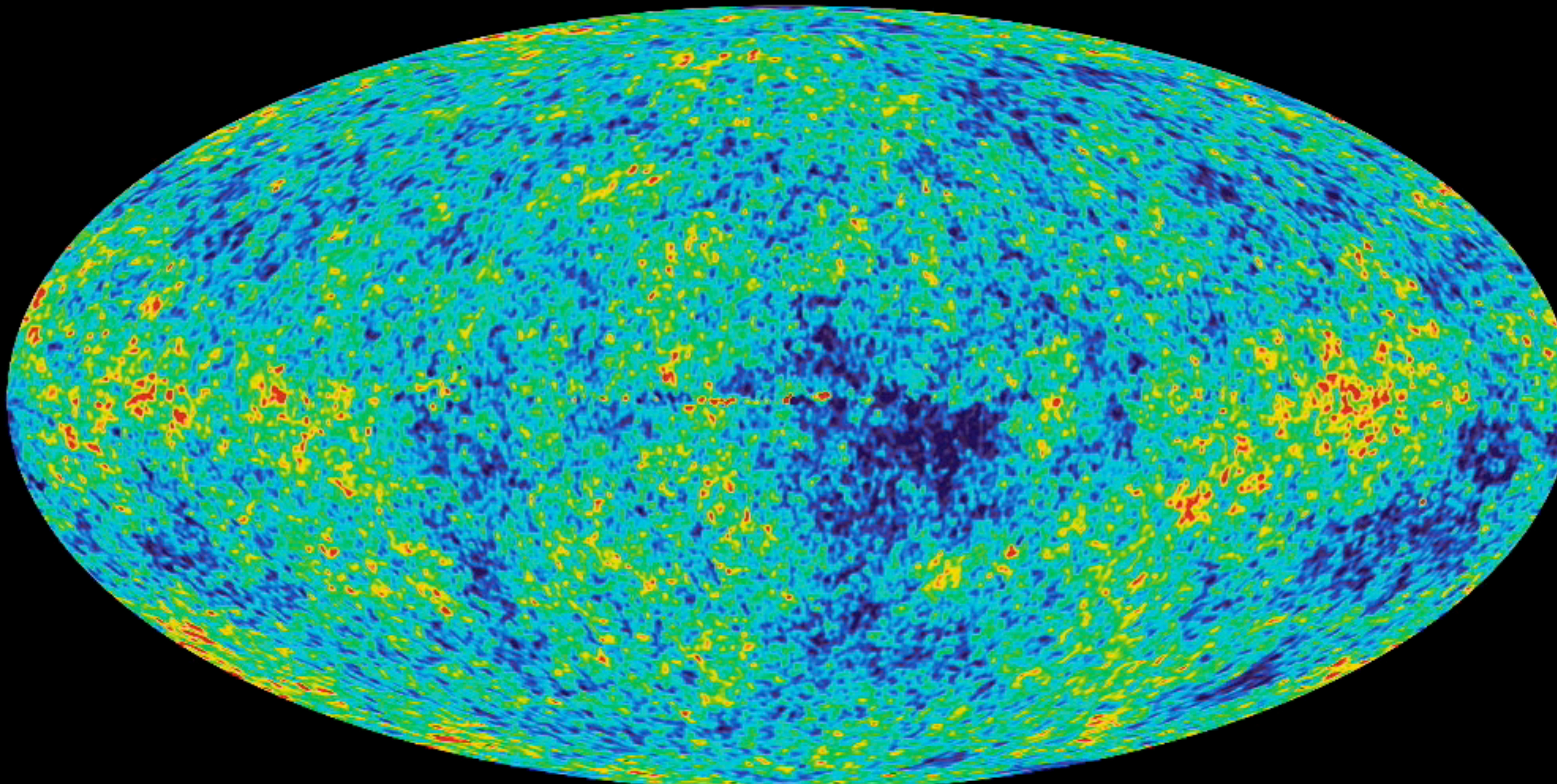
# Quantum Fluctuations

(Energy You Borrow From Vacuum)
= *h* / (Time For Which You Borrow Energy)

- 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 (don't faint just yet!)
- Time is short, so you can borrow a lot of energy:
  - *Quantum fluctuations were important during inflation!*

# Are we stardust?

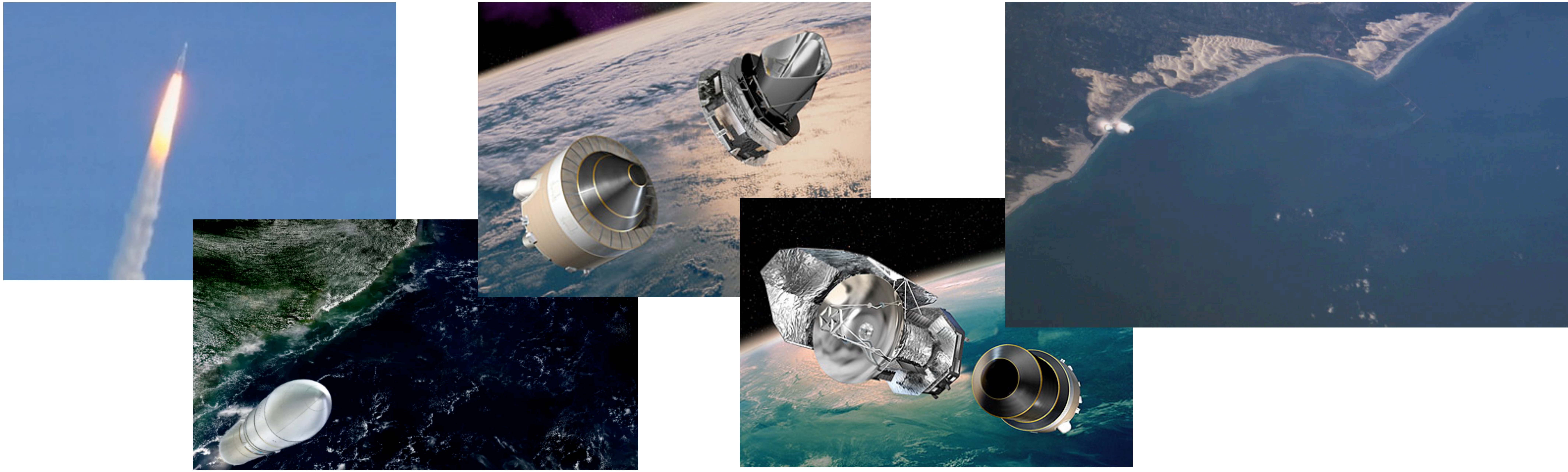
- Actually, we are more than stardust:
  - **We are children of Quantum Fluctuations**.
  - When the Universe was born and underwent inflation, quantum fluctuations were generated.
  - These quantum fluctuations were the seeds for ripples in matter and radiation.
- We were born in the places where there was more matter.
- And, we can (almost) directly observe the pattern of the quantum fluctuations using, e.g., ***CMB***!



# Recap

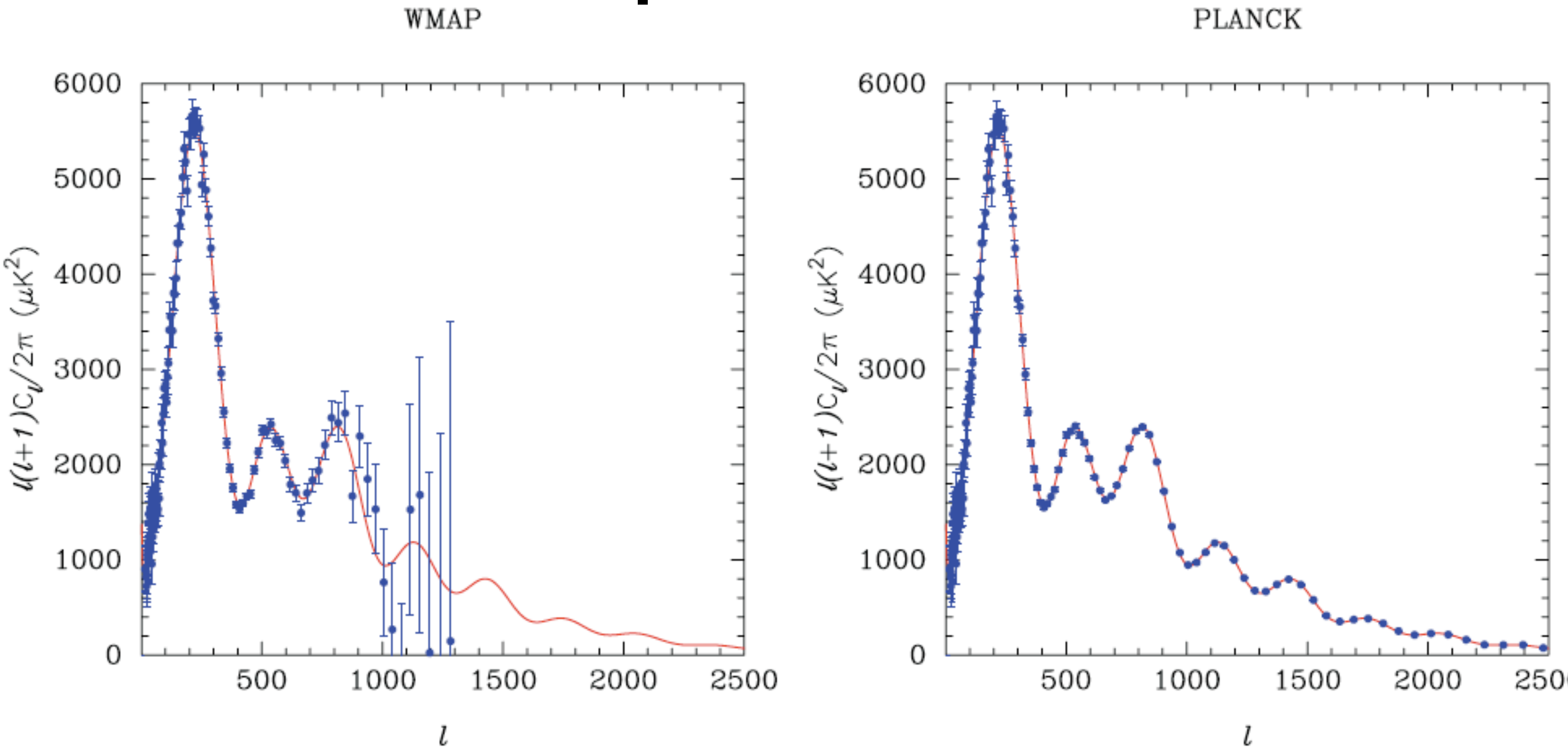
- CMB is the fossil light of the Big Bang, and the oldest light that one can ever hope to measure directly.
  - The present-day temperature is 2.7 K.
- The CMB photons were decoupled from electrons when the universe was 3000 K.
- The ripples in CMB form sound waves, and we can use these waves to measure the baryon density, dark matter density, geometry, the age of the universe, etc.
- We think that the cosmic inflation in the very early universe created these ripples from quantum fluctuations.

# 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 ~2012.

# Planck: Expected $C_l^{Temperature}$




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