Frontiers in Cosmology

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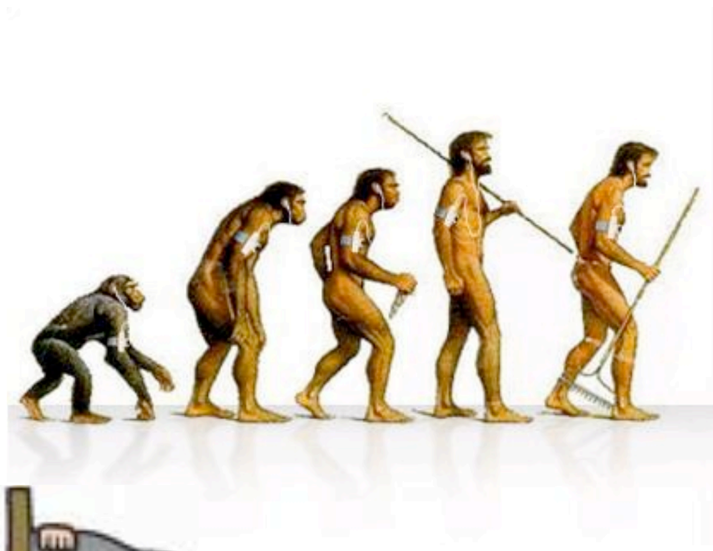
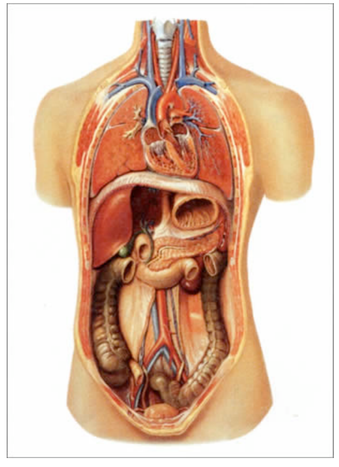
Great Lecture, February 7, 2009

From "Cosmic Voyage"

Cosmology - What is it?

- Study of **various properties of the Universe**, including:
  - Emergence
  - Evolution (History)
  - Structure
  - Composition
  - Etc.





Golden Age of Cosmology

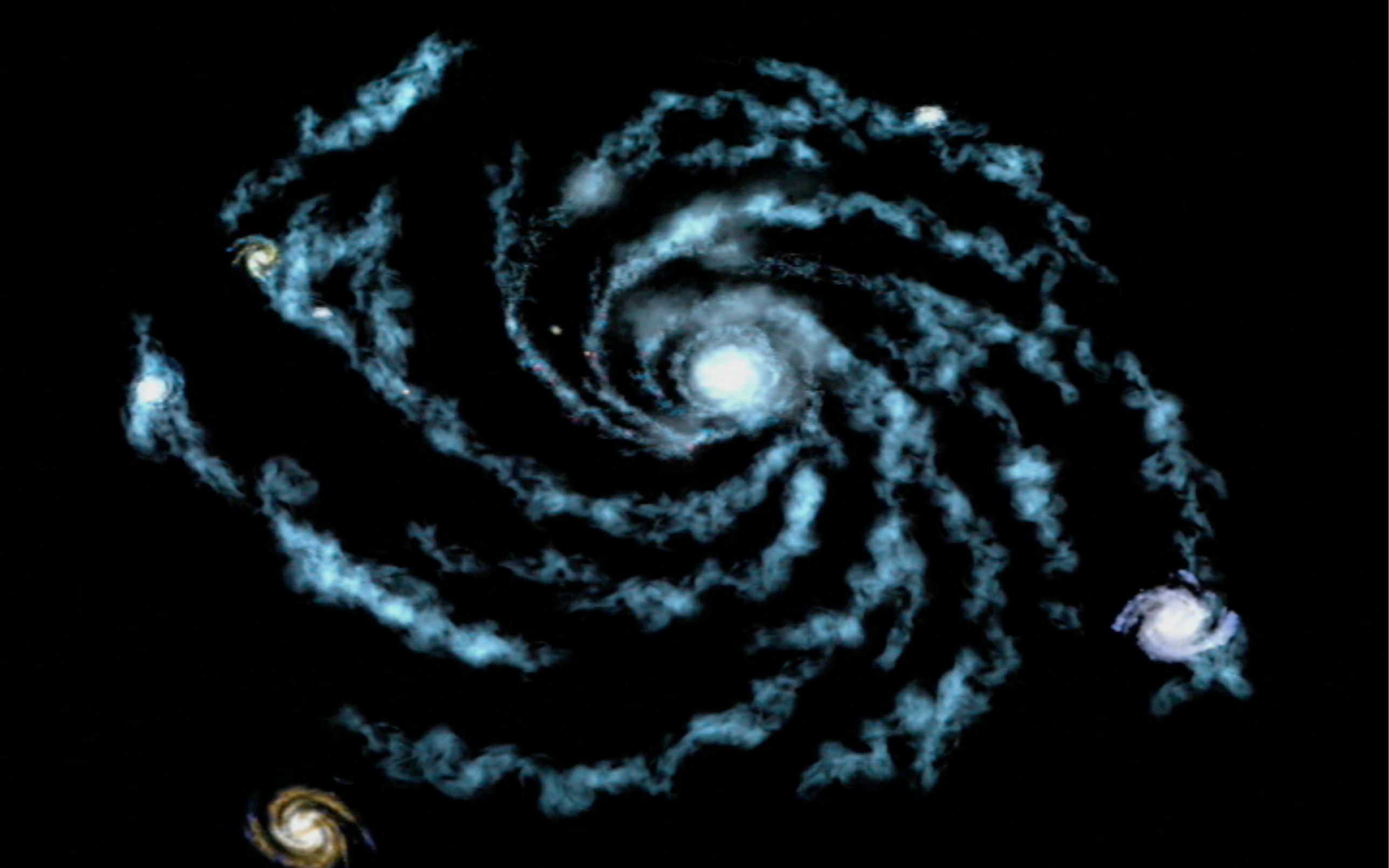
- **Why Golden Age?** Ask questions about our Universe. For most of them, we have good answers: the answers that were obtained over the last decade.
  - *How old is our Universe?*
    - 13.7±0.1 billion years old.
  - *How fast is our Universe expanding?*
    - At 100 Mpc distance, 70500±1300 km/s.

Golden Age of Cosmology

- **Why Golden Age?** Ask questions about our Universe. For most of them, we have good answers: the answers that were obtained over the last decade.
  - *What is the geometry of our observable Universe?*
    - Flat (Euclidean), to about 1% level.
  - When were the first generation of galaxies formed?
    - When our Universe was about 400 million years old.

How Do We Know That?

- An incredible collaboration between theory and observations in modern cosmology.
- **Both** theory and observations have experienced remarkable advances over the last decade.



Night Sky in Optical (~500nm)

courtesy University of Arizona

Night Sky in Microwave (~1mm)

courtesy University of Arizona

Night Sky in Microwave (~1mm)

Cosmic Microwave Background
(CMB)
Uniform Across the Entire Sky

courtesy University of Arizona

A. Penzias & R. 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.

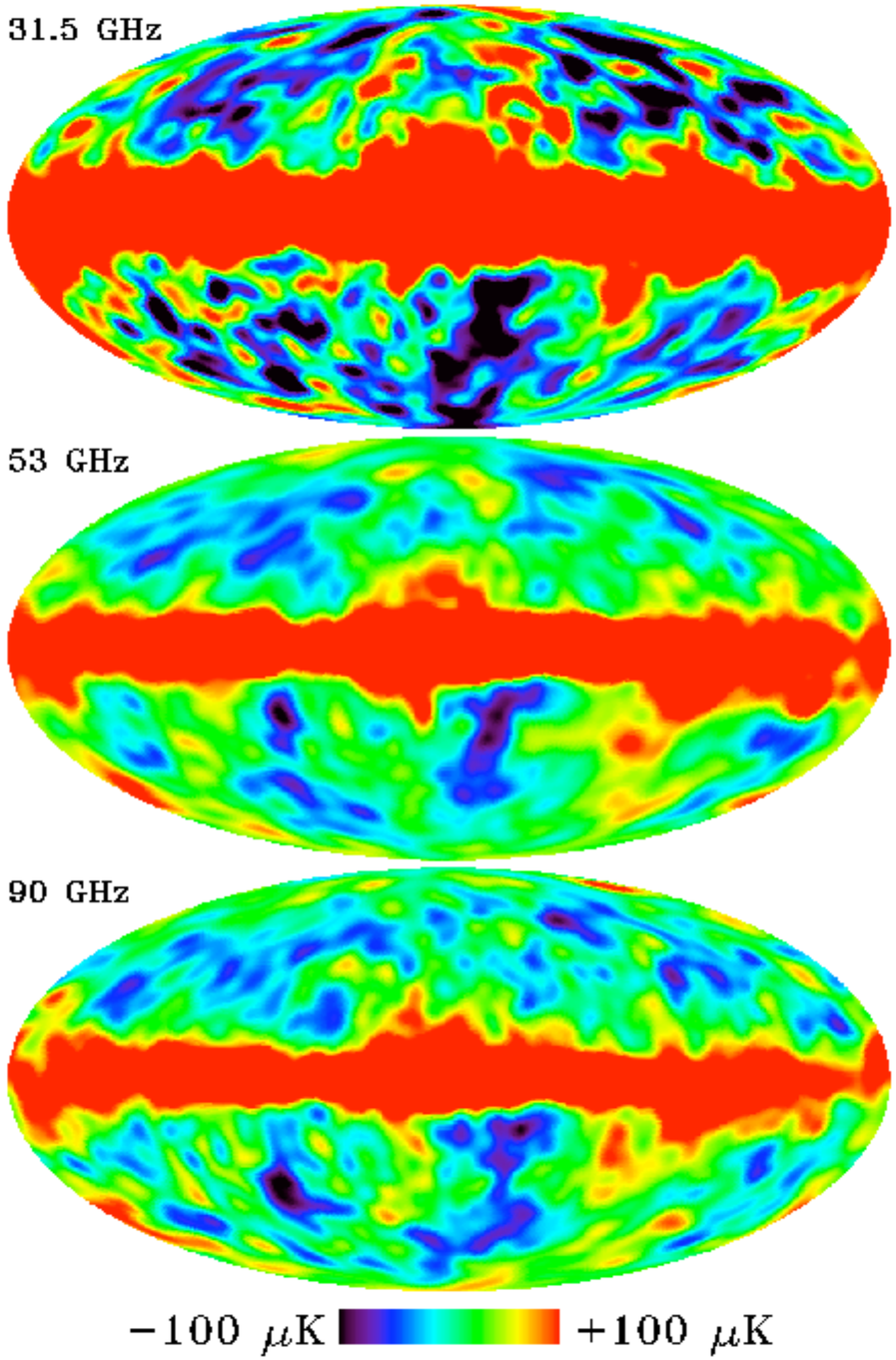
A. A. Penzias
R. W. Wilson

May 13, 1965

Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

- Isotropic
- Unpolarized

COBE/DMR, 1992



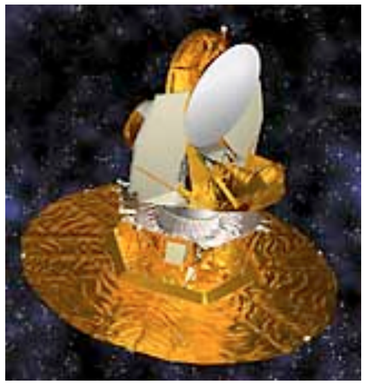
- **Isotropic?**
- **CMB is anisotropic! (at the 1/100,000 level)**

COBE to WMAP (x35 better resolution)

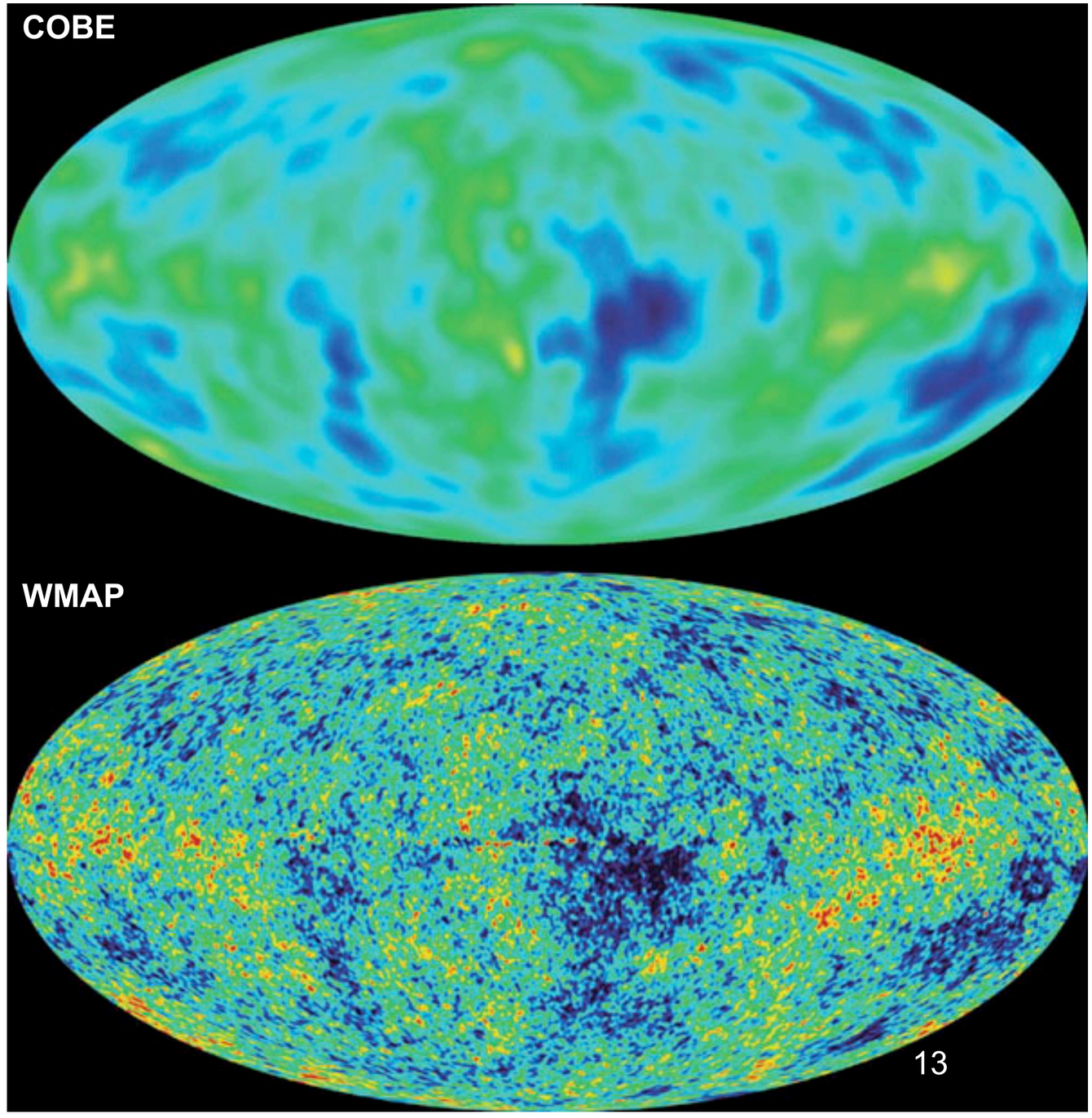
COBE
1989

Press Release from the Nobel Foundation

[COBE's] measurements also marked the inception of cosmology as a precise science. It was not long before **it was followed up,** for instance **by the WMAP satellite, which yielded even clearer images of the background radiation**.



WMAP
2001



Wilkinson Microwave Anisotropy Probe

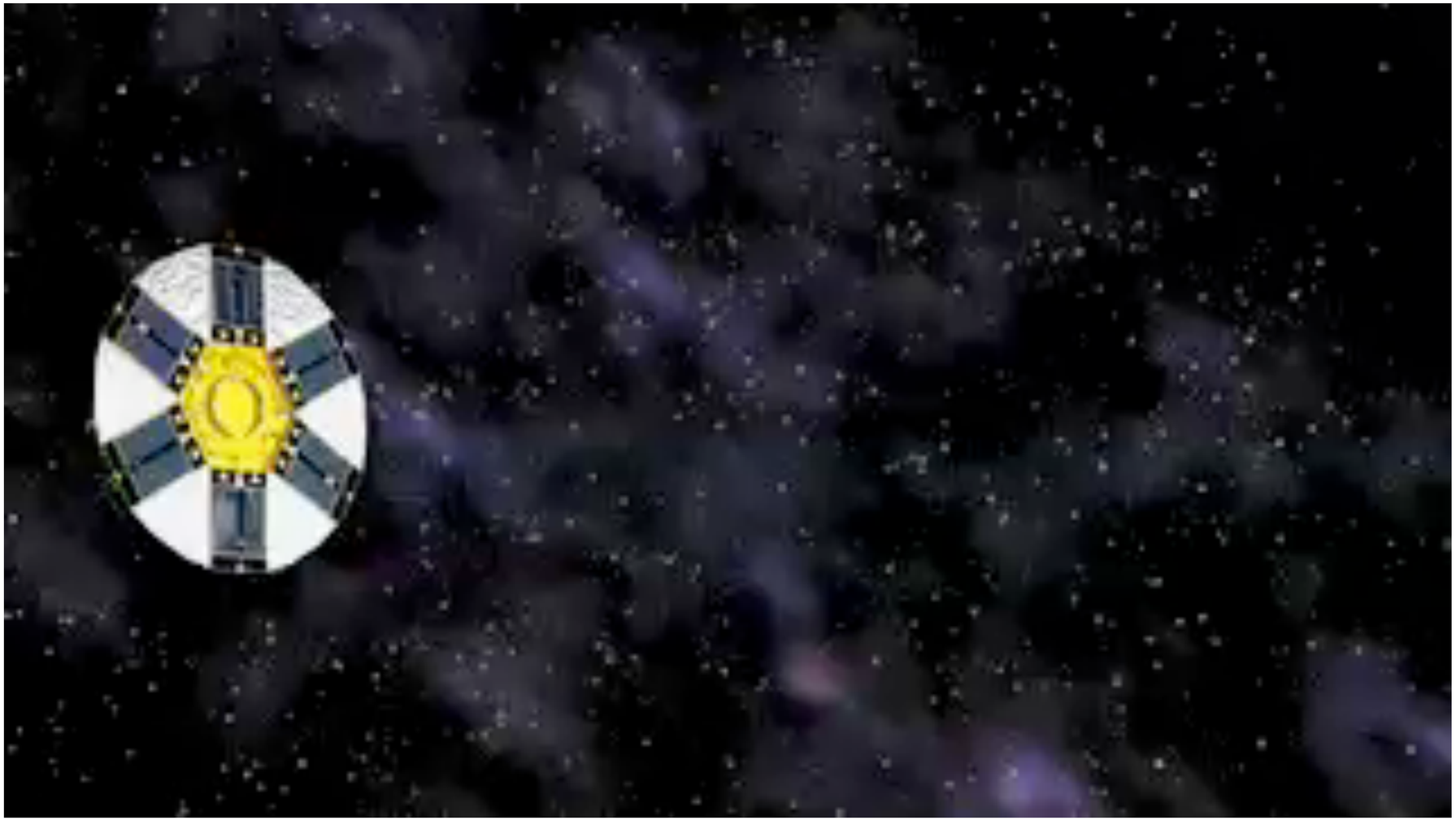
WMAP at Lagrange 2 (L2) Point

June 2001:
WMAP launched!

February 2003:
The first-year data release

March 2006:
The three-year data release

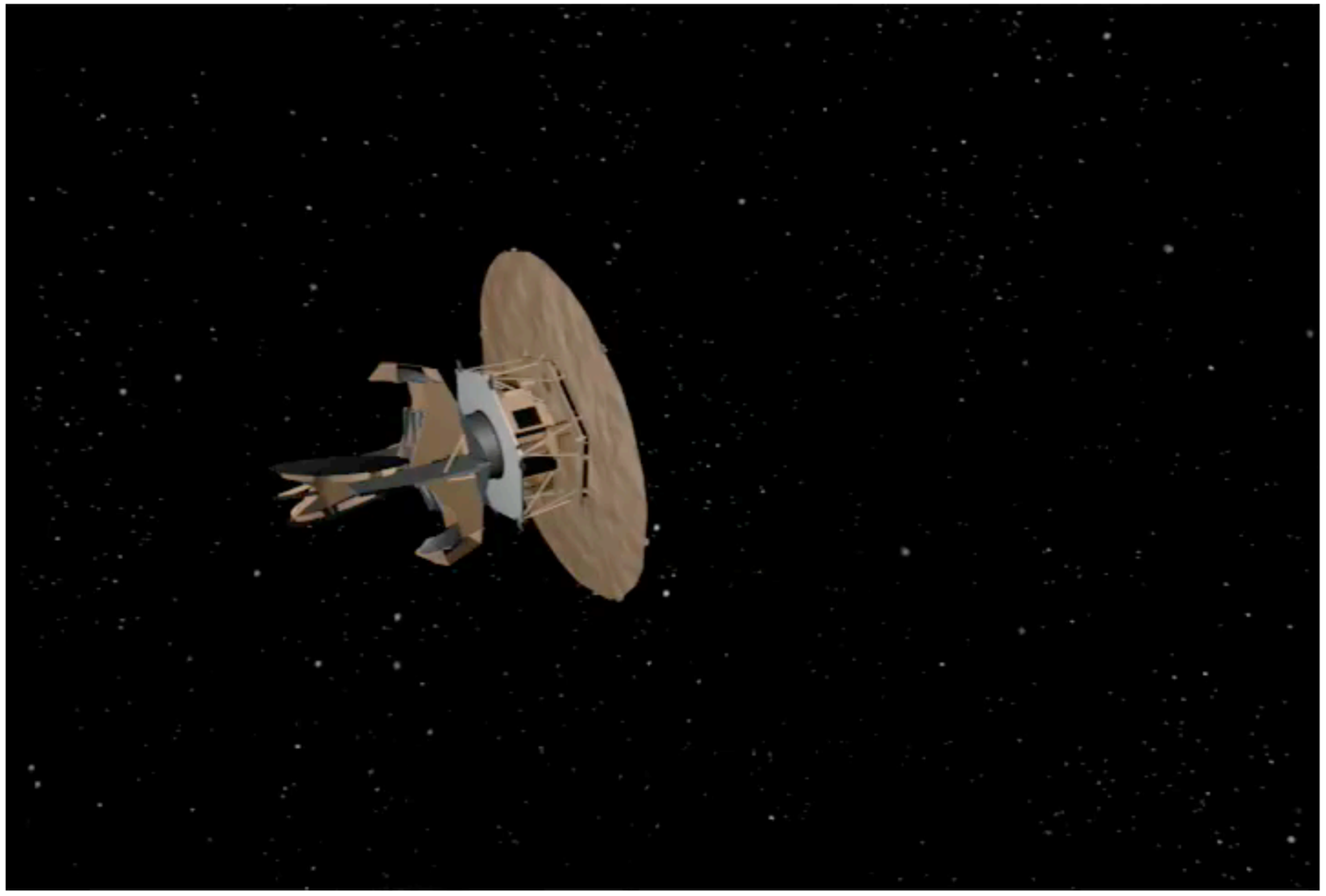
March 2008:
The five-year data release



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

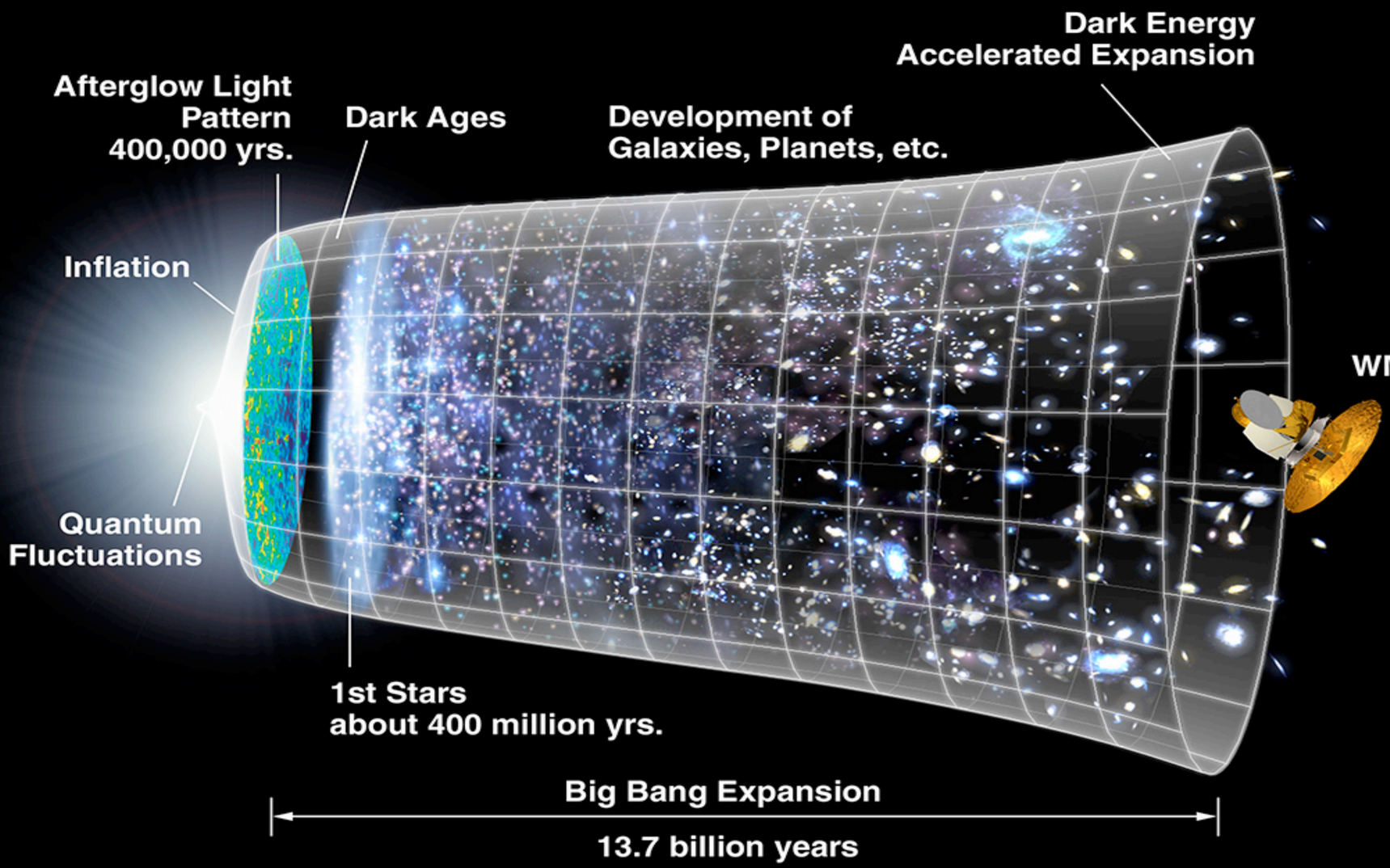
Journey Backwards in Time

- 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



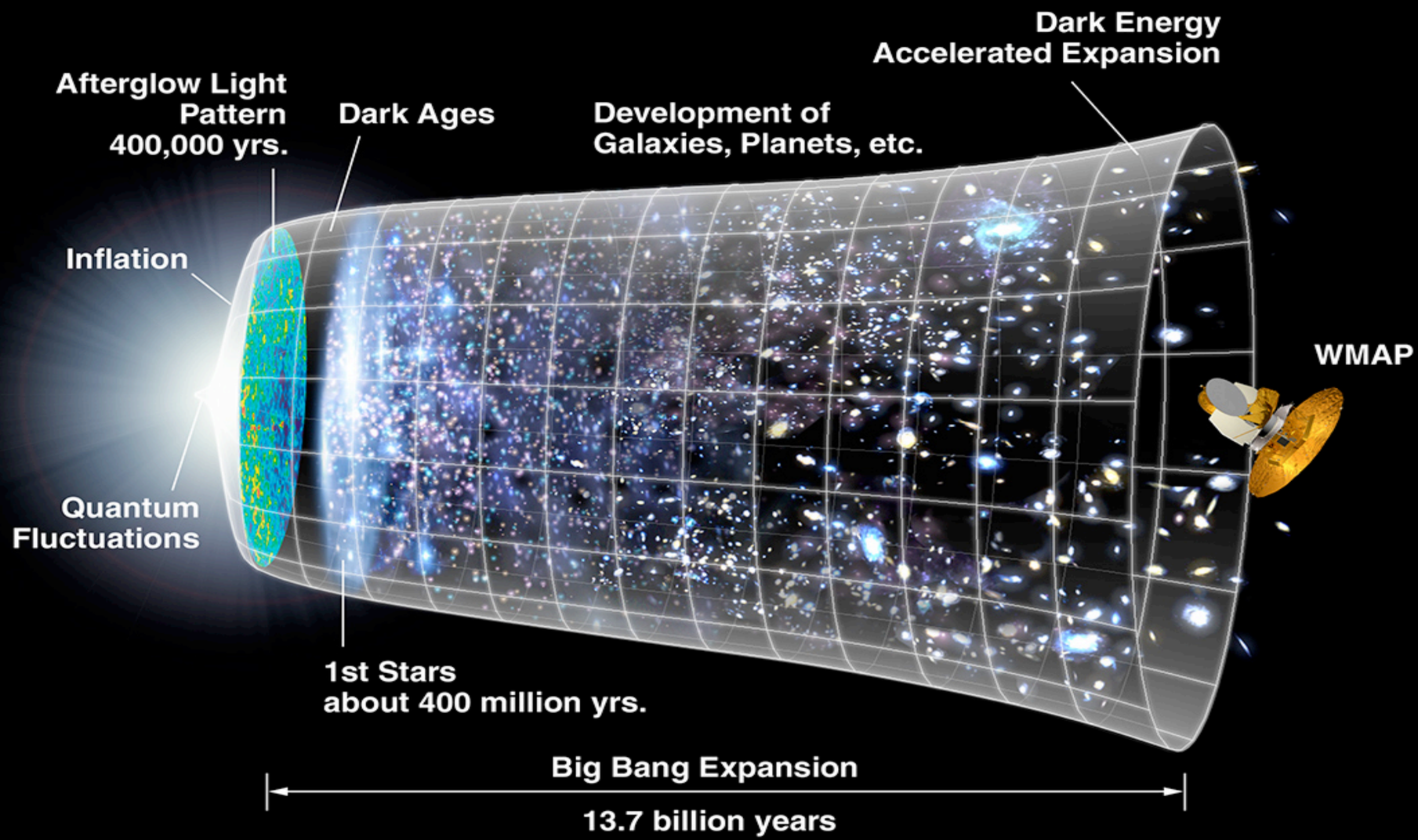
- CMB photons, after released from the cosmic plasma "soup," traveled for **13.7 billion years** to reach us.
- CMB collects information about the Universe as it travels through it.

CMB: A Messenger From the Early Universe...



NASA/WMAP Science Team

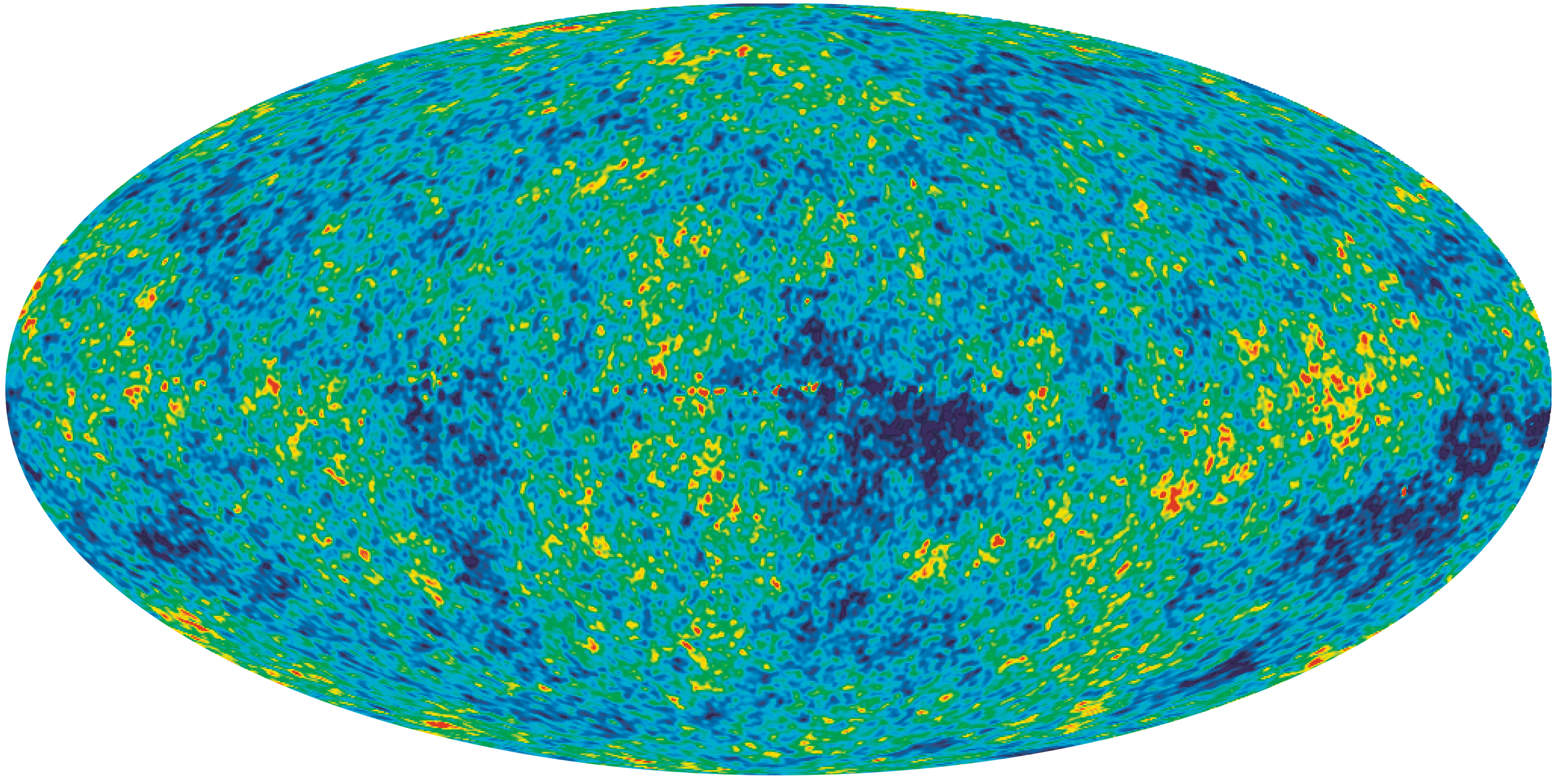
CMB: The Most Distant Light



- 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

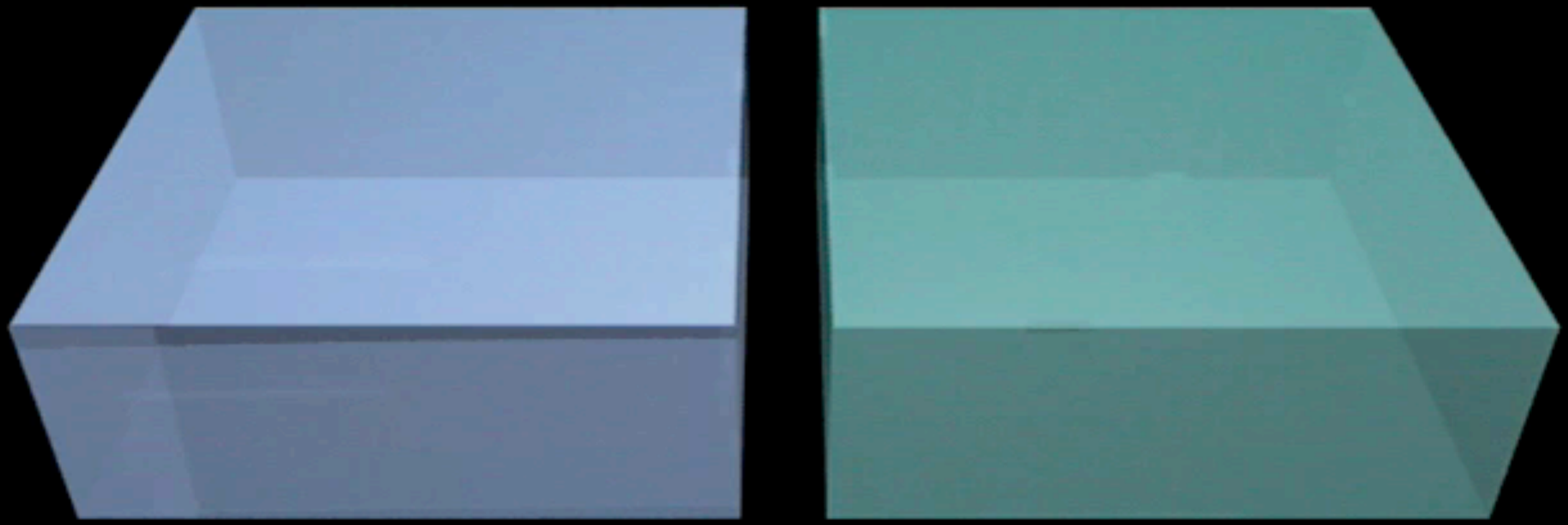
How were these ripples created?



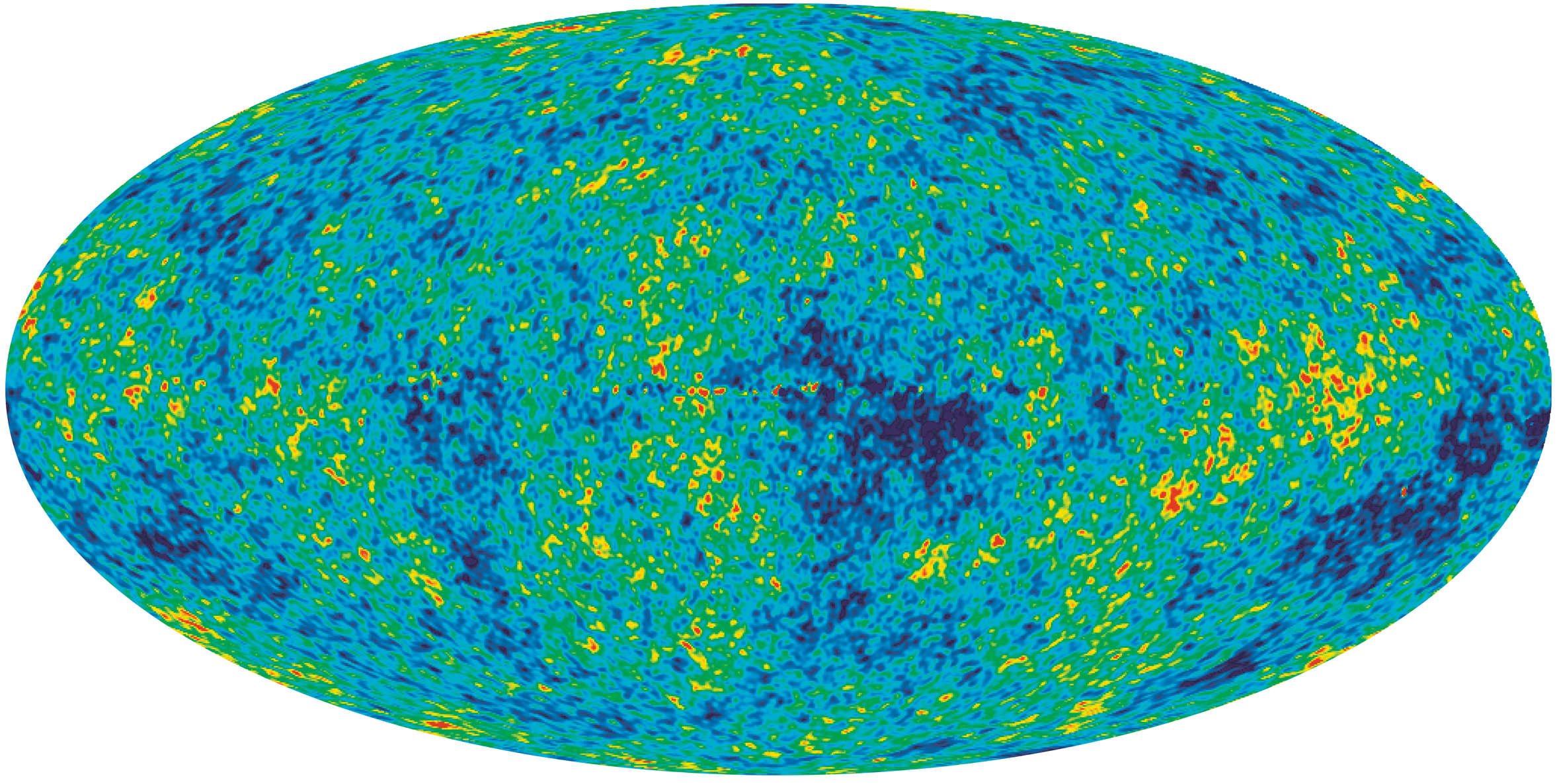
Here Comes the Power of ***Theory***

- 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
- What would happen if you "perturb" the soup?

The Cosmic Sound Wave

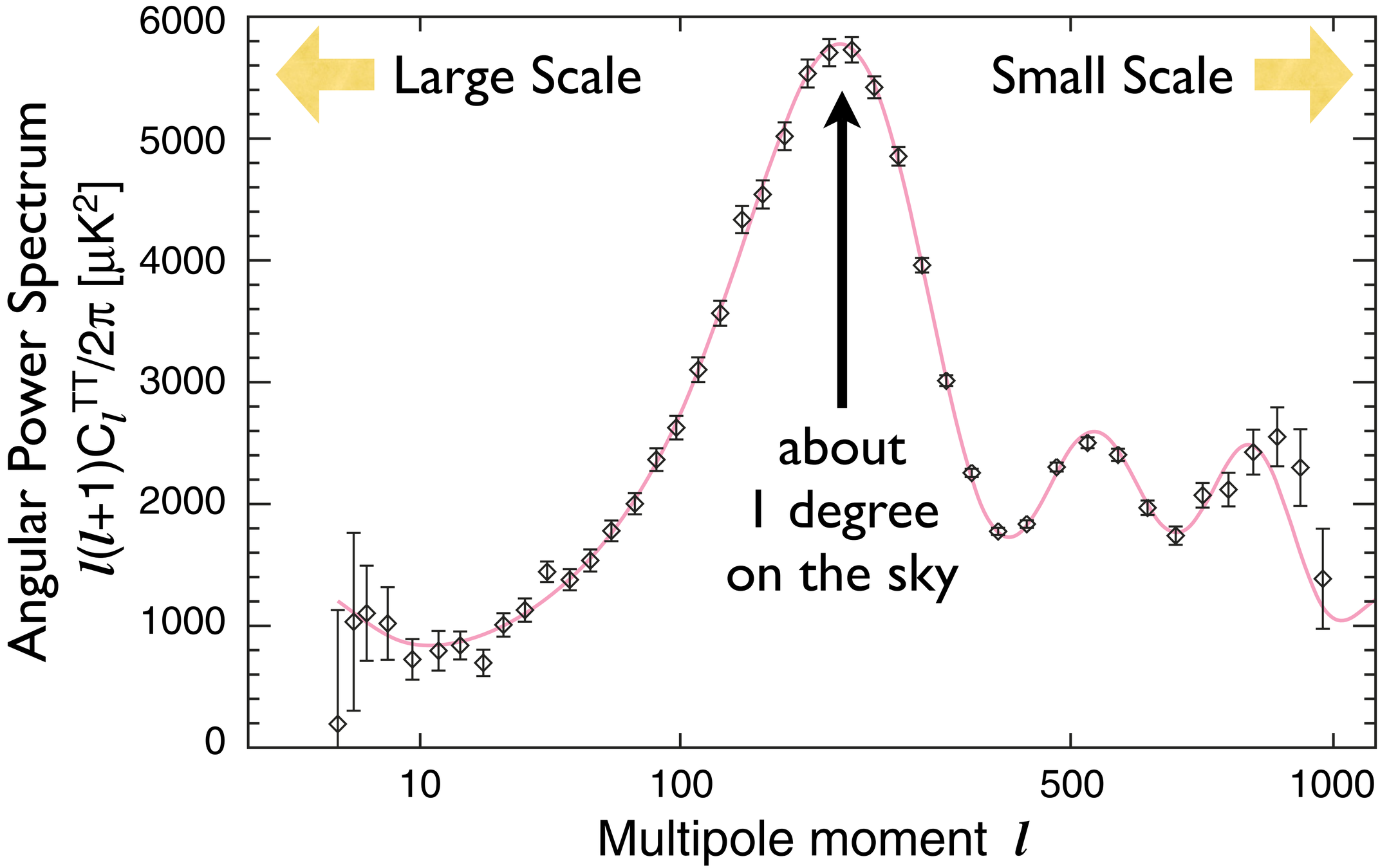


Can You See the Sound Wave?

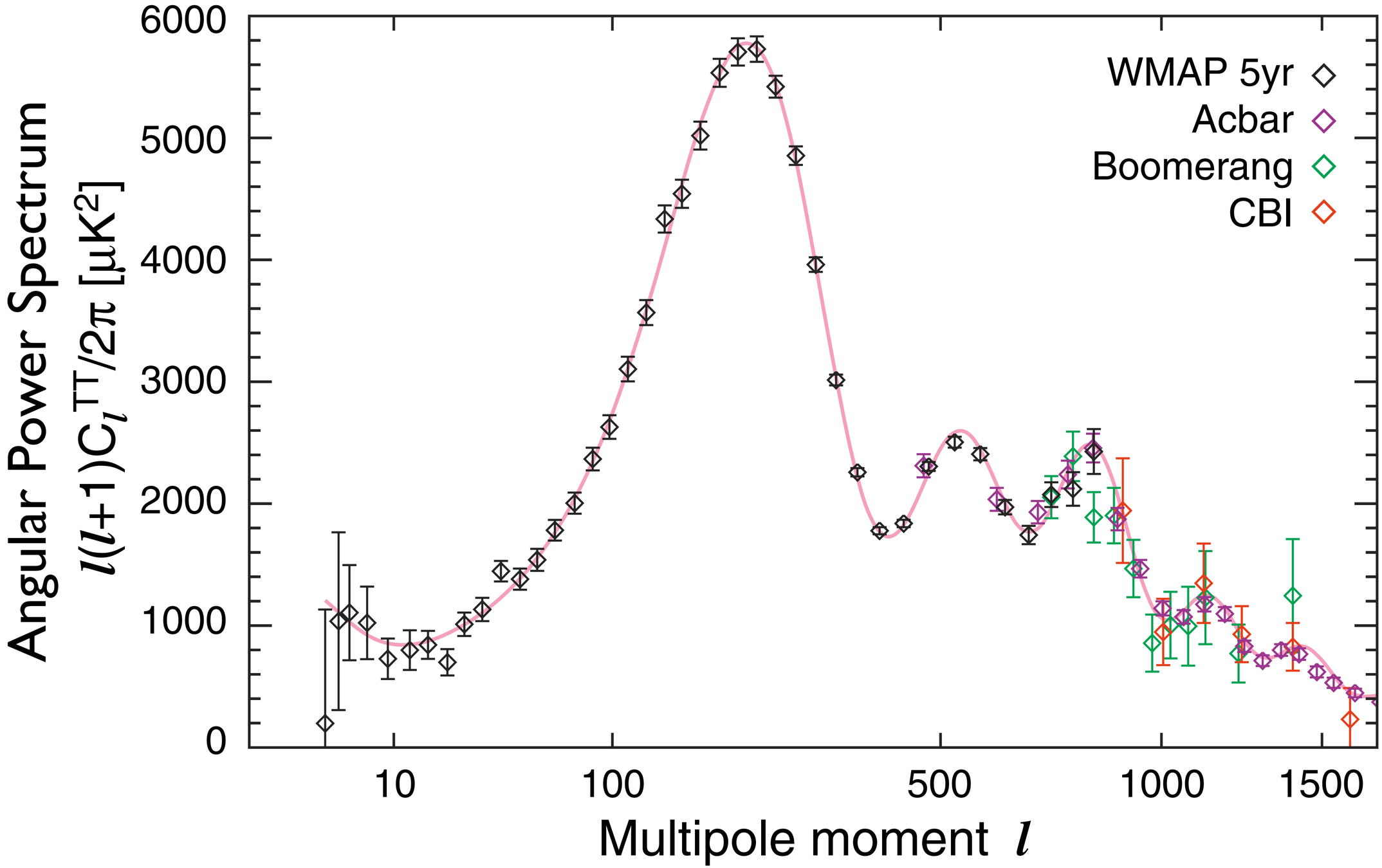


WMAP 5-year

The Spectral Analysis



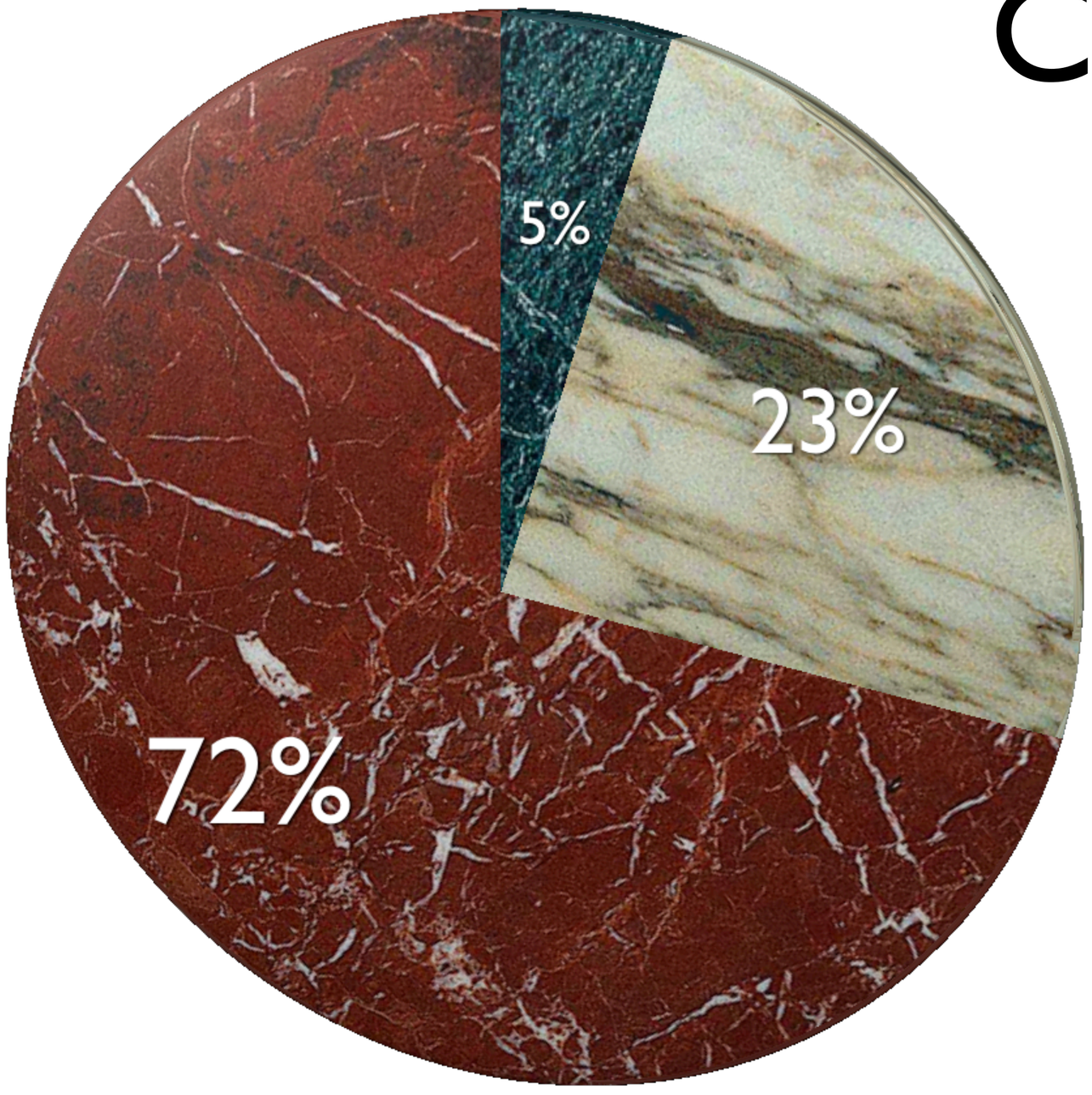
Theory and Observations Match



But, this is just the beginning

- A **real reason** why we think we are living in the Golden Age of Cosmology?

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

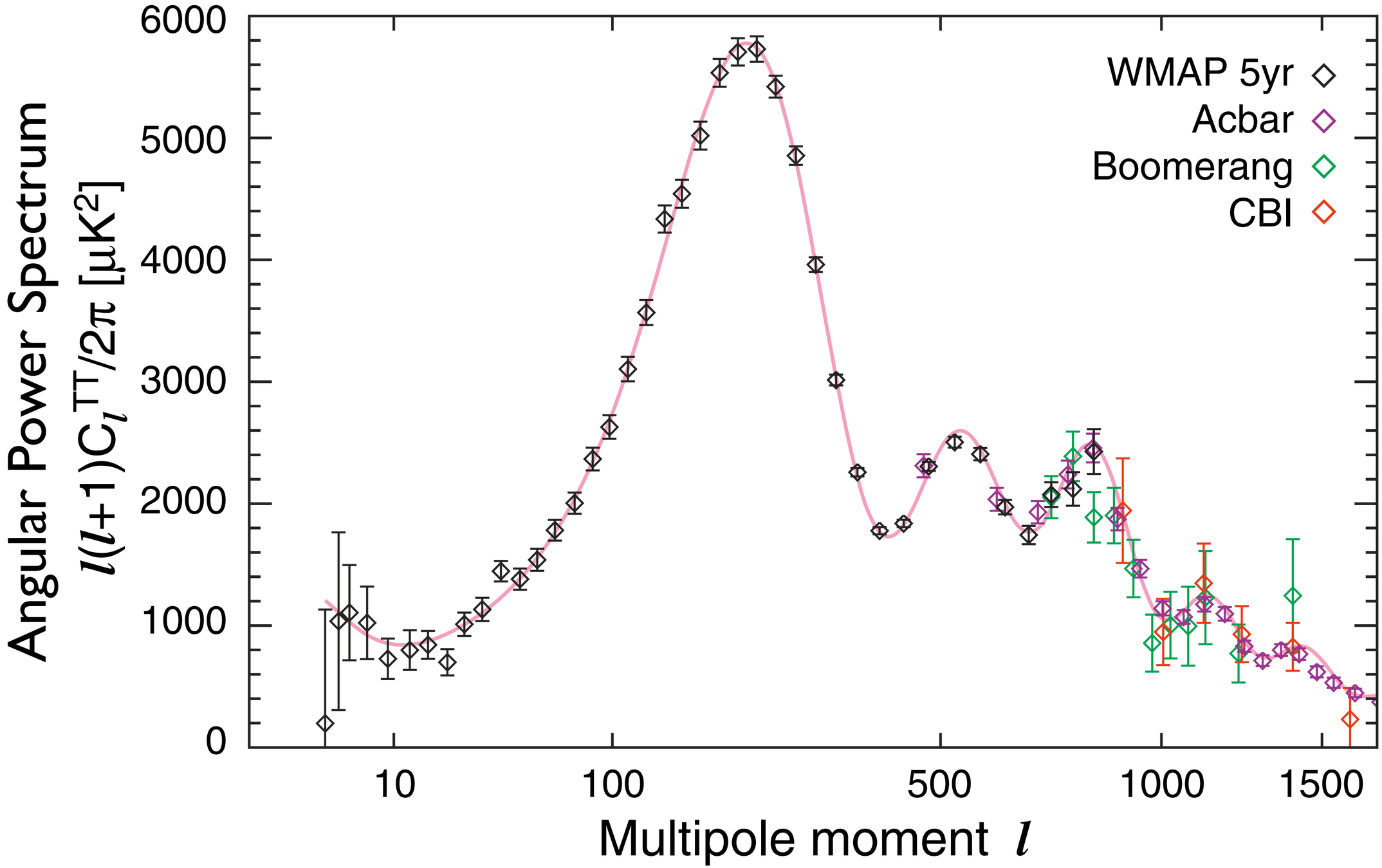
Golden Age of Cosmology

- **Q. Why Golden Age?**
- **A. Because we are facing extraordinary challenges.**
  - What is Dark Matter?
  - What is Dark Energy?
- Isn't that exciting?
- And, theoretical ideas and observations continue to collaborate and influence each other.
  - **That's the heart of the Texas Cosmology Center.**

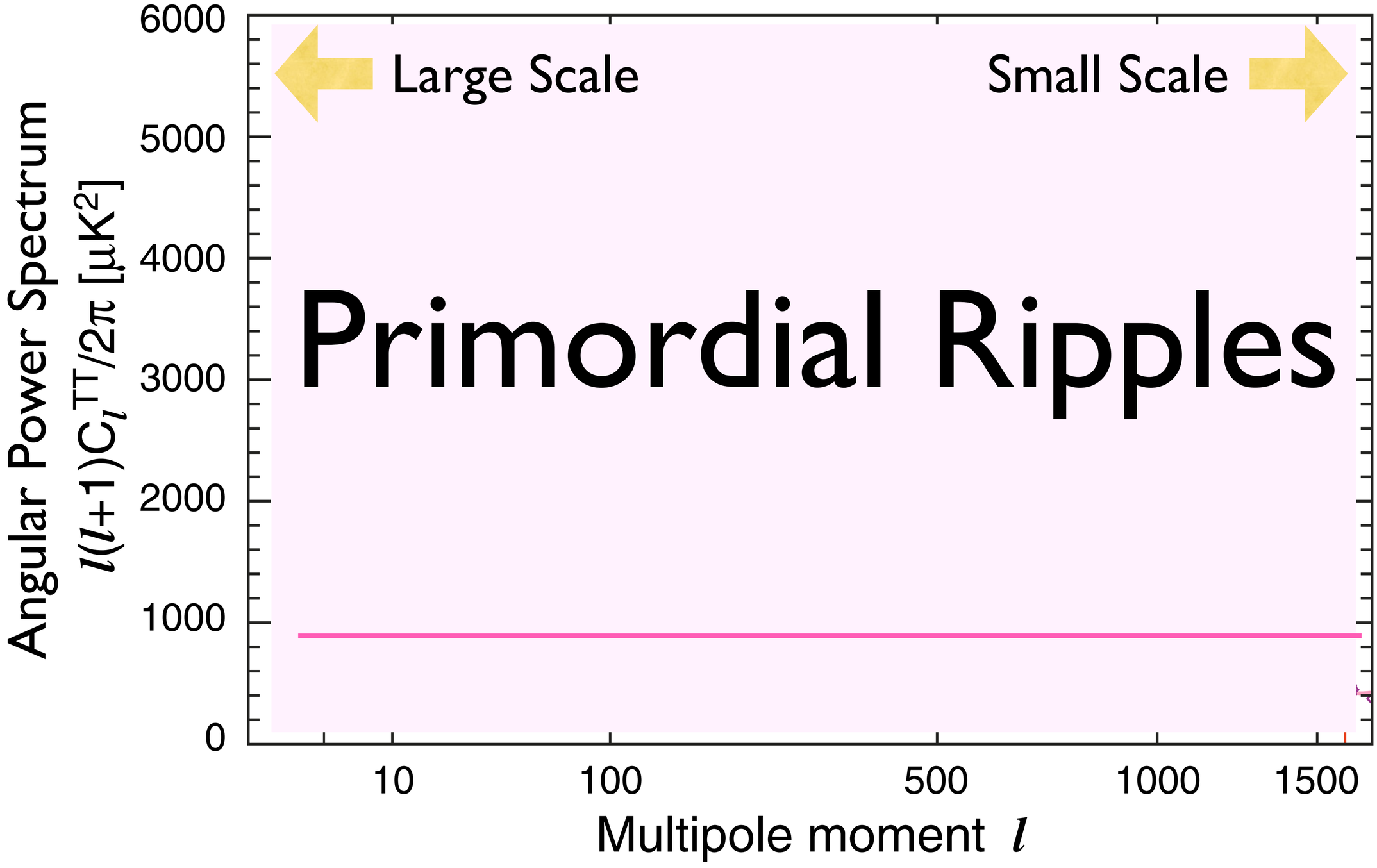
Even More Challenges

- 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?**

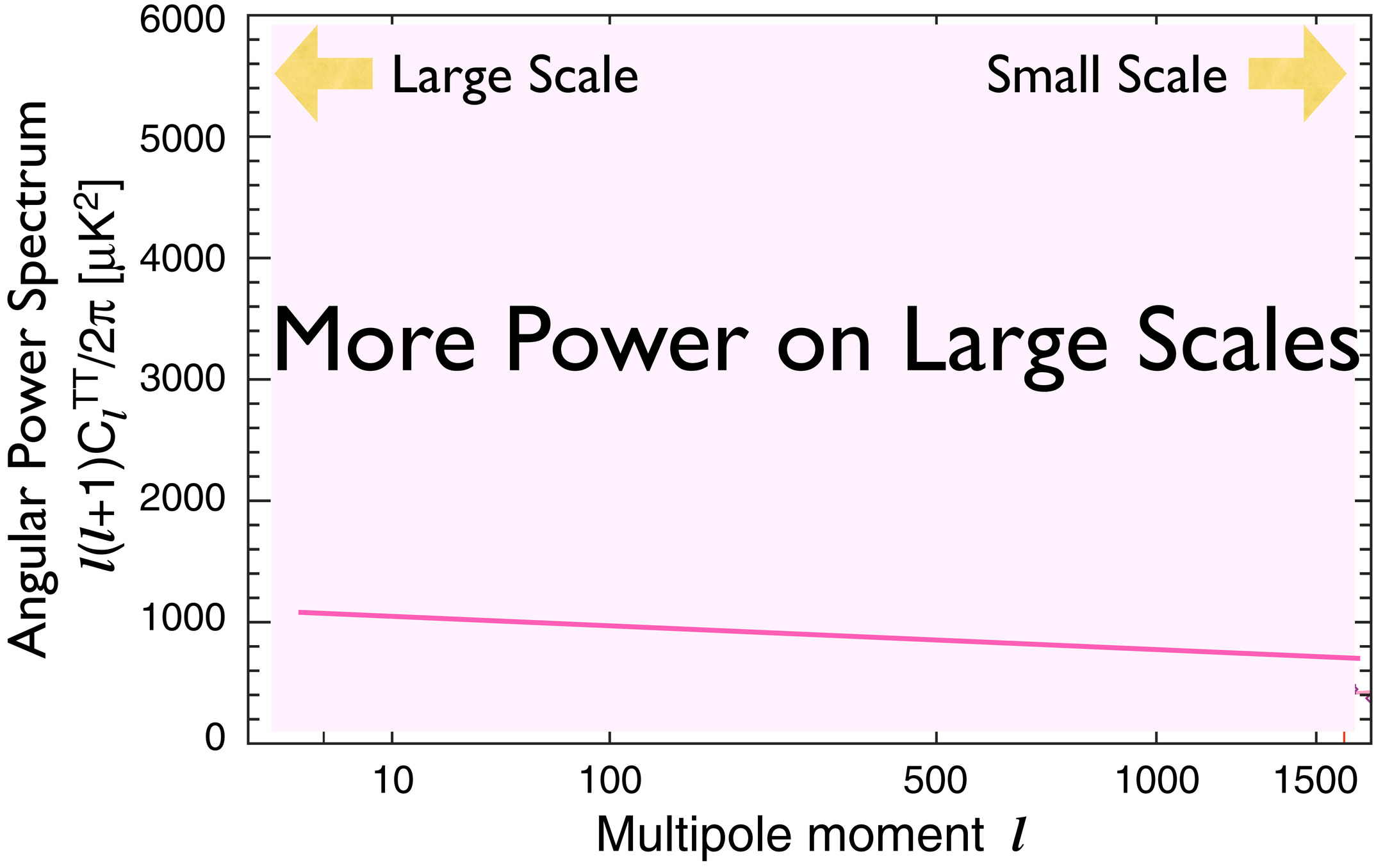
Decoding the Primordial Ripples



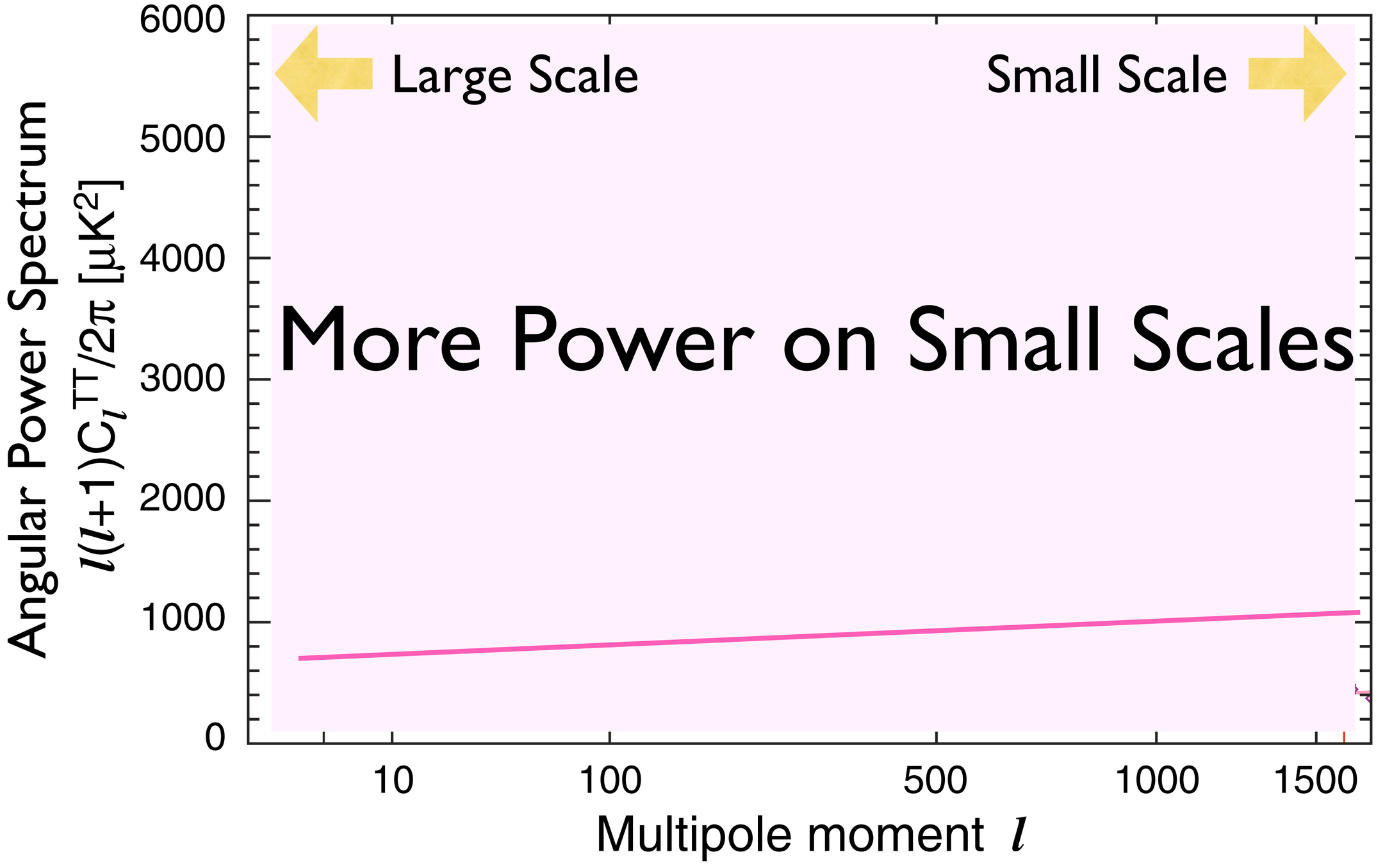
Getting rid of the Sound Waves



The Early Universe Could Have Done This Instead



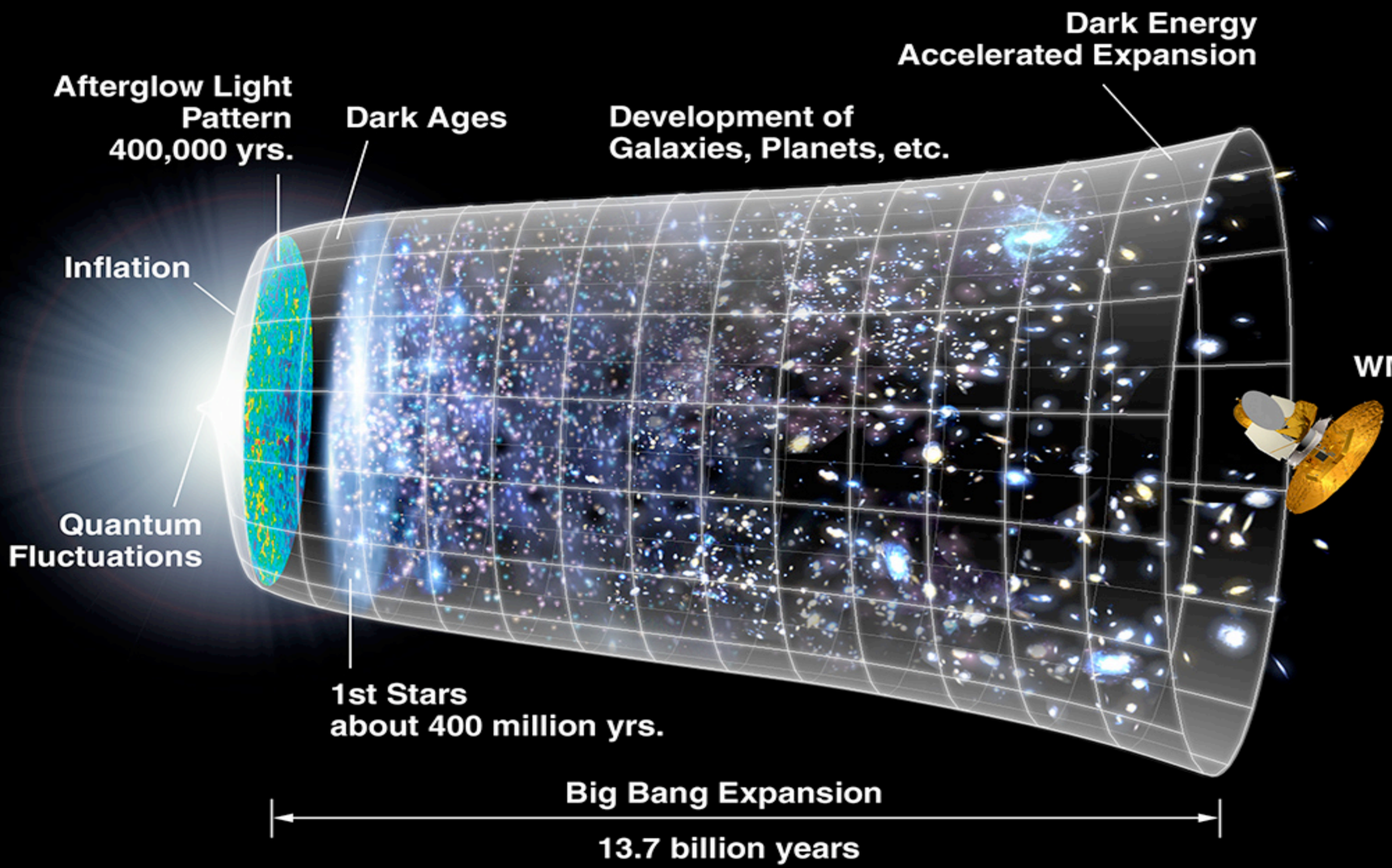
...or, This.


Large Scale
Small Scale
More Power on Small Scales
Angular Power Spectrum
$l(l+1)C_l^{TT}/2\pi$ [μK²]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l

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, 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 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.

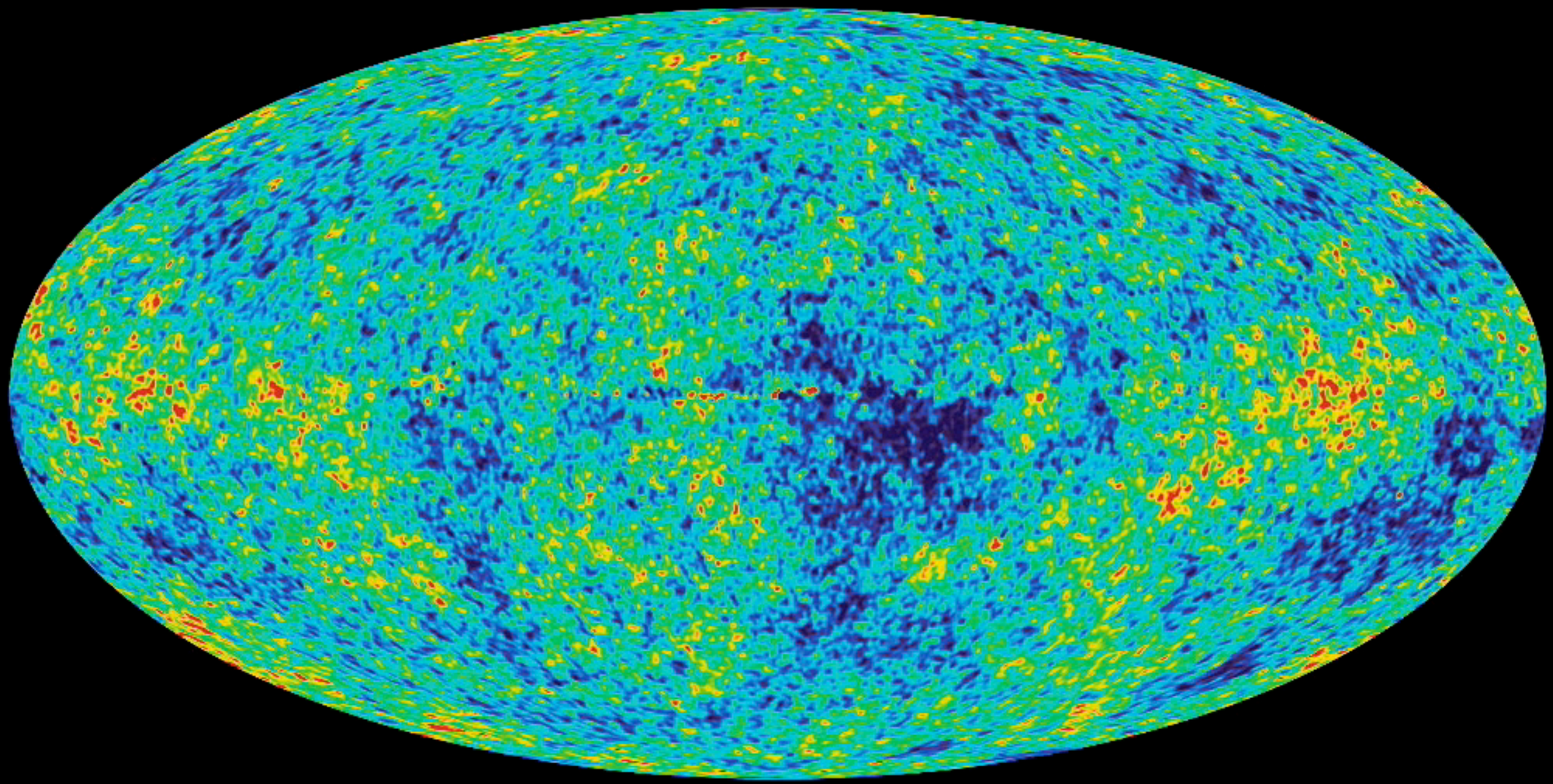
Quantum Fluctuations

(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.

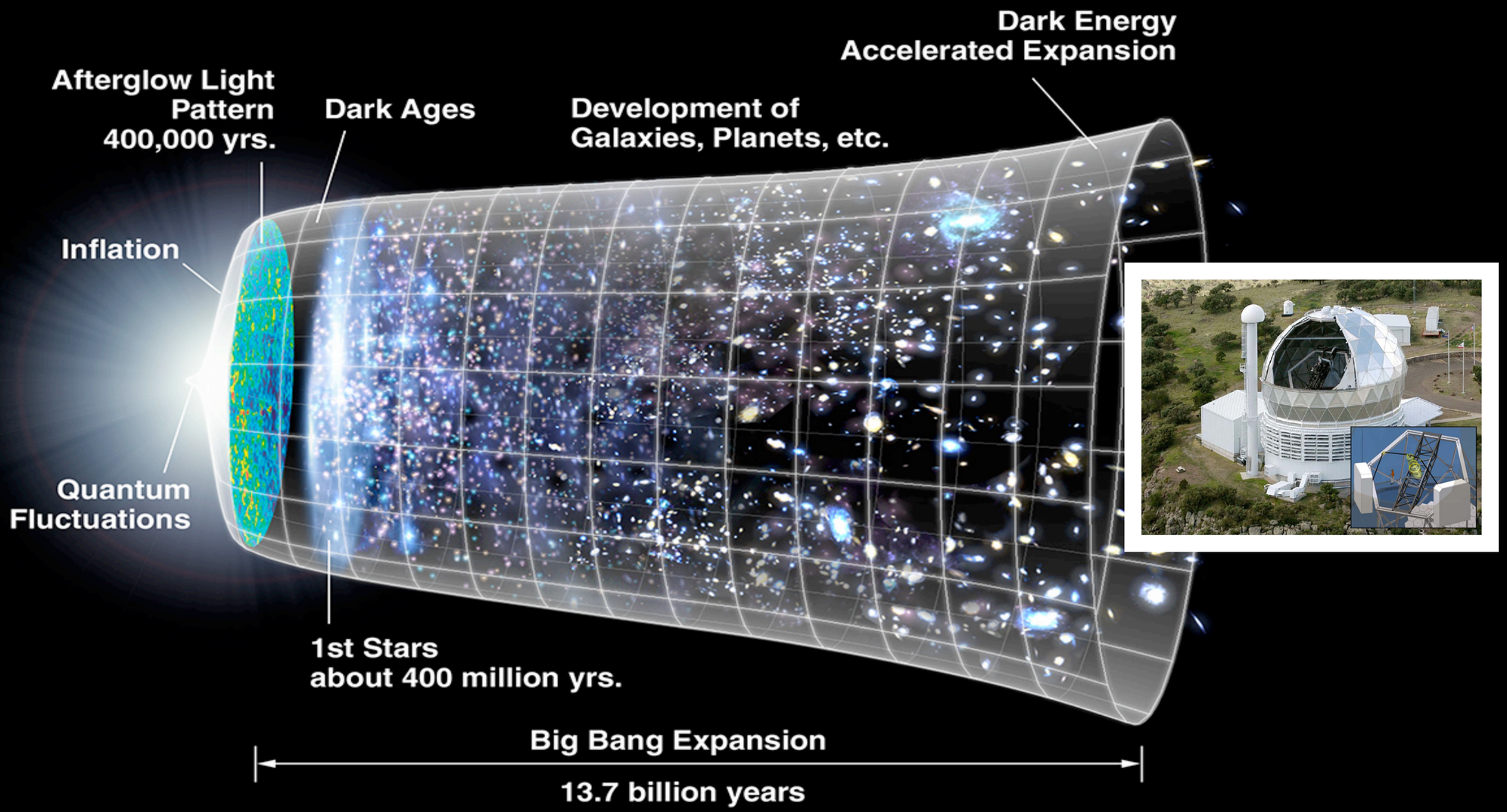


Frontiers in Cosmology

- What powered the Big Bang?
- What is Dark Matter?
- What is Dark Energy?
- How did the Structure emerge and evolve?

- Undoubtedly, a close collaboration between theory and observations will be necessary for solving these outstanding questions in modern cosmology.
- *And, Golden Age of Cosmology continues...*

What Will HETDEX Do?



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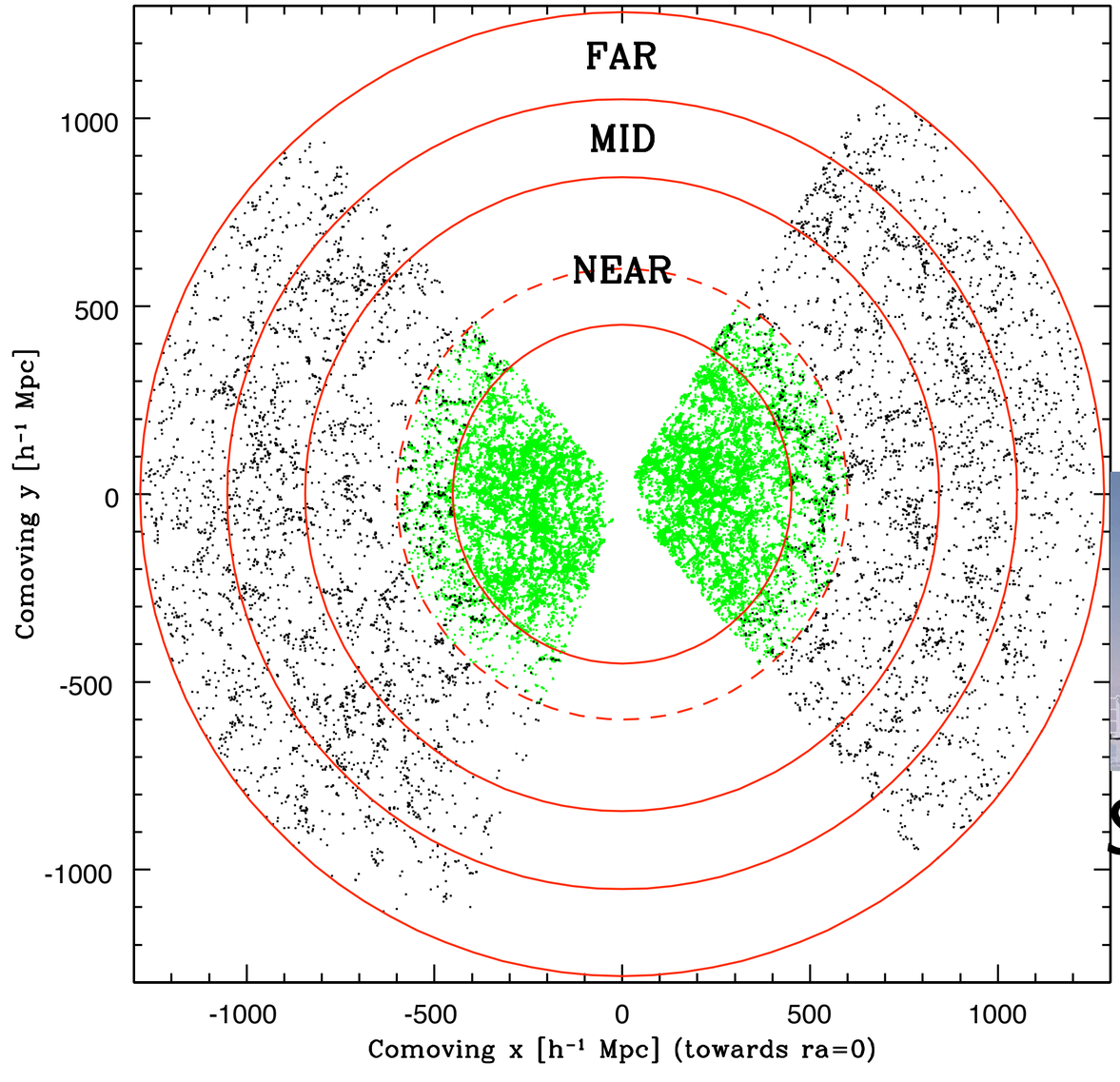
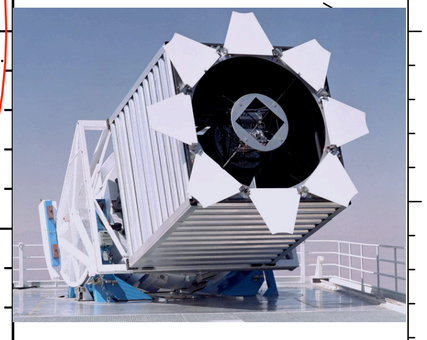
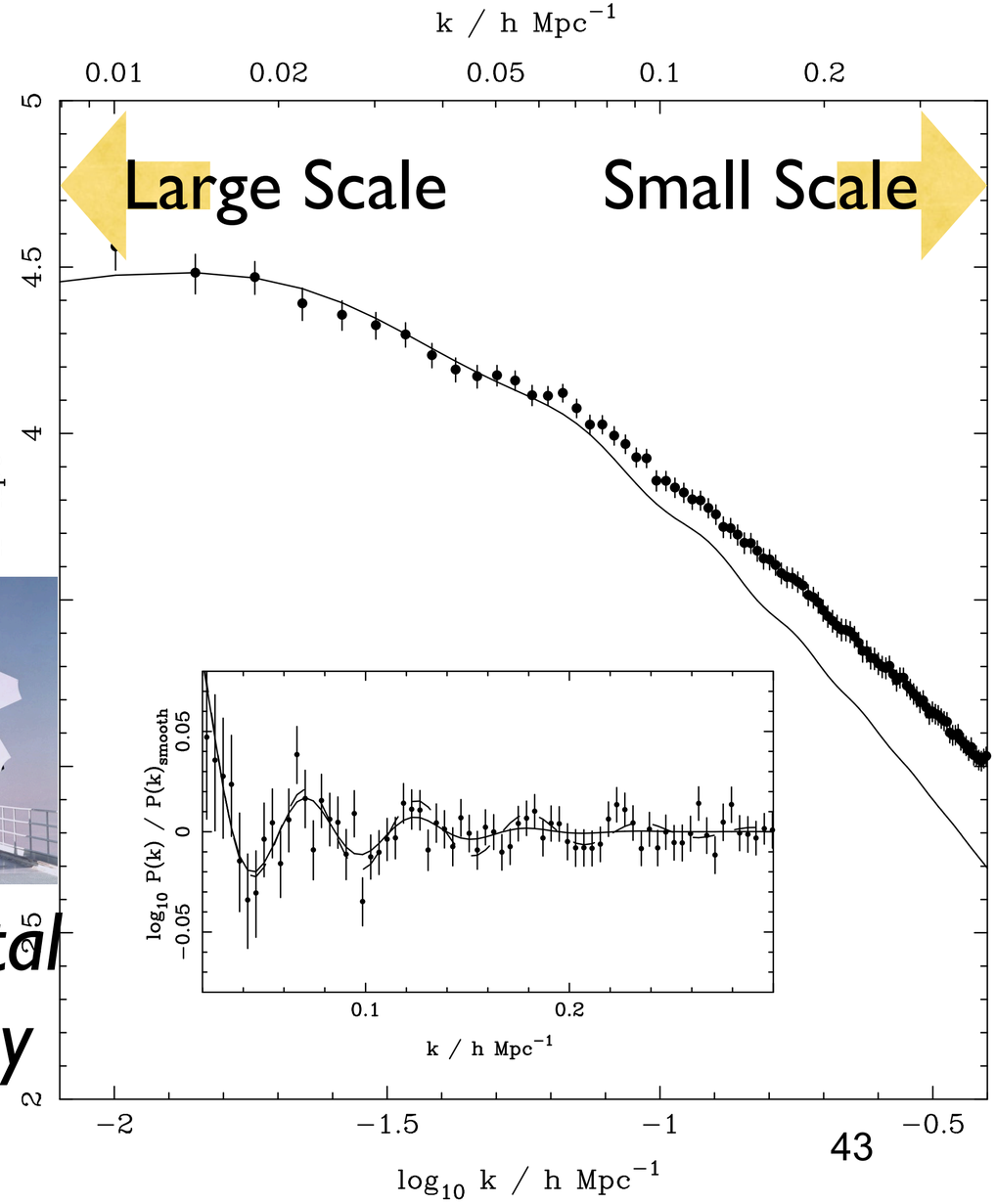
HETDEX: Sound Waves in the Distribution of Galaxies

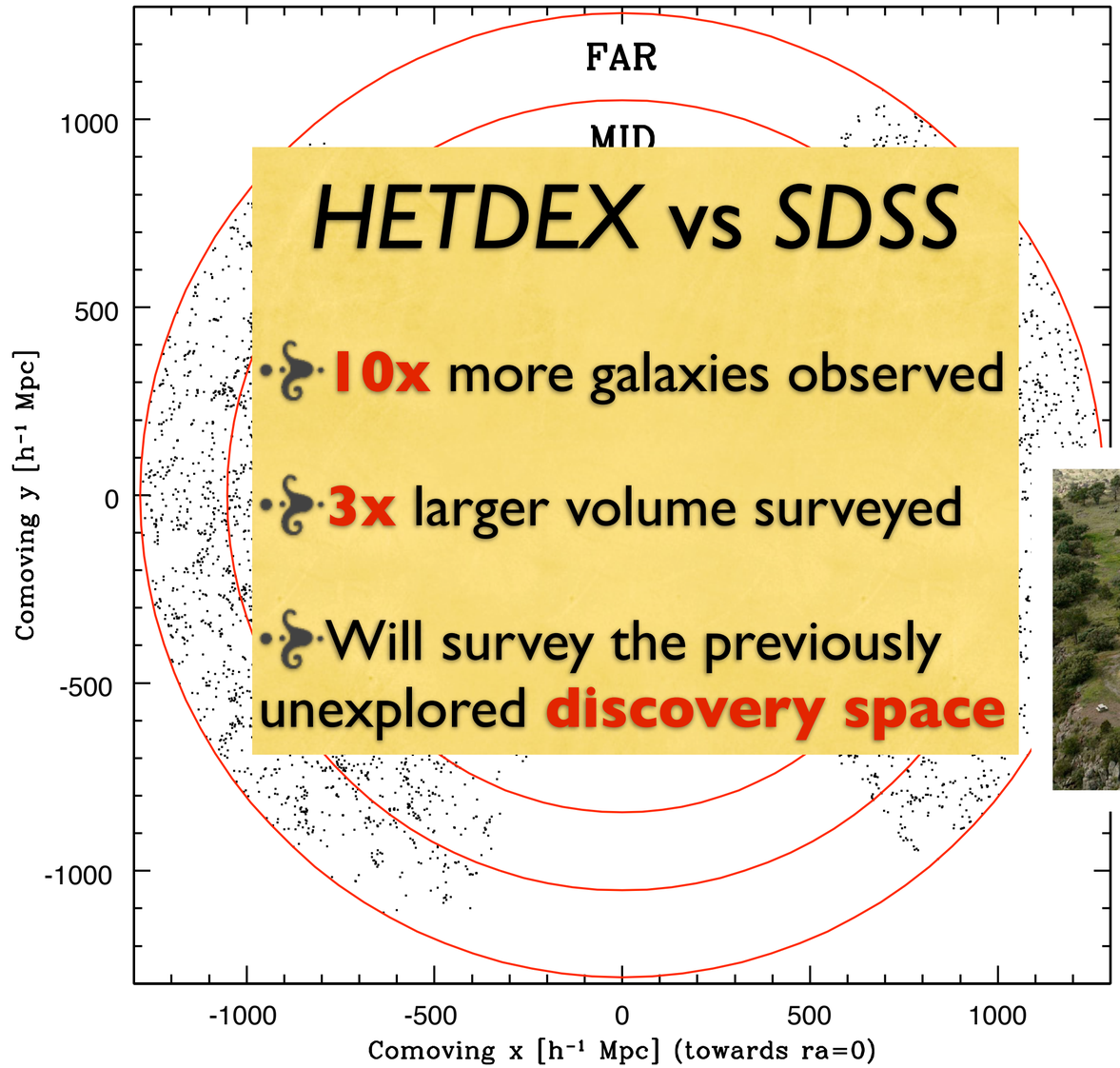




Sloan Digital Sky Survey



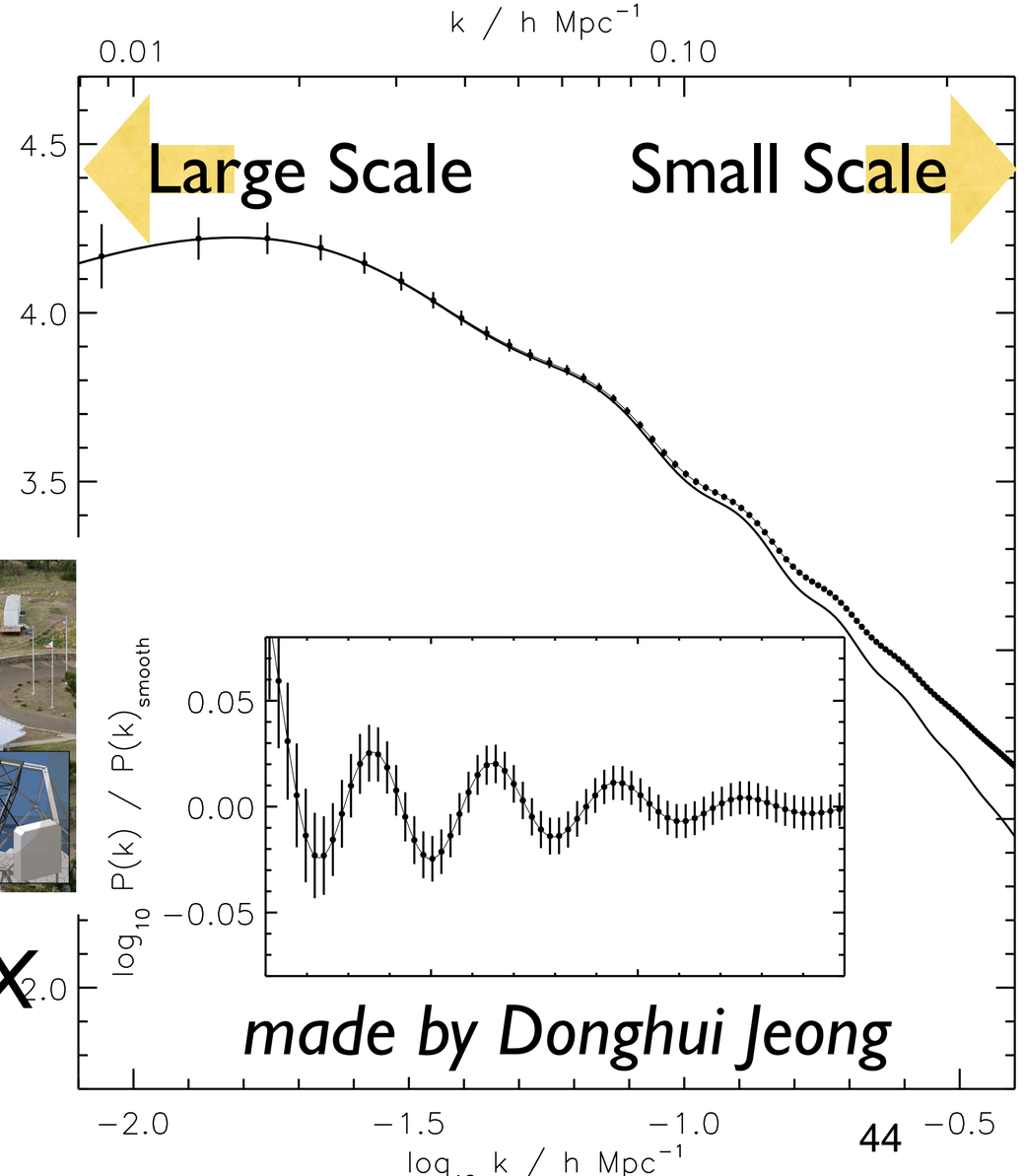
HETDEX: Sound Waves in the Distribution of Galaxies



HETDEX vs *SDSS*

- **10x** more galaxies observed
- **3x** larger volume surveyed
- Will survey the previously unexplored **discovery space**

HETDEX



made by Donghui Jeong

New University Research Unit

Texas Cosmology Center

Astronomy/Observatory

Volker Bromm

Karl Gebhardt

Gary Hill

Eiichiro Komatsu

Milos Milosavljevic

Paul Shapiro

Physics

Duane Dicus

Jacques Distler

Willy Fischler

Vadim Kaplunovsky

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