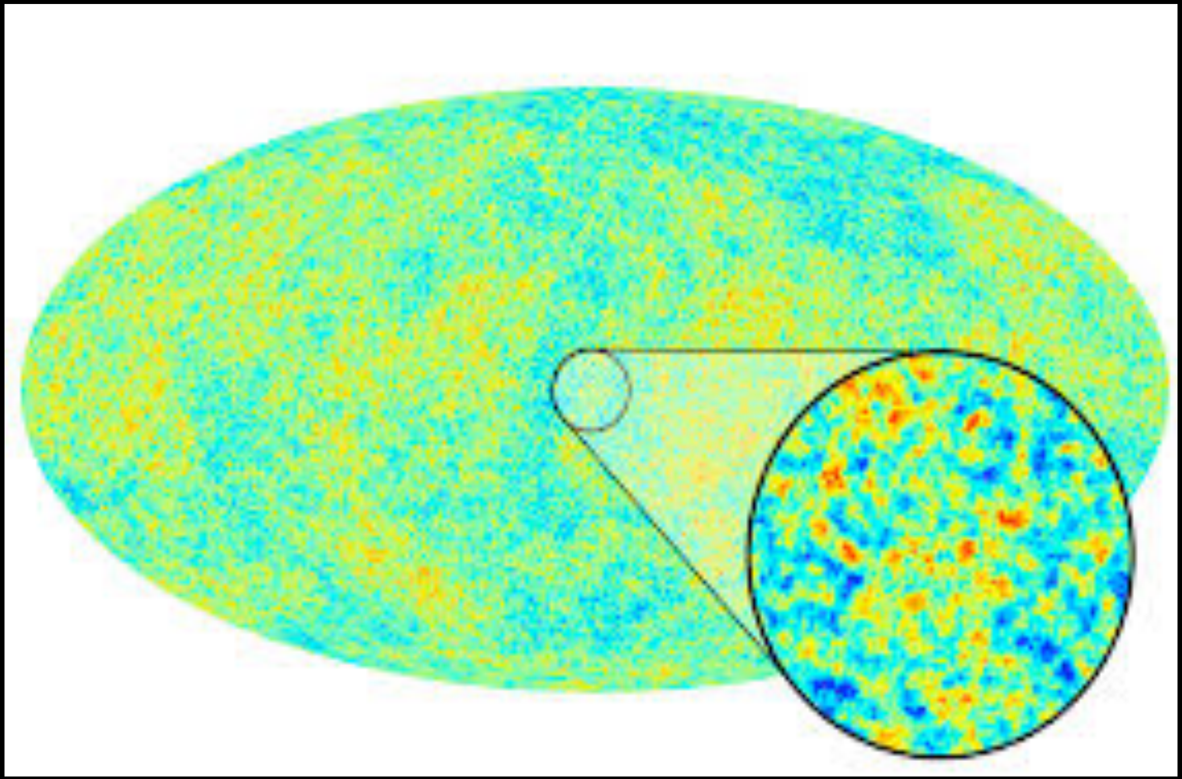
Our Simple But Strange Universe



David Spergel

Flatiron Institute

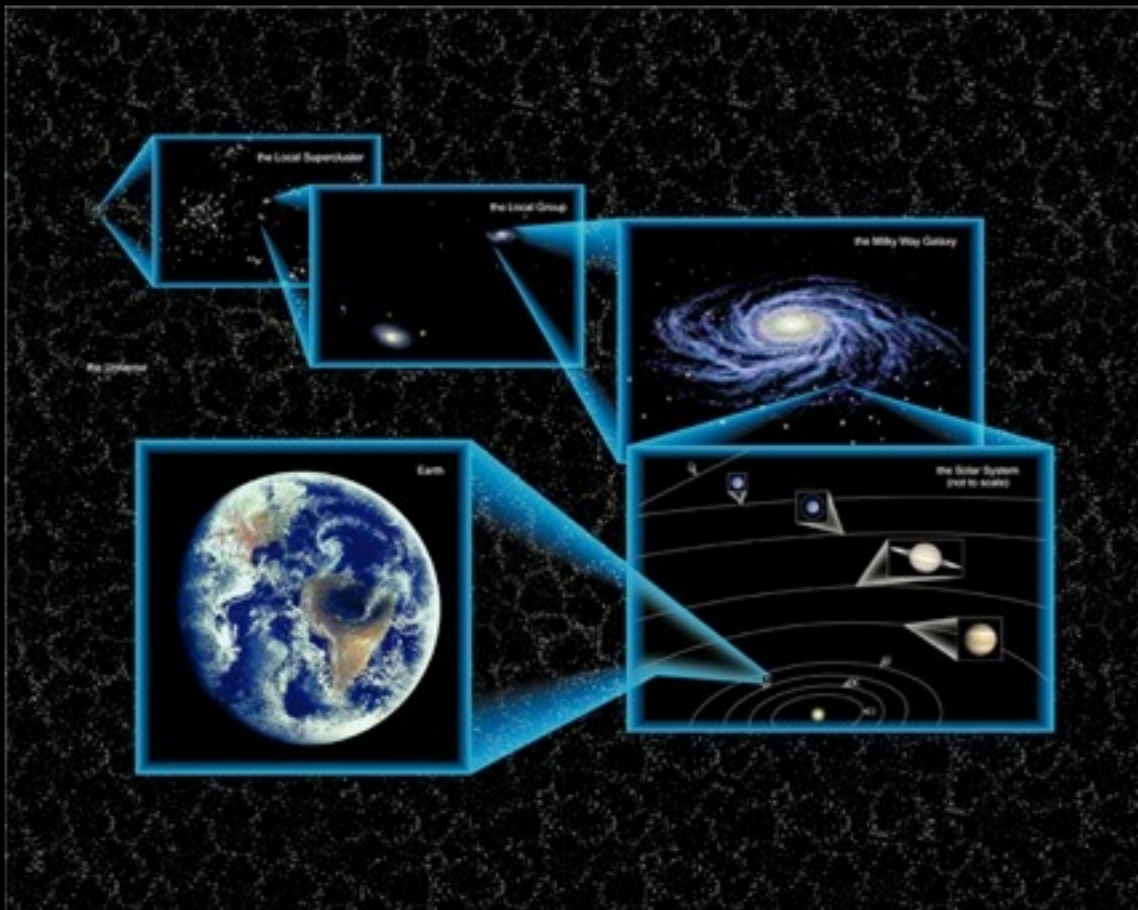
Our Simple But Strange Universe

Over the past twenty years, cosmologists have developed a simple model that fits a host of astronomical data:

- The same laws of physics are valid throughout space and time
- The total energy of the universe is zero (equivalently, the geometry of the universe is “flat”)
- The universe went through a period of early acceleration that generated a nearly scale-invariant spectrum of fluctuations
- The universe is composed of atoms, dark matter, and dark energy

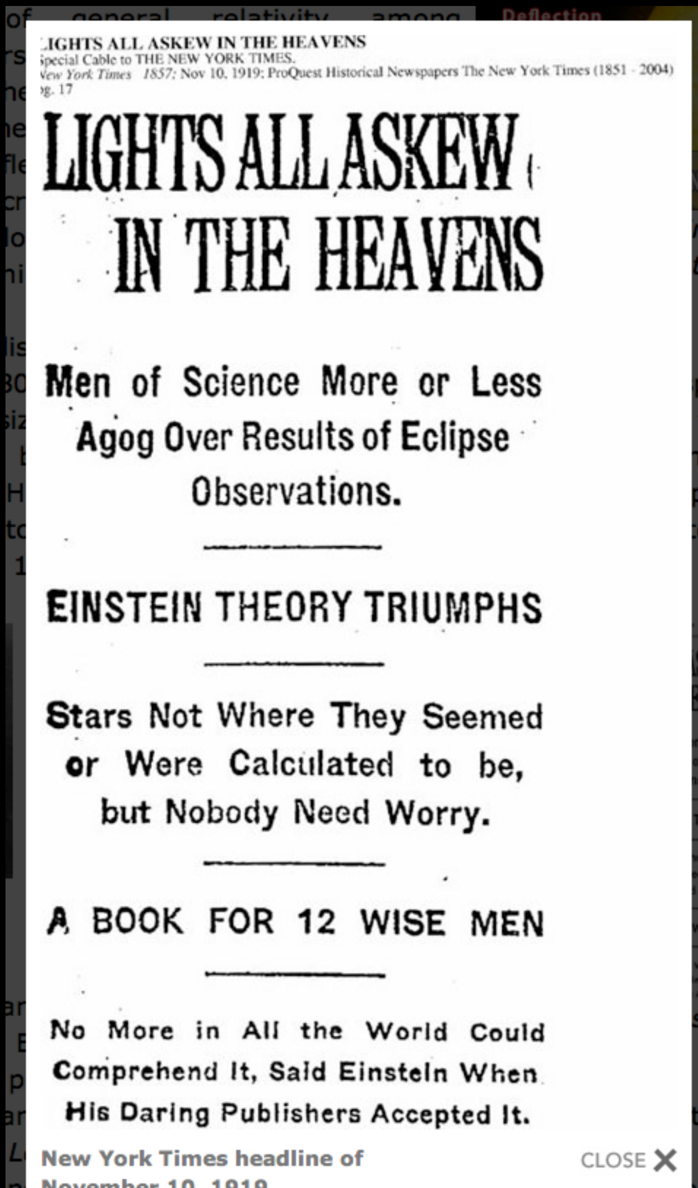
With 5 numbers, cosmologists can fit all of our astronomical data about the large-scale universe

When we look out in space, we look back in time



Our trip outward:
Cambridge
United Kingdom
Europe
Earth
Solar System
Milky Way
Local Group of Galaxies,
Universe

General Relativity



LIGHTS ALL ASKEW IN THE HEAVENS
Special Cable to THE NEW YORK TIMES.
New York Times 1857; Nov 10, 1919; ProQuest Historical Newspapers The New York Times (1851 - 2004)
pg. 17

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

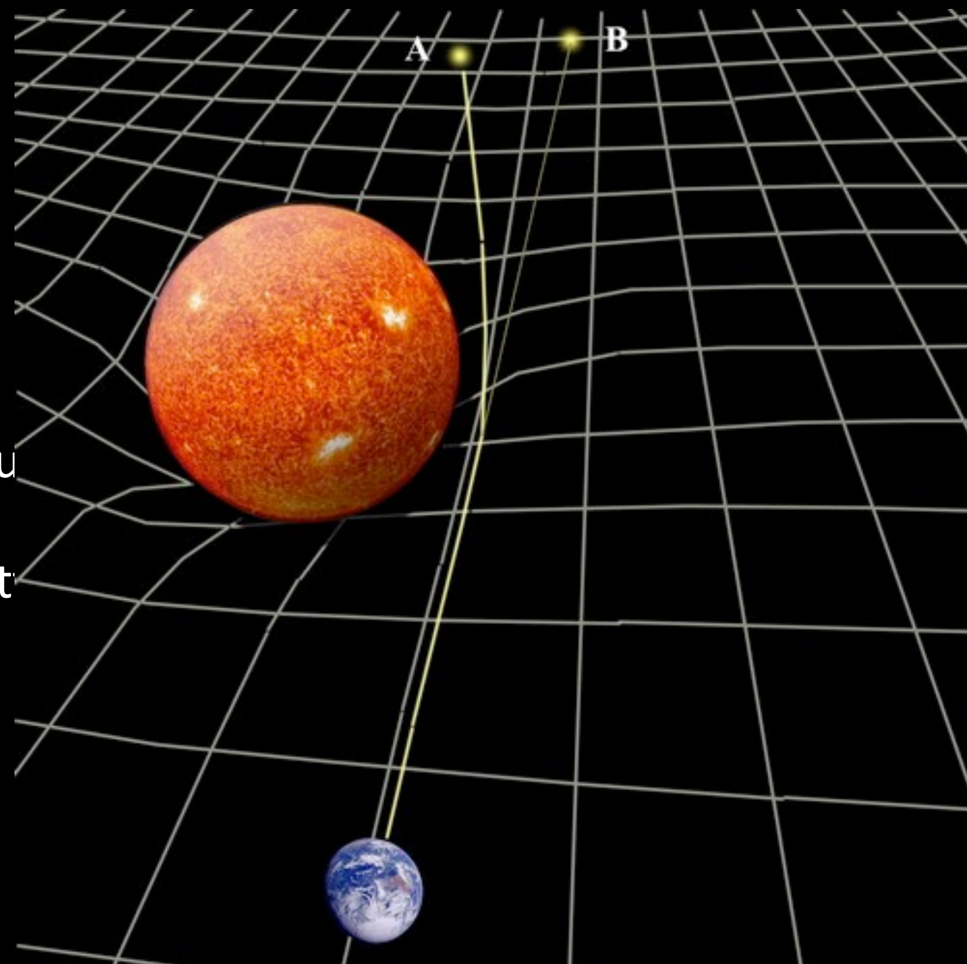
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

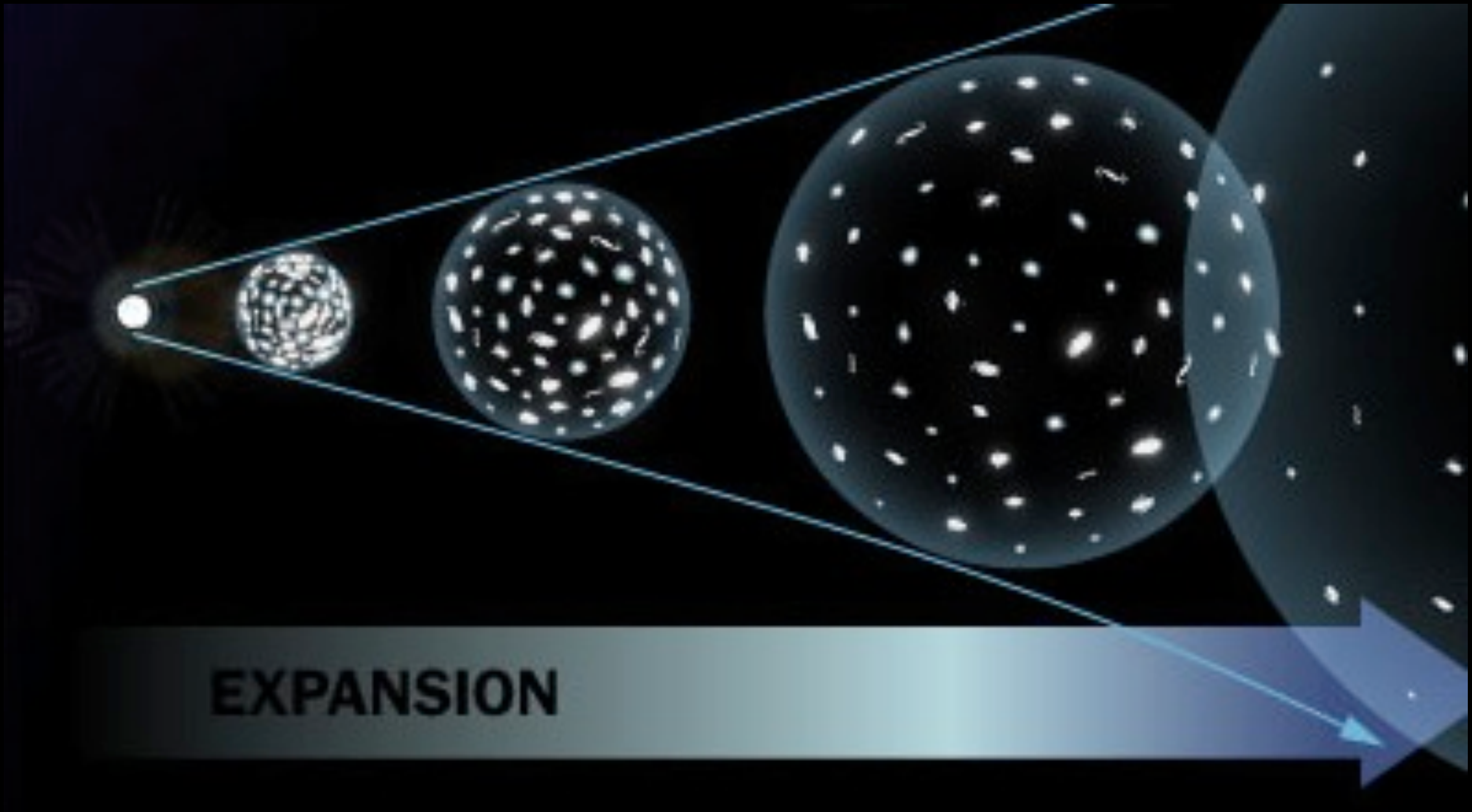
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

New York Times headline of November 10, 1919.

CLOSE ✕

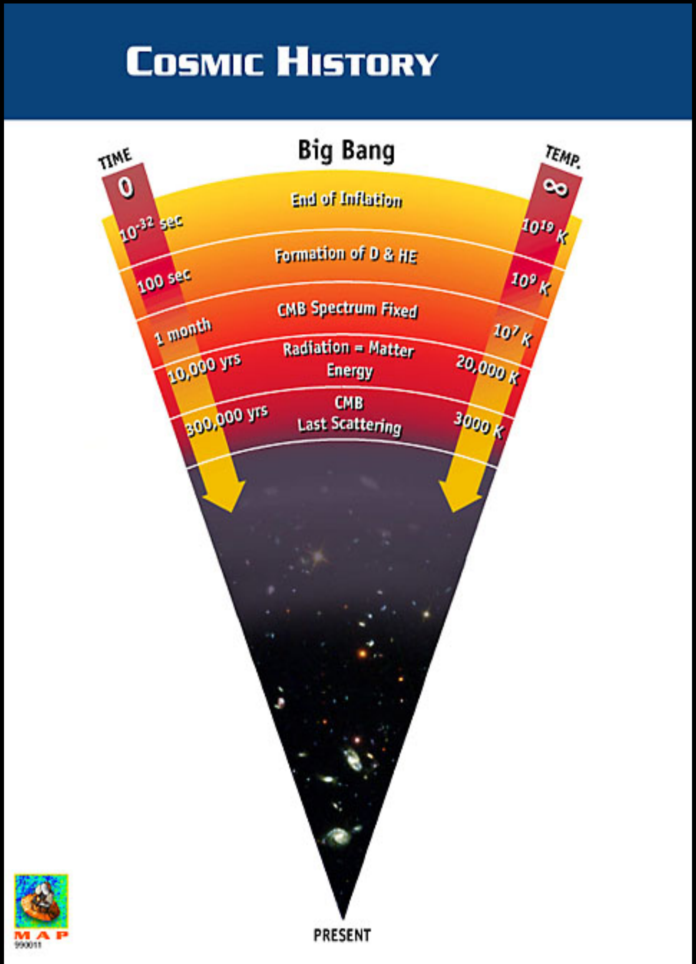


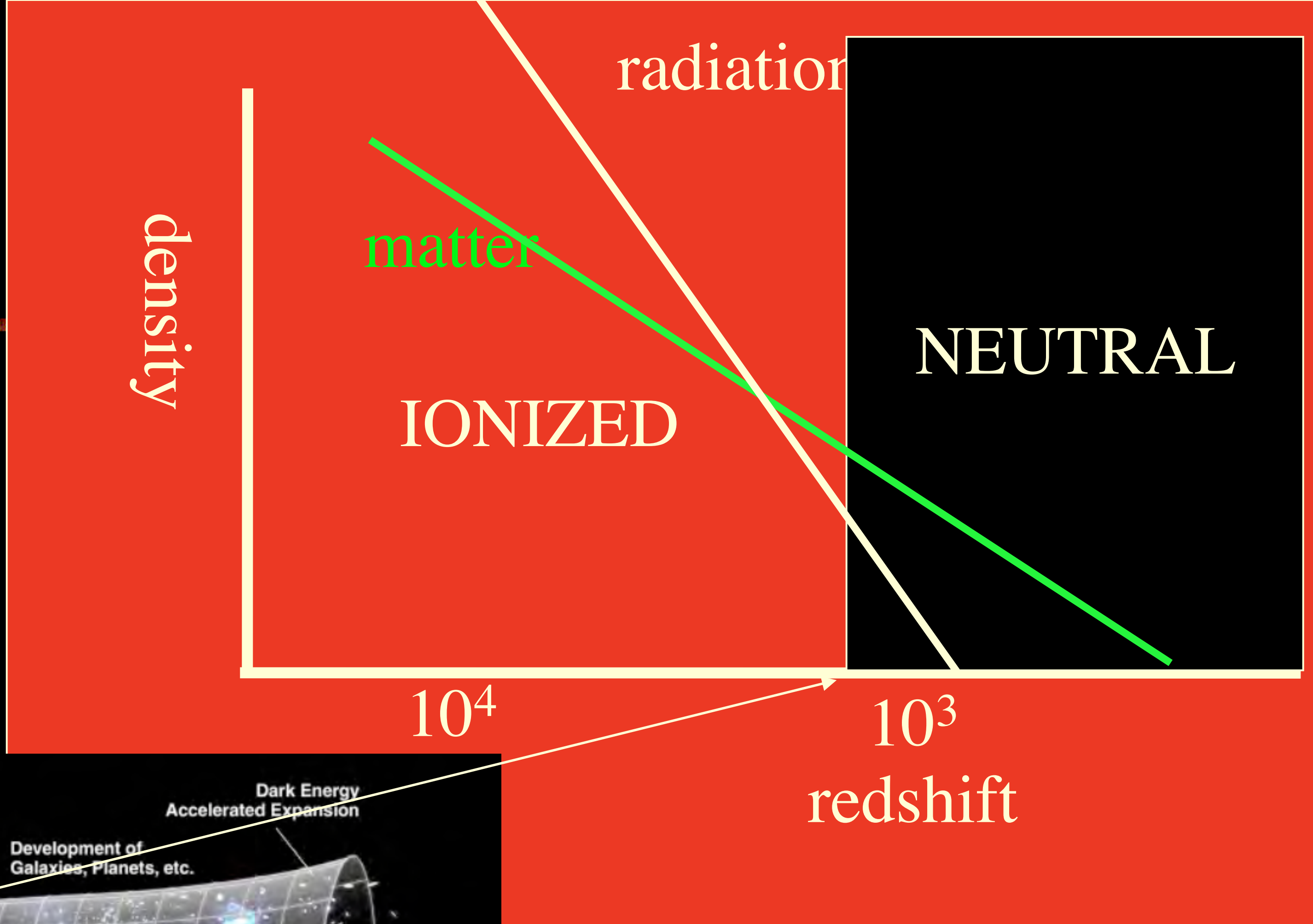
Expanding Universe

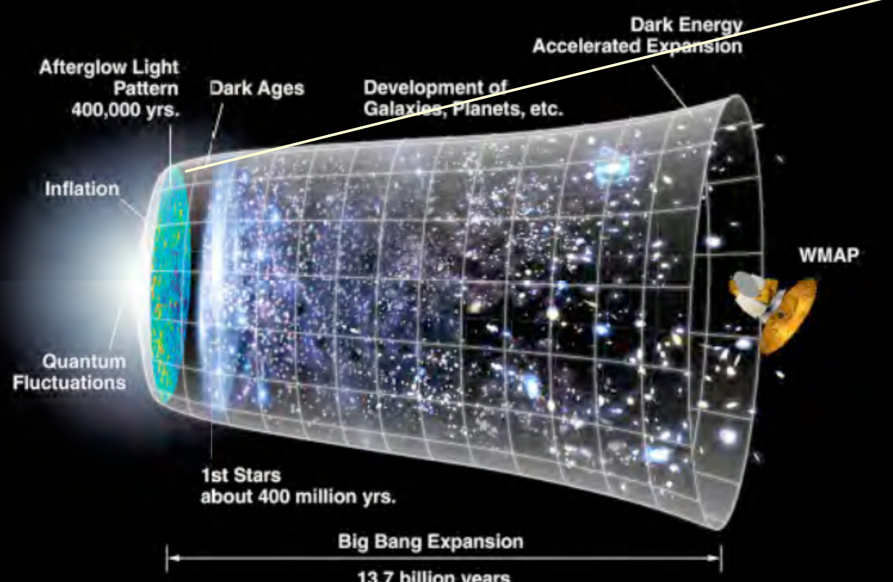


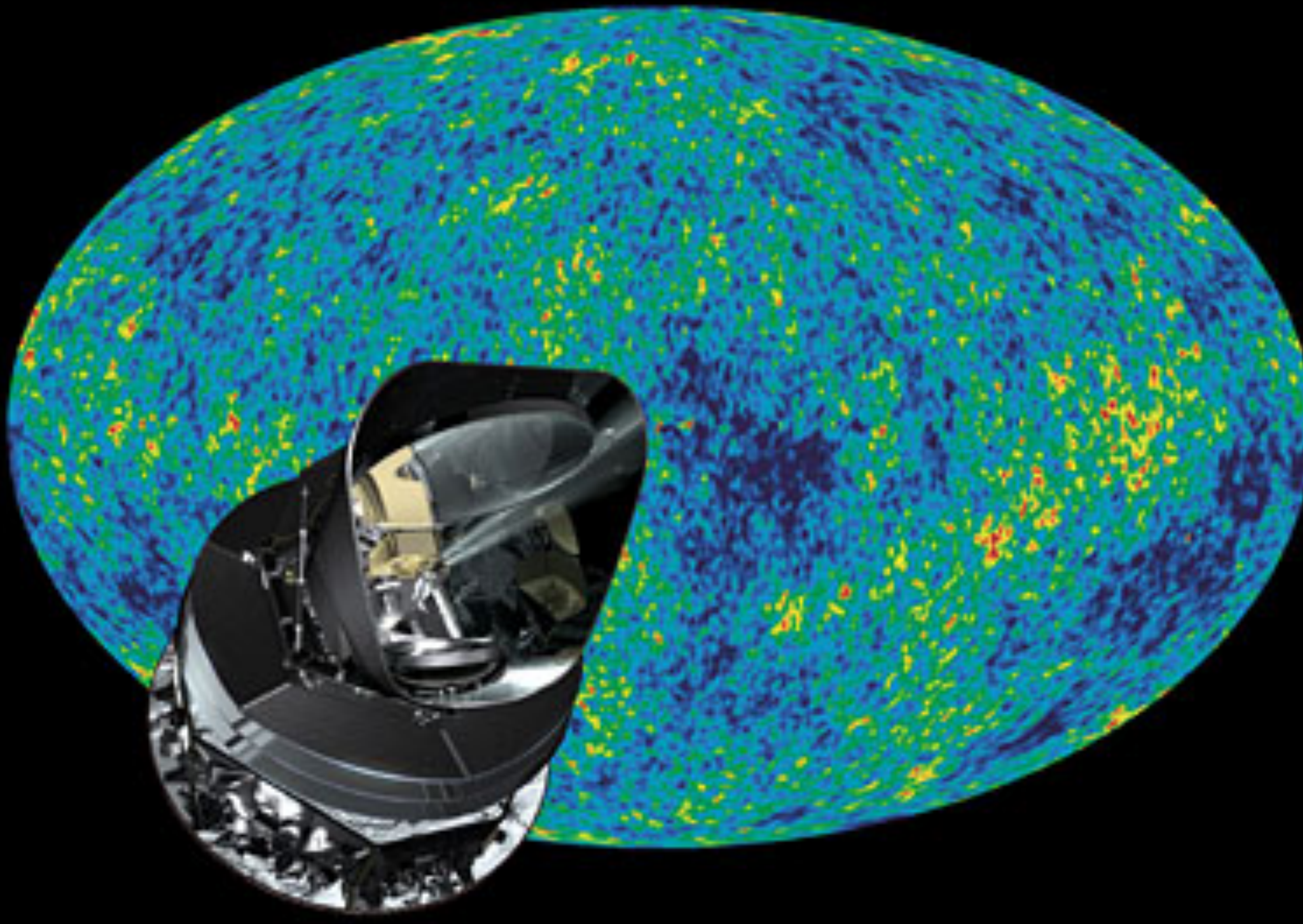
Quick History of the Universe

- Universe starts out hot, dense and filled with radiation
- As the universe expands, it cools.
  - During the first minutes, light elements form
  - After 400,000 years, atoms form
  - After 100,000,000 years, stars start to form
  - After 1 Billion years, galaxies and quasars form

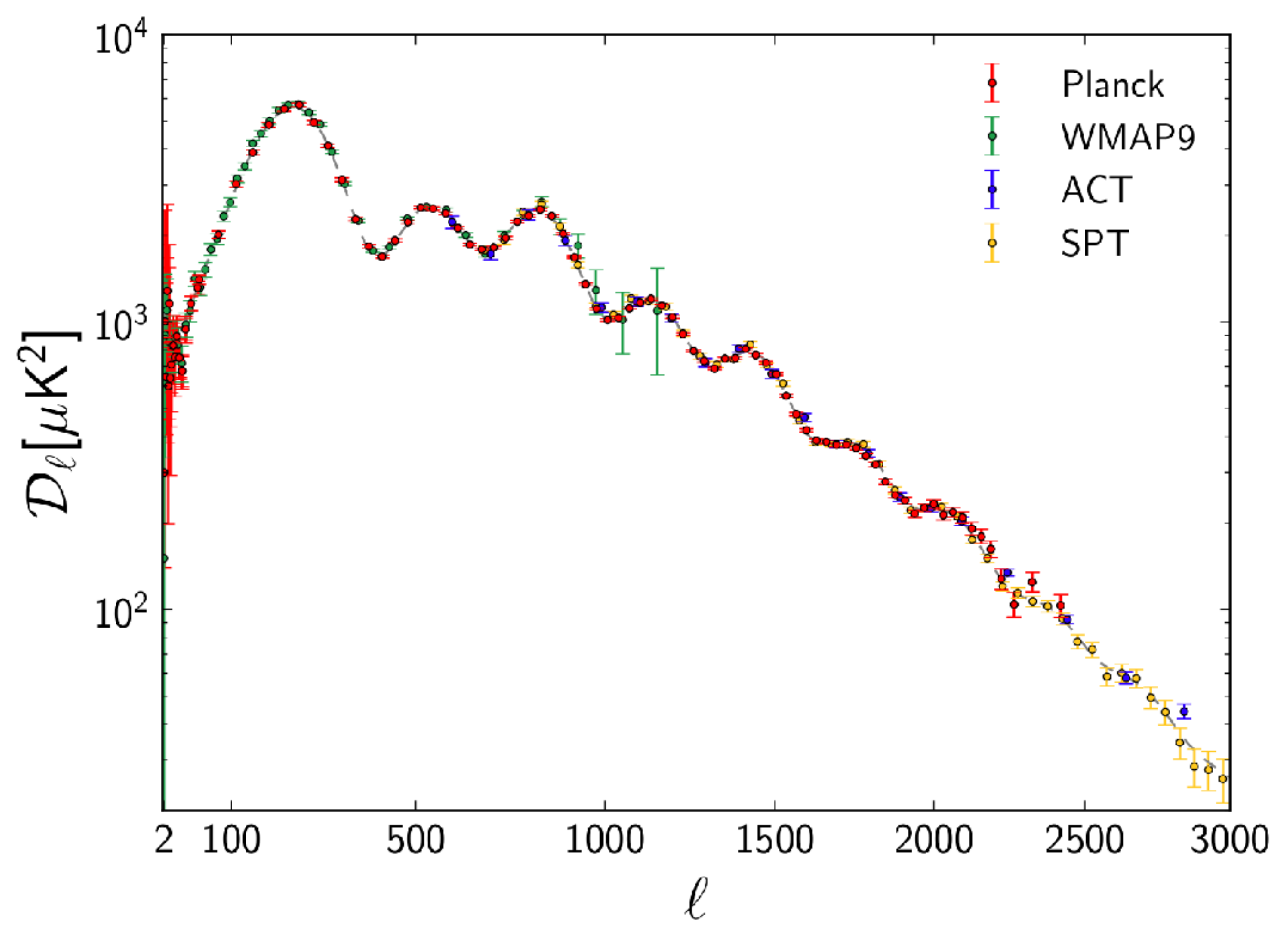


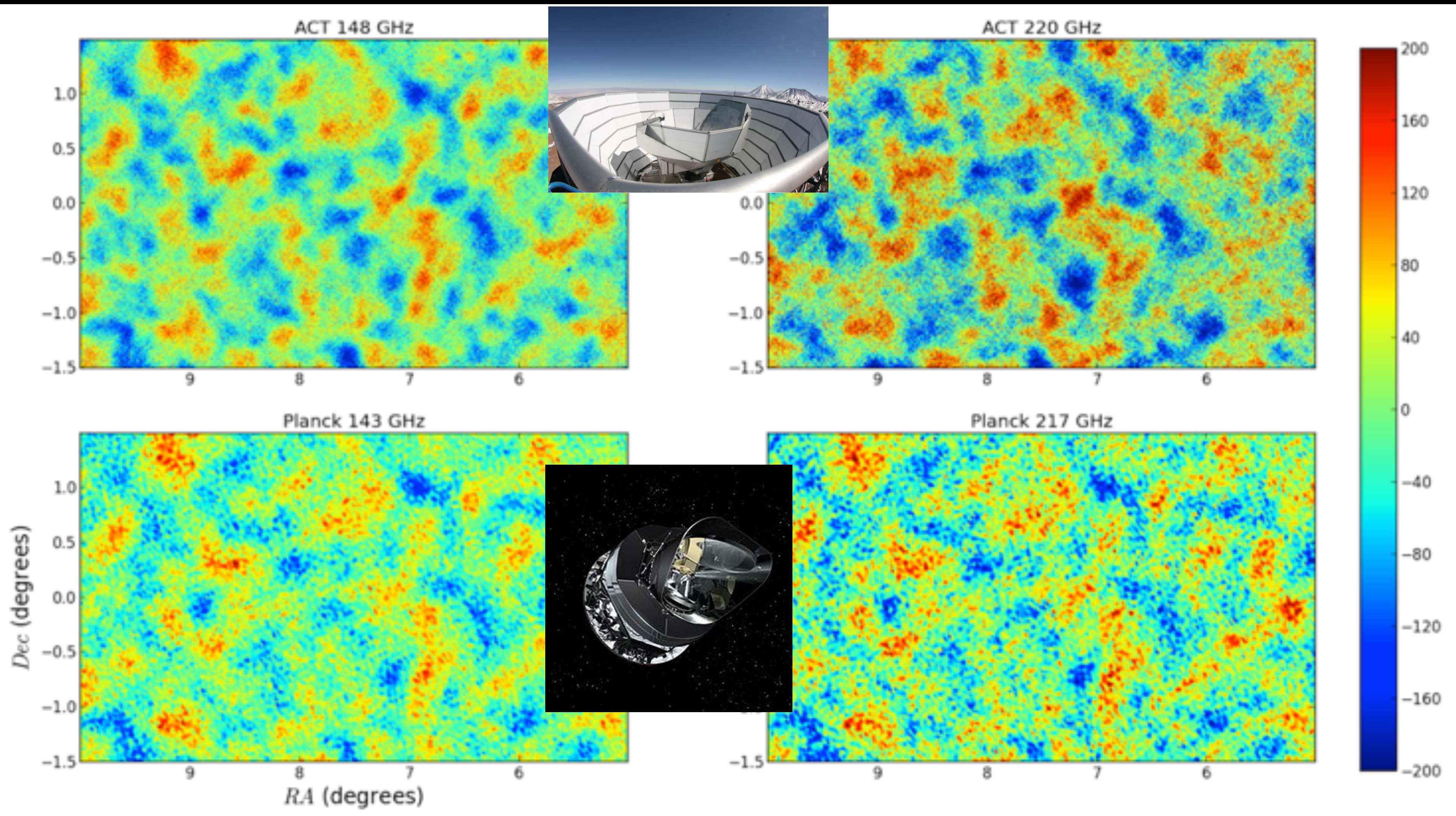

radiatio
matter
density
IONIZED
NEUTRAL
10^4
10^3
redshift


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years



Current Data




ACT 148 GHz
ACT 220 GHz
Planck 143 GHz
Planck 217 GHz
1.0
0.5
0.0
−0.5
−1.0
−1.5
9
8
7
6
Dec (degrees)
RA (degrees)
200
160
120
80
40
0
−40
−80
−120
−160
−200

Stacked Temperature Fluctuations

Planck Collaboration: The *Planck* mission

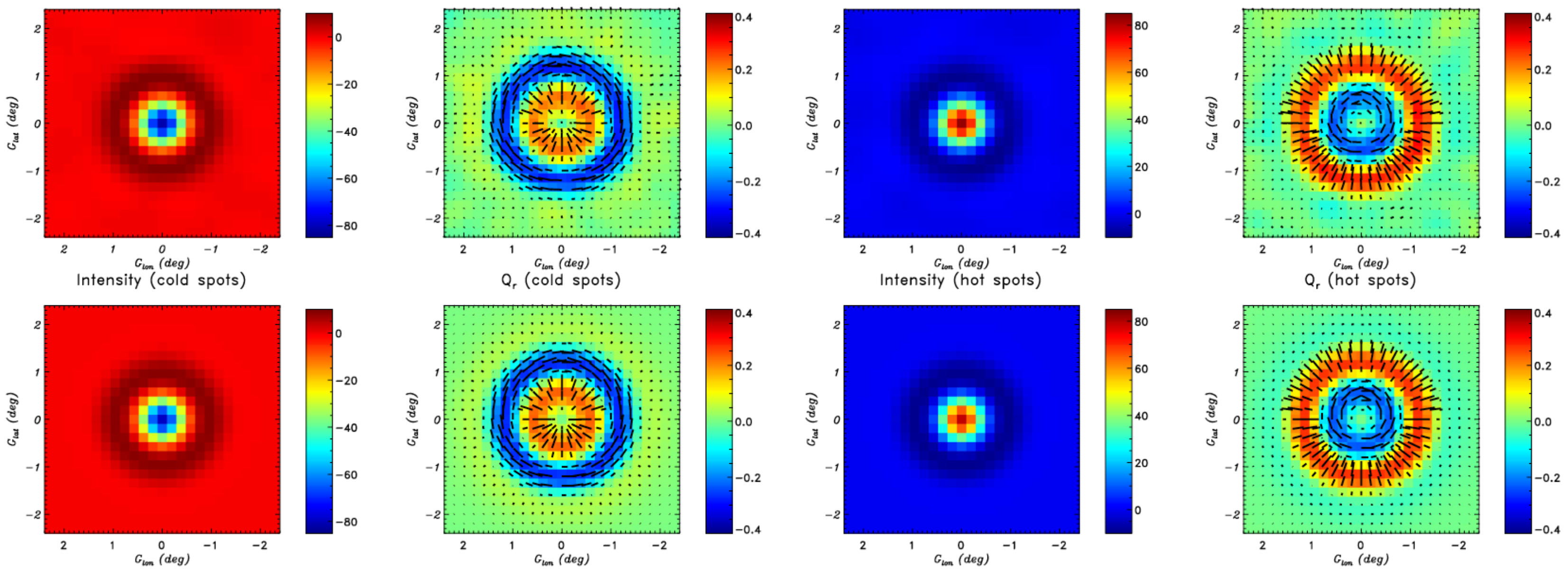
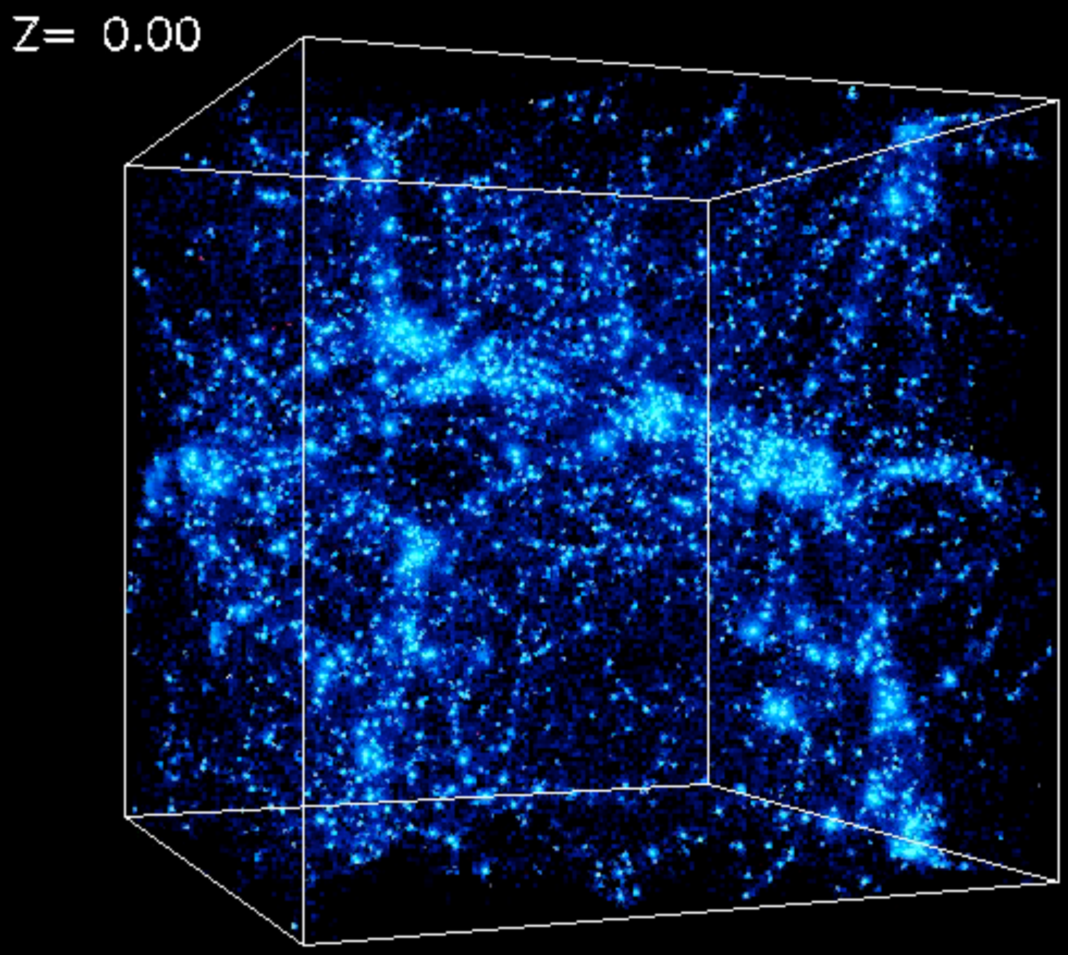


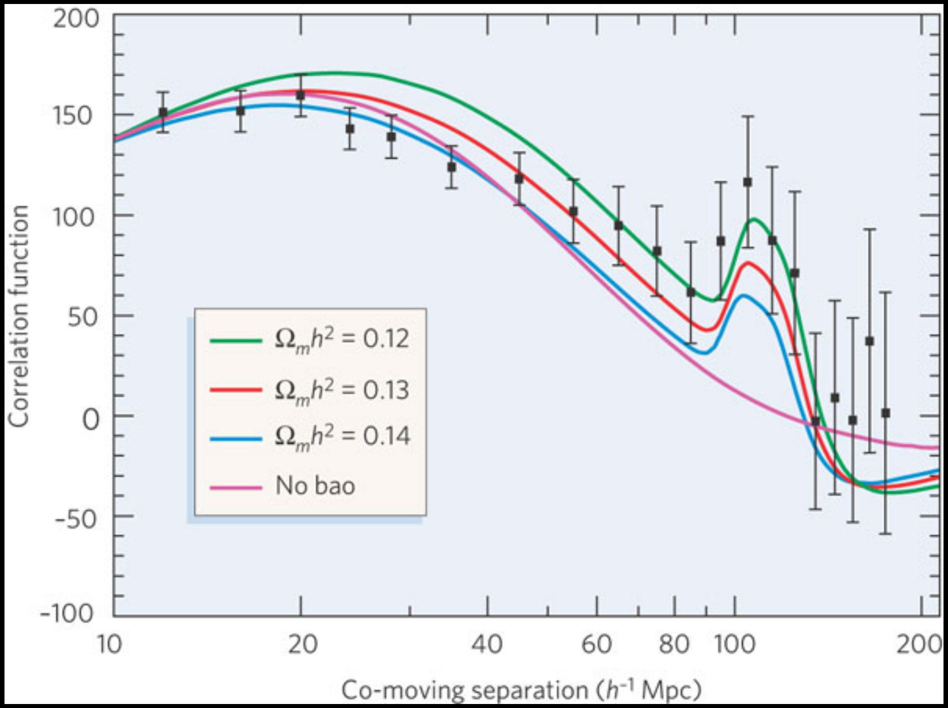
Fig. 27. Stacked maps of the CMB intensity I and polarization Q_r at the position of the temperature extrema, at a common resolution of 30 arcmin. Maps are displayed for CMB temperature cold spots (left) and hot spots (right) for the *Planck* CMB estimates (top row) and for the ΛCDM*Planck* best fit model prediction (bottom row).

Growth of Structure



National Center for Supercomputer Applications by Andrey Kravtsov

Sound Waves in the Sky



Bennett 2006

The Simplicity

- The primordial fluctuations traced by Planck can be described entirely by two numbers: an amplitude and a scale dependence
- The basic properties of the universe with only 3 additional numbers: its age, the density of atoms and the density of matter
- This model can fit not only the microwave background observations but our observations of the large-scale distributions of galaxies

The Strangeness

- Dark matter makes up most of the mass of our Galaxy and is composed of some new particle that is different from anything that we have ever observed.
- The universe is accelerating today. This acceleration appears to be driven by dark energy. Dark energy makes up 70% of the mass-energy of the universe
- Atomic matter ("normal stuff") makes up 5% of the universe

More Strangeness

- How did the universe begin? Is our universe unique? How will it end?
- What is the origin of the fluctuations traced by Planck and other CMB experiments?
  - Did the universe undergo an early epoch of expansion (“inflation”) that generated these fluctuations?
  - Are there other plausible mechanisms for generating these fluctuations?

Next Steps

- Test the simplicity
  - Hubble tension: 68 vs 73
- Explore the strangeness
  - Dark matter searches
  - GAIA observations of our Galaxy
  - Next generation surveys of large-scale structure
  - New ideas for dark matter and dark energy
  - Search for gravitational waves from the early universe