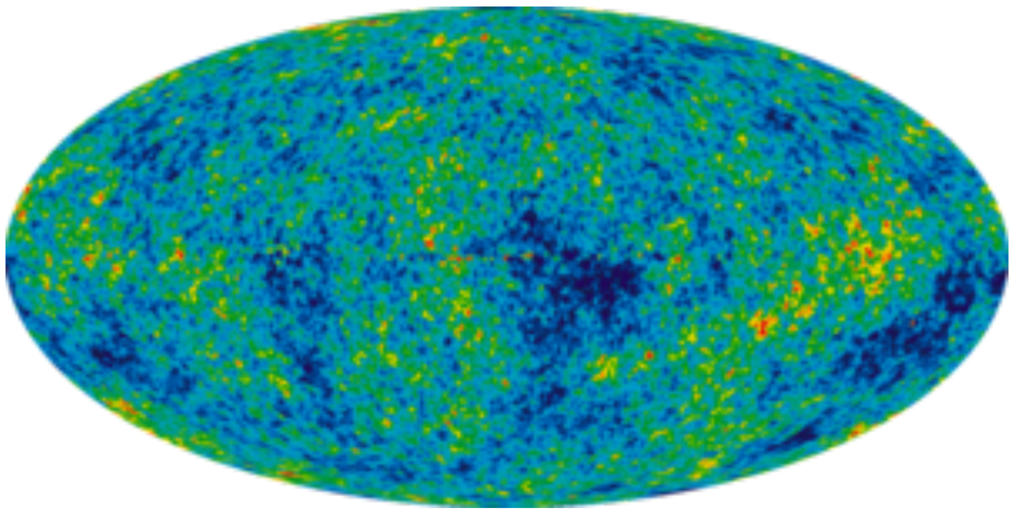
The Universe

Discovery of microwave background radiation

Working at Bell Labs in Holmdel, New Jersey, in 1964, Arno Penzias and Robert Wilson were experimenting with a supersensitive, 6 meter (20 ft) horn antenna originally built to detect radio waves

When Penzias and Wilson reduced their data they found a low, steady, mysterious noise that persisted in their receiver. This residual noise was 100 times more intense than they had expected, was evenly spread over the sky, and was present day and night. They were certain that the radiation they detected on a wavelength of 7.35 centimeters did not come from the Earth, the Sun, or our galaxy.

Universe: How it started



Map of small deviations in temperature of the cosmic microwave background radiation.

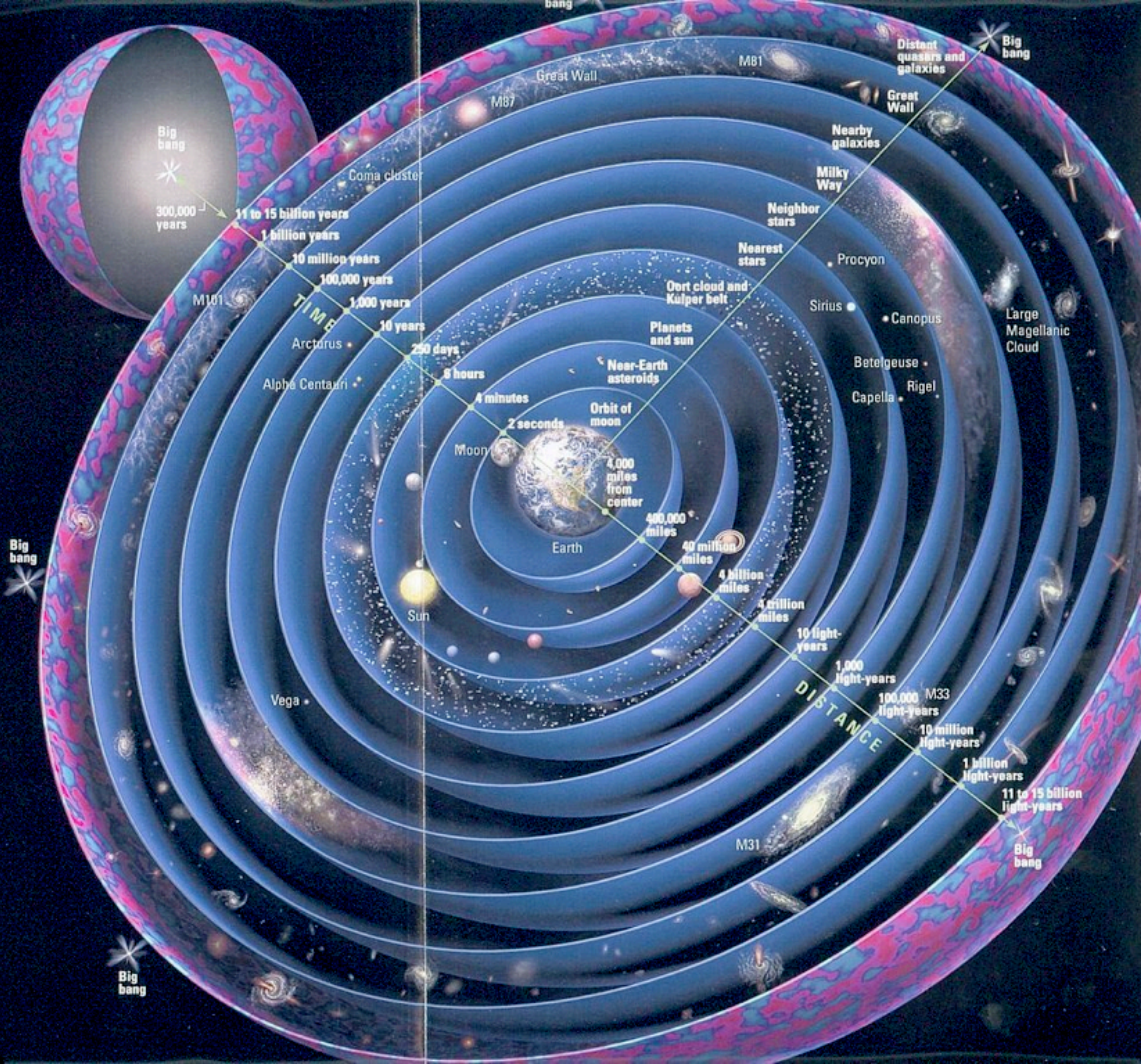
We are looking at the Universe when it was 100,000 years old. No galaxies. No stars or planets. Small waves traveling in quickly expanding hot Universe.

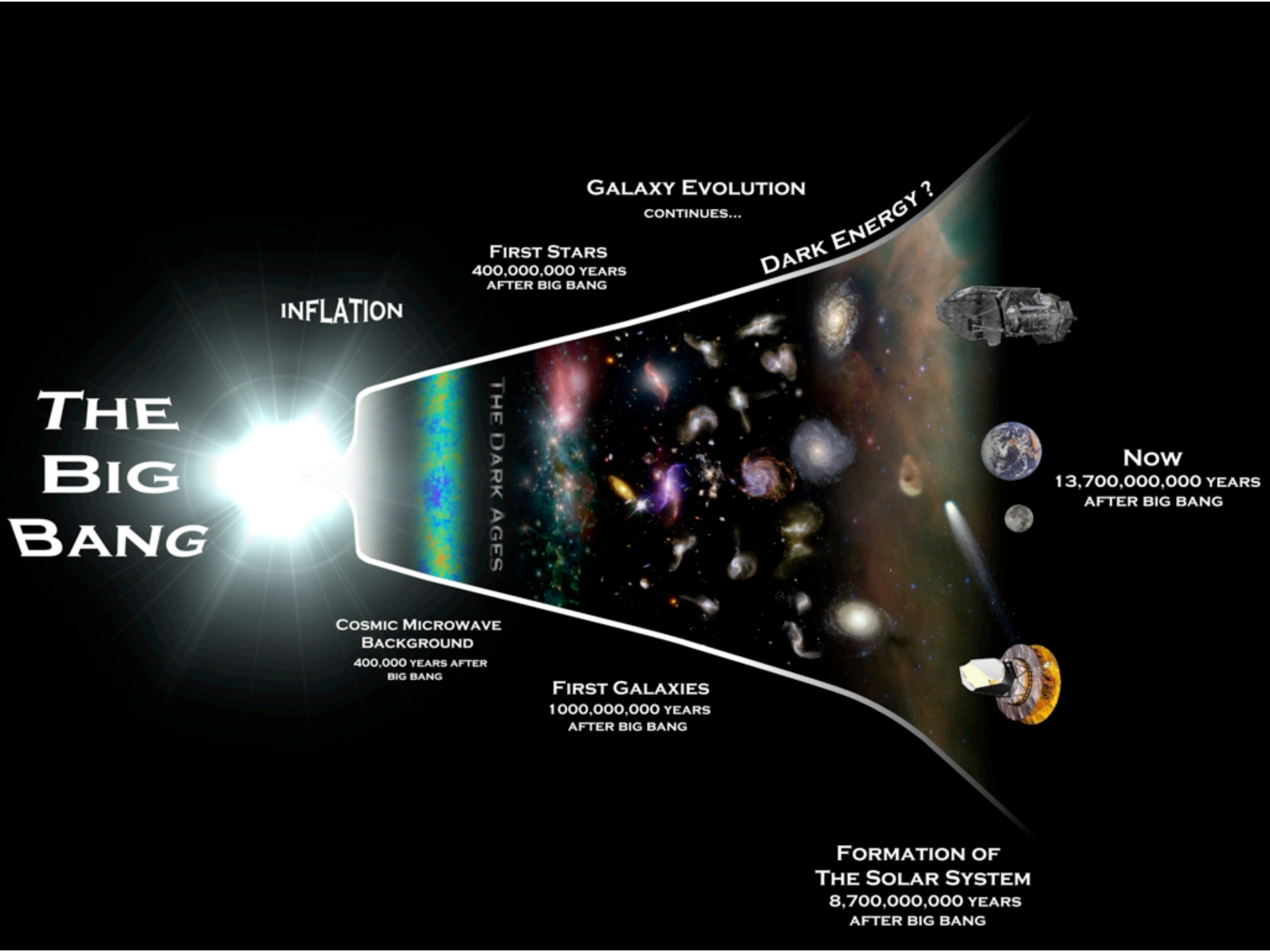
Photons emitted by this hot 3000 K plasma eventually reached us. It took them 13 billions years. Because the photons were traveling in the expanding Universe, their wavelengths became much longer (redshifted). Temperature of the microwave background radiation is now only 3 K.

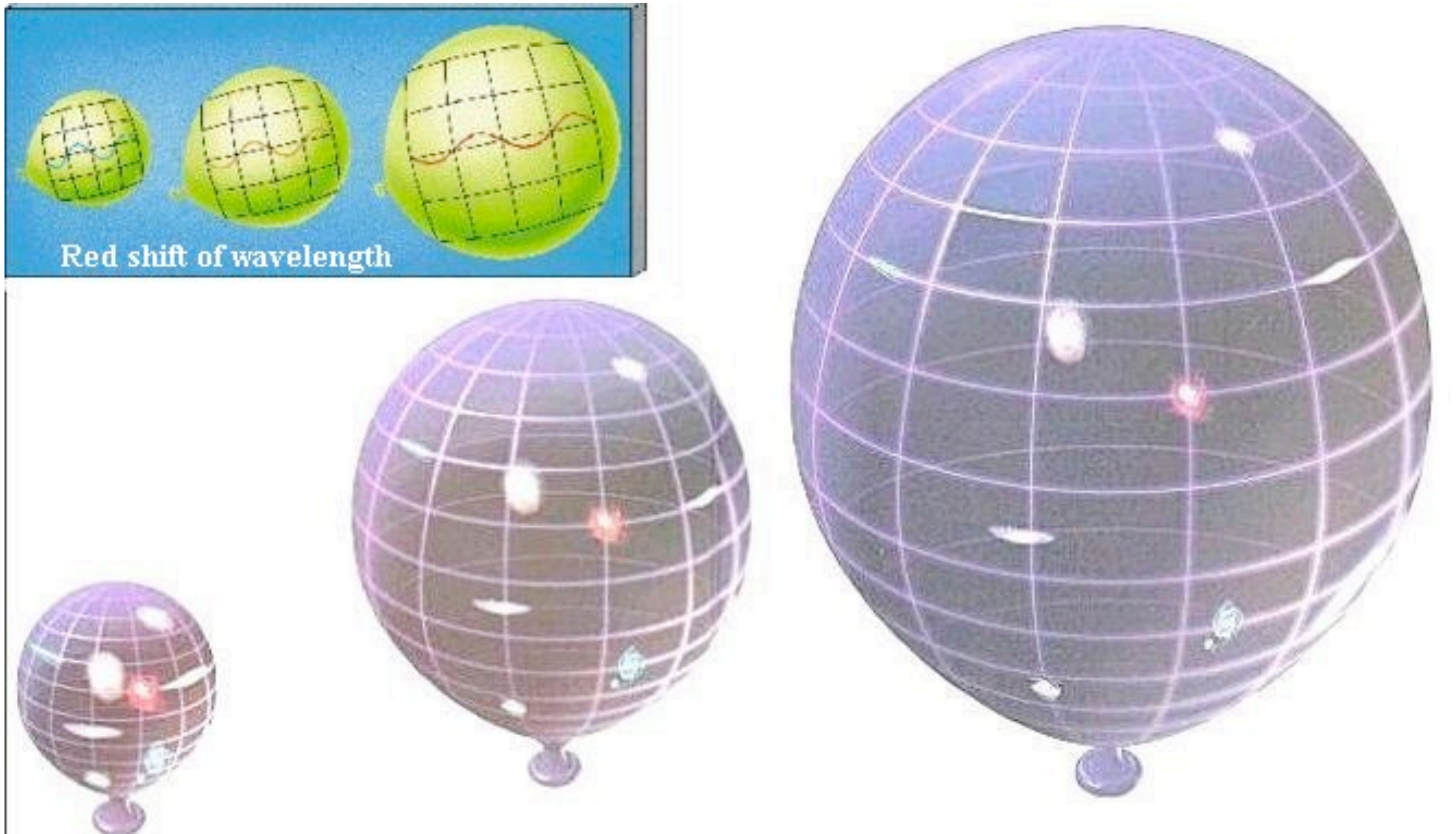
There are 100 photons in every cubic centimeter of the Universe - billions of time more than the number of photons emitted by stars.

The view from Earth

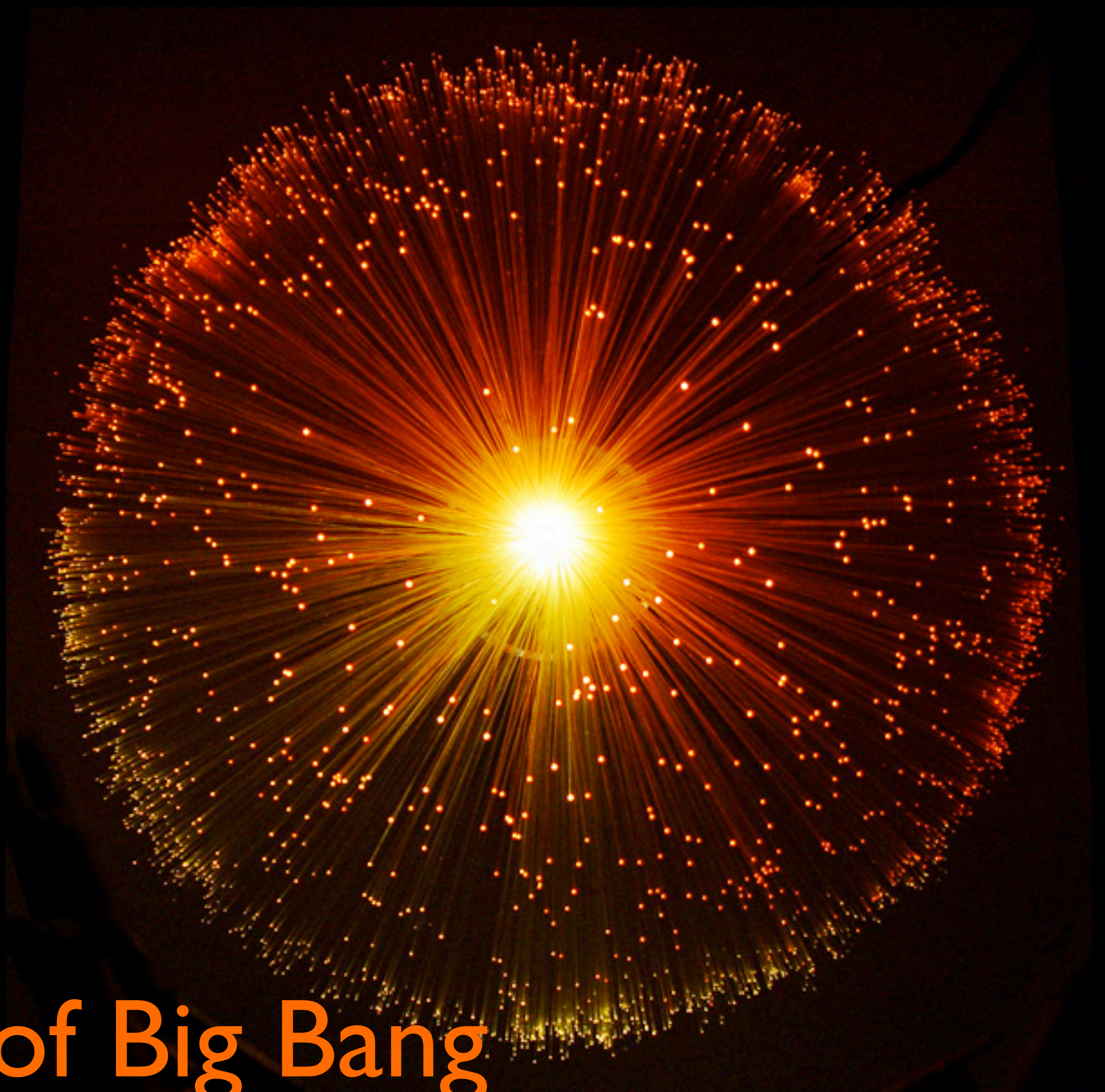
The ancients had it wrong: The Earth is not the center of the universe. But the Earth *is* at the center of the part of the universe that we can see. A being on a planet orbiting, say, a star in the galaxy M87 would see a different part of the universe, one centered on him. In a universe thought to be 11 to 15 billion years old, we can see out a distance of 11 to 15 billion light-years in all directions. From the Earth's viewpoint at midnight GMT, January 1, 2000, the elements of the cosmos will appear as they do here (right). Distances are not shown to scale but increase dramatically as they become more remote. The farther out we look, the farther back in time we see. Light takes 50 million years to arrive from M87, so we see it as it appeared 50 million years ago. The limit of our view is the time when the universe emerged from a state of hot plasma and became transparent, some 300,000 years after the big bang. That period is seen as the glow of the microwave background (shown in red and blue). If we could look beyond that veil, we would see—according to the standard models—the big bang itself, no matter in which direction we looked. [redacted]




THE BIG BANG
INFLATION
COSMIC MICROWAVE BACKGROUND
400,000 YEARS AFTER BIG BANG
THE DARK AGES
FIRST STARS
400,000,000 YEARS AFTER BIG BANG
FIRST GALAXIES
1000,000,000 YEARS AFTER BIG BANG
GALAXY EVOLUTION
CONTINUES...
DARK ENERGY ?
FORMATION OF THE SOLAR SYSTEM
8,700,000,000 YEARS AFTER BIG BANG
NOW
13,700,000,000 YEARS AFTER BIG BANG



Expanding distance between galaxies



Wrong, but often used pictures of Big Bang

Timeline of Big Bang

About 13.7 billions of years ago the observed part of the Universe started to expand very fast.

This expansion did not have a center of the expansion. The expansion is the same around every point in space.

The expansion was not an explosion. It was remarkably quiet with only very small ripples of patches of slightly dense and slightly under-dense in the space.

The Universe was initially very hot. It was filled with all possible particles: some exotic and some normal particles. As the Universe expanded it cooled and exotic particles died out.

When the Universe was about 100 seconds old, it was as hot and as dense as the center of our Sun. During that time some fraction of hydrogen nuclei merged and produced helium. The Universe was too cold for other reactions to produce heavier elements (such as carbon or oxygen). Those element were produced much later in stars.

Timeline of Big Bang

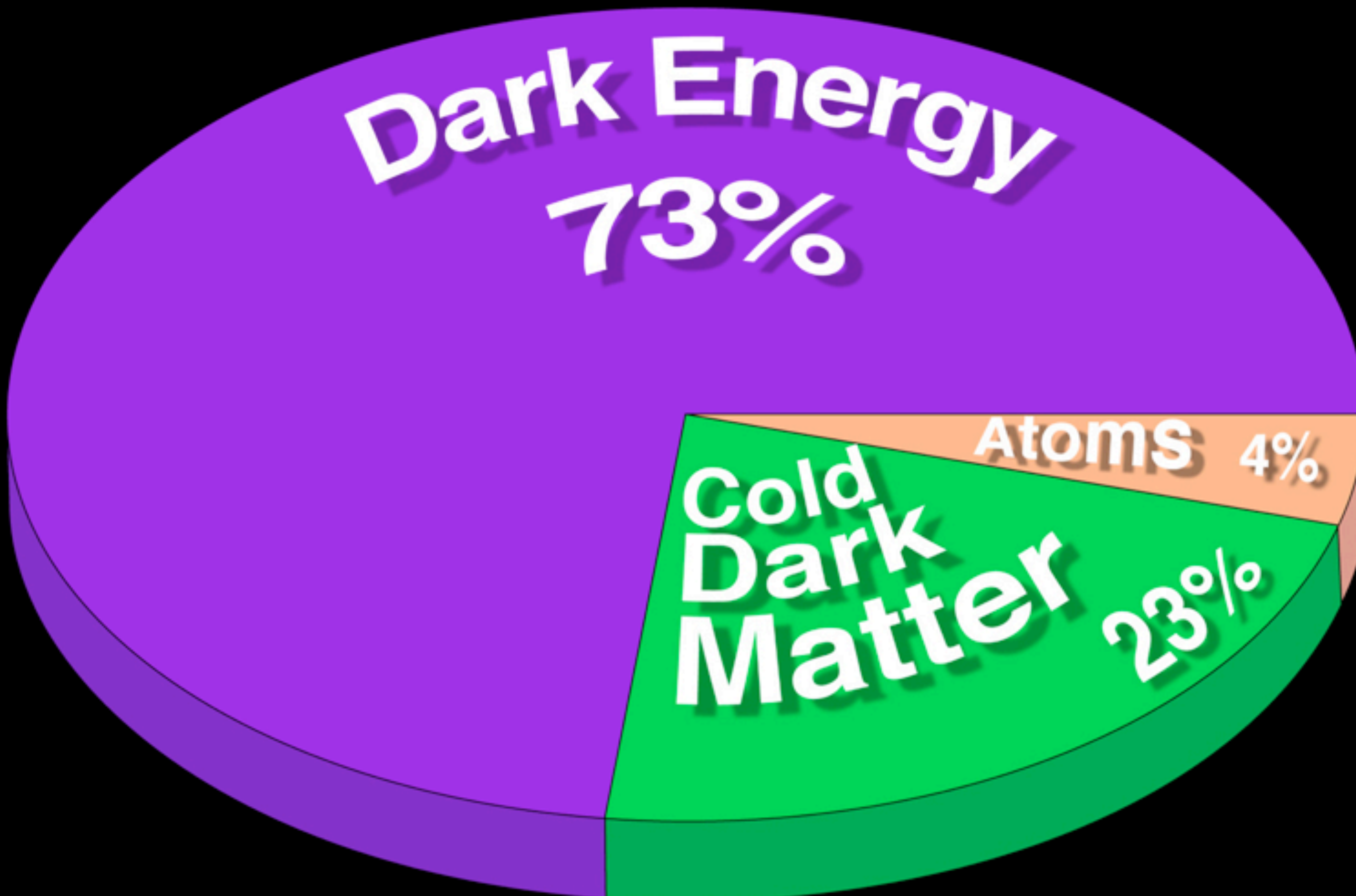
When the Universe was 400,000 yrs old and had temperature 3000 K, hydrogen recombined. At that moment the Universe became transparent. Now we receive photons, which were emitted at the moment of recombination.

First stars formed when the age of the Universe was 400 Myrs

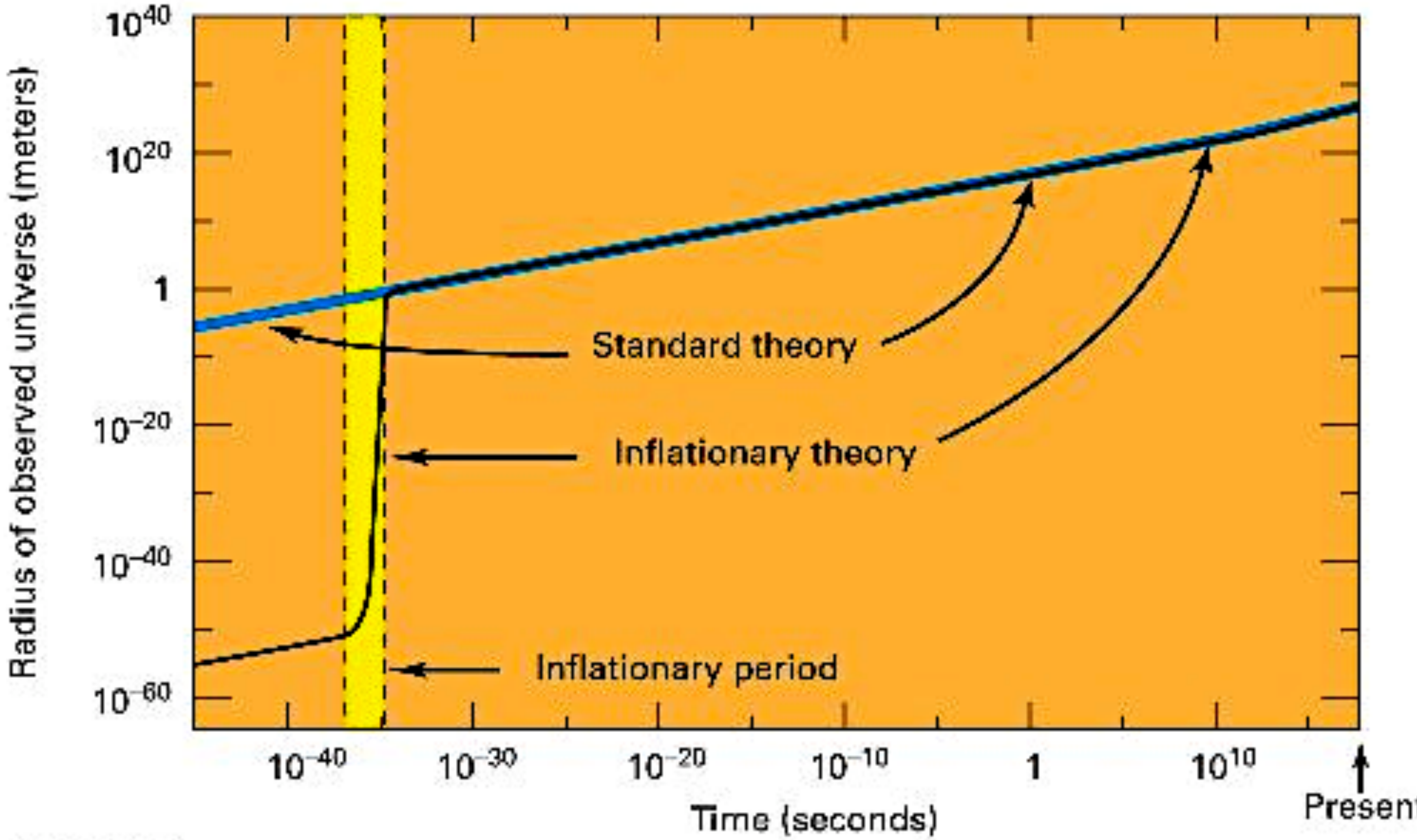
First galaxies formed when the age was 1 billion years.

Our Sun formed when the age was 9 billion years.

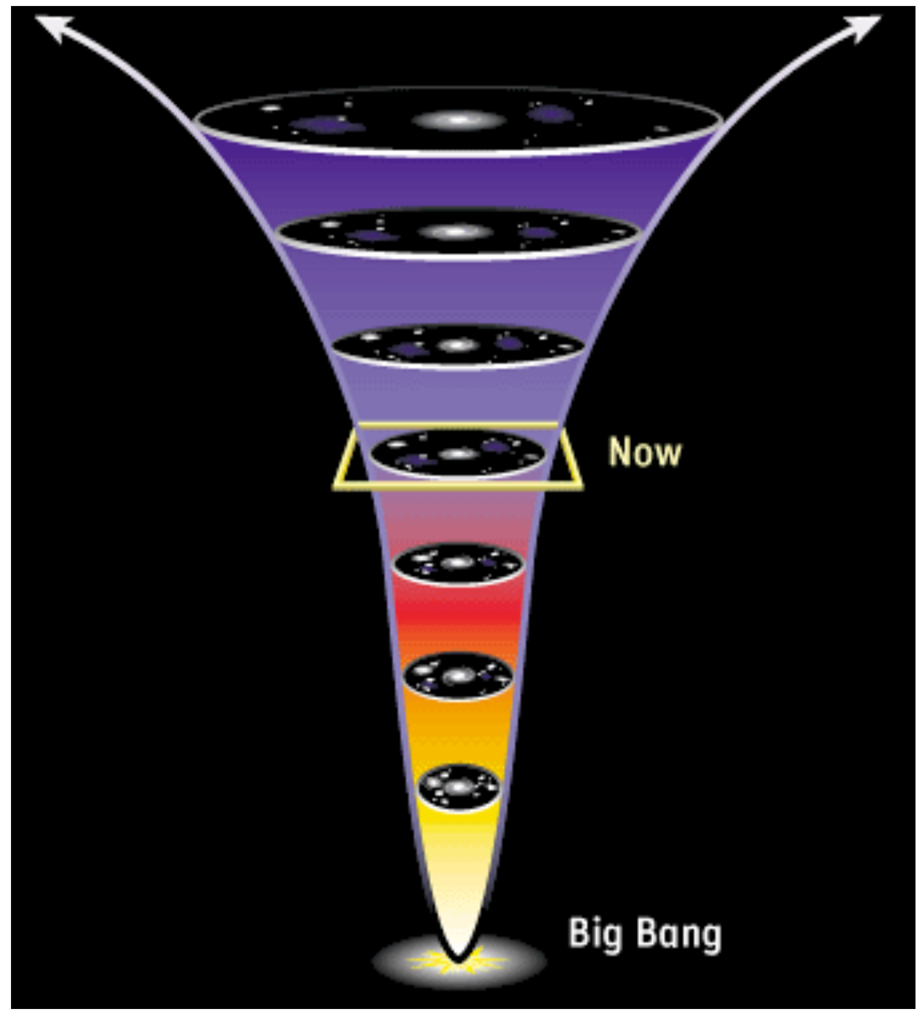
Composition of the Universe



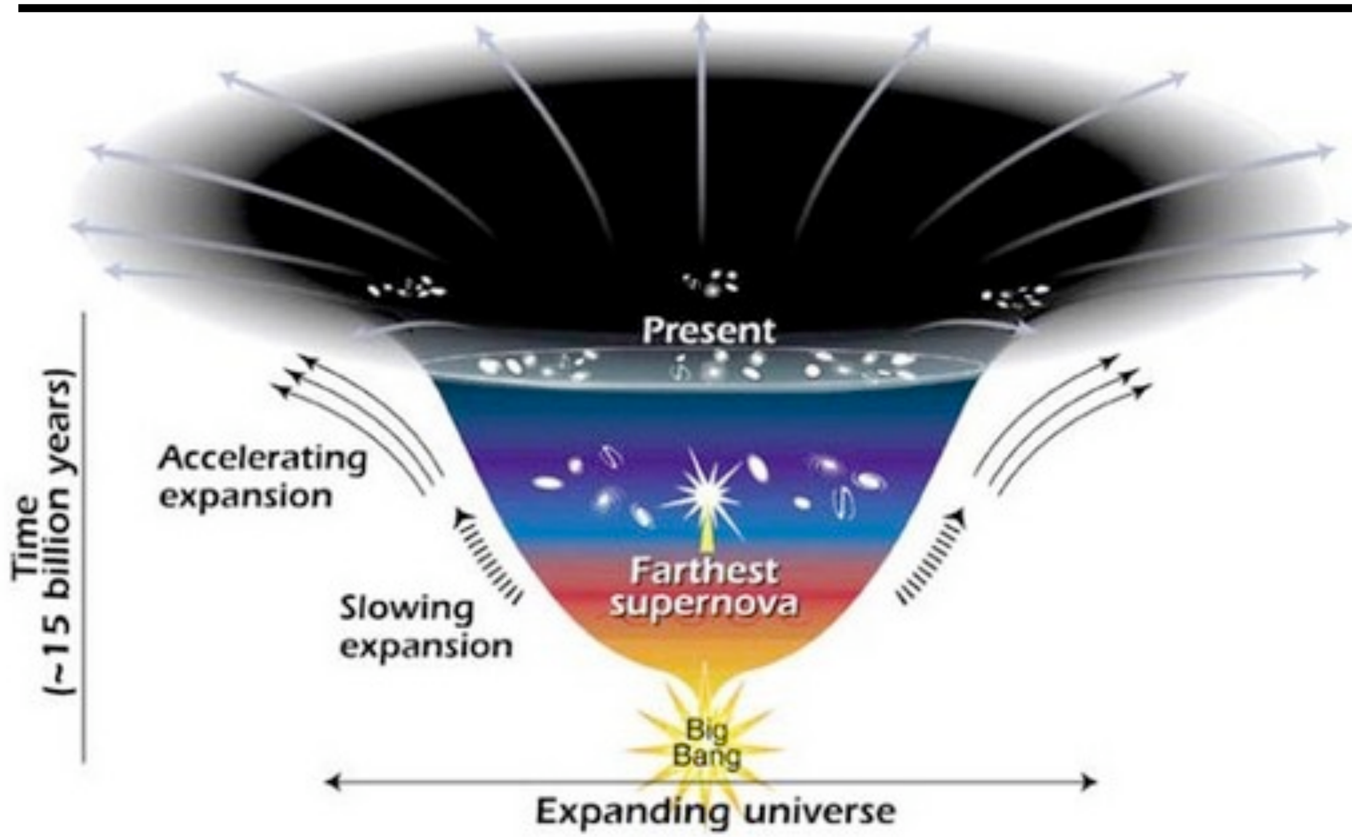
Before the Big Bang: Cosmic Inflation



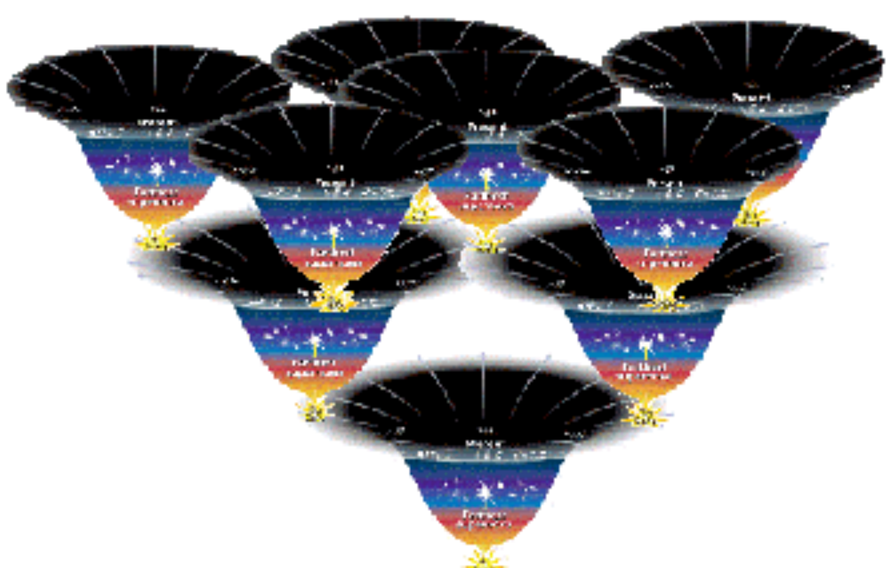
Future: Dark energy forces the Universe to expand even faster.



Inflation



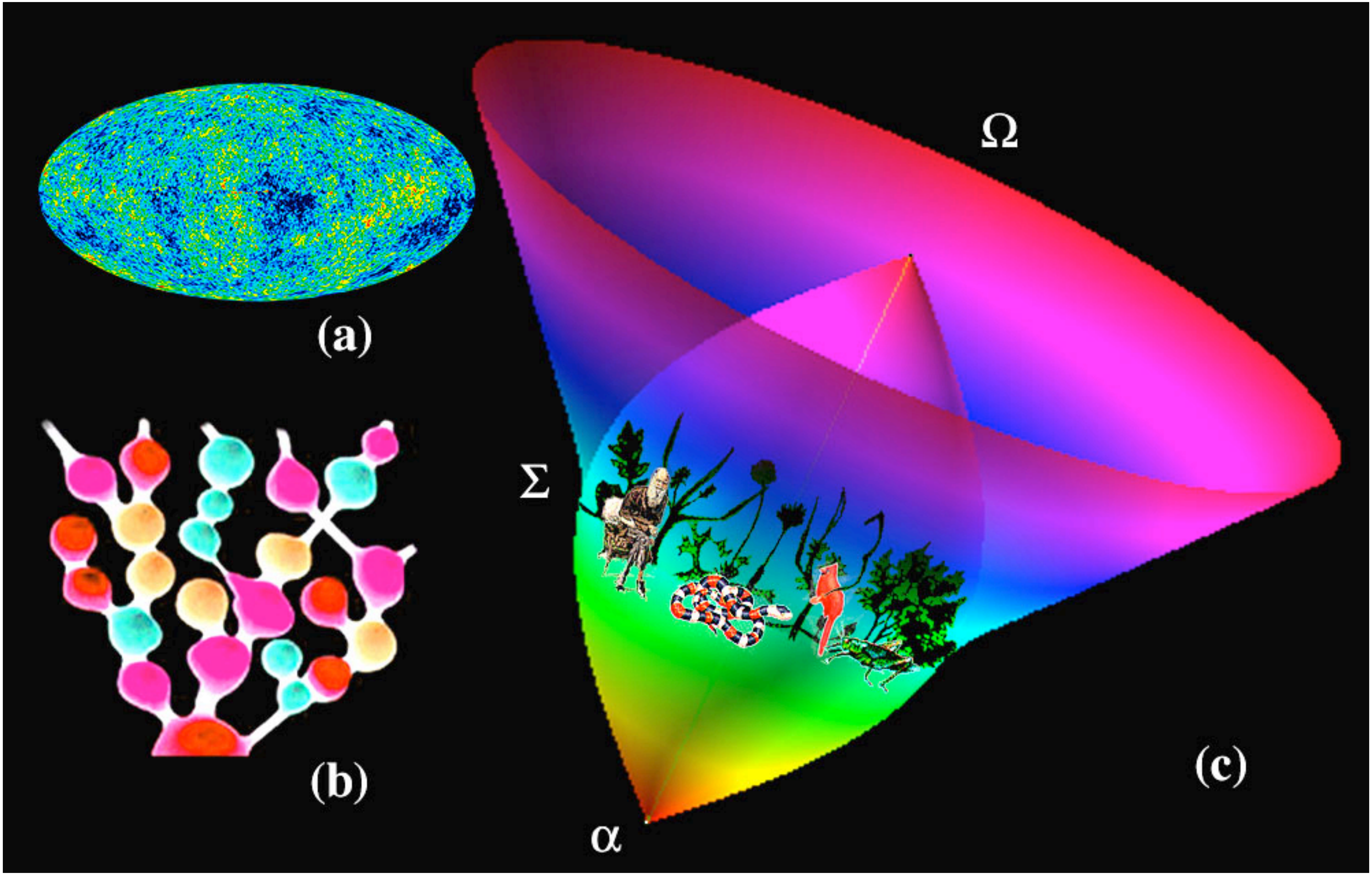
Chaotic Inflation



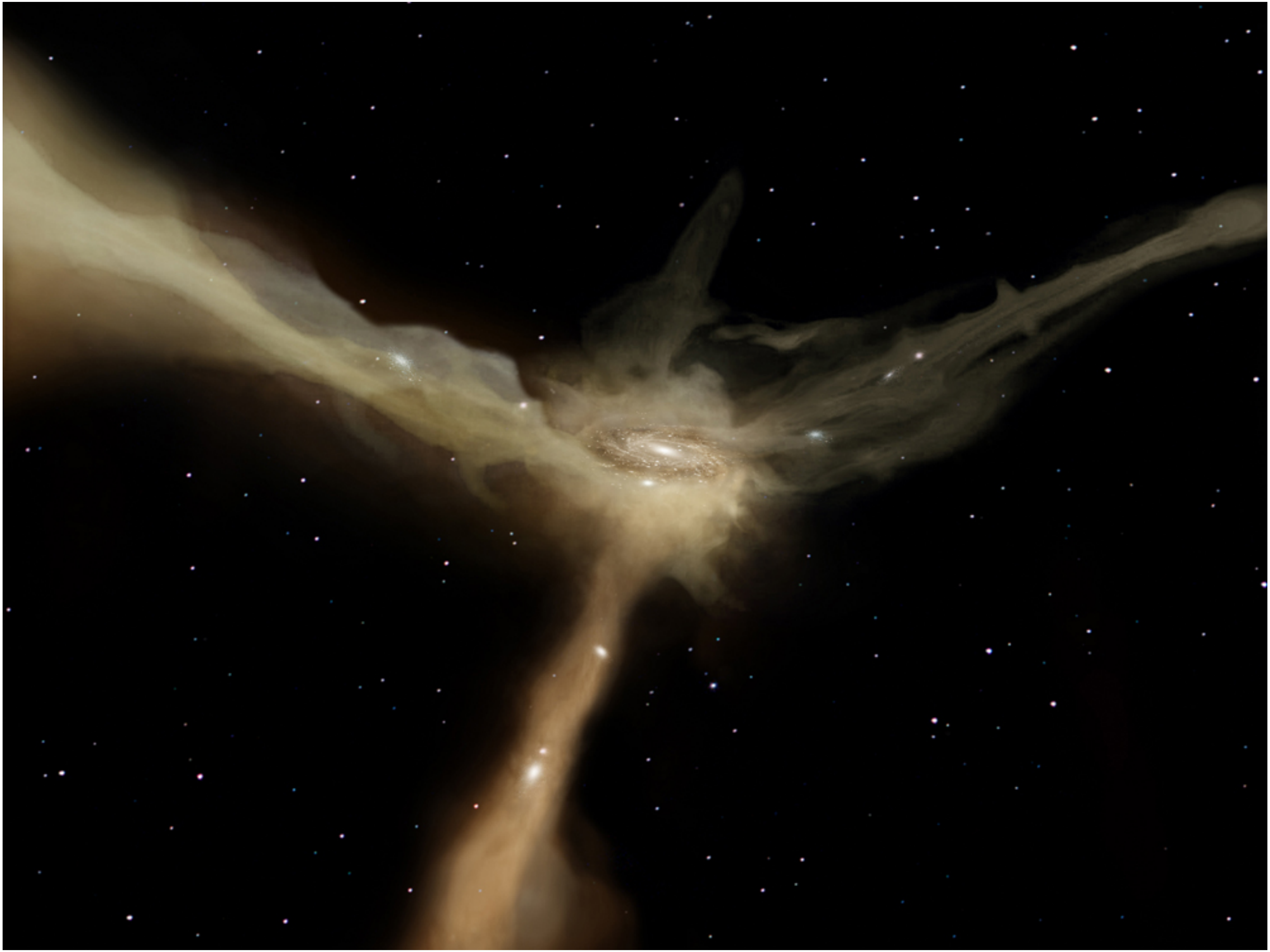
Andrei Linde

Born	March 2, 1948 (age 64) Moscow, Russian SFSR, Soviet Union (now Russia)
Citizenship	American
Nationality	Russian
Fields	Theoretical physics, cosmology
Institutions	Lebedev Physical Institute CERN Stanford University
Alma mater	Moscow State University
Doctoral advisor	David Kirzhnits
Known for	Cosmic inflation
Notable awards	Oscar Klein Medal (2002) Dirac Medal (2002) Gruber Cosmology Prize (2004) Fundamental Physics Prize (2012)

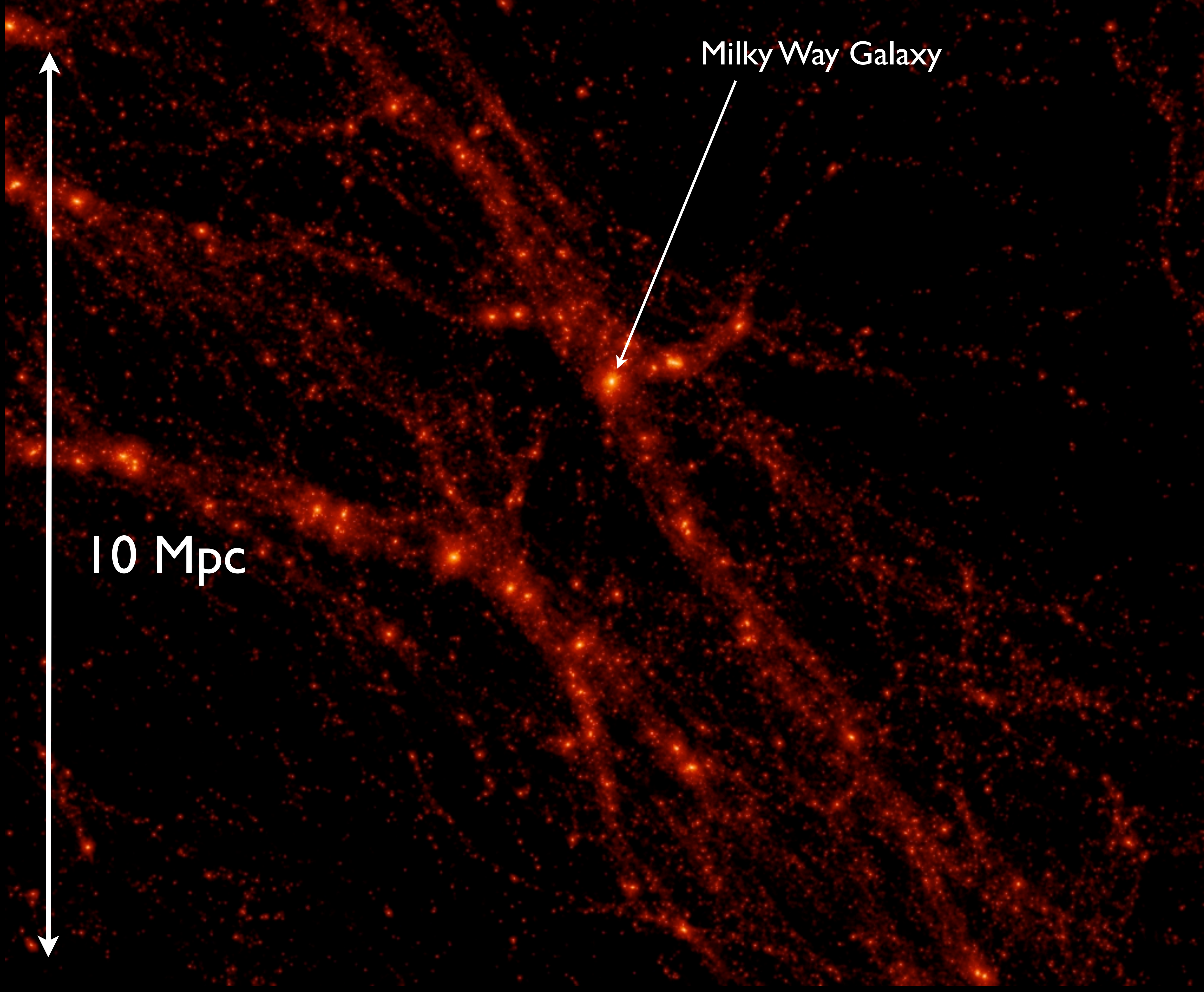
Chaotic Inflation



How Galaxies and first stars form.



Review: distribution of galaxies in space


Milky Way Galaxy
10 Mpc

Groups of Galaxies:

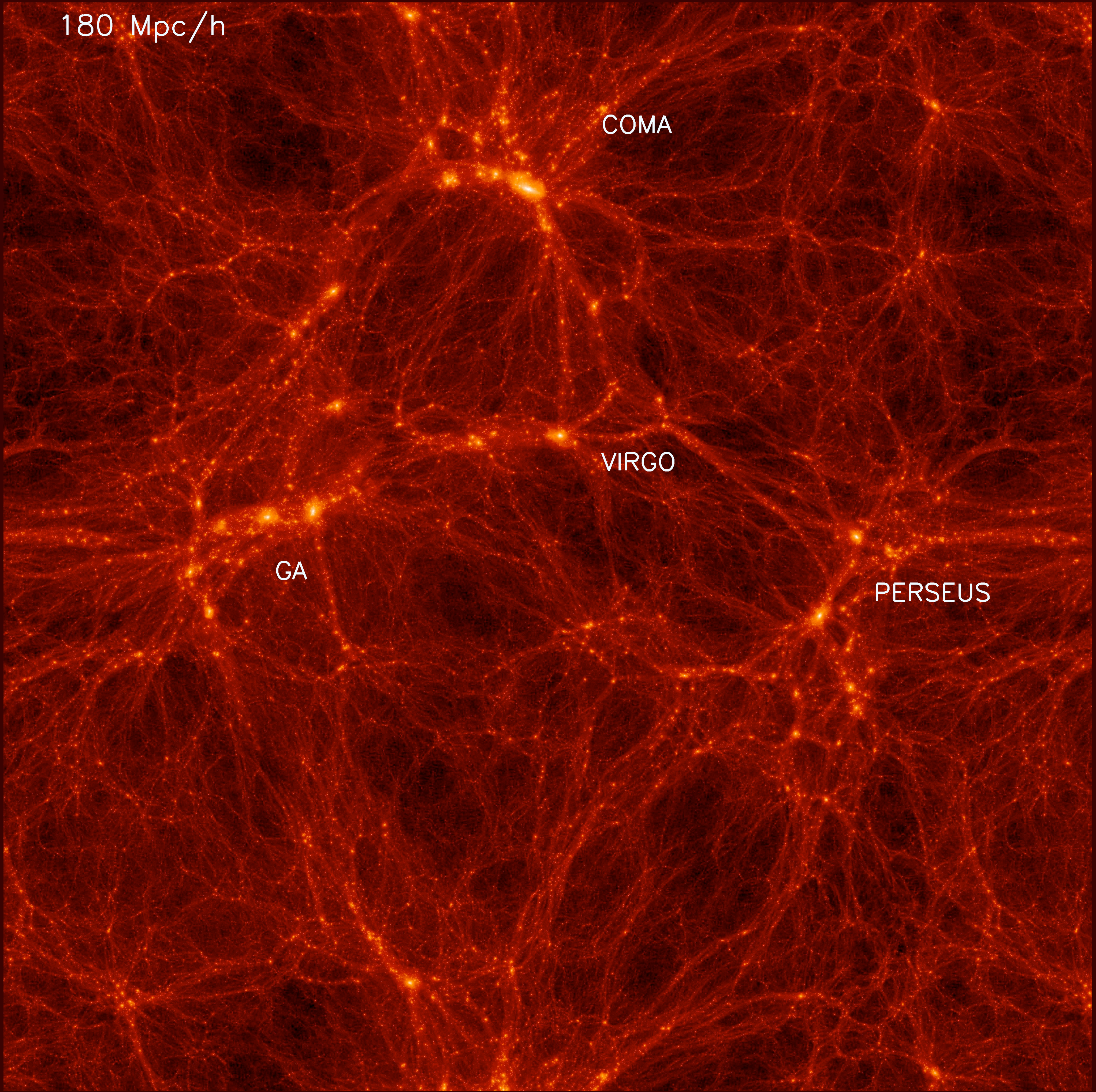
- 2-20 galaxies,
- size=0.5 Mpc,
- 1/2 of all galaxies belong to a group.
- Galaxies in groups are mostly spiral galaxies and irregulars.

Example:

- Local Group
- Our Galaxy
- Andromeda Nebula
- about 50 other small companions

Large-Scale Structure of Universe

Clusters, Filaments, Voids



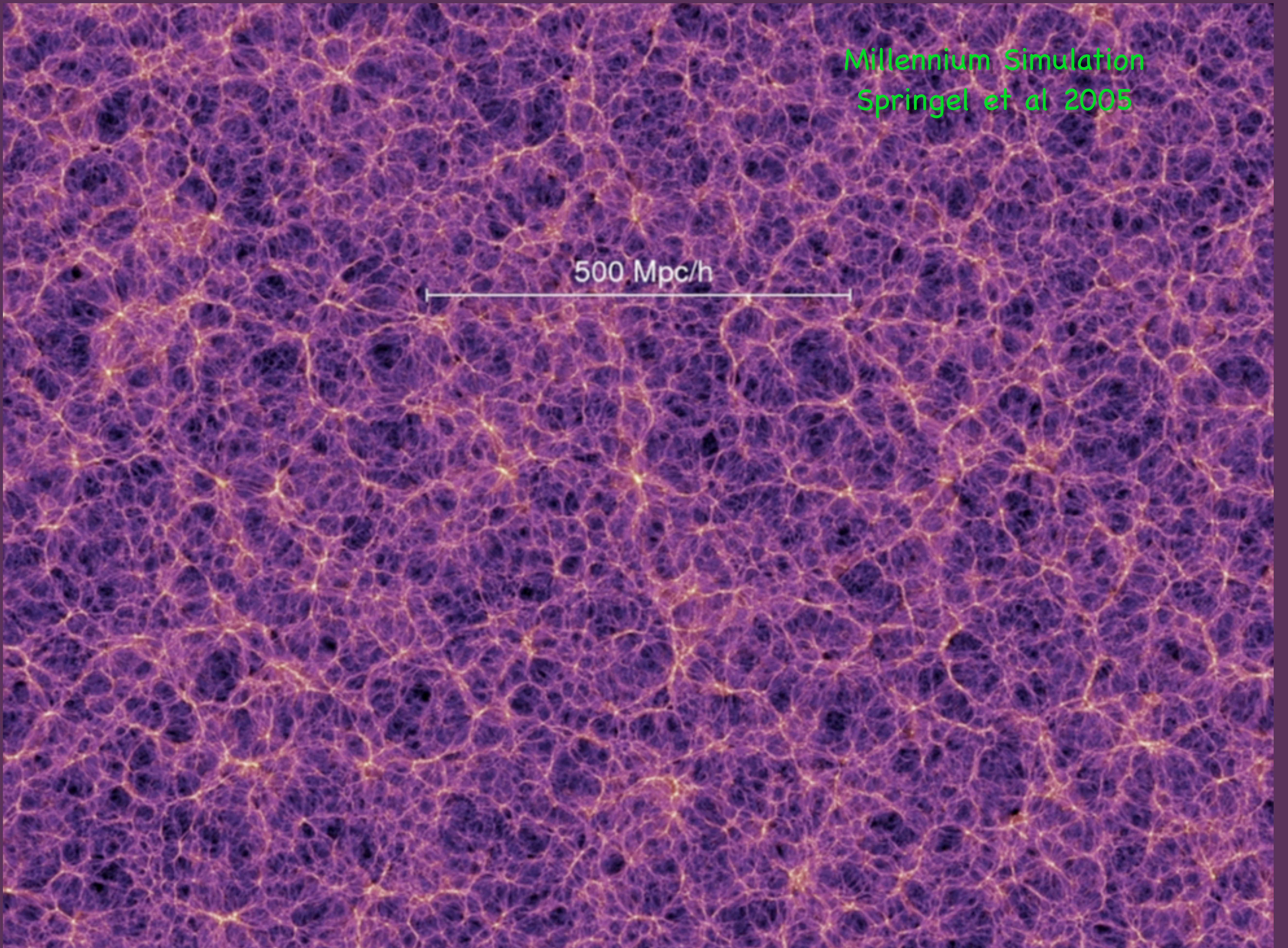
- Groups of Galaxies: 2-20 galaxies, size=0.5 Mpc, 1/2 of all galaxies belong to a group. Galaxies in groups are mostly spiral galaxies and irregulars.

- *Filaments*: a dozen or more galaxies in a chain, mostly spirals or irregulars, few Mpc long.

- *Clusters*: a thousand of galaxies, mostly ellipticals and spirals with a very small amount of gas. There is hot gas between galaxies (100 million degrees). Galaxies move with very large velocities: 1000 km/s. Size of clusters: 1- 3 Mpc. Often there is a large central elliptical galaxy.

- *Superclusters*: Long (30-100 Mpc) very anisotropic structures. Each supercluster includes many groups, filaments, and few clusters.

- *Voids*: Large, almost empty areas. The same linear size as for superclusters.


Millennium Simulation
Springel et al 2005
500 Mpc/h

Questions and Answers

Why are telescopes sometimes are called “time machines”?

1. because the author, H.G.Wells, used the term to describe telescopes in a book
2. because some of the oldest telescopes are still in use today
3. because observations of distant objects reveal them as they were in the past
4. it is wrong: you cannot travel into the past

A galaxy is 100 million light years away. How many years has its light taken to reach us?

Why does the observed microwave radiation from the Big Bang have such long wavelength (radio waves) instead of the very short wavelengths (ultraviolet) that might be expected from the high temperatures during the Big Bang?

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a. The radiation was hot went it was emmited, but it was redshifted (wavelength stretched) when the Universe expanded
b. The Universe was always cold
c. We can measure only radio waves, not ultaviolet

According to the Hubble law, if Galaxy A is ten times more distant than Galaxy B, then Galaxy A is