

Lecture 1: A Brief History of the Universe

Gong-Bo Zhao

Abstract

This lecture gives a first overview of modern cosmology. We introduce the hot Big Bang picture, explain why inflation is invoked, and summarize the main stages of cosmic history from the first fractions of a second to the present accelerated expansion. The goal is not yet a detailed derivation, but a clear physical timeline that will organize the rest of the course.

Learning goals

After this lecture, students should be able to:

- describe the major stages in the history of the Universe in the correct chronological order;
- explain the difference between the hot Big Bang model and the unknown physics of the initial singularity;
- state the main motivations for inflation;
- explain why the cosmic microwave background (CMB) is a cornerstone of observational cosmology;
- distinguish radiation domination, matter domination, and dark-energy domination.

1 What does cosmology study?

Cosmology studies the origin, large-scale evolution, and contents of the Universe. Its central questions include:

- How does the Universe expand with time?
- What is the Universe made of?
- How did galaxies and large-scale structure form?
- Why is the Universe so homogeneous, isotropic, and spatially close to flat on large scales?

The modern standard model of cosmology, usually called the Λ CDM model, gives a remarkably successful description of many observations. In this model, the late-time Universe contains radiation, baryons, cold dark matter, and dark energy. Later lectures will derive the equations behind this picture; here we first build an intuitive timeline.

2 The hot Big Bang picture

The phrase *Big Bang* is sometimes used loosely. In modern cosmology, it is safest to distinguish two statements:

1. The **hot Big Bang model** states that the early Universe was once extremely hot, dense, and rapidly expanding.

2. Extrapolating classical general relativity all the way back to $t = 0$ leads to a **singularity**. This does *not* mean that we already understand the true physics of the initial moment.

So, the hot Big Bang model is a successful description of the early thermal history of the Universe, while the very beginning likely requires a quantum theory of gravity.

3 A timeline of cosmic history

Table 1 summarizes the main stages discussed in this lecture. The times and redshifts are order-of-magnitude guides rather than numbers to memorize exactly.

Epoch	Typical time after Big Bang	Typical redshift	Main physical process
Inflation	about 10^{-36} – 10^{-32} s	extremely large	Rapid accelerated expansion; seeds of primordial perturbations
Primordial nucleosynthesis	about 1 s to a few minutes	about 10^9 – 10^8	Formation of light nuclei such as D, He, and a small amount of Li
Radiation domination	first $\sim 5 \times 10^4$ years	$z \gtrsim 3400$	Radiation controls the expansion rate
Recombination and photon decoupling	about 3.8×10^5 years	$z \approx 1100$	Neutral atoms form; CMB photons begin to free-stream
Matter domination	from equality to late times	$3400 \gtrsim z \gtrsim 0.3$	Structure growth becomes efficient; stars and galaxies form
Dark-energy domination	recent Universe	$z \lesssim 0.3$	Cosmic expansion becomes dominated by dark energy

Table 1: A schematic timeline of the standard cosmic history.

4 Inflation

The standard hot Big Bang model is very successful, but by itself it leaves several puzzles unexplained. Inflation was proposed to address these problems.

What is inflation?

Inflation is a period of very rapid accelerated expansion in the very early Universe. In simple models, the expansion is approximately exponential,

$$a(t) \propto e^{Ht},$$

for a short interval of time, where $a(t)$ is the scale factor and H is nearly constant.

Why do we need inflation?

Inflation was introduced mainly to explain:

- **The horizon problem:** Why do very distant regions of the CMB have nearly the same temperature even though, in a non-inflationary model, they would not have been in causal contact?

- **The flatness problem:** Why is the spatial curvature of the present Universe so close to zero?
- **The monopole problem:** Why do we not observe an abundance of heavy relics predicted in some high-energy theories?

Inflation also provides a mechanism for generating tiny primordial fluctuations from quantum fluctuations. These small fluctuations later grow into galaxies, clusters, and the cosmic web.

5 The radiation-dominated era

After inflation and reheating, the Universe is filled with a hot plasma of relativistic particles. At sufficiently early times, radiation dominates the total energy density, so the expansion is said to be *radiation dominated*.

Two important features characterize this era:

- The temperature of the Universe is extremely high, so particle interactions are frequent.
- The scale factor grows approximately as

$$a(t) \propto t^{1/2}.$$

Several major events occur during or near this period:

- **Primordial nucleosynthesis:** in the first few minutes, light nuclei are produced.
- **Matter-radiation equality:** at about 5×10^4 years after the Big Bang, matter and radiation contribute comparably to the total energy density.

6 Recombination, decoupling, and the CMB

In the early plasma, photons scatter efficiently off free electrons through Thomson scattering. As a result, photons, electrons, and baryons are tightly coupled, and the Universe is opaque.

As the Universe expands and cools, electrons combine with protons to form neutral hydrogen. This process is called *recombination*. Once the number of free electrons drops sharply, photons scatter much less often and begin to travel almost freely. This is called *photon decoupling*.

This transition occurs at roughly

$$t \approx 3.8 \times 10^5 \text{ yr}, \quad z \approx 1100.$$

The relic photons from this epoch are observed today as the **cosmic microwave background** (CMB), with a nearly perfect blackbody spectrum. The CMB is one of the most powerful probes of cosmology because it gives us a snapshot of the Universe when it was only about 380,000 years old.

Important conceptual point. The CMB does *not* show us the first instant of the Universe. Instead, it shows the earliest epoch from which photons can reach us directly. To probe earlier times, we need indirect methods, such as primordial element abundances, large-scale structure, neutrinos, or primordial gravitational waves.

7 The matter-dominated era and structure formation

After matter-radiation equality, non-relativistic matter dominates the energy budget for a long period. In this era, the scale factor evolves approximately as

$$a(t) \propto t^{2/3}.$$

This stage is crucial because density perturbations grow efficiently under gravity. The broad sequence is:

1. tiny primordial fluctuations are present after inflation;
2. dark matter overdensities grow gravitationally;
3. baryons fall into dark matter potential wells after recombination;
4. the first stars and galaxies form;
5. larger structures such as groups, clusters, filaments, and voids emerge.

Between recombination and the formation of the first stars, the Universe is sometimes called the *cosmic dark ages*. The first stars likely formed within the first few hundred million years, and their radiation later helped reionize the intergalactic medium.

8 The late-time accelerated expansion

Observations of Type Ia supernovae, together with other probes, show that the expansion of the Universe is accelerating at late times. This discovery was made in 1998 and is one of the foundations of modern cosmology.

A common misconception is that acceleration *contradicts* general relativity. In fact, general relativity can accommodate accelerated expansion if the Universe contains a component with sufficiently negative pressure, such as a cosmological constant. The big open question is therefore not whether acceleration is real, but *what causes it*.

Two broad possibilities are often discussed:

- **Dark energy:** a new component of the cosmic energy budget, with the cosmological constant as the simplest example;
- **Modified gravity:** general relativity may need to be altered on very large scales.

It is useful to distinguish two related statements:

- the Universe begins to **accelerate** at about $z \sim 0.7$;
- dark energy becomes **dominant in energy density** only later, at about $z \sim 0.3$.

9 Summary

The standard cosmic history can be summarized in one sentence:

The Universe expanded from an early hot, dense state; passed through inflation, radiation domination, recombination, matter domination, and structure formation; and is now in a phase of accelerated expansion.

For the rest of the course, this lecture provides the backbone. Later lectures will explain how we describe the expanding Universe mathematically, how perturbations evolve, and how observations test the model.

Suggested reading

- Scott Dodelson and Fabian Schmidt, *Modern Cosmology*, 2nd ed., Chapter 1.
- John Peacock, *Cosmological Physics*, selected introductory sections.

Exercises

1. Put the following epochs in chronological order: recombination, inflation, primordial nucleosynthesis, matter-radiation equality, late-time acceleration.
2. Explain in one paragraph why the CMB is often described as a “snapshot” of the early Universe.
3. During radiation domination, $a(t) \propto t^{1/2}$. Show that the Hubble parameter behaves as $H(t) = 1/(2t)$.
4. What problem would arise if the Universe had never experienced matter domination?