CHAPTER 13

COSMOLOGY

COSMOLOGY is the study of the origin, evolution, and macroscopic properties of the universe.

A. Earlier Views of the Universe:

1. **Geocentric Theory:** Earth is the immobile center of the universe and everything moves around the Earth (Aristotle, c. 350 BC).

   This was the most widely held theory up to the beginning of the 18th century.

2. **Heliocentric Theory:** The Sun is the center of the universe and the Earth is a planet and revolves around the sun like the other planets. The sun is a star and the other stars are very far away.

   The ancient Greek philosopher, Aristarchus, taught such a concept around c. 250 BC.

The ancient Greek philosopher Hipparchus, circa 150 BC, developed a working mathematical model of the geocentric theory by which it was possible to predict the positions of the planets in the sky.

However, as time went by, this model needed to be revised frequently.

In 120 AD, Claudius Ptolemy further improved a mathematical model of the geocentric theory, but it too eventually led to large disagreements with observations.

There were no other significant advances until the 16th Century, when Nicholas Kopernik (Copernicus), a polish prelate and scholar, made observations of planetary positions and developed a mathematical model for the heliocentric theory.
He showed that this model was able to predict the observed positions of the planets much more accurately and dependably than the best model for the geocentric theory. He published his results in a book, just before he died in 1542. With this book, a revolution in cosmology began.

In 1600, Tycho Brahe, a Danish astronomer, developed sighting instruments with which he was able to make the most precise positional measurements of the planets than anyone before. However, he too failed to find a parallax for any star and therefore concluded the Earth did not revolve around the Sun.

Between 1600 and 1620, Johannes Kepler, a German mathematician, analyzed Brahe's observations and deduced what are now called Kepler's 3 laws of planetary motion.
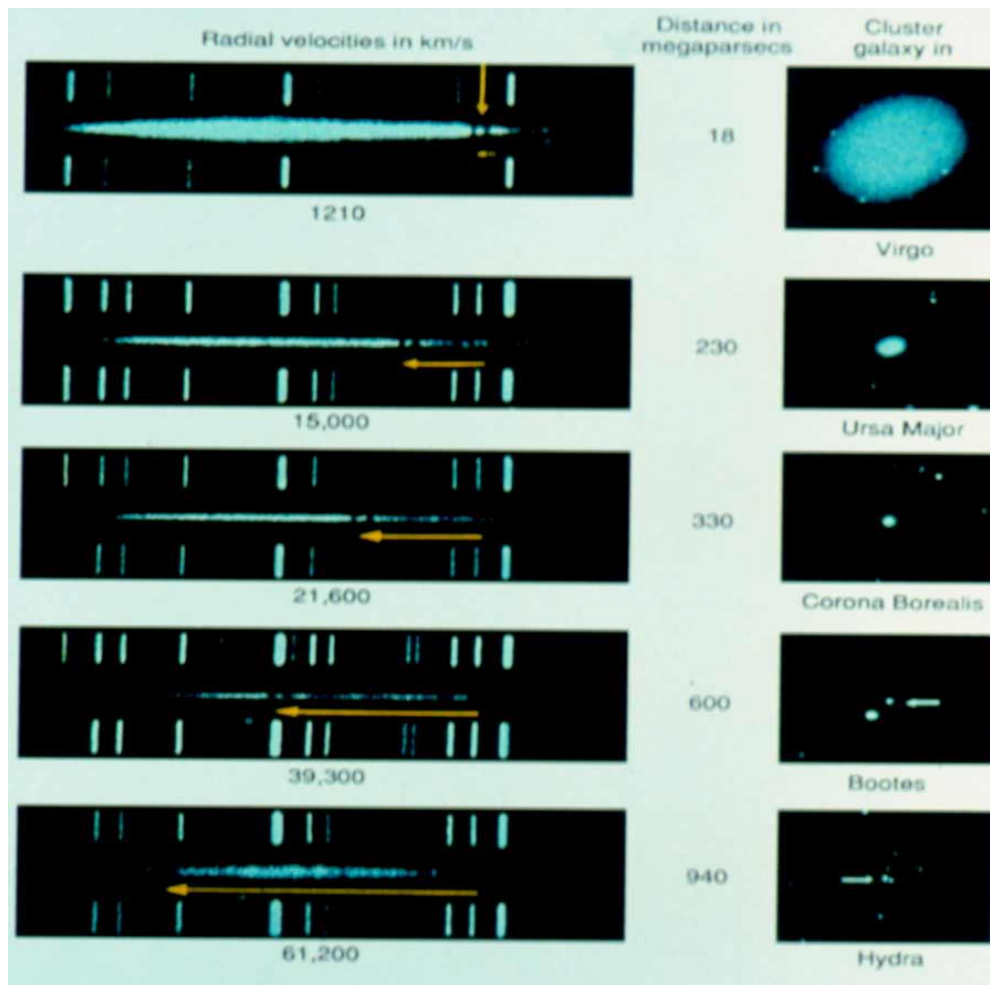
In 1671, Sir Issac Newton used these laws to help formulate the law of gravity.

B. Modern Cosmology

Basic Facts

1. Stars are not uniformly distributed throughout the universe but are organized into galaxies. There are no stars in the space between galaxies.

2. Galaxies are the basic building blocks of the universe.

3. Galaxies are organized into clusters of different sizes.

4. The different clusters of galaxies are distributed in a frothy or lace-like way throughout the universe.

5. The most distant cluster of galaxies is about 13.5 billion light years away. This sets a lower limit on the size of the visible universe.

6. In 1912, V. Slipher reported the results of a study of galactic motions indicating that all the galaxies outside the local group that he studied are moving away from us. This was unexpected.

   In 1927, E. Hubble and Humason undertook a study of the motions of galaxies to verify and extend Slipher's results.   Hubble also determined the distances of the galaxies to see if there was a relation between the two.   In the diagram below, spectra are shown for the brightest galaxies in different clusters at different distances. Two strong calcium lines are shown identified in the spectra by orange arrows that indicate their red Doppler shifts. Notice that the greater distance of the galaxy, the greater the red shift. The Doppler shifts are used to calculate the velocity of recession of the galaxy and hence the entire cluster.

Radial velocities in km/s	Distance in megaparsecs	Cluster galaxy in
1210	18	Virgo
15,000	230	Ursa Major
21,600	330	Corona Borealis
39,300	600	Bootes
61,200	940	Hydra

In 1929, Hubble published the results of this survey of radial velocities and distances for many different clusters of galaxies. The radial velocities were determined by measuring the Doppler effect in the spectra of the various galaxies that Hubble investigated.

The distances to these galaxies were determined using the Period-Luminosity Law for pulsating variable stars. This law gives the relationship between the period of pulsation and the absolute magnitude of such a star.

By monitoring the variation in the apparent brightness or magnitudes of the pulsating stars that he identified in the galaxies, Hubble was able to determine the period of such a variation, which is the same as the period of the star's pulsation.

Having determined the period of pulsation for a given star, the P-L law yields the absolute magnitude of the star. Knowing the absolute magnitudes and the apparent magnitudes of these stars, their distances may be calculated using the inverse square law.

In his 1929 paper, Hubble summarized the results of his investigation in the form of a graph, which is now known as the Hubble Diagram.

Hubble's original diagram has been updated but such updates are still called a Hubble Diagram. One is depicted to the right, where each black star represents an entire cluster of galaxies. In the above diagram, there is a linear correlation between distance and velocity of recession. That is, velocity or speed of recession is directly proportional to distance. This statement is symbolized as:
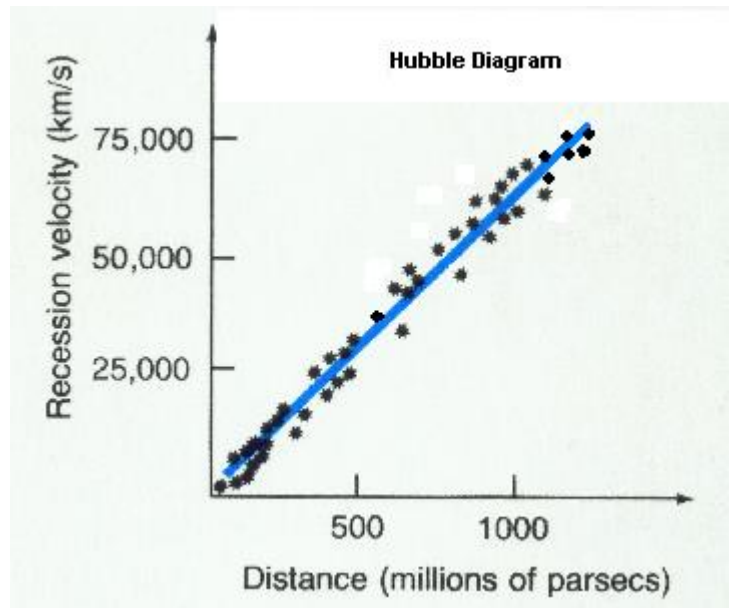
$$V_R \sim D$$

To make this proportionality into an equation we need to know the rate of change of V_R with distance **D.** This is the slope of the curve. Slope is defined in general as

slope = (difference in y) / (difference in x)

for any two variables x and y.

For a straight line, the slope has a single value and is therefore constant. In the Hubble diagram, the slope is called h, Hubble's constant. The equation for the straight line in Hubble's diagram may then be written as:

$$V_R = hD$$

The above equation expresses the relation between the distance of a cluster of galaxies and its recessional velocity and is the mathematical form for what is now called Hubble's Law. The verbal expression of this law is given below:

7. **Hubble's Law:** The farther away a cluster of galaxies is from us, the faster it moves away from us.

Hubble's Law is saying something about our universe. Hubble realized this and concluded his observations indicate that we live in an expanding universe.

8. **Hubble's Conclusion:** The universe is expanding at a constant rate everywhere.

Hubble's constant, h in the above equation, is actually the rate of expansion of the universe.

C. THE EXPANDING UNIVERSE

In fact the Hubble Diagram indicates that the universe is expanding at a constant rate everywhere. This can be understood in terms of the following analogy: Imagine a hypothetical universe that expands by a factor of 2 in a time of 2 years, as depicted in the schematic diagram below.
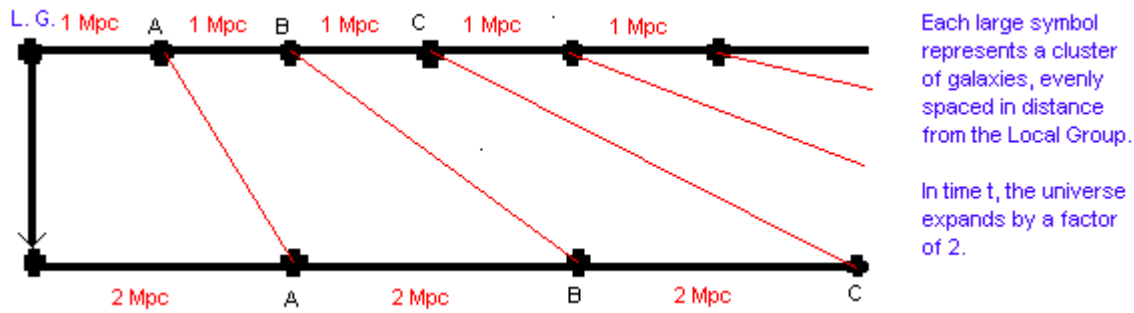
We measure the radial velocity for each cluster of galaxies to be $v_r = \Delta D/t$, where t is the time it takes to move the measured change in distance, ΔD. In the diagram above, the top part represents the universe 2 years ago. The different clusters are identified as A, B, etc. and are spaced 1 Mpc apart for simplicity. The numbers between the clusters indicate their spacings 2 years ago. The bottom is the universe now. Since 2 years have gone by, the universe has doubled in size, that is, every cluster is now twice as far away from its neighboring cluster.

Consider cluster A. It undergoes a change in distance, ΔD of 2-1 or1 Mpc in a time of 2 years, so $v_r = 1$ Mpc/2 yrs. = 0.5 Mpc per year. For cluster B, $\Delta D = 4-2 = 2$ Mpc and so $v_r = 1$ Mpc/yr. For cluster C, $\Delta D = 6-3 = 3$ Mpc in 2 years, so $v_r = 1.5$ Mpc/yr. , etc. If we now plot v_r vs. distance, we would get a linear relation between v_r and distance. In other words, for a universe that is expanding uniformly everywhere, any observer would see all other clusters receding with a speed that is directly proportional to distance, which is Hubble's Law.

Since light travels at a finite speed, the farther away we look, the further back in time we see. Hence, looking at very distant places in the universe is tantamount to looking far back into the past, when the universe was younger. Therefore, the straight line in Hubble's Diagram not only means the rate of expansion is the same everywhere, but that the rate of expansion has been constant over the age of the visible universe. If the rate of expansion had not been constant but were changing as time went

by, the relationship in the Hubble Diagram would be a curved line (a non-linear relationship), not a straight line.

In fact the Hubble Diagram indicates that the universe is expanding at a constant rate everywhere.

D. The Cosmological Principle (an assumption):

The laws of physics are the same everywhere in the universe.

The cosmological principle means that no matter where you are in the universe, you see the same phenomena. So no matter where you are in the universe, you will be led to the same laws by observing nature, including the law of gravity and Hubble's Law.

This means there are no special places in the universe: No center, edge or boundary exists.

In another attempt to visualize what it means for our universe to be expanding, consider as an analogy, the surface of a sphere or balloon. There is no special point on the surface of a sphere. Considering only the surface, there is no point that is the center and there is no edge.

The surface or fabric of the balloon is like our S-T continuum. However, the surface of a balloon is a 2D manifold, not a 4D one, so our analogy has its limitations. Like our 4D universe, the surface of a balloon has no special points; no center and no edge.

Imagine dots drawn randomly all over the surface of the balloon. These represent the various clusters of galaxies in our universe. As the balloon is made to expand, the fabric stretches and each dot

Coins on the surface of a balloon: an analogy for the expanding universe
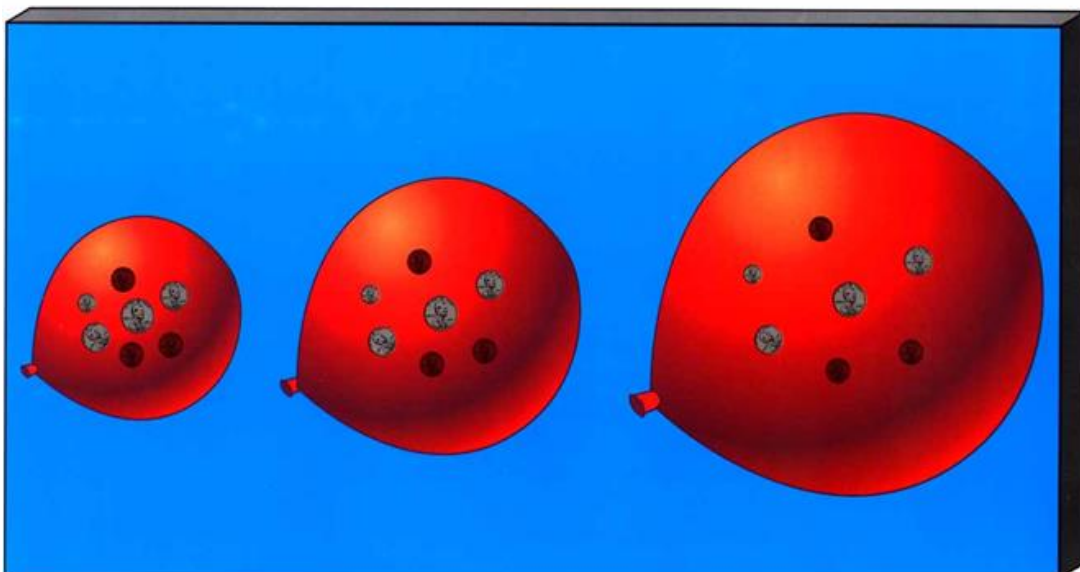
moves away from every other dot. This expansion is uniform over the entire surface of the balloon.

If you take any one dot and from that point make measurements to calculate the speeds of the

other points, you would obtain a result similar to Hubble's Law. As the balloon expands, its curvature becomes less severe.

In our universe, the stretching of the S-T continuum was initiated by an instability in the very early universe. The energy in the S-T continues today to result in the clusters of galaxies to move farther apart. As they move farther apart, the curvature of our universe decreases meaning the gravitational attraction between the galaxies decreases.

In our universe, the cosmological expansion does not apply to gravitationally bound systems, such as a galaxy or cluster of galaxies. Only the space between the clusters of galaxies is stretching.

E. WHAT ABOUT THE PAST?

The laws of physics are symmetric in time. That is, for a given set of conditions, the laws of physics make it possible to predict what happened in the past as well as what will happen in the future.

For example, the laws of physics enable us to calculate where any planet will be in the sky either in the future or in the past. Also, it is possible to predict the instant when and where an eclipse of the
Sun or Moon will occur or has occurred in the past. Historians have made use of this capability to date many events recorded in the Bible or in other ancient writings.

Therefore, we may use the laws of physics to extrapolate backwards in time from today, to learn what the universe was like in the past. However, there is a limit to how far back in time we can do this.

If the universe is expanding and its volume is increasing now, then, in the past, the universe was smaller and things must have been crowded closer together. In fact, this has been confirmed by studying the spacing of the clusters of galaxies that are far away. Recall that we see these clusters at a time when the universe was billions of years younger than it is today.

In 1931, **Monsignor Georges Henri Joseph Édouard Lemaître** (1894-1966) proposed what became known as the Big Bang theory of the origin of the Universe, which he called his 'hypothesis of the primeval atom'.

Lemaître was a Belgian Roman Catholic priest and professor of physics and astronomer at the University of Leuven in Belgium. He spent a year at the Harvard College Observatory in Cambridge, Massachusetts working with Harlow Shapley, who had just gained a name for his work on the structure of the galaxy, and then at the Massachusetts Institute of Technology, where he registered for the doctorate in sciences. After receiving his PhD, Lemaître, returned to Belgium and became a lecturer at the University of Leuven. He then published a report in which he presented his new idea built on Hubble's discovery of our expanding Universe. In his theory, he was able to derive the "Hubble law" and provided the first theoretical estimation of the Hubble constant (the rate of expansion of the universe). However, he had not yet developed the idea of the primeval atom. Instead, the initial state was taken as Einstein's own finite-size, static universe model.
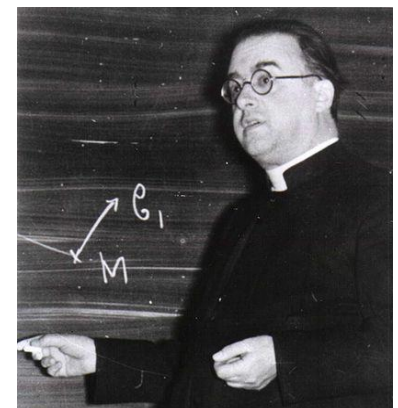
In 1931, after further investigation, he proposed that the Universe expanded from an initial point, which he called the "Primeval Atom," and then developed this idea in a paper published in the

renowned journal *Nature*. Lemaître himself described his theory as "the Cosmic Egg exploding at the moment of the creation"; it became better known as the "Big Bang Theory," the term having originally been a sarcastic remark of Fred Hoyle's, another famous British cosmologist who had a different interpretation of the expanding universe.

About 1940, the nuclear physicist and cosmologist, George A. Gamow (1904 – 1968) applied his talents and the laws of nuclear physics to understanding the early state of the universe. **Gamow** was a Ukrainian born physicist and cosmologist. He worked on subjects including the atomic nucleus, star formation, stellar nucleosynthesis, and later, the genetic code. Gamow worked at a number of establishments before fleeing the increased oppression in Russia and settling at George Washington University in 1934.

Like Lemaître, Gamow assumed the universe has always been expanding at the same rate that it is today. Therefore, billions of years ago, all the matter in the universe would be compressed into a state of very high density. Hence, all the galaxies, stars, planets, and people could not exist. He showed that even atoms could not exist in the early universe, and that protons, electrons, and neutrons would be unstable and could not exist either. Instead, the universe would consist only of hyper dense nuclear matter and gamma rays (extremely short wavelength electromagnetic radiation, even shorter than X-rays). That is the density would be greater than that found in the nucleus of an atom. The following is a summary Gamow's work:

The Physical Properties of the Primordial or Primeval Atom (the early state of the universe):

1. Size: microscopic

2. Density: hyperdense, $> 10^{13}$ gm/cm^3, which is the density of nuclear matter.

3. Temperature: $> 10^{12}$ Kelvins.

4. Composition: Hyperons and gamma-rays. (p^+, e^-, and n^0 could not exist).

5. Very unstable, and therefore it underwent an ultra rapid expansion.

This expansion was so fast that it was like an explosion, which has been nicknamed **the Big Bang** or the **Fireball Explosion.**
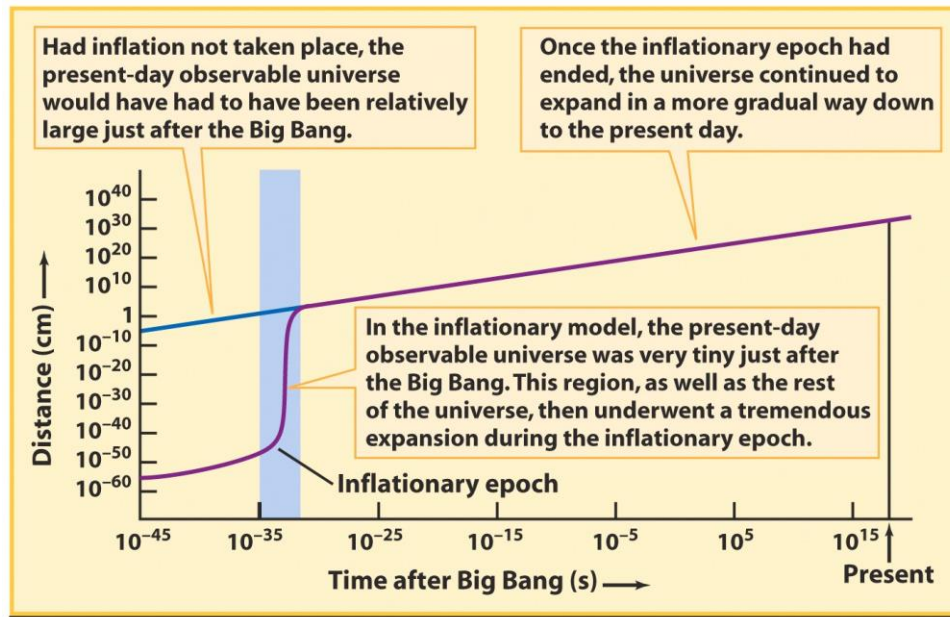
Since we cannot trace the universe back any further in time than this, the Big Bang is considered to have occurred at time t=0. It is not possible to know what the universe was like before this time or even whether it even existed.

When we say at t=0 the universe was confined to a microscopically small volume, this includes the matter as well as the entire S-T continuum. One cannot imagine that there is empty space outside of the primordial atom. The question of what is outside the universe can not be answered by science.

Very near to time 0, the universe was dominated by electromagnetic radiation but as the universe expanded conditions changed so that eventually some of the radiation transformed into matter in the form of hyperons.

Since, the hyperons are embedded or anchored to the S-T continuum, the expansion of the latter would cause the hyperons to accelerate to velocities close to the velocity of light.
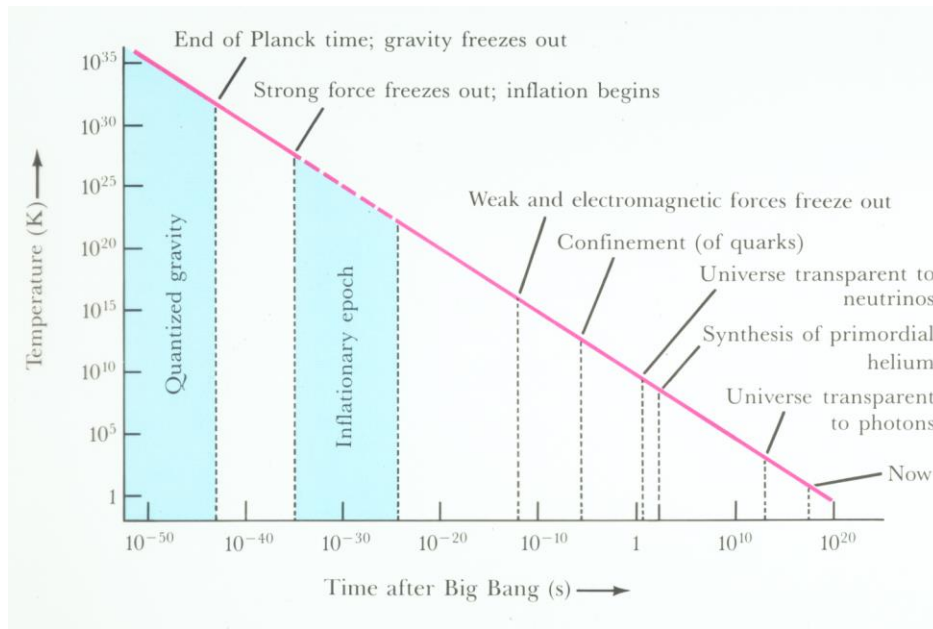
In a small fraction of a second the temperature, density and composition of the universe would have changed dramatically. In other words, the universe would have quickly evolved. This evolution slowed down as the universe expanded, but that evolution and expansion has continued until the present day. The evolution of the size of the universe is depicted in the following graphic:

Had inflation not taken place, the present-day observable universe would have had to have been relatively large just after the Big Bang.

Once the inflationary epoch had ended, the universe continued to expand in a more gradual way down to the present day.

In the inflationary model, the present-day observable universe was very tiny just after the Big Bang. This region, as well as the rest of the universe, then underwent a tremendous expansion during the inflationary epoch.

Inflationary epoch

Distance (cm)

10^{40}
10^{30}
10^{20}
10^{10}
1
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{-50}
10^{-60}

10^{-45} 10^{-35} 10^{-25} 10^{-15} 10^{-5} 10^{5} 10^{15}

Time after Big Bang (s) ⟶

Present

The temperature of the universe is defined in terms of the ambient radiation filling it vis-à-vis the laws of radiation. That is, the spectrum of the radiation filling the universe can be matched with a Planckian curve for some temperature and the peak intensity of the spectrum will be at a wavelength corresponding to a temperature given by Wien's Law.

Gamow predicted that such radiation should have a black body spectrum indicative of a temperature of about 3K. Such radiation was detected by Penzias and Wilson at the Bell Labs in New Jersey in 1963, thereby confirming the Big Bang Theory. For this discovery, Penzias and Wilson received the Nobel Prize in Physics. Unfortunately, Gamow, like Hubble, never received such an award.

The following diagram depicts graphically how the temperature of the universe has changed with time since the Big Bang. The diagram also shows segments of time when certain critical processes have occurred, such as when the weak and electromagnetic forces separated from one another. Physicists use the jargon that they froze out.

Go to Fireball Chronology