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Unit-II Origin of Universe

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UNIT 2

ORIGIN OF UNIVERSE

2.1 Introduction

The **origin of the universe** is one of the most profound questions in cosmology, addressing how everything—from the smallest particles to the vast expanses of space itself—came into existence. Understanding the origin of the universe involves a blend of theoretical physics, observational astronomy, and philosophical inquiry. Over the centuries, various ideas about the universe's beginnings have been proposed, ranging from mythological and religious explanations to modern scientific theories.

The most widely accepted scientific model of the universe's origin is the **Big Bang theory**, which suggests that the universe began as an infinitely hot, dense point—called a **singularity**—approximately 13.8 billion years ago and has been expanding ever since. This expansion led to the formation of the first subatomic particles, atoms, stars, galaxies, and eventually the complex structures we observe today.

In this context, understanding the **early history of the universe** is crucial for piecing together the timeline of events that shaped the cosmos from its initial singularity to the formation of galaxies and stars. The earliest stages of the universe are characterized by extreme conditions of temperature, density, and energy, far beyond what we can recreate in laboratories on Earth.

2.2 Early History of the Universe

The early history of the universe is a journey through extreme conditions that transformed a tiny, highly energetic point into the vast and complex cosmos we observe today. The stages of this evolution are outlined below, based on current cosmological models and observational evidence.

1. The Big Bang: The Beginning (t = 0)

The origin of the universe, as we understand it today, begins at **t = 0** with the **Big Bang**, a term that describes not an explosion in space, but rather an expansion of space itself. At this point, the universe was concentrated in an infinitely small, dense, and hot state known as a **singularity**. The Big Bang theory does not describe what happened at the exact moment of the bang, nor does it address what caused it, as the laws of physics break down at this singularity. However, it marks the beginning of space and time as we know them.

- **Singularity and Initial Conditions**: The universe began with an incredibly small volume containing all the energy and matter that would eventually expand and form galaxies, stars, and other cosmic structures. At this moment, the temperature and density were so high that typical physics did not apply.

2. Planck Era (0 to 10^{-43} seconds i.e., ~ 10^{-43} seconds after the Big Bang)

The **Planck era** is the earliest known stage of the universe, lasting from t=0 to approximately 10^{-43} seconds. During this time, the universe was unimaginably small and hot, with temperatures reaching up to 10^{32} Kelvin. The four fundamental forces of nature—gravity, electromagnetism, the strong nuclear force, and the weak nuclear force—are believed to have been unified in a single force at this point.

- **Quantum Gravity**: In this era, quantum mechanics and gravity were unified into a single framework known as **quantum gravity**, which is still not fully understood. The theory of everything (TOE) that would explain how gravity and quantum mechanics work together remains an open problem in theoretical physics.
- **Spacetime Singularities**: At such high densities, quantum fluctuations would dominate, and classical concepts of time and space would not hold. This era remains speculative as there is no definitive theory that can describe what happened.

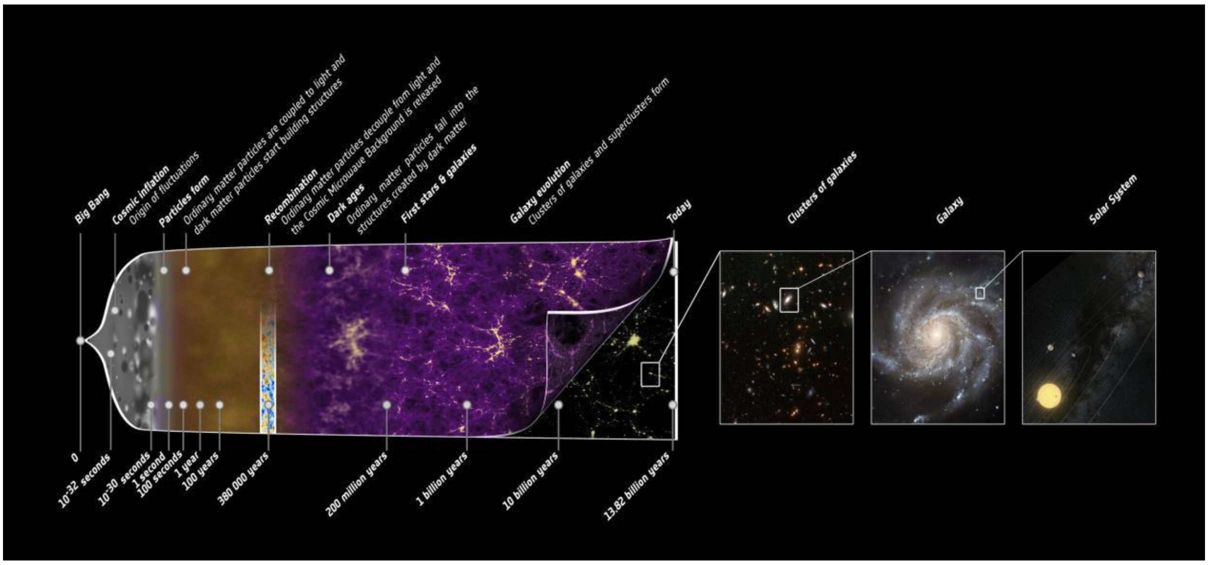

Fig: Early History of the Universe

3. Grand Unification Epoch (10^{-43} to 10^{-36} seconds)

During the **Grand Unification Epoch**, which occurred shortly after the Planck era, the universe was still extremely hot and dense. The temperature was high enough to keep the fundamental forces—gravity, electromagnetism, and the strong and weak nuclear forces—unified as a single force, known as the **Grand Unified Theory (GUT)** force.

- **Unification of Forces**: At temperatures around 10^{32}K, the strong, weak, and electromagnetic forces are theorized to merge into a single force. At the end of this period, the forces began to differentiate.
- **Inflation**: This phase is also thought to include the beginning of **cosmic inflation**, a rapid exponential expansion of the universe that stretched space-time by an enormous factor in a fraction of a second.

4. Inflationary Epoch (10^{-36} to 10^{-32} seconds)

The **Inflationary Epoch** is one of the most important phases in the early universe, in which the universe expanded at an enormous rate. During this period, the universe grew by a factor of at least 10^{26} in less than a trillionth of a second.

- **Inflation Theory**: This theory, proposed by Alan Guth in 1980, explains how the universe could have come to have the large-scale structure and uniform temperature that we observe today. Inflation smoothed out any initial irregularities, creating a nearly homogeneous and isotropic universe.
- **Quantum Fluctuations**: While inflation smoothed out the universe, it also created tiny quantum fluctuations. These fluctuations served as the seeds for the formation of cosmic structures like galaxies and clusters of galaxies. The slight irregularities in temperature and density were amplified as the universe continued to expand and cool.

5. Formation of Fundamental Particles (10^{-32} seconds to 1 second)

After inflation, the universe cooled sufficiently for the basic building blocks of matter to begin forming. The temperature decreased from 10^{27} K to about 10^{10} K, allowing the fundamental forces to separate into distinct interactions.

- **Quark-Gluon Plasma**: In this hot, dense state, quarks and gluons (the fundamental particles of matter and force) existed freely in a **quark-gluon plasma**, rather than forming protons and neutrons. The universe continued to expand and cool, allowing quarks to combine into protons and neutrons.

- **Particle Creation**: During this time, the universe was filled with an array of fundamental particles, including quarks, anti-quarks, electrons, positrons, neutrinos, and photons. As the universe expanded, the number of particles decreased due to pair annihilation, where matter and antimatter annihilated each other, leaving behind photons and neutrinos.

6. Nucleosynthesis (3 minutes to 20 minutes)

As the universe continued to cool, nucleosynthesis—the process of forming atomic nuclei—began to take place. This occurred between roughly **3 minutes to 20 minutes** after the Big Bang.

- **Formation of Light Elements**: During this period, protons and neutrons fused to form the first atomic nuclei, primarily **hydrogen**, **helium**, and small traces of **lithium**. This process is known as **Big Bang nucleosynthesis**.
- **Nucleosynthesis Process**: Initially, free neutrons and protons were too energetic to bind together, but as the universe cooled to a temperature around 10^9 K, nuclear reactions took place, creating deuterium (heavy hydrogen), helium-4, and small amounts of lithium and beryllium. Most of the universe's helium was formed during this period.

7. Recombination and the Decoupling of Matter and Radiation (380,000 years)

As the universe expanded and cooled, the next significant phase in its early history was **recombination**, which occurred roughly 380,000 years after the Big Bang.

- **Cooling and Formation of Atoms**: At this stage, the temperature of the universe dropped enough for electrons to combine with protons and form neutral hydrogen atoms. This allowed photons (light particles) to travel freely, decoupling from matter. The result was the release of the **Cosmic Microwave Background (CMB) radiation**, a faint afterglow from the early universe that we can still detect today.
- **Cosmic Microwave Background**: The CMB is the oldest observable light in the universe and provides a snapshot of the universe at the time of recombination. It is considered one of the key pieces of evidence supporting the Big Bang model.

8. Formation of First Stars and Galaxies (200 million to 1 billion years)

The next major phase in the early universe's history was the formation of the first **stars** and **galaxies**.

- **Cosmic Dark Ages**: Following recombination, the universe entered a period known as the **Cosmic Dark Ages**, during which there were no visible sources of light, and the universe was filled with neutral hydrogen gas.
- **Reionization**: About 200 million years after the Big Bang, the first stars formed, marking the end of the Dark Ages. These stars emitted ultraviolet light, which ionized the surrounding hydrogen gas. This period, known as **reionization**, fundamentally altered the conditions of the universe, making it more transparent to light.

9. Large-Scale Structure Formation (1 billion years and beyond)

As the universe continued to expand and cool, the matter within it began to clump together due to the gravitational attraction between particles. This led to the formation of **galaxies**, **clusters of galaxies**, and the **large-scale structure** of the universe that we observe today.

- **Cosmic Web**: Over billions of years, galaxies clustered into vast, interconnected structures known as the **cosmic web**, with long filaments of dark matter and gas connecting clusters of galaxies.
- **Galaxy Evolution**: Galaxies continued to evolve through processes like mergers, star formation, and the accretion of gas from their surroundings.

Understanding the Timeline and "10 to the Power of Minus"

The timeline presented in the **early history of the universe** details the sequence of events and physical processes that occurred from the moment of the **Big Bang** to the formation of galaxies and large-scale structures in the cosmos. The different time intervals, represented in **seconds** or **years**, describe how the universe evolved and cooled over immense periods of time.

The numbers written as **"10 to the power of minus"** (denoted as 10^{-x}) are a way of expressing very small timescales or quantities in physics, particularly when dealing with events that occurred during the extreme early universe.

Why the "10 to the Power of Minus" Notation?

The notation 10^{-x} is a shorthand used in **scientific notation** to express numbers that are **very small**. It's a way of simplifying and managing extremely large or small values that would otherwise be cumbersome to write out. For example:

- 10^{-1} means 0.1 (1/10).
- 10^{-2} means 0.01 (1/100).
- 10^{-43} means a number extremely close to zero, like 0.000…0001 (with 42 zeros after the decimal point).

In the context of cosmology, many of the events occurring right after the Big Bang happened on timescales that are extremely short. Instead of using long decimal numbers, scientists use scientific notation to represent them efficiently.

2.3 Big Bang Theory of the Universe

The **Big Bang theory** is the leading scientific explanation for the origin and evolution of the universe. It posits that the universe began from a singular, extremely hot, dense state roughly **13.8 billion years ago** and has been expanding ever since. This theory is based on a variety of observations and mathematical models that describe how the universe evolved from its earliest moments to the vast cosmos we observe today.

The Big Bang theory does not propose an explosion in space, but rather an **expansion of space itself**. In this expansive view, all matter, energy, space, and time originated from a singular point known as the **singularity**, a region of infinite density and temperature, and from there, the universe has been expanding and cooling ever since.

Historical Development of the Big Bang Theory

The idea of an expanding universe began to emerge in the early 20th century, following two critical discoveries:

Albert Einstein's Theory of General Relativity (1915): General relativity describes the gravitational dynamics of spacetime, providing a framework for understanding how large-scale structures like stars, galaxies, and the entire universe behave under the influence of gravity. However, Einstein initially believed that the universe was static and unchanging. To reconcile his equations with a static universe, he introduced the **cosmological constant**, a term that counteracted gravity's attractive force and kept the universe from collapsing. This idea was later discarded when it was realized that the universe is not static.

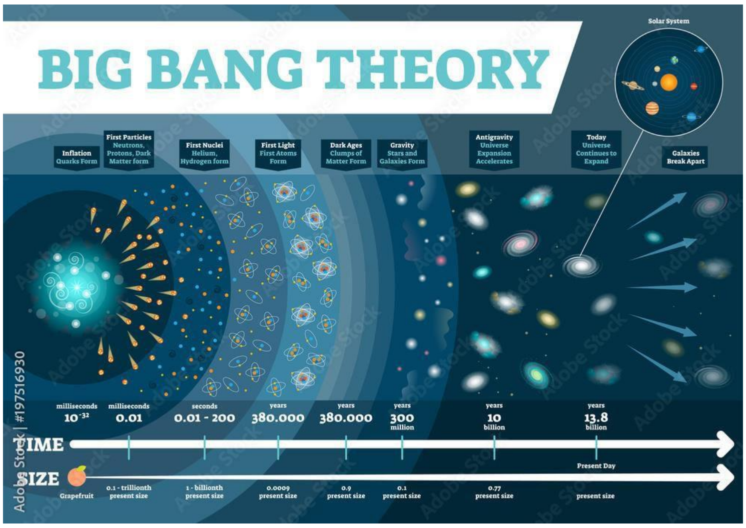

Fig: Big Bang Theory

1. **Edwin Hubble's Observation of the Expanding Universe (1929)**: Hubble discovered that galaxies are moving away from each other, and their velocity is proportional to their distance from Earth. This is known as **Hubble's Law**, and it provided the first direct evidence that the universe is expanding. Hubble's observations contradicted the static universe model and provided support for the idea that the universe had a dynamic, evolving origin.

In the 1940s and 1950s, the **cosmic microwave background (CMB)** radiation was predicted by physicists as a remnant of the hot, dense state of the early universe, further supporting the Big Bang model. The actual discovery of the CMB in 1965 by **Arno Penzias** and **Robert Wilson** provided the definitive observational evidence for the Big Bang theory.

Key Ideas of the Big Bang Theory

1. **The Beginning of the Universe**: The theory suggests that, at some moment in the past (about 13.8 billion years ago), all the matter and energy in the universe were concentrated in an infinitely small and dense point known as a **singularity**. The universe then began to expand, a process that continues today. This event marks the "Big Bang."

2. **Expansion of Space**: The Big Bang was not an explosion in a particular location of space; rather, it was an expansion of **space itself**. Every point in the universe is moving away from every other point, meaning that the universe is expanding. This is often referred to as the **expansion of the fabric of spacetime**.
3. **Cooling of the Universe**: As the universe expanded, it also began to cool. In the early moments (first few minutes), the temperature of the universe was so high that elementary particles (quarks, electrons, etc.) existed in a state of **plasma**. As it cooled, these particles began to combine into atoms, primarily hydrogen and helium, creating the first **atoms** in the universe.
4. **Cosmic Microwave Background Radiation (CMB)**: A crucial piece of evidence for the Big Bang theory is the **CMB**, which is the afterglow of the Big Bang. This faint radiation is a snapshot of the universe when it was just 380,000 years old. It provides a direct link to the universe's early conditions and supports the idea that the universe was once in a hot, dense state.
5. **Formation of Matter**: During the early universe, as temperatures dropped and matter began to form, the first simple atoms of hydrogen and helium were created through a process called **Big Bang nucleosynthesis**. These atoms later clumped together under gravity to form the first stars, galaxies, and larger structures in the universe.
6. **Redshift of Galaxies**: Another critical observation supporting the Big Bang theory is the **redshift** of light from distant galaxies. As the universe expands, the light from galaxies is stretched, causing it to shift toward the red end of the spectrum. This phenomenon, observed by **Edwin Hubble** in the 1920s, is consistent with the idea that the universe is expanding.

Timeline of the Universe's Evolution (according to the Big Bang Theory)

1. **The Singularity**: At time t=0, the universe existed as an extremely hot and dense point. This is where all the matter and energy in the universe originated.
2. **Inflation (10^{-36} to 10^{-32} seconds)**: A rapid and exponential expansion occurred, increasing the size of the universe by a factor of at least 10^{26} in a fraction of a second. This period, known as **cosmic inflation**, solved several cosmological problems, such as the uniformity of the universe (the flatness and horizon problems).
3. **Formation of Fundamental Particles (10^{-12} seconds)**: As the universe cooled, the energy began to condense into **fundamental particles** such as quarks, leptons (electrons), and neutrinos.

4. **Quark Epoch (1 second to 3 minutes)**: The universe was still too hot for protons and neutrons to form stable nuclei. During this time, quarks combined to form **protons** and **neutrons**.
5. **Big Bang Nucleosynthesis (3 minutes to 20 minutes)**: Protons and neutrons fused to form **atomic nuclei** like hydrogen and helium in a process known as **Big Bang nucleosynthesis**. The universe at this time was about a thousand times hotter than the core of the Sun.
6. **Photon Epoch (20 minutes to 380,000 years)**: As the universe continued to cool, electrons combined with protons to form neutral hydrogen atoms. This allowed photons (light particles) to travel freely through space, marking the **decoupling of matter and radiation**. This radiation is what we detect today as the **cosmic microwave background (CMB)**.
7. **Recombination and the Formation of Atoms (380,000 years)**: The universe cooled sufficiently for neutral atoms to form, and the photons decoupled from matter, leading to the **release of the CMB**.
8. **Dark Ages (380,000 years to 1 billion years)**: The universe entered a period known as the "Dark Ages" because there were no stars yet to light up the universe. Matter was distributed fairly evenly, and the universe was a cold and dark place.
9. **Formation of the First Stars (1 billion years)**: Gravity began to pull hydrogen and helium together to form the first stars and galaxies, leading to the end of the **Dark Ages**. These early stars started to ionize the surrounding gas, a process called **reionization**.
10. **Modern Universe (13.8 billion years)**: The universe continued to expand, and more complex structures such as galaxies, clusters, and superclusters of galaxies formed. The universe's expansion continues today, as evidenced by the observed **redshift** of distant galaxies.

Observational Evidence Supporting the Big Bang Theory

1. **Cosmic Microwave Background Radiation (CMB)**: The discovery of the CMB in 1965 by **Arno Penzias** and **Robert Wilson** provided strong evidence for the Big Bang. This faint radiation is a remnant of the early universe and offers a "snapshot" of the universe when it was just 380,000 years old.
2. **Hubble's Law and the Expanding Universe**: Edwin Hubble's observations in the 1920s showed that galaxies are receding from us, with the velocity of recession directly proportional to their distance. This expansion of the universe is a key prediction of the Big Bang theory.
3. **Abundance of Light Elements**: The Big Bang theory predicts the relative amounts of hydrogen, helium, and lithium produced in the early universe.

Observations of the cosmic abundance of these elements match the predictions of Big Bang nucleosynthesis, further supporting the theory.

4. **Large-Scale Structure**: The distribution of galaxies and clusters of galaxies in the universe today provides evidence for the evolution of the universe from a homogeneous, dense state to the large-scale structures we see today. Simulations of cosmic evolution show that structures like galaxies and galaxy clusters naturally emerge from the fluctuations in the early universe.