2.6 Dark Matter

What is Dark Matter?

Dark matter is a hypothetical form of matter that cannot be observed directly because it does not emit, absorb, or reflect electromagnetic radiation (such as visible light). However, its presence is inferred through its gravitational effects on visible matter, gravitational lensing, and its influence on the cosmic microwave background (CMB) radiation.

It does not interact with electromagnetic radiation, meaning it is **not luminous** (hence the name "dark"), but it is thought to interact with **normal matter** through **gravity**. Its mass influences the motions of galaxies and galaxy clusters, which is why scientists hypothesize that dark matter exists.

Properties of Dark Matter

1. **Gravitational Effects**: The most direct evidence for dark matter comes from the gravitational effects it has on visible matter. In particular, observations of the **rotation curves** of galaxies (i.e., how the speed of stars changes with their distance from the galactic center) show that the outer stars in galaxies rotate much faster than would be expected based on the mass of visible matter alone. This discrepancy suggests the presence of an unseen mass, or dark matter, that is providing extra gravitational pull.
2. **Galaxy Clusters**: The motion of galaxies within galaxy clusters and the way clusters gravitationally lens the light of background galaxies indicate that the mass of the cluster is far greater than the mass of visible matter in the galaxies. This unseen mass is also believed to be dark matter.

Cosmic Microwave Background (CMB): The CMB provides indirect evidence for dark matter by revealing small fluctuations in the density of matter in the early universe. These fluctuations provide clues about the amount of matter in the universe at the time of the **Big Bang**. The results from the **Planck satellite** and earlier surveys suggest that the universe's matter content includes a substantial amount of dark matter.

Non-luminous: Dark matter does not emit, absorb, or reflect electromagnetic radiation, meaning it doesn’t interact with light. This makes it impossible to detect directly with telescopes.

3. **Non-relativistic (Cold)**: Dark matter is believed to be **cold** (i.e., it moves at sub-relativistic speeds), unlike the **hot** dark matter proposed in earlier models. Cold dark matter (CDM) is essential to explain the large-scale structure of the universe, particularly the formation of galaxies and clusters of galaxies.
4. **Weakly Interacting**: Dark matter interacts via **gravity** and possibly through weak nuclear force, but it does not interact via electromagnetism, the strong nuclear force, or other known forces. This makes it extremely difficult to detect through traditional means.

2.7 Dark Energy

What is Dark Energy?

Dark energy is a mysterious form of energy that permeates all of space and accelerates the expansion of the universe. Unlike dark matter, which has mass and exerts a gravitational pull, dark energy has a **negative pressure** that accelerates the expansion of the universe.

While dark energy is an even more enigmatic concept than dark matter, it plays a key role in explaining the **accelerating expansion** of the universe, a discovery that was made in the late 1990s from the observation of distant **supernovae**.

Properties of Dark Energy

Accelerating Expansion: The discovery that the universe's expansion is accelerating, rather than slowing down as was once expected, was one of the most profound observations in cosmology. The observed acceleration is attributed to dark energy, which counteracts the attractive force of gravity and drives the expansion of the universe.
Negative Pressure: Dark energy is thought to have **negative pressure**, a property that leads to the repulsive force responsible for accelerating the expansion of the universe. The equation of state for dark energy is typically expressed as:

$$p = -\rho c^2$$

Where, p is the pressure, ρ is the energy density, and ccc is the speed of light. This equation signifies that dark energy has a **negative pressure** proportional to its energy density.**Uniform Distribution**: Unlike matter, which clumps under gravity, dark energy appears to be **uniformly distributed** throughout the universe. It does not form structures, which makes it different from dark matter.

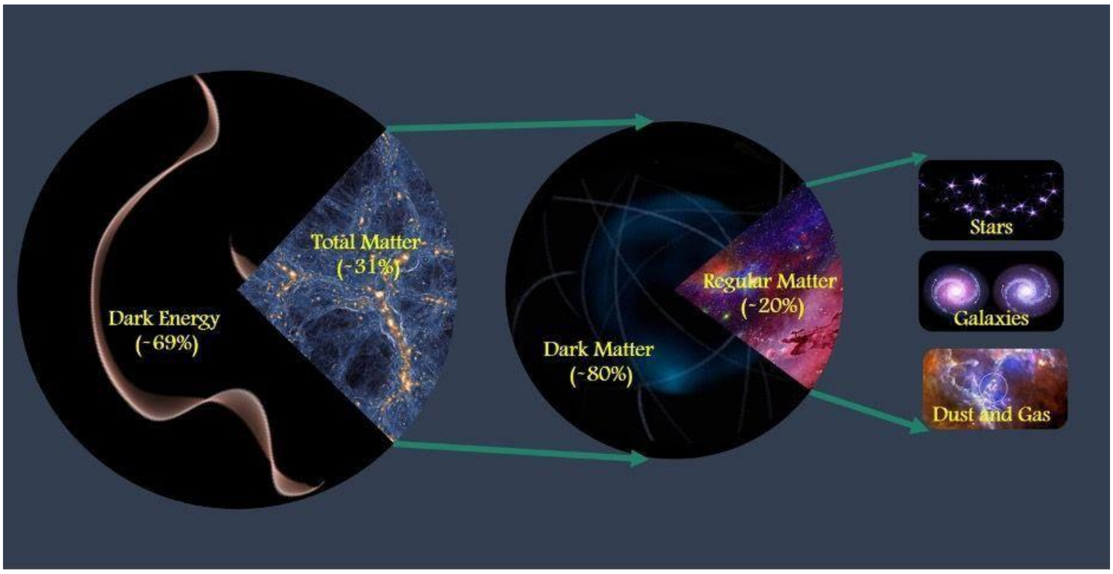

Fig: Dark Matter & Dark Energy

Theories of Dark Energy

Several hypotheses exist regarding the nature of dark energy, including:

1. **Cosmological Constant (LambdaΛ)**: The simplest explanation for dark energy is that it is a form of energy inherent to **space itself**. This idea is closely related to **Einstein's cosmological constant** (Λ), which was originally introduced by Einstein in his field equations of general relativity to account for a static universe. In modern cosmology, Λ represents the energy density of the vacuum, a constant value that causes the expansion of the universe to accelerate.
2. **Quintessence**: Quintessence is an alternative theory to the cosmological constant. In this model, dark energy is not constant but varies over time and space. It is associated with a **dynamical field** that evolves as the universe expands, unlike the cosmological constant, which is fixed.
3. **Extra Dimensions**: Some theories suggest that dark energy could be explained by the existence of **extra spatial dimensions** beyond the familiar three dimensions. These additional dimensions could alter the behavior of gravity at cosmological scales, leading to an accelerating expansion of the universe.
4. **Modification of Gravity**: Another possibility is that dark energy is a manifestation of **modifications to general relativity** at large distances. Some extensions of gravity, such as **f(R) gravity** or **brans-Dicke theory**, suggest that gravity behaves differently at very large scales, leading to accelerated expansion without the need for dark energy.