**Notable Examples of Quasars**

1. **3C 273**: The first quasar to be identified, and one of the most well-studied quasars. It is located in the constellation **Virgo** and is about **2.4 billion light-years** away. It is a **radio-loud** quasar.
2. **SDSS J0100+2802**: A particularly distant and massive quasar with a redshift of about **6.30**, located **12.8 billion light-years** away, making it one of the farthest known quasars.
3. **PKS 1830-211**: A **strong radio-loud quasar**, used to study the intergalactic medium due to absorption features in its spectrum.

**3. Significance of Active Galaxies and Quasars in Cosmology**

1. **Probing the Early Universe**:
   - Quasars, due to their immense luminosity and high redshift, serve as excellent probes of the early universe. Observing these distant objects allows astronomers to look back in time and study the conditions of the universe just a few billion years after the Big Bang.
2. **Understanding Black Hole Growth**:
   - The study of active galaxies and quasars provides crucial insights into the processes that lead to the formation and growth of supermassive black holes. The relationship between supermassive black holes and their host galaxies is central to understanding galaxy evolution.
3. **Testing Cosmological Models**:
   - The study of quasar redshifts and their distribution helps to test models of **cosmic expansion**, **dark energy**, and **large-scale structure**. The redshifts of quasars also provide information on the rate of expansion of the universe and the geometry of spacetime at large distances.

## 3.4 Galactic Rotation

**Galactic rotation** refers to the motion of stars, gas, and other matter within a galaxy, typically organized in a rotating disk-like structure. This rotation plays a key role in the structure and dynamics of galaxies, influencing their formation, evolution, and the behavior of material within them. The study of galactic rotation provides deep insights into fundamental astrophysical processes, including the nature of dark matter, gravitational dynamics, and the interaction between stars and interstellar matter.

### 1. Basic Concept of Galactic Rotation

In a **spiral galaxy** like the Milky Way, stars and gas clouds orbit the center of the galaxy in a disk-like structure. The central region of the galaxy (the bulge) is typically more spherical in shape, with stars moving in a variety of orbits. The outer regions of the galaxy, particularly in the disk, exhibit a characteristic **rotational pattern**, where stars and gas move in approximately circular orbits around the galactic center. This phenomenon is governed by the gravitational potential created by the mass distribution within the galaxy.

### 2. Observational Evidence for Galactic Rotation

#### Galaxy Rotation Curves

The motion of stars and gas clouds in a galaxy can be studied through their **rotation curves**. A **rotation curve** is a plot of the orbital velocity of stars or gas as a function of their distance from the galactic center. These curves provide essential information about the distribution of mass within the galaxy. There are two main ways to measure the rotation curve:

1. **Optical Spectroscopy**:
   - By observing the Doppler shift of spectral lines from stars, astronomers can measure the radial velocity (the component of velocity along the line of sight) of stars in a galaxy. This allows the construction of a rotation curve for the stellar component.
2. **Radio Observations of Gas**:
   - The motion of neutral hydrogen (HI) gas in the galactic disk can be measured through the 21 cm radio emission line. The Doppler shift of this line, due to the motion of the gas, reveals the velocity of the gas at various distances from the center, allowing the construction of a rotation curve for the gas component of the galaxy.

### 3. The Keplerian Rotation Curve (Classical Expectations)

Under Newtonian mechanics, the expected rotation curve of a galaxy (especially for spiral galaxies) can be described by **Keplerian motion**. According to Kepler's laws and Newton's law of gravitation, the orbital velocity of an object moving under the influence of gravity in a central mass should decrease with increasing distance from the central mass. This expectation is true for planetary motion around stars or for objects moving in a central gravitational potential.

- Kepler's 3rd Law: The orbital velocity v of an object orbiting a central mass should be proportional to $v \sim \frac{1}{\sqrt{r}}$, where r is the distance from the center of mass.

Thus, in a galaxy, one would expect the rotation curve to drop off as one moves farther from the galactic center. In practice, this means the velocity of stars and gas should decrease at large radii, resembling the motion of planets in our Solar System.

### 4. The Flat Rotation Curve (Observational Surprise)

When astronomers measured the rotation curves of galaxies, they found a surprising result: rather than decreasing at large distances from the center (as predicted by Keplerian dynamics), the orbital velocities of stars and gas **remain roughly constant** at large distances from the galactic center. This is known as the **flat rotation curve**.

- **Flat Rotation Curves**: In galaxies such as the Milky Way, the rotation curve flattens out beyond a certain radius. Instead of decreasing, the velocity stays nearly constant or even increases slightly as one moves outward in the galactic disk. This implies that the mass distribution in galaxies is not solely confined to the visible stars, and there must be additional mass beyond the visible matter, which we cannot directly observe.

This flatness in the rotation curve is one of the key pieces of evidence for the existence of **dark matter**—an unknown form of matter that does not emit, absorb, or reflect electromagnetic radiation, but whose presence can be inferred from gravitational effects on visible matter. Dark matter exerts a gravitational influence, providing the extra mass necessary to explain the observed rotation curves.

### 5. Theoretical Explanation for Galactic Rotation

#### The Role of Gravity

The rotation of a galaxy is primarily determined by gravitational forces. The mass of a galaxy is distributed in a variety of components:

1. **Stars**: The stellar component in the galaxy contributes to the total mass. In the case of spiral galaxies, the stars are distributed in a disk, with a central bulge and a disk extending outward.

2. **Gas and Dust**: Interstellar gas and dust contribute to the mass, particularly in the disk, and can be traced through spectral emission lines like the **21 cm emission** from neutral hydrogen.
3. **Dark Matter**: The most significant contributor to the mass, especially at large radii, is dark matter. It is hypothesized to form a **dark matter halo** that extends well beyond the visible disk, providing the gravitational pull needed to keep the rotation curve flat at large distances.

**Dark Matter Halo**

In the case of the Milky Way, and other spiral galaxies, it is widely believed that dark matter exists in the form of a **spherical halo** surrounding the galaxy. The halo is composed of dark matter particles that do not interact electromagnetically but have mass, and hence exert gravitational influence.

- The distribution of dark matter in the halo is thought to be more extended than the visible matter in the galaxy, with its density generally decreasing as a function of radius (following a **NFW profile**—Navarro-Frenk-White profile).

**The Baryonic Matter (Visible Matter) Contribution**

The visible matter in the galaxy, including stars, gas, and dust, contributes to the mass and, hence, to the gravitational potential in the inner regions of the galaxy. However, this component alone cannot explain the observed flat rotation curves at large radii.

1. **Bulge and Disk Components**: The mass of the central bulge and the stars in the galactic disk contribute significantly to the gravitational field in the inner regions of the galaxy. However, as you move farther out in the disk, the contribution of the visible matter becomes less significant compared to dark matter.
2. **Gas Dynamics**: The observed rotation curve of the gas (especially HI gas) follows a similar pattern to the stellar rotation curve, also flattening out at large radii, further supporting the presence of dark matter.

**6. Rotation Curve of the Milky Way**

In the case of the **Milky Way Galaxy**, the rotation curve has been measured using various methods, such as:

1. **HI 21 cm Line Observations**: The motion of HI gas in the outer regions of the galaxy has been traced using the Doppler shift of the **21 cm line** of

neutral hydrogen. This shows a rotation curve that flattens out beyond about 10-15 kpc from the center.

2. **Stellar Velocity Measurements**: The motion of stars in the Milky Way's disk has also been measured. These measurements also indicate that beyond 15 kpc, the velocities remain constant.

The rotation curve of the Milky Way has been used to model its mass distribution, revealing that the galaxy contains a significant amount of dark matter, which is not directly observable through electromagnetic radiation but inferred through gravitational effects.

### 7. Gravitational Effects on Galactic Rotation

Galactic rotation curves are not only influenced by visible and dark matter but also by other factors such as:

1. **Interactions with Other Galaxies**: Galaxies can experience tidal forces when they interact with nearby galaxies, which may perturb the motion of stars and gas within the galaxy. These interactions can cause distortions in the galaxy's rotation curve, especially in the case of **galaxy mergers**.
2. **Galaxy Shape**: The shape of the galaxy (spiral, elliptical, irregular) influences its rotation curve. Spiral galaxies typically have a disk-like structure with relatively flat rotation curves, while elliptical galaxies, which lack a distinct disk, may have more complex rotation profiles.
3. **Central Supermassive Black Hole**: Many galaxies, including the Milky Way, contain a **supermassive black hole** at their center. The presence of this black hole contributes to the overall mass in the central region, affecting the rotation curve. The influence of the supermassive black hole is significant within a few parsecs from the galactic center but becomes negligible at larger distances.

## 3.5 Stellar Populations

**Stellar populations** refer to distinct groups of stars that share similar characteristics, such as age, metallicity (chemical composition), and evolutionary state. These groups are used to classify stars and understand the processes of star formation, evolution, and the overall structure of galaxies. Stellar populations play a critical role in our understanding of galaxy formation, stellar evolution, and cosmology. In essence, by studying stellar populations, astronomers can probe the history of a galaxy, its star formation processes, and the physical conditions that governed its evolution.