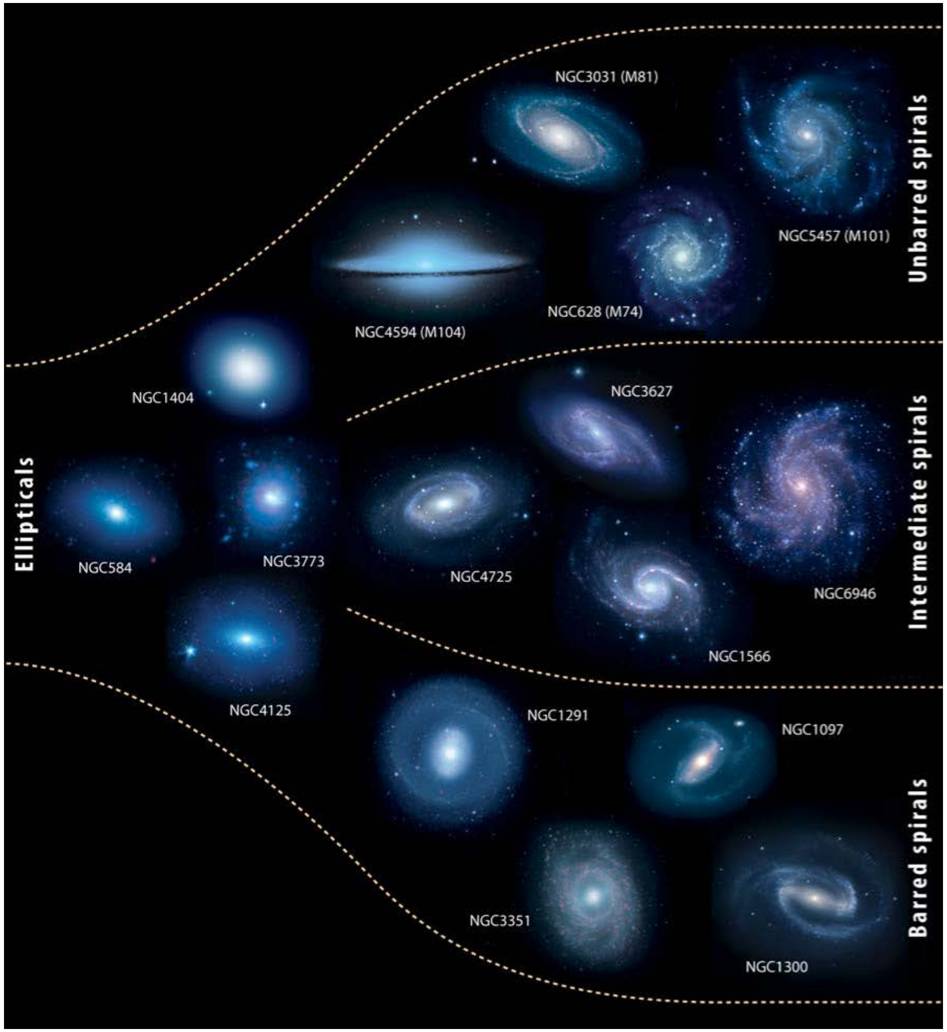
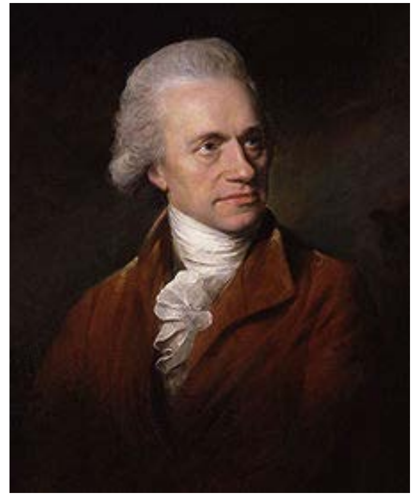
Galaxies and their Nuclei



The Milky Way and Island Universes

English astronomer Thomas Wright (1711–1786)



William Herschel German born British astronomer (1732–1822)

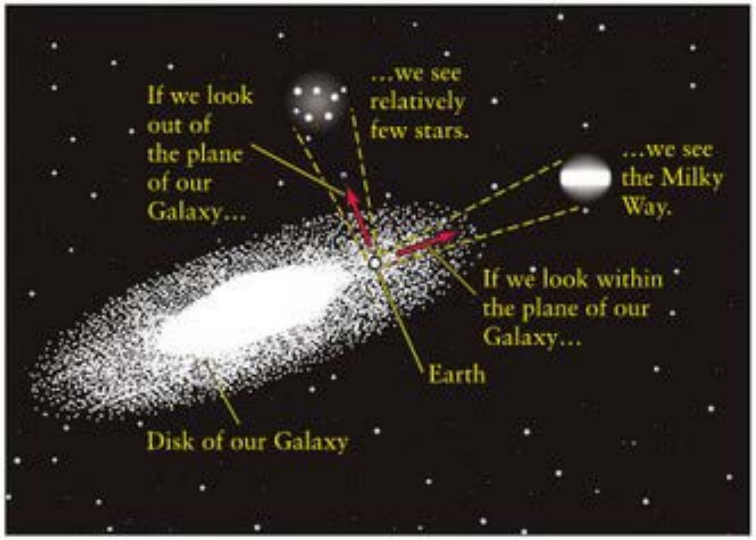
Edwin Hubble American astronomer (1889–1953)

Thomas Wright first suggested that the Milky Way can be explained by a thick disk of stars in which the solar system is embedded.

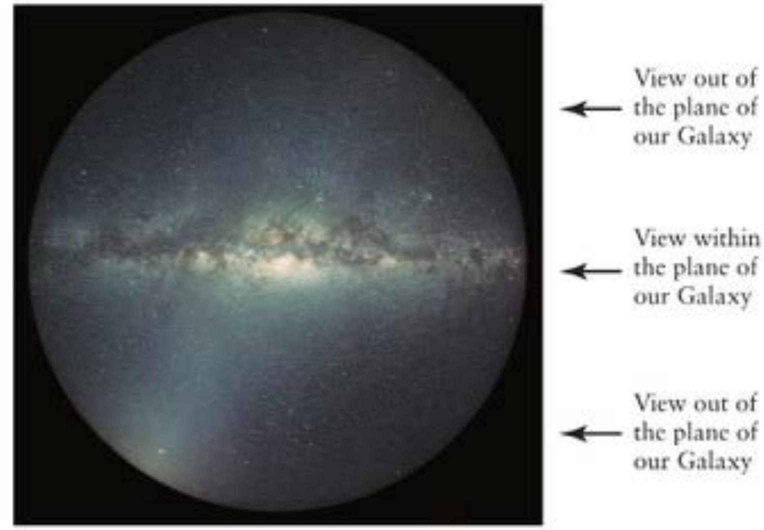
The first attempt based on observations to describe the shape of the Milky Way and the position of the Sun within it was carried out by **William Herschel**.

Edwin Hubble in the 1920s established the existence of distant galaxies.

Our Galaxy



(a)



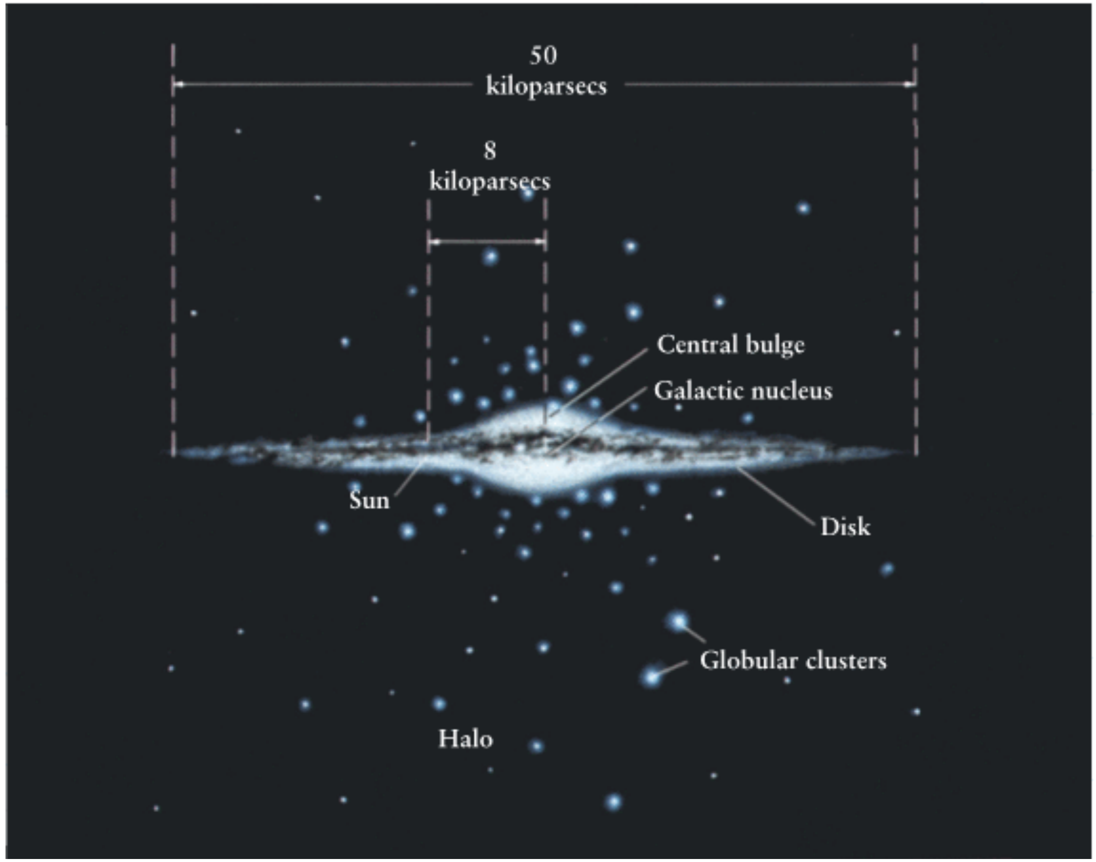
(b) RIVUXG

We are located in the disk of our galaxy and this is why the disk appears as a band of stars across the sky.

The **difficulty in locating our solar system in our galaxy is that interstellar extinction** allows one to only see the nearby stars and **makes distant objects appear dimmer**.

The key to finding our location in the galaxy is locating bright objects out of the plane of the galaxy. Astronomers use **globular clusters** to locate the position of our solar system with respect to the Galaxy.

Our Galaxy



There are three major components of our Galaxy: a disk, a central bulge, and a halo. The **disk** contains gas and dust along with metal-rich (Population I) stars. The **halo** is composed almost exclusively of old, metal-poor (Population II) stars. The central **bulge** is a mixture of Population I and Population II stars.

How did the Nuclei of Galaxies Form?

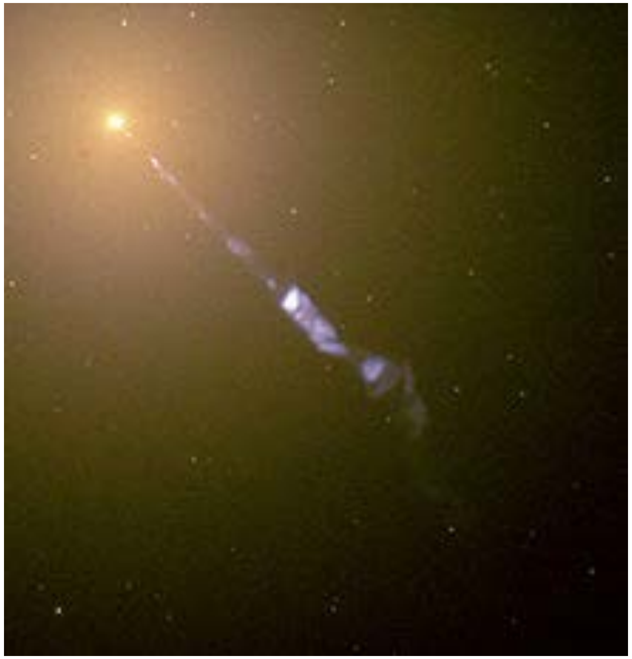
To understand how the nuclei of galaxies formed we need to understand how galaxies form and how their environments influence their formation and evolution.

Some unresolved questions:

What formed first the central black hole or the host galaxy? or did they form at the same time?

How did the central black holes of galaxies become so massive?

Why do some SMBHs have jets and others not?



A jet of particles is being emitted from the core of the elliptical radio galaxy M87.

Normal Galaxies

Normal galaxies are giant assemblages of stars, gas, dust and dark matter. What supports galaxies from gravitational collapse?

Answer: There is an equilibrium between the total kinetic energy of the stars due to their motion and the gravitational binding energy (produced by the total mass) of the galaxy (Virial Theorem).

Types of Galaxies: Spirals, Ellipticals and Irregulars

(b) Sb (M81)

(b) E3 (NGC 4406)

Spiral Galaxies

In **spiral galaxies** most of the stars and gas are concentrated in a circular disk.

Properties of Spiral Galaxies:

- A typical spiral galaxy has ~ 100 billion stars

- The mass in gas is ~ 0.1*Mstars

- Diameters of a spiral galaxies range between 5 – 250 kpc

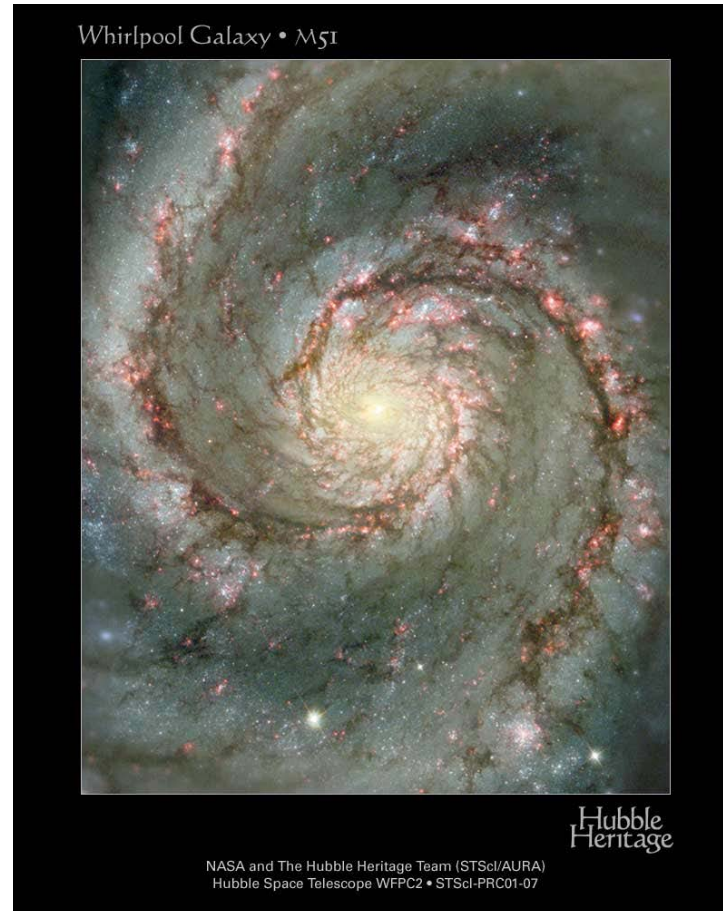
- Stars in the disk have orbits that are almost circular

- The sun takes about 200 million years to orbit the center of the Milky Way at a velocity of about 200 km/s

Spiral Galaxies

Spiral galaxies are characterized by **arched lanes of stars**. The spiral arms contain young, hot, blue stars and hydrogen gas, indicating ongoing star formation.

As the stars in the disk evolve they enrich the **interstellar medium** (ISM) with metals through stellar winds and supernova explosions. This metal enriched ISM will be used to form the next generation of stars that will therefore be metal rich.



Elliptical Galaxies

Elliptical galaxies are swarms of stars that follow complicated orbits.

The giant elliptical galaxy ESO 325-G004

Properties of Elliptical Galaxies

- A typical spiral galaxy has ~ $10^{8\text{-}12}$ stars
- **Elliptical galaxies contain very little amounts of gas, dust and almost no star formation**.
- Diameters of elliptical galaxies range between 1-200 kpc
- **Stars have orbits that have become randomized**.

Elliptical Galaxies

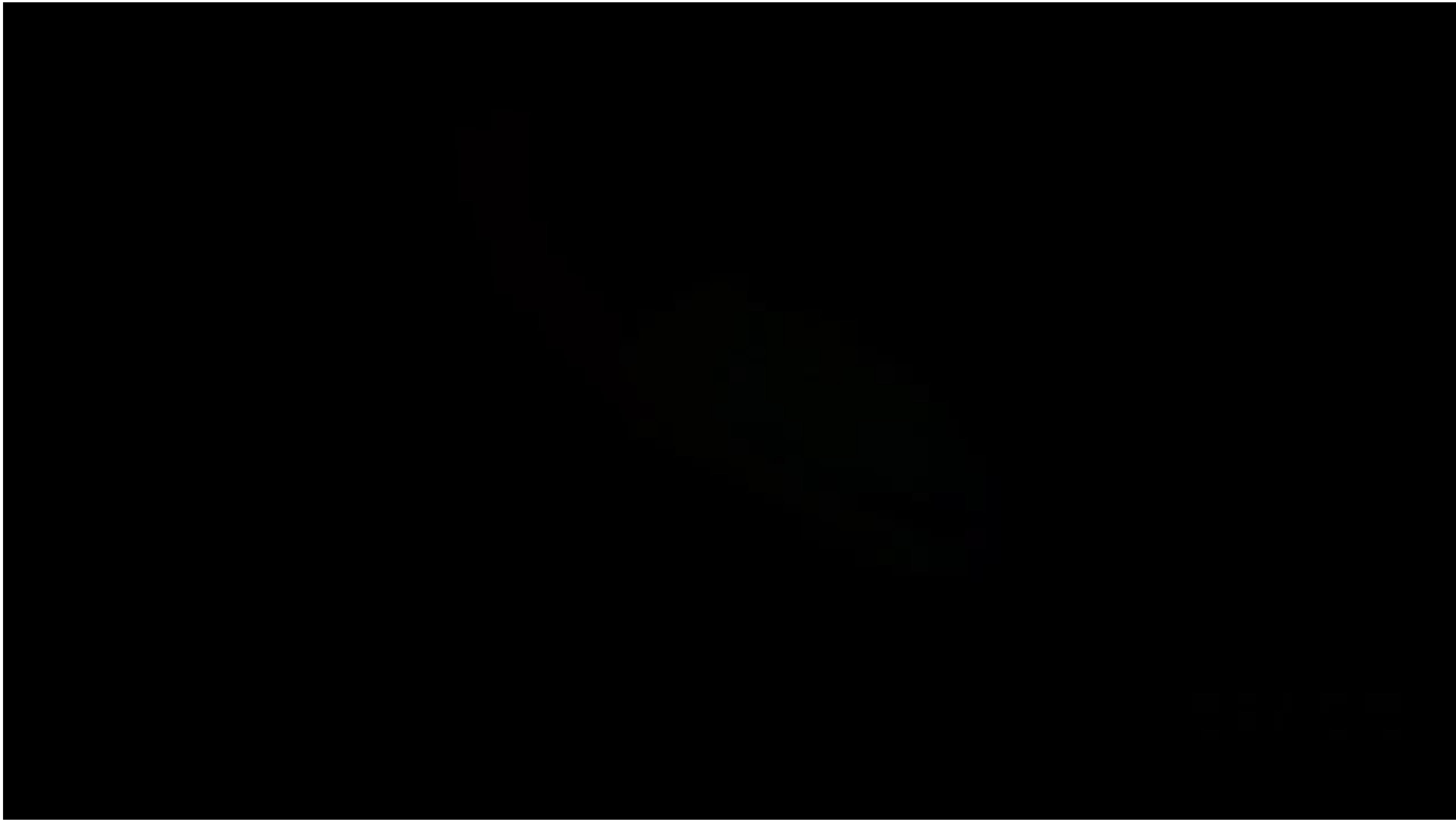
The giant elliptical galaxy ESO 325-G004

Elliptical galaxies are composed of mostly old red stars. Their appearance and classification partly depends on their orientation.

Feeding the Beast: Stellar Collisions and Tidal Disruptions

In general the **chance of a collision between stars** in a galaxy **is quite low**. Only in the center of a galaxy is there a slightly higher chance of collision.

Stellar collisions and tidal disruptions near the center may contribute to the **growth of the supermassive black hole** (SMBH).



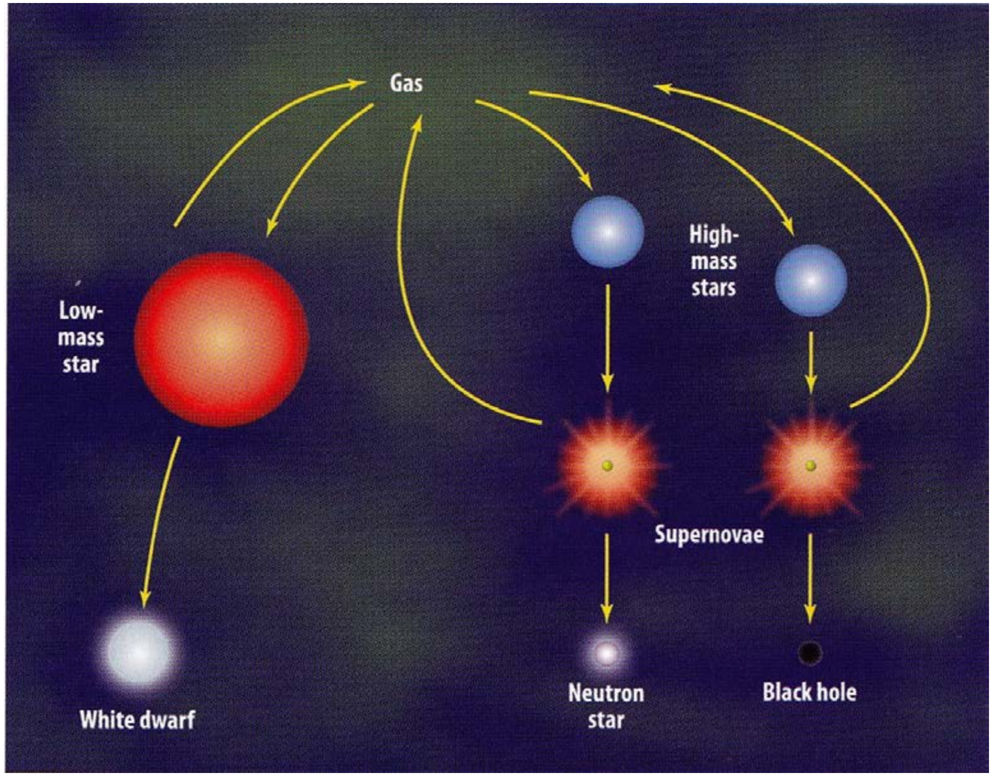
Recycling of Gas

Stars form from the collapse of cold dense gas. The more massive stars will explode into supernovae releasing heavy elements into the interstellar medium.

Some of the original mass will be taken out of circulation with the formation of compact objects such as white dwarfs, neutron stars, and black holes.

The dark linear feature centered in its comet-shaped trail is a proto-planetary disk. This structure located in the Orion Nebula is believed to be an edge on disk of gas in which a star and its retinue of planets are forming before our eyes.

Recycling of Gas



Gas incorporated in stars is recycled when the stars explode as supernovae or emit winds during their red giant phase of their evolution. The matter remaining behind in white dwarfs, neutron stars, and black holes is taken out of circulation.

Galaxy Formation

What determines whether a galaxy is elliptical or spiral is still an unresolved question.

Galaxy formation was well underway in the early Universe. For the highest redshift galaxies observed today ($z \sim 10$) the age of the Universe was ~ 0.482 billion years.

http://www.astro.ucla.edu/~wright/CosmoCalc.html

Galaxies are thought to have formed from small density fluctuations in the early Universe.

It is thought that a main component of galaxies that drives their evolution is an unknown form of matter called **dark matter.**

Dark Matter

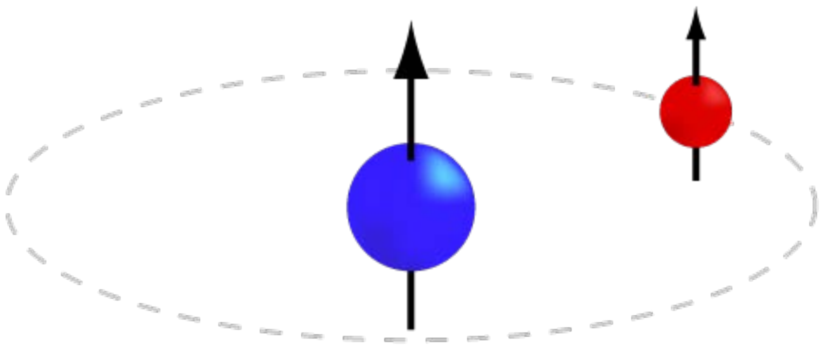
Dark matter does not emit or scatter electromagnetic radiation.

The presence of Dark Matter is inferred from its gravitational effects.

Evidence for the existence of dark matter is provided by maps of the speeds at which the disks of galaxies rotate at various distances from their centers.

Astronomers use the Doppler shifted 21 cm line to infer the speed of the gas in the disk.

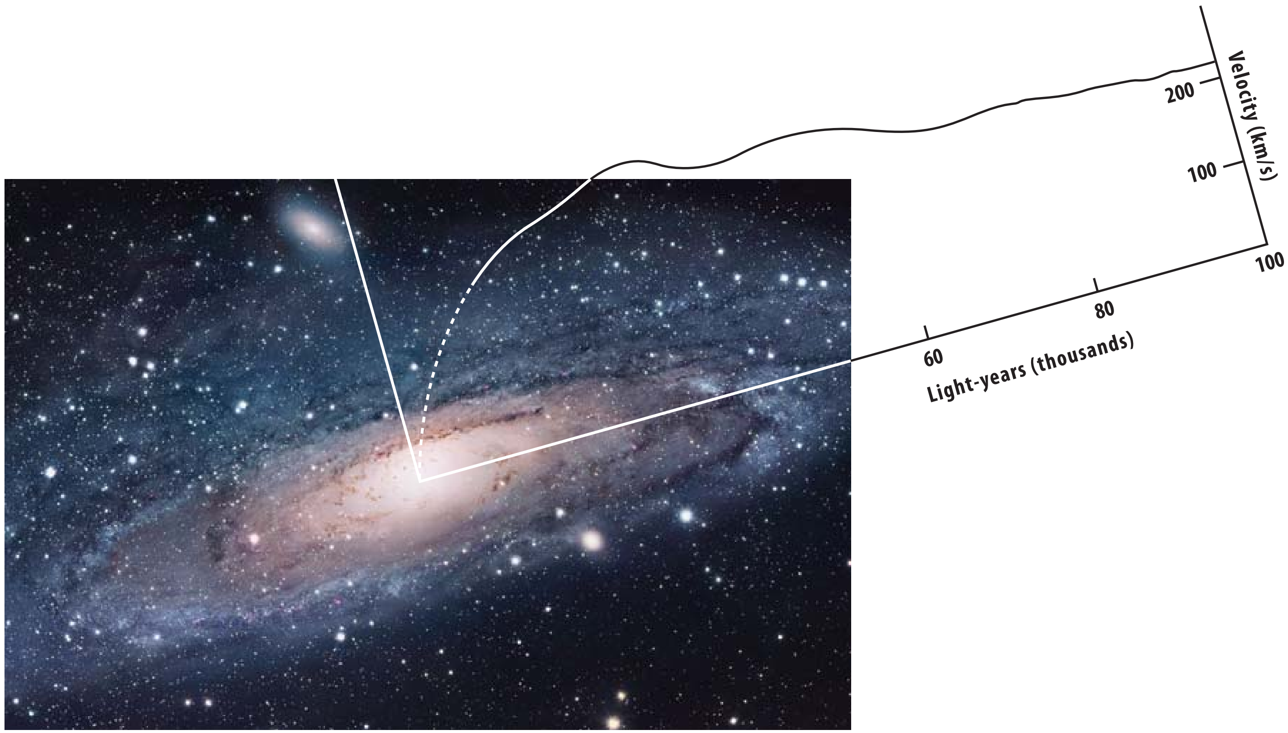
21 cm Line



21-centimeter line An electron orbiting a proton with parallel spins (pictured) has higher energy than if the spins were anti-parallel.

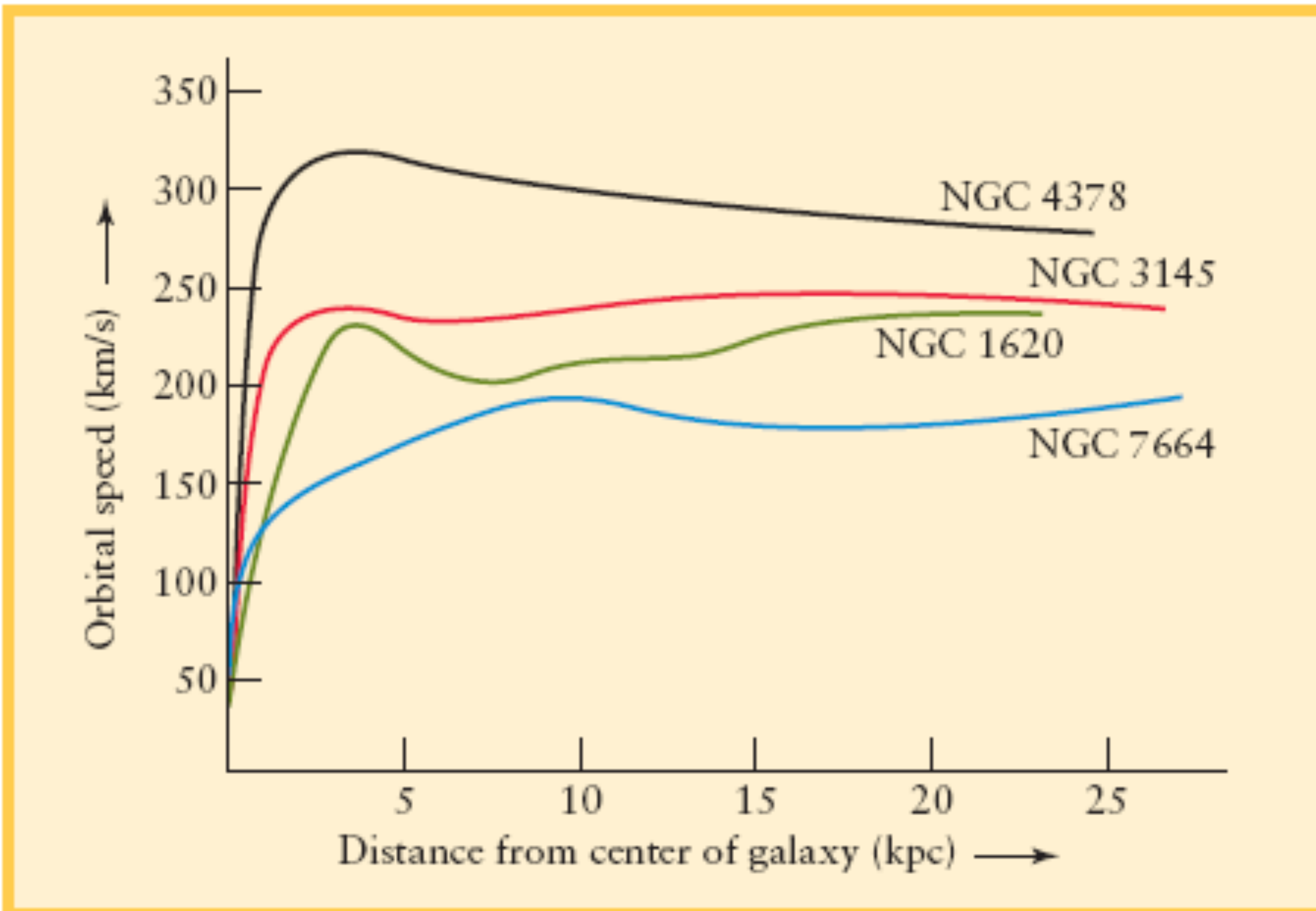
21 cm waves can penetrate the large clouds of interstellar cosmic dust that are opaque to visible light.

Dark Matter in Galaxies

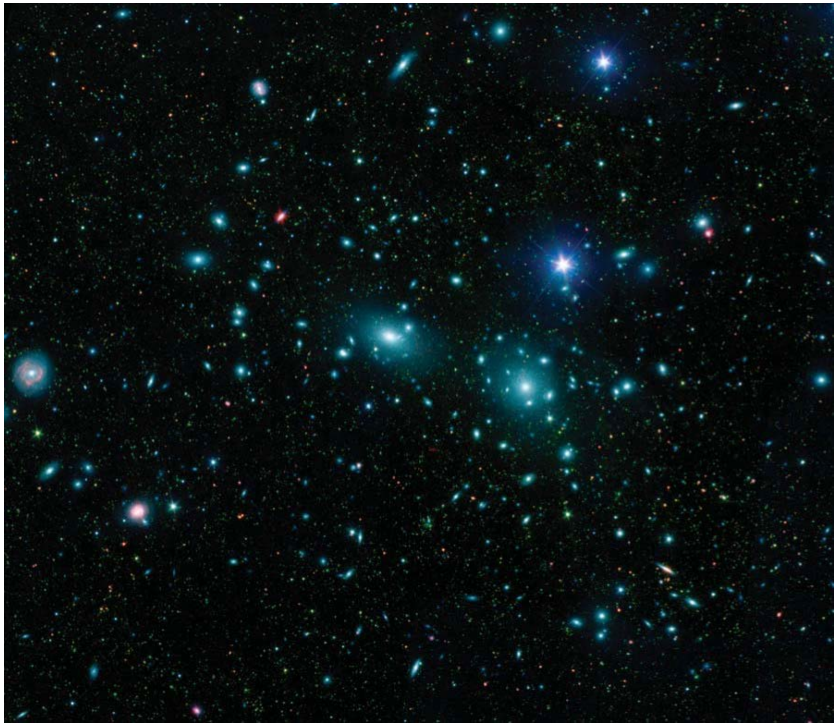


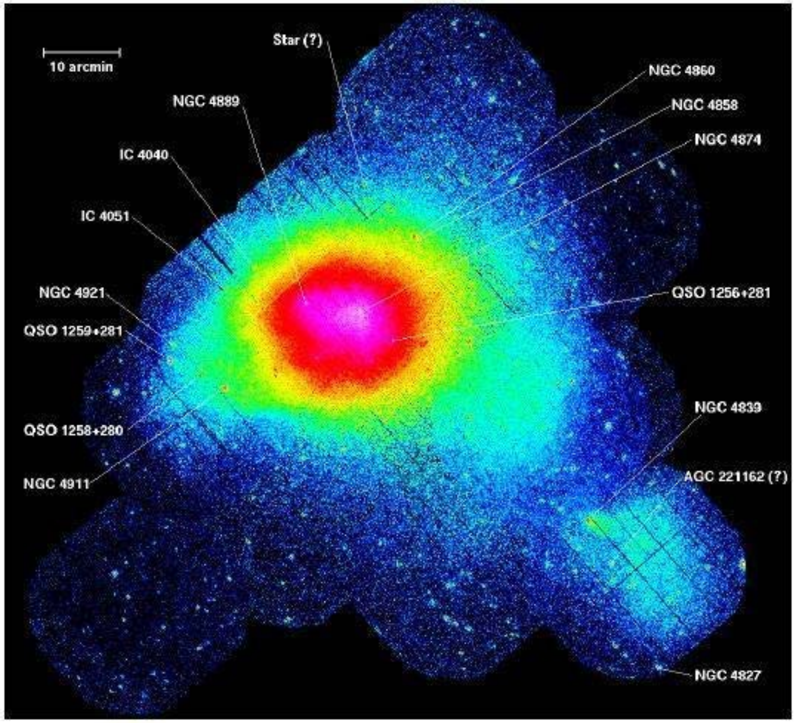
The observations of hydrogen 21 cm emission extend beyond the visible gas radius. So if most of the mass resided within the visible radius one would expect the velocity to fall off as $1/\sqrt{R}$. Instead, it remains almost constant to large distances.

Dark Matter in Galaxies



Dark Matter in Clusters of Galaxies

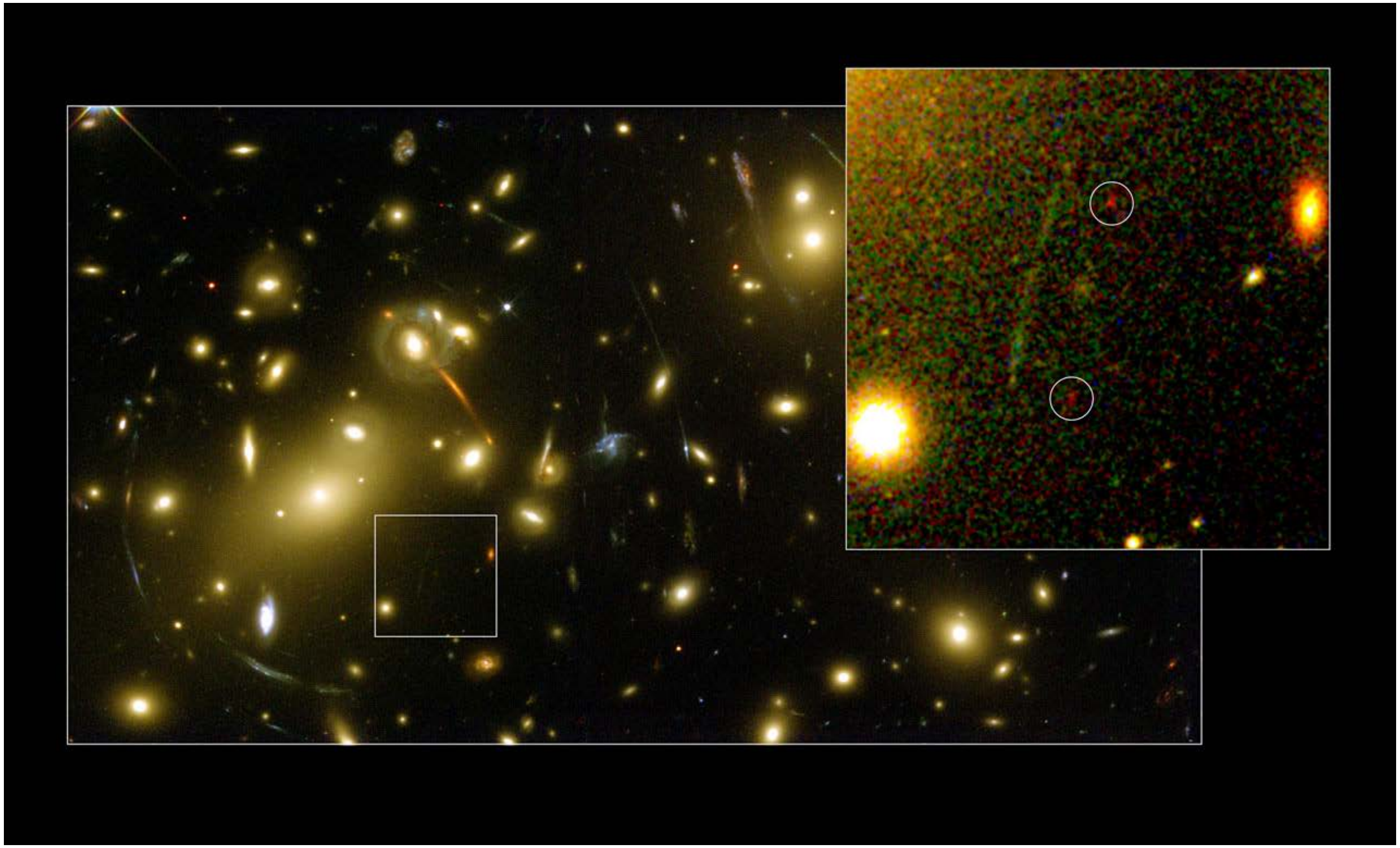




Coma Cluster of galaxies
Image courtesy of U. Briel, MPE Garching, Germany
European Space Agency

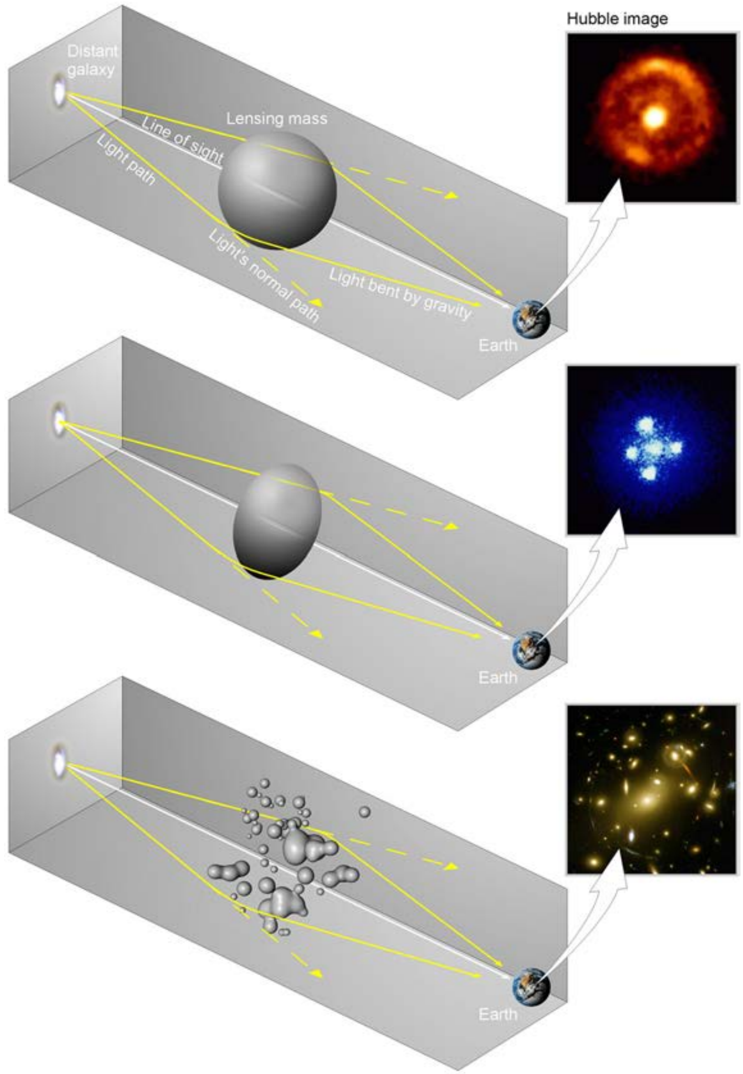
In the **Coma Cluster** there must be several times more mass in some "dark" form than stars or gas otherwise the galaxies and gas would fly away.
The left image of Coma combines visible (SDSS) and infrared (Spitzer) light.
The right image of Coma shows combined X-ray (XMM) observations of Coma.
One can infer the total mass (including dark matter) from the virial theorem.

Dark Matter in Clusters of Galaxies



The gravitational field of the galaxy cluster Abell 2218 distorts the images of more distant galaxies stretching them into arcs. The insert shows how the lensing has magnified a very distant background galaxy possibly a building block of today's galaxies. By measuring the amount of stretching it is possible to map out the dark and luminous matter of the cluster.

How the shape of a gravitational lens affects the lensed images



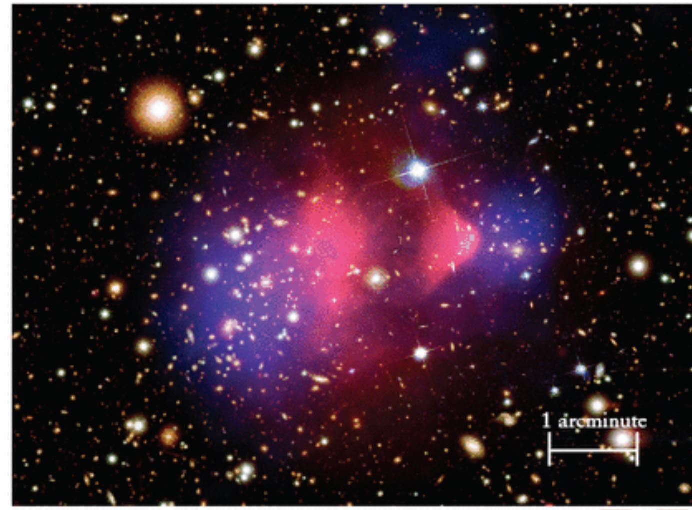
Detecting Dark Matter in Clusters of Galaxies

Example: The Bullet Cluster formed from the collision of two clusters

Using the weak lensing technique, astronomers have deduced that the dark mass in the clusters (blue) is separate from that of the hot gas.

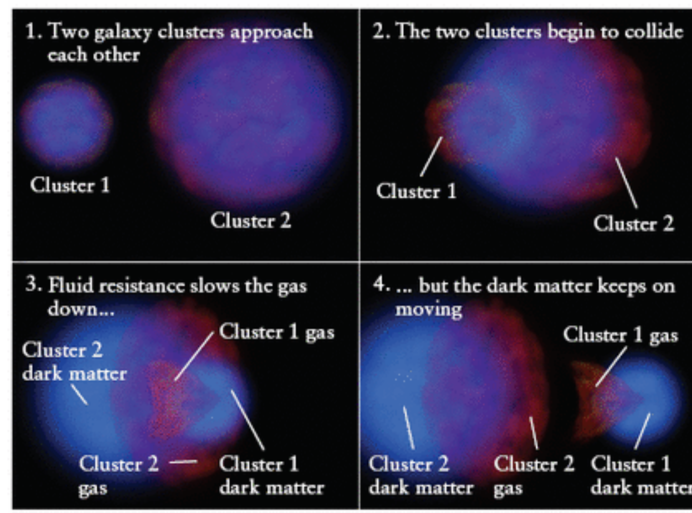
This separation was presumably produced by the high-speed collision in which the **gas particles collided with each other, while the stars and dark matter were unaffected.**

This provides direct evidence that most of the matter in the Bullet Cluster is dark matter.



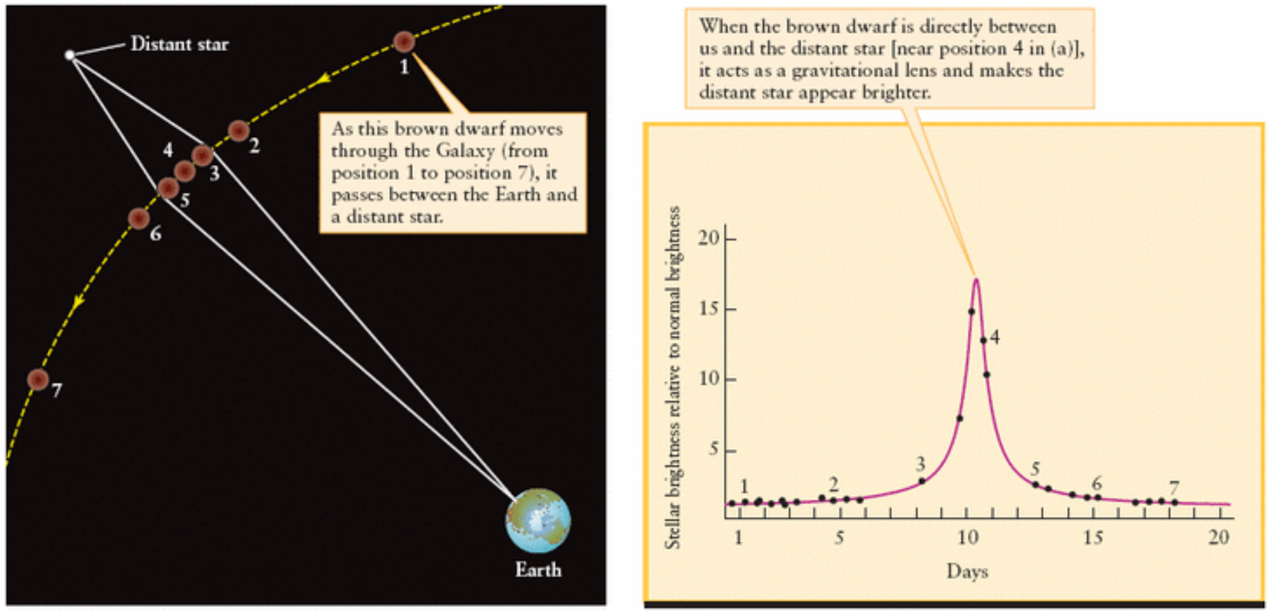
(a) Composite image of galaxy cluster 1E0657-56 showing visible galaxies, X-ray-emitting gas (red) and dark matter (blue)

R I V U X G



(b) A model of how the gas and dark matter in 1E0657-56 could have become separated

Dark Matter in our Galaxy



One speculation for dark matter is that it is composed of dim objects with masses of about ~ 1 $M_\odot$. These objects which would include **brown dwarfs** (object not massive enough to sustain H fusion), **white dwarfs, and black holes** are called **massive compact halo objects (MACHOs)**.

When a MACHO passes between a background star and us it will magnify the light from the star. The degree of magnification and the length of the event provide constraints on the mass of the MACHO object. Astronomers estimate that MACHO’s can only account for less than half of the dark matter halo.

Dark Matter in our Galaxy

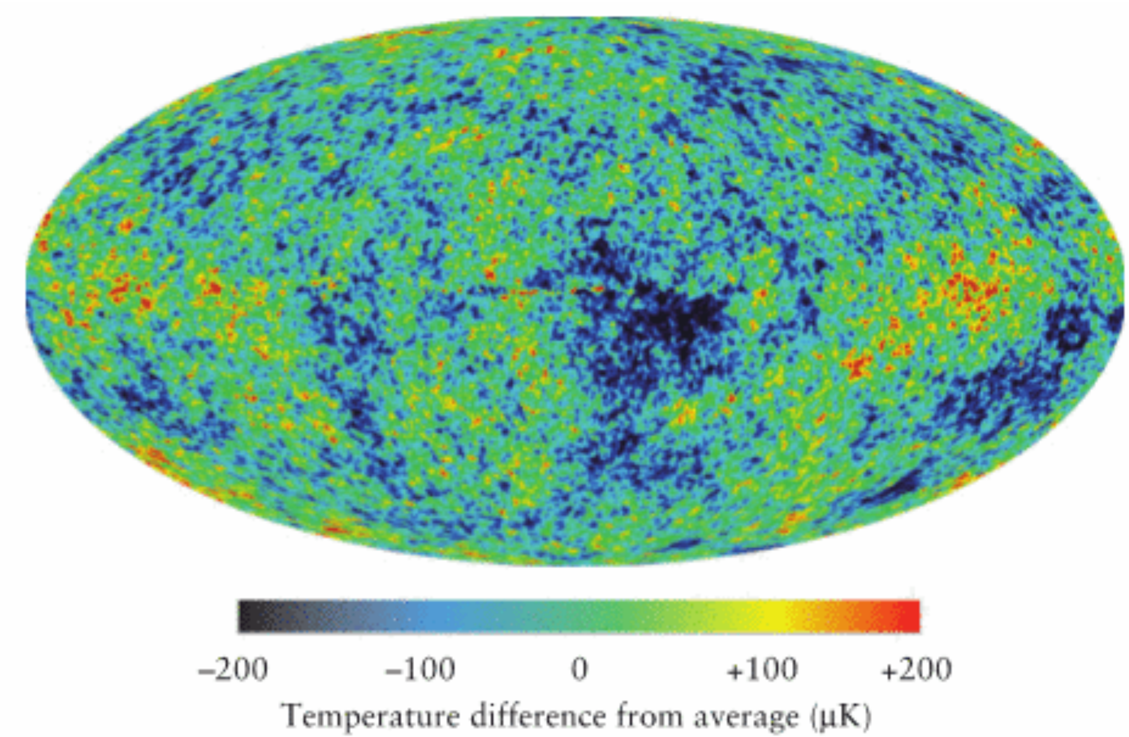
Various dark matter candidates recently proposed are made of more exotic forms of matter. One suggestion is that dark matter is made up of **weakly interacting massive particles** (**WIMPs**).

WIMPs do not interact with electromagnetism (photons) and they don’t interact with the strong nuclear force but they do interact with the weak force and gravity.

WIMPs are predicted by some particle theories and are expected to have masses between 10 to 10,000 times that of a proton.

Galaxy Formation

Step 1: Galaxies are thought to have arisen from small density fluctuations in the Universe formed just after the Big Bang.

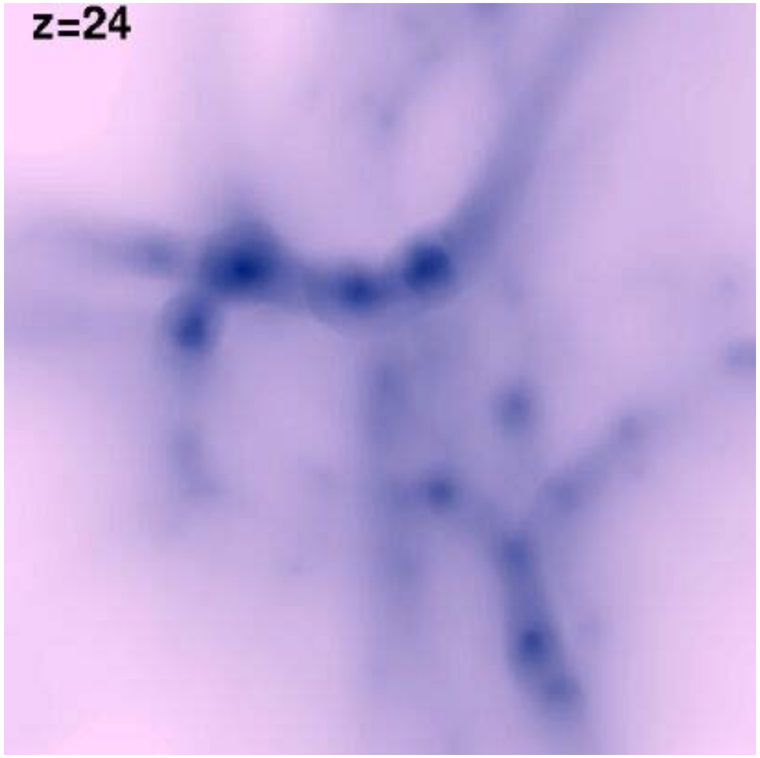


The detailed, all-sky picture of the infant universe created from five years of WMAP data. The image reveals 13.7 billion year old temperature fluctuations (shown as color differences) that correspond to the seeds that grew to become the galaxies. The bluer regions are lower temperature and higher density (why?).

Galaxy Formation

Step 2: Due to gravity these density fluctuations condense and coalesce. The **condensations** are primarily thought to have been made up of **dark matter.**

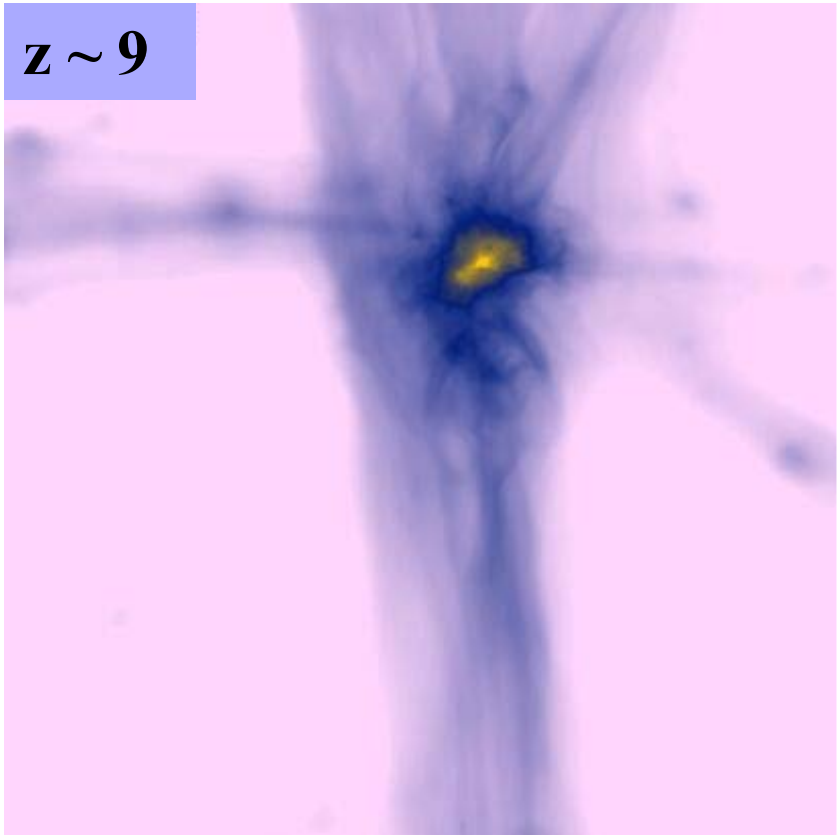
According to one computer simulation, some dark matter concentrations began to condense into a network of filaments and sheets that attracted hydrogen and helium gas through gravitational attraction at around 140 million years (z=24) after the Big Bang.



Galaxy Formation

Step 3: With the expansion of the Universe the **baryonic matter** (matter made up of protons and neutrons) cools down enough to form molecular hydrogen. This hydrogen falls deep into the dark matter halos perhaps forming the first stars.

Hydrogen and helium gas, that was attracted into large dark matter clumps of around one million Solar-masses, may have been able to fall into their cores and, unlike the dark matter, to begin further collapse into the **first stars** as soon as 550 million years after the Big Bang.



Galaxy Formation

Step 4: The **galaxy formation process is thought to be hierarchical** with smaller halos coalescing to form larger ones.
It is thought that clusters of stars may form in the center of each halo. The merger of these halos may produce the first **protogalaxies**.

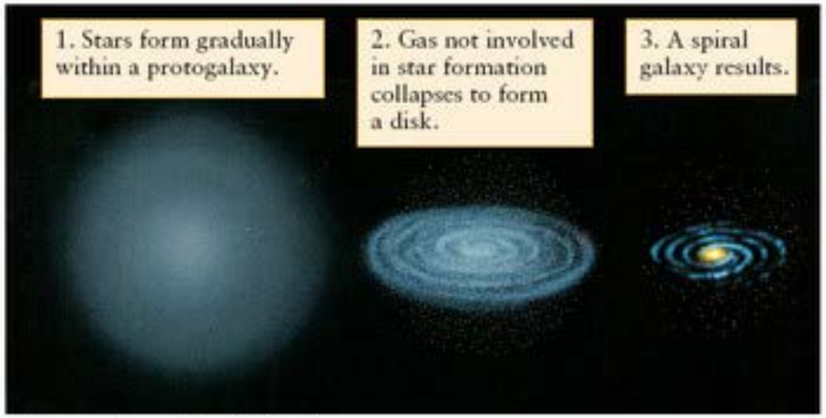
Collisions of similar size halos turns out to result in halos with large rotations. In these systems the stars tend to form disks and perhaps give rise to spiral galaxies.

Another factor that may determine whether a protogalaxy turns into a spiral or elliptical is its **initial star formation rate**.

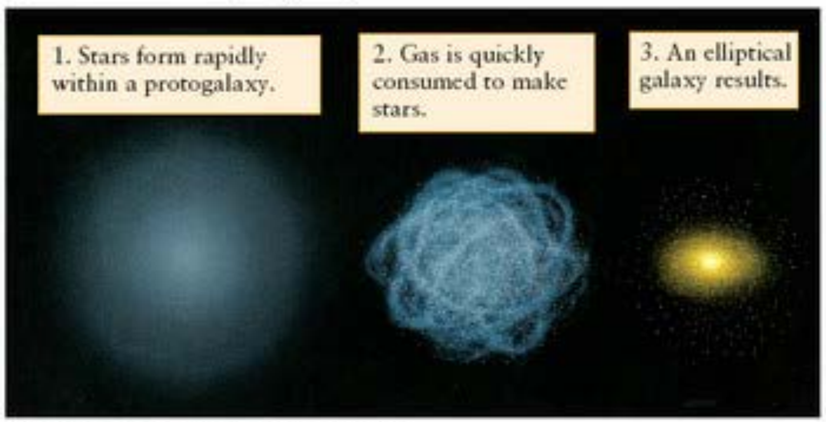
A protogalaxy with a **high star formation rate** early on will consume most of the gas and not form a disk resulting in an **elliptical galaxy**.

In a protogalaxy with a **low star formation rate** the unused gas will collapse to form a disk resulting in the formation of a **spiral galaxy**.

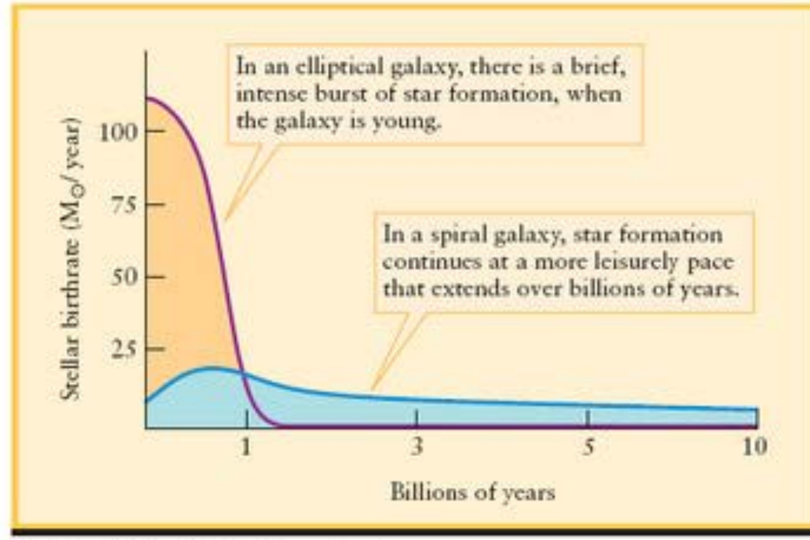
Spiral versus Elliptical Galaxies



(a) Formation of a spiral galaxy



(b) Formation of an elliptical galaxy



(c) The stellar birthrate in galaxies

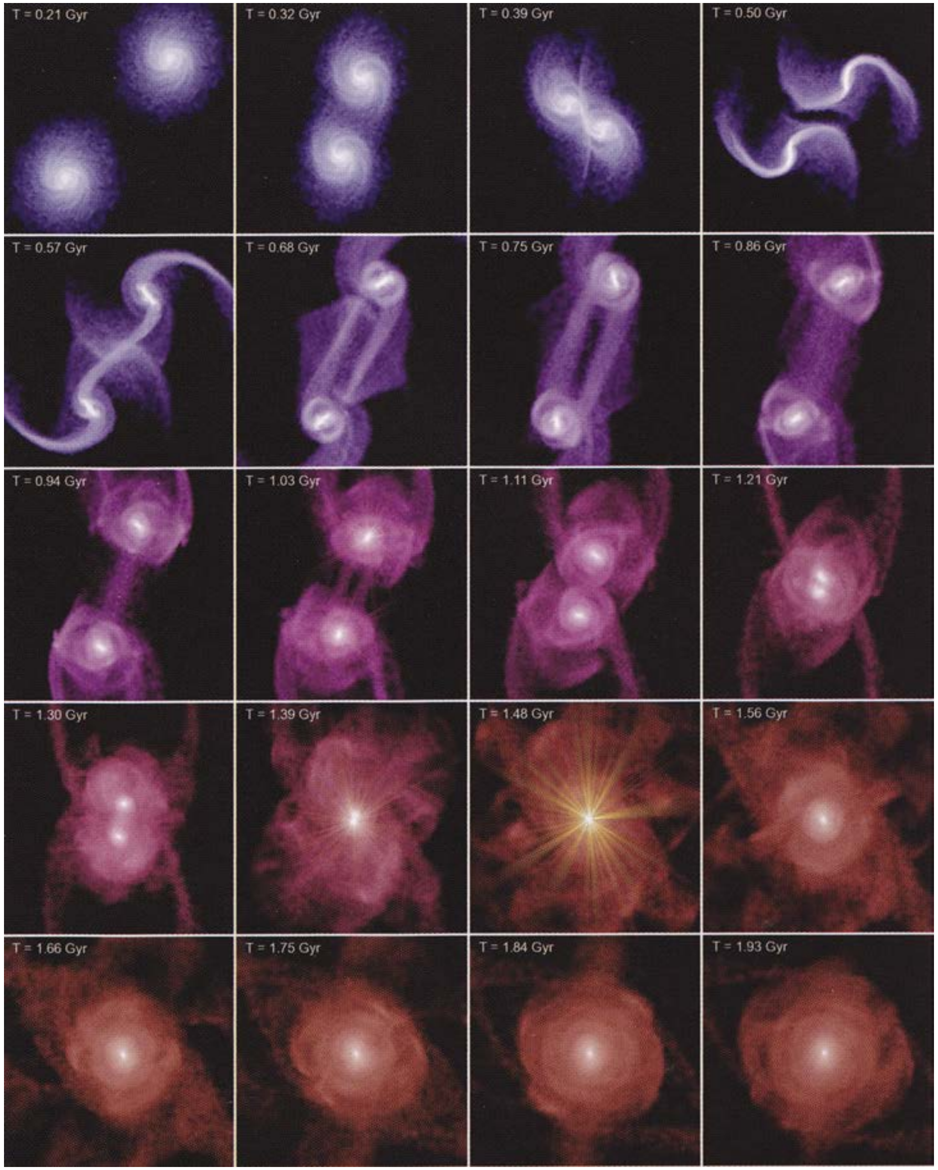
One idea to explain why some galaxies become spirals and other ellipticals is that if star formation is large during the formation of the protogalaxy all the gas will be consumed quickly to form stars and no disk is formed resulting in an elliptical galaxy. Conversely, if star formation is weak within a protogalaxy the gas will have time to settle and form a disk resulting in a spiral galaxy.

Galaxy Mergers

The merger of two spiral galaxies is depicted in these simulations by Lars Hernquist.

Each panel is 370 000 light years on a side and the simulation spans 2 billion years.

The brightness indicates the projected density of stars, while the gas color indicates that the gas content evolves from gas rich (blue) to gas poor (red). Note that the merger destroys the spiral structure, leaving behind a remnant that resembles an elliptical galaxy (red and dead).



Baryonic Matter Rules in Galactic Nuclei

In order for matter to settle into the core of a halo it needs to lose kinetic energy.

Baryonic matter can lose energy through radiative cooling and heat released in shocks resulting in the **accumulation of bayonic matter in the nucleus of a galaxy**.

Dark matter does not dissipate energy via electromagnetic radiation and does not settle in the core easily.

Galactic Nuclei

The **density of stars** increases dramatically near the nucleus of a galaxy.

In our galaxy the density of stars near the sun is ~ 0.006 stars per cubic light-year

Near the center of our galaxy the density is $\sim 10^6$ stars per cubic light-year

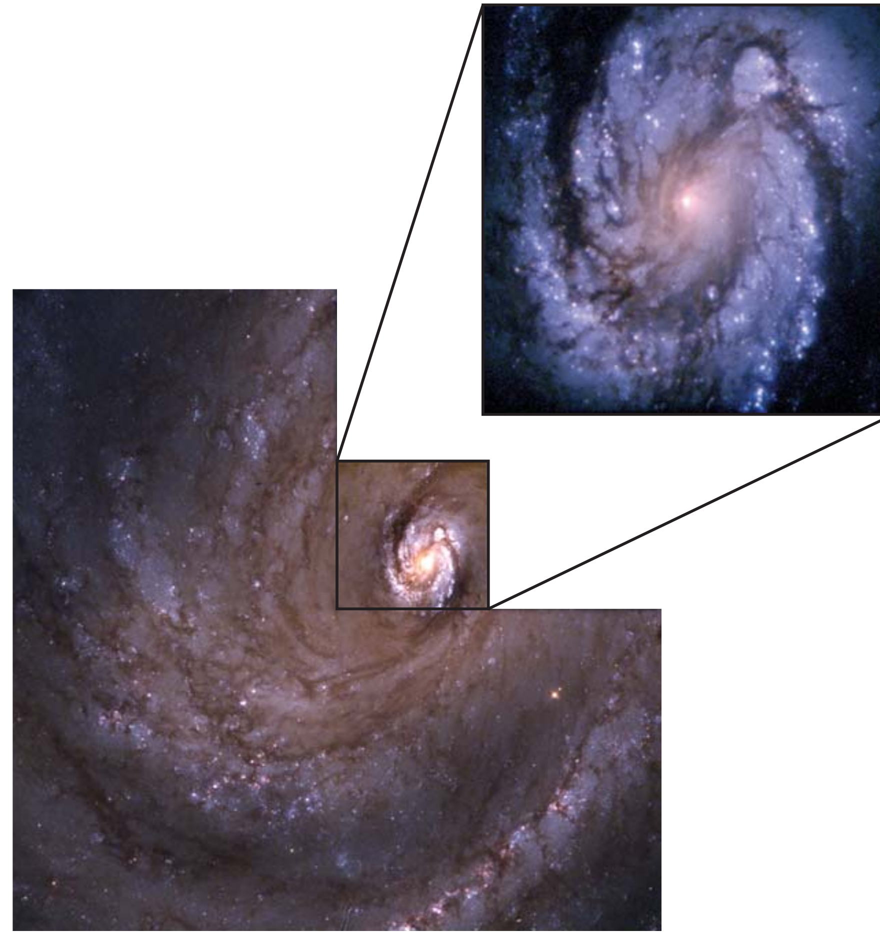
Because of the large stellar densities and large speeds near the nucleus it is expected that a violent stellar collision near our Galaxy's nucleus occurs once every 10,000 years.

The **outcome of a collision** between two stars will in part depend on the speed of the stars compared to the escape speed from their surface.

Collisions with speeds greater than the escape speed will result in the release of plumes of gas into space.

Collisions with speeds less than the escape speeds will likely result in the stars coalescing to form a more massive star.

We can imagine a steady progression near the nucleus where we go from a regime where most encounters lead to coalescence to encounters that lead to disruptive collisions.



Stellar encounters are thought to affect the evolution of the nucleus.