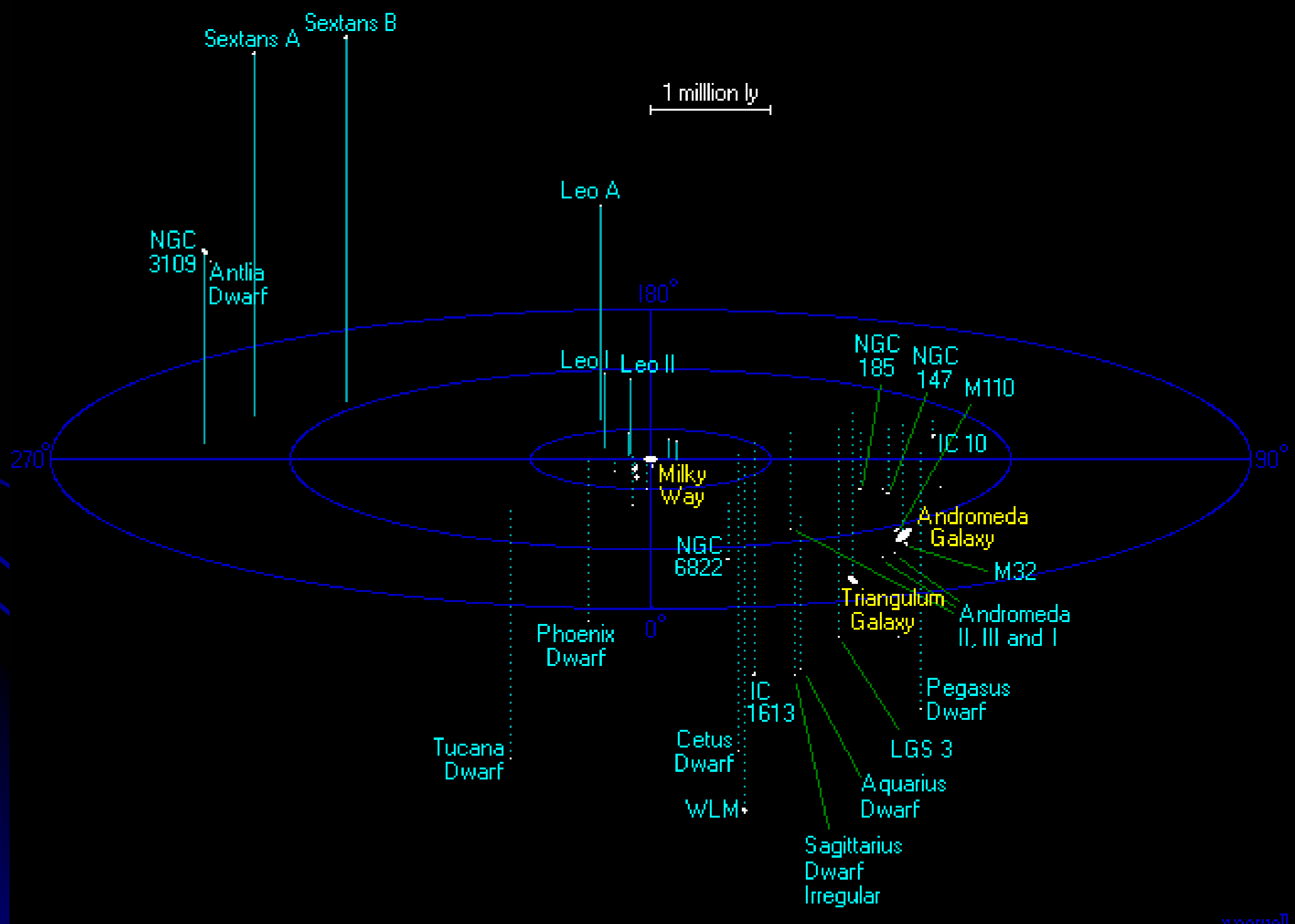
Relativistic Universe

Galaxies II

Galaxy Clusters

Most galaxies are clumped together in small groups or large galaxy clusters. Our galaxy is part of the Local Group.



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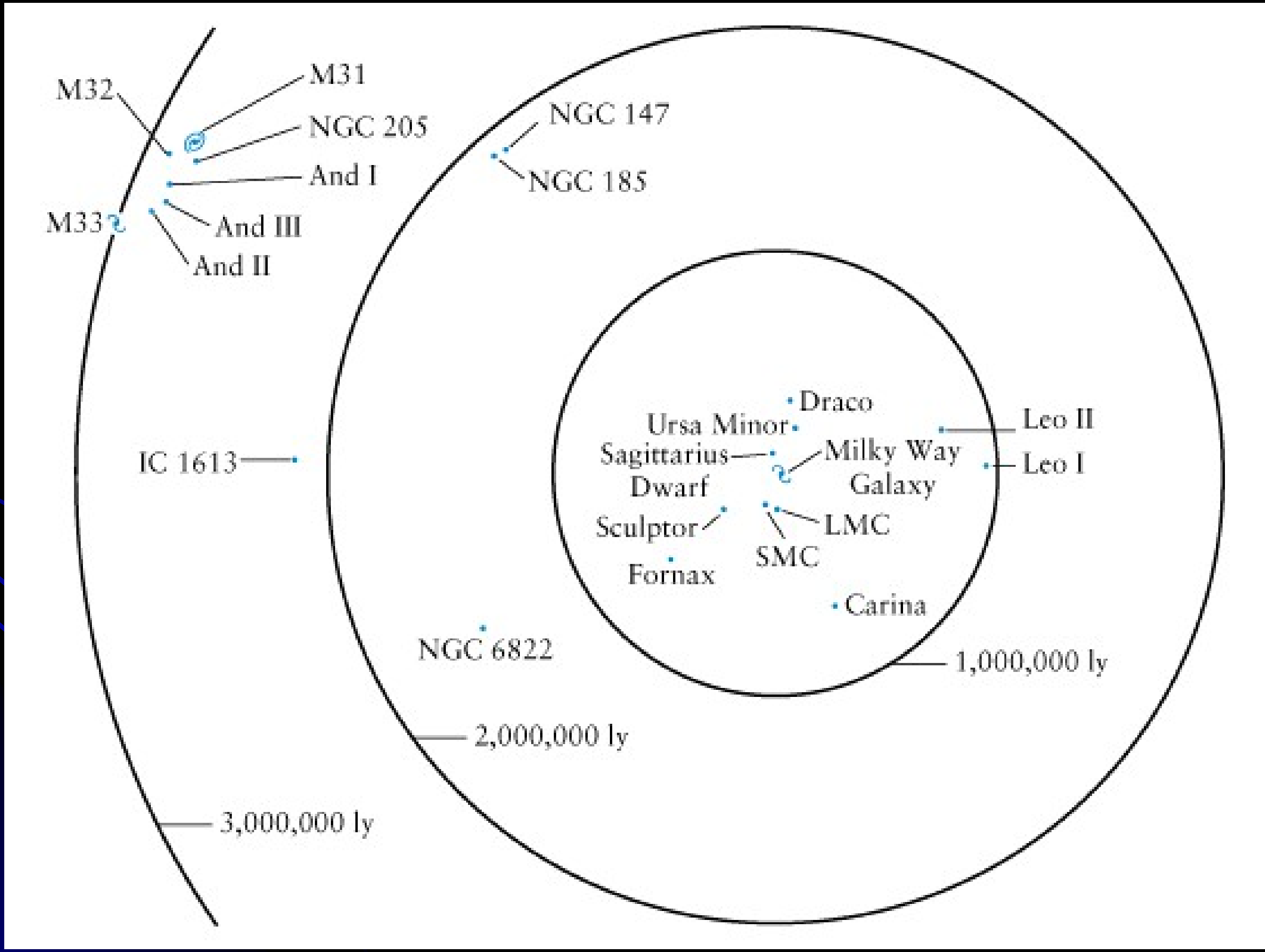
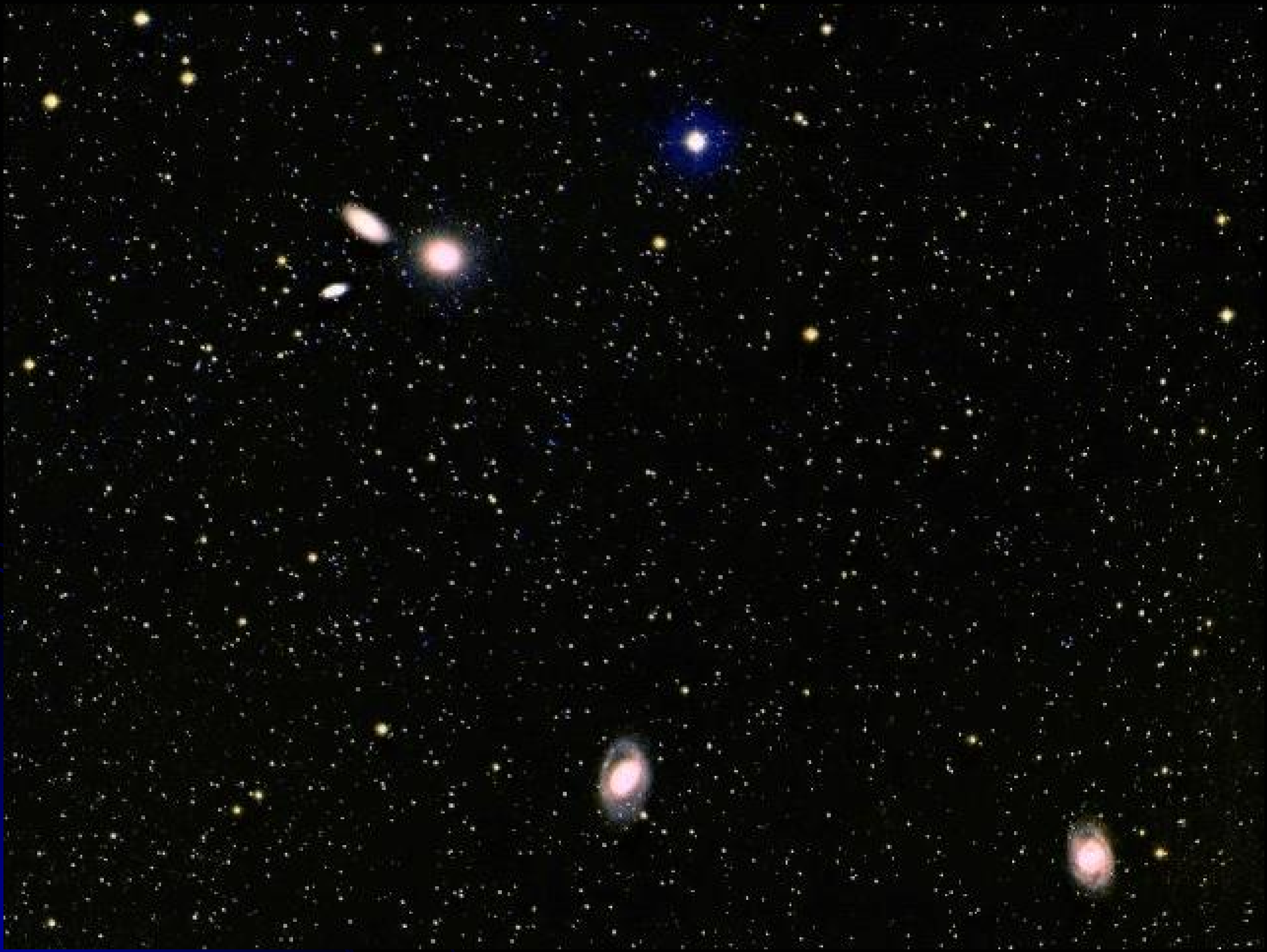


Local Group Galaxies

Plus about 30 other galaxies too small to include … and the Milky Way.

Example of a Small Group



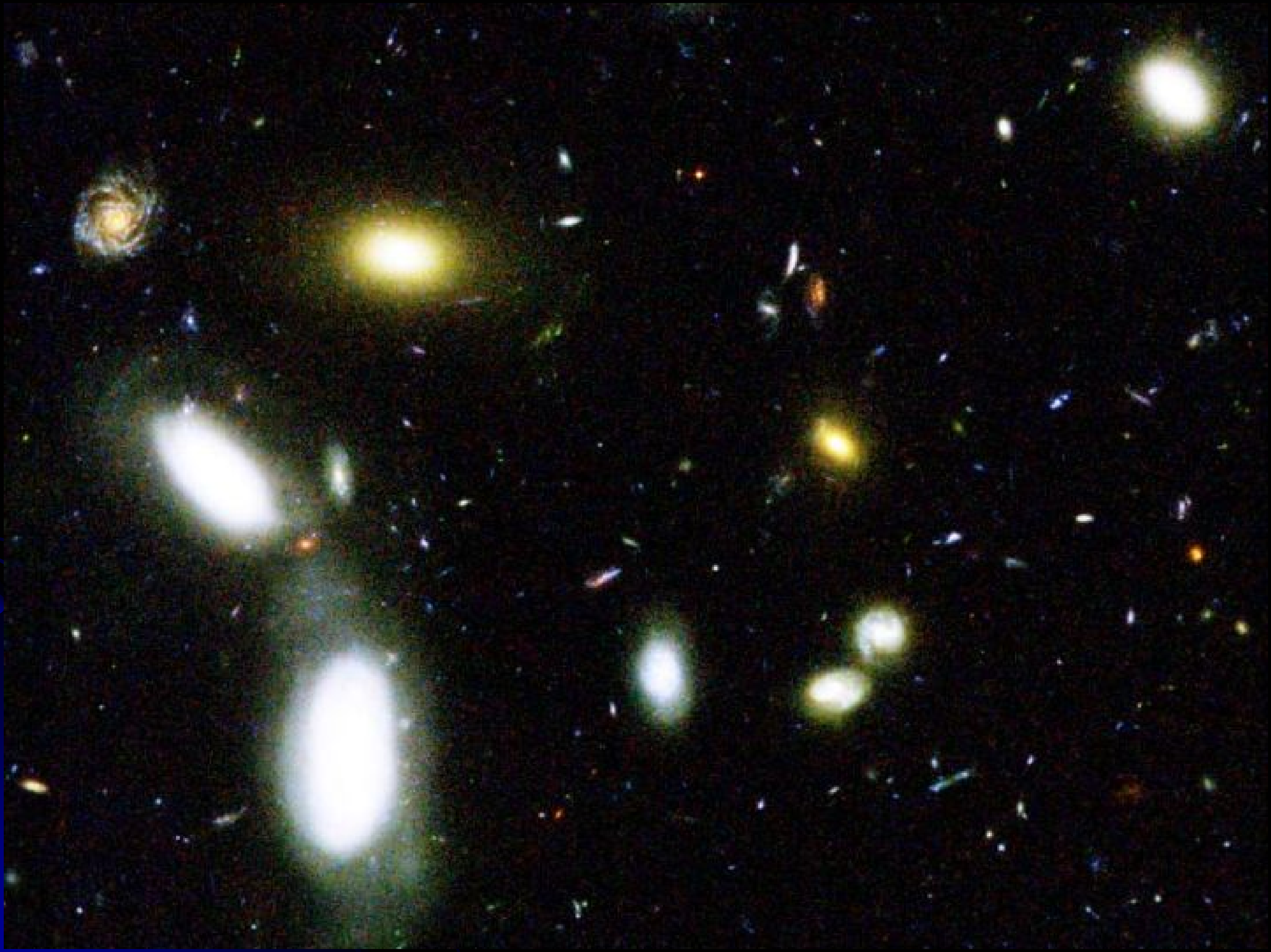
Example of a Small Group

Example of a Small Group

Example of a Medium Size Galaxy Group

Example of a Medium Size Galaxy Group

Example of a Medium Size Galaxy Group

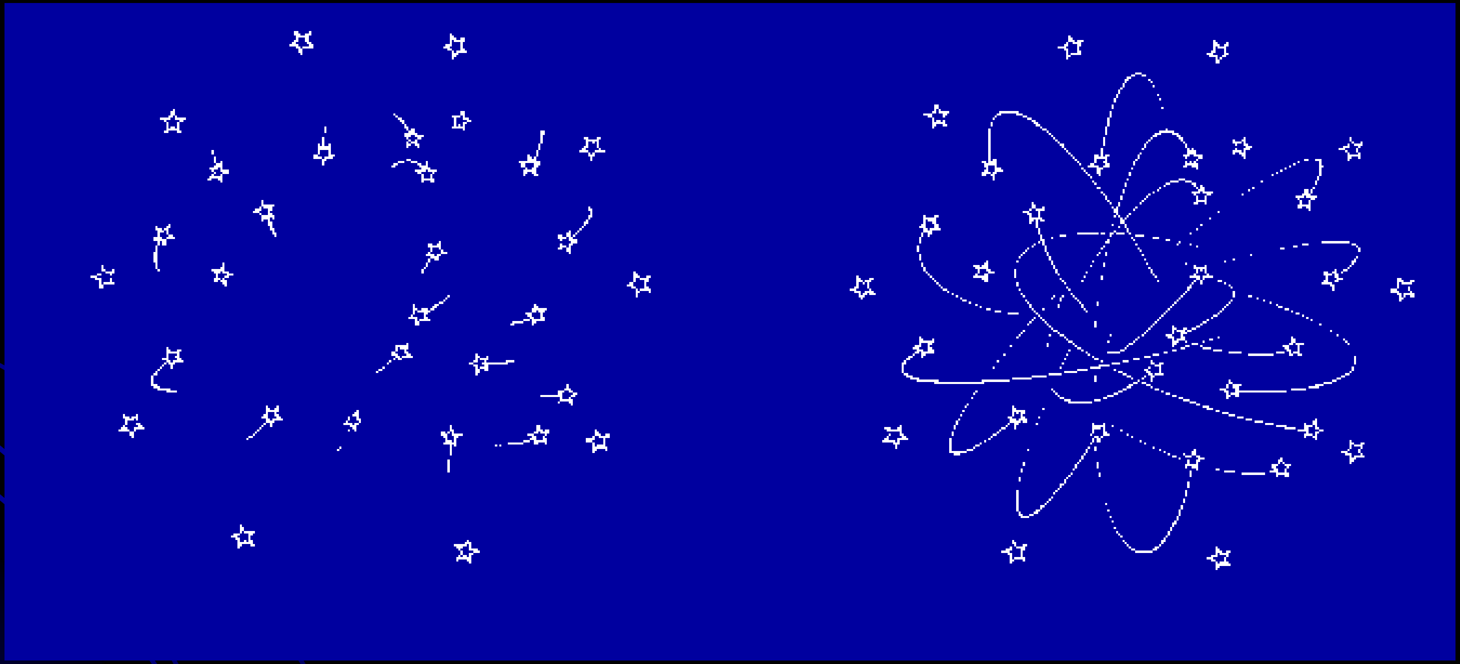


Example of a Large Galaxy Cluster

Example of a Large Galaxy Cluster

Mass Measurements in Galaxy Clusters

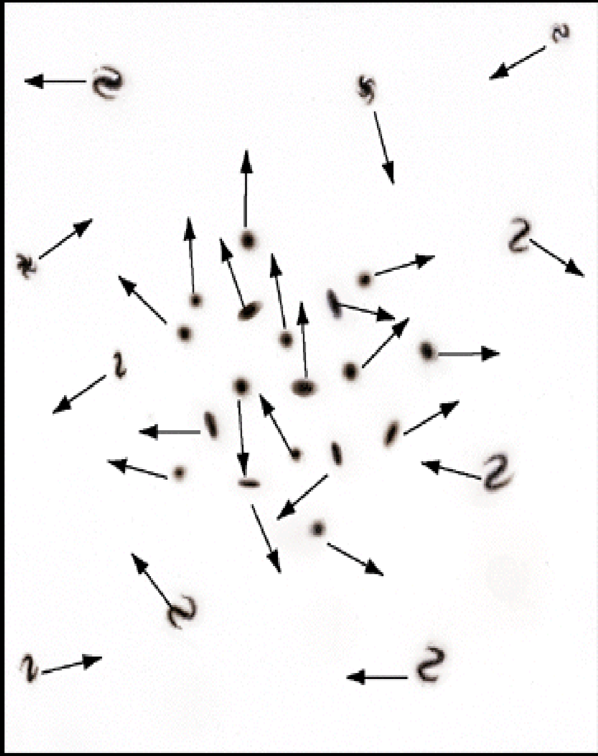
For a group of objects, there always must be balance between gravity and velocity. Too little velocity, and gravity takes over, making the cluster smaller. Too much velocity, and the objects escape the group's gravity (causing the group to evaporate).



By measuring the Doppler shifts of galaxies in a cluster, you can measure the cluster's gravity. And from gravity, you get mass.

The Mass of Clusters

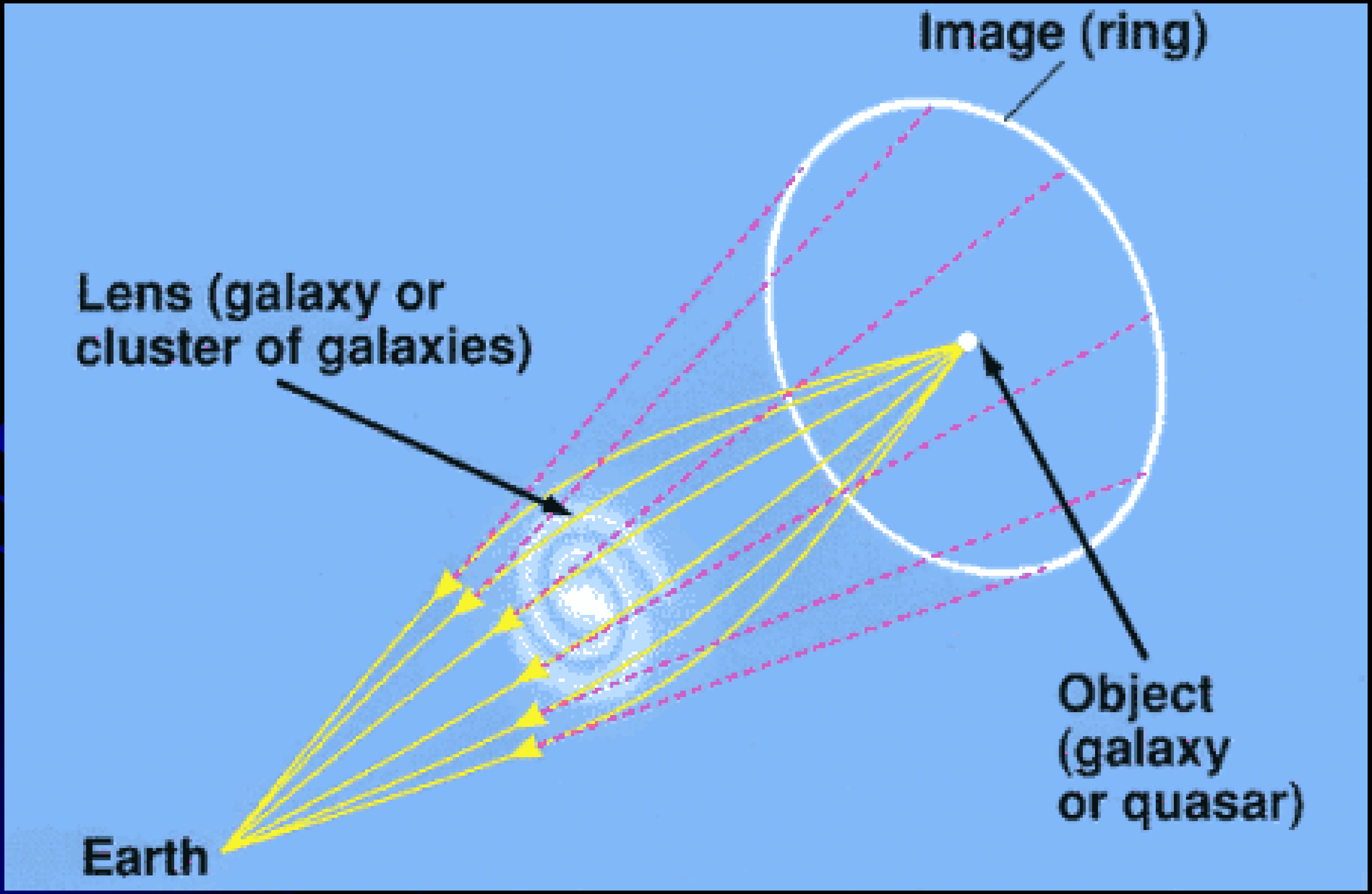
As Fritz Zwicky noticed in 1933, galaxies in clusters move much too fast for the amount of matter we see. The clusters must contain *a lot* of unseen matter providing extra gravity.



Once again – **dark matter**

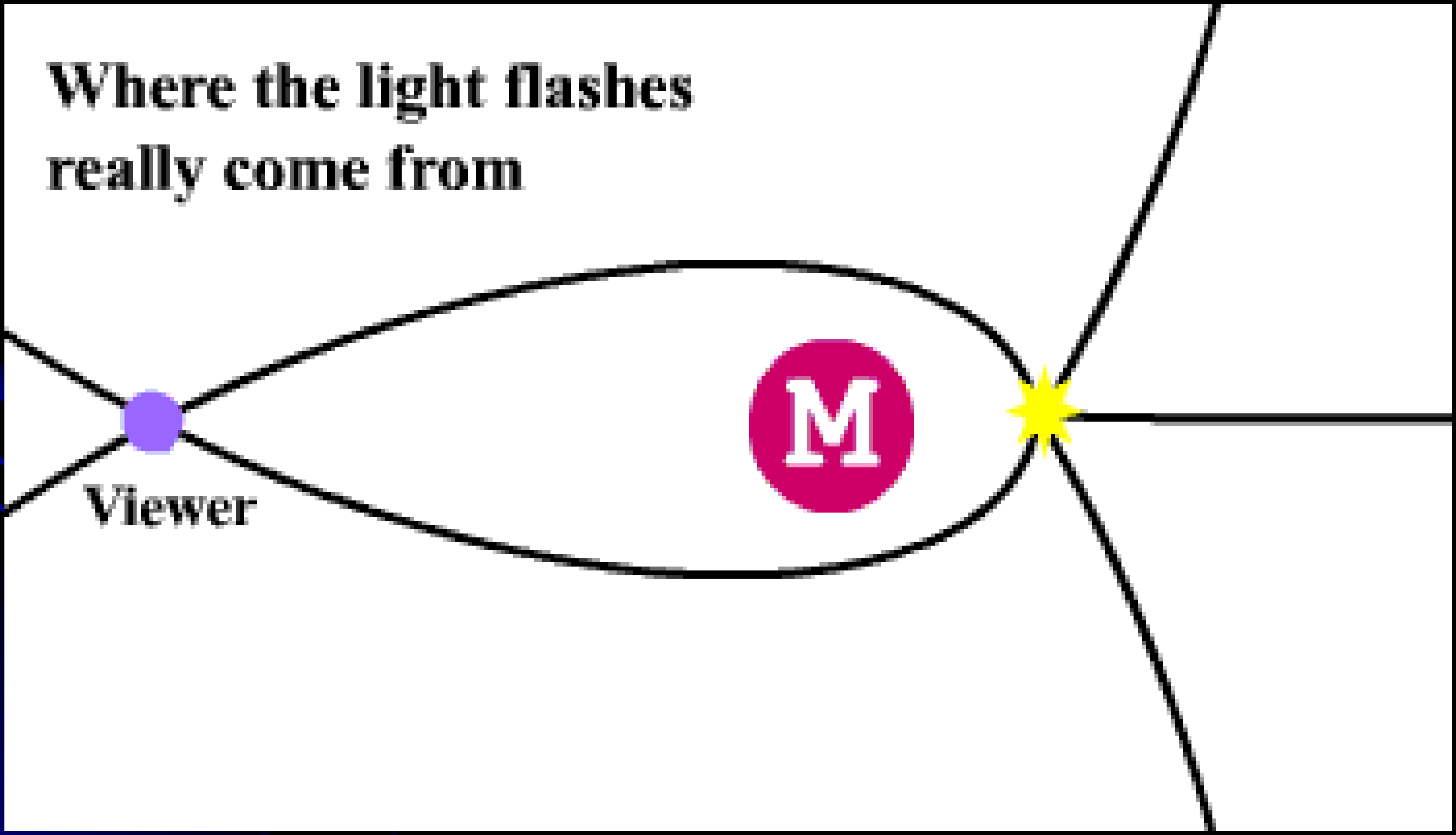
Gravitational Lenses

As we have seen, a light ray can be deflected by gravity. The greater the gravity, the greater the bending. As a result, a collection of matter can act as a gravitational lens.



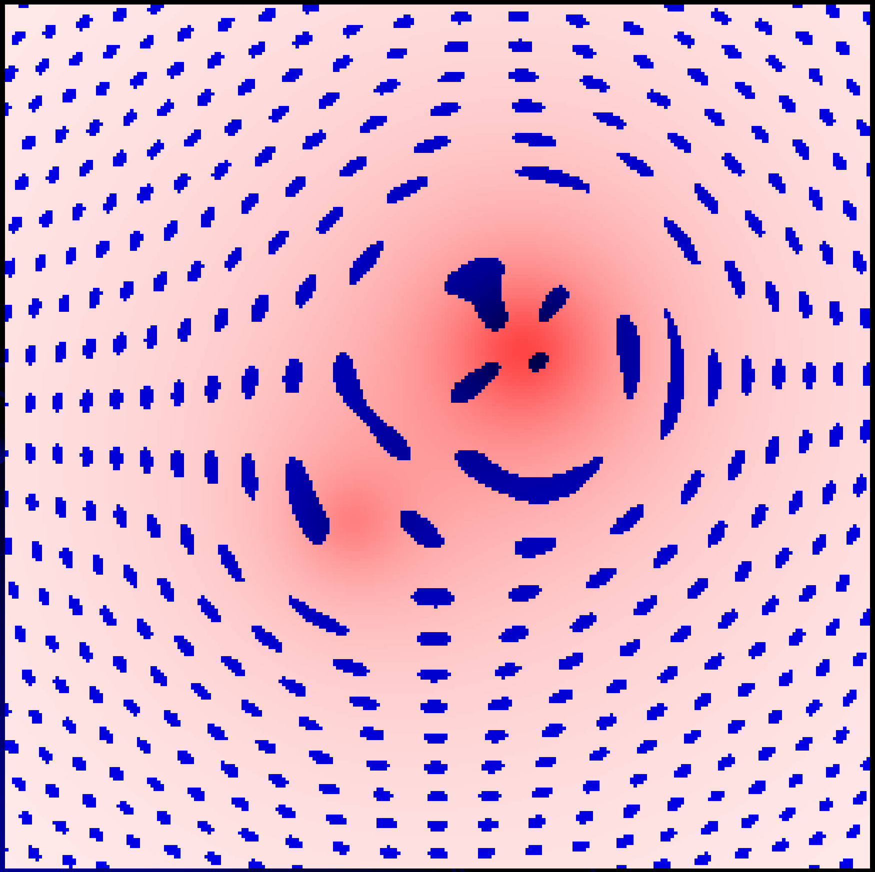
Gravitational Lenses

The greater the mass, the greater the gravity, and the greater the gravitational lens effect. A massive object can cause a large deflection in the light path. (It also greatly amplifies the light.)



Gravitational Lenses

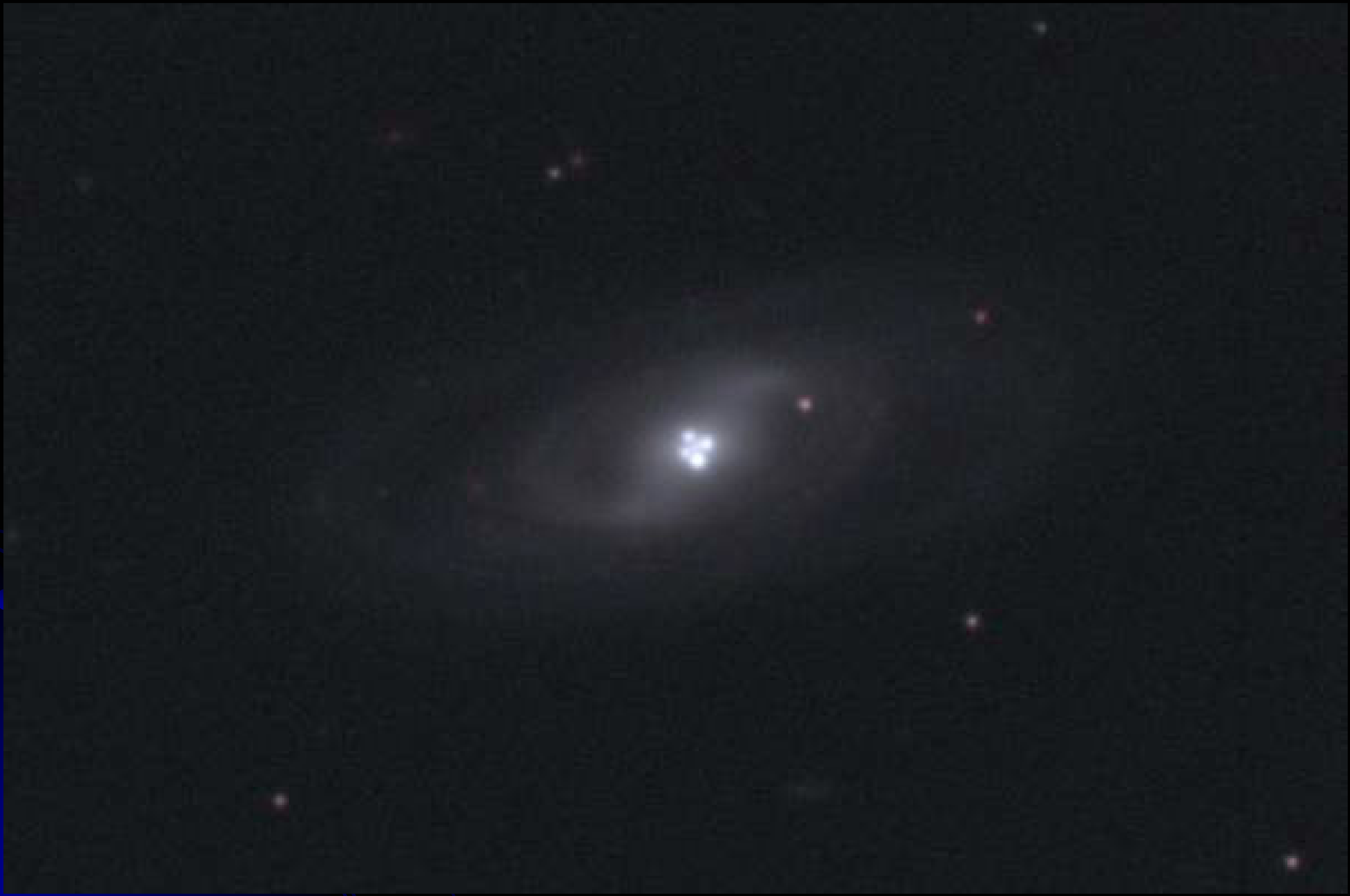
In the case of background point source, the result might be multiple images of the object. In the case of a larger source (*i.e.*, a galaxy), the result can be arcs and arclets.



In this image, the blue areas show background galaxies, while the red represents foreground mass.

Example of a Gravitational Lens

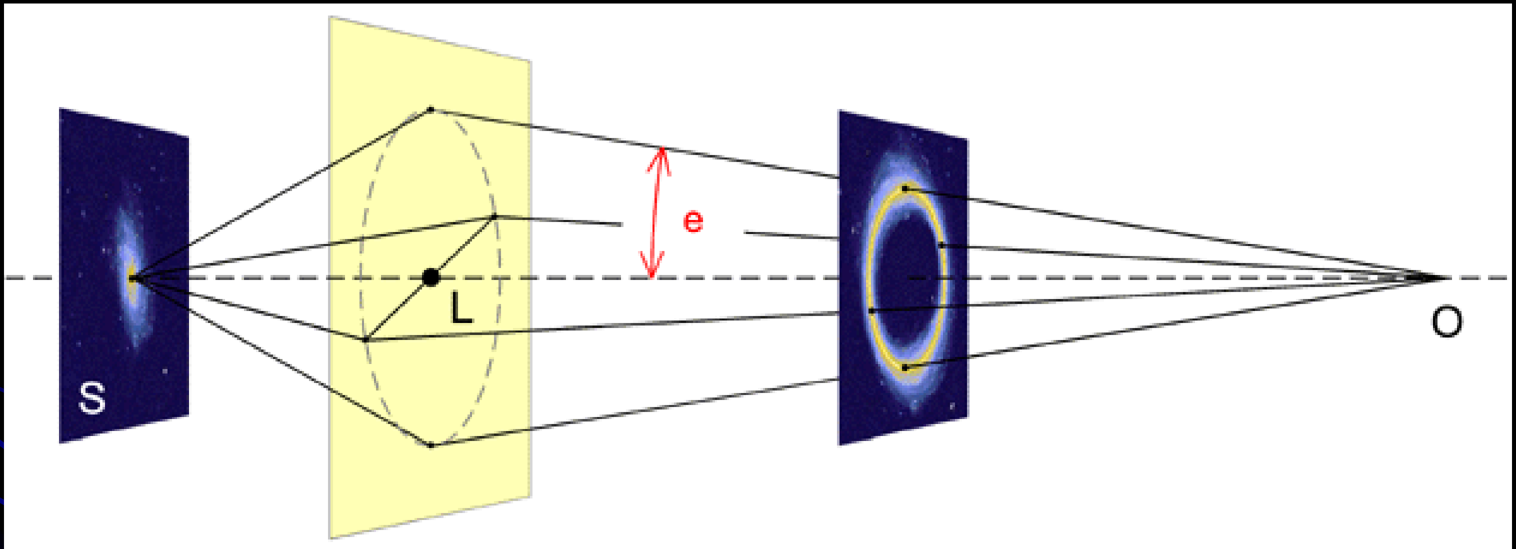
Example of a Gravitational Lens



Example of a Gravitational Lens

Gravitational Mass Measurements

By estimating the distance to the lens and the object, one can measure the deflection angle of the light. This angle allows you to estimate mass.



When astronomers do this, they find *a lot* more matter than is visible in the galaxy or the cluster. Galaxies and clusters contain **dark matter**.

Constituents of the Galaxy

- Interstellar Medium
  - Atomic Hydrogen – H I
  - Molecular Hydrogen – H_2
    - Traced by the molecule CO
  - Ionized Hydrogen – H II
  - Dust
- Stars
  - Population I
  - Population II

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- Stars
  - Population I
  - Population II
- Dark Matter

In fact, ~85% of the Milky Way's mass is **DARK**!

What is the Dark Matter?

From the observational point of view …

WE KNOW NOTHING!

From the theoretical point of view, the dark matter is ***not*** …

- stars, planets, black holes, neutron stars, rocks, atoms, molecules, or anything else that is, was, or will be made of protons, neutrons, or electrons.

From the theoretical point of view, the dark matter might be

- Neutrinos, neutralinos, axions, photinos, gravitinos, WIMPs, superWIMPs (also known as WIMPzillas), quark nuggets, or something else. (Of these, only the neutrino is known to exist, but neutrinos don’t seem to work.)

Or, Newton may be wrong.

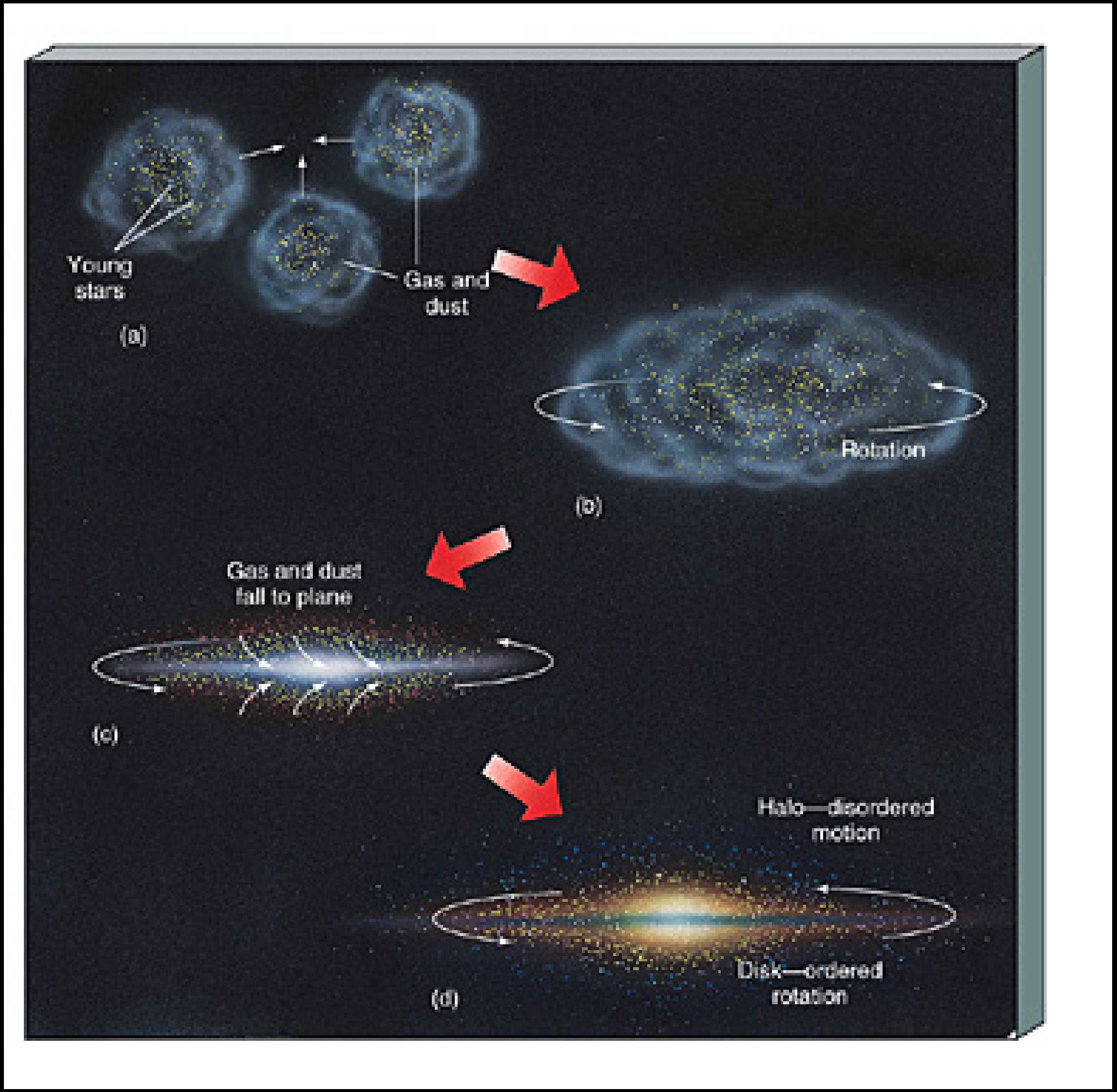
Clues to Galaxy Formation

- Star formation occurs in the disks of galaxies, but not their bulges or halos. Most of this star formation occurs in spiral arms.
- The bulge and halo of spiral galaxies only have old stars.
- Galaxies come in all sizes, but the very largest galaxies are ellipticals.
- Most elliptical galaxies are in rich galaxy clusters; most spiral galaxies avoid the centers of clusters.

Why is a Spiral Galaxy Flat?

Begin with a large cloud (or multiple gas clouds) of mostly hydrogen gas…

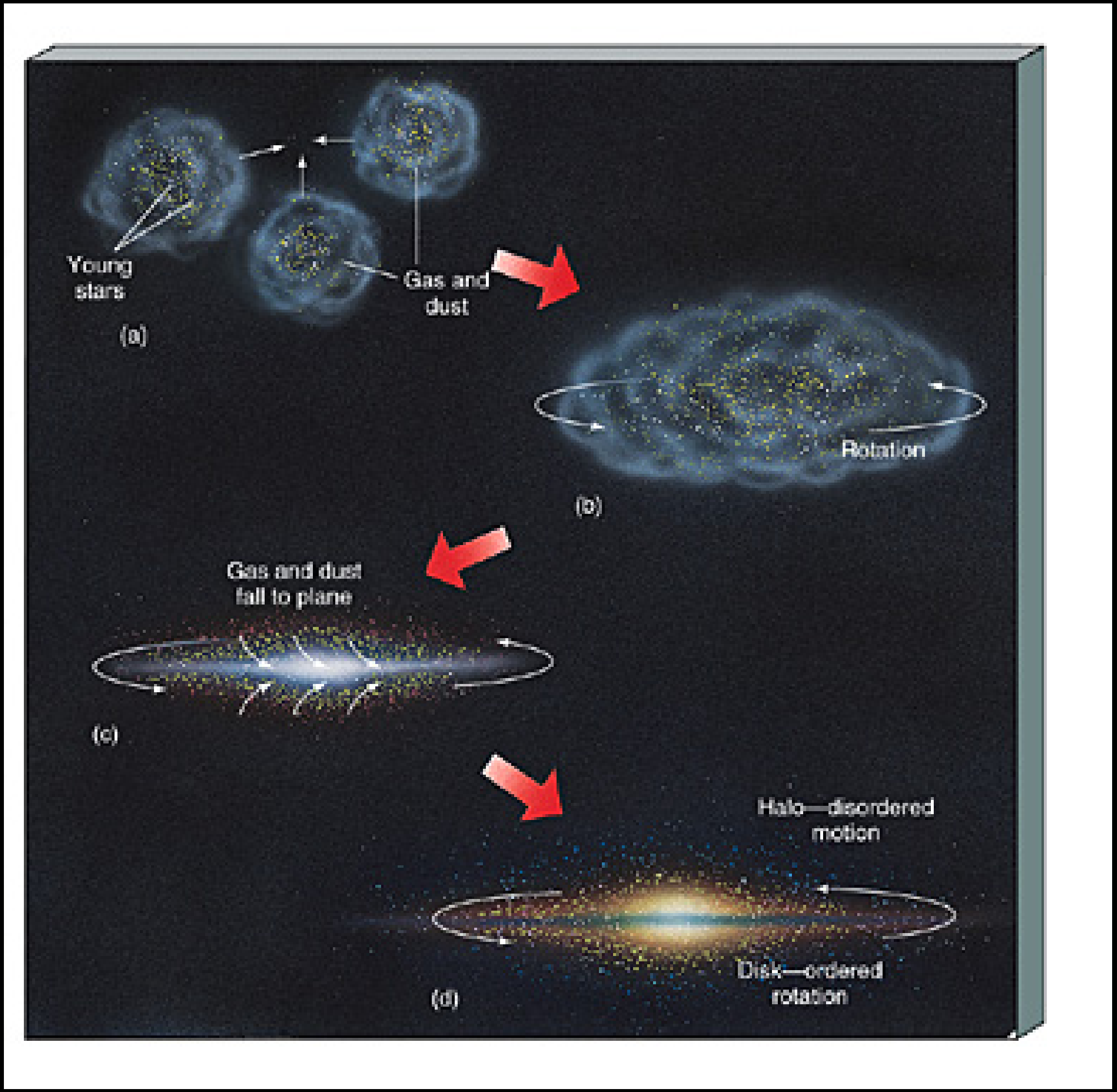
- Small gas clouds coalesce to make a large cloud.
- Self gravity begins to collapse the cloud.
- As the cloud gets smaller, it begins to rotate faster.
- Centripetal force prevents collapse of gas in the plane of rotation.



Why is a Spiral Galaxy Flat?

Centripetal force does not strongly effect the gas that is above and below the rotation plane. So …

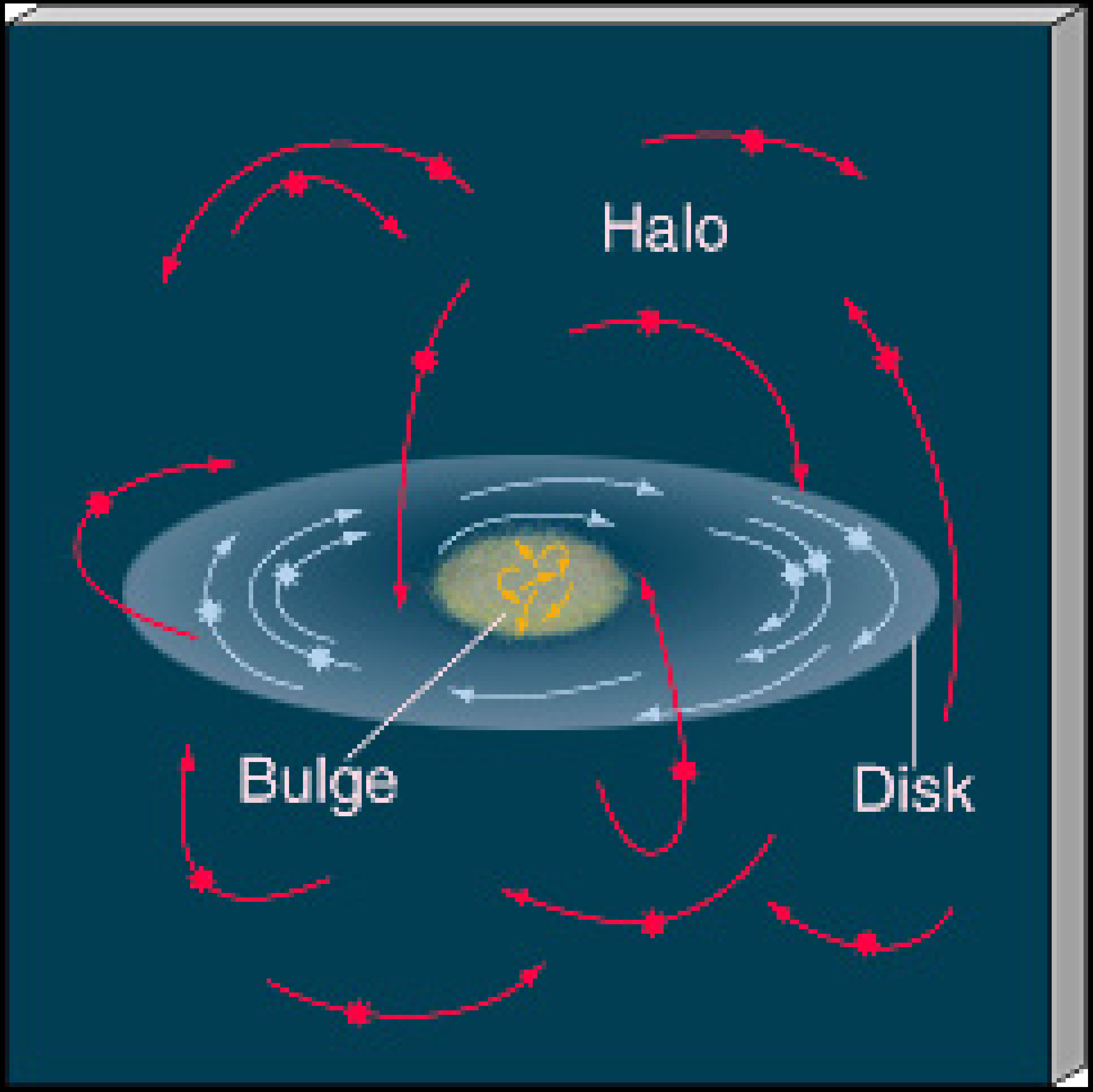
- Gas falling in from the top collides with gas falling in from the bottom. This gas sticks together and forms the galaxy's disk.
- All star formation now occurs in a disk (where all the gas is). The gas and stars rotate around the galactic center.



Why are Pop II Stars Not in the Plane?

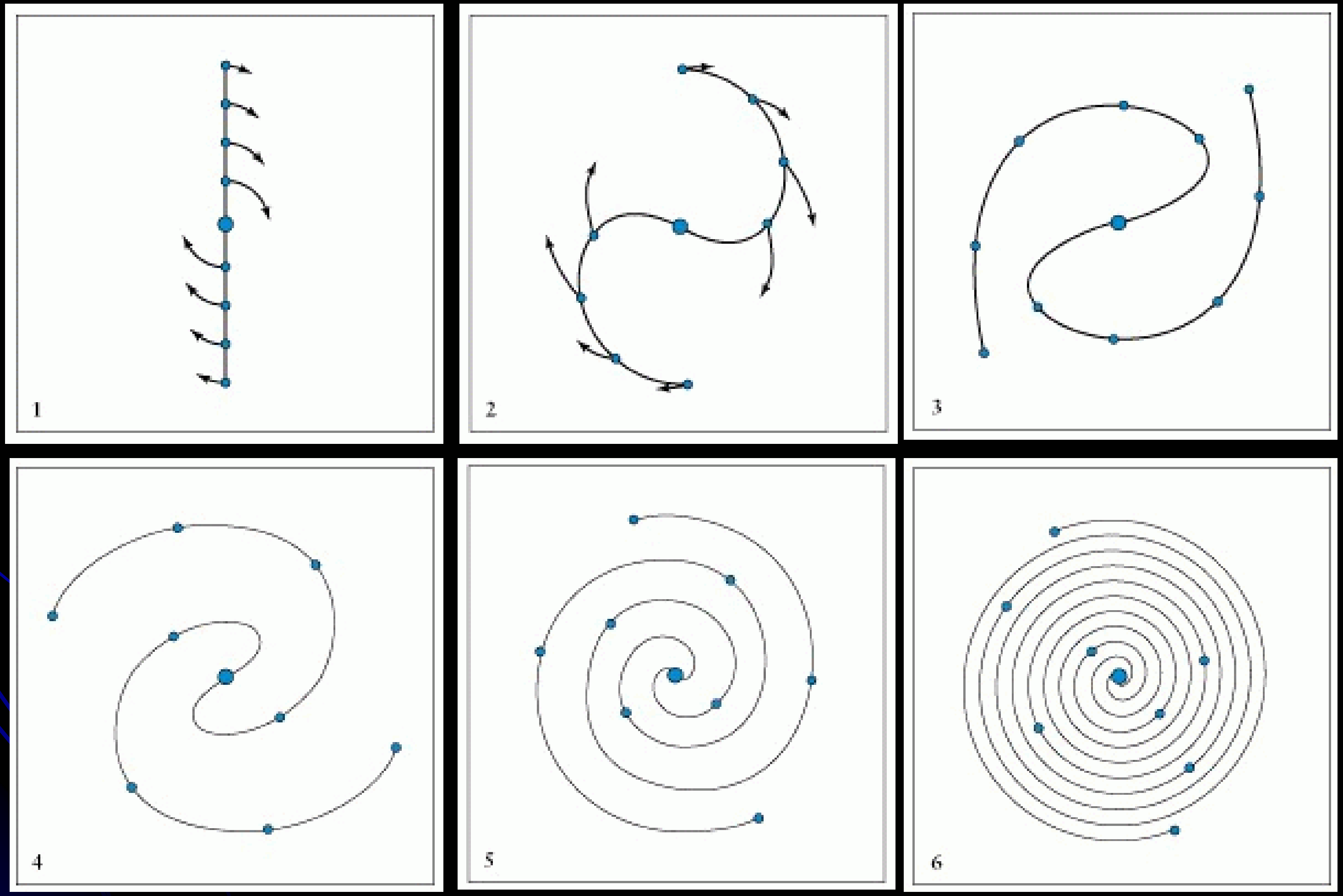
There are two possible reasons for this …

1) All stars which formed before the disk collapse stay in their original orbits. When stars collide with gas, nothing happens – they go right through the gas.
2) *you'll find out later*…



Why are there Spiral Arms?

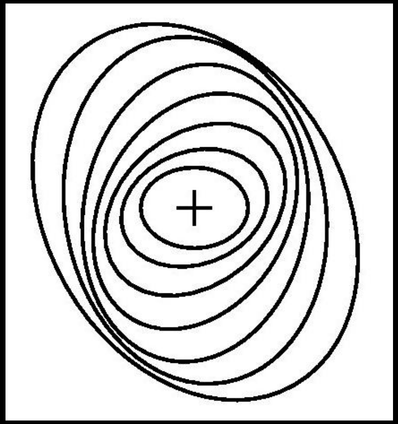
Stars near the galactic center don't need to travel far to circle the galaxy, but stars further out can take a long time to go around. An initial line of stars will be drawn out into a spiral.



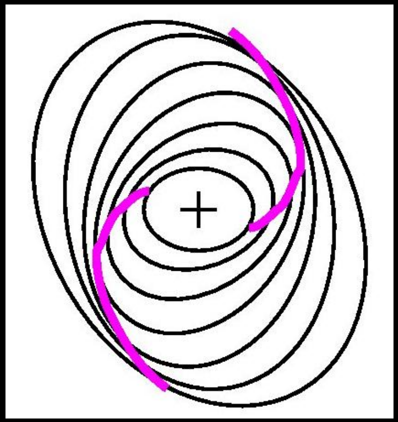
But this is <u>not</u> why galaxies have spiral arms!

Spiral Density Waves

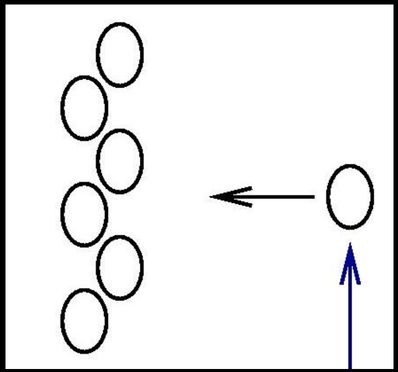
- The orbits in spiral galaxies are not quite circles – they are ellipses. These ellipses are slightly tilted with respect to each other.



- Thus there are regions of slightly higher density than their surroundings. The higher density means higher gravity.

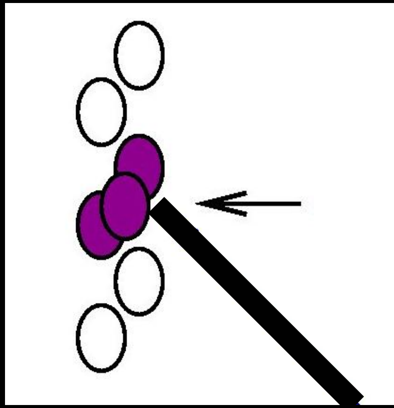


- Objects (such as a gas cloud) will be attracted to these regions and will drift towards them.

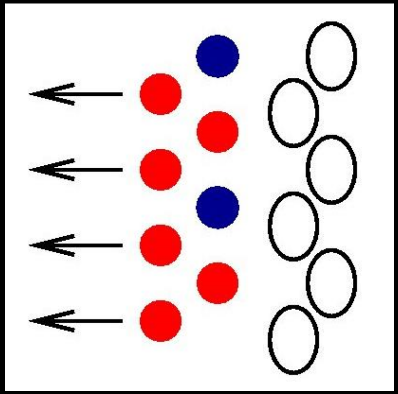


Spiral Density Waves

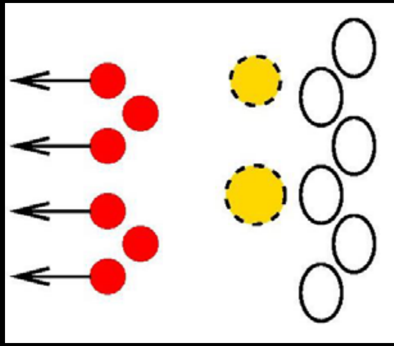
- When the gas cloud collides with other gas clouds, stars will be formed. (This is where most of the galaxy's star formation takes place.)



- Many of the stars will be faint, red main sequence stars, but some will be bright blue O and B stars. These stars will continue to drift through the region.

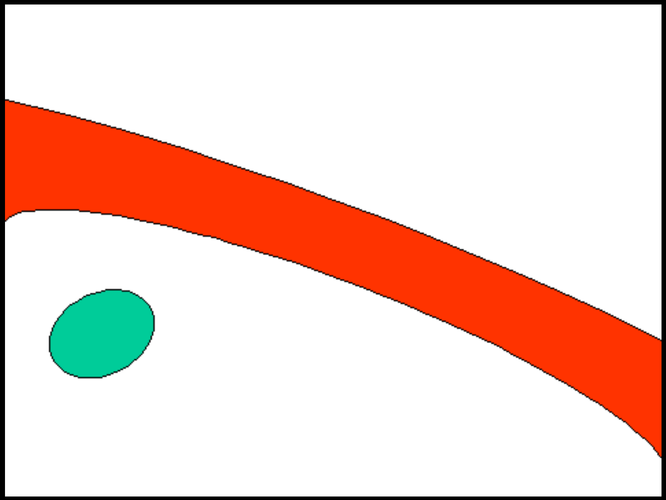


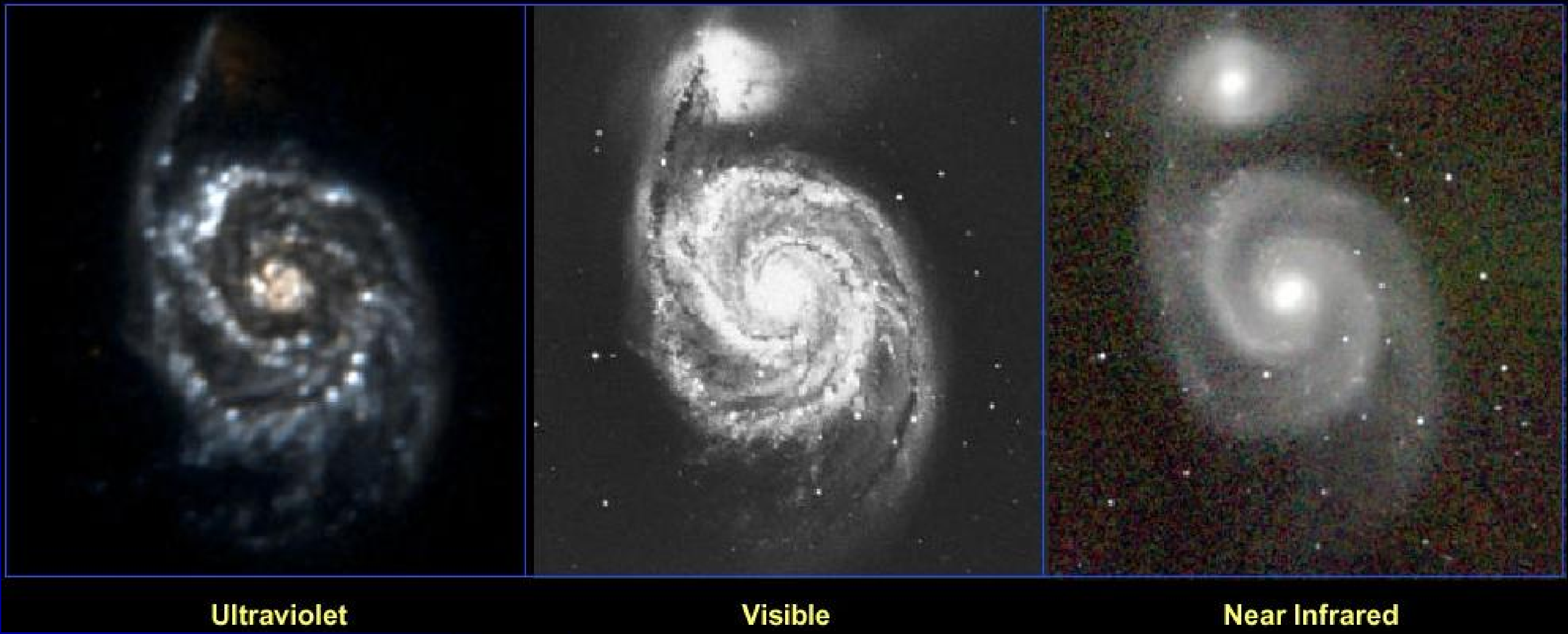
- The O and B stars don't go far before they go supernova. The brightest (and bluest) of a galaxy's stars will never be far from the spiral arm where they were born.



Spiral Density Waves

Since all the bright blue stars die before leaving the spiral arm, the spiral density waves must show up better at ultraviolet wavelengths.



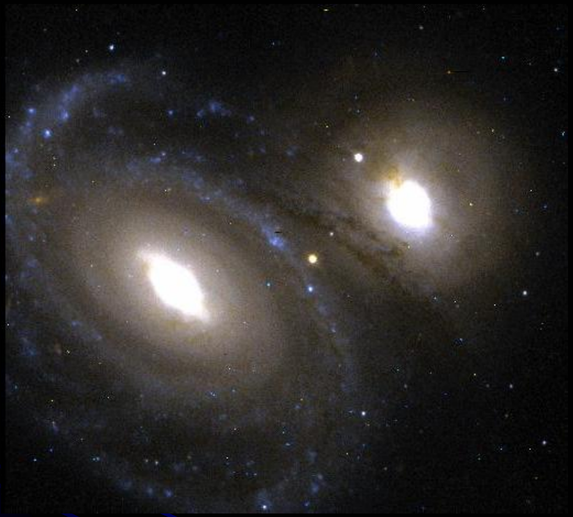


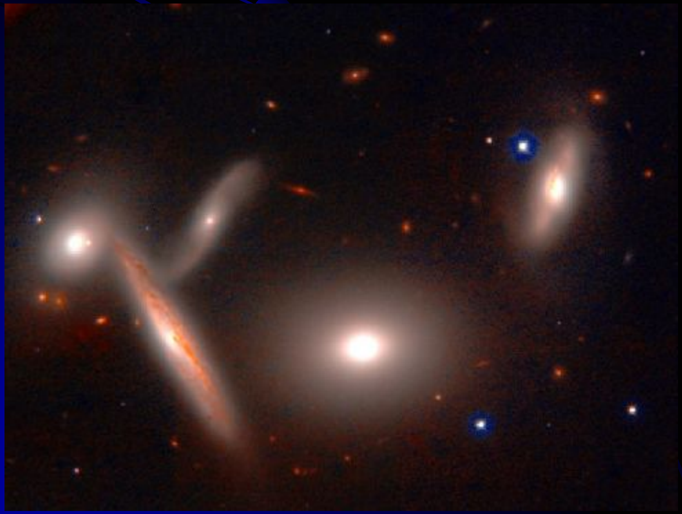
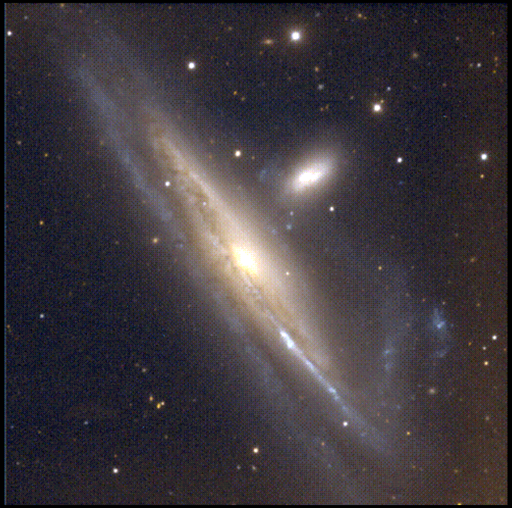
Spiral Bars

The explanation for spiral bars is much more complicated. Computer simulations show that spiral galaxies like to make bars – in fact, it is difficult to prevent bars from being made. But the physics of bar formation is complex, and not completely understood. We'll therefore leave it alone.

When Galaxies Collide

It is not uncommon for galaxies to gravitationally interact with each other, and even collide!




When Galaxies Collide




When Galaxies Collide

When galaxies collide, the stars do not. (They're much too far apart.) However,

- Galaxies can be tidally distorted, or even torn apart.
- The Hubble types of the galaxies can change.
- The gas clouds within each galaxy can collide. The increased density of gas can cause *lots* of star formation.
- The galaxy can produce lots of supernovae (from all the young O and B stars).

Exactly what happens depends on the relative sizes of the galaxies, their orientation, the direction of their rotation, and their original Hubble types.

Example 1: Two Large Galaxies

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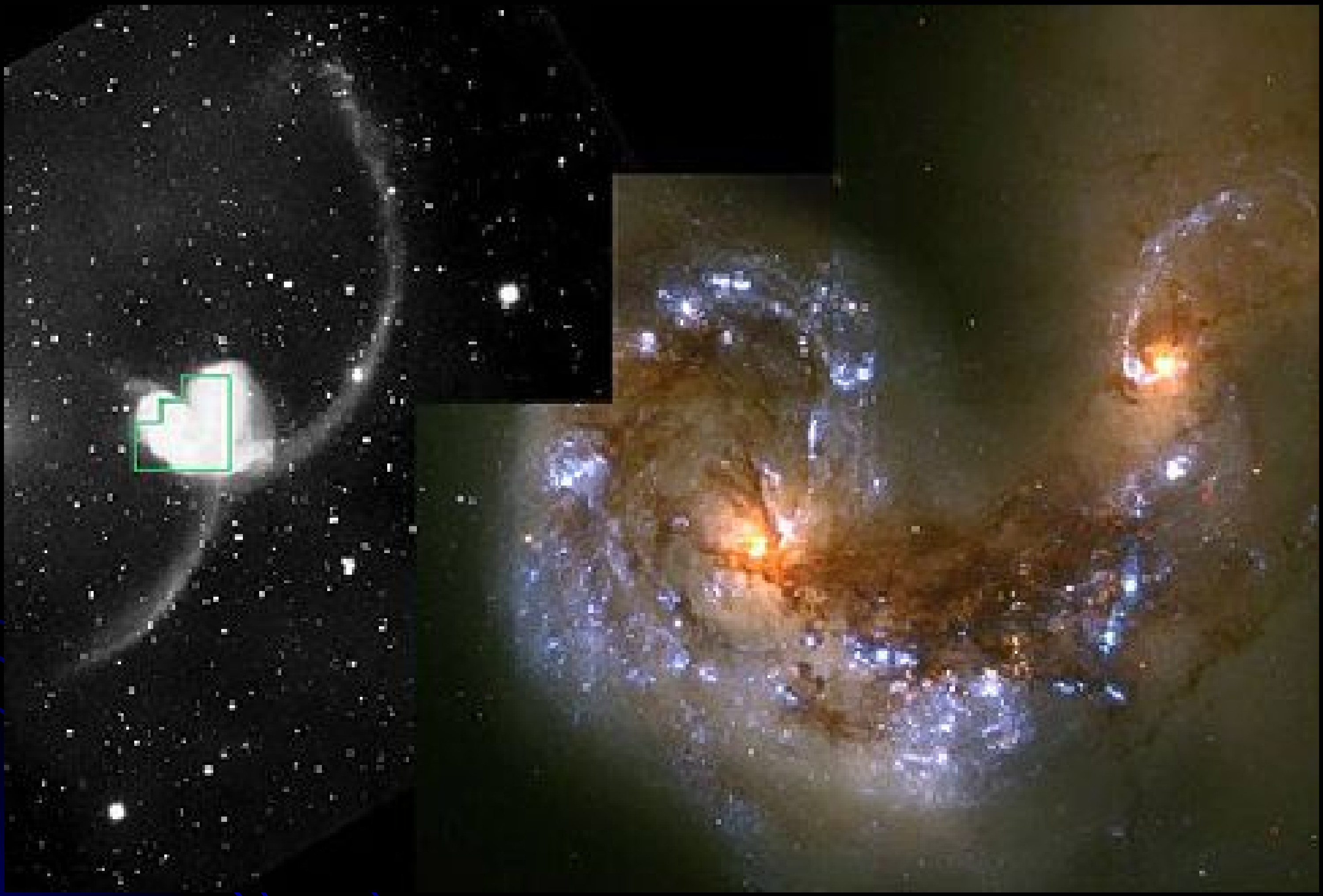
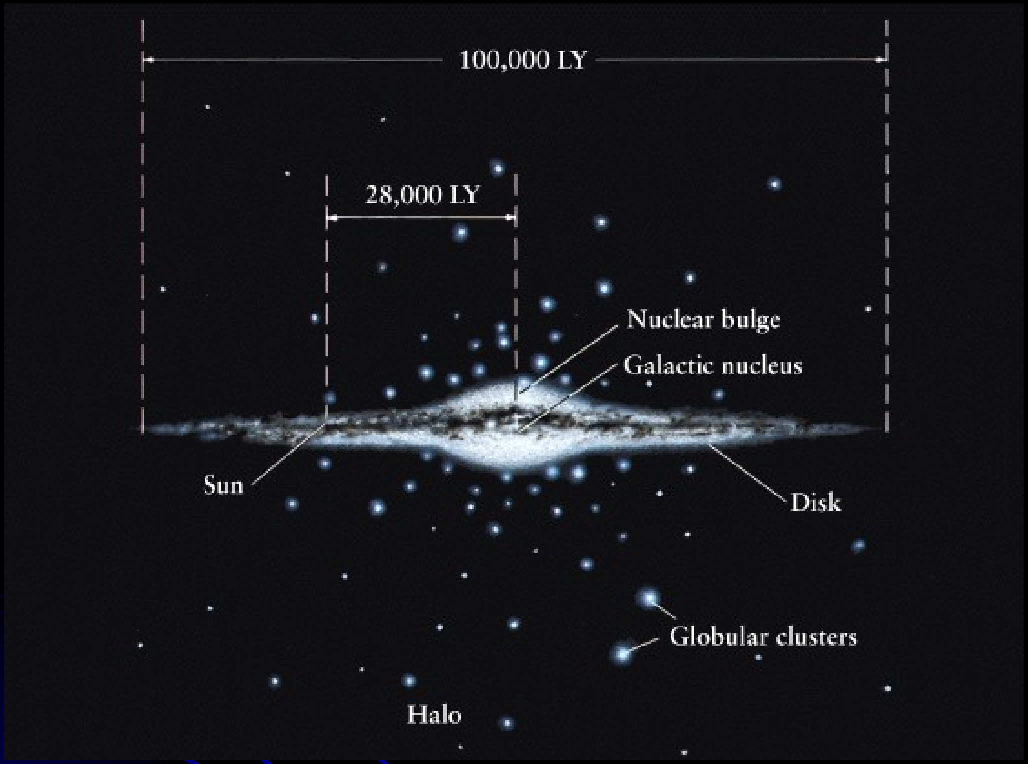
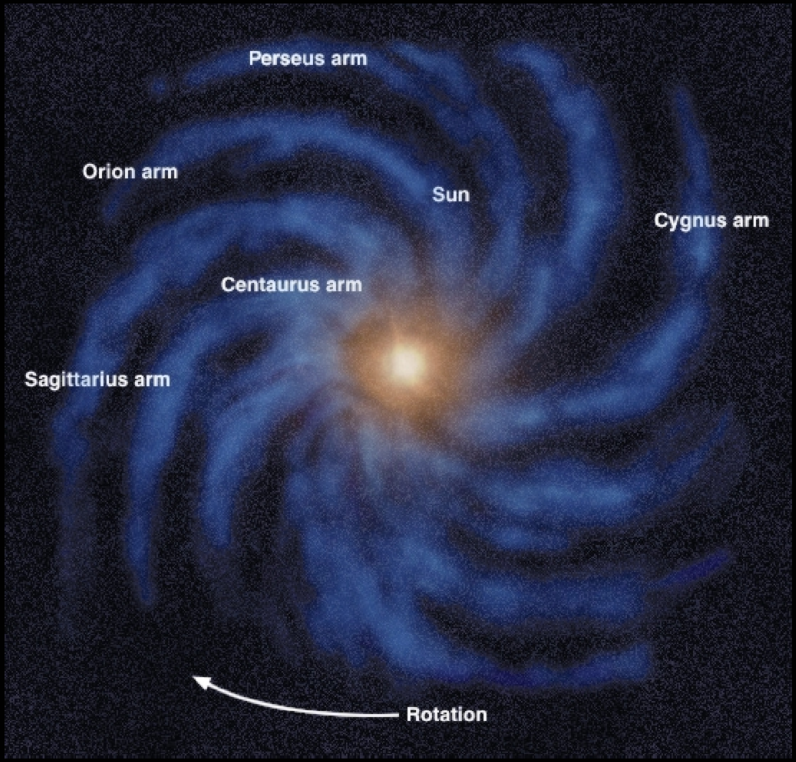


In the center of the system, large numbers of bright star clusters are being created

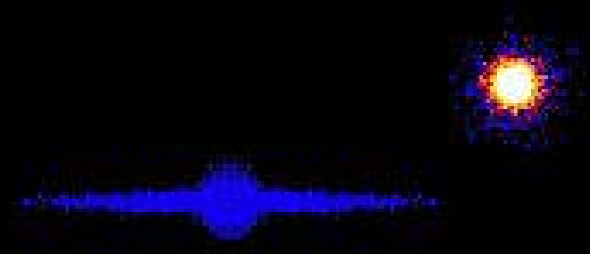
Example 2: The Milky Way and a Dwarf Galaxy





←A small dwarf galaxy

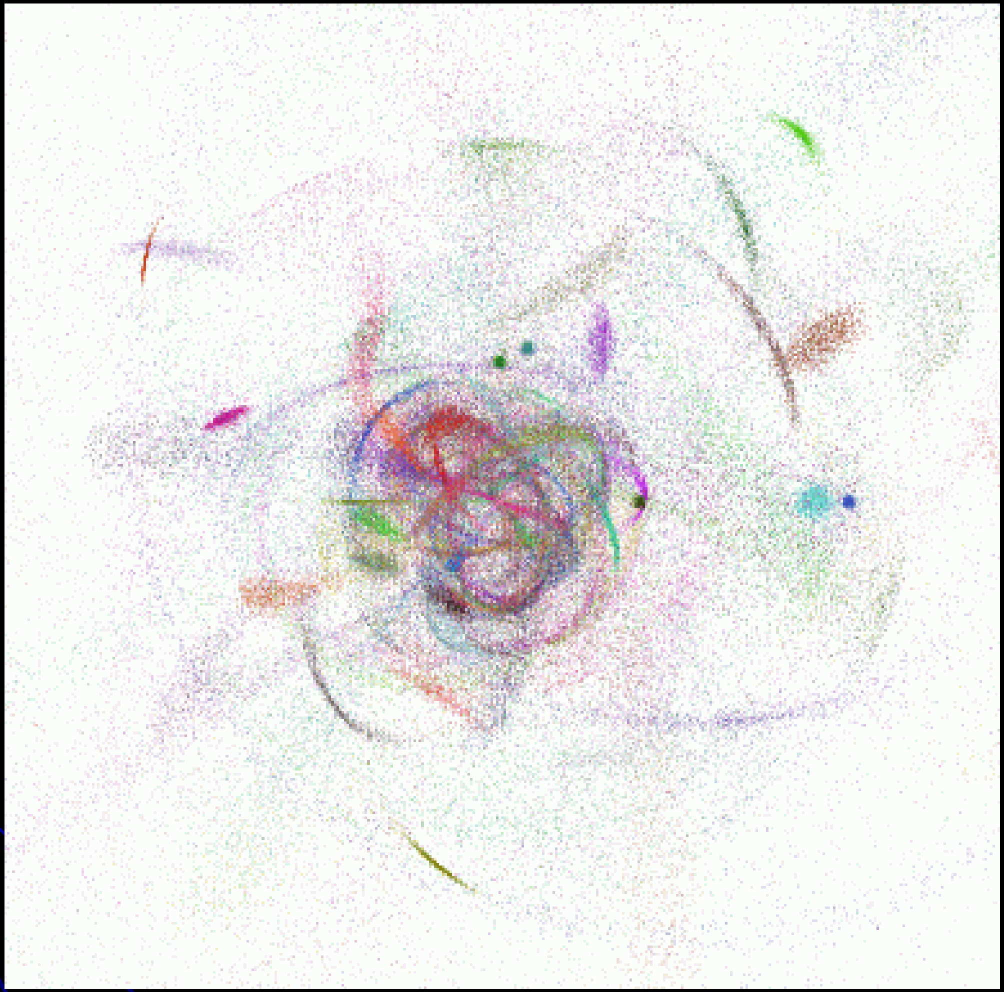
Example 2: The Milky Way and a Dwarf Galaxy



Example 2: The Milky Way and a Dwarf Galaxy

View of a galaxy *currently* being disrupted

Example 2: The Milky Way and a Dwarf Galaxy



Much of the Milky Way’s halo may consist of the remains of tidally disrupted galaxies.

Example 3: Two Large Galaxies

Example 3: Two Large Galaxies

“Young” Ellipticals

- A few ellipticals even show traces of past interactions

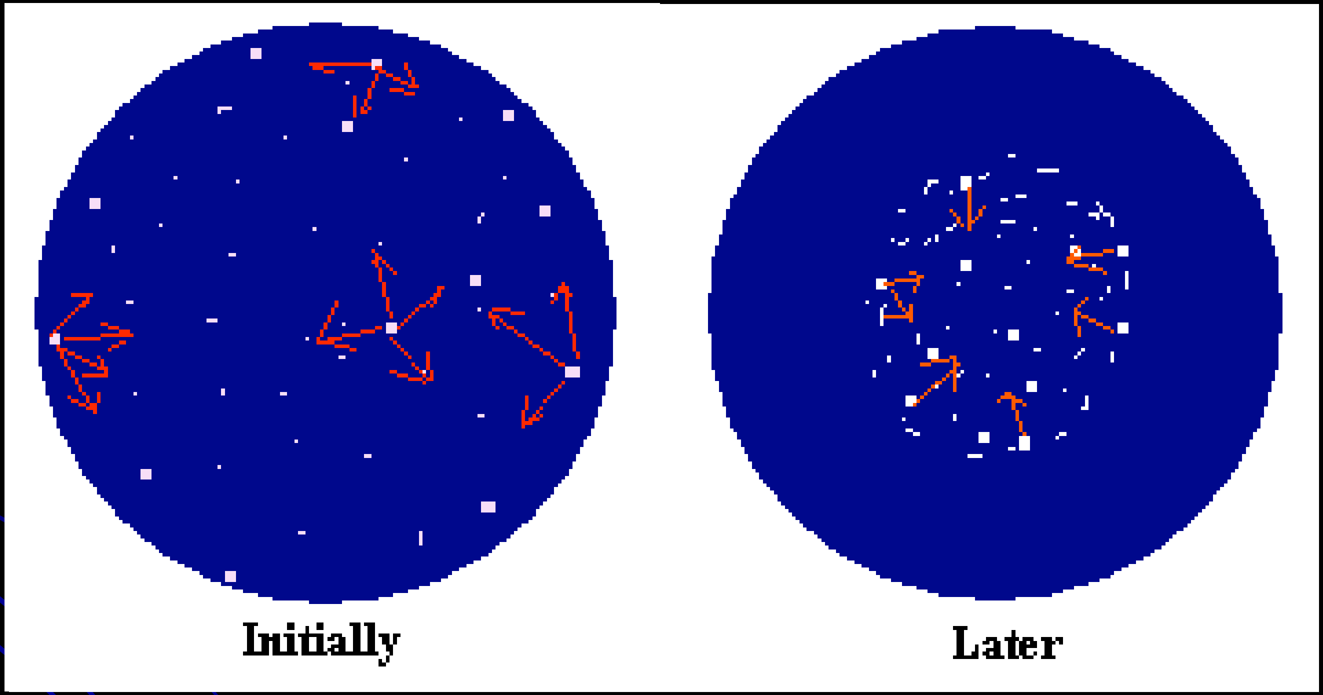
And now to cosmology …

at last!

Types of Universes

If you were to make a universe, would you give it a finite size, or make it infinite?

If you made it finite …

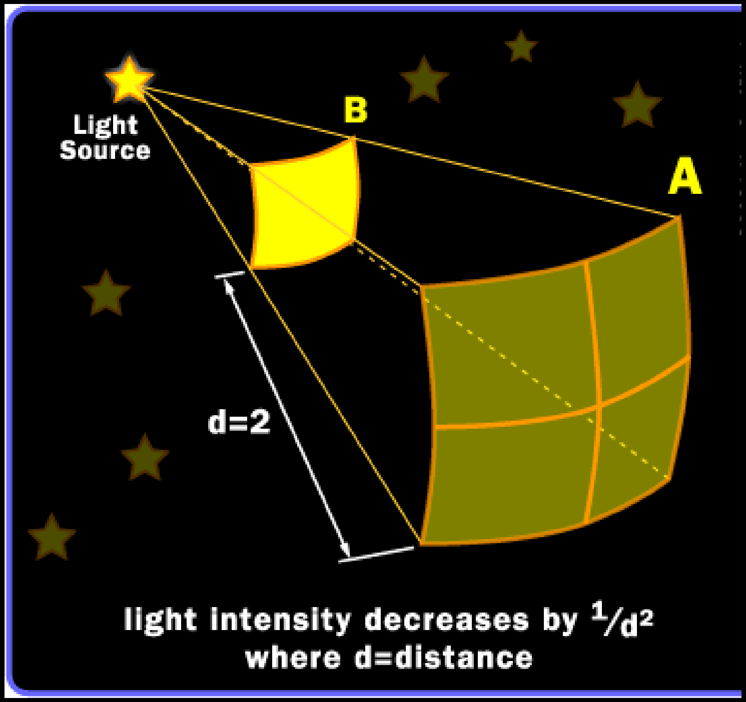


In a finite universe, gravity eventually takes over and causes a big collapse.

Types of Universes

If you were to make a universe, would you give it a finite size, or make it infinite?

If you made it infinite …

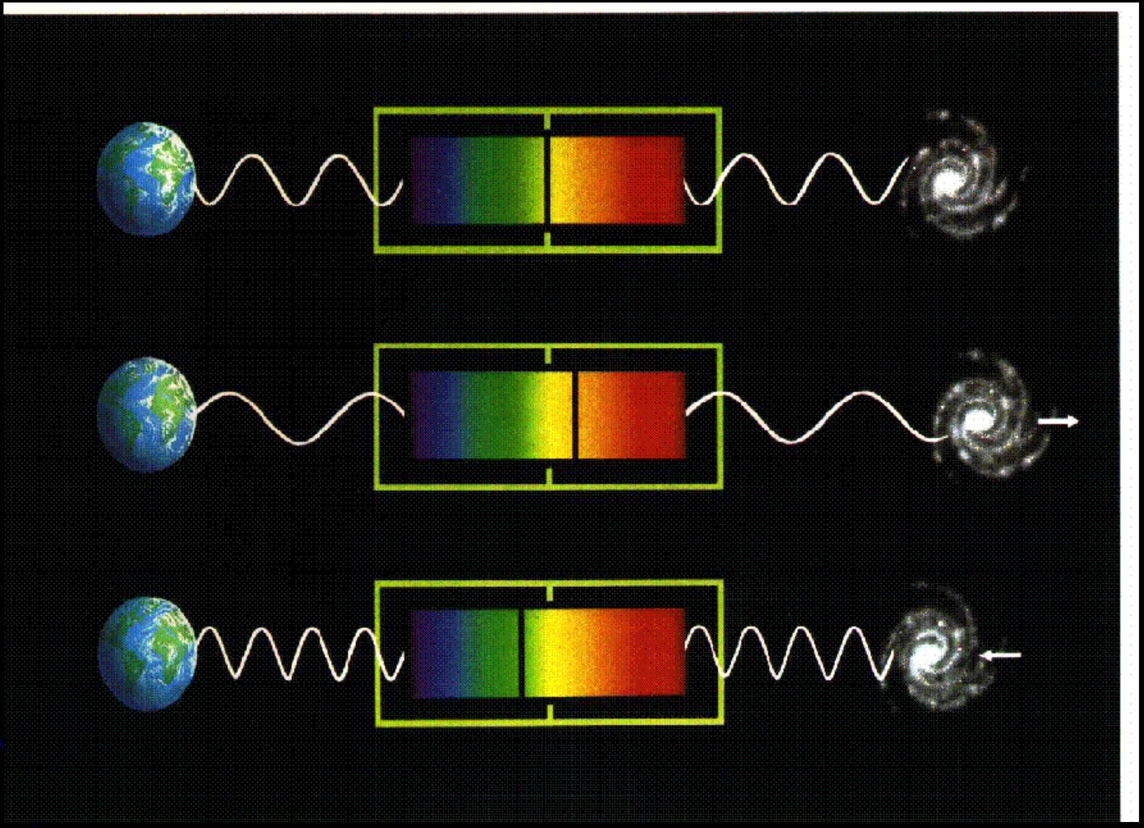


In an infinite universe, light would come from everywhere. The night sky would be bright! This is Olber’s paradox.

The Cosmological Constant

In 1918, Einstein realized the difficulty with a finite universe, and the impossibility of an infinite universe. So to keep the universe from collapsing, he postulated the existence of a Cosmological Constant (*i.e.,* an extra anti-gravity term to counteract attraction). This is represented by Λ.

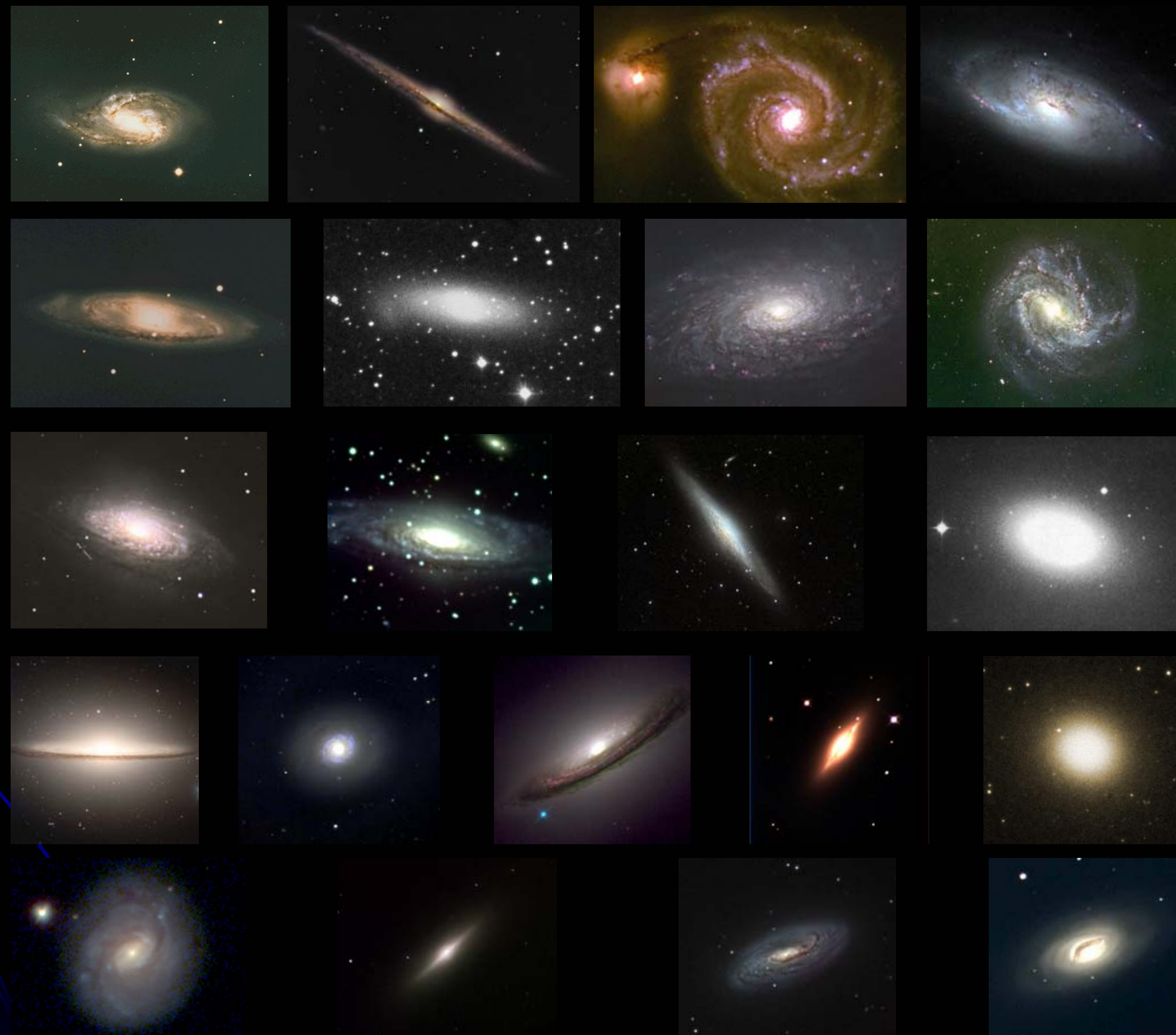
Meanwhile, Vesto Slipher was measuring the Doppler shifts of galaxies …



The Redshifts of Galaxies

Moving Toward Us

Moving Away From Us

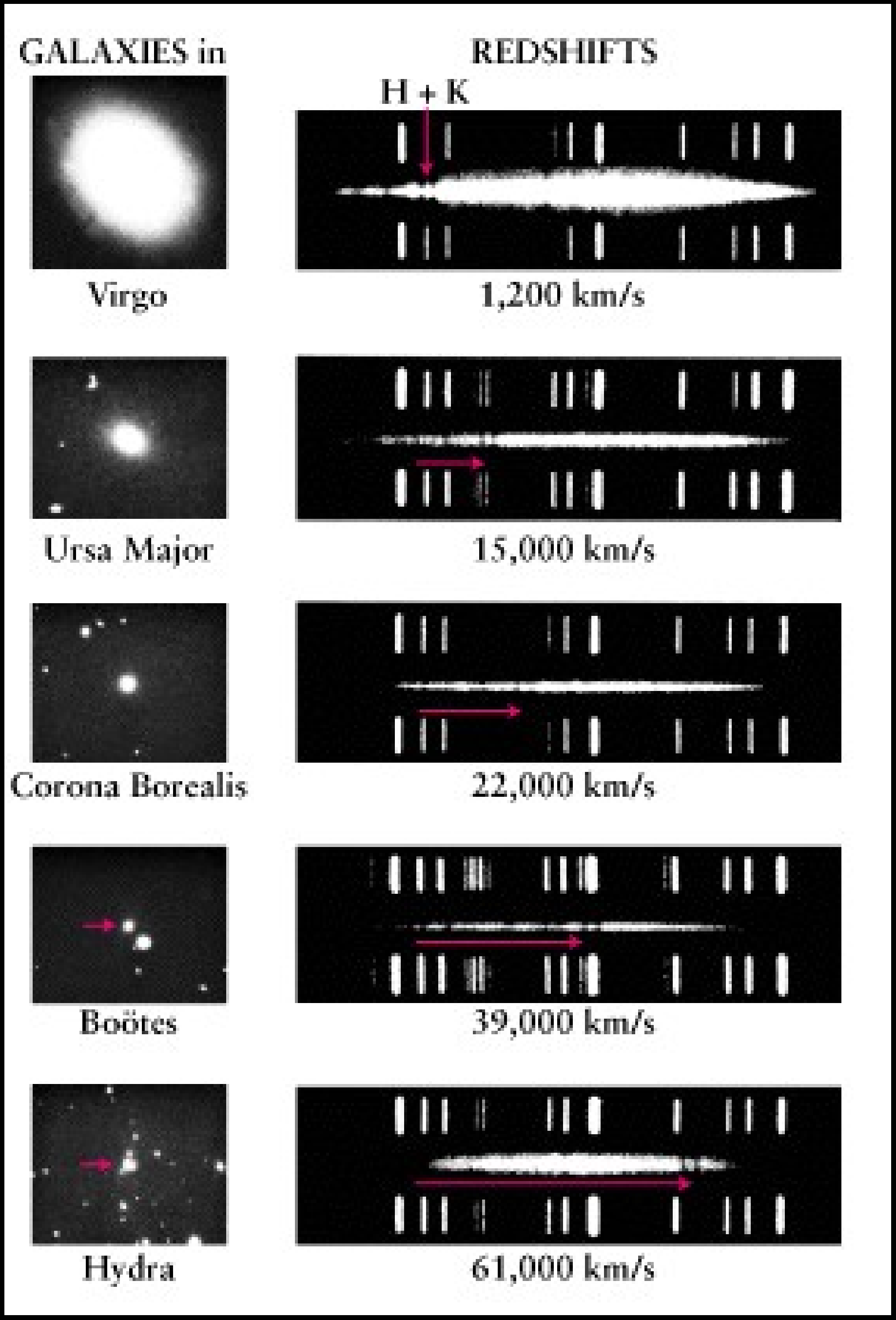


The Hubble Law

Edwin Hubble estimated the distances to Slipher's galaxies. He found that the larger the distance, the faster the galaxy was moving (away from us). In fact, the relationship between velocity and distance was simply

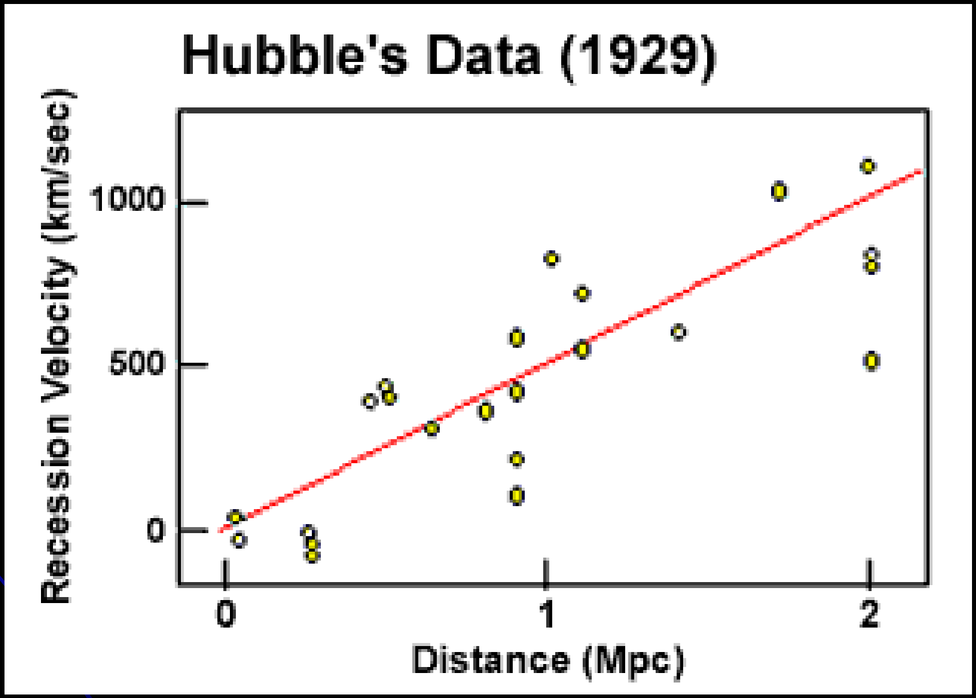
$$V = H\,D$$

where **V** is velocity (km/s)
D is distance (in Mpc)
H is the Hubble Constant



The Hubble Law

The Hubble Law is not perfect. In addition to its cosmological flow, each galaxy has a peculiar (random) velocity of 300 km/s. But at large distances, the Hubble flow dwarfs this component.



Hubble's original conclusion: $H_0 = 500$ km/s/Mpc

The Cosmological Principle

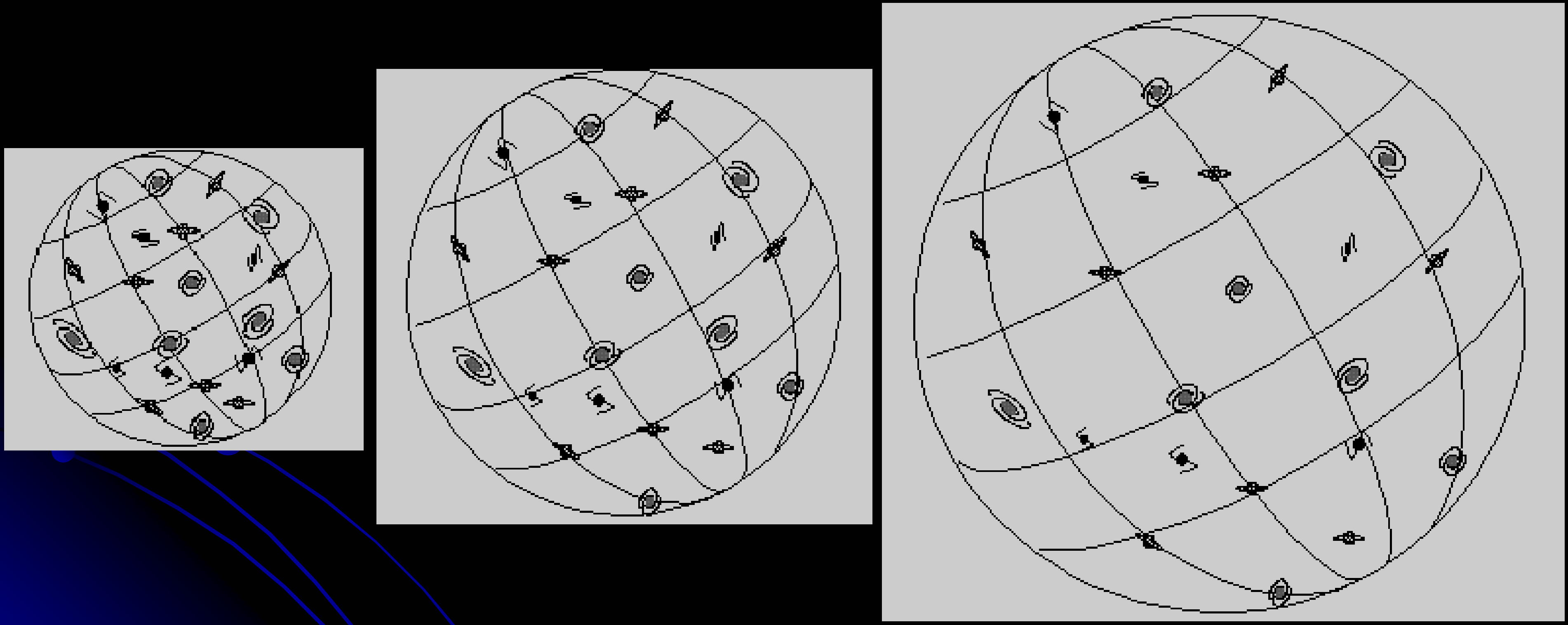
Since we are not at the center of our Solar System, our Galaxy, or our Local Group of galaxies, it is exceedingly likely that we're also not at the center of the universe. We therefore adopt the cosmological principle, which states that the universe (on average) must look the same to everyone, no matter where he/she/it is. In other words,

- the universe is (on average) homogeneous (*i.e.*, smooth)
- the universe is (on average) isotropic (no special direction)

Then why should the galaxies all be moving away from <u>*us*</u>*!*

The Balloon Analogy

It is as if all galaxies exist on the surface of a balloon. The space between all the galaxies is constantly increasing.



Important Note: We are not receding from each other. The stars in the Galaxy are not receding from each other. It is only the space between galaxies that is increasing.

The Dynamic Universe

The Hubble Law solves both the problem of universal collapse and Olber's paradox.

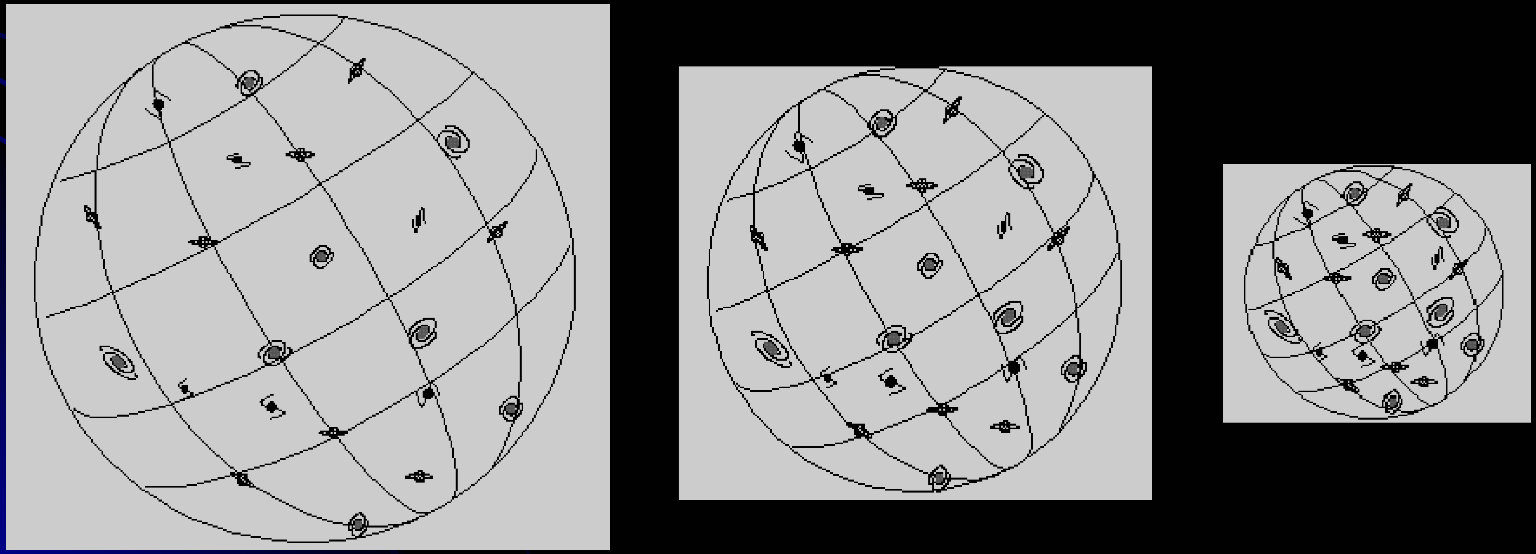
- Since the galaxies are moving away from each other, gravity will not necessarily cause a big collapse. So a finite universe is possible.
- The larger the distance, the larger the velocity. Galaxies at the other end of the universe have their light Doppler shifted out of the optical. No wonder the night sky is dark! Infinite universes are possible.

Einstein's reaction: "The Cosmological Constant was my greatest blunder."

An Age to the Universe

The Hubble Law implies the universe began with a Big Bang, which started the galaxies flying apart. It also implies a finite age to the universe. This age depends on two things:

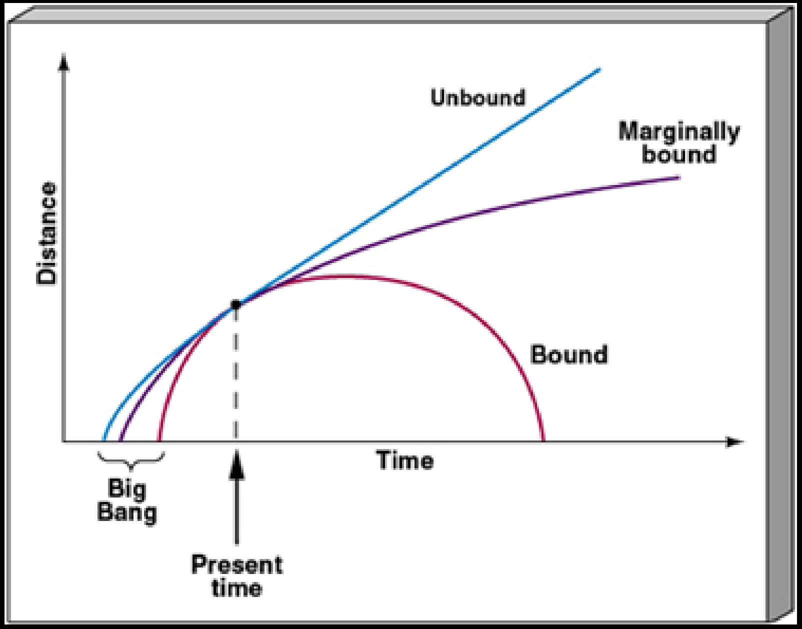
- The expansion rate of the universe. (“How fast are the galaxies flying apart?”)
- The density of the universe. (“How much is gravity slowing down the expansion?”)



A Fate to the Universe

The Hubble Law also implies 3 possible fates for the universe:

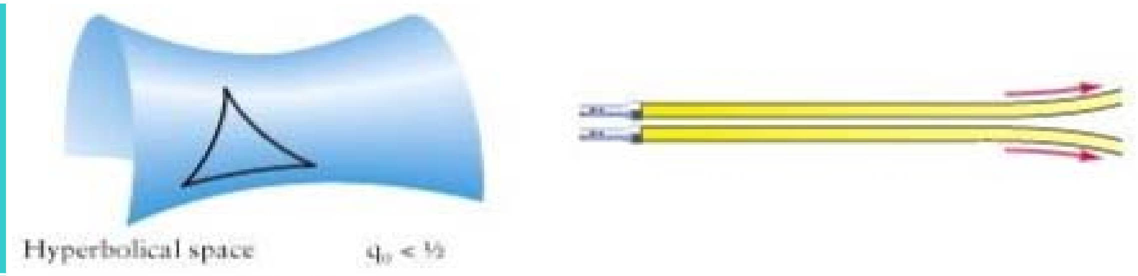
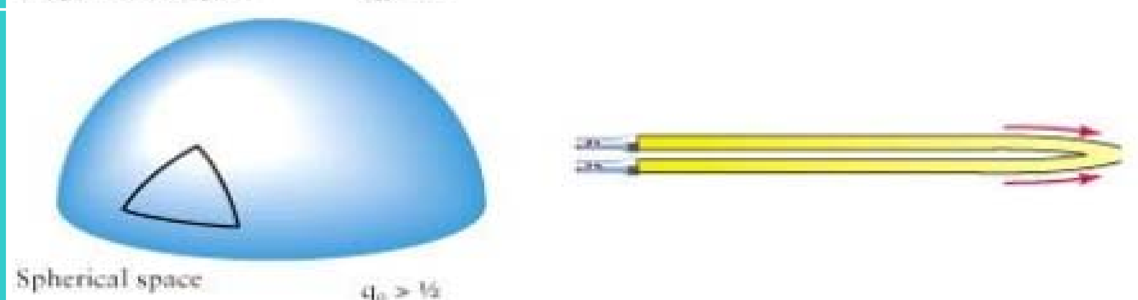
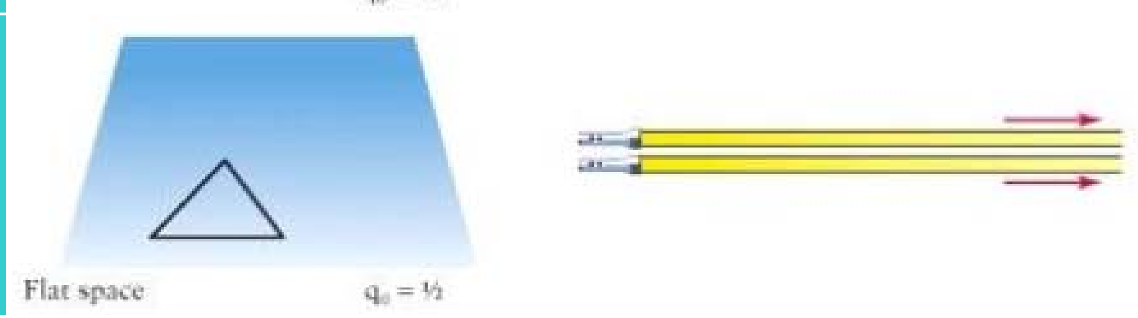
- The universe will expand forever (an unbound or open universe)
- Gravity will eventually reverse the expansion and cause the universe to collapse into a “Big Crunch” (a bound or closed universe)



- The universe is precisely balanced between open and closed (a marginally bound or flat universe)

The Shape of the Universe

According to Einstein, mass bends space. This means that the universe has a shape. This shape is related to the amount of matter in the universe.

Type	Shape of Universe
Open Universe	
Closed Universe	
Flat Universe	

The Age of the Universe

If there were no mass (*i.e.*, no gravity) in the universe, the Hubble expansion would proceed at a constant speed. The age of the universe would then just be given by **$1 / H_0$**.

In a real universe (with mass), gravity must have (over time) slowed the Hubble expansion. In the past, the galaxies were must have been moving apart faster. The age would therefore be less than **$1 / H_0$**. For a "flat" universe, it would be **two-thirds of $1 / H_0$**.

If you can measure **H_0**, you can estimate the age of the universe!

Note that **$H_0 = V / D$**, and velocities are easy to measure (through the Doppler shift.) So all you need to do is measure the distances to galaxies!