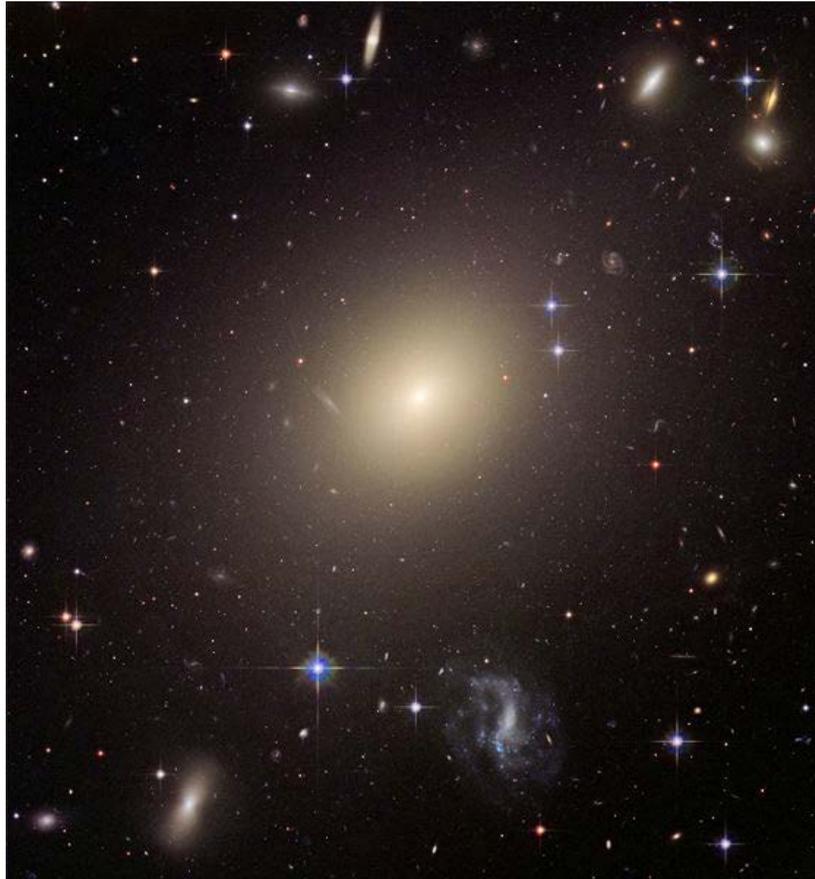


# Galaxies



The giant elliptical galaxy ESO 325-G004



The Whirlpool Galaxy

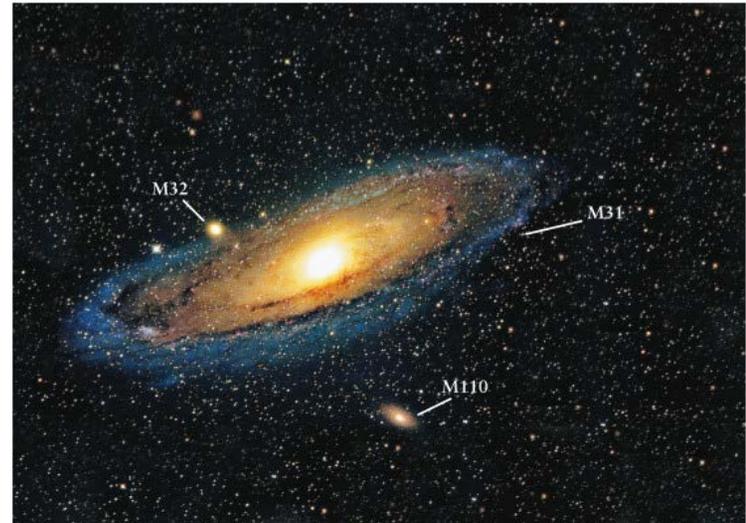
# Galaxies

In the early 1900's astronomers were debating whether objects that appeared to be nebulae with spirals were:

(a) objects located within our galaxy or,

(b) rotating systems of stars just like our Milky way but not a component of our galaxy.

Harlow Shapley and Heber Curtis debated this issue in DC in 1920. The issue was not resolved at the time.



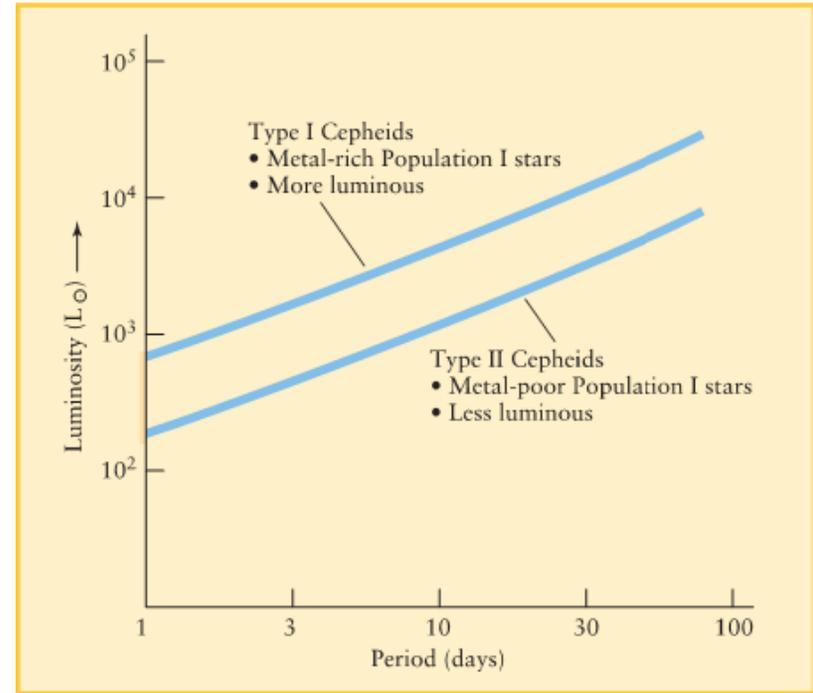
The nature of “spiral nebulae” was resolved with observations of Andromeda made by astronomer Edwin Hubble.

# Period-Luminosity Relations of Cepheids

Hubble was able to measure the distance to Andromeda by using the Cepheid method.

A measurement of the apparent magnitude (or flux) of an object combined with its absolute magnitude (or luminosity) that is inferred from the **Period-Luminosity relation** of Cepheids provides the distance to the object.

Distance to Andromeda  $\sim 2.5 \times 10^6$  light-years!



**Period-Luminosity Relations for Cepheids.** The greater the average luminosity of a Cepheid variable, the longer its period and the slower its pulsations. There are two distinct period-luminosity relations—one for Type I Cepheids and one for Type II Cepheids.

## Distance to galaxy IC 4182

### **Example: Galaxy IC 4182**

A metal rich Cepheid variable in IC 4182 has a period of 42 days. The period-luminosity relation gives a luminosity of  $33,000L_{\odot}$  which corresponds to an absolute magnitude of -6.5.

Observations indicate the apparent magnitude of this Cepheid to be  $m = +22.0$ . The distance to the Cepheid variable in IC 4182 is:

$$m - M = 5 \log d - 5$$

$$d = 10^{(m-M+5)/5} \text{ parsec} = 5 \times 10^6 \text{ parsec}$$

# Galaxies

**Table 24-1 Some Properties of Galaxies**

	Spiral (S) and barred spiral (SB) galaxies	Elliptical galaxies (E)	Irregular galaxies (Irr)
Mass ( $M_{\odot}$ )	$10^9$ to $4 \times 10^{11}$	$10^5$ to $10^{13}$	$10^8$ to $3 \times 10^{10}$
Luminosity ( $L_{\odot}$ )	$10^8$ to $2 \times 10^{10}$	$3 \times 10^5$ to $10^{11}$	$10^7$ to $10^9$
Diameter (kpc)	5 to 250	1 to 200	1 to 10
Stellar populations	Spiral arms: young Population I Nucleus and throughout disk: Population II and old Population I	Population II and old Population I	mostly Population I
Percentage of observed galaxies	77%	20%*	3%

*\*This percentage does not include dwarf elliptical galaxies that are as yet too dim and distant to detect. Hence, the actual percentage of galaxies that are ellipticals may be higher than shown here.*

Hubble originated a classification scheme for galaxies that is still used today. According to Hubble's classification scheme galaxies are grouped into:

Spirals (S)

Barred Spirals (SB)

Ellipticals (E)

Irregulars (Irr)

# Spiral Galaxies



(a) Sa (NGC 1357)



(b) Sb (M81)



(c) Sc (NGC 4321)

Hubble further classified spirals into :

**Sa galaxies:** smooth broad and tightly wrapped spiral arms with a large bulge (~4% of baryonic mass in dust and gas)

**Sb galaxies:** moderate-sized spirals and bulge (~8% of mass in dust and gas)

**Sc galaxies:** narrow loosely wrapped spirals and small bulge (~25% of mass in dust and gas)

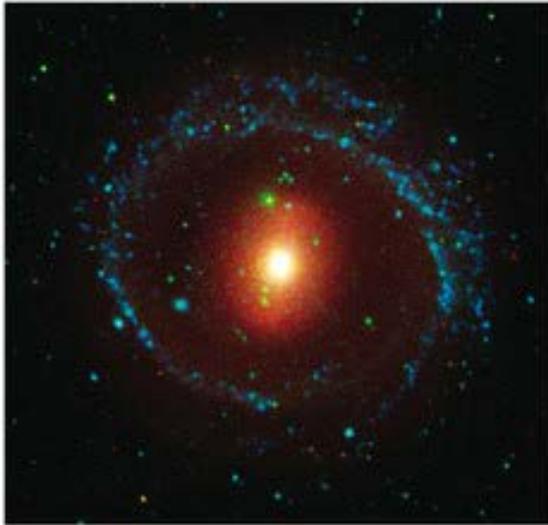
# Spiral Galaxies

Spiral galaxies are characterized by arched lanes of stars, just as is our own Milky Way Galaxy. The **spiral arms contain young, hot, blue stars and their associated H II regions**, indicating ongoing star formation.

As the **stars in the disk** evolve they **enrich the interstellar medium (ISM) with metals** through AGB winds and SN explosions. This metal enriched ISM will be used to form the next generation of stars that will therefore be metal rich. This is why most stars in the disks of Spirals are Population I stars.

The main difference between Sa, Sb and Sc galaxies is the relative amounts of gas and dust in them. The proportion of dust, gas and young stars increases from Sa to Sc galaxies.

# Barred Spiral Galaxies



(a) SBa (NGC 1291)



(b) SBb (M83)



(c) SBc (NGC 1365)

A **barred spiral galaxy** is a spiral galaxy with a central bar-shaped structure composed of stars. About 20 % of the spiral galaxies in the distant past possessed bars, compared with nearly 70 % of their modern counterparts.

**The bar** is thought to act as a mechanism that **channels gas inwards from the spiral arms**, in effect funneling the flow to create new stars and feeding the central supermassive black hole.

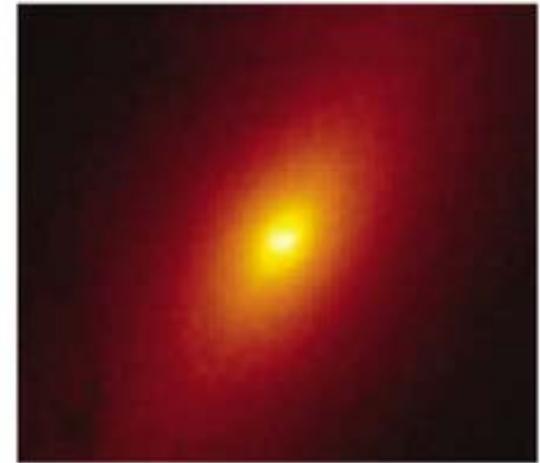
## Elliptical Galaxies



(a) E0 (M105)



(b) E3 (NGC 4406)



(c) E6 (NGC 3377)

Hubble classified **elliptical galaxies** according to how round or flattened they look. A galaxy that appears round is labeled E0, and the flattest-appearing elliptical galaxies are designated E7.

**Classifications E0 through E7 may not reflect the true shape** of elliptical galaxies. An E1 or E2 galaxy might actually be a very flattened disk of stars that we just happen to view face-on.

# Elliptical Galaxies

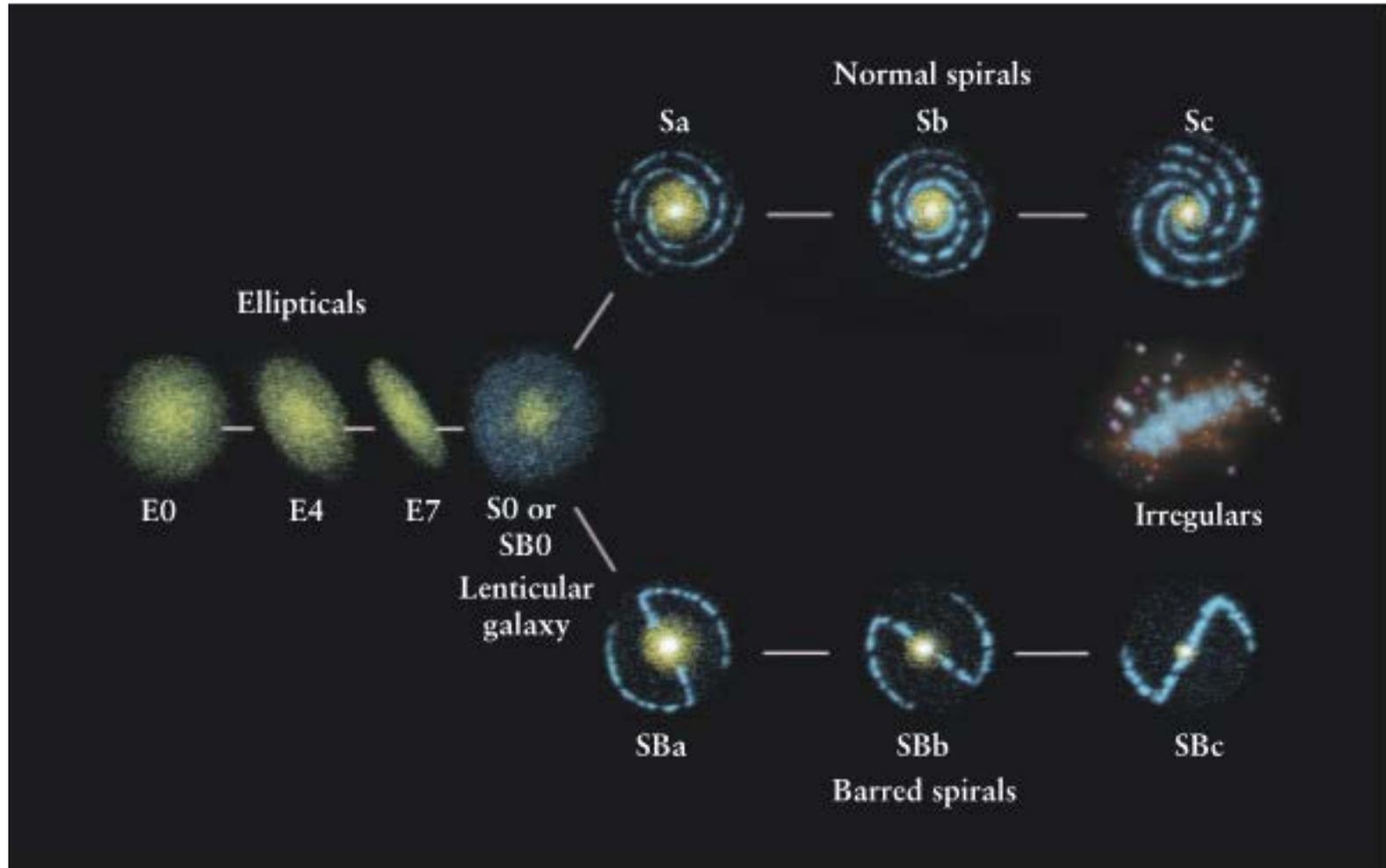
**Elliptical galaxies contain very little amounts of gas, dust and star formation.** They are composed of mostly old red Population II stars.

**Giant elliptical galaxies** are about 20 times larger than typical elliptical galaxies and often found in clusters of galaxies.

**Dwarf elliptical galaxies** contain only about a few million stars compared to 100 billion in the Milky way.

The **spectrum of a galaxy** consists of the sum of the spectra of all its stars. Their absorption lines are broadened because of the Doppler effect produced by orbiting stars.

# Hubble's Tuning Fork Diagram



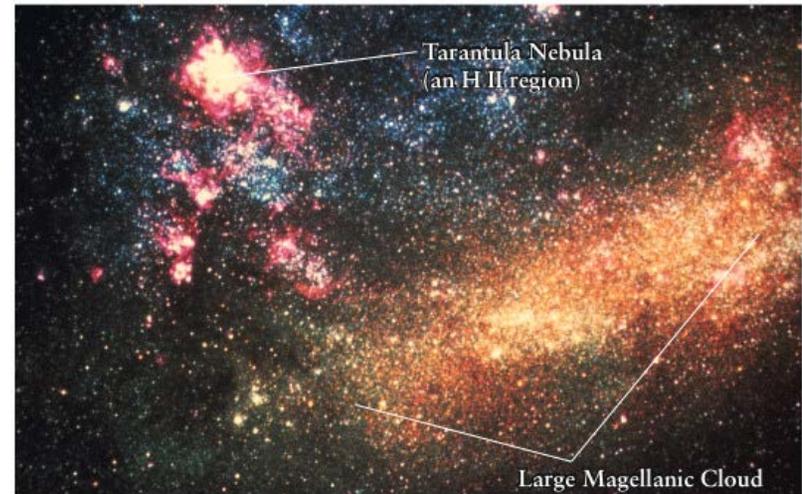
# Irregular Galaxies

Galaxies that do not fit into the scheme of elliptical or spiral galaxies are referred to as **irregulars**. They contain old and young stars and **are in general rich in gas and dust**.

Two types of Irregular Galaxies:

**Irr I** : contain many OB associations and HII regions  
(an OB association is a grouping of hot, young and massive stars predominately of spectral types O and B.)

**Irr II** : Have distorted shapes likely the result of collisions.



The Large Magellanic Cloud is a Irr I galaxy located at a distance of 179,000 ly.

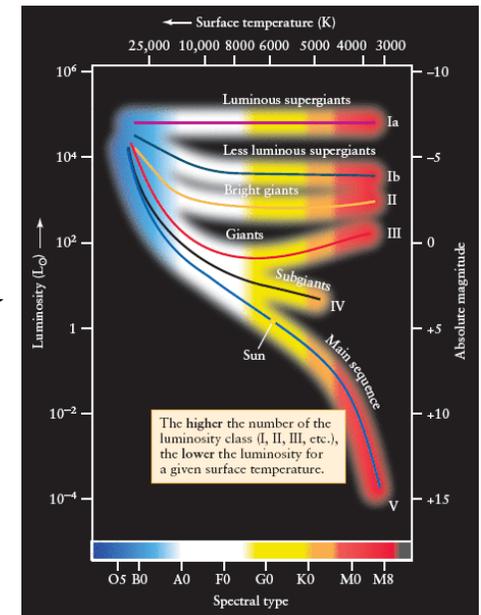
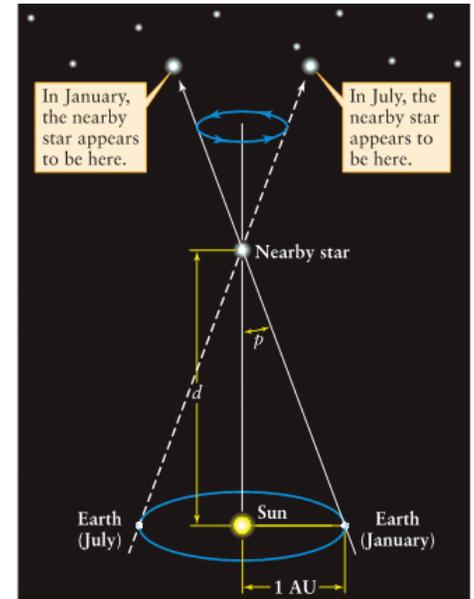
# Measuring the Distances to Galaxies

**Parallax** methods cannot be used to measure the distances to galaxies since they can only be used to measure objects relatively nearby.

The Hipparchos satellite can measure parallax angles as small as  $\sim 0.001$  arcsec.

$$d = (1/p) \text{ parsec, } p \text{ in arcsec.}$$

**Spectroscopic parallax** can measure objects accurately up to about 10 kpc. (From a stellar spectrum obtain the spectral type and luminosity class. Then use the HR diagram to infer luminosity or absolute magnitude. Combine absolute and apparent magnitude to determine distance using :  
 $m - M = 5 \log d - 5$



# Measuring the Distances to Galaxies

**Standard Candles:** Objects of known luminosity.

1.) *Cepheid Variables* : Supergiant pulsating stars where their periods are a function of their average luminosity.

Can be used to determine distances up to 100 Mly.

2.) *RR Lyrae Variables* : Pulsating horizontal branch stars of spectral class A with a period of less than a day. They are old, relatively low mass, metal-poor Population II stars.

Can be used to determine distances up to 300,000 ly.

3.) *SN Type Ia*: these supernovae occur when a white dwarf in a close binary system accretes enough matter from its companion to blow itself apart when  $M > 1.4 M_{\odot}$ . Their spectra lack hydrogen emission but contain a strong Si absorption line.

Can be used to determine distances up to  $3 \times 10^9$  ly.

## Measuring distances to Galaxies with SN Type Ia



(a) M100 in March 2002

R I **V** U X G



(b) M100 in February 2006, showing Supernova 2006X

R I **V** U X G

VLT images of M100 (a) before and (b) after a Type Ia supernova exploded within the galaxy in 2006. The distance to M100 ( $\sim 55$  Mly) is also known from observations of Cepheid variables, so this particular supernova can help calibrate Type Ia supernovae as distance indicators.

## Estimating the distances to Spiral Galaxies

Tully and Fischer found that the width of the hydrogen 21-cm line of a spiral galaxy is related to its luminosity. This is the **Tully-Fisher relation**.

$L \propto V_{\max}^{\alpha}$ , where  $\alpha = 3 - 4$  and  $V_{\max}$  is the maximum rotational velocity of the galaxy

The reason is that the faster a galaxy rotates the broader the 21 cm line becomes because of Doppler shifts of the receding and approaching sides of the galaxy.

Galaxies with faster rotational speeds are more massive and the more massive galaxies contain more stars and are therefore more luminous.

The Tully-Fisher relation can be used to determine the distance to spiral galaxies up to 100 Mpc.

## Estimating the distances to Elliptical Galaxies

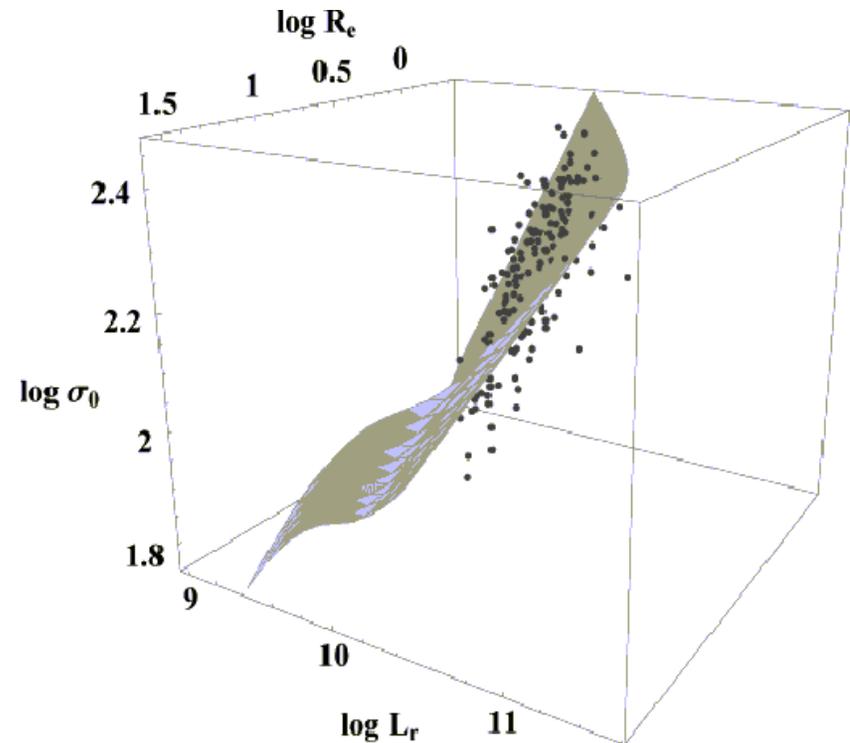
**The fundamental plane** is an empirical relation between the effective **size**, the average surface **brightness** and the central **velocity dispersion of the central stars** found in elliptical galaxies.

If one measures these three quantities for many elliptical galaxies and plots them they find that the points fall on a plane called the fundamental plane.

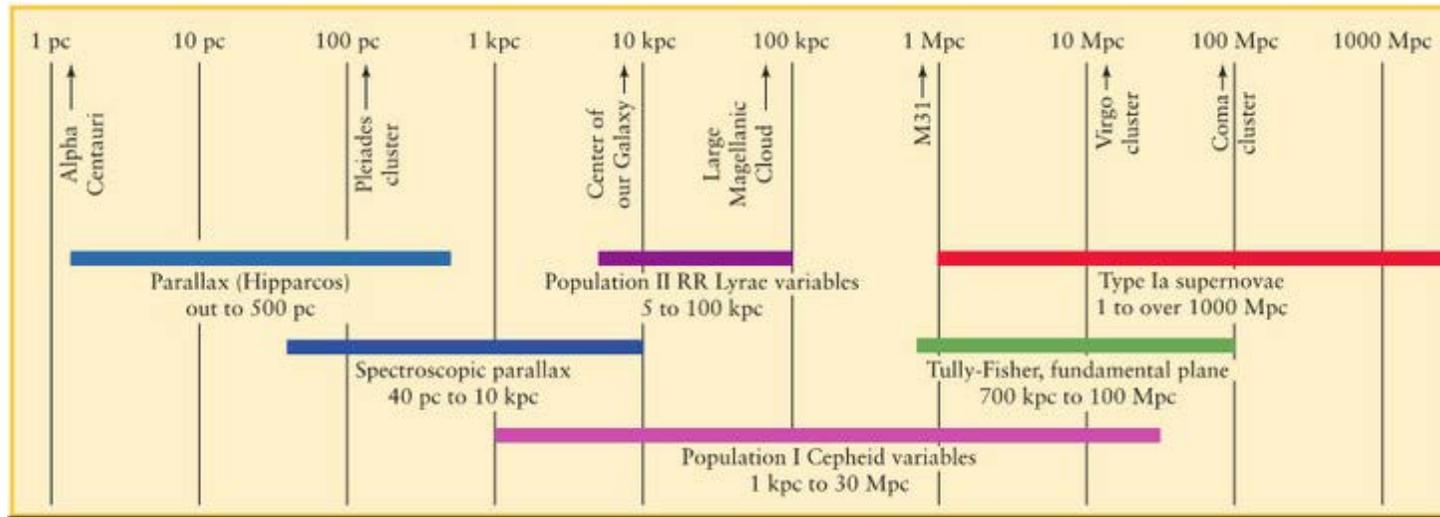
# Estimating the distances to Elliptical Galaxies

Having found the fundamental plane for nearby galaxies one can estimate the distance to remote elliptical galaxies:

First one measures the **velocity dispersion** of the stars and the **average surface brightness**. Then using the fundamental plane one can infer the **actual size** of the galaxy and use the small angle formula to estimate the distance.



# Distance Ladder

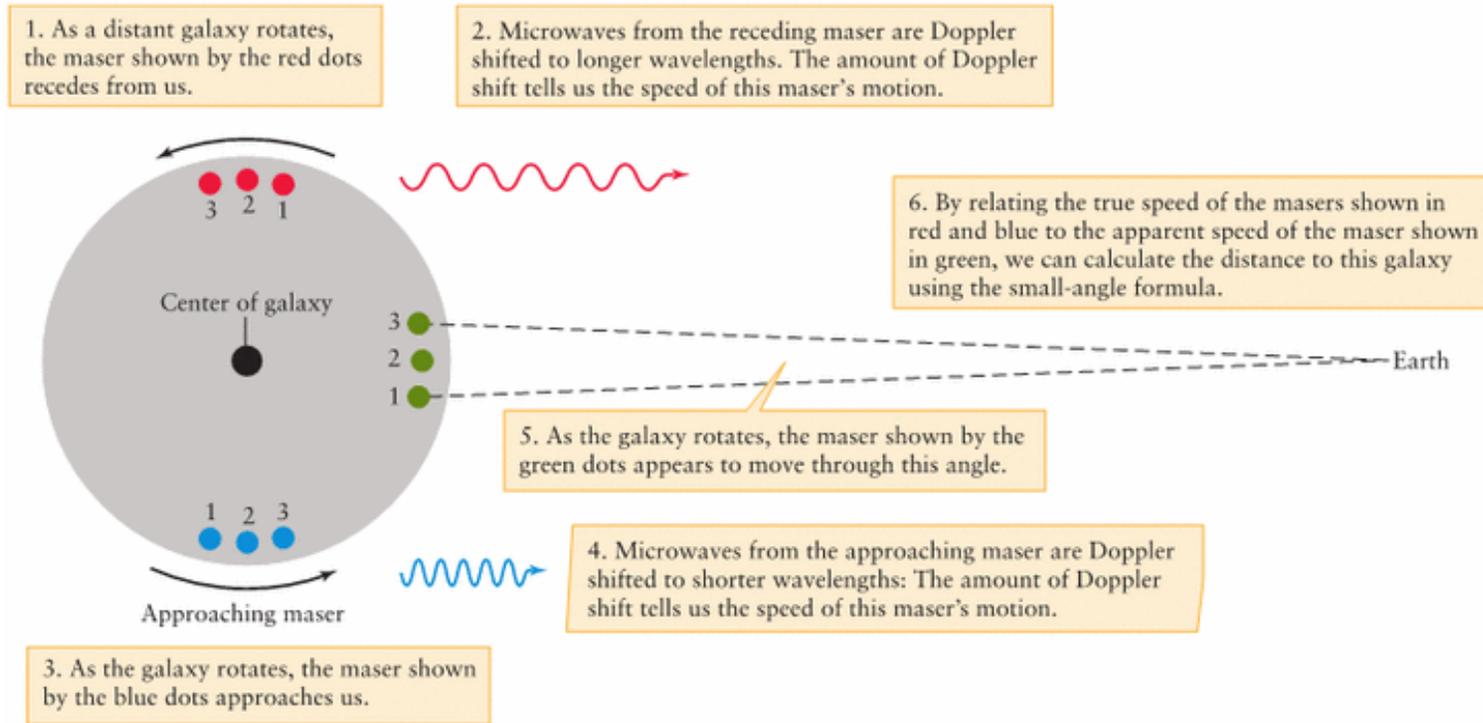


**Astronomers use a sequence of methods to determine the distance to very remote objects. This approach is called the **distance ladder**.**

Objects are found where their distances can be measured both with the accurate parallax method and the less accurate spectroscopic parallax and calibrate the spectroscopic method so it can be used at larger distances.

Next objects are found where their distance can be measured both with the spectroscopic parallax method and with Cepheid variables and calibrate the luminosities of the Cepheid variables and so on.

# Measuring Distances to Galaxies using Masers



Stars can stimulate water molecules in interstellar clouds to emit intense microwave radiation. As these water **masers** (Microwave Amplification by Stimulated Emission of Radiation) orbit a galaxy their spectra will be Doppler shifted. Then one measures the angular distance traveled by a maser per second across the galaxy. This is the maser's apparent velocity.

From the true and apparent speeds one can then use the small angle formula to infer the distance to the galaxy.

# Redshift

$$\frac{\lambda_{obs} - \lambda_0}{\lambda_0} = z$$

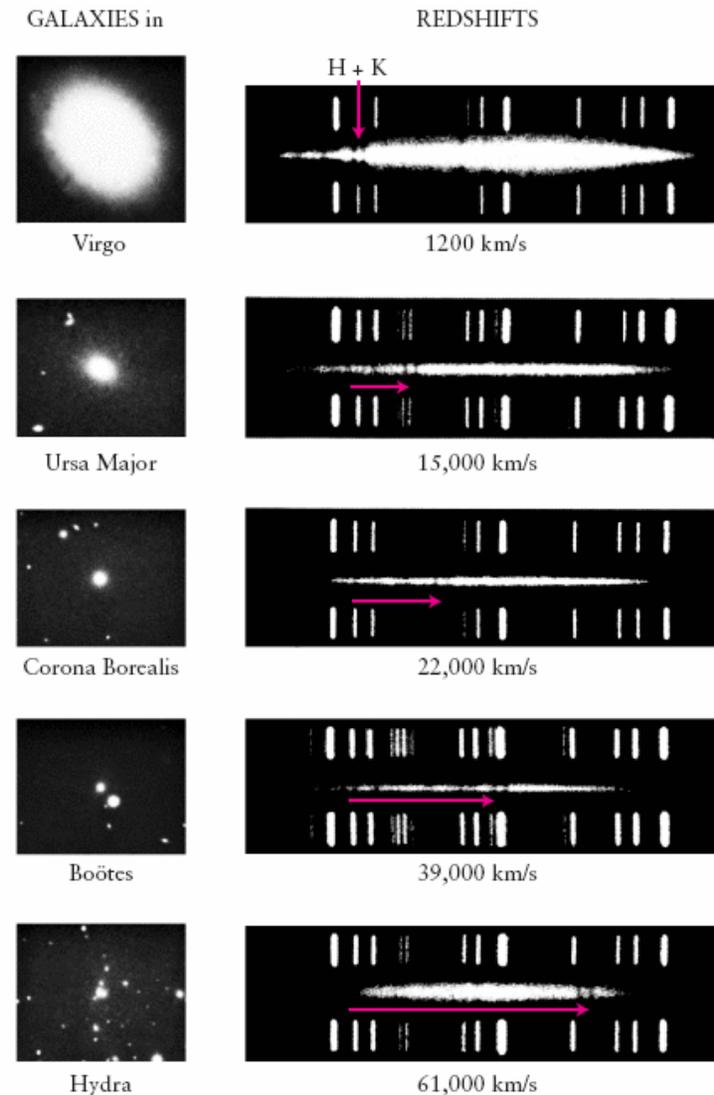
$\lambda_{obs}$  = the observed wavelength

$\lambda_0$  = the rest frame wavelength

$z$  = redshift of object

**Figure:** Each galaxy's spectrum is a bright band with dark absorption lines.

The bright lines above and below it are a comparison spectrum taken on Earth. The horizontal red arrows show how much the H and K lines of singly ionized calcium are redshifted in each galaxy's spectrum. Below each spectrum is the recessional velocity calculated from the redshift.



The more distant  
the galaxy...

...the greater its redshift and  
the more rapidly it is receding from us.

# The Hubble Law

The Hubble Law:

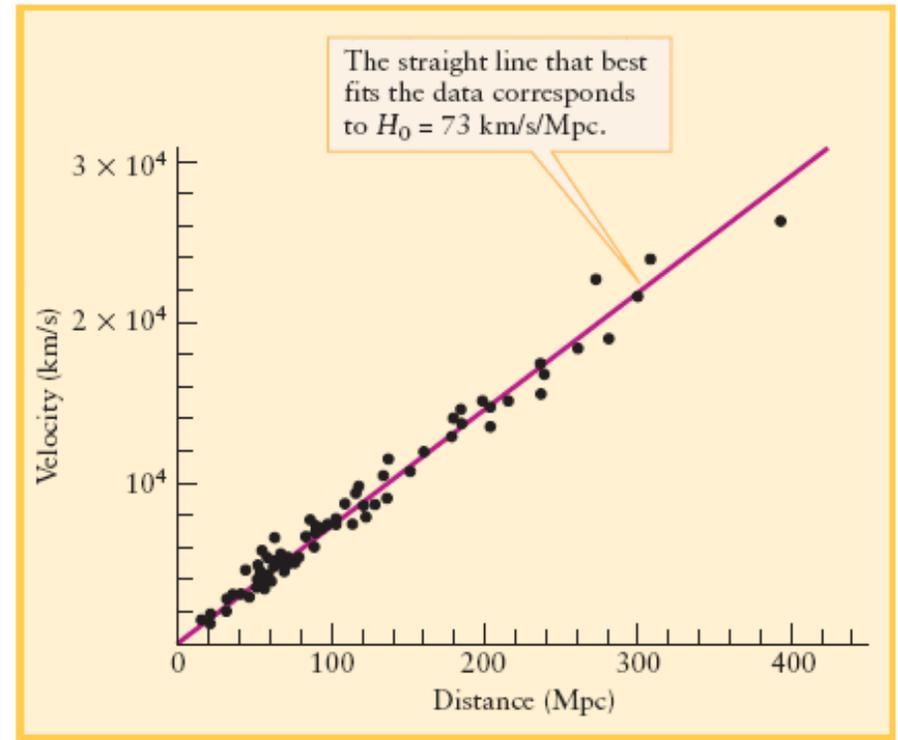
$$v = H_0 d$$

$v$  = recessional velocity of a galaxy,  $H_0$  = Hubble constant  
 $d$  = distance to the galaxy

$H_0 = 68 \text{ km/s/Mpc}$  (updated value)

Note that this is not a real velocity as in the Doppler effect but the apparent velocity due to the expansion of space. **For low redshift ( $z < 0.1$ )  $z \sim v/c$**

$z$



Hubble measured the recession velocities (from redshifts) and distances to galaxies (using Cepheid variable stars) and found that the more distant the galaxy the greater its recession velocity.

## Clusters of Galaxies

The Hercules cluster of galaxies just 650 million ly away.



**Clusters of galaxies** are the largest gravitationally bound objects in the Universe. Based on simulations the smallest structures collapsed first and eventually build the largest structures, such as clusters of galaxies.

## Properties of Clusters of Galaxies

Clusters of Galaxies contain between 100 - 2000 galaxies, hot X-ray emitting gas and dark matter. **Mass distribution:**

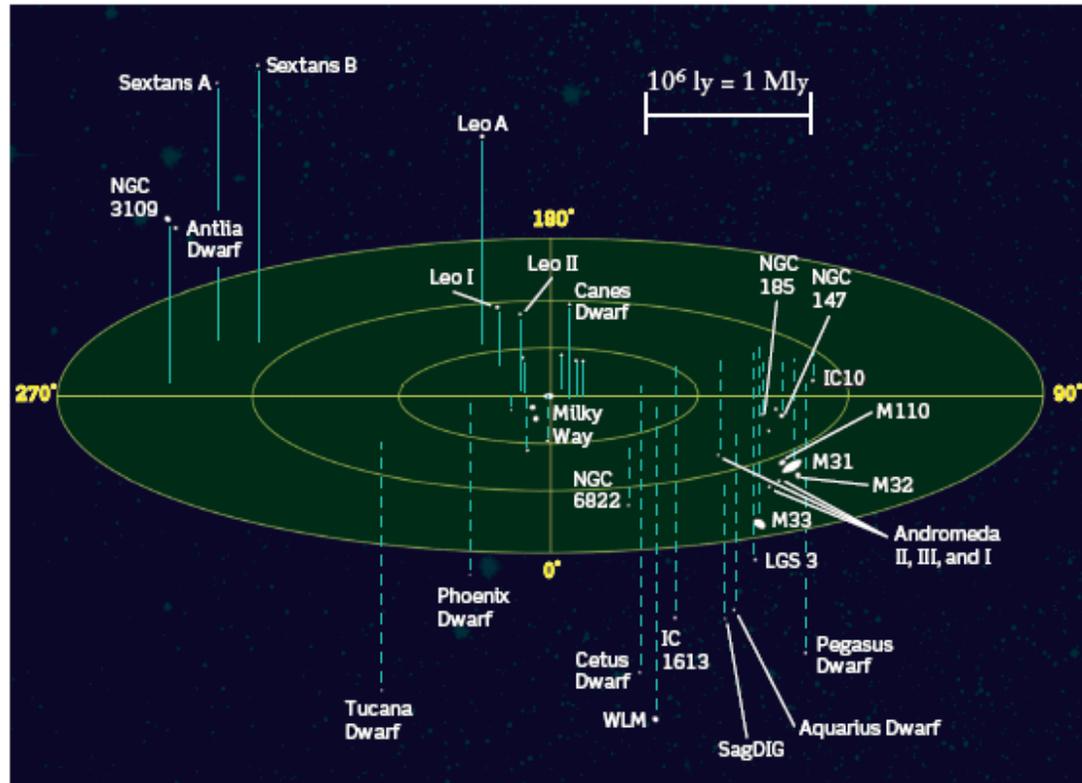
~5% in galaxies, ~10% in hot gas and ~85 % in dark matter.

- Total mass  $\sim 10^{14} - 10^{15} M_{\odot}$
- Diameter of 1– 2 Mpc
- Velocity dispersion (spread of galaxy velocities) of  $\sim 1000$  km/s

Clusters are classified as **rich or poor** (< 100 members) depending on the number of member galaxies. Poor Clusters are also called **groups**. The Milky Way belongs to the **Local Group**.

Cluster are also classified as **regular** (spherical shape) and **irregular** (non-spherical shape).

# Local Group



Members of the **Local Group** include:

Milky Way, M31, M33, Large and Small Magellanic Clouds, Leo I and Leo II, Canis Dwarf (only 42,000 ly from the center of the Milky Way) Ursa minor and Major Dwarfs, Sextans Dwarf, Sagittarius Dwarf.

## A rich and irregular cluster: Virgo Cluster

**Virgo** is a rich irregular cluster that **contains more than 2000 galaxies**.

Measurements of Cepheid variables in M100, a spiral galaxy in **Virgo**, give a distance of **56 million ly from Earth**.

**Irregular clusters** like Virgo and Hercules **contain an even mixture of galaxy types**.



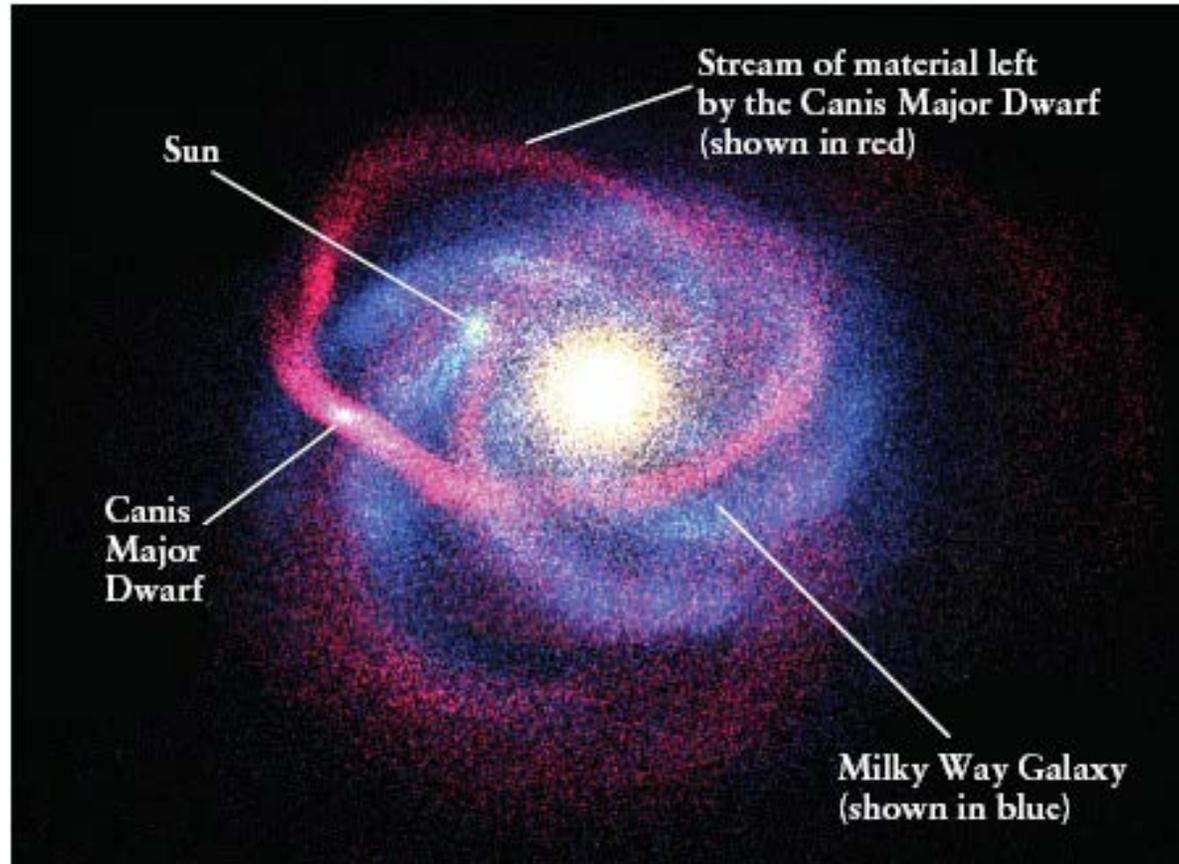
Several giant elliptical galaxies dominate the center of Virgo.

## A rich and regular cluster: Coma Cluster



Coma is a rich and regular cluster of galaxies about 300 million light years away. Rich and regular clusters like Coma contain mostly **elliptical and lenticular galaxies**.

## Tidal Forces on Canis Major from Milky Way



Material from Canis Major Dwarf is being pulled away from it by tidal forces from our Galaxy.

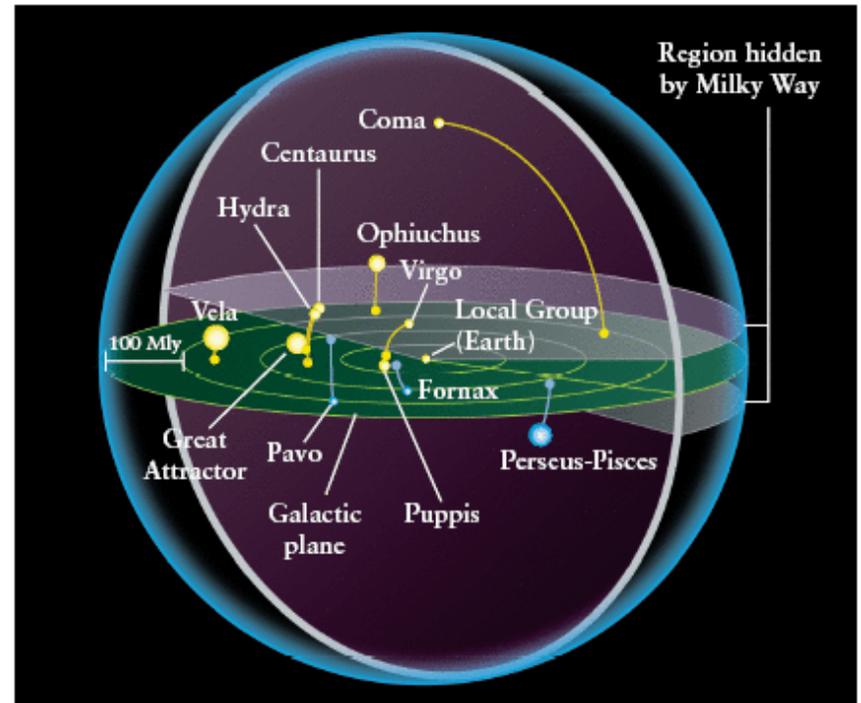
# Superclusters

Clusters of galaxies are also grouped in larger structures called **superclusters**.

A supercluster may contain tens of clusters of galaxies.

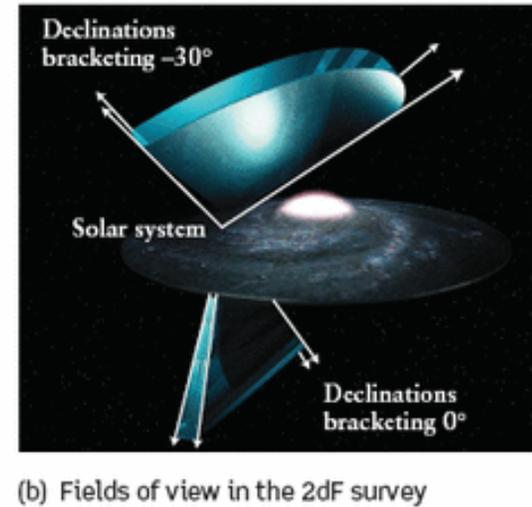
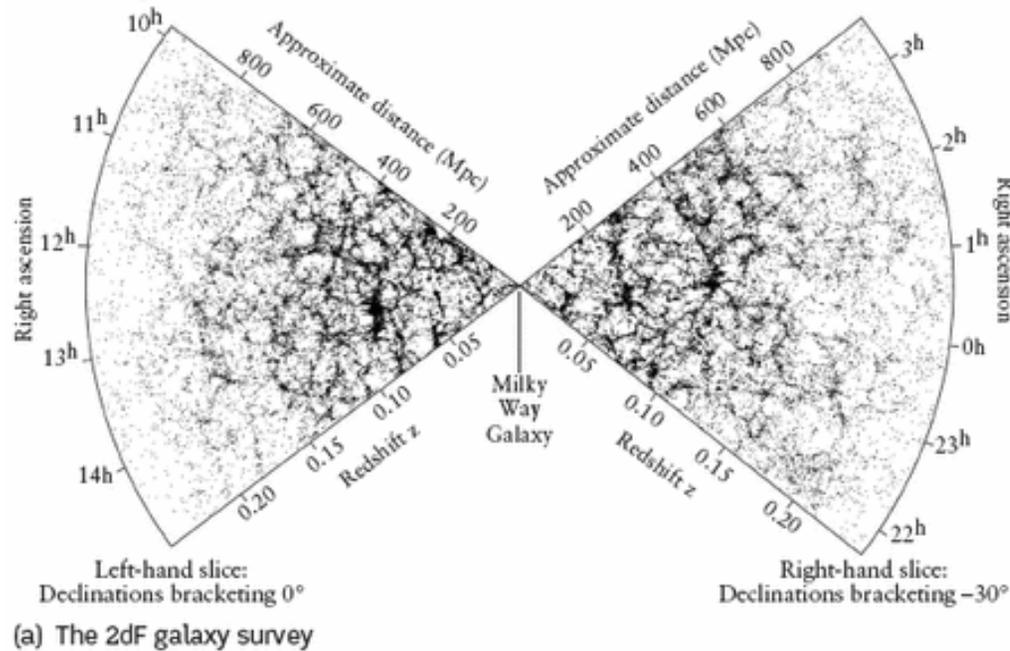
**Superclusters are not bound together by gravity** and the distances between members grows as the Universe expands.

The nearest supercluster goes out to Virgo and includes our Local Group and is called the **Virgo Supercluster**.



Nearby clusters of galaxies

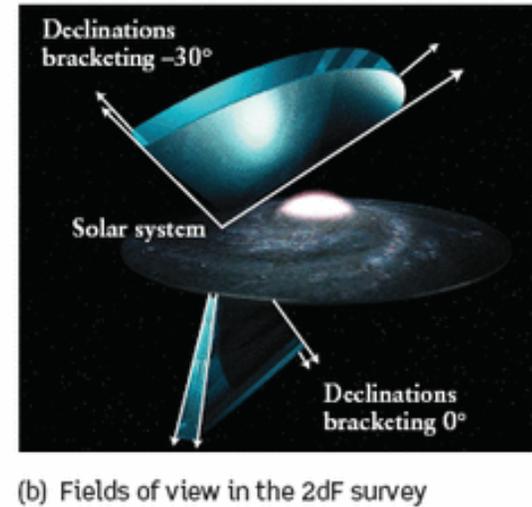
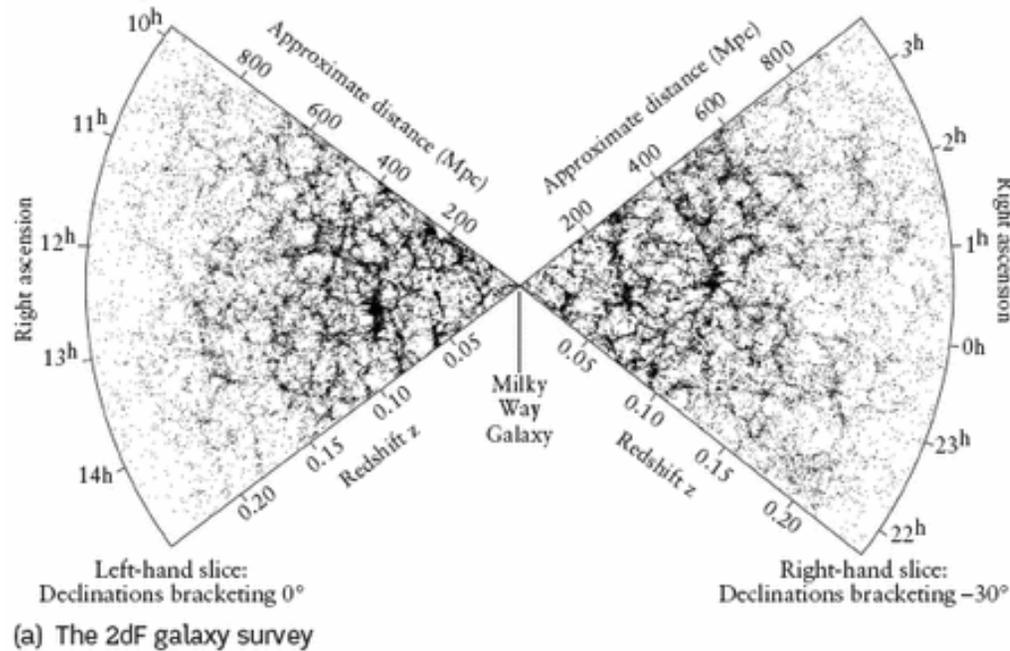
## Large Scale Distribution of Galaxies: Voids and Sheets



Three dimensional maps of galaxies in the nearby Universe are now available from the **Sloan Digital Sky Survey (SDSS)** and the **two degree field galactic redshift survey (2dFGRS)**.

These maps indicate that most galaxies are located on sheets several Mpc thick and separated by voids of sizes  $\sim 100$  Mpc.

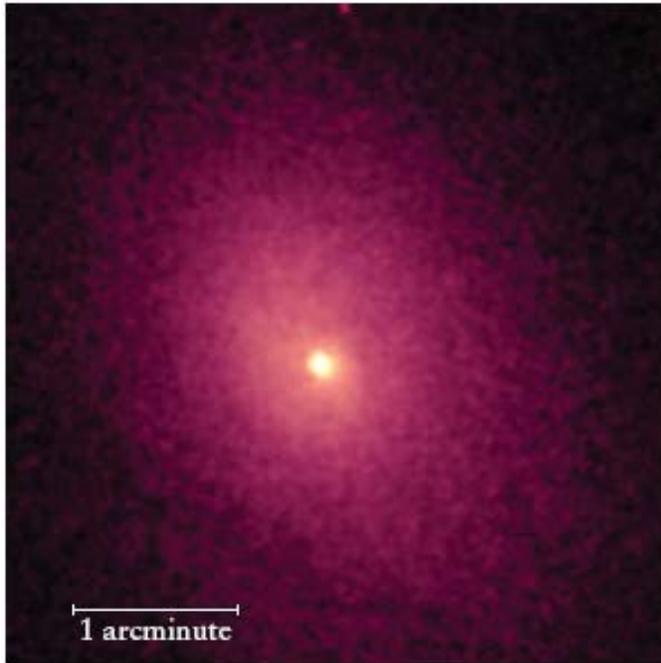
## Large Scale Distribution of Galaxies: Voids and Sheets



This pattern is similar to that of **soapsuds in a kitchen sink**, with sheets of soap film (analogous to galaxies) surrounding air bubbles (analogous to voids). Voids contain very few galaxies but may contain hydrogen clouds.

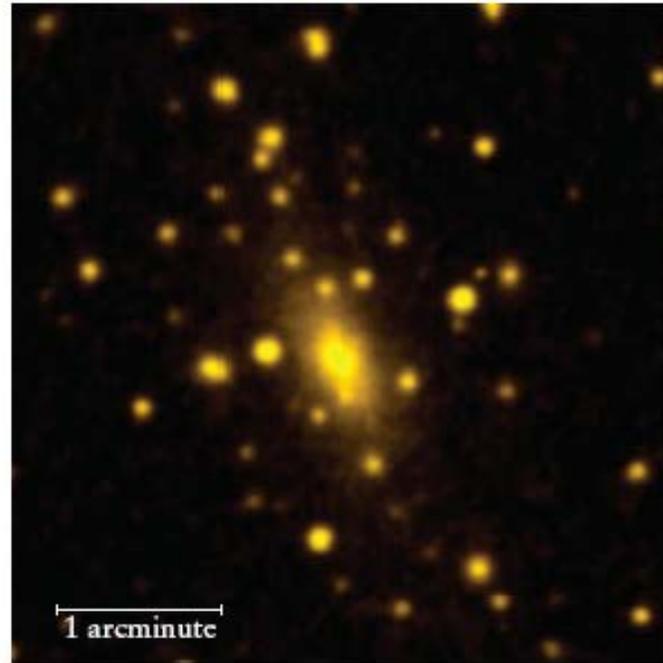
On scales much larger than 100 Mpc, the distribution of galaxies in the universe appears to be roughly uniform.

# Heating of Intracluster Medium



(a) An X-ray image of Abell 2029 shows emission from hot gas.

R I V U X G

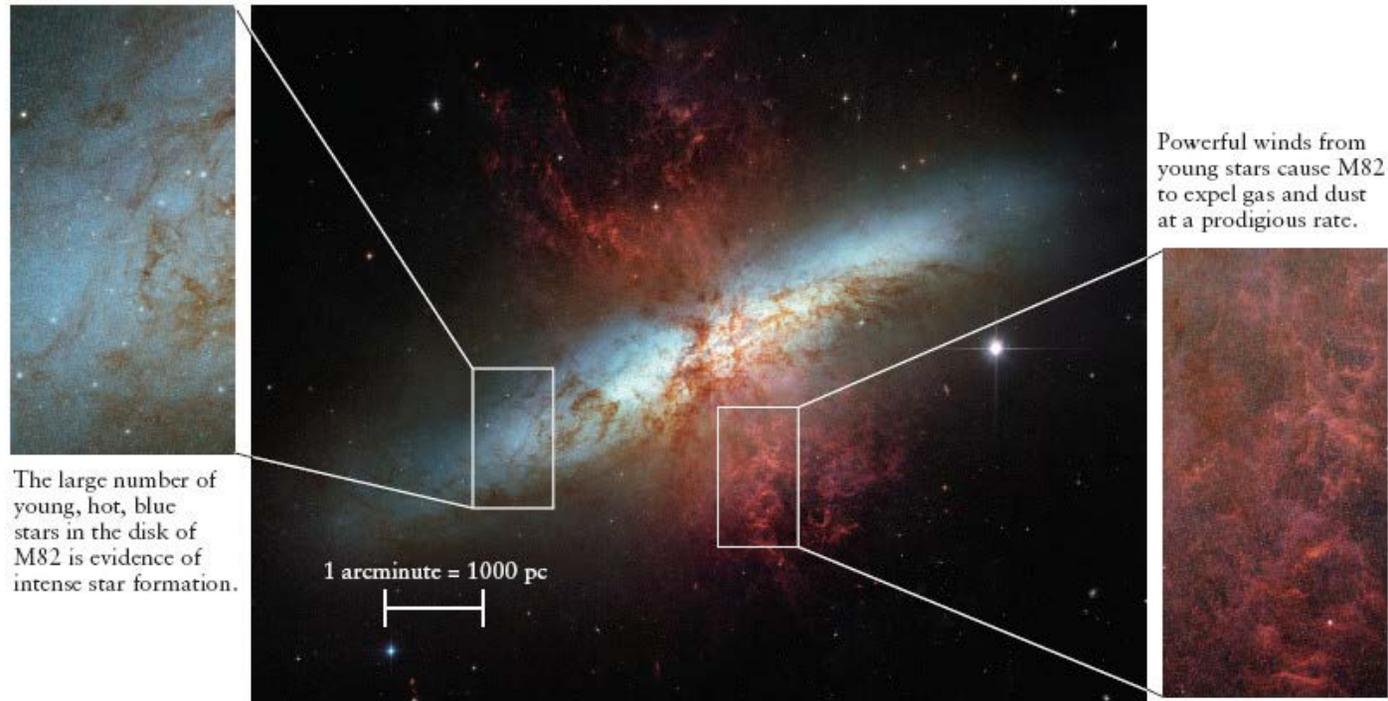


(b) A visible-light image of Abell 2029 shows the cluster's galaxies.

R I V U X G

The **Intracluster Medium** is heated to high temperatures primarily by the gravitational energy released during the formation of the cluster from smaller structures. Additional heating is provided by (a) winds from supernovae in the galaxies interacting with the ICM (b) by heating provided by the active galactic nucleus at the center of the cluster (c) collisions between galaxies and galaxies and the ICM.

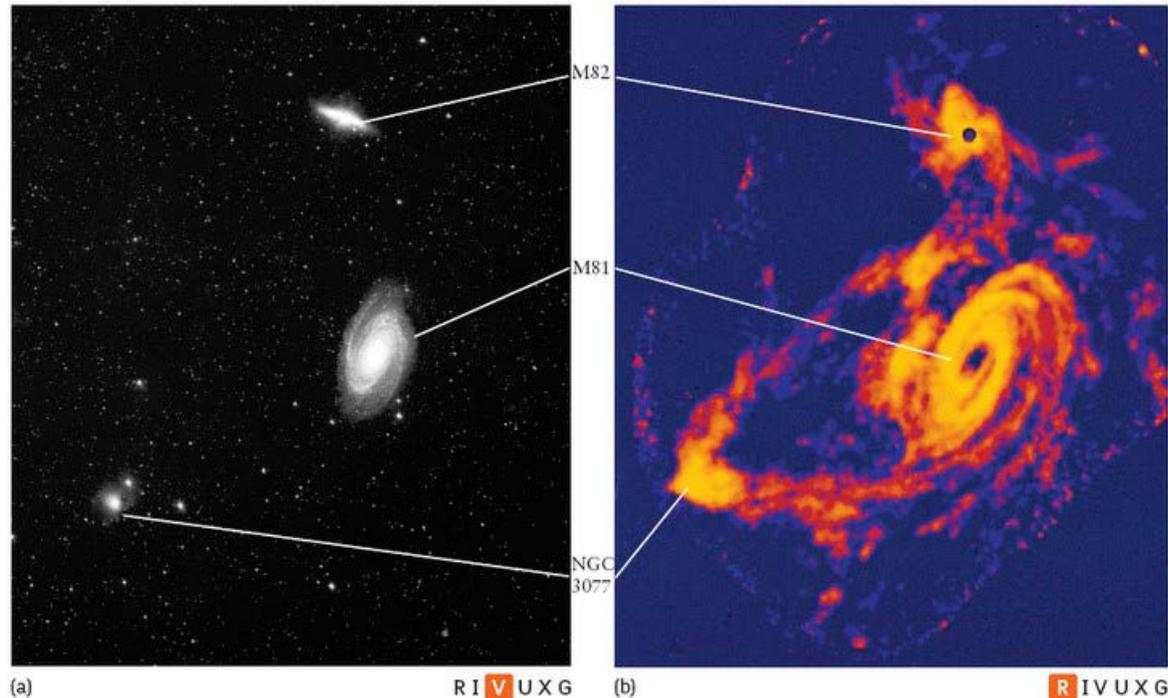
# Collision of Galaxies and Starburst Galaxies



**During the collision of two galaxies gas from both galaxies is brought into the central region of the merged galaxy where it is compressed and heated thus triggering star formation.**

Star formation can also be triggered by less violent collisions where the galaxies pass very near each other. A galaxy with a bright center produced by vigorous star formation surrounded by clouds of warm interstellar dust is called a **starburst galaxy**. An example of a starburst galaxy is M82.

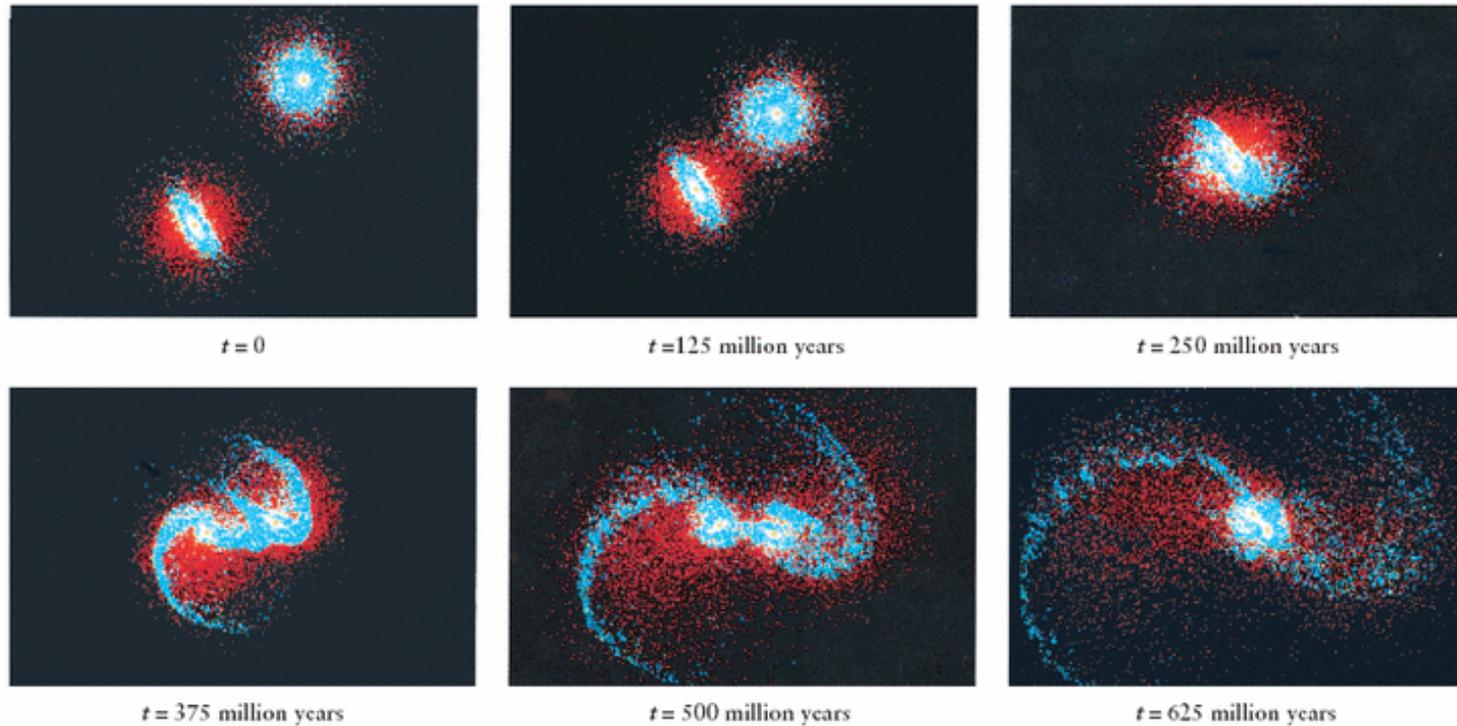
# Collision of Galaxies



An example of a possible **interaction between galaxies** within a cluster that may have **lead to intense star formation** is that between galaxies M82, M81 and NGC 3077. Streams of hydrogen gas appear to connect the three galaxies.

**A loop of hydrogen gas also appears to connect our Galaxy to the Large Magellanic Cloud** indicating a possible close interaction between the two galaxies in the past. This interaction may have triggered the star formation responsible for the formation of our own solar system.

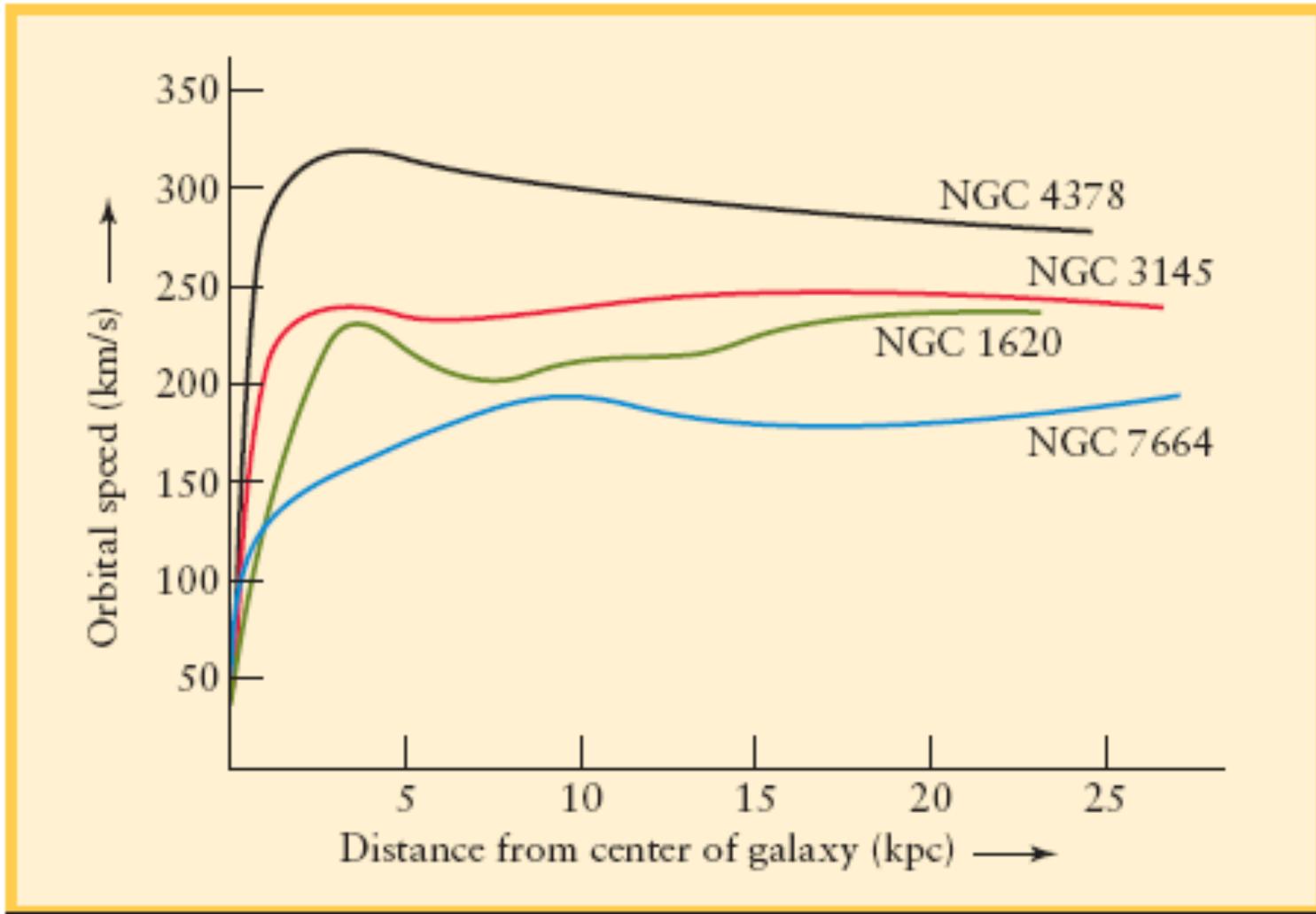
# Collisions of Galaxies



This simulation shows **the collision and merger of two galaxies** accompanied by an ejection of stars into intergalactic space. Stars in the disk of each galaxy are colored blue, while stars in their central bulges are yellow-white. Red indicates dark matter that surrounds each galaxy. The frames progress at 125-million-year intervals.

Our own Galaxy is expected to undergo a galactic collision with the Andromeda galaxy in about 6 billion years!

# Dark Matter in Galaxies



## Dark Matter in Clusters of Galaxies

The first indication of dark matter came from a 1933 study by Fritz Zwicky of the speed of the random motions of galaxies in the Coma cluster of galaxies. He found that 10 to 100 times more matter than could be detected in stars was needed to keep the galaxy cluster from flying apart.

Measurement of the **hot gas pressure** in galaxy clusters shows that there must be about 5-6 times as much dark matter as all the **stars and gas** we observe, or the hot gas in the cluster would escape.



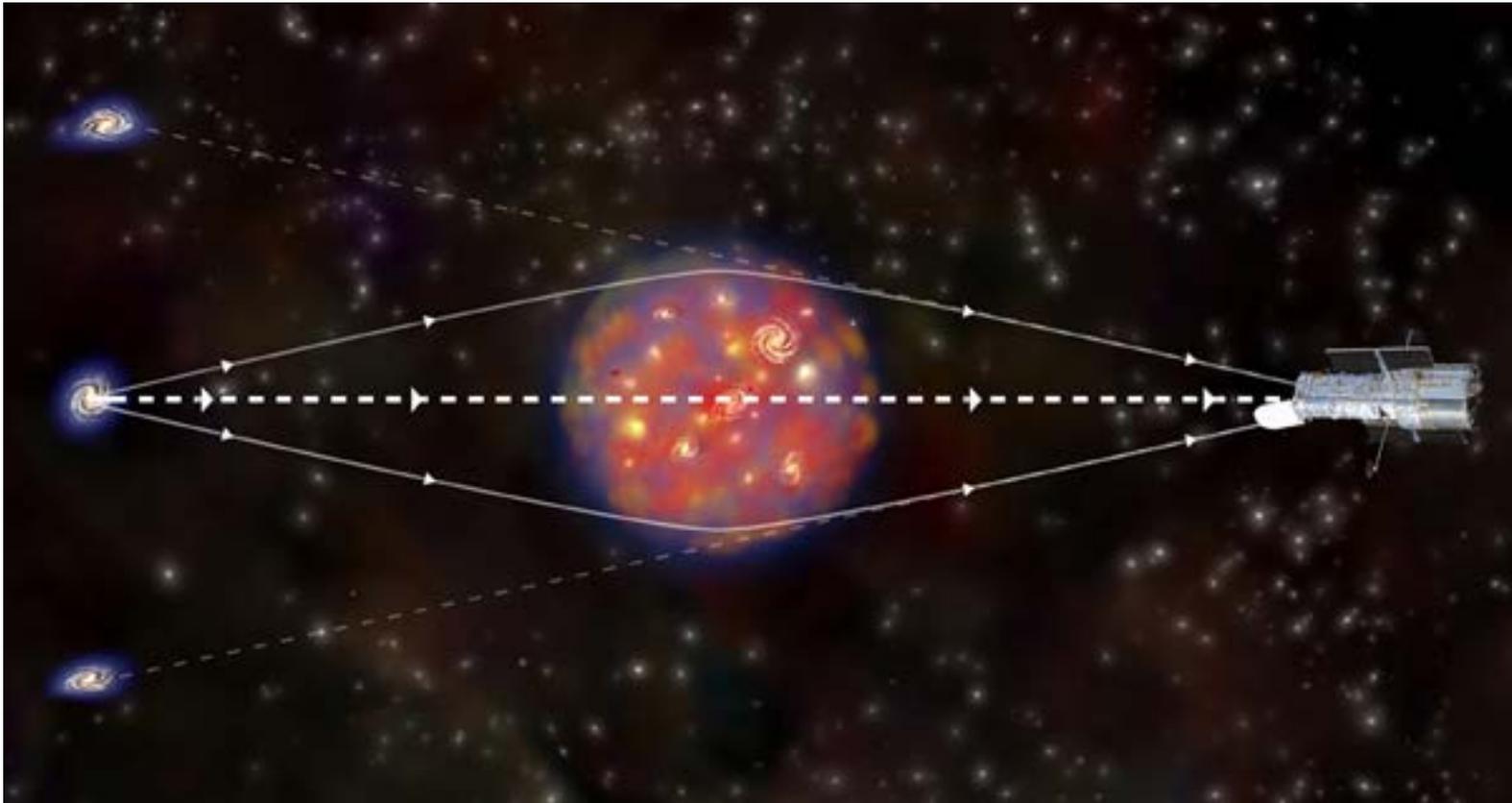
# Detecting Dark Matter in Clusters of Galaxies

One consequence of the warping of space by gravity is that the path of light from background galaxies is bent when it passes near a cluster of galaxies.

The images of the galaxies are distorted by this "**gravitational lensing**" effect, by an amount that depends on the mass of the cluster.

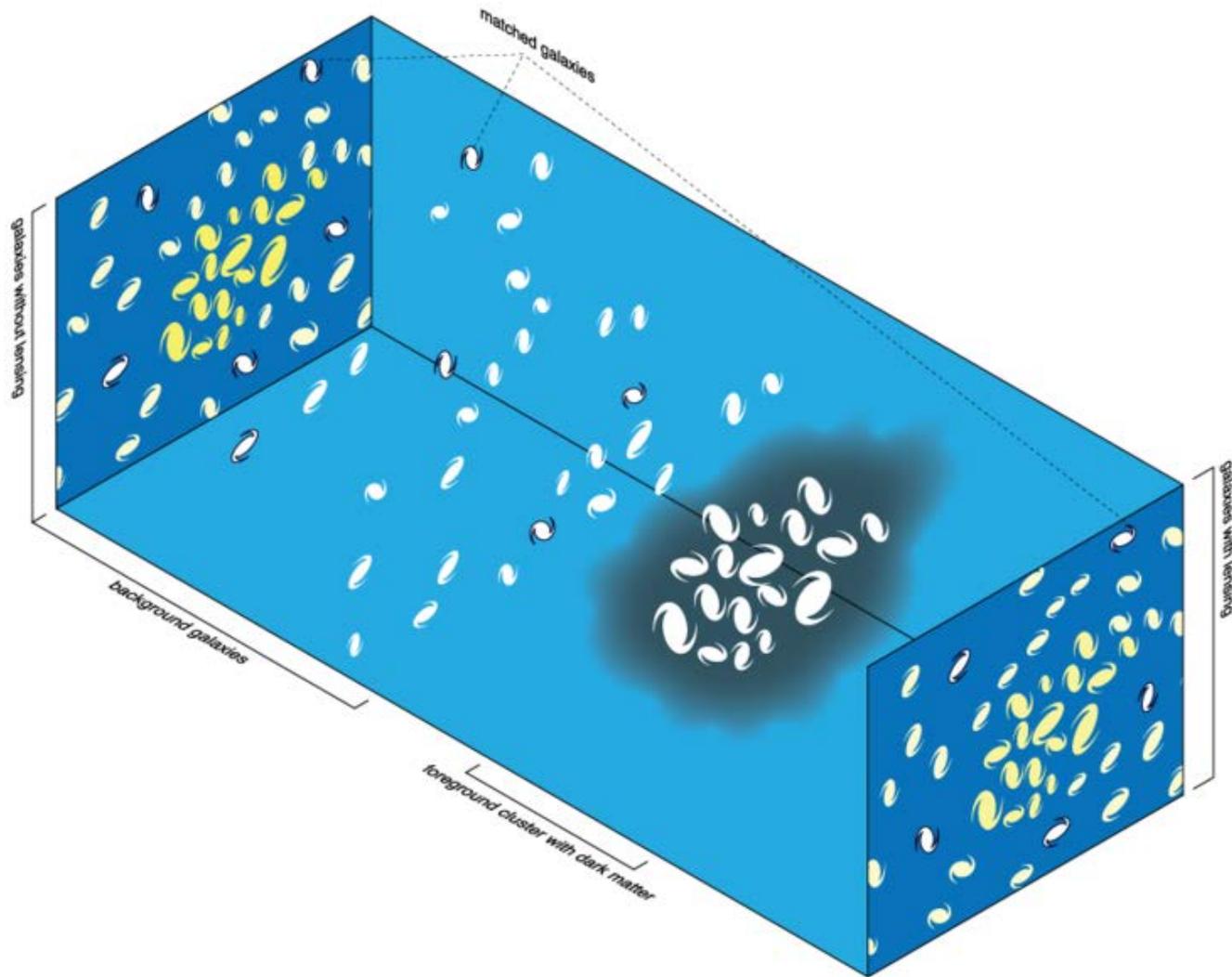
This method gives estimates for the amount of dark matter in galaxy clusters that is in good agreement with X-ray observations.

# Detecting Dark Matter in Clusters of Galaxies



Bending of light from background galaxies by the combined gravitational effect of the central elliptical galaxy and galaxy cluster can be used to estimate the mass of the cluster. **Strong lensing produces multiple images** of the background source.

# Detecting Dark Matter in Clusters of Galaxies



**Weak gravitational lensing** of background galaxies produces **distorted images** that can be analyzed to give an estimate of the mass of a cluster.

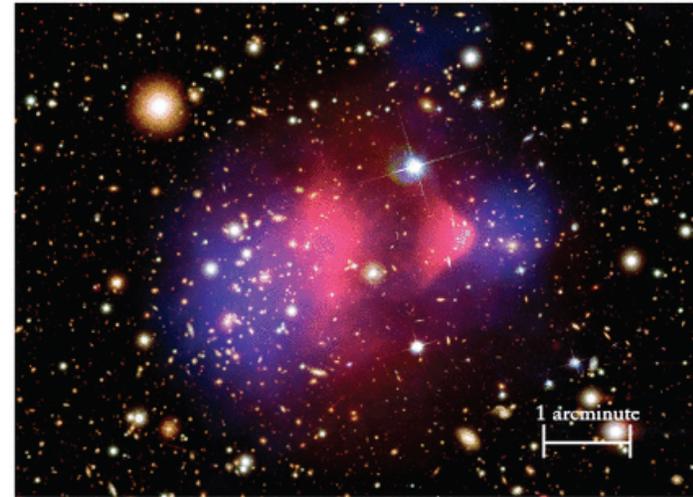
# Detecting Dark Matter in Clusters of Galaxies

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

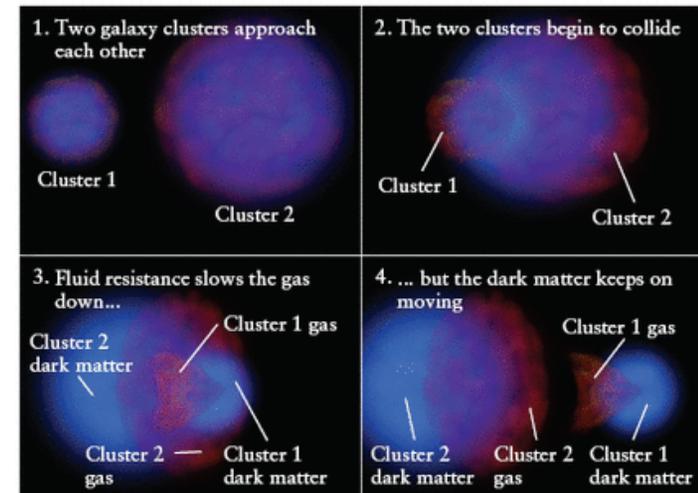
Using the weak lensing technique, astronomers have deduced that the dark mass in the clusters (blue) is separate from that of the hot gas.

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.

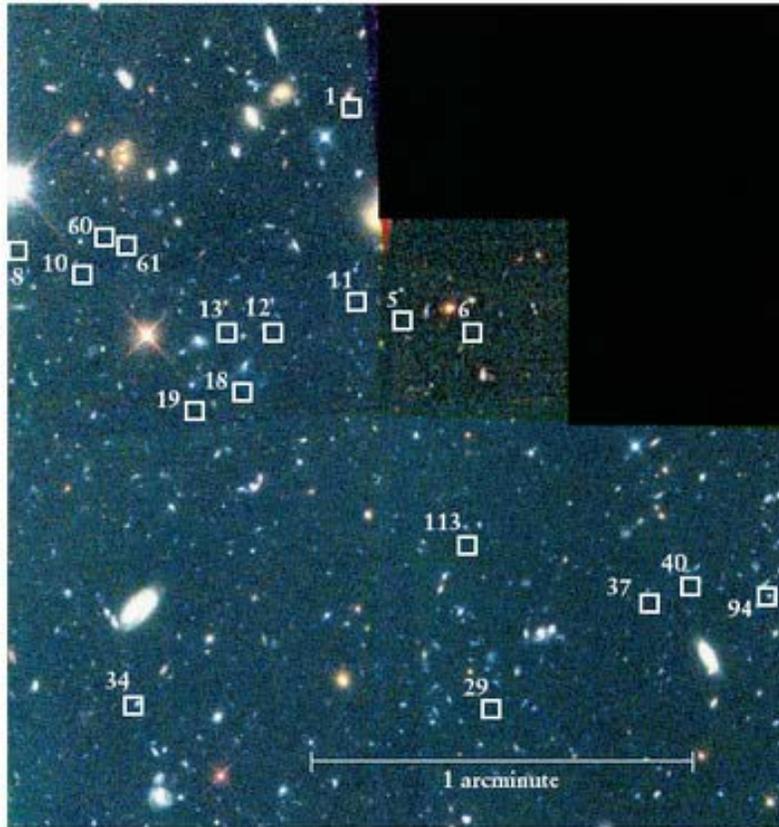


(a) Composite image of galaxy cluster 1E0657-56 showing visible galaxies, X-ray-emitting gas (red) and dark matter (blue) R I V U X G



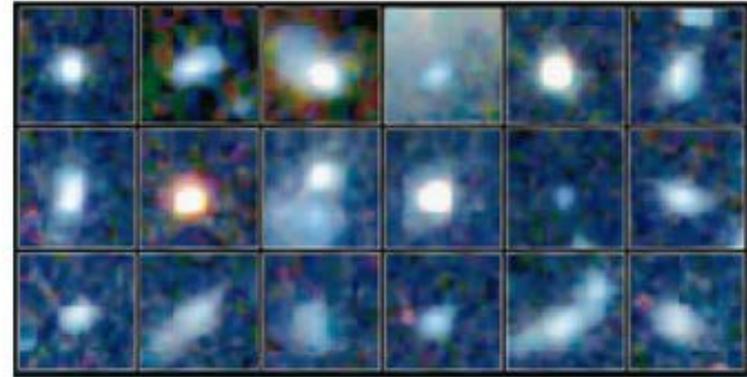
(b) A model of how the gas and dark matter in 1E0657-56 could have become separated

# Formation of the First Galaxies



(a) A portion of the constellation Hercules

These very deep observations with HST show us how galaxies looked like in the distant past some ~11 billion years ago.

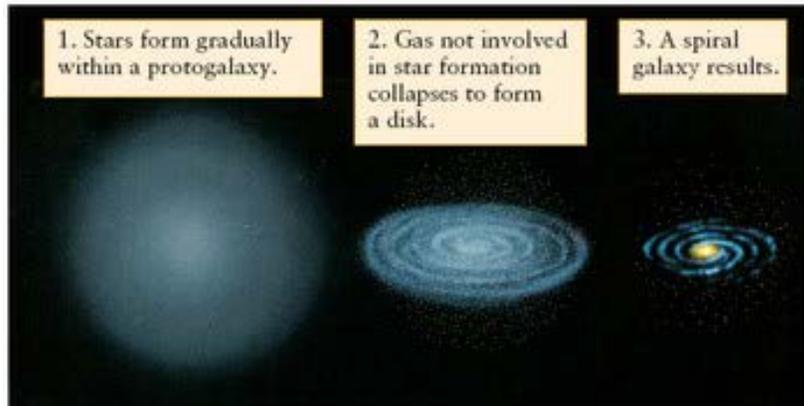


(b) Closeup images of the numbered objects in (a)

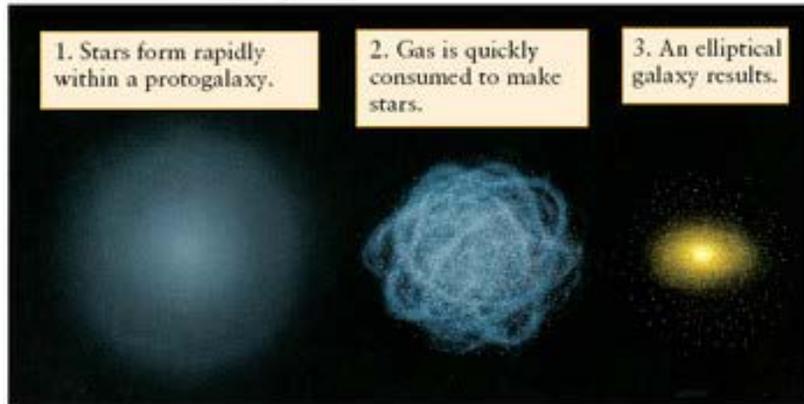
Recent observations of the very first galaxies in the Universe suggest that **galaxies formed from the merger of smaller objects**. This is often referred to as building galaxies from the "Bottom Up". The building blocks of galaxies are about a few 1000 ly across.

The **very first galaxies appear very blue** indicating significant star formation at this time.

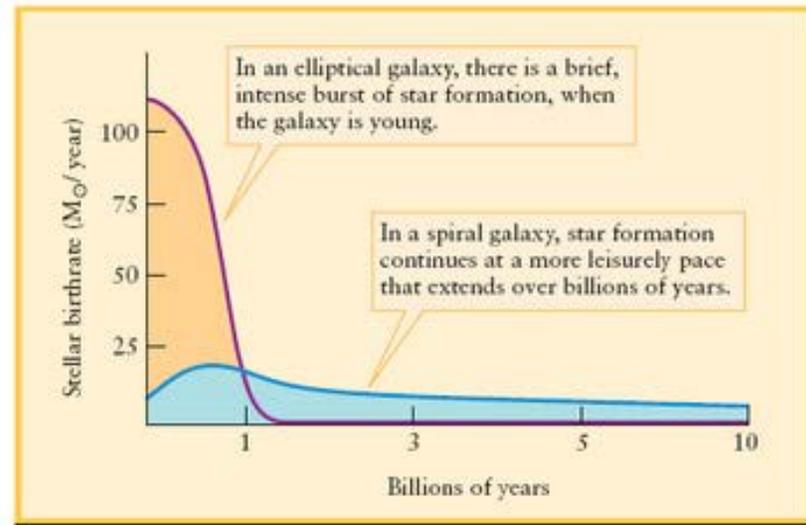
# Spiral versus Elliptical Galaxies



(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.