Galaxies

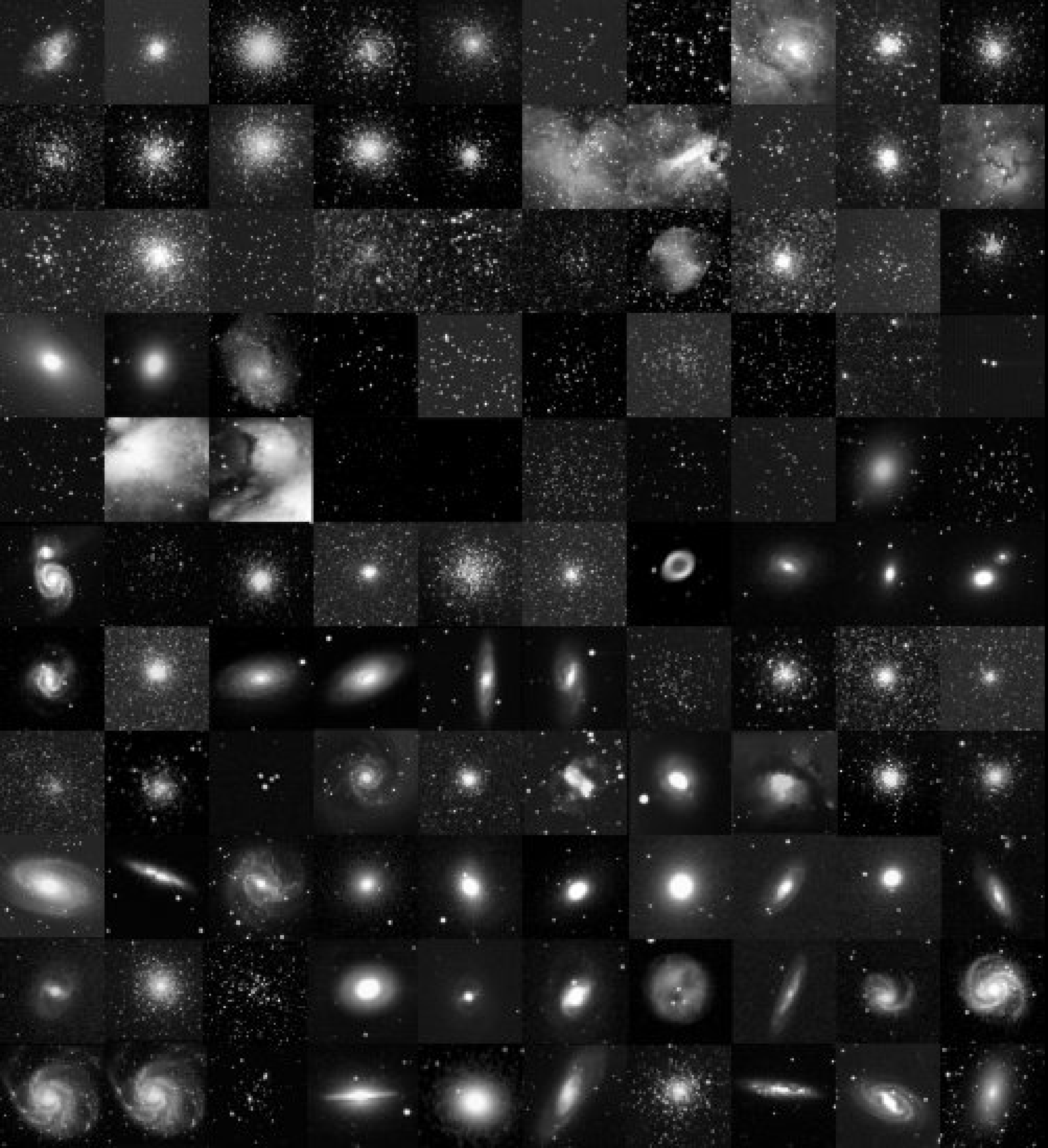
- How big is the Universe?
- Types of galaxies
- Distances to galaxies
- Clusters of galaxies
- Dark matter in galaxies and clusters
- Formation of galaxies

Why are Cepheid variable stars useful in determining distances?

A) They all have the same distance.
B) Their luminosity can be determined from their pulsation period.
C) They all have the same luminosity.
D) They all have the same radius.

How big is the Universe?

- Spiral nebulae were identified not long after development of the telescope around 1600
- In the 1600’s, it was suggested that spiral nebula are separate galaxies so far away that the stars blur together, but most people thought they were clouds of gas
- The question wasn’t resolved until 1923.

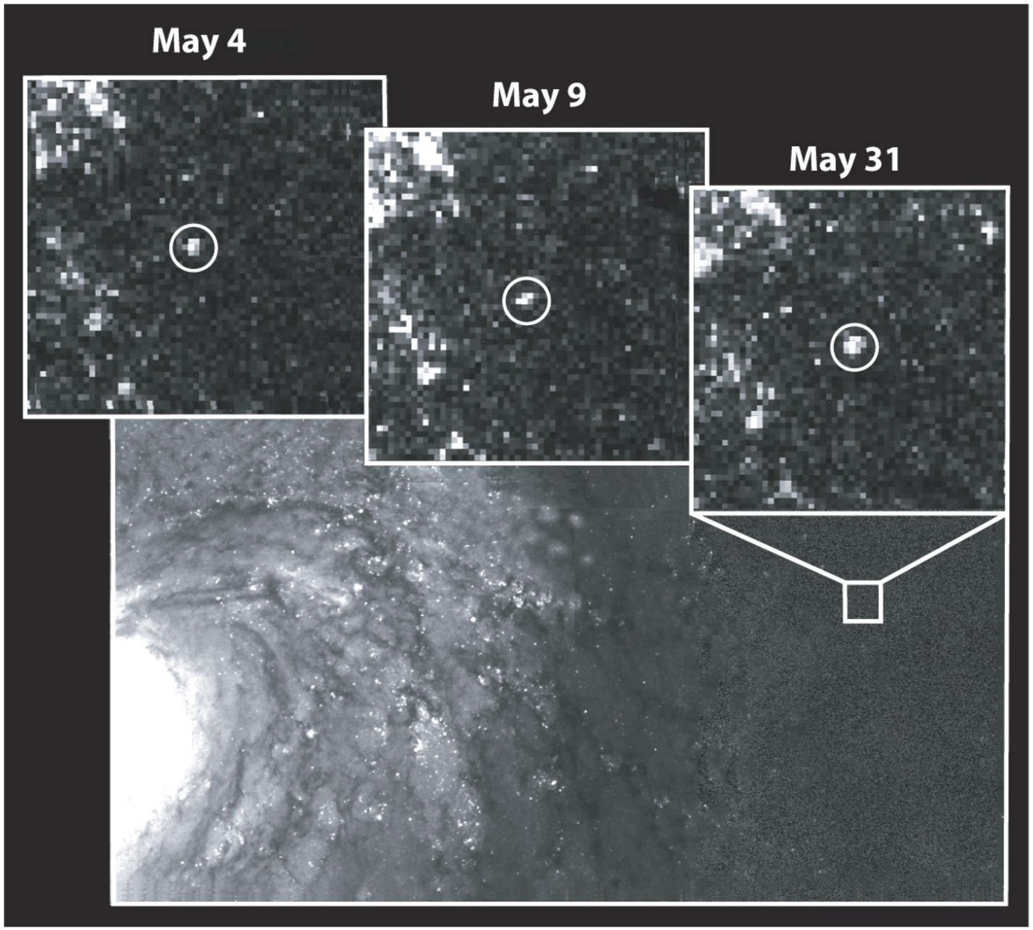


Are there different types of objects here?

Great debate

- Two astronomers held a great debate in 1920
- Harlow Shapley argued the Milky Way was the whole Universe
- Heber Curtis argued the Milky Way was just one of many galaxies – “island universes”
- Held in the Smithsonian's Museum of Natural History – the auditorium still looks the same

Distance to the Andromeda spiral nebula



- In 1923, Edwin Hubble found Cepheid variable in the Andromeda nebula and showed that the "nebula" was at a great distance, much larger than the size of the Milky Way.

How big is the Universe?

- Greeks (up about 100 B.C.)
  - Earth at Center
  - Universe extends to ‘sphere of Saturn’, largest measured distance is from Earth to Sun at several million miles
- Renaissance (1500-1650)
  - Sun at Center
  - Universe extends to `distant stars’ with inferred distance of about 100 billion miles, largest measured distance is from Sun to Saturn at about 1 billion miles

How big is the Universe?

- Parallax to stars
  - First parallax measured in 1838 to star 61 Cygni of 0.3 arcseconds for a distance of 11 ly = 7×10^{13} miles.
- Distance to center of Milky Way
  - from star counts 5000-10,000 ly (1785-1810)
  - from globular clusters 50,000 ly (1915)
- Distance to Andromeda nebula
  - from Cepheids 900,000 ly (1923)

Types of Galaxies

M100

NGC 1365

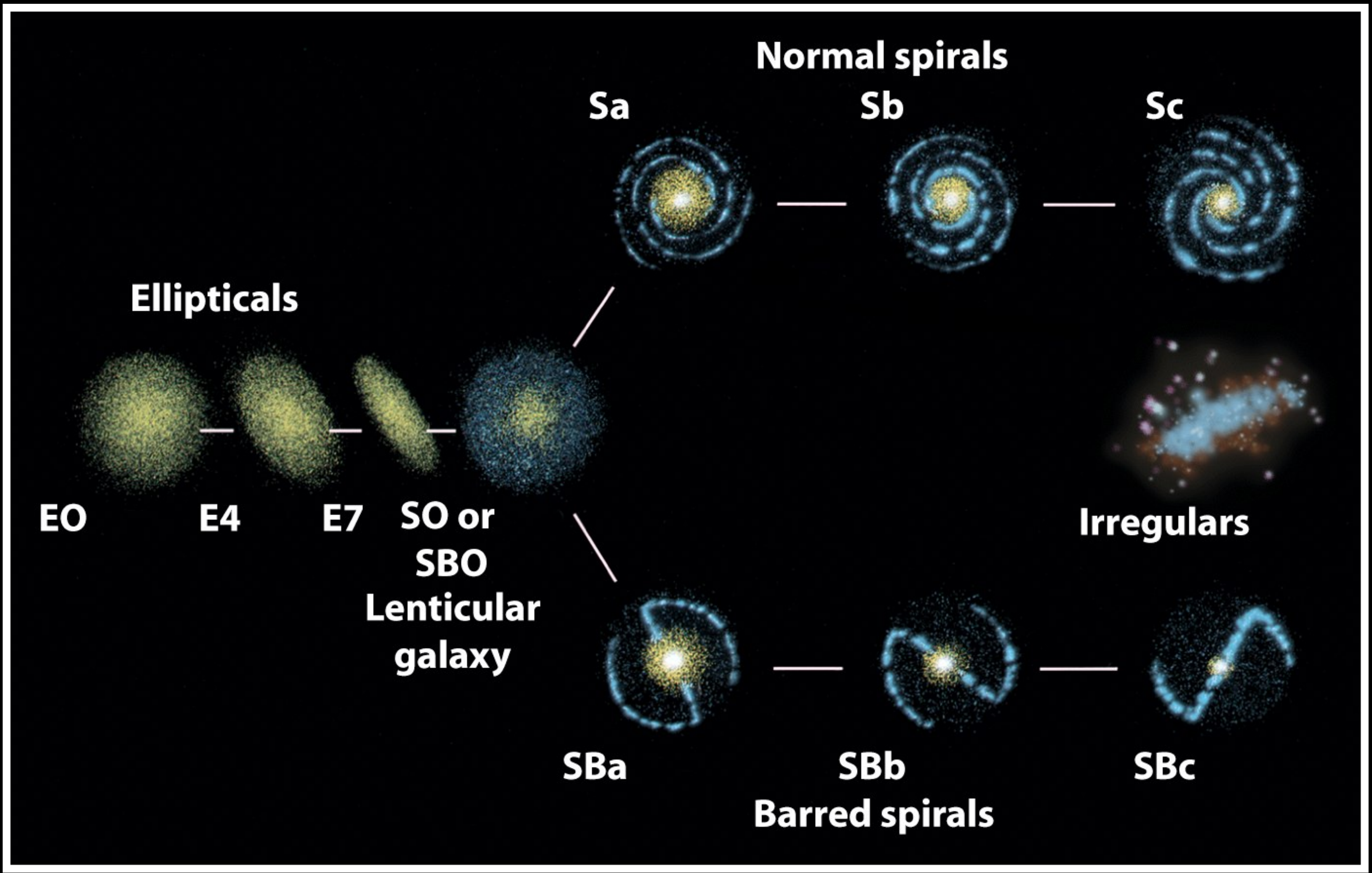

Barred Galaxy NGC 1365
(VLT UT1 + FORS1)
ESO PR Photo 08a/99 (27 February 1999)
© European Southern Observa

M87

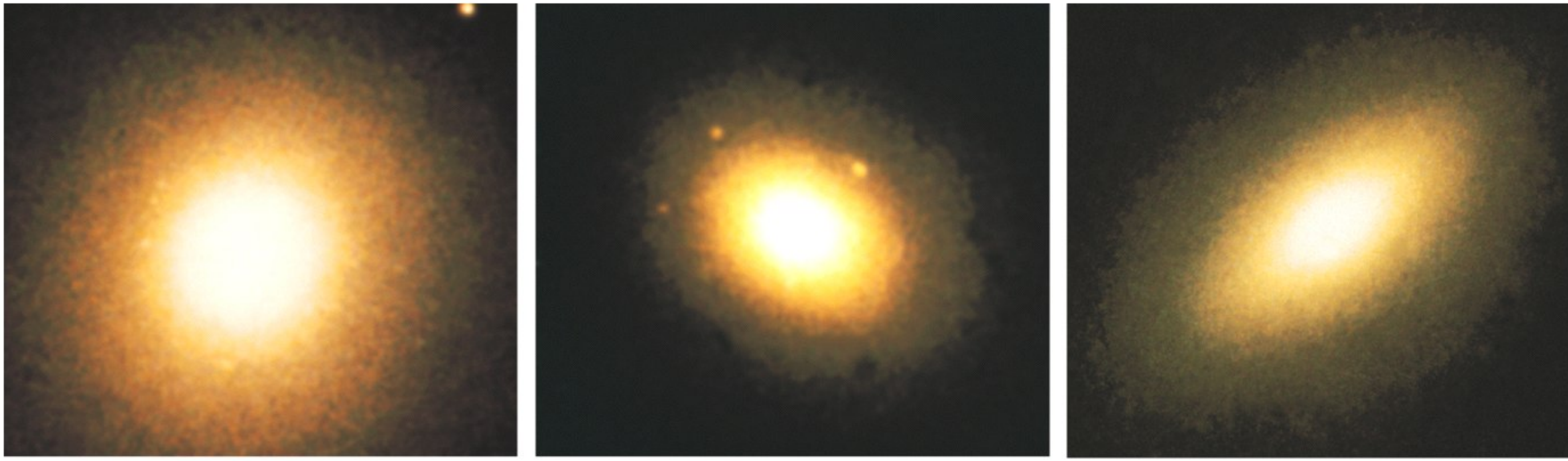
NGC
3377

NGC
4449

Classifying Galaxies



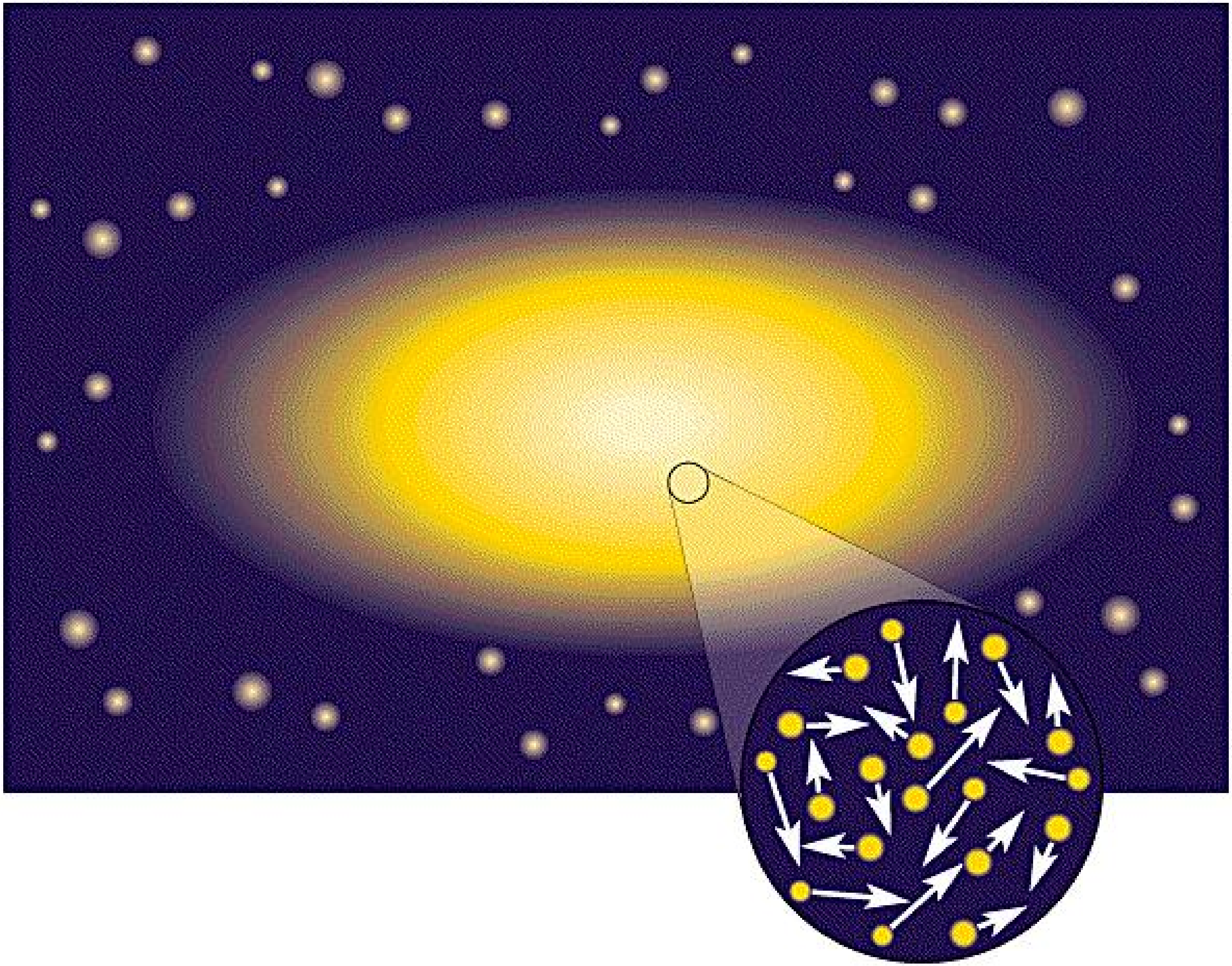
Elliptical galaxies



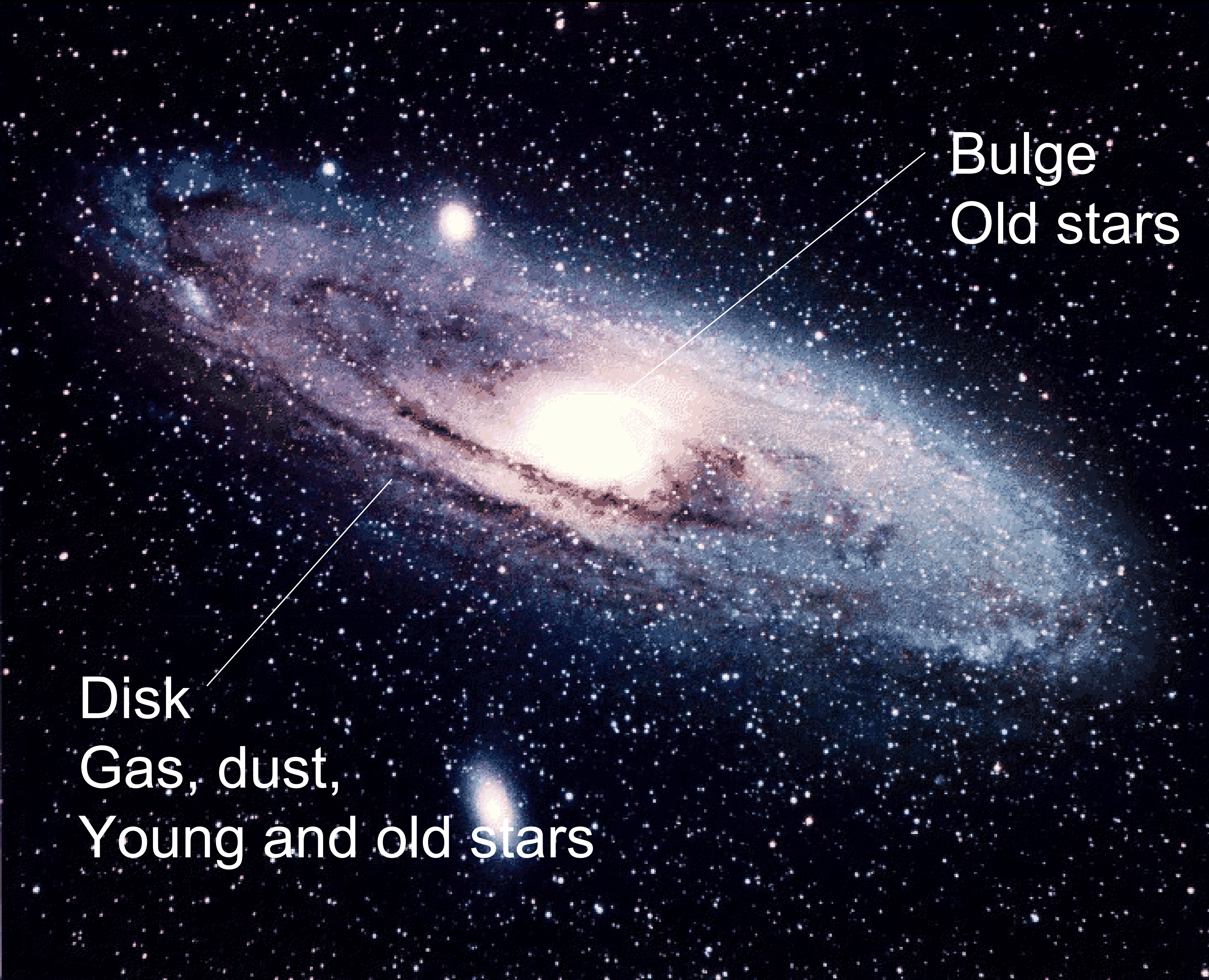
(a) E0 (M105) (b) E3 (NGC 4365) (c) E6 (NGC 3377)

- little interstellar gas and dust
- very little star formation
- mainly old stars (billions of years old)
- few or no young stars (millions of years old)

Elliptical galaxies




M86
M84

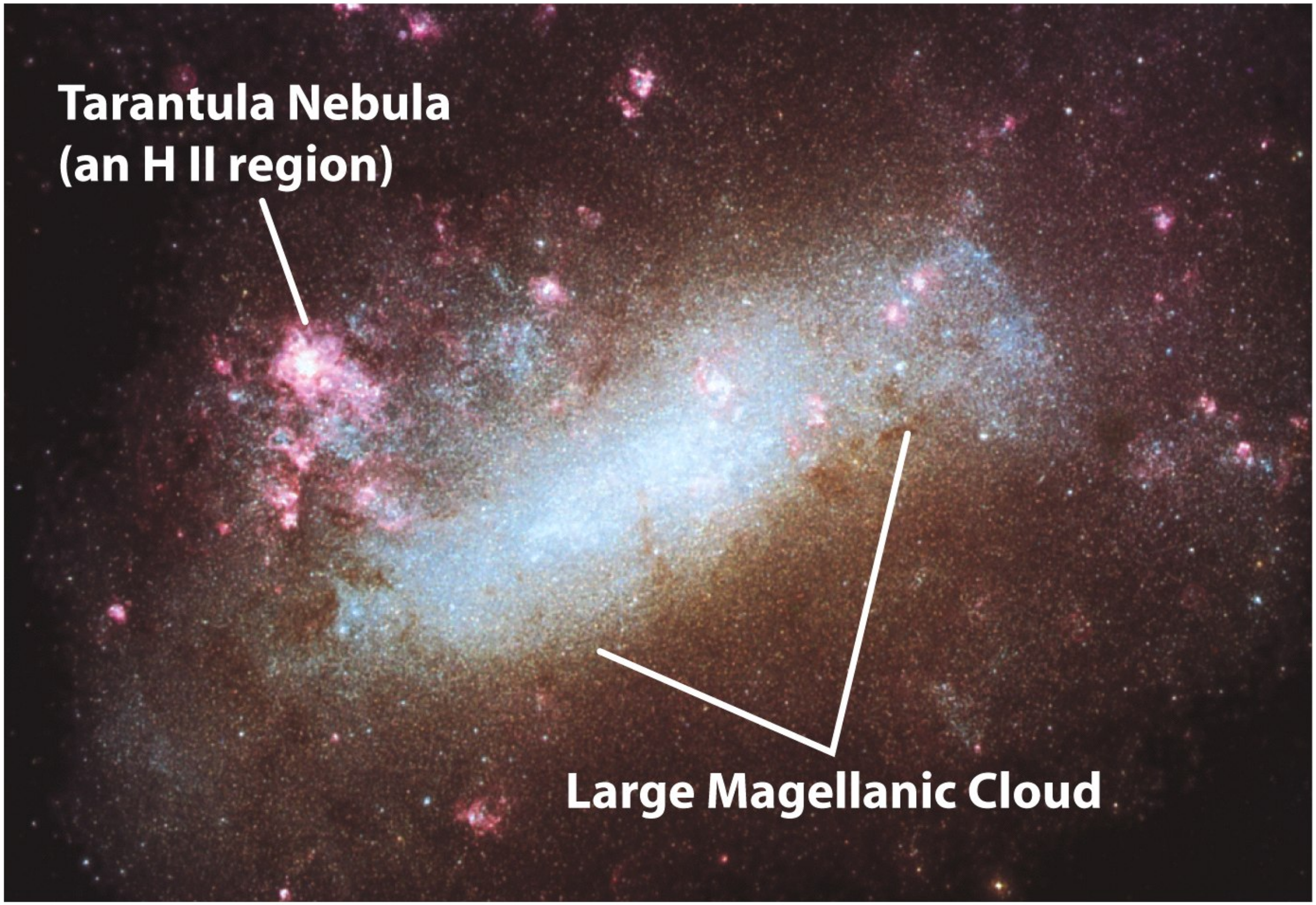

Bulge
Old stars
Disk
Gas, dust,
Young and old stars

Spirals vary in prominence of bulge, tightness of arms, presence of bar

(a) Sa (NGC 1357) (b) Sb (M81) (c) Sc (NGC 4321)

(a) SBa (NGC 4650) (b) SBb (M83) (c) SBc (NGC 1365)

Irregular galaxies have asymmetric shapes and usually lots of young stars



They are often found near other galaxies

The Milky Way galaxy is

A) irregular
B) elliptical
C) spiral
D) chocolate

In which type of galaxy are star's orbits distributed in random directions?

A) elliptical galaxies
B) spiral galaxies
C) barred spiral galaxies
D) blue galaxies

Which is **not** true of elliptical galaxies?

A) Their stars orbit in many different directions

B) They have large concentrations of gas

C) Some are formed in galaxy collisions

D) The contain mainly older stars

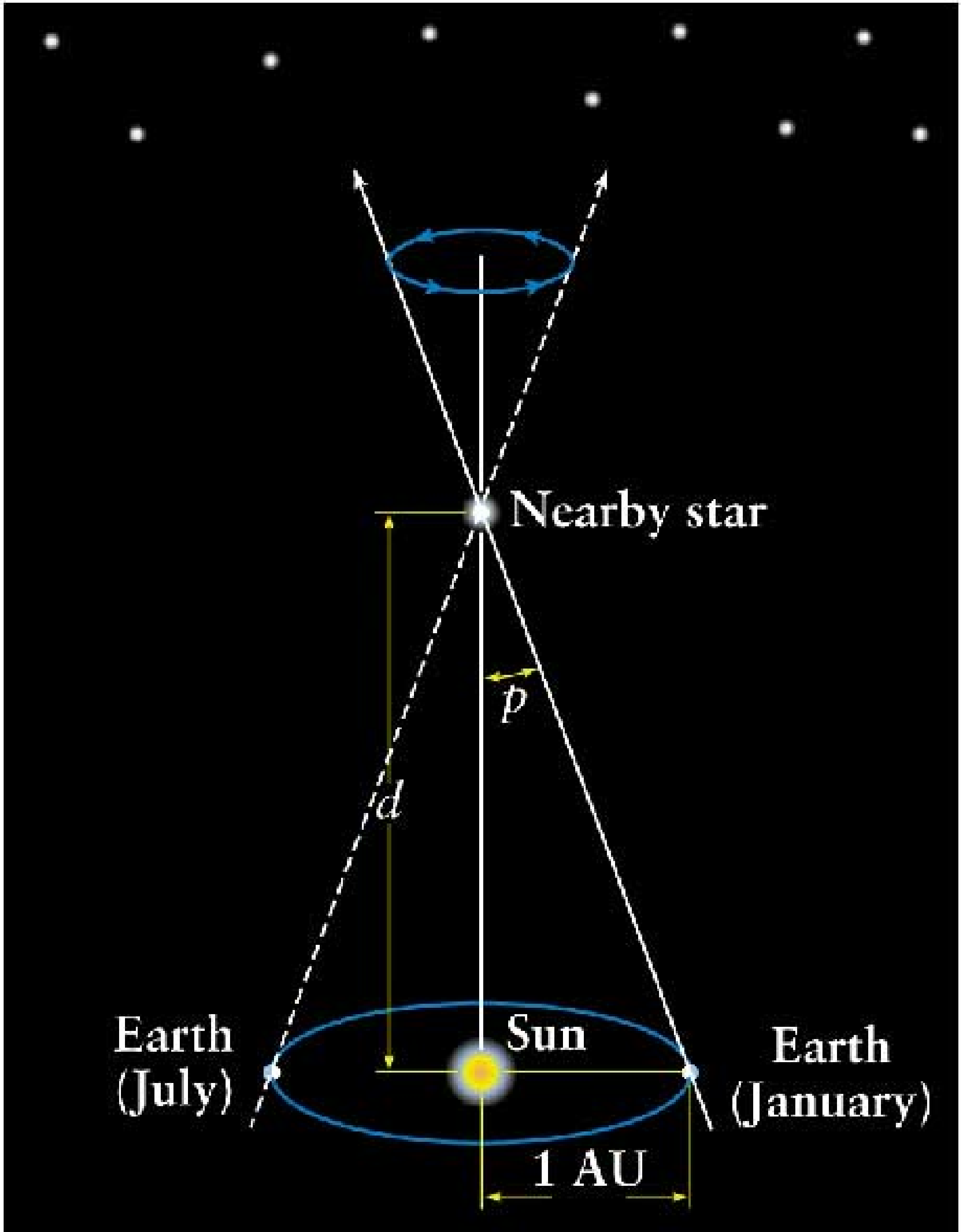
Why do elliptical galaxies tend to appear reddish in color?

A) They have large concentrations of hydrogen clouds that emit a characteristic reddish color.

B) They have large dust clouds that cause reddening.

C) They are composed mostly of old stars that are characteristically red.

Distances to Galaxies



a

Stellar Parallax

As the Earth moves from one side of the Sun to the other, a nearby star will seem to change its position relative to the distant background stars.

$$d = 1 / p$$

d = distance to nearby star in parsecs

p = parallax angle of that star in arcseconds

Stellar Parallax

- Most accurate parallax measurements are from the European Space Agency's Hipparcos mission.

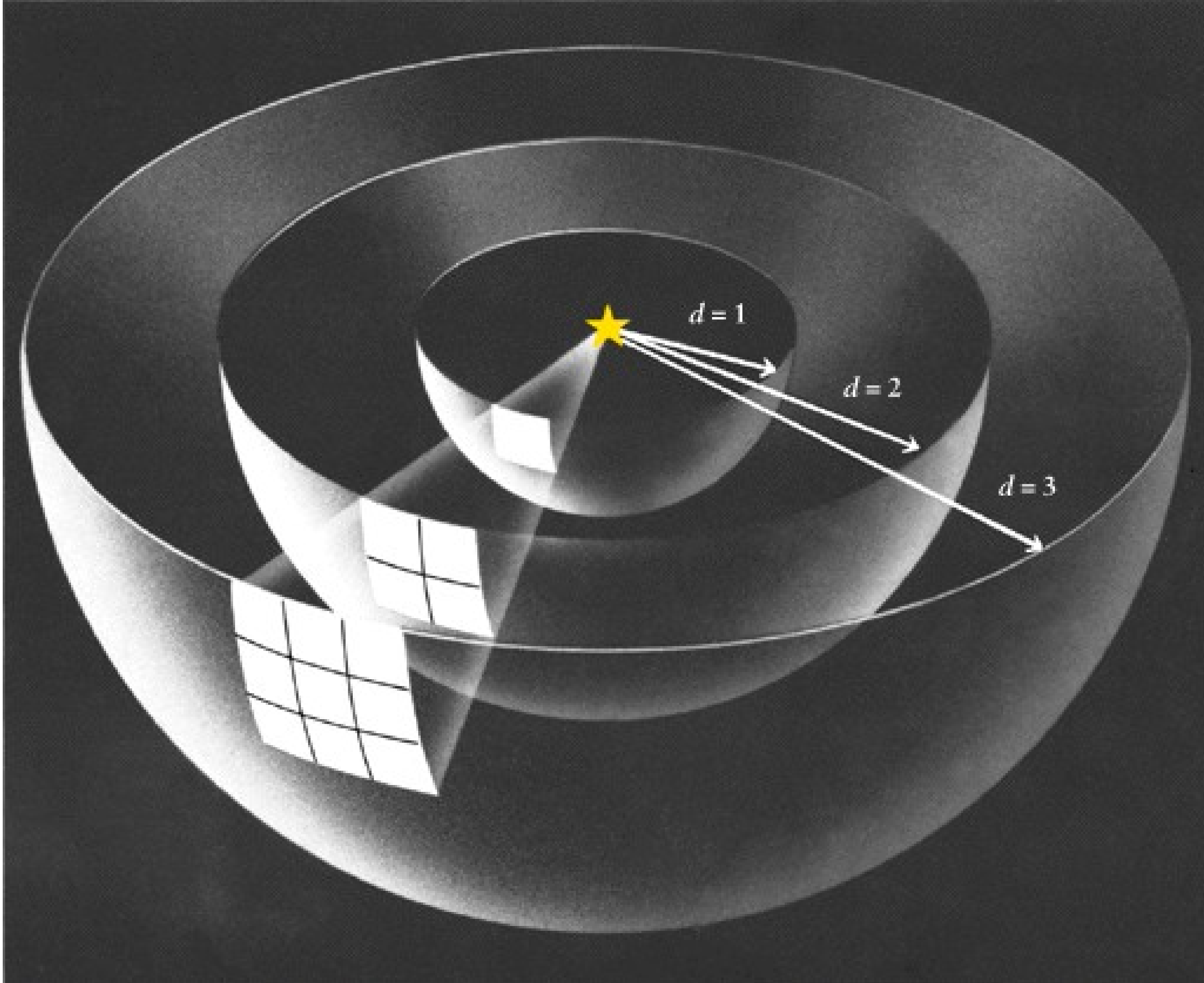
- Hipparcos could measure parallax as small as 0.001 arcseconds or distances as large as 1000 pc.

- How to find distance to objects farther than 1000 pc?

Flux and Luminosity

- Flux decreases as we get farther from the star – like 1/distance^2
- Mathematically, if we have two stars A and B

$$\frac{\text{Flux}_A}{\text{Flux}_B} = \frac{\text{Luminosity}_A}{\text{Luminosity}_B}\left(\frac{\text{Distance}_B}{\text{Distance}_A}\right)^2$$



d = 1
d = 2
d = 3

Standard Candles

$$\text{Luminosity}_A = \text{Luminosity}_B$$

$$\frac{\text{Flux}_A}{\text{Flux}_B} = \frac{\text{Luminosity}_A}{\text{Luminosity}_B}\left(\frac{\text{Distance}_B}{\text{Distance}_A}\right)^2$$

$$\frac{\text{Flux}_A}{\text{Flux}_B} = \left(\frac{\text{Distance}_B}{\text{Distance}_A}\right)^2$$

$$\frac{\text{Distance}_B}{\text{Distance}_A} = \sqrt{\frac{\text{Flux}_A}{\text{Flux}_B}}$$

Standard Candles

1. Measure the distance to star A to be 200 pc.
2. Measure the flux of star A.
3. Measure the flux of star B, which is known to have the same luminosity as star A, to be lower by a factor of 1600 (or the flux of A is 1600 times the flux of B).
4. Find the distance to star B.

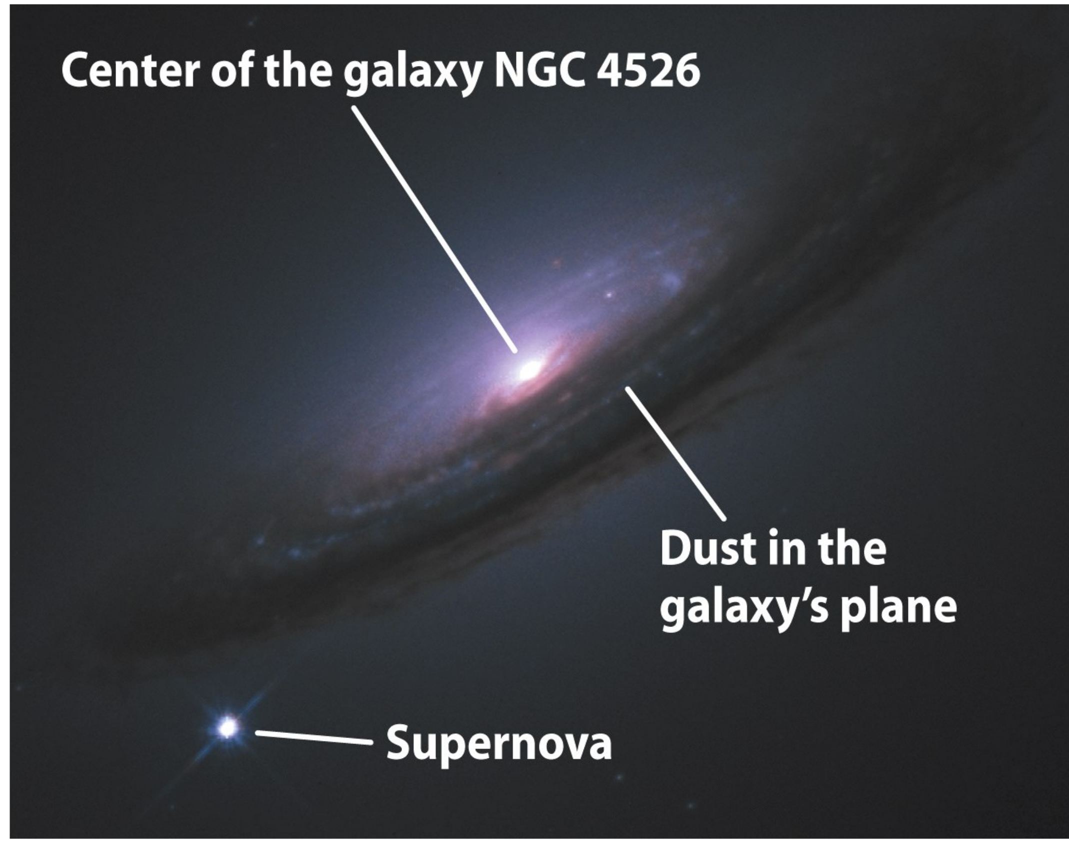
$$\frac{\text{Distance}_B}{\text{Distance}_A} = \sqrt{\frac{\text{Flux}_A}{\text{Flux}_B}} \qquad \frac{\text{Distance}_B}{200\ \text{pc}} = \sqrt{\frac{1600}{1}}$$

$$\text{Distance}_B = 40 \times 200\ \text{pc} = 8000\ \text{pc}$$

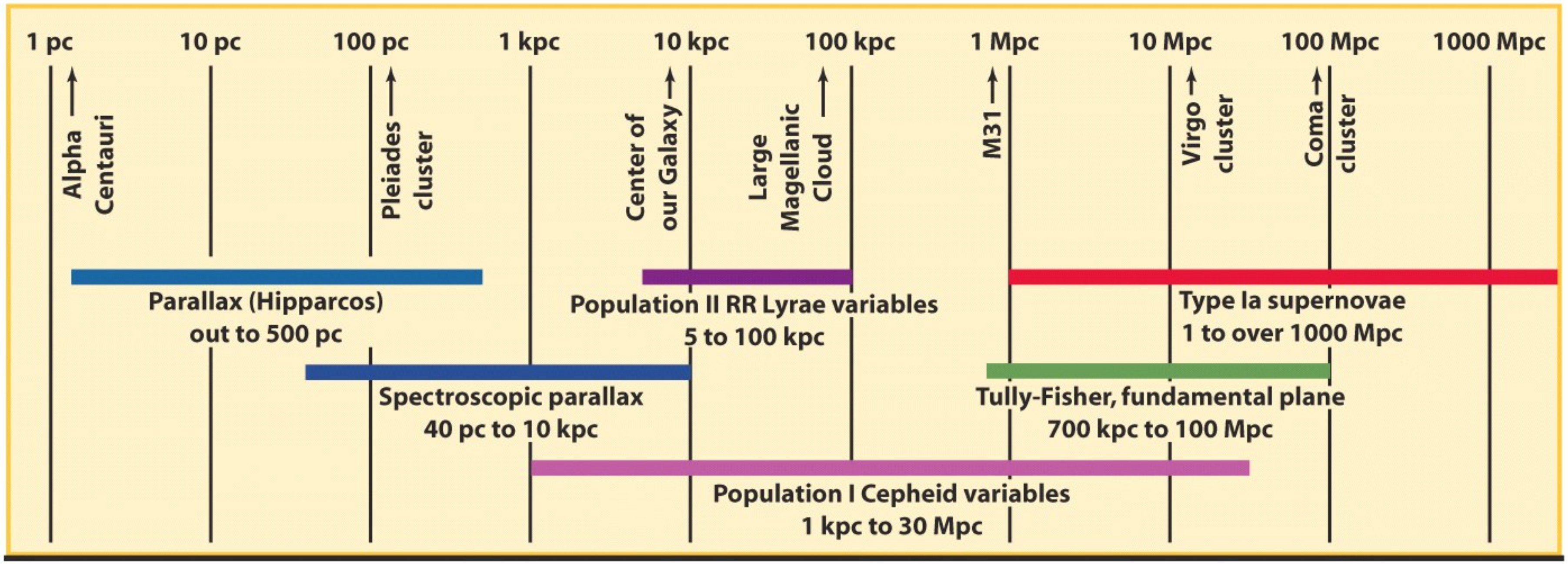
Distances to galaxies

Standard candles, such as Cepheid variables, the most luminous supergiants, globular clusters, H II regions, and Type Ia supernovae in a galaxy, are used in estimating intergalactic distances.

Type Ia supernovae do not all have the same luminosity, but there is a relationship between luminosity and duration.



The Distance Ladder



- Each stage in the ladder overlaps the previous and next
- Cepheid distances are critical
- Tully-Fisher, fundamental plane apply to whole galaxies
- Supernova are the best estimators at large distances

How was Hubble able to determine the distances of nearby galaxies?

A) by measuring trigonometric parallaxes

B) by observing Cepheid variables in them

C) by measuring the expansion speeds of supernova shells

D) by measuring their radial velocities

A Cepheid variable star is 900 times dimmer but has the same period as another Cepheid which is 100 pc away. How far is it?

A) 100 pc
B) 3000 pc
C) 90,000 pc
D) Really far

Which of the following is NOT a reason why Type Ia supernovae make useful standard candles?

A) They are very luminous.

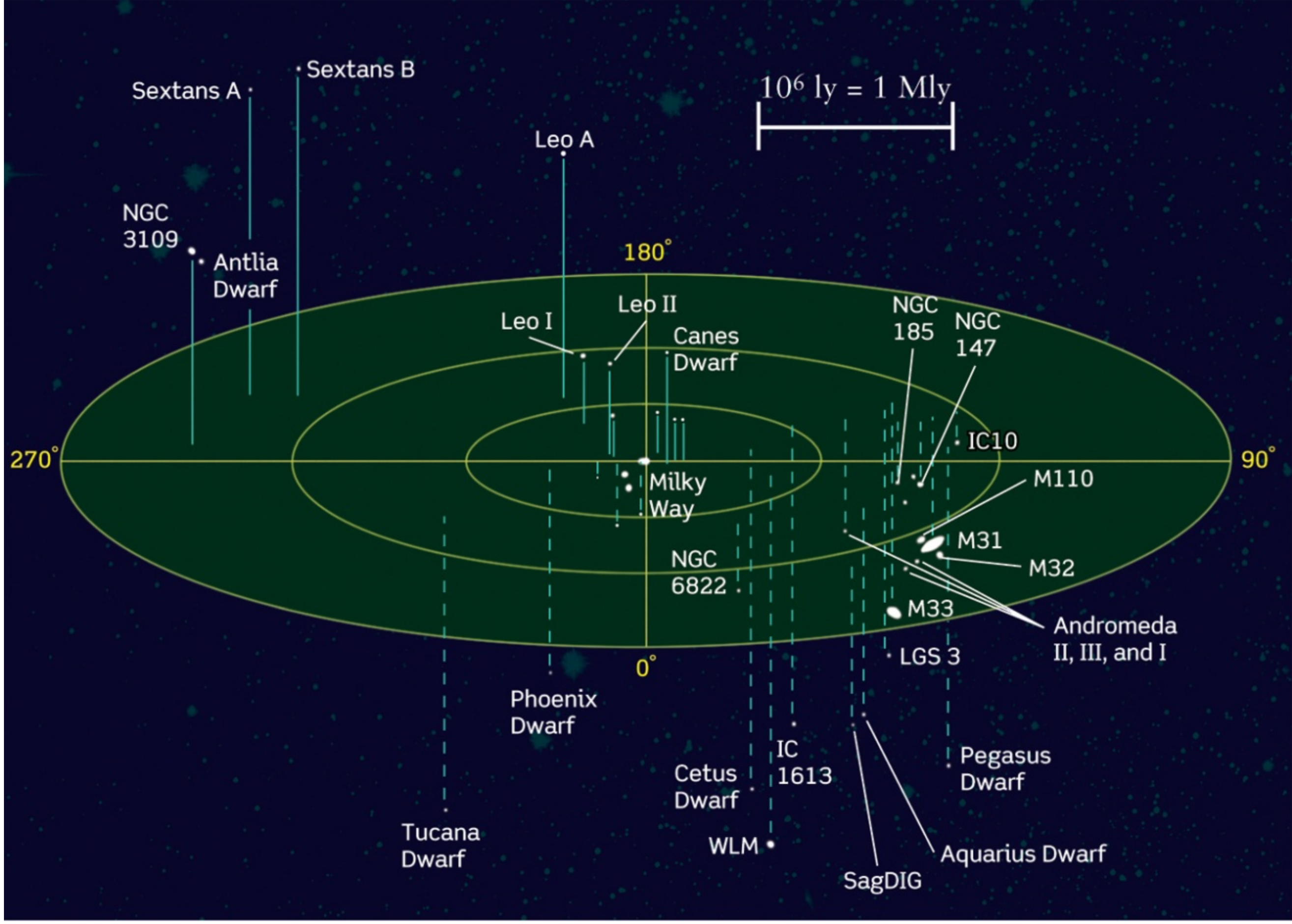
B) All Type Ia supernovae have the same maximum luminosity.

C) They are a common enough event in galaxies.

D) They are easily identifiable by their light curves.

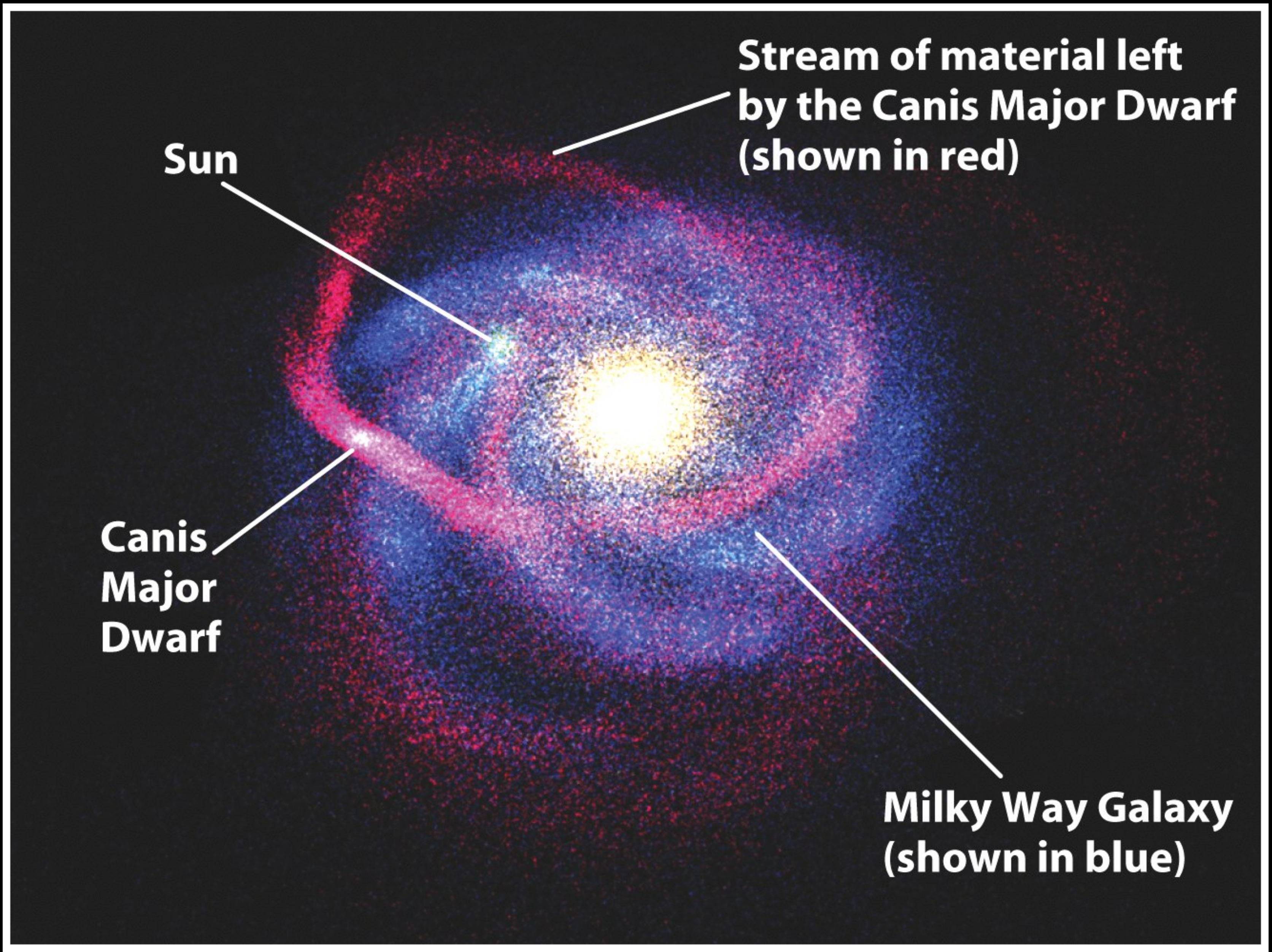
Groups, Clusters, and Super Clusters of Galaxies

The Local Group



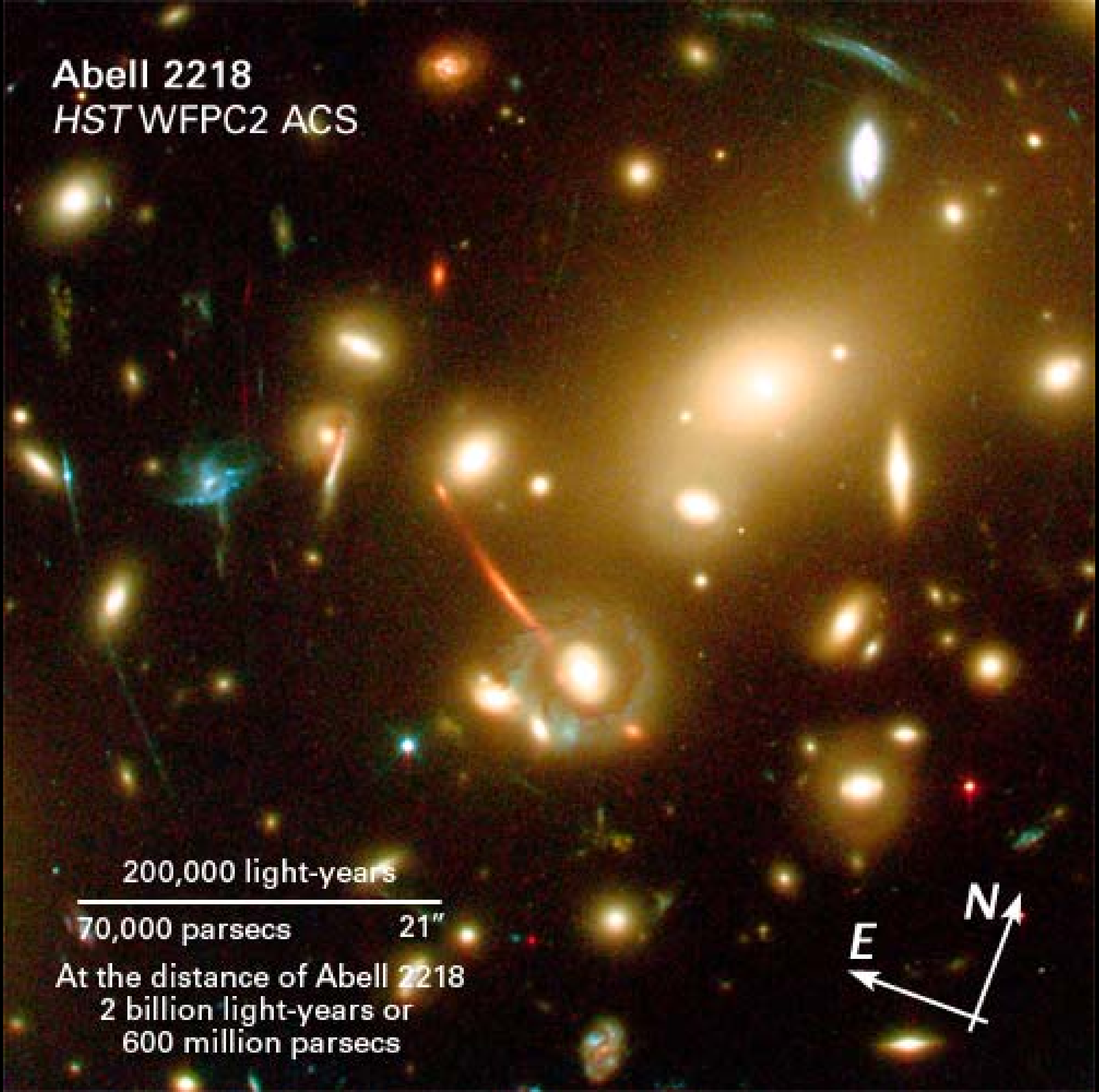
- The Milky Way is in the “Local Group”, a small galaxy cluster.
- The largest galaxy in the Local Group is M31, the Andromeda Galaxy. The Milky Way is in second place, followed by the spiral galaxy M33.
- Both the Milky Way and M31 are surrounded by a number of small satellite galaxies.

The Milky Way is eating its neighbors

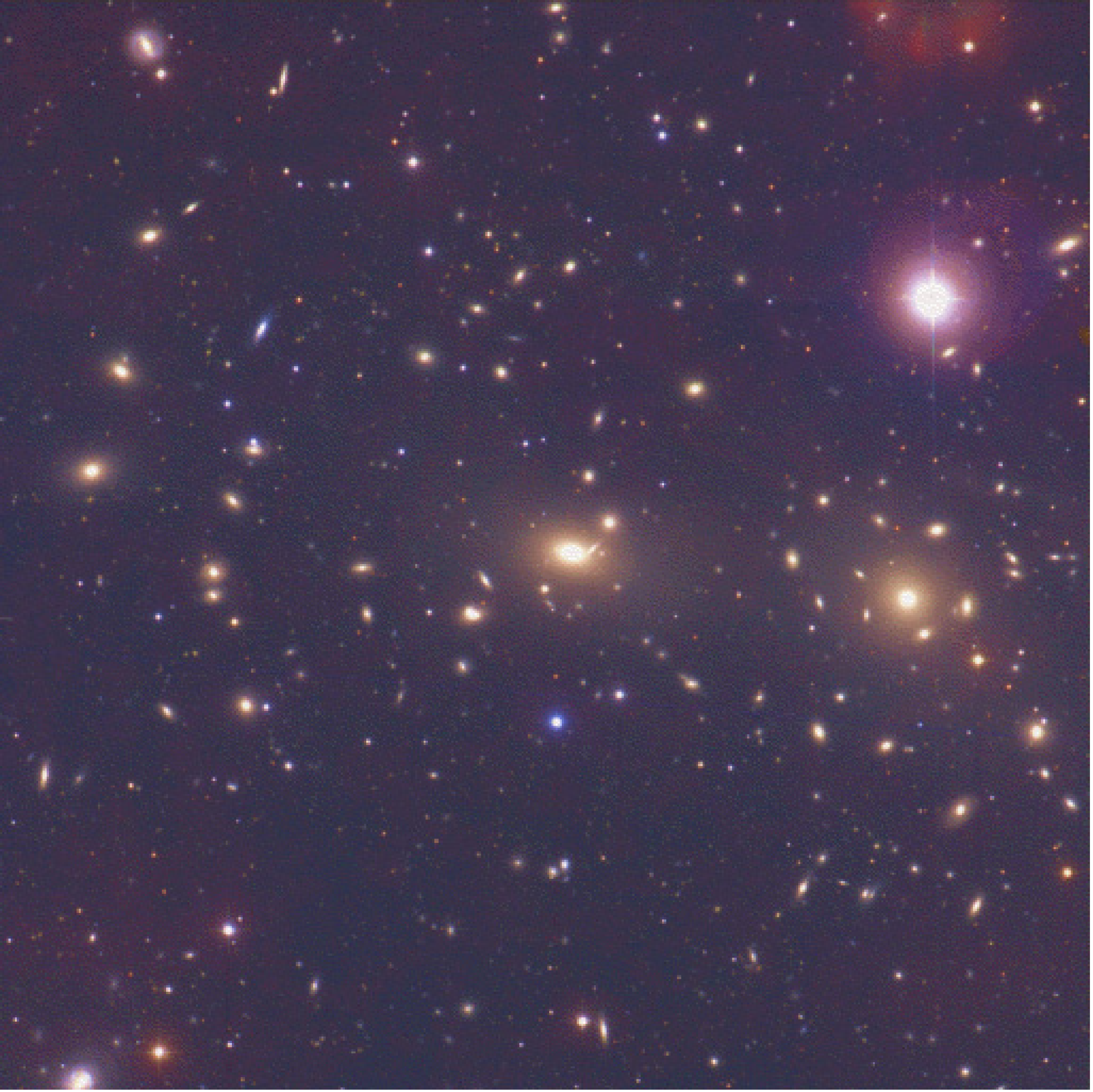



Stephane’s Quintet

Virgo cluster

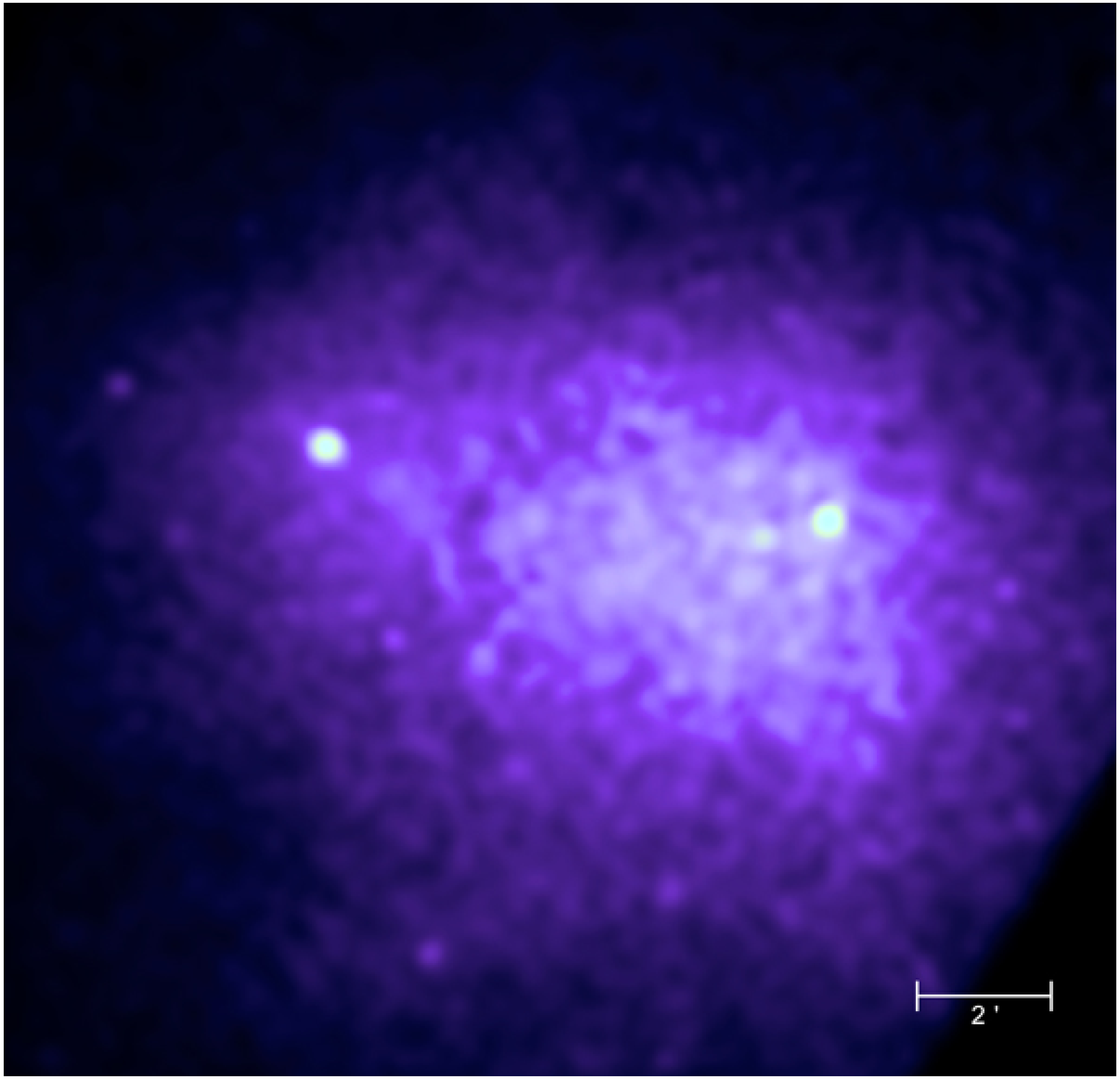


Abell 2218
HST WFPC2 ACS
200,000 light-years
70,000 parsecs
21″
At the distance of Abell 2218
2 billion light-years or
600 million parsecs
N
E



Coma cluster

Coma cluster in X-rays

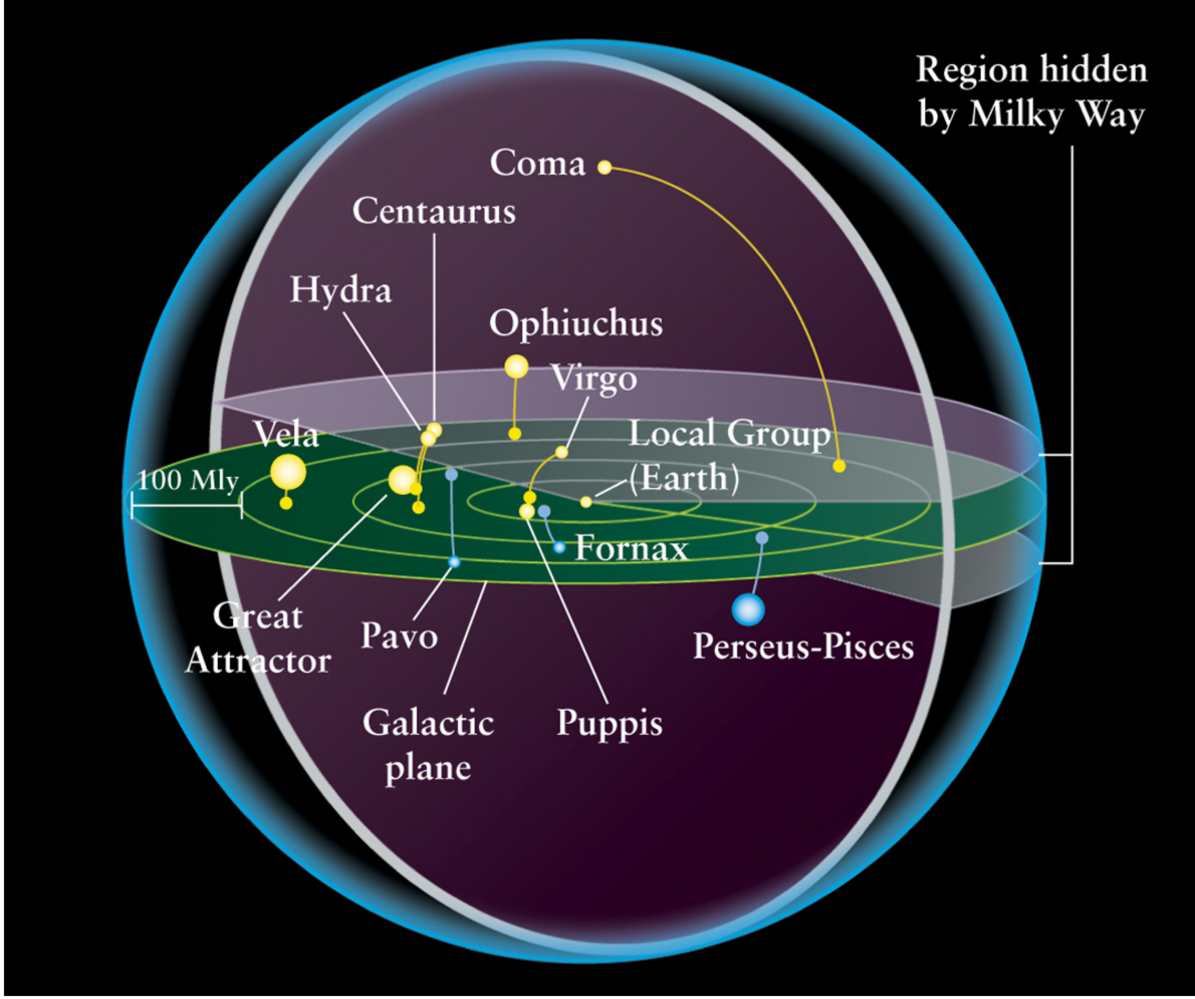


Coma cluster

- X-ray emitting gas is at a temperature of 100,000,000 K.
- The total X-ray luminosity is more than the luminosity of 100 billion Suns.

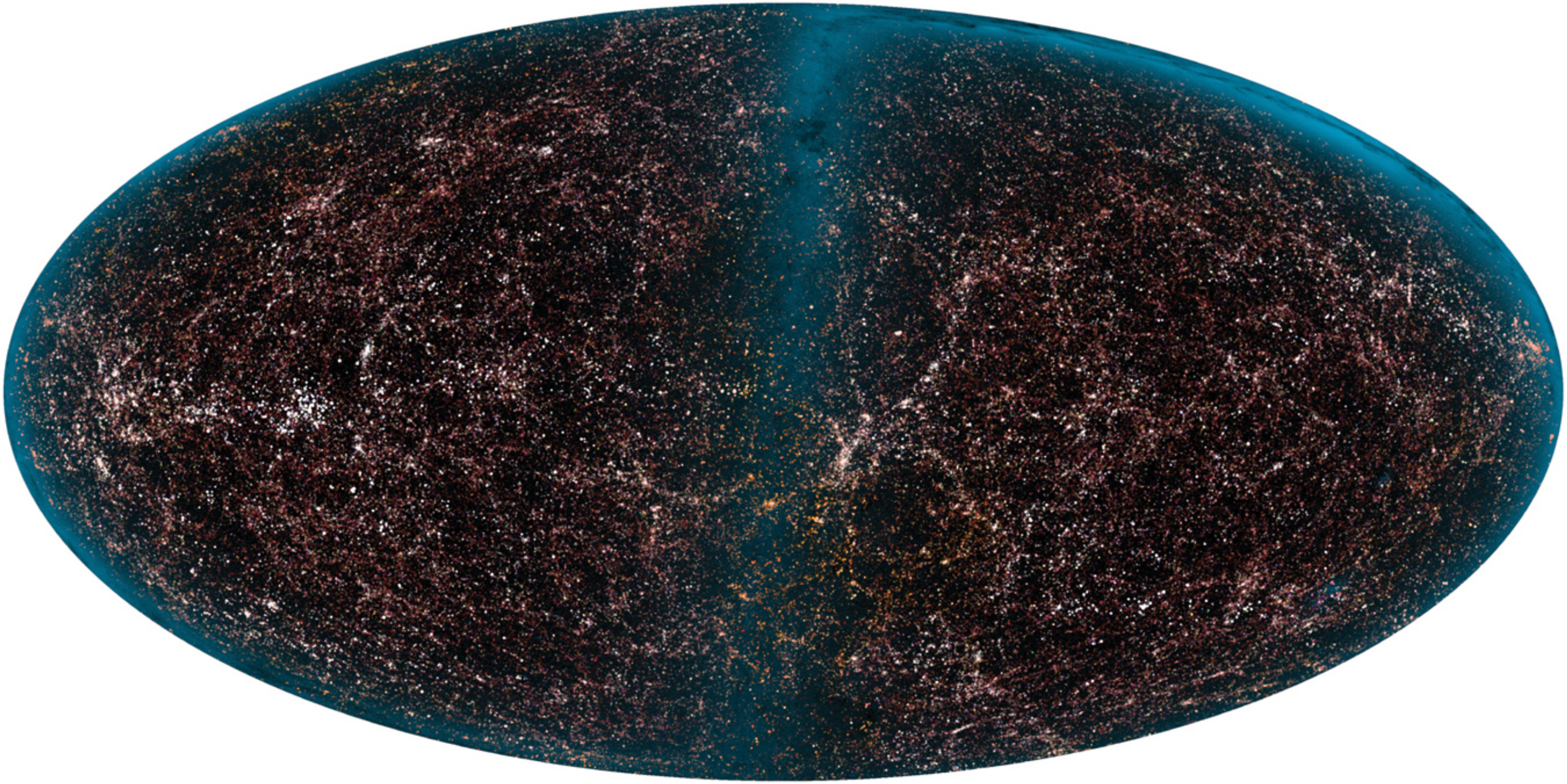
- From this, the amount of X-ray emitting gas can be calculated. The mass of X-ray emitting gas is greater than the mass in all the stars in all the galaxies in the cluster.

Clusters of Clusters



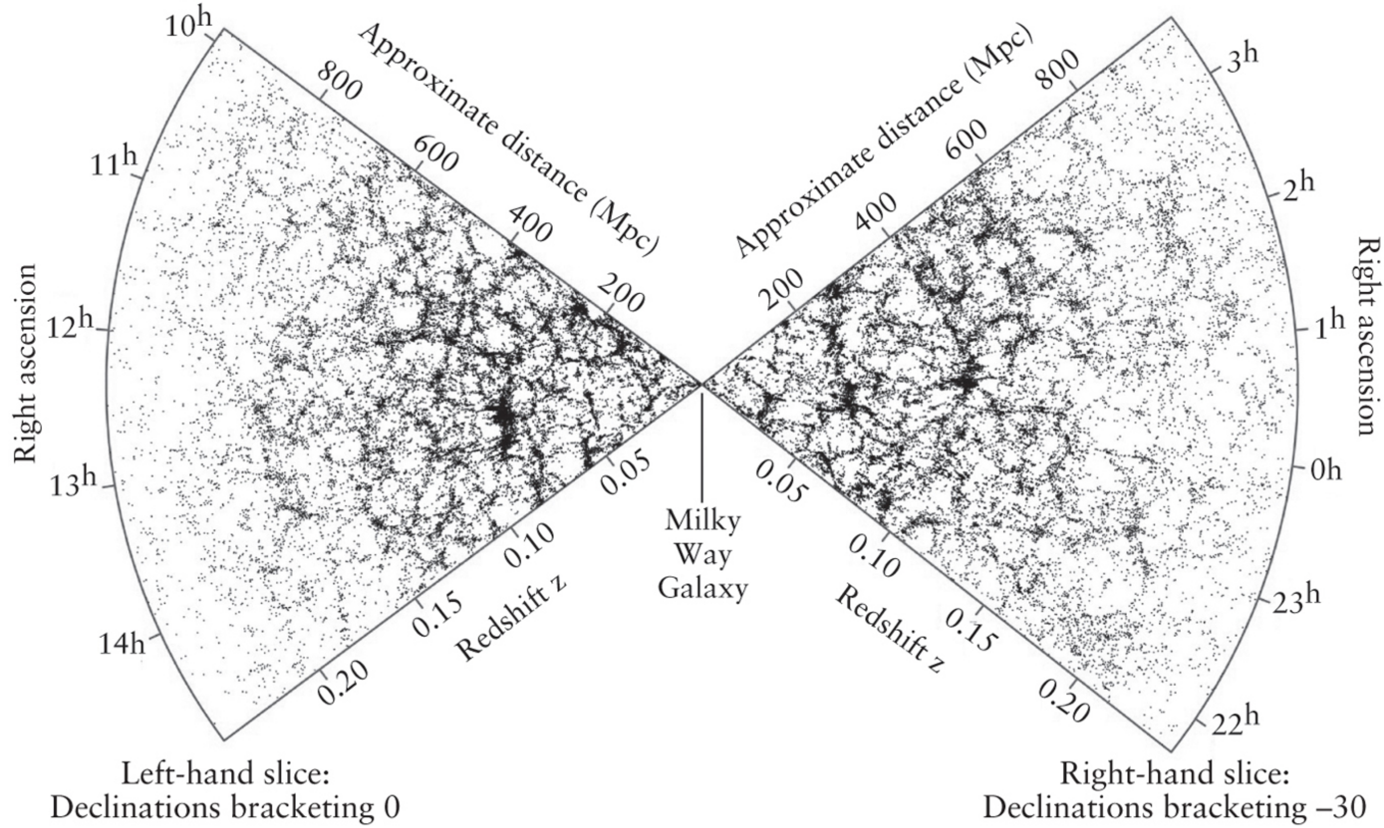
Clusters of galaxies are themselves grouped together in huge associations called ***superclusters.*** A typical supercluster contains dozens of individual clusters spread over a region of space up to 150 million light years across.

Structure in the Nearby Universe



Superclusters lie along filaments.
(2MASS Infrared image)

Large Scale Distribution of Galaxies



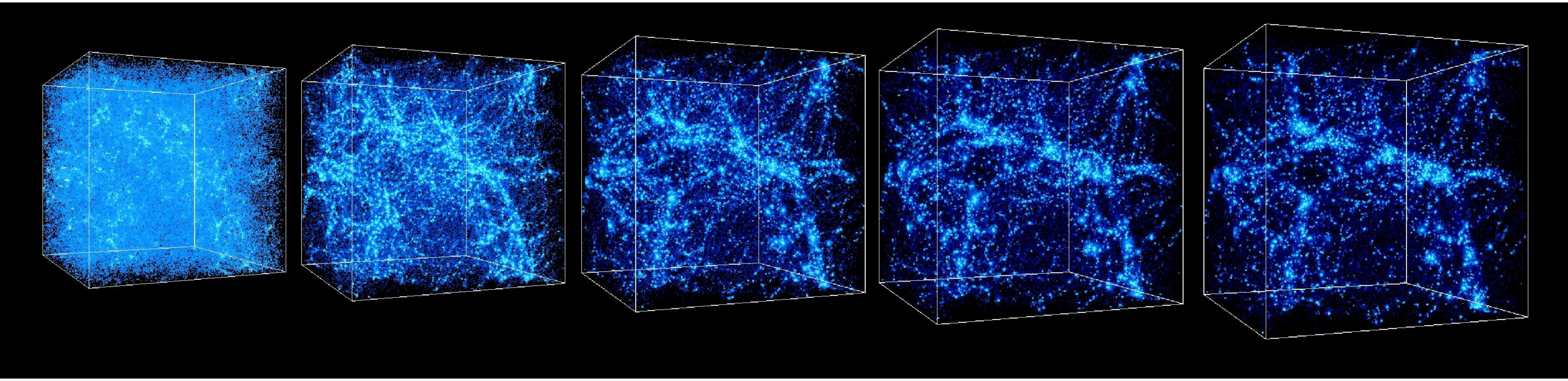
(a) The 2dF galaxy survey

- Each dot represents a galaxy.
- The map extends out to nearly 3 billion light-years from Earth.
- The galaxies lie on sheets, the largest structures known in the universe.
- There are enormous voids where few galaxies are found.
- On scales much larger than 100 Mpc, the distribution of galaxies appears to be roughly uniform.

Large Scale Structure

- Galaxies and clusters of galaxies are organized on irregular sheets separated by voids containing few galaxies.
- The density fluctuations seen in the cosmic microwave background are likely the seeds for the formation of the sheets, clusters, and galaxies.
- How that process occurs is now being worked out.

Simulation of Structure Formation



Movie

Dark Matter in Clusters of Galaxies

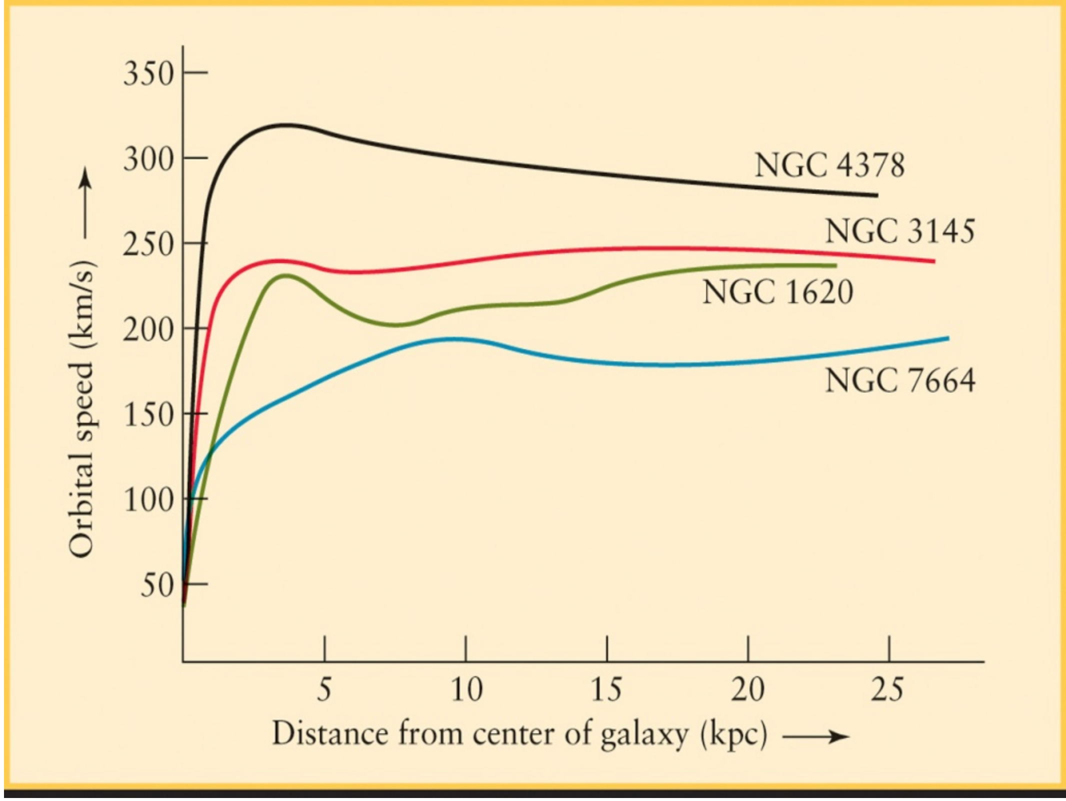
What evidence do we have that there is hidden mass in the Galaxy?

A) We observe cool clouds of hydrogen.
B) We infer this from the oscillation periods of RR Lyrae variable stars in globular clusters.
C) We observe flat rotation curve for stars in the Milky Way at large distances from the Galactic center?
D) We observe dusty regions in the Galactic plane.

The mass of the Milky Way is best determined by

A) measuring the total amount of hydrogen gas using the 21 cm line
B) counting the stars is contains
C) determining the gravitational force acting on stars
D) measuring the distribution of globular clusters

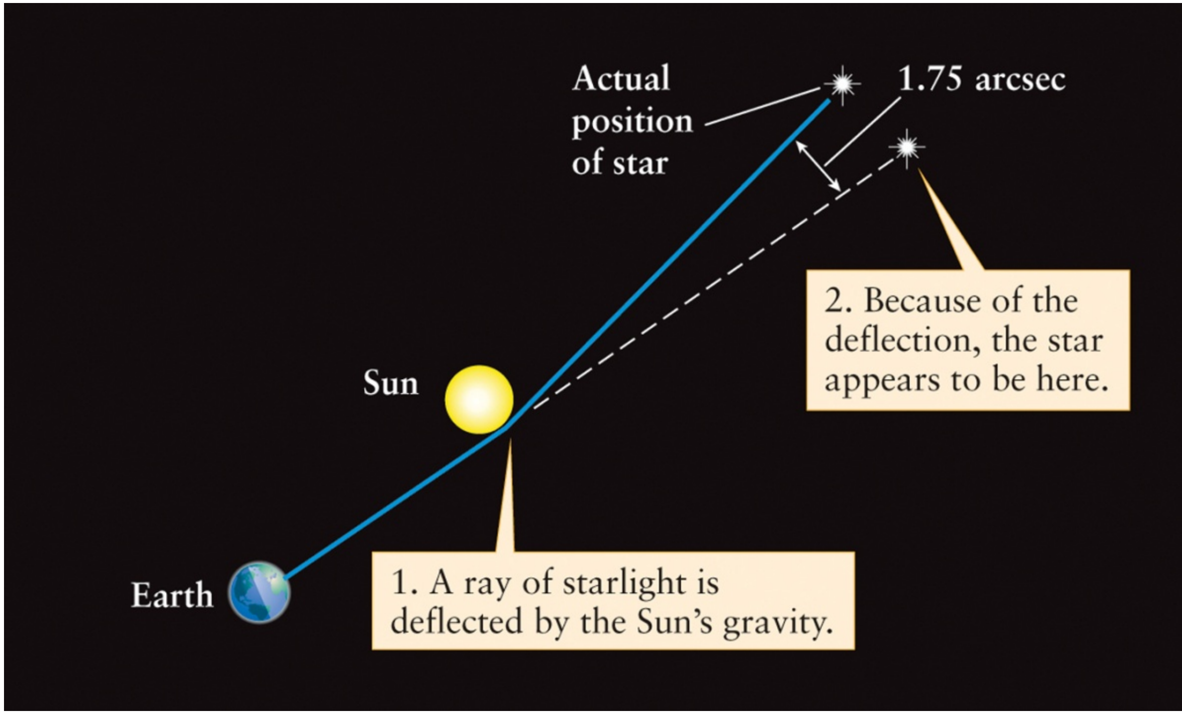
Dark matter can be inferred from motions of stars in galaxies or galaxies in clusters.



• Most spiral galaxies have flat rotation curves like the Milky Way, so they have dark matter.

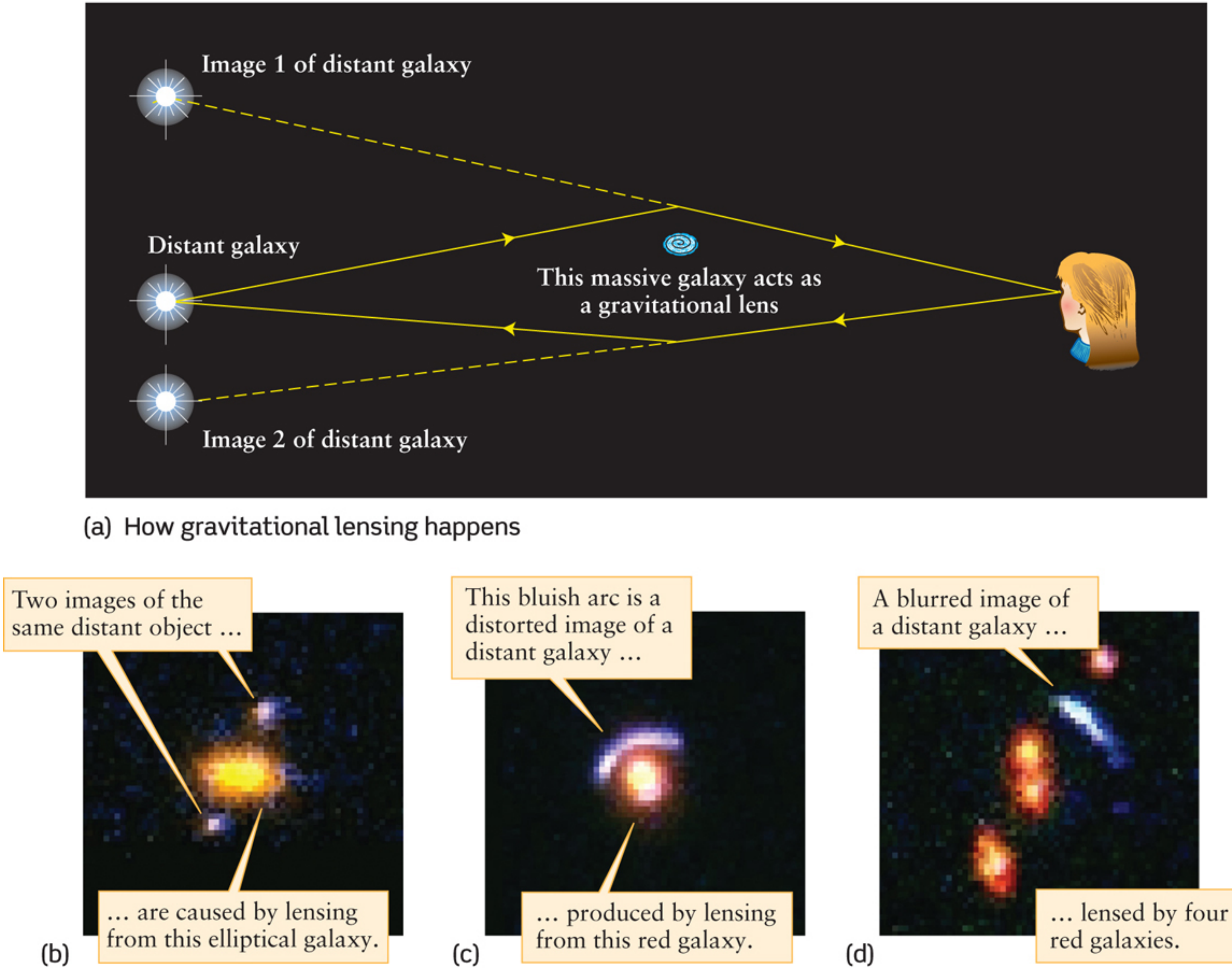
• One can examine how galaxies within a cluster orbit each other. Again, the orbital speeds are higher than expected if only visible matter (including gas visible in X-rays) is taken into account. Thus, clusters of galaxies have dark matter.

Gravitational Deflection of Light

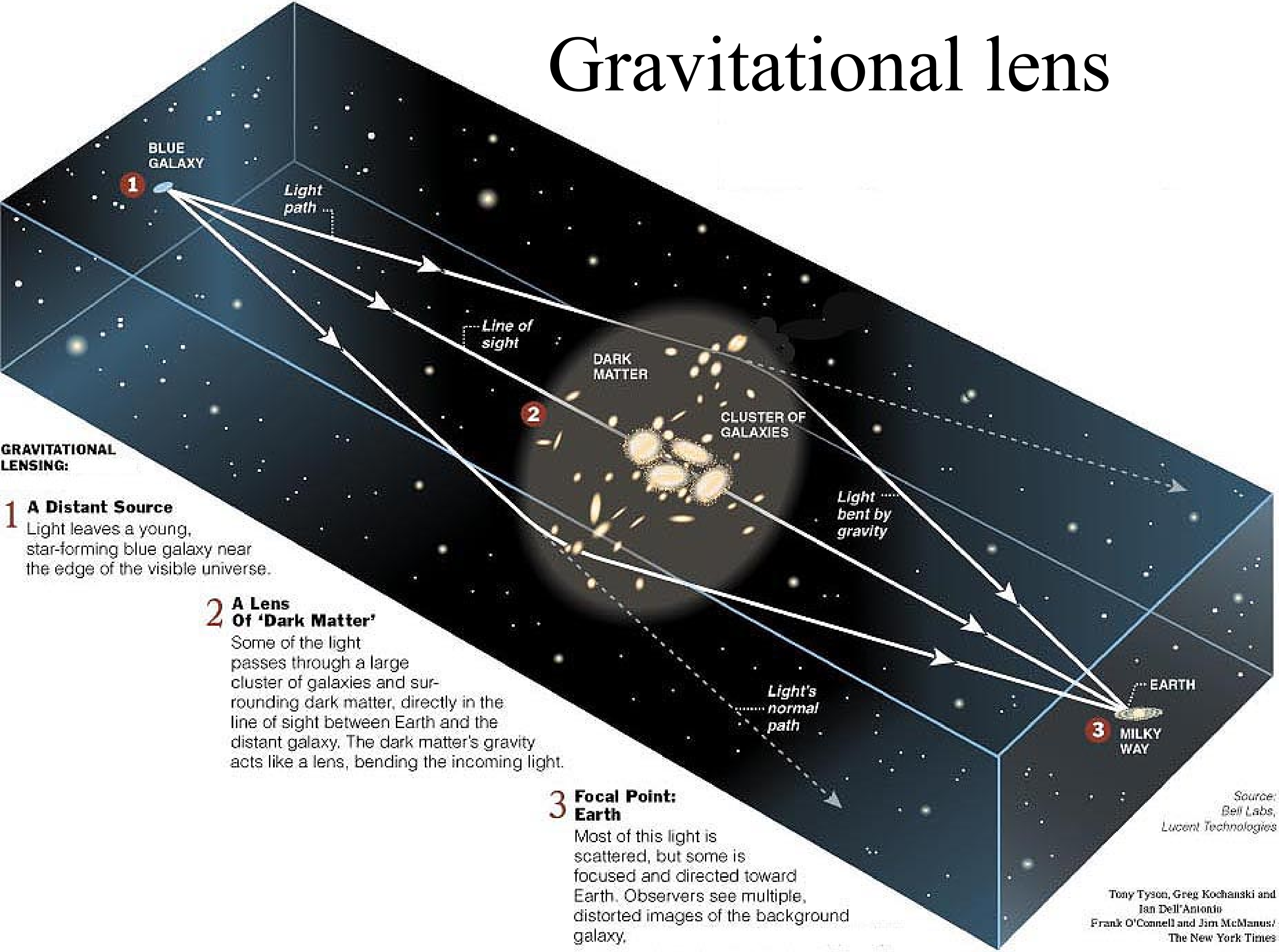


- A massive object warps spacetime around the itself and causes light rays traveling close to the object to move on curved paths.
- This was verified by Eddington for light deflection around the Sun measured during a solar eclipse.

Gravitational Lensing

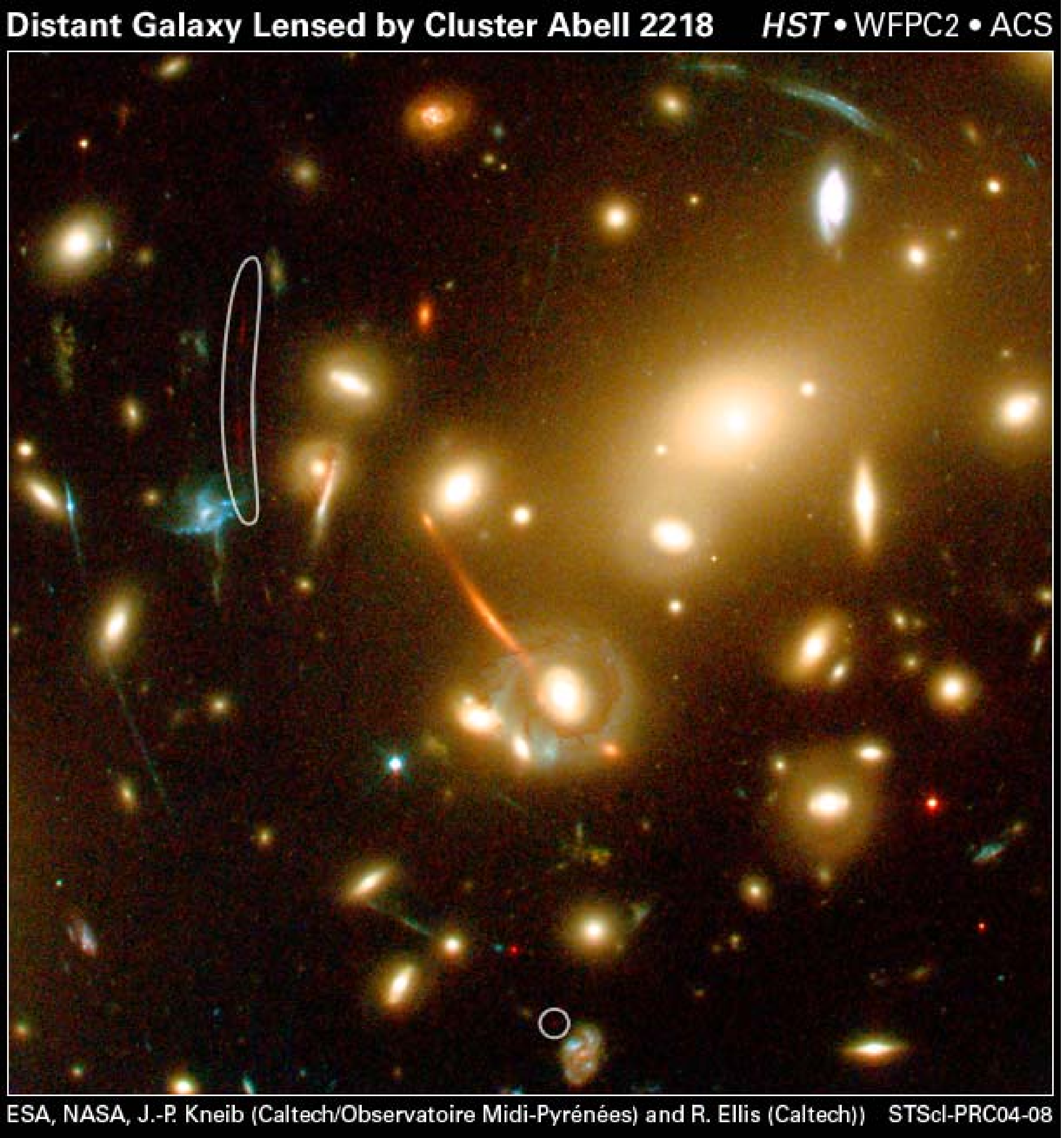


Gravitational lens



Gravitational lenses

- By measuring multiple images of one source, we can figure out the total mass in the lens. This provides an independent confirmation of dark matter.
- A lense can act as a huge telescope. The deepest images of the most distant galaxies are obtained with clusters acting as gravitational lenses.



The red Galaxy is 13 billion light years away.

We are seeing it 750 million years after the Big Bang.

We know that dark matter exists in galaxy clusters because galaxies within clusters

A) are moving faster than expected.

B) are being obscured by unseen objects more than expected.

C) are colliding with each other more frequently than expected.

D) contain more luminous O and B stars than expected.

Another way we know that dark matter exists in galaxy clusters is because

A) clusters produce large quantities of X-rays.

B) clusters bend light from background galaxies less than expected.

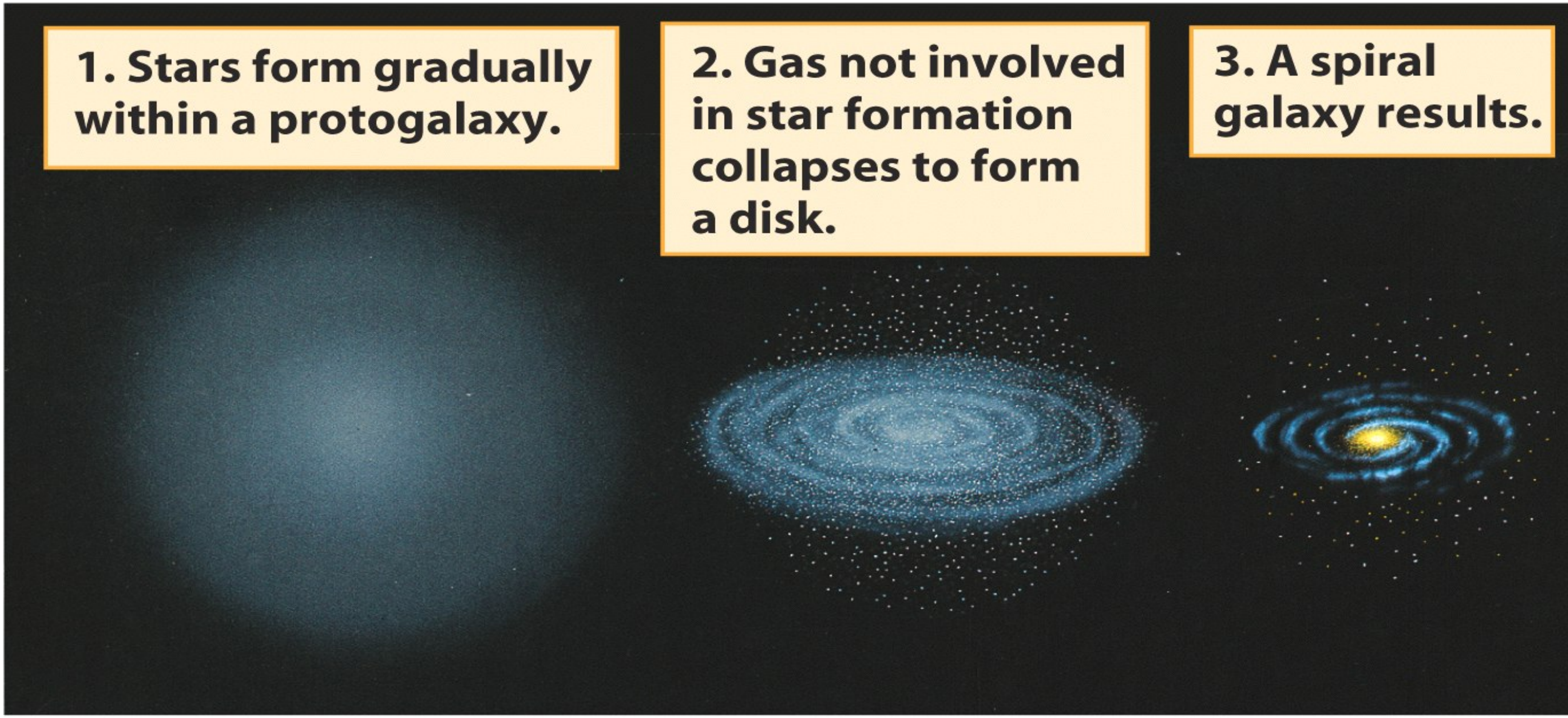
C) most clusters have an elliptical galaxy at their center.

D) clusters bend light from background galaxies more than expected.

Formation of Galaxies

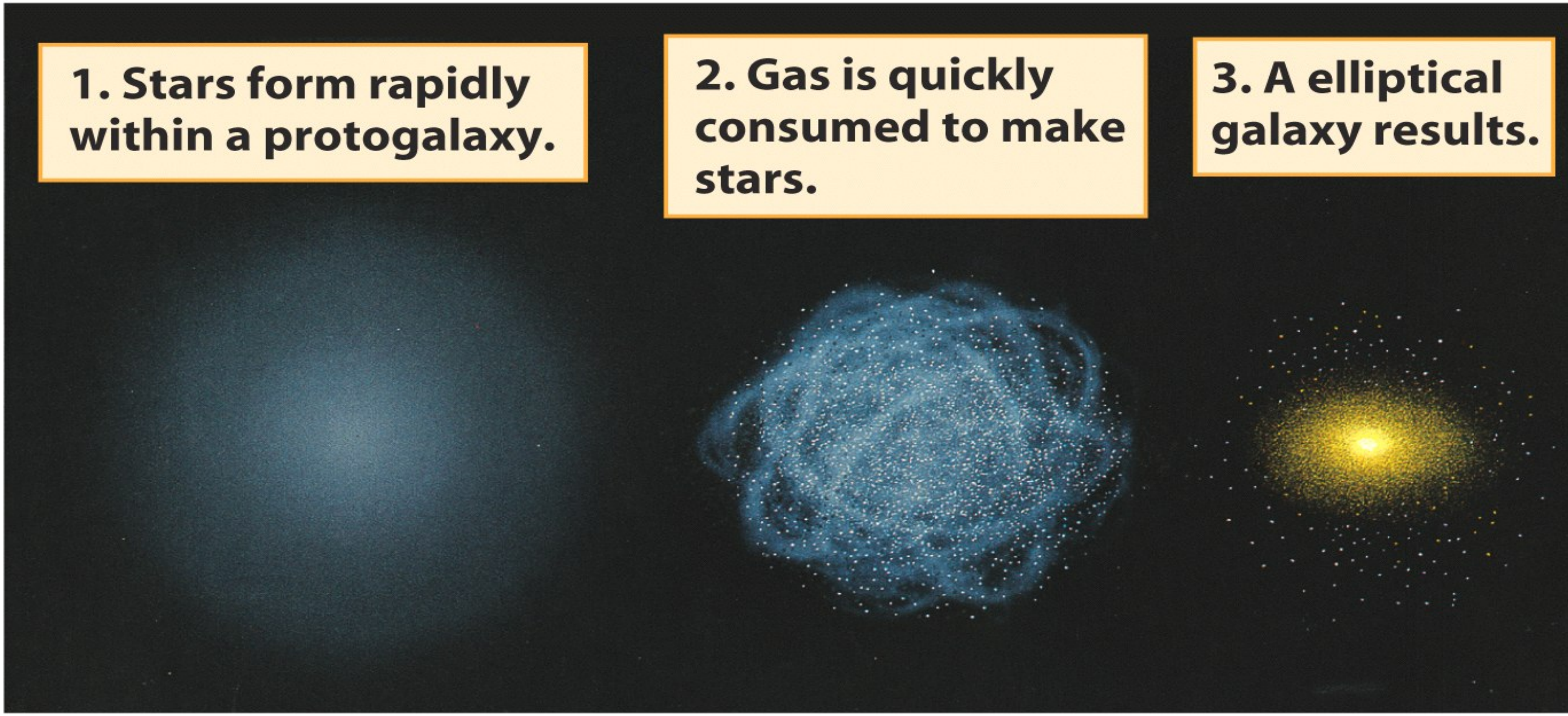
- Spiral versus elliptical
- Young Universe
- Collisions and Interactions
- Starbursts
- Elliptical galaxies

Formation of a Spiral Galaxy



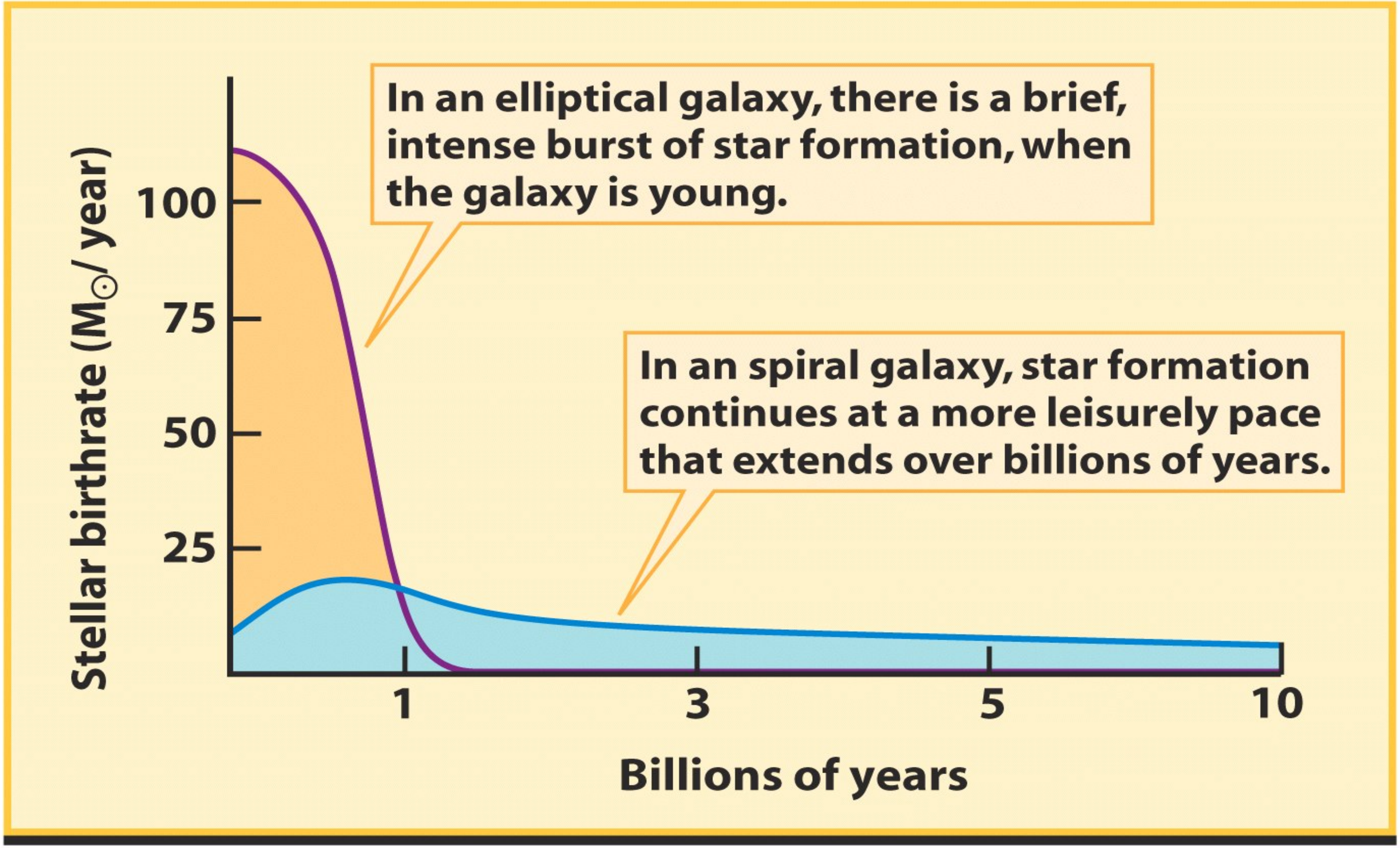
Formation of a spiral galaxy

Formation of an Elliptical Galaxy



Formation of an elliptical galaxy

Stellar Birthrate in Galaxies



The stellar birthrate in galaxies

Formation of Galaxies

- This picture of galaxy formation is incomplete
- Mergers, collisions, and interactions between galaxies are very important in their formation, particularly in the early stages of the Universe (why?)

Expansion of the Universe

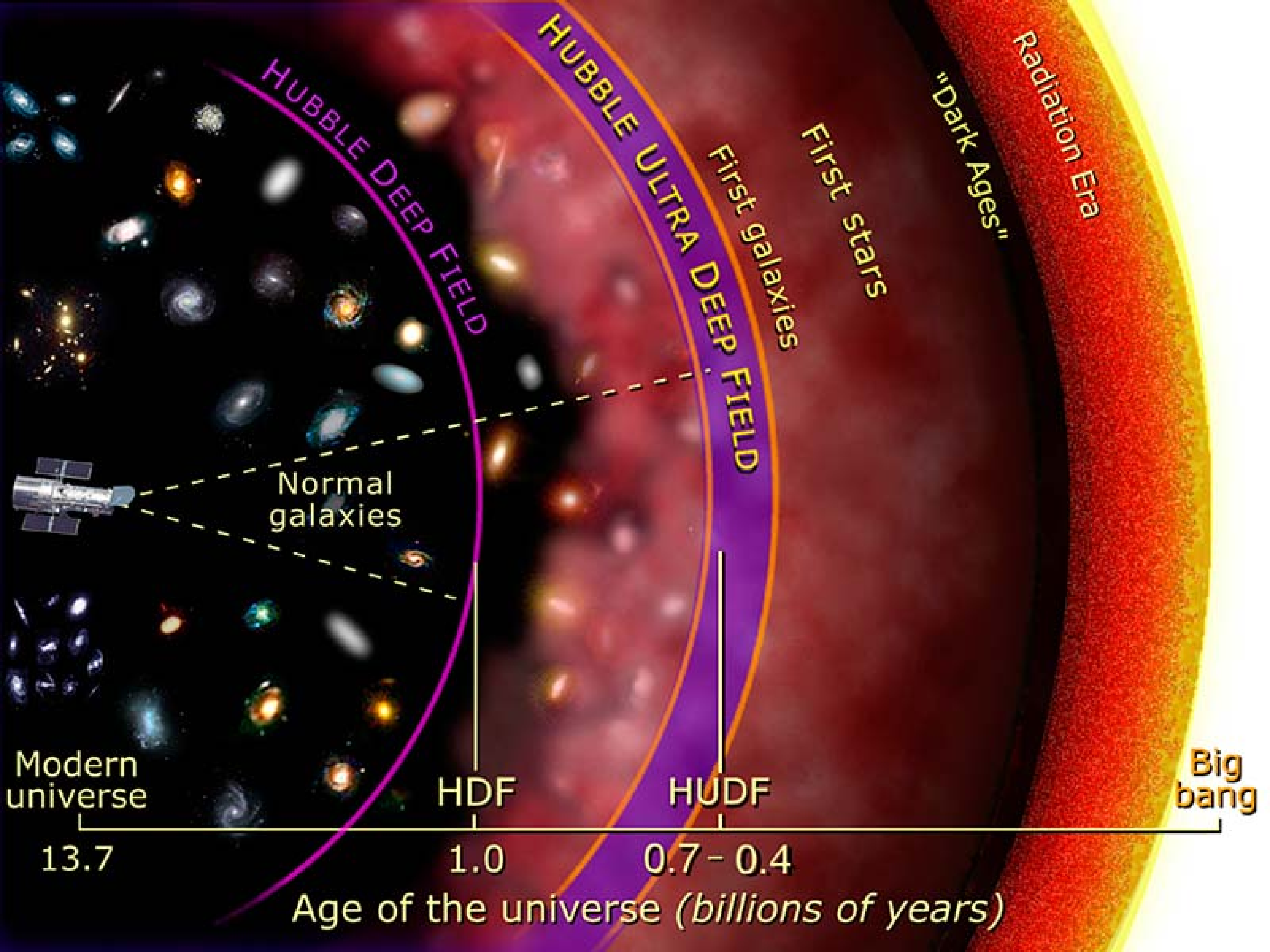
- The Universe is expanding
- This means that the Universe used to be smaller
- In the early stages of the Universe galaxies were closer together, therefore, they interacted more
- Since galaxies can merge, there were also more galaxies in the past

Young Universe

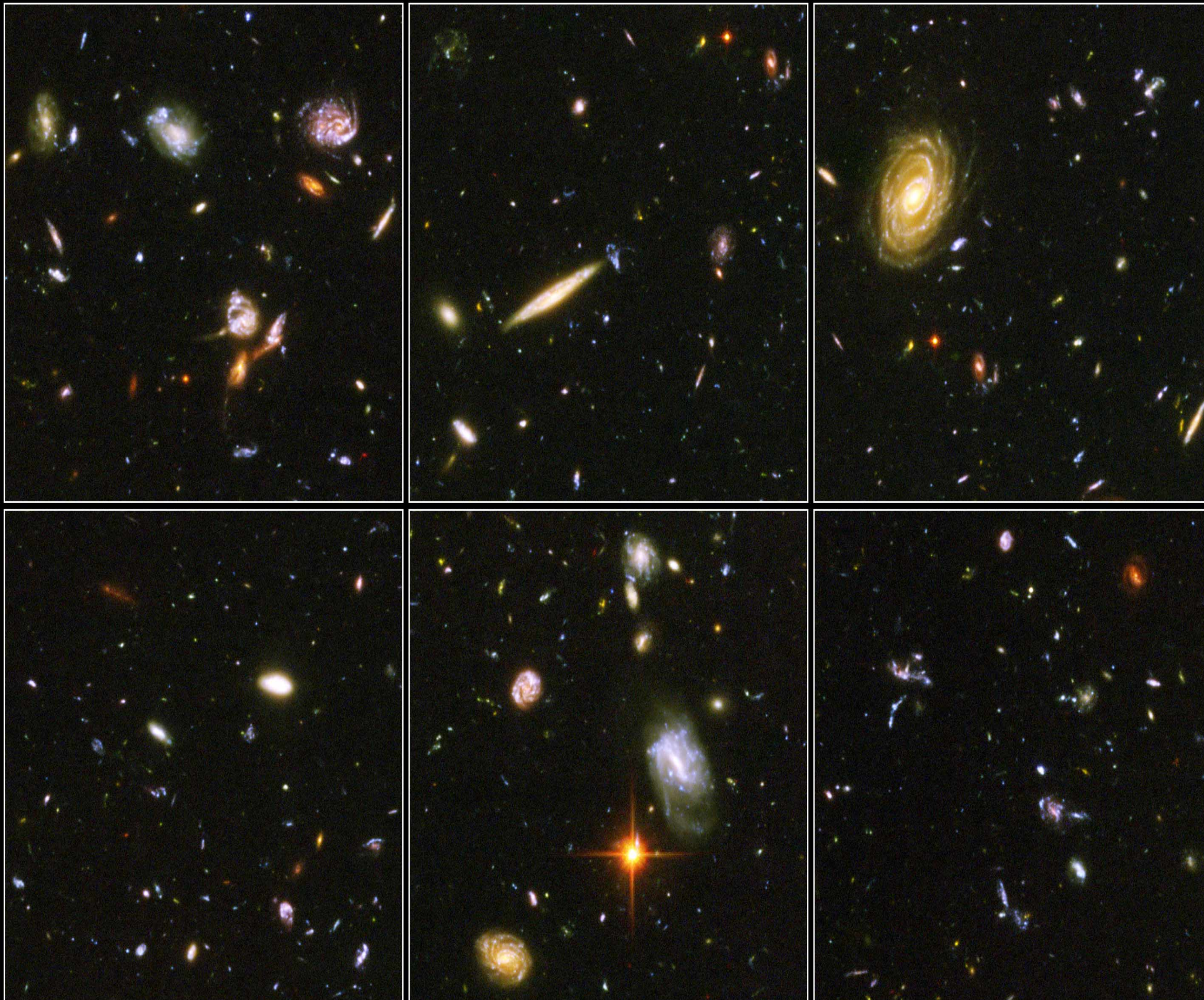
Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a



Hubble Deep Field
Hubble Ultra Deep Field
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

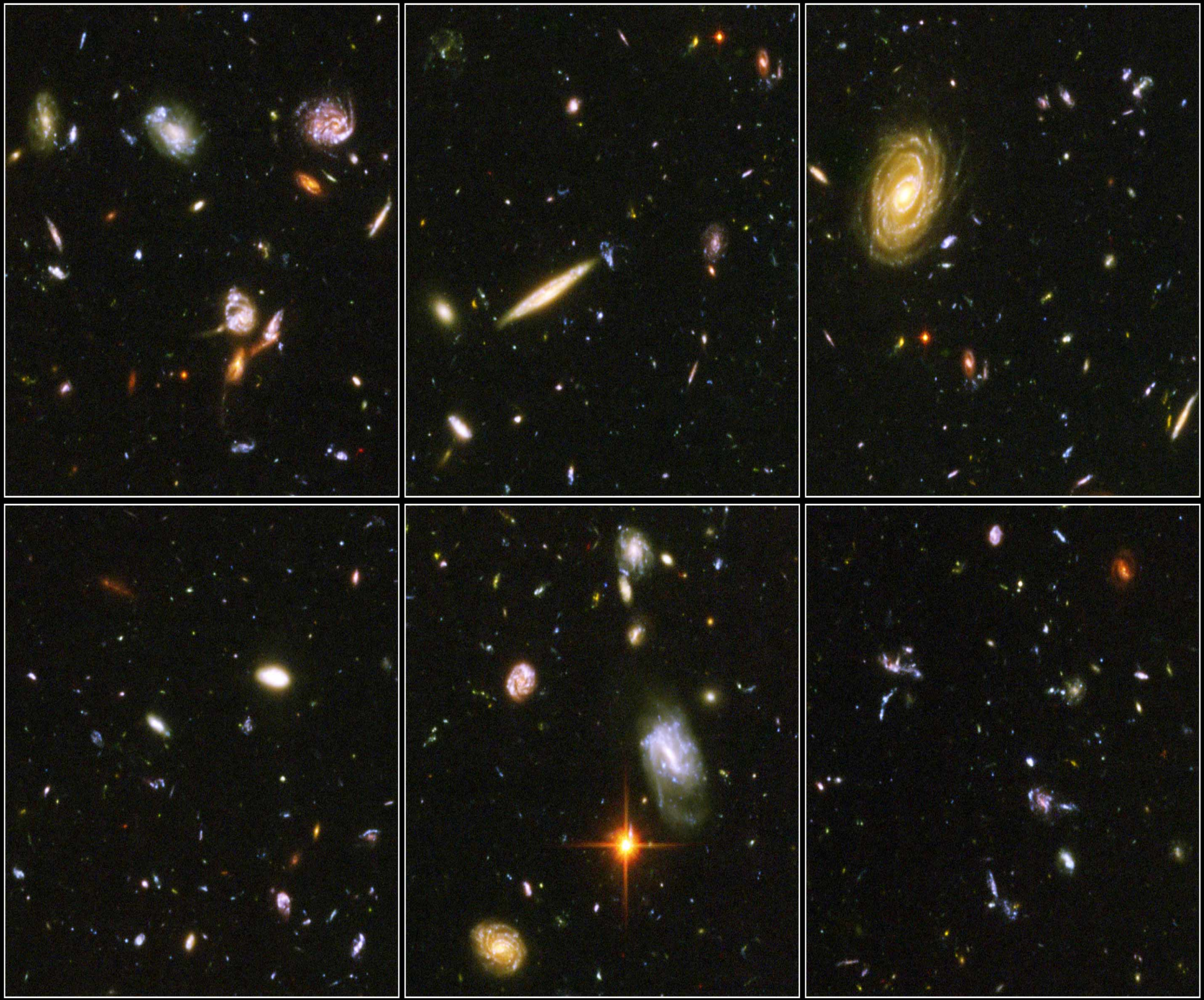


Hubble Ultra Deep Field Details

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07c



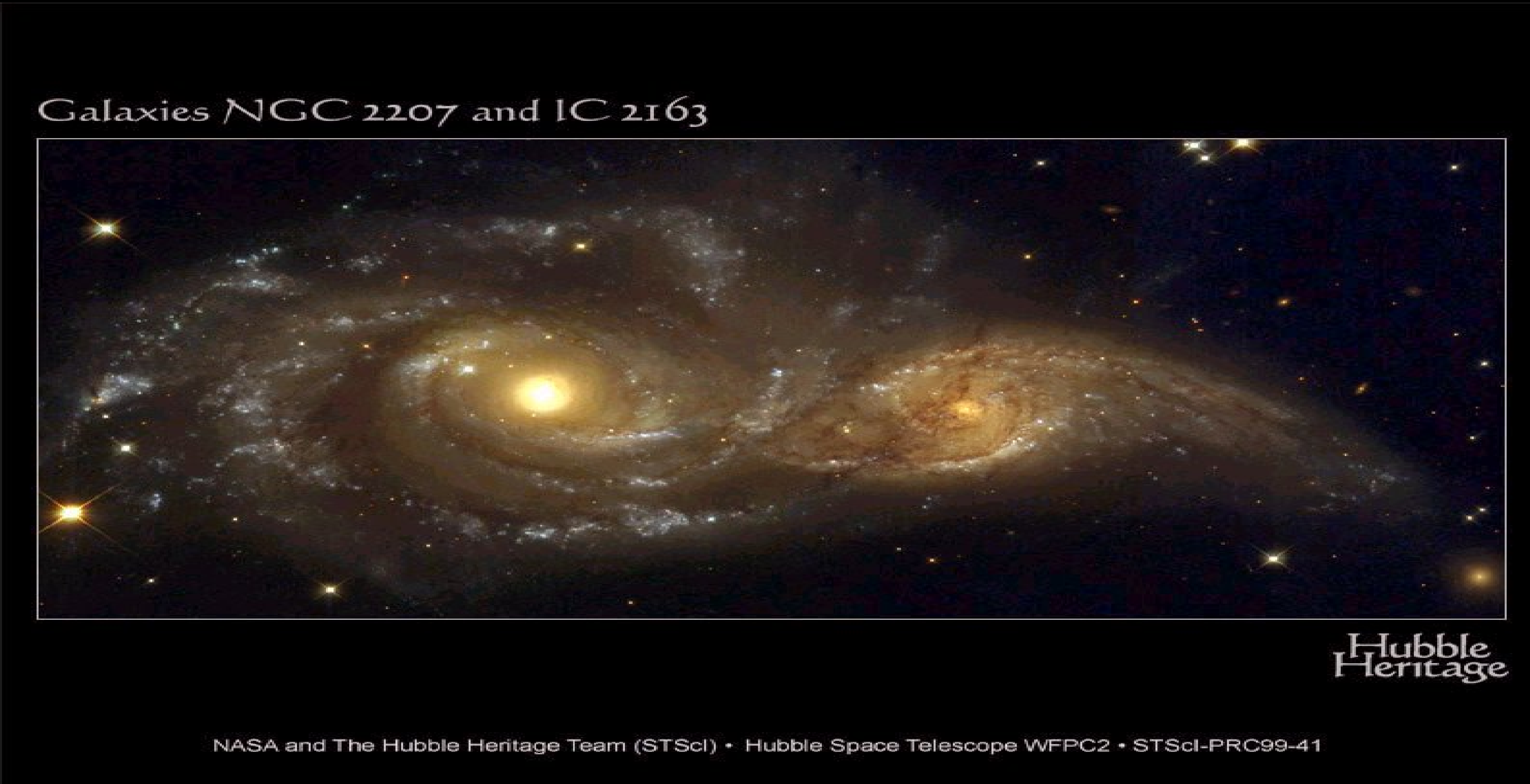
Hubble Ultra Deep Field Details

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

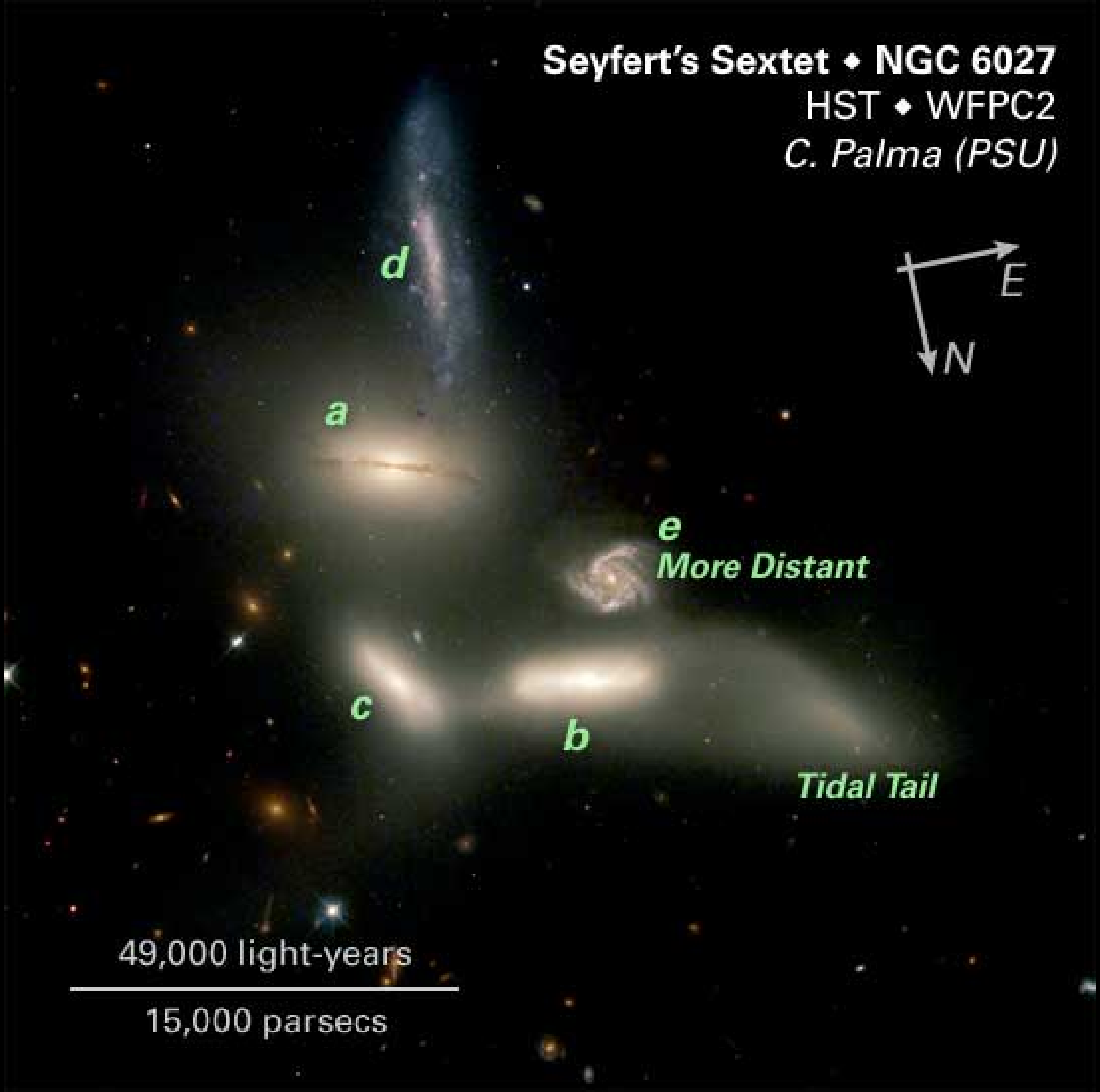
STScI-PRC04-07c

Colliding galaxies

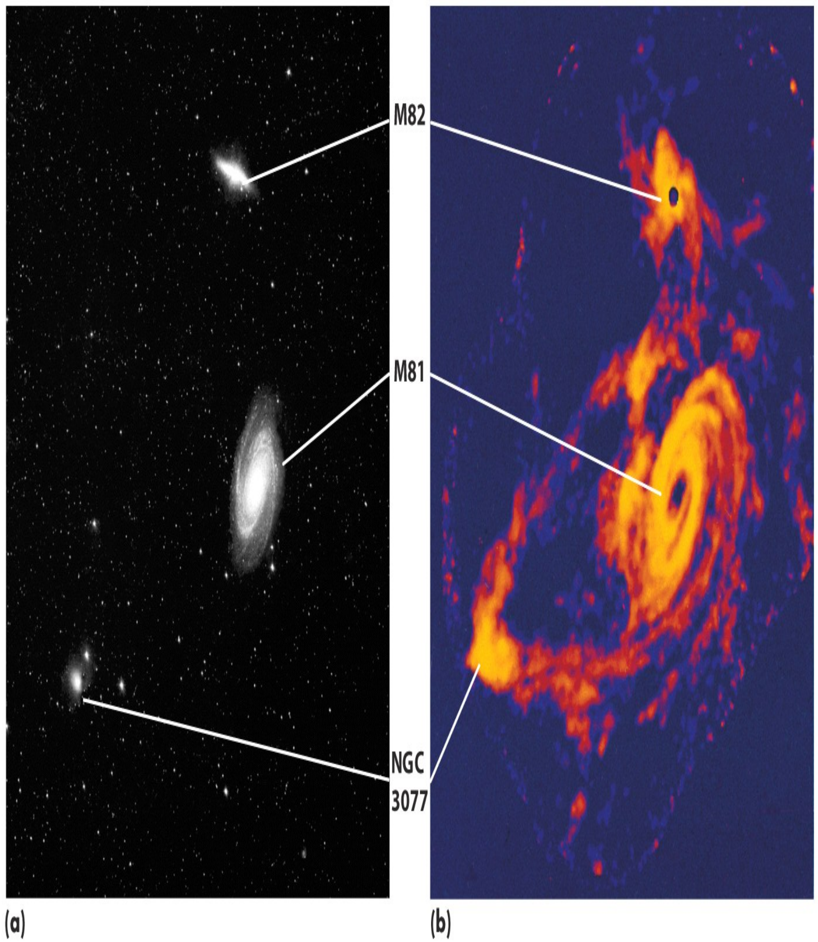


The Mice

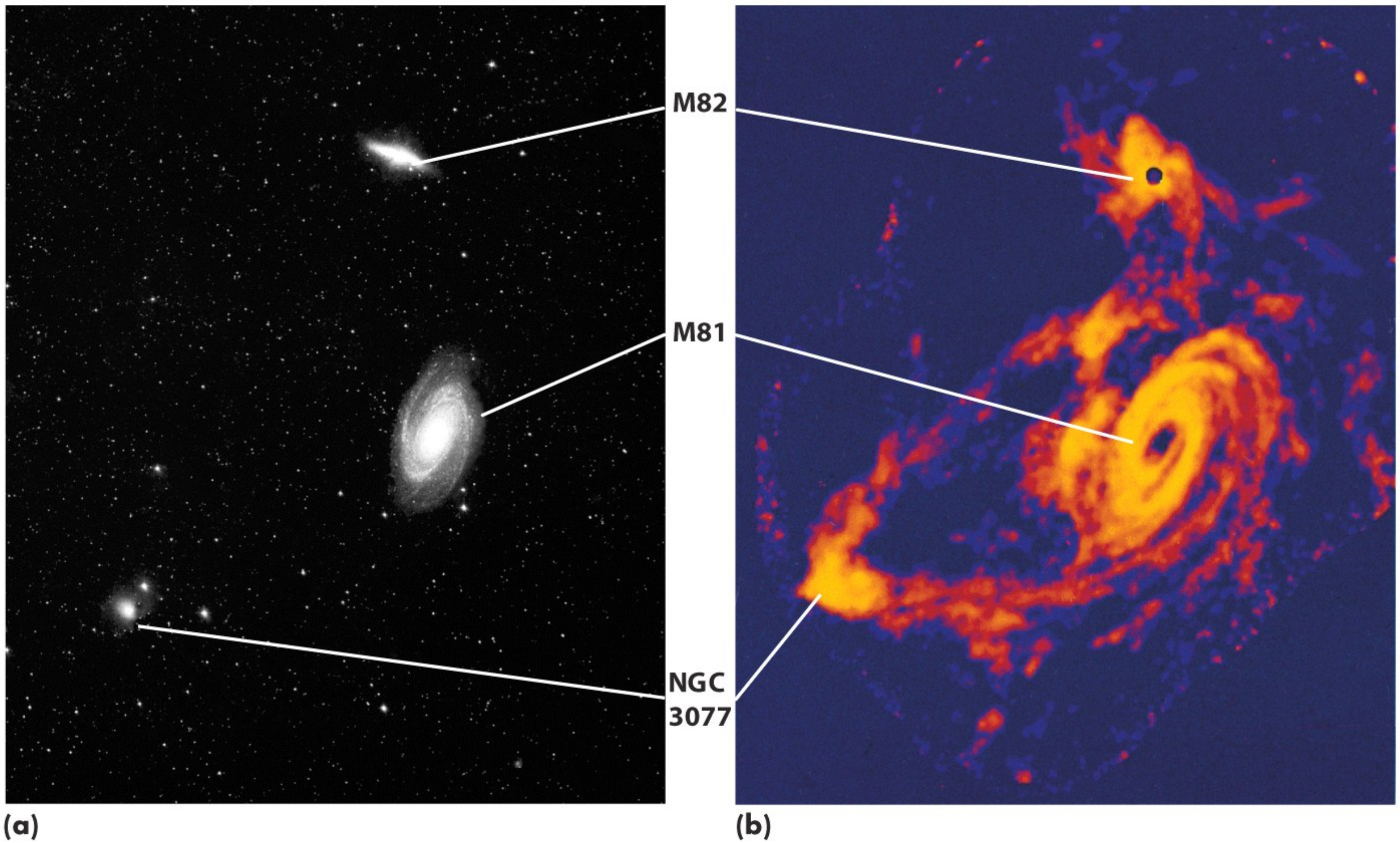
Cartwheel galaxy


Seyfert's Sextet ◆ NGC 6027
HST ◆ WFPC2
C. Palma (PSU)
d
E
N
a
e
More Distant
c
b
Tidal Tail
49,000 light-years
15,000 parsecs

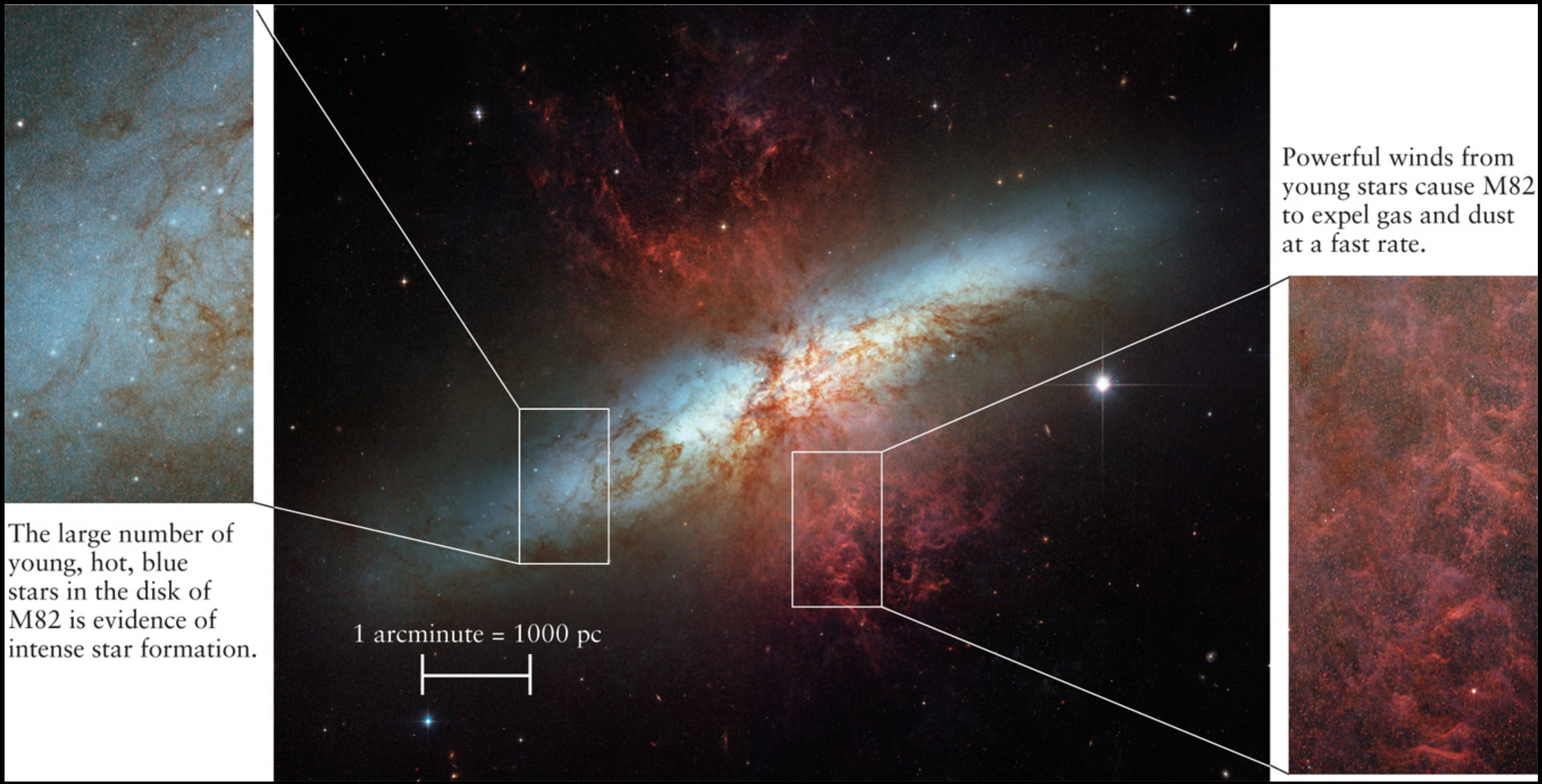
Interacting galaxies



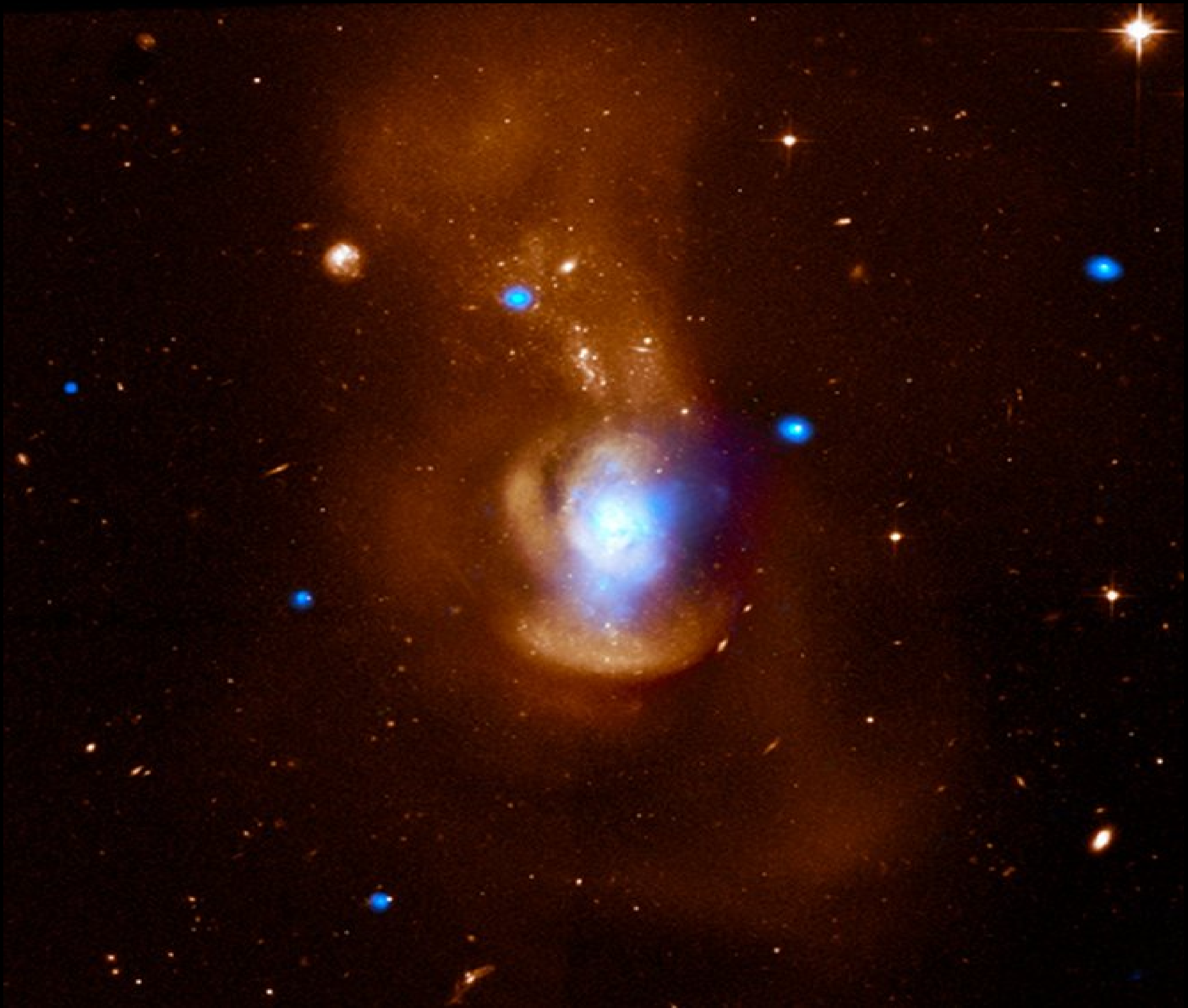
Interacting galaxies



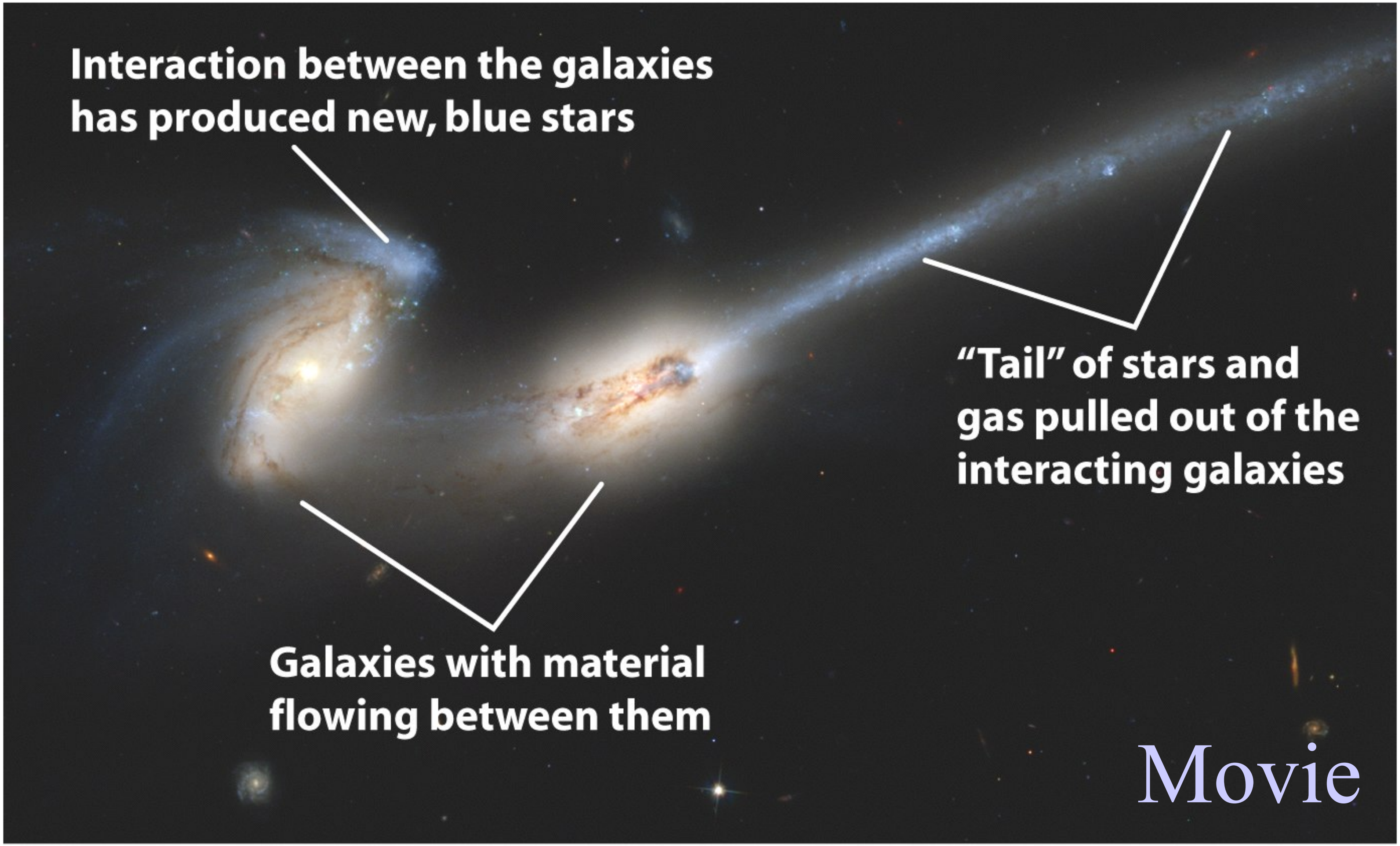
Starburst galaxy – M82



The 'Medusa' in optical and X-rays



Colliding galaxies

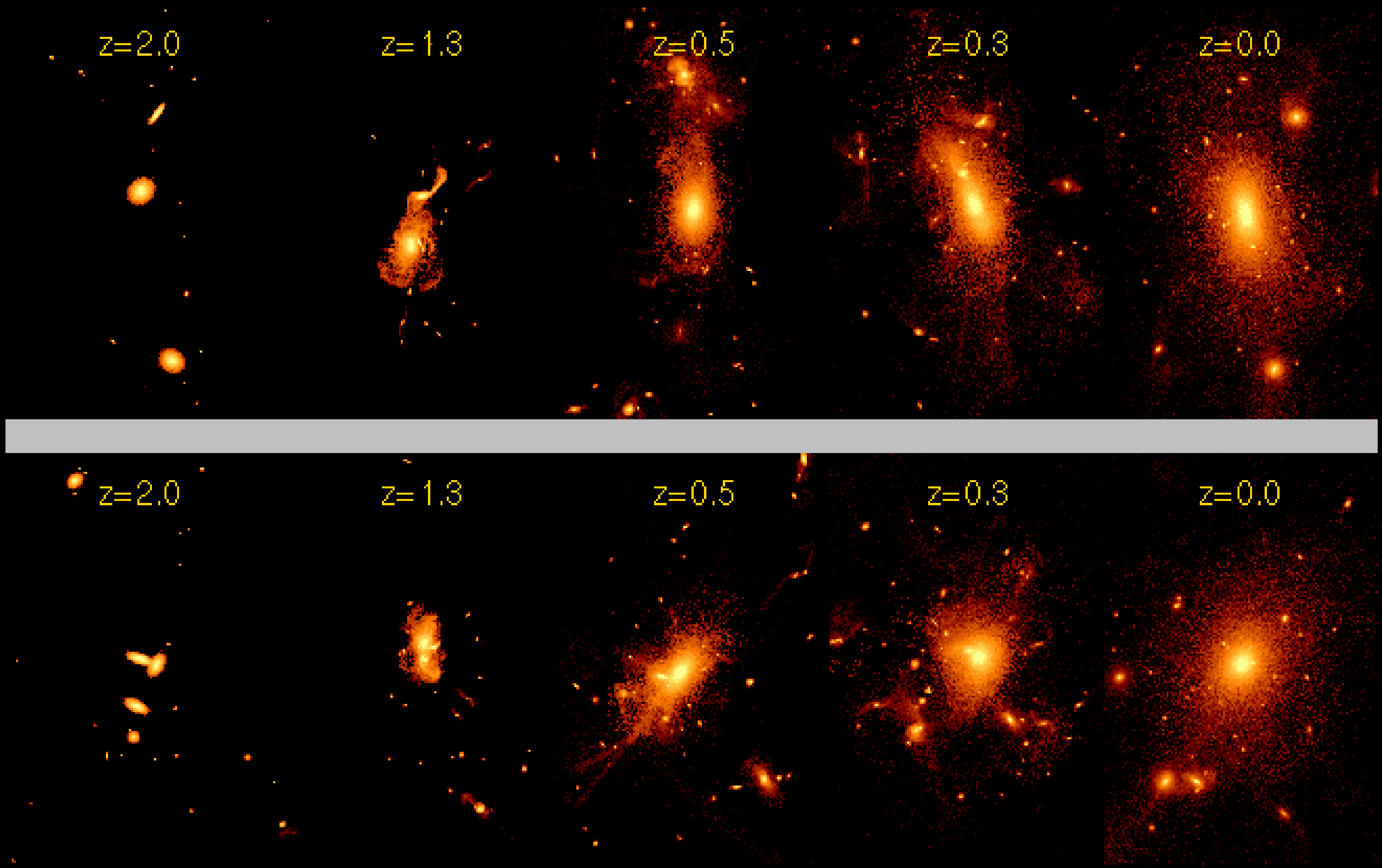


Movie

Galaxy interactions

- Interactions can rip stars out of galaxies, producing tidal tails
- Interactions can disturb gas in and between galaxies, producing starbursts
- Collisions can randomize stellar orbits leading to the formation of elliptical galaxies

Formation of an Elliptical Galaxy



Movie

Galaxy growth via interactions

- Galaxies initially form from mergers of several gas clouds
- Galaxies then are changed by interactions
- Galaxies grow gradually by galactic cannibalism
- Interactions disturb gas leading to starbursts
- Collisions can randomize stellar orbits leading to the formation of elliptical galaxies

Early in the history of the universe, which was NOT true?

A) galaxies were closer together
B) there were more galaxies
C) galaxies interacted more frequently
D) there were more elliptical galaxies

Which is **not** true of galaxy collisions?

A) They can randomize stellar orbits

B) They were more common in the early universe

C) They occur only between small galaxies

D) They lead to star formation

Review Questions

- What was the definitive evidence showing that “spiral nebulae” are actually entire galaxies outside of the the Milky Way?
- What are the types of galaxies?
- How do the rotation patterns of stars differ in elliptical versus spiral galaxies?
- What is the Local Group?

Review Questions

- How are elliptical versus spiral versus irregular galaxies formed?
- How do the star formation histories of elliptical versus spiral galaxies differ?
- Why do galaxy interactions tend to cause star formation?
- Was the population of galaxies different in the past?