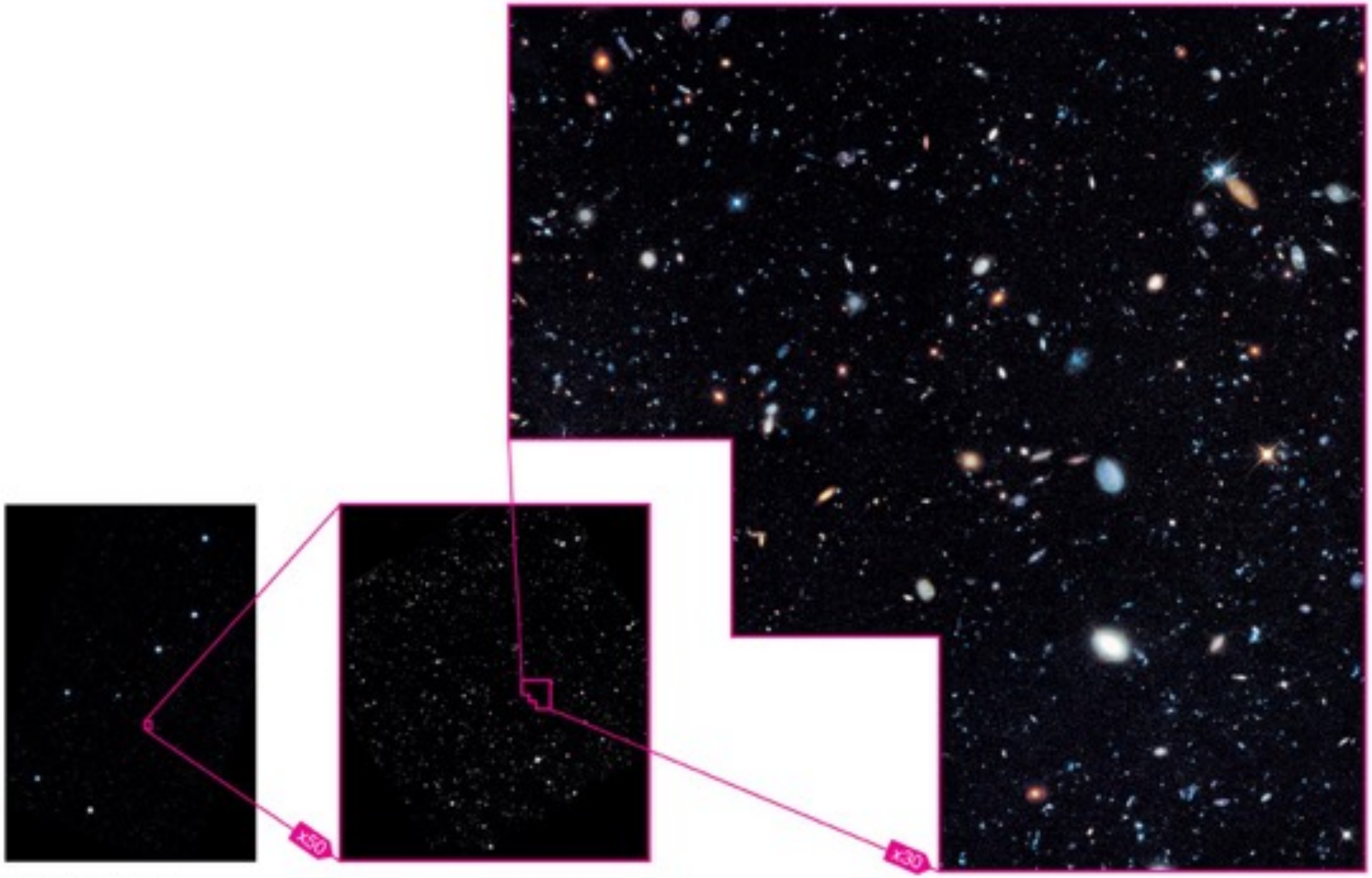
Chapter 20
Galaxies and the Foundation of Modern Cosmology

20.1 Islands of Stars

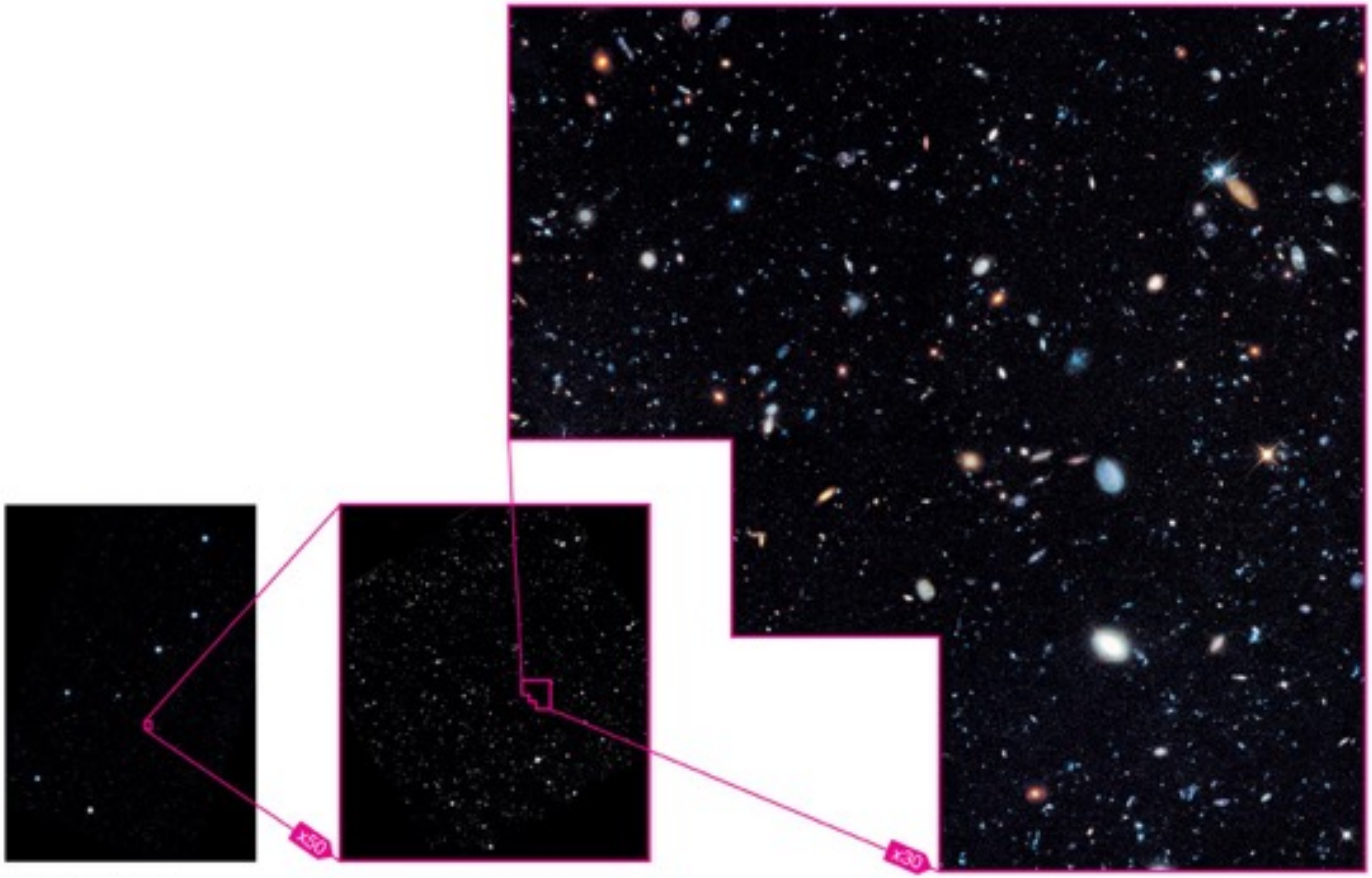
- How are the lives of galaxies connected with the history of the universe?
- What are the three major types of galaxies?
- How are galaxies grouped together?

How are the lives of galaxies connected with the history of the universe?

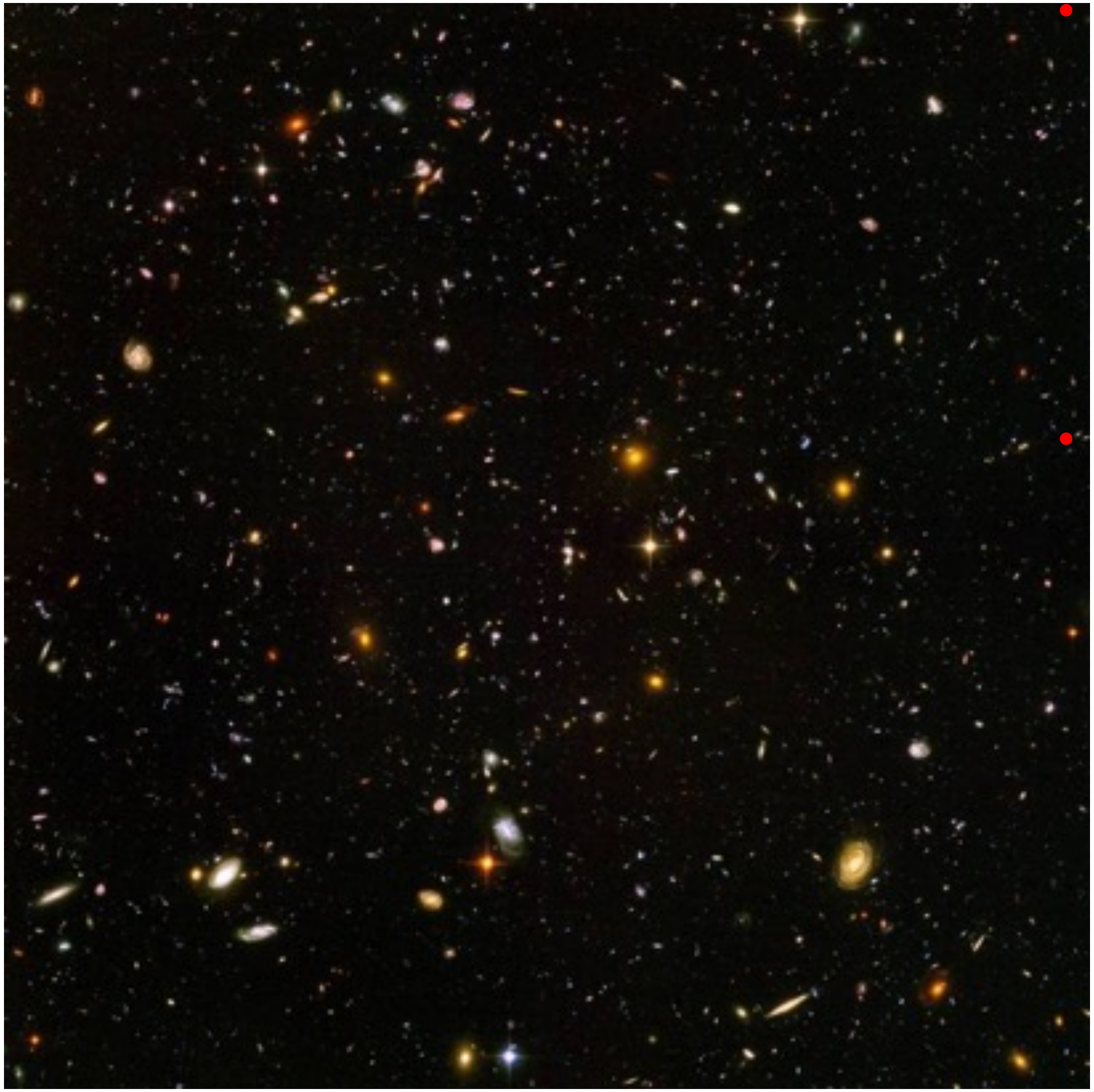


Hubble Deep Field

- Our deepest images of the universe show a great variety of galaxies, some of them billions of light-years away.



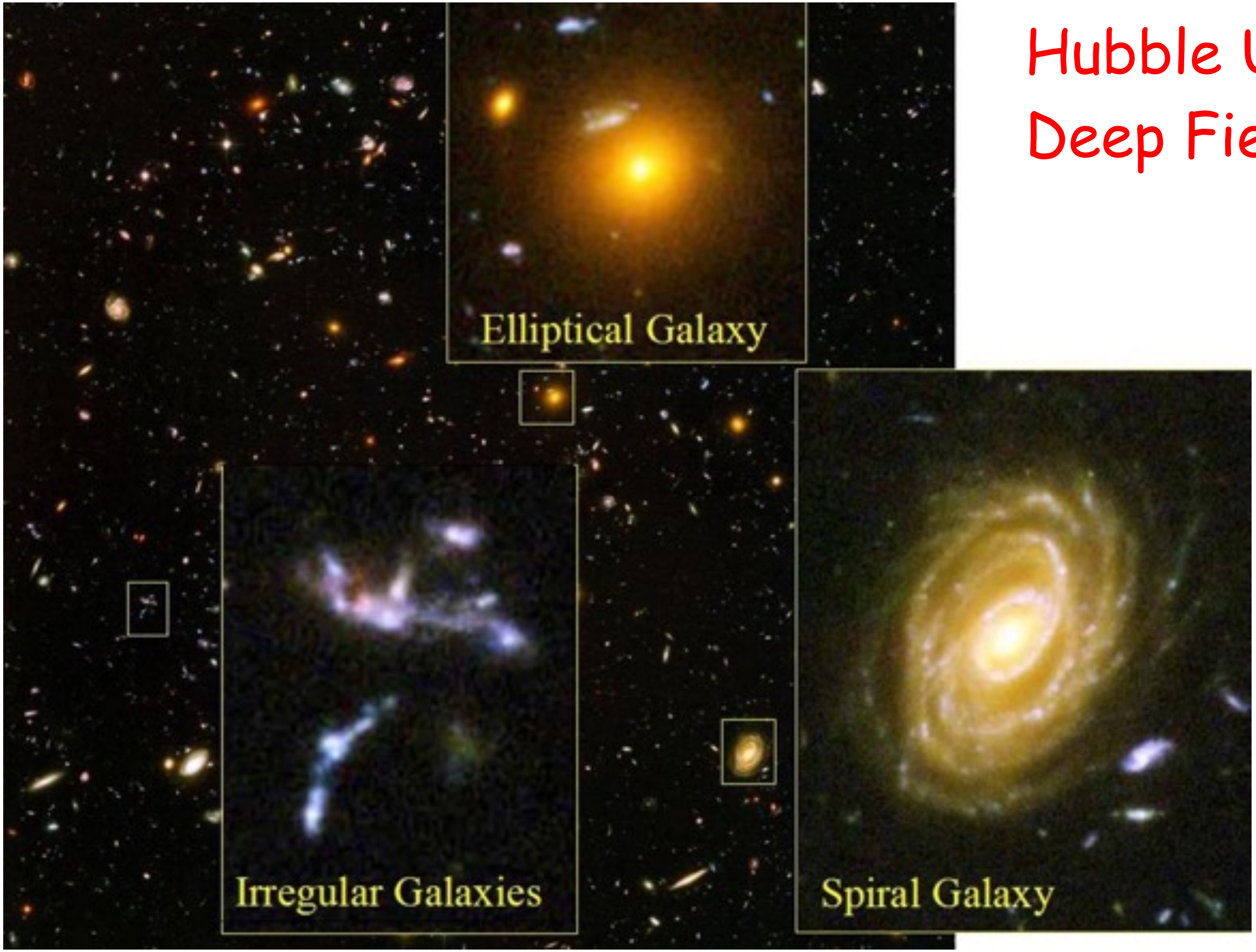
Galaxies and Cosmology



- A galaxy's age, its distance, and the age of the universe are all closely related.
- The study of galaxies is thus intimately connected with **cosmology**— the study of the structure and evolution of the universe.

What are the three major types of galaxies?

Hubble Ultra Deep Field



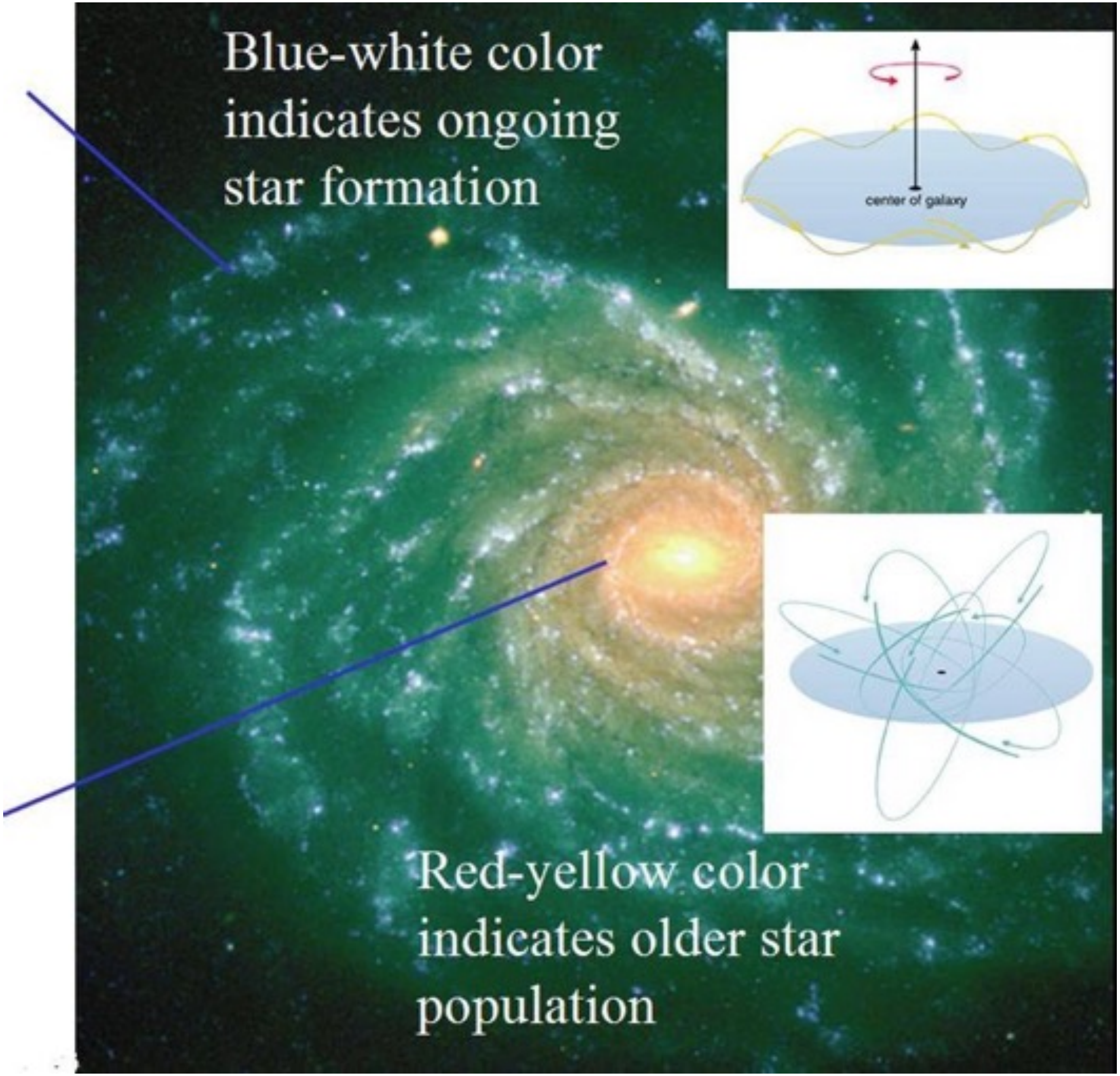

halo
disk
bulge
Spiral Galaxy

Disk component:
stars of all ages, many gas clouds

Spheroidal component:
bulge and halo, old stars, few gas clouds

Disk component: stars of all ages, many gas clouds

Spheroidal component: bulge and halo, old stars, few gas clouds



Thought Question

Why does ongoing star formation lead to a blue-white appearance?

A. There aren't any red or yellow stars.
B. Short-lived blue stars outshine the others.
C. Gas in the disk scatters blue light.

Barred spiral galaxy: has a bar of stars across the bulge

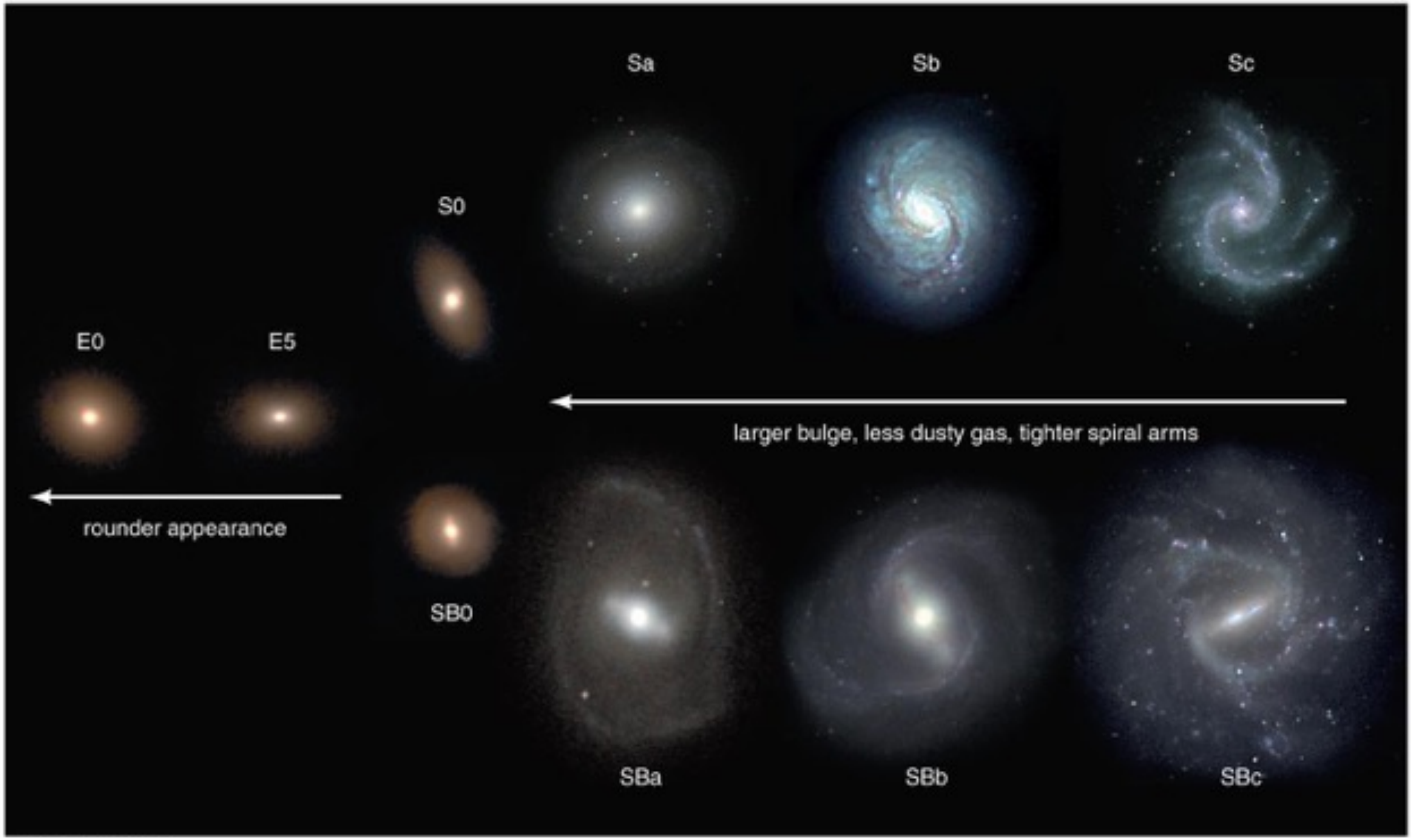
Lenticular galaxy: has a disk like a spiral galaxy but much less dusty gas (intermediate between spiral and elliptical)

Elliptical galaxy: all spheroidal component, virtually no disk component

Red-yellow color indicates older star population.

Irregular galaxy

Blue-white color indicates ongoing star formation.



Spheroid dominates

Hubble's galaxy classes

Disk dominates

How are galaxies grouped together?

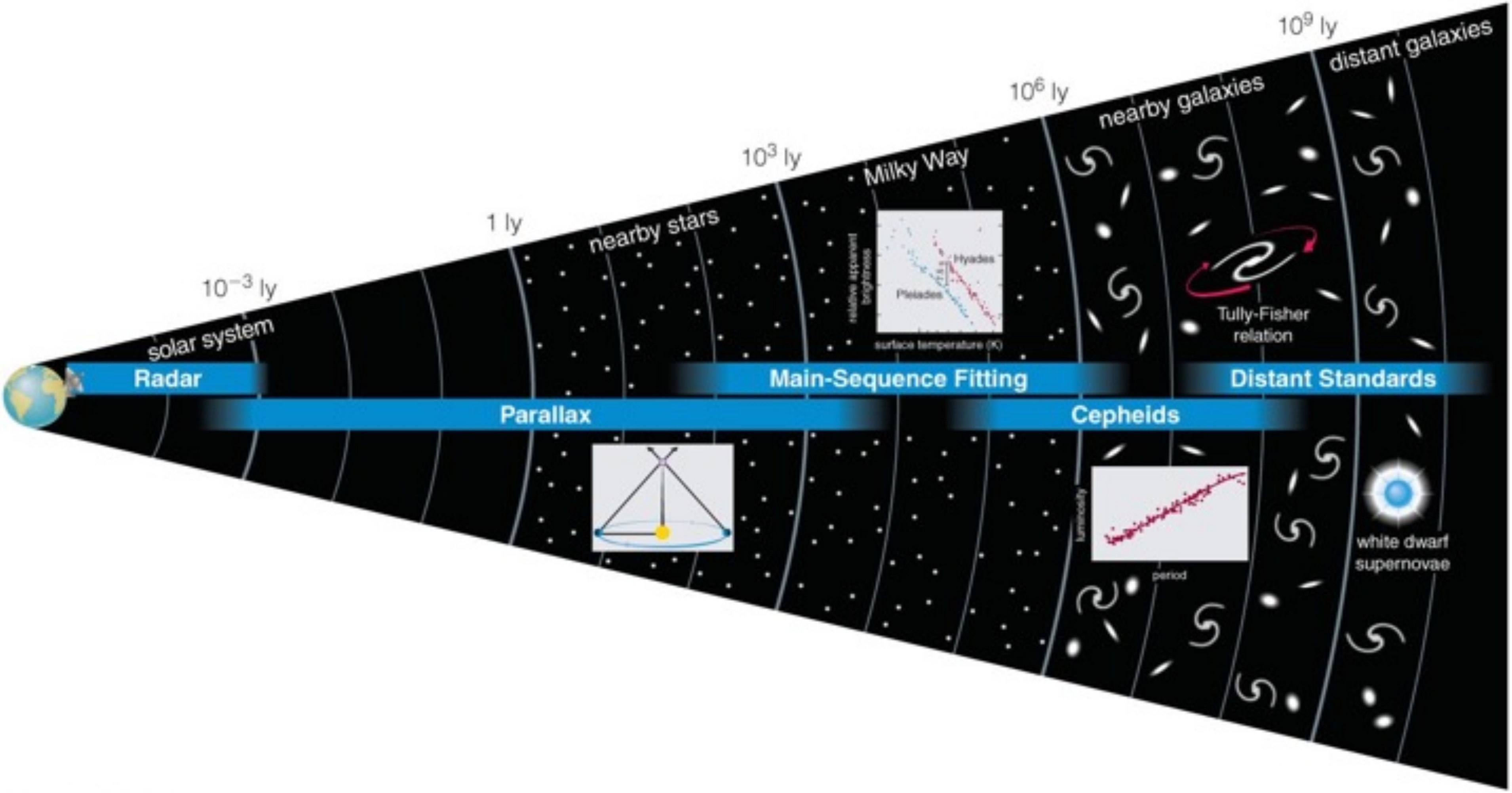
Spiral galaxies are often found in groups of galaxies (up to a few dozen galaxies).

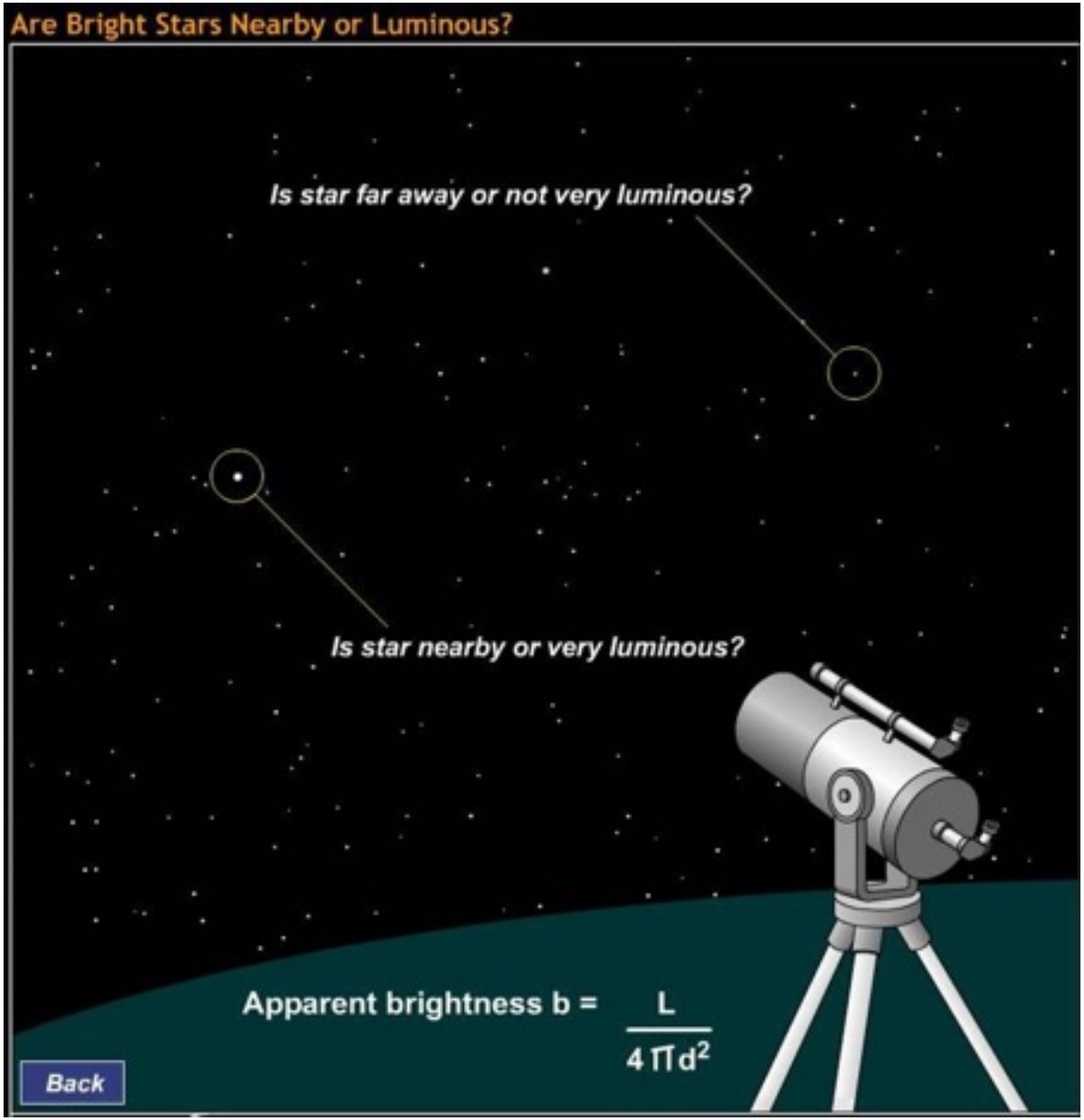
Elliptical galaxies are much more common in huge clusters of galaxies (hundreds to thousands of galaxies).

20.2 Measuring Galactic Distances

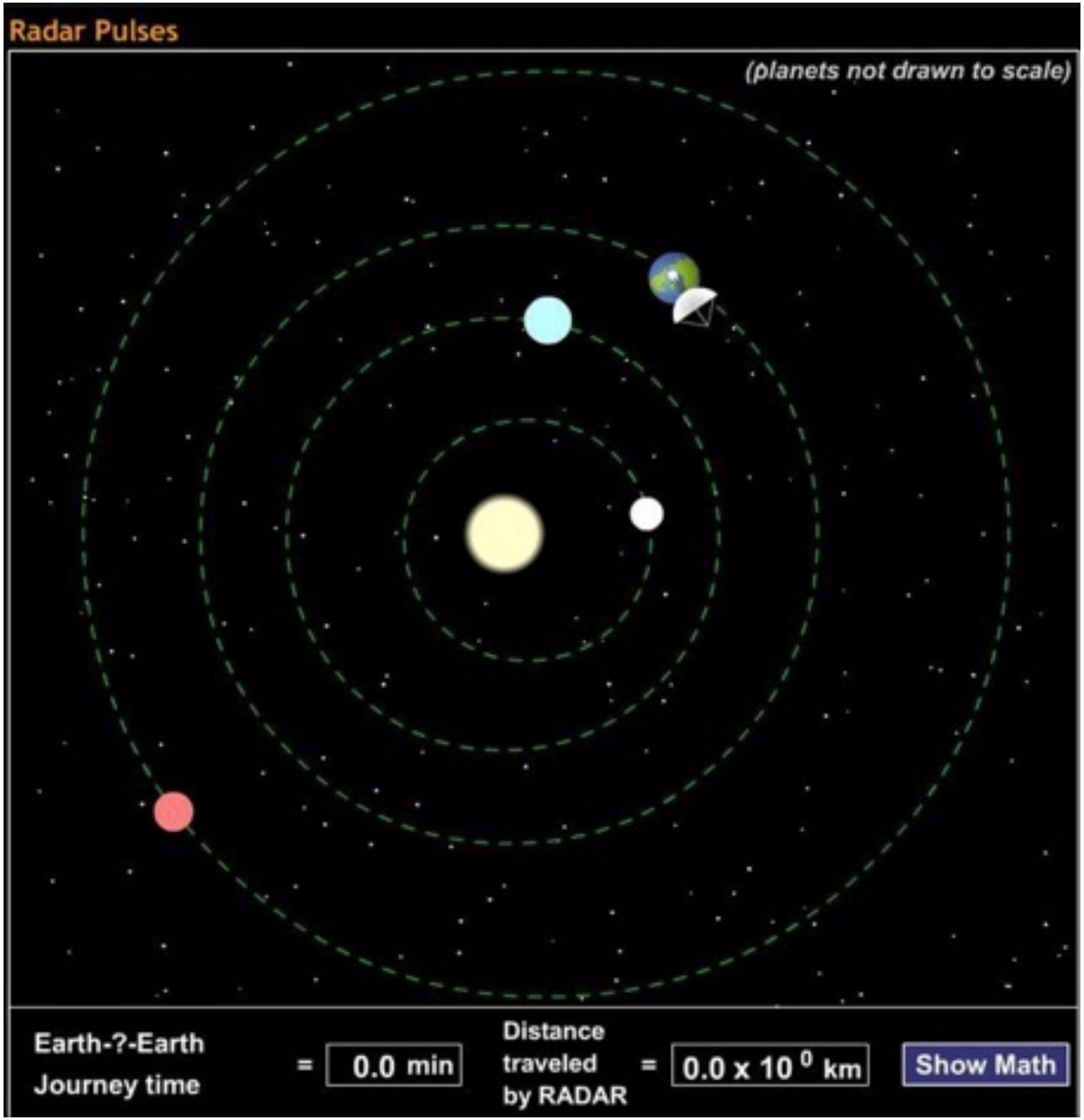
- How do we measure the distances to galaxies?

How do we measure the distances to galaxies?



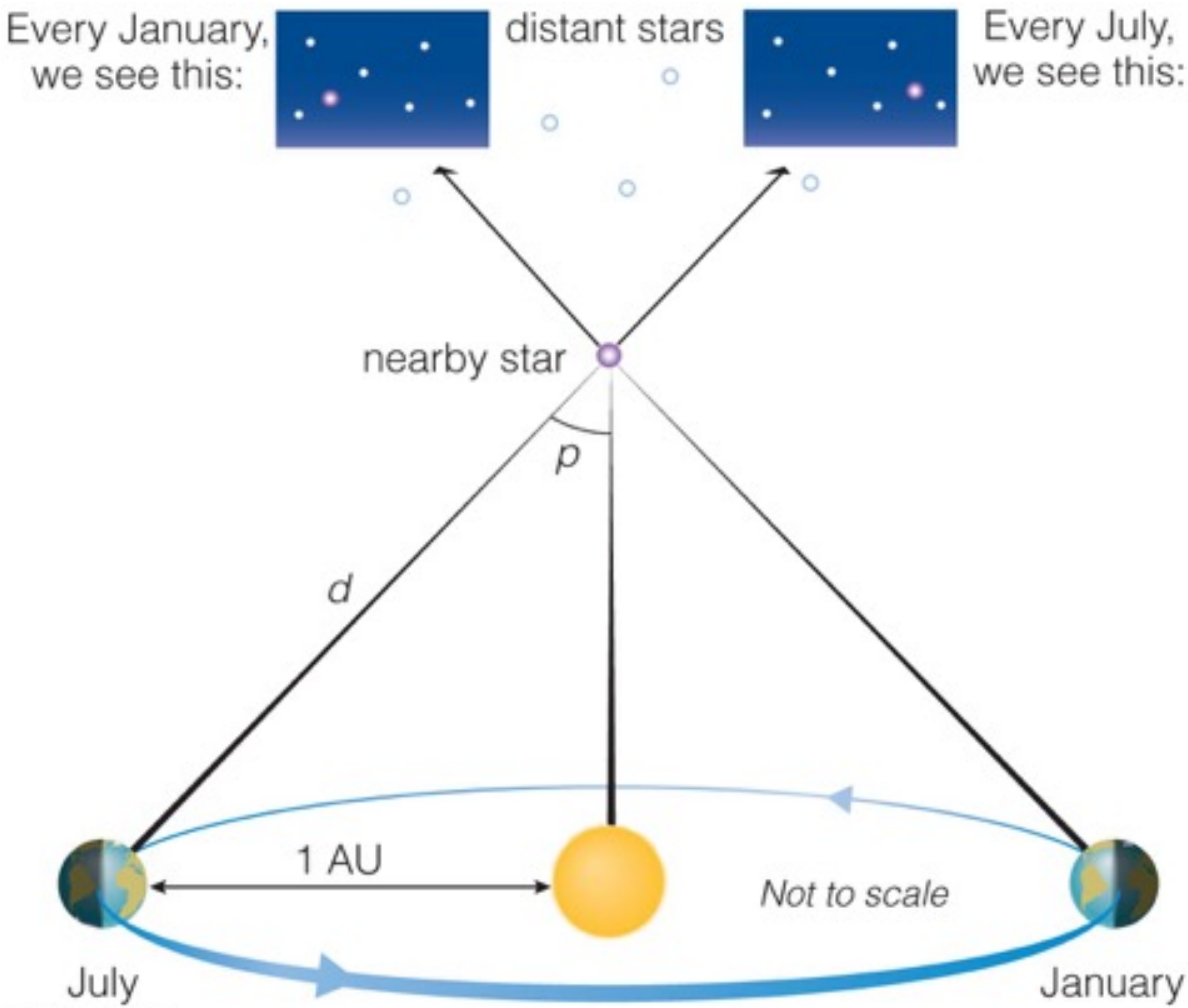


Brightness alone does not provide enough information to measure the distance to an object.



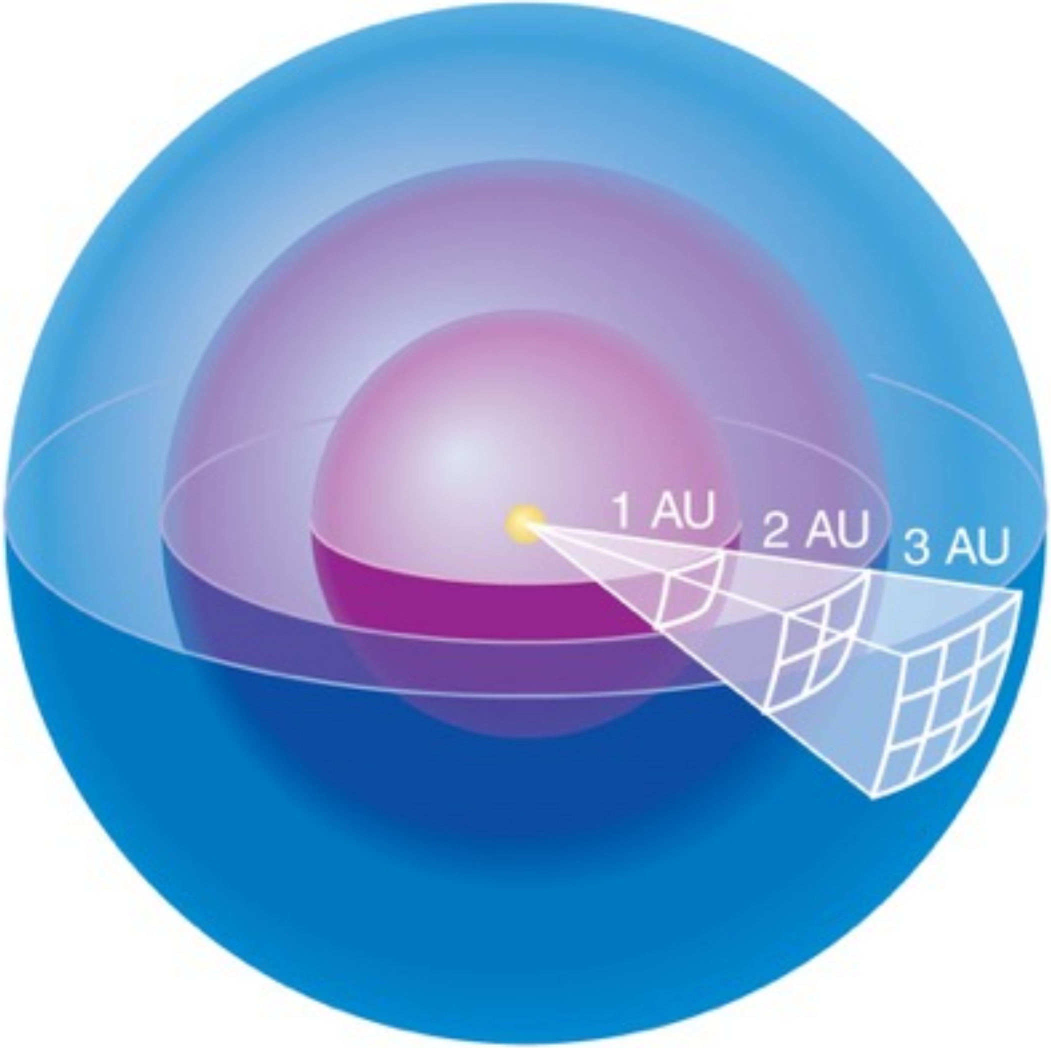
Step 1

Determine size of the solar system using radar.



Step 2

Determine the distances of stars out to a few hundred light-years using parallax.



Luminosity passing through each sphere is the same.

Area of sphere:

$$4\pi\ (\text{radius})^2$$

Divide luminosity by area to get brightness.

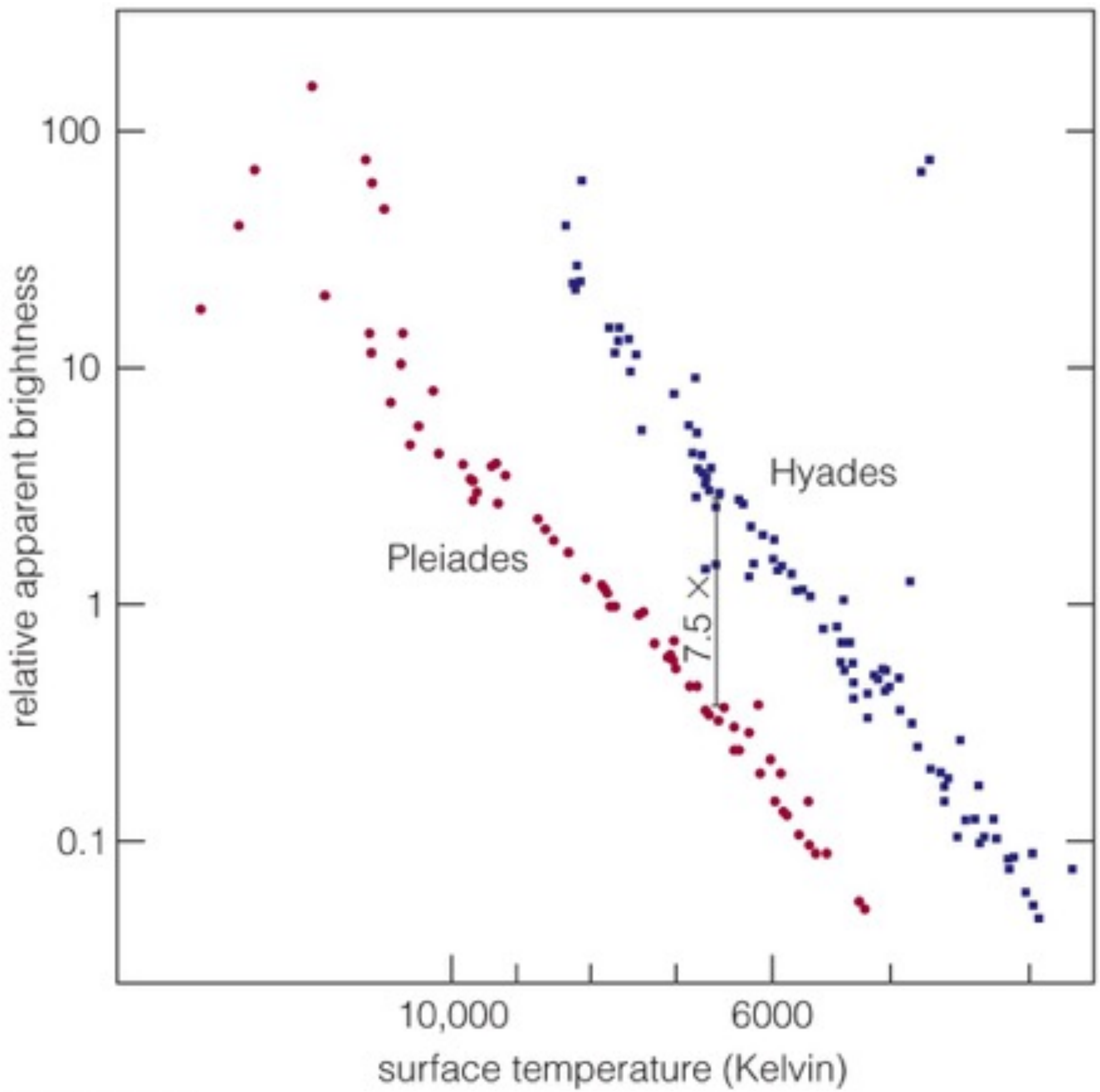
The relationship between apparent brightness and luminosity depends on distance:

$$\text{Brightness} = \frac{\text{Luminosity}}{4\pi\,(\text{distance})^2}$$

We can determine a star's distance if we know its luminosity and can measure its apparent brightness:

$$\text{Distance} = \sqrt{\frac{\text{Luminosity}}{4\pi \times \text{Brightness}}}$$

A standard candle is an object whose luminosity we can determine without measuring its distance.



Step 3

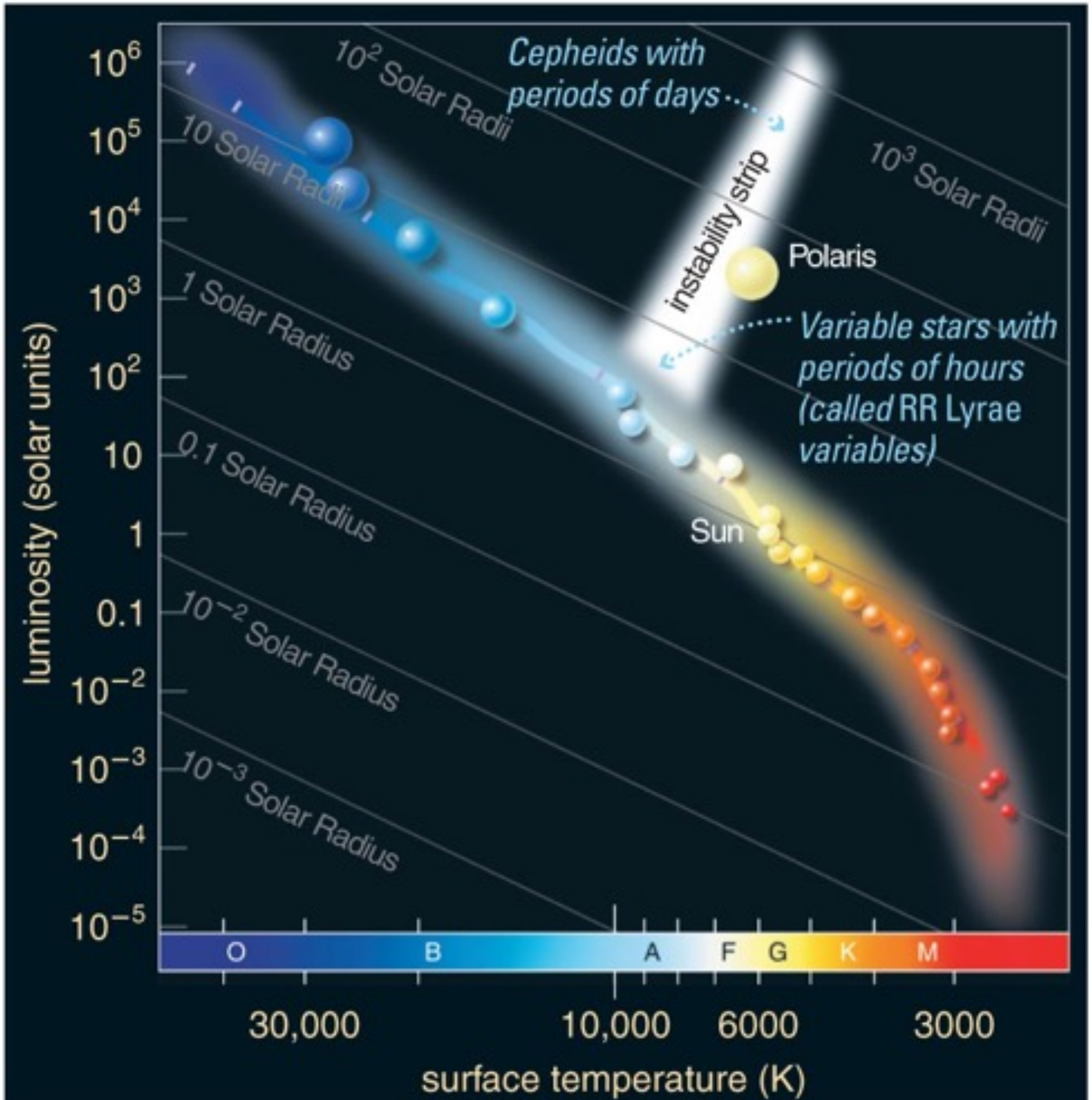
The apparent brightness of a star cluster's main sequence tells us its distance.

Knowing a star cluster's distance, we can determine the luminosity of each type of star within it.

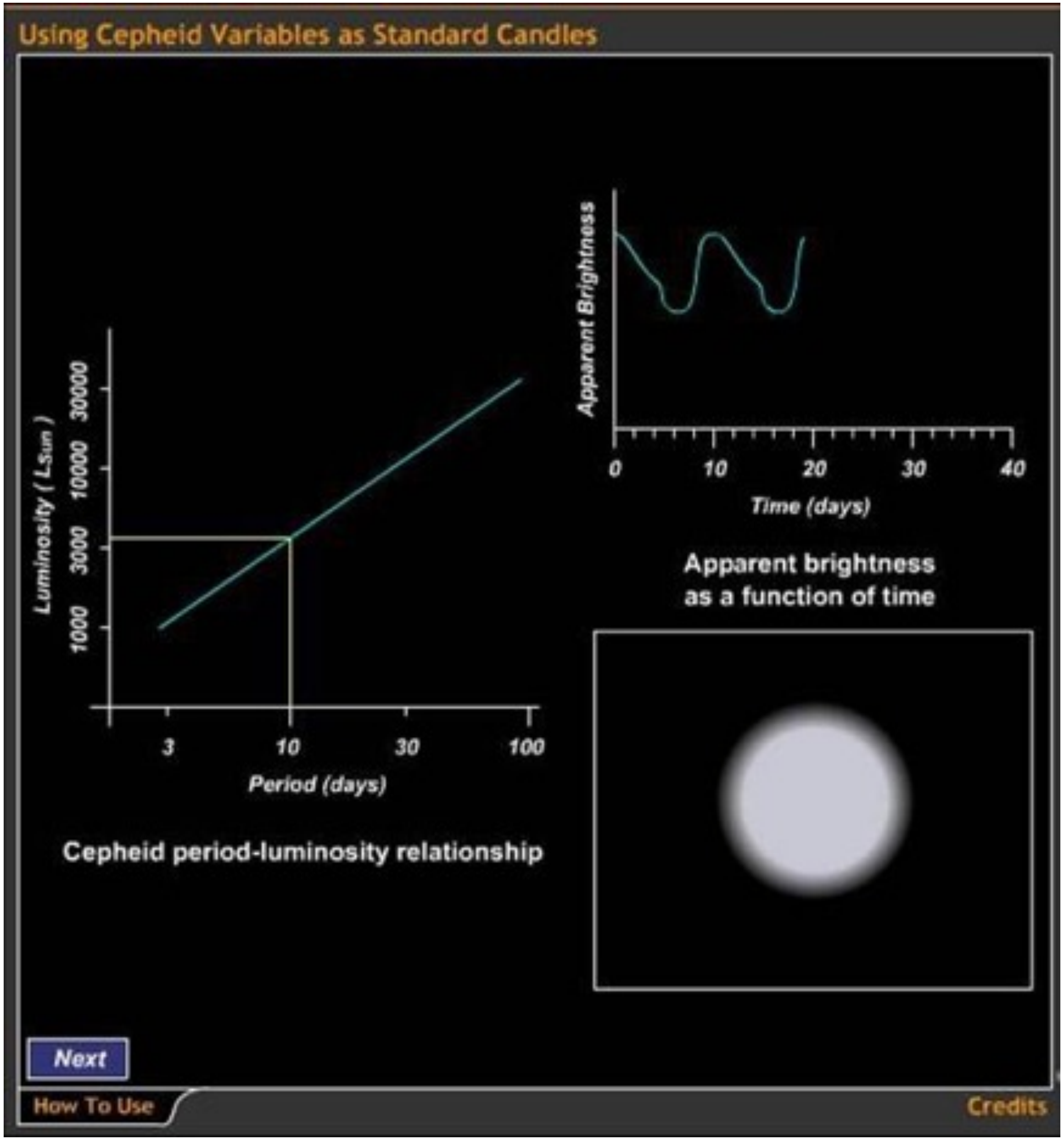
Thought Question

Which kind of stars are best for measuring large distances?

A. high-luminosity stars
B. low-luminosity stars

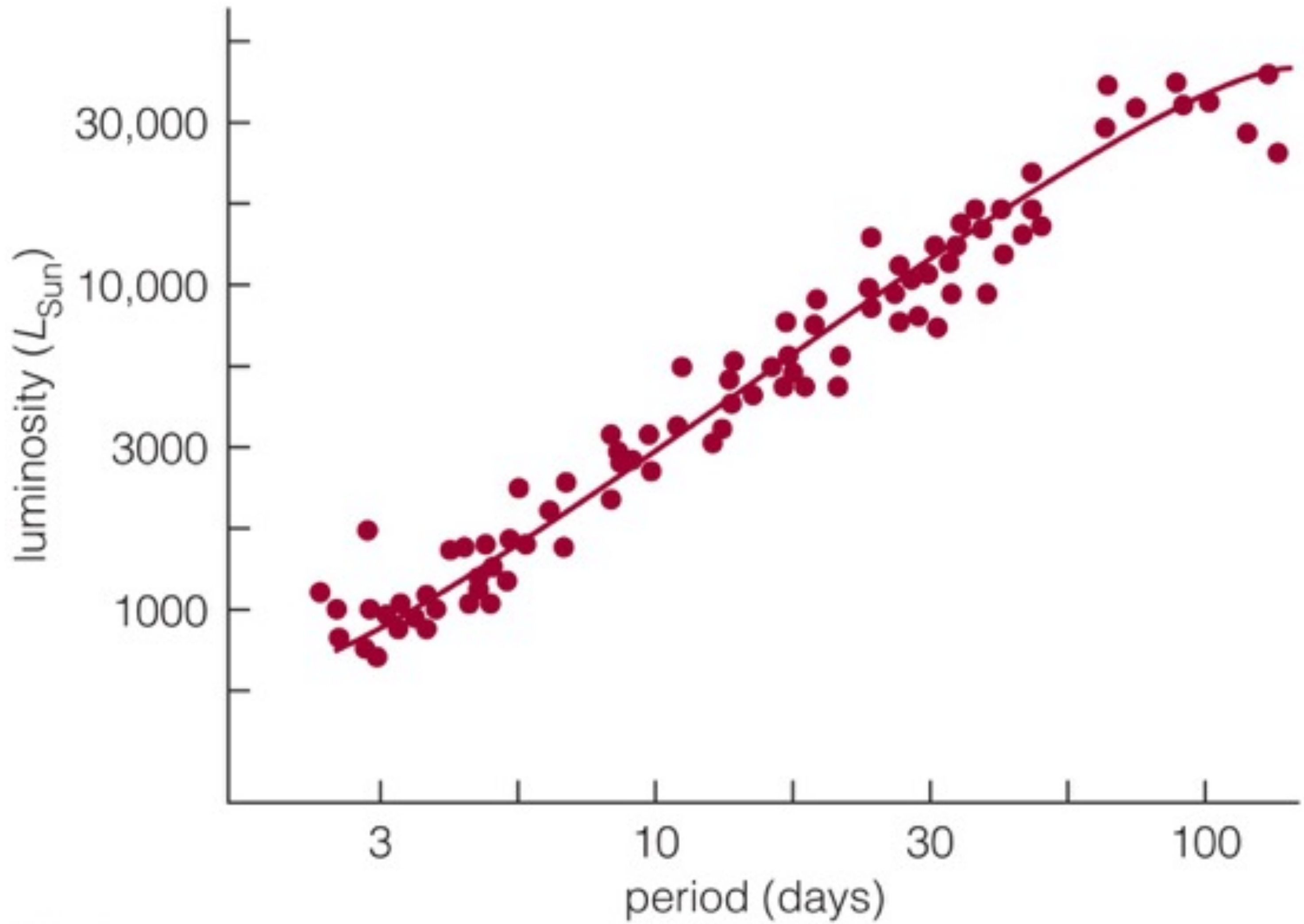


Cepheid variable stars are very luminous.

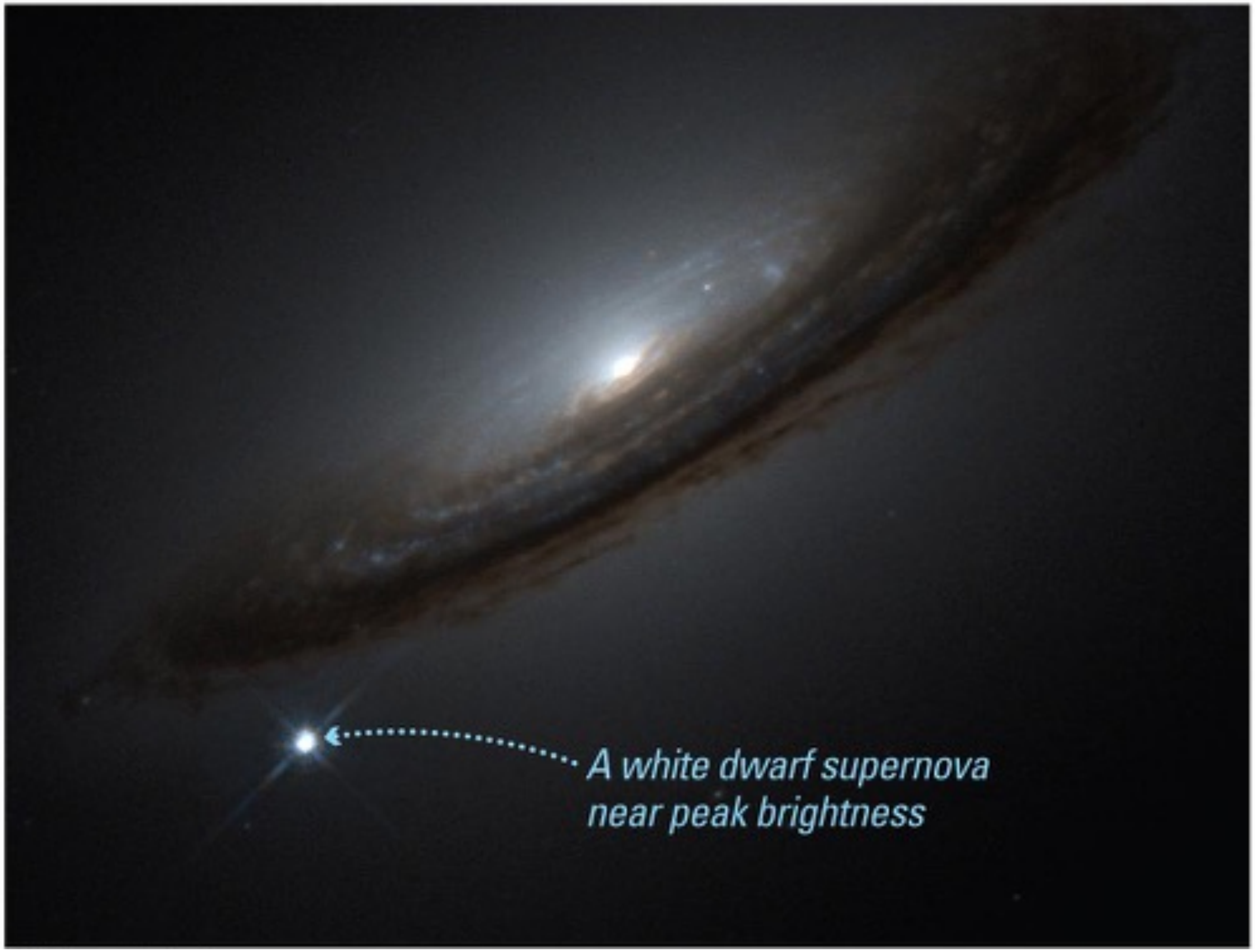


Step 4

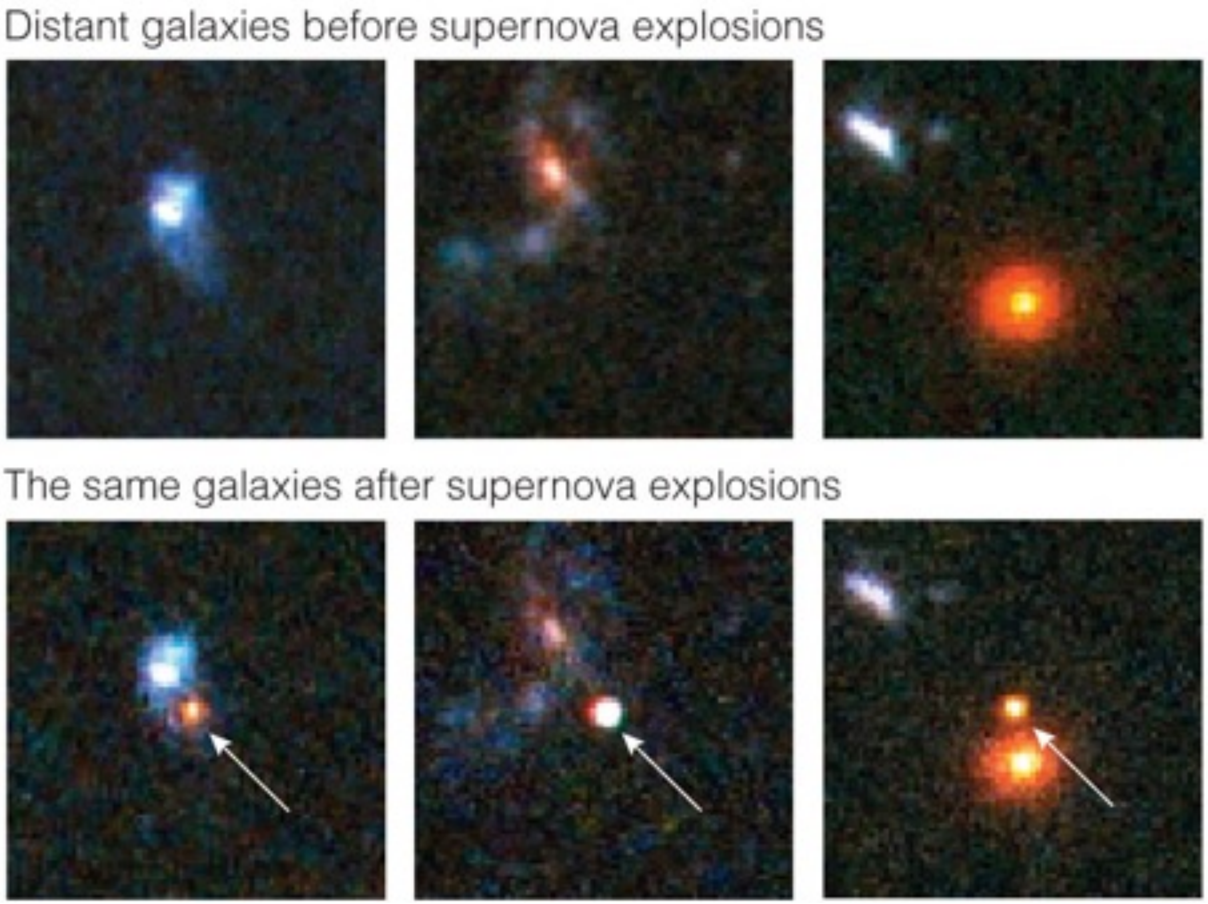
Because the period of Cepheid variable stars tells us their luminosities, we can use them as standard candles.



Cepheid variable stars with longer periods have greater luminosities.

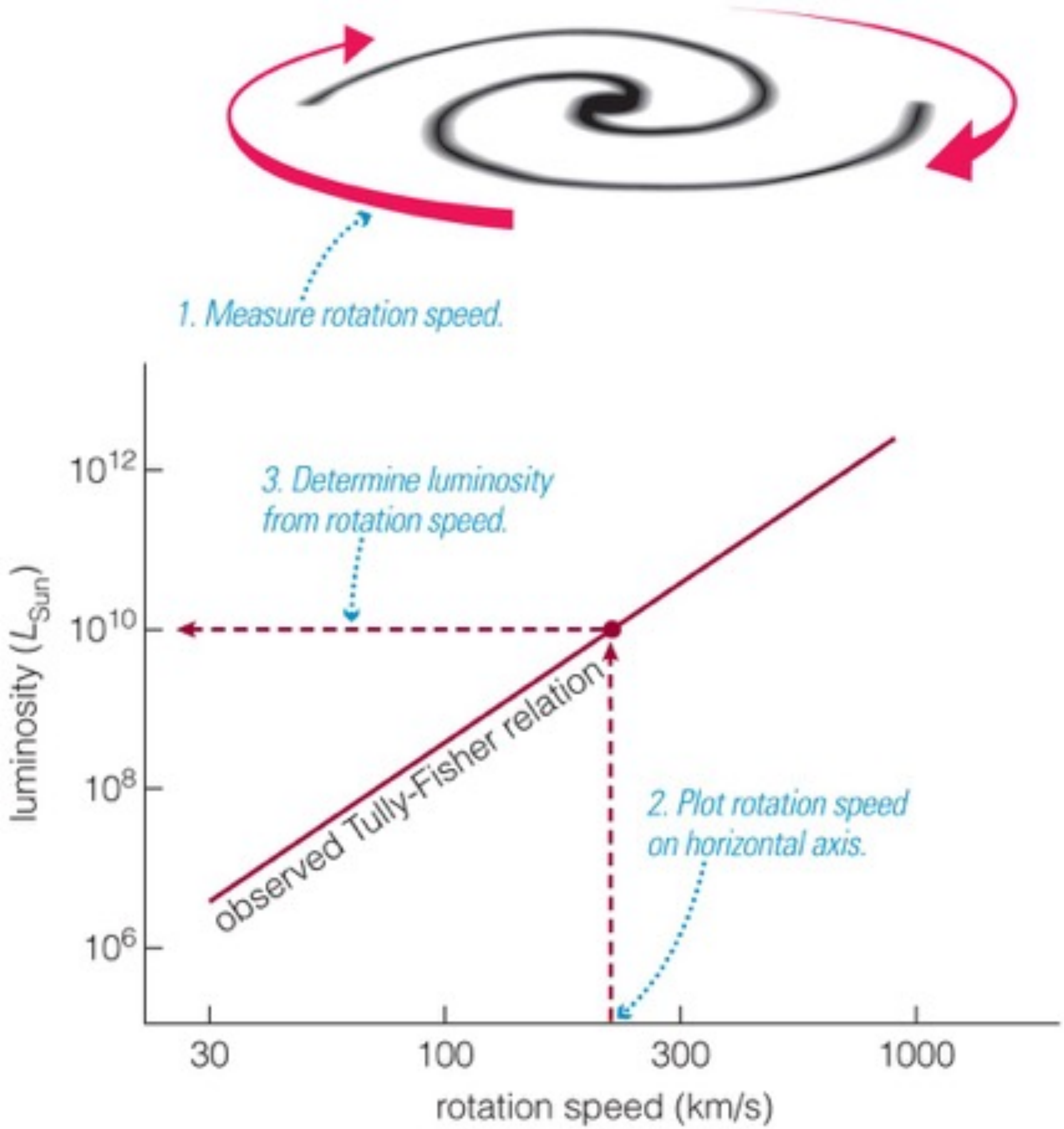


White-dwarf supernovae can also be used as standard candles.



Step 5

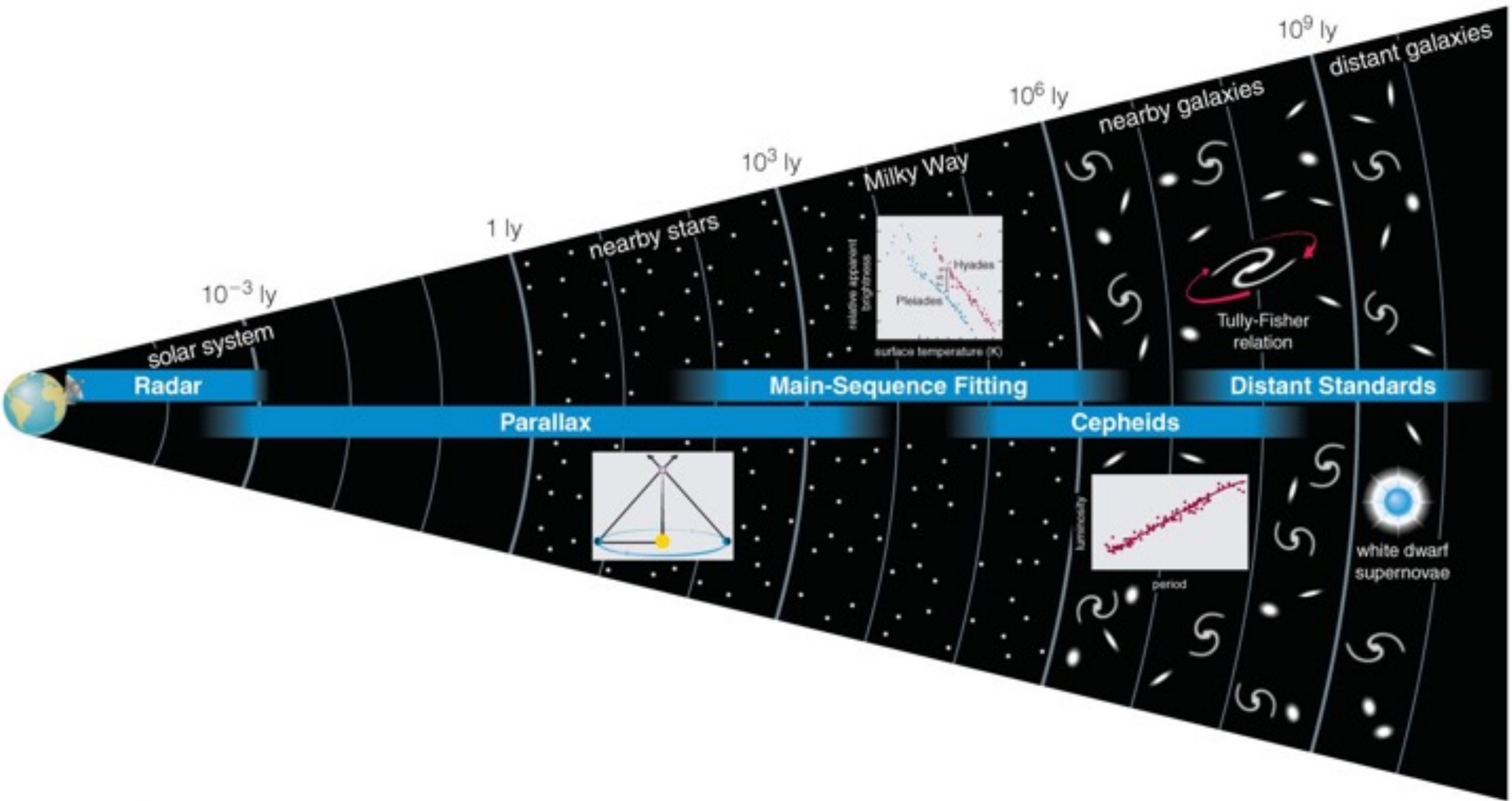
The apparent brightness of a white dwarf supernova tells us the distance to its galaxy (up to 10 billion light-years).



Tully-Fisher Relation

Entire galaxies can also be used as standard candles because a galaxy's luminosity is related to its rotation speed.

We measure galaxy distances using a chain of interdependent techniques.



20.3 Hubble's Law

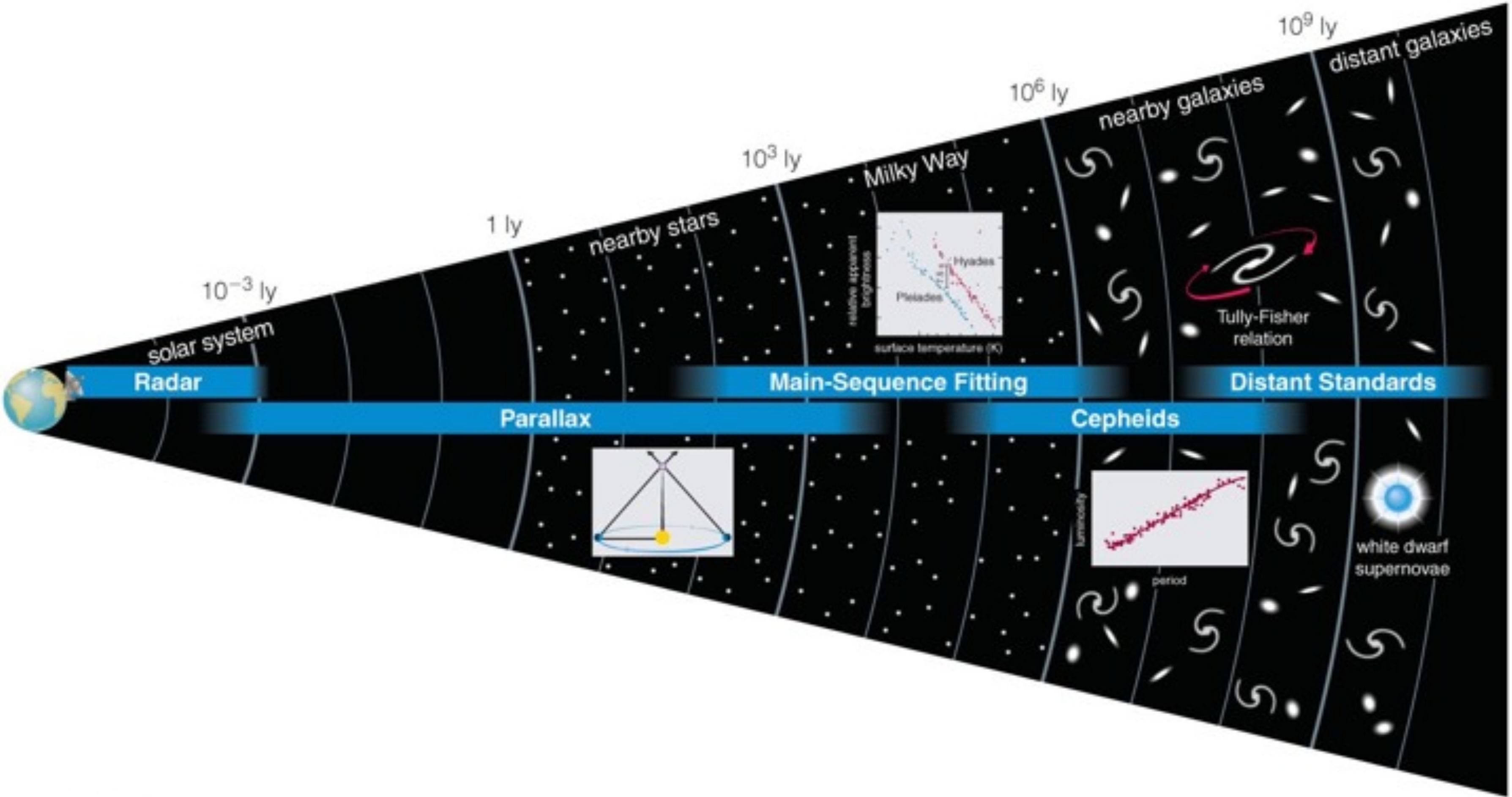
- How did Hubble prove that galaxies lie far beyond the Milky Way?
- What is Hubble's law?
- How do distance measurements tell us the age of the universe?
- How does the universe's expansion affect our distance measurements?

How did Hubble prove that galaxies lie far beyond the Milky Way?

The Puzzle of "Spiral Nebulae"

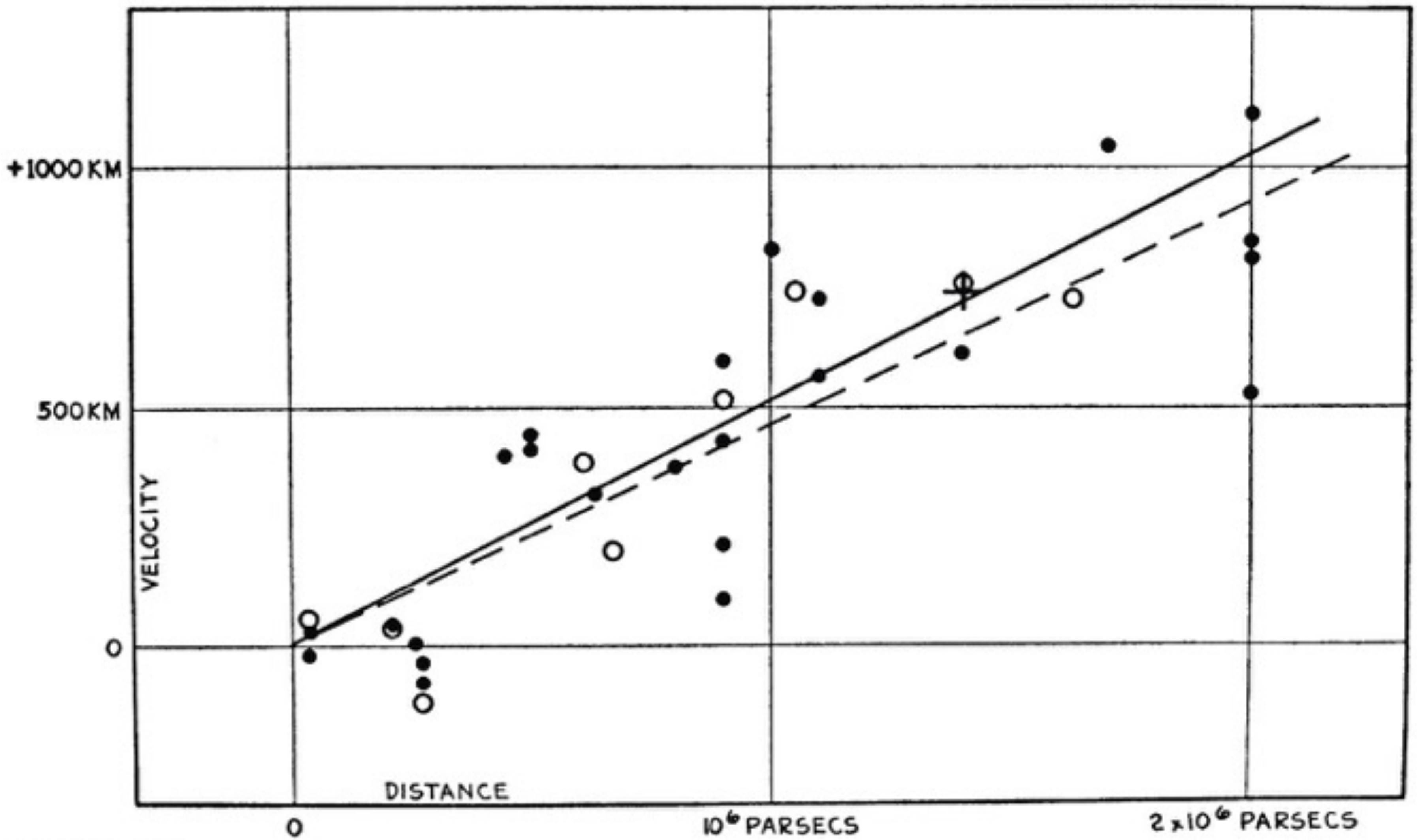
- Before Hubble, some scientists argued that "spiral nebulae" were entire galaxies like our Milky Way, while others maintained they were smaller collections of stars within the Milky Way.

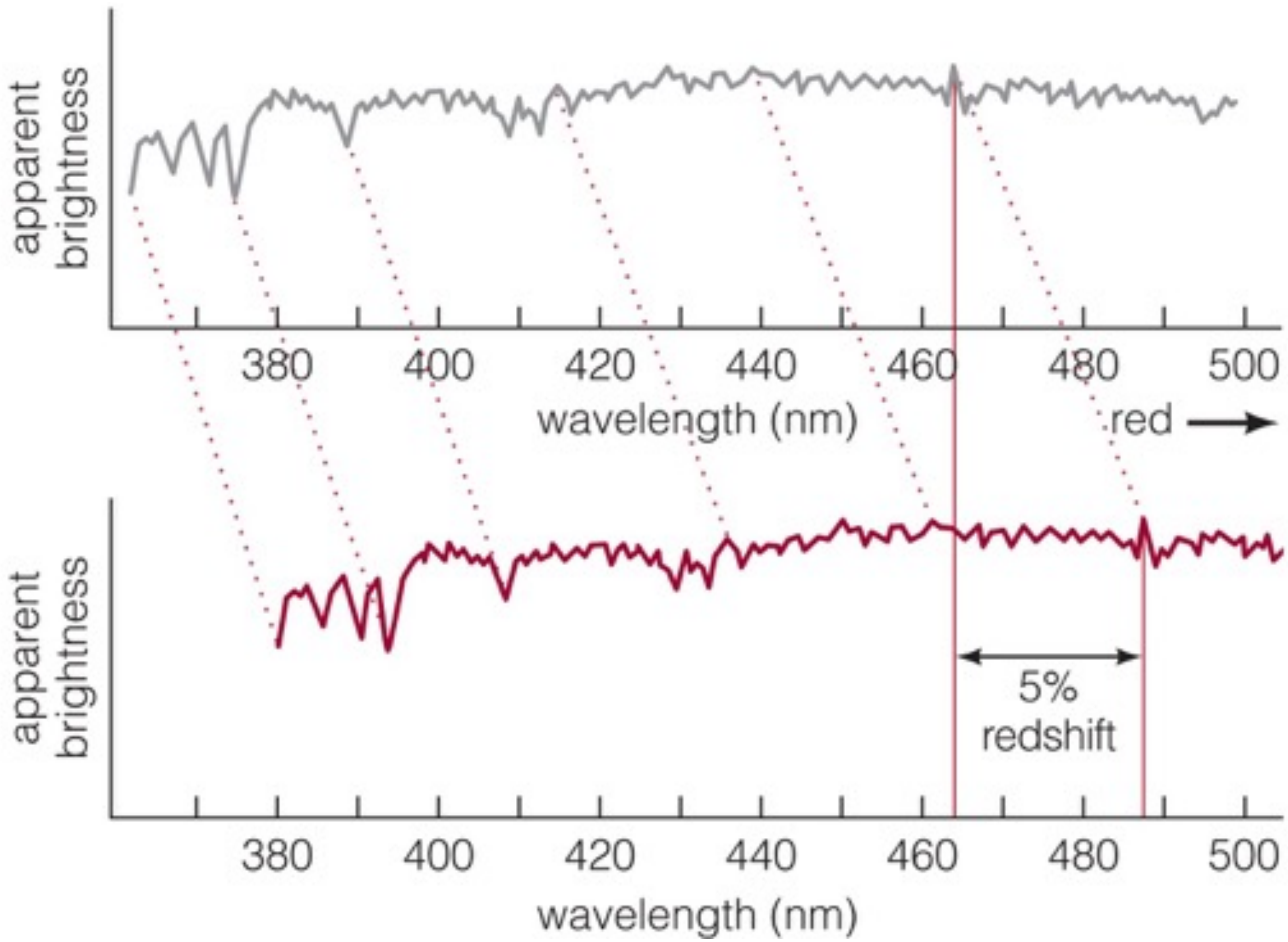
- The debate remained unsettled until Edwin Hubble finally measured their distances.



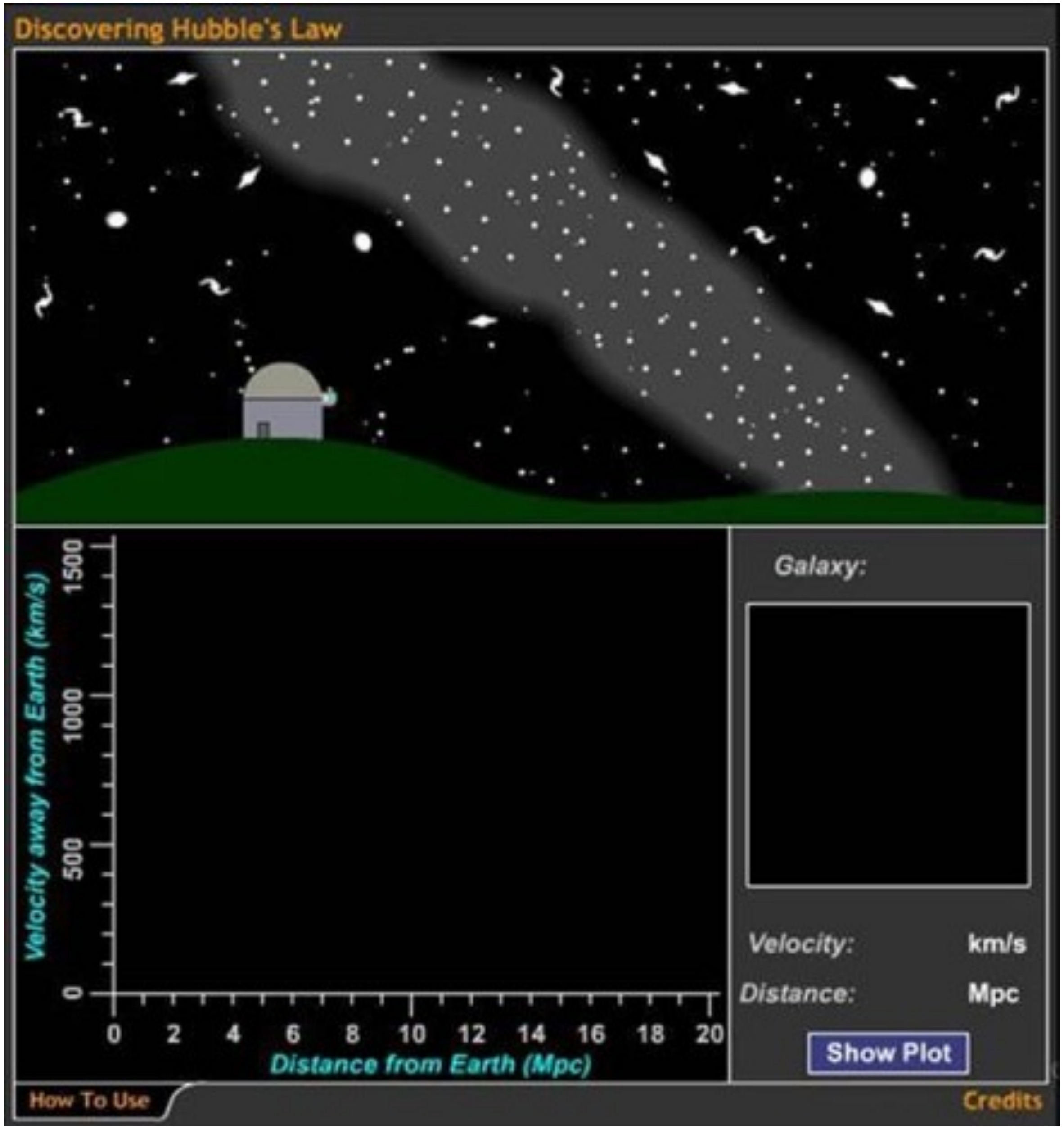
Hubble settled the debate by measuring the distance to the Andromeda Galaxy using Cepheid variables as standard candles.

What is Hubble's law?

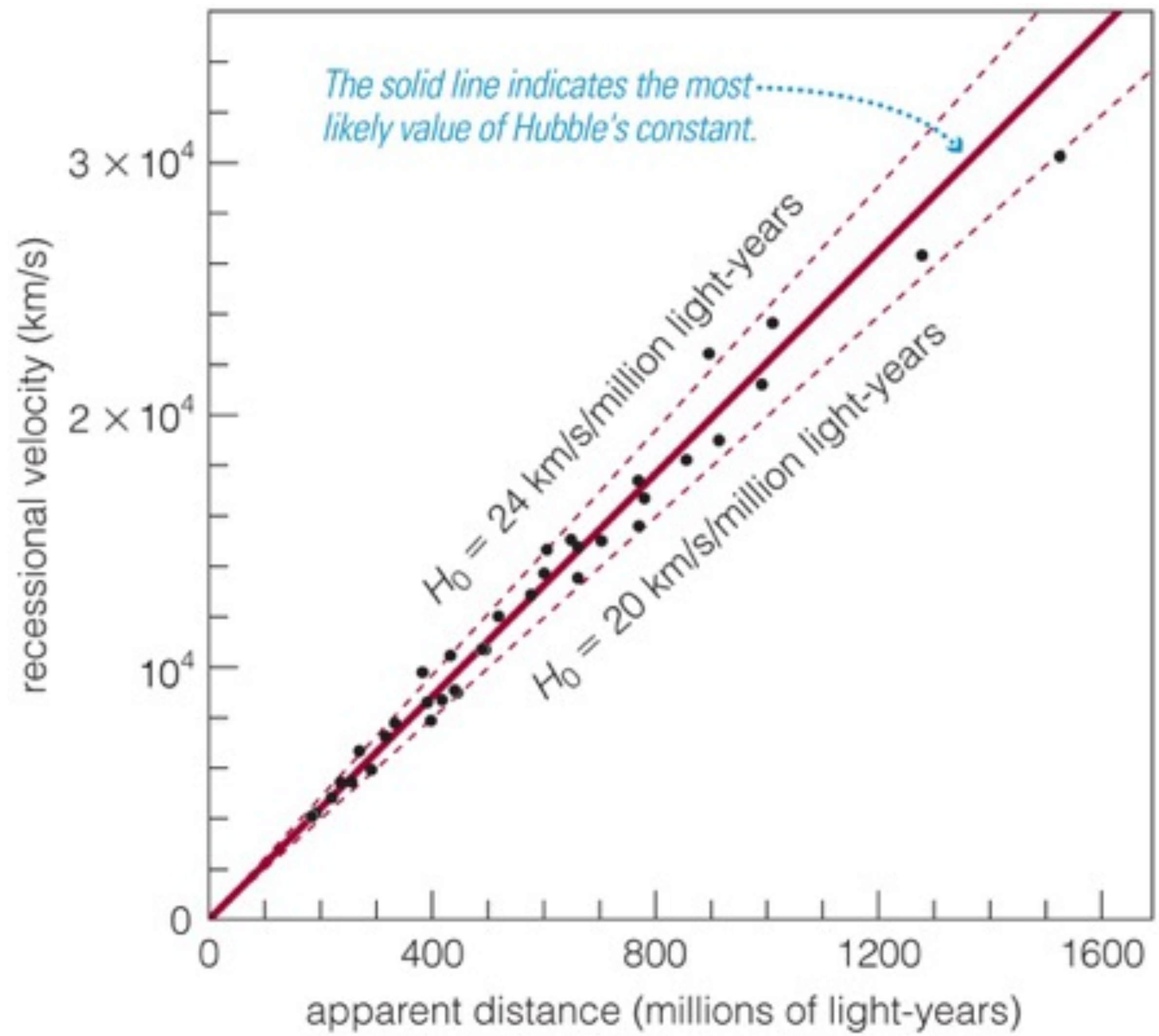




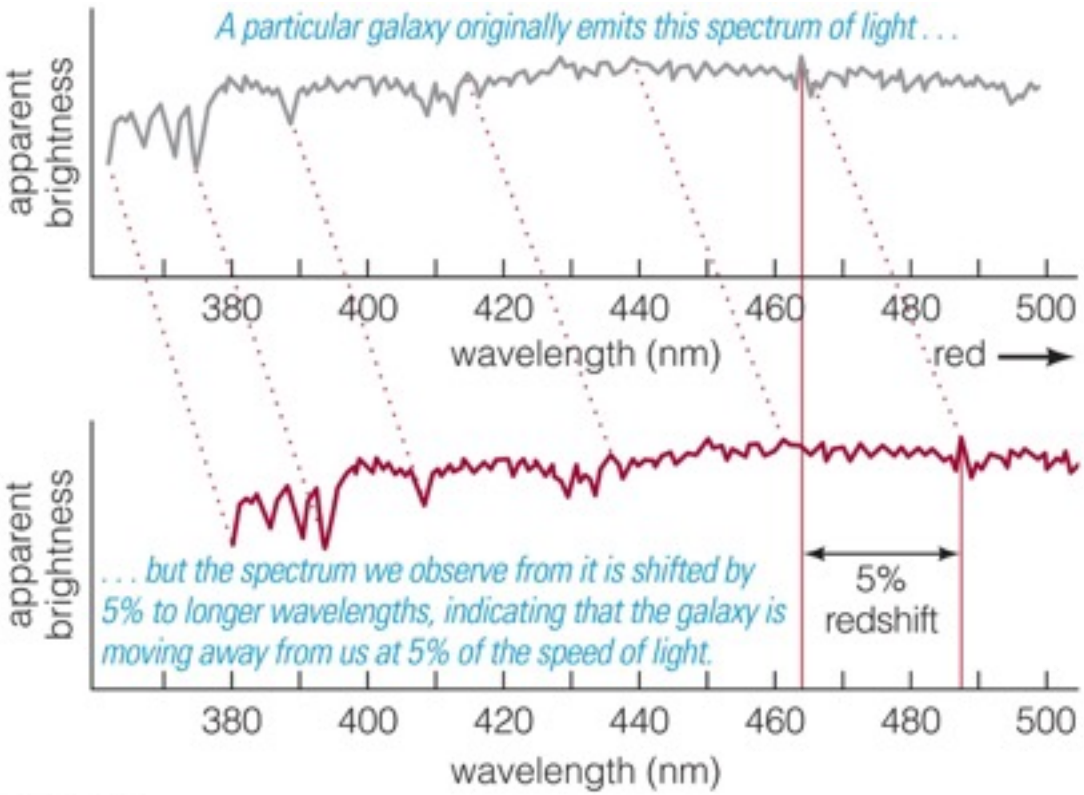
The spectral features of virtually all galaxies are redshifted, which means that they're all moving away from us.



By measuring distances to galaxies, Hubble found that redshift and distance are related in a special way.



Hubble's law: Velocity = H_0 × distance

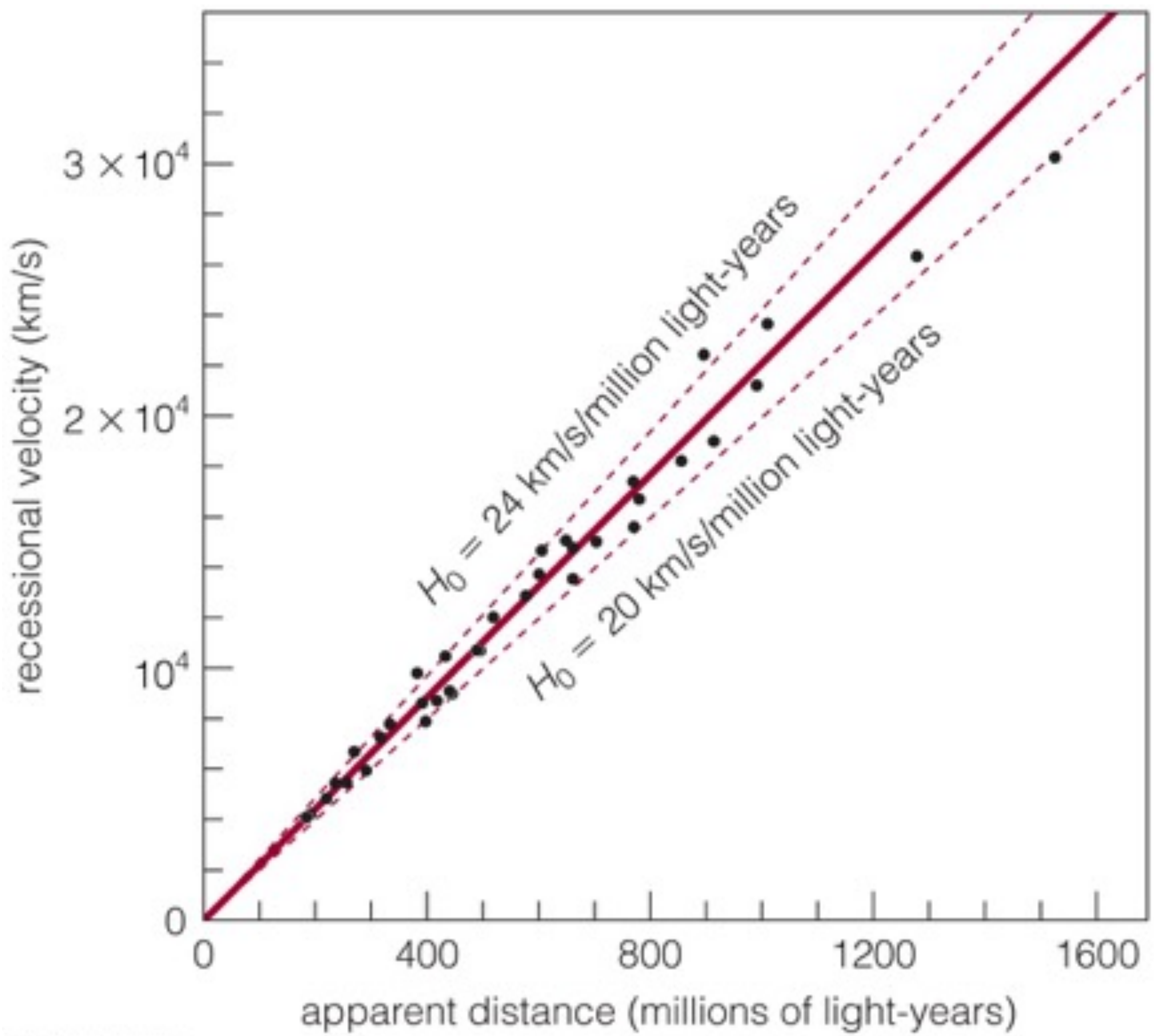


Redshift of a galaxy tells us its distance through Hubble's law:

$$\text{Distance} = \frac{\text{velocity}}{H_0}$$

Distances of the farthest galaxies are measured from their redshifts.

How do distance measurements tell us the age of the universe?



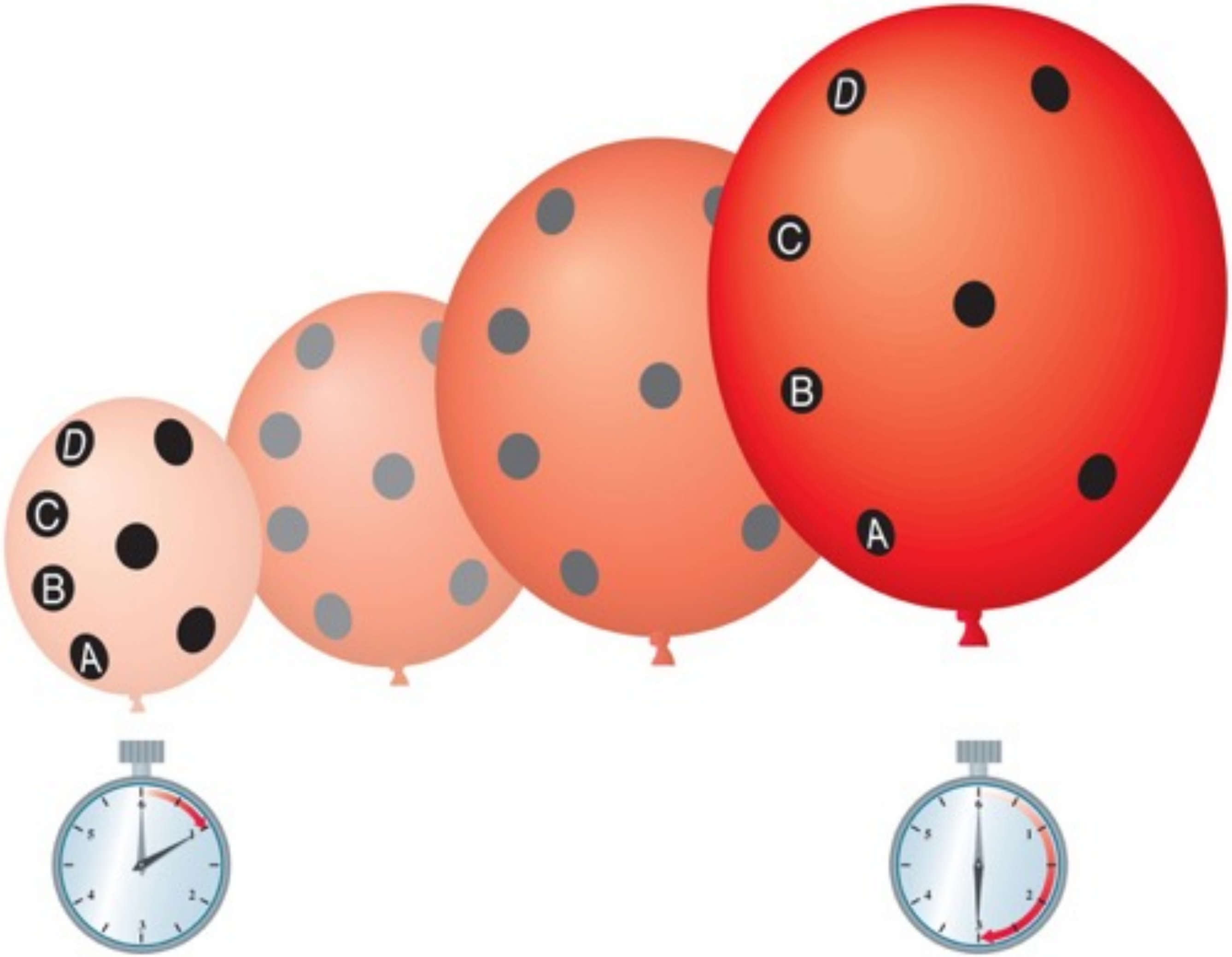
Thought Question

Your friend leaves your house. She later calls you on her cell phone, saying that she's been driving at 60 miles an hour directly away from you the whole time and is now 60 miles away. How long has she been gone?

A. 1 minute
B. 30 minutes
C. 60 minutes
D. 120 minutes

The expansion rate appears to be the same everywhere in space.

The universe has no center and no edge (as far as we can tell).



One example of something that expands but has no center or edge is the surface of a balloon.

Cosmological Principle

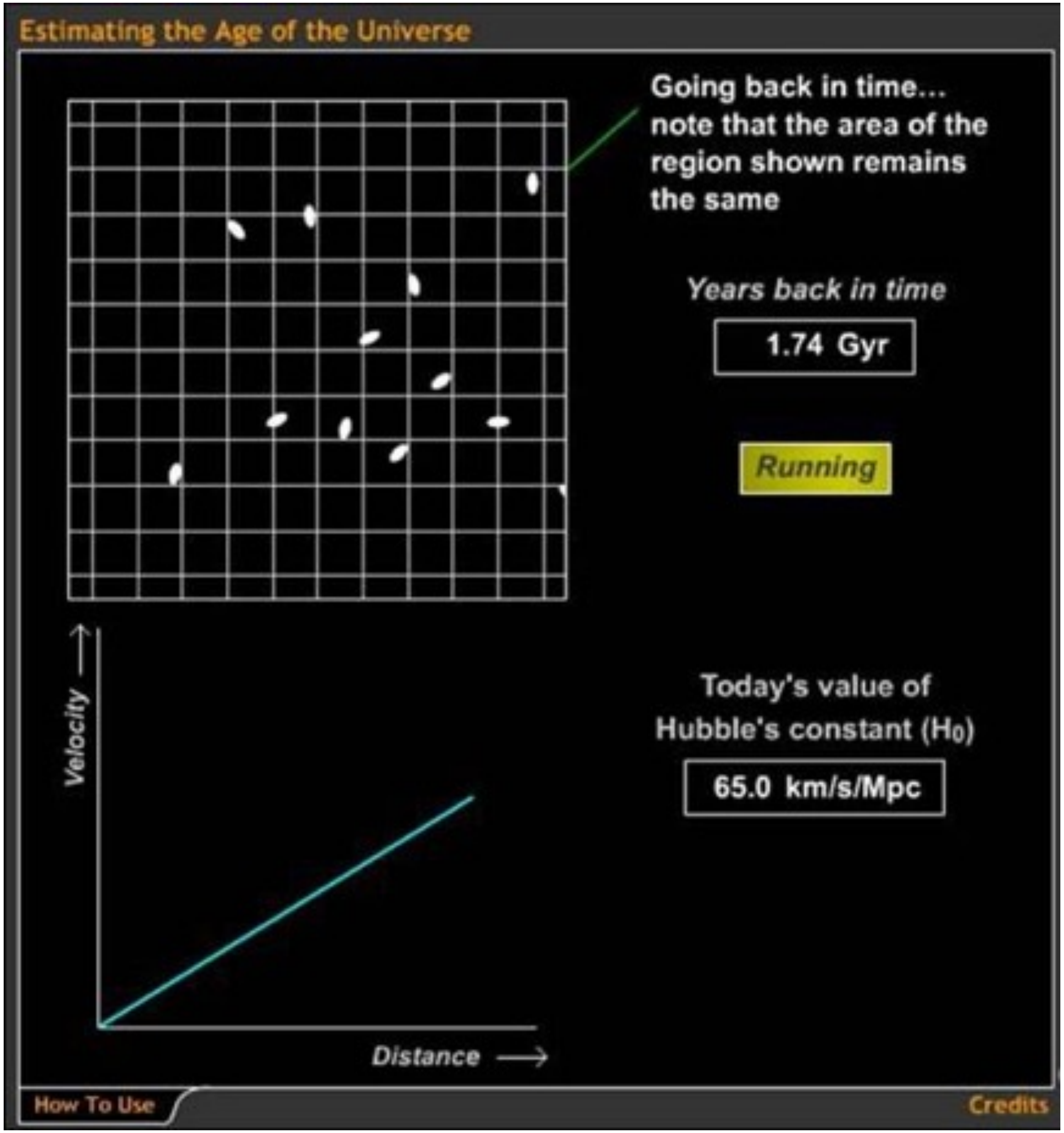
The universe looks about the same no matter where you are within it.

- Matter is evenly distributed on very large scales in the universe.
- It has no center or edges.
- The cosmological principle has not been proven beyond a doubt, but it is consistent with all observations to date.

Thought Question

You observe a galaxy moving away from you at 0.1 light-years per year, and it is now 1.4 billion light-years away from you. How long has it taken to get there?

A. 1 million years
B. 14 million years
C. 10 billion years
D. 14 billion years

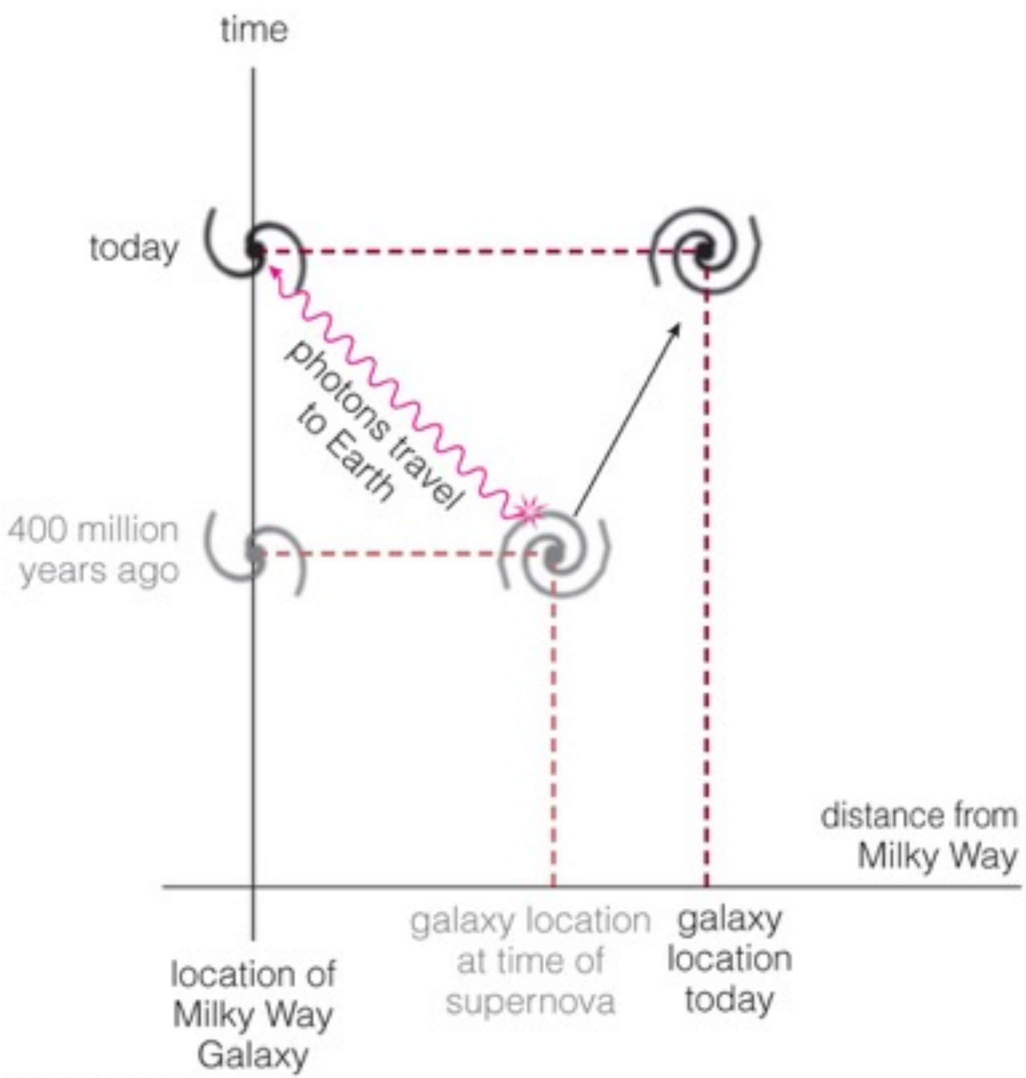


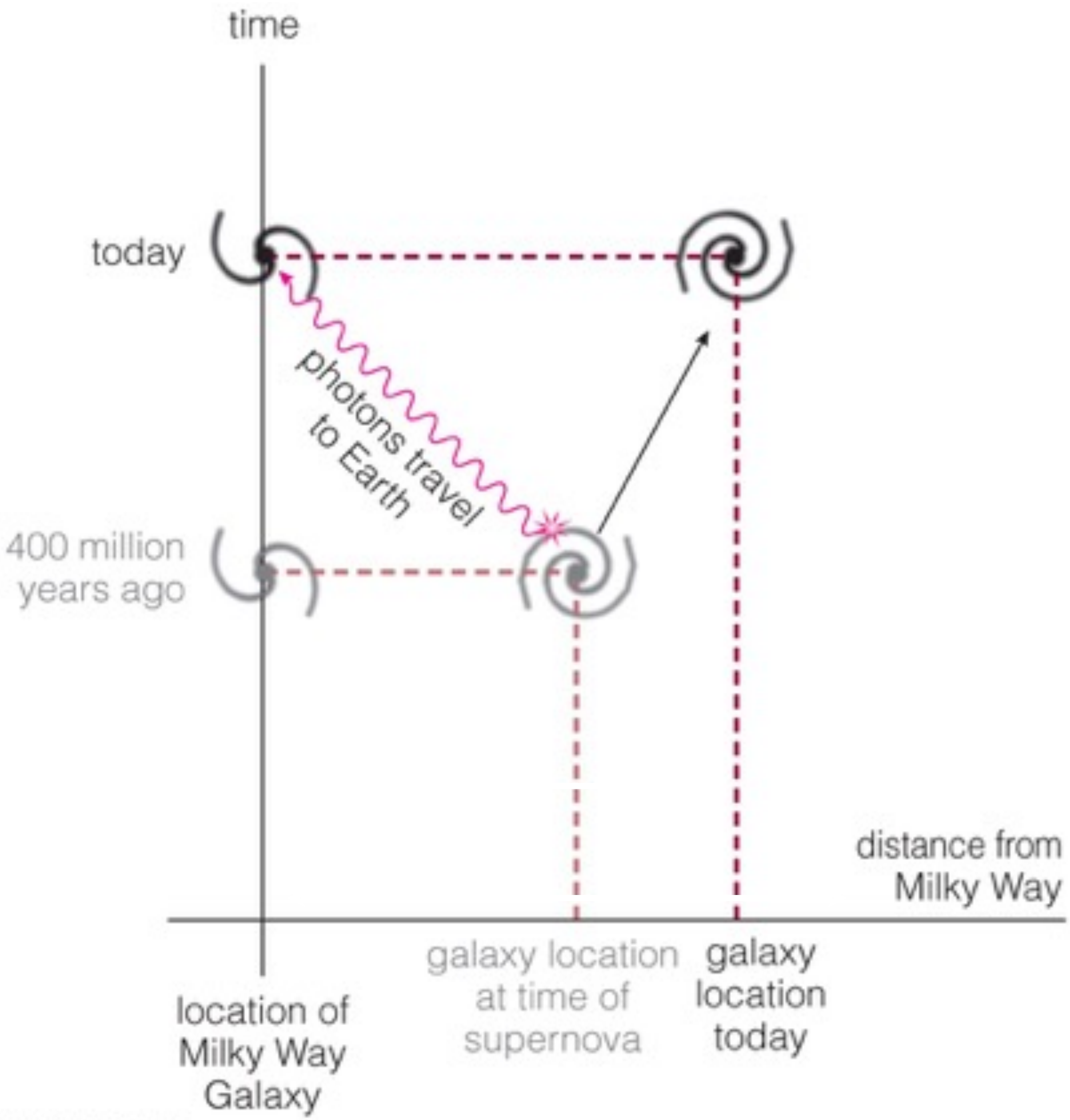
Hubble's constant tells us the age of universe because it relates the velocities and distances of all galaxies.

Age = $\frac{\text{Distance}}{\text{Velocity}}$

$\sim 1/H_0$

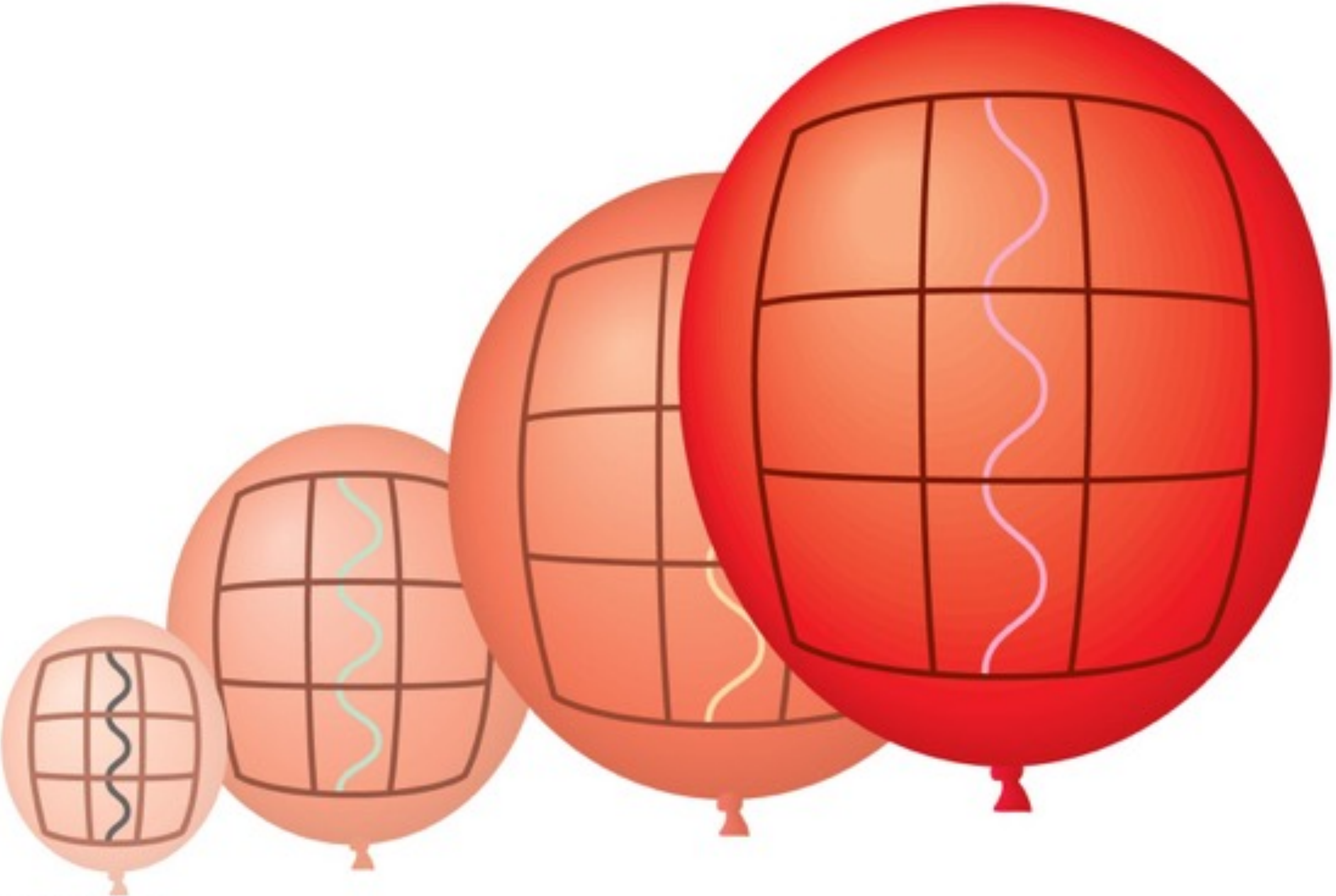
How does the universe's expansion affect our distance measurements?





Distances between faraway galaxies change while light travels.

Astronomers think in terms of lookback time rather than distance.



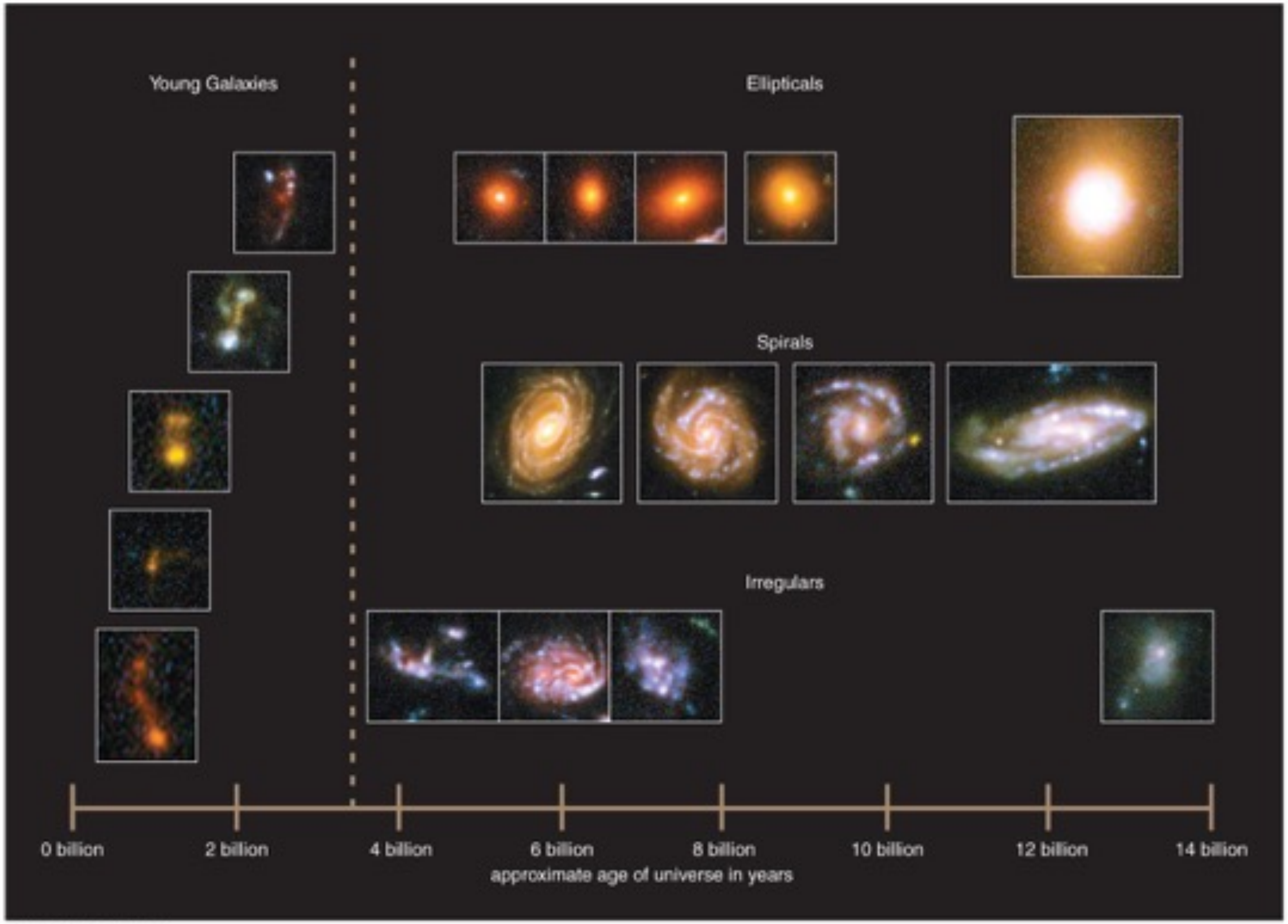
Expansion stretches photon wavelengths, causing a cosmological redshift directly related to lookback time

Chapter 21
Galaxy Evolution

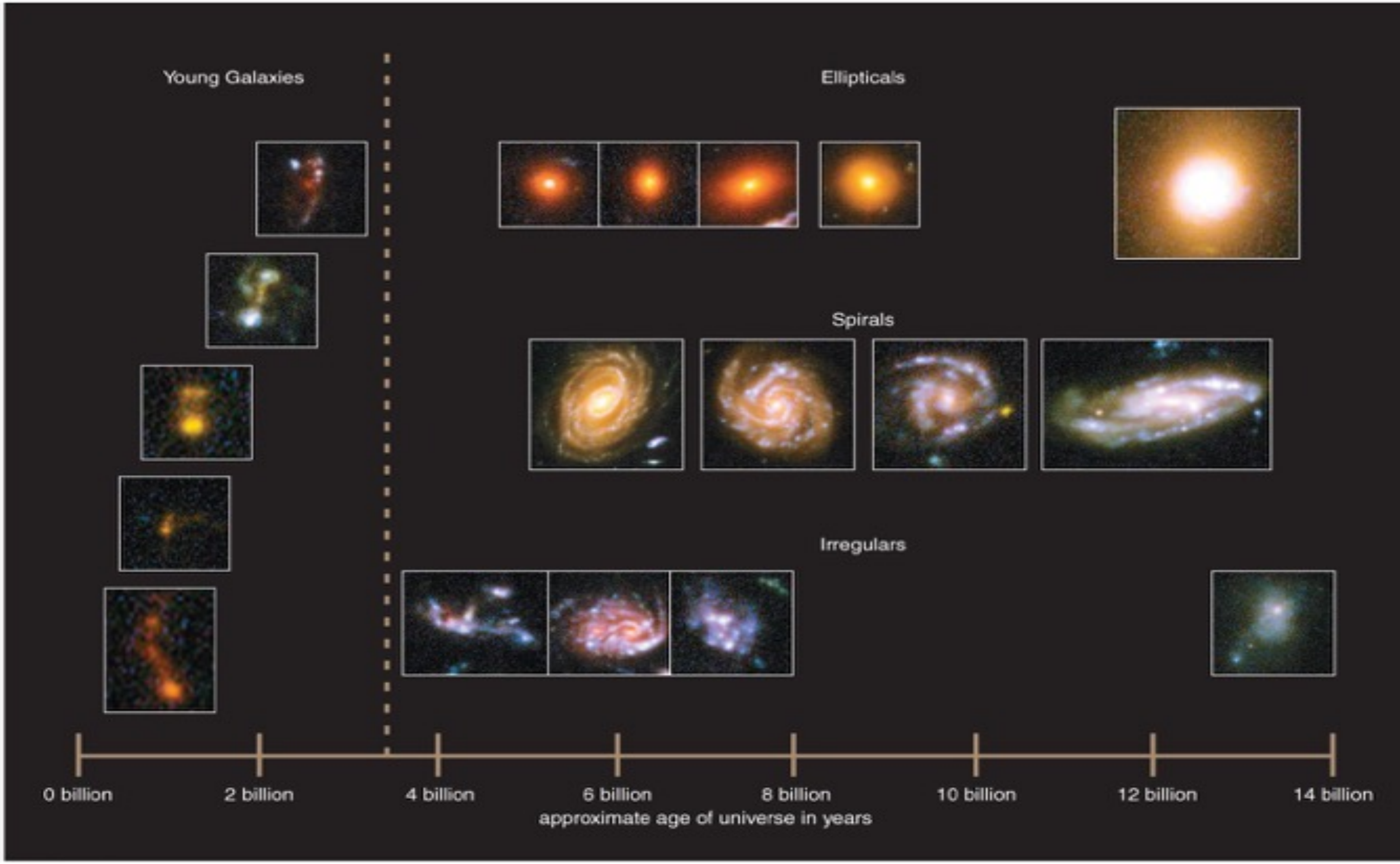
21.1 Looking Back Through Time

- How do we observe the life histories of galaxies?
- How did galaxies form?

How do we observe the life histories of galaxies?

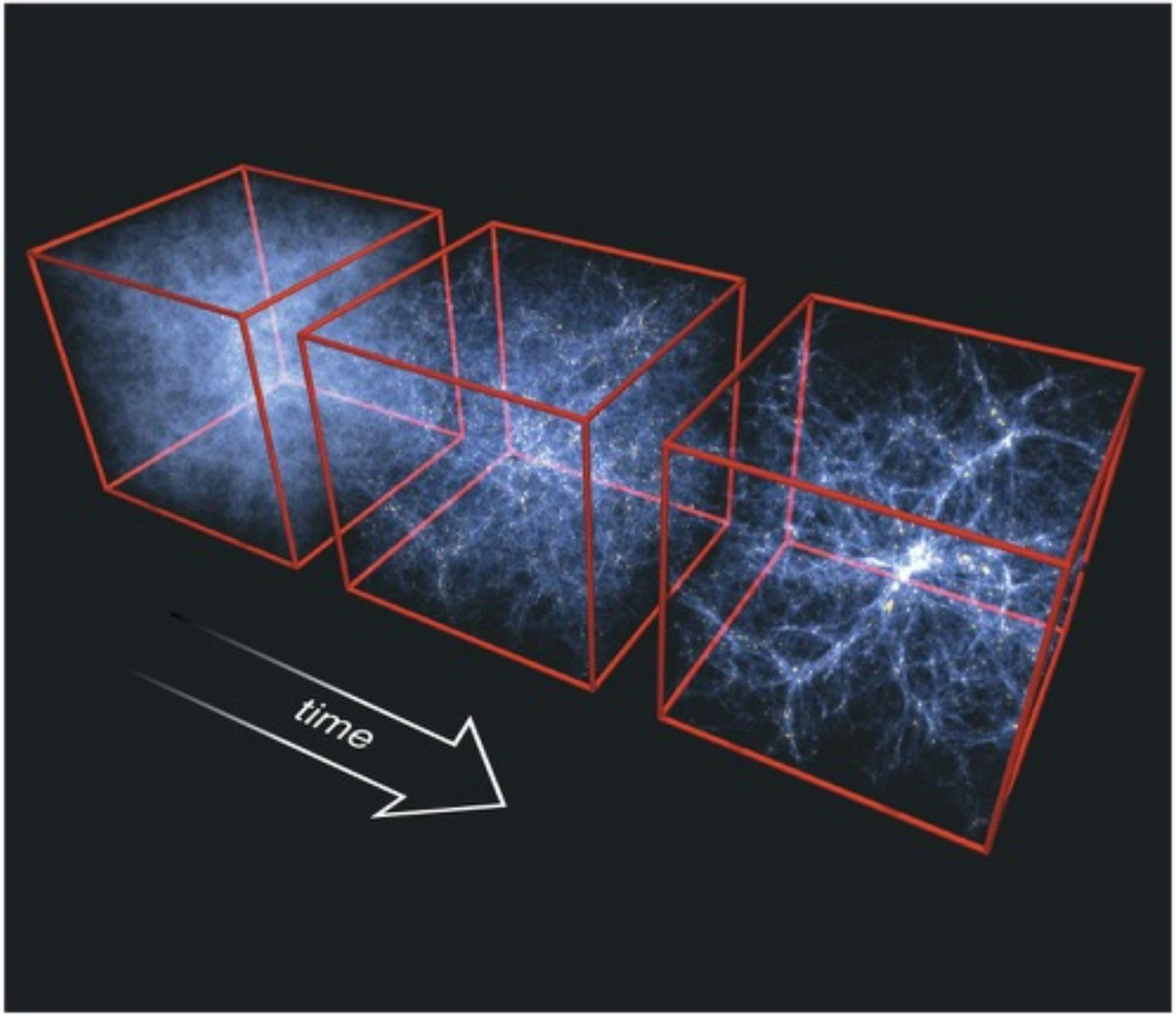


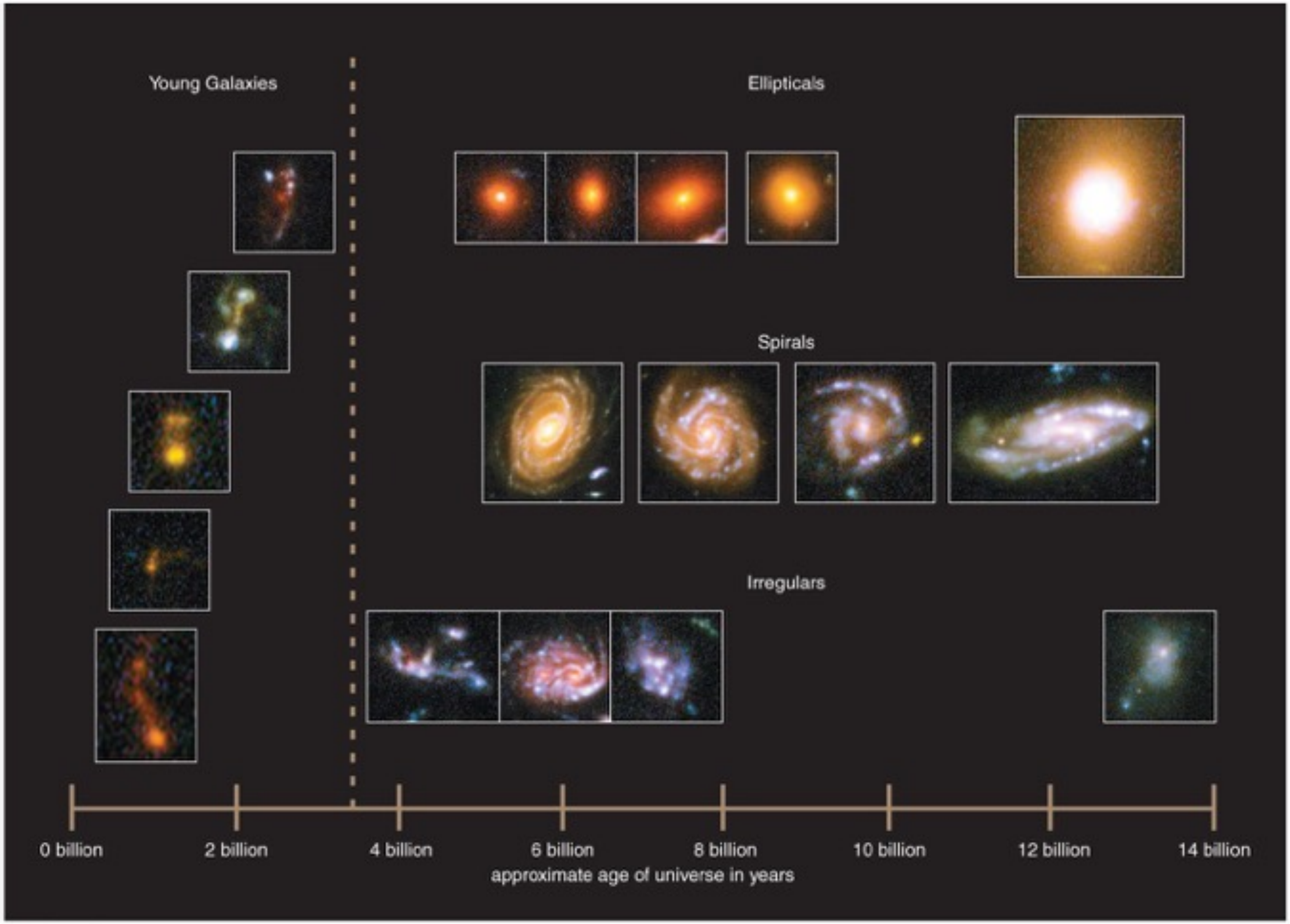
Deep observations show us very distant galaxies as they were much earlier in time (old light from young galaxies).



Observing galaxies at different distances shows us how they age.

How did galaxies form?

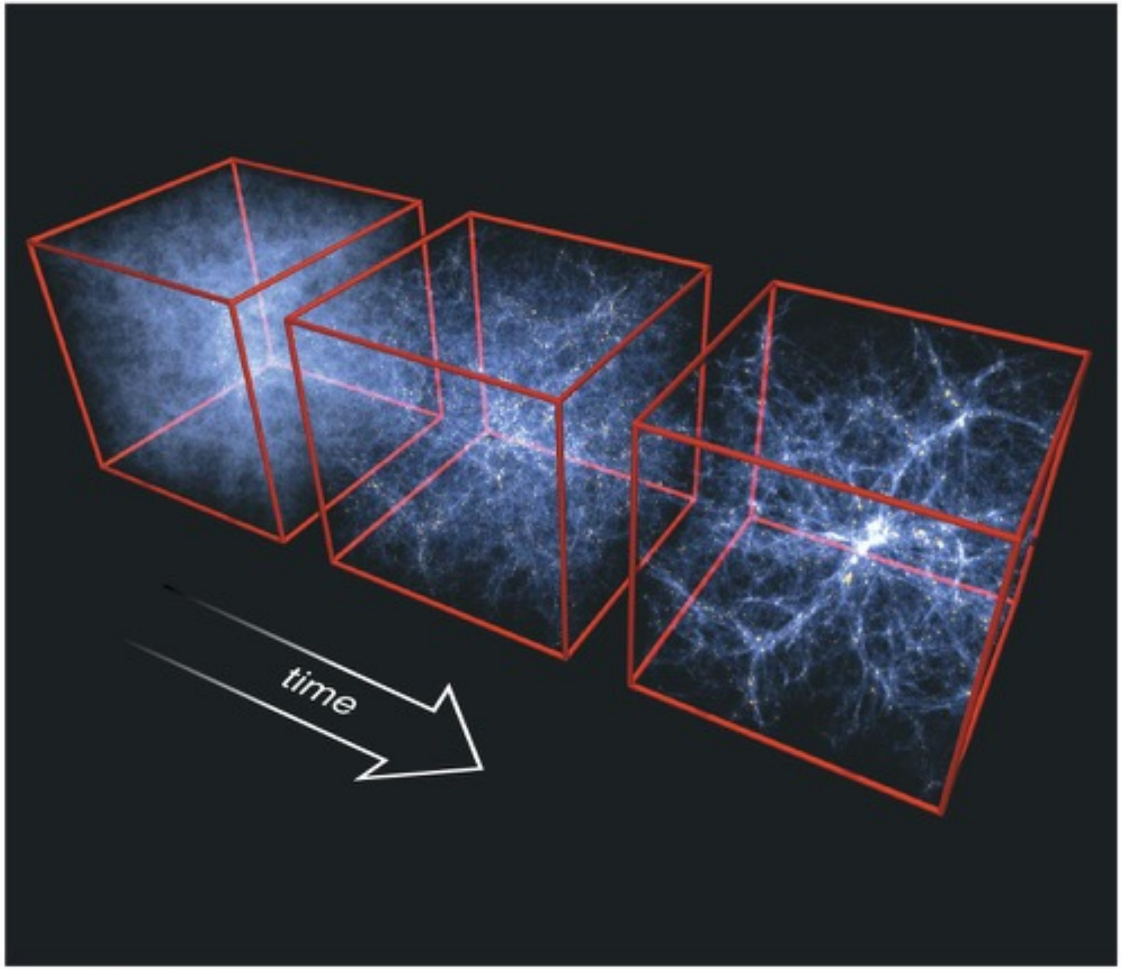


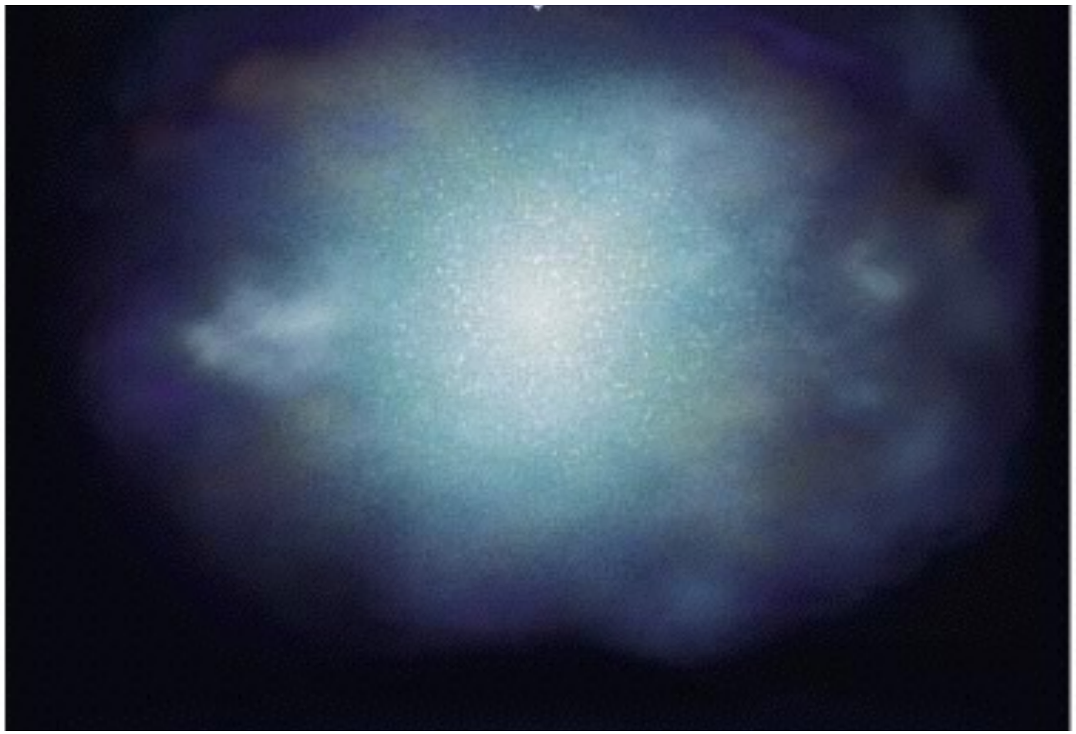


We still can't directly observe the earliest galaxies.

Our best models for galaxy formation assume:

- Matter originally filled all of space almost uniformly.
- Gravity of denser regions pulled in surrounding matter.





Denser regions contracted, forming protogalactic clouds.

Hydrogen and helium gas in these clouds formed the first stars.

Supernova explosions from the first stars kept much of the gas from forming stars. Leftover gas settled into a spinning disk due to the conservation of angular momentum.

NGC 4414

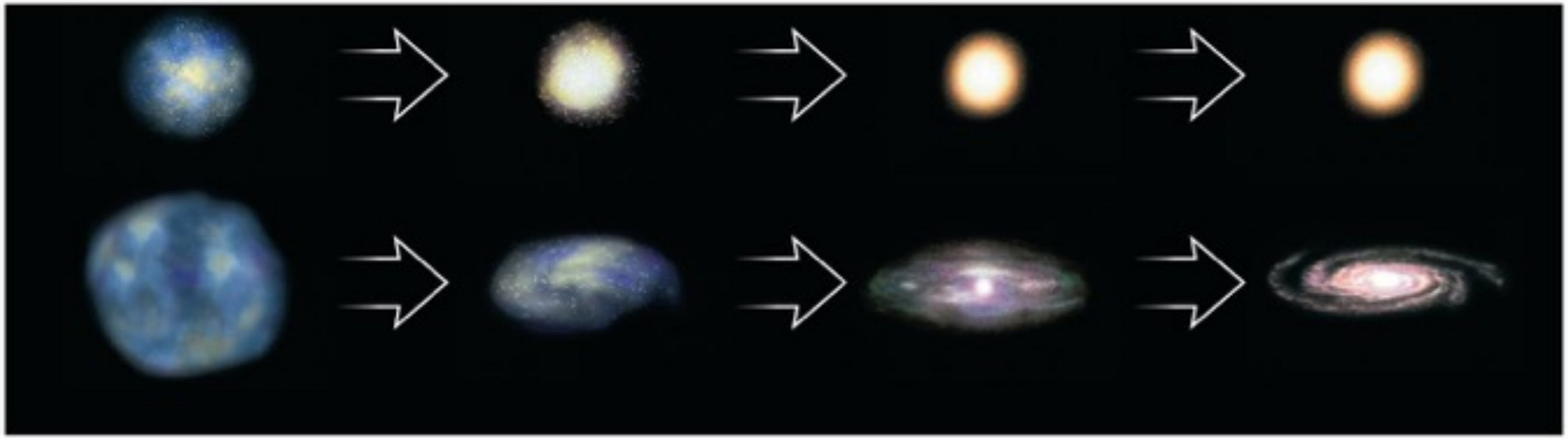
M87

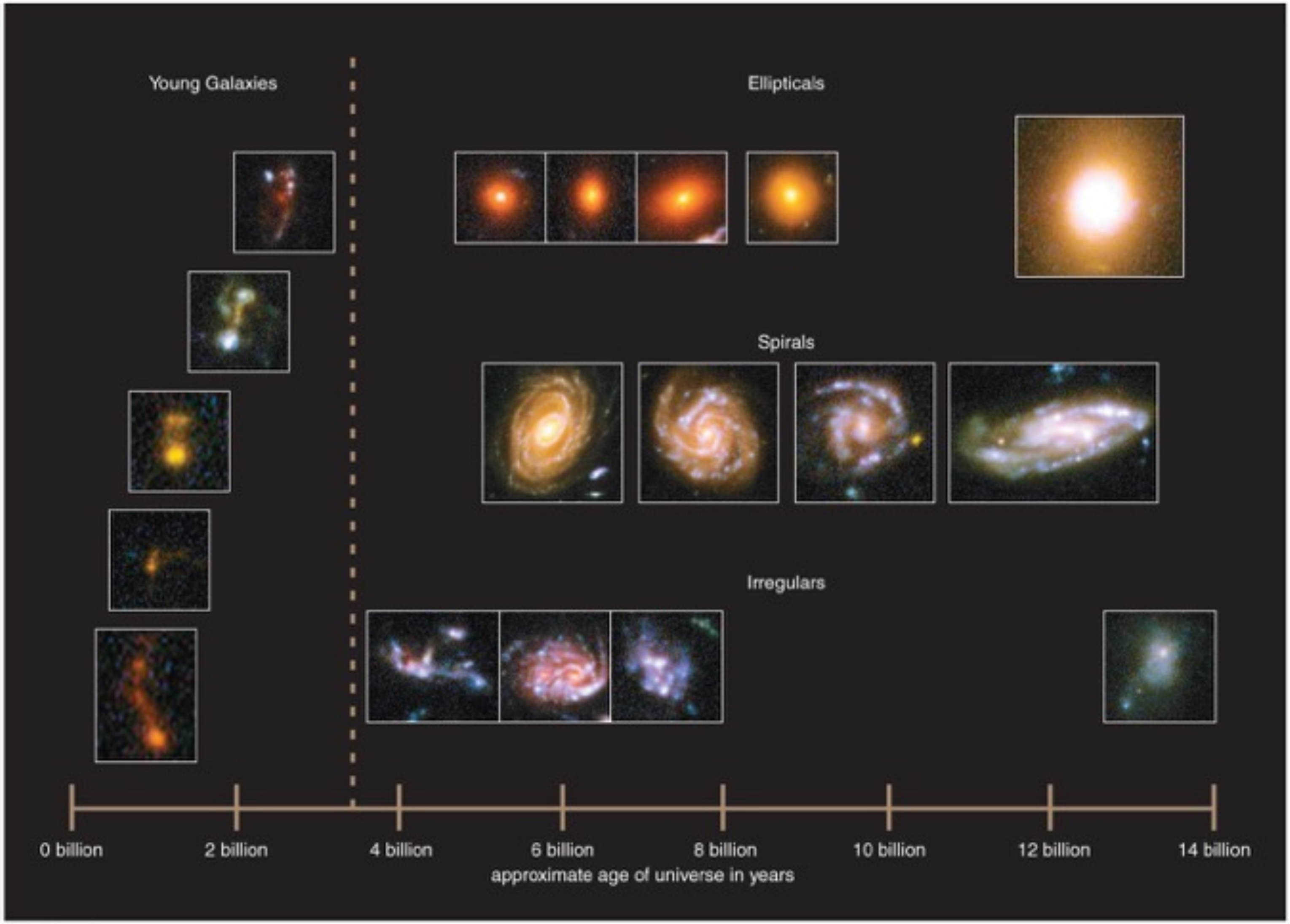
But why do some galaxies end up looking so different?

21.2 The Lives of Galaxies

- Why do galaxies differ?
- What are starbursts?

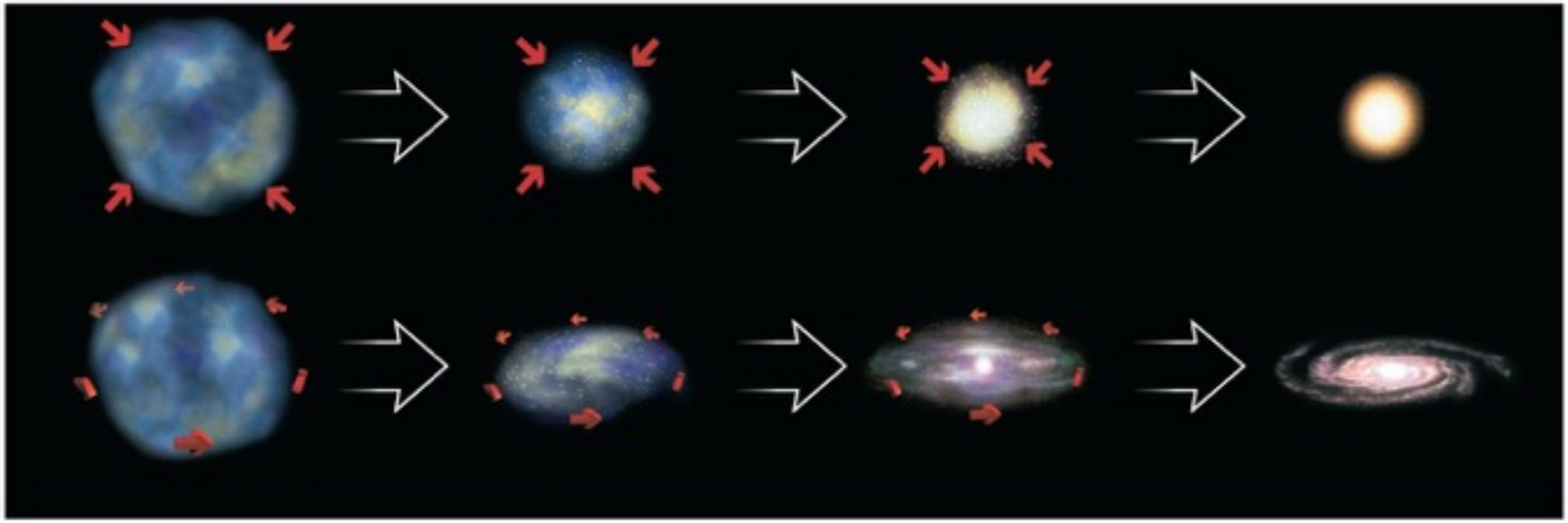
Why do galaxies differ?





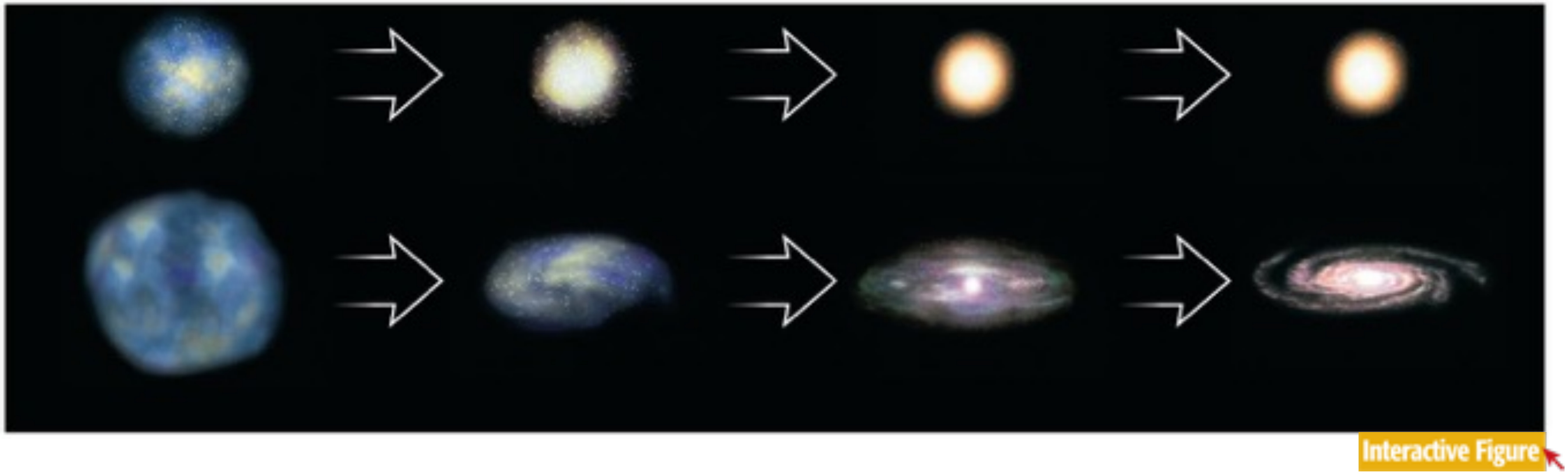
Why don't all galaxies have similar disks?

Conditions in Protogalactic Cloud?



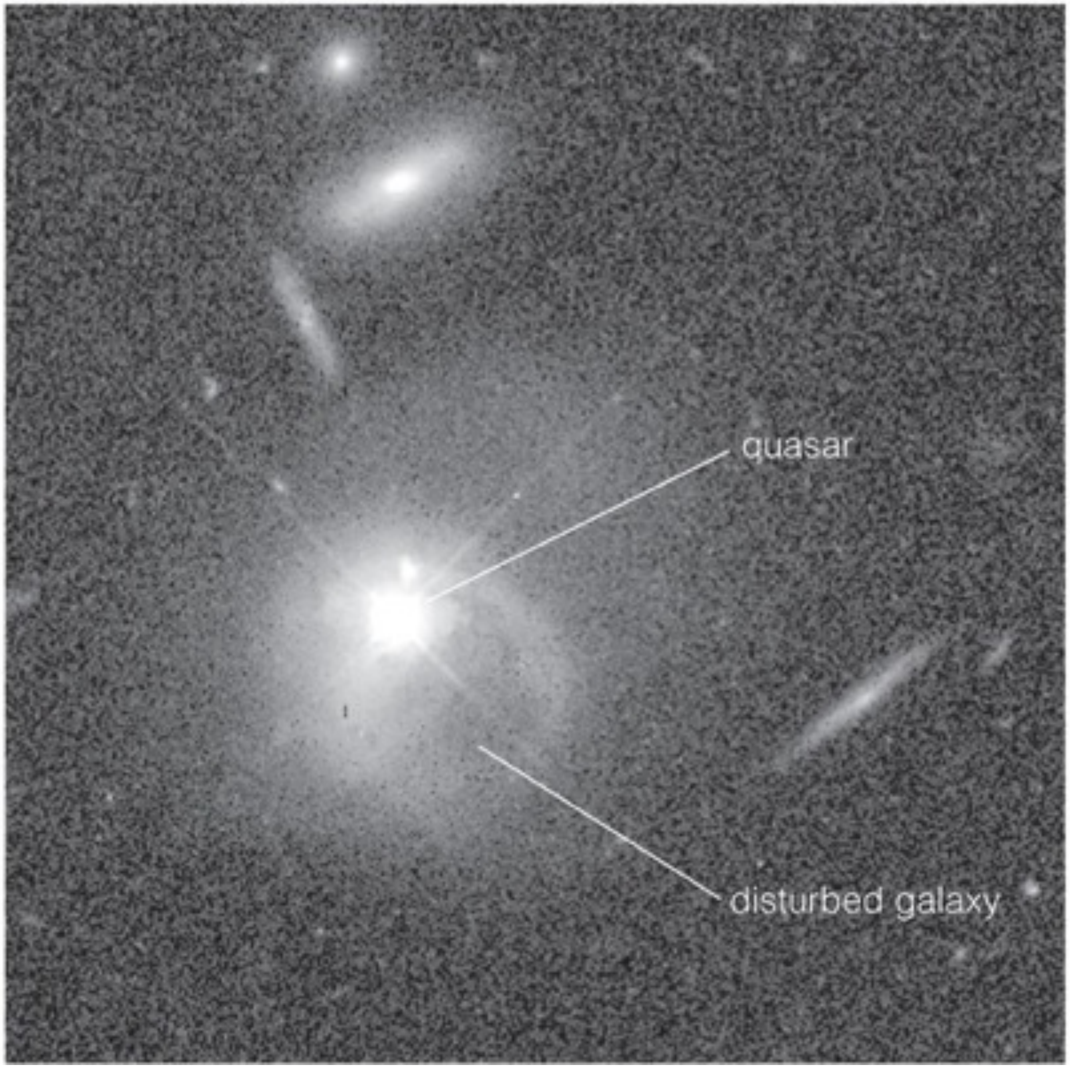
Spin: The initial angular momentum of the protogalactic cloud could determine the size of the resulting disk.

Conditions in Protogalactic Cloud?

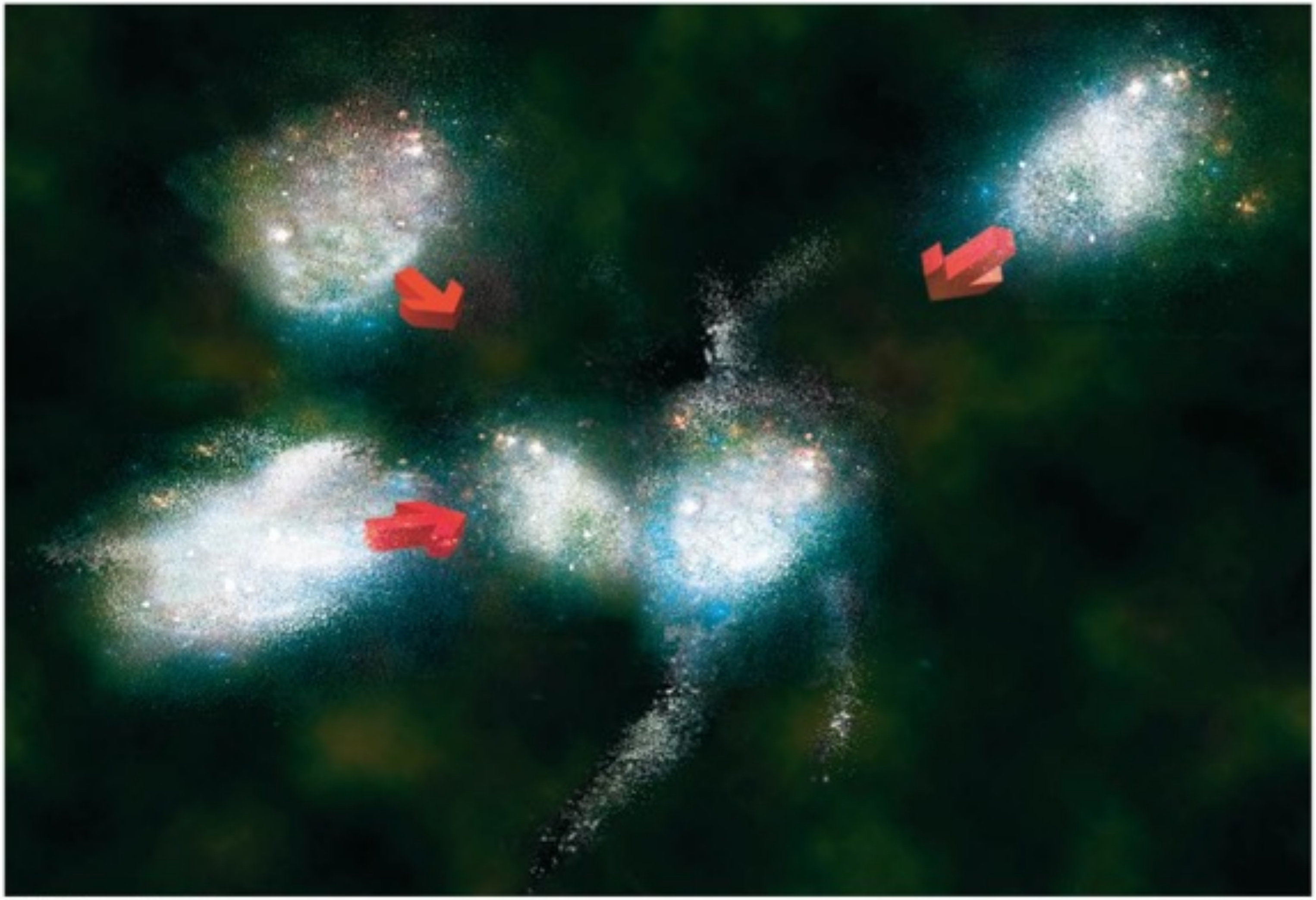


Density: Elliptical galaxies could come from dense protogalactic clouds that were able to cool and form stars before gas settled into a disk.

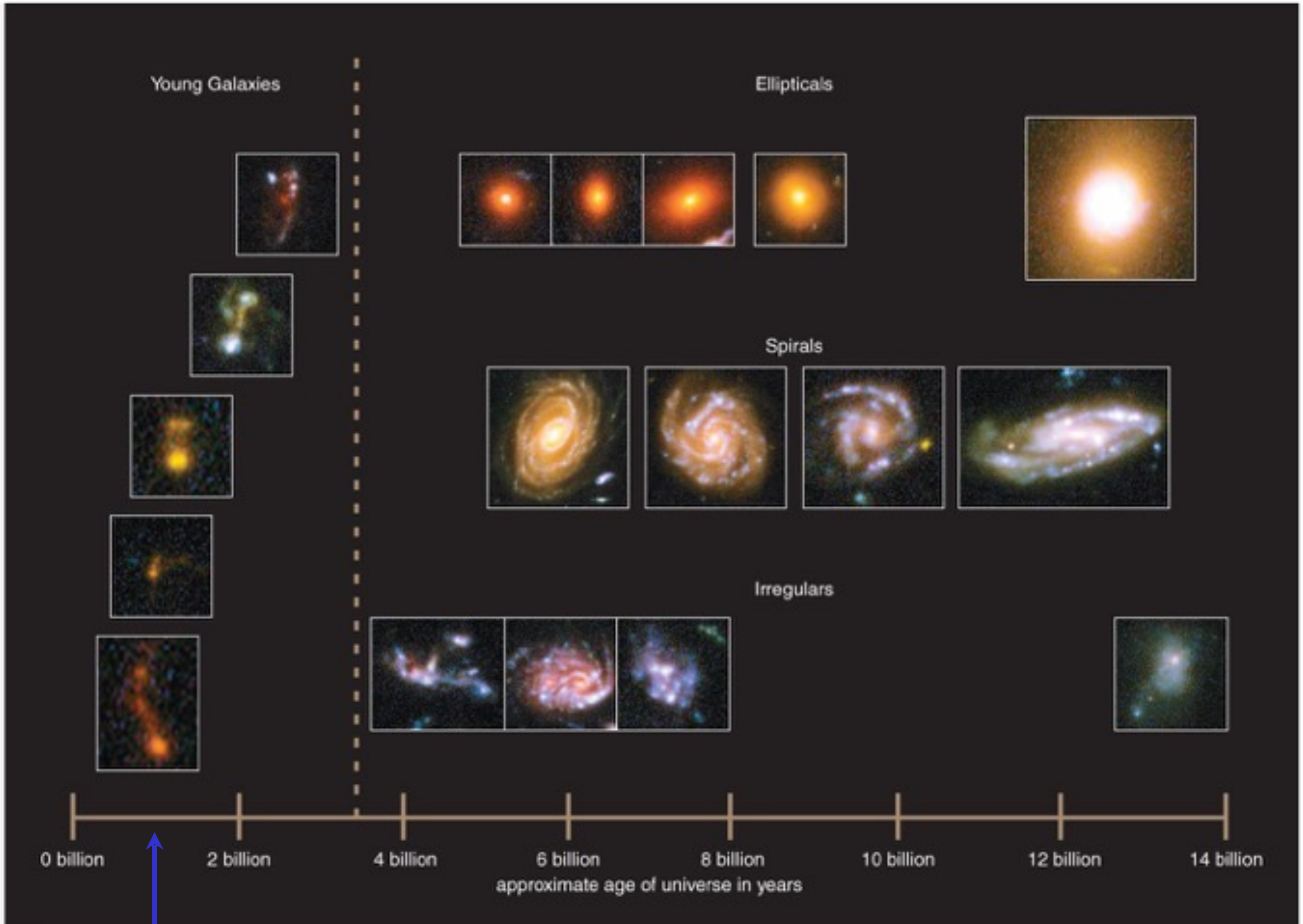
Distant Red Ellipticals



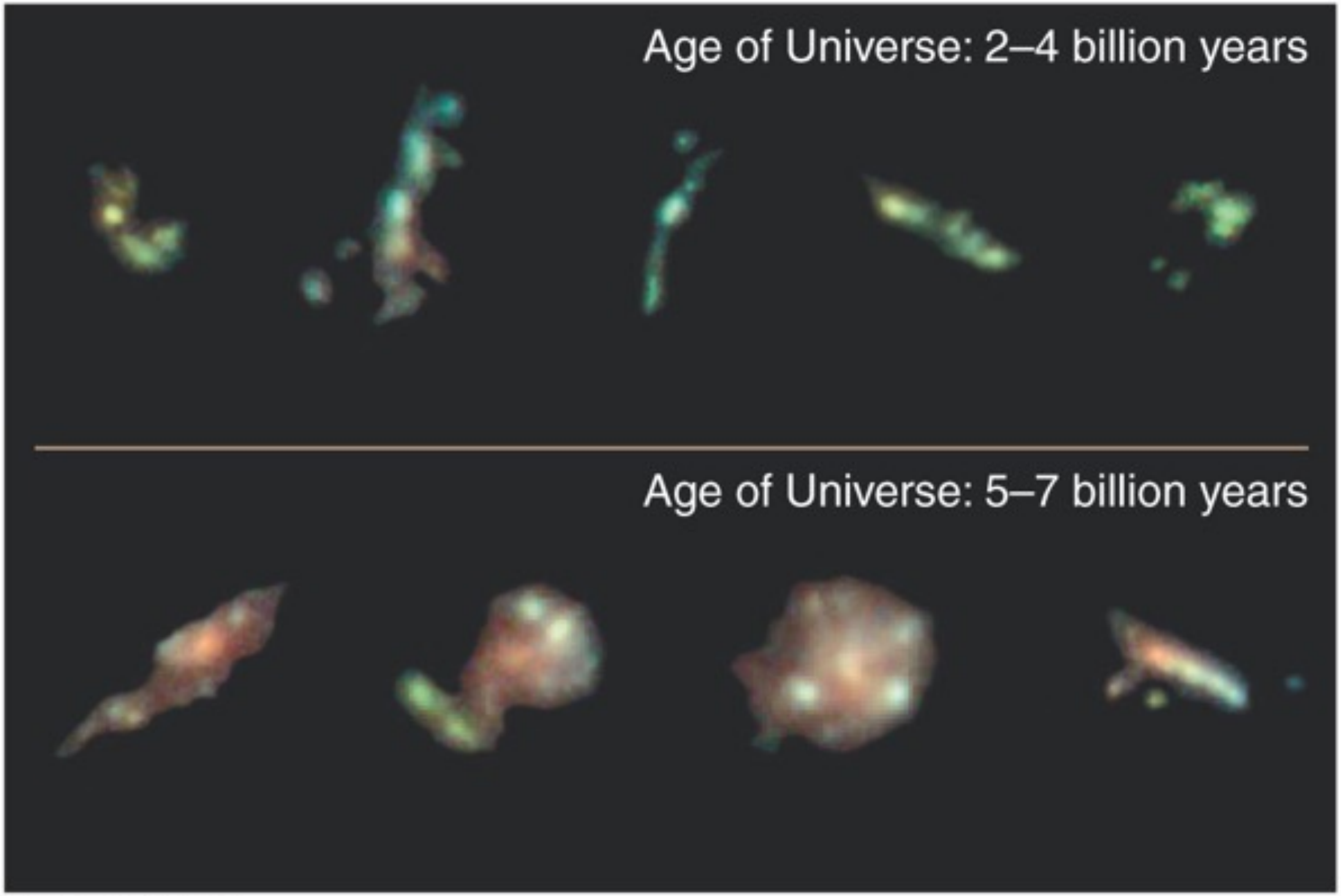
- Observations of some distant red elliptical galaxies support the idea that most of their stars formed very early in the history of the universe.



We must also consider the effects of collisions.

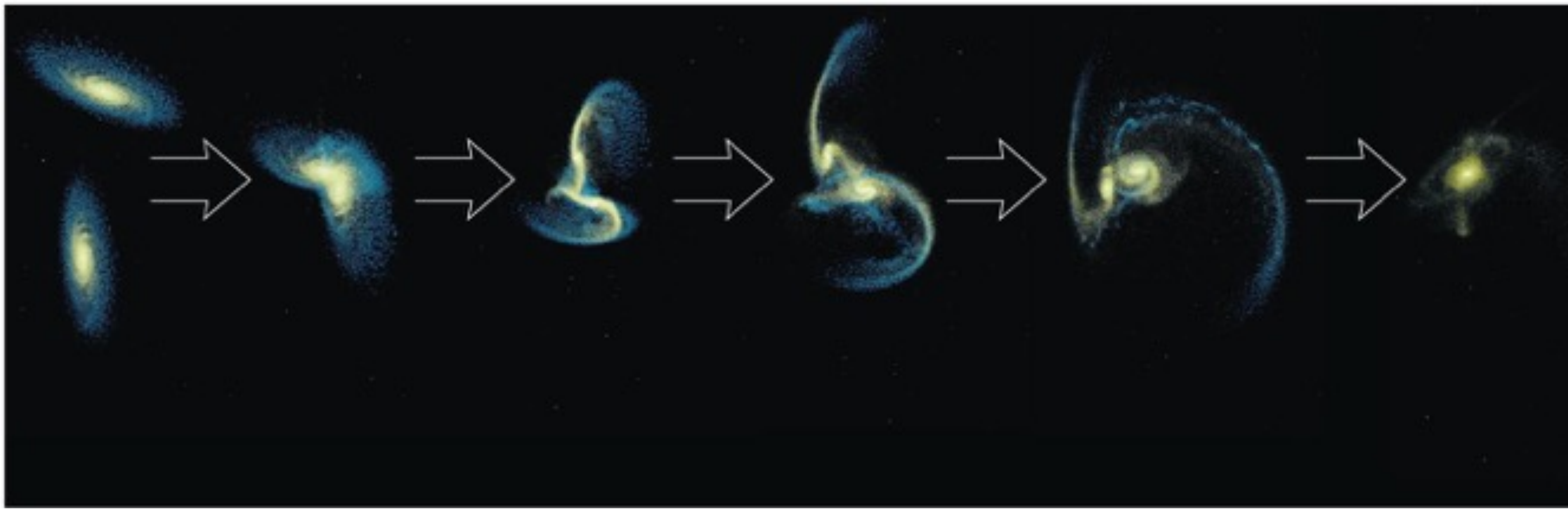


Collisions were much more likely early in time because galaxies were closer together.

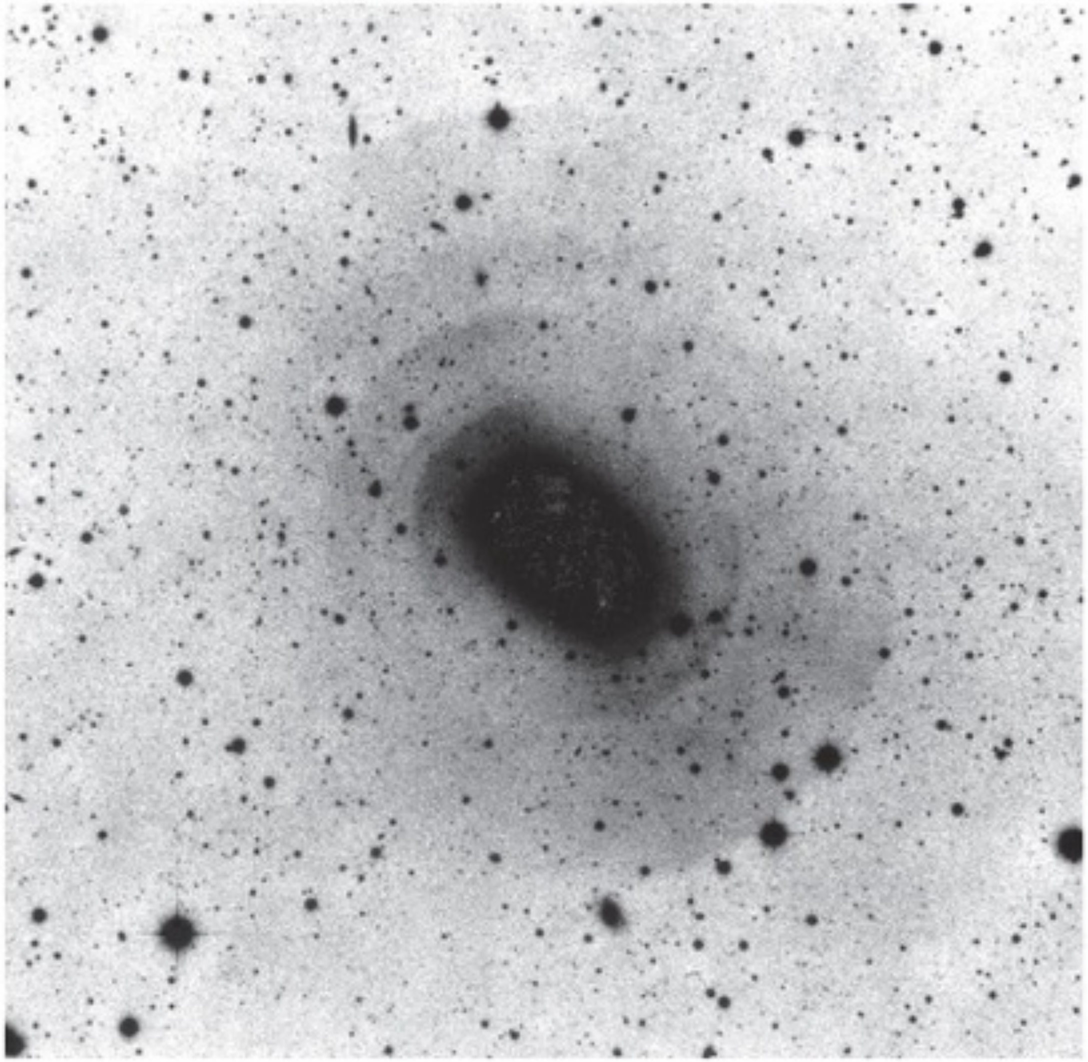


Many of the galaxies we see at great distances (and early times) do look violently disturbed.

The collisions we observe nearby trigger bursts of star formation.

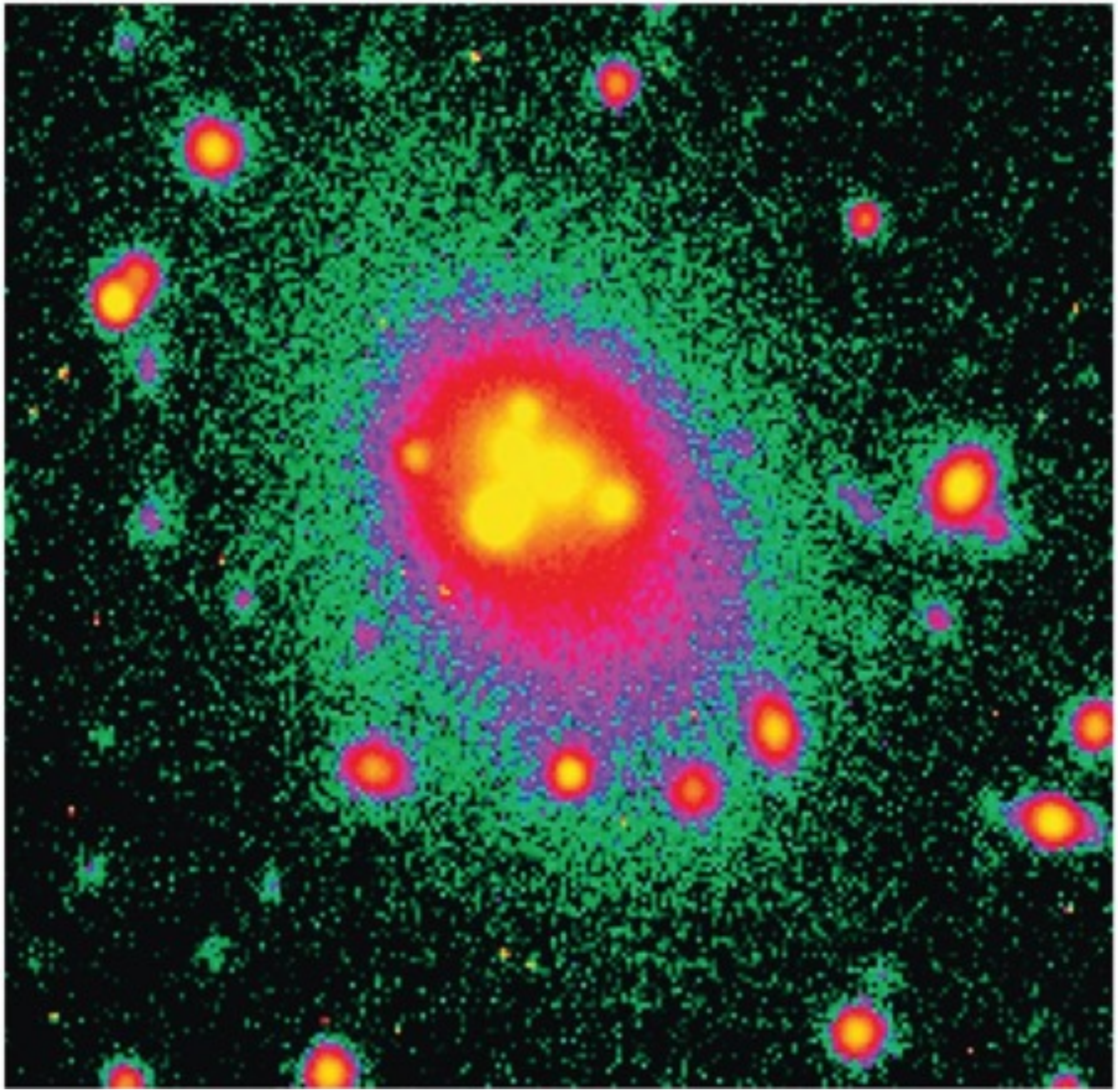


Modeling such collisions on a computer shows that two spiral galaxies can merge to make an elliptical.



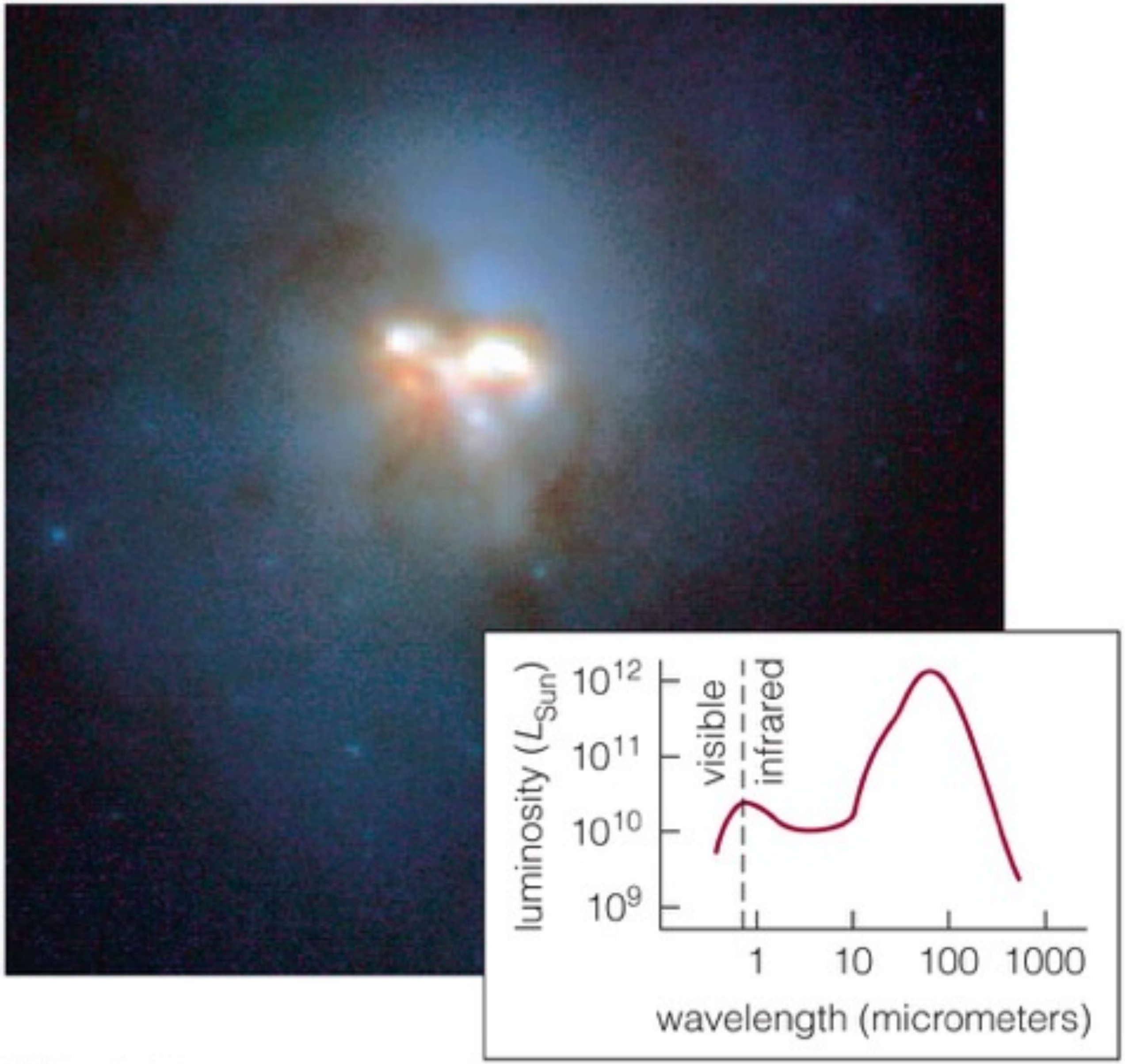
Shells of stars observed around some elliptical galaxies are probably the remains of past collisions.

Collisions may explain why elliptical galaxies tend to be found where galaxies are closer together.



Giant elliptical galaxies at the centers of clusters seem to have consumed a number of smaller galaxies.

What are starbursts?



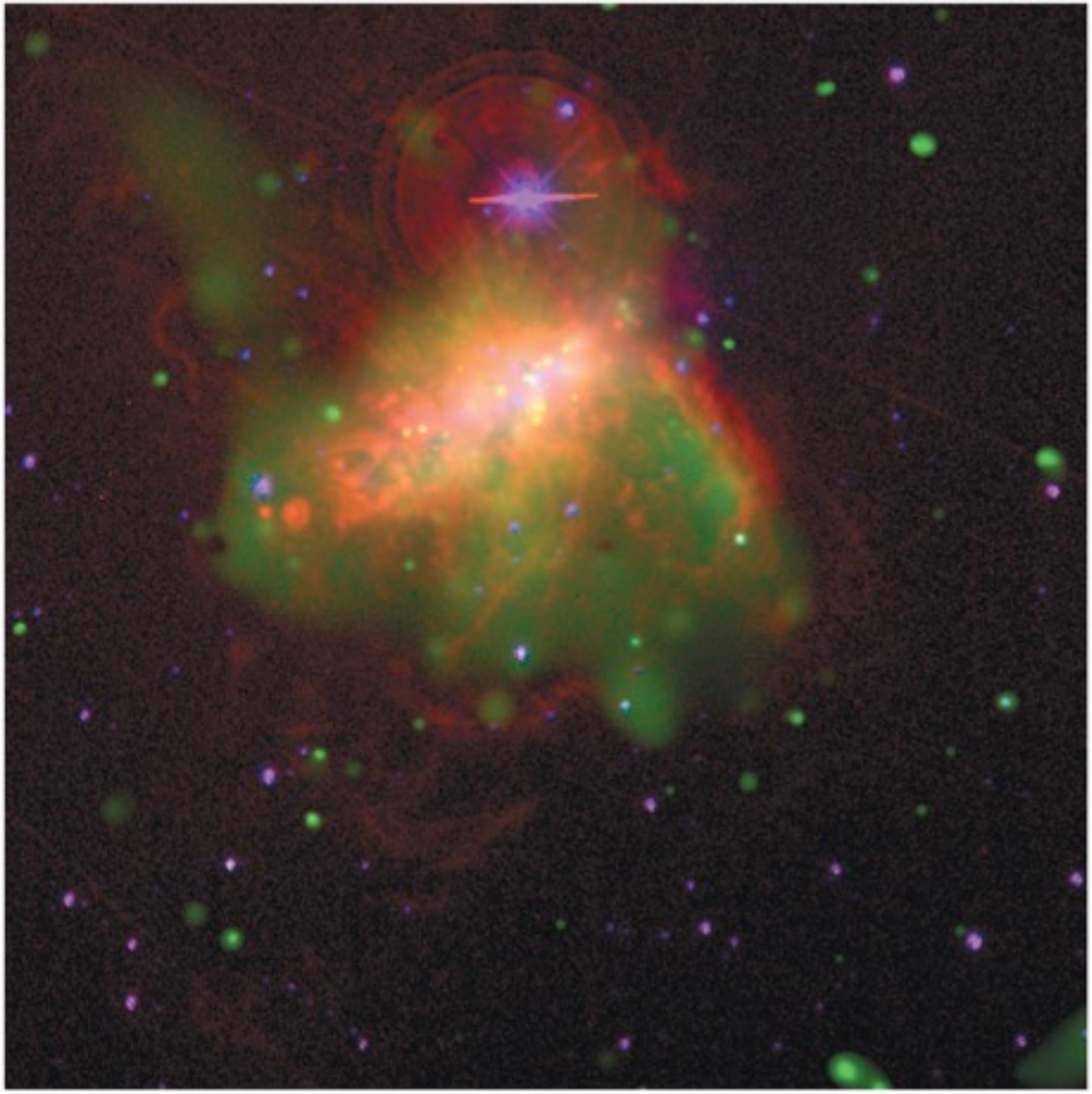
Starburst galaxies are forming stars so quickly that they would use up all their gas in less than a billion years.

Visible-light image

Intensity of supernova explosions in starburst galaxies can drive galactic winds.

X-ray image

Intensity of supernova explosions in starburst galaxies can drive galactic winds.

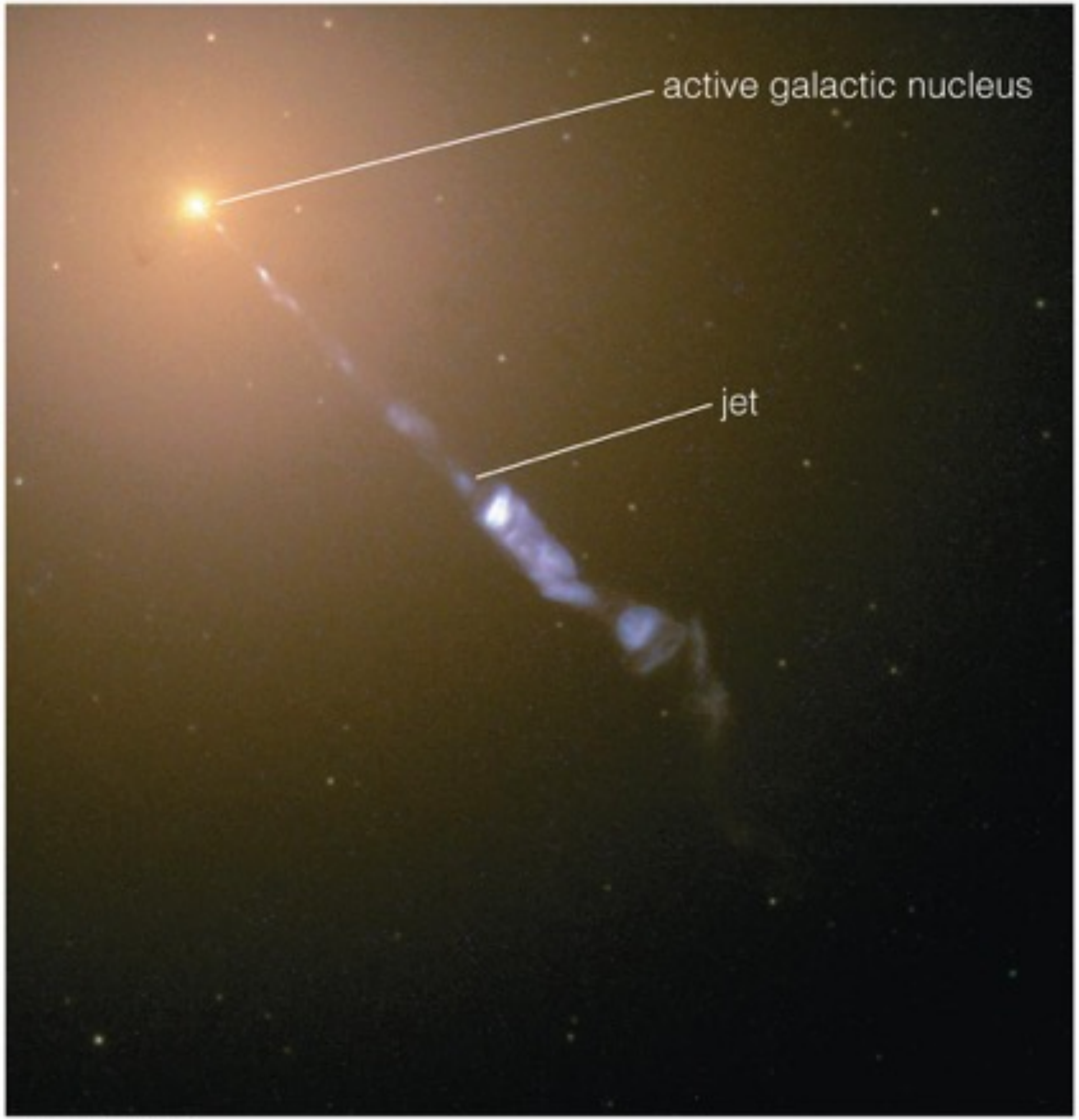


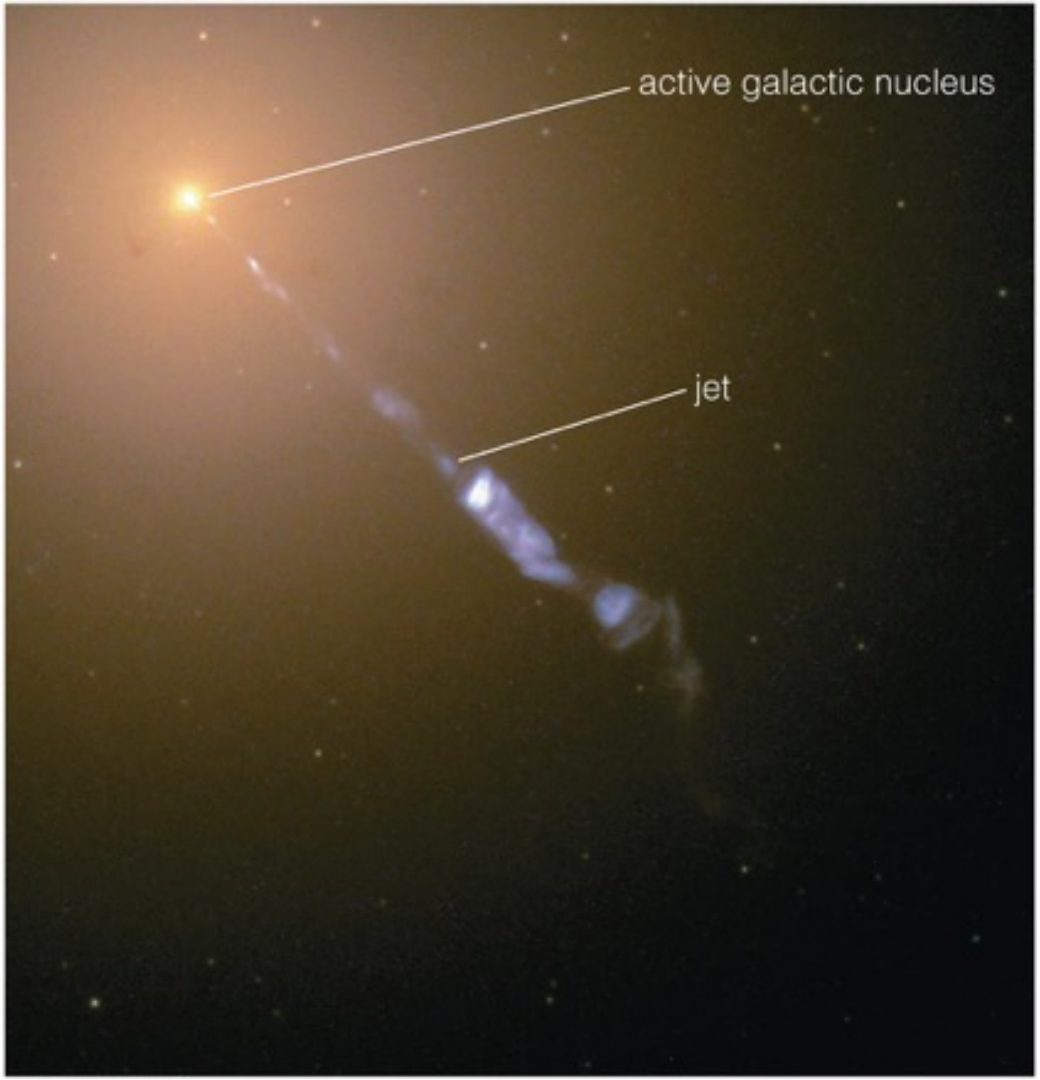
A galactic wind in a small galaxy can drive away most of its gas.

21.3 Quasars and Other Active Galactic Nuclei

- What are quasars?
- What is the power source for quasars and other active galactic nuclei?
- Do supermassive black holes really exist?
- How do quasars let us study gas between the galaxies?

What are quasars?

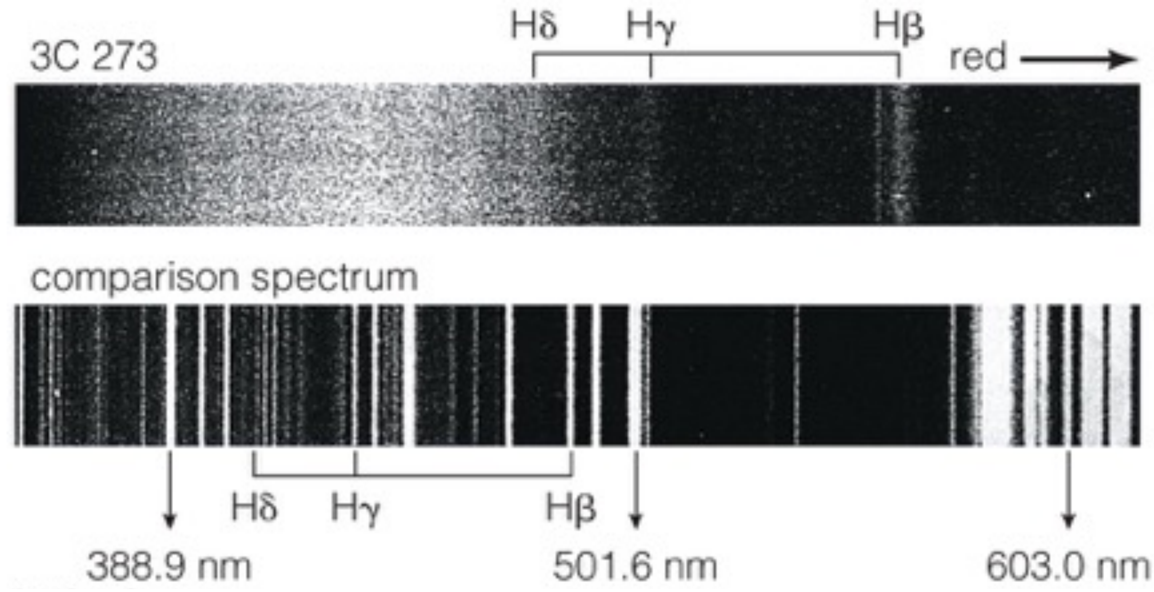




If the center of a galaxy is unusually bright, we call it an active galactic nucleus.

Quasars are the most luminous examples.

Active nucleus in Galaxy M87



The highly redshifted spectra of quasars indicate large distances.

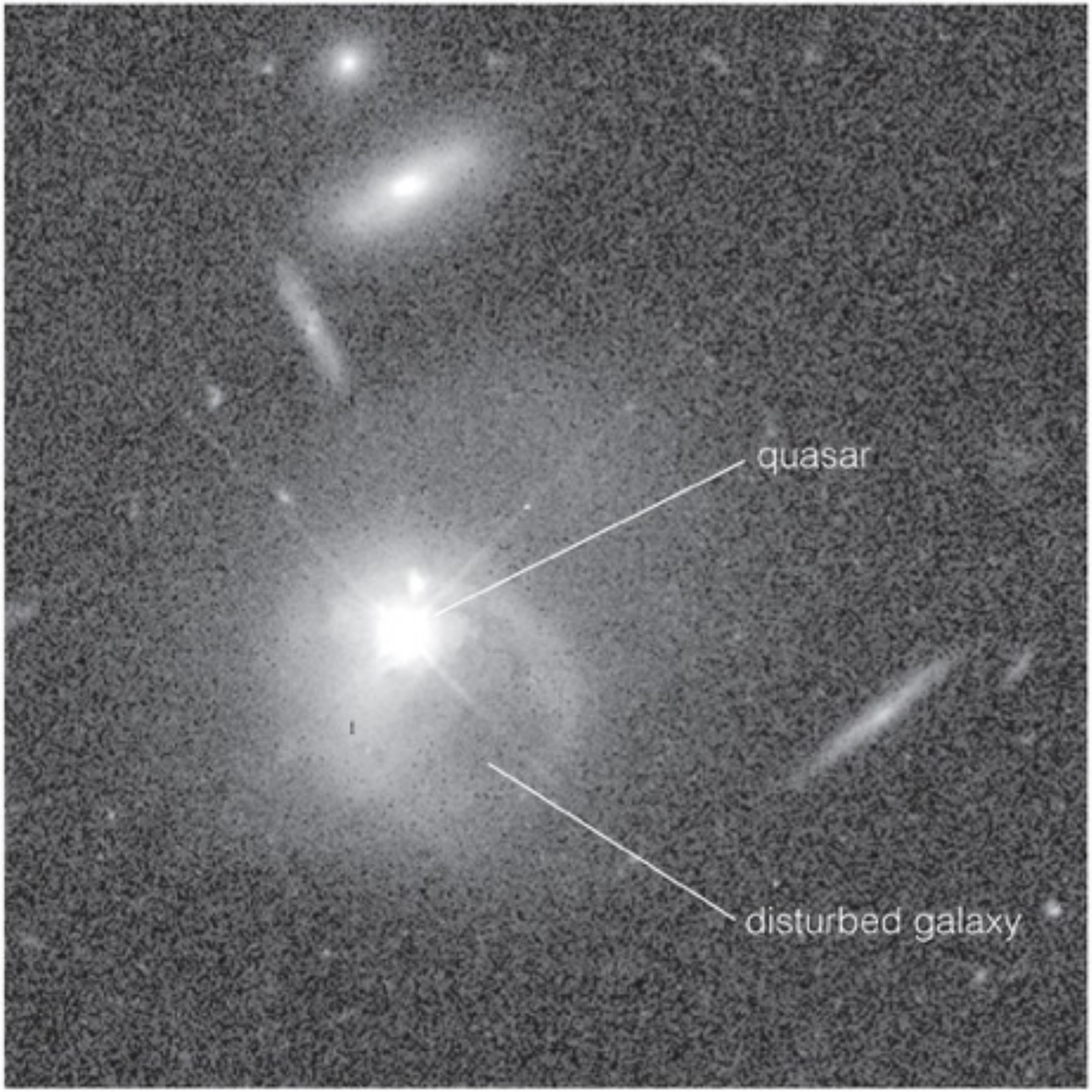
From brightness and distance we find that luminosities of some quasars are greater than 10^{12} L_{Sun}.

Variability shows that all this energy comes from a region smaller than our solar system.

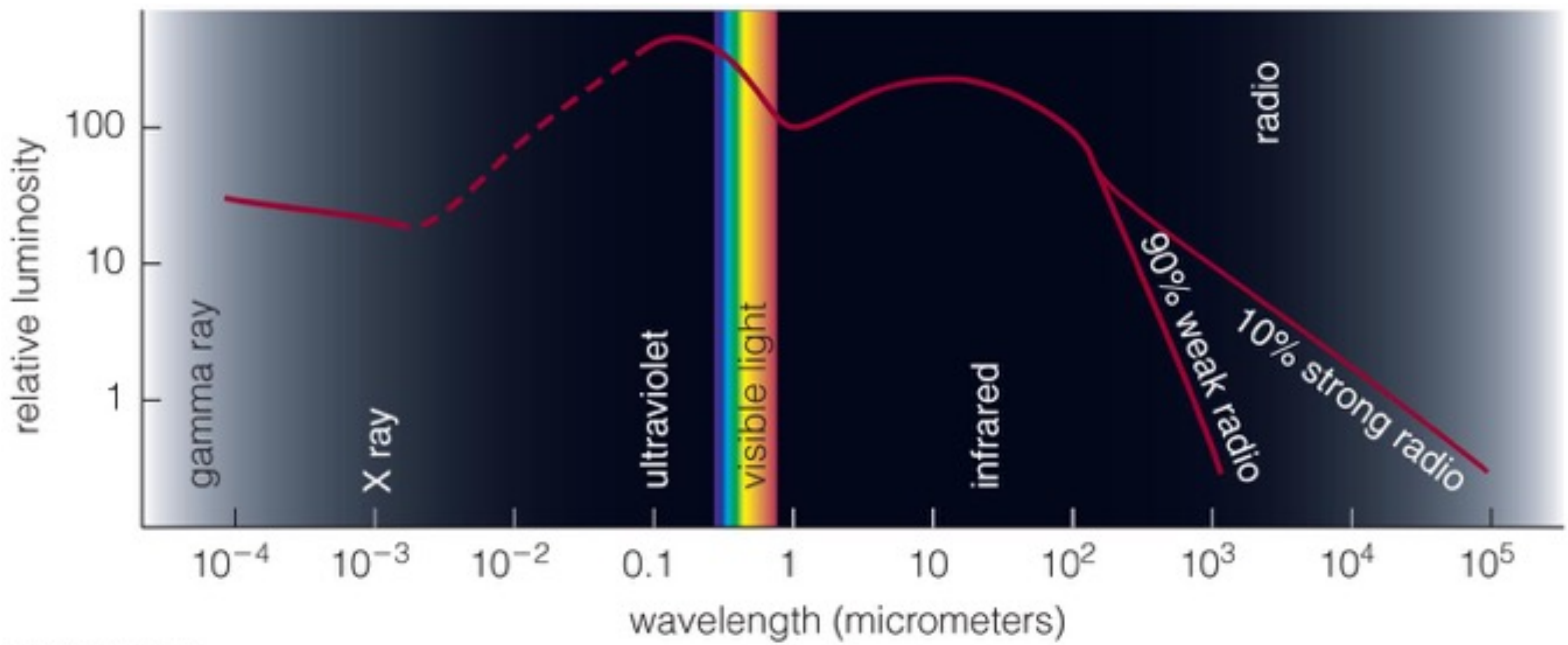
Thought Question

What can you conclude from the fact that quasars usually have very large redshifts?

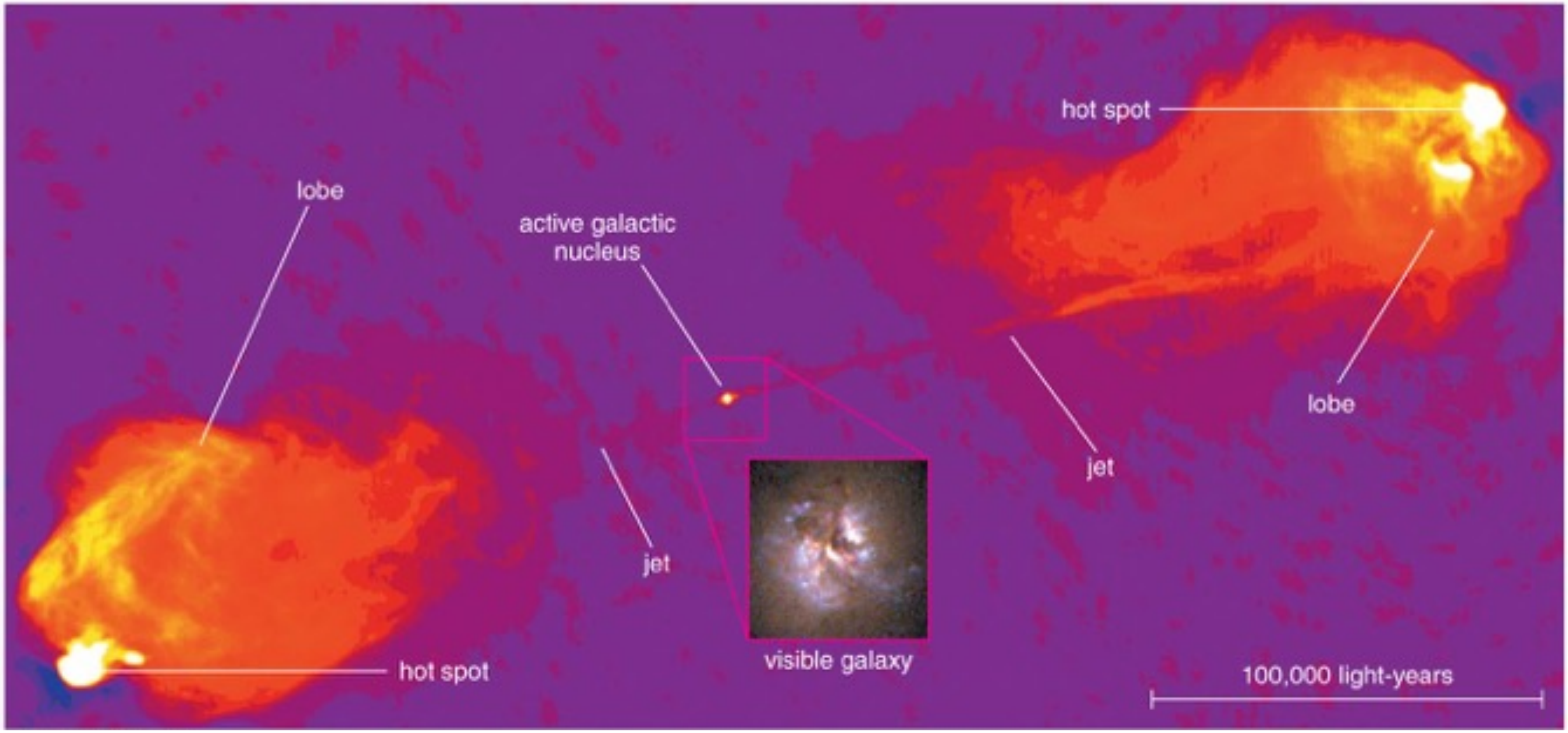
A. They are generally very distant.
B. They were more common early in time.
C. Galaxy collisions might turn them on.
D. Nearby galaxies might hold dead quasars.



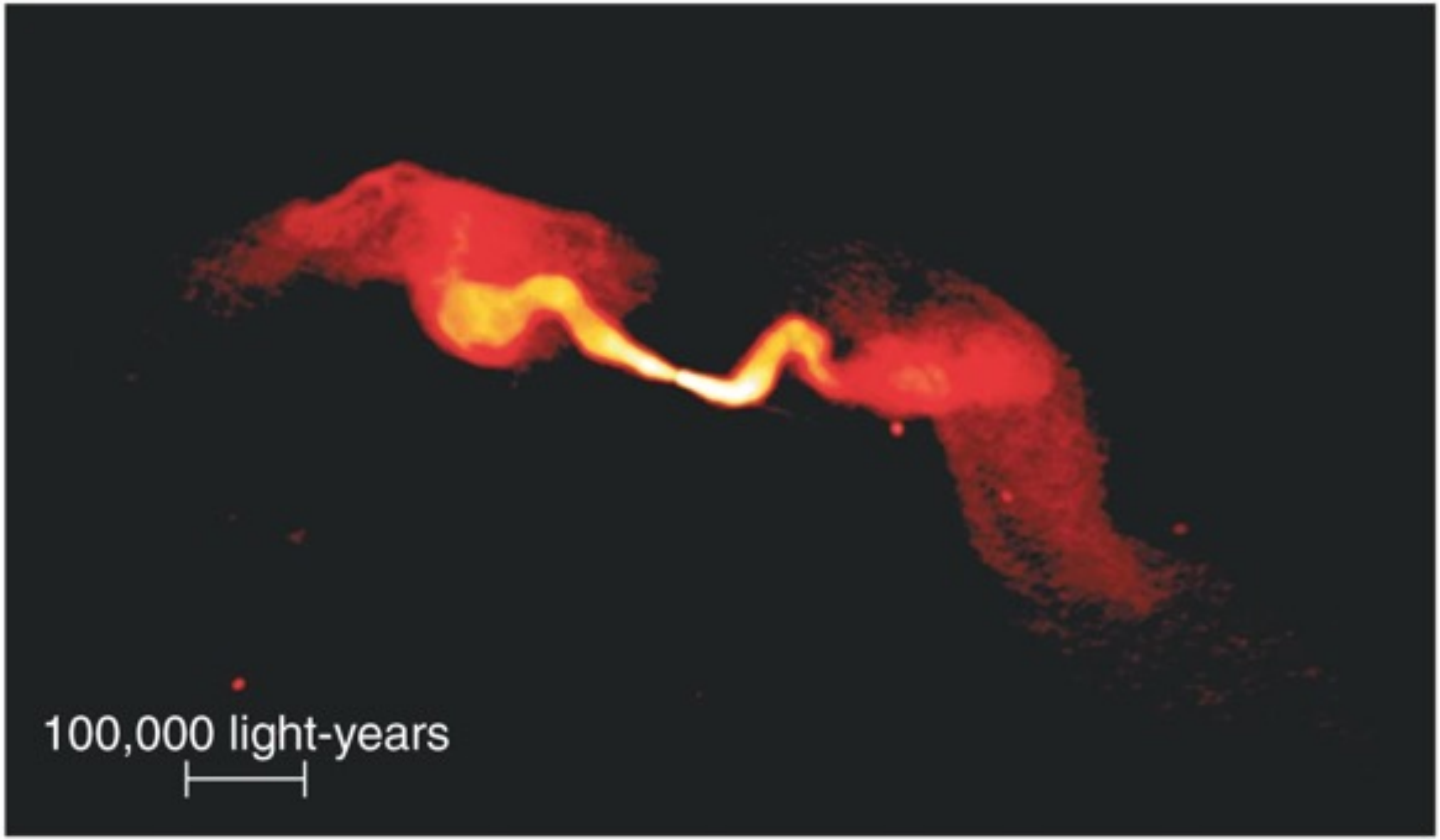
Galaxies around quasars sometimes appear disturbed by collisions.



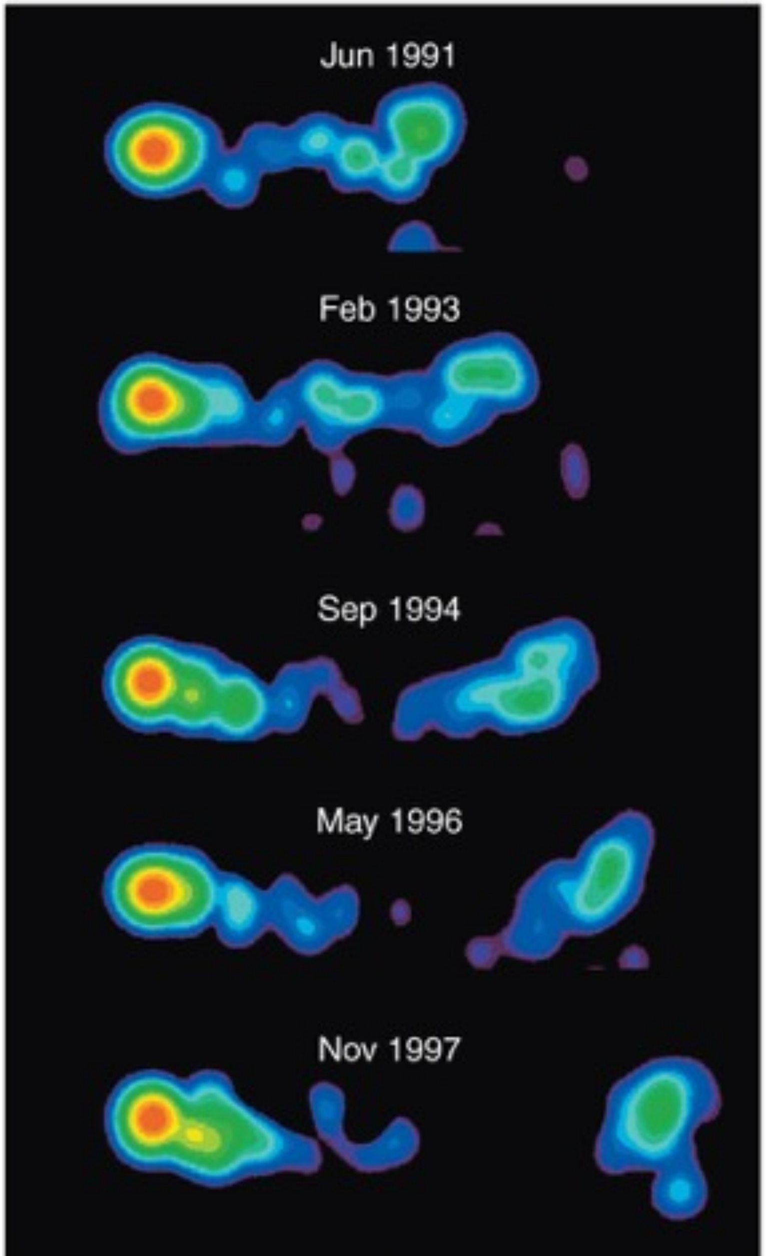
Quasars powerfully radiate energy over a wide range of wavelengths, indicating that they contain matter with a wide range of temperatures.



Radio galaxies contain active nuclei shooting out vast jets of plasma that emits radio waves coming from electrons that move at near light speed.

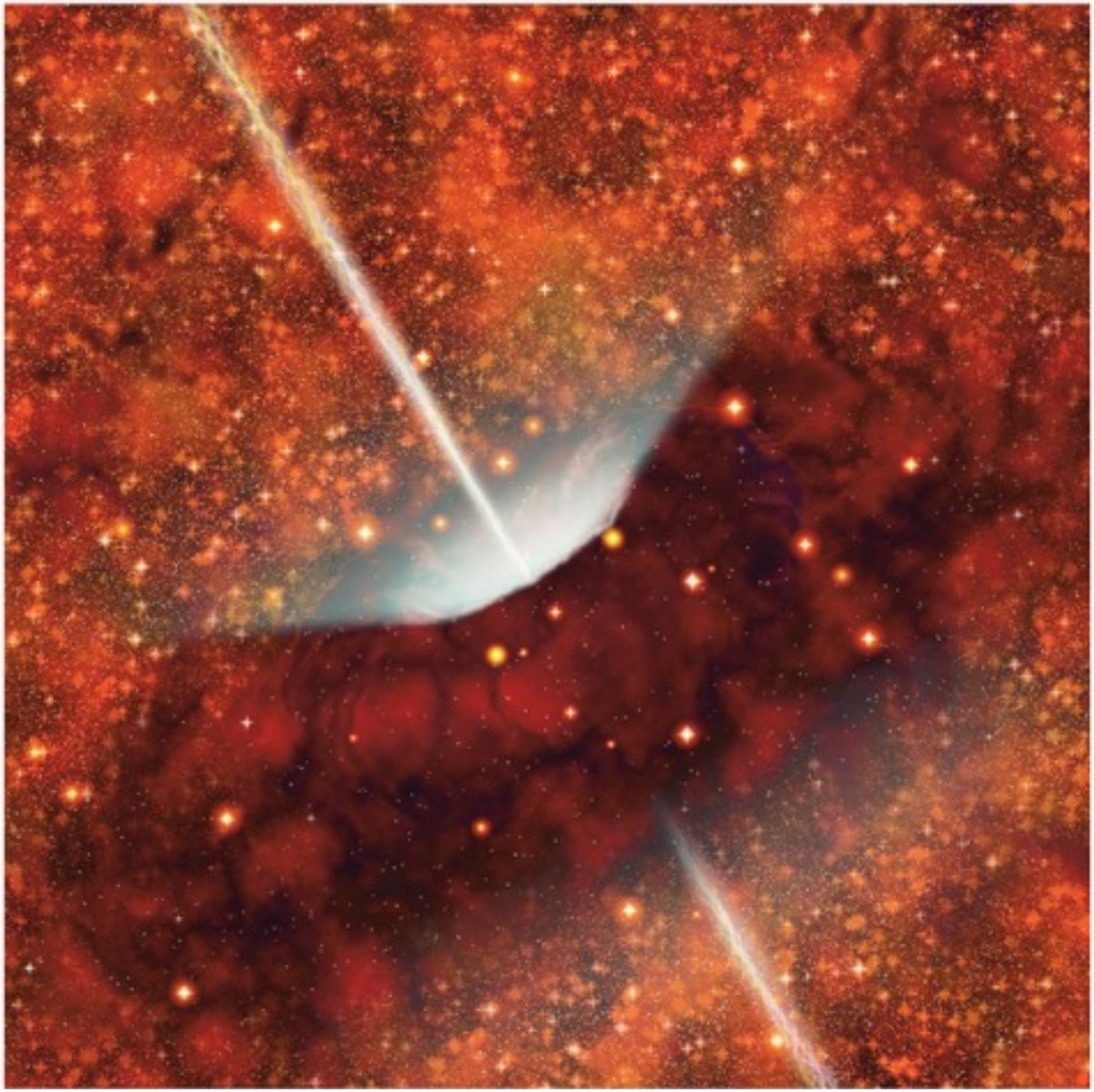


The lobes of radio galaxies can extend over hundreds of thousands of light-years.



An active galactic nucleus can shoot out blobs of plasma moving at nearly the speed of light.

These ejection speeds suggests the presence of a black hole.

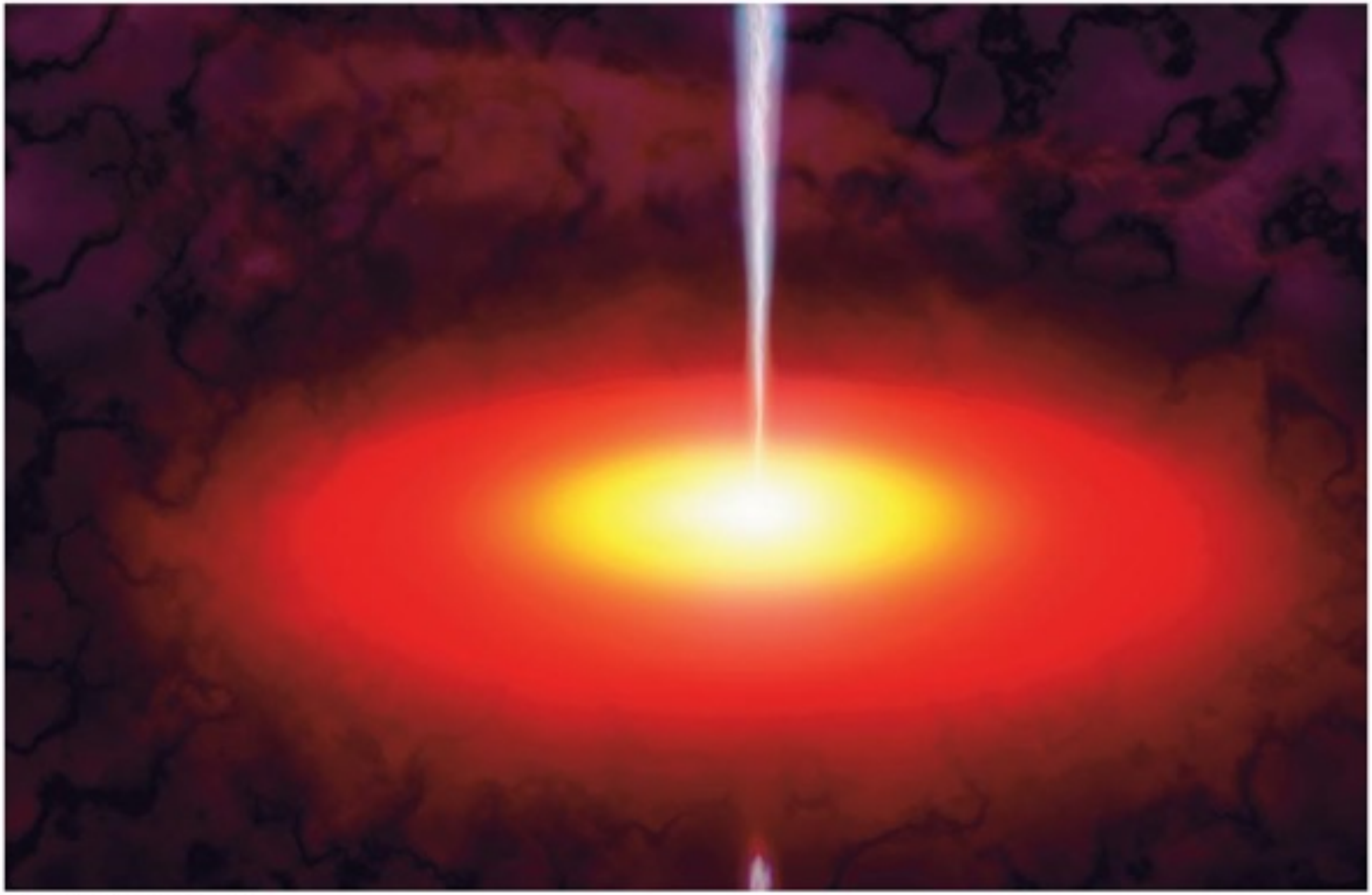


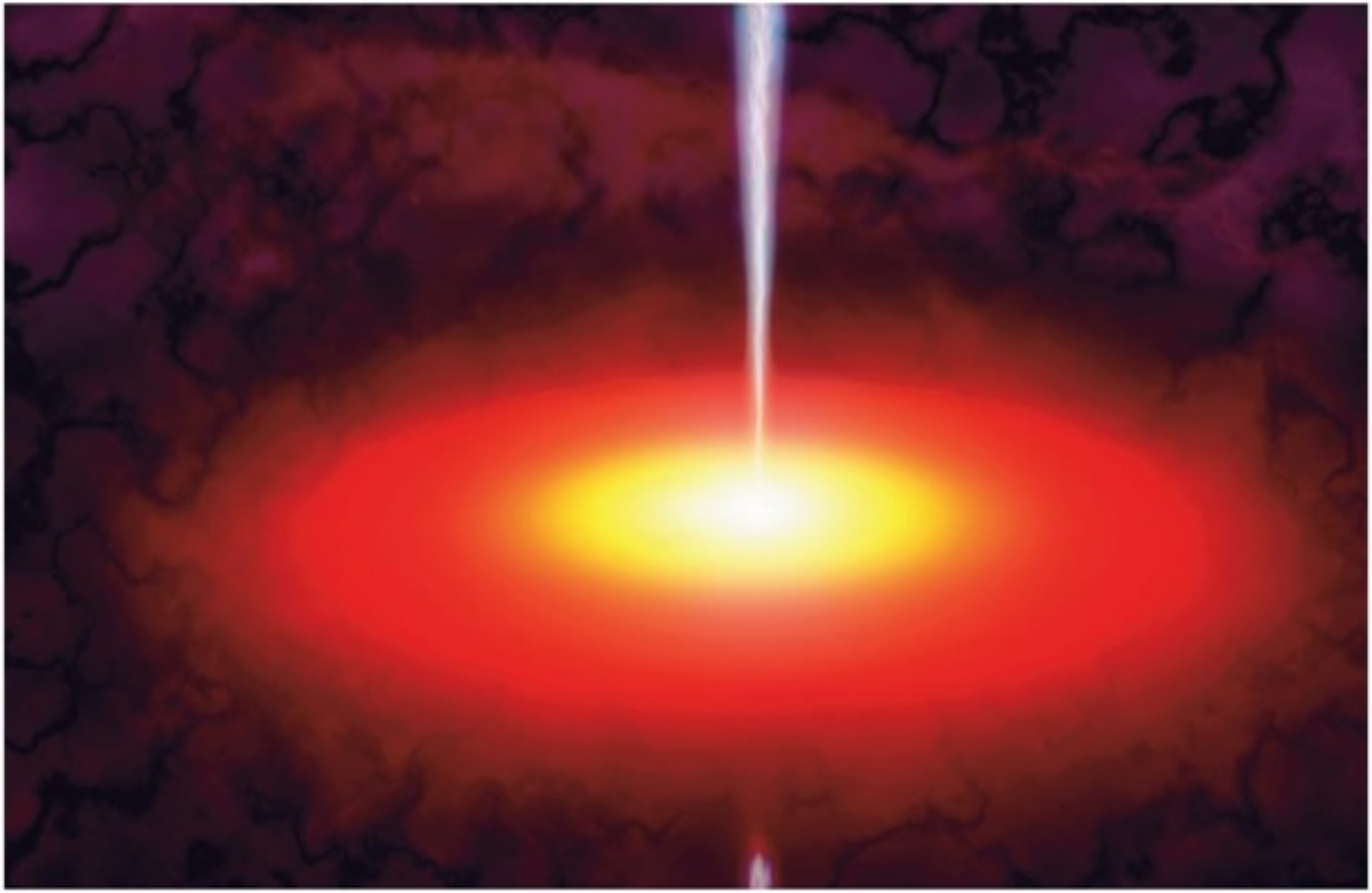
Radio galaxies don't appear as quasars because dusty gas clouds block our view of the accretion disk.

Characteristics of Active Galaxies

- Their luminosities can be enormous (>10^{12} L_{Sun}).
- Their luminosities can rapidly vary (come from a space smaller than solar system).
- They emit energy over a wide range of wavelengths (contain matter with a wide temperature range).
- Some galaxies drive jets of plasma at near light speed.

What is the power source for quasars and other active galactic nuclei?

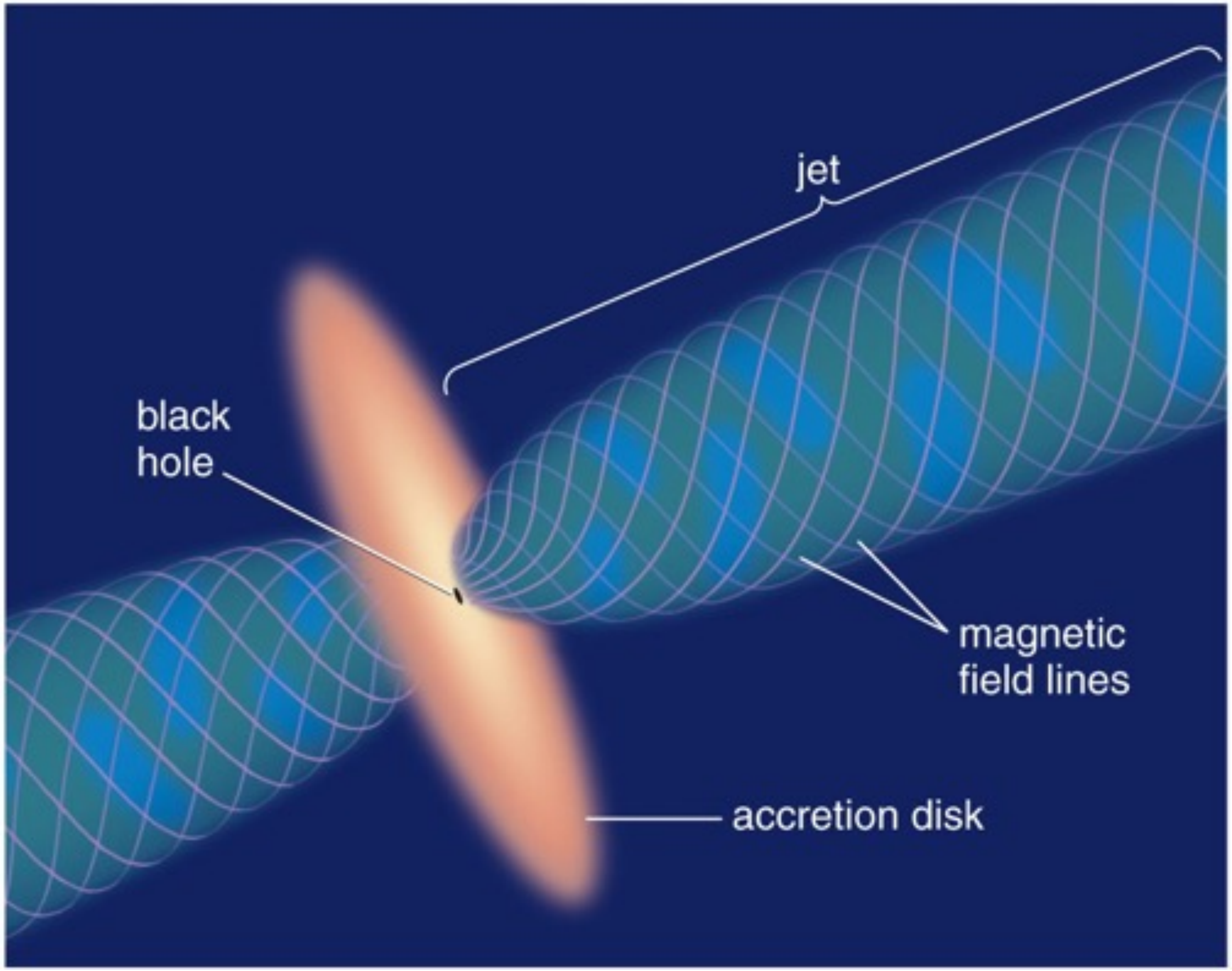




Accretion of gas onto a supermassive black hole appears to be the only way to explain all the properties of quasars.

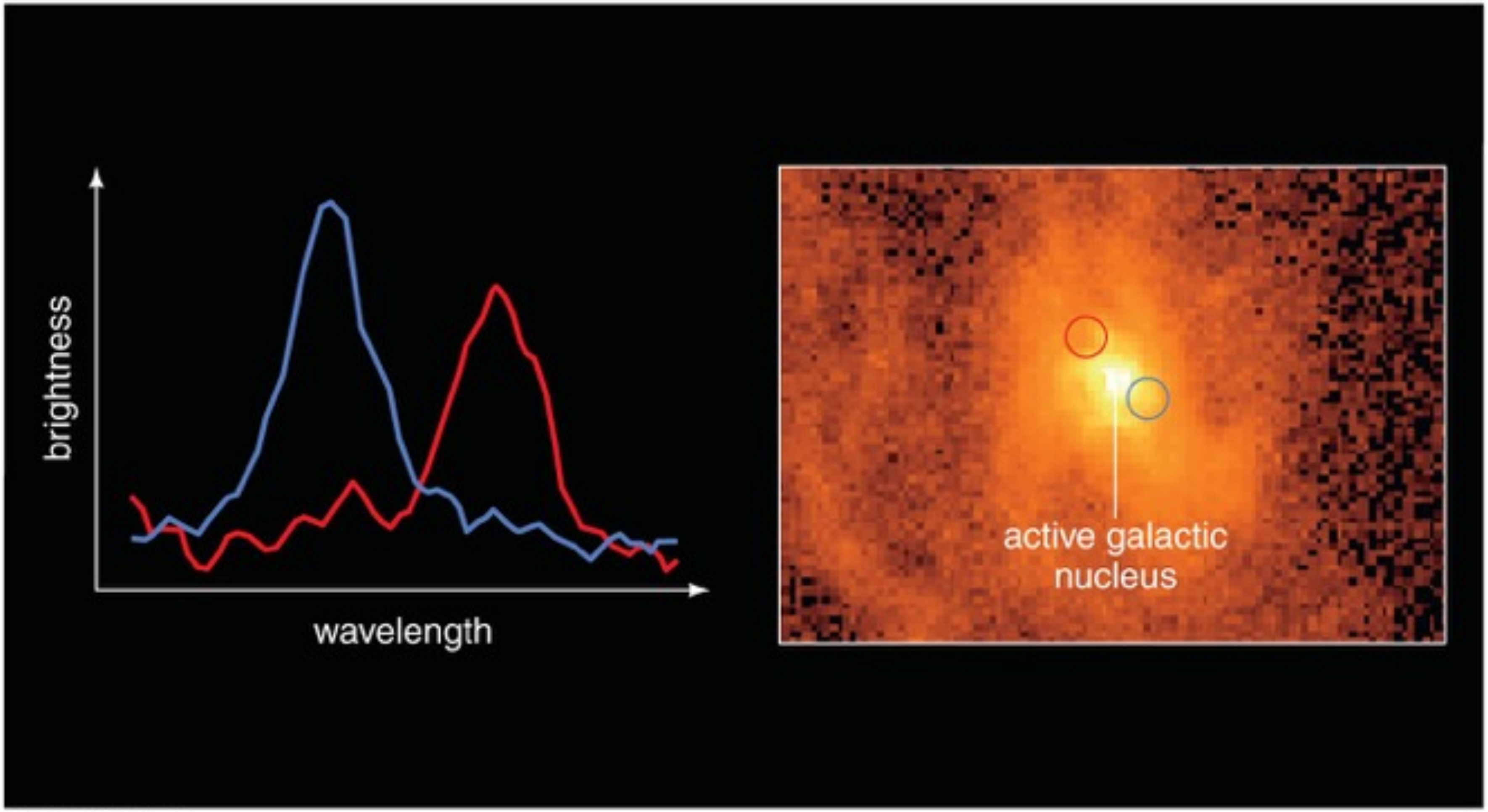
Energy from a Black Hole

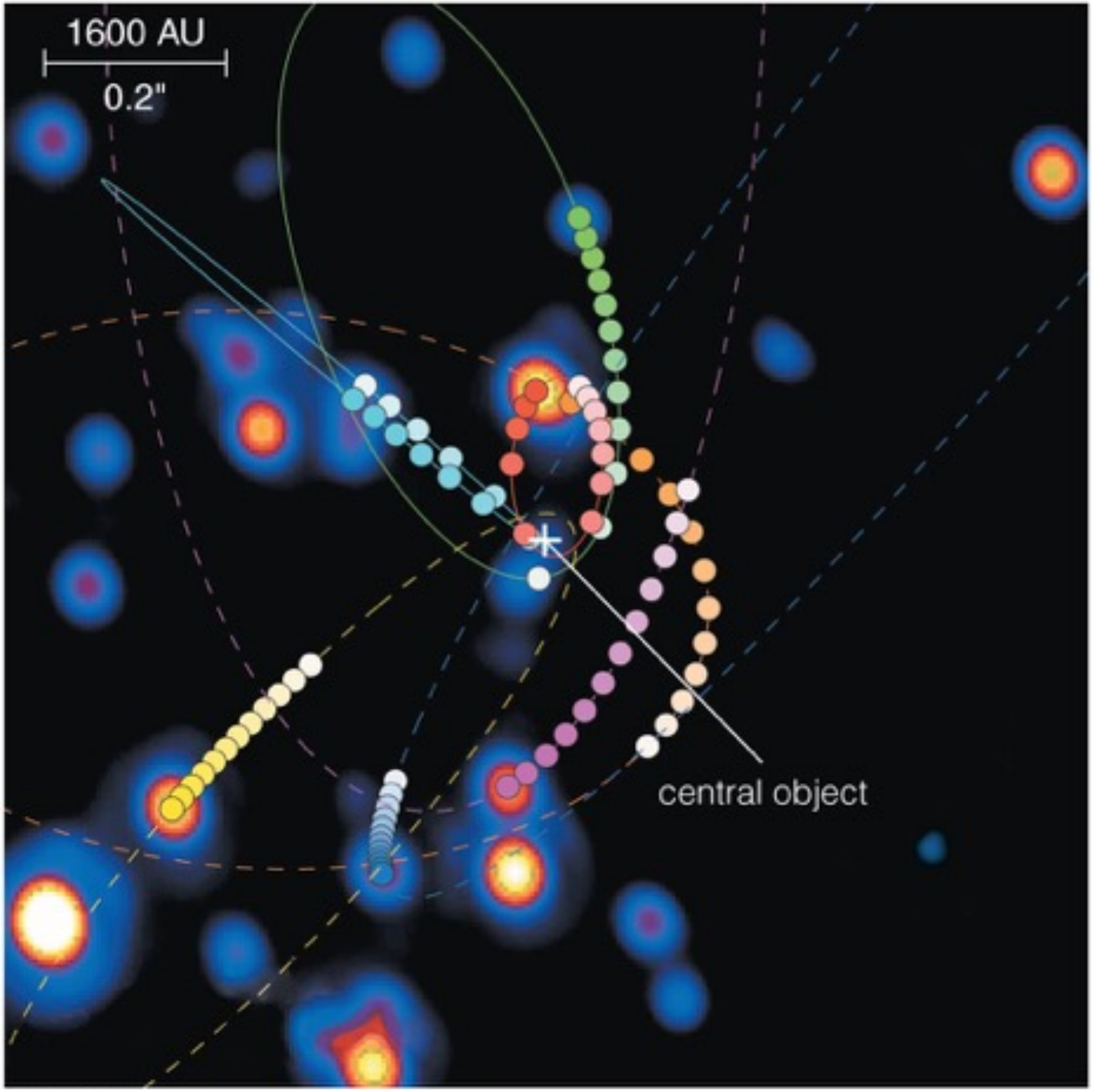
- Gravitational potential energy of matter falling into black hole turns into kinetic energy.
- Friction in an accretion disk turns kinetic energy into thermal energy (heat).
- Heat produces thermal radiation (photons).
- This process can convert 10 to 40% of $E = mc^2$ into radiation.



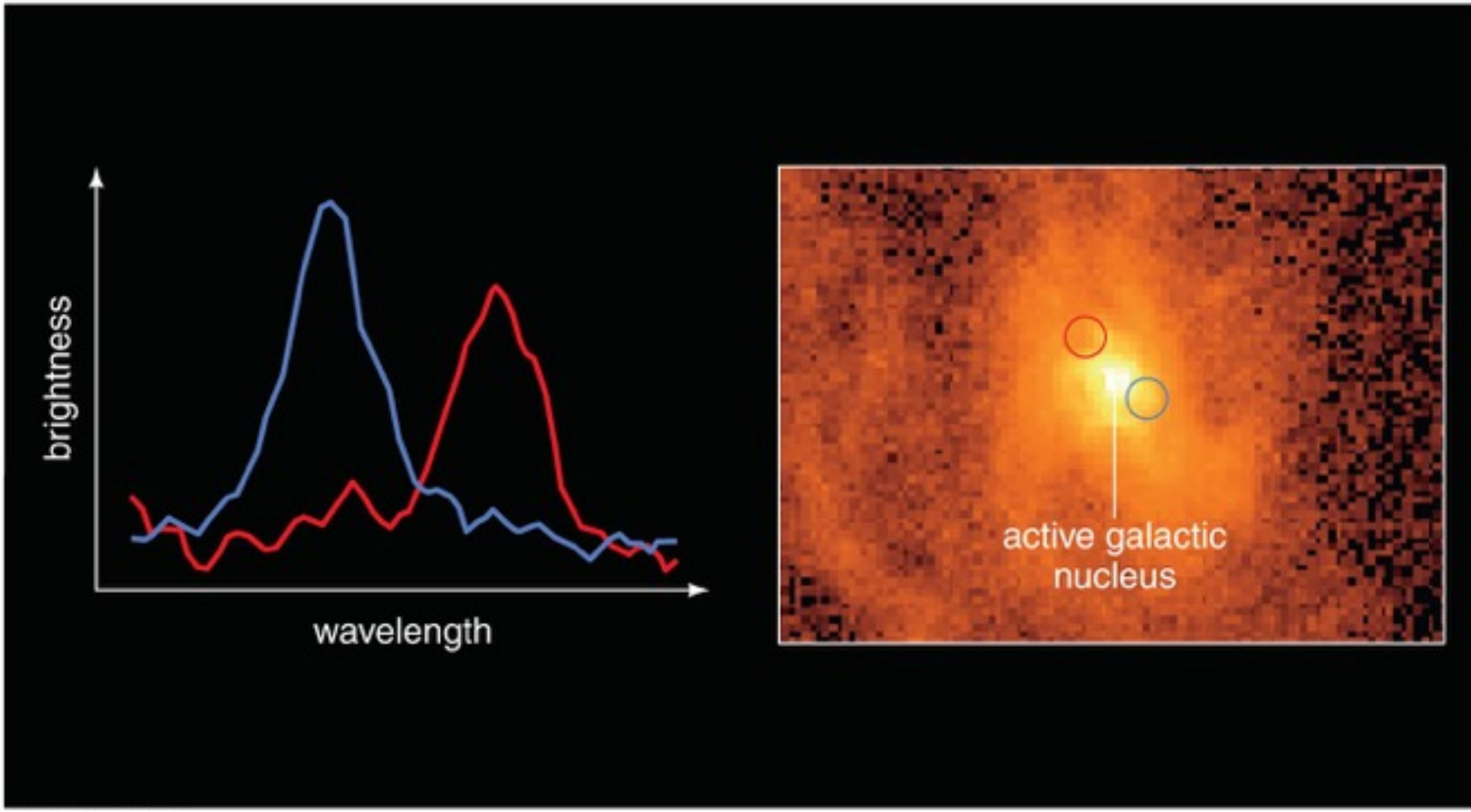
Jets are thought to come from twisting of magnetic field in the inner part of accretion disk.

Do supermassive black holes really exist?





Orbits of stars at center of Milky Way stars indicate a black hole with mass of 4 million M_{Sun}.

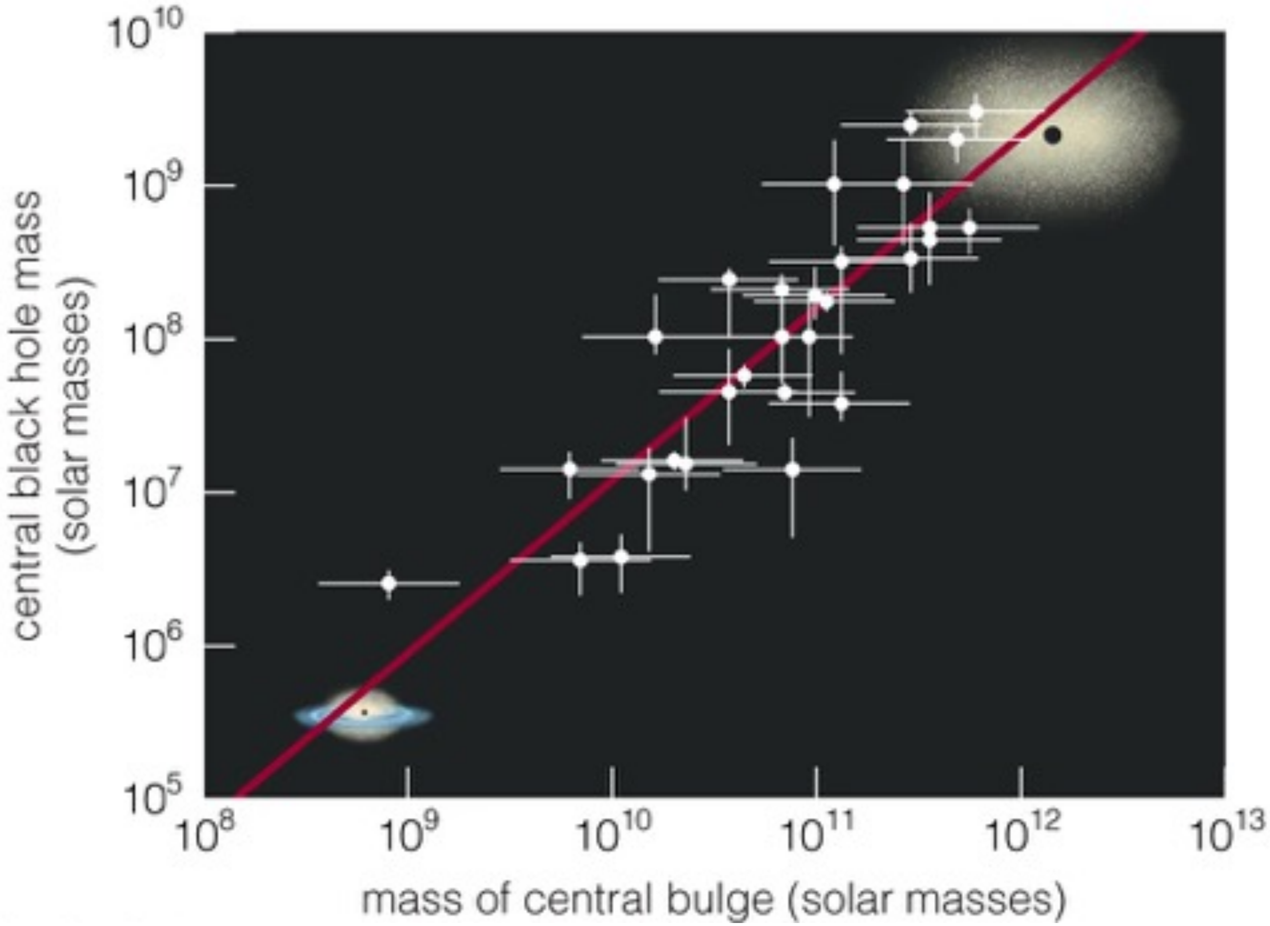


The orbital speed and distance of gas orbiting the center of Galaxy M87 indicate a black hole with mass of 3 billion M_{Sun}.

Black Holes in Galaxies

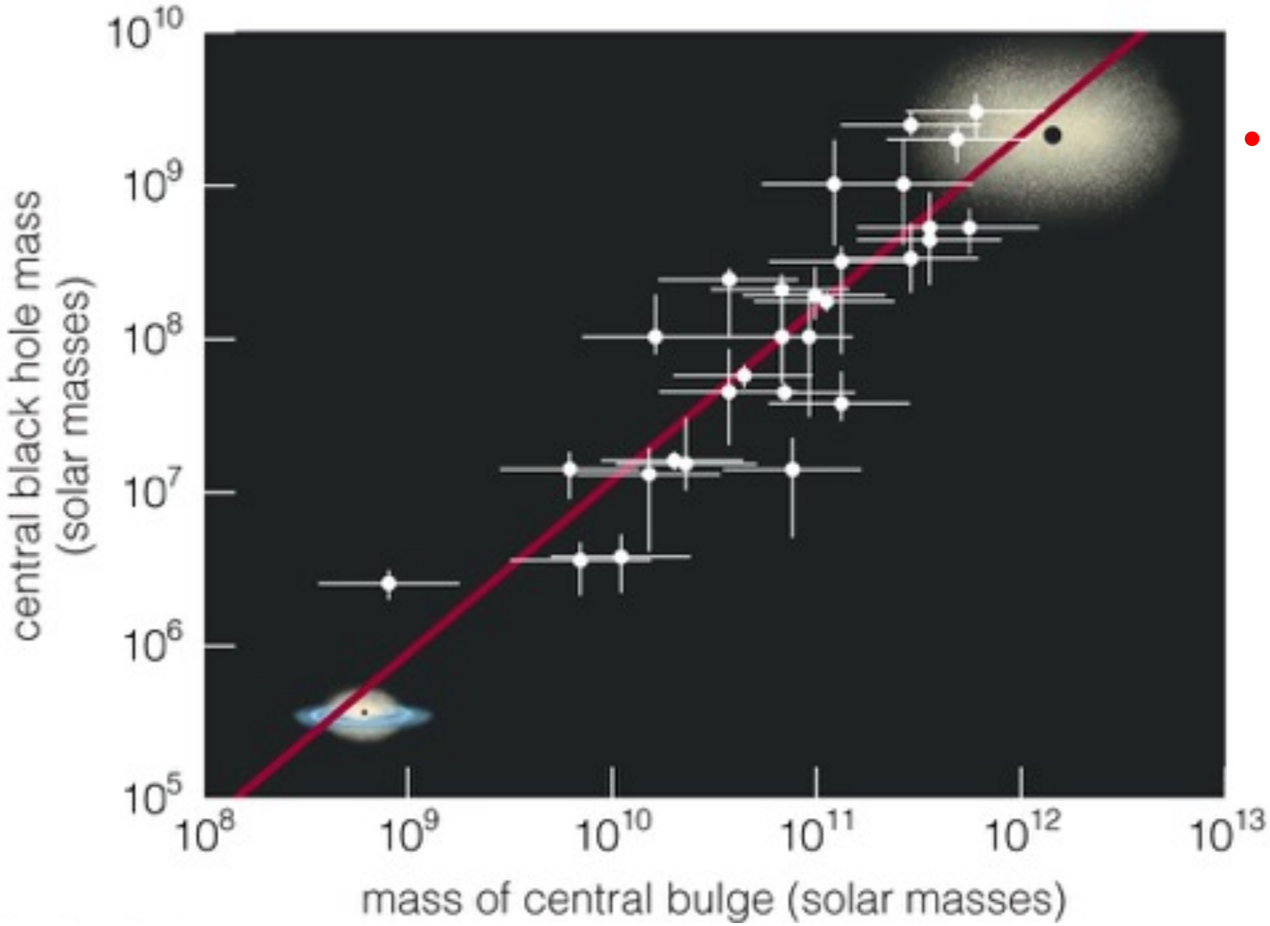
- Many nearby galaxies—perhaps all of them—have supermassive black holes at their centers.
- These black holes seem to be dormant active galactic nuclei.
- All galaxies may have passed through a quasar-like stage earlier in time.

Galaxies and Black Holes



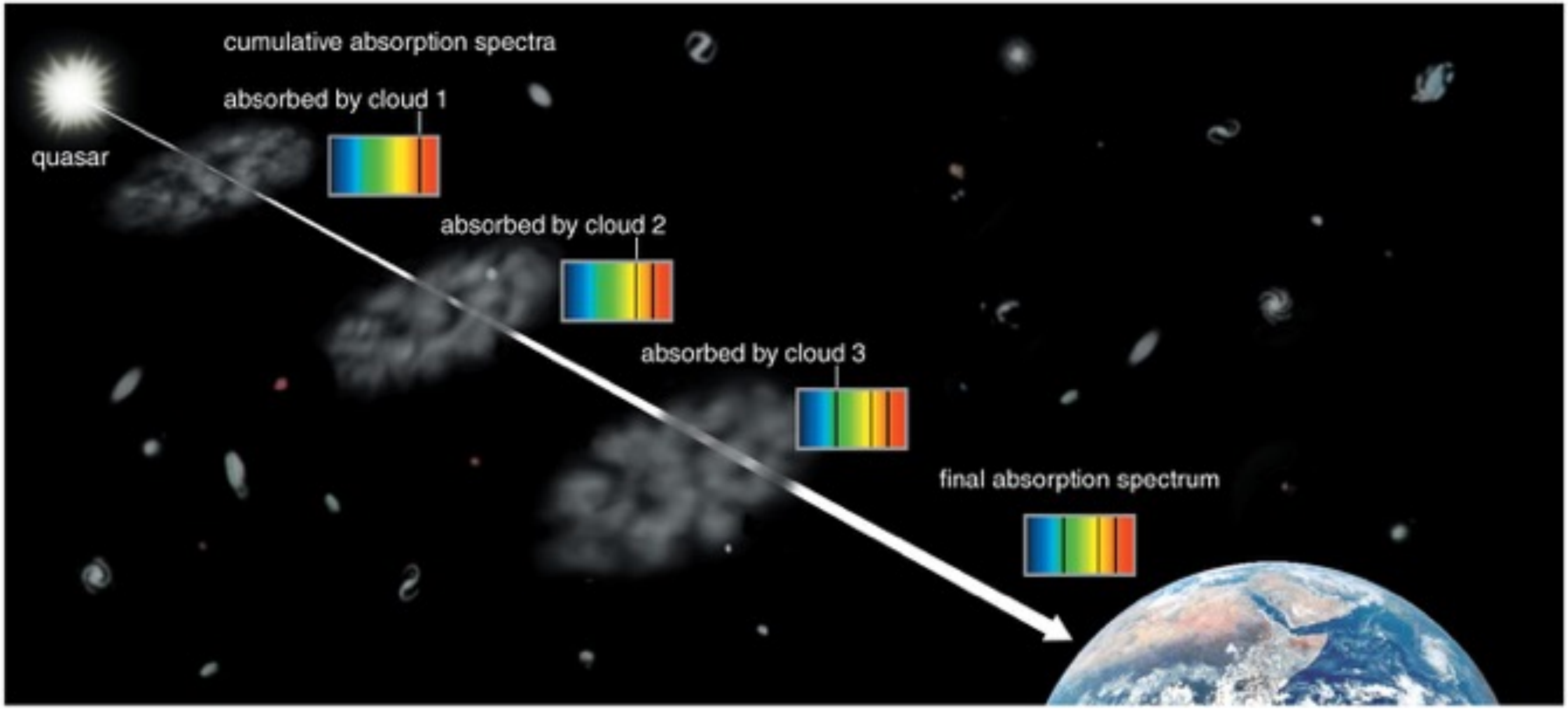
- The mass of a galaxy's central black hole is closely related to the mass of its bulge.

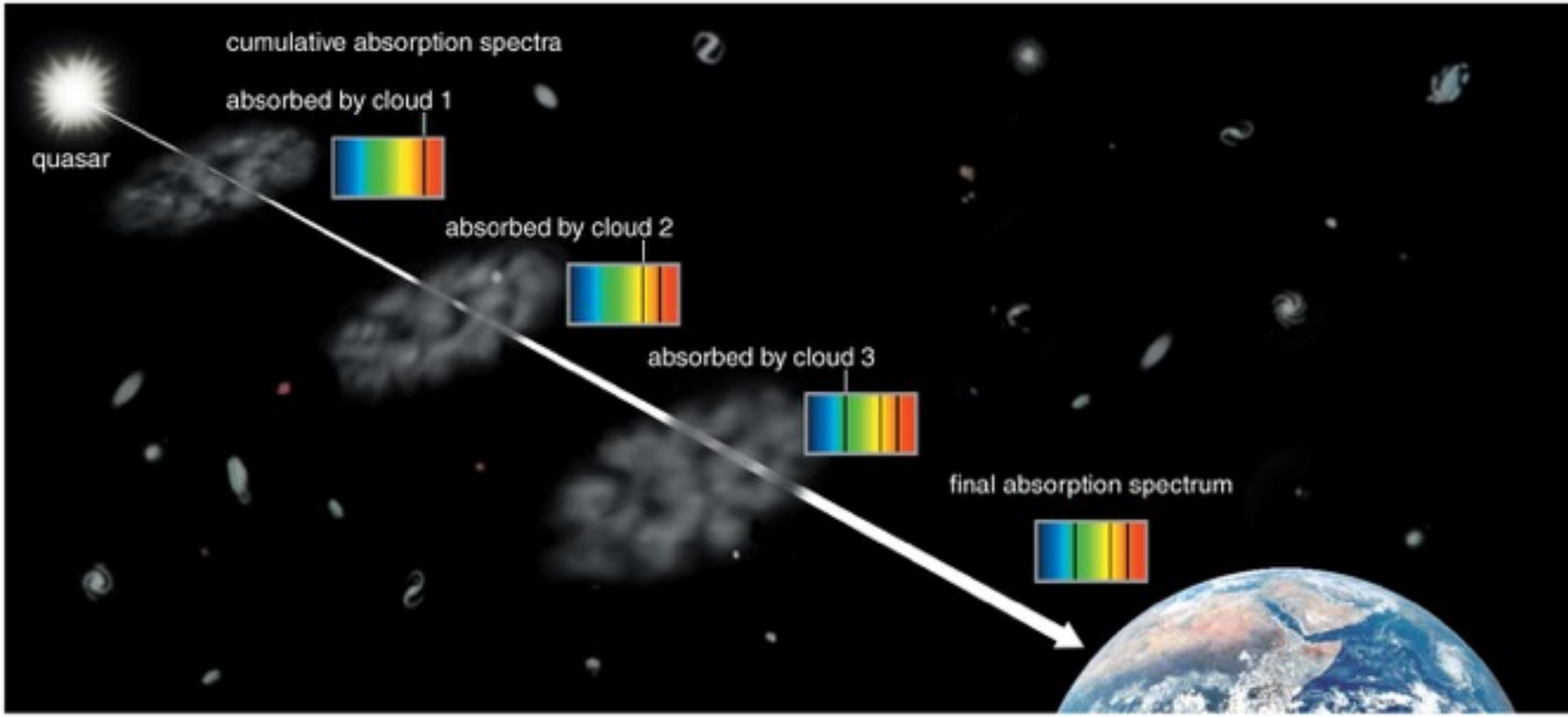
Galaxies and Black Holes



- The development of the central black hole must be somehow related to galaxy evolution.

How do quasars let us study gas between the galaxies?





Gas clouds between a quasar and Earth absorb some of the quasar's light.

We can learn about protogalactic clouds by studying the absorption lines they produce in quasar spectra.

Chapter 22
Dark Matter, Dark Energy, and the Fate of the Universe