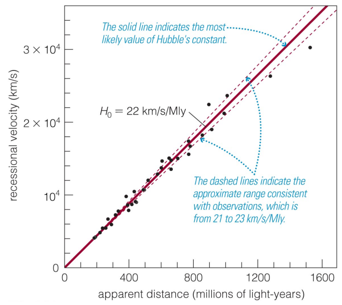
## •How do distance measurements tell us the age of the universe?






## 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



## Thought Question

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



## 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



## 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?

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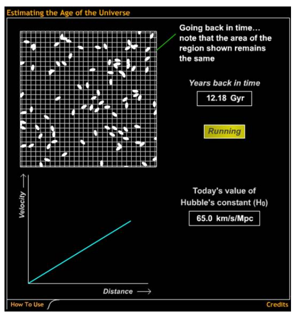
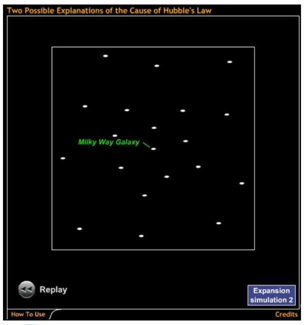



Hubble's constant tells us the age of the universe because it relates velocities and distances of all galaxies.

$$\text{Age} = \frac{\text{Distance}}{\text{Velocity}} \sim 1 / H_0$$

PLAY Estimating the Age of the Universe

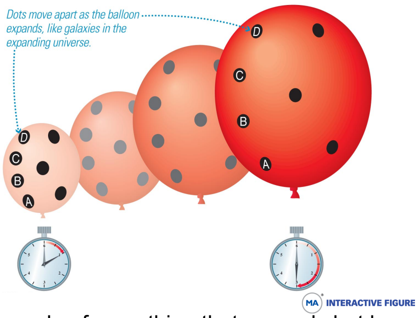



The expansion rate appears to be the same everywhere in space.

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

PLAY Two Possible Explanations of the Cause of Hubble's Law






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

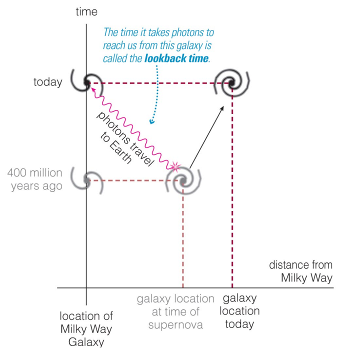


## Cosmological Principle

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

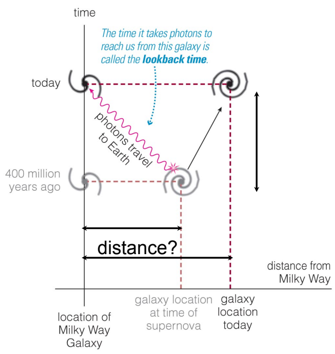
- Matter is evenly distributed on very large scales in the universe.
- No center and no edges
- Not proved but consistent with all observations to date






Distances between faraway galaxies change while light travels.

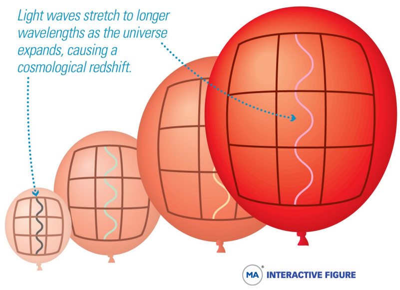





Distances between faraway galaxies change while light travels.

Astronomers think in terms of ***lookback time*** rather than distance.






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

## What have we learned?

- How do we measure the distances to galaxies?
  - The distance measurement chain begins with parallax measurements that build on radar ranging in our solar system.
  - Using parallax and the relationship between luminosity, distance, and brightness, we can calibrate a series of standard candles.
  - We can measure distances greater than 10 billion light-years using white dwarf supernovae as standard candles.



## What have we learned?

- What is Hubble's law?
  - The faster a galaxy is moving away from us, the greater its distance:

$$\text{velocity} = H_0 \times \text{distance}$$



## What have we learned?

- How do distance measurements tell us the age of the universe?
  - Measuring a galaxy's distance and speed allows us to figure out how long the galaxy took to reach its current distance.
  - Measuring Hubble's constant tells us that amount of time: about 14 billion years.



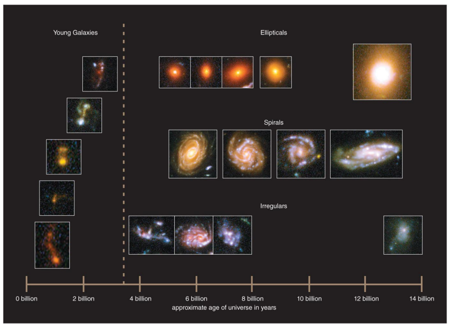
## 16.3 Galaxy Evolution

Our goals for learning:

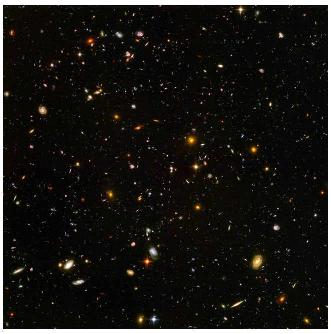
- How do we study galaxy evolution?
- Why do galaxies differ?



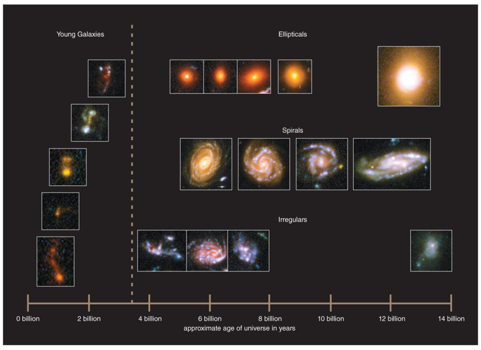
## How do we study galaxy evolution?





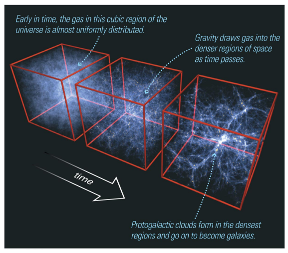
Deep observations show us very distant galaxies as they were much earlier in time (old light from young galaxies).






Modeling Galaxy Formation:

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

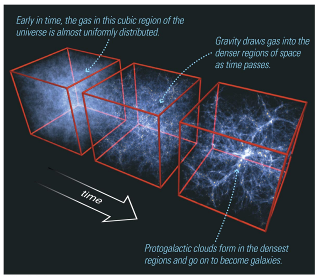





Denser regions contracted, forming ***protogalactic clouds.***

H and He gases 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.

***Conservation of angular momentum***



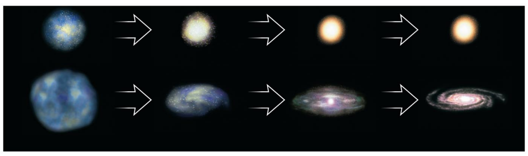
M101

M87

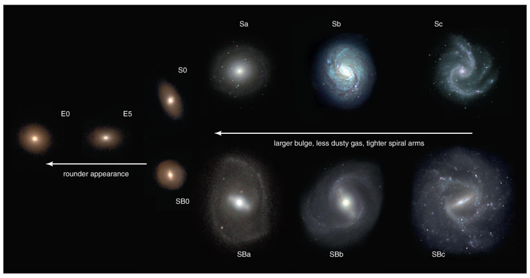
But why do some galaxies end up looking so different?



## Why do galaxies differ?



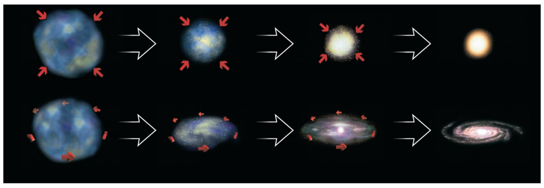
**b** The density of a protogalactic cloud may determine whether it ends up spiral or elliptical.




Why don't all galaxies have similar disks?



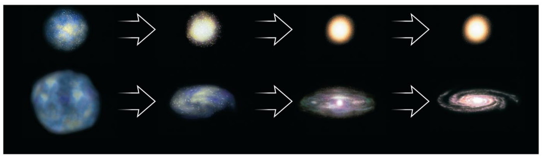
## Conditions in Protogalactic Cloud?




***Spin:*** Initial angular momentum of protogalactic cloud could determine the size of the resulting disk.



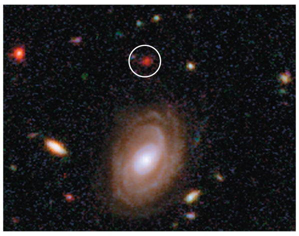
## Conditions in Protogalactic Cloud?



***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

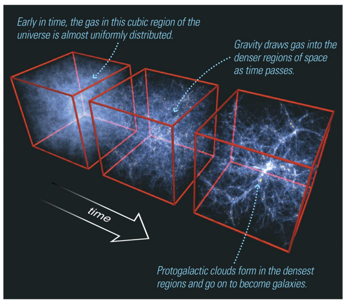


Observations of some distant red elliptical galaxies support the idea that most of their stars formed very early in the history of the universe.

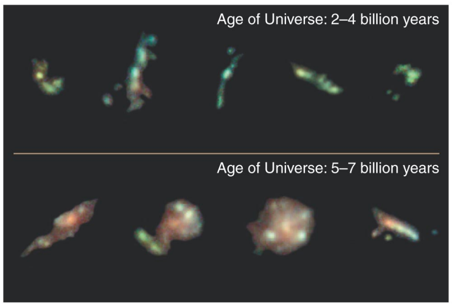


We must also consider the effects of collisions.






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

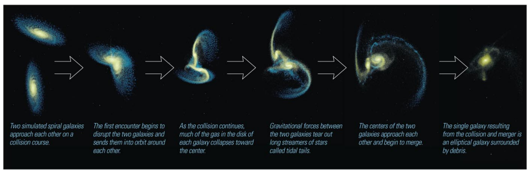



Many of the galaxies we see at great distances (and early times) do indeed look violently disturbed.




The collisions we observe nearby trigger bursts of star formation.

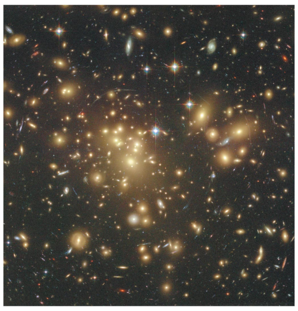





MA INTERACTIVE FIGURE

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





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



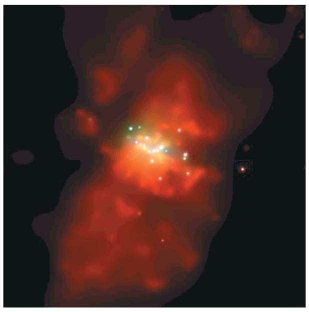

Giant elliptical galaxies at the centers of clusters seem to have consumed a number of smaller galaxies.



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

The intensity of supernova explosions in starburst galaxies can drive galactic winds.





X-ray image

The intensity of supernova explosions in starburst galaxies can drive galactic winds.



## What have we learned?

- How do we study galaxy evolution?
  - Deep observations of the universe are showing us the history of galaxies because we are seeing galaxies as they were at different ages.
  - We use computer modeling to match theory with observation.



## What have we learned?

- Why do galaxies differ?
  - Some of the differences between galaxies may arise from the conditions in their protogalactic clouds.
  - Collisions can also play a major role because they can transform two spiral galaxies into an elliptical galaxy.



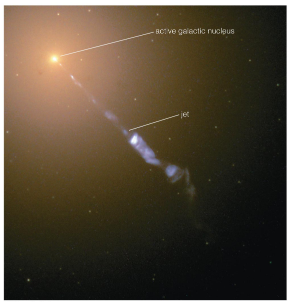
## 16.4 Active Galactic Nuclei

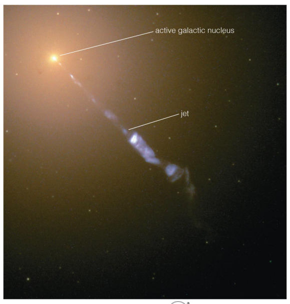
Our goals for learning:

- What is the evidence for supermassive black holes at the centers of galaxies?
- Why do we think the growth of central black holes is related to galaxy evolution?



## What is the evidence for supermassive black holes at the centers of galaxies?





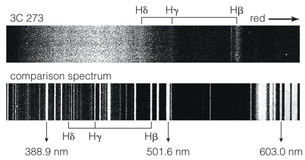

If the center of a galaxy is unusually bright, we call it an ***active galactic nucleus.***

The most luminous examples are called ***quasars.***

MA INTERACTIVE FIGURE

Active Nucleus in M87






The highly redshifted spectra of quasars indicate large distances.

From brightness and distance, we find that luminosities of some quasars are $>10^{12}L_{Sun}$!

Variability shows that all this energy comes from a region smaller than the 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.



## Thought Question

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

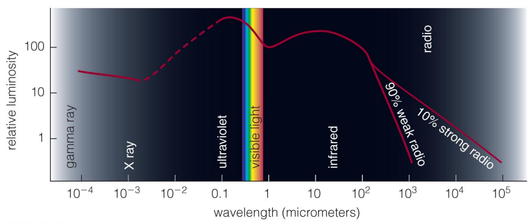
**A. They are generally very distant.**
**B. They were more common early in time.**
**C. Galaxy collisions might turn them on.**
**D. Nearby galaxies might hold dead quasars.**

***All of the above!***

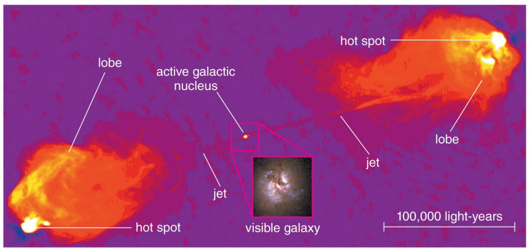



Galaxies around quasars sometimes appear disturbed by collisions.



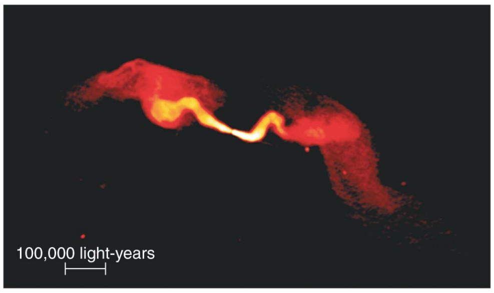



Quasars powerfully radiate energy over a very wide range of wavelengths, indicating that they contain matter with a wide range of temperatures.



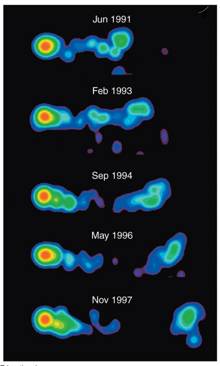

***Radio galaxies*** contain active nuclei shooting out vast jets of plasma, which emit radio waves coming from electrons moving at near light speed.






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

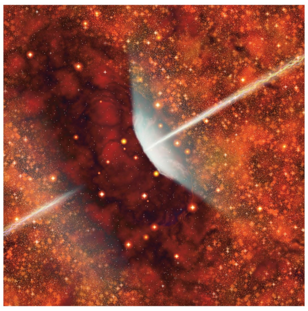





An active galactic nucleus can shoot out blobs of plasma moving at nearly the speed of light.

The speed of ejection suggests that a black hole is present.





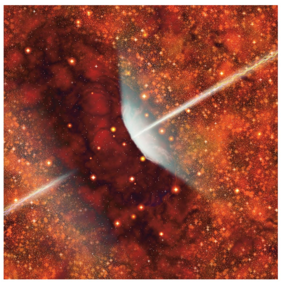
Radio galaxies don't appear as quasars because dusty gas clouds block our view of their accretion disks.



## Characteristics of Active Galaxies

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



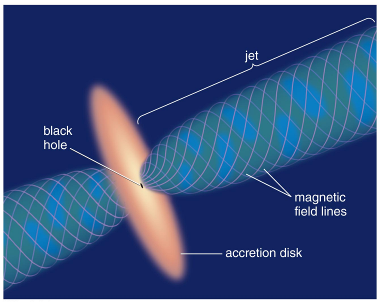


The accretion of gas onto a supermassive black hole appears to be the only way to explain all the properties of quasars.

## Energy from a Black Hole

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

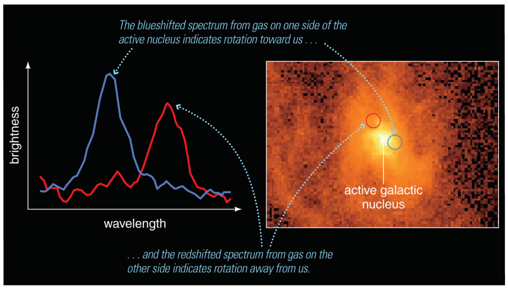




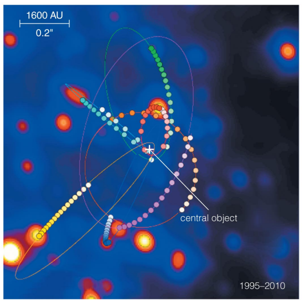

Jets are thought to come from the twisting of a magnetic field in the inner part of the accretion disk.



## Why do we think the growth of central black holes is related to galaxy evolution?

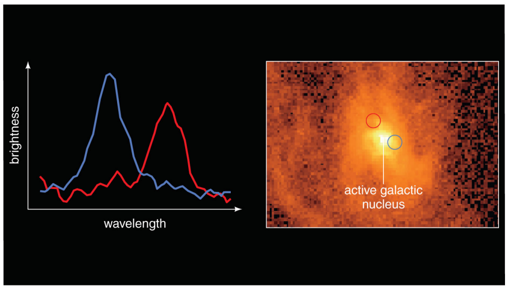





Orbits of stars at center of Milky Way indicate a black hole with mass of 4 million $M_{sun}$.





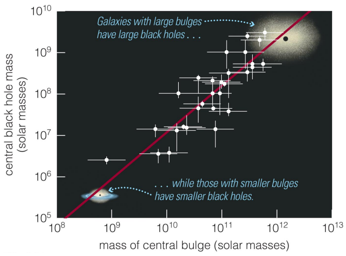

Orbital speed and distance of gas orbiting center of M87 indicate a black hole with mass of at least 3 billion $M_{sun}$.



## 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.

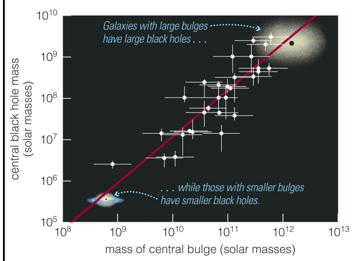
## Galaxies and Black Holes




- 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 a central black hole must somehow be related to galaxy evolution.



## What have we learned?

- What is the evidence for supermassive black holes at the centers of galaxies?
  - Active galactic nuclei are very bright objects seen in the centers of some galaxies, and quasars are the most luminous type.
  - The only model that adequately explains our observations holds that supermassive black holes are the power source.



## What have we learned?

- Why do we think the growth of central black holes is related to galaxy evolution?
  - Observations of stars and gas clouds orbiting the centers of galaxies indicate that many galaxies, perhaps all of them, have supermassive black holes.
  - The masses of the black holes are closely related to the properties of their home galaxies, suggesting a connection between the black hole and galaxy evolution.