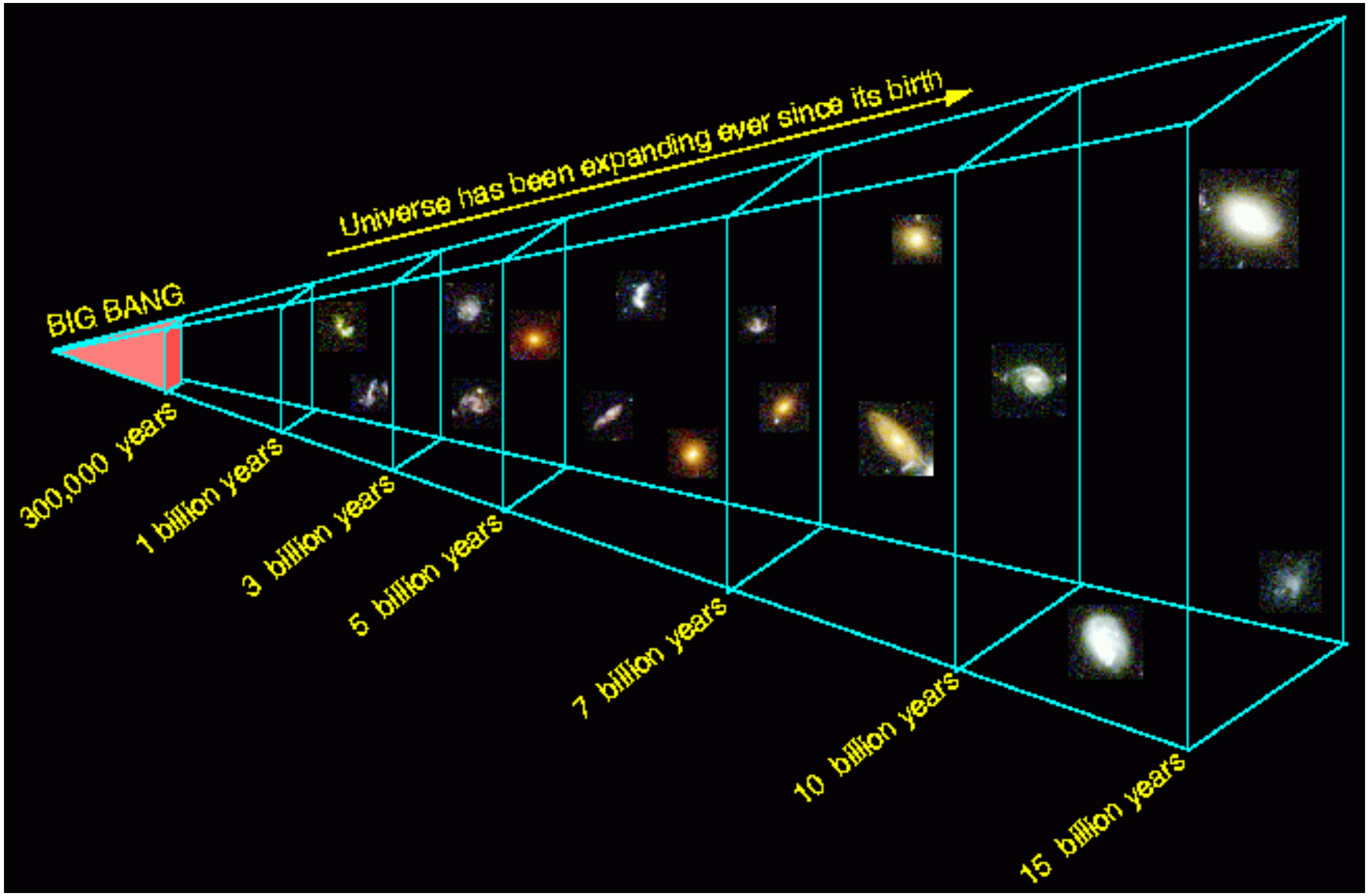
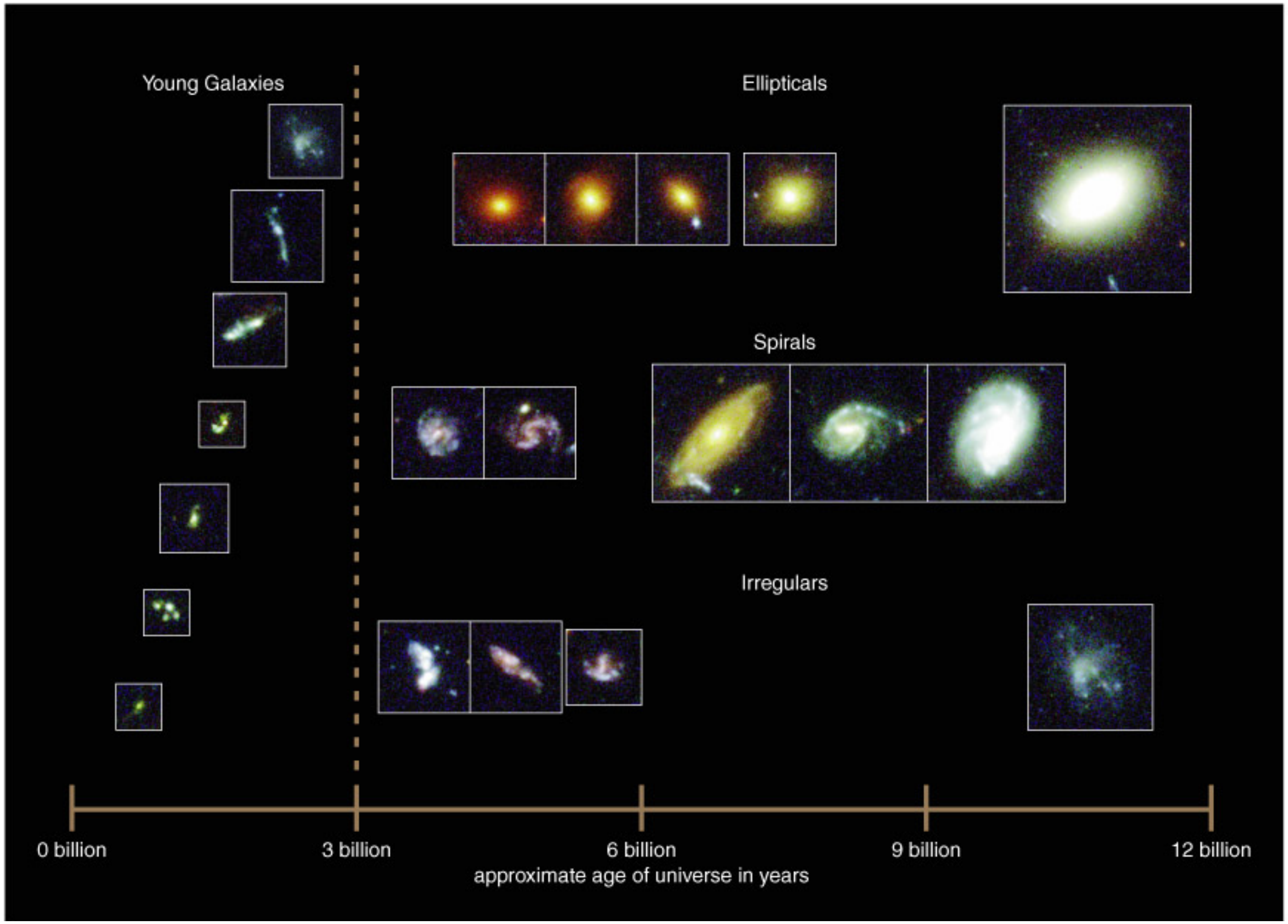
Lecture 24: Galaxy Evolution

How do we observe the life histories of galaxies?



Observations of very distant galaxies show them as they were much earlier in time

Galaxies over time



Observing galaxies at different *distances* shows us how they change over *time*.

Life histories of galaxies

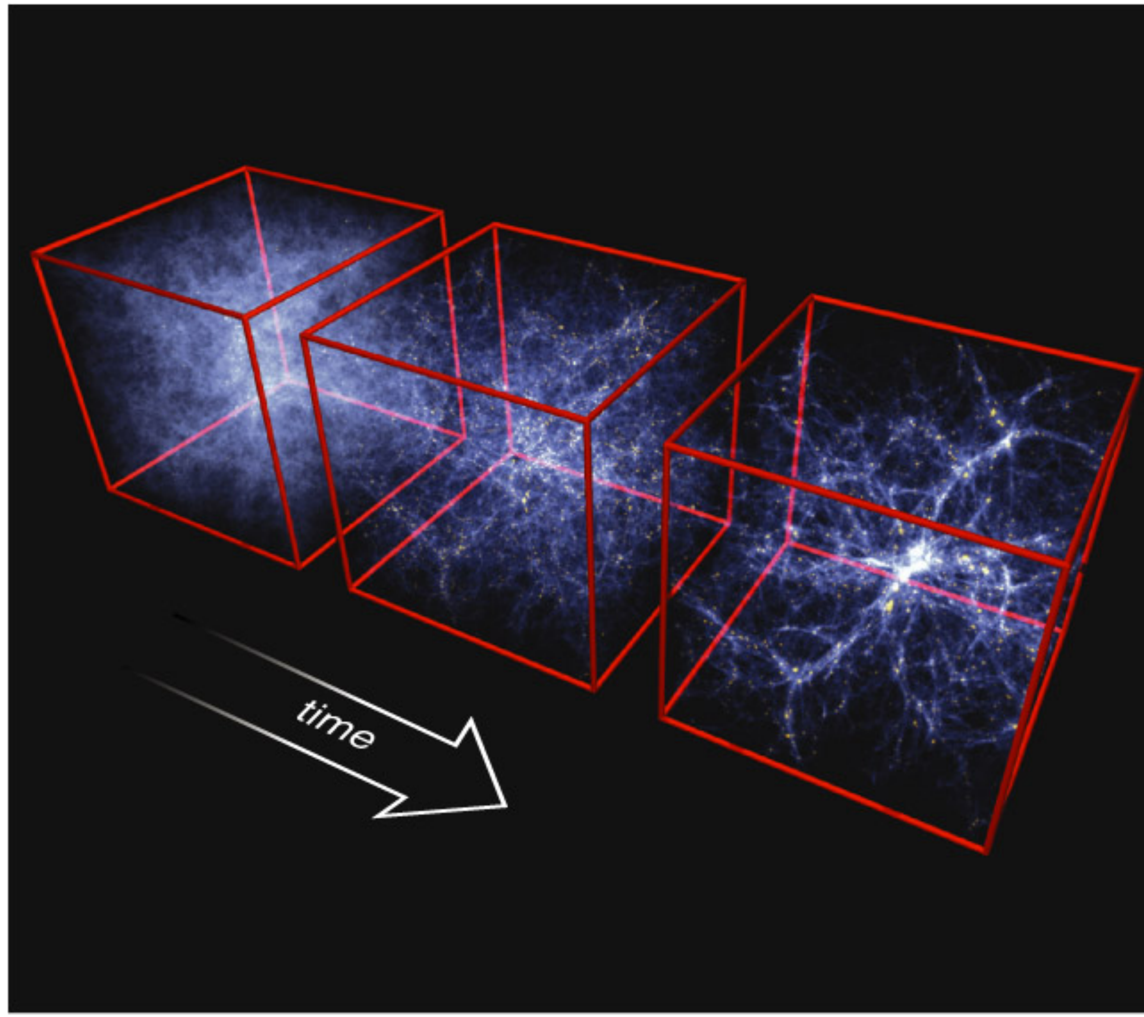
• Most galaxies formed about 13 billion years ago.
• Galaxies at "lookback time" of 10 billion years are seen at an age of 3 billion years
• We see young galaxies by looking far!

How did galaxies form?

Interactive Figure

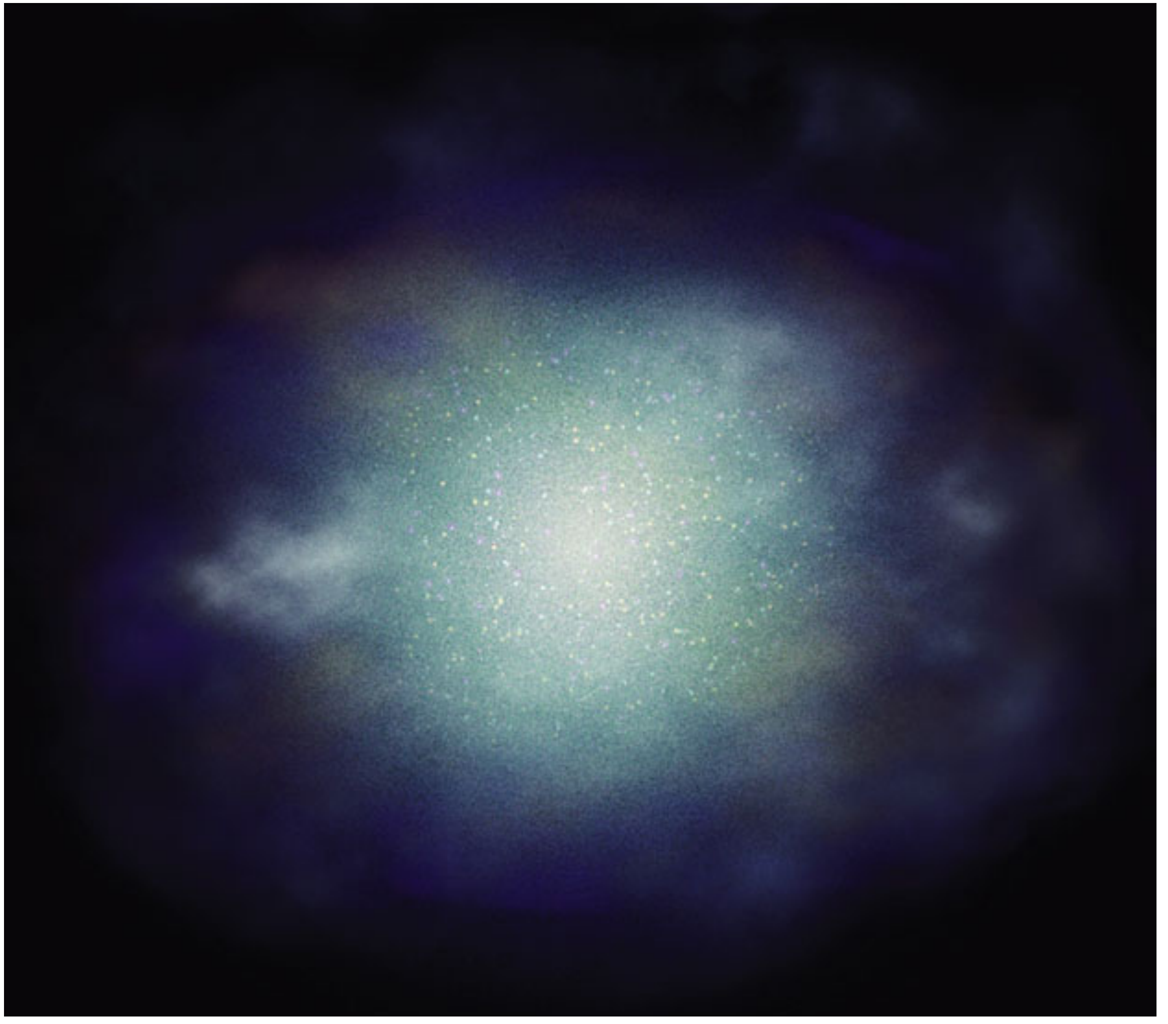
Our best models for galaxy formation indicate that…

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

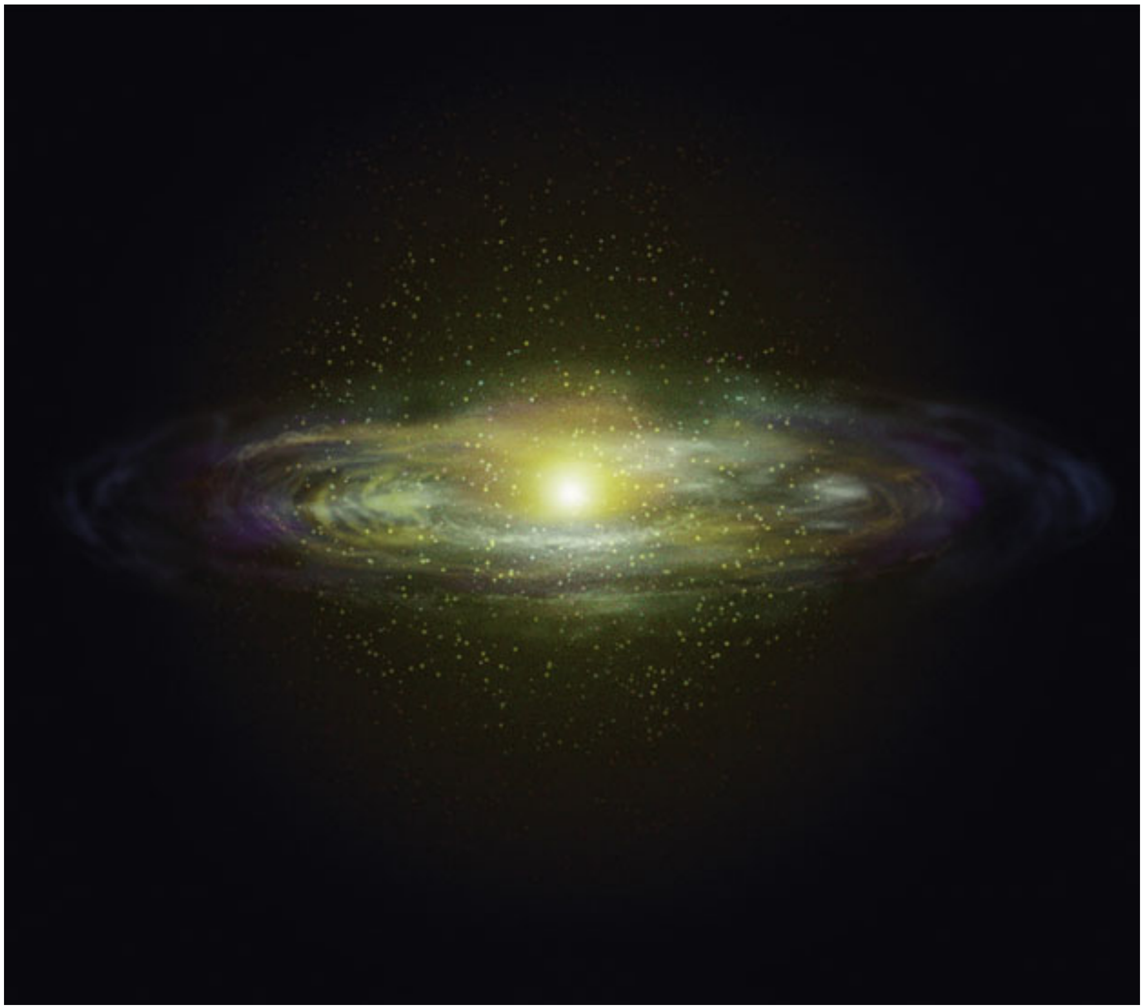


Galaxy formation

• Denser regions contracted, forming ***protogalactic clouds.***
• H and He in these clouds formed the first stars quickly before flattening.



Galaxy formation

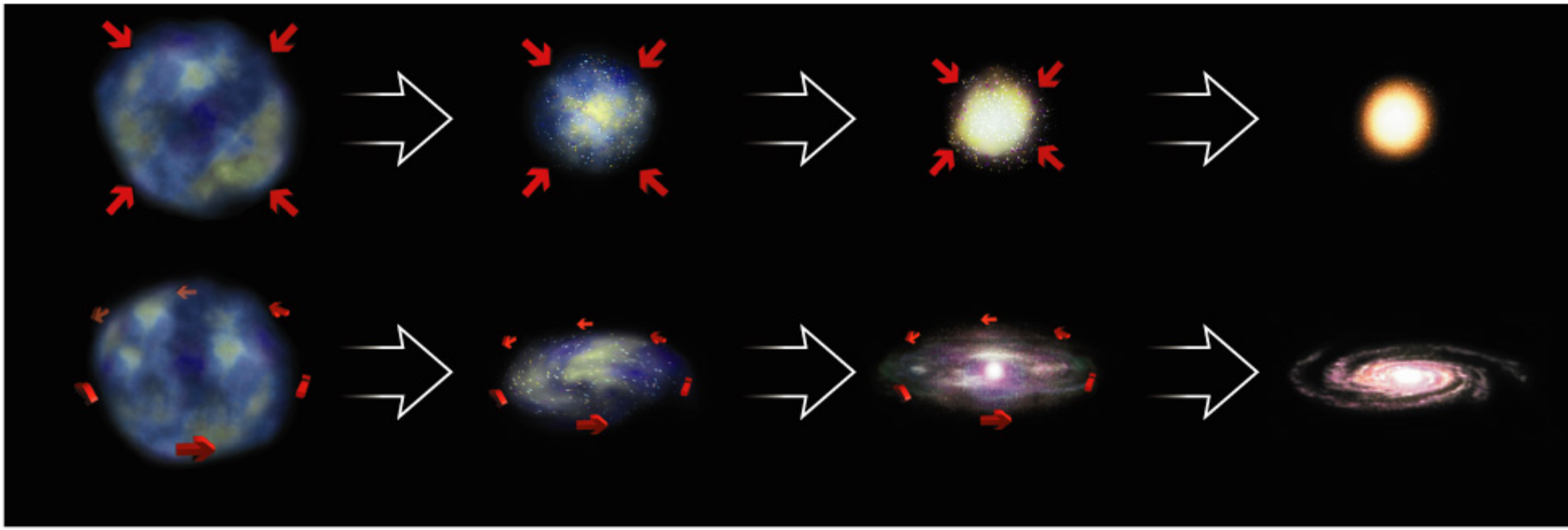


- Leftover matter settled into a spinning disk due to conservation of angular momentum

Why do galaxies differ?

Why do galaxies look so different;
some with disks, some without?

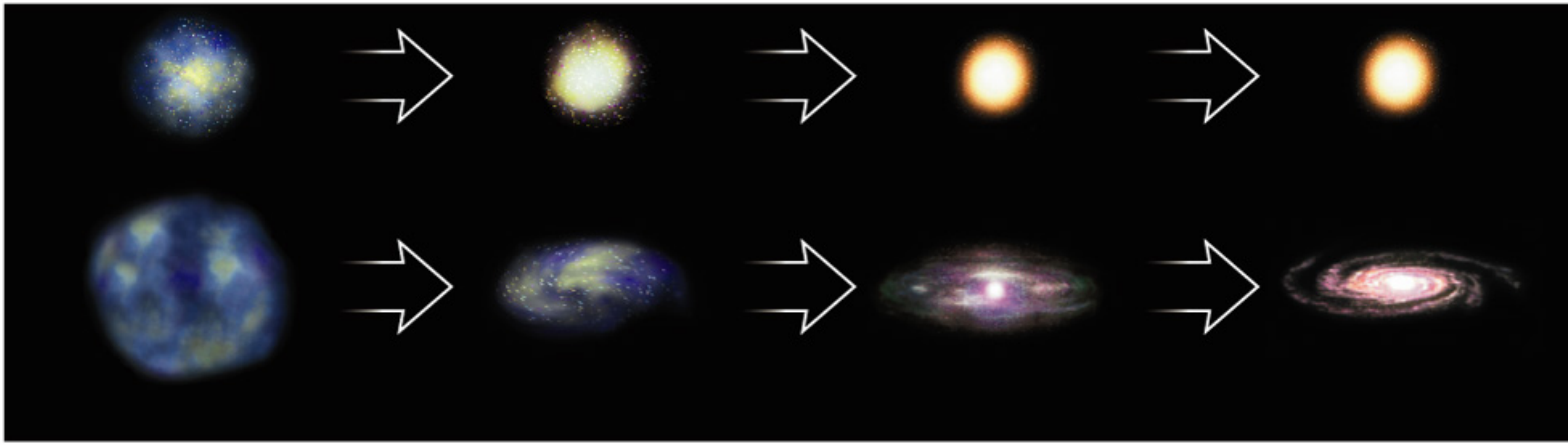
1. Initial conditions in Protogalactic Cloud



Spin: Initial angular momentum of protogalactic cloud determined the size of the resulting disk. *Lower spin tends to form an elliptical galaxy, higher spin, a spiral.*

PLAY Different Types of Galaxy Formation

1. Initial conditions in Protogalactic Cloud

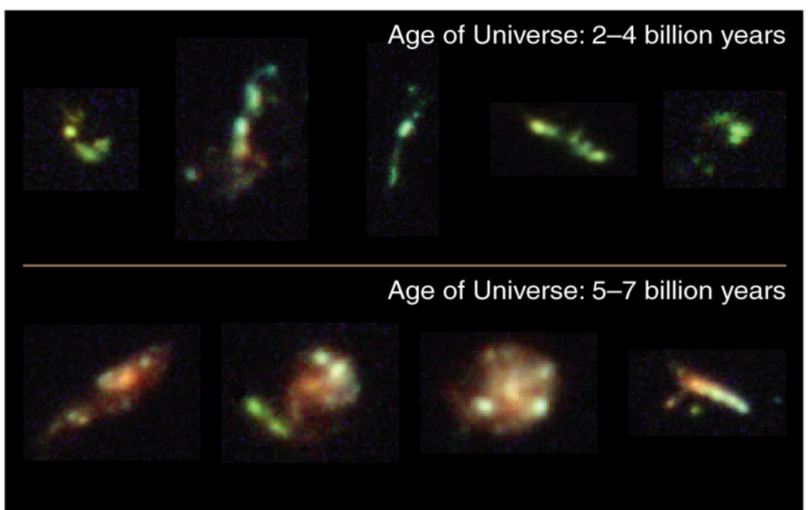


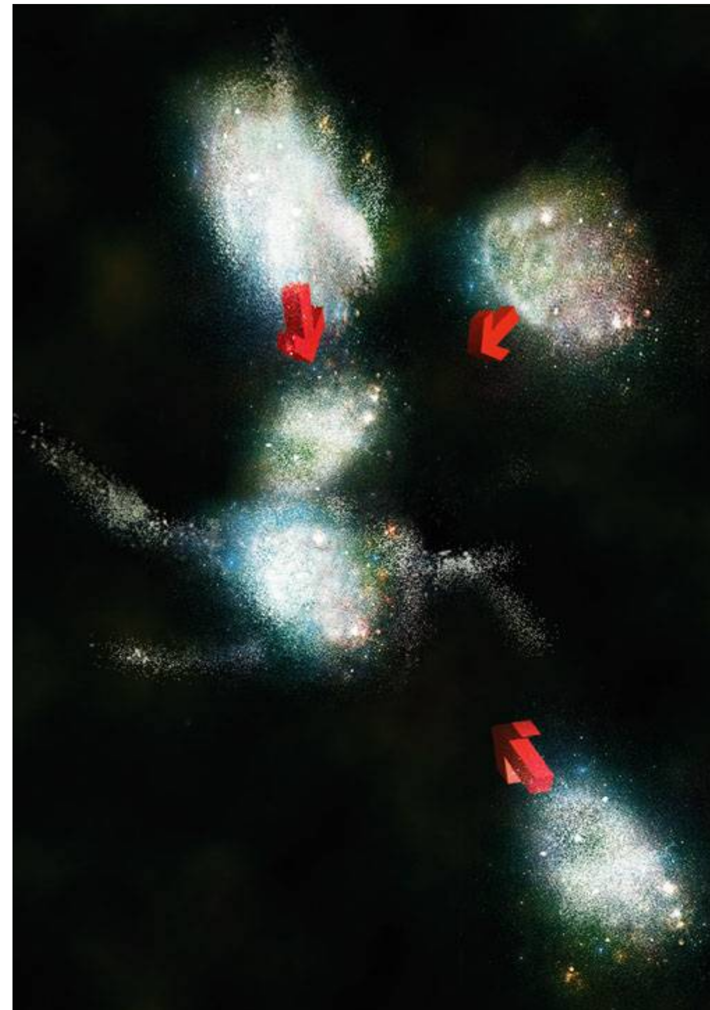
Density: Elliptical galaxies come from dense protogalactic clouds that were able to cool and form stars before gas settled into a disk. *Higher density tends to form an elliptical galaxy, lower density, a spiral.*

PLAY Different Types of Galaxy Formation

2. Collisions / mergers

- Collisions have a great effect on galaxies.
- They were more common early in time when universe was smaller, galaxies were closer together.
- Many galaxies at great distances (and early times) are violently disturbed.

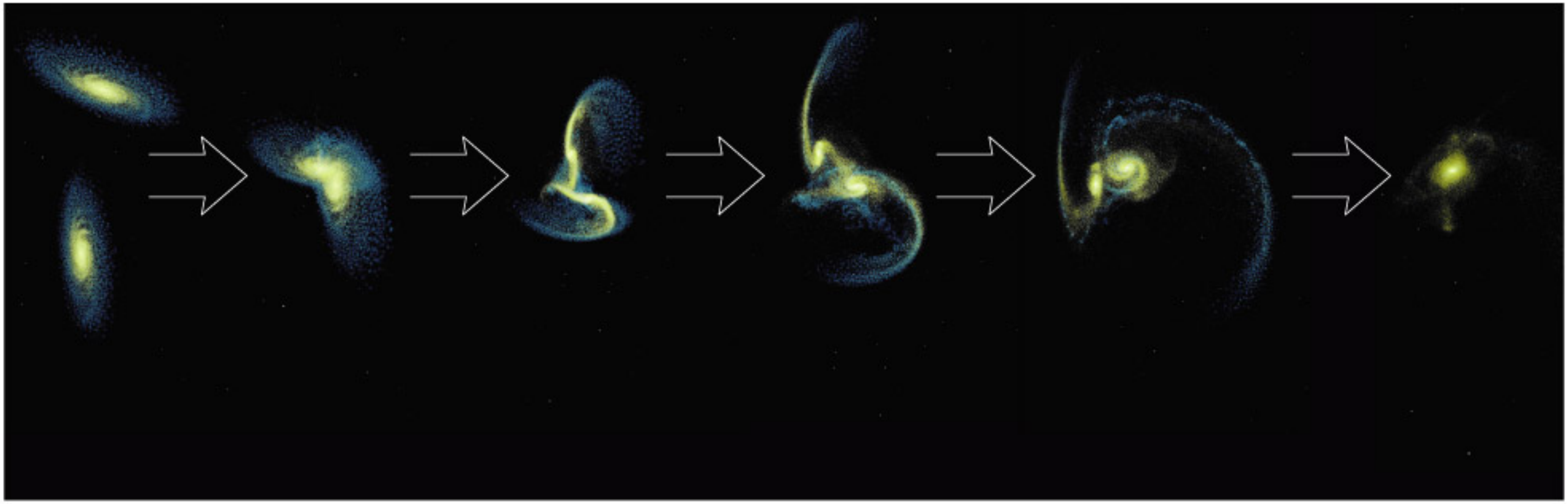




Collisions / mergers

Collisions trigger bursts of star formation – how?.

Galaxy mergers



Modeling such collisions shows that two spiral galaxies can merge into an elliptical.

Galaxy Collision Animation

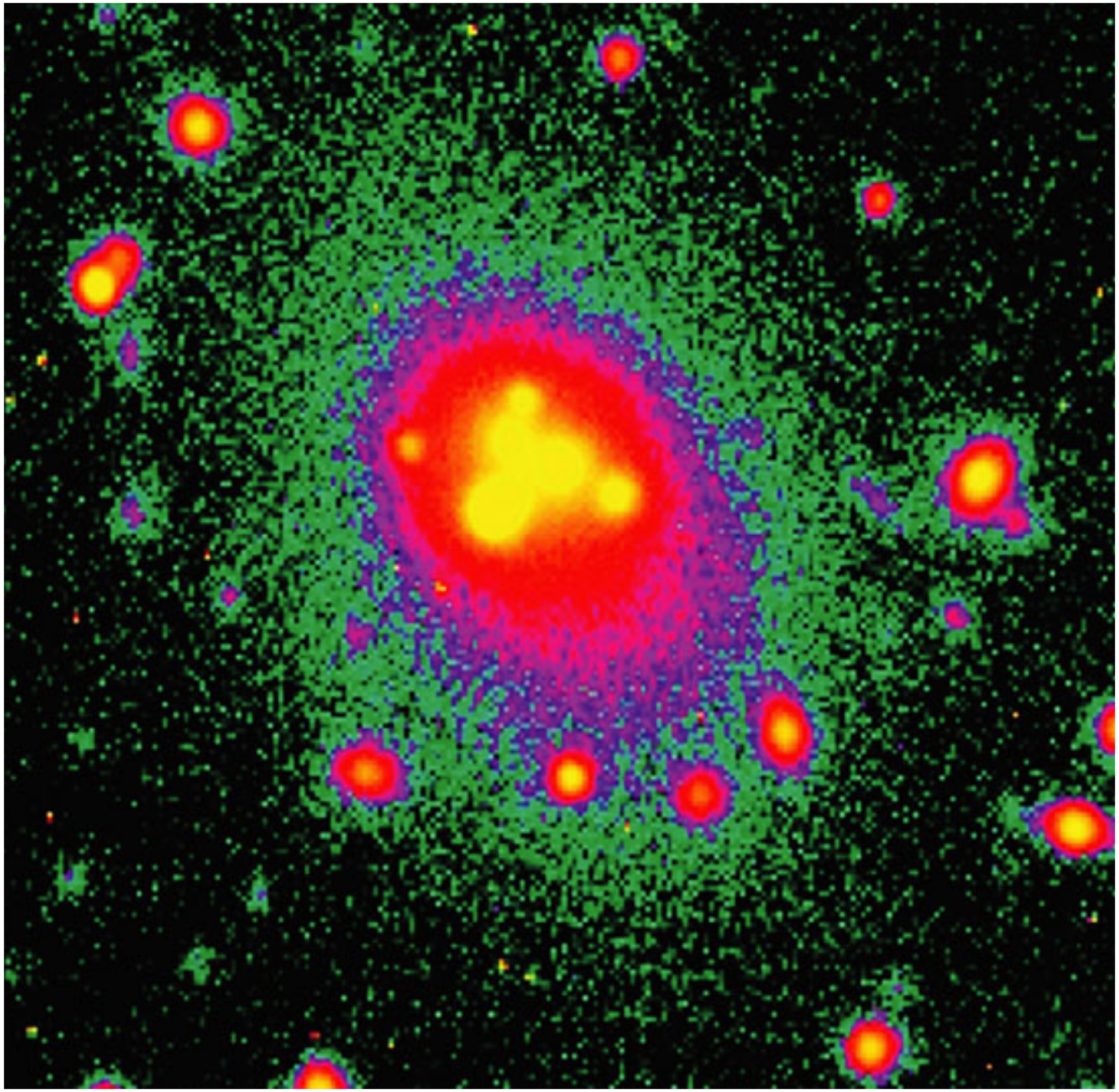
Interactive Figure

Galaxy mergers

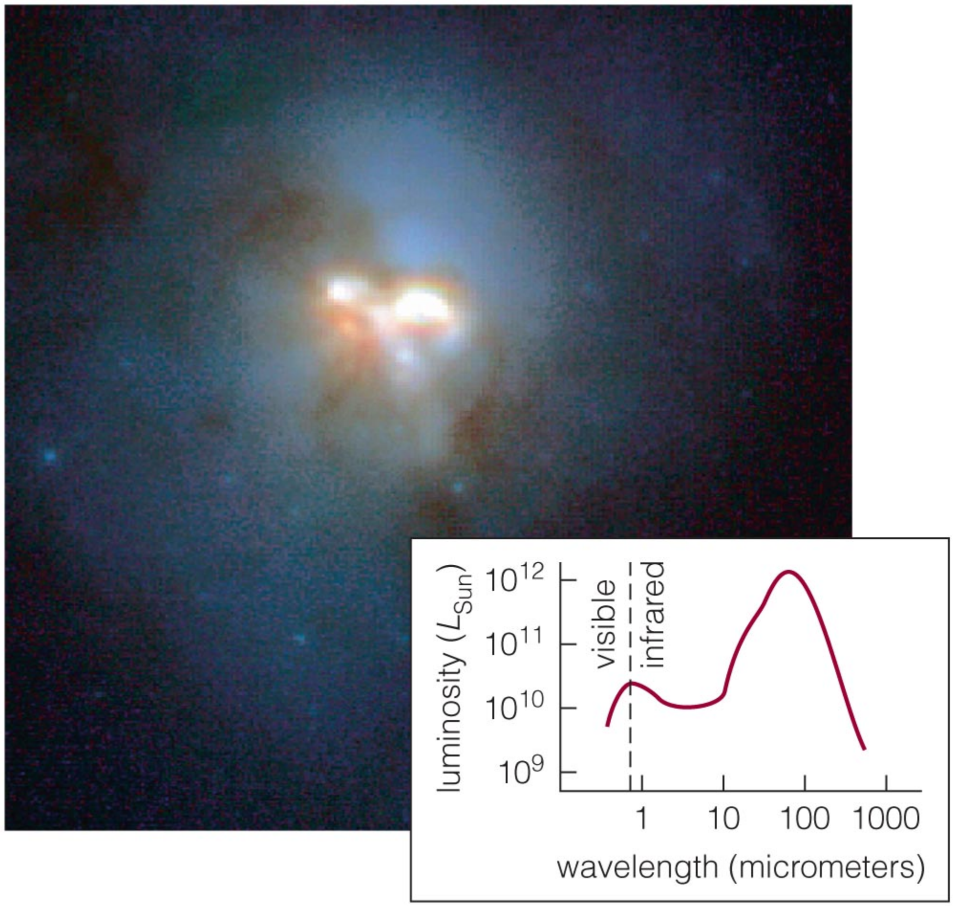
Mergers explain why elliptical galaxies are found where galaxies are closer together (clusters).

Galaxy mergers

Giant elliptical galaxies at the centers of clusters have consumed smaller galaxies.



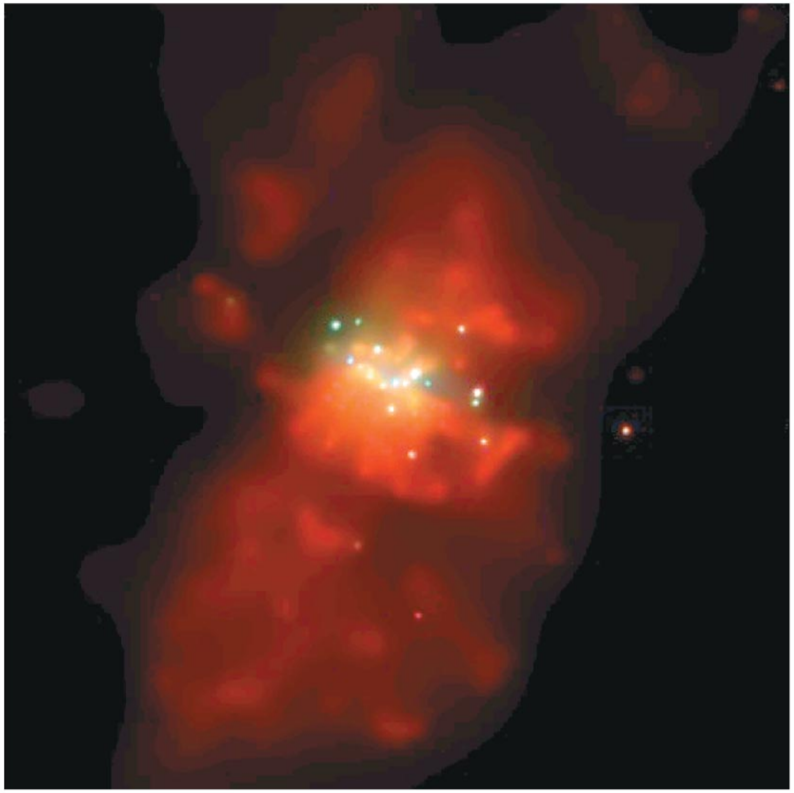
3. Star formation rate



- Galaxies differ greatly in the *rate* of star formation – spirals more, ellipticals little.
- **Starburst** galaxies form stars so quickly they use up their gas in less than a billion years.
- Infrared observations reveal high luminosity

3. Star formation rate

Visible-light image

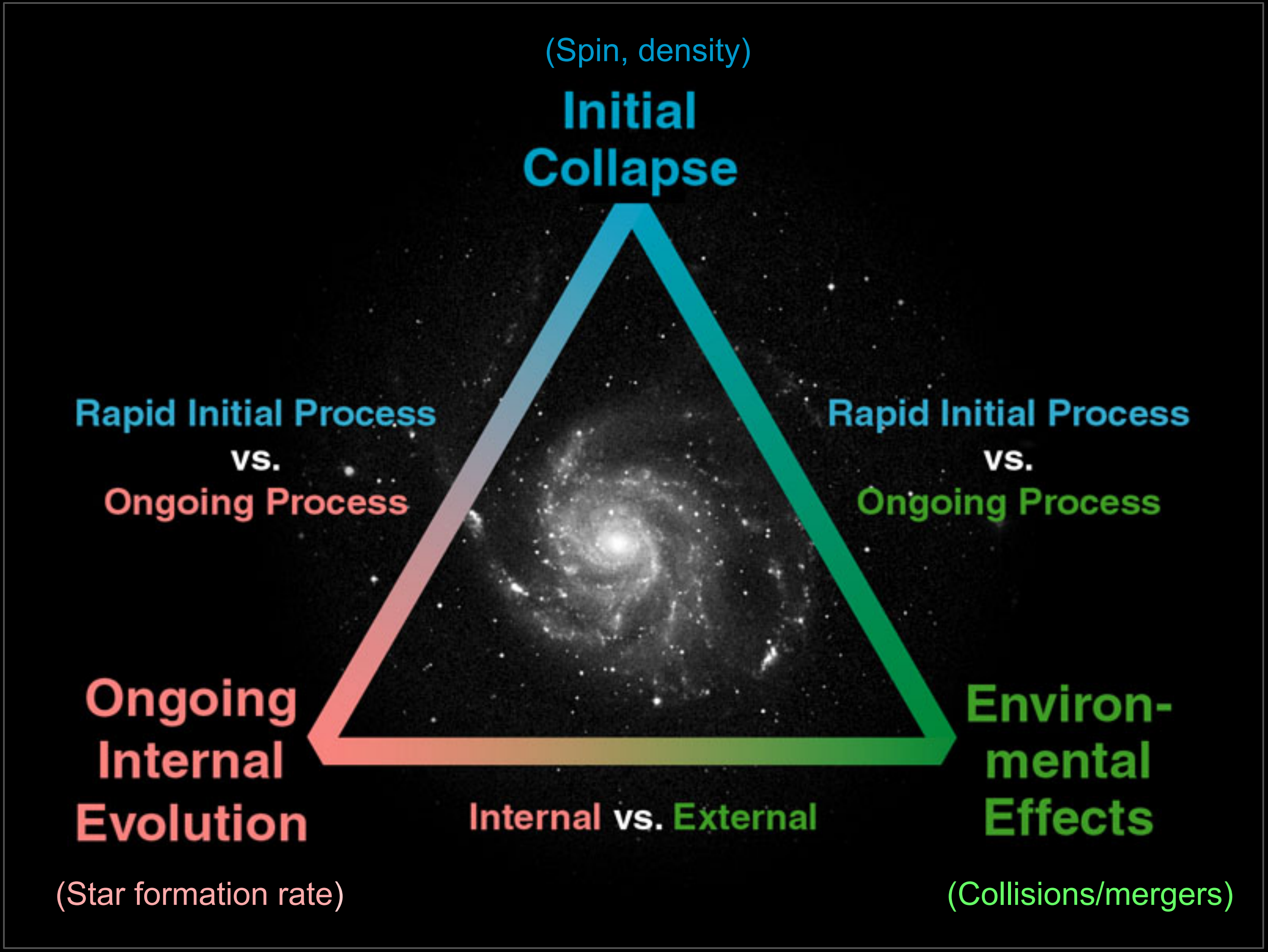


X-ray image

Intensity of supernova explosions in starburst galaxies can drive galactic winds, causing galaxy to lose gas.

Interactive Figure

Galaxy evolution factors



What have we learned?

Begin 3 minute review

What have we learned?

How do we observe the life histories of galaxies?

Deep observations of the universe are showing us the history of galaxies because we are seeing galaxies as they were at different ages.

How did galaxies form?

Models for galaxy formation assume that gravity made galaxies out of regions of the early universe that were slightly denser than their surroundings.

What have we learned?

Why do galaxies differ?

Some differences between galaxies arises from the **spin** and **density** of their protogalactic clouds.

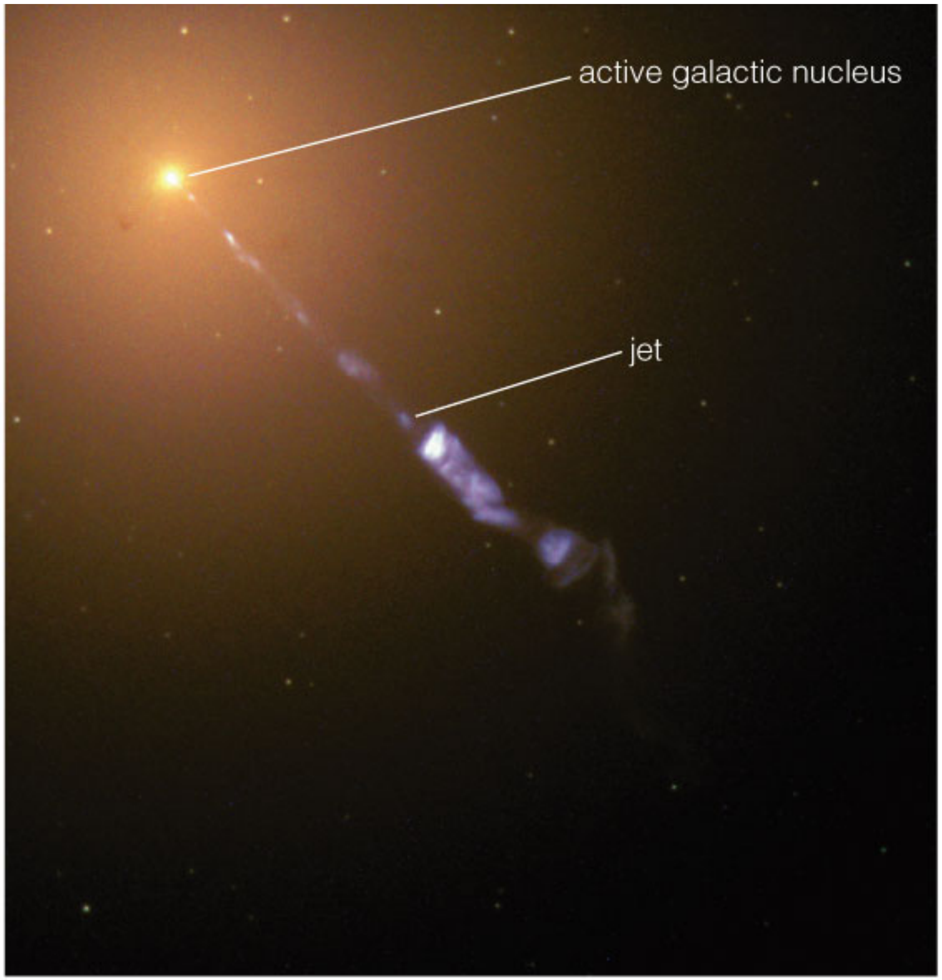
Collisions played a major role because they can transform two galaxies into one.

Star formation rate affects galaxies over time.

What are starburst galaxies?

A starburst galaxy is transforming its gas into stars much more rapidly than a normal galaxy.

Active galaxies



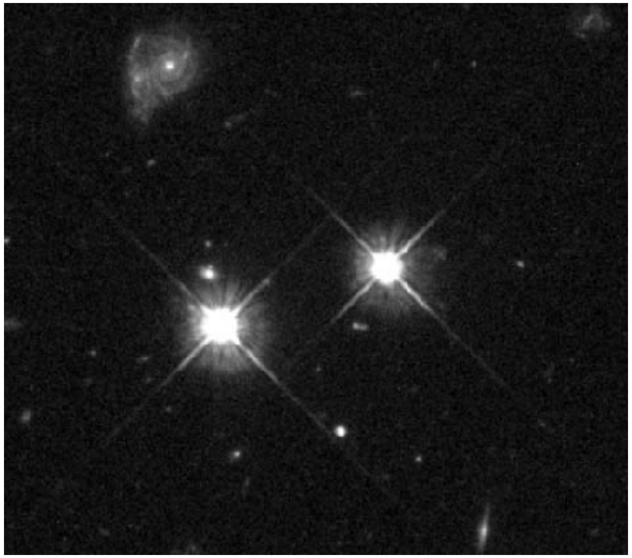
- An unusually bright galaxy center is an ***active galactic nucleus.***
- These can be much more luminous than the entire galaxy!

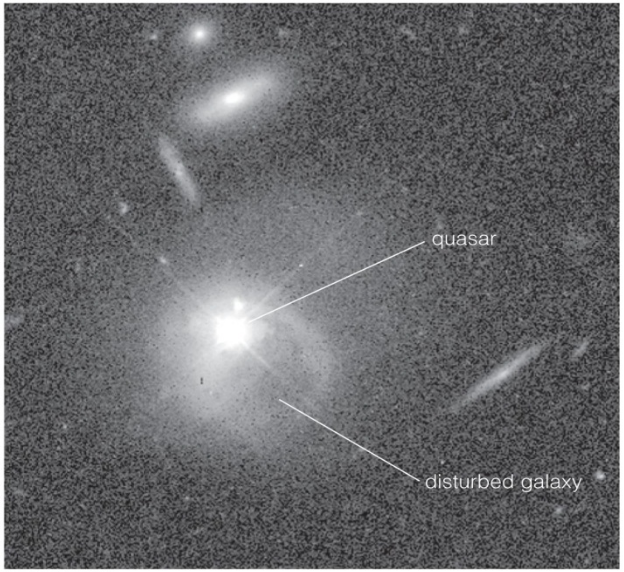
Active Nucleus in M87

PLAY M87 nucleus

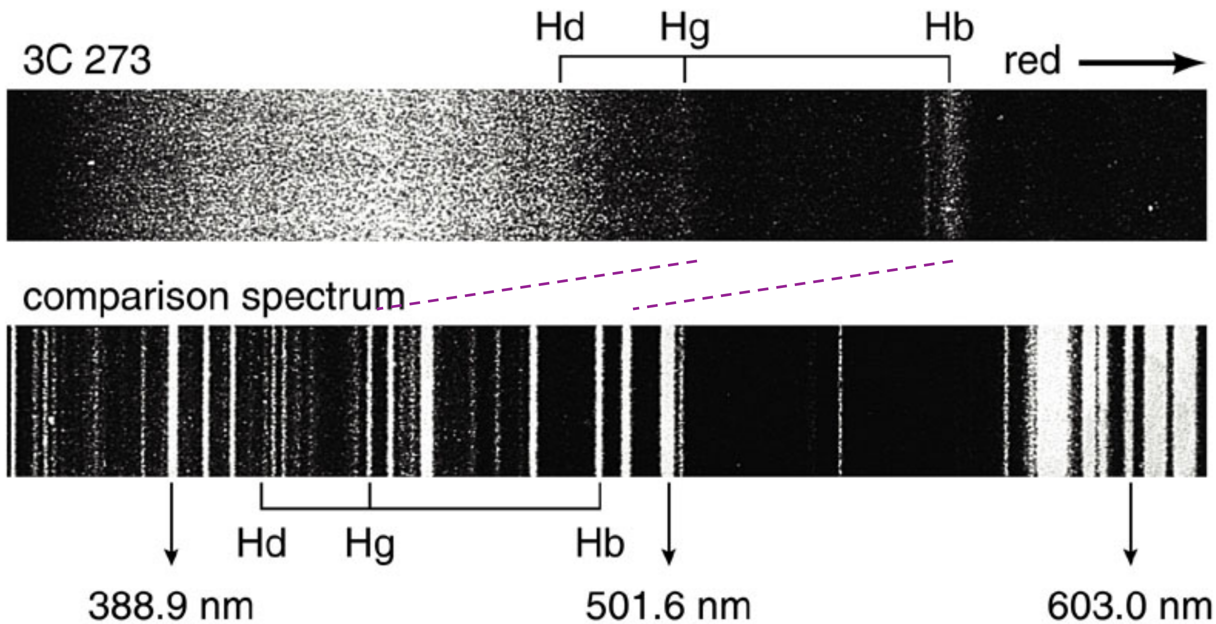
Quasars

- In the 1960s astronomers found “stars” with extreme redshifts
- Later, faint galaxies were seen surrounding these.
- **Quasars** are the most luminous examples of AGNs.





What are quasars?



- The highly redshifted spectra of quasars indicate **large distances**.
- From brightness and distance, we find **luminosities** of $>10^{12}\ L_{Sun}$!
- Variability shows that all this energy comes from a region smaller than our solar system!

Think/Pair/Share

What can you conclude from the fact that quasars usually have high luminosities and 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. Less distant galaxies might hold dead quasars.

Think/Pair/Share

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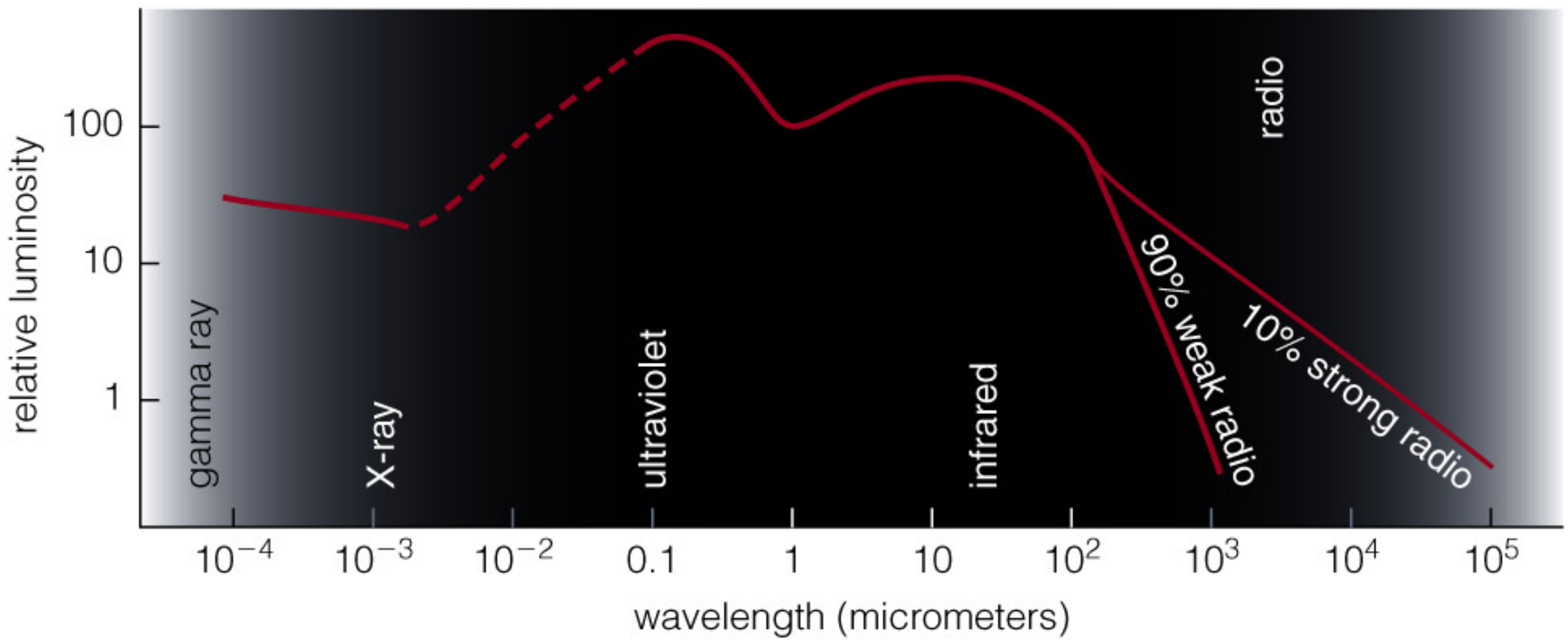
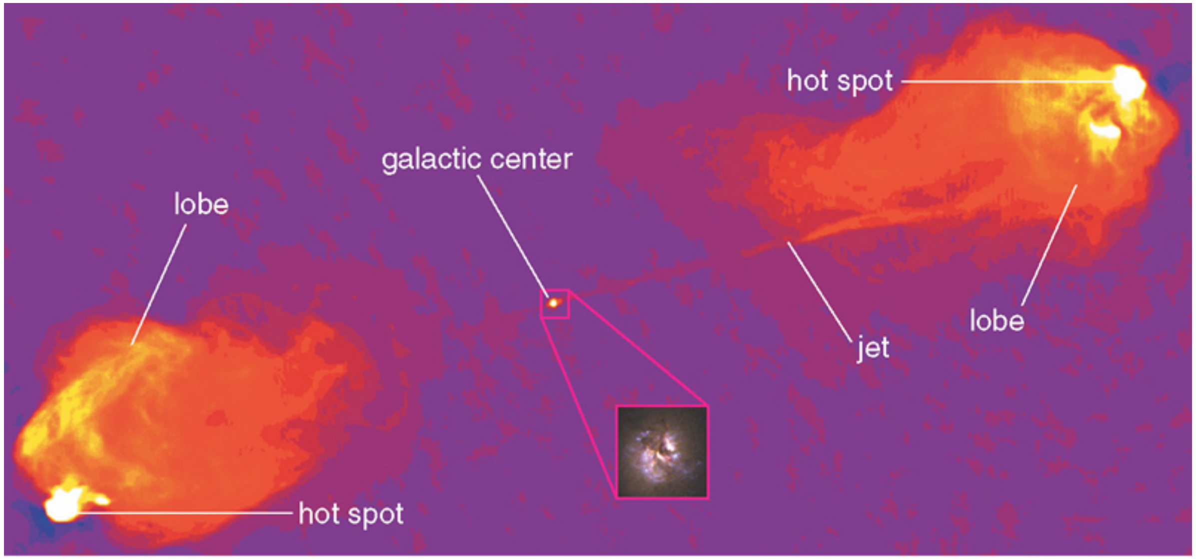
Quasars



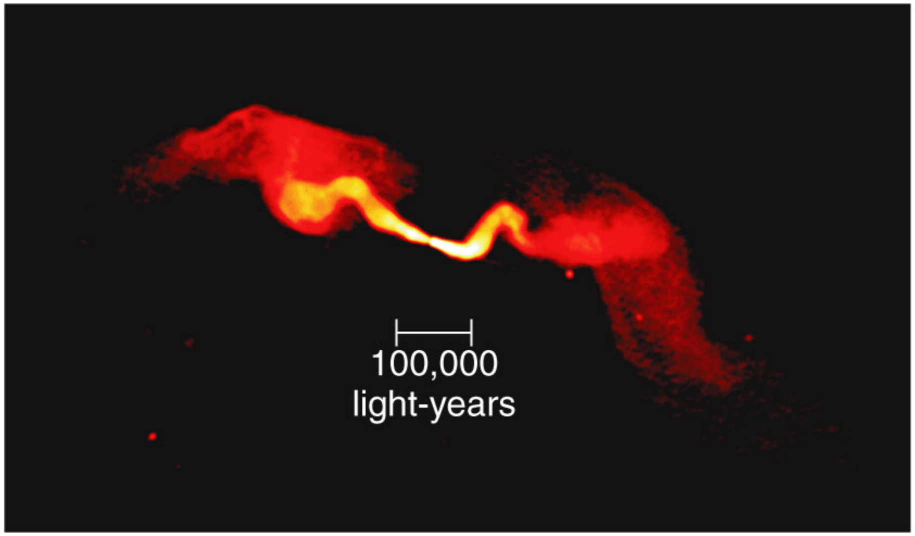
- Quasars radiate energy powerfully over a very wide range of wavelengths
- This indicates matter with a wide range of temperatures.

Radio galaxies



- ***Radio galaxies*** shoot out vast jets of plasma that emit radio waves.

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

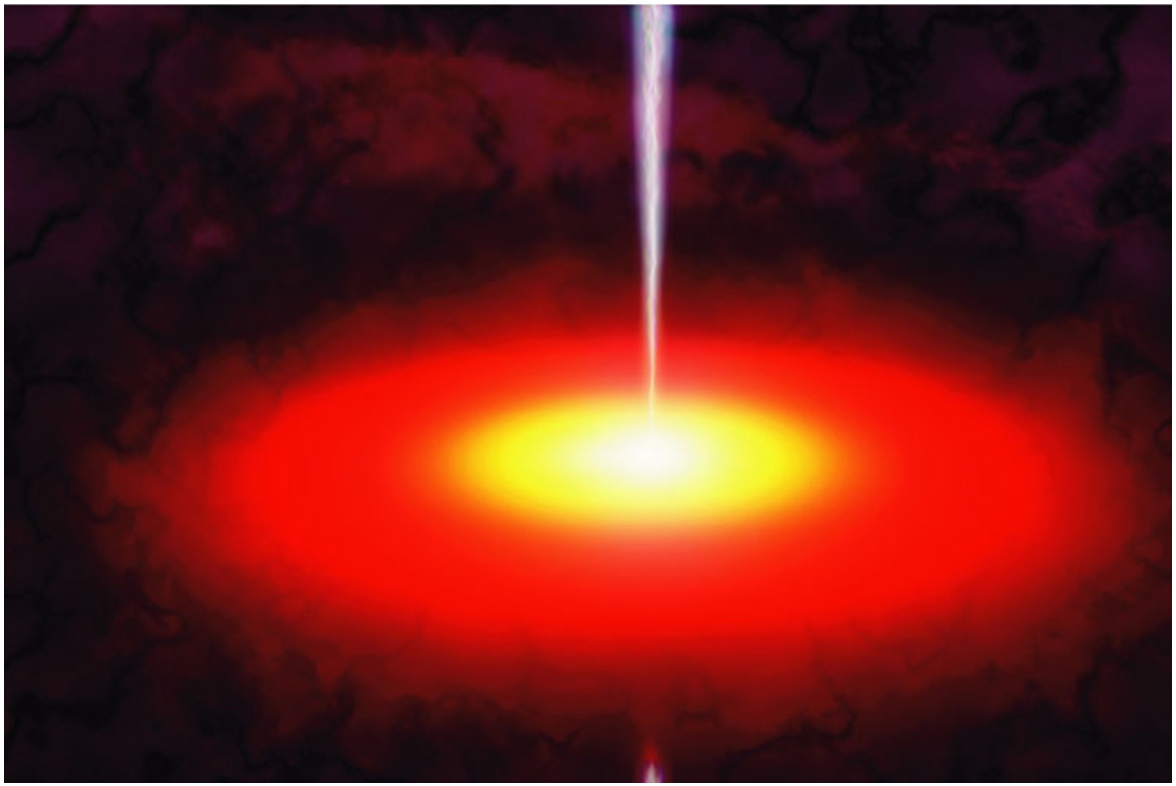


Characteristics of Active Galaxies

- Luminosity can be enormous ($>10^{12}\ L_{Sun}$)!
- Luminosity varies rapidly (comes from very small space).
- They emit energy over a wide range of wavelengths (matter with wide temperature range).
- Some drive enormous jets of plasma at near light speed.

What could explain all of this?

The power source for quasars and active galactic nuclei

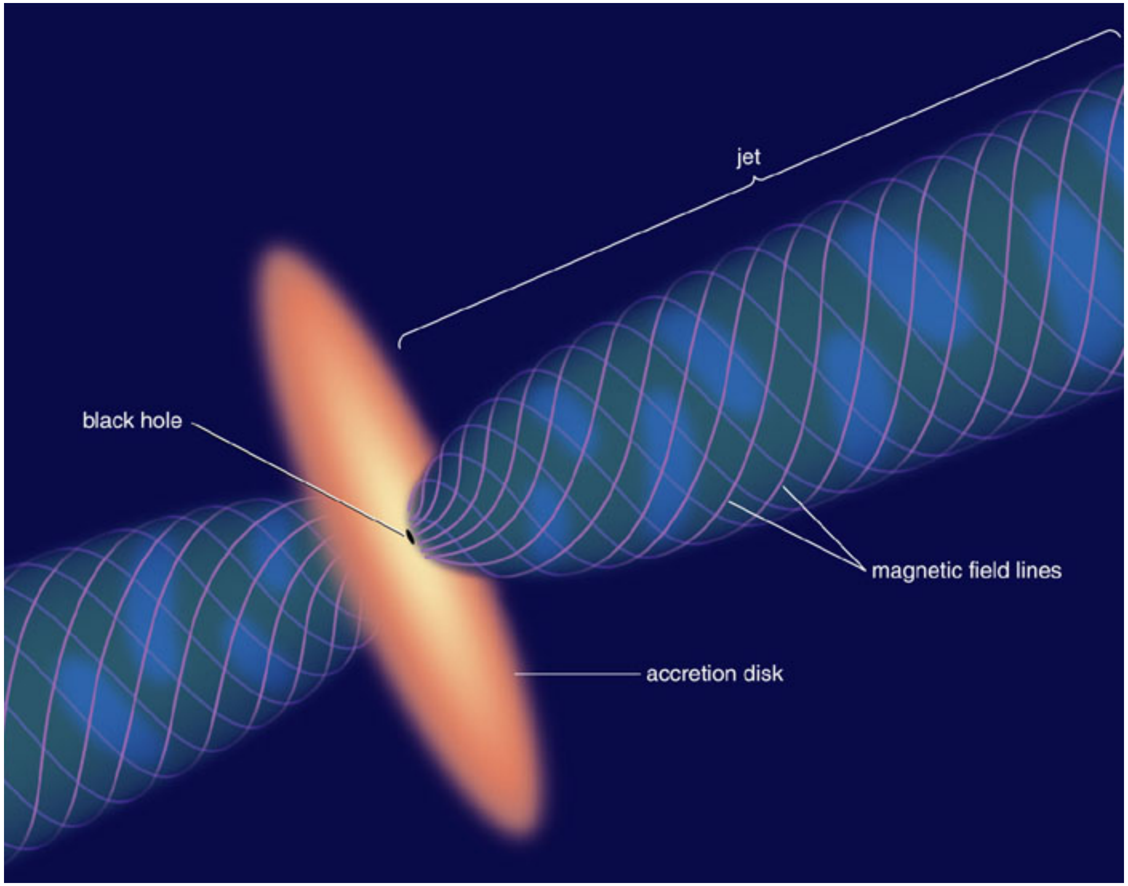


The accretion disk of a **supermassive black hole** explains the properties of quasars.

How do you get energy *from* a Black Hole?

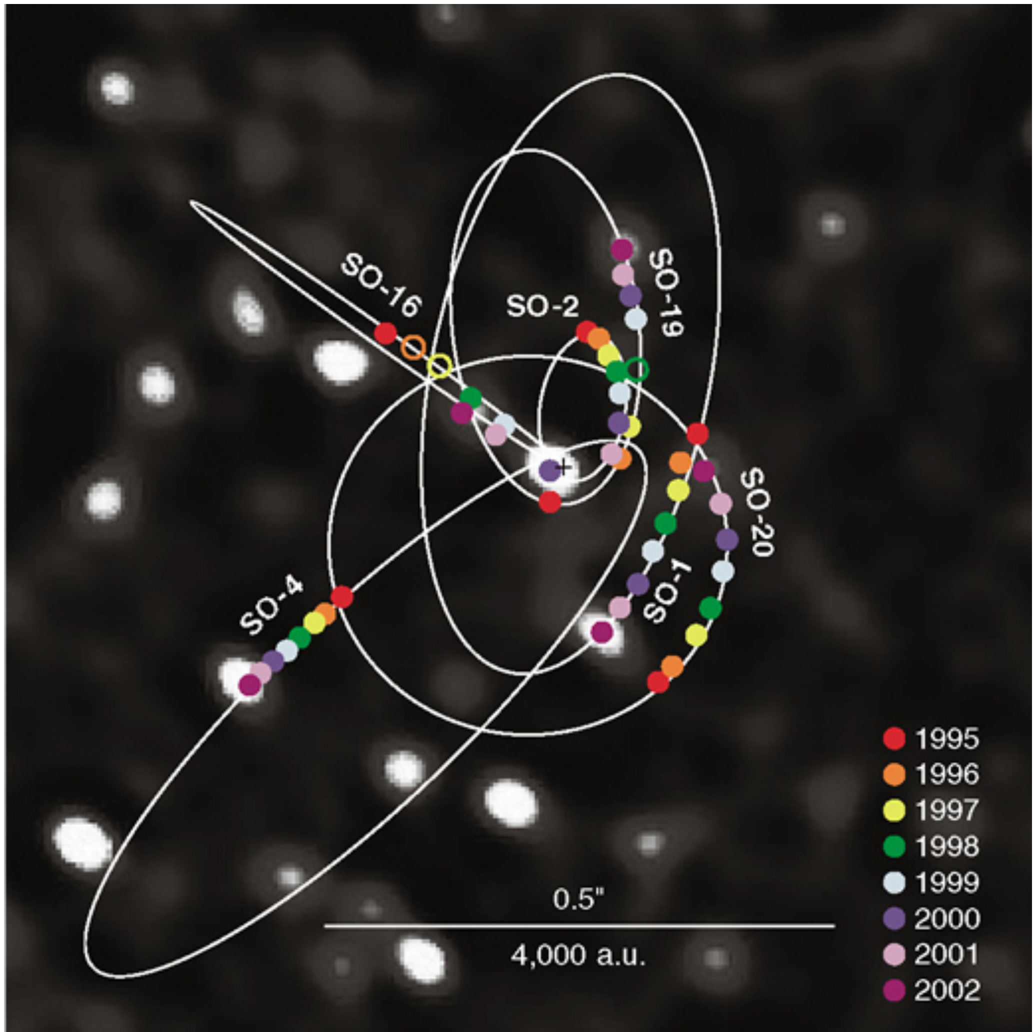
- Gravitational potential energy of matter falling into a black hole turns into kinetic energy.
- Friction in the accretion disk turns kinetic energy into thermal energy (heat).
- Heat produces thermal radiation (photons).
- This process can convert 10–40% of matter into radiation ($E = mc^2$)!

Energy from a Black Hole



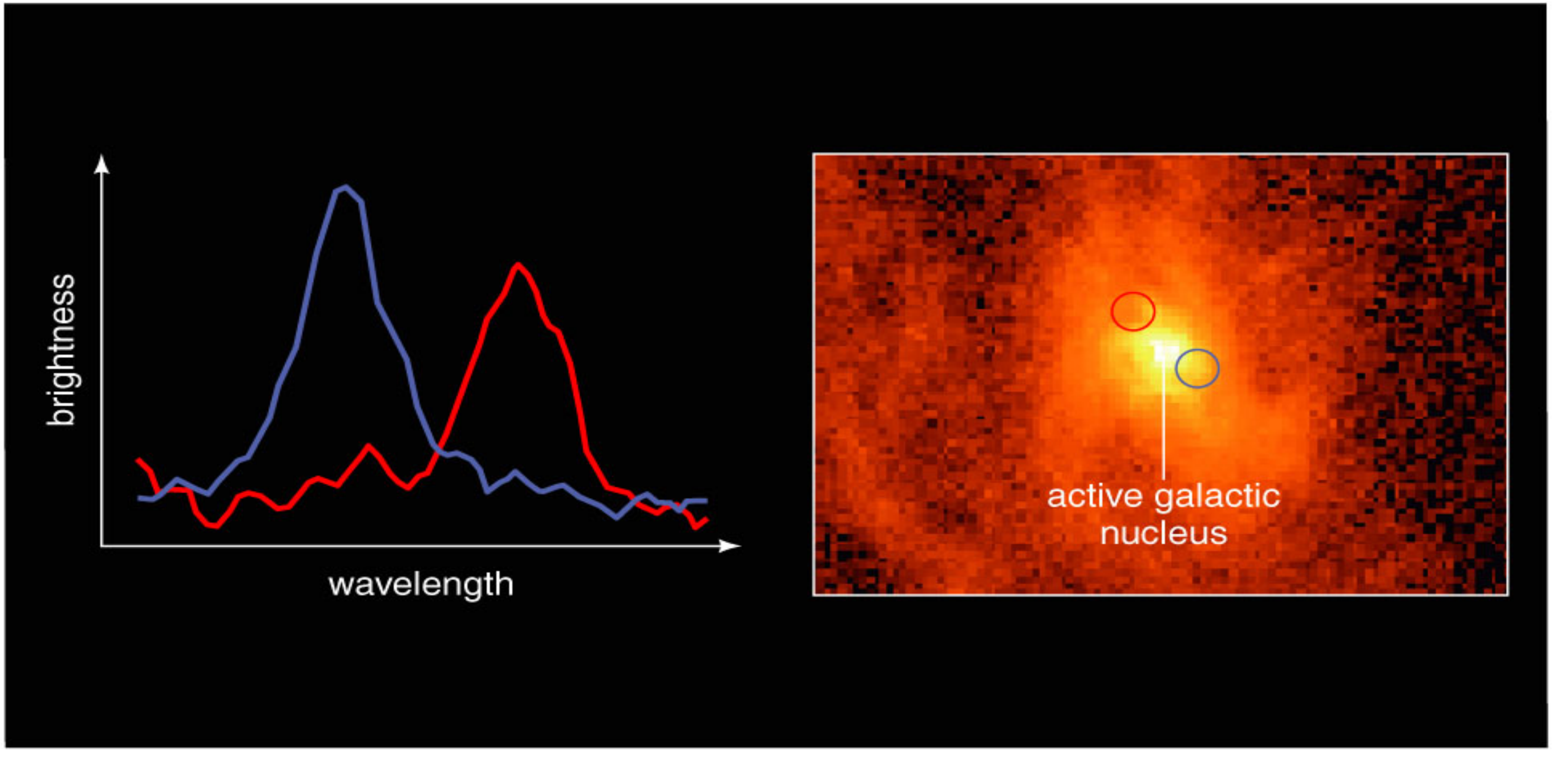
Jets come from the spinning beams of a magnetic field in the inner part of the accretion disk.

Supermassive black holes



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

Supermassive black holes really exist!

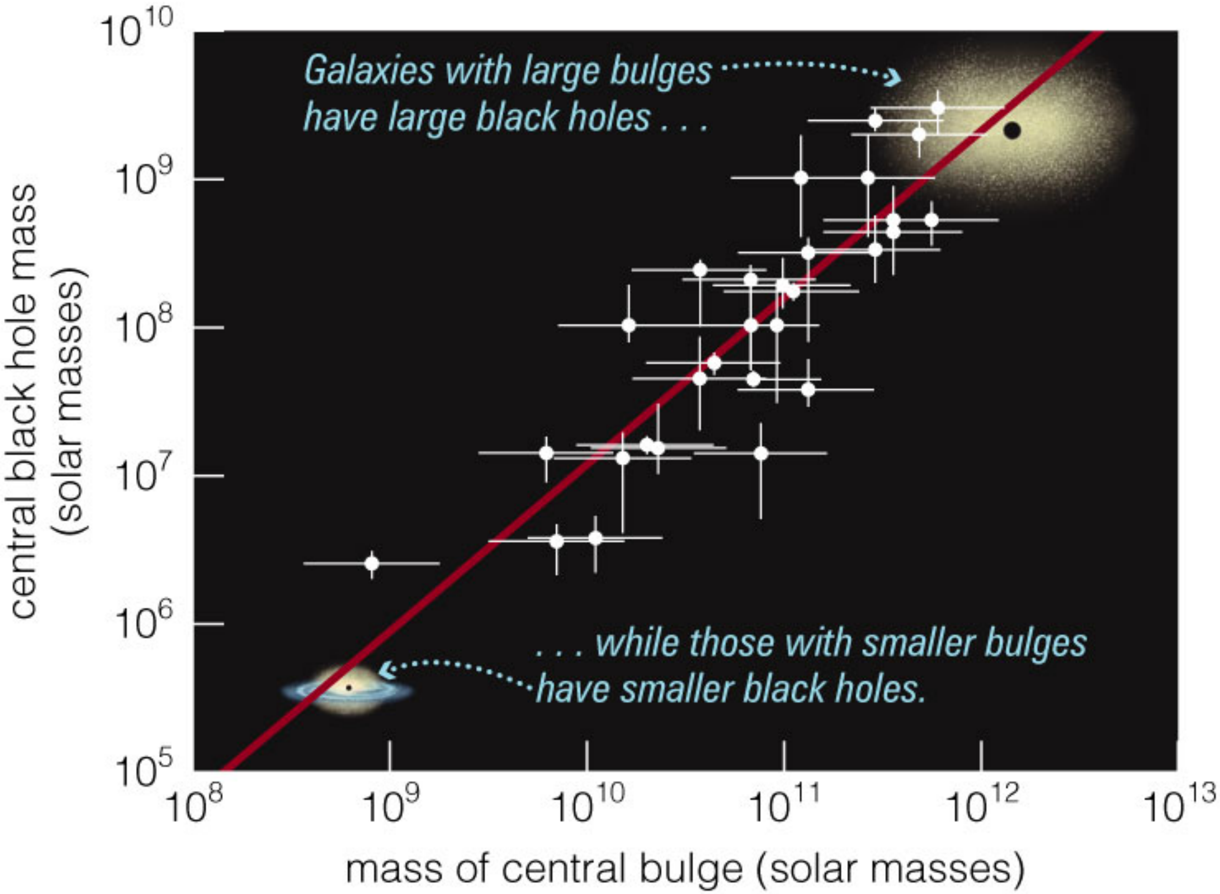


2. Orbital speed and distance of gas orbiting center of M87 indicate a black hole with mass of 3 *billion* M_{sun}!

Black Holes in Galaxies

- Most nearby galaxies 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 related (1/600) to the mass of its bulge.
- The development of a central black hole must be related to galaxy evolution.

What have we learned?

Begin 3 minute review

What have we learned?

What are quasars?

Active galactic nuclei are the very bright centers of some galaxies, and **quasars** are the most common type.

What is the power source for quasars and active galaxies?

The best model that explains observations is that **supermassive black holes** are the power source.

Do supermassive black holes really exist?

Observations indicate that most galaxies have supermassive black holes.