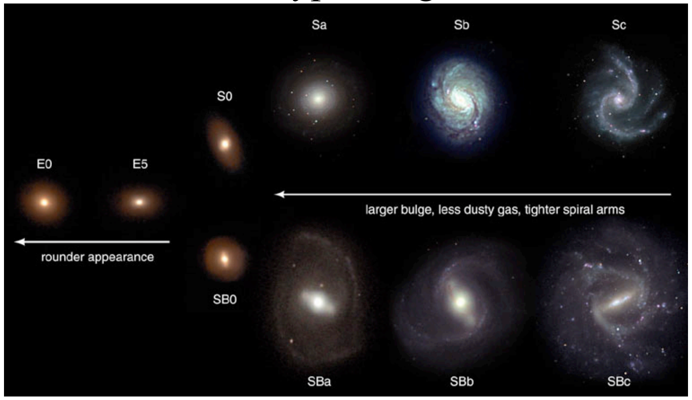
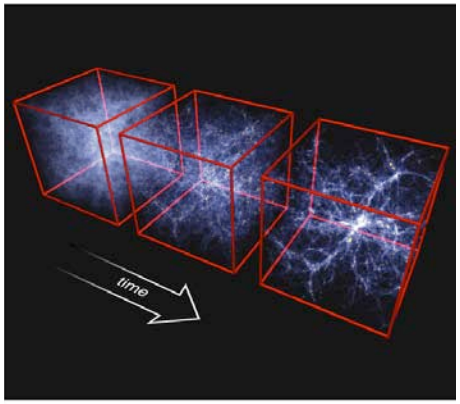
Lecture 16: Galaxy Formation and Evolution

A2020 Prof. Tom Megeath

Hubble's Tuning Fork: Why do we have different types of galaxies?

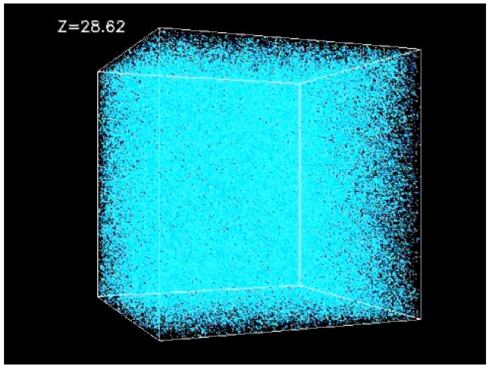




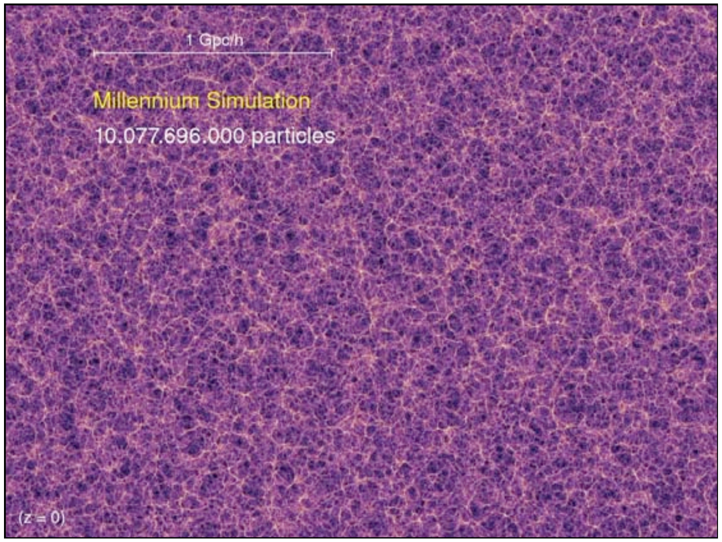
Our best models for galaxy formation assume:

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

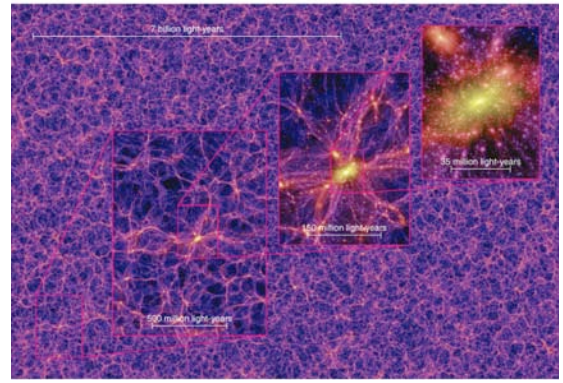
Formation of the Cosmic Web



http://cosmicweb.uchicago.edu/filaments.html



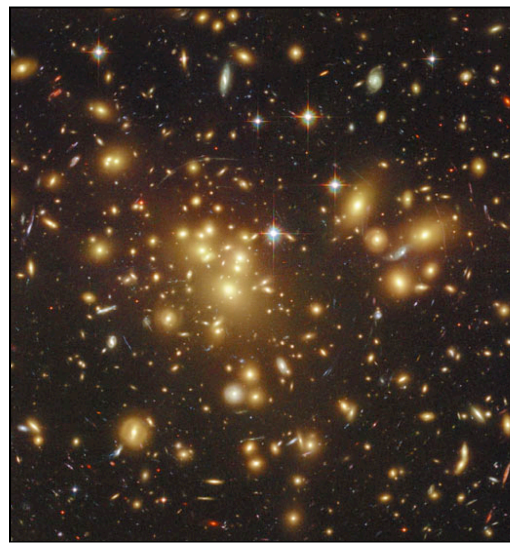
All Matter (Baryonic and Dark Matter) is Organized into a ***Cosmic Web***



Within this cosmic web are isolated galaxies, small groups of galaxies and large clusters of galaxies…..

Spiral galaxies are often found in ***groups*** of galaxies

(up to a few dozen galaxies)

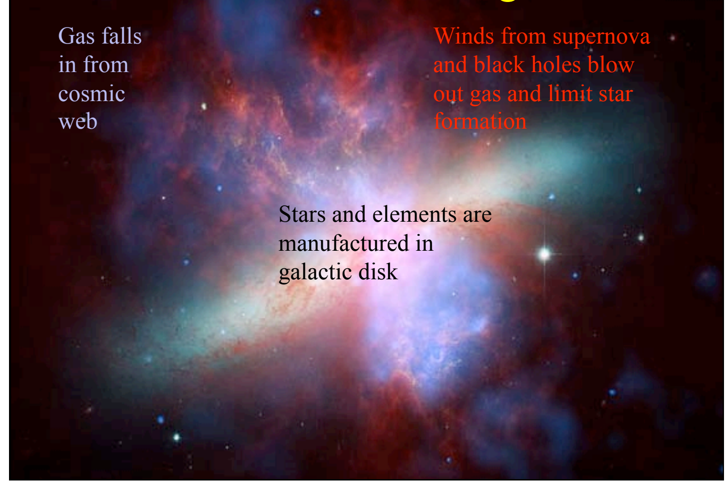


Elliptical galaxies are much more common in huge ***clusters*** of galaxies with hundreds to thousands of galaxies.

Abell 1689

M81 & M82: Nearby Galaxies

Galaxies are Star Making Machines



Traditional View of Galaxy Formation

Galaxies formed from protogalactic clouds

H and He gases in these clouds formed the first stars

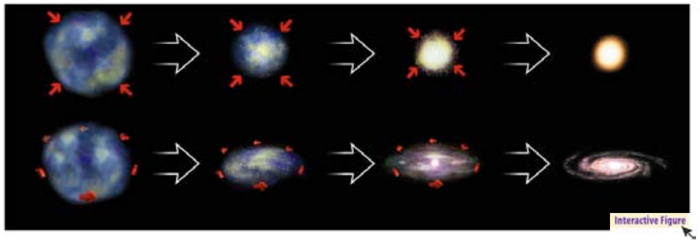
Supernova explosions from first stars kept much of the gas from forming stars

Leftover gas settled into spinning disk

Conservation of angular momentum

Traditional view of why galaxies differ

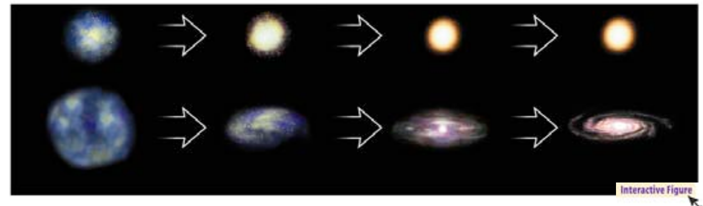
Conditions in Protogalactic Cloud?



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

Traditional view of why galaxies differ

Conditions in Protogalactic Cloud?



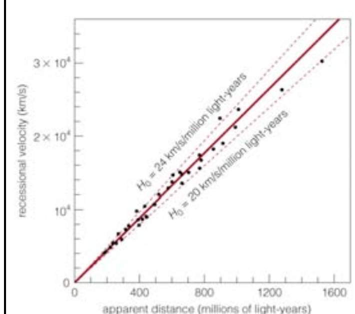
Density: Elliptical galaxies could come from dense protogalactic clouds that were able to cool and form stars before gas settled into a disk

Telescopes are time machines

Since it takes light time to travel from a galaxy to the Earth, we can observe galaxy evolution by looking at more and more distant galaxies.

One of the major challenges in astronomy is to construct a picture of galaxy formation by observing galaxies at different epochs in the history of the Universe.

Hubble's Law (know this!!!!)

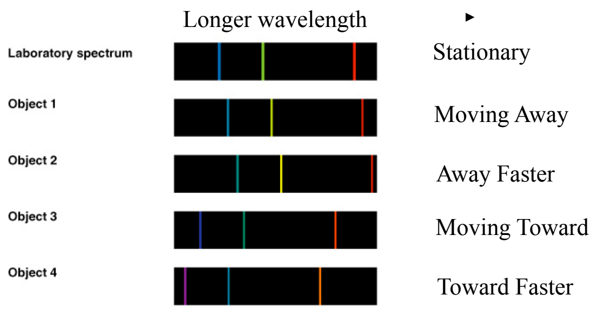


Hubble Ultra Deep Field

We can measure distances by the redshift of a galaxy.

By looking at a single patch of sky, we can see galaxies at many different distances

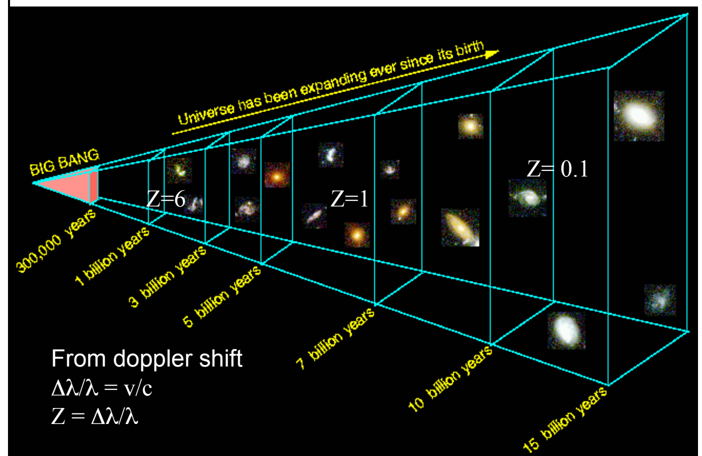
Measuring the Shift

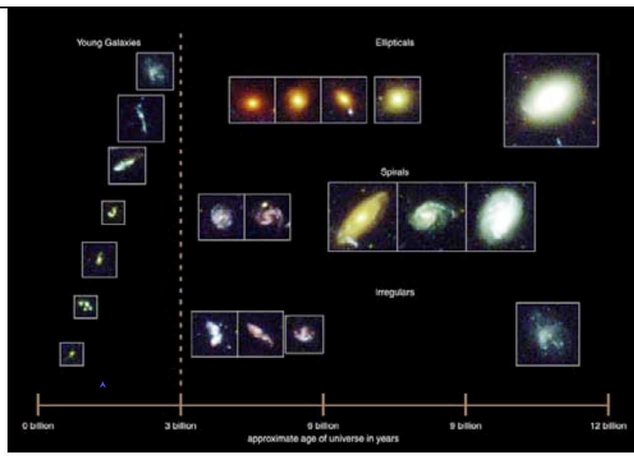


Change in wavelength = wavelength x velocity / speed of light

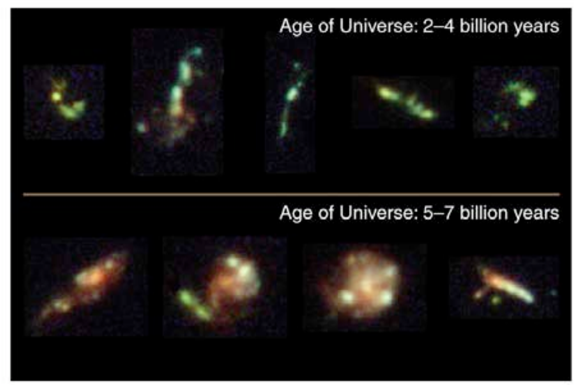
$Z = \Delta\lambda/\lambda = v/c$ if v much smaller than the speed of light

$Z = \Delta\lambda/\lambda$ = square root[(1+v/c)/(1-v/c)-1]



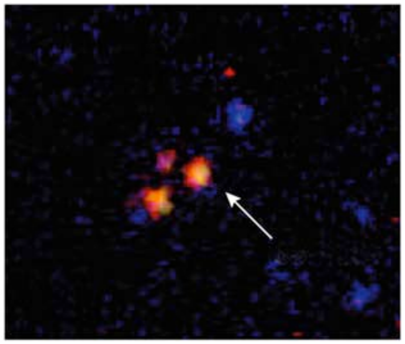


Collisions were much more likely early in time, because galaxies were closer together



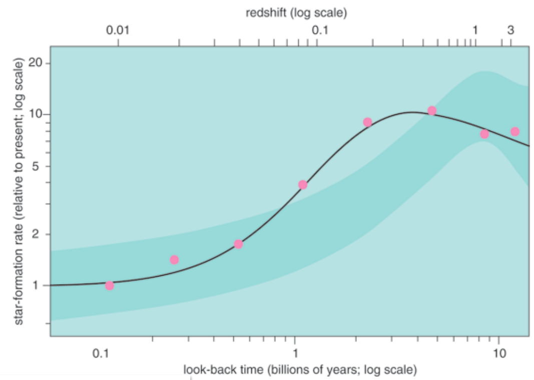
Many of the galaxies we see at great distances (and early times) indeed look violently disturbed

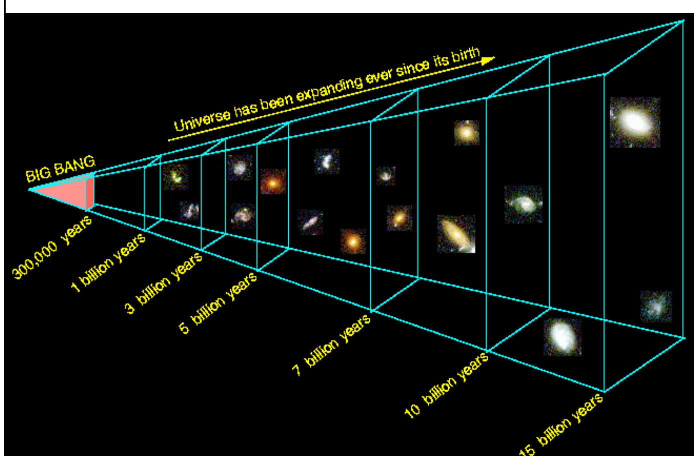
Distant Red Ellipticals



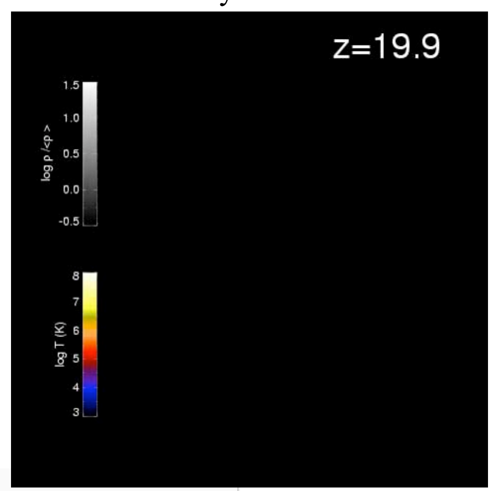
- Observations of some distant red elliptical galaxies support the idea that most of their stars formed very early in the history of the universe
- These elliptical seem to be parts of clusters of galaxies.

Star Formation over the History of the Universe





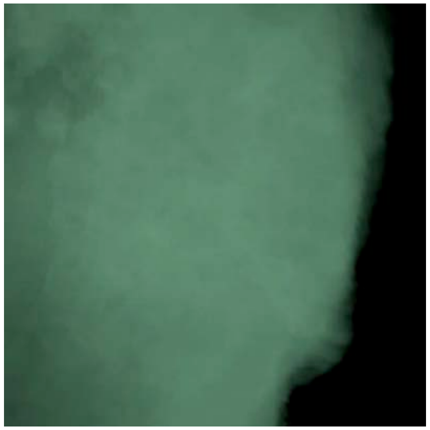
Galaxy Formation in the Cosmic Web



We still can't directly observe the earliest galaxies: we need to rely on simulations to guide us until observations become possible.

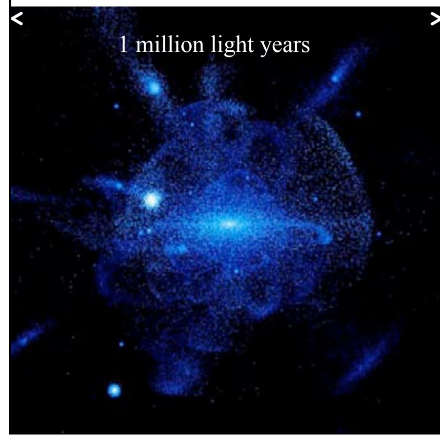
http://luca.as.arizona.edu/~oppen/IGM/general.html

Galaxy Formation in the Cosmic Web



http://www.astro.washington.edu/users/fabio/movies/hz3.cosmo50.248g2bwK.b.mpg

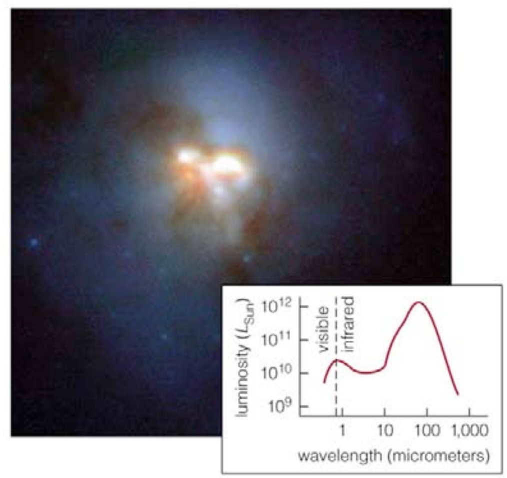
Map of Streams of Stars around our Galaxy



If we map the distribution of distant stars surrounding our galaxy, we find streams of stars: these are satellite galaxies being cannibalized by the Milky Way.

Johnston & Bullock

What are starbursts?

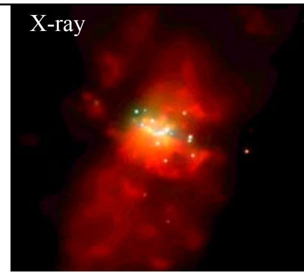


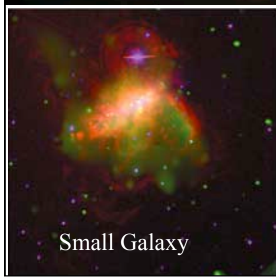
Starburst galaxies can have high luminosities (10^{12} solar luminosities - about 100 times of our galaxy).

They are forming stars so quickly (10 - 100 times faster than the rate of our galaxy) they would use up all their gas in less than a billion years. Thus we expect that there is a burst of star formation.

Starbursts may be triggered by encounters with other galaxies.

Most of the energy radiated in the infrared





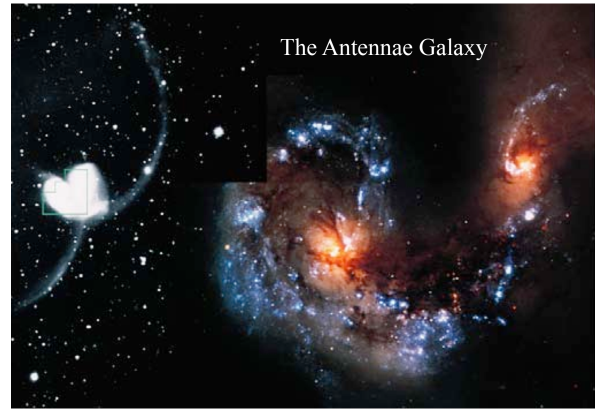
Galactic Winds

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.

This can slow down star formaion until the star burst is over.

What happens when galaxies collide?

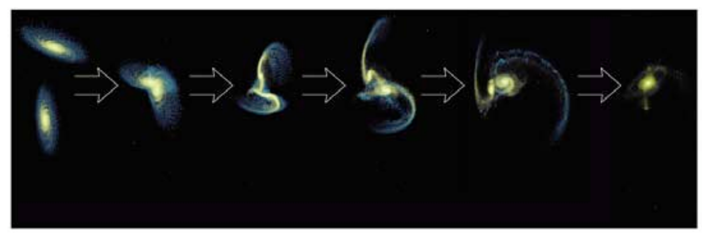


The stars don't collide, galaxies interact through gravity and collision of gas clouds in the ISM

The collisions we observe nearby trigger bursts of star formation

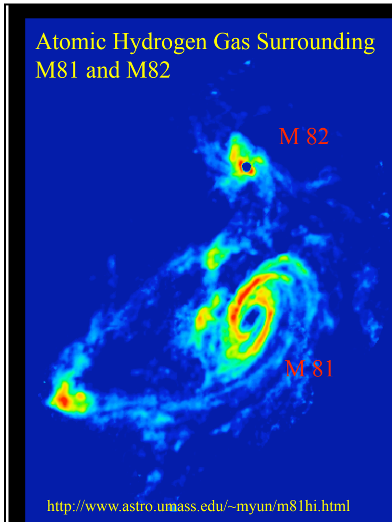
Galaxy collisions take millions to billions of years.

We use computer simulations to speed up time!

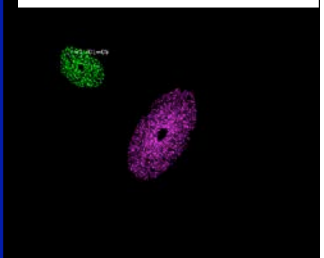


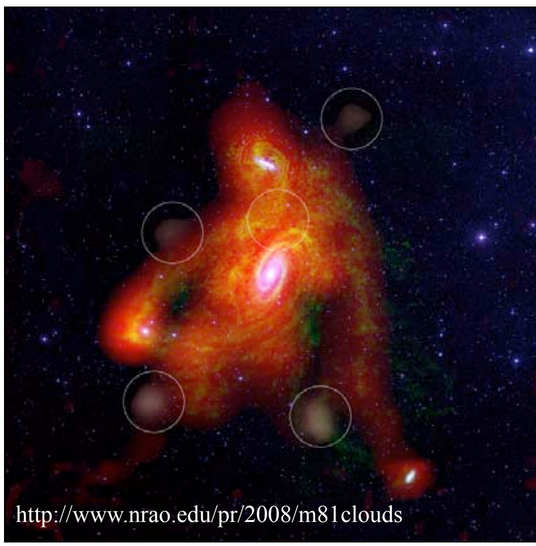
Modeling such collisions on a computer shows that two spiral galaxies can merge to make an elliptical

M81 & M82: Interacting Galaxies



These Galaxies are Interacting: M81, M82, and NGC 3077 (located 10 million light years away from the Earth)



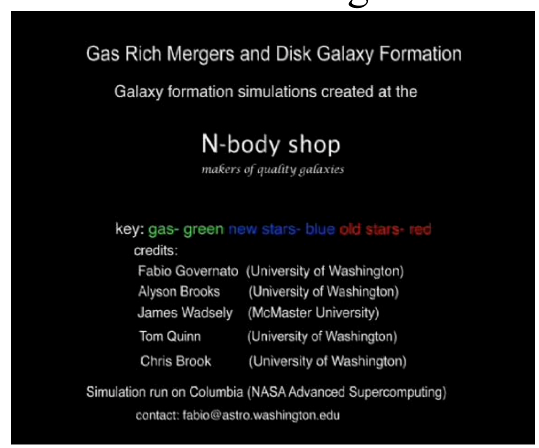


Combined map of visible light and hydrogen gas.

Each circle contains newly discovered gas cloud containing from 14 to 57 million times the mass of our Sun

Made with Green Bank Radio Telescope

Gas Rich Mergers

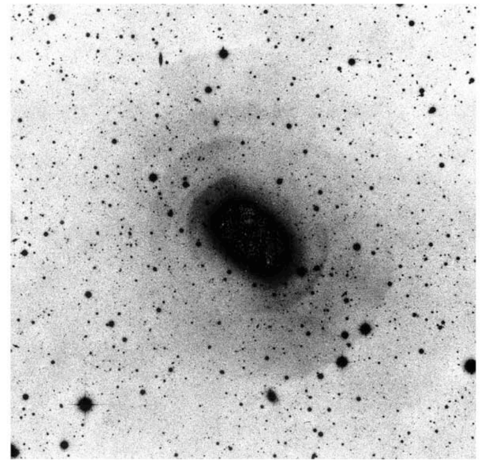


http://www.astro.washington.edu/users/fabio/movies/Merger.mpg

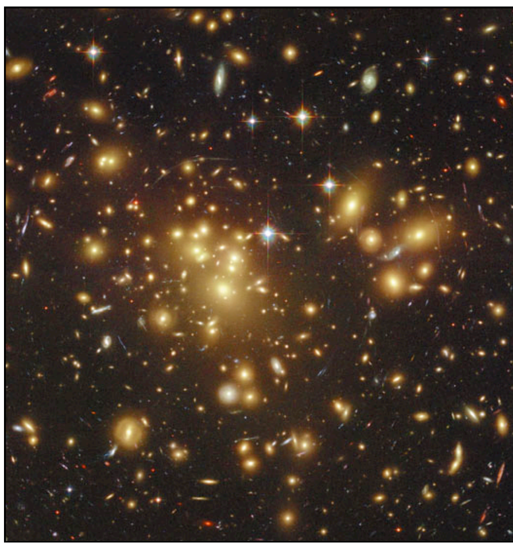
Making Elliptical Galaxies from Spiral Galaxies.

Modeling such collisions on a computer shows how galaxies at the center of a cluster merge to form a giant elliptical galaxy. Question – where does the gas go? Is it used up in violent star formation. Or are such mergers “dry” – i.e. most of the molecular gas is gone.

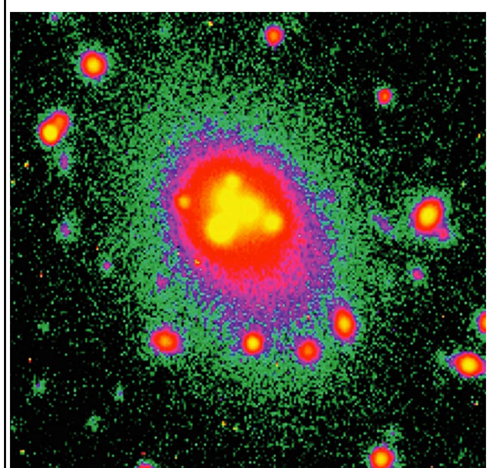
http://galaxydynamics.org/galacticencounters.html



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

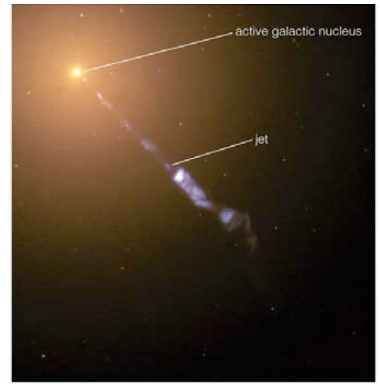


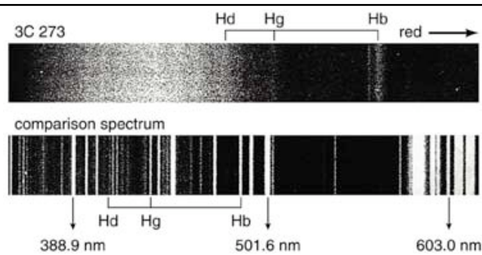
Giant elliptical galaxies at the centers of clusters seem to have consumed a number of smaller galaxies

What 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?
  - Our best models for galaxy formation assume that gravity made galaxies out of regions of the early universe that were slightly denser than their surroundings. The gas collapsed to form galaxies. Galaxies continue to cannibalize smaller galaxies and draw in gas as the evolve.
- What determines the morphologies of galaxy?
  - Gravity plus angular momentum leads to the formation of large disk galaxies (spiral galaxies) by pulling in gas from the cosmic web and through cannibalizing smaller galaxies.
  - Collisions and mergers can play a major role in galaxy growth and can induce starbursts. It is still being argued how important they are in spiral galaxy formation.
  - Mergers can transform spiral galaxies into an elliptical galaxy – thus ellipitical galaxies are typically found in the centers of galaxy clusters. Collisions thought to be very important in elliptical galaxy formation.
- What are starbursts?
  - A starburst galaxy is transforming its gas into stars much more rapidly than a normal galaxy, can be triggered by interactions between galaxies.
  - Winds from starbursts may blow out gas and limit star formation.

How do Black Holes Affect Galaxy Evolution?





QUASAR stands for QUASi-stellAR radio source.

First identified as bright radio sources - without visible counterparts

In 1962 Maarten Schmidt identified a "star" coincident with the radio source and obtained a spectrum. He discovered it was not a star, and named it a QUASAR.

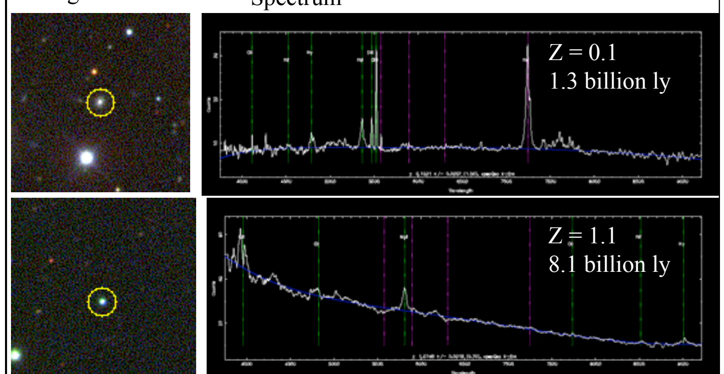
The highly redshifted spectra of the quasars indicated large distances (billions of light years!)

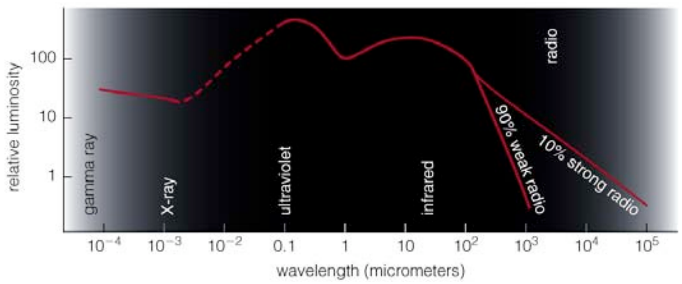
From brightness and distance we find that luminosities of some quasars are $>10^{12}\ L_{Sun}$

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

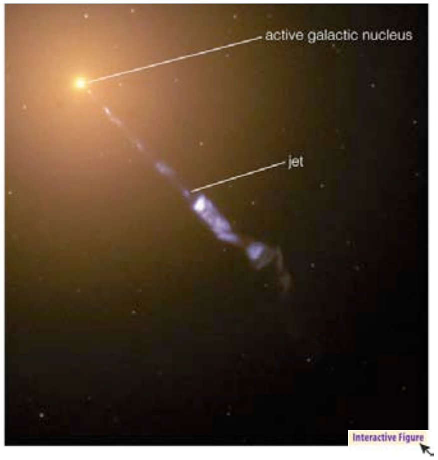
QUASARs from the Sloan Survey

Image | Spectrum





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



Active Nucleus in M87

What are QUASARS?

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

Quasars are the most luminous examples of AGN that were found only in the early universe.

Are found at distances of 12.7 billion light years to 800 million light years.

None are found near the Milky Way.

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?

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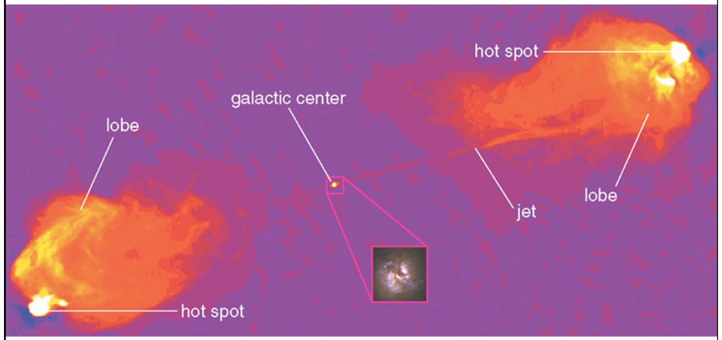
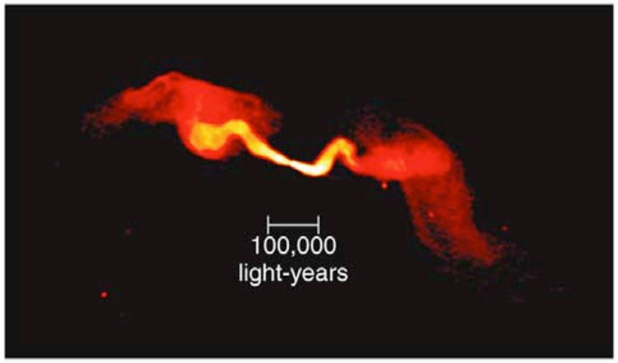
D. Nearby galaxies might hold dead quasars

All of the above!



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

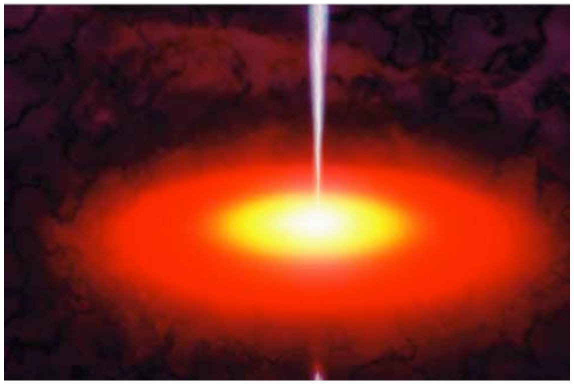


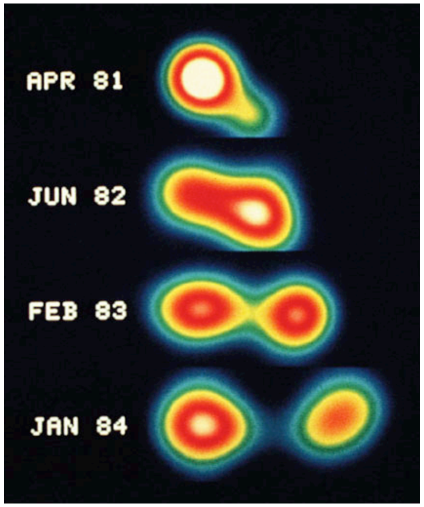
The lobes of radio galaxies can extend over hundreds of millions of light years

Characteristics of Active Galaxies

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

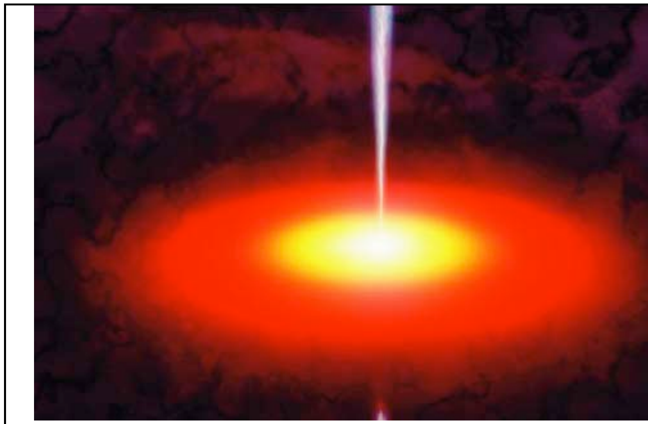
What is the power source for quasars and other active galactic nuclei?





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

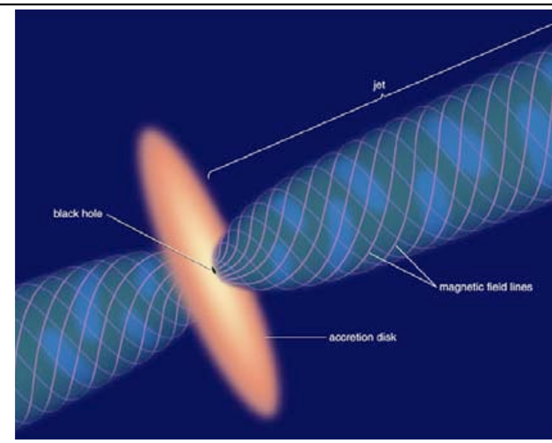
Speed of ejection suggests that a black hole is present



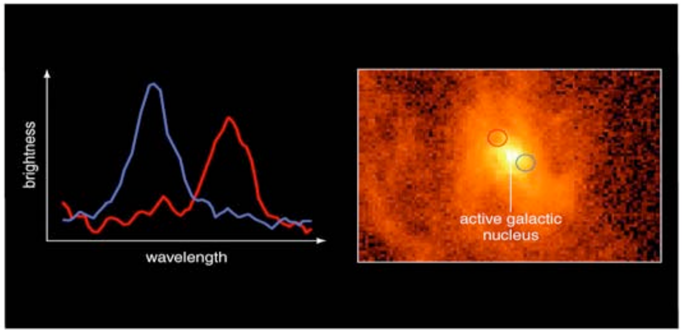
Accretion of gas onto a supermassive black hole appears to be the only way to explain all the properties of quasars

Energy from a Black Hole

- Gravitational potential energy of matter falling into black hole turns into kinetic energy
- Friction in 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
- QUASARs may swallow the equivalent of 10 stars per year to generate their power.



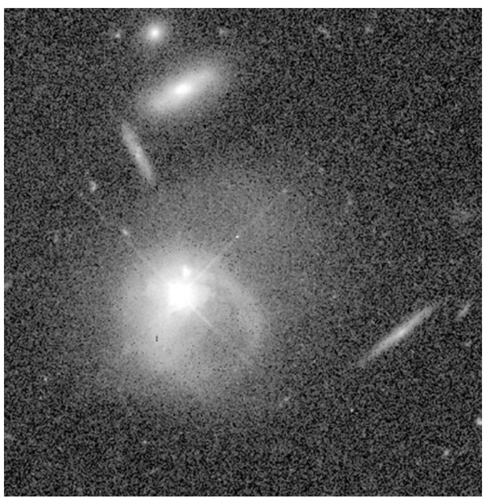
Jets are thought to come from twisting of magnetic field in the inner part of accretion disk



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

- 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

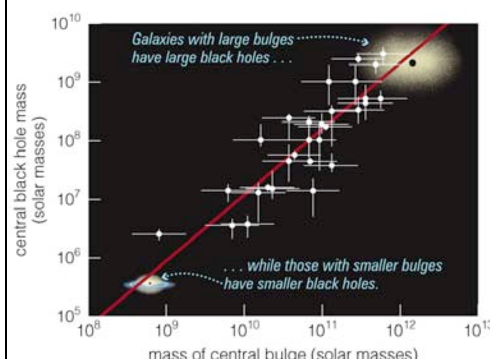


Galaxies around quasars sometimes appear disturbed by collisions

These may be AGN which are being fueled by gas funneled into the center of galaxies in these collisions.

These events were much more frequent when galaxies were closer together, thus Quasars were much more common in the past.

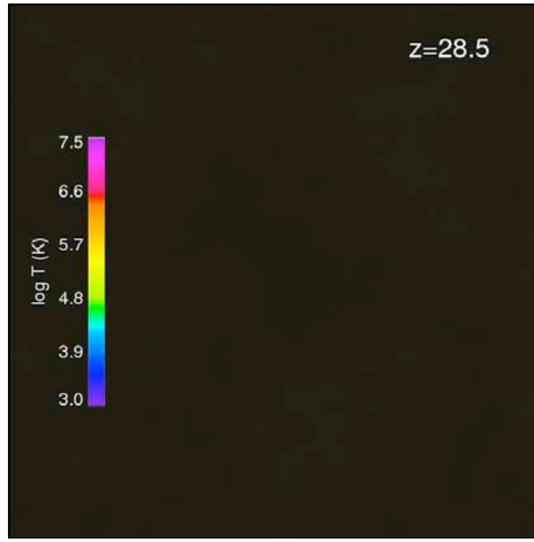
Galaxies and Black Holes



- Mass of a galaxy's central black hole is closely related to mass of its bulge
- Development of central black hole must be somehow related to galaxy evolution

What have we learned?

- What are quasars and active galactic nuclei?
  – Active galactic nuclei are very bright objects seen in the centers of some galaxies, and quasars are the most luminous type
- What is the power source for quasars and other active galactic nuclei?
  – The only model that adequately explains the observations holds that supermassive black holes are the power source
- Do supermassive black holes really exist?
  – Observations of stars and gas clouds orbiting at the centers of galaxies indicate that many galaxies, and perhaps all of them, have supermassive black holes
- Are black holes important in galaxy formation
  – There is a relationships between bulge size and black holes size



Epilogue: Formation of galaxies with feedback from galactic winds (from supernovae and black holes)

http://luca.as.arizona.edu/~oppen/IGM/general.html