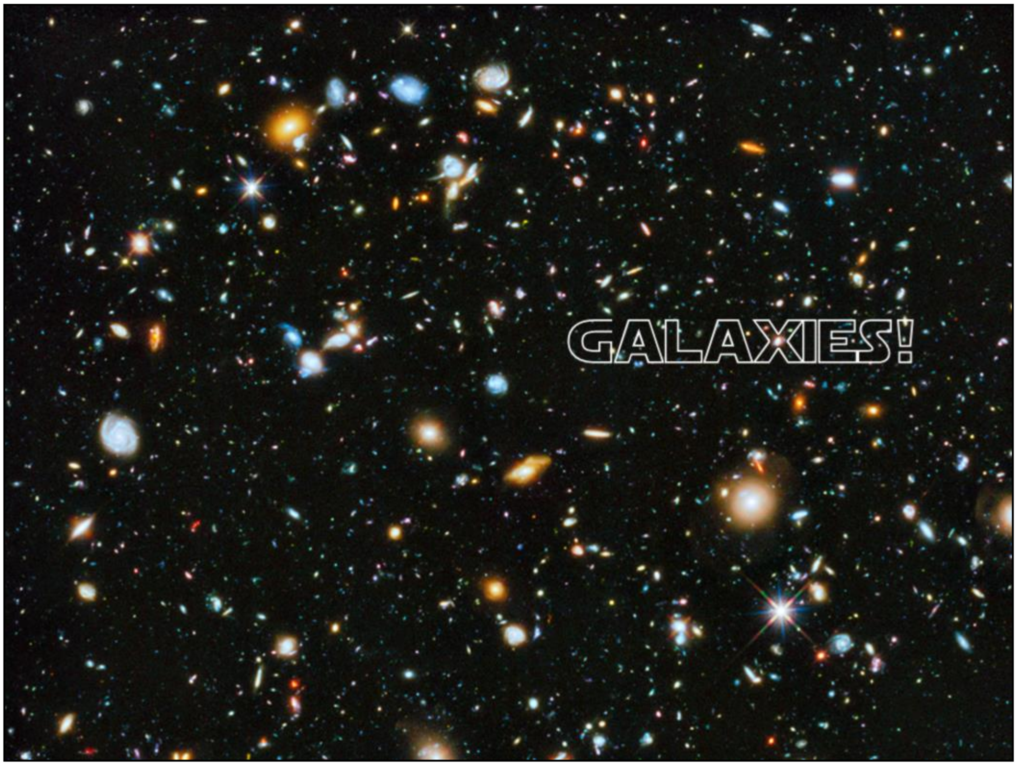
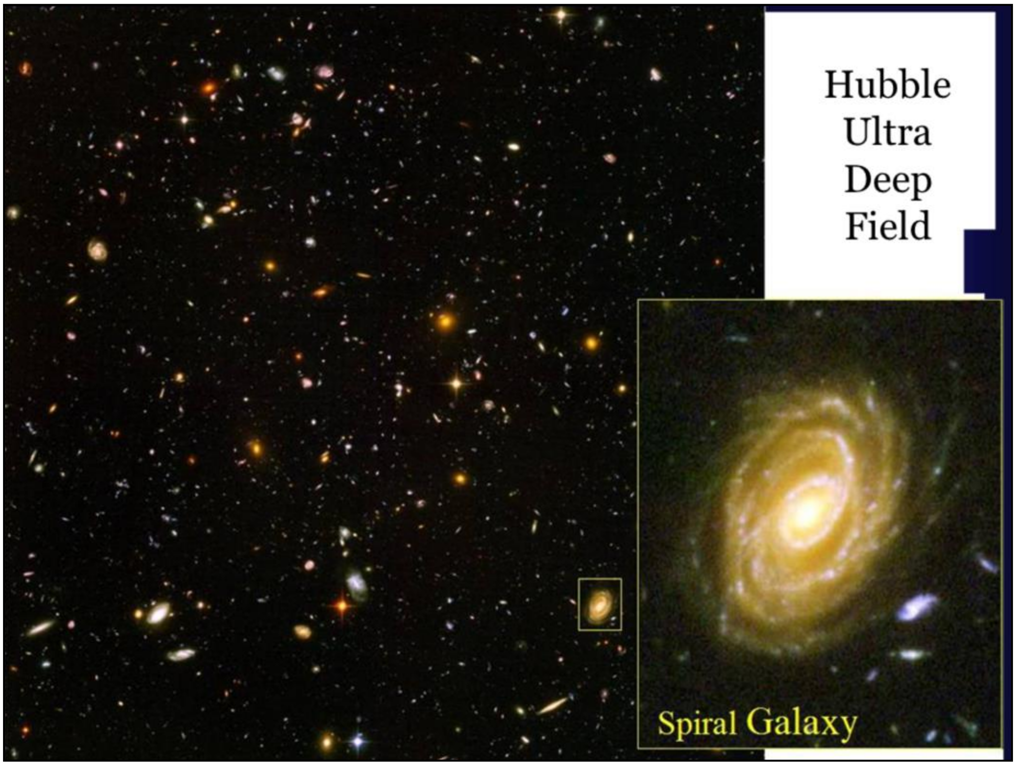
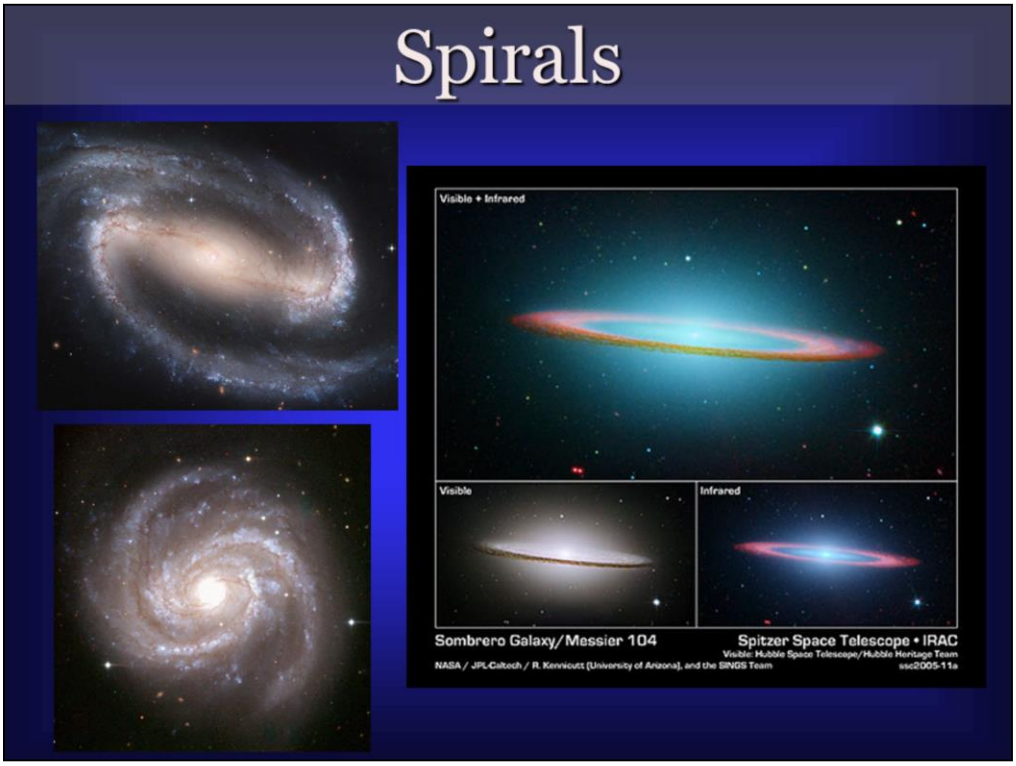


Hubble Ultra Deep Field, revised (2014)


Hubble
Ultra
Deep
Field
Spiral Galaxy



Spirals have a three component structure:

There is a thin disk composed of gas, dust, and stars.

In the center there is a bulge.

They are surrounded by a ellipsoidal halo.

Some spirals contain a bar that rotates like a rigid body

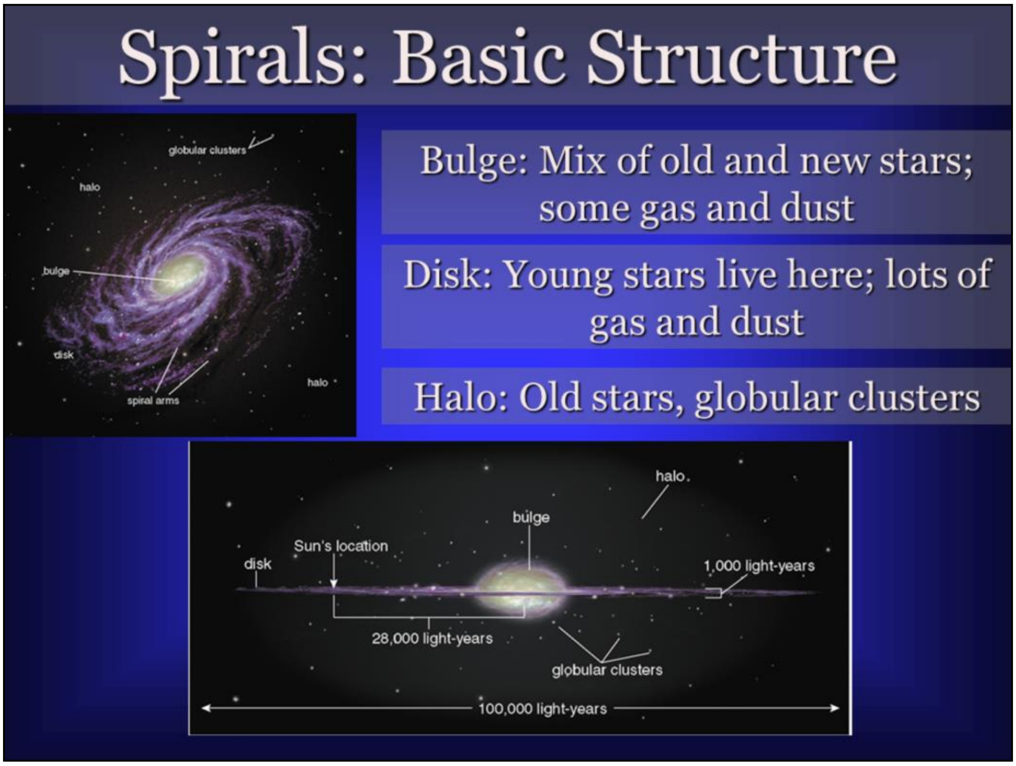
The arms are connected to the ends of the bar.

What a spiral galaxy looks like from out perspective depends on its inclination.

Some are face on, some are edge on, most are somewhere in between

The Sombrero Galaxy is nearly edge on. Above is a really cool image of it combining the visible image from HST with the infrared image from Spitzer.

In the infrared image, the dust in the disk pops out and looks really nifty.



Disk

A flat disk with a thickness that is 1/100th the length of the disk

Most of the younger stars lie in the disk

Open clusters, for example

Composed of stars, gas, and dust

Spiral arms are in the disk

Bulge

Central region of the galaxy

Contains a mixture of old and new stars

More tightly packed; higher densities

Halo

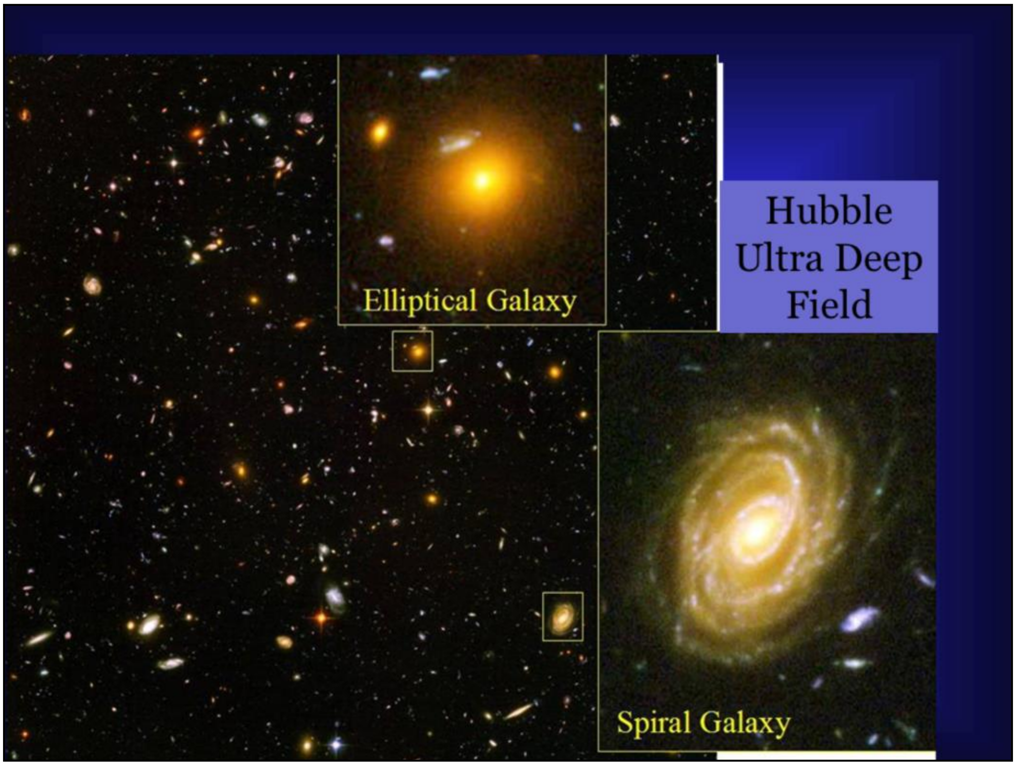
A sphere/ellipsoid that surrounds the disk and bulge of the galaxy

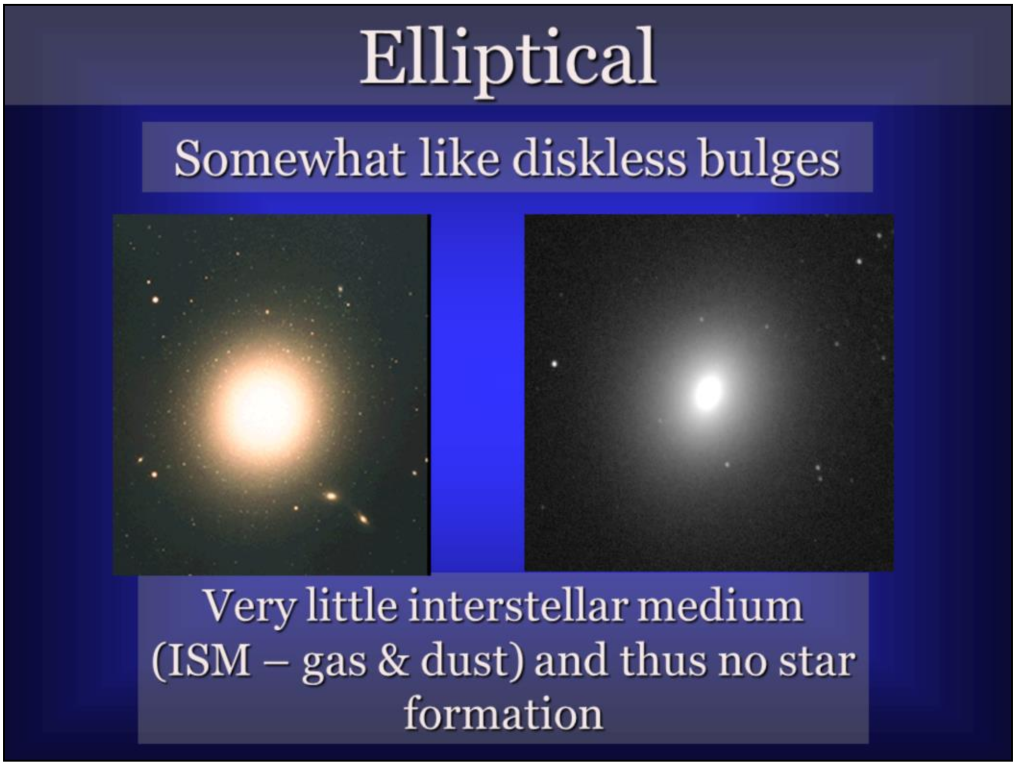
Contains older stars

Globular clusters

No gas and no dust, just stars

No star formation going on in the halo


Hubble Ultra Deep Field
Elliptical Galaxy
Spiral Galaxy



They have no disk.

About 10 percent of observed galaxies are ellipticals

The ISM consists mostly of low density very hot gas that emits in X-rays.

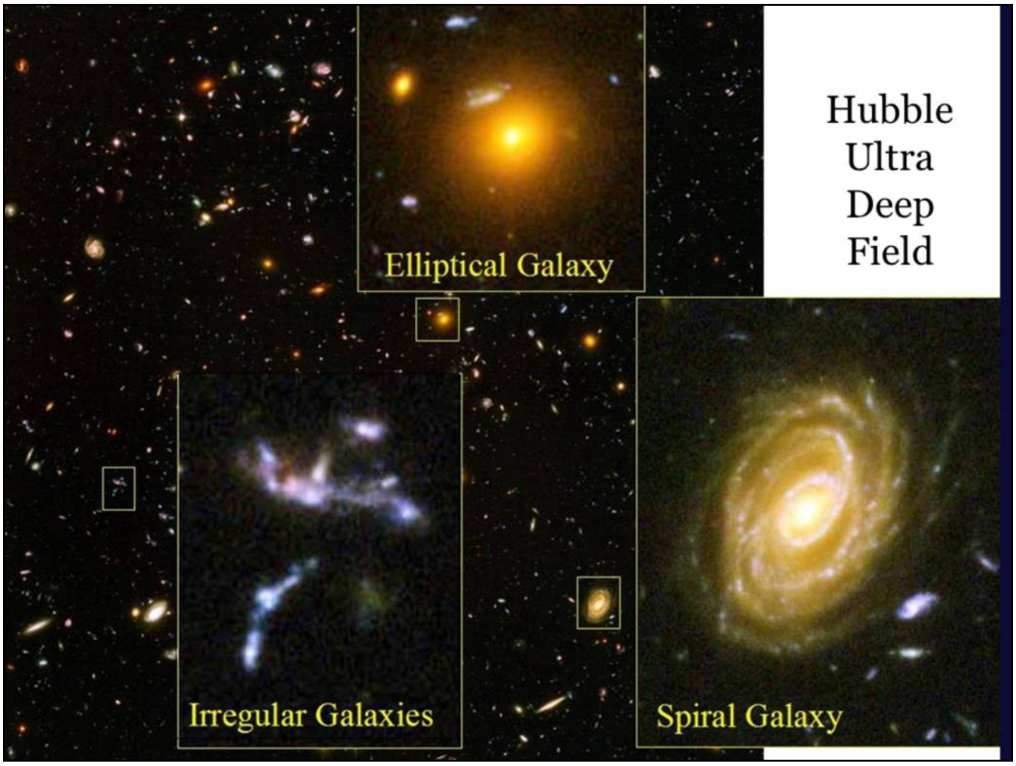
Since there is no ISM, there is no star formation so the stellar population tends to be lower mass redder stars.

Huge range of sizes.

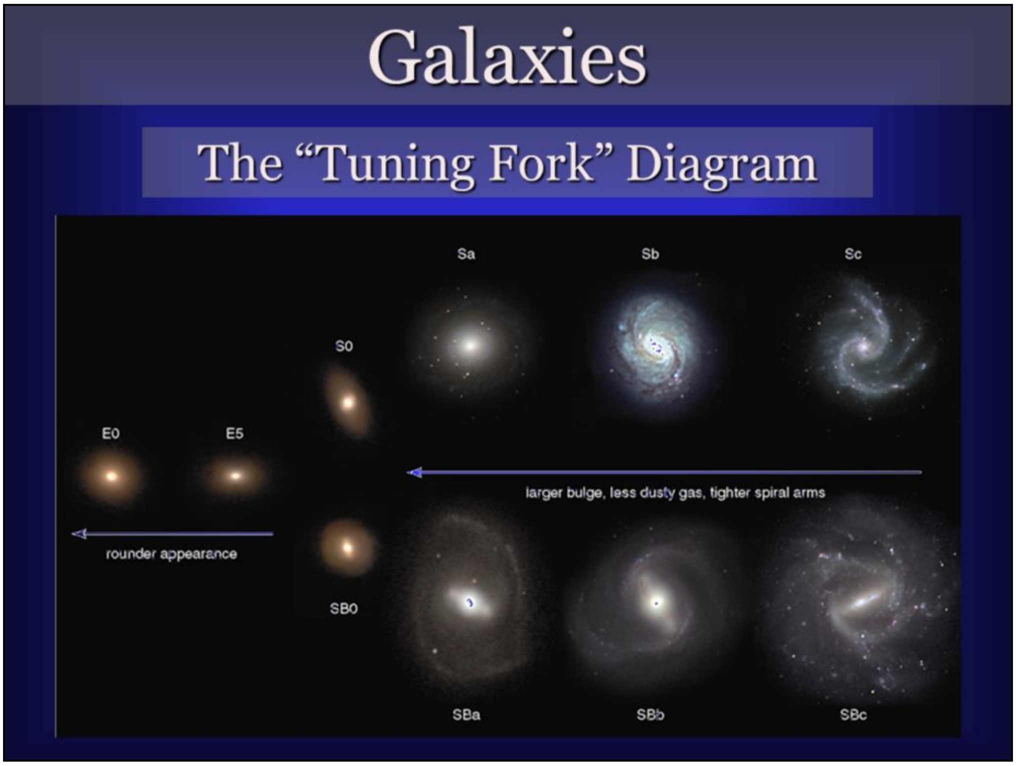
Dwarf ellipticals can be as small as 10 million solar masses, on the order of the globular clusters.

Giant ellipticals, like M87 can be as large as 10^{13} solar masses, among the largest galaxies in the universe.

Orbital motions are like those in the Bulge or Halo of the Milky Way… Highly elliptical orbits, no orderly motion like in a spiral.


Hubble
Ultra
Deep
Field
Elliptical Galaxy
Irregular Galaxies
Spiral Galaxy

Neither spiral or elliptical… They tend to have a mix of young and old stars
Generally have some gas and dust component.
They have more in common with spiral disks than with ellipticals.



The galaxy classification scheme was developed by Edwin Hubble in the 1920's

Elliptical galaxies are … well … elliptical.

The E0 types are more spherical.

The E5 types are more elliptical.

Then the diagram splits into S and SB

S type galaxies are spirals characterized by a bulge, disk, and spiral arms.

SB galaxies are barred spirals. They have a bar in the center that appears to rotate like a rigid body.

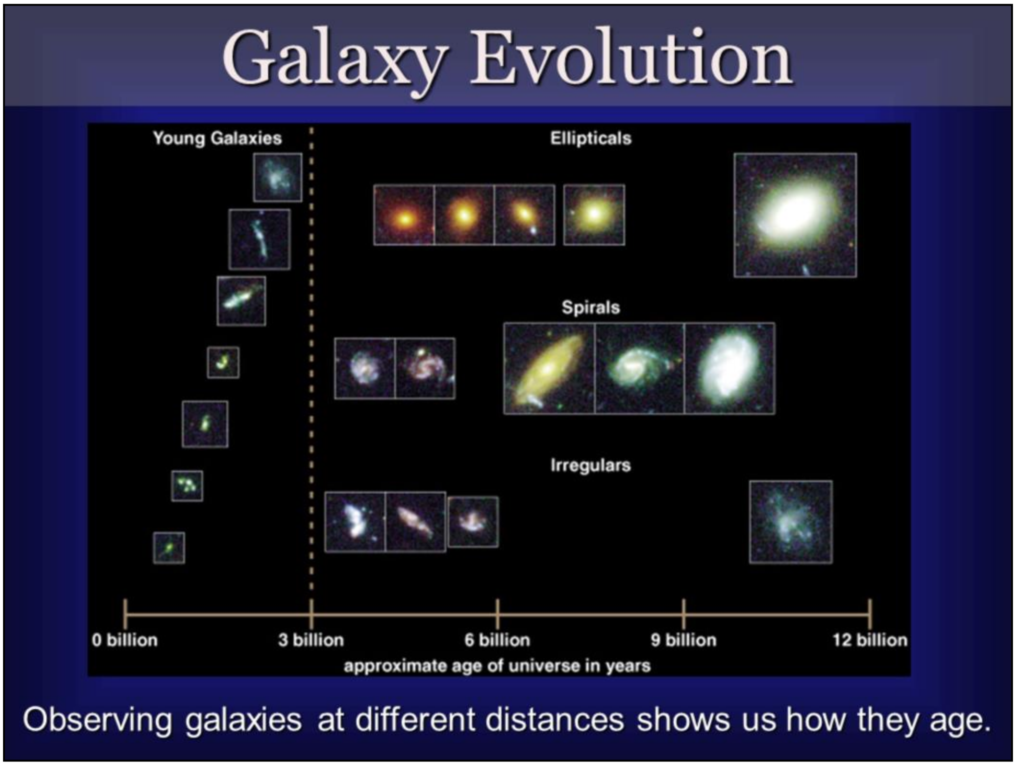
The S0 and SB0 are intermediate objects. Not quite elliptical and not quite spiral

Sa and SBa have loose spiral arms, large bulge to disk ratio, and low dust to gas ratio

Sc and SBc are the opposite. Tightly wound arms, small bulge to disk ratio, high dust to gas ratio

Irregular galaxies are not represented on the diagram. They don't fit well into any of the classifications.

All galaxy types come in a wide variety of sizes, from 100 million stars to more than a trillion.



The study of how galaxies change over time.

Of course galaxies evolve over long periods of time, so we can’t watch a single galaxy evolve.

We CAN see galaxies at various stages of evolution since looking out means looking back in time.

Greater distances or redshifts means that the galaxy was younger when it emitted its light.

The galaxy images above were taken from the Hubble Deep Field. Ages are based on redshift.

They only go back to about 2 billion years. We can’t see what the galaxies looked like when the universe very young.

Galaxy Formation

NGC 4414

M87

But why do some galaxies end up looking so different?

We make our assumptions, plug everything that we know about physics into the computer and turn the thing loose.

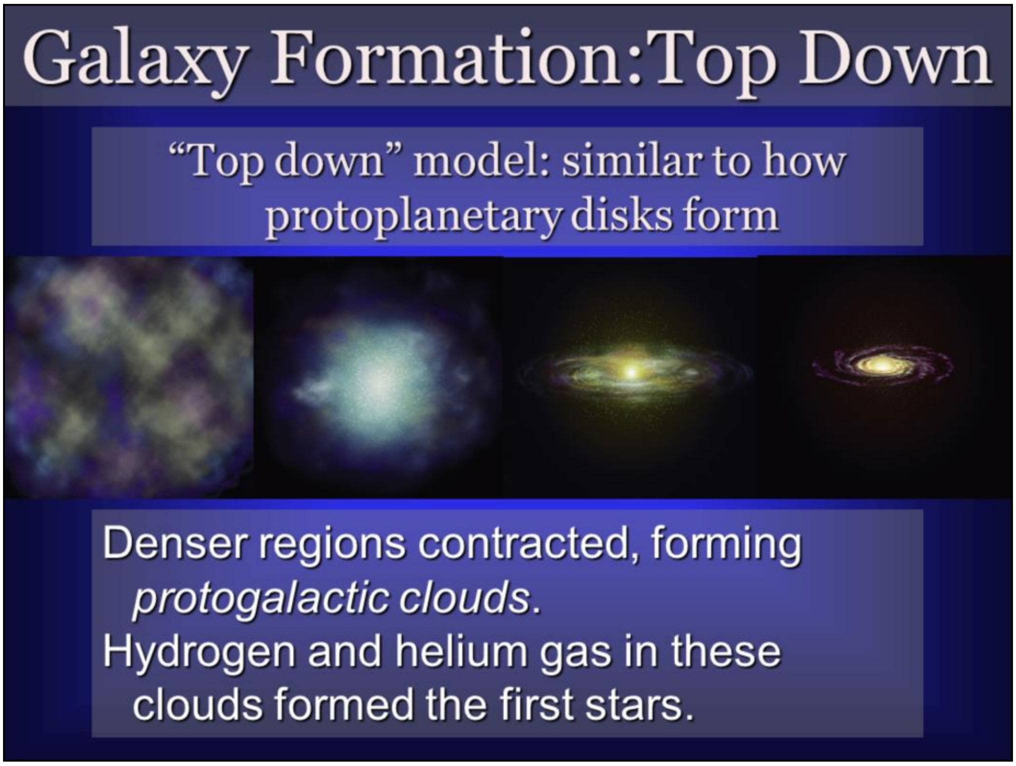
The slight over densities of the early universe eventually condensed into proto-galactic clouds.

The proto-galactic cloud contains only hydrogen and helium and a non-uniform density structure.

As the cloud collapses, halo stars begin to form.

The cloud had angular momentum, and as in the proto-planetary disk scenario, the disk of gas flattens.

Star formation is ongoing in the disk of the galaxy. The gas that used to be in the halo is now in the disk and star formation there ceases.



We make our assumptions, plug everything that we know about physics into the computer and turn the thing loose.

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The proto-galactic cloud contains only hydrogen and helium and a non-uniform density structure.

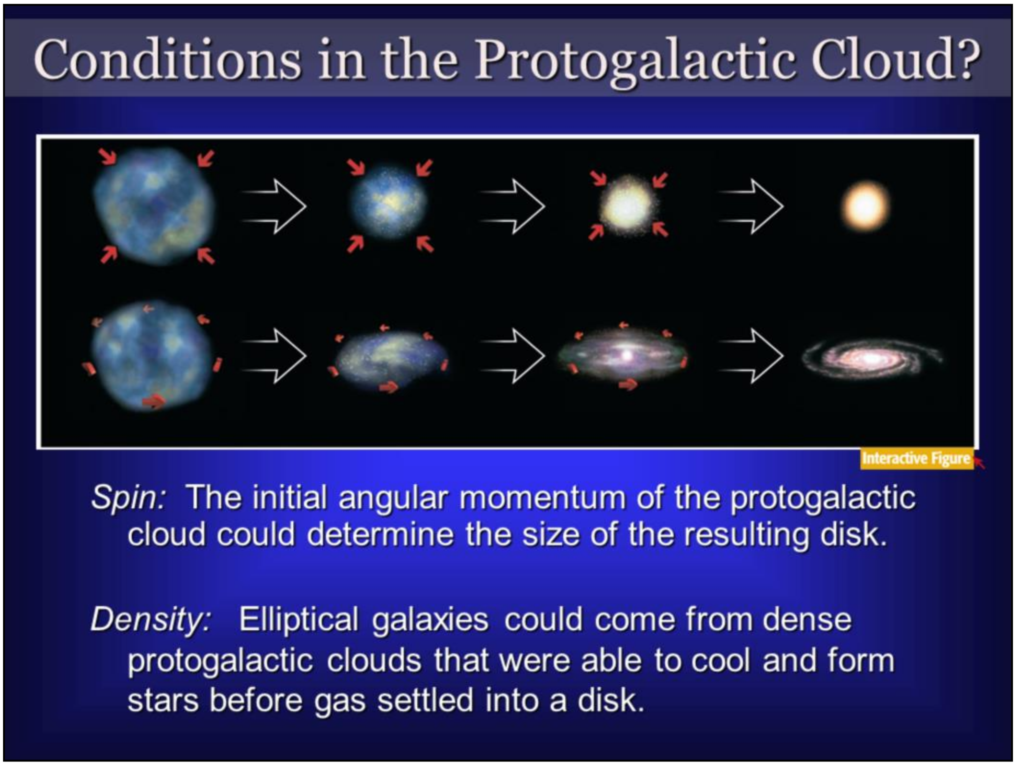
As the cloud collapses, halo stars begin to form.

The cloud had angular momentum. If it has a lot, it flattens into a disk like the proto-planetary disk scenario. Star formation is ongoing in the disk of the galaxy. The gas that used to be in the halo is now in the disk and star formation there ceases.

If it doesn't have much angular momentum, it may turn into an elliptical, forming all its stars before it collapses into a disk.

Ellipticals tend to form in tight clusters, so they most likely formed from areas of high density.

There are some giant ellipticals observed at high redshifts that have a red population of stars suggesting no ongoing star formation.



Low angular momentum versus high angular momentum cloud.

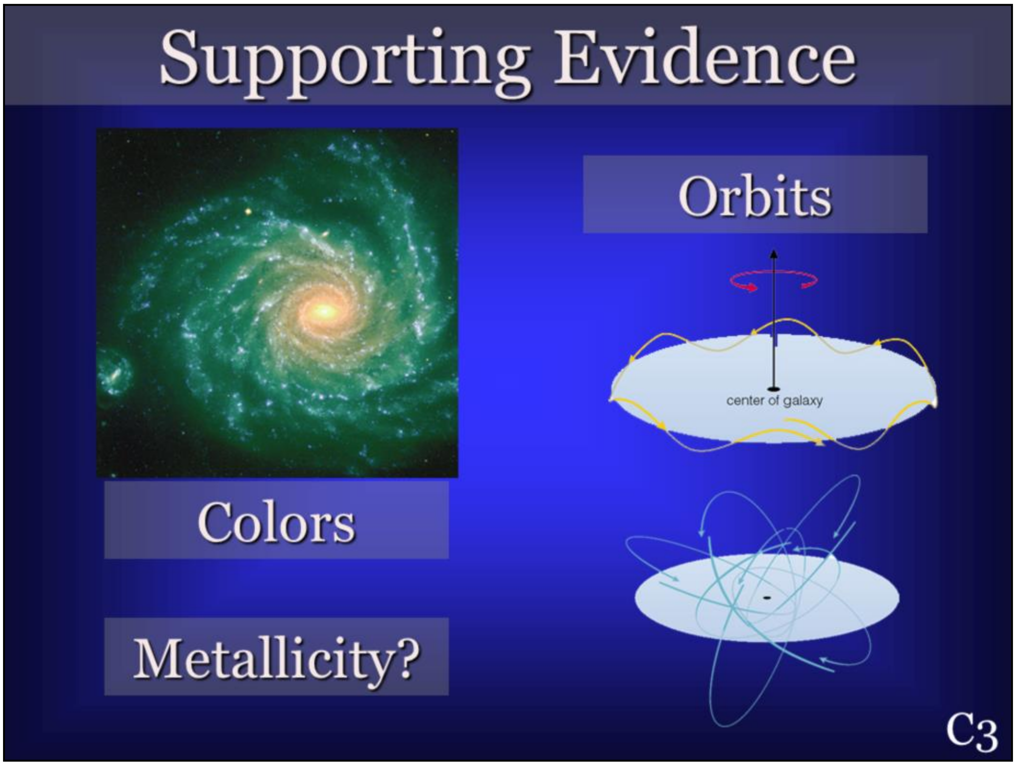
> Low angular momentum cloud turns into an elliptical
>
> High angular momentum cloud turns into a spiral.

Remember that ellipticals tend to form in tight clusters, so they most likely formed from areas of high density.

There are some giant ellipticals observed at high redshifts that have a red population of stars suggesting no ongoing star formation.

We expect high density clouds to cool more efficiently.

> Stars formed before viscosity in the gas could spin the disk out.
>
> The star formation rate was high enough that all the gas was used up.



Are our models correct?

The components of the various components of spiral galaxies provide clues.

The disks appear white with bits of blue. There must be ongoing star formation there.

The spheroidal component appears reddish suggesting an older population of stars. (remember that hot young blue stars die quickly)

It appears that the spheroidal component formed before the disk.

The orbits AND colors of milky way halo stars suggest that these stars formed before the proto-galactic cloud spun out into a disk OR were integrated into

the galaxy during mergers with other galaxies.

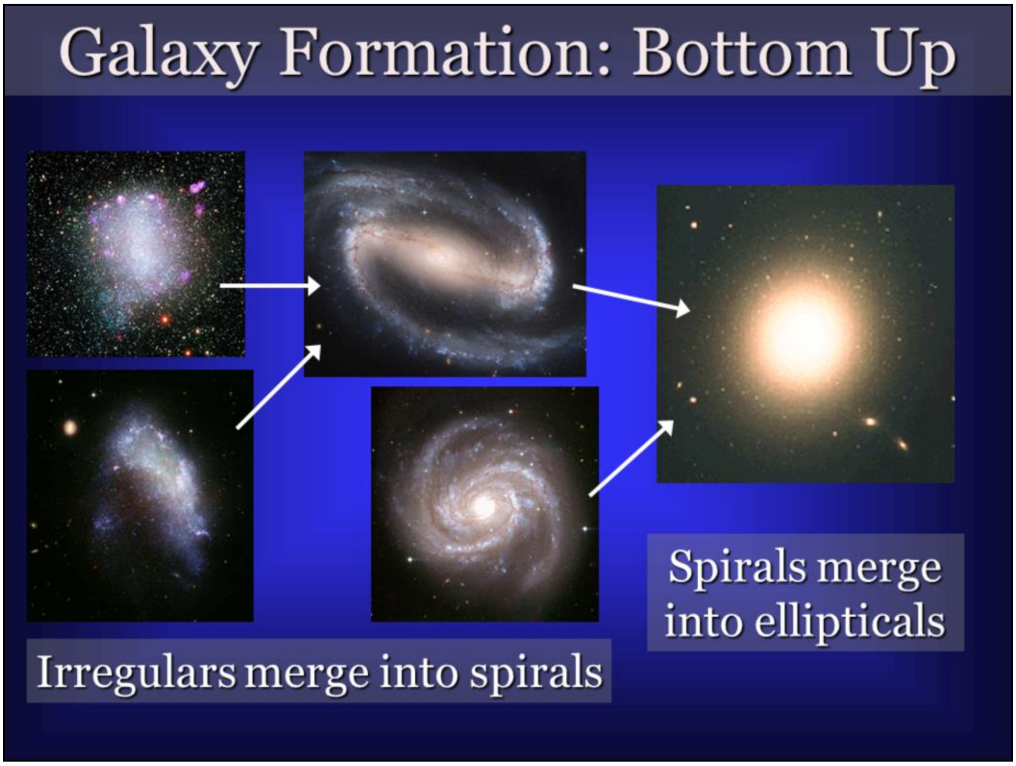
The disk stars orbit in circles around the galactic center, just like planets.

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.

Formation Scenarios

Or.....



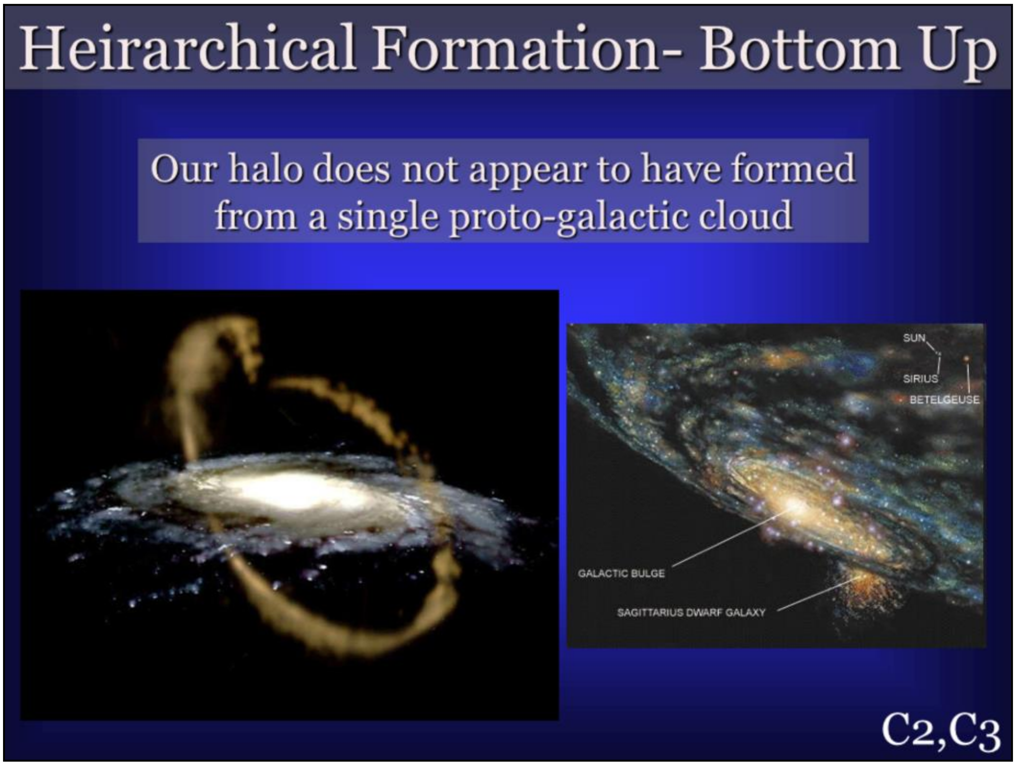
Irregulars form before the potentials get too large. Then they merge and form spirals – the stars become the halo and bulge while the gas settles down into a disk in the higher potential of the new galaxy, forming the disk. Shocks and density waves cause a new burst of star formation. If the irregulars don't have as much gas/dust they might form small ellipticals instead.

Spirals then merge to form large ellipticals. Much of the remaining gas/dust is stripped during the merging process, and you're left with a population of stars which then ages without new star formation (hot blue stars explode quickly, leaving the elliptical as a redder, old set of stars).

SHOW SIMULATIONs: https://www.youtube.com/watch?v=D-0GaBQ494E

http://apod.nasa.gov/apod/ap120717.html gas in filaments (large N-body sim) showing gas-rich mergers & Disk formation

https://www.youtube.com/watch?v=HP3x7TgvgR8 Andromeda vs. Milky Way -> elliptical



Above is an artists misconception of the Sagittarius dwarf

Halo stars are at least 12 billion years as told by the main sequence turnoff on the HR diagram.

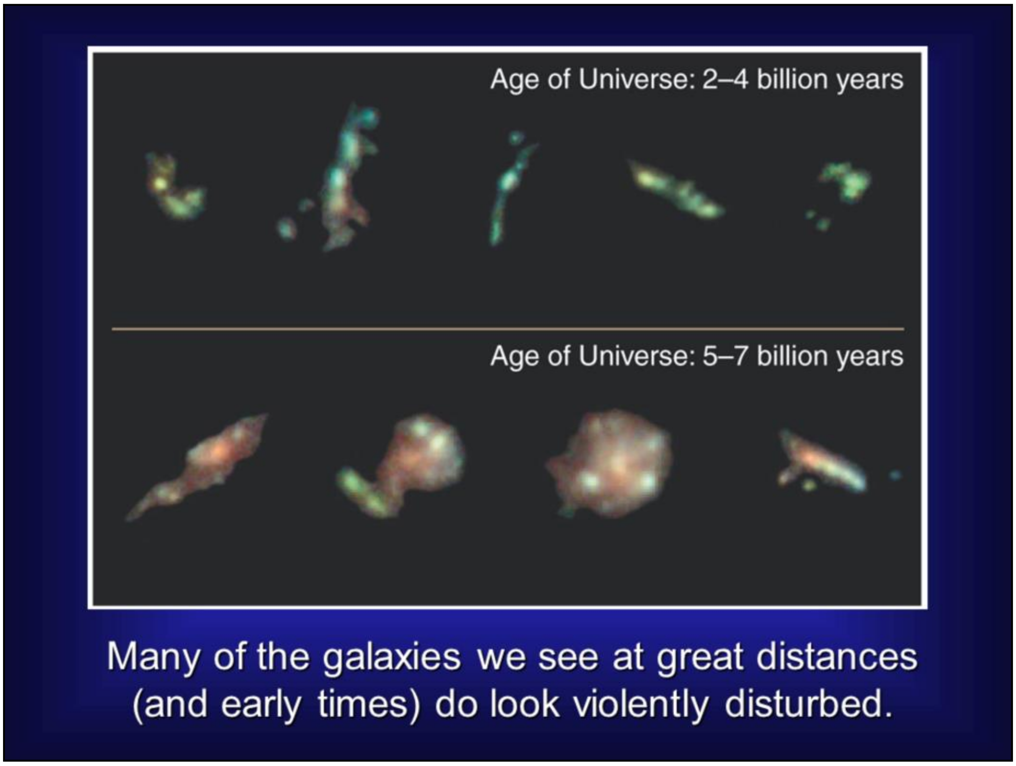
Halo stars are metal deficient compared to the Sun, so they must have formed from metal poor gas.

BUT, the halo stars do not have consistent metalicities, suggesting that they did not form from the same gas cloud.

The answer is not clear. It is likely that both the initial conditions of galaxy formation AND galaxy interactions are important.

The metal content does not simply decrease with distance from the galactic center.

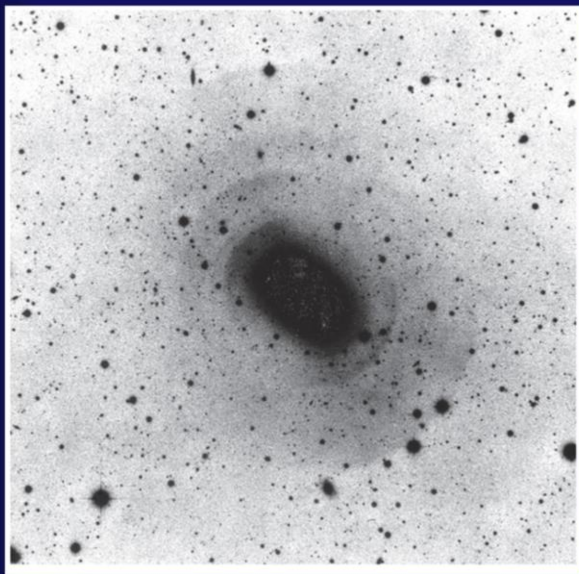
So… It appears that mergers may be the answer.


Age of Universe: 2–4 billion years
Age of Universe: 5–7 billion years
Many of the galaxies we see at great distances
(and early times) do look violently disturbed.

Stellar orbits get all bungled up and chaotic.

Star formation rate is so high that the gas gets blown out of the galaxy and becomes part of the ICM (intercluster medium).

What is left is an elliptical galaxy which has lost its gas. No new star formation means that it appears red.



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

Formation Differences

Which is correct?

The “bottom up” model?
The “top down” model?

To some extent,
probably both!!

Top-Down model

According to the top-down model, an Elliptical Galaxy would form if it had:

A) High Angular Momentum, Low Density
B) High Angular Momentum, High Density
C) Low Angular Momentum, Low Density
D) Low Angular Momentum, High Density

Top-Down model

According to the top-down model, a Spiral Galaxy would form if it had:

A) High Angular Momentum, Low Density
B) High Angular Momentum, High Density
C) Low Angular Momentum, Low Density
D) Low Angular Momentum, High Density

Bottom-Up model

According to the bottom-up model, a Spiral Galaxy would form if galaxy collisions had little gas

A) True
B) False

Bottom-Up model

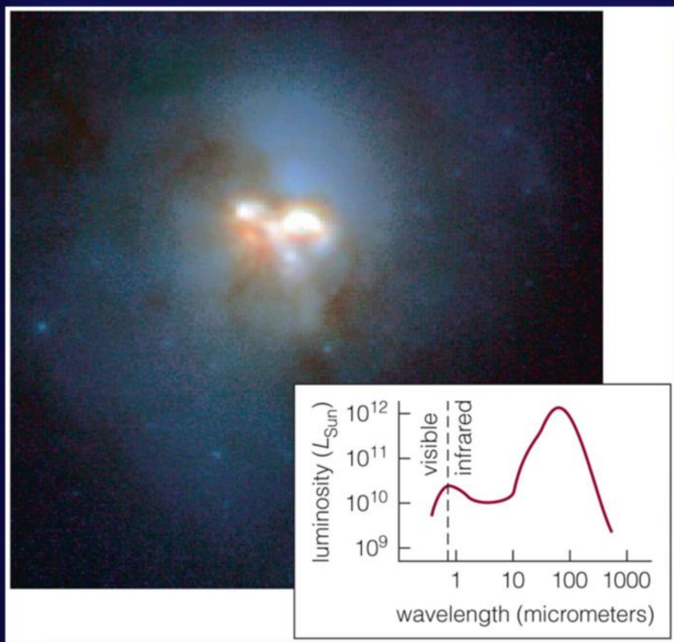
According to the bottom-up model, an Elliptical Galaxy could form if two spiral galaxies collided

A) True
B) False

Q: Where would the gas go?

Starbursts

The collisions we observe nearby trigger bursts of star formation.



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

Visible-light image

Interactive Figure

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.

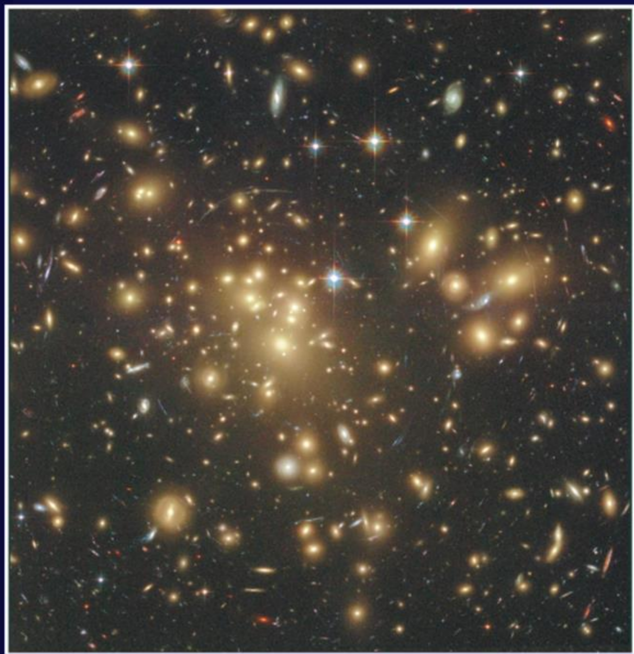
About 75% of large galaxies are spirals. They tend to hand out in loose groups of several galaxies

Our local group of galaxies contains two large spirals, the Milky Way and Andromeda as well as over 30 smaller galaxies.

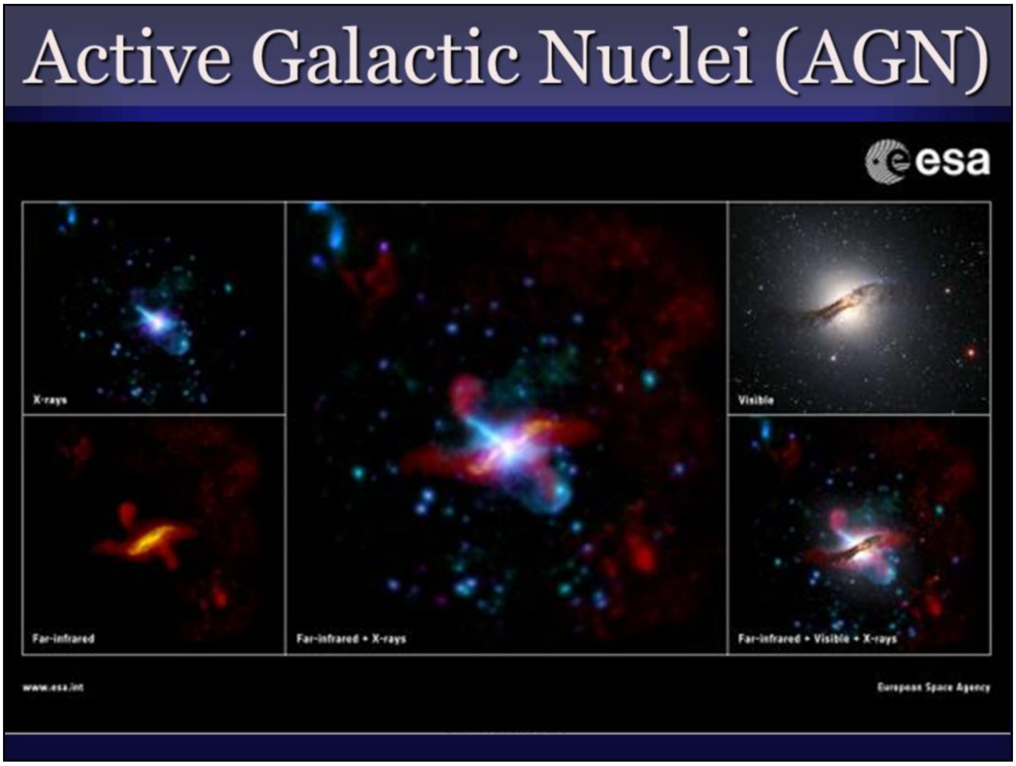
Clusters are larger than groups and tend to contain hundreds of galaxies.

Elliptical galaxies tend to hang out in large clusters.

Large elliptical galaxies are rare outside of clusters.

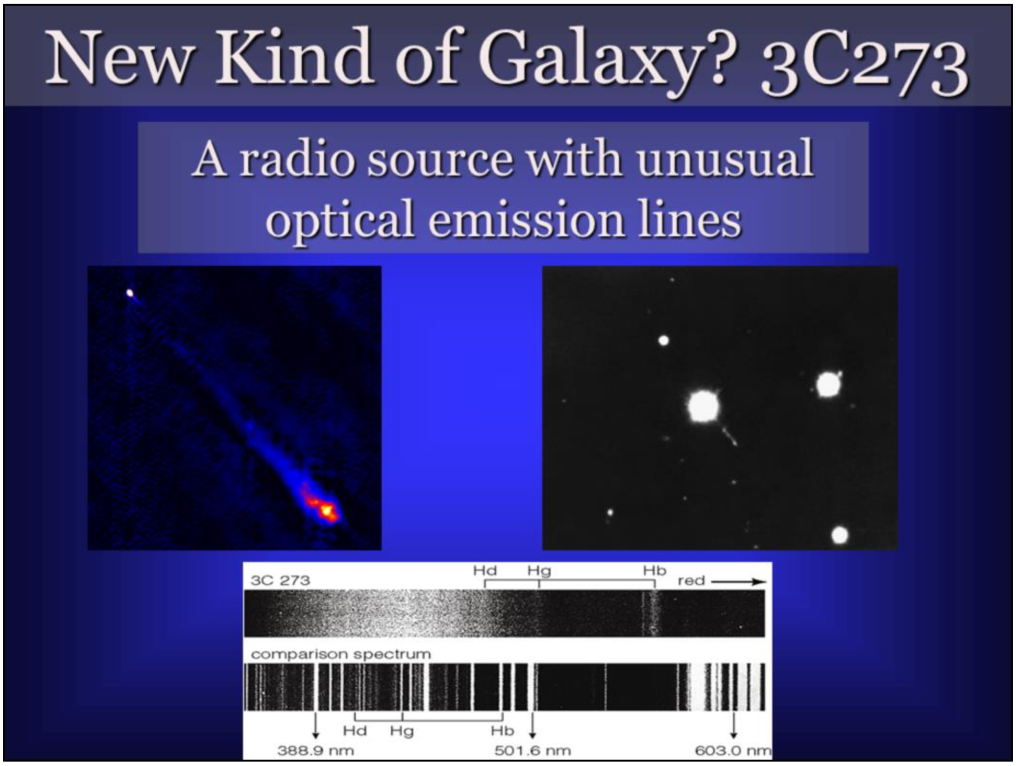


Collisions may explain why elliptical galaxies tend to be found where galaxies are closer together.



"The iconic Centaurus A galaxy, also known as NGC 5128, is the closest giant elliptical galaxy containing a radio-loud Active Galactic Nucleus (AGN). Upper left panel: New view of Centaurus A obtained with the EPIC camera on board ESA's XMM-Newton X-ray Observatory, which studied it in three different X-ray wavebands (in order of increasing energy, data from the three wavebands are shown in cyan, blue and purple, respectively).The X-ray image is available here. Lower left panel: New view of Centaurus A obtained with ESA's Herschel Space Observatory, combining data acquired with the PACS instrument at far-infrared wavelengths (shown in yellow) and with the SPIRE instrument at sub-millimetre wavelengths (shown in red), respectively. Central panel: Combined view of the Herschel and XMM-Newton images from the two panels on the left. Upper right panel: Image of Centaurus A at visible wavelengths, obtained with the MPG/ESO 2.2-metre Telescope at La Silla Observatory, Chile. Lower right panel: Combined view of the Herschel and XMM-Newton images from the two panels on the left and the visible waveband image from the upper right panel." -ESA

http://xmm2.esac.esa.int/external/xmm_mobi/gallery/agns.html

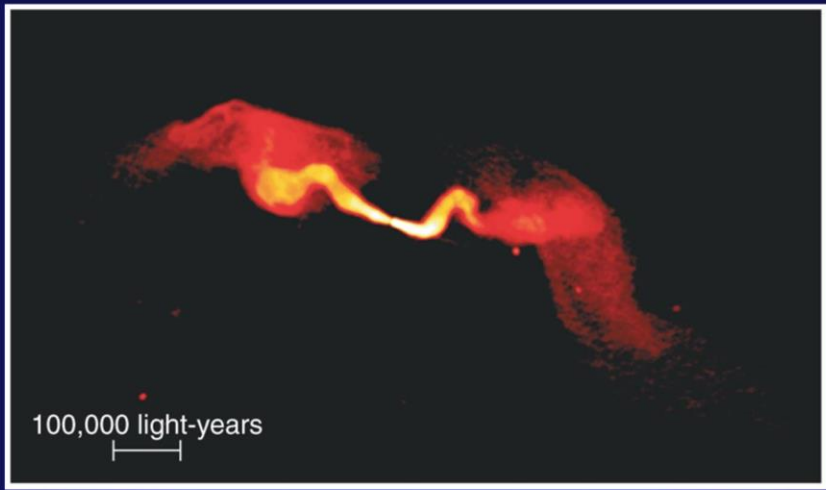


Trying to find optical counterparts of radio sources.
Most of them were galaxies.
This one was a blue star with an odd spectrum.

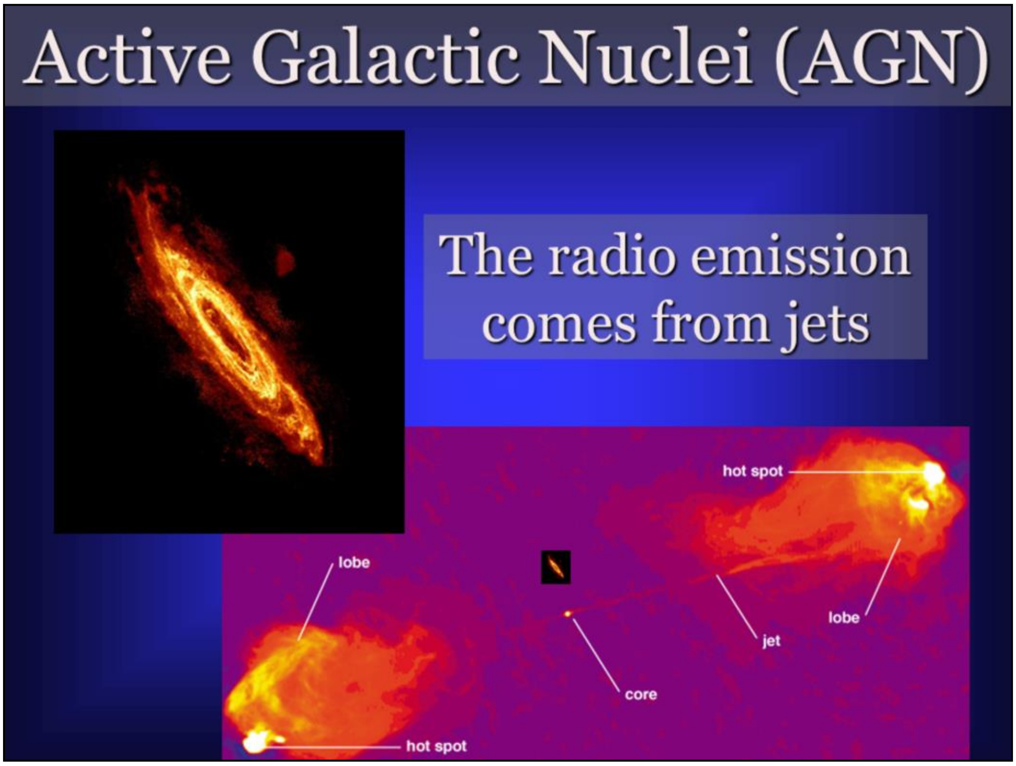
They soon figured out that the emission lines were highly red shifted hydrogen.

It was receding at 47,000 km/s!
Using Hubble's Law, that puts it at 2.2 billion light years! Wow!
That means it must have over 1 trillion solar luminosities.

Could there be another explanation for its red shift?

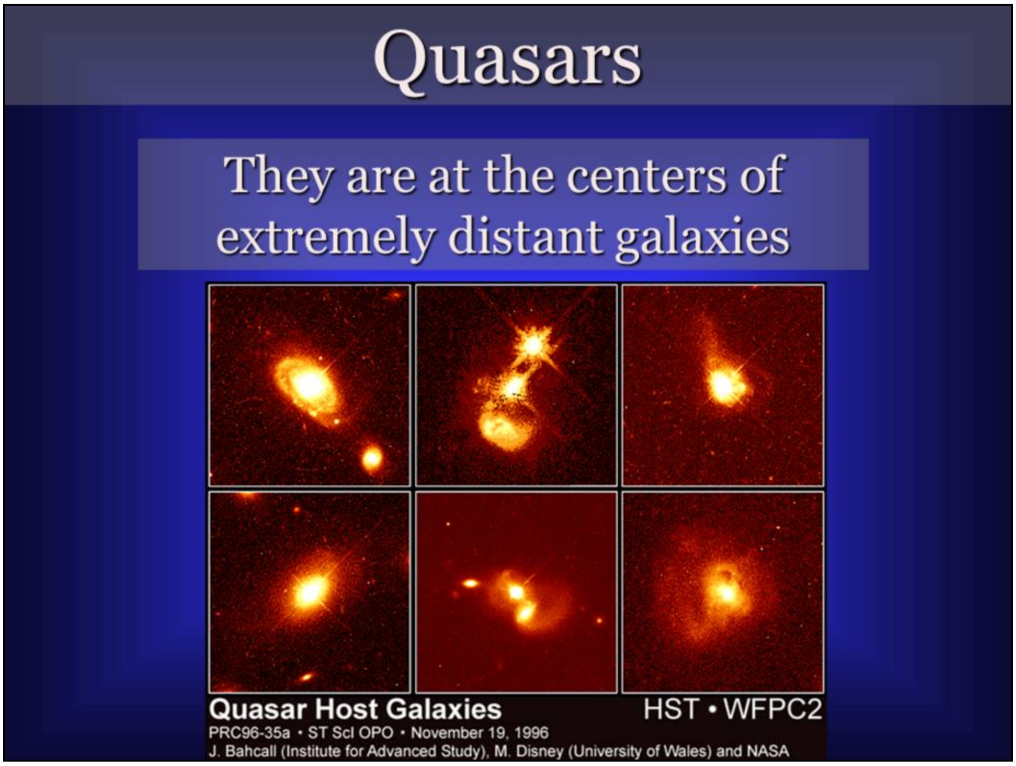


The lobes of radio galaxies can extend over hundreds of thousands of light-years.



Since their luminosities change on such small time scales, they must be very small. The size must be on the order of the variability

The radio lobes extend out to enormous distances, much larger than the disk of the galaxy.



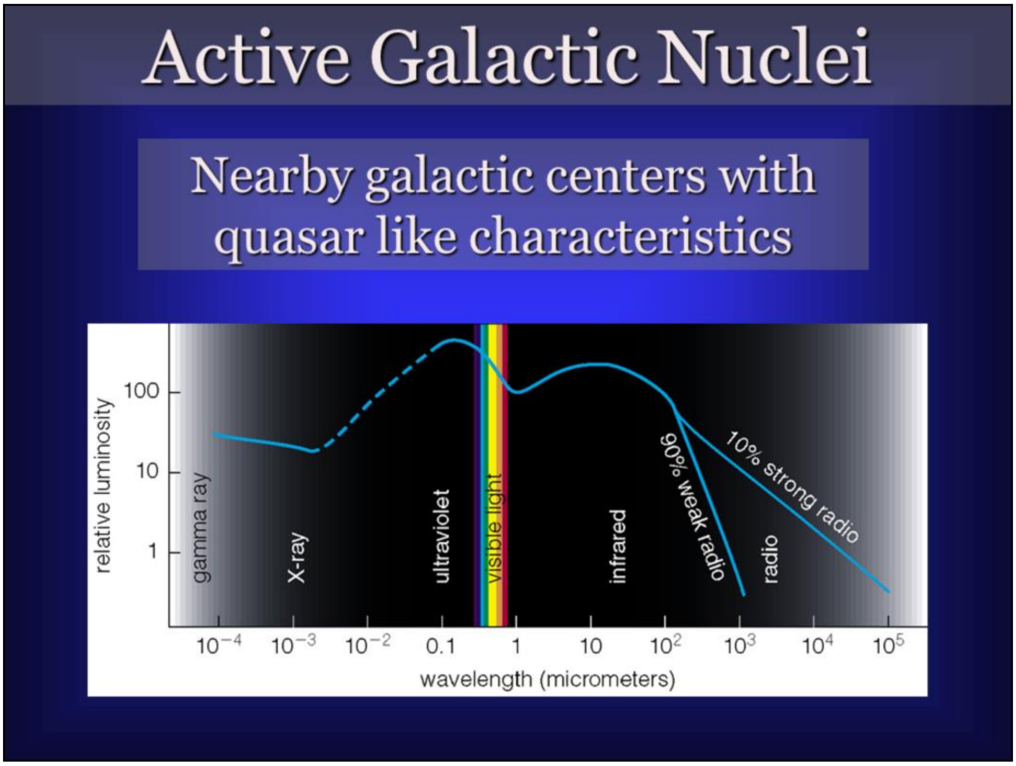
They are called quasars because they are quasi stellar objects.

Their spectrum, instead of looking like a blackbody, is flat, meaning that they have lots of power across the spectrum.

They outshine the entire galaxy. They are about 1000 times brighter than the Milky Way.

Highly variable on very short time scale (about an hour)

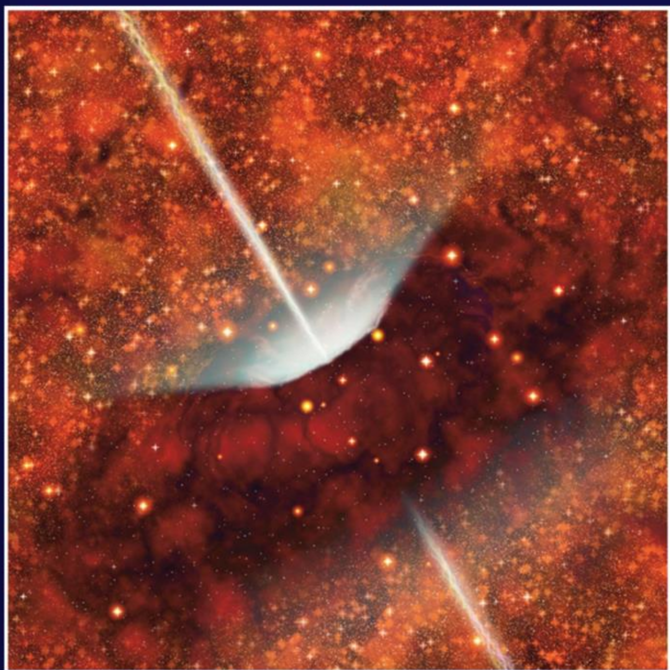
They all reside at high redshifts suggesting that they were common billions of years ago but not any more.



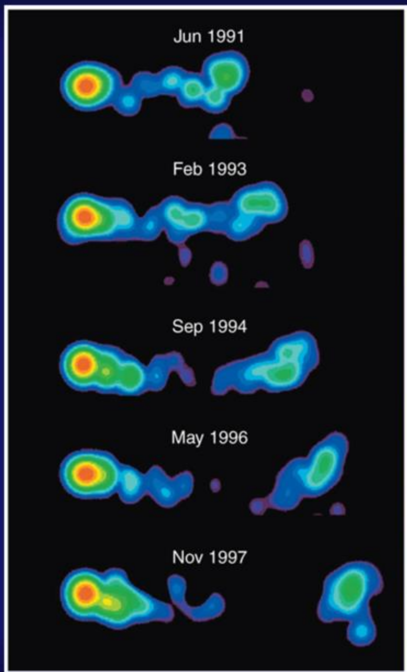
Except for their luminosities, AGN look much like quasars.

Its easier to see the host galaxy because it is closer and the central source isn't swamping the light from the entire galaxy.

The source of the emission is tiny. No telescope can resolve it.

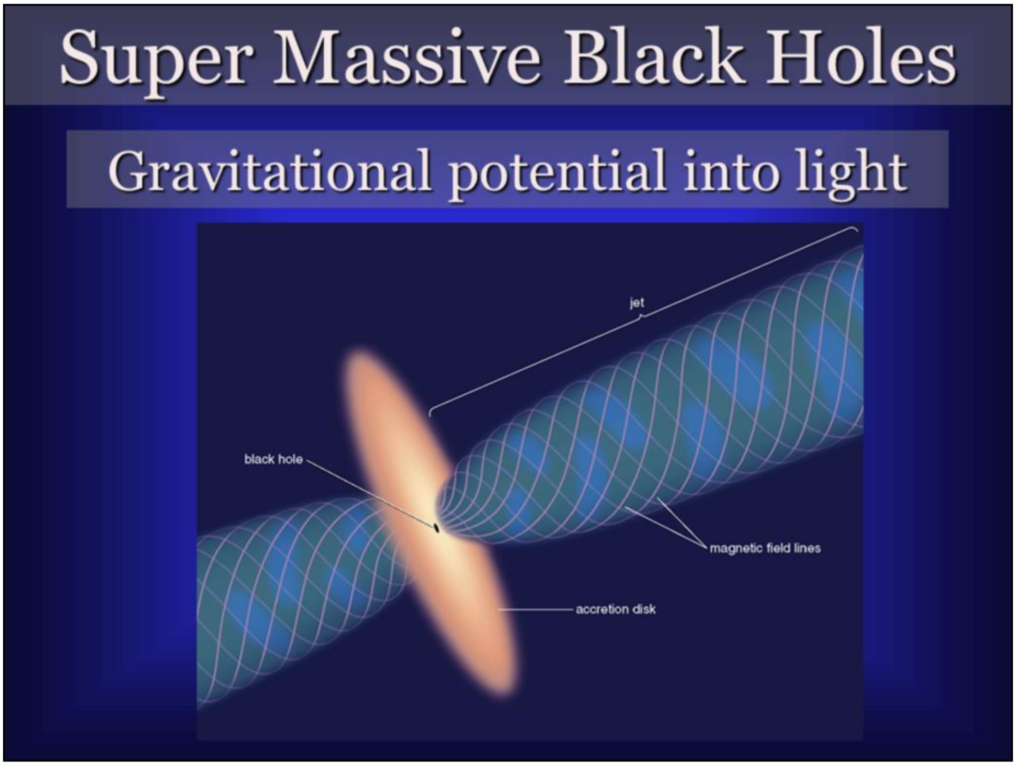


Radio galaxies don’t appear as quasars because dusty gas clouds block our view of the accretion disk.



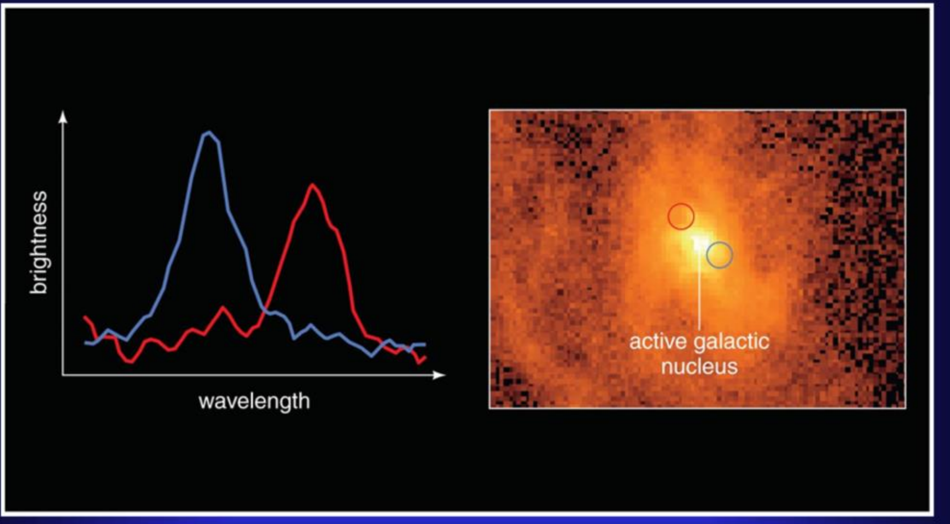
An active galactic nucleus can shoot out blobs of plasma moving at nearly the speed of light.

These ejection speeds suggests the presence of a black hole.



An accretion disk forms around the black hole.
It gets really hot and emits at a wide variety of wavelengths.
Twisty magnetic fields collimate the light.

Quasars must consume 17 solar masses per year to be as luminous as they are.



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