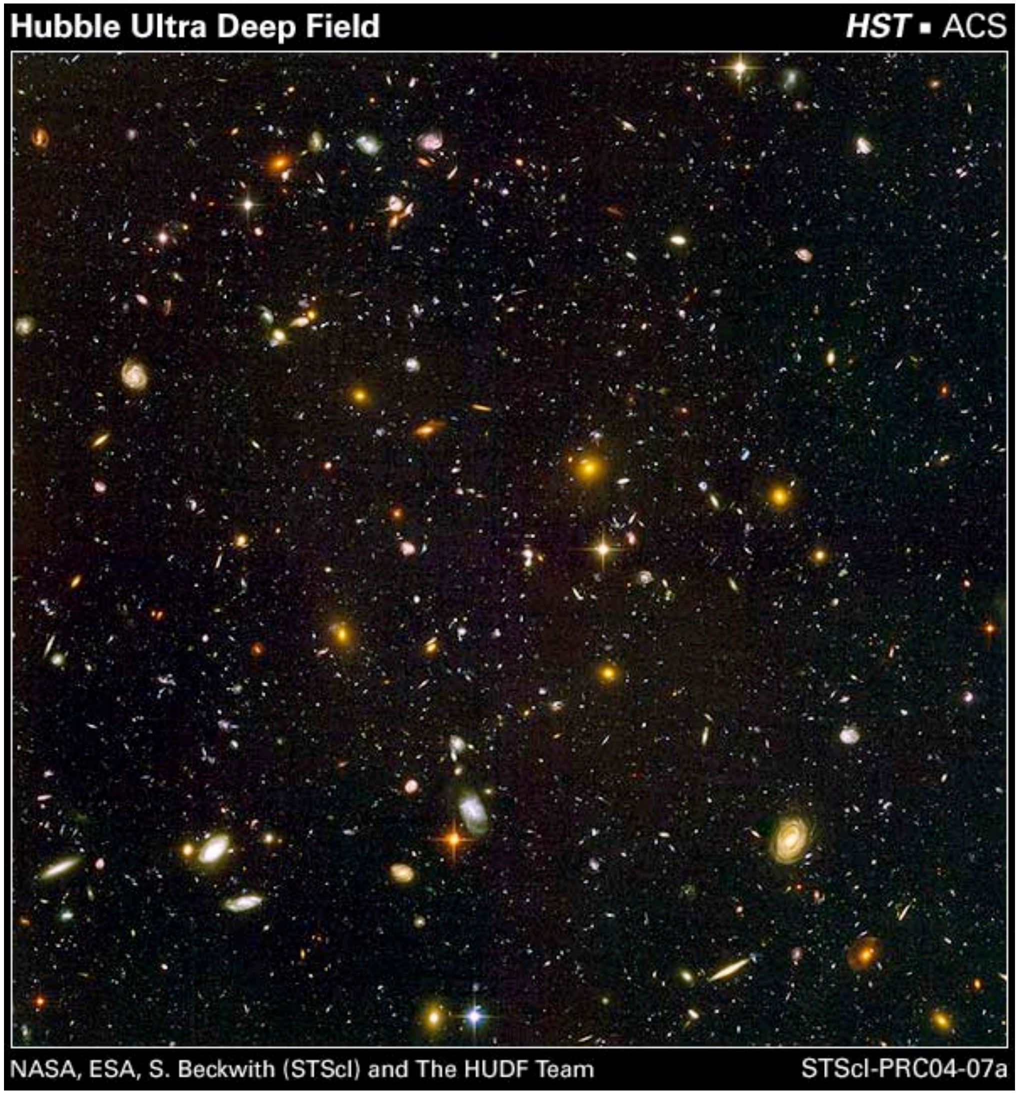
Galaxies and Active Galactic Nuclei

Most of the pinpricks of light that we can pick out with the naked eye are stars in our own galaxy. However, there are several galaxies that we can easily spot, such as the Magellanic Clouds (only visible from the southern hemisphere) and Andromeda (M31). So you might think that stars far outnumber galaxies....



The Hubble Ultra Deep Field (HUDF) is the deepest optical image ever obtained and contains over 10000 galaxies in an area whose diameter is only 1/10 of the full moon's extent. If we extrapolate this over the entire sky, that would be 1000 billion galaxies!

A Little Bit of History....

In the late 19th century Lord Rosse built the largest telescope of the day at his castle in Ireland. With its unparalleled light gathering power the “leviathon of Parsonstown” was used to show that the faint smudges of light catalogued by Charles Messier contained internal structure. These were the first observations of other galaxies. Lord Rosse called his galaxies “island universes” and concluded that they were distant nebulae full of stars

However, not everyone subscribed to this view. In 1920, the famous Shapley-Curtis debate took place with Harlow Shapley arguing that the spiral nebulae were contained in our own galaxy and Heber Curtis siding with Rosse.

The debate was settled by observations of Edwin Hubble with a new, bigger telescope (100 inches, compared with Rosse's 72) where he observed Cepheid variables and inferred very large distances for the spiral structures. This supported the view that these were indeed island universes exterior to the Milky Way. This was the first evidence that proved that there is a larger universe outside our own galaxy.

Galaxy Classification

Galaxies come in a variety of shapes, sizes and colours, so it is useful to adopt a classification scheme which allows us to group certain types of galaxies together according to “type”. Categories that we will use to classify galaxies include:

1) Shape (or morphology). We can define 3 main types of morphologies: spirals (with and without bars), ellipticals and irregulars. Different morphological types have different stellar populations, dust and gas fractions and ages. Morphology is the main way of classifying galaxies.

2) Colour. The colour of a galaxy is dominated by the colours of the stars that it contains. Therefore, an old galaxy which contains mostly red giant stars will look redder than a young galaxy that has a large population of hot, blue stars. Colour is closely linked to morphology.

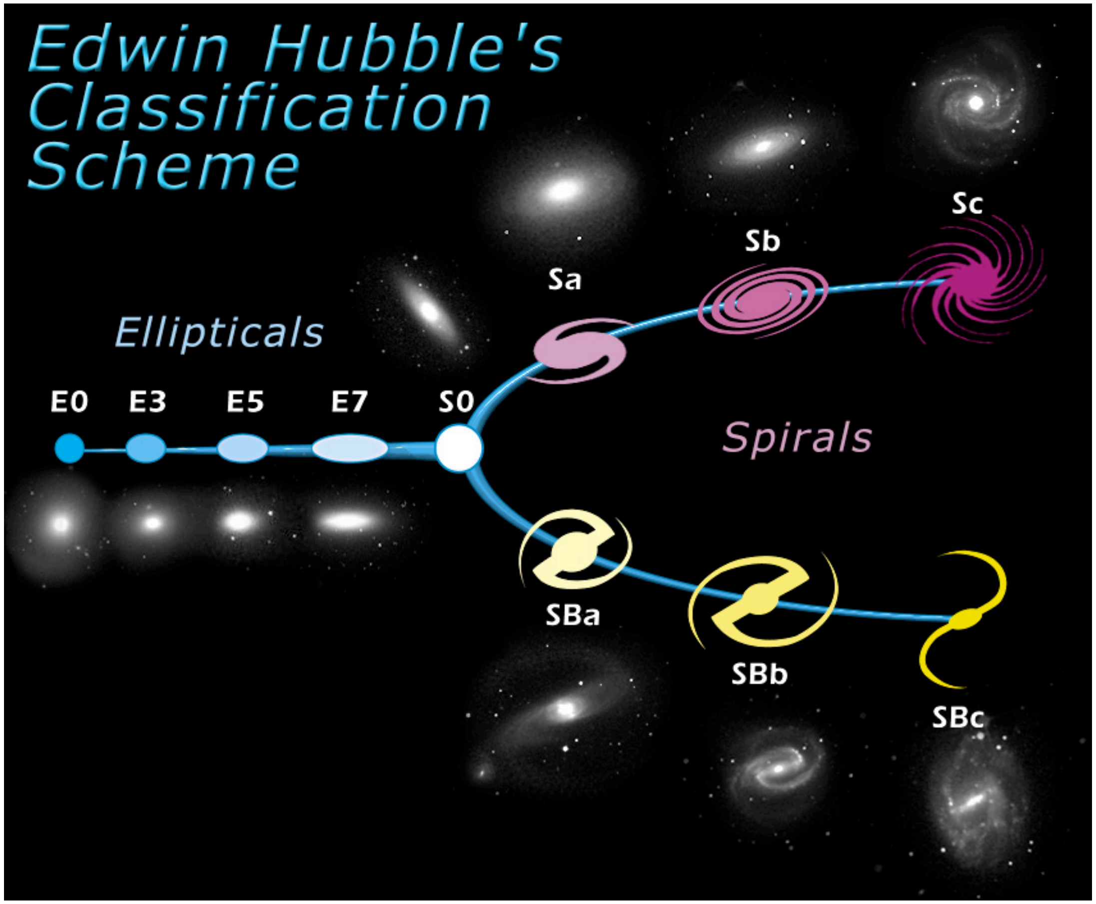
3) Size (i.e. diameter). We can measure the angular size of galaxies in arcseconds and use the small angle formula to convert this to a real diameter if we know the distance of the galaxy. Distances are most reliably determined using variable stars. A given morphological type can have a range of sizes.

4) Luminosity. Again, a galaxy's luminosity is dominated by its constituent stars. In order to convert the observed luminosity into a real luminosity, we again need to know the distance.A given morphological type can have a range of luminosities

5) Mass. This is usually measured using the technique of rotation curves that we met in the lectures on the Milky Way.

Galaxy Morphology

The Godfather of galaxy morphologies is Edwin Hubble: in the 1920s Hubble used the 100 inch telescope on Mt Wilson to take numerous photographic plates of galaxies and painstakingly classified them using a system still widely adopted today.



At one time, it was thought that the Hubble Tuning Fork diagram represented an evolutionary sequence. Although it is true that spiral galaxies tend to be bluer (and we therefore infer that they are younger) than elliptical galaxies, a single galaxy does not simply travel along the Hubble sequence as it ages.

Spiral Galaxies

About 70% of galaxies in catalogs are spirals. This does not necessarily mean that they are the most common type, because spirals contain large numbers of young, hot, bright stars. Spirals also contain a large amount of gas: this is the raw ingredient which leads to the large number of young stars.

Sa NGC 1357

Sb M81

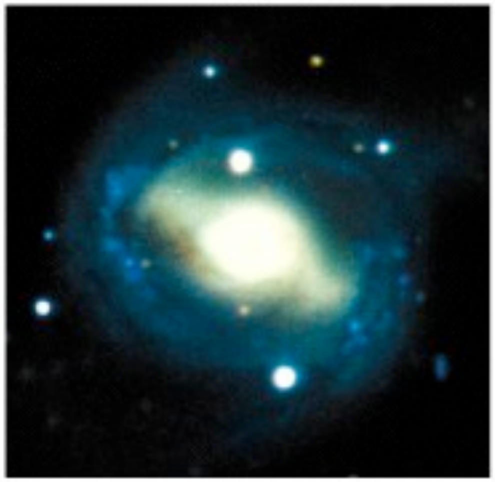
Sc NGC 4321

Spirals are classified into 3 types: Sa, Sb and Sc. These categories range from those that are dominated by a large nuclear bulge (Sa) with less gas and fewer young stars, to Sc galaxies which have smaller bulges and many hot bright stars.

Presumably, most spirals also have a halo component, just like the Milky Way. However, the stars in the halo are old, red and faint, and therefore much harder to see. In fact, we never directly observe the halo stars in external spiral galaxies.

Spiral Galaxies With Bars

About 1/3 of spiral galaxies have bars. The bar stretches across its nucleus (which is elongated) and the spiral arms start from the ends of the bar. Although stars rotate differentially in the disk, the bar rotates as a solid body. They play an important role in channelling gas towards the centre of the galaxy.



SBa NGC 4650

SBb M83

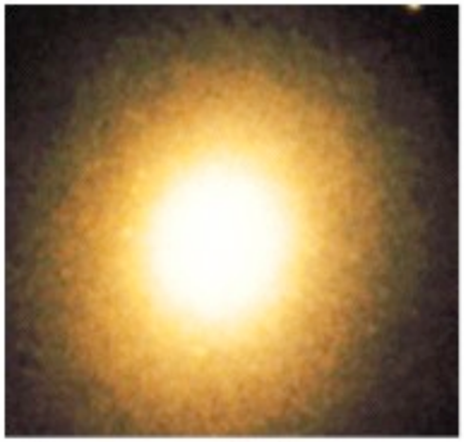
SBc NGC 1365

Barred spirals are classified into 3 types: SBa, SBb and SBc. The three categories go in order of increasing order of spiral arm openness. In order to be able to easily see a bar, the galaxy needs to be at least slightly face-on. Our own galaxy is a barred spiral.

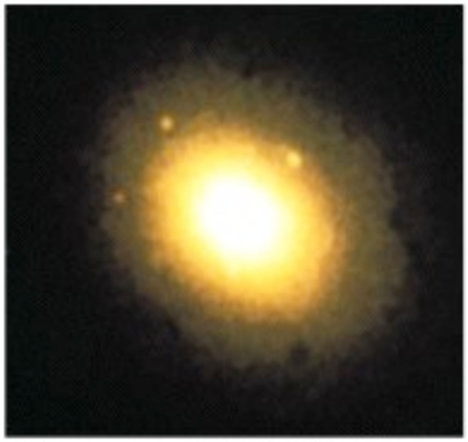
Spirals in a nutshell: Very common, bright, contain young stars, lots of gas and dust They have a disk and bulge component, spiral arms and may have a bar.

Elliptical Galaxies

As their name implies, this class of galaxy is round or elliptical. Their exact shape is quantified by measuring how round the galaxy is and putting it on a scale from 0 to 7. E0 galaxies are almost exactly round, whereas E7 galaxies are very elongated. Ellipticals, although fainter, are actually more common than spirals.



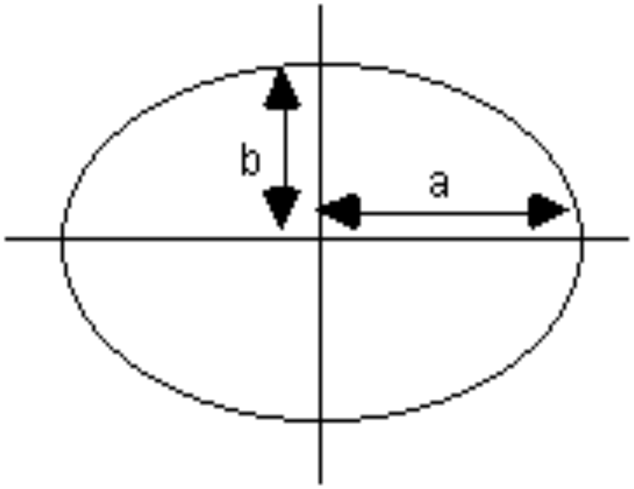
E0 M105



E3 NGC 4365

E6 NGC 3377

The E number is calculated by: $10 x(a-b)/ a$



We call 'a' the semi-major axis and 'b' the semi-minor axis.

Elliptical Galaxies

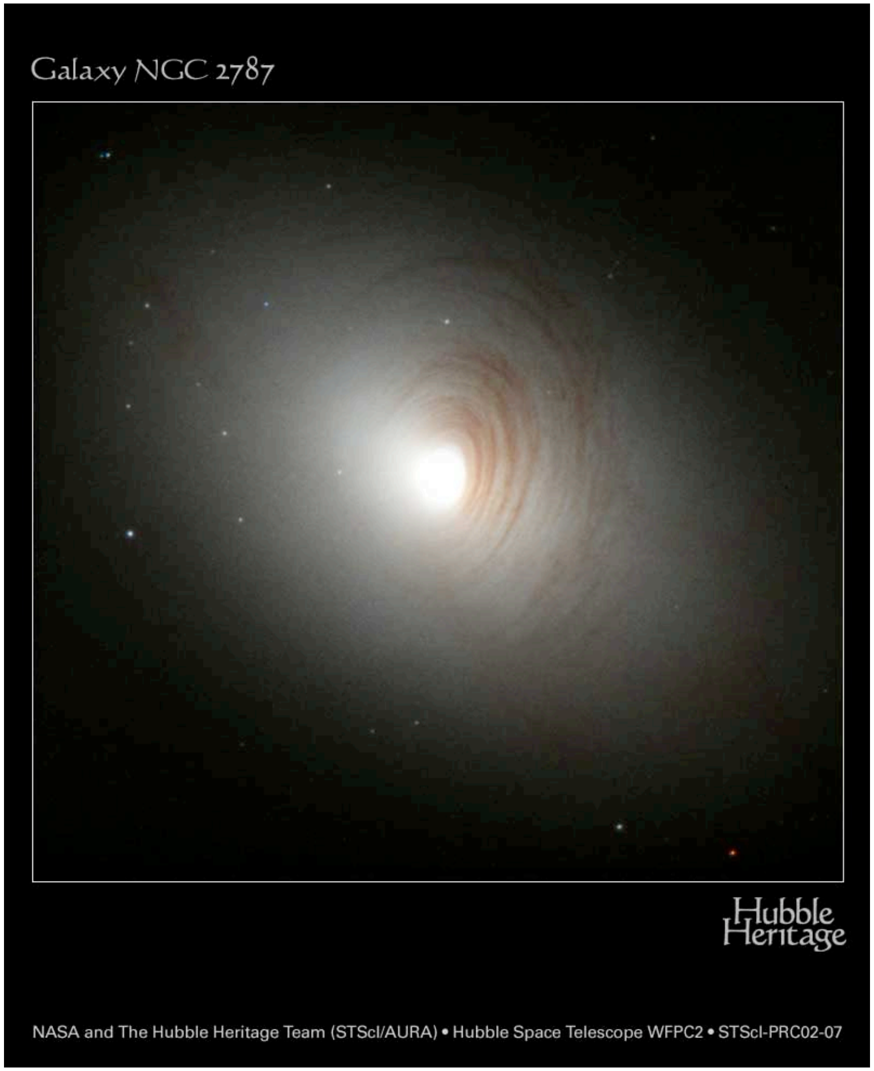
In contrast to spirals, ellipticals contain only older stars, so they look much redder than spirals. Ellipticals contain almost no gas and dust, so they can not form new generations of stars – their current stellar populations are evolving “passively” and are not being added to with new generations.

Ellipticals have none of the interesting structure of spirals: there is no disk, no halo, no spiral arms and no dust lanes. In fact, you can think of them as just one big nuclear bulge.

Ellipticals in a nutshell: old, red galaxies, not forming stars, no dust or gas, no disk, just spheroidal.

Lenticular Galaxies

Lenticular means lens-like (e.g. lente in spanish and lentille in french). Lenticular galaxies have disks and bulges, which give them their lens-like shape, but they have very little of the structure that spirals possess and are quite featureless

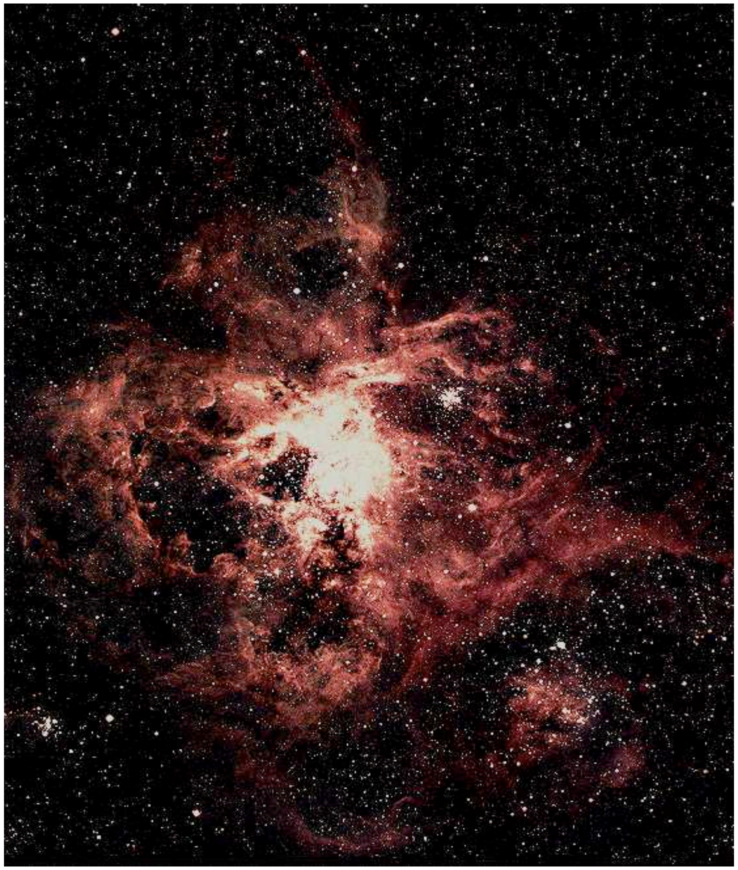


Lenticular galaxies have the classification "S0". This class of galaxies is little studied, but with new observations, e.g. with the Hubble space telescope we are discovering that they do have faint structures. This image of NGC 2787 shows very faint dust rings around a classic S0 galaxy.

Irregular Galaxies

Irregular (Irr) galaxies have no obvious shape and tend to be an amorphous, chaotic mix of gas, dust and stars. There are no spiral arms, no disk and no bulge. Irregulars tend to be quite faint. Irr galaxies make up about 25% of the total galaxy population.

Our 2 closest galactic neighbours, the Large and Small Magellanic Clouds (LMC and SMC) are irregulars. Star formation is quite active in these galaxies and they possess large reservoirs of gas that can feed stars for many generations. Evidence of this on-going star formation comes from the presence of hot, blue stars and emission nebulae such as the Tarantula:



Measuring the Distances to Galaxies

Before we consider the diameters and luminosities of galaxies, we must have at our disposal a technique for measuring their distances. So far, we have used AU/light minutes/hours for measuring the distances within the solar system, parsecs/light years for distances to nearby stars and kiloparsecs (1000 pc=1 kpc) for the most distant parts of the Galaxy.

Other galaxies are further away still, so we use megaparsecs. 1 Mpc = 1 million parsecs = 3.26 million light years = 3.1 x 10^{22} m. How many kilometres is that? How many cm?

There are several techniques that can be used as distance indicators to other galaxies. Often these methods rely on standard candles: objects whose absolute luminosity/magnitude we know very well, e.g:

Cepheid variables with well understood period luminosity relations are excellent distance indicators in nearby galaxies (closer than 25 Mpc (80 million ly)). Beyond this, they become too faint.

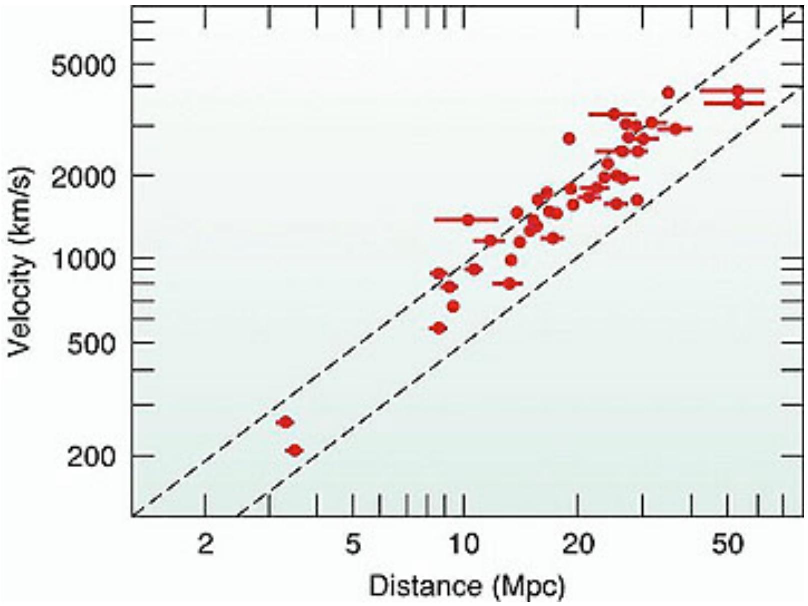
Type Ia supernovae (those that form via the collapse of a WD in a binary system) obtain well defined maximum luminosities. This technique is applicable for even distant galaxies because the SN is very bright.

Although these standard candles can provide quite accurate distances, they are unsatisfactory because we don't always have access to Cepheids and SN in all our observations. For example, what if we want to measure the distance to a far off galaxy but we've never observed a SN there?

The Hubble Law

In 1913, Slipher made the astonishing discovery that some of the faint “island universes” he was studying had measurable Doppler shifts. That is, that the spectra of these nebulous galaxies had their features redshifted, and the fainter the galaxy, the larger the redshift.

Edwin Hubble, 15 years later, measured many more of these Doppler shifts (or redshifts) and concluded that this was clear evidence that all other galaxies were receding from us. Moreover, the size of the redshift (or recession velocity) was directly proportional to its distance.

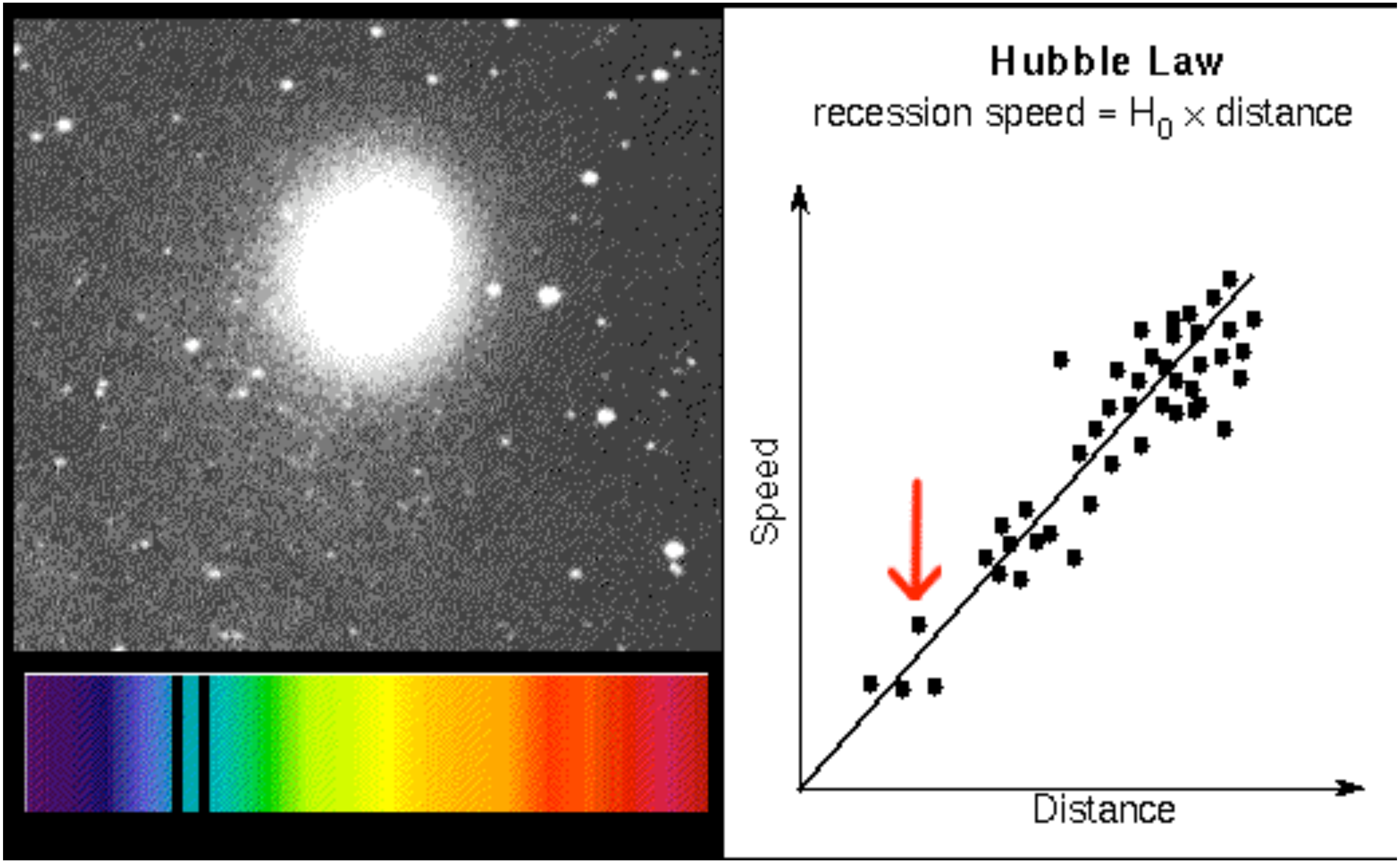


This simple relation between distance (D) and recessional velocity (V) can be written:

$$\mathbf{V = H \times D}$$

Where H is a constant that describes the gradient of the slope, and is called the Hubble constant (km/s/Mpc). Determining precisely the value of H is one of astronomy's holy grails.

This is one of the most important relations in astronomy, since it gives astronomers a simple way of measuring the distance to any celestial object.


Hubble Law
recession speed = H0 × distance
Speed
Distance

The Hubble Constant

The value of H was originally determined by Hubble to be around 200 km/s/Mpc, i.e. you added an extra 200 km/s to its recessional velocity for every Mpc in distance. However, these values came down considerably once more and better data were obtained. Nonetheless, there has been a long-standing controversy over the value of H, particularly between groups led by Allan Sandage (Hubble's student) and Gerard DeVaucouleurs. This discussion was known as “The Great Debate”.

Sandage, using Cepheid variables to calibrate his data, argued that H~100 km/s/Mpc, whereas DeVaucouleurs argued for a much smaller H~50 km/s/Mpc. Th most recent results from the Hubble Space Telescope have shown H=72 km/s/Mpc.

Example:
If a galaxy has its H alpha line shifted from 656 nm to 664 nm, what is the distance of the galaxy in Mpc (assume H=70 km/s/Mpc)?

First we have to convert the Doppler shift into a velocity. Recall that:

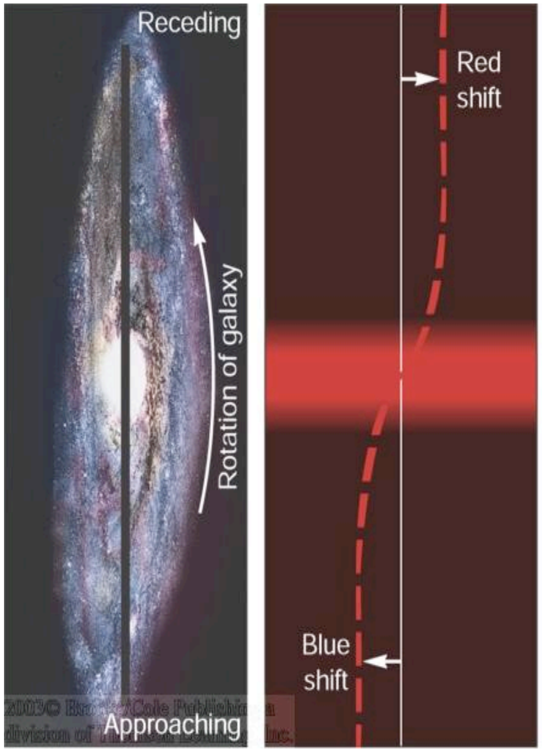
$$\frac{\text{change in wavelength}}{\text{original wavelength}} = \frac{\text{velocity}}{\text{speed of light}}$$

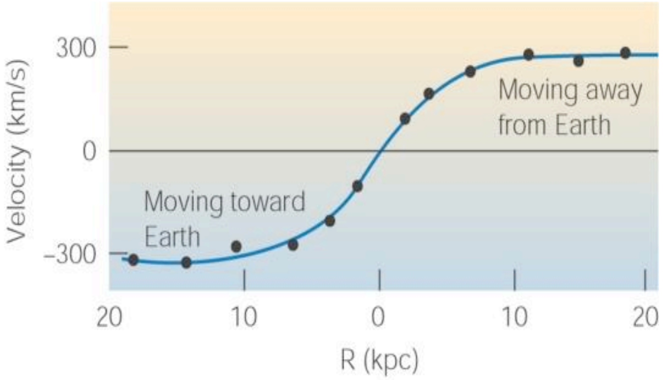
So here velocity = (664-656/656) x 300000 = 3658 km/s

Now we can use Hubble's law to find the distance from V=HD :
=> D=V/H = 3658 / 70 = 52 Mpc

How to Weigh a Galaxy

If a galaxy is rotating, we can study the speed at which it rotates. We saw in the lecture on the Milky Way that Kepler’s laws allow us to convert the rotation velocity into the mass inside the orbit.





If a galaxy is rotating, then one edge will be blueshifted as it moves towards us and the other edge will be redshifted as it rotates away from us (note that this is independent of the *galaxy's redshift*). This allows us to determine the velocity and plot a rotation curve, just like we saw for the Milky Way.

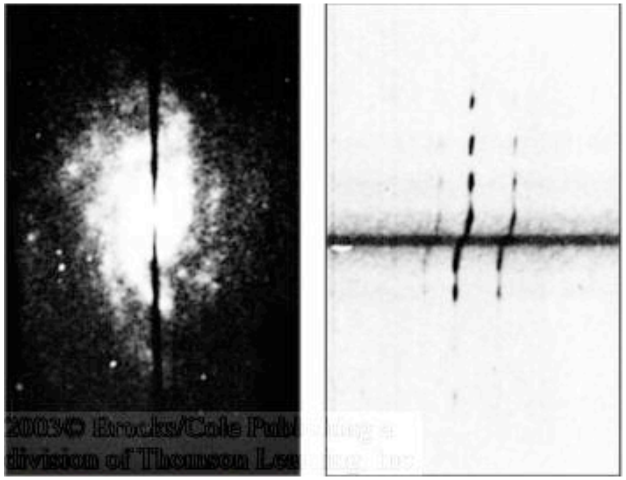
The exact rotation curve of a galaxy depends on how its mass is distributed, because the rotation velocity only feels the effect of mass inside its orbit.

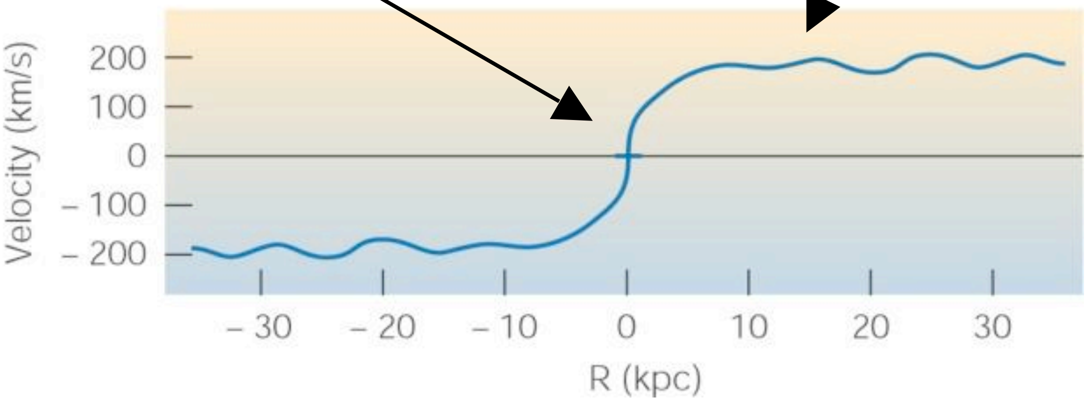
A Closer Look at Rotation Curves

$$V^2 = GM/R$$

In the inner parts of a galaxy, the rotation curve increases steeply with radius because the mass builds up quickly (more quickly than the radius increase).

The velocity flattens off when the mass distribution settles down: for most of the galaxy, the mass increases smoothly with radius, i.e. M/R is constant, and therefore so is the velocity

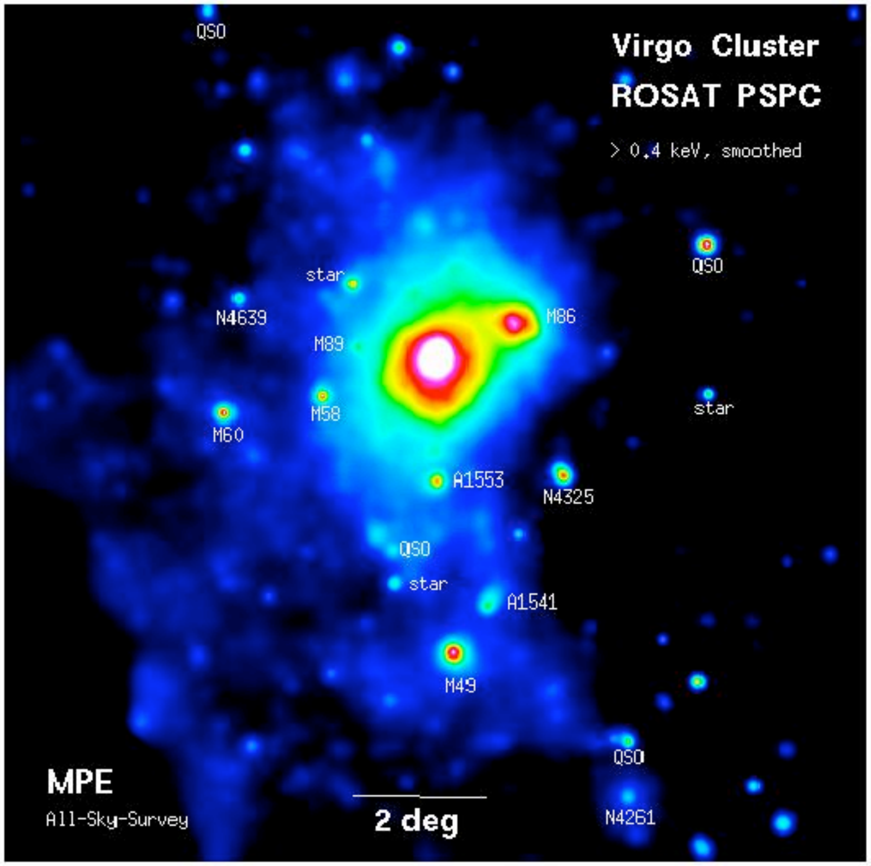

2003© Brooks/Cole Publishing a division of Thomson Learning, Inc.



Once we reach the “edge” of the galaxy, the velocity will start to decrease. This is because we keep increasing the radius, but the mass is no longer increasing. In practice, we rarely observe this turnover. Astronomers take this as evidence that there is a large amount of unseen dark matter lurking in the outskirts of most galaxies

Dark Matter

The shape of galaxy's rotation curves is just one piece of evidence that the luminous matter that we can directly detect in stars and galaxies is only a small fraction of the total mass, and that a large amount of mysterious dark matter is present in the universe.

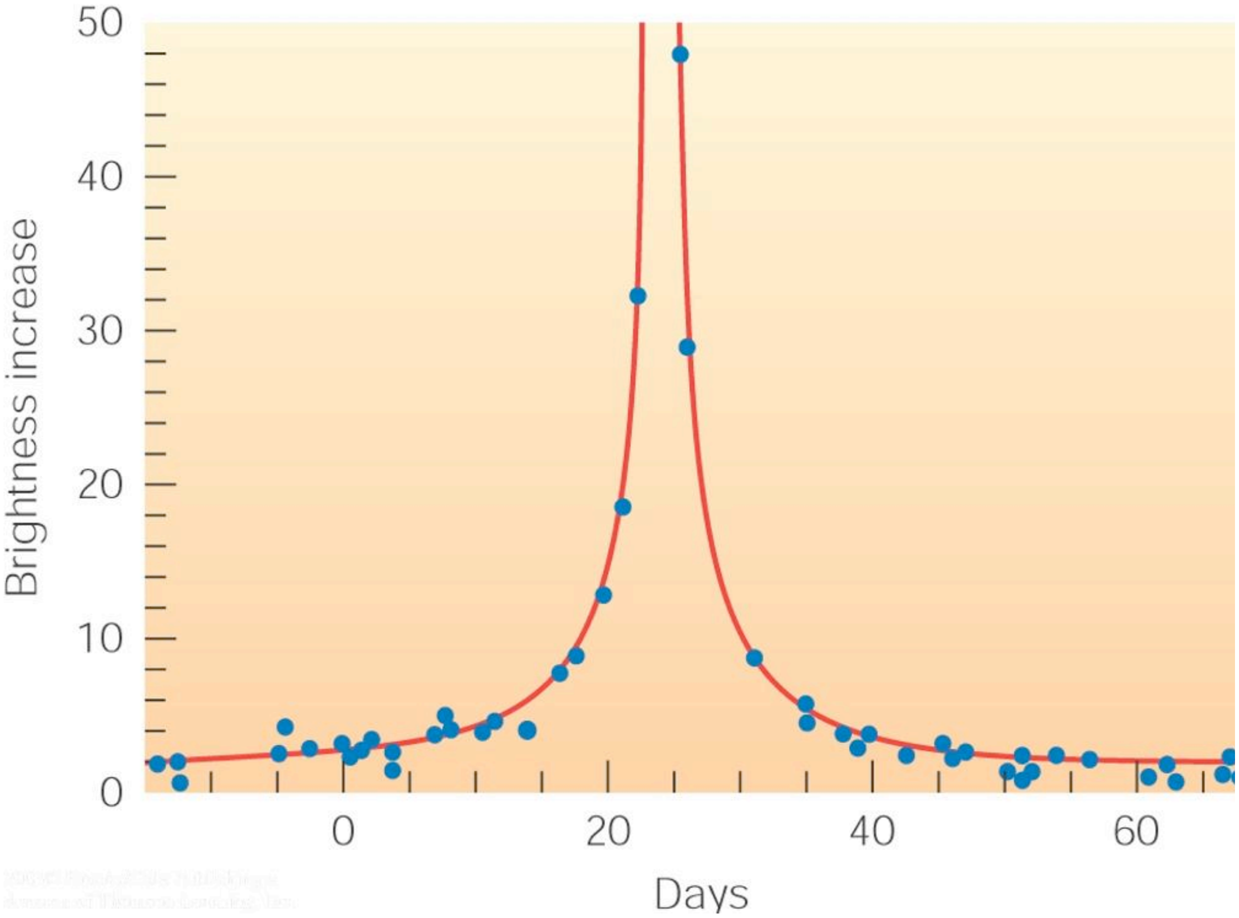


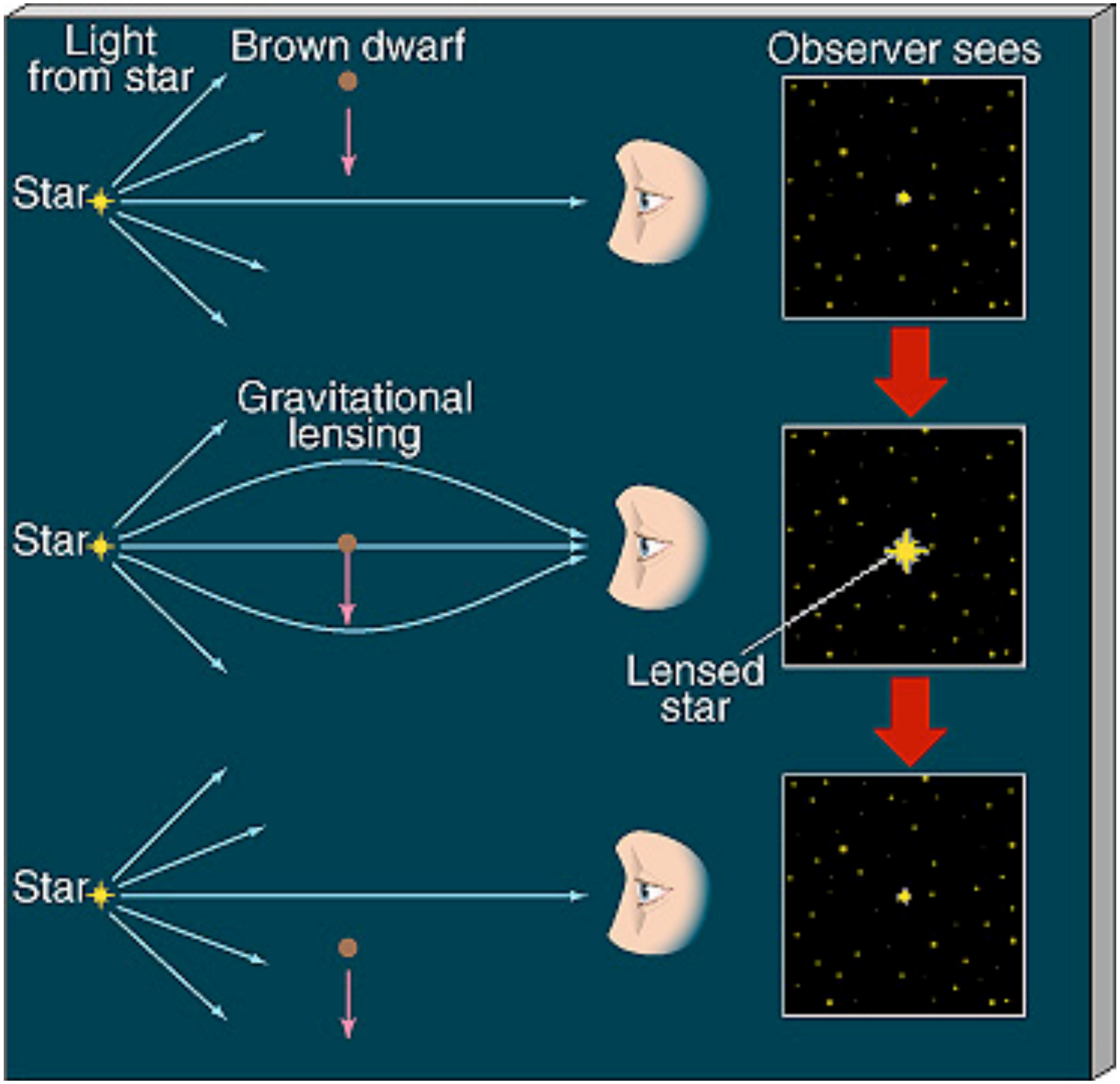
Further evidence of dark matter comes from observations of X-ray clusters. X-ray observations sample the very hot gas (remember that from Wien's law very hot temperatures correspond to very short wavelengths). The fact that clusters are bright in X-rays shows that they must gas that has temperatures around 1 million K.

However, this very high temperature means there is a lot of energy in clusters, so a lot of mass is required to stop the cluster flying apart. When we add up the masses of the galaxies we can see, this isn't enough, so there must be more dark matter binding the hot cluster together.

MACHOS

One candidate for dark matter is the Massive Compact Halo Object: MACHO. These are thought to be small objects the sizes of small stars or planets which are made of normal matter, in the galactic halo



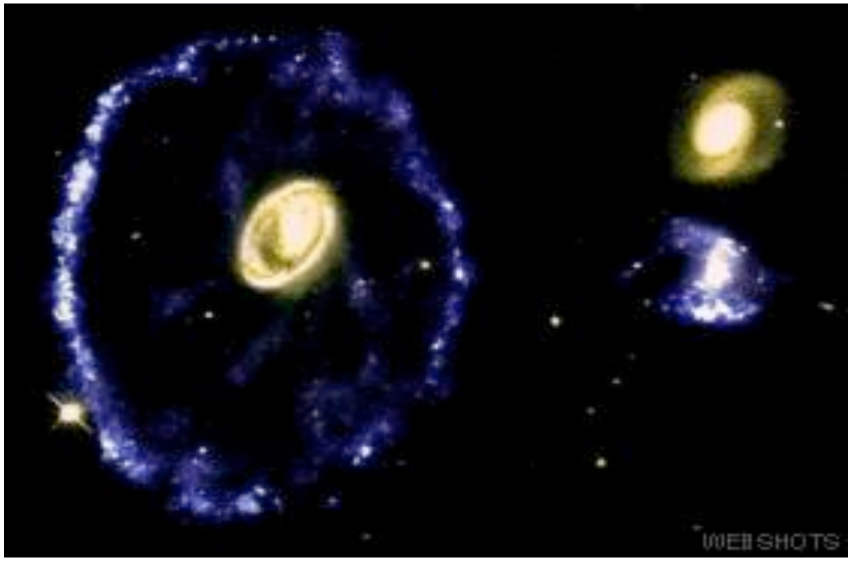


MACHOs can be detected by microlensing: when they pass in front of a halo star and make the star look momentarily brighter. BUT! Experiments haven't found any such true MACHO events. Dark matter remains a mystery.

Galaxy Collisions and Mergers

Galaxies do not evolve in isolation. Although galaxies are whizzing away from us (and each other, as we'll see when we study the Big Bang), they also have peculiar velocities – a random velocity component which can bring them into close proximity

The strong gravitational forces associated with massive galaxies can literally rip each other apart if they get too close (note that it is very unlikely that individual stars actually collide). When this happens, we observe tidal tails of debris. This is called galaxy harrassment.

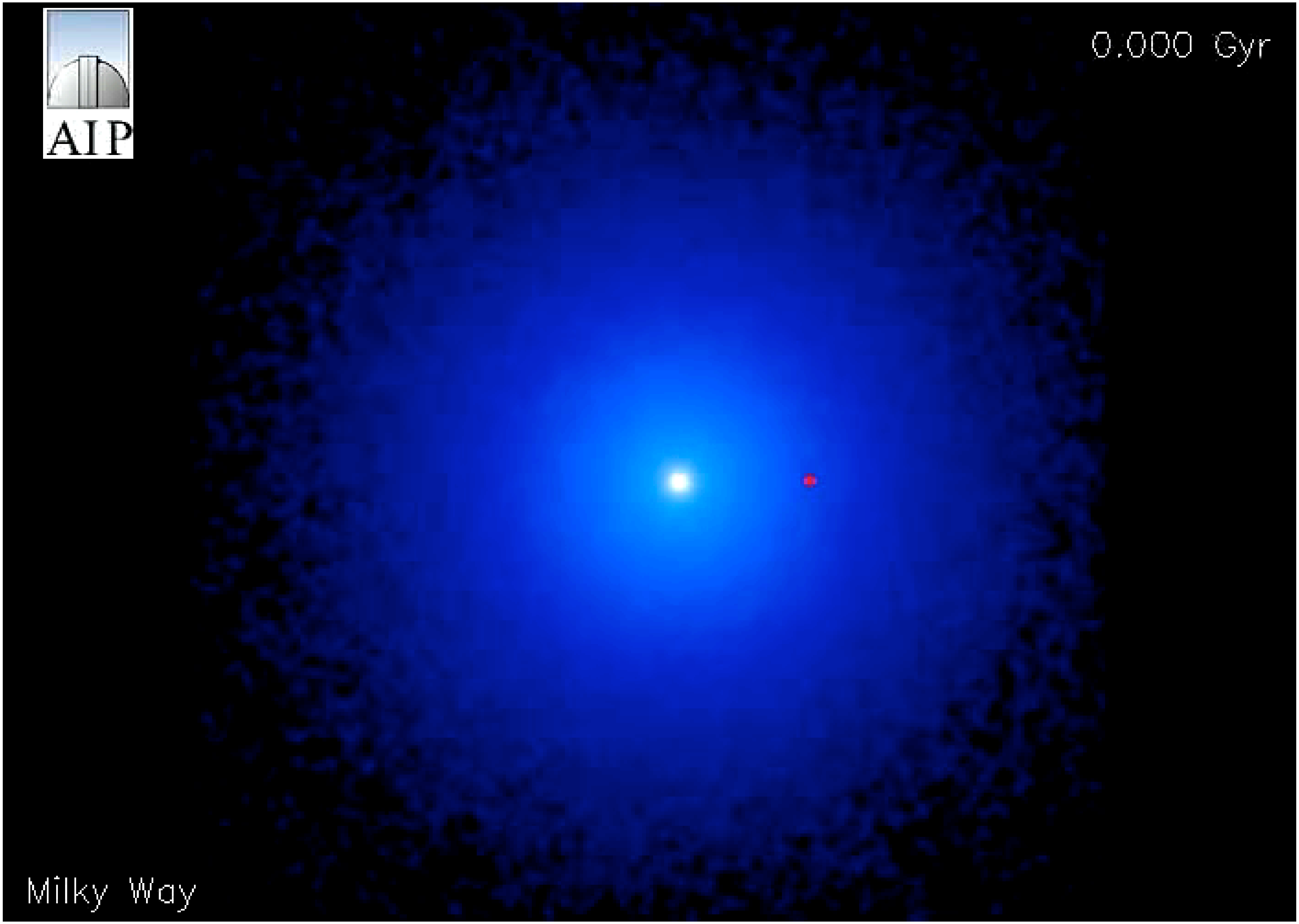


If the alignment between colliding galaxies is correct then ring galaxies are formed. This happens if one galaxy rips through a disk galaxy face on, stripping much of its material.

Galaxy interactions tend to trigger star formation: some of the most luminous star-forming galaxies have tails and other signs of recent merging activity.

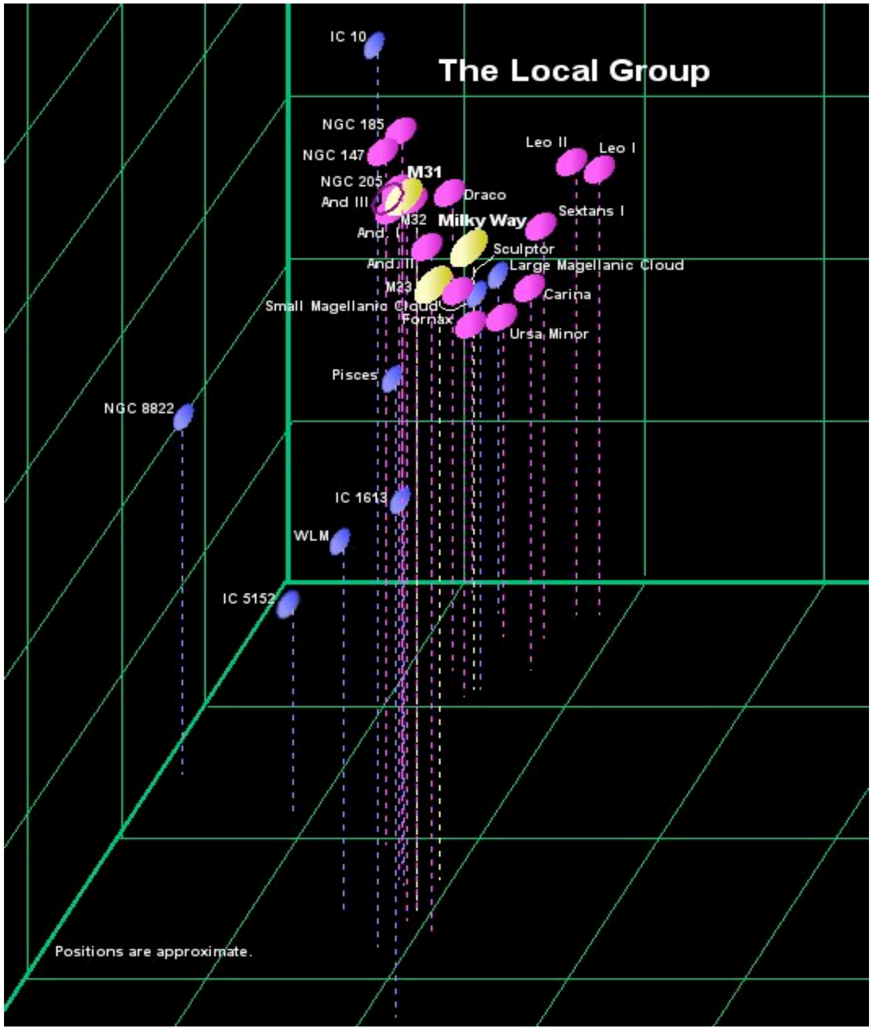
Galaxy merging is an important phase in galaxy evolution, because astronomers believe that massive galaxies like the Milky Way are built up by the accretion of smaller building blocks, or dwarf galaxies. The result of a merger depends on the mass of the initial components. A big galaxy like the Milky Way can consume a small dwarf galaxy without serious disruption (although it will destroy the small galaxy), but if two big disks collide, they will destroy each other and form an elliptical.

In the following simulation, we're going to see what might happen if the Milky Way collided with the nearest large spiral, Andromeda (M31)


0.000 Gyr
Milky Way

Groups of Galaxies

Most galaxies are not found in isolation, but in groups or clusters. Our Milky Way is found in a poor cluster of about 30 galaxies known as the Local Group. It has a diameter of about 5 million light years or 1.7 Mpc.



The Local Group consists of 3 large spiral galaxies: Andromeda (M31), M33 and the Milky Way. Although there are no massive ellipticals in the Local Group, there are several dwarf spheroidals which are like mini-ellipticals: Sculptor, Fornax and Leo I and II. There are also a number of irregular galaxies which include the LMC and the SMC.

Notice that the large spirals are in regions where there are many galaxies, but the irregulars tend to be more isolated. This is known as the morphology-density relation.

Galaxies in clusters are detached from the Hubble expansion

A Rogues Gallery of the Local Group

LMC/SMC: These are actually connected to each by the Magellanic Bridge and to the Milky Way by the Magellanic Stream. This is evidence of past interactions between these 3 galaxies.

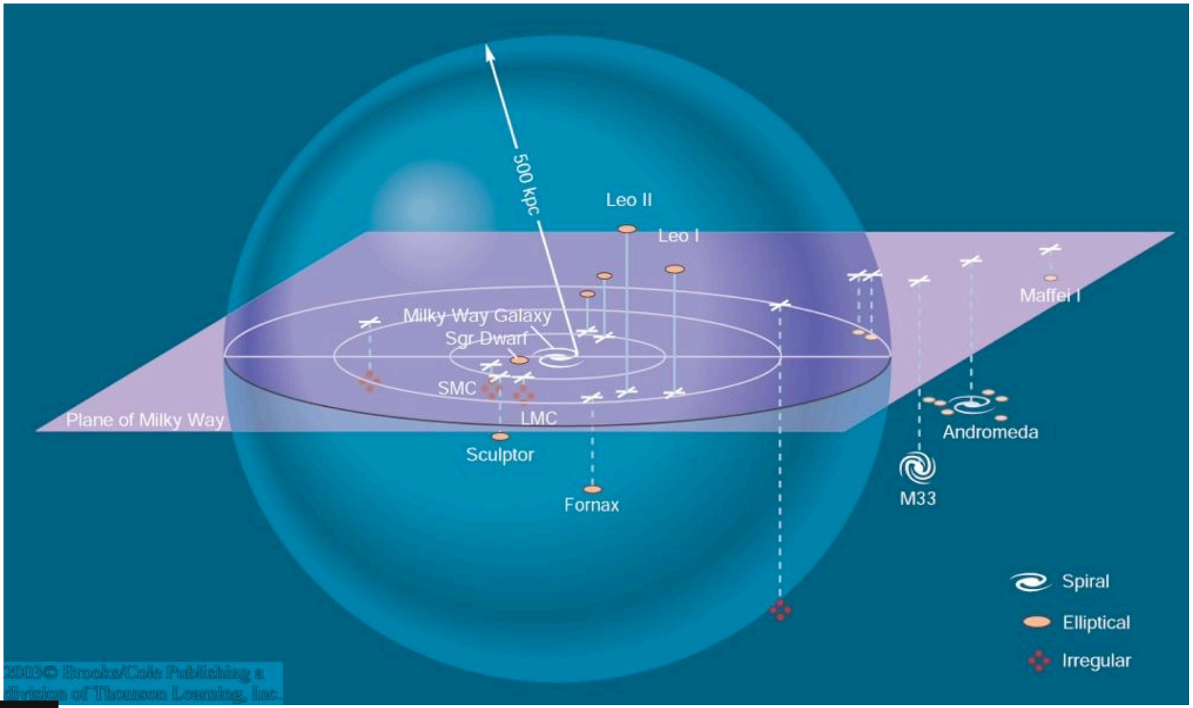
M31, one of the few spirals in the local group

Sculptor is one of numerous dwarf galaxies.

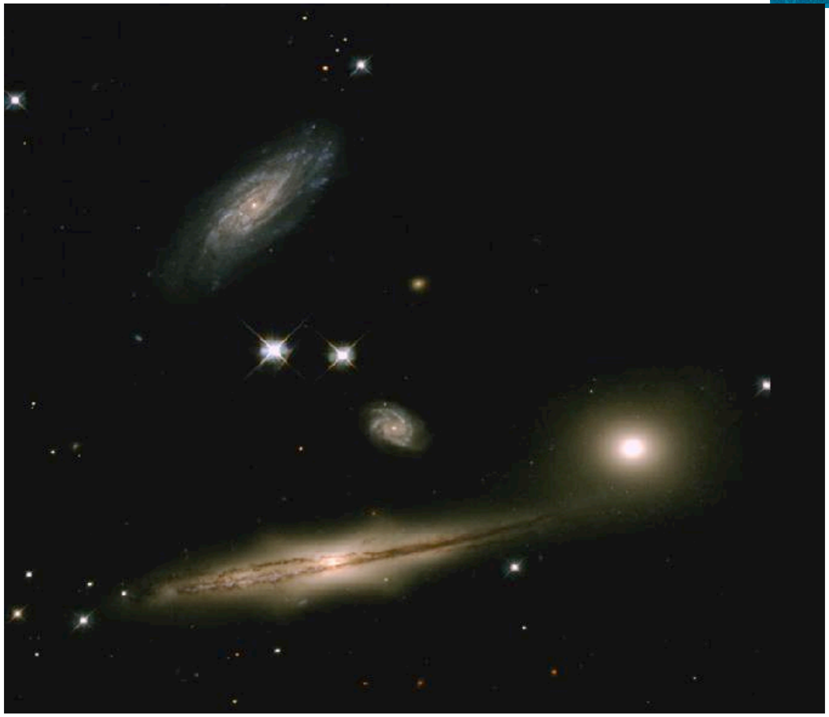
The total diameter of the Local Group is ~1Mpc and contains about 30 galaxies (but there may be several that we haven't found yet).

Compact Groups and Small Scale Clustering

The scale of the Local Group is quite large, and the number galaxies is quite modest, which is why we call it a poor cluster. Looking again at the Local Group we can see that it can actually be separated into 2 groups of galaxies that cluster around M31/M33 and those that cluster around the Milky Way.



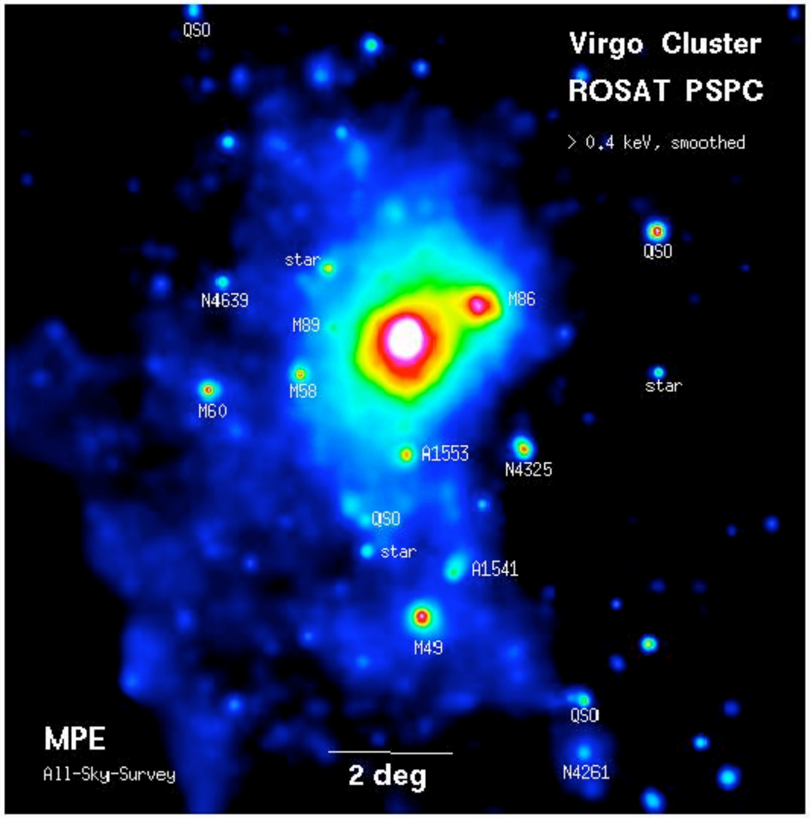
©2003 Brooks/Cole Publishing a division of Thomson Learning, Inc.

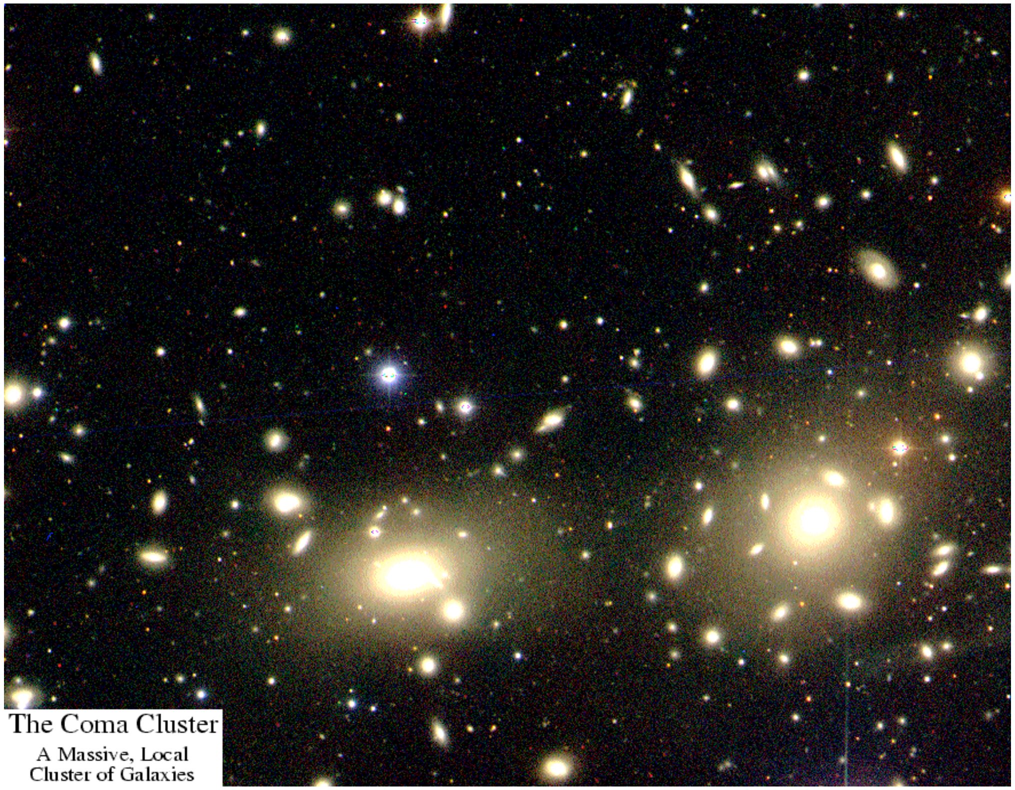


Groups contain fewer galaxies than poor clusters, usually less than 10 galaxies. There also exist compact groups (sometimes called Hickson compact groups after one of the astronomers who studied them). Hickson compact groups usually contain less than half a dozen galaxies, but they are all packed very close together.

Rich Galaxy Clusters

Rich galaxy clusters can be as large as 10 Mpc and contain up to several thousand galaxies. Two examples of rich clusters are Virgo and Coma.



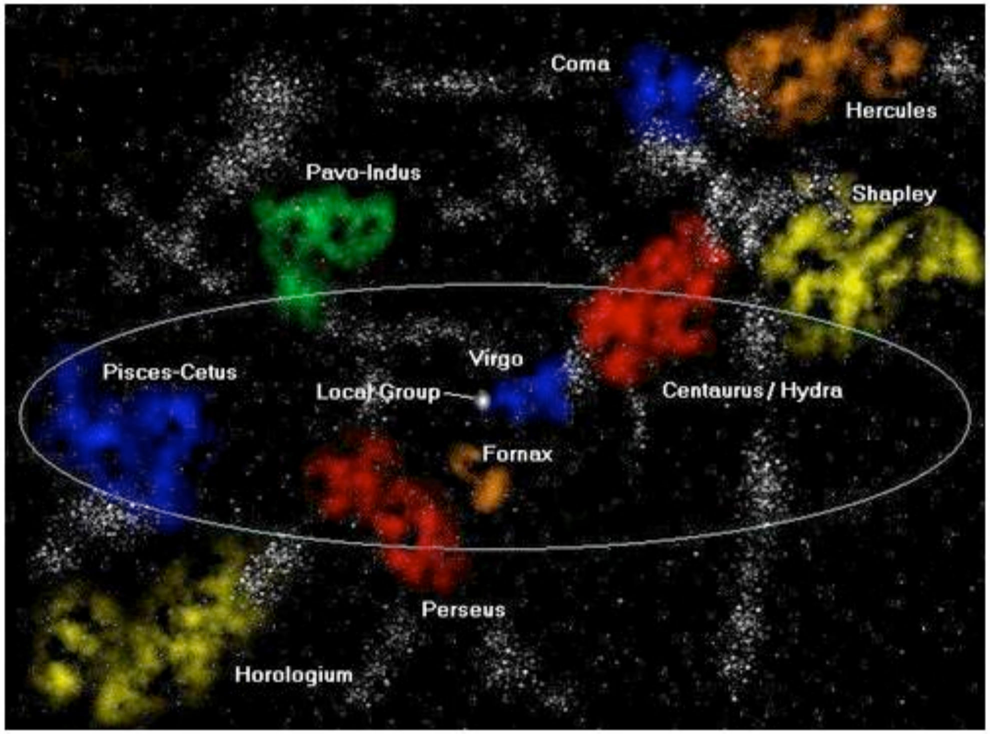

The Coma Cluster
A Massive, Local Cluster of Galaxies

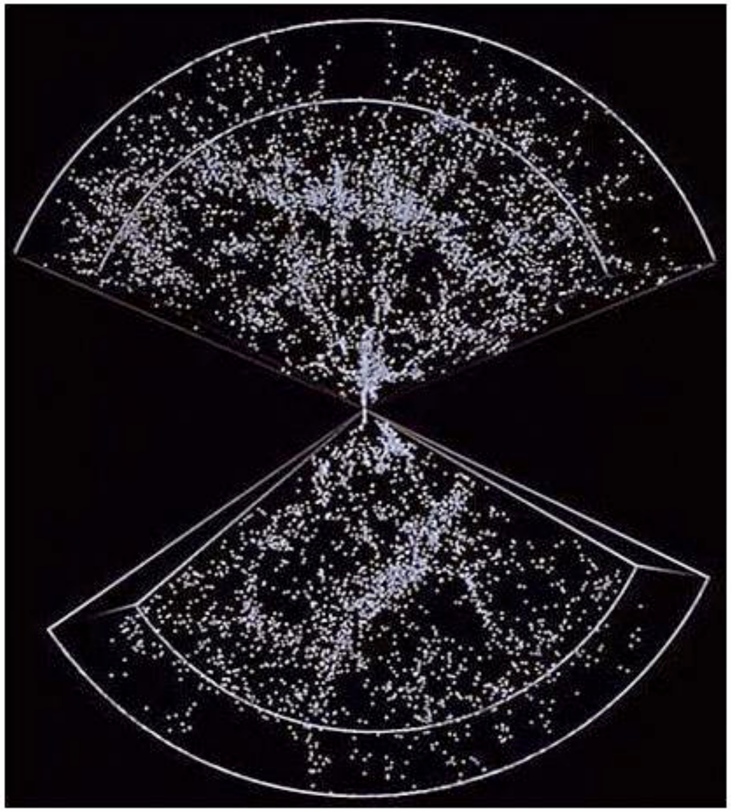
Virgo is relatively nearby, only about 55 Mpc away. At the centre of Virgo is a giant elliptical, M87. Rich clusters often have large ellipticals near their centres, which astronomers believe may have been formed as galaxies have merged in this crowded environment.

The Coma cluster is dominated by 2 very massive elliptical galaxies, with over 1000 other members known. Rich clusters such as this have relatively few spiral galaxies

Superclusters

Even galaxy clusters like to be social – clusters of clusters are called superclusters. The Local Group is part of a supercluster called (imaginatively) the Local Supercluster which is about 40 Mpc wide and contains several thousand galaxies and is roughly centred on the Virgo cluster.





So, galaxies cluster on all scales: any patch of sky will reveal patchy galaxy coverage, including overdensities and voids. Mapped over a large enough volume we can see the great structures that galaxies and their clusters map out:

Galaxy Evolution

How can we piece together the history of galaxy evolution using the snapshot of evidence we have available from current observations?

We know that spiral galaxies are relatively young and are still forming stars because they have stellar populations that are hot and massive and have plenty of gas left. Ellipticals, on the other hand, have only their old, red stellar population left, and no gas.

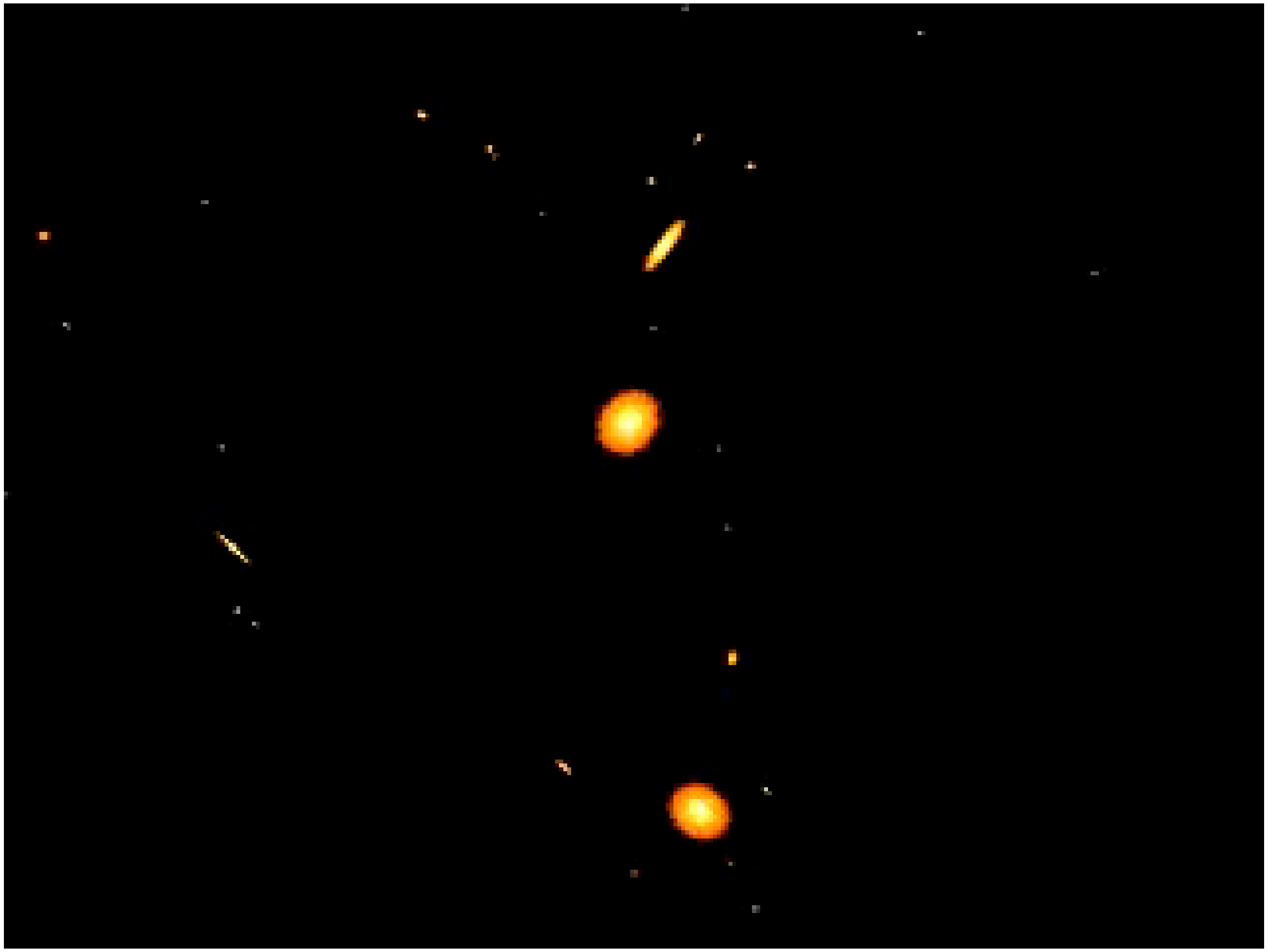
So, does this means that spirals become ellipticals? Yes, but only via the effect of mergers. Today most astronomers believe that massive galaxies are built up from small building blocks, this is called hierarchical galaxy formation.

We have already seen that ellipticals are likely to be the result of merging of two spiral galaxies. Evidence from this comes from:

1) Ellipticals are more common than spirals in rich clusters
2) Ellipticals are old galaxies, whereas spirals are young
3) Simulations show that spiral disks get disrupted in mergers and leave behind "spheroidal components"

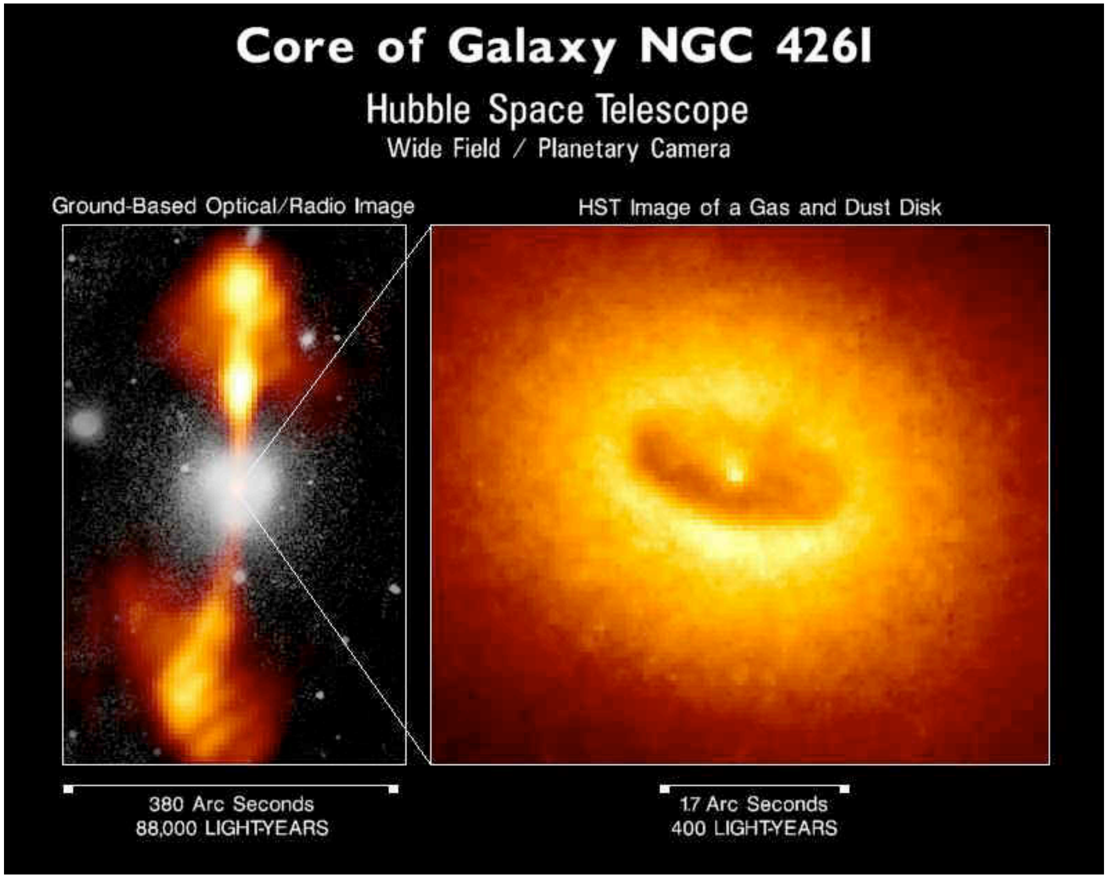
These interactions not only disrupt the disk, they can briefly induce some intense starbursts, but ultimately end up stripping the galaxy of most of its gas.

In this movie we see how many galaxies in a cluster can interact and eventually form a massive elliptical in the centre.



Active Galaxies

At the centre of the Milky Way is a black hole; we can't *see* the black hole, but we car infer its presence by the motion of stars in the Galactic nucleus, and the abundant radio and Xray emission. The majority of other galaxies also have black holes at their centres, and in some cases, they are much easier to identify than in the Milky Way.

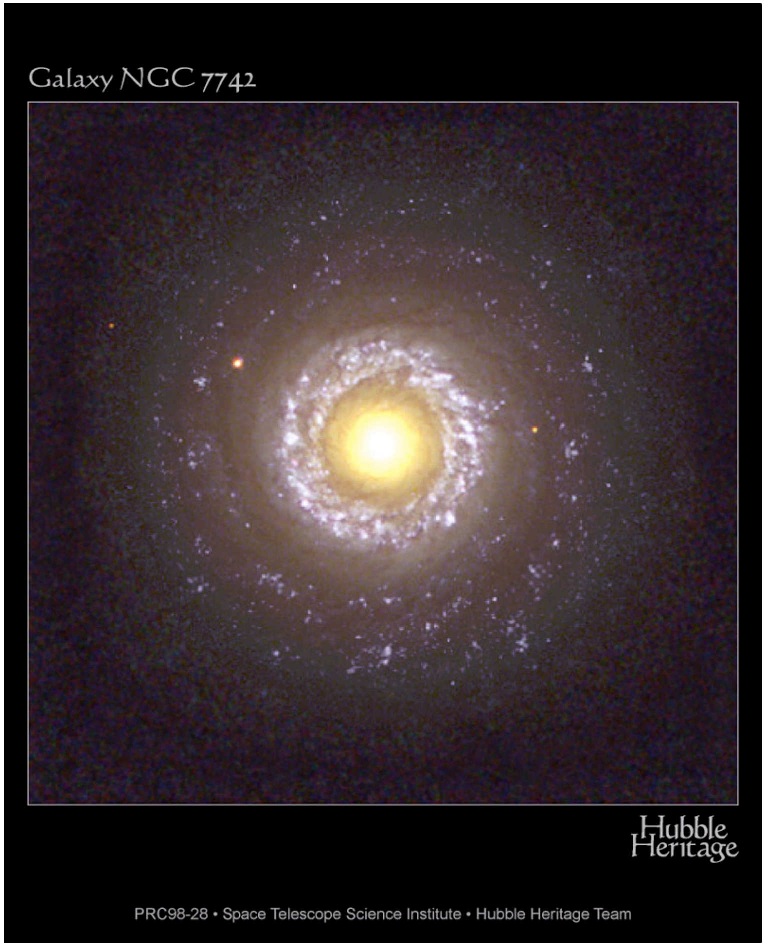


NGC 4261 is one of the 12 brightest elliptical galaxies in the Virgo cluster. It has strong radio jets that flow out of the galaxy and a giant disk of cold gas and dust that may be fuelling the central black hole.

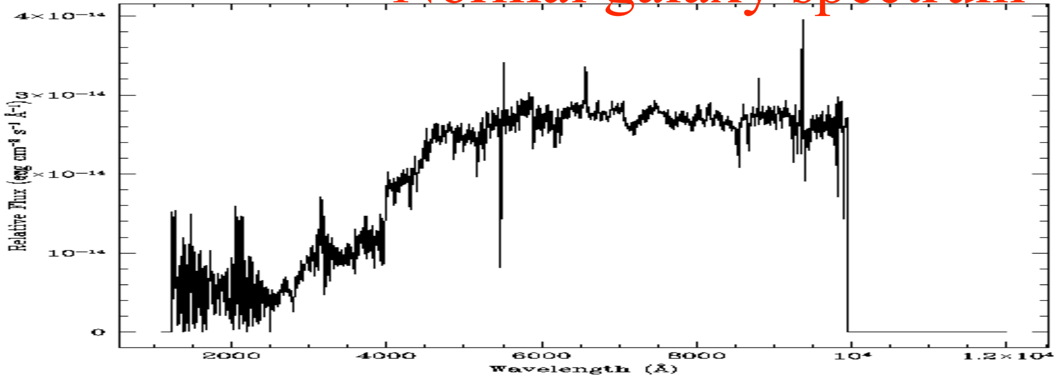
Galaxies in which the black hole is “switched on” and producing large amounts of energy are referred to as active galaxies, and the cores themselves are called active galactic nuclei (AGN).

Seyfert Galaxies

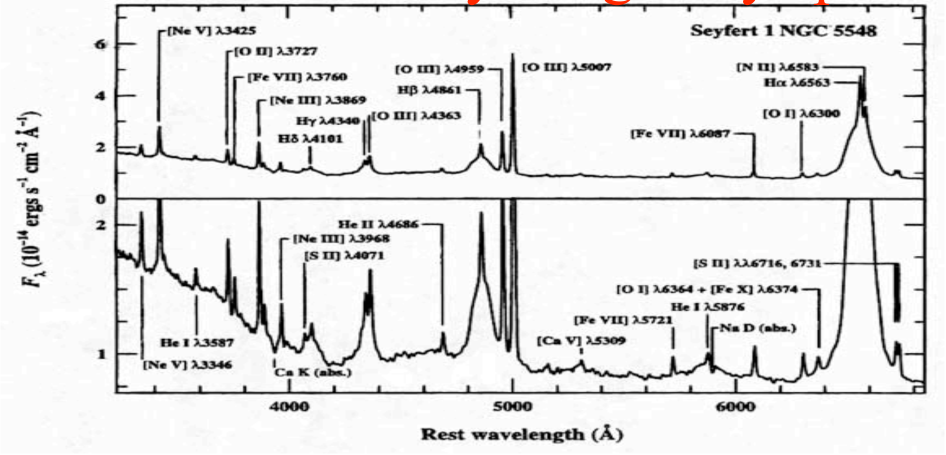
Active galaxies come in a number of varieties. In the most powerful cases, it can be hard to see the actual galaxy because of the luminosity of the central AGN. In the case of Seyfert galaxies we find normal looking spiral galaxies with bright nuclei, that have unusually strong, broad emission lines in their spectra.



Normal galaxy spectrum



Seyfert galaxy spectrum



The large width of these lines suggests a very hot gas, because the wavelengths have been strongly shifted towards both the red and the blue, which broadens the normally narrow lines.

Properties of Seyfert Galaxies

About 2% of spiral galaxies have spectra that classify them as Seyferts. The luminosity of Seyferts can fluctuate on timescales of a few months. As we saw in our discussion on pulsars, the size of an object can not be smaller than the light travel time across its diameter, so Seyfert nuclei most be less than a few light months across. Seyferts can be further classified into 2 types:

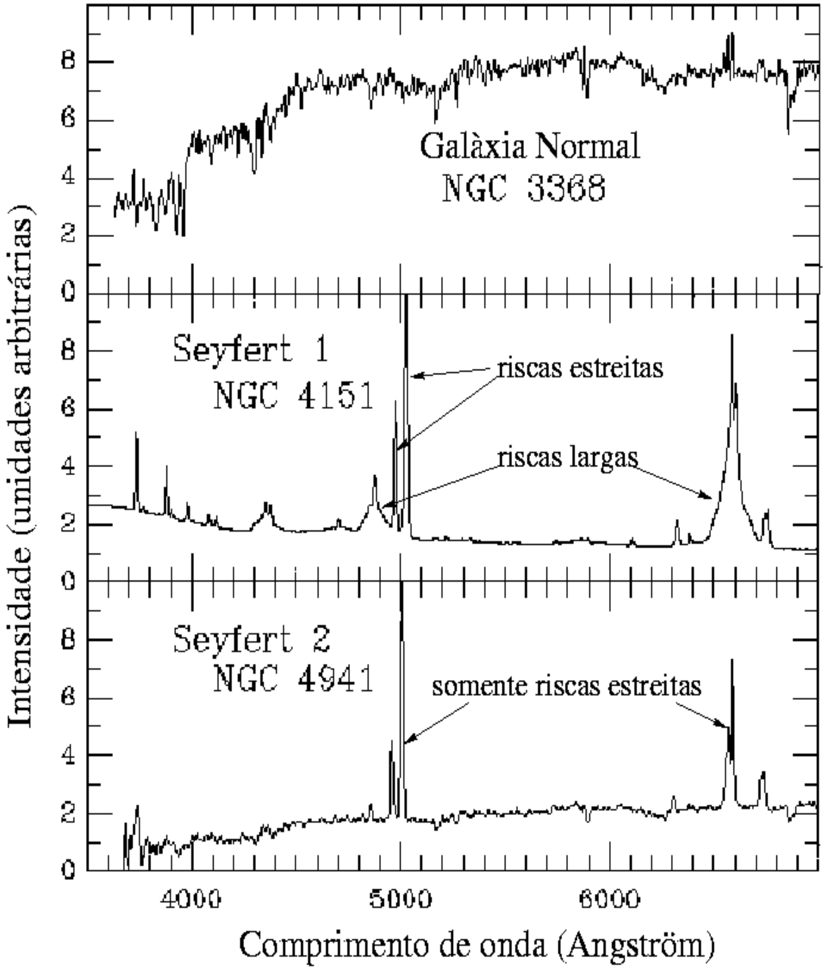
Type I Seyferts

Very luminous in the UV and Xray
Broad Emission lines

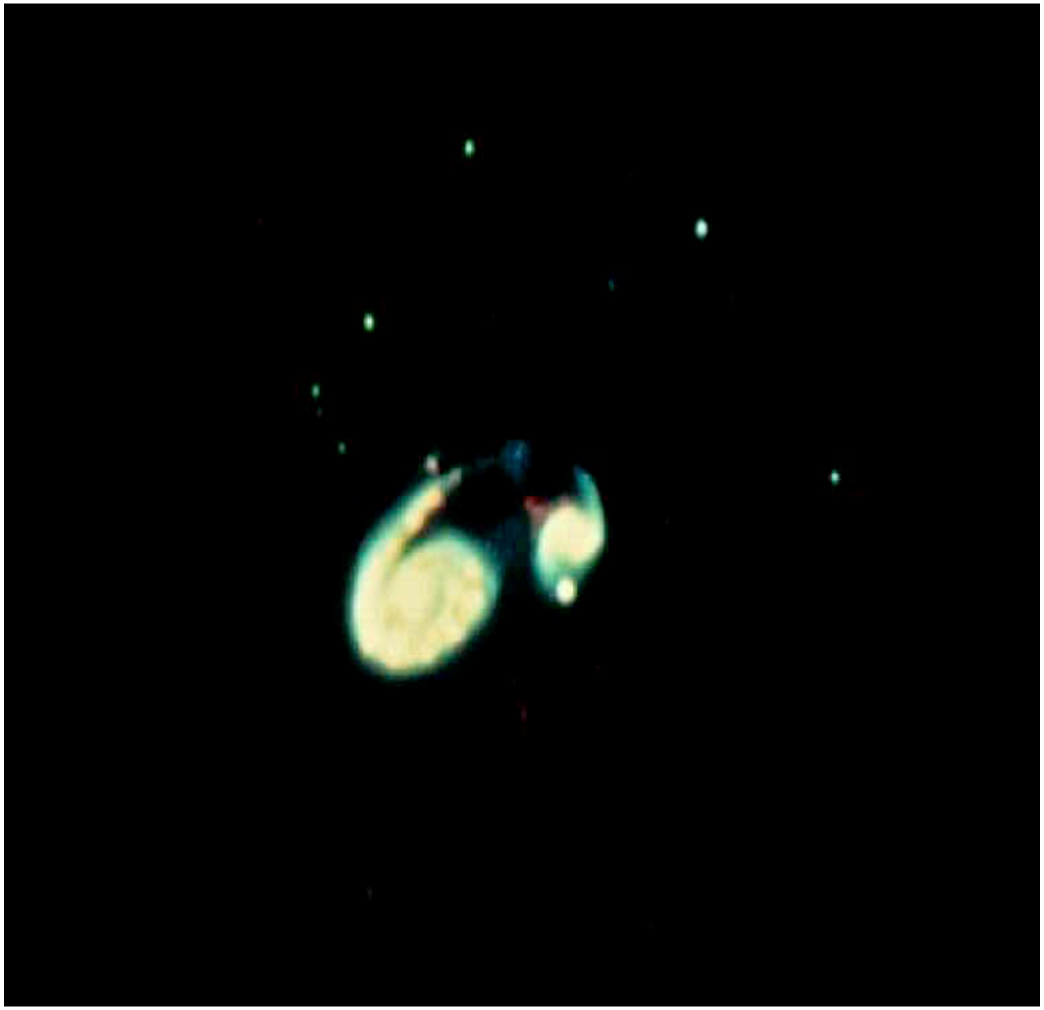
Type II Seyferts

Less luminous in Xray emission
Narrower emission lines

It is postulated that Type II Seyferts may be enshrouded by dust (possibly due to inclination angle), so some of their emission is absorbed.



Observational evidence shows us that a particularly high fraction of Seyfert galaxies are either interacting or possess tidal streams and debris that indicate that they have previously been disturbed. This leads us to believe that AGN may be associated with interactions. The violent tug-of-war occuring during interactions can throw gas into a black hole to feed it.



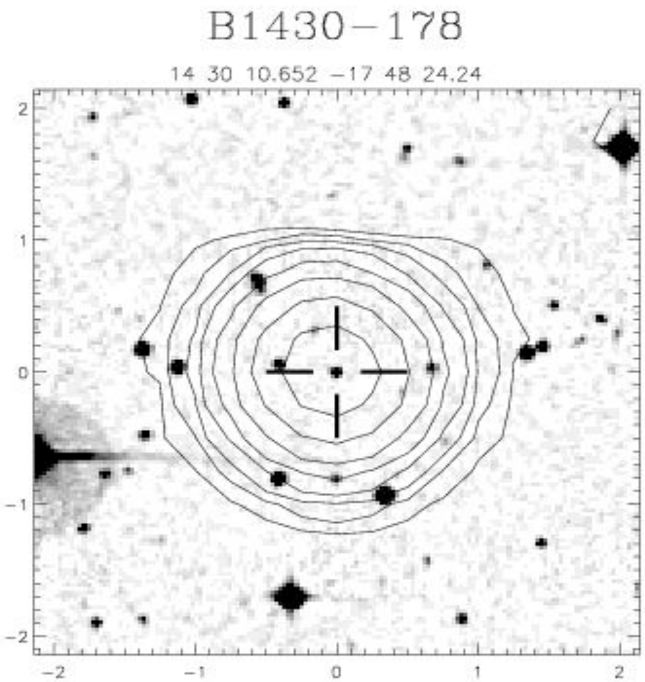
Radio Galaxies

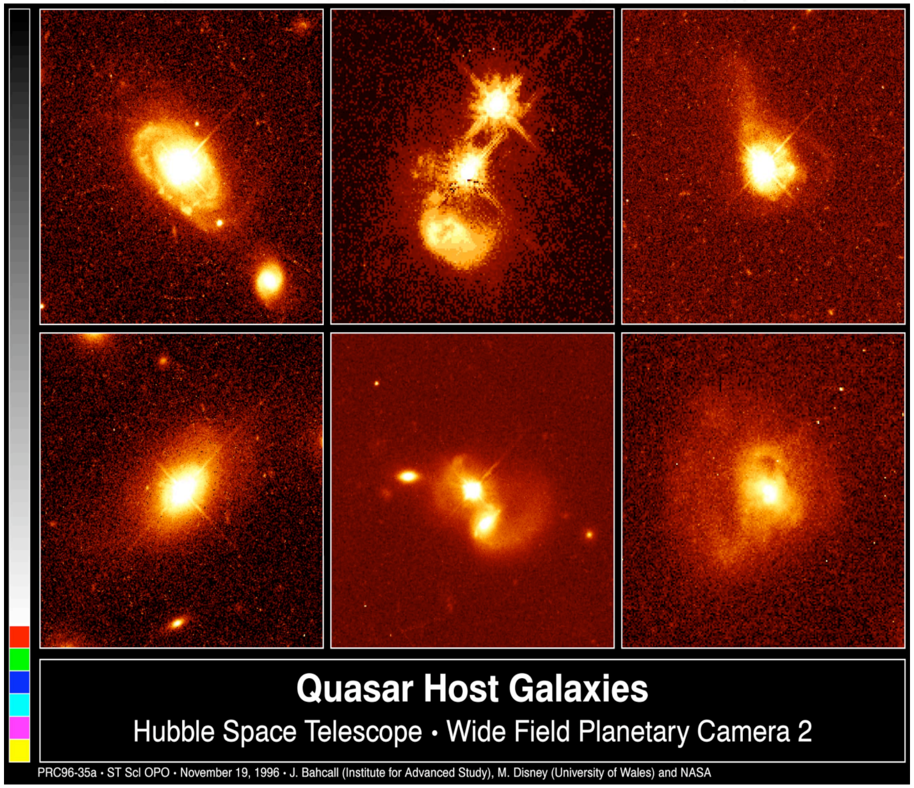
Many of the early examples of AGN were discovered with radio surveys. In the 1950s, it was found that some galaxies are particularly powerful sources of radio waves and were thus named radio galaxies. Radio jets are often beamed out of the main galaxy as it is seen in the optical. Centaurus A is one of the most famous radio galaxies, it's optical emission largely hidden by dust in a disk.

The process that causes these energetic jets is poorly understood, but it is believed that there is probably an accreting black hole at the centre of the galaxy (similar to a Seyfert) and that the conversion of this fuel to energy causes jets to get squeezed out into the lower density regions outside the galaxy.

Whereas seyfert galaxies are usually hosted by spirals, most radio galaxies are hosted by the more massive elliptical galaxies.

Quasars





In the 1960s, a series of radio catalogues was compiled using a radio telescope in Cambridge. Several powerful radio emitters were detected that did *not* look like galaxies, but were point sources that looked more like stars.

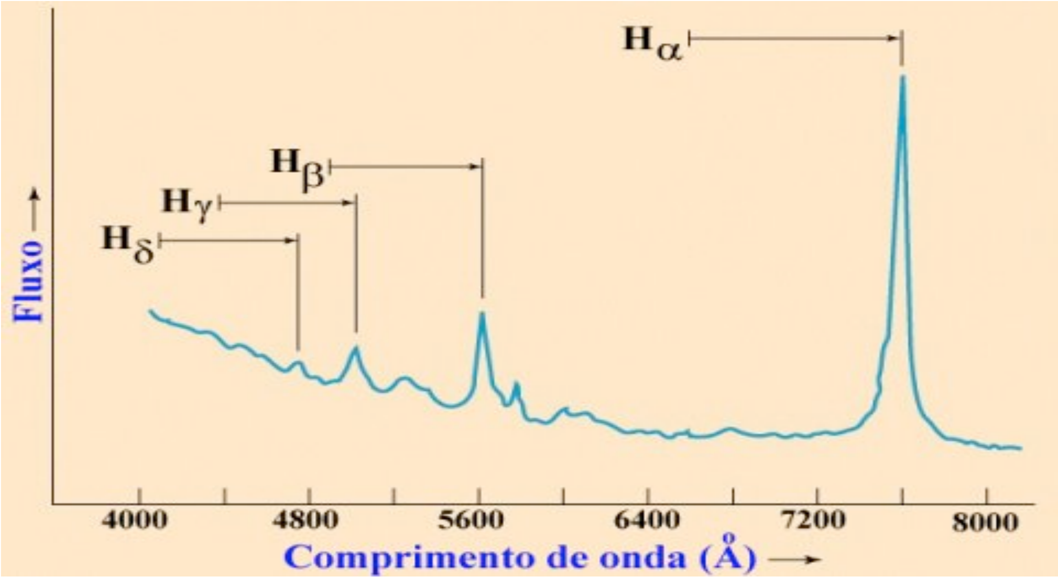
The idea that stars could be emitting all this radiation seemed ridiculous, so astronomers named them quasi-stellar objects, AKA QSOs or quasars. Note that not all QSOs are radio emitters, and strictly speaking only those that are radio loud should be called quasars.

Quasars can occur in a number of different types of host galaxy, but it seems that the most powerful ones are hosted by the most massive galaxies (i.e. ellipticals) whereas lower power QSOs occur in less massive spiral gaaxies

The nature of quasars had to remain a mystery until optical spectra could be taken; this is often the way in astronomy that imaging gives you a first glimpse whereas spectroscopy gives you detailed information about the physics and chemistry of an object.

One of the first quasars to be studied was 3C273, meaning it was the 273rd object in the third Cambridge catalogue. At first, this object mystified astronomers because they could not identify any of the strange emission line because their wavelengths did not match the familiar lines.

This QSO was discovered in 1963, and at that time, it was unheard of to have such large Doppler shifts, so it took a while to identify the emission lines that had been detected.



So we find that the Hα Balmer line is observed at 760 nm instead of 656 nm. From the Doppler formula this gives us a velocity = (760-656)/656 x 300000 = 48,000 km/s !! We can also use the Hubble law V=HD to determine a distance of 48000/70 = 680 Mpc. This made 3C273 by far the most distant object known in the universe.

Although this record was soon broken QSOs remain amongst the most distan objects that can be detected, due to their extreme luminosities

Redshift

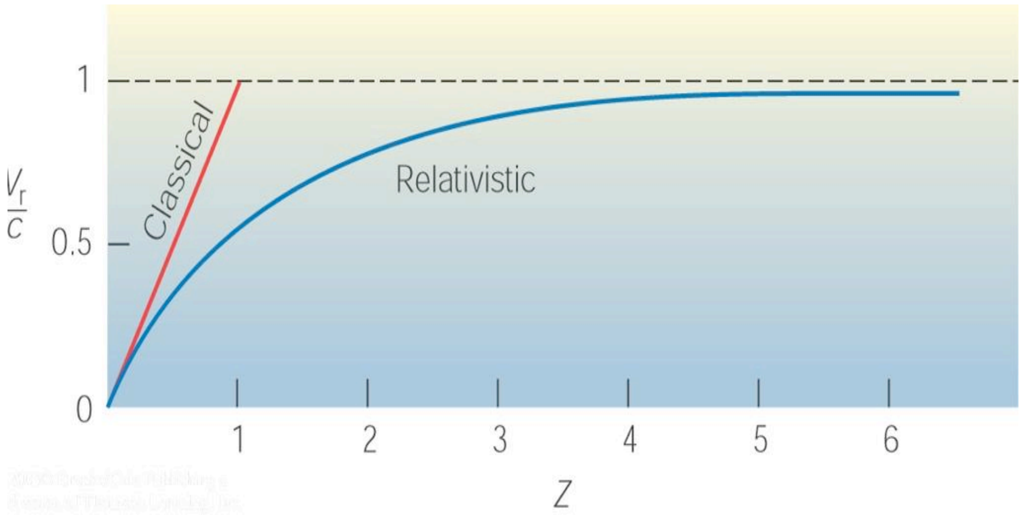
We have met several times the concept of Doppler shifts, and when studying the distances of galaxies using the Hubble law, we have used the term “recessional velocity”. When these velocities become very large, we need a more convenient measure, rather than using Mpc or km/s (because the Hubble law shows us that velocity and distance are related).

Redshift is the unit that we use to measure the distance to very distant obejects. We can re-write the Doppler formula:

$$\frac{\text{Change in wavelength}}{\text{Original wavelength}} = \frac{\text{velocity}}{\text{light speed}} = \frac{\Delta\lambda}{\lambda_0} = \text{redshift} = z$$

So, in the case of 3C273, the redshift was 48000/300000 = 0.16.

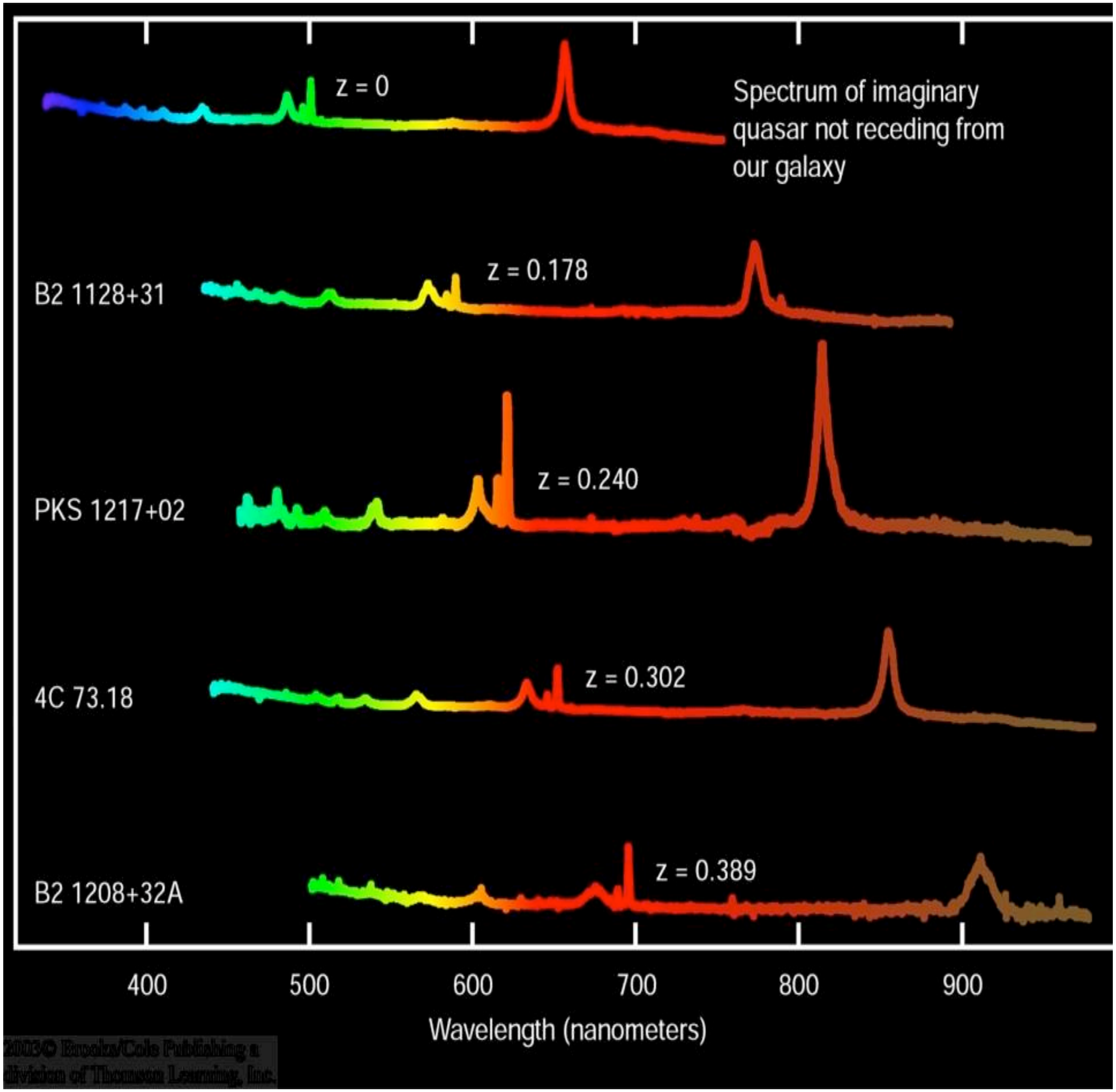
Some of the most distant quasars today have z~6, does this mean they are travelling at 6 times the speed of light? No! Einstein told us that nothing can travel faster than light.



For very distant objects (in reality, z>0.2 or so) the formula above does not apply, and we have to make a relativistic correction. This correction (which uses Einstein's theory of relativity) means that distant objects are never moving at more than lightspeed.

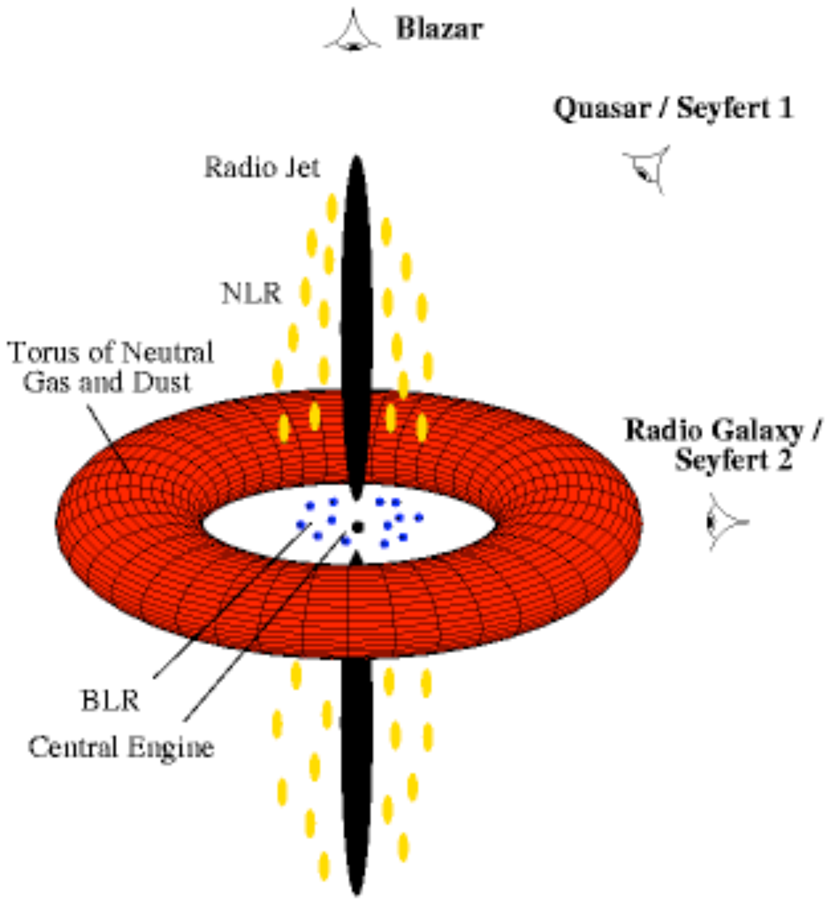
Whilst the redshift of an object is not a good indication of its recessional velocity above about z=0.2, we can still use the shifts in lines to calculate what the redshift is. And since redshift is still an indicator of distance, the redder emission lines indicate more distant objects.

E.g. A QSO at redshift 3 has its Hα line shifted by 656.3 x 3 = 1969 nm. That means we observe it at 1969+656.3=2625nm. This is way out in the IR.



The Unified AGN Model

We have come up with several different names for different AGN e.g. Seyferts, QSOs and radio galaxies. However, they all have seem to need black holes as their central engines. Can we come up with a single model that explains all the observed properties?



The unified model indicates that the various AGN have similar structures, but we see different “types” depending on orientation