Chemical evolution

Finished last time by saying that all elements heavier than hydrogen and helium were formed in stars. The younger a star, the more material from previous generations of stars it will contain, and the higher their *metallicity*.

Stars can be broadly split into two populations:

Population I stars formed recently & contain significant quantities of the heavier elements. The Sun is a Population I star.
Population II stars formed in the earlier universe, and contain only very small amounts of metals.

Population III stars are hypothetical, so far, but the very first stars to form in the universe must have contained no metals at all. Population II stars contain some metals, so can't have been the earliest.

Cosmic distances

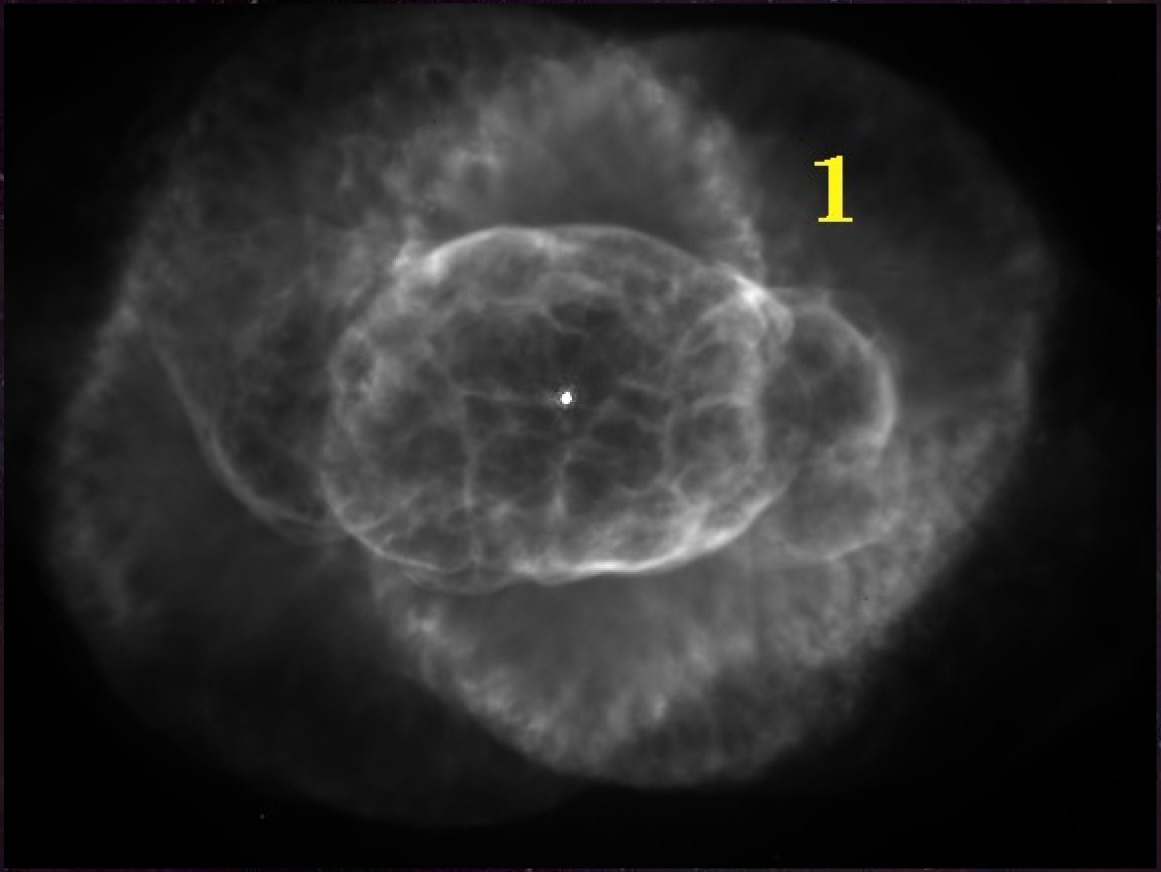
Discussed earlier that the most direct way to measure the distance to a star or other astronomical object is to measure its *parallax* – the small shift in its position over a year caused by the movement of the Earth from one side of its orbit to the other.

This is only accurate out to a few hundred parsecs at best. So how do we find out the distances to objects further away than that?

There is an elaborate set of interlinking distance measures which is used to work out the scale of the universe. It is known as the *cosmic distance ladder*.

Expansion parallax

Some astronomical objects are expanding – like planetary nebulae and supernova remnants. From spectroscopy, we can measure the velocity along the line of sight. If we can observe them over a long enough time to detect their expansion in the plane of the sky, we can directly measure the distance.



Expansion parallax

The Cat's Eye Nebula is at a distance of 1000 +- 300 parsecs. The Crab Nebula is at a distance of 2000+-500 parsecs.

Spectroscopic parallax

If we can work out the position of a star on the Hertzsprung-Russell diagram, we know its absolute magnitude, and therefore its distance.

If a star has broad spectral lines, then it probably lies on the main sequence. Its temperature is easily determined, and therefore its luminosity can simply be read off from the diagram.

This is known as *spectroscopic* parallax. It's not particularly accurate. And it's also not anything to do with parallax!

Main sequence fitting

More useful than the spectroscopic 'parallax' method for individual stars is the technique of *main sequence fitting*. If we observe a cluster of stars, and plot an HR diagram using apparent magnitude and temperature, we will see the main sequence.

The distance to the cluster is then easily determined from the difference between the apparent magnitude of its main sequence, compared to the absolute magnitude of the standard main sequence.

From an absolute and an apparent magnitude:

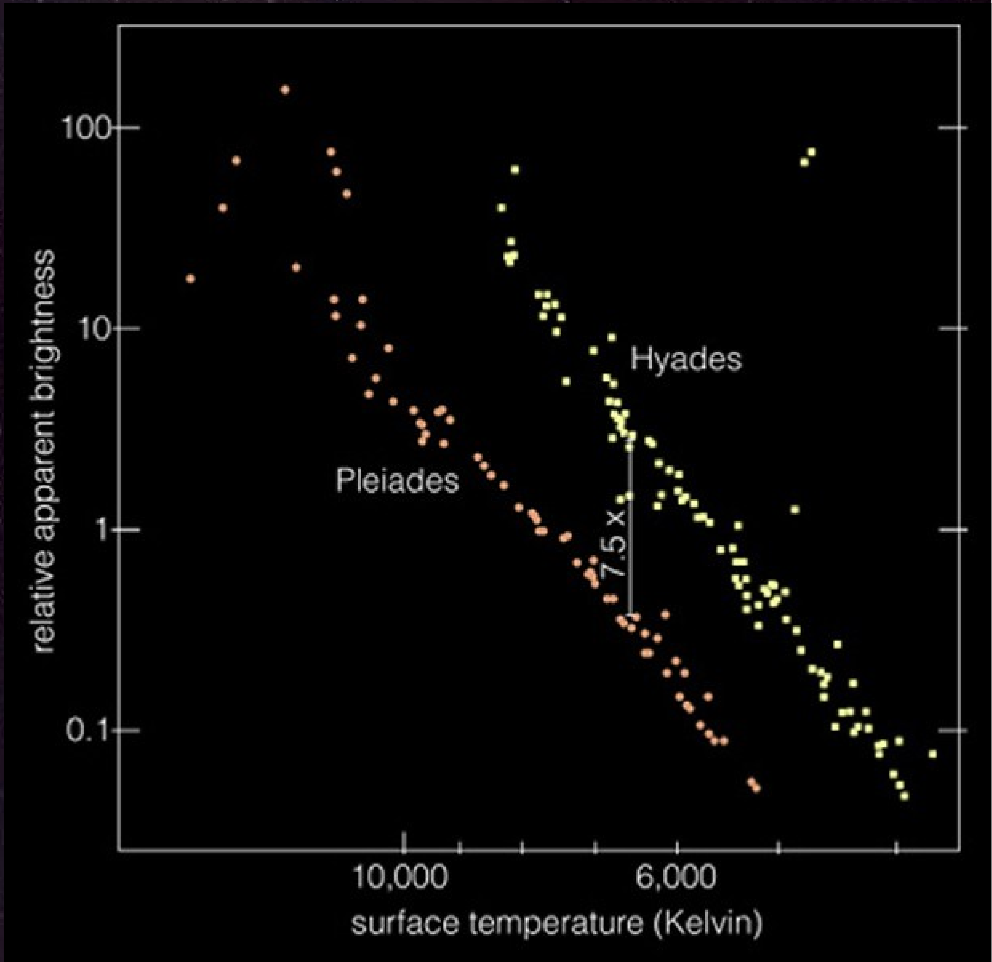
$$m - M = 5 \log d - 5$$

(m=apparent magnitude, M=absolute magnitude, d=distance in parsecs)

Main sequence fitting

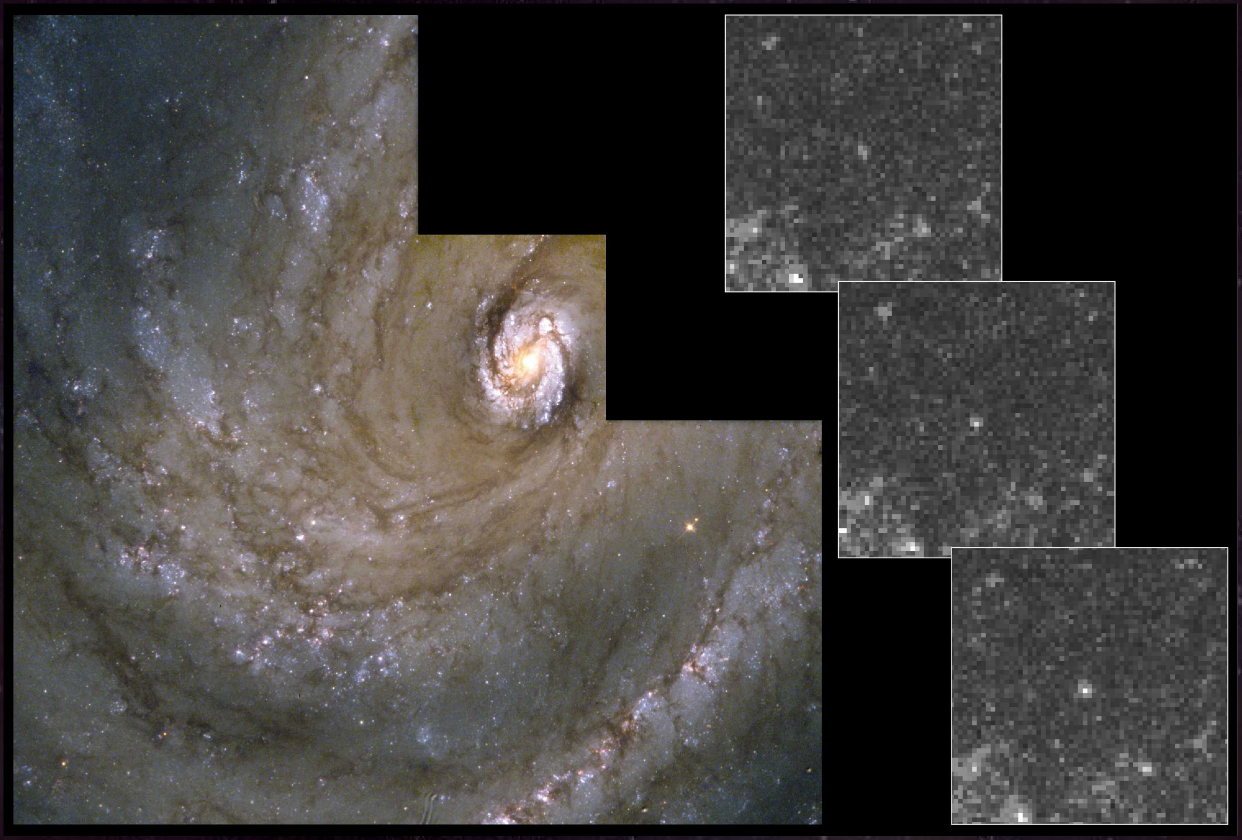
For example, plotting the Pleiades and the Hyades (two nearby star clusters, both in the constellation of Taurus) on an HR diagram, we see that the main sequence of the Hyades is about 7.5x brighter than the main sequence of the Pleiades.

From the inverse square law, this means that the distance to the Pleiades is $\sqrt{7.5} = 2.7$ times the distance to the Hyades.



Standard candles

As discussed earlier, many evolved stars go through phases where their brightness is variable. There are many types of variable stars, some very regular and some very irregular. One extremely useful type of variable star is called a *cepheid variable*, named after δ Cephei, the first known example. The pole star is also a cepheid



Standard candles

Cepheids brighten and fade extremely regularly over periods ranging from a few hours to a few weeks. They are are extremely useful because it turns out that their luminosity and period are tightly related – the longer the period, the brighter the Cepheid.

The brightest cepheids are many thousands of times brighter than the Sun. This means they can be seen out to large distances – as far away as 60 million light years.

Edwin Hubble observed cepheids in the Andromeda Galaxy, and thus showed that it was outside our own galaxy. One of the main aims of the Hubble Space Telescope was to observe cepheid variables in distant galaxies, to refine the cosmic distance scale.

Standard candles

Cepheids are one of the most important of the *standard candles* – objects whose absolute magnitude is known and so whose distance can easily be found.

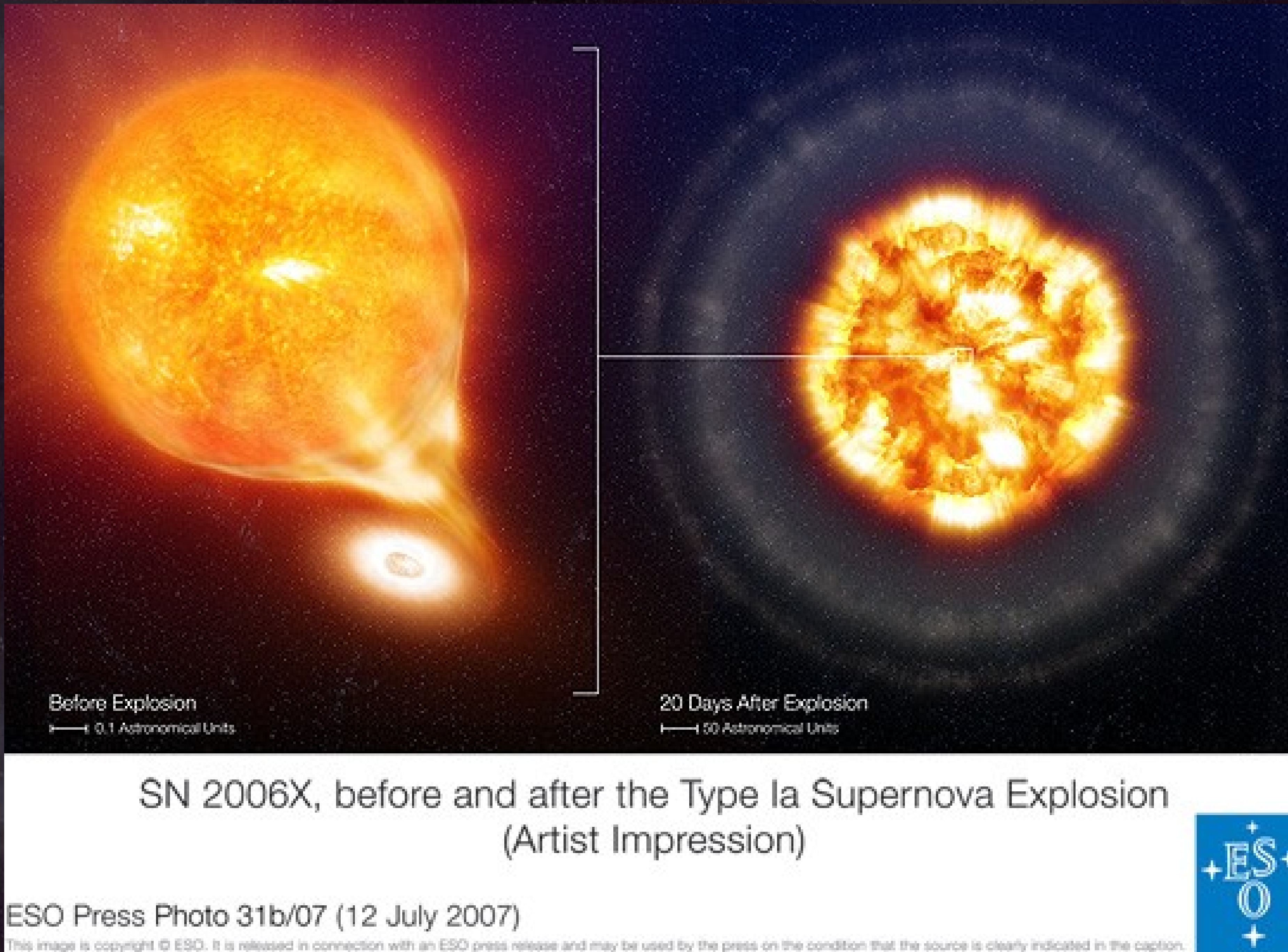
Other examples of standard candles are:

- RR Lyrae stars (similar to Cepheids but less luminous)
- planetary nebulae
- Type Ia supernovae

We talked about core-collapse supernovae, which are the end result of the lives of very massive stars. These are also called Type II supernovae

Type Ia supernovae result from binary system in which matter is flowing from a red giant onto a white dwarf.

Standard candles



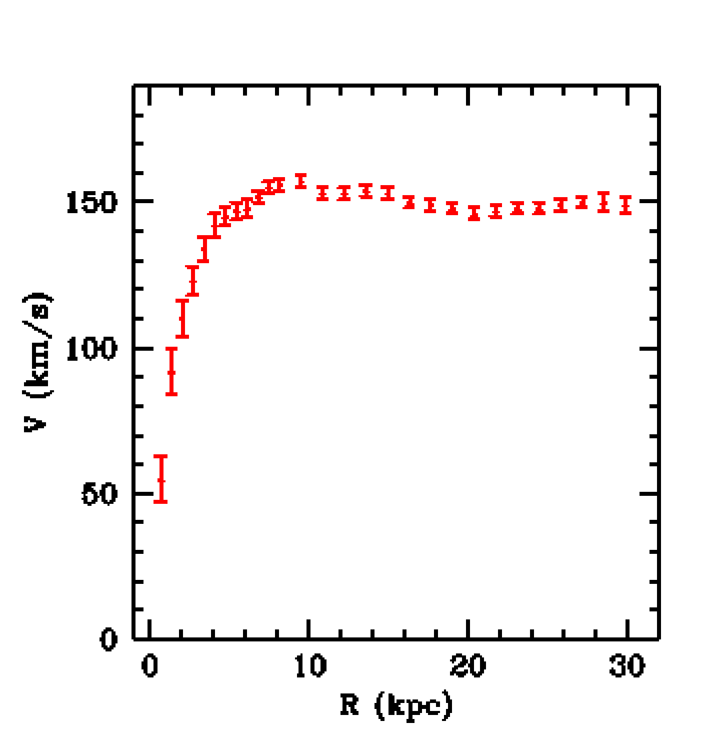
Standard candles

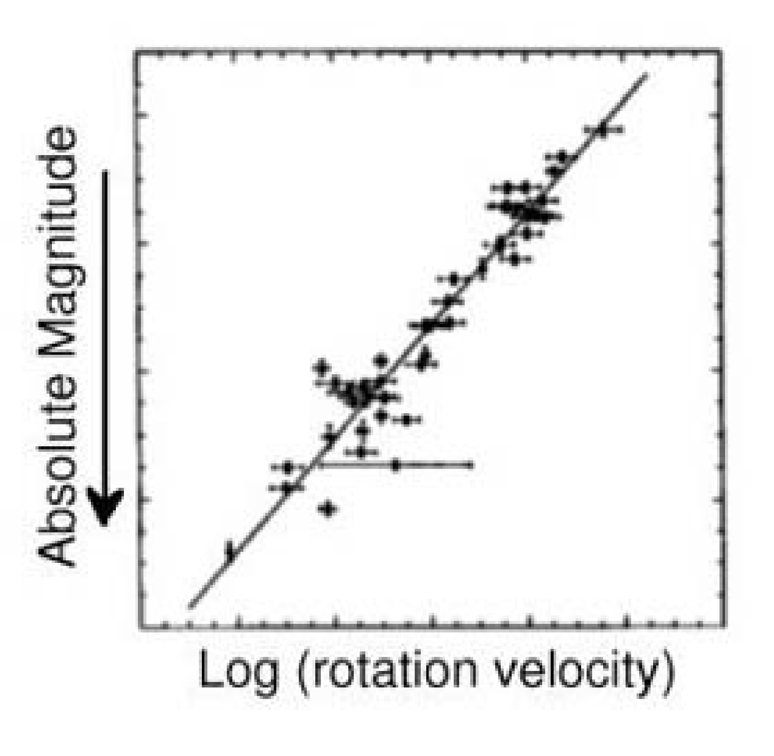
As it gets heavier, the temperature in the white dwarf rises. When the white dwarf reaches a critical mass, the temperature is high enough to trigger sudden explosive nuclear fusion, and the star explodes violently.

Greater distances

Using all these distance measuring techniques, the distances to many relatively nearby galaxies have been found.

It has been found that the *faster* the stars in a galaxy are orbiting the centre, the *brighter* the galaxy is. The relationship between rotation and luminosity is called the *Tully-Fisher Relation*





Hubble flow

Edwin Hubble was the first to find that all external galaxies (except the ones in the Local Group) are receding, and that the velocity of recession is proportional to the distance.

$$v = H_o D$$

H_o is a constant, with units of km/s/Mpc, called the Hubble Constant. It is one of the most important numbers in astronomy.

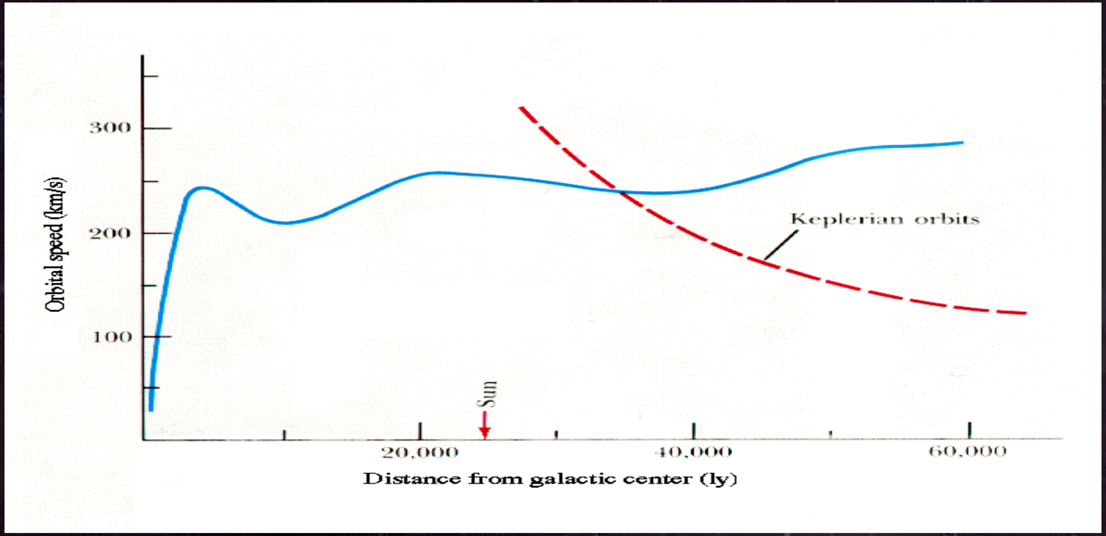
Using all the distance indicators discussed eventually allows us to estimate the Hubble Constant. The generally accepted value is about 70 km/s/Mpc.

Once it is known, then for very distant galaxies, measuring the redshift gives us an idea of the distance.

Dark materials...

Have mentioned galaxy rotation curves, and Type Ia supernovae. These have been the clues that the universe contains two extremely mysterious things – *dark matter* and *dark energy.*

When looking at a distant galaxy, if you assume that its *luminosity* is a good tracer of its *mass* (ie the brighter a part of the galaxy, the more mass there is there), then you cannot understand its rotation curve. It should not be flat but should be approximately *keplerian*.

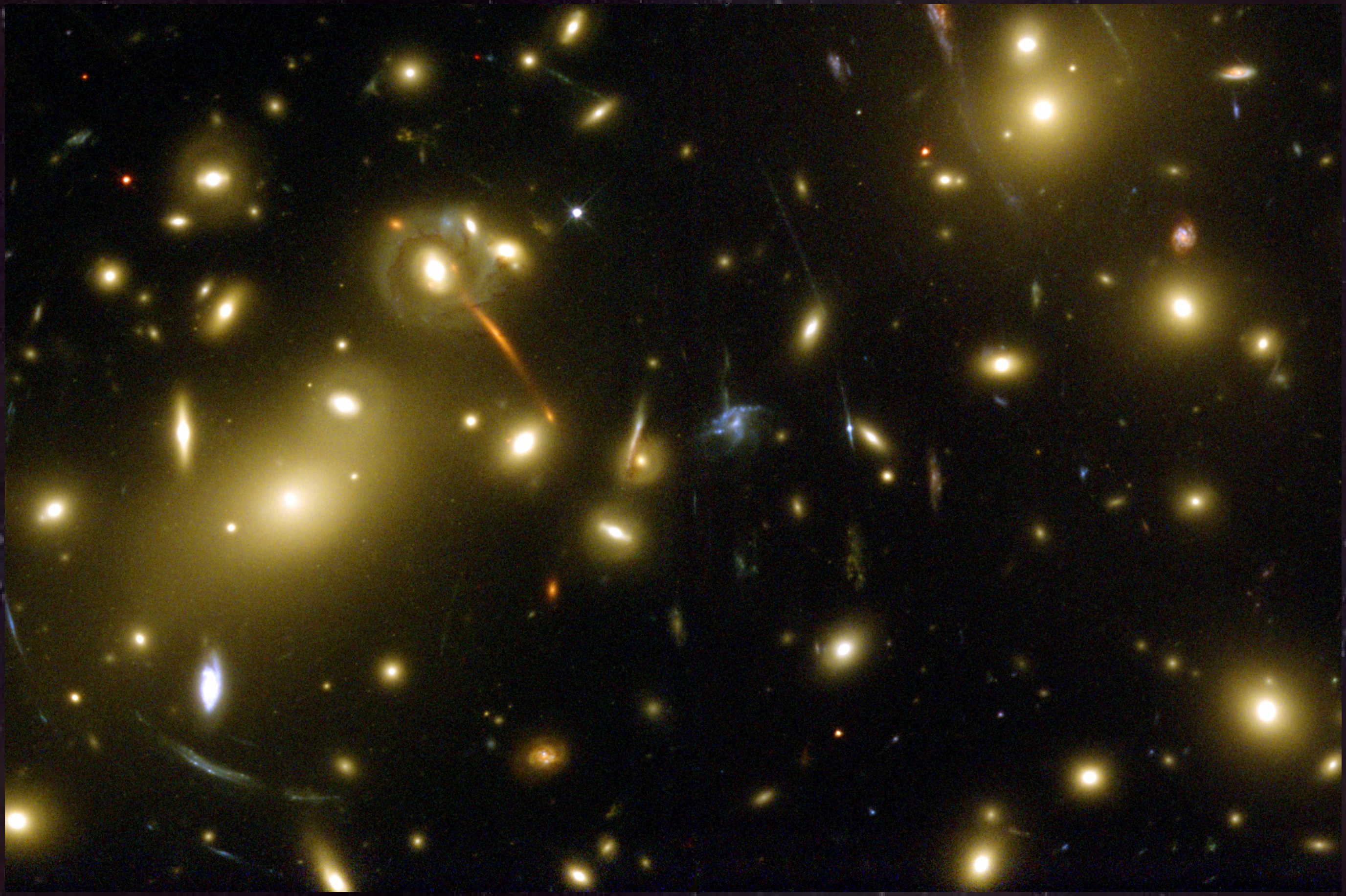


Dark materials...

Also, when looking at clusters of galaxies, Fritz Zwicky noticed in 1933 that the galaxies in the Coma cluster were moving far too fast to be gravitationally bound, unless there was a huge amount of mass in the cluster that was not emitting light.

Dark materials...

Clusters of galaxies can bend and magnify the light of other clusters of galaxies which are much more distant along the same line of sight. Again, the amount the light is magnified implies that there is a lot of mass in the clusters that we can't see.



Dark matter

It is now clear that 80-90% of the matter in the universe is not matter as we know it. It does not emit any electromagnetic radiation, it does not consist of atoms, and we only know it is there from its gravitational effect.

There is as yet no clear idea of what dark matter is. It could be *hot dark matter* – particles with a very small mass moving at speeds close to the speed of light. Neutrinos can be classed as hot dark matter, but our current understanding is that they can't possibly account for all the dark matter that is observed

Dark matter could also be *cold dark matter* – Weakly Interacting Massive Particles (WIMPs), or non-emitting objects like black holes or neutron stars, described as Massive Compact Halo Objects (MACHOs).

Dark energy

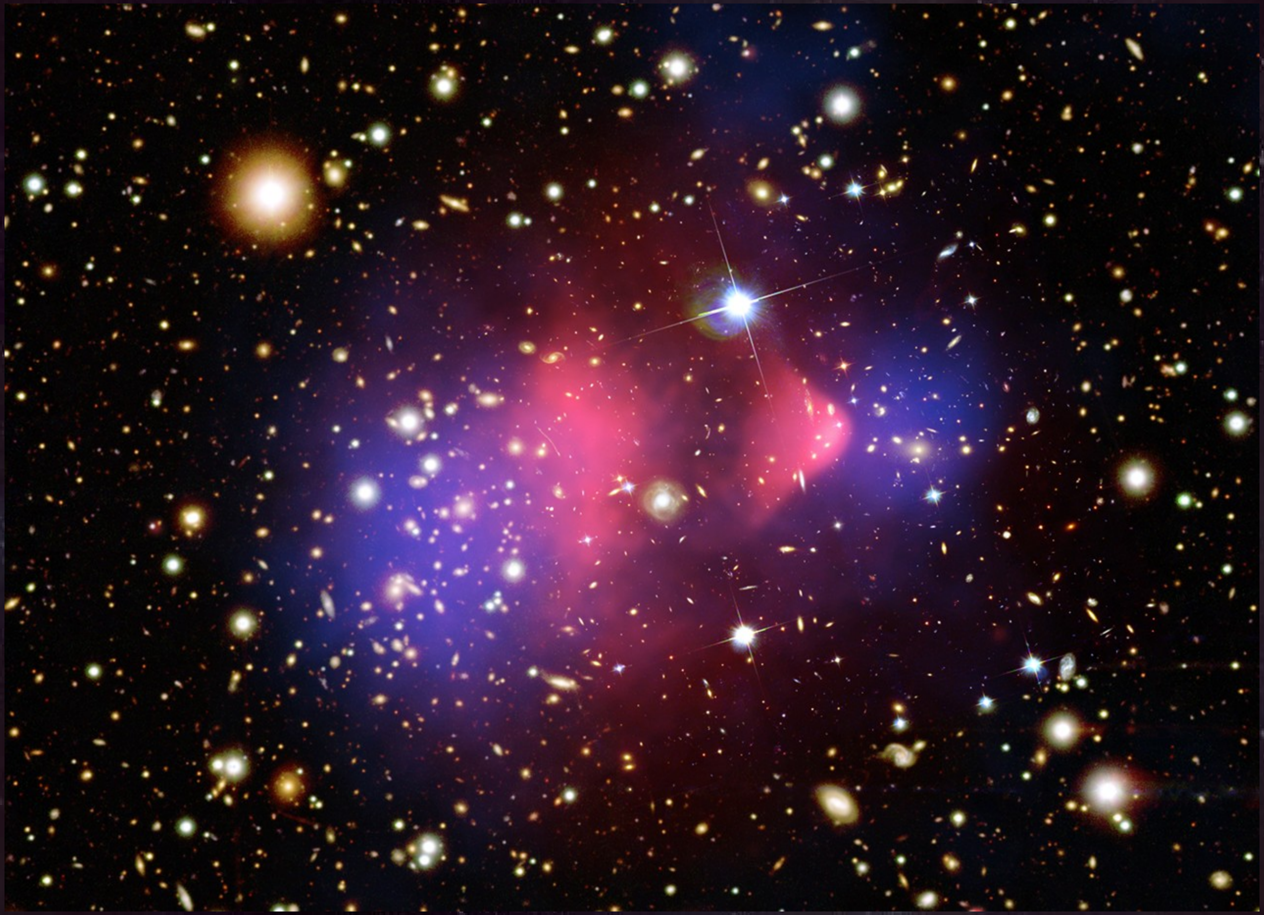
By 1998 it was clear that most of the universe was made of something completely unknown to science. And then things got suddenly worse.

Type Ia supernova are a very reliable standard candle. By observing very distant Type Ia supernovae, astronomers hoped to find out what the ultimate fate of the universe was – would it expand for ever, would it eventually stop expanding and contract, or did it have the critical mass required to just halt its expansion?

The answer – none of the above.

Dark energy

One recent interesting observation was of the Bullet Cluster – colliding galaxies in which the dark matter appears to have been separated from the visible matter by the collision.



Dark energy

The universe's expansion is not slowing down – it is accelerating. Very distant supernovae are always fainter than can be explained by a non-accelerating universe.

The observed acceleration implies that about 74% of the *mass-energy* of the universe is in the form of something that is neither normal matter or dark matter, but *dark energy* – something which is causing negative pressure and counteracting the gravitational force of all the matter in the universe.

Summary

96% of the universe is completely mysterious. Good job – otherwise this course would have lasted 25 times as long..

Any questions?