Lecture_18

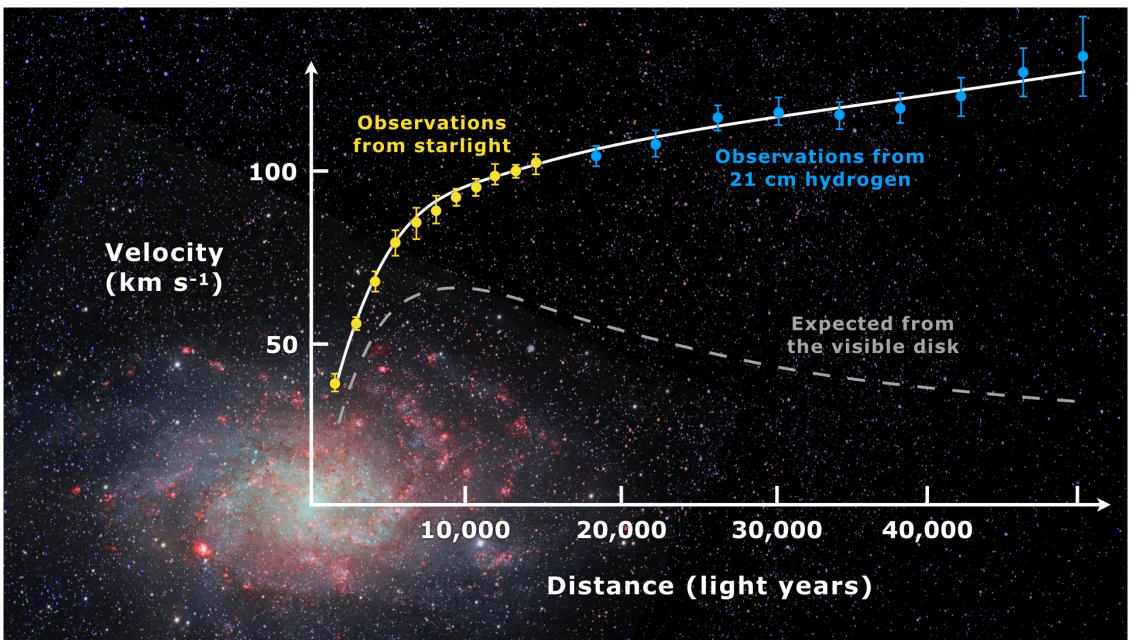
April 11, 2024

1 Galaxy rotation curves

At the very end of the last lecture, we found for a centrally dense galaxy (that is, there is less and less mass enclosed within a sphere of radius R as R increases), the Keplarian velocity of stars should go as

$$v(r) \propto \frac{1}{r^{1/2}}.$$

That is, the further out into the Milky Way we look, the slower stars should be orbiting. This is at odds with the observed rotational velocities of stars (not just in the Milky Way, but throughout the Universe), as shown below.



This shows that the velocity tends towards some near constant value the further out we go. This suggests that the M enclosed must be increasing proportionally to R. This is at odds with the luminosities of these regions, as the lminosity of galaxies drops off very quickly with radius. Thus, whatever matter is being enclosed must be dark - thus, **dark matter**. There are a few candidates for particles that fit the required effects of dark matter, but we won't discuss them here.

1.1 The nucleus of the Milky Way

Within the constellation of Sagattarius, there's a very compact region (a few parsecs wide) that is emitting large amounts of radio and X-ray radiation. These energies of radiation are not normally produced in large quantities by stars, and more often associated with accretion of material on an object. So this suggests that there is some object within the Milky Way centre that is accreting a significant amount of material.

How are we to measure the mass of this object? Recalling that Kepler's 3rd Law can be written as

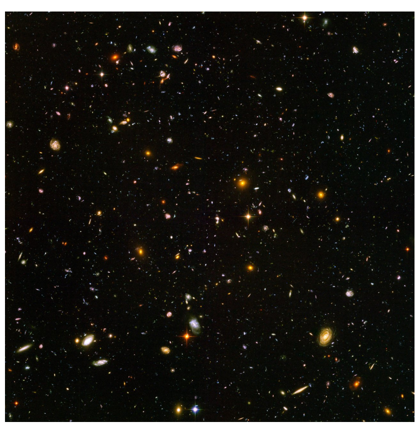
$$M_1 + M_2 = \frac{a^3}{P^2}$$

when the masses are in solar masses, the orbital separation is in astronomical units, and P is in years. There's a particular star that astronomers have been able to track over the last few decades as it orbits the galactic centre. This star, SO-2, has a semimajor axis of $a = 920$ AU (which has been calculated by measuring the size of the orbit in radians, and converting to distance by assuming the galactic centre lies 8.3 kpc away), and has an orbital period of 14.5 years. You can see an animation of this orbit here: https://www.youtube.com/watch?v=1rKF9hFcn_k. Using Kepler's law, we then calculate that the total mass $M_1 + M_2 = 3.7 \times 10^6$ $M_\odot$. Assuming the mass of SO-2 is negligible, this means the object that SO-2 is orbiting has a mass several million times that of the Sun.

There is no other object we can think of squeezing into such a confined space of a few pc and have this mass other than a black hole. As such, this is observational evidnece for a super massive black hole residing at the centre of the Milky Way, and nearly all galaxies. In fact, in recent years, we've managed to get photos of some of them (https://www.eso.org/public/news/eso1907/).

2 Galaxies

Between September 2003 and January 2004, the Hubble space telescope spent a total of 11 days observing an apparently blank patch of sky. The image of this field after combining all of these data together is shown below, and goes to show that it was not such a blank field of space. (Image credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team).

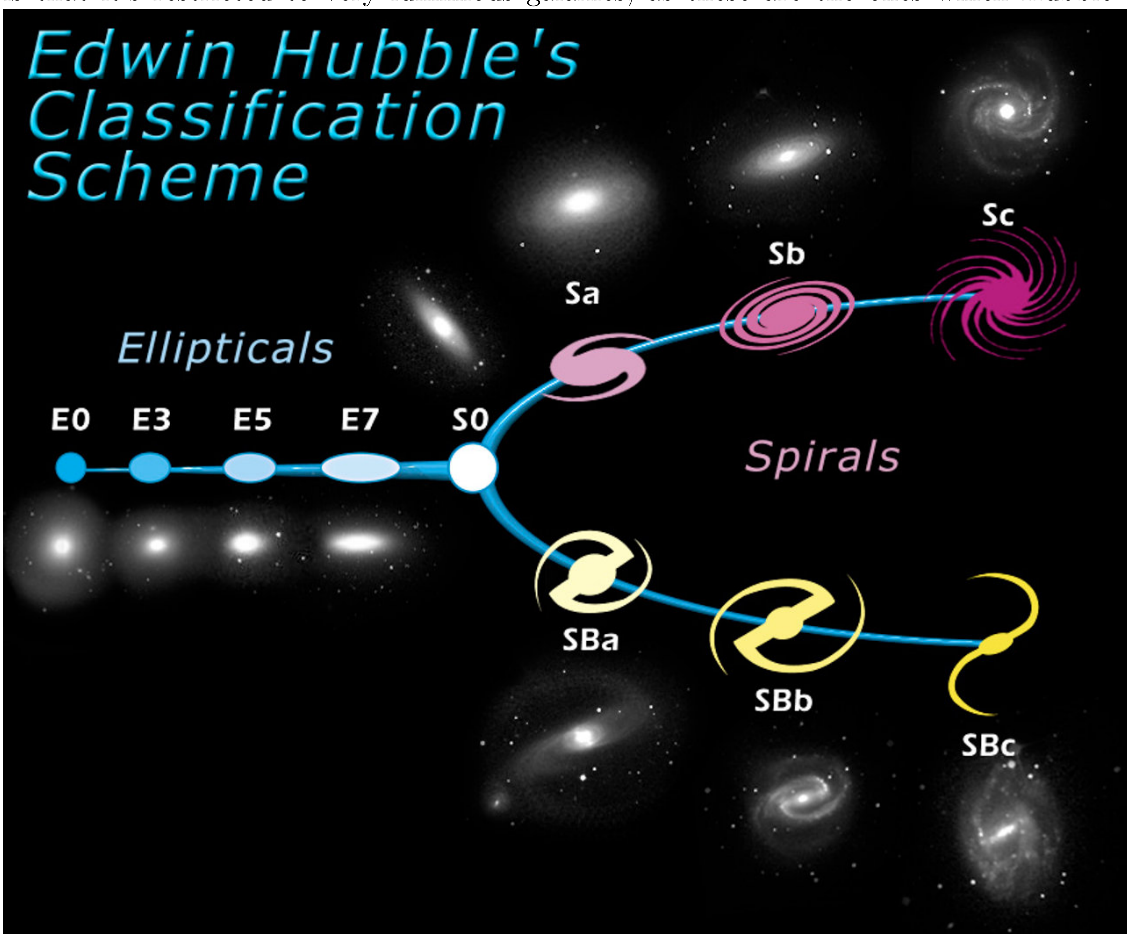


There are a couple of key take aways from this image. First, there are roughly 10,000 galaxies in this image which has a field of view of 3 arcmin X 3 arcmin. Assuming that this patch of sky is not special in anyway (that is, the Universe is isotropic and homogeneous), it implies that there should be 170 billion galaxies covering the entire night sky.

Second, there are many different types of galaxies visible in this image with different morphologies and colours.

2.1 Galaxy classes

The first attempt to classify galaxies into distinct types was done by Edwin Hubble, who separated the classes by morphology. In his scheme, there are three main classifications: **elliptical**, **spiral**, and **irregular**. Below shows a typical tuning fork diagram, which shows how the classes are related to each other. (Credit: NASA & ESA). The main limitation of this scheme is that it's restricted to very luminious galaxies, as these are the ones which Hubble could see.



Hubble ordered the galaxies in this direction as he assumed that galaxies form as ellipticals and gradually evolve into spirals (which turns out to be wrong...). But this still turns out to be a useful way of classifying galaxies. Let's look at each of the subgroups in a bit more detail.

2.1.1 Ellipticals

Elliptical galaxies are smooth, elliptical blobs with no evidence for dust lanes within them. Assuming they are ellipses, then their shape (semimajor and semiminor axes) can be described by one of:

- The axis ratio $q = b/a$
- The ellipticity $\varepsilon = 1 - q$
- The eccentricity $e = (1 - q^2)^{1/2}$ of the galaxy.

As such, Hubble labelled elliptical galaxies as E**n**, where n was 10 times the ellipticity (so 0 was circular, 7 is highly elliptical). The surface brightness of elliptical galaxies goes as

$$\log I \propto -r^{1/4}$$

2.1.2 Spirals

Spiral galaxies have (obviously) spiral arms, which are most easily seen when the systems are viewed face on. The first person to note the spiral structure of these Galaxies was Lord Rosse using the Leviathan of Parsonstown (in Birr). Every spiral galaxy has a bulge, a rotating disc, and spiral arms within the disc (like the Milky Way). There are 3 principle classes:

- Sa: large bulge, tightly wound arms, little gas or dust.
- Sb: medium bulge, moderately wound arms, some amounts of gas or dust.
- Sc: small bulge, lossely wound spiral arms, lots of gas and dust.

Additionally, if there is a very obvious bar running across the galaxy, then the classification becomes SB. The surface brightness follows the relation

$$\log I \propto -r$$

2.1.3 Irregular

These galaxies lack any regular shape. They are rich in gas, and have substantial amounts of ongoing star formation. The small magallenic cloud is such a galaxy.

2.1.4 Dwarf galaxies

Small, diffuse galaxies which are low in both surface brightness and total luminosity are not included in the above categories as they could not be seen with telescopes at the time Hubble was classifying galaxies. These **dwarf galaxies** are important, as it appears that, like with M dwarfs for stars, dwarf galaxies are the most common type of galaxy.