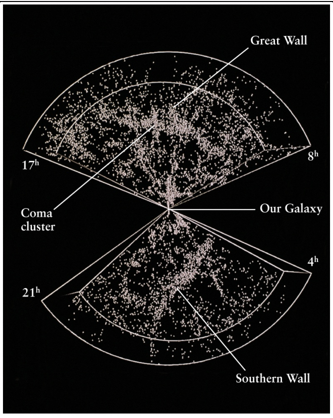
# Lecture 3: Cosmology and the Age of the Universe

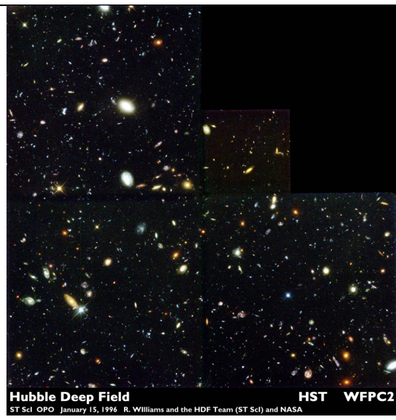
## Large Scale Structure

On the very largest scales, clusters of galaxies are distributed near to other clusters of galaxies, forming what we call “large scale structure” – networks or filaments connecting thousands of galaxies, interconnected through the “cosmic web”, together with vast voids of near-empty space where relatively few galaxies are found.

Galaxies are seen to the limits of observation, as far as the biggest telescopes in the world can see.  The Hubble Deep Field shows that this large scale structure extends across the entire observable universe, in all directions where astronomers have looked.




Large Scale Structure.  Maps of the distributions of galaxies as charted by the world’s most powerful telescope.  They show vast filamentary structures of galaxies – including the “Great Wall”, as well as vast voids with few galaxies in them.




The Hubble Deep Field, as originally imaged by the Hubble Space Telescope.  Every object in this image, covering a tiny field of view, aside from a single foreground star in our Galaxy, is a distant galaxy.  The furthest is over 10 billion light years away from us.

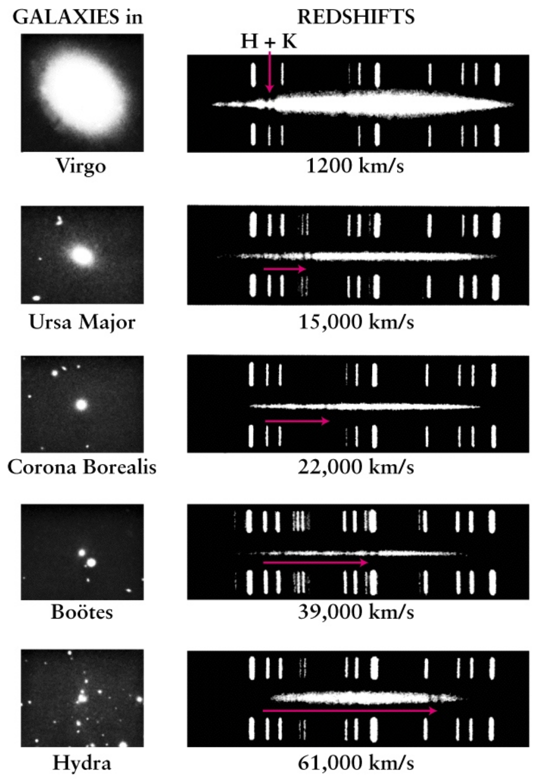
## Hubble’s Law

Edwin Hubble (1929), in one of the great experiments of science, measured:

i. The distances to several galaxies,
ii. Their speeds, as given by the redshift formula.

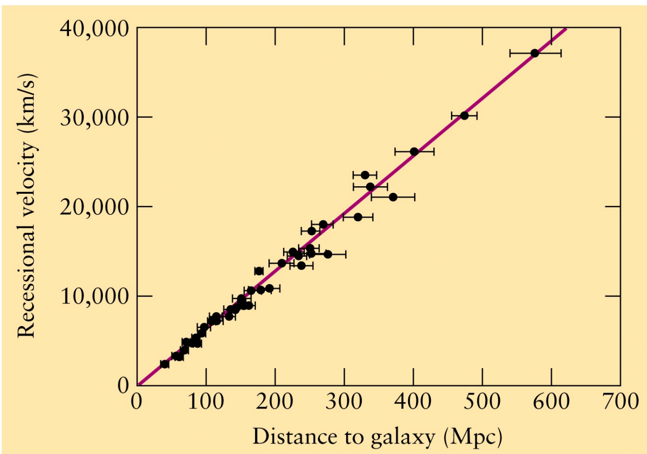
He found two remarkable results:

i. Apart from a few nearby galaxies, <u>all</u> were receding from us,
ii. The more distant the galaxy, the faster it is moving away from us.




Hubble's great experiment. The distances to bright galaxies were measured on the left by assuming that the most luminous galaxy in a cluster of galaxies all have the same luminosity. Hence the apparent size is related to the distance. The redshift was found by measuring emission from calcium lines ("H + K" lines) and used to find the galaxy velocities. Hubble found that the distance of a galaxy is proportional to the speed of recession.

In particular, Hubble found a linear relation between speed and distance.




The linear relation is given by $v = H_0 D$ where $v$ is the velocity and $D$ is the distance.

This is known as Hubble's Law.

$H_0$ is a constant, now known as Hubble's Constant. It measures the rate of expansion of the Universe.

Hubble measured $H_0$ to be 500 km / s / Mpc (or 500 km $s^{-1}$ $Mpc^{-1}$ to use the correct notation).

Today, the best determined value is $H_0 = 73$ km / s / Mpc.

Note that the units of km and Mpc are both distances, so that they can be cancelled to yield Hubble's constant in units of 1/time or $s^{-1}$, as would be expected for a rate of expansion.

$$H_0 = 73\ \mathrm{km/s/Mpc} = \frac{73\ \times\ 1000\ \mathrm{m/s}}{3.0 \times 10^{16} \times 10^{6}\ \mathrm{m}} = 2.4\ \times\ 10^{-18}\ \mathrm{s}^{-1}$$

But $H_0$ = 73 km/s/Mpc is the "natural" form of the unit given that velocities are generally measured in km/s and distances in Mpc for galaxies.

## The Hubble-Lemaitre Law

In 2019 the International Astronomical Union (IAU) decided to recognise the contribution of the Belgian astronomer Georges Lemaitre to formulating our concept of the expanding universe by renaming the law as the "Hubble-Lemaitre Law".

In 1927, two years before Hubble published his famous result, Lemaitre published published a paper (in French) entitled *Un Universe homogeneous de masses constant et de rayon croissant rendant de la Vitesse radiate des nébuleuses extra-galactiques.* In English, this translates to "A homogeneous Universe of constant mass and growing radius accounting for the radial velocity of extragalactic nebulae".

Essentially this is the same result as Hubble's Law – the further an object is away the faster it moves away from us! In his paper Lemaitre provided the first estimate of what we now call Hubble's constant, based on the (rather limited) observations of galaxies then available.

Through a vote of the world's professional astronomers in 2019, the IAU have decided that Hubble's Law should now be known as the Hubble-Lemaitre Law, recognising where credit is due in science.

See our Astronotes article at https://armaghplanet.com/the-hubble-lemaitre-law-recognising-where-credit-is-due-in-science.html (or go to http://armagh.space and find the link to Astronotes on the top menu bar and then search for Lemaitre) to learn more!

## The Age of the Universe

Suppose that the rate of expansion of the Universe is constant.
i.e. that $H_0$ really is a constant, and is not changing with time as the Universe evolves.

Then, at some distant time in the past, all the galaxies were "together";
i.e. the Universe had a beginning!

Suppose this happened at a time $T$ ago.

Then, a galaxy moving away from us at speed $v$ is now at a distance $vT$ from us.

We know that $v = H_0 D$
so $vT = H_0 DT$
But since $D = vT$
then we have $1 = H_0 T$.
$\therefore T = 1/H_0$

i.e. the Age of the Universe is given by $1/H_0$.

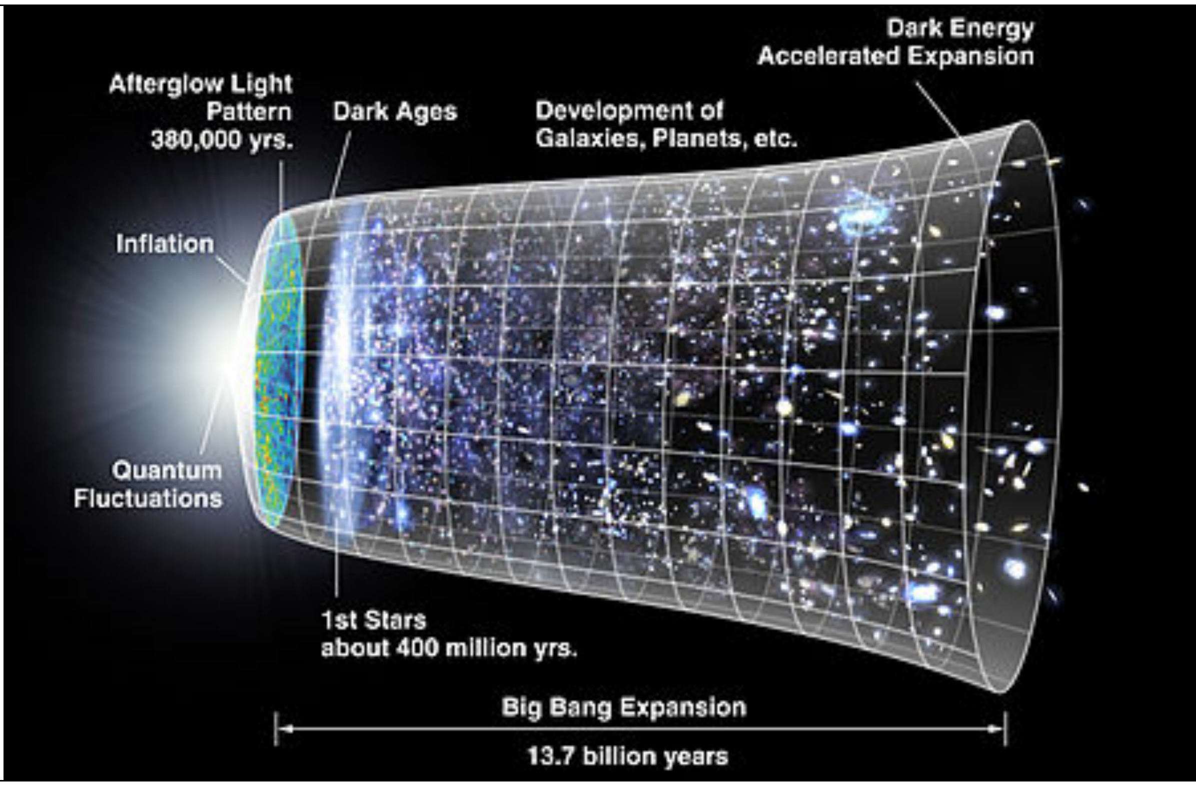
Thus $T = \frac{1}{2.4\times10^{-18} s^{-1}}$

But 1 year = $3.16 \times 10^7$ s (roughly 24 x 60 x 60 x 365¼ s).

So that $T = \frac{1}{3.16 \times 10^7 \times 2.4\times10^{-18}}$ yr = $1.3 \times 10^{10}$ years = 13 billion years.

The rate of expansion of the Universe is not actually constant with time. Astronomers now have the ability to measure how it changes. Our current best determination for the age of the Universe, taking this into account, is 13.77 ± 0.059 billion years. So our simple linear estimate is remarkably close!

In fact, we now believe that the rate of expansion is actually increasing! i.e. that the Universe is accelerating as it grows older, driver by a mysterious "dark energy" which we don't yet know anything about?? This is perhaps the biggest mystery in science today?!




Schematic diagram illustrating the *entire history of the Universe*, from the time of the Big Bang to the present day, 13.7 billion years later. Initially there was an extremely rapid period of expansion (known as "inflation"). The Universe has been exanding steadily since then, for most of the past 13 billion years, as stars and galaxies have formed. However, relatively recently the rate of expansion appears to have increased, driven by a mysterious "dark energy" whose nature we do not yet understand. Perhaps you might be able to solve this mystery one day?!

*Note: you do not need to know this for A Level Physics!*