1

Introduction for non-astronomers

1.1 Our expanding universe

The universe began about 13 thousand million years ago, in a hot Big Bang. During a brief period known as “inflation”, which lasted only for a tiny fraction of a second, the universe expanded rapidly. Immediately after inflation, the rate of expansion dropped dramatically; but the universe continued to expand slowly. The universe then coasted for the next 9 thousand million years. During all that time however, this expansion was being gradually slowed by the gravitational attraction of the universe’s own contents, which was trying to pull it back together. The gravity of normal “baryonic” matter (which includes stars, dust, and everything else that we can see around us) was being helped in this task by an additional component of invisible “dark matter”. Although dark matter seems to have the same gravitational attraction as baryonic matter, it does not emit light, at any wavelength. This makes it very difficult to detect directly, and it is only by the indirect gravitational influence of dark matter that we know it is there at all.

During this slow overall expansion, small, isolated pockets of mass began to collapse. The first stars and galaxies were formed from clouds of hydrogen in the early universe. Figure 1.1 shows galaxies after about 6 thousand million years of evolution, some already with spiral arms that resemble those in the modern Milky Way. As more galaxies were created, their random motions within the universe brought them into collisions with their neighbours. Galaxies merged, a process that further changed their shapes; and galaxies joined together into gravitationally-bound groups or clusters. This hierarchical growth has continued until today, creating a complex filamentary network of large-scale structure, from the bottom up. The most massive objects in the universe are now giant super-clusters of galaxies, each having captured several thousand individual galaxies and weighing some 100-1000 billion times the mass of the sun.

Around 4 thousand million years ago, the universe appears to have entered a new and unexpected stage of evolution. By that time, the universe's expansion had diluted both its baryonic and its dark matter content. As the influence of their gravity weakened, a previously unnoticed form of mass-energy began to emerge into dominance from underneath it. Frustratingly, this substance is again not directly visible, and it has been given the equally unilluminating name "dark energy". The properties of dark energy are less-understood and even more peculiar than those of dark matter. For instance, it has a strange negative pressure. This acts like a source of anti-gravity, and is beginning to re-accelerate the expansion of the universe, long after the big bang. Science fact can indeed turn out stranger than science fiction!

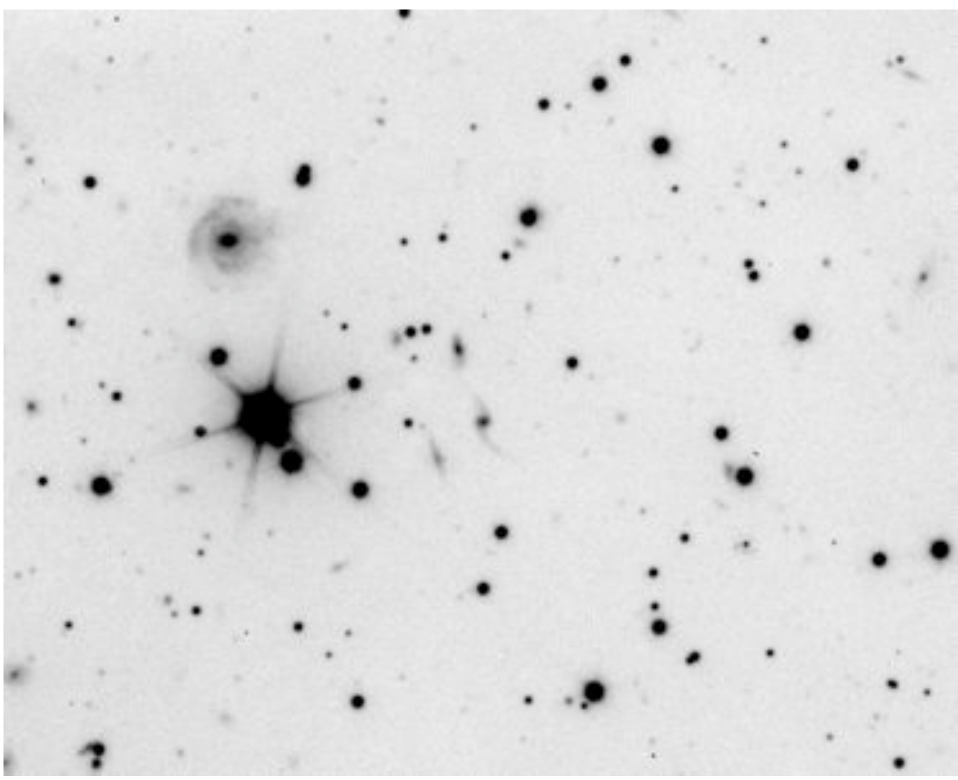

Figure 1.1: A deep image of the night sky taken with the 10m Keck telescope on Mauna Kea, Hawaii. The large, hexagonal object is a bright foreground star; everything else is a distant galaxy. Because of the finite speed of light, we see these galaxies as they would have looked a long time ago. The faintest objects are from the early universe and are the progenitors of galaxies like the Milky Way. The size of this whole image is just 2×1.5 minutes of arc: It would take almost 300 of these patches to cover the full moon.

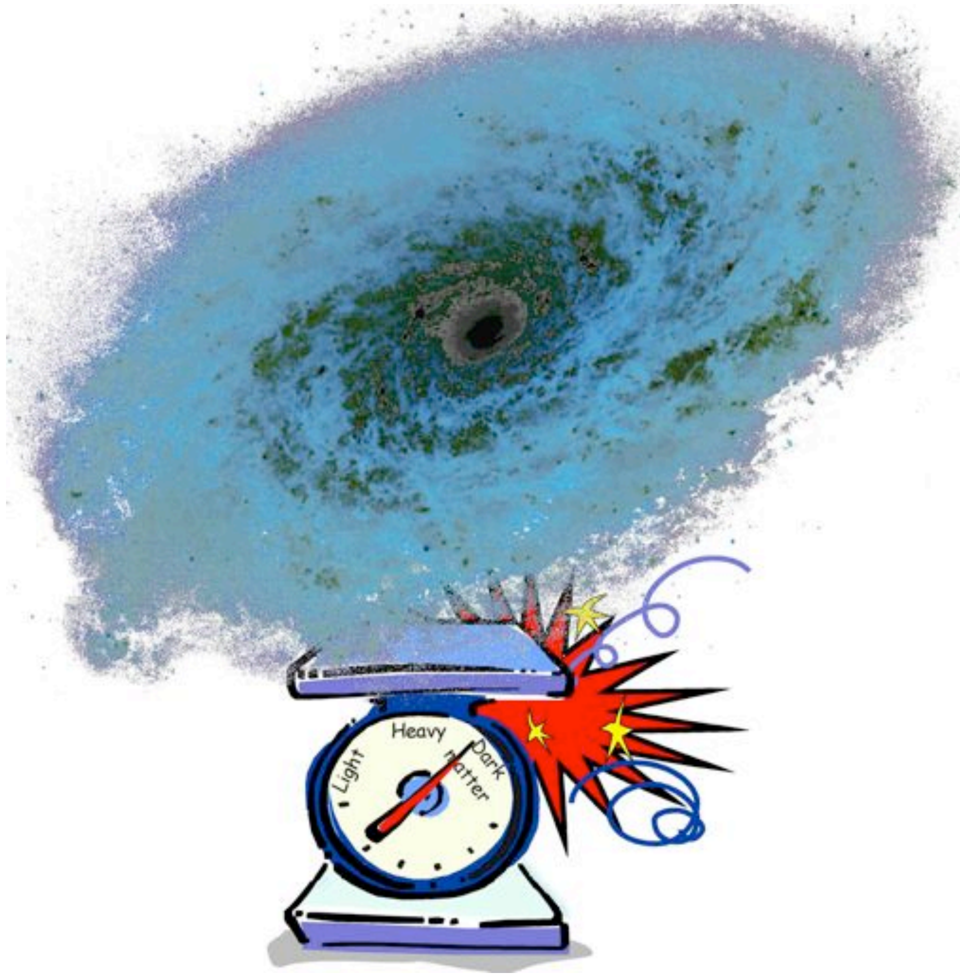

Figure 1.2: An increasing number of astrophysical phenomena cannot be accounted for if the mass in the universe were limited to the normal "baryonic" matter that forms stars and shines in the night sky. Spiral galaxies like NGC 4414 (Hubble Space Telescope image courtesy of NASA)spin around too fast at their edges. Whole galaxies stay gravitationally bound within clusters, despite reaching speed that ought to fling them out. All of these objects, and the universe itself, must contain an extra and mysterious component of invisible "dark matter". There is about five times as much dark matter in the universe as there is baryonic matter: enough to also affect the overall evolution of the universe.

1.2 The dark side of the universe

Normal baryonic matter makes up only about a sixth of the mass in the universe today, distributed amongst dust clouds, stars and galaxies. This amount is insufficient to account for an increasing array of astrophysical phenomena without an additional component of dark matter. For example, spiral galaxies like the Milky Way or galaxy NGC 4414 (shown in figure 1.2) spin around faster at their edges than would be possible if they only contained the mass within their visible stars. Clusters of galaxies must also be far more massive than they seem from counting just their visible light, because the galaxies in them sustain velocities that would otherwise fling them out of the cluster.

And if the entire mass of the universe were limited to only the visible galaxies and clusters of galaxies, the rapid expansion started by the Big Bang could not yet have been sufficiently slowed for the world around us to be assembled. Indeed, if there turns out to be a lot of dark matter, the expansion of the universe will eventually stop, and it will collapse back in on itself for a "Big Crunch" in another few tens of thousand million years. On the other hand, the new dark energy component may instead re-accelerate the expansion of the universe, and eventually tear it apart in a "Big Rip"!

We are left with the unsettling prospect that our fate, along with some 83% of the mass in the universe, is of completely unknown form. Theories in cosmology and astrophysics are chiefly able to deal with just mass and gravity; they cannot therefore distinguish between baryonic and dark matter. Dark energy is even further beyond everyday experience, and it is a bewildering coincidence that mankind has evolved at precisely the same moment that dark energy becomes important. Standard physics does not yet have a satisfactory explanation for either of these substances. Indeed, we know neither *what* they are, nor even exactly *where* they are!

I shall not be able to directly investigate the nature of dark matter or dark energy in this thesis, but I will examine how much dark matter there is, and begin to find out how it is distributed. Is it spread thinly but everywhere, in a uniform soup? Or is it clumpy, with substructure like clusters, walls and voids? The first port of call in any exploration has always been to draw a map of the unexplored territory, and to figure out the size of whatever it is that we're up against. In the search for dark matter, the map will certainly be large, and the "You Are Here" sign is going to be right at the centre. We shall embark on this exploration using a technique rooted in Einstein's theory of General Relativity, but which has only been of practical use within the last ten years. Recent advances in telescope technology and the improved precision of optical instruments have made this measurement possible.

1.3 Using gravity to look around corners

Of all the theories drummed home by earnest physics teachers, the first one to forget is that light always travels in straight lines! Although this is certainly true most of the time, it is not always necessary. And the reason for this comes down to the way that gravity works. Gravity goes one better than dropping apples onto unsuspecting scientists' heads. According to general relativity, gravity in fact bends the entire fabric of the universe!

A common way to demonstrate this bending needs a big sheet of rubber (see figure 1.3). The rubber sheet represents a two-dimensional slice through space. When the mass of a planet or a star is placed in the centre of the sheet, the rubber sheet stretches, and the grid drawn upon it is warped. In figure 1.3, the central mass has sunk out of view. A second massive body is illustrated by the yellow sphere. This experiences the

Figure 1.3: Rubber sheet analogy to describe the distortions wrought into the fabric of space and time by the action of gravity. A mass in the centre of the grid, which has sunk out of view off the bottom of the image, has stretched space around it like a sheet of rubber. A second mass, shown as a yellow sphere, will either fall into or orbit around the first mass, depending upon its initial velocity along the sheet. But because the very universe has been distorted, so is everything within it: not just falling apples and orbiting planets, but even the previously straight paths of light rays.

curved space around the first object as gravitational pull towards the centre. An apple would fall towards the centre of the Earth. A planet would either fall into the sun or orbit safely around it, depending upon its initial velocity along the sheet.

But gravity is more subtle than that. Since the entire fabric of the universe has been stretched, *every* part of the tapestry woven into it becomes distorted. This even includes rays of light. The light paths that were once straight lines now also curve towards the central mass. For example, a black hole is just an object so extremely dense that nearby light paths are curved right in on themselves, so the light can never escape. Near a massive object, it is therefore possible to see around corners. The first experimental confirmation of this theory came during a solar eclipse in 1919. It is obviously impossible to see stars next to the sun most of the time. But when the moon passed in front of the sun, and the sky went dark, their positions could be measured. Stars near the sun had moved slightly from their normal positions, because the sun's gravity was deflecting their light. In fact, light rays which graze the surface of the sun are bent by $1.75''$, or 0.0005°. Modern techniques using radio telescopes to accurately determine the positions

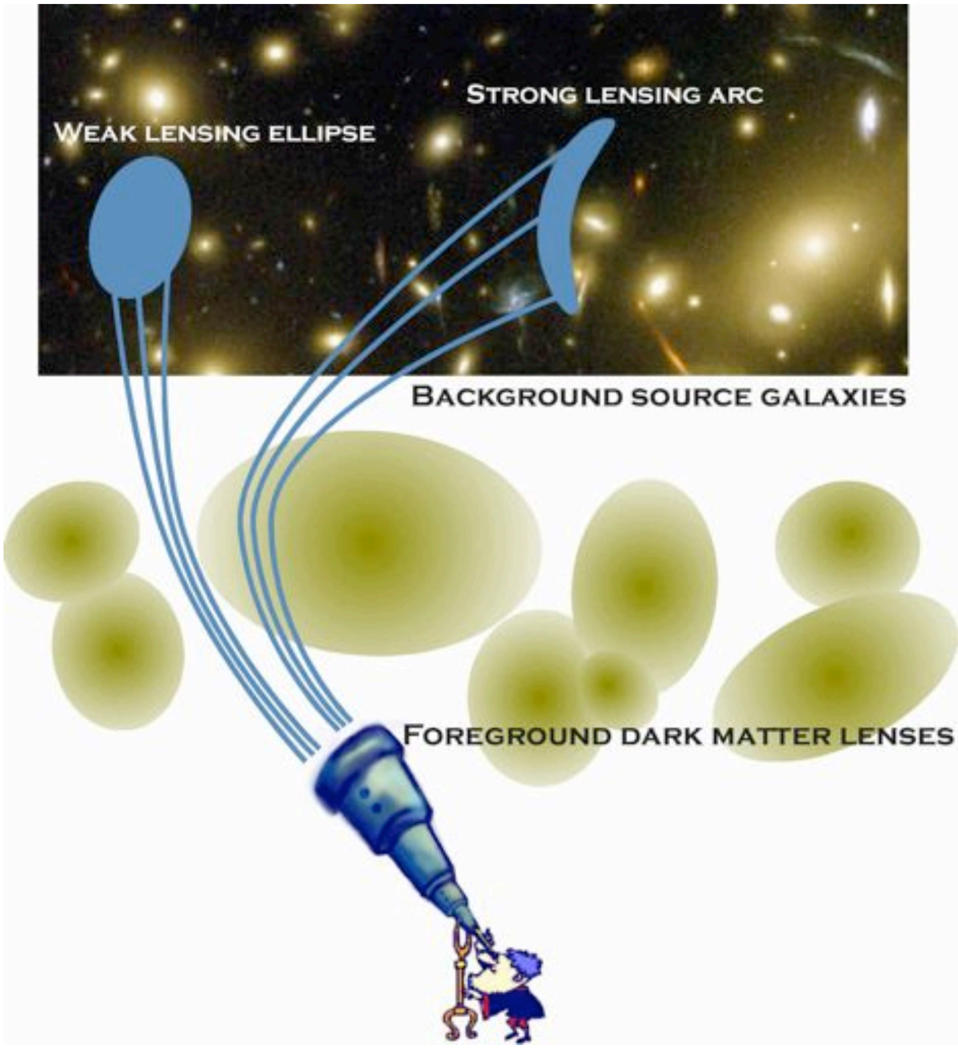

Figure 1.4: Exaggerated cartoon illustrating the effect of gravitational lensing. Foreground dark matter haloes around galaxy clusters deflect the light paths from background galaxies and distort their shapes. A circular source in the "weak lensing" regime around the outskirts of a cluster is stretched into an ellipse observed from Earth. If the light passes through the "strong lensing" regime near the centre of a cluster, the source can be highly distorted into giant arcs and multiple images. In the background is a Hubble Space Telscope image of cluster Abell 2218 (source: NASA).

of stars have confirmed the theory with astonishing precision.

Crucially, this light deflection is due only to the gravitational pull of the central object. As that mass increases, light is deflected through larger and larger angles. And because gravity does not distinguish between baryonic matter and dark matter, a measurement of this effect will be sensitive to the *total* mass of an object, irrespective of its nature and composition. Now that our telescopes are capable of measuring the small angles involved, we can explore the universe in ways that were previously unavailable to astronomy. Using just basic geometry to work out some deflection angles, we can map out the otherwise invisible distribution of dark matter.

1.3.1 Strong gravitational lensing

The distortion of light rays is greatest near massive clusters of galaxies like Abell 2218, which is shown in the background of figure 1.4. This cluster is so massive that the light from galaxies behind it has been deflected through angles large enough to stretch their images into arcs. In fact, each background galaxy may be visible as several distinct arcs, like the “multiply-imaged” pair of light blue objects in the top right-hand corner. In this case, there were at least two different routes that the light could take around the cluster and still get deflected towards the Earth. If a background galaxy is lined up exactly with the foreground cluster, light from it can take any route around the intervening mass, so the arcs stretch into a full circle known as an *Einstein ring*.

Gravitational light deflection is known as “lensing” because a similar bending and focussing of light also happens in the lens from a pair of spectacles or a magnifying glass. The arcs in figure 1.4 have also been highly magnified by the gravitational lensing of cluster Abell 2218. A massive cluster acts like a giant natural telescope, enabling us to see fainter or more distant objects than is otherwise possible. The arcs are indeed much farther away than similarly bright objects elsewhere in the figure. That extra distance makes this picture fascinating, because the finite speed of light means that its light has taken a long time to reach us. In fact, light from the faintest arcs around Abell 2218 left a galaxy up to 12 thousand million years ago, letting us directly observe conditions in the very early universe.

1.3.2 Weak gravitational lensing

Clusters of galaxies are relatively rare objects. To measure the *average* density of the universe today, we need to look away from clusters and find a more representative sample. The large-scale distribution of galaxies has already been investigated using surveys like the Anglo-Australian Telscope’s “2dF” survey, named after the instrument’s 2 square degree field of view. Results from 2dF, reproduced in figure 1.5, show that galaxies are distributed in a cellular network, with small concentrations making up filaments and walls around huge empty voids.

The network of 2dF galaxies roughly trace the foreground mass distribution, which gravitationally lenses background objectss — although in less spectacular style than around massive clusters. Light gets only slightly deflected when it passes through the large-scale structure or the outskirts of a cluster. In the same way that text appears distorted when it is viewed through the edge of a cheap magnifying glass, the images of distant galaxies appear slightly stretched in one direction. All distant galaxies are viewed through this ubiquitous network, and weak lensing makes any deep observation seem like a view through a distorted window pane, or one of those terrible glass bricks used in 1970’s bathrooms.

The small distortions created by weak gravitational lensing are not visible to the naked eye, and are not detectable in the image of any individual galaxy. The distortion has to be measured statistically, by averaging the shapes of many distant galaxies in a patch of sky. The galaxies' own spiral or elliptical shapes cancel out when they are averaged, and produce a circle. However, if the shapes of adjacent galaxies have all been elongated a little *in the same direction*, the residual after averaging will instead be an ellipse like that shown in figure 1.4. From the orientation and axis ratio of such ellipses, it is possible to infer the intervening mass along a lone of sight. The mass can then be mapped out to determine the location of dark matter clumps, and analysed statistically to measure the total weight of the universe.

At the risk of spoiling the ending, but to save your searching through the rest of this thesis, I shall give away the answer. The average density of the universe is approximately 10^{-23} grams (about one hydrogen atom plus five equivalent units of dark matter) per cubic metre. That might not seem much, but then the universe is *very* big!

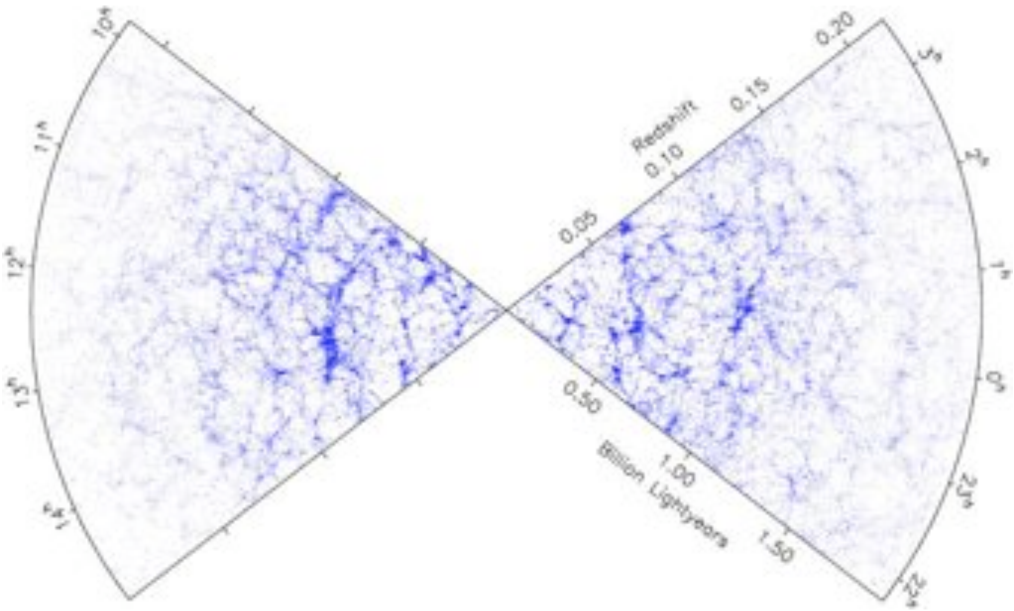

Figure 1.5: The large-scale structure of the universe seen by the Anglo-Australian Telescope 2dF Galaxy Redshift Survey (Colless *et al.* 2001). The Earth is at the centre, and every blue dot represents the location of a galaxy in two thin slices extending out into the universe. The observed density of galaxies decreases far away from the Earth because they appear fainter and are more difficult to detect. Notice the cellular and filamentary patterns in the distribution of large-scale structure. These all act as small gravitational lenses, distorting light rays from background galaxies as they navigate through this network to produce the cosmic shear effect.