1.4 Observational cosmology

The fate of the Universe is controlled by the parameters Ω_m, Ω_r, and Ω_Λ which, according to current theories, define the composition of the "stuff" that makes up our Universe. The quest for these three numbers takes up a large fraction of observational cosmology. In this search, a wide range of techniques from physics and astronomy have been brought to bear; we have already seen how gravitational lensing has been used to search for MACHOs and to measure the dark matter in clusters of galaxies. Later in this segment we will examine in detail methods using the Cosmic Microwave Background. Here we quickly review the other important methods.

1.4.1 The particle zoo

To start with, what can physics tell us about the contents of the Universe? There are hundreds of different types of subatomic particles known, but most of them disintegrate in a fraction of a microsecond. In cosmology we are only interested in stable particles, and this gets us down to the following:

- electrons
- protons (which are, of course, the nuclei of hydrogen atoms)
- neutrons; on their own, neutrons disintegrate in about 11 minutes, but they can be stable if bound together with protons in the nucleus of an atom.
- three different flavours of neutrino (each with its anti-neutrino).
- photons.

In addition to particles, gravitational waves may contribute a significant energy density to the Universe, especially at early times.

Protons and electrons are equally numerous: there is no net electric charge in the Universe; otherwise, electric repulsion would overwhelm gravity, and planets, stars and galaxies would disintegrate (or rather, could never form). Cosmologists refer to ordinary matter made of electrons and atomic nuclei as **baryonic matter** (a misuse of a term from particle physics). In principle anti-matter, made of anti-protons, etc., is also stable, but if there was any significant amount of it in our Universe we would see a lot more gamma-rays from matter-anti-matter annihilation.

Neutrinos are the lightest known stable particles, apart from photons. They have no electric charge and only interact with each other and other types of matter via gravity and the weak nuclear force, which makes them very hard to detect. For a long time it was thought that they had zero rest mass, and therefore, like photons, moved at the speed of light. Within the last year it has been confirmed that neutrinos do have a finite mass, which means that as they lose energy in the expansion of the Universe they should eventually become non-relativistic and count as matter.

In other words, according to known physics, the stuff in the Universe consists of baryonic matter (which contributes to Ω_m), photons and gravitational waves (which contribute to Ω_r), and neutrinos and anti-neutrinos (which contribute to Ω_r at early times and later to Ω_m).

1.4.2 Photons (and neutrinos)

We can directly observe the photon content of the Universe. Ninety percent of the photon energy is in the Cosmic Microwave Background, which has an energy density of 4.20×10^{-14} Jm^{-3}, corresponding to $\Omega_{photon} = 1.22\times10^{-5}$. This is negligible today but these photons have been conserved since the Big Bang, and extrapolating back in time they become very important at $z > 10^4$. The other 10% of the photon energy density has been generated by stars and quasars over the history of the Universe. These photons tell us everything we can know about the early history of the galaxies, but their energy density has always been negligible, because the earliest of these photons were generated after $z \approx 10$.

According to big bang theory, neutrinos and antineutrinos should have nearly matched photons for energy density in the early Universe: $\Omega_\nu = 0.681\,\Omega_{photon}$. Using the lower limit for the neutrino mass from recent experiments, the present $\Omega_\nu > 10^{-3}$; on the other hand, almost certainly $\Omega_\nu < 0.1$, or neutrinos would have had a visible effect on the large-scale structure.

1.4.3 Matter

1.4.3.1 Observing Baryons

Stars are the most obvious form of baryonic matter in the Universe. In the Solar System, the Sun contains 99.87% of all the baryons, so it was once hoped that a plausible way of measuring the baryonic density would be to measure the total amount of starlight and hence work out the typical density in stars. Both the measurement and the calculation are very tricky, and so it was something of a relief when it became apparent at the end of the 20th century that in fact the majority of visible baryons are *not* in stars but in clouds of intergalactic gas.

For instance, in clusters of galaxies the gas has a temperature of 10^7 to 10^8 K, and emits X-rays which allow us to measure it quite accurately (Fig. 1.13) The total mass in gas is typically around ten times the mass in the stars of the galaxies within the cluster. Outside clusters, the gas is much cooler ($\leq 10^5$ K) and so radiates much less, but it produces absorption lines in the spectra of distant quasars, which allows us to estimate the total mass.

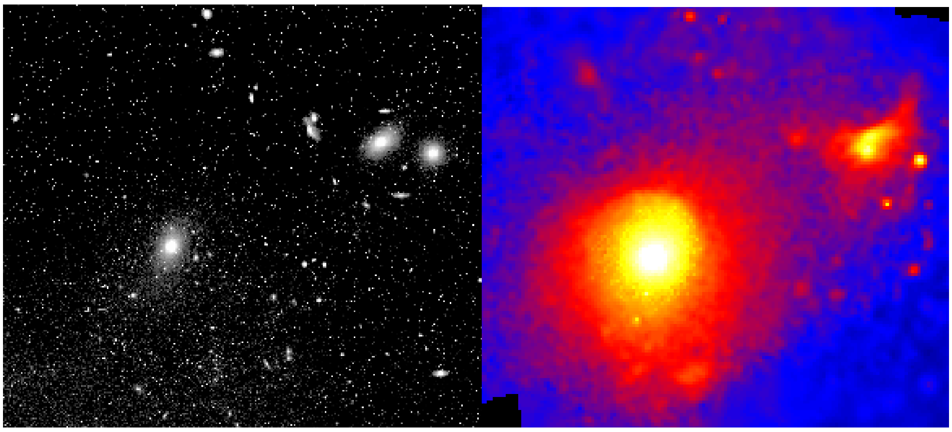

Figure 1.13: A cluster of galaxies as seen through an optical telescope (left, from the Digital Sky Survey), which detects starlight from the individual galaxies, and through the ROSAT X-ray telescope (right) which detects emission from the hot gas between the galaxies. Most of the baryonic mass in the cluster is in the gas, not the stars.

A recent assessment of data on the "visible" baryonic matter including both stars and gas gave $\Omega_{baryon} \approx 0.02$ (Fukugita et al. 1998). This is dominated by a rather uncertain estimate of intergalactic gas in typical groups of galaxies like our own.

1.4.3.2 Weighing the Universe

As well as directly observing radiation from matter, we can track its presence by looking at its gravitational effects. The attempt to do so in other galaxies is described by Strobel, and leads to the conclusion that the large majority of the mass of galaxies is **dark matter**.

We can apply the same equations on a larger scale, looking at the random motion of galaxies in clusters of galaxies. We can also use atoms in the hot gas in clusters (where we get the speed from the gas temperature, revealed by its X-ray spectrum). In the previous part of this course, we saw that the masses of galaxies and clusters can also be measured via gravitational lensing.

On the largest scales, gravity is not strong enough to overcome the Hubble flow, but can affect it. Galaxies are not scattered at random through the Universe, but form a pattern called the **cosmic web** which consists of great filaments and sheets of galaxies, separated by **voids** which seem to contain very little matter (Fig 1.14). Clusters of galaxies form at the joins between filaments. The largest voids are up to 100 Mpc across; only when averaged on scales larger than this is the Universe close to homogeneous. On smaller scales the gravitational force from the dense regions of the cosmic web decelerates the Hubble flow around them, and by the same token increases the flow out of the voids, so there is a net flow of matter from voids to sheets, sheets to filaments, and filaments to the clusters. These flows add "peculiar redshifts" to the cosmological redshift, which can be estimated in two ways. The simple one is to subtract $H0r/c$ from the observed redshift (Fig. 1.15); uncertainties in the distance r make the resulting values rather inaccurate. More subtly, we can analyse the map of galaxies in "redshift space" (Fig. 1.14): peculiar redshifts distort the map in the radial direction only, and we can estimate their amplitude by assuming that in reality the pattern is statistically isotropic. Either way, the amplitude of peculiar redshifts allows us to estimate the density of matter in the cosmic web.

All these techniques agree with each other in showing that galaxies are embedded in dark **haloes** which contain hundreds of times more mass that their visible stars, and so substantially more mass than the visible baryons, even including the intergalactic gas. By the same token this matter outweighs the expected neutrino density. Applied to the largest scales, the estimate is $\Omega_m \approx 0.35 \pm 0.1$. What is needed is a form of matter which can be gravitationally bound to galaxies, and is also undetectable by its emission or absorption. To bind to galaxies, random speeds of particles must be less than the escape velocity (typically a few hundred kilometres per second), so the matter is cold ($v \ll c$). We call it **cold dark matter**, or CDM.

This all assumes that Newtonian theory (or GR, which in this context gives the same answers) works on sizes comparable to galaxies and larger. An alternative viewpoint is that the standard theory is an approximation valid on only small scales, and the dark matter is a figment caused by using an incorrect formula. The most developed version of this approach is a theory called **MOND**, for **MO**dified **N**ewtonian **D**ynamics, according to which Newton's 2nd law $F = ma$ breaks down for very small accelerations. Although MOND has been remarkably successful in accounting for the rotation speeds of galaxies, it has not yet proved possible to combine it with other known laws of physics, in particular relativity theory, to make a coherent whole. Most cosmologists find it easier to accept so-far undetected forms of matter than radical revisions to the laws of dynamics. After all, it is not that easy to detect something at a range of thousands of light years.

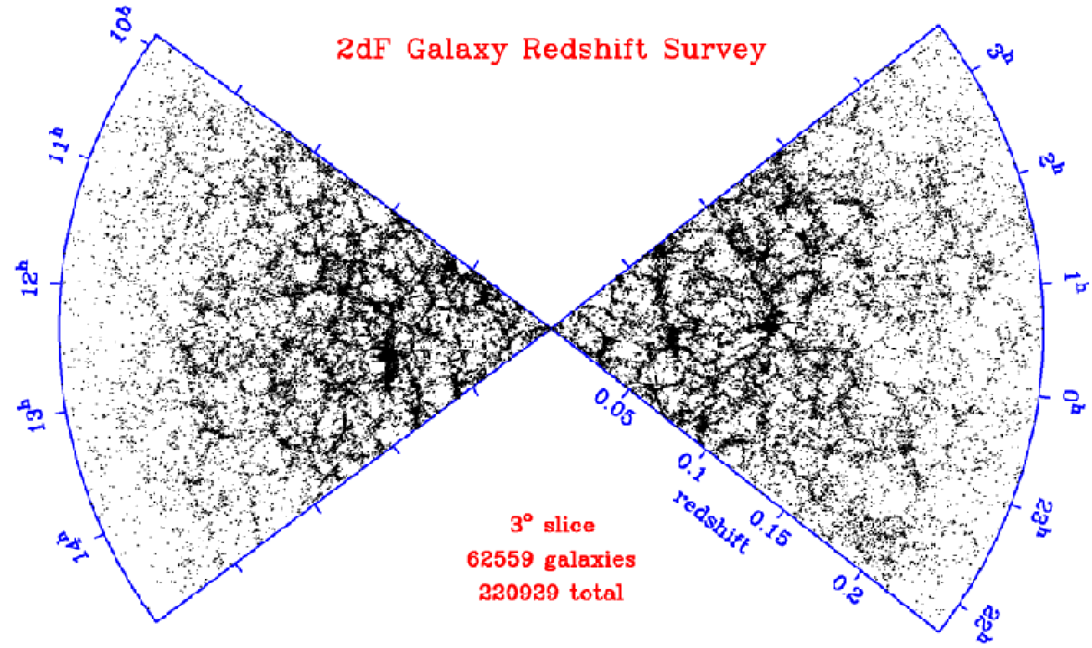

Figure 1.14: A slice through the cosmic web, from the 2dF Galaxy Redshift Survey. The 2dF instrument on the Anglo-Australian Telescope can measure 400 redshifts simultaneously. It is being used to observe 250,000 galaxies along two narrow strips on opposite sides of the sky. The plot shows the positions of the galaxies, placing each at its "redshift distance" $d = cz/H0$. The density of galaxies declines at large distances because only the most luminous galaxies there are bright enough for their redshift to be measured. Credit: John Peacock and the 2dFGRS team. Click here for a larger-scale version.

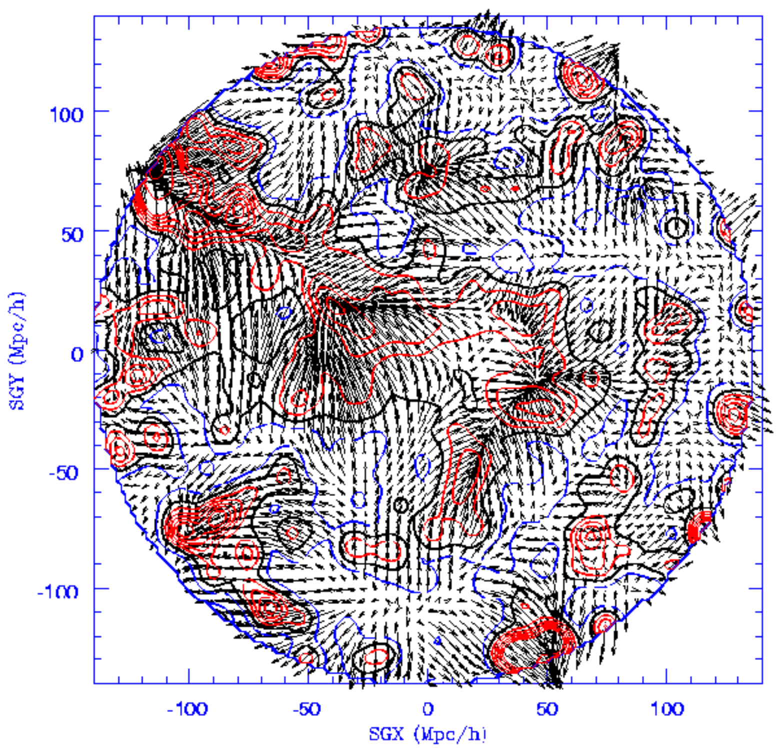

Figure 1.15: The local cosmic flow. This plot represents a slice through space with our Galaxy at the centre. The vectors show the predicted peculiar velocities assuming that the local density of matter is proportional to the density of galaxies. . Click here for a larger-scale version.

1. To escape the conclusion that there is a lot of dark matter, would you have to have acceleration greater or less than F/m?
Answers to question at end of this document.

1.4.3.3 Dark Stars?

Could the CDM be made of baryonic matter? This is very unlikely if the matter is a thin gas filling a large fraction of space, as gas will almost always be visible via either absorption or emission. On the other hand, a large number of dense compact objects such as planets, very low mass stars, burnt-out stars (i.e. **white dwarfs**) or black holes, could lock up vast quantities of mass between them, and yet still be so sparse in space that they never reveal themselves by blocking out a background star. All of these produce very little emission for their mass, and would have been missed by the searches for visible matter mentioned above. They are generically known as **MACHOs**, for **M**assive **C**ompact **H**alo **O**bjects. As we saw in the course segment on Gravitational Lenses, MACHOs in our Galaxy can be detected by gravitational microlensing. As mentioned there, the micro-lenses being detected seem to consist of ordinary low-mass stars or possibly white dwarfs. This work shows that MACHOs can make up at most about 20% of the dark halo of our Galaxy.

There are two other lines of evidence which suggests that MACHOs can account for only a small part of the dark matter. These are techniques which measure the baryon density in the early Universe, generically known as **baryometers**. The first is the theory of **Big Bang nucleosynthesis**, (Section 2.3.3) which predicts that the abundance of helium and other elements formed in the big bang can be related to the present-day baryon density. This approach yields $\Omega_{baryon} h^2 = 0.02 \pm 0.01$. The second baryometer is based on the pattern of fluctuations in the CMB (Section2.6.2). It gives results in close agreement with those from big bang nucleosynthesis.

The baryometer results clearly show that $\Omega_{baryon} \ll \Omega_m$. They do allow a MACHO density as high as that of visible baryons, but uncertainties are so large that it is also possible that MACHOs are negligible compared to the intergalactic gas.

1.4.4 The particle bestiary

We are faced with a dilemma: dynamical measures of mass say that the density parameter is $\Omega_m \approx 0.35$, while combining baryometers with our best understanding of the (so far undetected) cosmic neutrino background and stretching the uncertainties to the limit, known particles could contribute only $\Omega_{baryon} + \Omega_\nu < 0.15$. Almost certainly, any stable particle that was electrically charged or subject to the strong nuclear force would have been discovered in the laboratory by now, since they would interact strongly with known particles. We are therefore looking for a type of particle which interacts with known matter only via gravity, perhaps the weak nuclear force, and perhaps via other weak interactions so far undiscovered. The generic name is **WIMP**, for **W**eakly **I**nteracting **M**assive **P**article. WIMPs would be "dark" by definition, of course.

Particle theorists have invented a large number of particles which fit the bill, such as the axion, axino, gravitino, mirror particle, neutralino, photino, Q-ball, sterile neutrino, sneutrino and more. These so-far imaginary particles appear in theories which attempt to go beyond the "standard model" of particle physics. The standard model explains all known particles and their interactions, but at the cost of several dozen parameters (e.g. particle masses) which have unexplained values, even though they show tantalising signs of some hidden regularity. Since the various particles are predicted by competing theories, at most only a few of them can really exist; and of course there may be real WIMPs which have not yet been thought of. Currently, more than 20 experiments are trying to detect WIMPs from our Galactic halo as they pass through the laboratory.[1.2] So far, no clear detection has been made, but this is not surprising as the experiments are so far barely sensitive enough to succeed on the most optimistic predictions.

To cosmologists the various types of WIMP are interchangeable; the particle physics just provides an excuse to include enough matter to explain the dynamical measurements.

1.4.5 Dark Energy

In 1997, the astronomical world was stunned by unexpected results from two projects to find distant **Type Ia supernovae**, the closest thing to a genuine standard candle that cosmology has to offer. Both groups found that distant supernovae were fainter than expected for their redshift; assuming that the luminosity really is the same for all, they must be further away than expected. The two datasets combined are shown in Fig. 1.16.

What does this tell us? The `expected' distances come from working back assuming the current rate of expansion, and using the redshift to tell us how much the Universe has expanded between the time the light left the supernovae and now (the furthest supernovae were at $z \approx 1$, so this was a factor of around two). As the distance is larger than we thought, the light has taken more time than we thought to get here; in other words, the Universe took more time to expand from half its current size than you would expect from the current rate of expansion. This can only mean that the expansion is getting faster with time, as if there was some anti-gravity force hurling the galaxies apart; as we have seen, we label the mysterious stuff that has this effect as dark energy. We have already seen that the number of gravitational lenses at large distances puts strong constraints on the quantity of dark energy. In Section 2.6.3 we will see how, combined with CMB data, all these constraints give a consistent picture in which dark energy makes up around two thirds of the total present-day energy density in the Universe.

Answers to questions

1. To escape the conclusion that there is a lot of dark matter, would you have to have acceleration greater or less than F/m?

Answer to question

The outer regions of spiral galaxies rotate too fast for the rotation to be explained by the visible matter (c.f. Strobel's notes). To maintain circular motion with speed v requires an acceleration towards the centre of v^2/r, so MOND requires a *larger* acceleration than the prediction of Newtonian theory, $a = F/m$.

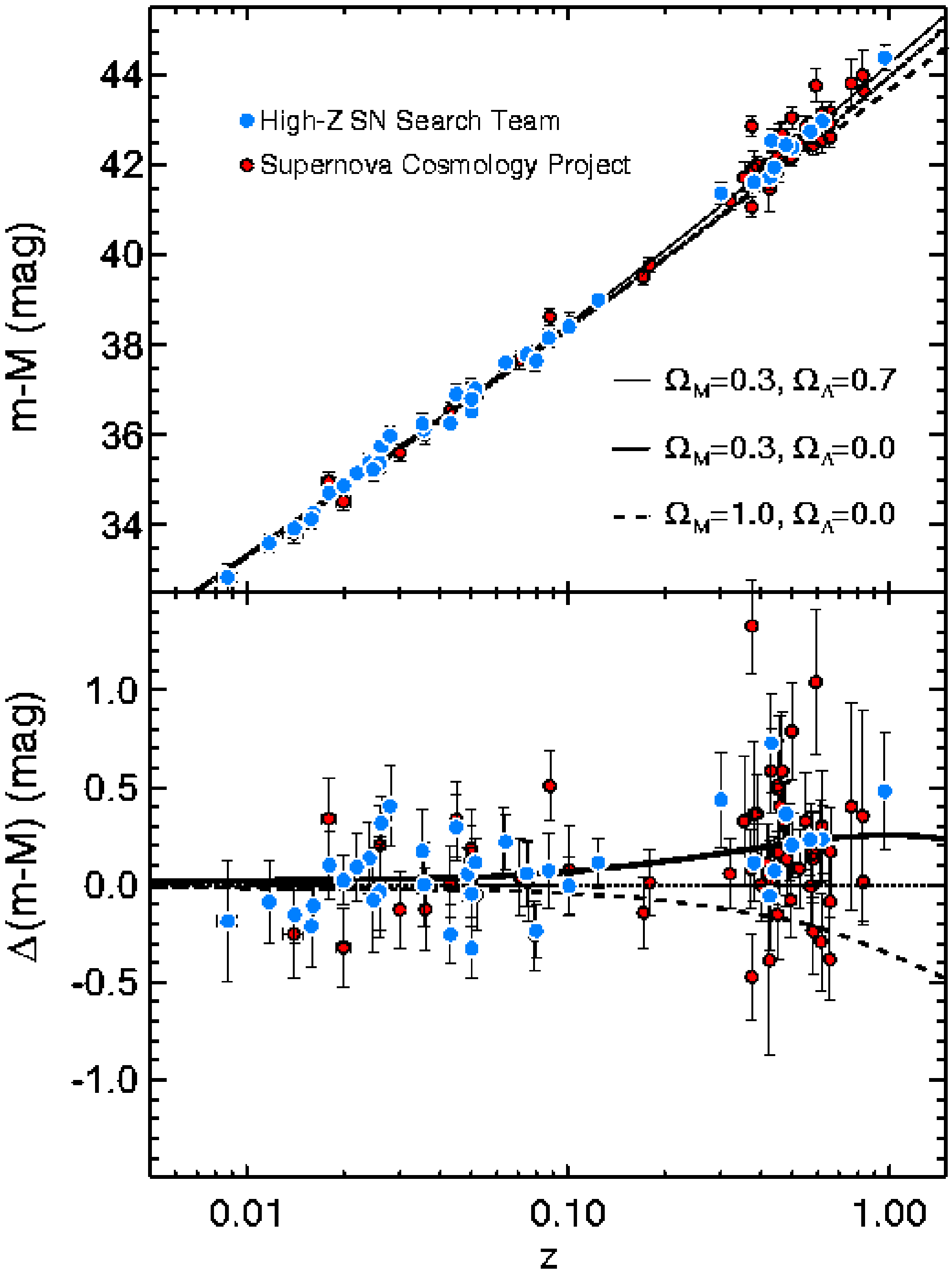

Figure 1.16: The magnitude vs. redshift results for Type Ia Supernovae. Note that larger magnitude means lower flux density; therefore, as the supernovae tend to fall above the straight-line extrapolation at high redshift, they are fainter than predicted.