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Introduction

1.1 The dark and the light

The Universe, as we gaze at it at night, is a vast, predominantly dark and for the most part unknown expanse, interspersed with myriads of pinpricks of light. When we consider that these light spots are at enormously large distances, we realize that they must be incredibly bright in order to be visible at all from so far away. Occasionally, some of these specks of light get much brighter, and some of them which were not even seen with the naked eye before become in a few days the brightest spot in the entire night sky, their brightness having increased a billion-fold or more against the immutable-looking dark background. Thus, we have come to realize that the Universe is characterized by what Renaissance artists called *chiaroscuro*, referring to the contrast between light and dark, which is both stark and subtle at the same time. In the case of the Universe, the contrasts can be enormous and surprisingly violent, as well as of a subtlety which beggars the imagination. In this book we will focus on these contrasts between the vast, unknown properties of the dark Universe and its most violent outpourings of energy, light and particles.

According to current observations and our best theoretical understanding, the Universe is made up of different forms of mass, or rather of mass-energies, since as we know from special relativity, to every mass there corresponds an energy $E = mc^2$ and vice versa, where E is energy, m is mass and c is the speed of light. About 74% of the Universe's total energy content is in the form of *dark energy*, a very strange component whose true nature we are completely ignorant of. All we know about it at present is what it appears to do to us and to the rest of the massive objects in the Universe: it affects the rate of the expansion of the Universe. The next most prominent mass-energy component in the

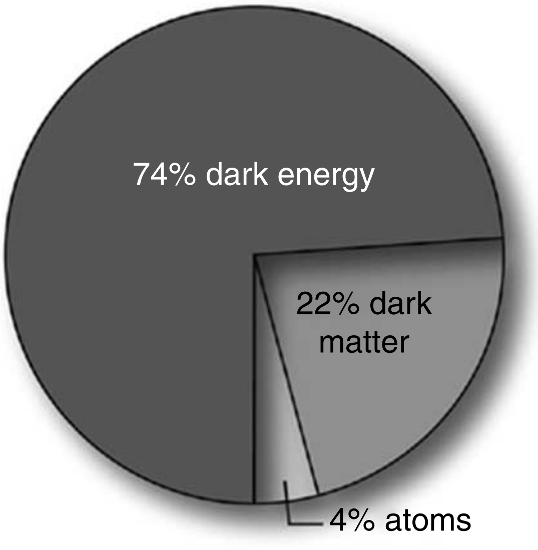

Figure 1.1 Relative amount of different forms of mass-energy densities in the Universe.
Source: SNAP project website.

Universe, amounting to about 22% of the total, is in the form of *dark matter* (another "dark" constituent!), of whose nature we are only slightly less ignorant than we are about dark energy. Despite 30 years of pondering it, all we know for sure about dark matter is how it affects the gravitational attraction felt by the "normal" matter of galaxies, we know roughly how it is distributed in space, and we can rule out some classes of objects as being responsible for it. The remaining fraction of the mass-energy of the Universe amounts to 4%, which is in the form of "normal" everyday baryons, or atoms (Fig. 1.1), although only about one in 10 of these ($\sim 0.5\%$) emit light or detectable radiation, a very modest-looking contribution indeed. Physicists have taken to describing these two types of components as the dark and the light sectors of the Universe.

1.2 Where the fires burn

In the deep dark night of the Universe, the tiny bright specks of light shine as reassuring outposts, or so it would seem. These small corners of the Universe where we feel warm and at home form that portion which we *can* probe with our various instruments, telescopes, satellites, accelerators and laboratory experiments. In fact, this portion of the Universe makes up for its relatively small size with its sheer brilliance, and upon closer inspection, with its concentrated violence.

The most obvious denizens of the light sector, just from their sheer numbers, are the so-called main sequence stars, of which the Sun is a very ordinary example. The Sun's luminosity, that is its energy output per unit time, is $L \simeq 4 \times 10^{33}\,\mathrm{erg\,s^{-1}} \equiv 4 \times 10^{27}$ watts, which can also be expressed as 5×10^{23} horsepower.[1] Most of this energy, in the case of the Sun, is in the form of "optical" light, to which our eyes are sensitive, with smaller fractions in the infrared and in the ultraviolet parts of the electromagnetic spectrum. There are other stars which emit most of their electromagnetic radiation outside the optical range, either at shorter or longer wavelengths. Like the Sun, all stars shine because of nuclear reactions going on in their core, which results in their emitting copious amounts of neutrinos, a type of elementary particle, the stellar neutrino luminosity being in general comparable to the electromagnetic luminosity.

Despite their huge power, stars are just the lumpen proletariat of the Universe, humble light-bugs compared to some of the rare, lavish energy plutocrats which arise occasionally here and there. When they occur, the sky is pierced by extremely concentrated outbursts of high energy radiation pouring out from them, which make the normal stars pale by comparison, outshining them by a factor of a billion or more over periods of weeks. These outlandish events are called supernovae, and besides their optical and other forms of electromagnetic radiation, we have managed to measure on at least one occasion their neutrino luminosity as well. They are also thought to be powerful sources of other forms of cosmic rays, and to a lesser degree of gravitational waves, which however have not so far been detected. Some of these supernovae occur as a consequence of the collapse of the inner core of massive stars, while others are due to smaller stars slowly gaining mass until a nuclear deflagration occurs. In many cases, the collapse leaves behind an extremely compact remnant called a neutron star, composed of matter whose density is extremely high, comparable to that of atomic nuclei.

The most extreme stellar outbursts, however, appear to occur as a result of the core collapse of the most massive stars leading to the formation of a black

[1] We use the common scientific notation where a quantity written as, say, 6×10^X is equivalent, in the usual decimal notation, to 6 followed by X zeros before the decimal point, for instance, $6 \times 10^3 \equiv 6000$, or in general, the first number followed by X figures, with zeros added after the significant figures to make up X figures after the first one, for instance, $1.56 \times 10^4 = 15\,600$.

hole, or as a result of the merger of two compact stars leading to a black hole. The black hole formation may perhaps proceed through an intermediate stage as a neutron star with an extremely high magnetic field. These cataclysmic events are called "gamma-ray bursts", or GRBs. They flare up very fast, and for short periods of time (seconds or minutes), their brightness can exceed the total luminosity of the rest of the observable Universe.

Slower flares of even higher total energy occur in some galaxies, made up of billions or trillions of stars. These are related to massive black holes which lurk at the center of most galaxies, millions to billions of times more massive than the stellar mass black holes. As gas or stars fall in and are stretched and ripped apart by the enormous gravitational fields of these black holes, the resulting heated gas leads to correspondingly brighter electromagnetic flaring episodes, spread out over longer times, and recurring fitfully. These flaring episodes on the galactic scale have brightnesses which exceed thousands or tens of thousands of times the luminosity of the more peaceful steady-state emission produced by their stars or by the low and steady accretion of gas onto the black hole. Yet, bright as these electromagnetic galactic flares are, observations as well as simple physical arguments tell us that many of them must be accompanied by comparable or even larger outpours of energy in the form of cosmic rays, neutrinos and gravitational waves (Fig. 1.2).

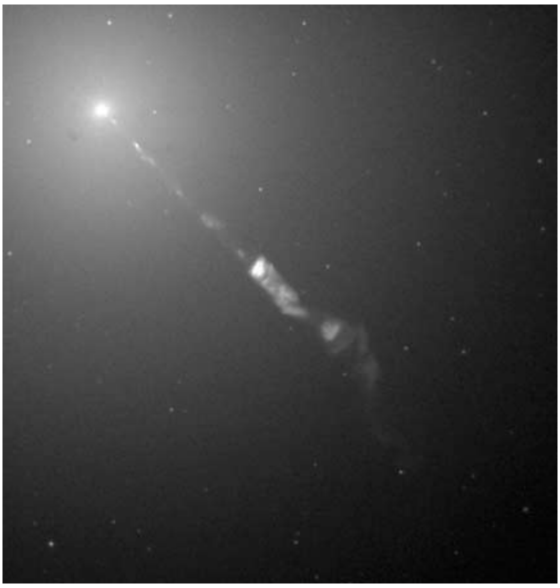

Figure 1.2 A relativistic jet shooting out from the massive black hole at the center of the active galaxy M87, which is an incredibly energetic source of photons and particles.
Source: NASA Hubble Space Telescope.

1.3 The vast dark sea

The looming bulk of the dark Universe, alas, provides the greatest and least tractable mysteries. What are the dark energy and the dark matter, and what can we do to find out what they are, and how they operate?

Of these, dark matter appears to offer somewhat more promising or at least straightforward approaches for its investigation. For more than three decades, it has been studied indirectly through its gravitational effects on normal, visible matter. However, direct methods of investigation, such as capturing or analyzing the effects of dark matter interacting within laboratory detectors, appear at least possible as well. If the dark matter is not made up of hard-to-detect macroscopic objects, as seems to be the case after long and fruitless searches, it should consist of hard-to-detect elementary particles, for which there are some possible candidates. Those in the known arsenal of the Standard Model of particle physics, such as electromagnetic radiation at hard-to-detect frequencies, or neutrinos, appear to be ruled out. But there are many plausible extensions of the Standard Model which predict particles that could fit the bill, such as various types of weakly interacting massive particles (graced with the acronym WIMPS), or another type of hypothetical wimpy particle called axions. WIMPS are thought to be able to annihilate each other to produce neutrinos, which are in principle detectable with large neutrino detectors such as IceCube under the Antarctic ice or KM3NeT under the Mediterranean sea. In deep underground laboratories, WIMPS are also being searched for through the weak recoil they would impart to nuclei with which they (very rarely) interact. And one of the prime targets of large particle accelerators such as the new Large Hadron Collider (LHC) near Geneva, in Switzerland, is the detection of "something missing" when accounting for the energy budget of colliding high energy particles, which could indicate the creation of WIMPS. The latter, being weakly interacting, would leave the detector unnoticed, without paying their bill, so to speak, but leaving a noticeable gap in the collision energy balance.

Dark matter WIMPS can also annihilate by interacting with each other, leading to distinctive gamma-ray signatures which are being searched for with, among others, the recently launched Fermi Gamma-ray Space Telescope (formerly known as GLAST), and also with ground-based devices called imaging air Cherenkov telescopes (IACTs), such as HESS, VERITAS, MAGIC and CANGAROO. Besides their more spectacular and speculative task of probing the dark matter sector of the Universe, these space and ground instruments earn a hard living through honest, untiring and only slightly less spectacular studies of the more extreme forms of "normal" matter, such as black holes, gamma-ray bursts, supernovae, active galaxies, etc.

Dark energy is even harder to grasp, both experimentally and conceptually, than dark matter. The experimental study of dark energy is, for now, mainly confined to indirect methods. As in the case for dark matter, dark energy manifests itself most blatantly through its dynamical effects on the large scale behavior of the normal visible matter, in particular on the apparent acceleration of the expansion rate of the Universe. This is being studied by a variety of large scale optical surveys of distant objects, with new and proposed ground- and space-based experiments.

However, a theoretical understanding of the nature of dark energy, of what it is and how it fits in with the fundamental forces and other constituents of the Universe, remains perhaps the most challenging task of theoretical physics and astrophysics. If it is indeed a fundamental physical property, the answer is likely to lie at the interface between gravitation and quantum mechanics.

1.4 The great beyond

The study of both dark matter and dark energy pushes at the boundaries of particle physics and appears to require a unification of quantum mechanics and gravity, which is currently the most ambitious goal of theoretical physics. A major and very active component of this quest is the exploration of particle theories "beyond the Standard Model" (BSM). There are two major arenas where this is being played out. First, terrestrial experiments on very large particle accelerators such as the LHC or deep underground detectors such as Super-Kamiokande in Kamioka, Japan; experiments underway at Gran Sasso Laboratory in Italy and at the planned Deep Underground Science and Engineering Laboratory (DUSEL) in the USA, among others (Fig. 1.3). Second, theoretical models of processes in the very early Universe and related cosmological observations.

One critical epoch in the early history of the Universe is the so-called electroweak transition epoch, when the thermal energies of particles in the Universe had values comparable to those that are achievable in the LHC. There is also an even earlier epoch, during which an episode of greatly accelerated expansion is thought to have occurred. This is called the epoch of inflation, at a time when the Universe would have been so dense and hot that so-called Grand Unified Theories (GUTs) of particle physics hypothesize that three of the known forces of nature, the strong, the weak and the electromagnetic forces, would have been unified into a single interaction (e.g. [1]). And even earlier than that, at the so-called Planck epoch, the fourth force, gravity, would also have become comparable in strength to the other three forces, and the structure of space-time itself would have been a jumble of random quantum fluctuations. Somewhere in this imposing, chaotic landscape may lie the clues to unravel the nature of dark energy and its connection to the rest of physics, or at least that is the hope.

Figure 1.3 Aerial view of CERN, the European Center for Nuclear Research in Geneva, and the surrounding region. Three rings are visible, the largest of which (27 km in circumference) is the Large Hadron Collider (LHC). One of the goals of the LHC is the investigation of dark matter, within the broader context of physics beyond the Standard Model.
Source: CERN.

Another area where the microcosmos and the macrocosmos are intermeshed is the cross-fertilization between high energy physics and black hole astrophysics. One potentially interesting and exotic aspect of this arises in so-called low energy extra-dimensional theories (which are beyond the Standard Model, since they involve more dimensions than the usual four of space-time, e.g. [2]), where there is a possibility that proton collisions in the LHC at teraelectronvolt (TeV) energies could produce very small black holes. While the probability of this is acknowledged to be extremely low, even upper limits on it would provide useful constraints on possible non-standard models. Incidentally, it is worth noting that concerns that such microscopic laboratory black holes could pose a danger have been shown to be groundless [3, 4]. On a more abstract plane, black holes and particle physics mingle intimately in theories of quantum gravity. Both string theories and quantum loop gravity have made advances in describing the quantum properties of black holes, and have derived more or less self-consistent descriptions of black hole quantities such as the mass, spin, charge, information content, entropy, etc. [5–7]. However, these pursuits are still in their early stages, and the road ahead remains largely unfathomable.

It has also been suspected for a long time that black holes may play a role in the evolution of the early Universe. Some of the speculations include, for example, that black hole formation could lead to the currently observed photon-to-baryon ratio; that black holes could hide baryons which might otherwise have caused departures from the observed nuclear abundances of the chemical elements; that black holes might act as dark matter, or as a catalyst for nucleating galaxies, etc. Another speculation is that black holes could provide a feedback mechanism which, out of many possible Universes (the so-called multiverse [8]), selects the one where we happen to live [6]. And of course, the rate at which small and large black holes form in the more recent Universe, which is susceptible to direct observation, would provide a very powerful tool for tracing the dynamics and the evolution of star, galaxy and large scale structure formation. Ultra-high energy cosmic rays, neutrinos and gravitational waves, whether associated with these black holes, or perhaps other more exotic phenomena, will certainly provide unique probes to extend our current reach into the depths of the Universe.

1.5 The next steps

Mountaineers are familiar with the feeling of straining to climb a mountain range whose summit they can see and which apparently has only blue sky beyond, only to reach the presumed summit and discover that the view from there now opens new vistas of another, even higher mountain ridge. The process then repeats itself time after time, until (at least in earthly mountaineering) a final top is reached. The same is known from everyday hard work at an apparently impossibly large task; we know that the only way to accomplish it is to do it one step at a time, one day at a time, and just concentrate on the immediate task ahead, until we reach our goal.

What are some of the direction signposts and the first steps we can take towards these vast unknown territories of the Universe? Starting with the visible sector, the greatest challenges in the astrophysical arena are twofold: understanding the nature and dynamics of the expanding dark Universe, and unraveling the inner workings of its brightest concentrated high energy sources, such as supernovae, gamma-ray sources, super-massive black holes and their related objects. Due to their extreme brightness, which makes it possible to detect them out to the farthest reaches of the Universe, another crucial role of these sources and their messengers may be their acting as tracers of the development and dynamics of the Universe at the dawn of the stellar and galaxy formation epochs. Our horizons could be extended to even larger distances than now being reached if we were to detect from them ultra-high energy

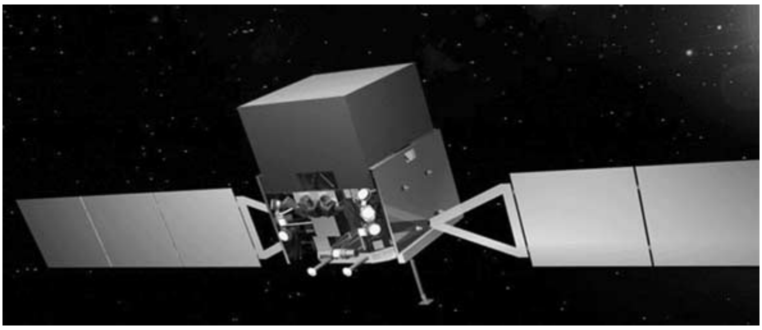

Figure 1.4 Artist's view of the Fermi Gamma Ray Space Telescope, launched in 2008, which is observing distant gamma-ray bursts, active galactic nuclei, pulsars and other objects, as well as providing limits on cosmic rays and setting constraints on dark matter models.
Source: NASA.

neutrinos resulting from ultra-high energy cosmic rays. Gravitational waves arising in these objects would also be able to reach us without any absorption from the largest distances, and these are the target of large gravitational wave observatories such as the Laser Interferometric Gravitational Wave Observatory (LIGO) in the USA, a similar observatory called VIRGO near Pisa in Italy, and a planned European spacecraft called the Laser Interferometer Space Antenna (LISA). Together with the more obvious visible tracers, these may help to track the "bulk" properties of the dark energy, as well as the details of the dark matter distribution (Fig. 1.4).

The most energetic type of radiation known so far, either from the laboratory or from the cosmos, are the ultra-high energy cosmic rays, and a major question is their possible relation to black holes, either massive or stellar. Are these cosmic rays astrophysical in origin, and related to active galactic nuclei, to gamma-ray bursts, or to supernovae? If so, they may shed light on the origin and nature of these objects. Or, alternatively, could they be the product of exotic processes beyond the Standard Model of particle physics in the early Universe? For their part, independently of any relation to ultra-high energy cosmic rays, the physics of black holes in active galactic nuclei and in stellar systems, gamma-ray bursts and supernovae involves extraordinary mass and energy densities which probe states of matter beyond anything which the laboratory can provide. And, as a population, they may play a very significant role in the development of large scale structure in the Universe.

Whatever their origin, at the enormous energies of 10^{20} eV the ultra-high energy cosmic rays surpass anything achievable in earthly accelerators, and provide an intimate link between the cosmological macrocosmos and the microscopic world of particle physics, at energies which may disclose features beyond the Standard Model of particle physics. This possibility remains even if, as it increasingly appears, they are not the product of the decay of exotic particles, but rather result from astrophysical acceleration in active galactic nuclei or in gamma-ray bursts. In all cases, the center of mass-energies in the collision of such cosmic rays with protons in the Earth's upper atmosphere is hundreds or thousands of times larger than the highest energies in the LHC.

The neutrinos arising from the interactions of cosmic rays at these energies also surpass by orders of magnitude any neutrino energies achievable in laboratories. Neutrino interactions, both at these terrestrially unachievable energies and at lower energies, are especially interesting, because neutrinos provide to date the only clear experimental evidence for physics beyond the Standard Model, through the phenomenon known as neutrino oscillations. This is related to the (non-Standard Model) phenomenon of the neutrinos having a small mass, which leads to neutrinos of different types changing identities as they travel over very large distances. The best known example of this is electron-type neutrinos from the interior of the Sun changing into muon-type neutrinos, as they make their way to the Earth. These "neutrino-flavor" changes and related phenomena are the subject of numerous laboratory, reactor, accelerator and underground experiments, using both terrestrially generated and cosmic neutrinos.

Such neutrino properties could have a direct bearing on the reason why the Universe consists mainly of matter (as opposed to anti-matter), instead of being a symmetric mixture of both. While the Universe may have started out with a uniform mixture, at some early point an imbalance must have set in leading to the survival mainly of matter, or baryons, a process called baryogenesis. Some of the leading theories attempting to address baryogenesis start out from leptogenesis, a process where leptons (which include neutrinos and other lighter particles such as electrons, etc.) become asymmetrical, which later through the weak interactions of baryons could lead to a baryon asymmetry.