Fundamental Ideas in Cosmology

Scientific, philosophical and sociological critical perspectives

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Cover image: Cosmology research, conceptual image. Image credit: Nicolle R Fuller / Science Photo Library.

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Abstract

Cosmological hypotheses should be very cautiously proposed and even more cautiously received. This scepticism is well-founded. There are scientific, philosophical and sociological arguments to support this claim. Cosmology is not a science like others since it contains more speculative elements than is usual in other branches of physics, with the possible exception of particle physics. The goal of cosmology is also more ambitious than routine theories in physics: cosmology aims to understand everything in our Universe without limit.

Physical observations (redshifts, cosmic microwave background radiation, abundance of light elements, formation and evolution of galaxies, large-scale structure) find explanations within the standard model, although many times after a number of ad hoc corrections. Nevertheless, the expression ‘crisis in cosmology’ stubbornly reverberates in the scientific literature: the higher the precision with which the standard cosmological model tries to fit the data, the greater the number of tensions that arise. Moreover, there are alternative explanations for most of the observations.

Only the standard model is considered by most professional cosmologists, while the challenges of the most fundamental ideas of modern cosmology are usually neglected, owing mainly to sociological factors. Funding, research positions, prestige, telescope time, publication in top journals, citations, conferences, and other resources are dedicated almost exclusively to standard cosmology. Moreover, religious, philosophical, economic, and political ideologies in a world dominated by anglophone culture also influence the contents of cosmological ideas. Nonetheless, the Universe is no mere social construct (a typical postmodern notion). Quite the contrary: the Universe exists independently of our human affairs. Although its global description may be misrepresented by our models, some of its properties and partial truths are derivable through scientific analysis.

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Martín López-Corredoira (1970–; Spain) obtained doctorates in Physics at the University of La Laguna (Tenerife, Canary Islands, Spain) in 1997 and Philosophy at the University of Seville (Spain) in 2003. He is staff researcher at the 'Instituto de Astrofísica de Canarias' (IAC, Tenerife) working in the fields of galaxies and cosmology, and has published more than 100 papers in major astrophysical journals (ApJ, AJ, A&A, MNRAS, IJMPD mainly), about half of them as first author. His contributions to cosmology include tests of different models, cosmic microwave background radiation anisotropies, large-scale structure of the Universe, ages of galaxies at high redshift, variations of constants and alternative gravity scenarios, historical evolution of measurements of cosmological parameters, and anomalous redshifts. His philosophical work includes the philosophy, sociology and history of science, the philosophy of nature and metaphysics (better termed anti-metaphysics), and other themes relating to political and ethical topics. The author is, in a broad sense, a philosopher-scientist, within a realist, materialist and sceptical tradition of continental European philosophy, but steadfastly eschewing from postmodern approaches. Previous published books include *Against the Tide. A Critical Review by Scientists of How Physics and Astronomy Get Done* (2008; as editor) and *The Twilight of the Scientific Age* (2013); and other titles in Spanish.

Chapter 1

Historical and conceptual introduction to the standard cosmological model

Some basic details, fundamental tenets, and observational pillars of the present-day version of the standard ΛCDM cosmological model are offered. This includes the historical development of the hypothesis, from Einstein to the present, and even farther back in time, to search for the origin of the fundamental ideas, along with the equations that relate the concepts of cosmology with the mathematical expression of the metric derived from general relativity. Reasons for scepticism concerning the theory are pointed out, to be further developed in later chapters.

1.1 Fundamental ideas in cosmology

Physical cosmology is a relatively recent area of scientific research, with roughly one century of life counting from the first cosmological speculations based on Einstein's general relativity. However, the interest of humanity in understanding the origin or eternity of the whole known Universe is as old as human culture, and is implicit or explicit in many cosmogonies contained in religious and philosophical ideas.

Among human societies there have always been some individuals with too ambitious megalomaniacal thoughts or delusions of grandeur[1] who considered that the whole of existence could be grasped in their hands, and they were pretty sure of their representations of the cosmos, obliging the society of their epochs to believe that they have reached absolute truths concerning the order of the Universe. In contrast, most people need to believe in something, they need to have the sensation that the forces that move the world are well identified, even if mysterious or

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[1] The terms 'delusions of grandeur' and 'megalomaniacal thoughts' do not refer here to any kind of psychological judgement, but aim to characterise individuals whose ambitions regarding their creations or conquests exceed reality. For instance, these terms have been applied to personalities such as Napoléon Bonaparte (1769–1821) for his ambitious dream of conquering all of Europe. In the field of knowledge, however, we are clearly not dealing with any such ambition for political power, but more with a certain lack of recognition of our limits in achieving a complete knowledge of the entire Universe.

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embedded in dark elements. Only a few sceptical thinkers dared to make such claims as, 'I know only that I know nothing' (Socrates (470–399 BC)). The huge empty spaces of the cosmos and the darkness of night produce fear. Blaise Pascal (1623–1662) wrote, 'when I consider the short duration of my life, swallowed up in an eternity before and after, the little space I fill engulfed in the infinite immensity of spaces whereof I know nothing, and which know nothing of me, I am terrified. The eternal silence of these infinite spaces frightens me'. This fear makes people yearn for certainties, either gods or the solved mysteries of the Universe; hence, the creators of fantasies can achieve success in their epochs with reference to the global comprehension of nature. One may even imagine prehistoric magicians or priests looking at the sky with a mixed feeling of wonder and fear in their quest to understand how it all works, thus conceiving mainly religious ideas. Humanity has evolved, but some psychological motivations have changed little. Although our science is very different from religion or metaphysics and can claim much higher credibility, some humans—modern priests of science—still think they can get a complete explanation of the vast Universe. In that sense science has certain common characteristics with the distant past.

Even from its earliest stages, the rapidity of the development of physical cosmology did not prevent its creators from having complete faith in their speculative models, and—less than a century later—scientists today claim to have reached a fairly solid model, so much so that they no longer deem it necessary to discuss the fundamental ideas underlying cosmology. Rather, they claim, it is now time to concentrate on 'precision cosmology' (e.g., Primack 2005), in which only the minutiae of the theory are fine-tuned. In this current paradigm of the standard cosmological model, the fundamental properties of the Universe are believed to be well understood, with only minor adjustments to the basic model remaining to be made. The global picture of an expanding Universe originating during a singularity during the *Big Bang* is now taken for granted, and certain basic properties of the Universe are now considered to be known with amazing accuracy. For instance, the age of the Universe is calculated to be 13.787 ± 0.020 Gyr (Planck Collaboration 2020). It is difficult to believe that the precision with which we can determine the age of the Universe (20 million years) is much higher than that of the age of our planet. Does it not sound like the same kind of ambition that has accompanied the story of many previous representations of the cosmos throughout history? Indeed, this is reminiscent of the calculation by James Ussher (1581–1653) of the time and date of the creation within Christian religion as 'the entrance of the night preceding the 23rd day of October (…) the year before Christ 4004'.

The present book follows a different direction with respect to the one that is fashionable nowadays, which asserts that further discussion of the basic tenets of cosmology is ruled out. I shall attempt to show that 'fundamental ideas in cosmology' still warrant discussion, as there are many doubts concerning their validity, and there is a dearth of discussion of possibly erroneous statements concerning the foundations of standard cosmology. There is a significant number of results in isolated and disconnected papers that are usually ignored by leading cosmologists, and which are challenging and critical of the standard model. There are several observations that do not fit well into the current model. These observations, while posing a problem, are dismissed as peculiarities that will soon be fixed within the framework of an otherwise correct model. My intention here is to bring together many of these 'heretical' papers in order to help the more open-minded cosmologist to search the bibliography for tests of, and problems with, the standard model. The purpose of this is to give voice and visibility to those investigators who present and discuss observations that are unexplained, or apparently at odds with, the current standard cosmological model.

Most cosmologists are quite sure that they have the correct theory, and that they do not need to think about possible major flaws in the basic notions of their standard theory. They do not usually work within the framework of truly alternative cosmologies with different fundamentals[2] because they feel that these do not at present seriously compete with the standard model. These alternative models are certainly less developed because cosmologists do not work on them. It is a vicious circle. I consider this restrictive view to be unfair and I attempt here to open the door to further discussion of the fundamental observations of cosmology.

I critically review the most important assumptions of the standard cosmological scenarios. Some observations are discussed in order to show that the facts have not been strictly proven in some cases. Elsewhere, I show the durability of the standard theory against certain tests. I have chosen to review the general aspects of the foundations of cosmology as a whole rather than concentrate on certain branches of it because I am interested in expressing the caveats and open questions as a whole in order to extract global conclusions on cosmology. The goal is to bring together the work of many researchers who are not yet fully convinced of the standard view, thus allowing them to present their innovative ideas on theoretical or observational cosmology. I admit that some of the caveats presented may no longer hold, and that some of the observational measurements may be incorrect. Nonetheless, establishing who is right or wrong is not my mission here and I take no responsibility for the contents of the critical papers or those of the defenders of the standard model. I am conscious that many critical papers may need further analysis with regard to the problems they posit before reaching a firm conclusion on whether the standard model is correct or not. But my role here is not to defend any of the ideas in the citations listed in the bibliography, but to remain neutral and show that the debate is alive, and that the game of creating a definitive cosmological theory is not over yet.

The aim of this book is not to criticise one theory in order to promote another, substituting one too ambitious enterprise by another, but rather to describe a socio-cultural state of the art in cooking cosmological recipes, letting different voices be heard within a healthy tradition of pluralism. I can already advance the general conclusion, whose details will be given throughout this book: a sceptical view, a

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[2] I mean with important variations in the fundamentals of the model, such as questioning the expansion of the Universe, the alternative origin of the cosmic microwave background radiation or light elements, etc. Instead, they merely investigate the same cosmological model with the same fundamentals and play with different dark energy models or other small variations.

perspective of considering that we are still very far from that complete view of the Universe, and a recognition that, although there are many elements in theories that bring knowledge of some partial reality of the cosmos, we are far from having a complete picture. There are too many elements of our culture that contaminate our research to permit us to consider the global cosmological enterprise as a purely scientific and objective one.

This book is divided into three parts. The first part (chapters 1 and 2) gives some basic descriptions of the theoretical ideas underlying cosmological theories; the second part (chapters 3–7) presents the recent debate concerning the comparison of observational data with the fundamental ideas of the standard cosmological model; the third part (chapters 8–10) offers philosophical and sociological perspectives. While the first two parts present scientific contents in the literature, the third is more a personal interpretation of the topics covered in this book. Nothing lasts forever, neither cosmological theories and their arguments in favour or against, nor any other perspectives. Nonetheless, the reader needs to bear in mind that the technical discussions in the scientific part will most probably become outdated within a few decades. If this book were to be read after, say, 2100, when new problems and discussions would presumably have arisen in cosmology, the text of the first two parts would most probably be considered obsolete. There are indeed some topics discussed in this book that are already considered obsolete, but which are included in order to provide a broad overview of debates in recent decades. Nevertheless, the viewpoints in the third part might still remain valid, since they are general reflections on science and humanity and the mentality of cosmologists at any given epoch.

1.2 Cosmology in western culture before the twentieth century

Every civilisation has its own cosmology that attempts to explain the order of our visible cosmos, although the observable Universe was of course much smaller in the past than it is today, and almost restricted to the Earth, Moon, Sun and planets of the solar system and the sphere of fixed stars. The most primitive societies have only proposed magical–animistic or mythological–religious cosmological views. Advanced civilisations have developed more rational perspectives. There are also many metaphysical ideas related to our vision of the totality of the existence (*Weltanschauung*), instead of cosmology. Only astronomical views concerning cosmology are expounded here, leaving aside all ethnoastronomical aspects. I do not offer a full description of every cosmology in the history of astronomy—not even of astronomical cosmologies generated in western culture, since a proper treatment of these would require several books. That is not my purpose here, but I briefly mention some of them to illustrate the paths humanity has taken before reaching our present-day scientific outlook.

Within western culture, it was ancient Greece that witnessed the dawn of reason and an empirical approach that gave rise to philosophy and the natural sciences, thus setting a new horizon of intellectual ideas that tried to explain our cosmos. Indeed, cosmological speculation and natural philosophy were born together, and both disciplines flourished together at different periods throughout history

(Gale 1993). Thales of Miletus (c. 623–c. 545 BC) devised a cosmology based on water as the essence of all matter, with the Earth as a flat disc floating on a vast sea, ideas that were indeed contained in previous Mesopotamian or Babylonian cosmologies. Anaximander (c. 610–c. 546 BC) conceived a Universe with the Earth at its centre. Among his many other achievements, he was already aware that the Moon reflected the light of the Sun and described the Earth as spherical—so already at that time the idea of a flat Earth was obsolete—and knew the origin of equinoxes and solstices. Also, Pythagoras (c. 570–c. 490 BC) and his disciples knew that the Earth was spherical and had decomposed solar motion into two components: a yearly and a daily one. Philolaus (c. 470–c. 385 BC), a follower of Pythagoras, proposed a model in which the Earth, Moon, Sun and planets all moved around a central fire. Since the Earth was much closer to this central fire than the rest of the heaven bodies, it would be almost at the centre of the Universe. More fully developed mathematical models or philosophical considerations applied to the planetary motions would come later, as conceived in the mind of Plato (c. 427–347 BC), Eudoxus of Cnidus (c. 390–c. 337 BC), Aristotle (385–322 BC), and Heraclides Ponticus (c. 390–c. 310 BC), all from a geocentric point of view. Heliocentric models would start with Aristarchus of Samos (c. 310–c. 230 BC) and Seleucus of Seleucia (c. 190–c. 150 BC). As is well known, however, the Aristotelian geocentric view, maintained by Apollonius of Perga (c. 262–c. 190 BC) and Ptolemy (AD c. 100-c. 170), would prevail until the end of the Middle Ages in western civilisation. The soul of the cosmos in Plato's view was its principle of eternal and recurring circular and uniform motions, and this doctrine prevailed in Aristotle's writings and generated later models, even the heliocentric ones. In Ptolemaic astronomy, there was a complex machinery of epicycles, equants and deferents, devised to save the idea of uniform circular motion with the Earth at the centre.

Not only were the motions of the planets, together with those of the Earth, Moon and Sun, given explanations, but other astronomical considerations extended the cosmological horizon. The Milky Way was a very evident visible structure in the sky. Although ancient philosophers had no idea of its dimensions or the distances involved, speculation concerning its nature flourished very early on. For instance, Anaxagoras (500–428 BC) posited that the Milky Way was a reflection of light emitted by stars different from the Sun. Theoretical speculations about the size of the Universe were also in the mind of Greek philosophers. Archelaus (nicknamed 'the physicist', fl. 5th century BC), a disciple of Anaxagoras and master of Socrates, claimed that the Universe has no limits. Archimedes of Syracuse (c. 287–c. 212 BC) would also make the Universe vastly larger than was then believed, because no stellar parallaxes were measurable at that time, and a moving Earth in a heliocentric model should produce a parallax in the apparent positions of the fixed stars, unless the stars were too far away for their parallaxes to be measured. However, Archimedes proposed a maximum size of 0.5 parsec by assuming that the ratio of the diameter of the Universe to the diameter of the orbit of the Earth around the Sun was equal to the ratio of the diameter of the orbit of the Earth around the Sun to the diameter of the Earth.

The medieval schoolmen absorbed parts of the cosmologies of Plato and Aristotle, although adding other elements connected to religion. For instance, in 1225, the bishop Robert Grosseteste (1175–1253) described a cosmological model reminiscent of the present one, in which the Universe is created in an explosion and subsequent condensation. God issued His first fiat, 'Let there be light', and at that precise instant light issued from the divine and entered matter. The power of this luminosity was not so great as to produce a further expansion of the outermost parts of this mass to the highest degree. Grosseteste speculated that there was some form of coupling between light and matter, consequently giving rise to the material body of the entire cosmos. Expansion takes place when matter reaches a minimum density and subsequent emission of light from the outer region leads to the creation of the inner bodily mass so as to create nine celestial spheres (Sparavigna 2014, Bower *et al* 2018).

In *The Divine Comedy*, an allegorical vision of the afterlife and Christian world-view, Dante Alighieri (*c.* 1265–1321) offers a typical example of cosmovision. He puts the Earth at the centre of the Universe in accordance with the Aristotelian model. Inside the Earth is found Hell, divided into nine circles, representing increasing levels of sin. Between the surface of the Earth and sphere of the Moon lies Purgatory. Outwards, the Earth is surrounded by whirling spheres made of transparent solid matter. Added to the eight Aristotelian spheres corresponding to the planets, Moon, Sun, and the fixed stars, there is a ninth sphere, the *primum mobile*, the source of the motion of all the inner planetary spheres. Beyond the *primum mobile* lies the spiritual Universe, the mind of God, or Empyrean heaven; this sphere thus marks the boundary between the natural and supernatural worlds (see figure 1.1). This is certainly not a purely scientific approach, but a religious interpretation mixed with previous scientific ideas. Some of its elements might still be present in some degree in the construction of putatively *scientific* modern cosmology (Binggeli 2006, 2017) (see section 9.3). The cosmologies of much older religions, such as Vedism, developed in 1700–1100 BC, or Jainism (c. 500 AD), also provided fanciful explanations of the entire Universe. In the Middle Age, other cultures gave place to more sophisticated scientific models of the solar system such as that of Aryabhata (476–550), Nilakantha Somayaji (1444–1544) in India, and those of the Maragha school in Muslim countries (13th–16th centuries) based on the Aristotelian model.

The new change of paradigm, or recovery of an old one proposed by Aristarchus of Samos, arose in Europe with Nicolaus Copernicus (1473–1543), Giordano Bruno (1548–1600), Galileo Galilei (1564–1642) and Johannes Kepler (1571–1630), who reintroduced and finally established the heliocentric model. With Kepler's discovery of his first two laws of planetary motion, introducing elliptical orbits and abandoning uniform circular motion in the heavens, the stage was set for the development by Isaac Newton (1643–1727) of a new physics and theory of universal gravitation. Moreover, beyond the solar system, Bruno defended an infinite Universe with an infinite number of suns (stars), and Galilei was the first to observe the Milky Way Galaxy as individual stars through the telescope, instead of a continuous cloud or nebulosity as previously thought. The new ideas and observations expanded the limits of the Universe far beyond the solar system, and the new cosmologies would

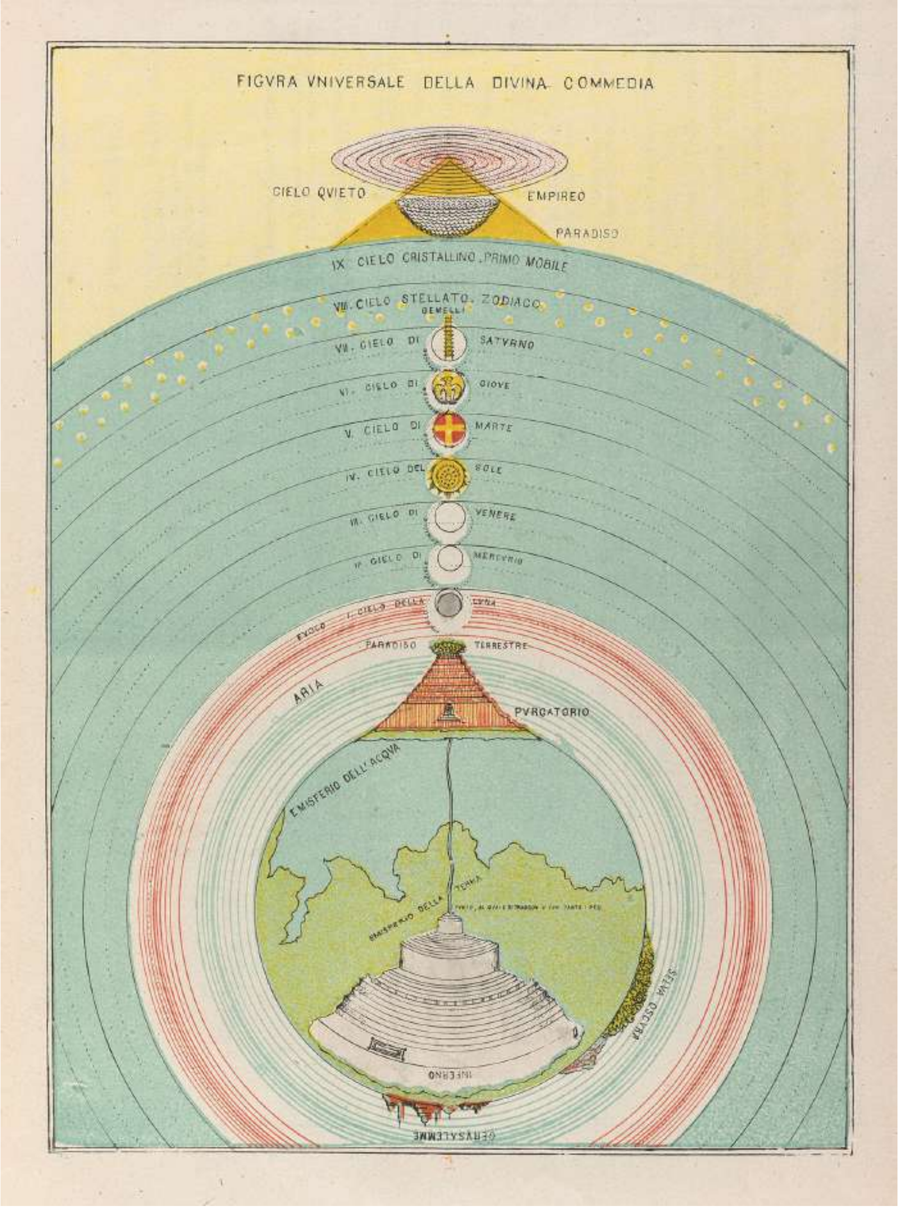

Figure 1.1. Dante's Universe as illustrated by Michelangelo Caetani (1804–1882), Duke of Sermoneta and Prince of Teano (Reproduced from https://commons.wikimedia.org/wiki/File:Michelangelo_Caetani,_Overview_of_the_Divine_Comedy,_1855_Cornell_CUL_PJM_1071_01.jpg. Original Caetani 1821. Image stated to be in the public domain.).

have to give explanations for this new, much wider, scenario, which would be either infinite or at least include all of the visible stars in the Milky Way.

Newton's physical cosmology—leaving aside his religious beliefs—was the scenario in which to refer a scientific vision of the Universe in 18th and 19th centuries, thanks in particular to his theory of gravitation, which imposed some order in the dynamics of the stars and planets, and also the asteroids, comets, Moon and Sun, which constituted all the astronomical objects then known. The cosmological question in Newton's physics, however, posed a great problem that needed to be solved: Bentley's paradox concerning the permanence and stability of the system. Why has not the whole Universe collapsed through the action of gravity? According to Newton, each star in a finite Universe should be attracted towards every other star, such that they all fall together at some central point. Newton acknowledged the problem in a letter to Richard Bentley (1662–1742), a leading Cambridge philosopher at the time (Kerzsberg 1986). Newton also thought about solving this issue with an infinite Universe containing a totally homogeneous distribution of mass, but he realised that this was an unstable solution: even a very small nudge exerted on a star would cause a slight deviation from uniformity in the mass distribution that would produce a cascade causing all matter to collapse. In the end, Newton skipped the paradox by claiming that God prevented the collapse by making 'constant minute corrections', so this stability and permanence must be an action of God (Kerzsberg 1986). The impression after the end of 17th century was that there were no cosmological models that could be fully understood in scientific terms, but that key to understanding was through a thorough understanding of the gravitational interaction among the different bodies of the Universe. This idea has remained embedded in the mentality of all cosmologists, who still think that a gravity theory immediately gives us a cosmological theory.

Western intellectuals of the 18th century were impressed by the power of Newtonian physics + gravitation in comprehending all astronomical phenomena; they were in awe of the genius of the mathematician who could unlock the secrets of the Universe. Newton's laws served not only to explain the observed motions of the planets, but also to make predictions of other events. Society has always been fascinated by predictions, such as the supposed first ever prediction of a solar eclipse by Thales of Miletus in 585 BC, or the confirmation by Eddington and his collaborators in 1919 of Einstein's theory of general relativity with the measurement of the Sun's deflection of the light from stars observed during an eclipse. All these events drew people towards reason and science, as happened, for example, when Edmund Halley (1656–1742) predicted the return of the comet later named after him in late 1758–early 1759, which earned him much acclaim when his successful prediction gloriously vindicated Newton's theory of gravitation (Wallis 1984). We might perhaps compare the physicists who could manipulate gravity equations to foretell how the heavens moved to the magicians and prophets of primitive societies. There is the suggestion of a sense of immensely powerful mini-gods who alone understand the Universe as a whole, and this sense of wonder is the essence of cosmology as an intellectual movement. Consequently, when the next towering genius of gravitation arrived in the form of Einstein, the ground was laid for further claims to possessing keys to understanding the entire Universe, as we shall see in the next section.

The word *Cosmology* applied to the study of the Universe as a whole was first used in a work on metaphysics *Cosmologia Generalis* (1731) by Christian Wolff (1679–1754), a scientific study of the Universe which involved physics, astronomy and philosophy, but also including esotericism and religion. Nonetheless, 18th and 19th science would be more devoted to a Universe without metaphysics, without God, a materialistic science, aimed at understanding not only the structure and dynamics of matter, but also its origin and evolution.

In 1750, Thomas Wright (1711–1786) published *An Original Theory or New Hypothesis of the Universe*, in which he suggested that the stars were located in spherical shells or rings around a centre by which they were attracted and gave it some metaphysical interpretation. He envisaged the Milky Way to be a transversal section of the Universe when viewed from the great centre. The philosopher Immanuel Kant (1724–1804) read the book by Wright and did not accept the supernatural claims but, inspired by it, proposed in his work *Allgemeine Naturgeschichte und Theories des Himmels* (1755) that the Universe to comprise a number of 'island universes', and gravity to create a hierarchical structure of planets around stars, the stars accumulating to form island universes, which would also be clustered into groups of island universes. At the beginning of the 20th century, this scenario would be confirmed, the galaxies being these island universes and the Milky Way itself a galaxy. Johann Heinrich Lambert (1728–1777) also developed a theory of the generation of the Universe that was similar to the nebular hypothesis that Wright and Kant had proposed. Lambert published his own version of the nebular hypothesis of the origin of the solar system in *Cosmologische Briefe über die Einrichtung des Weltbaues* later, in 1761, although started independently in 1749, before Wright's and Kant's publications. Lambert hypothesised that the Sun was part of a group of stars which travelled together through the Milky Way, and that there were many such groupings (star systems) throughout the Galaxy. The appearance of the Milky Way could be accounted for by assuming it to be made of a ring of stars all about equally distant (Gray 1978).

The nineteenth century would be more conservative in its speculations concerning cosmological scenarios and more focused on the development of a serious science, such as astrophysics, which tried to explain certain phenomena in the Universe separately. Nonetheless, there are remarkable examples of the interest of different scientists and thinkers on the mysteries of the extension of the cosmos in space and time. Heinrich Wilhelm Olbers (1758–1840) put forth his famous paradox, according to which the darkness of the night sky conflicts with the assumption of an infinite and eternal static Universe, the only possibility in terms of Newtonian physics. Indeed, the idea had already been proposed much earlier, for instance by Thomas Digges (c. 1546–1595).

The poet and writer Edgar Allan Poe (1809–1849) would speculate a solution to this paradox and would also suggest the expansion and collapse of the Universe in his literary text *Eureka: a Prose Poem* (1848): he rejected the idea of an infinite Universe to solve Olber's paradox and reasoned that a Universe governed by gravitation would collapse into a heap if not kept apart by some form of repulsion. Poe postulated that God had, in an enormous explosion at the creation, thrust all the stars apart which would first expand and then contract into a final catastrophe, the end of the world. The similarity of this scenario with the present one may us lead to think that, although scientifically unexplained, a Universe in expansion was already in the air before the Newtonian gravity was substituted to make possible this fantasy of Poe. But in Poe's idea of a finite Universe we have the problem of the borders of the Universe, which could not be explained by the poet in a logical way.

Another key element in this century would be the mathematical development of non-Euclidean geometries with more than two dimensions. The Russian mathematician Nicolái Lobachevsky (1792–1856) stated that if space is either Euclidean or negatively curved, like the surface of a saddle, it must be infinite. However, there are flat non-Euclidean universes that may be finite. Using a two-dimensional analogy, such a space could have the topology of a giant torus (Silk 2001). There are indeed 18 distinct types of flat spaces, with only ten of them being compact, the others being infinite in one or more directions (Silk 2001). This gives a solution to Olbers' paradox, by making possible a finite Universe without borders. The non-Euclidean geometries would also be an element to be included in the metrics of the cosmological models to be developed in the next century. In particular, Bernhard Riemann (1826–1866) founded the field of Riemannian geometry, a tool that would later prove to be necessary for the mathematical formulation of general relativity.

1.3 Origin and evolution of the standard cosmological model

There remains much to discuss concerning the origin and evolution of the Universe. It may still not be clear whether the Universe had a beginning or not, or whether its evolution followed the present models or not. There are aspects of nature that still defy explanation, especially where great distances in space and time are concerned and for which the history of the Universe that cannot be probed at present. Nevertheless, the scientific community is much closer to hand, and it is easier to track the origin and evolution of human ideas, together with their causes and motivations.

Since the beginning of the 20th century, a continuous evolution and perfection of what we today call the standard cosmological model has been produced, although some authors like to distinguish separate periods within this evolution. For instance, Lerner (1991) distinguished four periods prior to 1991: (1) before the end of World War II; (2) between 1945 and 1965, from Gamow to the official discovery of the cosmic microwave background radiation; (3) between 1965 and 1980; (4) from 1980 onwards, with the introduction of inflation. Another possible historical division of the development of cosmology into six periods was proposed by Luminet (2008): (1) initial period (1917–1927); (2) the period of development (1927–1945); (3) the period of consolidation (1945–1965); (4) the period of acceptance (1965–1980); (5) the period of enlargement (1980–1998), and (6) the period of high precision experimental cosmology (1998–); which is equivalent to Lerner's proposal with the exception that Lerner's first period is subdivided into two blocks, and after 1998, the year of the establishment of the dark energy hypothesis, is added a new period, which of course was not contained in Lerner's division because it had been stated much sooner, in 1991. Certainly, there are phase transitions—small revolutions—within the smooth evolution. Locating them in time is somewhat subjective; it is easier to see history as a continuous quest for the confirmation of an idea conceived *a priori*.

At the beginning of 20th century, two great achievements in physics and astronomy initiated the journey towards the standard cosmological model as we know it today.

First, the observational evidence for the existence of many galaxies separated by very large distances—much larger than the usual distances managed by astronomers previously—the Milky Way thus being only one galaxy among many. It was definitively established after a period of discussion that finished with the Great Debate in 1920 (Hetherington 1993) between the American astronomers Heber D Curtis (1872–1942), who defended the hypothesis that some nebulae (now called galaxies) were not part of the Milky Way but were located at very large distances from it, and Harlow Shapley (1885–1972), who claimed that these nebulae were part of the Milky Way. At first, Shapley was more convincing among astronomers[3]. Curtis was later demonstrated to be the clear winner, although Shapley was at least right in his statement that the Sun was not at the centre of the Milky Way. In my opinion, this was the most important revolution in astronomy after Copernicus and Galilei. The Sun was now no longer at the centre of our Galaxy, and the Milky Way no longer occupied a privileged position in the Universe, but was merely one galaxy among many other galaxies. A fresh blow to the belief that our civilisation and our planet occupy an important position in the Universe. This achievement gave rise to the subsequent development of extragalactic astronomy and, implicitly, a new cosmological vision was emerging out of this scenario: a vision of a Universe of vast spaces, impossible to imagine, where galaxies are the fundamental components in a larger-scale structure.

The other great achievement came from physics in the form of Albert Einstein's (1879–1955) general relativity. Certainly, his earlier discovery of special relativity was also very important, but for astronomical, and particularly from the perspective of cosmology, general relativity was the long-awaited breakthrough. Newton's magnificent achievements had blocked the free expansion of cosmological ideas because of the problems in solving the stability of systems without an eventual collapse and having recourse to godly intervention[4]. Einstein was like a Messiah of Gravity, resurrecting fervour for a global comprehension of the Universe. The manifestations of the new paradigm would come immediately after among many of the brightest minds in physics and astronomy (plus the many thousands of amateurs who try to imitate him or challenge relativity today). The father of general relativity himself produced the first steps towards a cosmology in an early proposal (Einstein 1917) when he posited a static model that included a cosmological constant to guarantee stability. He would later recognise this proposal as his 'biggest blunder'. This hurry to produce a cosmology, only two years after the publication of general relativity, may be the reason why this first approach did not last long. It evidences

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[3] Indeed, Shapley was more interested in defending the hypothesis that the size of the Milky Way was very large (diameter of 100 kpc) and that the question of spiral nebulae was secondary, but he was wrong on both counts. Another concern of Shapley's in the debate was his candidacy for the directorship of the Harvard college Observatory.

[4] Indeed, a model of an expanding Universe could be obtained even within a Newtonian cosmology, as was shown by Milne (1933, 1934), by maintaining an infinite Euclidean space, with Newtonian gravity and regarding expansion as a pure Doppler effect in the recession of the galaxies. Many facts and equations that were explained by the standard model with general relativity could also be explained with Newtonian cosmology. There remained some problems (stability, Olbers' paradox), but there were also proposals to solve them without general relativity (Baryshev and Teerikorpi 2012 [section 7.1.3]).

how eager Einstein and his contemporaries were to probe the deep truths of the wider Universe.

The models that would constitute the basis of our present standard cosmology came a little later. The basic idea assumed is that the current Universe is homogeneous on a large scale, and that the distances among all the different objects are currently growing owing to the expansion of the Universe, a recession of objects with respect to one another on a large scale. On small scales, different objects could cluster together because their gravitational attraction overcomes the expansion. The Russian physicist Alexander Friedmann (1888–1925) developed the basic aspects of the application of general relativity to a cosmological model (Friedmann 1922, 1924).

The German astronomer Carl Wirtz (1876–1939) noted in 1924 a correlation between the faintness of a galaxy and its redshift. Edwin P Hubble (1889–1953) and Milton Humason (1891–1972) measured the distance of a number of galaxies during the same year and would later find the famous Hubble–Lemaître law of the linear relationship between radial velocities and distances. The redshifts used by Hubble had been measured by Vesto Slipher (1875–1969), published by Arthur S Eddington (1882–1944) (Eddington 1923) and added to by Humason (1929) before Hubble (1929)'s famous announcement, interpreting the law as a proof of the expansion of the Universe, whose theoretical models were known to Hubble (Sandage 1995). It is curious that Hubble derived his law using a sample of only 24 nearby galaxies. At such small distances, peculiar motions dominate over recession. Therefore, his famous discovery was based on a coincidence that all the galaxies with dominant peculiar motions happened by chance to follow a linear law of velocity with distance. This shows us how often the theoretical preconceptions guide research (Bonometto 2001).

Prior to Hubble's publication in 1927, the Belgian Catholic priest, physicist and astronomer Georges Lemaître (1894–1966) developed a theoretical model of an expanding Universe in an extension of the work of Friedmann. The work by Lemaître (1927) was published in French in a small Belgian journal, and also tells us about the recession of galaxies and the recession rate in the linear velocity–distance relationship, including an analysis of observational data, as rediscovered later by Hubble in 1929. Hubble did not cite the paper by Lemaître and took all credit for the discovery of the expansion of the Universe. His collaborator Humason told once in an interview offered in 1965 that Hubble knew about the velocity–distance relationship of Lemaître from a talk offered at an IAU meeting in Holland in 1928 (Llallena Rojo 2017 [p 90]), although it is not entirely clear whether this was true or whether Hubble was really unaware of Lemaître's discovery.

In 1931, Lemaître's paper of 1927 was translated into English for the journal *Monthly Notices of the Royal Astronomical Society* (MNRAS) and this translation completely omitted some paragraphs and formulae from the original paper that referred to the analysis of data showing a recession of galaxies and the Hubble–Lemaître law (Nussbaumer and Bieri 2009, Bergh 2011, Block 2012). The reasons for this omission have been widely discussed (Block 2012). It was later clarified (Livio 2011, Luminet 2013) that Lemaître himself did the translation of his paper and deliberately omitted the relevant paragraphs. Lemaître wrote in a letter to the editor of MNRAS: 'I did not find advisable to reprint the provisional discussion of radial velocities which is clearly of no actual interest, and also the geometrical note, which could be replaced by a small bibliography of ancient and new papers on the subject. I join a French text with indication of the passages omitted in the translation.' What an awkward action!

Another line of development of the cosmological model was suggested by the Japanese physicist Seitaro Suzuki, who suggested that the observed helium–hydrogen ratio might be explained 'if the cosmos had, at the creation, the temperature higher than 10^9 degrees' (Suzuki 1928). Lemaître in 1931, with the expansion and the arrow of time from the second law of thermodynamics in mind, developed his concept of the 'primeval atom' (Lemaître 1931, 1946), the first version of what later would be called the 'Big Bang'. According to him, the initial state of matter in the Universe might be thought of as a sea of neutrons. Lemaître thought that cosmic rays were relics of primordial decays of atoms, which was demonstrated later to be wrong. Moreover, his ideas on stellar evolution were also demonstrated to be wrong during the 1930s so, by the end of the decade, the primeval-atom hypothesis had been generally rejected by the scientific community.

Another important protagonist during the gestation of modern cosmology was the above-mentioned British astronomer Arthur S Eddington (1882–1944), who was one of the main scientists responsible for spreading and publicising general relativity and its implications for cosmology, apart from giving the most remarkable impulse to the theory by his observations of the solar eclipse in 1919. Eddington (1929, 1931) was also a defender of a finite Universe and the extrapolation of the second law of thermodynamics to the whole Universe. Another British physicist supporting this approach was James Jeans (1877–1946), in a work titled 'The Physics of the Universe' (Jeans 1928). Lemaître and Eddington proposed philosophical arguments that excluded infinite universes that were also compatible with general relativity.

Some philosophers or historians of science (e.g., Gale 1993) consider the birth of modern cosmology to have occurred on 29 September 1931, when the British Association convened a special session devoted solely to the topic 'The Evolution of the Universe' (Dingle 1931). At the meeting, all the major cosmological workers had reached consensus on two essential points: (1) they had a science; (2) this science was deployed about the general theory of relativity as its central model. Hubble, however, refrained from accepting the consensus of a relativistic model of an expanding Universe until at least 1937.

After World War II, George Gamow (1904–1968), a Russian physicist who emigrated to US in 1934 where he would develop his cosmological ideas, compared the detonation of an atomic bomb with the origin of the Universe and popularised the 'Big Bang'[5] theory (Gamow 1947). He and one of his students, Ralph Alpher

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[5] In fact, the name 'Big Bang' was not given by Gamow, but by one of the opponents of his theory, Fred Hoyle (1915–2001), who dubbed Gamow's primaeval atom theory as the 'Big Bang' in order to ridicule it. However, the name caught on. Several decades later, in 1993, the journal *Sky & Telescope* set a competition for a suitable alternative name for the standard theory. After receiving many proposals, they could not find anything to beat 'Big Bang'. Hoyle would say 'Words are like harpoons, once they go in, they are very hard to pull out' (Horgan 1996 [chapter 4]).

(1921–2007), published a paper in 1948. Gamow, who had certain sense of humour, decided to put the reputed physicist Hans Bethe (1906–2005) as second author, even though he had not participated in the development of the paper, so the result was a paper by Alpher, Bethe and Gamow (Alpher *et al* 1948), to rhyme with ‘alpha, beta and gamma’. Later, Robert Herman (1914–1997) joined the research team, but—according to Gamow—he stubbornly refused to change his name to ‘Delter’.

Rather than searching for an explanation of cosmic rays, as Lemaître did, Gamow and his collaborators attempted to explain the abundance of the elements, assuming that there was no process that could explain the present-day abundances. They contended that the heavier elements must have been formed during an early hot initial stage of expansion, since they thought that stars could not achieve temperatures high enough to produce them. This would be rejected by Hoyle (1946, 1947), who showed that heavy elements can indeed be formed in the stars. A detailed theory by Margaret Burbidge (1919–2020) and collaborators would later show how stars could produce elements in proportions very close to those observed to exist (Burbidge *et al* 1957). However, the theory by Burbidge *et al* could not explain the abundances of helium, a quarter of all matter, and it was hard to see how certain light elements (deuterium, lithium, beryllium and boron) could survive at all. Another attempt was made at the beginning of the 1960s by the Soviet physicist Yákov Zel’dovich (1914–1987), who proposed a cold Universe scenario that predicted the conversion of all matter not into helium, as in the former version, but into pure hydrogen (Zel’dovich 1963).

Alpher and Herman (1949) and Gamow (1953) also predicted an early stage of the Universe that would produce a relic radiation that could be observed at present as a background in microwave wavelengths, corresponding to the epoch of decoupling of matter and radiation. Alpher and Herman calculated the necessary mass density of neutrons and protons to make the helium abundance agree with the observed value (Burbidge 2006). Nevertheless, Gamow and his coworkers were of the opinion that the detection of that microwave radiation was completely unfeasible (Novikov 2001). The first published recognition of the relic radiation as a detectable microwave phenomenon was in 1964 by the Russian cosmologists Andrei Doroshkevich (1937–) and Igor Dmitriyevich Novikov (1935–) (Doroshkevich and Novikov 1964). Then came the official discovery of the cosmic microwave background radiation by Arno Allan Penzias (1933–) and Robert Woodrow Wilson (1936-) (Penzias and Wilson 1965), although this same radiation had been previously directly or indirectly observed by other researchers[6].

Another piece of evidence supporting the standard model of the expanding Universe came from Malcolm Longair (1941–) and Martin Ryle (1918–1984), who

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[6] Shmaonov (1957) from the former Soviet Union was measuring radio waves coming from space at a wavelength of 3.2 cm and concluded that the absolute effective temperature of the background radiation appeared to be 4 ± 3 K, independent of the direction of the sky. It is also possible that a team of Japanese radio astronomers measured this radiation at the beginning of 1950s (Novikov 2001). It was also found by Andrew MacKellar (1910–1960) in 1941 as the radiation necessary to excite rotating cyanide molecules (Novikov 2001). Herzberg (1950) also mentions that there is a strange excitation of molecular spectra, as if a 2.3 K radiation existed.

argued that the data indicate that the Universe must be evolving (Longair 1966, Ryle 1968). The galaxies at high redshift—that is, at great distance—showed distributions and properties different from those at low redshift. Since at larger distances we are observing the past Universe, given the limited speed of light, this implies that the distant galaxies belong to an epoch of the Universe that was much earlier than the present one. This would be a strong argument against alternative models, particularly the steady state model (see section 2.2), which assumed that the Universe never changes. The story of the understanding of galaxy evolution also involves Philip James Edwin Peebles' (1935–; Nobel Prize for Physics in 2019) initial suggestion of a galaxy formation model that starts in the early Universe with baryon only perturbations to get around the smoothness of the Cosmic Background Radiation (Peebles and Yu 1970).

This confirmation of the predicted microwave radiation, even if the predictions did not completely fit the observations (see section 5.1), and evolution of the Universe gave confidence to those cosmologists who supported the standard model. Many hitherto sceptical physicists and astronomers became convinced that they now had a solid theory. By the mid-seventies, cosmologists' confidence was such that they felt able to describe in intimate detail events of the first minutes of the Universe (Weinberg 1977). Nonetheless, there were problems that remained to be solved, such as why the Universe appeared to be the same in all directions (isotropic), why the cosmic microwave background radiation was evenly distributed, and why its anisotropies were so small. Why was the Universe flat and the geometry nearly Euclidean? How did the large-scale structure of the cosmos originate? Clearly, work on the fundamental pillars of the cosmological edifice remained to be done.

In the 1980s, proposals were brought forth to solve these pending problems, with inflation as the leading idea in the solution of cosmological problems at the beginning of the Universe, and the idea of non-baryonic dark matter as a new paradigm that allows the theory to fit the numbers of some observations. Grand Unified Theories of particle physics would also support the existence of non-baryonic dark matter. In chapter 3, I give details of the motivation and evolution of these two ideas. Also, the joining of cosmology and particle physics and scenarios containing baby universes, wormholes, superstrings and other exotic ideas were born. This excess of theoretical speculation not based on observations has led some authors to call this epoch the era of post-modern cosmology (Bonometto 2001). This union between cosmology and particle physics is due in part to the halting of particle physics experiments because of their escalating cost, a situation that led many particle physicists to move over into cosmology, wishfully contemplating the Universe as the great accelerator in the sky (Disney 2000, White 2007). Alas, particle physicists lack the necessary astronomical background—complained Disney —to appreciate how soft an observational, as opposed to an experimental science, of necessity has to be.

In the 1990s, a third patch was applied to the theory in an effort to solve new inconsistencies with the data in the form of dark energy, which supposedly produced acceleration in the cosmic expansion. The problems to be solved were basically the new Hubble–Lemaître diagrams with type Ia supernovae as putative standard candles, the numbers obtained from cosmic microwave background radiation anisotropies, and especially estimates of the age of the Universe, which were inconsistent with the calculated ages of the oldest stars. I will offer further details about the emergence of the dark energy idea in chapter 3.

The renovated standard model including these new elements added ad hoc would come to be called the ΛCDM cosmological model, where Λ stands for dark energy and CDM stands for cold dark matter, the favoured subgroup of models of non-baryonic dark matter[7]. A graphical scheme like the one given in figure 1.2 represents

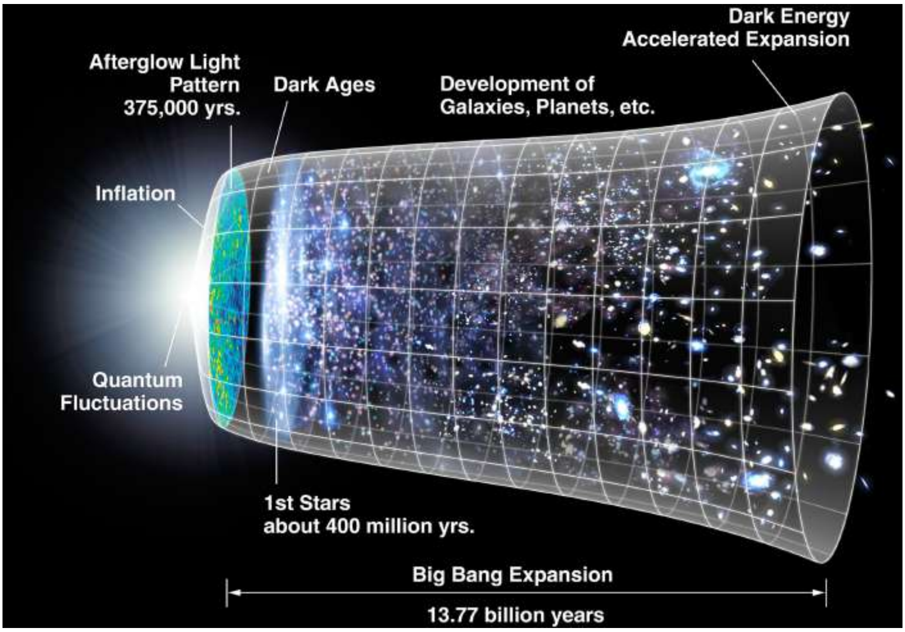

Figure 1.2. Graphical representation of the evolution of the Universe over 13.77 billion years, including a period of 'inflation' that produced a burst of exponential growth in the Universe. Later, the expansion of the Universe gradually slowed down as the matter gravitationally pulled in on itself. More recently, the expansion has begun to speed up again as the repulsive effects of dark energy have come to dominate the expansion of the Universe. The Cosmic Microwave Background Radiation was formed 375 thousand years after the beginning of the Universe. (Reproduced from https://map.gsfc.nasa.gov/media/060915/index.html by NASA/WMAP Science Team, WMAP # 60915, uploaded 30 May 2018. Image stated to be in the public domain).

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[7] The definition of cold or hot dark matter refers to the velocity of the particles that constitute it, which grows when the mass of the particles is lower, so cold matter means massive particles. In the cold dark matter (CDM) theory, the structure of the large-scale distribution of galaxies grows hierarchically, with small objects collapsing under self-gravity first and then merging in a continuous hierarchy to form larger and more massive objects. It is the opposite of the hot dark matter (HDM) paradigm, which was more commonly used in the early 1980s, where structure does not form hierarchically (bottom-up), but forms by fragmentation (top-down), with the largest superclusters forming first in flat pancake-like sheets and subsequently fragmenting into smaller pieces that constitute the galaxies. There are also models that are a mixture of cold and hot dark matter, called warm dark matter (WDM), or interacting dark matter (iDM) that have been competing with CDM in recent years (e.g., Bose *et al* 2019).

the Universe according to the standard model. Some cosmologists referred to it as ‘concordance cosmology’, to emphasise that this model is in agreement with all the known observations. As said by Merritt (2017), when cosmologists speak of ‘concordance’, they mean that it is possible to find a single set of parameters that provides an acceptable fit to the conjunction of observational data sets, but not that there is an independent confirmation of the value of any single parameter.

Some authors, critical of the standard model (e.g., Stubss 2007, Hartnett 2008), prefer to call it ‘consensus cosmology’ rather than ‘concordance cosmology’, wishing to emphasise that this new cosmology is above all a sociological question of agreement among powerful scientific teams in order to establish the orthodoxy of a fundamental dogma. This agreement would be mainly between two powerful cosmological groups, the teams dedicated to the analysis of supernovae and the cosmic microwave background, who found a rough coincidence in the necessary amount of dark energy, although with large error bars, that reinforced their belief that they had discovered an absolute truth, thus compelling the rest of the community to accept this truth as a solid standard, while at the same time discarding the results of other less powerful cosmological groups that presented different values of the parameters. Talking about consensus cosmology, Rudolph (‘Rudy’) Schild (1940–) once queried, ‘Which consensus? Do you know who consented? A bunch of guys at Princeton who drink too much tea together’ (Unzicker and Jones 2013 [chapter 3]).

With this, we reach 1998 to cover the period from the beginning of the period of precision cosmology until today (e.g., Primack 2005, Luminet 2008). Rather than major discoveries or proposals, I would emphasise the lack of discussion on the fundamental ideas in cosmology dating from this epoch, when it becomes a tenet of belief that all the major problems have been solved. This state of complacency has resulted in an excess of confidence in the robustness and superiority of the standard model with respect to any alternative model. Certainly, some minor topics are being debated, such as the equation of state of dark energy, the types of inflation or the coldness or hotness of dark matter, but these are subtleties within the major fundamental scheme. This is the epoch in which the main enterprise of cosmology consists in spending big money on megaprojects that will achieve accurate measurements of the values of the cosmological parameters and solve any small problems that remain to be explained. This is also the epoch of highest social recognition of cosmology: Not only do schools, museums, and popular science journals talk about the Big Bang as well established, to be compared to Darwin’s evolution and natural selection theory, but cosmology now occupies a privileged ranking among the most prestigious natural sciences. For instance, cosmology and its dark elements have been awarded with Nobel Prizes in Physics in 2011 and 2019, respectively for the putative discovery of the dark energy that produces the acceleration of the expansion, and for the inclusion of the dark components in our understanding of the Universe. One may wonder whether unconfirmed quasi-metaphysical speculations should properly form part of the body of recognised knowledge of physics, leaving behind the conservative tradition of Nobel committees not awarding prizes for speculative proposals. Einstein did not receive either of his Nobel Prizes for his discovery of special and general relativity; neither did Curtis for his definitive recognition of the true nature of galaxies in the Great Debate of 1920. Neither Lemaître nor Hubble received the Nobel Prize for their discovery of the expansion of the Universe, but we now have committees that give maximum awards for the highly speculative proposal of the acceleration of the expansion, whose reality has yet to be confirmed. We certainly do live in very a special time for cosmology. However, as we will see in later chapters, this brand of epistemological optimism has declined with time, and the expression 'crisis in cosmology' is stubbornly reverberating in the media. The initial expectation of removing the pending minor problems arising from increased accuracy of measurements has backfired: the higher the precision with which the standard cosmological model tries to fit the data, the greater the number of tensions that arise, the problems proliferating rather than diminishing. There will be much discussion of these tensions throughout chapters 3–7.

1.4 Pillars of the standard model

1.4.1 General relativity and basic equations of the standard cosmological model

Students and professional researchers in theoretical cosmology are used to thinking that they have understood everything about the topic after having learned mathematically to formalise a set of simplistic ideas, but merely knowing how to solve some equations does not mean that we can lay any claim to understanding the Universe[8] and, even if we have understood all of the physical or metaphysical backgrounds of a cosmological model, who says that this is the true representation of the Cosmos? Understanding the Universe is too ambitious an enterprise, and I would be satisfied if I could understand the humans that produced ideas about the Universe. It is the precise purpose of the present book to try to understand where these ideas stem from, and the astronomical observations and social influences that have motivated them, by reviewing hundreds of references related to the subject. The reader may find the technical details in the bibliography, of which I present a summary description in the coming chapters. I also encourage the lay reader of these pages to undertake the reading of other technical books on cosmology, among the vast number of texts available in technical libraries. I will not recommend any text in particular, because it is difficult to choose among the excellent books and review papers that have been written.

Presenting the mathematical developments or technicalities of observational techniques as a subject for undergraduate or postgraduate students is not the aim of the present pages, whose purpose is rather to offer a critical discussion oriented towards professionals who have already learnt or have been working on cosmological research. Also, specialists in the history, philosophy and sociology of science will find in these pages the fundamental ideas of cosmology and the debates

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[8] As expressed by the philosopher Friedrich Nietzsche (1844–1900): 'The calculation of the world, the possibility of expressing with formulae all the things that are happening, is it understanding? What would we understand about a musical composition if we calculated all of the things in it that are calculable and reducible to formulae' (*The Will to Power*).

concerning it without having to lose themselves in a skein of equations whose disentangling consumes most of the efforts of the reader. Nonetheless, even though mathematical developments are not an essential part of this work, I would like to show in this section some basic equations for the benefit of those readers with knowledge of physics but without a previous knowledge of cosmology (the rest of this section may be skipped by the reader with insufficient knowledge of physics).

In the usual metric notation in gravitation, ds denotes a certain infinitesimal interval within a particular mathematical space with N dimensions and is related to the interval in each dimension x_μ ($\mu = 1, \dots, N$) by

$$ds^2 = \sum\nolimits_{\mu=1}^{N} \sum\nolimits_{\nu=1}^{N} g_{\mu\nu} dx_\mu dx_\nu. \tag{1.1}$$

In tensor notation, the right-hand side of this equation is usually written as $g_{\mu\nu}dx^\mu dx^\nu$, where the multiplication of variables with subindex and superindex denotes a sum over the index; $g_{\mu\nu}$ are the components of the metric tensor. In the application to our 4-dimensional spacetime (three dimensions for space and one for time), the simplest example in a Euclidean static space (Lorentzian–Minkowski manifold) is, in Cartesian coordinates:

$$ds^2 = dt^2 - \frac{1}{c^2}(dx^2 + dy^2 + dz^2), \tag{1.2}$$

or, equivalently, expressed in spherical coordinates (r, θ and ϕ are the three variables that define a position of a point in the space)

$$ds^2 = dt^2 - \frac{1}{c^2}(dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2). \tag{1.3}$$

One of the core ideas of general relativity is that the metric of spacetime is determined by the matter and energy content, and that the dynamics of particles is determined by the geodesic in the geometry that minimises ds between two points in that spacetime. The coefficients $g_{\mu\nu}$ of the metric follow

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \tag{1.4}$$

where $R_{\mu\nu}$ are the components of the Ricci curvature tensor, which is a function of $g_{\mu\nu}$ and its first and second derivatives with respect to the variables $x_{\mu\nu}$, and reflects the degree to which the geometry of a given metric tensor differs from that of Euclidean space; $R \equiv \sum\nolimits_{\mu=1}^{N} \sum\nolimits_{\nu=1}^{N} g_{\mu\nu} R_{\mu\nu}$ is the scalar curvature; Λ is the cosmological constant (or quintessence if we allowed it to vary with time instead of being a constant); and $T_{\mu\nu}$ is the stress–energy tensor. In a perfect fluid, i.e. one with an isotropic pressure p and a unique density ρ and no viscosity, it follows that

$$T_{\mu\nu} = (\rho + p) u_\mu u_\nu - p g_{\mu\nu}, \tag{1.5}$$

where $u_\mu \equiv \frac{dx_\mu}{ds}$.

The starting point of the standard cosmological model is the cosmological principle, which decrees that the Universe on a large scale is homogeneous and isotropic, and is expanding. The standard model assumes a Friedmann–Lemaître-Robertson–Walker (FLRW) spacetime, which gives a metric

$$ds^2 = dt^2 - \frac{a^2(t)}{c^2}\left(\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right), \tag{1.6}$$

where k stands for the curvature and is constant with time, being equal to zero for a flat metric, positive for a closed Universe and negative for an open Universe; $a(t)$ is an adimensional scale factor that changes with time t due to the expansion, with $a(t_0) = 1$ and t_0 representing our present epoch. Again, r, θ, and ϕ are the three variables in spherical coordinates that define the position of a point in space, but here they stand for comoving coordinates; that is, they do not take into account the expansion. The physical coordinates are derived when we multiply the common scale factor $a(t)$ by the comoving coordinates. In order to know $a(t)$, one needs to know the field equations obtained through the use of general relativity, and the equation of state of the different components.

When the FLRW metric is used in conjunction with the Einstein field equations (1.4), we obtain the two equations that were studied by Friedmann (Wesson 2014). The assumption that the density ρ and pressure p of the cosmological fluid are isotropic and homogeneous renders the partial differential equations (1.4) as ordinary differential equations in the scale factor $a(t)$:

$$8\pi G\rho = 3\left(\frac{\dot{a}^2}{a^2} + \frac{kc^2}{a^2}\right) - \Lambda c^2, \tag{1.7}$$

$$\frac{8\pi Gp}{c^2} = -2\frac{\ddot{a}}{a} - \frac{\dot{a}^2}{a^2} - \frac{kc^2}{a^2} + \Lambda c^2. \tag{1.8}$$

Joining these two equations, we get

$$\ddot{a} = \frac{-4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)a + \frac{\Lambda c^2}{3}a, \tag{1.9}$$

$$\dot{\rho} = -\left(\rho + \frac{p}{c^2}\right)\left(\frac{3\dot{a}}{a}\right). \tag{1.10}$$

A positive cosmological constant Λ experiences repulsion, producing an acceleration of the expansion. If $\Lambda = 0$ we have the Friedmann models, which were the favoured ones before the reintroduction of the cosmological constant (dark energy) in the 1990s. Equation (1.10) indicates a stability relation for the Universe, in the sense that the density adjusts in proportion to the expansion rate and the combination density and pressure.

The cosmological redshift z (different from a Doppler effect) is a better parameter to use as a cosmological measure than either the distance or the time. For an object in which the spectral lines emitted at wavelength λ_{emitted} are observed at a wavelength $\lambda_{\text{observed}}$, the definition of redshift is $z \equiv \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$ In terms of the scale factor of the FLRW metric at present (t_0) and at the emission epoch (t_e), it is given by $(1 + z) = \frac{a(t_0)}{a(t_e)}$. The Hubble–Lemaître constant H_0 relates to the previous equations as $H_0 \equiv \frac{\dot{a}(t_0)}{a(t_0)}$.

In equations (1.7), (1.8), we observe that the Λ term behaves mathematically as an extra substance, known as dark energy, in vacuum space with density ρ_Λ and pressure p_Λ such that

$$\rho_\Lambda = \frac{-p_\Lambda}{c^2} = \frac{\Lambda c^2}{8\pi G}. \tag{1.11}$$

Note that a positive Λ produces a positive vacuum density with negative pressure. We can define a total density $\rho_t \equiv \rho + \rho_\Lambda$ and total pressure $p_t \equiv p + p_\Lambda$. The term included with density ρ and pressure p can also be decomposed in two terms that carry some energy: matter (m) and radiation (r), so $\rho = \rho_m + \rho_r$, $p = p_m + p_r$. The Friedmann equations can be solved when we have the equation of state that governs the different components of the density, assumed to be perfect fluids $p_i = \omega_i \rho_i c^2$, where the index i denotes the components Λ, m, or r. Hence, we can rearrange equations (1.7), (1.9) into

$$8\pi G \rho_t = 3\left(\frac{\dot{a}^2}{a^2} + \frac{kc^2}{a^2}\right), \tag{1.12}$$

$$\ddot{a} = \frac{-4\pi G}{3}\left[\sum\nolimits_i \rho_i (1 + 3\omega_i)\right]. \tag{1.13}$$

The equation of state of matter is $\omega_m = 0$ while for radiation $\omega_r = 1/3$, and for the Λ term is usually taken as $\omega_\Lambda = -1$ although it can be left as a free parameter too (Cappi 2001). Defining the ratios $\Omega_i \equiv \frac{\rho_i}{\rho_c}$, where $\rho_c \equiv = \frac{3H^2}{8\pi G}$, $H(t) = \frac{\dot{a}(t)}{a(t)}$; and $\Omega_k \equiv -\frac{k\ c^2}{H\ a}$, we can rewrite equation (1.12) as:

$$\Omega_t = \Omega_m + \Omega_r + \Omega_\Lambda = 1 - \Omega_k. \tag{1.14}$$

The comoving distance from us to a source with redshift z can be written as:

$$r(z) = \frac{c}{H_0} \int_0^z \frac{dx}{E(x)}, \tag{1.15}$$

where

$$E(z) = \sqrt{\Omega_k (1 + z)^2 + \Omega_m (1 + z)^3 + \Omega_r (1 + z)^4 + \Omega_\Lambda (1 + z)^{3(1+\omega_\Lambda)}}. \tag{1.16}$$

The look back time of a source redshift z is

$$t(z) = \frac{1}{H_0} \int_0^z \frac{dx}{(1 + x)E(x)}. \tag{1.17}$$

There are two other commonly used definitions of distance from us to a source of redshift z: the luminosity distance and the angular distance. The luminosity distance, d_L, follows the relationship in an equivalent Euclidean Universe of total flux F related to the total luminosity of an object by $F = \frac{L}{4\pi d_L^2}$. It is obtained from the comoving distance $r(z)$ as

$$d_L(z) = \left\{ \begin{matrix} \frac{c(1+z)}{H_0\sqrt{-\Omega_k}} \sin\left(\frac{H_0\sqrt{-\Omega_k}\, r(z)}{c}\right), & \Omega_k < 0 \\ (1+z)r(z), & \Omega_k = 0 \\ \frac{c(1+z)}{H_0\sqrt{\Omega_k}} \sinh\left(\frac{H_0\sqrt{\Omega_k}\, r(z)}{c}\right), & \Omega_k > 0 \end{matrix} \right\}. \tag{1.18}$$

The angular distance d_A is defined such that it behaves as in an Euclidean space, making the linear size D of an object proportional to its angular size α and inversely proportional to that distance; i.e. $\alpha = \frac{D}{d_A}$. The way to calculate it within the standard cosmology is:

$$d_A(z) = \frac{d_L(z)}{(1+z)^2}. \tag{1.19}$$

The set of equations of this subsection define the geometry of the Universe and are used for all kinds of tests relating different quantities: the angular size test, the Hubble–Lemaître diagram relating fluxes with redshifts, etc. We shall see many examples in chapter 4. Nevertheless, the physics of cosmology does not end with these equations. There is much more, related to all the different phenomena that can be modelled within the standard scenario. First, we have not included in these equations inflation (see section 3.2), which modifies $a(t)$ for the early times of the Universe. Predictions of the abundances of the light elements, to be compared with the observed abundances (see chapter 6), comes from the specific nuclear physics developed to tackle that question. Also, the cosmic microwave background radiation (see chapter 5) can be explained independent of the relativistic geometrical description. Of course, the Friedmann cosmological equations are necessary to derive the conditions of density and pressure that give way to other events, but this physics is not implicit in general relativity alone. The large-scale structure and evolution of galaxies (see chapter 7) is pure gravitational in nature in the standard model, but it requires further mathematics, usually with the help of computer simulations, since the above expression accounts only for the average properties of the distribution of matter on very large scales, but not the fluctuations with respect to the average that form clusters of galaxies, filaments, and voids. In any case, the basic paradigm, the framework that supports the mathematical construction of the cosmological edifice is contained in the above equations.

This cosmology is built on the simplistic idea that the whole Universe is an expanding, homogeneous (on a large scale), and isotropic distribution of matter, radiation, and dark energy whose dynamics is governed by gravity and only by gravity, the same general relativity laws being assumed to hold everywhere and throughout time. These are assumptions that cannot be considered as irrefutably solid pillars. There are indeed alternative models based on different assumptions, some of which will be reviewed in chapter 2. In any case, even if we assume that the standard model has been built on the correct foundations, is it, perhaps, not a little pretentious that we give these equations the name of *cosmology*, which embodies knowledge about the entire existing physical world?

1.4.2 Observational pillars

It was already mentioned in the brief historical overview the observations that led cosmologists to believe they have a model that truly represents the Universe. I summarise them:

- The redshifts of all galaxies follow the Hubble–Lemaître law, by which they are related to the distance of the galaxy, plus the Doppler effect due to their peculiar motions. This was interpreted as a proof of the expansion of the Universe. In chapter 4, this fundamental pillar will be discussed.
- The cosmic microwave background radiation of 2.725 K coming from all directions with very small anisotropies is compatible with a high energy primordial Universe. In the standard model, fluctuations in the hot matter–radiation fluid at $z_{\rm rec} \approx 1100$ oscillate like sound waves. The peaks (Sakharov oscillations) in the power spectrum are a consequence of these sound waves, which we see at the epoch of recombination $z_{\rm rec}$. This pillar will be discussed in chapter 5.
- The abundance pattern of the light elements is to be explained in terms of primordial nucleosynthesis. This will be discussed in chapter 6.
- The defenders of the standard model think that the formation and evolution of galaxies can only be explained in terms of gravitation in the cold (or warm) dark matter theory of an expanding Universe. The present-day scenario is one of hierarchical formation, in which the galaxies are formed in continuous episodes of accretion and merging during their evolution. This will be examined in chapter 7.
- Olbers' paradox, the fact that the night is dark, is solved with a finite Universe, and general relativity provides the scenario for a finite although unlimited and borderless Universe. Even an infinite Universe is possible within the general relativistic context, but the limited speed of light limits the horizon within which galaxies are visible, thus solving Olbers' paradox. Indeed, the key question is the limited age of the Universe rather than its limited size, and that the Universe is not eternal but had a beginning 13.8 Gyr ago forms part of the basic assumptions of the standard models. The question of whether there are objects in the Universe older than this proposed age will be discussed in chapter 7.

Some observations will be discussed or rediscussed in order to show that these supposedly established facts have not been strictly proven in some cases, but also, in other cases to show the solidity of the standard theory against certain tests.

1.5 Towards a sceptical position on cosmology

Scepticism has played an important role in the history of ideas. Reasonable doubts have led the human intellect towards new horizons, it has enabled humanity to avoid dogmas and be open-minded. In philosophy, there is a great tradition of epistemological scepticism, even to the extreme of denying the possibility of knowledge. One of the most remarkable thinkers with this view was the pre-Socratic philosopher Gorgias (c. 483 BC–375 BC), who argued that nothing exists, that even if there were something we could not know it, and that even if we could know it we could not communicate it to others (Jones 1952 [p 60]); the school of Academic Scepticism during 3rd and 2nd century BC also denied that knowledge is possible, although they held that some beliefs are more reasonable or probable than others (Popkin 1967). There is indeed some degree of scepticism in most philosophers, although some of them, such as the modern philosophers René Descartes (1596–1650) and David Hume (1711–1776), regard doubt as the most important element of their philosophies.

Science cannot adopt such an extreme scepticism as that of Gorgias, otherwise there would not be science since there would be no motivation to obtain or communicate knowledge on the grounds that nature would be deemed not to exist. Science is based on the assumption that nature certainly does exist, and that we can obtain knowledge about it. But scientific method is cautious and does not accept as truth the first idea that enters the researcher's head. 'Therefore, the most rational stance as a scientist is to doubt all or almost all explanations, interpretations, and evidence in science, as they are all tentative' (Brewer 2020 [chapter 61]). There is a tradition among good scientists to cast doubt upon many important discoveries, and this has been good for science, because it obliged it to consolidate and corroborate theories until they could no longer be reasonably doubted. For instance, in the development of modern atomic theory since John Dalton (1766–1844), much doubt was cast on the real existence of atoms, even as late as the beginning of the 20th century. Scientists today no longer doubt the existence of atoms; if any did, they would lose all credibility among their peers. This solidity of science has proved beneficial and has been gained through the painstaking construction of hypotheses, thanks to the prudent attitude of many scientists who thought like natural philosophers rather than theologians. Hence, waiting a few generations before treating the existence of dark matter and dark energy as an incontrovertible truth would be a wise move.

Cosmological hypotheses in particular should be very cautiously proposed and even more cautiously received. Whether modern physical cosmology is a science at all is topic to be discussed elsewhere (see chapter 10). In any case, even if accepted as scientific enterprise, cosmology would not be a science like others since it contains more speculative elements than is usual in other branches of physics, except, perhaps, particle physics. The goal of cosmology is also more ambitious than the usual theories in physics. For example, astrophysics contains certain branches, such as stellar physics, galactic structure, etc, that have a limited number of topics to understand, but cosmology aims to understand everything without limit. Given that it is a mere one century of existence as a science, in only one century since the beginning of its construction, its claims must be taken with a grain of salt.

To put it bluntly, if we compare figures 1.1 and 1.2, can we not see that we are playing the same game now as many centuries ago? If we forget about the scientific explanations, I see in both figures a similar state of mind that tries to represent the cosmos in several layers with the elements that we have developed in our fantasies. The astronomer Bruno Binggeli (1953–) indeed thinks that this similarity is not a coincidence and compares modern cosmology to a symbolic expression of the states of our mind (Binggeli 2006) (see section 9.3). Examining the history of cosmological ideas, as we have done in this chapter, we can see humanity stumbling over the same stone again and again. Like a *matryoshka* doll with infinite layers although open from the inside out, our western culture since ancient Greece has been opening the different layers of our Universe hoping to find the last one, and every time it finds a new element (galaxies, dark matter, dark energy, …), naively thinking that the last piece that completes the understanding of the vast Universe has finally been found. Other astrophysicists have also noted this historical similarity: Jayant V Narlikar (1938–) says, 'There is one trait which the cosmologists of old seem to share with their modern counterparts, viz. their fond wish that the mystery of the nature of the Universe would be solved in their lifetime' (Narlikar 2001). The astrophysicist Michael J ('Mike') Disney (1937–) calls it the 'fortunate epoch' assumption, the idea that we live in the first human epoch that possesses the technical means to tease out the crucial observations (Disney 2000).

Mike Disney is indeed a remarkable example of the modern sceptical astrophysicist, with a long career of contributing significant advances to extragalactic astrophysics. In his bold paper 'The case against cosmology' (Disney 2000), he identifies present-day cosmology as a dogma with a series of gratuitous or quasi-gratuitous assumptions: apart from the above-mentioned 'fortunate epoch', there is: the 'non-theological' assumption, according to which speculations are not made which cannot, at least in principle, be tested against observational or experimental data; the 'good-luck' assumption, under which the portion of the Universe susceptible to observation is supposed to be representative of the cosmos as a whole; the 'simplicity' assumption that the Universe was constructed using a significantly lower number of free parameters than the number of clean and independent observations we can make; and the 'non-circularity' assumption that the laws of physics that have significantly controlled the Universe since its beginning are, or can be, known to us from considerations outside cosmology itself. He concludes:

> We believe the most charitable thing that can be said of such statements is that they are naive in the extreme and betray a complete lack of understanding of history, of the huge difference between an observational and an experimental science, and of the peculiar limitations of cosmology as a scientific discipline (Disney 2000).
>
> Only beasts could remain indifferent to questions about the origin, structure and fate of the cosmos in which they live. Only saints could resign themselves to never knowing the answers. The upshot has been that every civilization

> known to anthropology has put together such meagre observations as it possesses, has interpreted them in the light of currently fashionable ideas, and then manufactured as plausible a cosmological story as it can to tell its students and its children. The trouble is that none of those cosmologies have stood the test of time. Have we any reason to be more confident in the Big Bang Cosmology (BBC) which is fashionable today? (Disney 2011)

We may interpret this as too daring, too exaggerated a parody that is out of place in the present cosmological scene. Ćirković (2002) criticises Disney (2000), saying that his claims are rhetorical with no new ideas about the sociology and philosophy of science, and that his critique is unfair, biased, and constrained within an extreme inductivism. Other disciplines operate in a similar way to cosmology and they are sciences, says Ćirković. But we could also pay attention to some of Disney's sentences and see that there is some background of truth in what he claims, in spite of the exaggeration.

In any case, Disney's position is an exception within the exception of anti-Big Bang cosmologists. Most (professional or amateur) researchers who are critical with the standard model still live in the delusion of grandeur that accompanied the creators of the Big Bang theory by believing that this theory can be substituted by another, an alternative model (see chapter 2 for many examples), in most cases created by themselves. A sceptical attitude is common among philosophers of science and academics with a humanistic education, an attitude that is usually accompanied by an anti-scientific stance and a vision that 'man is the measure of all things' (Protagoras, c. 485 BC–c. 411 BC), putting everything in the same sack, and reducing any natural truth to a cultural relativistic standpoint so they do not distinguish between the truths of cosmology and the truths of other particular sciences. This is no better than the misguided attitude of those tavern philosophers who, with no training in either philosophy or science, declare their disbelief in the Big Bang while presenting no justification for their claim.

Not all attitudes and ideas have the same value, regardless of their number of followers. As a matter of fact, if we remove from cosmology those opinions of dogmatic individuals, both orthodox and heterodox, those with no idea of modern cosmology, and those who adopt clearly anti-scientific positions, the number of individuals is very small. *Pulchrum est paucorum hominum*[9]. Here, 'beauty' takes the form of the brilliance of intellect, which observes with rigour and reason transcends mere delusion. But, of course, being part of a very small group—that group often consisting of just one person—with some ideas in common does not necessarily give us a clearer perspective. A belief that one is an unacknowledged genius or that one's views happen to coincide with the majority are insufficient qualification in the quest for knowledge. Chapter 8 will be dedicated to the sociological aspects of cosmology and to an analysis of why individuals orientate their research towards either orthodox or heterodox positions.

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[9] 'Beauty is for the few', an expression from the original German edition of Nietzsche's *Twilight of the Gods*.

The view that will be developed in this book is certainly sceptical vis-à-vis the standard cosmological model, but this scepticism is not mere pose. It must be argued with the same kinds of scientific arguments that are used to defend the standard model, with due reference to the observational pillars that support the fundamental ideas of modern cosmology. This may leave us open to an accusation of adopting an instrumentalist stance[10] with regard to cosmology (Soler Gil 2012), on the grounds that we say it works insofar as it explains the observations because many elements were introduced ad hoc to make it work. However, I am not saying that no model contains any truth or reality, since such an attitude would reduce scepticism in cosmology to another dogma in itself. As a matter of fact, I will show in chapters 3–7 that there are some partial realities in the standard model that look quite robust. The overall picture of a Universe completely understood by the theory is somewhat hazy, but at least some partial truths can be observed in quite a clear-cut way.

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[10] In the philosophy of science, instrumentalism is the opposite of realism in the interpretation of a scientific theory. From an instrumentalist viewpoint, a successful scientific theory reveals no truth about nature's unobservable objects, but is merely a set of mathematical formulae that work successfully to predict observations that state or summarise regularities. The classical example is the Ptolemaic geocentric model, which, even being a false representation of the solar system, was able to predict, albeit far from accurately, the positions of the planets.

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