Chapter 1

Cosmological Constant and Dark Energy: Historical Insights

Emilio Elizalde

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/51697

1. Introduction

In this Chapter we are going to discuss about the large scale structure of the Universe. In particular, about the laws of Physics which allow us to describe and try to understand the present Universe behavior as a whole, as a global structure. These physical laws, when they are brought to their most extreme consequences---to their limits in their respective domains of applicability---are able to give us a plausible idea of how the origin of our Universe could happen to occur and also of how, expectedly, its future evolution and its end will finally take place.

The vision we have now of the so-called global or large-scale Universe (what astrophysicists term the extragalactic Universe) began to get shape during the second and third decades of the past Century. We should start by saying that, at that time, everybody thought that the Universe was reduced to just our own galaxy, the Milky Way. It is indeed true that a very large number of nebulae had been observed by then, but there was no clear proof that these objects were not within the domains of our own galaxy. Actually, the first nebulae had been already identified many centuries ago by Ptolemy who, in his celebrated work Almagest [1], reported five in AD 150. Later, Persian, Arabic and Chinese astronomers, among others, discovered some more nebulae, along several centuries of the History of Mankind. Concerning scientific publications, Edmond Halley [2] was the first to report six nebulae in the year 1715, Charles Messier [3] catalogued 103 of them in 1781 (now called Messier objects), while confessing his interest was "detecting comets, and nebulae could just be mistaken for them, thus wasting time." William Herschel and his sister Caroline published three full catalogues of nebulae, one after the other [4], between 1786 and 1802, where a total of 2510 nebulae where identified. However, in all these cases the dominant belief was that these objects were merely unresolved clusters of stars, in need of more powerful telescopes. On 26 April 1920, in the Baird auditorium of the Smithsonian Museum of Natural History a debate took place (called now by astronomers, in retrospective, the Great Debate), on the basis of two works by Harlow Shapley and Heber Curtis, later published in the Bulletin of the National Research Council. During the day, the two scientists presented independent technical results on "The Scale of the Universe" and then took part in a joint discussion in the evening. Shapley defended the Milky Way to be the entirety of the Universe and believed that objects as Andromeda and the Spiral Nebulae were just part of it. Curtis, on the contrary, affirmed that Andromeda and other nebulae were separate galaxies, or "island universes" (a term invented by the philosopher Immanuel Kant, who also believed that the spiral nebulae were extragalactic). Curtis showed that there were more novae in Andromeda than in the Milky Way and argued that it would be very unlikely within the same galaxy to have so many more novae in one small section of the galaxy than in the other sections. This led him to support Andromeda as a separate galaxy with its own signature age and rate of novae occurrences. He also mentioned Doppler redshifts found in many nebulae. Following this debate, by 1922 it had become clear that many nebulae were most probably other galaxies, far away from our own.

Figure 1. Claudius Ptolemaeus, c. AD 90 – c. AD 168.

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Figure 2. Edmond Halley, 1656 – 1742. Charles Messier, 1730 – 1817.

Figure 3. Sir Frederick William Herschel, 1738 – 1822. Caroline Lucretia Herschel, 1750 – 1848.

2. An expanding Universe

But it was Edwin Hubble [5] who, between 1922 and 1924, presented a definite proof that one of this nebulae, Andromeda, was at a distance of some 800.000 light years from us and, therefore, far beyond the limits of our own galaxy, the Milky Way. In this way, he definitely changed the until then predominant vision of our Universe, and opened to human knowledge the much more complex extragalactic Universe, whose theoretical study is one of the main goals of this Chapter [6].

Another very important fact, this one from the theoretical perspective, is that when Albert Einstein constructed, at the beginning of the second decade of last century and starting from very basic physical postulates–as the principles of covariance and equivalence of the laws of Physics–his theory of General Relativity (GR), scientists (himself included) where firmly convinced that our Universe was stationary. Static, in the more appropriate terminology, albeit rather counterintuitive, since this does not mean that celestial bodies do not move, but that stars and their clusters, in their wandering and distribution, would always have remained from the utmost far past, and would continue to do so into the utmost far future, as we see them at present, with no essential changes. No beginning or end of the Universe was foreseeable, nor needed or called for. But, to his extreme disappointment, Einstein realized that a Universe of this sort was not compatible with his equations, that is, the static universe is not a solution of Einstein's field equations for GR. The reason (not difficult to see) is that a universe of this kind cannot be stable: it will ultimately collapse with time owing to the attraction of the gravity force, against which there is no available protection. This led Einstein astray, until he came up with a solution. While keeping all physical principles that led him to construct his equations (there are ten of them, in scalar language, six of which are independent, but only one in tensorial representation), there was still the remaining freedom to introduce an extra term, a constant (with either sign) multiplied by the metric tensor. This is the now famous cosmological constant, but the problem was that it had no physical interpretation, of any sort. However, endowed with the right sign, it did produce a repulsive pressure to exactly counter the gravitational attraction and keep the universe solution static. Einstein was happy with this arrangement for some years (later it was proven that this solution was not stable, but this is considered nowadays to be just a technical detail that played no major role in the scientific discussion of the time).

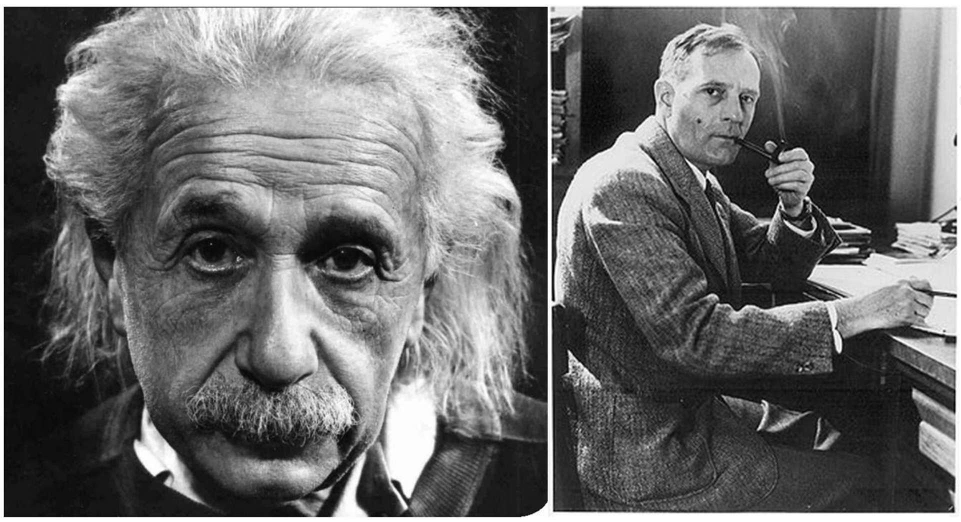

Figure 4. Albert Einstein, 1879 – 1955.   Edwin Hubble, 1889 – 1953.

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The best known, by far, of the equations Einstein discovered (and probably the most famous equation ever written) is: E = m c^2 and corresponds to his Special Relativity theory (SR). It has a very deep physical meaning, since it establishes the equivalence between mass and energy, as two forms of one and the same physical quantity, thus susceptible to be transformed one into the other, and vice versa. The conversion factor is enormous (the velocity of light squared), meaning that a very small quantity of mass will give rise to an enormous amount of energy –as nuclear power plants prove every day (and very destructive bombs did in the past, to the shame of the Humankind). In any case, here we are not referring to this Einstein's equation (which will not be discussed any further), but to the so-called Einstein's field equations [7], actually only one in tensorial language, namely

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

which he published in 1915. This is an extraordinary formula: it connects, in a very precise way, Mathematics with Physics, by establishing that the curvature, R, of space-time (a pure mathematical concept, the reference, coordinate system, so to say) is proportional to (namely, it will be affected or even determined by) the stress-energy tensor, T, which contains the whole of the mass-energy momentum (already unified by SR, as we just said) of the Universe. The proportionality factors are the universal Newton constant, G, the speed of light, c, to the fourth inverse power, and the numbers 8 and π, while Λ is the already mentioned cosmological constant, which multiplies g, the metric of space-time itself. This last term is the one that was absent in Einstein's initial formulation of GR.

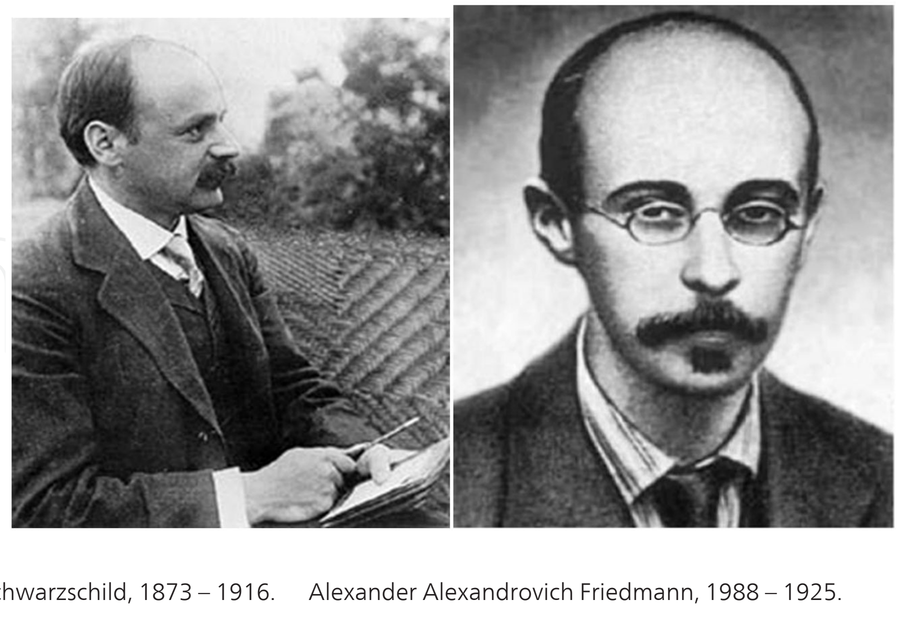

Figure 5. Karl Schwarzschild, 1873 – 1916. Alexander Alexandrovich Friedmann, 1988 – 1925.

Soon Karl Schwarzschild (letter to Einstein from December 1915) found a solution to Einstein's equations (the original ones, without the cosmological constant), which corresponds to what is now know as a black hole (see below). Einstein was very surprised to see this so beautiful solution and wrote back to Schwarzschild congratulating him and admitting he had never thought that such a simple and elegant solution to his so complicated equations could exist.

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

There is now evidence that Einstein himself had been working hard to find such solution but failed, probably because he was looking for a more general one. Schwarzschild's insight was namely to look for the simplest, with spherical symmetry. And Alexander Friedmann, in 1922, obtained another solution, which is derived by solving the now called Friedmann equations:

$$\begin{aligned} &\left(\frac{\dot{a}}{a}\right)^2 + \frac{kc^2}{a^2} - \frac{\Lambda c^2}{3} = \frac{8\pi G}{3}\rho, \\ &2\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 + \frac{kc^2}{a^2} - \Lambda c^2 = -\frac{8\pi G}{c^2}p. \end{aligned} \tag{3}$$

These are nowadays more commonly written in terms of the Hubble parameter, H,

$$\begin{aligned} &H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}, \\ &\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right), \end{aligned} \tag{4}$$

and they are even much more interesting for cosmology than Schwarzschild's solution, because they correspond to the whole Universe. Friedmann's early death in 1925, at the age of 37, from typhoid fever, prevented him from realizing that, indeed, his solution would describe an expanding universe. This honor was reserved to the Belgian priest, astronomer and physicist Monsignor Georges Lemaître who, being not aware of Friedmann's important finding, went to re-discover essentially the same solution while he was working at the Massachusetts Institute of Technology on his second PhD Thesis, which he submitted in 1925. Before, Lemaître had already obtained a doctorate from Leuven university in 1920 and had been ordained a priest three years later, just before going to Cambridge University, to start working in cosmology under Arthur Eddington. In Cambridge, Massachusetts, he worked with Harlow Shapley, already quite famous (as mentioned above) for his work on nebulae.

The case is that, around the same time, Willem de Sitter had also been working on a universe solution (now called de Sitter space), which is the maximally symmetric vacuum solution of Einstein's field equations with a positive (therefore repulsive) cosmological constant

Λ, which corresponds to positive vacuum energy density and negative pressure. As a submanifold, de Sitter space is in essence the one sheeted hyperboloid

$$-x_0^2 + \sum_{i=1}^{n} x_i^2 = \alpha^2, \tag{5}$$

being α some positive constant which has dimensions of length. Topologically, de Sitter space is R × Sn⁻¹. A de Sitter universe has no ordinary matter content, but just a positive cosmological constant which yields the Hubble expansion rate, H, as

$$H\alpha\sqrt{\Lambda}. \tag{6}$$

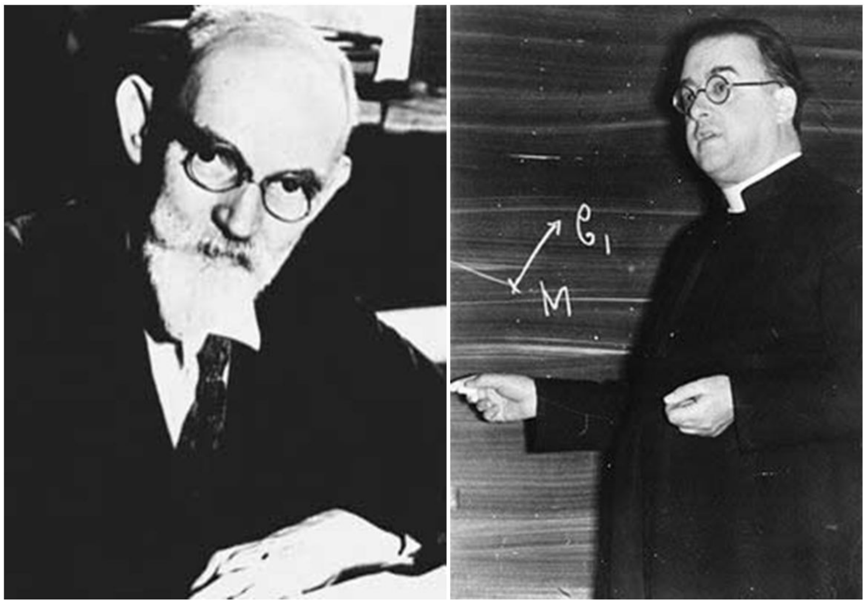

Figure 6. Willem de Sitter, 1872 – 1934. Monsignor Georges Henri Joseph Édouard Lemaître, 1894 – 1966.

It is then immediate to obtain the scale factor as

$$a(t) = e^{Ht}, \tag{7}$$

where H is Hubble's constant and t is time. This was a very simple solution of Einstein's equations that undoubtedly corresponded to an expanding universe. In fact, in 1917 de Sitter had theorized, for the first time, that the Universe might be expanding. The big problem with his solution was, however, that it only could describe a universe devoid of matter, just a vacuum, and this seemed to be at that time not very useful or physically meaningful. Nowadays, on the contrary, this solution has gained extreme importance, as an asymptotic case to describe with good approximation the most probable final stages of the evolution of our Universe (if it will go on expanding forever) and also, as we shall see latter in more detail (even more in other Chapters), the initial stages, as the inflationary epoch: the fact that the de Sitter expansion is exactly exponential is very helpful in the construction of inflationary models.

But let us continue with Lemaître. During his two-year stay in Cambridge, MA, he visited Vesto Slipher, at the Lowell Observatory in Arizona, and also Edwin Hubble, at Mount Wilson, in California, who had already accumulated at that time important evidence on the spectral displacements towards longer light wavelengths (redshift) of a large number of far distant nebulae. Actually, the most consistent earlier evidence of the redshift of distant nebulae had been gathered by Slipher who, already in 1912, had published his first results on the surprisingly large recessional velocity of the Andromeda nebula and, in 1914, at the American Astronomical Society's meeting at Evanston, Illinois, had announced radial velocities for fifteen spirals, reporting that "in the great majority of cases the nebula is receding; the largest velocities are all positive and the striking preponderance of the positive sign indicates a general fleeing from us or the Milky Way." Slipher was seeing the nebulae recede at up to 1,100 kilometers per second, the greatest celestial velocities that had ever been observed. He was so clear and convincing that chronicles say that when Slipher described his equipment and techniques along with his results, he received an unprecedented standing ovation. But the interpretation of the redshifts as true movements of the galaxies was not generally accepted then. De Sitter, for one, posited that the nebulae might only appear to be moving, the light waves themselves getting longer and longer as the light traveled towards Earth because of some interstellar processes.

Figure 7. Vesto Melvin Slipher, 1875 – 1969. Henrietta Swan Leavitt, 1868 – 1921.

When Hubble arrived at Mount Wilson, California, in 1919, the prevailing view of the cosmos was that the universe consisted entirely of the Milky Way Galaxy. Using the new Hooker telescope at Mt. Wilson, Hubble identified Cepheid variable stars in several spiral nebulae, including the Andromeda and the Triangulum nebulae. His observations, made in 1922–1923, proved conclusively that these nebulae were much too distant to be part of the Milky Way and should be considered as separate galaxies. This was the first clear evidence of the “island universe” theory. Hubble, who was then 35, found opposition to his results in the astronomy establishment and his finding was first published in the New York Times, on November 23, 1924, before being formally presented in the 1925 meeting of the American Astronomical Society. As said, most important in this discovery was the identification of the Cepheid variable stars in those nebulae, and this brings us to Henrietta S. Leavitt, who, in 1912, discovered the very important period-luminosity relation: a straight line relationship between the luminosity and the logarithm of the period of variability of these brilliant stars. Leavitt was a distinguished member of the so-called “women human computers” brought in at Harvard College by Edward C. Pickering to measure and catalog the brightness of stars in the observatory's photographic plate collection. In particular, her results came from the study, during several years, of 1,777 variable stars. Hubble did publicly recognize the importance of Leavitt’s discovery for his own (saying even that she deserved the Nobel Prize). It is interesting to describe the now common explanation for the pulsation of Cepheid variables, which have been for many decades the “standard candles” for measuring distances at galaxy scales and were crucial, e.g., for the precise determination of Hubble’s law. It is the so-called Eddington valve mechanism, based on the fact that doubly ionized helium is more opaque than singly ionized one. At the dimmest part of a Cepheid's cycle, the ionized gas in the outer layers of the star is more opaque. The gas is then heated by the star's radiation, temperature increases and it begins to expand. As it expands, it cools, and becomes single ionized and thus more transparent, allowing the radiation to escape. Thus the expansion stops, and gas falls back to the star due to gravitational attraction, and the process starts again.

In 1929 Hubble derived his important velocity-distance relationship for nebulae using, as he later wrote to Slipher, “your velocities and my distances.” Hubble acknowledged Slipher's seminal contribution to his own work by declaring that “the first steps in a new field are the most difficult and the most significant. Once the barrier is forced, further development is relatively simple.” Before that, however, we should go back again to Lemaître, who had visited in 1924-25 both Slipher and Hubble to learn about their results first hand. He also attended the meeting of the American Astronomical Society in Washington DC, in 1925, where Hubble announced his discovery that certain spiral nebulae, previously thought to be gaseous clouds within the Milky Way, were actually separate galaxies. Lemaître realized that the new galaxies could be used to test certain predictions of the general relativity equations and, soon after the meeting, he started to work on his own cosmological model. He realized the uniformity of the recession speed of the galaxies (yet nebulae), in different directions, and the fact that the redshift seemed to be proportional to the known distances to them, and concluded that the recession speed of these celestial objects could be better understood not as proper displacements of the galaxies, but much more naturally as a stretching of space itself, a true expansion of the fabric of our Universe! And this was not as crazy as it could seem at first sight, since his solution to Einstein’s equations (recall, the same as Friedmann's) could be actually interpreted as corresponding to an expanding Universe. Theory and observations incredibly matched!

3. The Big Bang

Lemaître was still half-way to these conclusions when he submitted his PhD thesis at MIT in 1925, but he completed his work two years later and published it in an obscure Belgian journal in 1927. The retreat of distant nebulae, he wrote in his paper, is "a cosmical effect of the expansion of the universe." He even estimated a rate of expansion close to the figure that Hubble eventually calculated and published two years later. And at a scientific meeting in Brussels, in 1927, the young priest cornered Einstein and tried to persuade him. We do not know his exact words, but presumably they must have been something like: "Sehen Sie, Herr Einstein, your static model for the Universe, with a cosmological constant, does not stand, since it is not stable in the far past. But, on the other hand, you do not need a cosmological constant, your original equations are all right! In fact, I have found a solution to these equations which can be interpreted as describing an expanding Universe. And, on the other hand, the redshifts of distant galaxies, as found by astronomers, as Slipher and Hubble, most naturally account for an expansion of the space containing the galaxies, and not for arbitrary displacements of the galaxies themselves, since exactly the same pattern is seen in any direction!" But, as quoted later by Lemaître, Einstein's reply was utterly disappointing to him. He answered: "Monsieur Lemaître, I can find no mistake in your calculations, but your physical insight is abominable." Einstein, the great genius, the master of space and time, was not ready to imagine a universe in which this space-time was stretching! It took him more than two years to accept this. And now, when we are teaching the expanding universe to high-school student, or even to popular audiences, we pretend they should get this concept on the spot! Lemaître's paper was finally noticed by Eddington and with his help it was reprinted in 1931 in the Monthly Notices of the Royal Astronomical Society; it explained clearly, using Lemaître's (Friedmann's) solution, why Hubble saw the velocities of the galaxies steadily increase with distance. The same year, in the much prestigious journal Nature, Lemaître suggested that all the mass-energy of the universe was once packed within a "unique quantum," which he later called the "primeval atom." This was the logical conclusion of his looking back in time in the Universe evolution: an immediate consequence of his model was that long time ago the Universe was much smaller and that, going even more backwards, that it had had an origin. In 1933 he resumed his theory of the expanding Universe and published a more detailed version in the Annals of the Scientific Society of Brussels, finally achieving his greatest popularity (his name is now, however, rather forgotten by the younger generations of astronomers and physicists). From Lemaître's scenario arose the current vision of the Big Bang (albeit not this name, as we will soon see), a model that has shaped there since the thought of cosmologists as strongly as the idea of crystalline spheres, popularized by Ptolemy (who was already mentioned at the beginning), influenced natural philosophers through the Middle Ages. It took Einstein over two years to understand that Lemaître's model was right and, then, he abhorred of the cosmological constant by pronouncing his very famous sentence: “Away with the cosmological constant. This was the biggest blunder in my life” (in German: “Weg mit der kosmologischen Konstante. Dass war die grösste Eselei meines Lebens”). He clearly realized that, had he truly believed in his field equations, he could have predicted that the Universe was actually expanding (and not static), much before anybody else. (Quite in the same way, say, as Dirac predicted the existence of the positive electron, the positron, because it was a second solution of his quantum equation for the electron, impossible to get rid of by natural arguments.)

Figure 8. Albert Einstein and Georges Lemaître.

It is easy to understand that the Church, which had been so disappointed with the findings of Galileo several centuries ago and had condemned him for his defense of a sun-centered universe, was extremely happy with Lemaître's scenario. He was lauded and raised to the rank of monsignor and was made a fellow, and later president, of the Pontifical Academy of Sciences. But Lemaître always recoiled from any suggestion that his primeval atom had been inspired by the biblical story of Genesis. He insisted, throughout his life, that his theory about the origin of space and time sprang solely from the equations before him. However, the name Bib Bang, after which this theory is known today, was actually an occurrence of a rival scientist, Fred Hoyle, who in a BBC radio program, broadcasted on March 28th, 1949, pronounced these magic two words for the first time. Just the year before, Hoyle, Thomas Gold and Hermann Bondi had issued a theory, that was to became quite famous under the name of the Steady State theory, which involved a creation field (called the C-field), which created matter and energy constantly in wider regions of the Universe in a rather smooth manner. These researchers had realized the impossibility of the whole matter-energy of our Universe having been all packed once within a unique quantum or primeval atom. This could have no sense and a creation process needed to be involved. They were very clever to solve the question how to create matter-energy from 'nothing', constantly and at 'zero-cost,' since they realized that any positive amount of ordinary matter and energy would be compensated by the same amount of negative energy which corresponds to the associated gravitational potential (which in GR does also have negative energy content!). This observation was extremely important, since it anticipated the physical principles involved in inflationary theories; indeed, it has been widely recognized that the steady state theory anticipated inflation. Actually, the possibility that the negative energy of gravity could supply the positive energy for the matter of the universe was suggested by Richard Tolman already in 1932, although a viable mechanism for the energy transfer was not indicated. In any case, just translating this physics to Lemaître's scenario would mean that an unbelievably enormous amount of matter and energy should be created instantly, at the very moment of the origin of our Universe. After these considerations the reader should be prepared to understand the words that Fred Hoyle uttered on that occasion. In the BBC program Hoyle tried to push up his theory, as being much more reasonable, in contraposition to Lemaître's one. At a point, he refuted, in a very disrespectful manner, that: "The whole of the matter in the universe was created in one Big Bang in a particular time in the remote past." Hoyle could never imagine that these two words, pronounced with the purpose to absolutely discredit the rival theory, would serve from that moment on to identify what is nowadays the most accepted theory of the Universe, a name that any school child knows. This was clearly not Hoyle's intention. Before going on, a last word on Lemaître's primeval atom scenario. It may seem incredible that this wrong, physically unsustainable idea (again, the whole energy of the universe could never in the past have been concentrated in a nutshell) can be still found nowadays in popular books on cosmology that are being issued by scientific writers having no idea about the physical principles underlying inflation, quantum gravity, or even the more primitive steady state theory. The creation of matter and energy from a void, de Sitter state is key to inflationary models and, as already said, the steady state theory gave a first clear hint to how this could be done while respecting all basic physical principles including energy conservation.

In the year 1963, Arno Allan Penzias and Robert Woodrow Wilson started a project, at the Bell Labs in New Jersey, on the recalibration of a 20-foot horn-reflector, that had been previously employed for a number of years for satellite work, and which they wanted to prepare for use in radioastronomy. Even if, at that time, there were at several other places much more powerful radio-telescopes available, this seven meter, very modest horn reflector had some special features they wanted to exploit for high-precision measurements in the 21 cm band, a wavelength at which the galactic halo would be bright enough in order to be detected, and at which the line corresponding to neutral hydrogen atoms could be observed. They wanted, in particular, to detect the presence of hydrogen in clusters of galaxies (this development is very nicely described, and in much more detail, in the Nobel Lecture by Wilson [8]). After having carried out a number of measurements during several months, Penzias and Wilson did not manage to get rid of a very light but persistent noise, which translated into temperature was an excess of some 2 to 4 K, and which it was exactly the same in all directions, day and night. Indeed, the antenna temperature should have been only the sum of the atmospheric contribution, so-called temperature of the sky (due to microwave absorption by the terrestrial atmosphere), of 2.3 K, and the radiation from the walls of the antenna and ground, of 1 K. Unless Penzias and Wilson could understand what they first called "antenna problem" their 21 cm galactic halo experiment would not be feasible. So they went through a number of possible reasons for the temperature excess and tested for them. They considered the possibility of some terrestrial source and pointed their antenna towards different directions, in particular to New York City, but the variation was always insignificant. They also took into account the possible influence of the radiation from our Galaxy, but they checked this could not contribute decisively, either. They also ruled out discrete extraterrestrial radio sources as the source of the excess radiation as they had a spectrum similar to that of the Galaxy. For some time they lived with the antenna temperature problem and concentrated on measurements in which it was not critical. One day they discovered that a pair of pigeons was roosting up in the horn and had covered part of it with (in their own words) 'what all city dwellers know well.' They cleaned the mess, and later, in the spring of 1965, they thoroughly cleaned out the horn-reflector and put aluminum tape over the riveted joints, but only a small reduction in antenna temperature was obtained. In this way, a whole year passed.

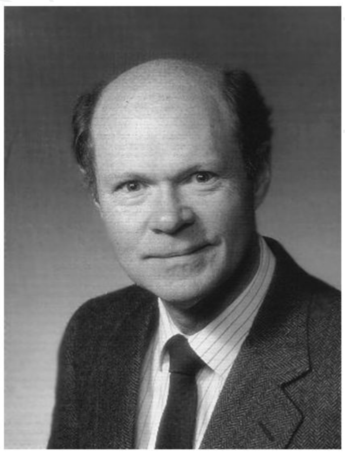

Figure 9. Arno Allan Penzias (born April 26, 1933). Robert Woodrow Wilson (born January 10, 1936).

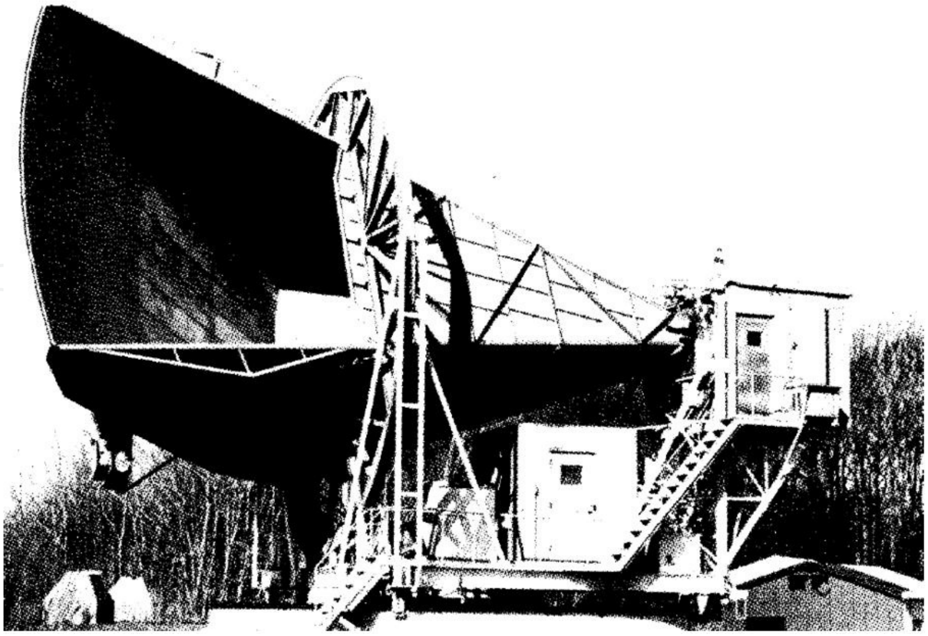

Figure 10. Big Bang detection: Penzias and Wilson's 20-foot horn-reflector.

At the same time, in Princeton, only 60 km away, R.H. Dicke, P.J.E. Peebles and D.T.

Figure 11. Robert H. Dicke, 1916 – 1997. Philip J. E. Peebles, born April 25, 1935. David T. Wilkinson, 1935 – 2002.

Wilkinson where working on a paper where they tried to guess the characteristics that a microwave radiation that would come from a very dense universe, in its origin (possibly pulsating), should have; that is to say, under the conditions that they thought could correspond to those of the Big Bang. The sequence of events which led to the unraveling of the mystery began one day when Penzias was talking to Bernard Burke of MIT about other matters and mentioned the unexplained noise. Burke recalled hearing about the work of the theoretical group in Princeton on radiation in the universe. In the preprint, Peebles, following Dicke's suggestion calculated that the universe should be filled with a relic blackbody radiation at a minimum temperature of 10 K. Shortly after sending the preprint, Dicke and his coworkers visited Penzias and Wilson and were quickly convinced of the accuracy of their measurements. They agreed to a side-by-side publication of two letters in the Astrophysical Journal - a letter on the theory from Princeton [9] and one on the measured excess temperature from Bell Laboratories [10]. Penzias and Wilson were careful to exclude any discussion of the cosmological theory of the origin of background radiation from their letter, because they had not been involved in any of that work and thought, that their measurement was independent of the theory and might outlive it. After the meeting, an experimental group was set up in Princeton to complete their own measurement with the expectation that the background temperature would be about 3 K. There was the great expectation that what Penzias and Wilson had detected could be in fact the Big Bang itself! However, the final confirmation of this extraordinarily important cosmological discovery took several years yet.

And the first additional evidence did not actually come from the experimental group at Princeton, but from a totally different, indirect measurement. Indeed, it came out from rescuing from oblivion a measurement that had been made thirty years earlier by W.S. Adams and T. Dunhan Jr., who had discovered several faint optical interstellar absorption lines which were later identified with the molecules CH, CH+, and CN. In the case of CN, in addition to the ground state, absorption was seen from the first rotationally excited state. This was reanalyzed in 1965-66, and it was realized that the CN is in equilibrium with the background radiation, since there is no other significant source of excitation where these molecules are located. In December 1965, P.G. Roll and D.T. Wilkinson [11] completed their measurement of 3.0 ± 0.5 K at 3.2 cm, the first confirming microwave measurement, which was followed shortly by T.F. Howell and J.R. Shakeshaft's value of 2.8 ± 0.6 K at 20.7 cm [12] and then by Penzias and Wilson’s one of 3.2 K ± 1 K at 21.1 cm [13]. By mid 1966 the intensity of the microwave background radiation had been shown to be close to 3 K between 21 cm and 2.6 mm, almost two orders of magnitude in wavelength. This was already very close to the present, highly accurate value of 2,725 K.

In the same way that the first experimental evidence for the cosmic microwave background radiation was obtained (but unrecognized) long before 1965, it soon was realized that the theoretical prediction had been made, at least sixteen years before Penzias and Wilson’s detection, by George Gamow (a former student of Friedmann) in 1948, and improved by R.A. Alpher and R.C. Herman, in 1949 [14]. Those authors are now recognized as the first who theoretically predicted the cosmic radiation associated to the Big Bang, for which they calculated a value of 5 K, approximately (a very nice figure that they later spoiled, bringing it to 28 K). We will finish this section with the well known fact that Arno Penzias and Robert Wilson were laureated with the 1978 Nobel Prize in Physics by their very important discovery, which can be considered as one the milestone findings in Human History. The Universe had indeed an origin, the fabric of space was stretching and, as clearly understood by Lemaître, Friedmann’s solution to Einstein’s equations was a unique, real description of our Universe. The stationary universe, also under its more modern form of the steady state theory, was dead.

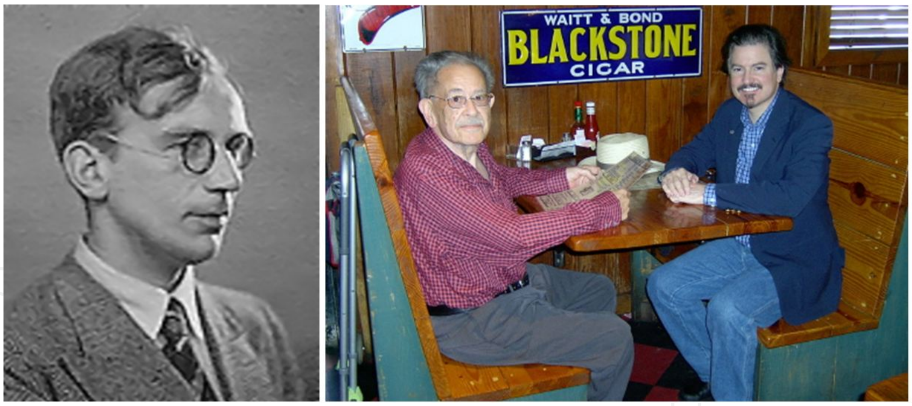

Figure 12. George Gamow, 1904 – 1968. Ralph Asher Alpher, 1921 – 2007 (with Victor S. Alpher, in Tampa, Florida).

4. The Big Bang modified: Inflation

However, the original Big Bang theory had to be modified, what occurred at the beginning of the eighties, in order to solve several very serious discrepancies it had accumulated when comparing it with the most accurate astronomical observations of the cosmos, specifically, concerning what happened during the very first second in the history of the Universe. It was realized that the expansion during this first second could by no means be an ordinary one, understanding by this the one that has taken place later in its evolution, say, kind of a linear one. A very special stage had to be devised to account for what occurred in this initial instant of time (well, in fact one second is a very, very long time at this scale). This stage is generically called inflation, and its formulation is mainly due to Allan Guth, Katsuhiko Sato, Andrei Linde, Andreas Albrecht, Paul Steinhardt, Alexei Starobinsky, Slava Mukhanov, G.V. Chibisov, and a large list of other scientist (the number and classes of models are actually still growing, nowadays). The name inflation comes from the fact that the Universe expansion had to be enormous, incredibly big during an extremely small instant of time (of the order of 10^{-33} seconds). In this infinitesimal fraction of a second the Universe expanded from the size of a peanut to that of the present Milky Way (in volume, an increase of at least 75 orders of magnitude). Actually, in the inflationary theory the Universe begins incredibly small, some 10^{-24} cm, a hundred billion times smaller than a proton. And, at the same time, during inflation it cools down abruptly (supercooling) by 5 orders of magnitude, from some 10^{27} K to 10^{22} K. This relatively low temperature is maintained during the inflationary phase. When inflation ends the temperature returns to the pre-inflationary temperature; this is called reheating or thermalization because the large potential energy of the inflaton field decays into particles and electromagnetic radiation, which fills the universe, starting in this way the radiation dominated phase of the Universe. Because the very nature of inflation is not known, this process is still poorly understood. As explained before, energy conservation is consistent with physics during the whole process: this lies in the subtle behavior of gravity, already present in Newtonian physics, where we know that the energy of the gravitational potential is always negative, a fact which is maintained in GR. The development and

http://dx.doi.org/10.5772/51697

shaping of the concept of inflation constitutes, for different reasons, another brilliant page in the history leading to our present knowledge of the cosmos.

The first to come up to this very revolutionary idea was Allan Guth, born in 1947 and who studied (both graduation and PhD) at MIT, from 1964 to 1971. During the following nine years he was, successively, a PostDoc at Princeton, Columbia, Cornell and Stanford (SLAC), all of them top class Universities. But Guth did not manage to jump over this level and get a real contract. In 1978 he was at Cornell while his career was up in the air and he badly needed to find a permanent job to support his wife and son. Someday, a fellow PostDoc called Henry Tye (now a professor at Cornell) proposed him to study jointly the problem of monopole production in the very early Universe. Guth got interested in this subject so that when Robert Dicke (whom we have already mentioned before) came to give a seminar, he attended it with much interest. Guth was very intrigued by Dicke's conclusion that the traditional Big Bang theory had severe problems and that it was leaving out something important. There was the problem of flatness (also called Dicke's coincidence): the fact that the matter density of the Universe was so close to the critical mass corresponding to a flat (Euclidean) Universe. Also the horizon problem, namely the fact that the Universe is so perfectly homogeneous and isotropic at large enough scales, which is in absolutely good agreement with the cosmological principle. And to these problems Guth and Tye added, as a results of their specific study, the problem of absence of magnetic monopoles, which should actually be very abundant in the present Universe, but it is the case that (with the only exception of Blas Cabrera, who reported finding one in 1982) nobody has ever seen any of them. One should note, however, that John Preskill, at Harvard at that time, had published a result in the same direction before Guth and Tye. Anyway, all these problems and the sudden interest of Guth on cosmology kept him busy for two years. His personal description of how, in a sleepless night, he suddenly thought of a mechanism in order to solve these severe problems, all of them at once, is better than any science fiction story. Looking back at the situation, now we can say that it was very risky on his side, being just a PostDoc fellow without a tenured job, to propose such a revolutionary mechanism as the inflationary model, what he did in 1980. Guth first made public his ideas in a seminar at SLAC on January 23, 1980. In August, he submitted his paper, entitled "The Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems," to the Physical Review, and was published in January 1981 [15]. Soon after, he captured the interest of several universities and got several offers which he rejected, until he had the possibility to come back to MIT, as an associate visiting professor in 1980. His scientific career has been growing since then. Not without some problems at the beginning, however: it was discovered that his initial model had an important flaw, which was corrected by Andrei Linde (now at Stanford) and, independently, by Paul Steinhardt (Princeton) and Andreas Albrecht (Davies). The modified theory was given the name of "new inflation." The works of Katsuhiko Sato, who about the same time as Guth proposed a much related theory and of Alexei Starobinsky, who argued at about the same time that quantum corrections to gravity would replace the initial singularity of the universe with an exponentially expanding de Sitter phase, must be mentioned, as well. In particular the last one is getting more and more popular recently, in a unifying context to be explained later. The Spanish researcher Jaume Garriga, at Barcelona University, has published influential papers in this area, too.

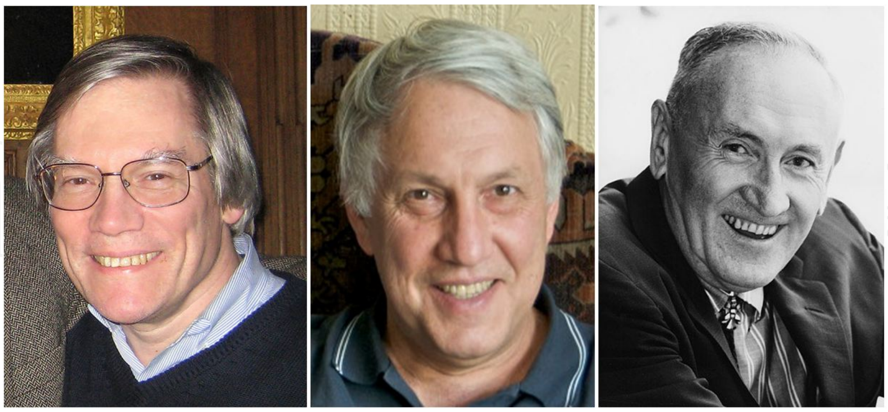

Figure 13. Allan Guth Andrei Linde Fritz Zwicky, 1898 – 1974

Nowadays, under the name of inflation there are over fifty different theories which have evolved from Guth's original idea. Borrowing of energy from the gravitational field is the basic principle of the inflationary paradigm, completely different from the classical Big Bang theory, where all matter-energy in the universe was assumed to be there from the beginning (as explained above). In Guth's words: "Inflation provides a mechanism by which the entire universe can develop from just a few ounces of primordial matter." As a final consequence of all these developments, the so called standard cosmological model, or FLRW (Friedmann-Lemaître-Robertson-Walker) model emerged. The two last names appear here because, between 1935 and 1937, the mathematicians Howard P. Robertson and Arthur G. Walker rigorously proved that the FLRW metric is the only one possible, on a spacetime that is spatially homogeneous and isotropic. In other words, they showed that the solution to Einstein's equations found by Friedmann and later by Lemaître was unique in describing the Universe we live in. Let us pause to ponder, for a second, the extraordinary beauty of this cosmological model as a description of the Universe: to the uniqueness of Einstein's field equation (the only freedom being the cosmological constant) we add up the fact that the solution is also single. We have arrived to just one possible mathematical description of our Universe, and the inflation paradigm opens a possible way to understand how it could be created, without violating the basic conservation principles of Physics. This last point will however require further elaboration.

5. Dark matter

Before that, however, we need go back in time and explain about another very important problem in cosmology which appeared for the first time, in a compelling, clear way, in 1933 when the Swiss astrophysicist Fritz Zwicky, at CALTECH, unveiled it from his detailed observations of the most exterior galaxies of the Coma cluster. It should be mentioned, however, that two years before Zwicky, Einstein and de Sitter had already published a paper where they considered a most probable theoretical existence of enormous amounts of matter in the Universe which did not emit light. It had also been postulated by Jan Oort, one year before Zwicky, to account for the orbital velocities of some stars in the Milky Way. But Zwicky's calculations, based on the use of the virial theorem, where much more convincing. According to them, the gravity of the visible galaxies in the Coma cluster was too small in order to possibly account for the large speeds of the more exterior galaxies. A big amount of mass was missing! This was called the missing mass problem and Zwicky referred to this unseen matter as dunkle Materie (dark matter). Since those years, more and more different observations indicated the presence of dark matter in the universe, such as the anomalous rotational speeds of galaxies, gravitational lensing by galaxy clusters, such as the Bullet Cluster, the temperature distribution of hot gas in galaxies and clusters, and other.

Very famous astronomers in this context now are Vera Rubin and Kent Ford for their seminal papers published around 1975. It so happened that during some forty years after Zwicky's discovery no other corroborating observations appeared and the problem was almost forgotten. But in the early 70s, Vera Rubin, a young astronomer at the Carnegie Institution of Washington, presented findings based on a new, very sensitive spectrograph that could measure the velocity curve of edge-on spiral galaxies to a great degree of accuracy. In 1975, in a meeting of the American Astronomical Society, Rubin and Ford announced their important discovery that most stars in spiral galaxies orbit at roughly the same speed, implying that their mass densities were uniform well beyond the locations of most of the visible stars in the galaxy. In 1980 they published a paper [16] which has had enormous influence in modern cosmology, where they summarized the results of over a decade of work on this subject. Their results have shaken the very grounds of Newton's universal law of gravity since they undoubtedly indicate either that Newton's results are not applicable to the Universe at large distances (the error obtained is certainly enormous) or that a very important part of the mass of spiral galaxies must be located in the galactic halo region, which is extremely dark in relation with the central part.

At the beginning and for some time these results met very strong skepticism by the community of astronomers. But Rubin, a brave and stubborn scientist, never changed her conviction that her results were correct. They have been subsequently checked to enormous precision and there is now no more doubt that an important problem to be explained is facing us. The most accepted conclusion is the existence of dark matter, that is, ordinary matter made up of particles that we cannot see for some reason. There are many candidates for dark matter but, while this is the most generally accepted conclusion, there still remains open the other mentioned possibility, namely that Newton's laws need to be modified at large distances (modified gravities, MOG, MOND, and other theories). Actually, Rubin herself is a convinced supporter of this second possibility. The debate continues and it is very lively nowadays.

To finish with this point let us summarize that, talking in terms of dark matter, for what we now know it must constitute an enormous amount of ordinary (that is, gravitating) matter, ten times as abundant as visible galaxies. And we infer its existence not just by the clear gravitational effects we have mentioned, as the observed anomalies in the rotation curves of spiral galaxies (just described), and which account for the rotational speeds of the exterior stars of the galaxy as a function of the distance of the start to the galactic center, but also from the rotation of the so-called satellite galaxies of our Milky Way (and of Andromeda, too), some of which can already be measured with enough accuracy as they turn around our own galaxy (resp. Andromeda), in a way very similar to how planets describe orbits around the Sun. The extraordinary regularities found in the trajectories of such satellite galaxies constitute a really thrilling, very active research field at present. A different way to trace the presence of dark matter is through gravitational lensing (both macro and micro lensing). Its effects are very apparent there, as a notorious amplification of the power of gravitational lenses, compared with the case that the effect would be just due to the visible stellar objects. In clusters as, for instance, Abell 1689, the observed, very strong effects cannot by any means be explained as being produced by its visible mass only. And in the case of the Bullet cluster one clearly detects an enormous mass acting as a gravitational lens and which is completely separated from the barionic, visible mass which emits X rays.

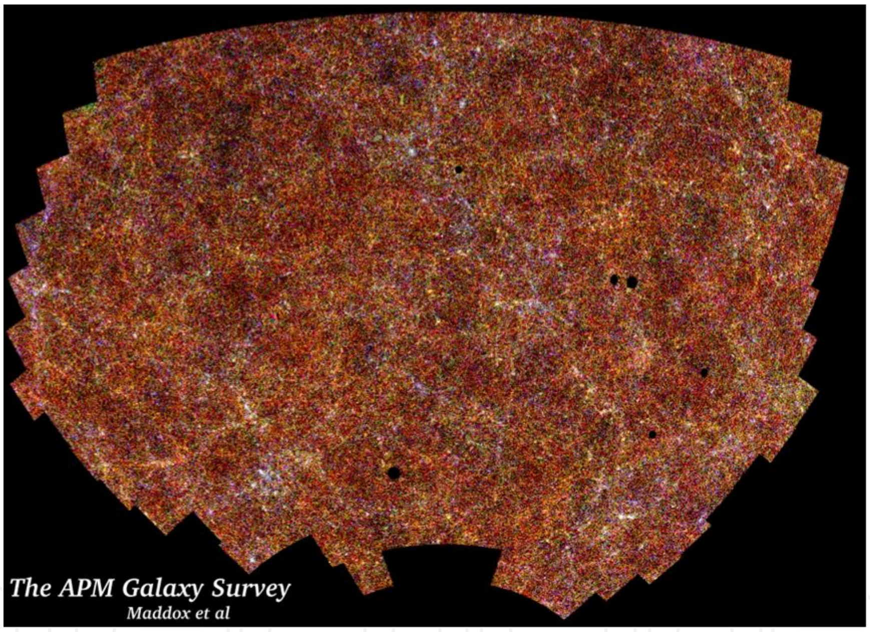

Figure 14. Two Million Galaxies: S. Maddox (Nottingham U.) et al., APM Survey, Astrophys. Dept. Oxford U.

We certainly do not know yet what dark matter is made of, neither why we cannot see it. But we do know that the discovered neutrino mass (neutrinos being indeed invisible!) is not enough to account for it; and also that adding up the masses of big, Jupiter like planets (so called MACHOs, which are also very difficult to see) is again not enough in order to explain the missing amount of mass. But astroparticle physicists got indeed a good number of other possible candidates, as axions, neutralinos and other (they come from the breakdown of certain fundamental symmetries in particle and quantum field theories). What we know is that they must be elusive particles, very weekly coupled with any of the known physical fields since, on the contrary, its presence would have been detected already. It is for this reason that the generic name WIMPs (weakly interacting massive particles) has been proposed to generically name any particle of this sort as a dark matter candidate.

6. The Universe in depth

Another very important landmark in the knowledge of the cosmos at large scale was the publication, in 1986 of the first map of the Universe in three dimensions. In fact, it was only a very thin slice of an angular sector of the same but it was extremely important and completely changed the vision astronomers and other scientists had of it. Up to then, the only representations of the cosmos were in form of two dimensional projections on the celestial sphere, as still is (and serves as a very good example) the APM Galaxy Survey, which contains two million galaxies. Even if, in comparison, the Harvard CfA strip of Valérie de Lapparent, Margaret Geller and John Huchra [17], contained only a total of 1,100 galaxies, what was most important was that for 584 of them their distance from us could be determined (through the observation of their cosmological redshift). And this allowed, for the first time in History, to see a part of our Universe in the elusive third dimension: the distance from us. Actually the plot looks again two-dimensional, since the slice is represented as flat but, again, the spatial structures created by the disposition of the galaxies and clusters, away from us, had never been seen before.

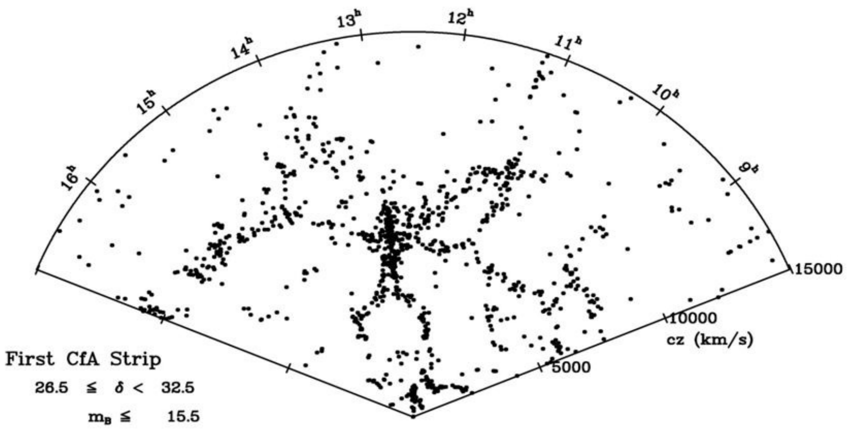

Figure 15. The first slice of the CfA Survey, by Valerie de Lapparent, Margaret Geller and John Huchra, published in 1986.

The impact of this work was spectacular, also due in part to the shapes of these point structures, showing that the distribution of galaxies in space was anything but random, with galaxies actually appearing to be distributed on surfaces, almost bubble like, surrounding large empty regions, or "voids." Anyone could easily identify what looked like a human being (the man), another shape looked like a thumb imprint (God's thumb) pointing towards us, and so on. But the most intriguing fact, for scientists, was the presence in the whole picture of such very large regions devoid of any galaxy (voids), while they concentrated on the verge of these voids, and forming filaments and large walls (as the so-called Great Wall).

Many astronomers, but also a good number of prestigious theoretical physicists and even mathematicians who had never before dealt with cosmological issues started to work on this point distribution, trying to find some fundamental model that could possibly generate such peculiar pattern in the Universe evolution. Astronomers, on their side, tried to find new observational confirmation of this large-scale behavior of galaxies and clusters. Collaborations of pure theoreticians and astronomers flourished, as was the case of Edward Witten with Jeremiah Ostriker. That same year, in Spain, in the historical Peñíscola Castle, we had a five-day workshop of GIFT (Interuniversity Group of Theoretical Physics) where Ricky Kolb and Mike Turner were invited to present such recent and astonishing developments. This author was there and felt immediately captivated by such map. Coming back from the workshop he handed a problem to Enrique Gaztañaga (who was, by the way, in search of a subject for his PhD Thesis): to provide an effective mathematical characterization of the point distribution, more simple than the usual higher-order point correlation statistics, and to try to generate such point distribution from a phenomenological model by taking into account, essentially, the gravitational attraction. This was the origin of our large-scale cosmology group in our Institute ICE-CSIC and IEEC, in Barcelona. When more and more precise surveys, of millions of galaxies with redshifts, as the 2d Field, where carried out, all these spectacular forms have smoothly disappeared:

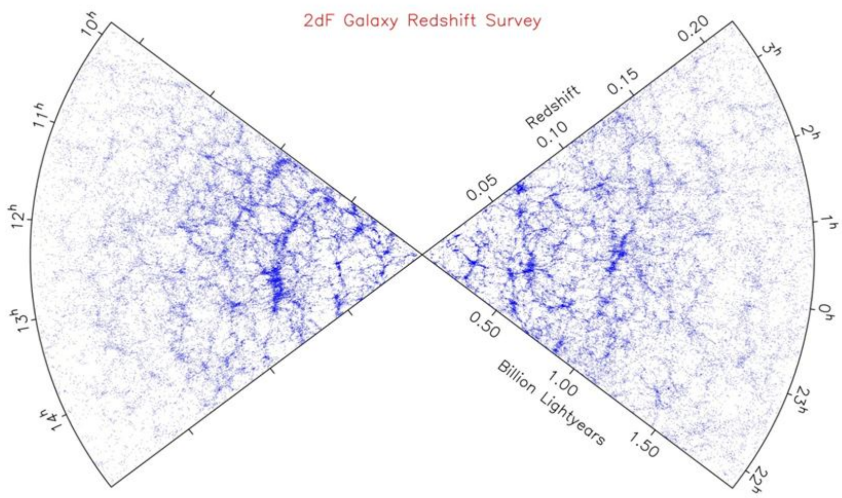

Figure 16. The 2dF Galaxy Redshift Survey (2dFGRS), by M.M. Colless, et al, 2001.

almost all were generated by errors in the computation of distances, due to the fact that the redshift produced by the Universe expansion gets mixed with the redshift coming from the proper movements of the galaxy with respect to other celestial bodies in its neighborhood and from the movement of the observer, which are sometimes not easy to disentangle. Some of the big structures remain, however, as is the case of the Great Wall, and of the voids surrounded by galaxies on their surfaces. Moreover, on top of slices we have now true 3-dimensional representations of the observed data, together with computer simulations depicting a very rich and marvelous web structure. However, the problem to obtain this large scale pattern starting from a fundamental theory remains, to large extent, open.

Summarizing a lot, cosmologists know now that our Universe is not static nor in a steady state. Quite on the contrary, it had a very spectacular origin some 13,730 million years ago, what we know with an error of less than 1%, according to the most recent (7th year) data from the WMAP (Wilkinson Microwave Anisotropy Probe) satellite, and to the first data coming from the PLANCK mission, and from different terrestrial observatories. All astronomical tests that have been carried out until now have confirmed, without the slightest doubt and with increasing accuracy, the new Big Bang theory, that is, the one which includes inflation (although, concerning this last, a too-large number of different, competing models still remains). But this is by no means the last word.

7. The expansion accelerates

Until the end of last Century, cosmologists were convinced that the expansion of the fabric of the Universe, originated in the Big Bang, was uniform. Up to then the main challenge of cosmology at large scale was to determine if the mass-energy density, ϱ, of our cosmos was large enough (above critical) so that it would be able to completely stop this expansion at some point in the future—an instant after which the Universe would begin to contract, to finally finish in a so-called Big Crunch—or if, quite on the contrary, this energy density ϱ was smaller, subcritical, and thus unable to stop the Universe expansion completely, ever in the future. In this case, expansion would continue forever, even if, of course, there was no doubt that the action of gravity would certainly decelerate the expansion rate, this was crystal clear. The most precise observations carried out until then indicated that the actual value of ϱ was indeed very close to the critical value, ϱ_c, being in fact quite difficult to determine if it was, in fact, above or below such value.

This situation radically changed just before the end of the Century, because of two different analyses of very precise observations carried out —with the big Hubble Space Telescope— on type Ia supernovae by two teams, each comprising some thirty scientists. The two groups wanted to measure with high precision the deceleration, caused by gravity attraction, on the expansion rate of the Universe, by calibrating the variation in this expansion rate with distance. To their enormous surprise, the values obtained by both teams were completely unexpected, and matched with each other. The first to issue results, in 1998, was the High-z Supernova Search Team an Australian-American project, led by Brian Schmidt and Adam Riess, while the other group, with the name Supernova Cosmology Project and led by Saul Perlmutter at Lawrence Berkeley National Laboratory, published independent results the year after, 1999. The author cannot help mentioning that one of the members in this last collaboration is the Spanish astronomer Pilar Ruiz Lapuente, from Barcelona University. The common and very clear conclusion of the two observations was that the expansion of the Universe is nowadays accelerating and not decelerating, and that it has been accelerating for a long period of time in the past. This was one of these moments in History where you have something in front of your eyes that you really do not believe. You cannot explain it with the scientific tools at your hand. The impact of this discovery on our knowledge of the Universe was extraordinary and the three researchers who led the teams have been awarded the 2011 Nobel Prize in Physics. The first conclusion seems quite clear: in order that this acceleration can occur a force must be present, as we already know since Galileo, XVI C, and Newton, XVII C, but in this case the force must be acting constantly at the level of the whole cosmos! The question is now, what kind of force can have this property in order to produce the desired acceleration?

Figure 17. Saul Perlmutter Brian Schmidt Adam Riess

Thinking for a while, it is not difficult to explain the problem even to a non-specialist. An expanding Universe, as in the case of the Bing Bang theory, does not need any force to expand forever, just an initial impulse, for a short interval of time, as when we throw a stone in the air. In this case, owing to the enormous mass of the Earth we are sure the stone will stop flying and come back; but if the Earth was the size of a mountain this same stone would never return. As already explained, at cosmological level everything just depends on the mass density of the whole Universe being larger or smaller than the critical value, ϱ_c, which marks the difference between the situation when the Universe would continue expanding forever and the one in which it would stop expanding, to start contracting back. But now, in order that the stone can accelerate, a force must act on it all the time, as with an accelerating car. As in the case of dark matter, nobody knows yet what produces this acceleration of the Universe expansion, and this missing energy is generically called dark energy. In fact a (too large) number of possible explanations have arisen, which can be roughly classified into three types.

The first one is the most natural and immediate, but in no way the simplest to match. Coming back where we started, with Einstein's equation, the only possibility to provide a repulsive force there is by introducing again the cosmological constant, Λ, with the appropriate sign. There is no other freedom but, fortunately, we still have this one! Regretfully, however, as with Einstein's, there is a big question mark behind it, namely, what is the physical nature of Λ? Where does it come from? This brings us to explain about another crucial revolution which took place in Physics during the first thirty years of the past Century: Quantum Mechanics. This is probably the most radical change in our conception of the world that has ever happened. In spite of Richard Feynman saying that "nobody can understand QM," the fact that it works to enormous precision for the description of nature is witnessed by the unchallenged 14 to 15 digit matching in the results of some particle physics experiments. Already Wolfgang Pauli in the 20's, and then Yakov Zel'dovich in the 60's, among others, clearly realized that if the fluctuations of the quantum vacuum—which are always there owing to W. Heisenberg's uncertainty principle and have a magnitude of the order of Planck's constant— are taken into account in Einstein's equation (as a valid form of energy satisfying the equivalence principle), then their contribution at cosmological scale (which happens to go together with Λ) would be enormously big. In principle, infinitely so, albeit we know that through a regularization and renormalization process the number is rendered finite. But even then it is still enormous: some 60 to 120 orders of magnitude larger than needed in order to explain the observed Universe acceleration. This is the famous cosmological constant problem, which was around since the first attempts to reconcile General Relativity and Quantum Physics appeared (although, at first, the problem was just to explain why vacuum fluctuations yielded a zero contribution, not a very small one, as now). Some very important physicists, as the Nobel Prize laureate Steven Weinberg [18], have been working for years on this problem, without real success. The reader must be adverted that, in these discussions, the concepts of cosmological constant and of quantum vacuum fluctuations are taken as one and the same thing, the reason being that there is no other possible contribution to Λ which is known up to now.

Another possible explanation is that there might exist some peculiar energy fluid filling the Universe (of course not of ordinary nature, as in the case of dark matter). There are many different models, with fancy names, for this fluid: quintessence, k-essence, Chaplygin gas, Galileons, and many more. The third possible explanation is the most radical of all, from the theoretical viewpoint and as seen from the whole description of the History of the Universe as summarized in the present article: maybe something is in error when trying to apply Einstein's General Relativity to cosmological scales, so that this marvelous theory may need be modified at these scales (as also Newton's equations might have to be modified too, in order to account for the missing dark matter). The reader will find full details of these thrilling issues in the other chapters of the Book. Let me here just note that modifications of Einstein's equation usually proceed by way of introducing additional terms with higher order powers on the Ricci curvature, R, a general function f(R), and/or higher order derivatives. In fact some of these terms are difficult to avoid when one considers quantum corrections to Einstein's equation, as Alexey Starobinsky and collaborators did already at the beginning of the eighties, finding in this way a model that would, to start, produce inflation and which can be modified to possibly account for its present acceleration, too. Scientists do not know yet the right answer, nor if the Universe acceleration is actually constant. To this end, the derivative of the acceleration should be obtained, what is still impossible with the quality of present data.

We should add that, for some time, the interpretation of the Ia Supernovae results as implying a Universal acceleration were controverted, some possible explanations involving a non-

Copernican view of the position of our local galaxy group in the cosmos were published (we could be in one of these enormous voids surrounded by very massive structures), and even very recently some alternative interpretation has appeared. However, Type Ia Supernovae are very good standard candles for the redshift range where the observations were carried out, since they have a very strong and consistent brightness along considerable cosmological distances; moreover, since 1990 several other independent proofs have been added to check the results. Among them, the impact of acceleration on the fluctuations of the cosmic microwave background, where measures have been carried out on the imprint of the acceleration on the gravitational potential wells which contribute to the integrated Sachs-Wolfe effect (and translate into colder and hotter spots in the CMB map). Also, the effect of acceleration on the gravitational lenses, and the one that it has on the large scale structures of the Universe, on the basis of the phenomenon known as acoustic baryon oscillations (BAO). All these observations are absolutely independent from each other and this contributes to the fact that there remains little doubt today that the Universe expansion accelerates. The Dark Energy Survey project (DES) is being set to provide new measurements, integrating all these different techniques, with participation of a group of our Institute ICE-CSIC and IEEC, led by Enrique Gaztañaga.

Figure 18. Jaume Garriga, UB Enrique Gaztañaga, CSIC Sergei D. Odintsov, ICREA Emilio Elizalde, CSIC

As already mentioned, a promising possibility to explain the acceleration consists in modifying Einstein's equation, that is GR itself, at least at large scales, entering the so-called f(R) or scalar-tensor theories, in their different variants. In our group of the Institute for Space Science (ICE-CSIC) and of the Catalan Institute of Space Research (IEEC), led by Sergei D. Odintsov and the author of this Chapter, we are presently working on this kind of models with a long list of international collaborators. As clearly stated at the beginning, all present day cosmology is based on Einstein's equation, thus, in making this step we are entering a new age in our knowledge of the cosmos. Yet to be seen is if it will finally be a successful one. As advanced, there are different ways to depart from GR, one of the most popular is by extending the Hilbert-Einstein action by the addition of a function, f(R), in principle arbitrary, of the Ricci curvature, R. A theory of this kind was first proposed by Hagen Kleinert and Hans-Jürgen Schmidt, and independently by Salvatore Capozziello, in 2002. Already from the beginning this theory was related with quintessence, in which a scalar field with time evolution is incorporated to GR. The discussion about f(R) theories being in fact equivalent to scalar-tensor ones is still open today. At the classical level they are most probably equivalent, but at the quantum level the answer seems to be clearly negative. The recent and extremely important discovery of the Higgs field will surely give a spectacular thrust to this kind of models. In fact, in a paper of 2004 by Elizalde, Odintsov and Shin'ichi Nojiri (now at Nagoya University, Japan)[19] there was an independent proposal of the so-called quintom dark energy: one phantom plus one quintessence scalar which could have a relation with the discovered Higgs.

And with this we have reached the very final stage of our general description of our knowledge of the cosmos at large scales. There are still no observations to confirm or disprove these last theories. A lot more about them and all the most recent developments is to be found in the other chapters of this Book. Some very promising results seem to indicate that, within f(R) theories, there is the possibility to build, with blocks of a really fundamental theory, as string or M theory, a fully-fledged model which could describe all the stages of the evolution of the cosmos, from the Big Bang through inflation, reheating and recombination, to the present accelerated expansion and on towards the end of the Universe in a de Sitter asymptotic phase, which is the most plausible one (although some compelling models with future singularities, as the Big Rip, or either pulsating universes, cannot be excluded with present data). Adding up our knowledge of the Universe, we must shamefully confess that over 95% of it is, as of today, ‘terra ignota.’ But this is actually good for Science, since it means that, in front of us, there is a lot to be discovered, hopefully soon!

8. The origin of the Universe

Even more uncertain is the explanation of the creation of the Universe, of the very instant when it came to being. We are more or less acquainted with the corresponding passage of the Bible. Looking now at the descriptions of scientists, Stephen Hawking and Roger Penrose did important work on the subject, which has been influential for several decades, with the conclusion (obtained again under very general and natural conditions) that such instant is (or it was until recently) a mathematical singularity and, therefore, beyond reach of any kind of physical interpretation. This result was quite disappointing but, fortunately, it just affects classical theories and does not take into account quantum corrections which generically soften the singularities, or even make them completely disappear. Making the story short, there are new models (Alex Vilenkin and also Andrei Linde have been working on them since over twenty years ago) in which one can sidestep the singularity problem: by combining inflation with quantum fluctuations of the vacuum state of a primordial system in which a spark or miniscule particle---a “twist in matter and space-time” so-called “Hawking-Turok instanton”---would be able, at zero-energy cost (as explained already), to ignite inflation which, on its turn, would amplify the negligibly small quantum fluctuations (of Planck’s constant magnitude) of the vacuum, giving rise, in this way, to the cosmic fluctuations (of order 10^{-5}) which we clearly observe on the CMB plot below. This is the most ancient map of the Universe that we have been able to capture until now. It corresponds to when it was some 370,000 years old. Just before that, the Universe was like a very dense and hot soup of quarks, gluons and elementary particles. It was absolutely dark, light being unable to travel in it, since photons, even if continuously created, where destroyed immediately, through recombination with the neighboring particles at such high densities. But the Universe was expanding and the temperature went down until it reached a value below the ionization threshold of the lightest of all atoms: that of hydrogen. All of a sudden, hydrogen precipitated at cosmic scale and, in this way, for the very first time in History, the very first light of the first cosmic dawn started to fill out the entire Universe. And this light is still reaching us from the most remote corners of the cosmos, and we can see it in all its brightness with the very curious eyes of our satellites as COBE, WMAP and PLANCK, which have transformed it into images, each time more and more clear, of the most ancient map of the Universe we now have. Putting all pieces together the so-called standard cosmological model, or ΛCDM (Cold Dark Matter with a cosmological constant, Λ) could be constructed and remains unchallenged till now.

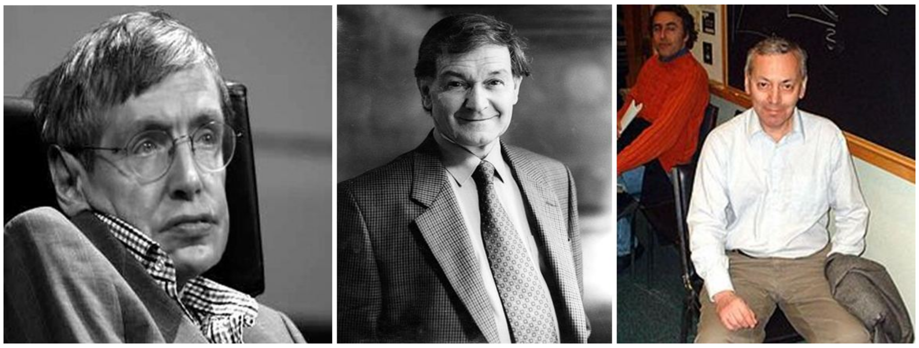

Figure 19. Stephen Hawking Roger Penrose Alex Vilenkin

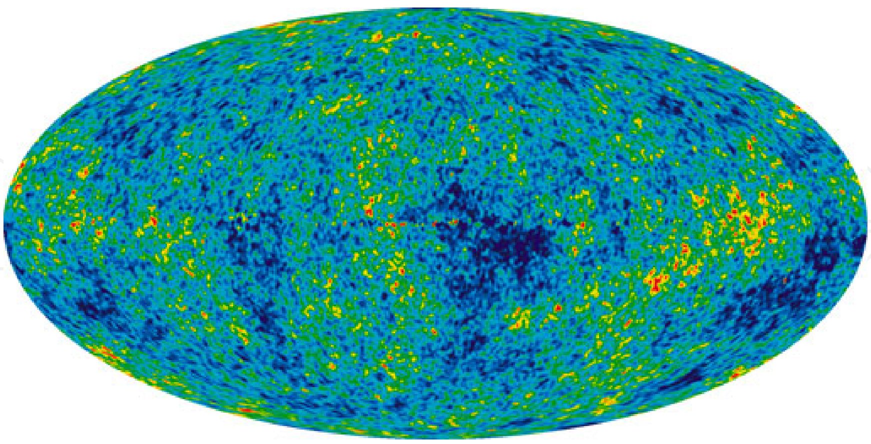

Figure 20. CMB Seven Year Microwave Sky, NASA/WMAP Science Team.

In order to proceed further into the observation of the origin --- eventually until the very origin of time --- we will need much better eyes. To start, those capable of processing the information hidden in the primordial gravitational waves, what we expect to be able to do in one to two decades from now (projects LISA, BBO, DECIGO, etc.). In that way we will obtain pictures of a much younger Universe and inflation could be eventually confirmed. But what is a real challenge for present day Physics, at least without involving any form of the anthropic principle (which in its strong version states that the properties of the Universe, the universal constants must be such that they need allow intelligent life to exist, that is, our presence as observers), is to develop a model for the origin and evolution of a single Universe like ours. The most advanced, and only feasible, theories will always produce a multiverse, that is, an uncountable collection of universes, of all possible kinds of sizes and properties, one of which, by mere chance, would be the one we happen to live in. But, until no observational proof of the existence of a multiverse is obtained, these theories will yet stay beyond the frontiers of Physics, and rather in the domain of science fiction. It must be acknowledged that these theories have been built up by very competent scientists and that they do not contravene any of the basic laws of nature. But in order to enter its realm, as in the case of the other theories discussed in this Chapter, compelling observational evidence must first be found.

As last word, among theorists there is still the much extended idea that the ultimate answer will be found, sooner or later, within string (or M) theory, the so-called “theory of everything.” But a too common mistake at different moments in the History of Science has been the strong belief that one already had on its hands the final theory, that all what was left to do was just polish it a bit, fill up some small holes, and carry out more precise calculations. Errors in the past have been flagrant and were committed by some of the most brilliant scientists of each generation. The author of this Chapter defends the idea that a new theory will emerge, sooner or later, which will be very different from the ones we now have at disposal, and which will radically change our vision of the world, as much as General Relativity and Quantum Mechanics did one hundred years ago.

Author details

Emilio Elizalde*

Address all correspondence to: elizalde@ieec.uab.es

Consejo Superior de Investigaciones Científicas, ICE/CSIC and IEEC Campus UAB, Facultat de Ciències, Spain

References

[1] Ptolemy, Claudius. (1515). *University of Vienna: Almagest*, http://www.univie.ac.at/hwastro/rare/1515_ptolemae.htm.

[2] Halley, Edmund. (1714-16). An account of several nebulae or lucid spots like clouds, lately discovered among the fixt stars by help of the telescope. *Philosophical Transactions*, 39, 390-392.

[3] Messier, Charles. (1781). Catalogue des Nébuleuses & des amas d'Étoiles. *Connoissance des Temps*, 1784, 227-267, [Bibcode: 1781CdT.1784.227M].

[4] Herschel, William, & Herschel, Caroline. (1786). Catalogue of One Thousand New Nebulae and Clusters of Stars. *Philosophical transactions*, Vol.Royal Society GB.

[5] Hubble, Edwin P. (1937). *The Observational Approach to Cosmology (Oxford)*.

[6] Bartusiak, Marcia. ,(2010). The Day We Found the Universe. (Random House Digital)

[7] Einstein, Albert. (1915). Die Feldgleichungen der Gravitation. *Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin*, 844-847, http://nausikaa2.mpiwg-berlin.mpg.de/cgi-bin/toc/toc.x.cgi?dir=6E3MAXK4&step=thumb.

[8] Wilson, Robert W. (1978). The Cosmic Microwave Background Radiation. *Nobel Lecture*, http://nobelprize.org/nobel_prizes/physics/laureates/1978/wilson-lecture.pdf.

[9] Dicke, R. H., Peebles, P. J. E., Roll, P. G., & Wilkinson, D. T. (1965). *Ap. J.*, 142, 4-14.

[10] Penzias, A. A., & Wilson, R. W. (1965). *Ap. J.*, 142, 420.

[11] Roll, P. G., & Wilkinson, D. T. (1966). *Physical Review Letters*, 16, 405.

[12] Howell, T. F., & Shakeshaft, J. R. (1966). *Nature*, 210, 138.

[13] Penzias, A. A., & Wilson, R. W. (1967). *Astron. J.*, 72, 315.

[14] Gamow, G. (1948). The Origin of Elements and the Separation of Galaxies. The evolution of the universe. On the Relative Abundance of the Elements. One, Two, Three...Infinity. *Physical Review*, 74, 505, *Nature*, 162, 680, AlpherR.A.HermanR., 1948, *Physical Review*, 74, 1577, GamowG, 1974, *Viking Press*, revised 1961; Dover P.

[15] Guth, Alan H. (1981). Inflationary universe: A possible solution to the horizon and flatness problems. *Phys. Rev. D*, 23, 347.

[16] Rubin, V., Thonnard, N., & Ford, W. K. , Jr. (1980). Rotational Properties of 21 Sc Galaxies with a Large Range of Luminosities and Radii from NGC 4605 (R=4kpc) to UGC 2885 (R=122kpc). *Astrophysical Journal*, 238, 471.

[17] de Lapparent, V., Geller, M. J., & Huchra, J. P. (1986). A slice of the universe. *Astrophysical Journal, Letters to the Editor*, 302, L1-L5, March 1.

[18] Weinberg, Steven. (1989). The cosmological constant problem. Dreams of a Final Theory: the search for the fundamental laws of nature. The First Three Minutes. *Rev. Mod. Phys.*, 61, 1-23, *Vintage Press*, 1993, *Basic Books, 1977; updated 1993*.

[19] Elizalde, E., Nojiri, S., & Odintsov, S. D. (2004). Late-time cosmology in (phantom) scalar-tensor theory: dark energy and the cosmic speed-up. *Phys. Rev.*, D70, 04359.