Opening Lecture	Bollettino Accademia Gioenia Sci. Nat.	Vol. 42	N.° 370	pp. 1 - 18	Catania 2009	ISSN 0393 - 7143

Big-Bang, Evoluzione dell'Universo, e Mistero di Λ

Lectio Magistralis in Occasion of the Opening Ceremony of the Accademia Gioenia CLXXXV Year, 20 February 2009

LUCIO PATERNÒ

Department of Physics and Astronomy, Astrophysics Section, University of Catania, Città Universitaria, Via S. Sofia 78, 95123 Catania, Italy
(e-mail: lpaterno@ct.astro.it)

RIASSUNTO

La cosmologia moderna ebbe inizio nel 1915 quando Albert Einstein enunciò la teoria della Relatività Generale e scoprì con sorpresa e disappunto che le equazioni predicevano un universo in espansione o contrazione, contrariamente alle idee Newtoniane dominanti e la prevalente teologia di quei tempi. Queste idee indussero Einstein a modificare le sue equazioni introducendo un termine repulsivo, la costante cosmologica Λ, per controbilanciare l'azione attrattiva della gravità rendendo così l'universo statico. Ma nel 1929 Edwin Hubble scoprì che tutte le galassie mostravano un moto di recessione proporzionale alla loro distanza, stabilendo la celebre legge dell'espansione dell'universo. Alla luce di questa scoperta Einstein dichiarò che l'introduzione di Λ fu il più grave errore della sua carriera. Altre scoperte fondamentali a partire dagli anni sessanta, come la radiazione cosmica di microonde (CMB), i conteggi delle radiogalassie e la teoria della nucleosintesi primordiale, hanno chiaramente dimostrato che l'universo si originò da un'esplosione primordiale, il Big Bang, avvenuta circa 14 miliardi di anni addietro ed è in continua espansione. Più recentemente alcune missioni spaziali hanno rivelato piccole fluttuazioni di temperatura nella CMB che hanno permesso di determinare la geometria piatta, Euclidea, dell'universo con la conseguenza che dovette esserci un'epoca inflazionaria nell'universo primordiale in cui le sue dimensioni aumentarono di 10^{50} volte in 10^{-33} s. L'universo attuale è costituito dal 4% di materia barionica ordinaria, dal 23% di materia oscura non barionica e dal 73% di una forma non ben conosciuta di energia oscura che produce un'espansione accelerata. In questo scenario la costante cosmologica, ripudiata da Einstein, gioca un ruolo fondamentale nella dinamica dell'universo.

Parole chiave: Cosmologia – Big Bang – Universo Primordiale – Relatività Generale – Costante Cosmologica.

SUMMARY

Big-Bang, Evolution of the Universe, and Mystery of Λ

The modern cosmology was born in 1915 when Albert Einstein established the theory of General Relativity and discovered, with surprise and disappointment, that the equations were consistent with an universe expanding or contracting, contrarily to the dominant Newtonian ideas and the prevalent theology of those times. These ideas induced Einstein to modify his equations by introducing a repulsive term, the cosmological constant Λ, for balancing the attractive action of gravity and rendering the universe static. However in 1929 Edwin Hubble discovered that all the observed galaxies showed a recessional motion whose intensity was proportional to distance so establishing the famous law of the expansion of the universe. In the light of this discovery, Einstein declared that the introduction of Λ was the biggest mistake of his career. Other fundamental discoveries starting from the sixties, such as the cosmic microwave background (CMB), the counts of radio-galaxies and the theory of primordial nucleosynthesis, clearly demonstrated that the universe owed its origin to a primordial explosion about 14 billion years ago, the Big Bang, and is in a continuous expansion. More recently space missions have detected small temperature fluctuations in the CMB that permitted us to infer the flat, Euclidean, geometry of the universe and by consequence a necessary inflationary epoch in the primordial universe during which its size increased by 10^{50} times in 10^{-33} s. The present universe is constituted by 4% of ordinary baryonic matter, 23% of non-baryonic dark matter and 73% of a not well understood form of dark energy that produces an accelerated expansion of the universe. In this scenario the cosmological constant, rejected by Einstein, plays a fundamental role in the dynamics of the universe.

Keywords: Cosmology – Big Bang – Primordial Universe – General Relativity – Cosmological Constant.

1 Introduction

The question about the origin and the end of the universe in which we live was posed since the time of the human appearance on our planet. However until when the modern science and technology did not develop, any conjecture about the nature and evolution of the universe remained merely an act of faith.

The progresses of Astrophysics in the last forty years, owing to the advent of new ground-based and space technologies, were constellated by making-epoch discoveries comparable to the fundamental ones of the Physics in the first fifty years of the XX century. These discoveries enabled the astronomers to acquire a deep knowledge of the universe, though not definitive. The space missions, besides the accurate analysis *in situ* of the components of the solar system with the consequent knowledge of its formation, opened the universe to the optical observations extended until its remote limits and to the observations in electromagnetic radiation spectral regions precluded to ground-based observations, such as the ultraviolet, infrared, X and γ bands. A new, extremely *coloured* universe opened to the observations that allowed the deep knowledge of a series of phenomena not visible before, such as the birth and formation of stars in the interstellar dusty clouds, the structure and dynamics of galaxies and clusters of galaxies, the Quasar, very powerful energy emitters whose engine is constituted by a black hole billion times more massive than our Sun, the γ-ray bursts, the most intense energy sources of the universe which are located at its boundaries and are produced by the explosions of the primordial supernovae stars, called hypernovae.

The modern Cosmology was born in 1915 when Albert Einstein established the theory of General Relativity and discovered with some surprise and disappointment that equations were consistent with an expanding or contracting universe. At that time the ideas that permeate the cosmology were dominated by the theory of Newton based on the assumption of a static and immutable universe as a consequence of the uniform distribution of matter in all the space in such a way that gravity could not act in denser regions so causing collapses with the formation of large cluster of matter, not observed with the old technologies. The Newtonian ideas and the prevalent theology of that time induced Einstein to doubt of his revolutionary results and led him to modify his elegant equations by introducing a repulsive term, the cosmological constant Λ, for balancing the attractive action of gravitational field and rendering the universe static.

The use of Λ was rejected by Einstein as his career biggest mistake when Edwin Hubble established in 1929 his famous law on galaxy recession demonstrating that the universe is in expansion, so that he posed $\Lambda = 0$ in the successive cosmological models. After Hubble, other basic discoveries, such as the cosmic microwave background (CMB), the primordial nucleosynthesis theory and the counts of radio-galaxies, posed firm grounds on the idea that the universe was born from an initial explosion, the Big Bang, and is still expanding at the rate established by the Hubble law.

Several experiments demonstrated the validity of the theory of Relativity, Special and General, and the most important consequences of this theory for Cosmology depend on the finite velocity of the light and the impossibility of treating space and time as separate entities. These consequences imply that farther one looks into the space farther one looks into the time and that the space-time geometry is modelled by the presence of mass and energy. Therefore to study the origins of the universe one should observe the phenomena occurring at its farthest edge, located at an estimated distance of about 14 billion light-years, where the first photon escaped from the radiation impenetrable Big Bang fire-ball.

More recently, three new space experiments, COBE (1991), BOOMERANG (2000), and WMAP (2003), discovered thermal micro-fluctuations of the order of $10\,\mu$K in the CMB, interpreted as the imprints of the past history of the universe. These fluctuations allowed the astrophysicists to infer the large scale geometrical properties of the universe that appears to be flat (Euclidean geometry). However, with $\Lambda = 0$, the universe density matter, both baryonic and dark, estimated through the dynamics of clusters of galaxies appears to be largely sub-critical indicating a non-flat geometry but an open type one. Therefore we face two contradictory measurements that lead to two different space geometries. This inconsistence can only be removed if we re-establish the role of the rejected cosmological constant Λ in the Einstein equations.

2 The Einstein Cosmic Equation

The final result of the theory of General Relativity, developed by Einstein in 1915, is the field equation that describes the space-time curvature as a function of the density of matter and energy. The original tensorial form of the equation that includes the cosmological constant Λ is the following:

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

where $R_{\mu\nu}$ is the Ricci's curvature tensor, $g_{\mu\nu}$ is the space-time metric tensor, R the scalar curvature namely the trace of $R_{\mu\nu}$, $T_{\mu\nu}$ is the tensor matter-energy, c is the light-speed in the vacuum, and G is the universal gravitation constant. On the hypothesis of large scale homogeneity and isotropy of the universe, the so-called cosmological principle, the tensorial Eq. (1) can be reduced to the following more domestic ordinary differential equation:

$$\frac{\dot{R}^2}{R^2c^2} + \frac{k}{R^2} - \frac{\Lambda}{3} = \frac{8\pi G}{3c^2}(\varrho_r + \varrho_m) \tag{2}$$

where $R(t)$ is the scale factor, namely the radius of the universe as a function of time t, k is the scalar curvature ($k = 0$ flat Euclidean universe, $k > 0$ close universe, $k < 0$ open universe), ϱ_r and ϱ_m are the radiation energy and matter densities respectively, and the dot represents the time derivative. Equation (2) still contains Λ as a term for balancing the attractive action of gravity owing to the presence of radiation and matter. The terms ϱ_r and ϱ_m are the following:

$$\varrho_r = \frac{4\sigma T^4}{c^3}\ ; \qquad \varrho_m = \frac{3\mathrm{M}}{4\pi R^3} \tag{3}$$

where σ is the Stefan-Boltzmann constant of the radiation theory, T is the temperature of the field of radiation in thermodynamic equilibrium, and M the total mass of the universe.

As already outlined, the validity of the theory of Relativity, Special and General, has been proven by several experiments, the first and most famous of which was the determination of the deflection of the star-light rays, caused by the presence of the Sun's mass, observed by Sir Arthur Eddington during the total solar eclipse of May 29^{th}, 1919 (1). Other more recent validity proves are the explanation of the advancement of the Mercury's perihelion, the increase of the decay-time of elementary particles accelerated to approach the light-speed, the gravitational lensing effect observed when a galaxy or a cluster of galaxies interplay between a distant source and the observer, greatly enhancing the brightness of the distant source, the gravitational redshift of spectral lines that has recently been observed in the proximity of very massive black holes, and the delay of clocks near a gravitational field with respect to those far from it. All these effects were predicted by the Einstein's theory for bodies moving at speeds comparable with the light-speed and in presence of strong gravitational fields.

3 The Hubble Law

Immediately after the Einstein's theory was published, Edwin Hubble, *the mariner of nebulae*, initiated a systematic study of the so-called nebulae, that appeared as diffuse objects to the vision of the telescopes of that time and were argument of dispute among the astronomers who did not yet establish whether they were located in our galaxy or outside, essentially because the scientists did not have the possibility of measuring great distances. However, the existence of very bright pulsating stars called Cepheids was known since some years before Hubble started in his survey. As discovered by Leavitt and Pickering in 1912 (2), these stars have the peculiarity that their pulsation period is related to their absolute magnitude M, whose relationship is described by the following formula:

$$M = -2.81 \log P - 1.43 \tag{4}$$

where P is the pulsation period measured in days. The knowledge of the absolute magnitude, connected to the intrinsic emitting power of the star, is the necessary ingredient for determining its distance once the apparent magnitude m, connected to the radiation flux Φ at ground through the Pogson law [$m = -2.5 \log(\Phi/\Phi_0)$ with Φ_0 a standard reference flux[1]], has been measured:

$$m - M = 5 \log d - 5 \tag{5}$$

where d is the distance measured in pc (parsec, 1 pc = 3.26 light-years) and the difference $m - M$ is called distance modulus. Thus the Cepheids constituted the first standard candles for measuring the distances in the universe to an upper limit of about 100 million light-years, well outside our galaxy whose size is about 0.1 million light-years. The period-magnitude relationship [Eq. (4)] was calibrated with galactic Cepheids for which the distances could be measured with different methods.

Hubble first discovered one of these Cepheids in the near, great galaxy Andromeda (M31) and established its distance in some 1 million light-years, about two times shorter than the modern determinations but certainly outside our galaxy. Along a period of some 5 years Hubble observed 18 galaxies measuring their optical spectra and distances. He discovered that all the galaxies were characterized by a recessional motion, determined by the Doppler redshift of spectral lines, whose speed was proportional to the distance. In 1929 he announced during a meeting of the American Academy of Sciences his law of the expansion of the universe (3):

$$V_r = H_0 d \tag{6}$$

where V_r (km s^{-1}) is the recessional velocity, the so-called Hubble flux, d (Mpc, Megaparsec) the distance, and H_0 (km s^{-1} Mpc^{-1}) the Hubble constant. In Fig. 1 is shown the original diagram of Hubble where in the horizontal axis is plotted the distance in pc and in the vertical one the recessional velocity of the observed galaxies in kms^{-1}. The slope of the interpolating line represents

[1] The magnitudes decrease with increasing radiation flux having also negative values, so that fainter is the star higher is its magnitude value.

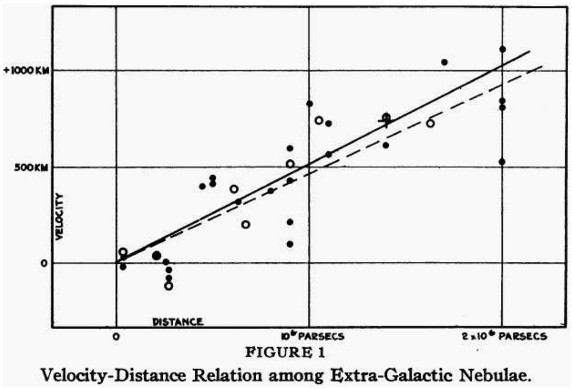

Figure 1: The original Hubble's diagram showing the velocity-distance relationship for extra-galactic *nebulae* presented in 1929 at a meeting of the American Academy of Sciences.

the Hubble constant H_0 defined in Eq. (6); the value of H_0 resulting from Hubble's observations was 500 km s^{-1} Mpc^{-1}. The inverse $H_0^{-1}$of the Hubble constant represents a time that defines the age of the universe in virtue of Eq. (6). The value of H_0 found by Hubble reflected on an age of the universe of about 2 billion years. Today we know that the measurements of Hubble were affected by severe errors due to the old observing technologies that led to greatly overestimate H_0 and by consequence to greatly underestimate the age of the universe.

After Hubble's times until to the very recent ones the precise determination of H_0 assumed a fundamental role for the development of cosmological models.

4 The 4 Cornerstones of Big Bang

The original Hubble law was based on the observations of galaxies where the brightest Cepheids could be visible with the telescopes of that time, whose apparent magnitude limits were about $m = 20$. Since the brightest Cepheids have absolute magnitudes of the order of $M = -7$ ($P \simeq 100$ days), then through Eq. (5) it is deduced that the distances probed by Hubble could not be larger than 2 million pc or 6.5 million light-years, as is evident from Fig. 1. In modern times with the advent in 1992 of the Hubble Space Telescope the exploration of the universe could be extended to the observations of objects with $m = 28$ corresponding for Cepheids to distances of about 100 million light-years. However, much more powerful standard candles are the supernovae of Ia type, carbon-oxygen white-dwarf stars in a binary system with a red-giant star as companion that feeds matter onto the white-dwarf until to overcome its critical mass of about 1.4 solar masses, so causing a destructive explosion owing to the nuclear carbon detonation. This explosion produces a fixed maximum brightness equivalent to an object of $M = -19$, 6×10^4 times brighter than the brightest Cepheids, so permitting the exploration of the universe until its most remote space limits and by consequence the exploration of its origin.

Owing to the construction of new generation large telescopes with effective collecting areas up to 200 m^2, 20 times larger than those used at the Hubble time, a multitude of supernovae Ia has been discovered in various galaxies located from the vicinity of our galaxy to the most remote ones, so verifying the validity of the Hubble law over large distances up to the boundaries of the universe. These new precise determinations pose firm grounds on the validity of the Hubble law describing the expansion of the universe. The most recent value of the Hubble constant, derived form the results of an international project, is $H_0 = 72 \pm 4$ kms^{-1} Mpc^{-1} (4) that implies an age of the universe of 13.6 ± 1 billion years. In Fig. 2 is shown the Hubble diagram as derived from the combined observations of several objects located at different distances d, expressed in Mpc, as functions of their redshift z or recessional velocity; in fact $z = \Delta\lambda/\lambda$ represents the Doppler shift $\Delta\lambda$ of spectral lines with respect to their rest wavelength λ and is connected with the recessional velocity V_r through the following relativistic formula:

$$z = \left(\frac{c + V_r}{c - V_r}\right)^{1/2} - 1 \tag{7}$$

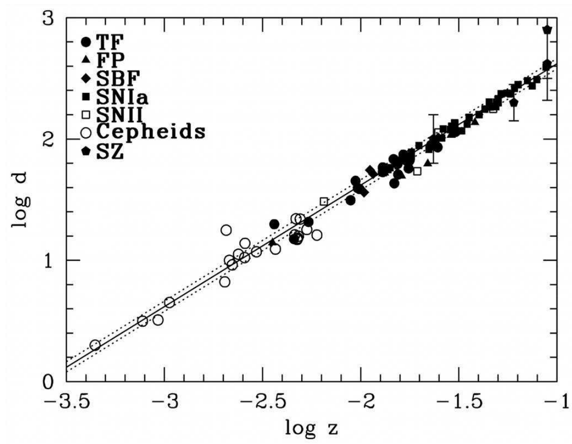

Figure 2: The modern Hubble diagram as obtained form the results of an international project (4).

The Hubble law constitutes the first cornerstone on which the theory of Big Bang is based, as the initial big explosion caused the expansion of the universe.

The second cornerstone is the casual discovery in 1965 of the cosmic microwave background by Penzias and Wilson (5) who were conducting experiments on the propagation of microwaves for radio transmissions through the Earth's atmosphere. They measured in their devices a persistent background noise independently of the orientation of their antennas with the consequence that the noise could not be produced by some local disturb, but it should have been produced by a signal coming from the space. They proved that the signal had the spectral characteristics of a black-body emission at the temperature of about 3 K ($\simeq -270$°C) and that the microwave emission was isotropic (6).

Three modern space experiments, COBE in 1991 (7), BOOMERANG in 2000 (8), WMAP in 2003 (9), confirmed the perfect black-body nature of the CMB emission corresponding to a temperature $T = 2.728 \pm 0.004$ K as shown in Fig. 3. The CMB emission at low temperature is interpreted as the ashes of the primordial explosion that occurred at very high temperatures.

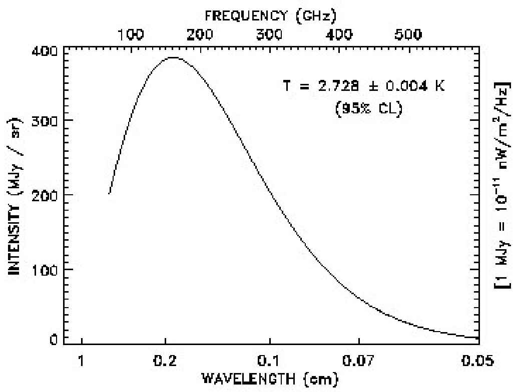

Figure 3: The CMB spectrum as obtained from the modern space experiments.

The third cornerstone is based on the illuminating article on the origin of the elements published by Hoyle et al. in 1956 (10). The authors describe the primordial nucleosynthesis of the elements subsequent to the Big Bang when the universe was hot enough to fuse the hydrogen into deuterium (D), helium-3 (^{3}He) and helium-4 (^{4}He) and then lithium-7 (^{7}Li), but could not form by fusion elements heavier than lithium because the universe became cooler as it expanded. The modern observations indicate that the present cosmic abundances of ^{4}He and D are about 25% and 1% by mass respectively with traces of ^{7}Li, the same amount estimated theoretically by the authors. The heavier elements were produced inside the hot central regions of the primordial massive stars, as described in the fundamental article by Burbidge et al. in 1957 (11), and then polluted into the space as consequence of their explosion as supernovae. Therefore the new generation stars, as our Sun and by consequence the solar system, formed in an environment rich of heavy elements. In Fig. 4 is shown the behaviour of the creation of the primordial elements that happened in the first 3 min after the Big Bang as deduced from modern calculations by Yang et al. (12) whose results are similar to those obtained by Hoyle et al. in 1956.

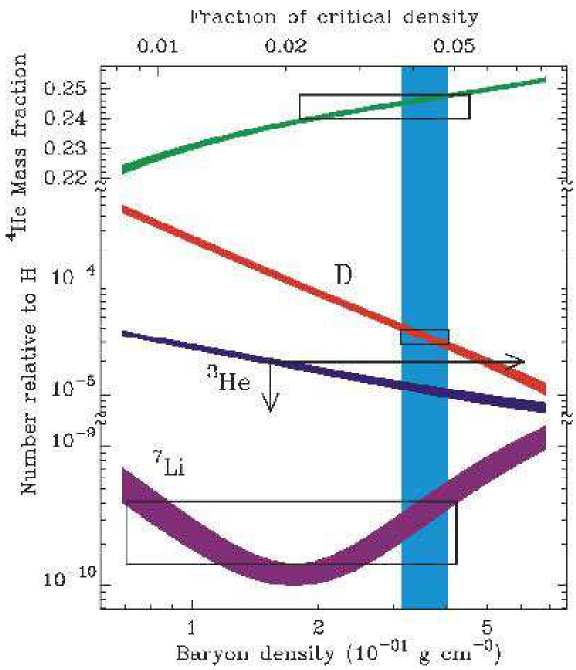

Figure 4: The behaviour of the creation of the primordial elements ^{4}He (top curve), D, ^{3}He and ^{7}Li that happened within the first 3 min after the Big Bang.

The fourth cornerstone supporting the theory of Big Bang relies with the counts of radio-galaxies that, owing to the deep penetration of the radio-waves into the Earth's atmosphere, constituted the easiest observable objects in the far universe, when at those times (1973) space observations were precluded. If the universe was infinite and uniform, since the number of the objects N increases with the cube of distance d and their radio-flux S decreases with the square of d, then the following relationship linking N to S should be valid:

$$\log N = -\frac{3}{2} \log S \tag{8}$$

Equation (5) expresses the famous $\log N - \log S$ relationship and indicates that as the radio-flux decreases for the farthest galaxies the number of the observed objects should increase with the 3/2 power, contrarily to what appears from an inspection of Fig. 5 where are reported the first results of the counts of radio-galaxies by Katgert et al. in 1973 (13). It is easily seen that below a unity of flux (a special measure for radio-astronomical measurements) the number of the objects decreases dramatically, indicating that the universe is finite and non uniform as one could expect form the theory of Big Bang.

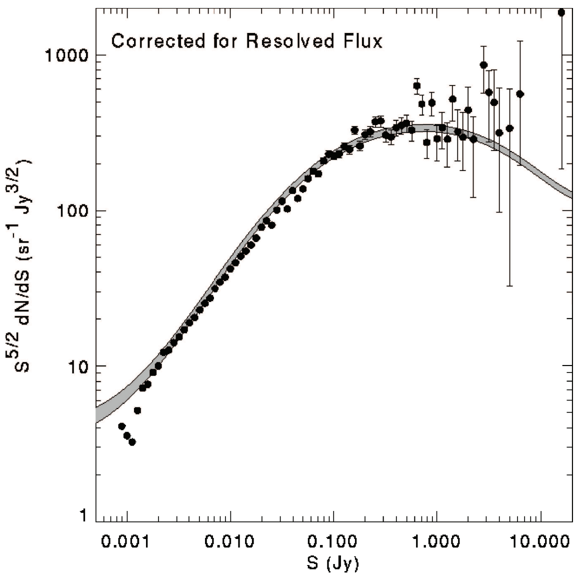

Figure 5: The first log N – log S diagram of radio-galaxies showing the sharp decrease of the number of objects below the unity radio-flux. This diagram was obtained by Katgert et al. in 1973 (13) and is the demonstration that the universe is not infinite but it presently reached a limit to its expansion.

5 The Matter in the Universe

In the light of the Hubble law of the expansion of the universe described by Eq. (6), the quantity $\dot{R}/R$ into Eq. (2) represents the rate of the expansion of the universe, namely the Hubble constant H_0. From Eq. (2) for $\Lambda = 0$ the necessary condition for having a flat universe ($k = 0$) (Einstein – De Sitter universe) is the following:

$$\varrho_c = \varrho_r + \varrho_m = \frac{3H_0^2}{8\pi G} \tag{9}$$

For $H_0 = 72\,\mathrm{kms^{-1}\,Mpc^{-1}}$, as the modern measurements indicate, the total density of the universe should be $\varrho_c = 9.72 \times 10^{-30}\,\mathrm{g\,cm^{-3}}$, where ϱ_c is the critical density for a flat universe. In the expanding universe the decreasing of $\varrho_r \propto R^{-4}$ is faster than the decreasing of $\varrho_m \propto R^{-3}$, where R is the radius of the universe. The present value of ϱ_r can be estimated by the temperature of CMB through Eq. (3) and it results to be $4.63 \times 10^{-34}\,\mathrm{g\,cm^{-3}}$ negligible with respect to the critical density. Therefore ϱ_m should be of the order of ϱ_c itself. In the primordial very hot universe radiation dominated while presently the universe is dominated by matter, the equilibrium between radiation and matter being reached some 10,000 years after Big Bang. On expressing the matter density in terms of the critical density, we define the parameter $\Omega_m = \varrho_m/\varrho_c$; with this definition, neglecting ϱ_r, from Eqs. (2) and (9) we obtain:

$$k = \frac{R^2 H_0^2}{c^2}\,(\Omega_m - 1) \tag{10}$$

Equation (10), obtained for $\Lambda = 0$, links the geometric properties of the universe, k, to the amount of density of matter with respect to the critical one, Ω_m. If the density of matter in the universe exceeds the critical one ($\Omega_m > 1$) then $k > 0$ and the universe is closed; if the density is just critical ($\Omega_m = 1$) then $k = 0$ and the universe is flat; if the density is sub-critical ($\Omega_m < 1$) then $k < 0$ and the universe is open, as shown in Fig. 6. The expansion and the fate of the universe are therefore determined by the value of Ω_m as schematically illustrated in Fig. 7 (Friedmann-Robertson-Walker universe). For $\Omega_m > 1$ (curve labelled *Bound*) the universe reaches a maximum expansion then,

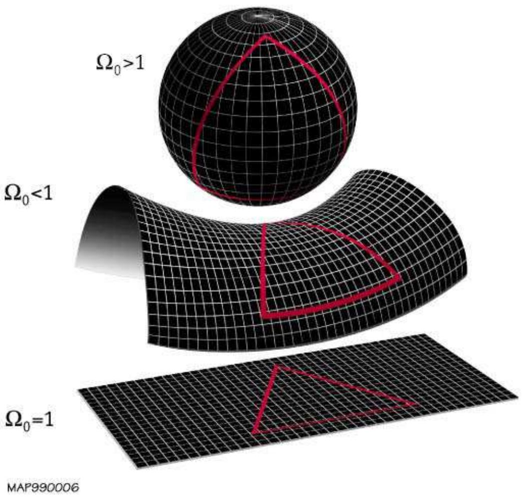

Figure 6: The various geometries of the universe depend on the value of the density of matter $\Omega_0 = \Omega_m$

since the density exceeds the critical one, the gravity produces a subsequent contraction until to reach the initial conditions of Big Bang (Big Crunch); for $\Omega_m = 1$ (curve labelled *Marginally Bound*) the universe expands smoothly, since the gravity just balance the initial acceleration, and it will reach an infinite radius in an infinite time; for $\Omega_m < 1$ (curve labelled *Unbound*) the expansion is more rapid.

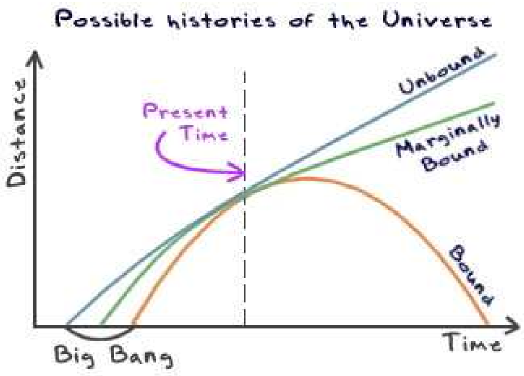

Figure 7: The history and the fate of the expanding universe as a function of the density of matter Ω_m for $\Lambda = 0$; in the vertical axis is plotted the size of the universe and in the horizontal one the time after the Big Bang.

The value of Ω_m can be estimated through the determination of the ratio mass – luminosity, M/L , of the clusters of galaxies. For the normal stars this ratio is of the order of unity indicating that the luminosity is only produced by the ordinary baryonic matter constituted by atoms. However when the astrophysicists initiated the study of galaxies for determining their masses they faced a new extraordinary problem; they found that the ratios M/L for galaxies were a factor of ten greater than those determined for stars, namely that a different form of non luminous matter should have been present in galaxies. The galaxies are constituted by hundred billions of stars and therefore is unconceivable that the estimate of their masses is based on the counts of stars. The estimate is based on the measurement of the rotational velocity as a function of the distance from the centre by means of radio-astronomical techniques, and from the balance between gravitational and centrifugal forces is possible to infer the total mass of a galaxy. For a multitude of galaxies observed the total mass necessary for accounting the behaviour of rotation resulted always about ten times larger than that constituted by the luminous stars, interstellar gas and dusts, including the estimate of the mass contribution of white dwarf, neutron stars and black holes. This excess of mass is attributed to a form of non-baryonic matter, the dark matter, whose nature is not yet well understood and whose effects manifest themselves only through the gravitational interaction; the most accepted nature of the dark matter is presently constituted by WIMPS (Weakly Interacting Massive Particles), perhaps microscopic black holes not yet evaporated that formed in the primordial universe.

However in order to infer the total amount of mass in the universe the observation of single galaxies does not constitute an efficient method. The study of clusters of galaxies, groups of galaxies formed by some thousand galaxies gravitationally interacting, through the measurement of their motions and the application of the virial theorem, that links gravitational to the kinetic energy, permits to deduce the total mass present in the clusters. The ratio M/L for all the clusters observed is in average a factor of about one hundred larger than the luminous mass contained in the clusters, that indicates that the universe is dominated by the non-baryonic dark matter. From the observations of a multitude of clusters of galaxies and other statistical considerations, it is deduced that the matter density of the universe is $\varrho_m \simeq 2.6 \times 10^{-30}$ g cm^{-3} $< \varrho_c$, that means $\Omega_m = 0.27 < 1$, with a distribution of 23% non-baryonic dark matter and 4% ordinary baryonic matter, half of which luminous. These data indicate that, by assuming $\Lambda = 0$, the universe should be open and its evolution described by the *Unbound* curve of Fig. 7.

6 CMB Temperature Anisotropy

Temperature anisotropies, or fluctuations, or inhomogeneities, in the CMB were predicted since 1972 by Zel'dovich (17) but it was not before 1992 that they were detected by the differential radiometer instrument onboard the satellite COBE (18). Subsequently, the existence of these temperature anisotropies was confirmed by other two more precise space experiments, the stratospheric balloon BOOMERANG that was first launched from South Pole in 1998 (19), and WMAP, a satellite launched in 2001 (14), that is capable of exploring all the sky differently from BOOMERANG that could explore only a portion of it owing to the short time of the flight (about 20 days). The results of WMAP fully confirmed the validity of those of BOOMERANG (Fig. 8).

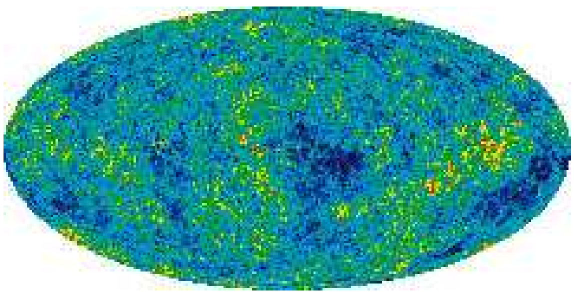

Figure 8: The all-sky image of the CMB temperature anisotropy as obtained by the satellite WMAP in 2003 (14).

The power spectrum of CMB anisotropies, namely the angular size distribution of CMB anisotropies, marks important signatures on the structure of the universe. Figure 9 shows the power spectrum as reconstructed by various measurements (15), (16) where the square of the normalized temperature fluctuations (μK^2) is plotted versus the multipole moment ℓ, or spherical harmonic degree, that is connected to the angular size of temperature inhomogeneities. On the data are overimposed the curves that represent the predictions of three current cosmological models whose behaviour is quite similar, that means that the anisotropy data describe fundamental properties of the universe independently of models. Each of the three peaks in Fig. 9 represents an important feature of the universe.

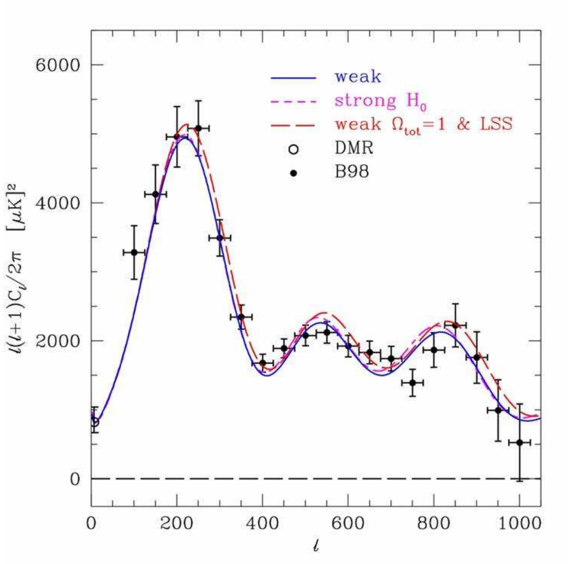

Figure 9: The power spectrum of CMB temperature anisotropy in terms of multipole moment or angular scale as obtained by WMAP in 2006 (15) and BOOMERANG in 2005 (16). The peak at the multipole 220 corresponds to an angular size of 1°.

The structure of CMB anisotropies is principally determined by two effects, acoustic oscillations and diffusion damping. The acoustic oscillations arise because of the competition between photons and baryons in the early universe plasma. The radiation pressure of photons tends to erase anisotropies, whereas the gravitational attraction of the baryons makes them to collapse to form dense haloes. These two effects compete to create acoustic oscillations which reflect in the characteristic peak structure of CMB. The peaks correspond to resonances in which photons decouple from matter when a particular oscillation mode is enhanced at its maximum amplitude. The first highest peak at the multipole moment $\ell = 220$, corresponding to an angular scale of 1°, determines the curvature of the universe, namely k; the second peak at $\ell \simeq 500$ determines the amount of baryonic matter, while the third, located at $\ell \simeq 850$, is connected with the dark matter density. These anisotropies that originated in the small, early universe are now reproduced in cosmic scales giving rise to the CMB inhomogeneities and the non uniform, quasi-filamentary distribution of the clusters of galaxies as shown in Fig. 10 that represents the cone-diagram where is plotted the location of the galaxies in clusters as a function of their recessional velocity, or distance, observed in a portion of sky about 2° wide. Since the distribution has the appearance of fingers this diagram is also called the *God's fingers*. The size of inhomogeneities as determined by the main peak in Fig. 9 is related to the path of the light-rays in the space-time; if their size is larger than 1° the universe is closed, if it smaller than 1° the universe is open, while if the size of inhomogeneities is just 1° the universe is flat, or Euclidean, as illustrated in Fig. 11. The heights of the two secondary peaks in the CMB anisotropy power spectrum are consistent with the amount of baryonic and dark matter as determined from the analysis of motions in galaxy clusters. As we shall see the flatness of the universe and the imprints in CMB of the primordial quantum fluctuations depend on an abrupt expansion (inflation) of the order of a factor 10^{50} in 10^{-33} s that happened 10^{-35} s after the Big Bang.

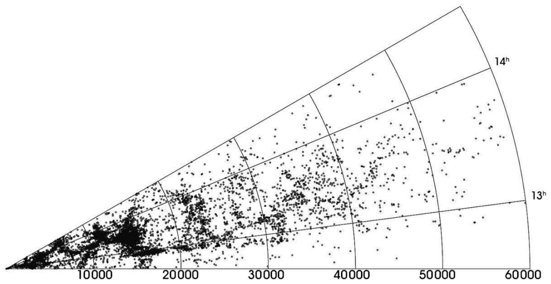

Figure 10: The cone diagram of distribution of galaxies in clusters where is shown their location as a function of recessional velocity, or distance, relative to a portion of sky about 2° wide.

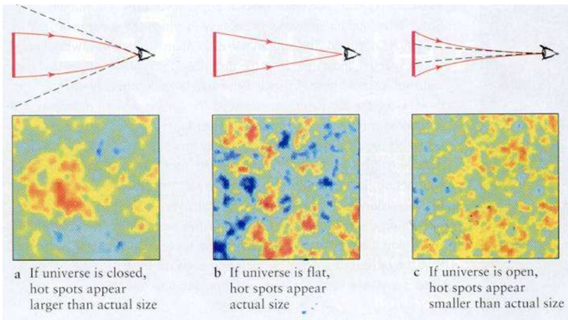

Figure 11: The size of CMB anisotropies and the curvature of the universe.

7 The Primordial Universe

The composition of the universe during its first few minutes of existence was profoundly different from that of the present universe. In nature exist four fundamental forces, gravity, electromagnetism, strong and weak nuclear forces. The first two are long range forces, though the gravity only, the weakest of the 4 forces, extends its effects toward the infinite, while the electric and magnetic forces vanish over large volumes because of the parity of positive and negative charges and the unavoidable existence of a north magnetic pole for each south magnetic pole. The gravity is attractive for all the ordinary matter determining the behaviour of the orbits of planets, evolution of the stars, galaxies, cluster of galaxies, and all the other large scale phenomena in the universe. The second two are very short range forces which act inside the atomic nuclei at distances of about 10^{-13} cm; the strong force keeps together protons and neutron in atomic nuclei against the repulsive electromagnetic force of protons, while the weak force governs the radioactive decays as the transformation of neutrons into protons or whenever occurs a change of type of quarks inside the proton and neutrons themselves.

In the period from the Big Bang to 10^{-43} s after it, called the quantum gravity era or the Planck era, all four forces were unified, equally strong and behaved in the same way as an unique force; in this period the universe was incredibly small $R < 10^{-33}$ cm and hot $T > 10^{32}$ K. In Fig. 12 is shown the evolution of the four forces as a function of time; in the figure is also indicated the temperature with the corresponding energy in GeV (10^9 eV) as given by the expression $\epsilon\,(\mathrm{GeV}) \simeq 10^{-13}\,T(\mathrm{K})$. At Planck time ($t = 10^{-43}$ s; $R = 10^{-33}$ cm; $T = 10^{32}$ K) the gravity first decoupled from the other forces becoming the weakest of them. The relationship between gravity and the other three forces is still uncertain because the theory of superstrings (Supersymmetric Theory of Strings), that relies on the vibrational properties of a least 10-dimensional space-time to create the fundamental forces and the elementary particles, including the graviton or quantum of gravity, is not yet well established, though promising. At Planck time the remaining three forces were unified

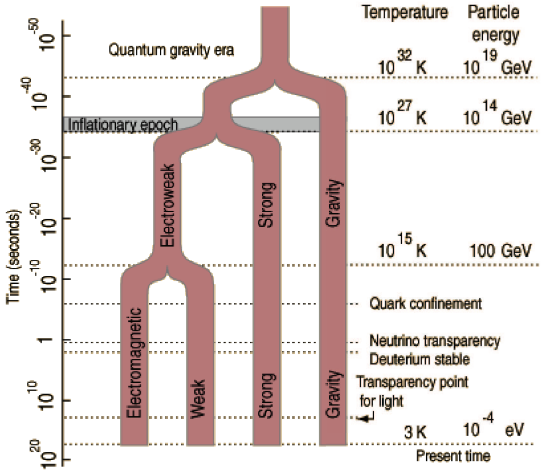

Figure 12: The 4 forces of nature were unified at the quantum gravity or Planck era, then as the universe expanded and became cooler they decoupled.

and described as one by the GUT (Grand Unified Theory); after the Planck time the universe initiated its expansion at the initial rate, so creating the space-time in which we presently live, and the temperature dropped to 10^{27} K in 10^{-35} s causing the decoupling of the strong force from the electromagnetic and weak ones, which remained unified as the electroweak force. This decoupling is connected with the abrupt transition from an unstable phase of the universe, called false vacuum, to the stable phase of the true vacuum; this transition happened in the time interval between 10^{-35} s to 10^{-33} s and the radius of the universe experienced a dramatic, sudden expansion (inflation) increasing by a factor of 10^{50}, as illustrated in Fig. 13 where the modern inflationary theory is compared with the old standard theory that predicted an expansion at the initial rate. In quantum field theory a false vacuum is a metastable sector of space that corresponds to a local minimum of energy but not to the lowest one; therefore there is the sudden phase transition (instanton effect) via the quantum tunnel effect to the lowest energy state owing to quantum fluctuations or creation and annihilation of high energy virtual particles.

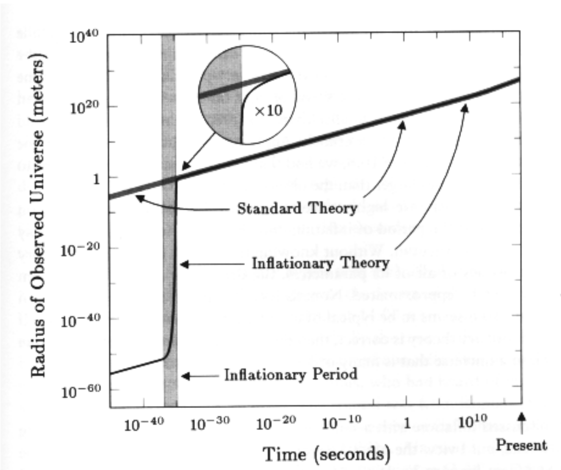

Figure 13: The evolution of the radius of the universe predicted by the modern inflationary theory compared with the old standard theory that predicts an expansion at the initial rate.

As pre-announced in Section 6 the inflation is responsible for the large scale isotropy and homogeneity of the present universe; in fact if the universe had continued to expand at the rate calculated for the Planck time, today we should see different parts of the universe with very significant temperature differences. The quantum fluctuations that occurred on microscopic scales at the pre-inflationary epoch were stretched by inflation to scales comparable with those of clusters of galaxies, namely that the tiny quantum fluctuations ultimately became the seeds for the formation of the large scale structures, of the order of 0.3 billion light-years, that presently we see in the universe as illustrated in Fig. 10, with the consequence that isotropy and homogeneity are concepts that involve scales larger than 1 billion light-years.

The end of the inflationary epoch heralded the first formation of elementary particles, quarks, electrons, neutrinos and their antiparticles all immersed in a bath of energetic photons at temperatures larger than 10^{15} K, and the universe resumed the relatively smooth initial expansion rate. When the temperature dropped to 10^{15} K after 10^{-12} s the electroweak force separated into the electromagnetic and weak nuclear forces and the four forces started to behave separated as today. The next significant event is calculated to have occurred after a μs after Big Bang when the temperature was 10^{13} K too cool for the quarks could survive as separate particles, and consequently they were forced to be confined in protons and neutrons and their antiparticles. In the first second the universe was so hot (T $\geq$ 10^{10} K) that photons were very energetic γ rays and could create pairs of particles and antiparticles continuously annihilating and reproducing. However, if all particles had annihilated their antiparticles in the early universe no matter would be left at all, but we see that universe is constituted by matter with a negligible amount of antimatter observed; since particles and antiparticles are created or destroyed in pairs, one should expect that they are found in equal numbers in the universe today. The fact that the nature of our universe prefers matter is attributed to the breaking of symmetry (Charge-Parity violation) probably due to the rupture of the electroweak force, related to the Higss boson, the *God's particle*, that governs the masses of elementary particles. If only a particle survived by chance among a billion of particles and antiparticles which mutually annihilated, this is sufficient to explain the present amount of matter and absence of antimatter.

When the universe was at the temperature of 10^{10} K, that happened about 1 s after Big Bang, with decreasing density it became transparent to neutrinos which were free to fill the space in an enormous number, about 1 billion per proton. In the successive three minutes first was formed the stable deuterium nucleus and then were produced the primordial nuclei of helium and lithium at temperatures of about $10^7 - 10^8$ K. As outlined in Section 5, in the early universe the radiation density was much larger than the matter density, but with expansion the radiation density decreased faster than matter density, the equality having been reached about $10,000$ years after Big Bang at a temperature of about 10^5 K. The present universe is amply dominated by matter, the radiation density being about four orders of magnitude lower, but the number of the microwave, cool photons per cubic meter exceeds by about a factor of 1 billion the present number of hydrogen atoms per cubic meter.

At temperatures of about 10^5 K and densities of about 10^{-15} g cm^{-3} matter and radiation were still in thermodynamic equilibrium and the electrons were energetic enough to prevent the formation of hydrogen and helium atoms while the ultraviolet photons underwent frequent collisions with free electrons, being scattered in all directions, and ionized the few atoms formed, being adsorbed and reemitted in all directions, the radiation being trapped in a completely opaque plasma fireball.

This situation persisted until when the temperature dropped to about 10^4 K and the era of recombination started to take place in which the electrons recombined with hydrogen and helium nuclei to form the first atoms. However it was about $380,000$ years later that the universe became transparent to radiation and the first photon could escape from the fireball reaching us, the surface of the universe from which the first photon escaped being called *last scattering surface*.

The CMB (see Fig. 8) contains the most ancient photons we expect ever to be able to observe and is a ghostly relic of the earlier dazzling splendor of the universe.

8 The Reinstatement of Λ and the End of the Universe

The power spectrum of CMB anisotropies clearly shows that the universe is flat, namely that the curvature parameter should be $k = 0$, and that the density matter, baryonic plus dark, as deduced from both clusters of galaxies and CMB anisotropy power spectrum, is sub-critical and gives $\Omega_m = 0.27$. These two results cannot be reconciled on the basis of Eq. (10) obtained for $\Lambda = 0$, for which the universe should be open with $k < 0$.

The results become mutually consistent only if we reintroduce the cosmological constant Λ as originally predicted by Einstein. Thus from Eq. (2) we obtain the following equation:

$$k = \frac{R^2 H_0^2}{c^2} (\Omega_m + \Omega_\Lambda - 1) \tag{11}$$

where $\Omega_\Lambda = c^2\Lambda/3H_0^2$ represents a sort of dark energy whose nature is obscure. From Eq. (11) it is evident that the reintroduction of Λ requires that $\Omega_m + \Omega_\Lambda = 1$ for a flat universe with the consequence that $\Omega_\Lambda = 0.73$ with Λ a positive constant. The expected value of Ω_Λ from the the quantum field theory is 10^{120}, some 120 orders of magnitude greater than that deduced from cosmological observations, the most disastrous disagreement never found between theory and observation. On the other hand if the value of Ω_Λ was the one predicted by the theory, the expansion of the universe would have been so fast that no stars and galaxies could be formed by the gravitational force action.

This disagreement constitutes one of the biggest mysteries of the present physics: on one hand the field theory that account for the existence of the various elementary particles and on the other hand the needs of cosmology for accounting the observations.

The nature of Λ is still matter of debate even if it is now almost commonly accepted that it acts as a sort of anti-gravitational energy, the dark energy of the vacuum, which determines an accelerate expansion of the universe once radiation and matter densities diminish their attracting forces as the expansion proceeds.

This idea is corroborated by the fact that the supernovae observed at the edge of the universe ($z > 0.5$) appear fainter than what predicted by the Hubble law, namely that they are farther than what expected on the basis of the normal Hubble expansion and therefore they experience an accelerated expansion. Figure 14 shows a magnitude-redshift diagram as obtained from the observations in the framework of the Supernova Cosmology Project (20), where the difference of the distance modulus $\Delta(m - M)$ with respect to a reference one is plotted versus the redshift z for a number of supernovae of Ia type. The horizontal reference line that intersects the zero of $\Delta(m - M)$

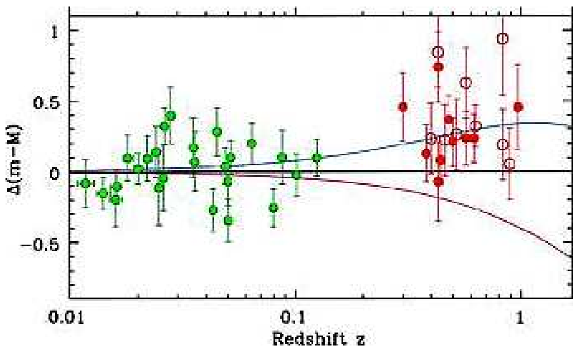

Figure 14: The magnitude-redshift diagram for supernovae of Ia type; the $\Delta(m - M) = 0$ line indicates an universe of Einstein-De Sitter type with $\Lambda = 0$ and $\Omega_m = 1$, while the bottom curve a close, decelerating universe and the upper curve, where the supernova data are displayed, an open, accelerating universe with dark energy. Data were carried out in the framework of Supernova Cosmology Project (20).

corresponds to the Einstein-De Sitter universe with $\Lambda = 0$ and $\Omega_m = 1$ ($k = 0$) expanding at the present Hubble rate as calculated from Eqs. 5, 6, and 7. The bottom curve describes the case of an universe with $\Lambda = 0$ and $\Omega_m > 1$ ($k > 0$), namely a close, decelerating universe for which the supernova magnitudes should be lower than those described by the previous situation . The upper curve shows an accelerating universe with dark energy ($\Omega_\Lambda = 0.73$, $\Omega_m = 0.27$), and all the observed points tend to lie on this curve indicating a $\Delta(m - M) \simeq 0.5$ for $z \simeq 1$, consistent with objects displayed some 20% farther in the universe than they should do if dark energy did not act.

Therefore all the modern measurements from the cosmic microwave background and mass – luminosity ratio of the clusters of galaxies to the faint supernovae at high redshifts seem to indicate that the present universe is made by a small quantity of baryonic matter (4% half of which luminous), by dark matter (23%) and by a large quantity of dark energy (73%), and the reintroduction of Λ into the Einstein's cosmic equation is a necessary ingredient for explaining the present cosmological data. The evolution of an universe with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, values close to the ones measured, is illustrated by the top curve of Fig. 15 that is similar to Fig. 7 in which are plotted only the curves for $\Omega_\Lambda = 0$. Detailed calculations indicate that the end of such an universe

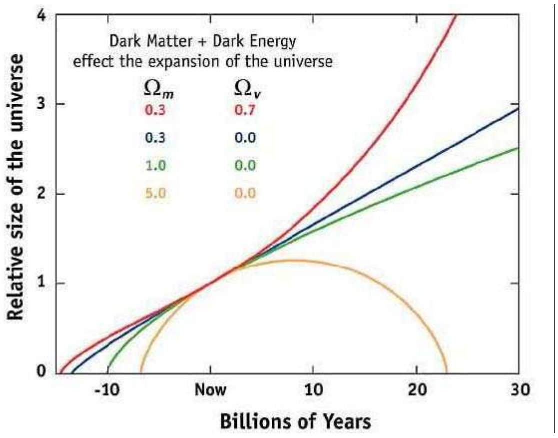

Figure 15: The history and the fate of the expanding universe as a function of the density of matter Ω_m for $\Omega_\Lambda = 0$ (the three lower curves) and $\Omega_\Lambda = 0.7$ (the top curve) as the modern data indicate; in the vertical axis is plotted the size of the universe and in the horizontal one the time after the Big Bang.

will happen 35 billion years after the Big Bang (about 20 billion years from now) with a Big Rip, exactly the contrary of the Big Crunch, caused by the continuous, accelerated expansion which first separate the galaxies from their clusters and the constituens from the single galaxies, then break up the stellar systems and the single stars, then the electrons from their atoms and finally reduce the nuclei in single elementary particles that become so distant that they cannot *see* each other so leaving the universe *eternally frozen* and *empty*.

9 Concluding Remarks

All the data collected from precise measurements of cosmological paramenters concorde in indicating that the universe was born by an initial explosion, the Big Bang, some 13 – 14 billion years ago, that it experienced an abrupt expansion in an earliest epoch that produced the present flatness and homogeneity and that the density matter is sub-critical. The modern measuremens also indicate that the cosmological constant Λ, initially rejected by Einstein, plays a fundamental role for explaining both the space flatness and the fainter brightness of the far supernovae, and all the data predict an universe expanding at an accelerate rate and a cool end (Big Rip).

However some questions are still matter of debate on the nature of dark matter and dark energy. Though there are some space experiments for investigating the true nature of dark matter no conclusions have been reached until now leaving the answer about its composition to the only theoretical conjectures. Its presence seems to be acquired with certainty because its gravitational effects on the large mass distribution of galaxies, unless to admit that the universal gravitation theory fails at very large distances as some scientists, who claim for a modified gravity, are substaining.

As previously outlined in Section 8, the dark energy, that reflects in a positive but small value of Ω_Λ, owe its anti-gravity action to the false vacuum energy in the earliest epochs of the universe. This implies an equation of state $p = w\varrho$, where ϱ is the false vacuum density, with a negative w; the theory indicates that for $-1 \leq w < 0$ the universe would expand at a rate higher than that predicted in the absence of dark energy but at a finite velocity, whilst for $w < -1$ the expansion caused by the dark energy should reach an infinite velocity so determining the Big Rip. Unfortunately the attempts to measure w did not give firm results until now, and this remains an open question of the modern cosmology.

Another point of discussion, as already seen in Section 8, is the fact that the quantum theory of fields, on which is based the description of the earliest instants of the universe, predicts a natural value of Ω_Λ in an absurd disagreement with the needs of cosmological observations, being 120 orders of magnitude larger. Nevertheless the cosmological observations require a precise value of Ω_Λ, infinitely smaller than the natural value, that implies that the parameters of the nature are regulated in a so extremely fine way that it seems innatural.

A different approach claims for a hypothetical fifth force, the quintessence, whose nature is of the same type as the dark energy with $w < -1/3$ but variable with the cosmic time in such a way that the expansion of the universe is self-adjusting at the different epochs never reaching the situation for the Big Rip taking place. Recent crossed determinations based on CMB and supernovae measurements indicate that $w \cong -1$ (21).

All the above mentioned arguments are the open questions of cosmology whose study is presently in full expansion with the perspective of obtaining important results in a near future.

10 Acknowledgements

I would like to gratefully acknowledge the President and Council of the Accademia Gioenia for the kind invitation to present this lecture in occasion of the opening ceremony of the CLXXXV Academic Year.

References

[1] Eddington, A. S. 1919, *The Observatory* 42, 119

[2] Leavitt, H. S. and Pickering, E. C. 1912, *Harvard College Observatory Circular* 173, 1

[3] Hubble, E. 1929, *Proc. National Academy of Sciences USA* 15, 168

[4] Freedmann, W. L., Madore, B. F., Gibson, B. K. et al. 2001, *Astrophysical Journal* 553, 47

[5] Penzias, A. A. and Wilson, R. W. 1966, *Astrophysical Journal* 146, 666

[6] Wilson, R. W. and Penzias, A. A. 1967, *Science* 156, 1100

[7] Mather, J. C., Hauser, M. G., Bennet, C. L. et al. 1991, *Advances Space Research* 11, 193

[8] de Bernardis, P., Ade, R. A. R., Artusa, R. et al. 2000, *Nature* 404, 955

[9] Hinshaw, G., Spergel, D. N., Verde, L. et al. 2003 *Astrophysical Journal Suppl. Series* 148, 135

[10] Hoyle, F., Fowler, W. A., Burbidge, G. R. and Burbidge E. M. 1956 *Science* 124, 611

[11] Burbidge, E. M., Burbidge, G.R., Fowler, W. A. and Hoyle, F. 1957, *Review of Modern Physics* 29, 547

[12] Yang, J., Turner, M. S., Schramm, D. N. et al. 1984, *Astrophysical Journal* 281, 493

[13] Katgert, P., Katgert-Markelijn, J. K., Le Poole, R. S. and Van der Laan, H. 1973, *Astronomy and Astrophysics* 23, 171

[14] Bennet, C. L. et al. (WMAP collaboration) 2003, *Astrophysical Journal Suppl. Series* 148, 1

[15] de Olibeira-Costa, A. and Tegmark, M. 2006, *Physical Review D* 74.02.3005

[16] Tristram, M., Patanchon, G., Macias-Pérez, J. C. 2005, *Astronomy and Astrophysics* 436, 785

[17] Zel'dovich, Yaa B. 1972, *Monthly Notices of the Royal Astronomical Society* 160, 1P

[18] Smoot, G. F. et al. (COBE collaboration) 1992, *Astrophysical Journal Letters* 396, L1

[19] de Bernardis, P. et al. (BOOMERANG collaboration) 2002, *Astrophysical Journal* 564, 559

[20] Knop, R. A., Aldering, G., Anamuallah, R. et al. 2003, *Astrophysical Journal* 598, 102

[21] Figueroa, D. G., Verde, L. and Jimenez, R. 2008, *Journal of Cosmology and Astroparticle Physics* 10, 38