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Cosmology: from Pomeranchuk to the present day

A D Dolgov

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Contents

Abstract. A review of half a century of cosmology is presented for an intended audience of elementary particle physicists. The review is based on a half-hour seminar talk (at the Institute of Theoretical and Experimental Physics, ITEP) and is therefore brief and superficial. The introductory historical section is mostly devoted to the fundamental work done in, but not always known outside, Russia (USSR). Foundational works and astronomical observations instrumental in shaping the field are discussed, as are inflation, baryosynthesis, dark matter and dark energy, vacuum energy, large-scale gravity modifications, and microwave background angular fluctuations. The presentation is admittedly not entirely objective but rather is given from the Russian (ITEP) perspective and is influenced by the author's personal views and biases.

1. Introduction. Some pieces of history

Slightly more than half a century ago, cosmology was an outcast from the respectable scientific family. The widespread attitude was well characterized by an ironic quotation from L D Landau: "always in error but never in doubt," which the author of this review heard from Ya B Zeldovich. Nevertheless, at that very time, much outstanding work was done which entered the corpus of modern cosmology. Of course, in connection with the hot universe model (or Big Bang cosmology), we must mention the names of Friedmann [1, 2], who on the basis of the Einstein equations predicted the Universe's expansion, later discovered by Lemaitre [3] (see [4]) and Hubble [5], and surely Gamow [6], who is justly the father of Big Bang cosmology.

Returning to the more recent epoch, we recall the pioneering papers by Zeldovich [7, 8] of 1965, where the freezing (in Russian literature, 'quenching') of massive stable particles in cosmology was first calculated on the basis of the fundamental equation derived there, which is currently a cornerstone for calculations of the density of dark matter particles in the Universe. Twelve years later, this equation was applied to the calculations of the cosmological density of heavy neutral leptons [9, 10] and not really fairly obtained the name of the Lee–Weinberg equation.

The pioneering work by Kobzarev, Okun, and Pomeranchuk [11] on possible mirror-particle dark matter was done at approximately the same time in 1966, long before dark matter became one of the popular themes in cosmology and particle physics.

In the same year, 1966, the paper by Gershtein and Zeldovich on the cosmological bound on the neutrino mass was published. It has to be admitted that the attitude of the scientific establishment to this work was quite skeptical, in the spirit of the Landau utterance mentioned above. However, it is now commonly accepted that the most precise device to weigh neutrinos is the telescope (see below). The work of Gerstein and Zeldovich was essentially repeated six years later by Cowsic and McClelland [13]; however, the authors made two essential mistakes, which resulted in a bound

A D Dolgov Novosibirsk State University,
ul. Pirogova 2, 630090 Novosibirsk, Russian Federation;
Alikhanov Institute for Theoretical and Experimental Physics,
Russian Federation State Scientific Center,
ul. B Cheremushkinskaya 25, 117218 Moscow, Russian Federation
E-mail: dolgov@fe.infn.it
Dipartimento di Fisica e Scienze della Terra, Università degli Studi
di Ferrara Polo Scientifico e Tecnologico — Edificio C,
Via Saragat 1, 44122 Ferrara, Italy;
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Ferrara
Polo Scientifico e Tecnologico — Edificio C,
Via Saragat 1, 44122 Ferrara, Italy

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approximately seven times stronger. Nevertheless, the cosmological bound on the neutrino mass was for a long time called the Cowsic–McClelland bound, which was absolutely unjust.

A year later, in 1967, Andrei Sakharov [14] suggested a remarkable mechanism to explain the baryon asymmetry of the Universe, i.e., of the observed predominance of matter over antimatter. He formulated three sufficient conditions for dynamical generation of the asymmetry: 1) breaking of C and CP invariance; 2) deviation from thermal equilibrium; 3) nonconservation of the baryon number. Even at that 'ancient' time, there were no doubts about the first two conditions, but nobody believed that the hypothesis of nonconservation of baryons might be true. Nowadays, it is practically an experimental fact proved by astronomers.

Until 1965, the cold universe model was the commanding one among Russian cosmologists, due to the dominant influence of Zeldovich. The situation radically changed after the discovery of the cosmic microwave background radiation (CMB), made by Penzias and Wilson [15], who came upon it accidentally, testing an antenna designed for detecting weak microwave radiation. Several years before this discovery, in 1957, Ter Shamaonov [16] registered similar radiation, although with lower accuracy, when he worked on calibration of the antenna for the RATAN-600 giant radiotelescope that was then under construction. The importance of this observation was not understood at that time because the hot universe model was then not popular in the Soviet Union. Still, half a year before Penzias and Wilson's discovery, and despite the hostile attitude of the establishment to Big Bang cosmology, a paper by Doroshkevich and Novikov [17] on the possibility of observing the cosmic microwave background radiation was published. In this work, the most favorable frequency band for the observation was specified. In this connection, we again mention Gamow [6], who predicted the existence of the cosmic microwave background arriving to us from the early hot stage of the Universe's evolution.

The measured frequency spectrum of the microwave background is very accurately given (with a precision of about 10^{-4}) by the equilibrium Bose – Einstein spectrum

$$f = \left(\exp\frac{\omega}{T} - 1\right)^{-1}, \tag{1.1}$$

with the temperature $T = 2.7260 \pm 0.0013$ K and a vanishing chemical potential, $\mu/T < 10^{-4}$. The temperature of radiation arriving from different patches in the sky is almost ideally the same. Before the 1980s, this equality of the temperature all over the sky was considered one of the greatest cosmological mysteries, because celestial points separated by more than one degree never knew about each other in the usual Friedmann cosmology (see the discussion about the inflationary paradigm below).

However, this cheerless perfection is a bit broken: very small temperature fluctuations δT must exist, and they are indeed observed. The point is that the universe is noticeably inhomogeneous. There are stars, galaxies, and clusters and superclusters of galaxies. All that cannot evolve from a perfectly homogeneous world. Hence, there must be small but nonvanishing density perturbations, and such perturbations would be imprinted in the angular fluctuations of the CMB temperature.

The first measurements of δT were done in the early 1990s [19]. According to them, $\delta T/T = 10^{-4} - 10^{-5}$ in different frequency and angular scales. In an earlier study by the Russian satellite Relict [20], only the quadrupole anisotropy was detected and, unfortunately, with a rather poor precision, $6.6 \times 10^{-6} < \delta T_2/T < 3.3 \times 10^{-5}$.

It is interesting that at the time the detectors for measuring angular CMB fluctuations were discussed, the magnitude of δT was expected to be much larger than was subsequently observed. Larger temperature fluctuations should exist in the Universe without dark matter (DM). The dominating presence of DM in the universe allowed for a much smaller value of $\delta T/T$. If this had been known in advance, the search for temperature fluctuations would probably have been postponed until better times. Thus, sometimes incorrect theoretical expectations stimulate successful experiments.

2. Contemporary Universe

To date, a huge number of precise measurements of $\delta T/T$ have been accumulated, the measurements done on balloons and satellite detectors, in particular, on WMAP (Fig. 1). Recently, new results from the Planck mission have been published, which greatly exceed all others in accuracy (Fig. 2). Analysis of the spectrum of the angular fluctuations of CMB allows determining cosmological parameters with unprecedented precision. The measurements of CMB temperature fluctuations definitively brought cosmology into the exact science 'club'.

Returning to the precision of observations in the 1960s, we recall that the Hubble parameter was known up to a factor of two: $H = 50 - 100$ km s^{-1} Mpc^{-1}. The baryon-to-photon ratio was known even more poorly: $N_B/N_\gamma = 10^{-9\pm1}$. In this connection, I recall an acidic comment by a well-known physicist during my talk on cosmological baryon asymmetry at an ITEP seminar: "What kind of science is it, where the error enters the exponent?" At this ancient time, people believed that the usual baryonic matter made up practically 100% of the Universe's mass. The first seriously perceived observations that shook this belief appeared only in 1974 [21,

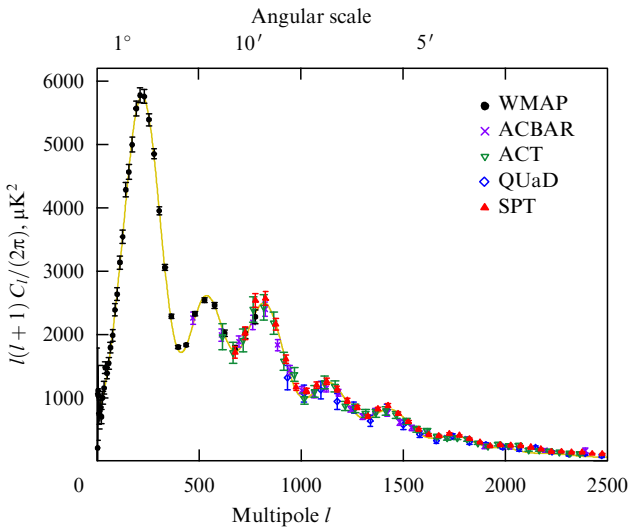

Figure 1. Combined data of temperature fluctuations before the Planck mission. Here, C_l is the amplitude of the fluctuation δT squared for the multipole l. ACBAR: Arcminute Cosmology Bolometer Array Receiver; ACT: Advanced Communications Technology satellite; QUaD: QUEST (Q and U Extra-Galactic Sub-mm Telescope) at DASI (Degree Angular Scale Interferometer); SPT: Satellite Positioning Technology.

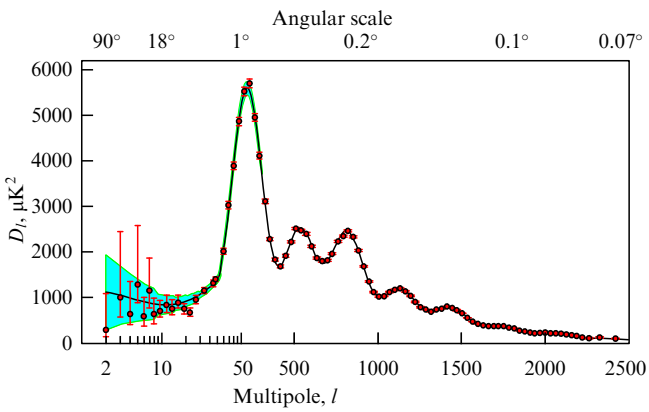

Figure 2. Temperature fluctuations of CMB according to Planck measurements. The notation is the same as in Fig. 1, with $D_l = C_l l(l+1)/(2\pi)$.

22], although already 40 years earlier there had been serious indications that the Universe was not so simple [23, 24].

Nowadays, practically nobody doubts that baryons contribute a petty 5% fraction of the whole cosmological matter, while the dominant 95% remains unknown. This unknown part, in turn, consists of two parts: dark matter (DM), whose contribution is around 25%, and dark energy (DE), contributing approximately 70%. There are many possible forms of DM. They may be stable elementary particles that are not yet known, compact stellar-like objects, or black holes, but in all cases they have normal gravitational interactions. As regards dark energy, it is a mysterious substance that drives the accelerated cosmological expansion and, in this sense, antigravitates. Mainly the following two sources of cosmic acceleration are considered: a light scalar field or a modification of gravity at large scales. We discuss them in what follows.

In cosmology, the fraction of energy density of one form of matter or another, ρ_j, is expressed through the dimensional parameter $\Omega_j = \rho_j/\rho_c$, where ρ_c is the so-called critical energy density, determined from the first Friedmann equation with $k = 0$:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\,\rho_{\rm tot}}{3m_{\rm Pl}^2} - \frac{k}{a^2}\,, \tag{2.1}$$

where $a(t)$ is the cosmological scale factor that characterizes the Universe's expansion, $\rho_{\rm tot}$ is the total average cosmological energy density, and k is a constant usually taken as $k = +1$ (closed universe), $k = -1$ (open 'curved' universe) and $k = 0$ (open flat universe).

According to contemporary combined astronomical data, the Hubble parameter is known with an accuracy of about 2%: $H = 67.3 \pm 1.2$ km s^{-1} Mpc^{-1}. The measurement of H based only on the Planck data is sightly less precise (see below). Knowing H, we can find the value of the critical energy density:

$$\rho_c = \frac{3H^2 m_{\rm Pl}^2}{8\pi} = 0.85 \times 10^{-29}\ {\rm g\,cm^{-3}}\,. \tag{2.2}$$

As we mentioned above, the ratio $\Omega_{\rm tot} = \rho_{\rm tot}/\rho_c$ determines the three-dimensional geometry of the Universe. If $\Omega_{\rm tot} > 1$, then the Universe is closed and has the geometry of a three-dimensional sphere. For $\Omega_{\rm tot} < 1$, the Universe is open and has the geometry of a three-dimensional hyperboloid. In the special and seemingly quite improbable case $\Omega_{\rm tot} = 1$, the Universe's geometry is the flat Euclidean one. Surprisingly, just this special case is realized in nature. According to the existing data, $\Omega_{\rm tot} = 1 \pm 0.02$. Inflationary theory predicts that $\Omega_{\rm tot} = 1$ with a much better precision, at the level of 10^{-4}.

Not so long ago, it was believed that the final destiny of the Universe would be uniquely determined by its geometry: an open universe (including a flat one) would expand forever, while for a closed universe, expansion would ultimately turn into contraction. Indeed, because the energy density of usual matter decreases faster than $1/a^2$, it follows from Eqn (2.1) that for a closed universe, H becomes equal to zero in a finite time, while for an open universe, H is always positive, tending to zero asymptotically. However, dark energy breaks this connection and, independently of geometry, the universe will expand forever only if the DE equation of state does not change in some distant future.

A simple linear equation of state is usually taken:

$$P = w\rho\,, \tag{2.3}$$

where P is the pressure density and w is a constant parameter, different for different forms of matter. For example, for non-relativistic matter, for which $P \ll \rho$, it is assumed that $w_{\rm nr} = 0$; for relativistic matter, $w_{\rm rel} = 1/3$. For dark energy, according to the observations, $w_{\rm DE} = -1.13^{+0.13}_{-0.10}$.

From the second Friedmann equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi\,G_{\rm N}}{3}\,(\rho + 3P)\,, \tag{2.4}$$

we can conclude that for $w < -1/3$, cosmological acceleration becomes positive, as is indicated by contemporary astronomical data. It is practically established that the Universe expanded with acceleration at the very early stage during the so-called inflation. This primordial thrust led to the creation of our large Universe, suitable for life, out of a microscopically small initial state. Antigravity created by negative pressure is necessary for life. In the world governed by the Newtonian theory, in which the source of gravitational force is a positive definite mass, life would be impossible.

Two comments are in order. First, even in general relativity (GR), antigravity can appear only for infinitely large systems. Any finite object in canonical GR always gravitates. Second, if gravity is modified at large scales to create cosmological acceleration, gravitational repulsion can emerge, even in finite systems [25].

The Planck measurements result in the following values of the basic cosmological parameters:

$$H = 67.9 \pm 1.5 \quad (71.0 \pm 2.5)\ {\rm km\ s^{-1}\ Mpc}\,, \tag{2.5}$$

$$\Omega_{\rm b} = 4.9\,\% \quad (4.5\,\%)\,, \tag{2.6}$$

$$\Omega_{\rm DM} = 26.8\,\% \quad (22.7\,\%)\,, \tag{2.7}$$

$$\Omega_{\rm DE} = 68.3\,\% \quad (72.8\,\%)\,. \tag{2.8}$$

The numbers in parentheses indicate the corresponding parameter values that were accepted before publication of the Planck data.

Close magnitudes of the Ω parameters for absolutely different forms of matter give rise to the so-called problem of cosmic conspiracy. Indeed, according to the present understanding, the densities of baryons, dark matter, and dark energy are not connected to each other and could be

different by several (many) orders of magnitude. A natural explanation of their proximity is not yet known.

In the not so distant past, the most accurate way to determine the total amount of baryons in the Universe was by analyzing Big Bang nucleosynthesis (see below). Presently, CMB gives a compatible but much more precise value for the baryonic density. It is intriguing that less than 50% of all baryons are observed directly, and where the rest of them are hidden is not yet known.

In addition to baryons, dark matter, and dark energy, the Universe is populated by CMB photons with $\Omega_{\rm CMB} = 4.8 \times 10^{-5}$ and neutrinos for whose density only the upper and lower bounds $\Omega_\nu < 5 \times 10^{-3}$ and $\Omega_\nu > 10^{-3}$ are known. The latter bound follows not from astronomy but from the lower bound on the neutrino mass obtained from the analysis of neutrino oscillations, $\Delta m^2 = 0.0024\ {\rm eV}^2$, while cosmology allows calculating the number density of neutrinos today: $n_\nu = 112\ {\rm cm}^{-3}$, as was done by Gerstein and Zeldovich [12].

One of Planck's most impressive results is a very strong upper bound on the neutrino mass:

$$\sum m_\nu < 0.23 \quad {\rm eV}\,, \tag{2.9}$$

where the sum is taken over the three known neutrino types. Keeping in mind their very small mass differences, we conclude that the mass of any neutrino does not exceed 0.08 eV. For comparison, the best bound on the neutrino mass obtained in direct experiments is about 2 eV. It is remarkable that the best device to weigh neutrinos is the telescope.

Apart from that, the Planck measurements lead to an upper bound on the effective number of neutrino species, $N_\nu^{\rm eff} = 3.30 \pm 0.27$, which is comparable with and even a little stronger than the one obtained from Big Bang nucleosynthesis. It is probably worthwhile to explain that $N_\nu^{\rm eff}$ is the number of light or massless particle species with the energy density equal to that of usual equilibrium neutrinos. For example, $N_\nu^{\rm eff} = 3.1$ means that there are some new particles in the plasma with the energy density equal to 0.1 of the energy density of the usual neutrinos, which are in thermal equilibrium with photons and electron–positron pairs. The standard theory (without any new particles) predicts $N_\nu^{\rm eff} = 3.046$. The excess of 0.012 over 3 comes from diminishing the equilibrium photon density due to plasma corrections [26], because the neutrino density is normalized to the density of photons in CMB. The remaining 0.034 comes from neutrino heating by the annihilation of hotter electron–positron pairs in the primeval plasma [27–31].

We note in conclusion that the shape of the spectrum of the angular fluctuations of the CMB temperature perfectly well confirms the qualitative features of the standard cosmological model and allows precisely measuring the basic cosmological parameters. However, there are unexplained anomalies at large angles: too small amplitudes of multipoles with low l and very large left–right asymmetry with respect to the ecliptic.

3. Inflation

The Friedmann cosmology very well described the Universe starting from some mysterious singularity point up to the present time, explaining the baryon asymmetry of the universe, observed abundances of light elements, which were synthesized during the first few minutes after creation of the Universe, equilibrium microwave background radiation, and large-scale structure formation given the spectrum of the initial density perturbations (see, e.g., reviews [32, 33]).

However, many important features of the Friedmann model were inexplicable, such as:

(1) The equality of the CMB temperature over the whole sky, despite the fact that two points in the sky separated by more than one degree never knew anything about each other.

(2) Quasi-homogeneity of the universe at large scales.

(3) The proximity of $\Omega_{\rm tot}$ to unity, even with a very low precision of the order of unity. To realize such a value close to unity, Ω must be precisely fine-tuned to unity in the early universe, e.g., there should be $|\Omega_{\rm tot} - 1| < 10^{-16}$ during BBN and the fine tuning at the Planck epoch must be truly astonishing, $|\Omega_{\rm tot} - 1| < 10^{-60}$. During this epoch, the space–time curvature was of the order of $m_{\rm Pl}^2$ or even higher, and hence classical space–time did not exist. It was the earliest period in the history of the Universe to which we could extrapolate our knowledge of the evolution of the universe and classical gravity back in time.

(4) The existence of small density perturbations at astronomically large scales, which were necessary for large-scale structure formation. No reasonable mechanism for the generation of such perturbations was known.

(5) And last but not the least, the driving force causing the Universe's expansion uniformly at distances much larger than the cosmological horizon.

All these problems were solved in an economical and beautiful way by the hypothesis that, at a pre-Big-Bang stage, the Universe expanded exponentially (or quasi-exponentially). To understand this better, it would be instructive to present a few simple equations.

According to the law of covariant conservation of the energy–momentum tensor for a homogeneous matter distribution, we have

$$\dot\rho + 3H(\rho + P) = 0\,. \tag{3.1}$$

For a vacuum-like equation of state, with $P = -\rho$ (or $w = -1$), the energy density does not change during cosmological expansion. Correspondingly, the Hubble parameter also remains constant [see Eqn (2.1)] and hence the expansion proceeds exponentially due to the powerful antigravity of vacuum-like energy. Such a space–time is called the De Sitter space.

If for one reason or another the equation of state with $w = -1$ was realized in the early universe, even in a microscopically small patch of space, then, due to an exponential expansion of this tiny volume, our huge Universe could be formed out of practically nothing. The conditions almost everywhere in such a Universe must be the same, except for remote boundary regions, because the Universe came from a huge stretching of a causally connected bubble. This solves problems 1 and 2 above.

It is astonishing that the mass of matter in the initial bubble could be microscopically tiny, $M_{in} \sim \rho_{in} l_{in}^3$, where ρ_{in} and l_{in} are the initial energy density and the size of the bubble. This is incomparable to the total mass of the Universe inflated from this bubble, but the energy conservation law is not violated.

According to Eqn (2.1) the role of the last term in the r.h.s. exponentially decreases during inflation, and this effect can

easily create the necessary fine tuning mentioned in problem 3 above.

The wavelength of quantum fluctuations exponentially increases together with the scale factor, and it turns from microscopically small into astronomically large. Apart from that, the fluctuation amplitude becomes somewhat larger. This mechanism naturally creates density perturbations required for large-scale structure formation, i.e., for the creation of galaxies and their clusters. The spectrum of perturbations in this scenario can be calculated and agrees well with astronomical observations. Nowadays, this is a commonly accepted mechanism of creation of perturbations at astronomically large scales.

The first paper where the inflationary hypothesis was used for the solution of some problems indicated above was published by Kazanas [34]. A little later, a more detailed and better known paper by Guth [35] appeared. The generation of density perturbations and their spectrum were first calculated by Mukhanov and Chibisov [36] in the framework of Starobinsky's [37, 38] R^2-model (see below). According to their results, the spectrum has a power-law shape with the spectral index $n = 0.96$. This result agrees well with the recent Planck data and is considered a strong support of the Starobinsky model. However, the analysis is model dependent and, for example, in a model with millicharged particles [39], the spectral index can be higher. In particular, the flat Harrison–Zeldovich spectrum [40, 41] with $n = 1$ may remain viable.

Two possible sources of inflation are discussed in the literature: a quasi-homogeneous scalar field, or inflaton, and gravity modification at large curvature. The most beautiful of the inflaton models is probably the chaotic inflation suggested by Linde [42]. According to this model, any scalar field ϕ, homogeneous at the Hubble scale and with a slowly varying potential such that $U''(\phi) < H^2$, would lead to an exponential expansion in the early Universe, which quite naturally would last sufficiently long, such that all the visible parts of the Universe and even the parts far beyond would be created by such a colossally inflated initially quasi-homogeneous region. Gravity modifications at large curvatures are usually based on introducing an additional nonlinear term into the standard GR action, $R \to R - R^2/m^2$, where m is a constant parameter with the dimension of mass, as was suggested by Starobinsky. Such terms can be generated by radiative corrections to the usual GR action [37, 38]. However, radiative corrections generate not only the terms that depend on R but also more complicated terms, e.g., those proportional the square of the Ricci tensor, $R_{\mu\nu}R^{\mu\nu}$. These lead to some undesirable properties of the theory, such as the emergence of ghosts and tachyons.

We note that the introduction of terms quadratic in curvature into the action has limited applicability, because, for very large curvatures, the effective action becomes more complicated. Roughly speaking, instead of being proportional to R^2, the corrections occur in the denominator, e.g., due to an increase in particle effective masses in strong gravitational fields.

The successful solution to the fundamental problems of the Friedmann cosmology and the quantitative prediction of the shape of the spectrum of inflationary density perturbations permits us to regard inflation as an experimentally — or better to say, observationally — established fact. An additional strong argument in favor of inflation would be the registration of long gravitational waves generated during inflation [43, 40]. However, the intensity of such waves is model dependent and may be quite low, and therefore their absence would not kill the inflationary scenario, while their detection would be one more proof of its validity.

According to the inflationary picture, the universe initially looked like dark expanding emptiness, until the inflaton field dropped such that the Hubble parameter became smaller than the inflaton mass (or the potential curvature became larger than H). After that, ϕ started to oscillate simultaneously and everywhere, producing elementary particles mostly with masses smaller than m_ϕ. This moment of explosive particle production would be proper to call the 'Big Bang'. There is an amazing similarity of this process to that described in the Bible: "...the earth was without form, and void; and darkness was upon the face of the deep," and then all of a sudden: "let there be light." However, in contrast to the Bible, the inflationary picture is described by well-defined mathematical equations and permits making quantitative predictions that agree with astronomical observations.

In conclusion, we mention the important fact that inflation is possible only if the baryon number is not conserved [45, 46]. Indeed, for a sufficiently long inflation, the cosmological energy density must be (approximately) constant. However, if the baryon number is conserved, the necessary constancy of ρ is impossible. Because inflation seems to be the only way to create a universe suitable for life, then it follows from our existence that baryons are not conserved and hence there is a nonzero probability of discovering proton decay or neutron–antineutron oscillations. It is amusing that half a century ago, the statement was exactly opposite: "Our existence proves that the baryon number is not conserved," which, as we know now, is not correct.

4. Standard Cosmological Model

As a result of the impressive development of theory and fantastic progress in astronomical observations of all possible messengers from the Universe, the Standard Cosmological Model (SCM) has been established. The model will hardly change in its essential features at the phenomenological level. The SCM successfully describes cosmological history, starting from inflation to the present day. However, there are some clouds in this sky, albeit possibly not so serious as the two famous clouds of Lord Kelvin, the ultraviolet catastrophe and the Michelson–Morley problem, out of which the heavy rains of quantum mechanics and relativity theory poured. On the other hand, we cannot rule out that the cosmological clouds will also lead to similar grave thunderstorms. In any case, modern cosmology surely demands new physics beyond the minimal Standard Model of particle physics.

The theoretical foundation of the SCM is general relativity, although its validity is constantly questioned, especially in recent times, both for large and small curvatures, e.g., in the above-mentioned R^2-theory and $F(R)$ theories discussed below in Section 6. In addition to GR, the chemical content of the cosmological matter, i.e., a set of fundamental particles and fields and their equations of state, must be specified. It is worth noting that the state of the system cannot always be described by an equation of state, or, in other words, the pressure density cannot always be expressed as a function of the energy density locally, i.e., at the same instant and in the same spatial point. In this case,

dynamical equations of motion can serve instead of the equation of state.

The main epochs of the cosmological history in crude approximation follow.

4.1 Inflation

Inflation is the initial inflationary stage when, due to a sufficiently long exponential expansion, our astronomically large Universe was created. To create our huge Universe almost homogeneous at the scale of the present-day horizon and with the same CMB temperature over all the sky, the necessary increase in the scale factor during the inflationary period had to be at least 60–70 Hubble times, such that $a(t)$ increases by not less than $\exp(60-70) = 10^{26}-10^{30}$. As was argued in Section 3, inflation is practically an 'experimental' fact. Strictly speaking, we know nothing about the epoch before the inflation, and it is even unclear if the concept of time existed before inflation. According to Linde's ideas [42], it is quite probable that classical space–time did not exist before inflation, and 'before' is not a well-defined notion. Hence, this period is still terra incognita. Nevertheless, there are some vigorous attempts to describe the Universe in the preinflationary epoch, formulating the so-called pre-Big-Bang cosmology, although it may be proper to call the end of inflation the Big Bang.

4.2 Big Bang

At some moment, the energy density of the inflaton decreased to a value at which the Hubble parameter $H \sim \sqrt{\rho_{\rm infl}}/m_{\rm Pl}$ became smaller than the inflaton mass (if $m_\phi = 0$, we can speak about the properly defined slope of the potential). From this moment on, a slow roll-down of the inflaton toward the minimum of the potential turned into oscillations around it. These oscillations resulted in the production of elementary particles with a non-negligible coupling to the inflaton. This moment, when the cold expanding emptiness turned into hot cosmological plasma, is natural to call the Big Bang. A list of the first papers on particle production by the inflaton and the heating of the Universe is presented in Refs [47–53].

4.3 Baryogenesis and possible antimatter creation

The excess of matter over antimatter observed in the Universe is simply and beautifully explained by Sakharov's mechanisms [14], but only in principle. There are myriads of different scenarios of baryogenesis [54–58], but it is not known which of them occurred in reality. It is even possible that several different mechanisms operated. Moreover, the models of baryogenesis are possible where any of three of Sakharov's conditions is not obligatory (see the second paper in Ref. [55]).

The observation of primordial cosmic antimatter would be very important for understanding the baryogenesis mechanism. The search for it is being actively undertaken using several apparatuses: BESS, PAMELA, AMS, and more sensitive detectors are under development. All the existing devices are dedicated to searching for antihelium nuclei, but so far not a single antihelium nucleus has been detected. All antiprotons and positrons observed to date are almost certainly secondarily produced in cosmic ray interactions or as a result of catastrophic stellar processes. However, even against this dull background, there are two phenomena of unknown origin. First, there is an intensive source of photons with the energy 0.511 MeV in the galactic center [59–65]. This energy is exactly equal to the photon energy from the two-photon annihilation of e^+e^- pairs at rest. It would be exciting if there were a clump of antimatter in the galactic center, but the absence of higher-energy quanta from $\bar{p}p$ annihilation apparently rules out such a possibility. The second mysterious fact is an excess of high-energy positrons with $E \sim 100$ GeV in cosmic rays discovered by PAMELA [66] and confirmed by the Fermi [67] and AMS [68] space missions.

4.4 Primordial or Big Bang nucleosynthesis (BBN)

This was always considered one of the cornerstones of Big Bang cosmology, because the abundance of light elements, ^{4}He, ^{2}H, and ^{3}He, which were synthesized in the very early Universe at temperatures in the range from 1 MeV down to 60–70 keV, when the Universe's age was from 1 to 200 s, very well agree with observations, and there is no other known way to create them. Currently, there is only one piece of data where a disagreement between theory and observations is found: the observed amount of ^{7}Li is smaller than theoretically predicted by a factor of three. This may indicate some new physical phenomena, e.g., the existence of new elementary particles or, more probably, is the result of an erroneous interpretation of the data. The observed abundances of ^{4}He and deuterium over many years were used to derive bounds on the concentration of unknown light particles in the primeval plasma. These bounds are presented in the form of effective neutrino species [see the discussion after Eqn (2.9)]. At different times, these bounds varied from $N_\nu^{\rm eff} < 4$ to $N_\nu^{\rm eff} < 3.1$. Surprisingly, recent observations indicate that $N_\nu^{\rm eff} > 3$, but do not contradict the canonical number 3.046 within the existing error bars. For example, the latest measurement of the primordial abundance of ^{4}He [69] leads to the conclusion that $N_\nu^{\rm eff} = 3.51 \pm 0.35$ (68% CL), and the data on deuterium [70] are best described with $N_\nu^{\rm eff} = 3.28 \pm 0.28$. The future will tell whether these results are evidence of a discovery of new light elementary particles, which are now called dark radiation, or the data will finally converge to the canonical value $N_\nu^{\rm eff} = 3.046$, but it will be wonderful to discover new elementary particles (e.g., a sterile neutrino, which might explain anomalies observed in neutrino oscillations) by just looking up at the sky.

We finally note that the abundance of the deuterium produced strongly depends on the total baryon density in the Universe. This is why primordial deuterium is called the baryometer. Now the cosmic microwave background can claim this title as well.

4.5 Hydrogen recombination and cosmic microwave background radiation

Due to the very large magnitude of elastic photon–electron scattering, the mean free path of photons in the primeval plasma in the early Universe was much shorter than the cosmological horizon. Hence, photons slowly diffused in this medium. The situation crucially changed after hydrogen recombination at the temperature $T = 3000$ K, i.e., at the redshift $z_{\rm rec} \approx 1100$, when electrons and protons formed neutral atoms, for which the cross section of scattering of longwave photons sharply decreased. After that, the photons started to freely propagate in the Universe, bringing us information about their temperature during the recombination epoch all over the sky. As we mentioned in Section 2, the measured angular temperature fluctuations allow quite

accurately determining the fundamental cosmological parameters.

4.6 Formation of the large-scale structure of the Universe

Small density perturbations, created during inflation, stayed with a virtually constant amplitude for a large part of the history of the Universe. To be more precise, the relative density contrast $\Delta = \delta\rho/\rho$ did not change during the radiation-dominated stage. In a static world, the gravitational attraction of the regions with excessive density would lead to an exponential increase in Δ, as was shown at the beginning of the last century by Jeans [71]. Cosmological expansion slows this increase, and it turns at most into a power-law one. In fact, it can be shown that at the cosmological stage, when relativistic matter dominated, the relative density contrast was increasing no faster than the logarithm of the scale factor, and could therefore be regarded as practically constant. The essential increase in density perturbations started at the stage of dominance of nonrelativistic matter or, as is commonly said, the matter-dominated (MD) stage, which began at the redshift $z_{\rm eq} \approx 10^4$. Theory says that at this stage, Δ increases as the cosmological scale factor, i.e., from the onset of the MD stage, it may increase by four orders of magnitude.[1] This is exactly what is necessary for the initial density perturbations to be equal to $\Delta \sim 10^{-4}$, which are known from the measurements of the temperature fluctuations of CMB. After the density contrast reached unity, the perturbations started to increase very rapidly, and that is how systems with a huge density contrast $\Delta \gg 1$ can be created.

5. Dark matter

The simple considerations presented in Section 4.6 already permit us to conclude that the dominant part of matter in the Universe must be invisible, i.e., matter that does not interact with electromagnetic radiation, and in particular with light. It is called dark matter (DM), although a more precise word would be 'invisible matter', because 'dark' means that the matter absorbs light, while invisible matter simply does not interact with it. Without DM, the formation of the structure in the usual matter could not start at $z \approx 10^4$, because the strong light pressure would inhibit an increase in perturbations. This increase could start only after hydrogen recombination at $z \approx 10^3$, meaning, in turn, that the perturbations would increase at most by a factor of 10^3 and could not reach unity to the present time. On the other hand, the light pressure does not prevent an increase in DM perturbations, and they could therefore start rising already at $z_{\rm eq} \approx 10^4$. Later, after recombination, usual matter would be able to fall into the potential wells prepared by DM. Hence, without DM, life in the Universe would not have appeared yet, and might never appear.

Apart from the qualitative arguments presented above, there are numerous precise data that unambiguously prove the existence of DM and precisely measure the amount of it. Among them are the following:

(1) Flat rotational curves. The velocities of gas particles and satellites galaxy around a larger galaxy do not decrease as $v \sim 1/\sqrt{r}$ with the distance, as expected, but tend to a constant value. This shows that there is invisible matter around the galaxy with the density decreasing as $1/r^2$.

(2) Gravitational lensing of distant light sources permits estimating the amount of matter on the way from the source to Earth and shows that the amount of invisible matter is approximately five times larger than that of visible matter.

(3) Equilibrium of hot gas in rich galactic clusters also requires approximately five times more matter than is directly observed.

(4) The quantitative analysis of large-scale structure formation, including so-called baryon acoustic oscillations (BAOs), also leads to the conclusion about the dominant role of DM.

(5) Analysis of the spectrum of CMB angular fluctuations.

All these different pieces of data agree well with each other, giving the value $\Omega_{\rm m} \approx 0.3$ for the total cosmological fraction of dark and baryonic matter, of which the baryonic matter makes up $\Omega_{\rm b} \approx 0.05$. More precise values are presented above in Eqns (2.6) and (2.7).

From the astronomical standpoint, dark matter can be separated into three classes: hot (HDM), warm (WDM), and cold (CDM), depending on the characteristic damping scale. This scale is essentially the free streaming length $l_{\rm FS}$ of the DM particles until they stop due to the cosmological redshift. For HDM, the mass inside their free streaming length is larger than the galactic mass, $M_{\rm FS} > M_{\rm gal} \sim 10^{12} M_\odot$. An example of an HDM particle is the neutrino, for which $M_{\rm FS} \sim m_{\rm Pl}^3/m_\nu^2 \sim 10^{17} M_\odot (1\ {\rm eV}/m_\nu)^2$.

For warm dark matter, $M_{\rm FS} \sim M_{\rm gal}$. Warm dark matter particles may consist of sterile neutrinos with the mass in the keV range or pseudogoldstone bosons with similar properties.

Popular candidates for CDM particles are the lightest supersymmetric particles (LSPs) with masses in the range $m \sim 100-1000$ GeV or some other weakly interacting massive particles (WIMPs). Recently, CDM made of LSPs has somewhat lost its attractiveness because such particles have not been discovered at the LHC. Nevertheless, LSPs with higher masses (above the LHC threshold) are still being discussed, but at the expense of some modification of the standard cosmological evolution. Another natural candidate for a CDM particle is the axion, despite its vanishingly small mass $m_{\rm a} \lesssim 10^{-5}$ eV. Axions are cold particles because they are produced at rest and hence their free streaming length is much shorter than the galactic size.

A separate group of possible CDM particles consists of so-called massive astrophysical compact halo objects (MACHOs). This group may consist of dwarf stars of low luminosity with masses comparable to the solar mass or primordial black holes with $M > 10^{16}$ g.

Mirror particles from an entire mirror world, similar but not identical to ours, may constitute a very interesting group of all kinds of DM particles.

Apart from that, some more exotic possibilities might be realized, e.g., quark nuggets, topological or nontopological solitons, or something new not included in this list.

The canonically most popular model at the present time is the ΛCDM model, i.e., the model where the dominant form of matter in the Universe is cold DM plus dark energy in the form of the Lambda term or, in other words, vacuum energy. Vacuum energy is discussed in more detail in Section 6. This model well describes gross features of the observed large-scale

[1] Pioneering work on the evolution of density perturbations in cosmology was done by Lifshits [72, 73]. An up-to-date presentation of the theory can be found, for example, in books [74, 75].

structure, but some details do not fit into the model. Among them, there are:

(1) Missing galactic satellites. The CDM model predicts an-order-of-magnitude more galactic satellites (i.e., smaller galaxies gravitationally bound to the host large galaxy) than observed.

(2) Destruction of the galactic disk. Even if the number of satellites is reduced by star formation winds, many smaller tightly bound DM systems would survive and destroy the galactic disk by gravitational heating.

(3) Cusps in galactic centers. Theory predicts a singular matter distribution in galactic centers, $\rho_{\rm DM} \sim r^{-\kappa}$ with $\kappa = 1 - 2$, while a smooth profile is observed.

(4) Excessive angular momentum of galaxies. The CDM model predicts a galactic angular momentum several times smaller than the observed one.

These problems possibly arise because of insufficient precision of numerical simulations or due to neglect of essential physical effects, e.g., of the role of baryonic matter. A more revolutionary explanation is the introduction of another form of DM with different properties, e.g., self-interacting DM such as mirror matter. However, this explanation has its own serious obstacles. In view of these problems, the WDM hypothesis is gaining more and more popularity. The best choice would be a mixture of CDM and WDM, but this assumption makes the cosmic conspiracy problem deeper, because four forms of matter, not the 'good old' three (baryonic, CDM, and dark energy), should then have energy densities of comparable magnitudes.

6. Dark energy and/or modified gravity

Dark energy is an unknown substance that forces the Universe to expand with acceleration. According to observations, it has the equation of state $P = w\rho$ with $w = -1.13^{+0.13}_{-0.10}$. If $w < -1$, the density of dark energy would increase with time and reach an infinite value during a finite interval. Such a catastrophe may be avoided if w is greater than or equal to -1 or w depends on time and will shift to a safe value $w \geqslant -1$ in the future.

Equation (2.4) shows that for such w, acceleration is positive, as required. However, w may shift to a nonnegative value in the future, and we then return to the old decelerated cosmology.

During the last two decades, different kinds of data in favor of accelerated expansion have been accumulated:

(1) In the 1990s, the Universe age crisis arose. For the Hubble parameter exceeding 70 km s^{-1} Mpc^{-1}, the calculated age of the universe was less than 10 billion years, especially if the total energy density was equal to the critical one, as predicted by the inflationary theory. On the other hand, nuclear chronology and the age of old stellar clusters required $t_{\rm U} \geqslant 13$ billion years. The Universe's age can be expressed in terms of the present-day values of the Hubble parameter and densities of different forms of matter as

$$t_{\rm U} = \frac{1}{H}\int_0^1 \frac{{\rm d}x}{\sqrt{1 - \Omega_{\rm tot} + \Omega_{\rm m}/x + \Omega_{\rm r}/x^2 + x^2\Omega_{\rm v}}}\,, \qquad (6.1)$$

where $\Omega_{\rm tot}$ is the total relative cosmological energy density and $\Omega_{\rm r,m,v}$ are the contributions from relativistic, nonrelativistic, and vacuum-like energies. Evidently, for $\Omega_{\rm m} = 0.3$ and $\Omega_{\rm v} = 0.7$, the age of the Universe would be close to 13 billion year, in agreement with the data.

(2) As mentioned above, the set of many independent kinds of measurements gives the value $\Omega_{\rm m} = 0.3$, while the spectrum of CMB angular fluctuations (in particular, the position of the first acoustic peak) requires $\Omega_{\rm tot} = 1$, in agreement with the inflationary prediction. In addition, the analysis of the large-scale structure not only shows that $\Omega_{\rm m} = 0.3$ but also demonstrates a suppression of structure formation at large scales. This can be explained by accelerated expansion.

(3) Direct evidence of cosmic acceleration was presented by the discovery of the dimming of distant supernovae at redshifts of the order of unity. There are strong arguments that such supernovae, SN1a, are standard candles, and therefore their diminished brightness indicates that they are at a larger distance than expected, and hence the universe should expand faster than it would with the usual Friedmann expansion regime. For their work where this phenomenon was observed, three astronomers, S Perlmutter, B P Schmidt, and A G Riess, were awarded the Nobel Prize of 2011, as it is stated, "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae." It is noteworthy that an alternative explanation of the effect by the attenuation of light from distant supernovae in the interstellar and intergalactic media can be excluded, because the effect is not monotonic as a function of the redshift. It first increases with z and then decreases. This is in agreement with a dark energy interpretation, because $\rho_{\rm m}$ increases with z, while $\rho_{\rm v}$ remains constant.

A light scalar field is considered the simplest agent that could induce accelerated expansion with an almost constant amplitude. The energy–momentum tensor of such a field has the form

$$T_{\mu\nu} = \partial_\mu\phi\,\partial_\mu\phi - \frac{1}{2}\,g_{\mu\nu}\left[\partial_\alpha\phi\,\partial^\alpha\phi - U(\phi)\right]. \qquad (6.2)$$

For a quasi-homogeneous field $T_{\mu\nu}$, this tensor becomes (approximately) proportional to the metric tensor, $T_{\mu\nu} \sim g_{\mu\nu}$, realizing the vacuum-like equation of state $w \approx -1$, which leads to cosmic acceleration.

Another possible mechanism of creating accelerated expansion is the modification of gravity at large distances by introducing an additional term, nonlinear in curvature, into the gravitational action:

$$S = \frac{m_{\rm Pl}^2}{16\pi}\int {\rm d}^4x\sqrt{-g}\,\left[R + F(R)\right]. \qquad (6.3)$$

The first such models [76, 77] with $F(R) = -\mu^4/R$, where μ is a constant parameter with the dimension of mass, could induce an accelerated expansion, but led to a strong instability of the gravitational equation inside celestial bodies [78]. To fix this problem, further modifications of gravity were suggested, such as [79–81]

$$F(R) = \lambda R_0\left[\left(1 + \frac{R^2}{R_0^2}\right)^{-n} - 1\right] - \frac{R^2}{6m^2}\,, \qquad (6.4)$$

or others similar to it, where the function $F(R)$ is chosen such that the corresponding equations of motion in the vacuum have the solution $R = {\rm const}$, describing the de Sitter space–time.

The problem of dark energy is closely related to the vacuum energy problem or, equivalently, the cosmological constant problem (or the Lambda term). In an attempt to

apply the GR equations to cosmology, Einstein found that there are no stationary solutions and suggested correcting this 'flaw' by adding a cosmological constant Λ [82] to the gravitational field equations:

$$R_{\mu\nu} - \frac{1}{2}\, g_{\mu\nu} R - \Lambda g_{\mu\nu} = \frac{8\pi}{m_{\rm Pl}^2}\, T_{\mu\nu}\,. \tag{6.5}$$

Later, it became clear that the cosmological constant is equivalent to vacuum energy with the energy-momentum tensor

$$T_{\mu\nu}^{\rm vac} = g_{\mu\nu}\rho^{\rm vac} \tag{6.6}$$

and the equation of state $P = -\rho$.

It might be natural to assume that dark energy coincides with vacuum energy, but the theoretical evaluation of different contributions to the vacuum energy exceeds the observed value by 50–100 orders of magnitude. Especially impressive is the contribution to the vacuum energy from the effects of quantum chromodynamics (QCD). It is established that the QCD vacuum is not empty but is filled with condensates of gluon and quark fields [83, 84] with a negative energy density that is 45 orders of magnitude larger in absolute value than the cosmological energy density. Such condensates are absolutely necessary to obtain the correct value of the proton mass, which grossly exceeds the sum of masses of constituent quarks. Inside the proton, the condensate is destroyed by quarks, and hence the proton mass is not equal to the sum of quark masses minus the binding energy, but also includes the mass of the condensate inside the proton volume, $V_{\rm p} \sim 1/(100\ {\rm MeV})^3$:

$$m_{\rm p} = 2m_{\rm u} + m_{\rm d} + |\rho_{\rm vac}^{\rm QCD}|\, V_{\rm p} \approx 1\ {\rm GeV}\,, \tag{6.7}$$

where $m_{\rm u} \sim m_{\rm d} \sim 5$ MeV and

$$\rho_{\rm vac}^{\rm QCD} \approx -10^{45}\rho_{\rm c}\,. \tag{6.8}$$

One of the deepest mysteries of Nature is what compensates the negative $\rho_{\rm vac}^{\rm QCD}$, such that a vacuum energy that is positive but 10^{45} smaller in magnitude emerges as a result. It seems evident that something must 'live' in the vacuum to achieve the necessary compensation. Of course, it is impossible to formally exclude the boring possibility that QCD and other contributions to the vacuum energy are precisely compensated by a fantastically fine-tuned subtraction constant. Together with the anthropic principle and the assumption of an almost infinite number of worlds with different values of the subtraction constant, such a solution to the vacuum energy problem does not even look too unnatural. Anyway, it seems that the solution to the dark energy problem is impossible without understanding the closely related vacuum energy problem.

7. Conclusion

Instead of a conclusion, we make a list, evidently incomplete, of unsolved cosmological and astrophysical problems. Some of them have been mentioned in the body of the talk, while the others, which were omitted due to a lack of space and time, are mentioned now simply because they are important and interesting. So, here are the questions to which we do not yet have answers:

(1) What are the DM particles?

(2) Which is the mechanism of cosmological acceleration: scalar field, modified gravity, or none of the above?

(3) What is the explanation of the cosmic conspiracy that leads to comparable values of different forms of energy, $\Omega_{\rm b} \sim \Omega_{\rm DM} \sim \Omega_{\rm DE}$?

(4) Which of many scenarios of baryogenesis is realized in nature? Or are there several?

(5) Is there primordial cosmic antimatter? Will the search for antinuclei at the PAMELA, BESS, and AMS detectors have a chance to be successful, or we will have to wait for a new generation of detectors?

(6) What is the mechanism of the intensive emission of the 0.511 MeV line from the galactic center?

(7) How can the excess of positrons in cosmic rays with energies about 100 GeV, observed by PAMELA, Fermi, and AMS, be explained?

(8) What is the mechanism of production of ultrahigh energy cosmic rays? Is there the Greissen–Zatsepin–Kuzmin cutoff?

(9) How were the supermassive black holes observed in galactic centers created? Did they appear in the already formed galaxies or were they produced earlier and did they serve as seeds of galaxy formation?

(10) What is the mechanism of creation of quasars at high redshifts and why is the metallicity in their neighborhood so high?

(11) What is the mechanism of gamma-burst emissions?

(12) How were galactic and intergalactic magnetic fields generated?

(13) What is the origin of CMB anomalies at large angles or low multipoles?

(14) How will the discrepancy between theory and observation of ^{7}Li be resolved? What is it: an error in observations (or their interpretation) or new physics?

(15) Does dark radiation, indicated by BBN and by the spectrum of angular fluctuations of CMB, exist?

(16) And last, but surely not least, what compensates the experimentally known contribution of the QCD condensate to the vacuum energy with a 10^{-45} precision?

This is by no means a complete list of problems, but it already demonstrates the tremendous progress of cosmology over the last half century and shows how exciting this field of science has become. After it became an exact science, cosmology solved many old problems, but opened up a variety of new ones.

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