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Quantum Universe

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Contents

Abstract. In March 2013, following an accurate processing of available measurement data, the Planck Scientific Collaboration published the highest-resolution photograph ever of the early Universe when it was only a few hundred thousand years old. The photograph showed galactic seeds in sufficient detail to test some nontrivial theoretical predictions made more than thirty years ago. Most amazing was that all predictions were confirmed to be remarkably accurate. With no exaggeration, we may consider it established experimentally that quantum physics, which is normally assumed to be relevant on the atomic and subatomic scale, also works on the scale of the entire Universe, determining its structure with all its galaxies, stars, and planets.

Keywords: cosmology, early Universe, cosmic microwave background, quantum fluctuations, structure of the Universe

1. Introduction. Hubble expansion and cosmic microwave background

Naturally, scientists and philosophers have always thought about the origin of our Universe. However, over thousands of years, all theories about the Universe remained unsupported theological and philosophical speculation. Cosmology began taking shape as a natural science less than 100 years ago. Namely, only in 1923, after finishing construction of a 100-inch telescope at the Mount Wilson Observatory near Los Angeles, did Edwin Hubble resolve individual stars in the Andromeda nebula and prove that it lies outside our Galaxy. This discovery heralded the beginning of extragalactic astronomy. Today, it is firmly established that the observed part of the Universe contains about 100 billion galaxies. There are clusters of several billion stars in galaxies about 100 thousand light years across, which are in turn separated by several million light years from each other. From the analysis of spectra of remote galaxies, Hubble discovered that they are somewhat redshifted, and interpreted this redshift as a Doppler shift caused by galaxy recession. Moreover, he discovered that spectra of more distant galaxies show a higher redshift and are therefore receding from us with a velocity v proportional to the distance r to the galaxy,

$$v = Hr ,$$

where the proportionality coefficient H is called the Hubble constant. After Hubble's discovery, it became clear that our Universe is not static and eternal but is expanding and was therefore formed at some time in the past. To estimate the age of the Universe, we can forget for the moment about gravity, which decelerates the expansion velocity, and simply divide the distance between galaxies by their relative velocity to find

$$t \approx \frac{r}{v} = \frac{1}{H} .$$

The first measurement of H made by Hubble suffered from systematic errors, and therefore the age of the Universe turned out to be significantly underestimated. Presently, this age is determined quite precisely to be around 13 bln years.

Hubble's discovery was the beginning of scientific cosmology. But it was not totally unexpected. In 1922, Alexander Friedmann found that Einstein's equations predict in general that the Universe must either expand or contract. Moreover, by assuming that the total mass of the Universe is 100 bln times the mass of our Galaxy, Friedmann estimated that the age of the Universe should be around 10 bln years [1]. Thus, Hubble's discovery can be considered a brilliant confirmation of Firedmann's theoretical prediction.

For many years, the discovery of the expansion of the Universe was a unique experimentally confirmed fact in cosmology. Only 30 years later, another fact was established. In 1964, Arno Penzias and Robert Wilson discovered

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persistent noise in a radio antenna. Because the intensity of the radio noise was independent of the location in the sky, it was natural to assume that this emission had a relic origin; it existed in the Universe almost since its birth and therefore should have a thermal Planckian spectrum. By measuring the radiation intensity at a wavelength of several cm, Penzias and Wilson determined that the radiation temperature must fall within the range 2.5–4.5 K. The relic radiation (cosmic microwave background, CMB) is homogeneous, permeating all of space, while baryonic matter is mostly concentrated in galaxies. The number of CMB quanta greatly exceeds the number of baryons: for each baryon, there are about one billion photons.

The discovery of CMB laid the foundation of the theory of a hot Universe (Big Bang). When the Universe expands, the radiation temperature decreases inversely proportionally to its size. Therefore, when the Universe was 1000 times as small and its age was only about 300 thousand years, the CMB temperature was about 3000 K. This is sufficient to ionize almost all hydrogen, which comprises about 75% of the baryonic matter. At higher temperatures, the radiation was scattered on free electrons, and the Universe was opaque to relic photons. Only after the temperature dropped below 3000 K did most electrons recombine with protons to form neutral hydrogen atoms, and later the Universe became transparent to most CMB quanta. The time during which neutral hydrogen formed is called the recombination epoch. The recombination, clearly, was not instantaneous, its duration being about 100,000 years.

The theory of hydrogen recombination was elaborated by Yakov Zel'dovich, Vladimir Kurt, and Rashid Sunyaev [2] in 1968. The main feature of this theory is that the 2s–1s two-photon atomic transition in hydrogen, which has a low probability, turned out to be significant for recombination. Presently, the recombination theory is excellently confirmed by data on the CMB temperature fluctuations, and the polarization curves obtained in the 'Planck' experiment enable measurements of the two-photon decay of the 2s state of hydrogen with an accuracy of up to 5%, which is much higher than the laboratory accuracy, and thus demonstrates the capabilities of precision cosmology.

After the Universe became transparent to radiation, most photons did not scatter, and they therefore allow us to obtain a direct snapshot of the early Universe at an age of only several hundred thousand years. This snapshot, first obtained by Penzias and Wilson, demonstrated that, although today we observe galaxies, stars, and other structures, no such structures or their seeds were seen at all in the past. If matter, including the CMB, were distributed somewhat more inhomogeneously, Penzias and Wilson would have seen CMB temperature variations in different directions across the sky. The absence of such variations could be explained by the fact that either the Big Bang theory is completely wrong or the sensitivity of radio detectors is insufficient. Naturally, theorists of the 1970s preferred the second explanation, and experimentalists tried unsuccessfully to find the temperature fluctuations. Notably, one of the main purposes of the RATAN-600[1] 600 m radio telescope constructed in the USSR in the 1970s was to search for CMB temperature fluctuations.

[1] RATAN is the Russian abbreviation for "Radio Astronomical Telescope of the Academy of Sciences."

Returning to the history, it is important to note the following: the fact that the Universe could be very hot in the past was not fully unexpected in the 20th century. From observations of spectral lines, it was known that 75% of the baryonic matter in the Universe consists of hydrogen, 25% of helium-4, and all other elements are present in tiny amounts. While the origin of heavy elements could be explained by thermonuclear reactions in stars, the origin of helium-4 was difficult to understand. Indeed, the assumption that all helium was also synthesized in stars implies that the sky brightness should be at least 100 times higher than we actually observe. Therefore, in the 1940s, George Gamow [3] and his colleagues Ralf Alpher and Robert Herman [4] came to the conclusion that most of the helium was produced in a hot early Universe, when the temperature was very high. All the energy liberated in the synthesis was thermalized, and the radiation cooled in the course of later expansion. Thus, the puzzle of the origin of helium was solved. Although the calculations by Gamow, Alpher, and Herman were not fully correct, they were lucky to correctly guess the present-day CMB temperature, which was measured by Penzias and Wilson 15 years later. Further calculations by Robert Wagoner, William Fowler, and Fred Hoyle in 1967 fully confirmed that the chemical abundance of helium and other light elements indeed can be explained by the Big Bang theory [5].

2. Galaxy formation problem

In 1976, I was a student at the Moscow Institute for Physics and Technology. After overcoming many hurdles raised by the institute administration, I managed to move to the subfaculty headed by Vitaly Ginzburg. I was eager to study cosmology despite the fact that most physicists at that time, as I now clearly realize, did not pay any serious attention to theoretical speculations about the Universe. Only owing to the scientific democracy of Ginzburg, who became my academic advisor in three years, was I able to study what I was really interested in. As Ginzburg repeated many times, "My role as a supervisor is to not keep you from your work."

When I started studying cosmology, all the science about the origin of the Universe was based on 'one and half' experimental facts. Indeed, but for rare exceptions, almost everybody accepted that the Universe was indeed expanding. With regard to the origin of the CMB, however, there was no such firm certainty. Although the vast majority of cosmologists were almost sure of the primordial origin of the CMB, this was not firmly established, and from time to time papers suggesting alternative explanations were published. To settle the doubts, the CMB spectrum had to be measured with high accuracy to ensure that it indeed was Planckian in a broad frequency range, including the Wien part of the spectrum, to which the atmosphere is opaque. In the late 1970s, the results of balloon measurements were still contradictory.

In the late 1970s, one of the serious problems for cosmologists (whose number was a fraction of what it is now) was galaxy formation from some given initial perturbations. CMB observations suggested that the Universe had no structure at the time it was a tenth of a percent the size it is today. Naturally, the question arises: How then were galaxies formed? It was clear that gravitational instability should play the key role. Indeed, in normal conditions gravity is an attractive force. Therefore, if there is an inhomogeneous matter distribution, then the regions with higher density attract matter from regions with lower density until these are fully exempted. Thus, the mater distribution eventually becomes highly inhomogeneous, and most baryons appear in galaxies. Nevertheless, for big inhomogeneities to arise from the gravitational instability, some primordial fluctuations are needed. How strong these perturbations should be depends on the efficiency of gravitational instability.

At the beginning of the 20th century, James Jeans found that in a static, nonexpanding Universe, instabilities grow exponentially [6]. However, as was shown by Eugene Lifshits in 1946, the growth of instabilities in an expanding Universe is much slower [7]. The correct interpretation of Lifshits's calculations means that on scales exceeding the size of a causally connected region, the inhomogeneities are fully 'frozen', and only after the instabilities enter the cosmological horizon and become causally connected can their amplitude experience a power-law increase in time, becoming directly proportional to the size of the Universe. This implies that on galactic scales, all primordial fluctuations were frozen for the first 100,000 years and could increase only after that by 10,000 times at most.

Thus, to explain the structure of the Universe, it is necessary to assume that the density of matter at the recombination was not distributed homogeneously, and there were deviations from the mean value at a level of about 0.01%. These small matter density variations should be accompanied by CMB temperature fluctuations. Therefore, the natural question arises: Why do we not see the temperature fluctuations (around 0.01%) in the snapshot taken by Penzias and Wilson? If the CMB radiation is indeed of primordial origin, the temperature fluctuations should have been seen in the snapshot!

The first theoretical estimates of the expected temperature fluctuations, made by Rashid Sunyaev, Yakov Zel'dovich [8], Jim Peebles, and Jer Yu [9] in 1970, were not precise enough to clearly contradict the experimental results, and the absence of CMB temperature fluctuations could well be explained by insufficient sensitivity of the detectors. At the same time, it was absolutely clear that if the Big Bang theory is correct, such fluctuations should be ultimately discovered with higher-sensitivity detectors.

The unsatisfactory state of observational cosmology in the 1970s–1980s also explains why many different theories of galaxy formation existed at that time. Regarding the character of perturbations, in particular, it could be assumed that at some initial time both baryons and radiation were distributed in space slightly inhomogeneously, but at the same time the number of photons per baryon was constant in space. Such perturbations are called adiabatic.

The theory of adiabatic perturbations was developed predominantly in the Soviet Union. As at that time, dark energy and nonbaryonic dark matter were unknown, and this theory did not fit well with astrophysical observations. Therefore, abroad, in the USA in particular, the theory of entropy perturbations was favored, which was believed to much better correspond to observations. The theory of entropy perturbations assumes that initially only baryons were distributed inhomogeneously on a homogeneous CMB background. Finally, even the vortex theory of galaxy formation, which is incompatible with the Friedmann theory of the expanding early Universe, was considered viable.

Also, nothing was known about the statistical properties of primordial perturbations. It could be assumed that either the primordial perturbations are described by a random Gaussian process or they encode additional information and are strongly non-Gaussian. For example, the theory of cosmic strings and textures, very popular in the 1980s, predicts a very strong non-Gaussianity of primordial perturbations.

3. Quantum fluctuations

Unsurprisingly, after initial attempts to add to the list of galaxy formation theories, I was ultimately frustrated and turned to a more academic field, which at that time had nothing to do with observations. Namely, together with my co-author Gennady Chibisov, we decided to clarify the nature of primordial inhomogeneities that could subsequently lead to galaxy formation. By assuming a priori that for some unknown reasons the Universe was created in a maximum homogeneous state, we posed the question as to whether unavoidable quantum fluctuations in the initial matter distribution could be responsible for the structure formation in the Universe.

In the mid-1970s, when we started exploring this problem, there were almost no publications dedicated to this issue. Subsequently, when our work was already completed, we discovered the paper by Andrei Sakharov [10], in which as early as 1965 he attempted to quantize cosmological perturbations in the framework of the cold Universe model. Because it is impossible to amplify quantum fluctuations in that case, Sakharov's paper [10] went unnoticed.

The first problem we faced was how to quantize perturbations in a hydrodynamic medium with gravitation taken into account. The quantization of linearized gravitational waves was well known, but nobody had seriously attempted to quantize the gravitational field induced by quantum matter inhomogeneities. The Heisenberg uncertainty relation unavoidably leads to minimal inhomogeneities, and we would like to know under which conditions, if any, such inhomogeneities could be sufficient to form galaxies. At first glance, the idea seemed a bit crazy, because quantum effects are usually important on atomic or smaller scales. However, it should be kept in mind that immediately after the creation of the Universe, all the matter of our Galaxy was concentrated in a region less than the atomic size. This is why quantum mechanics could be essential on scales that are now huge due to expansion of the Universe. If we were right, this expansion would be the missing link connecting the atomic and galactic scales, micro- and macrophysics.

In the spring of 1980, the formal quantum theory of cosmological perturbations was almost completed. Based on this theory, we proved that in an expanding Universe, where gravity is always an attractive force and slows expansion, it is impossible to amplify quantum fluctuations to the necessary amplitude. We also managed to show that quantum fluctuations could be amplified only by assuming that, at the beginning, the Universe passed through the stage of an accelerated quasi-de Sitter expansion, during which gravity effectively acted as a repulsive force (antigravity) [11]. Using the model of such a stage, proposed by Alexey Starobinsky in 1980 [12] to solve the initial singularity problem, we found that quantum fluctuations destroy the de Sitter stage in a finite time interval, and therefore the singularity problem cannot be solved in such a way. On the other hand, it was shown that when this stage is long enough, the initial quantum inhomogeneities are amplified to the necessary values, and the perturbation spectrum was calculated.

Thus, by the end of 1980, we had almost completed the theory of the quantum origin of structures in the Universe, and the paper with the final perturbation spectrum was published in May 1981 in *JETP Letters* [13]. A year after the publication of our paper, Steven Hawking, using other methods, independently came to the same conclusions [14].

At approximately the same time, Alan Guth noted that the stage of accelerated expansion (which he dubbed cosmological inflation) could help to explain why the Universe is homogeneous and isotropic on large scales, as well as to solve the problems of causality and the absence of magnetic monopoles (at that time, most of the elementary particle physicists believed in the Grand Unification theory, where monopoles are unavoidable) [15]. A similar idea was suggested by Robert Brout, François Englert, and Edgar Gunzig [16], but remained unnoticed by the broad community. [2] Guth tried to justify the existence of accelerated expansion by the presence of a scalar field condensate, but could not propose a specific model to ensure smooth transition from accelerated expansion to the decelerated Friedmann expansion. In scalar field models, this problem was solved by Andrey Linde in 1982–1983 [20, 21].

Later, I was able to show that the predictions of the theory of quantum cosmological perturbations are independent of the specific model of the quasi-de Sitter expansion, and remain the same as in our original model. Only the amplitude of primordial gravitational waves, predicted by Starobinsky [22] as early as 1979, can significantly vary from model to model.

Thus, the predictions obtained by us in 1981 turned out to be universal. Namely, we discovered that if the initial perturbations originated from primordial quantum fluctuations, they must be (a) adiabatic, (b) Gaussian, and the gravitational potential amplitude should increase logarithmically with scale. In addition, unless special assumptions are made on the duration of the stage at which quantum fluctuations amplify, the present-day geometry of the Universe on large scales should be necessarily Euclidean.

As noted above, the adiabaticity means that although the density of baryons and dark matter can slightly vary in space, the number of photons per baryon (or per cold dark matter particle) should be originally strictly constant in all space.

The metric of a flat (Euclidean) Friedmann Universe with small perturbations can be represented in the form

$$\mathrm{d}s^2 = a^2(\eta)\left[(1+2\Phi)\,\mathrm{d}\eta^2 - (1-2\Phi)\;\delta_{ik}\,\mathrm{d}x^i\,\mathrm{d}x^k\right],$$

where $a(\eta)$ is the scale factor characterizing the Universe expansion and Φ is the space-dependent gravitational potential caused by perturbations. Because the initial perturbations arose due to amplification of Gaussian quantum fluctuations by an external classical field (the gravitational field of the accelerating Universe), the resulting gravitational potential should be described by a Gaussian random field $\Phi_{\rm gauss}$ up to second-order corrections due to the nonlinearity of Einsten's equations, i.e.,

$$\Phi = \Phi_{\rm gauss} + f_{\rm NL}\Phi^2\,,$$

where the parameter $f_{\rm NL}$ should be of the order of unity, $f_{\rm NL} = O(1)$. The gravitational potential on galactic scales is $O(1)\times 10^{-5}$; a non-Gaussian admixture should not exceed 10^{-9}.

[2] The possibility of the Universe passing through a de Sitter stage was first pointed out by Gliner [17–19].

Finally, the finest and most striking prediction of the theory pertains to the perturbation spectrum. As we discovered, immediately after the completion of the accelerated expansion stage, the gravitational potential amplitude should increase logarithmically with the scale λ:

$$\Phi(\lambda) \propto \ln\frac{\lambda}{\lambda_\gamma}\,.$$

The physical reason for the unavoidable logarithmic amplitude increase is the need to smoothly transit from the accelerated expansion to the ordinary Friedmann stage. In the range of scales observable today, the logarithmic dependence can be approximated by a power law:

$$\Phi^2 \propto \lambda^{1-n_{\rm s}}\,,$$

where the spectral index $n_{\rm s}$ on galactic scales must be expressed as

$$n_{\rm s} = 1 - \frac{\mathrm{d}\ln\Phi^2}{\mathrm{d}\ln\lambda} = 1 - \frac{2}{\ln\left(\lambda_{\rm gal}/\lambda_\gamma\right)} \approx 0.96\,.$$

In the case of a flat spectrum, where the amplitude is independent of scale, the spectral index would be equal to unity. But the theory predicted unavoidable deviations of $n_{\rm s}$ from unity at the 4% level. These four percent are determined by the ratio of galactic scales $\lambda_{\rm gal}$ to the characteristic length of the CMB radiation λ_γ, and thus directly reveal the relation between micro- and macrophysics.

To reproduce the observed amplitude of perturbations, $\Phi \approx 10^{-5}$, we should assume that quantum fluctuations amplified when the density of the Universe was only 10^{12} times less that the Planckian density and the age of the Universe was as small as 10^{-36} s. Clearly, microphysics at such high energies is unknown. But, after the transition to the decelerating Friedmann expansion, the quantum galaxy seeds remained frozen for about 100,000 years by the causality principle. Therefore, unknown high-energy physics was actually unimportant for them. On the other hand, when the seeds started growing in 100,000 years, energies became so low that the physical situation was fully controlled.

Thus, the simple assumption that the structure of the Universe arose from initial quantum fluctuations leads to four very nontrivial predictions: (1) the presence of Euclidean geometry on large scales, (2) the adiabaticity of perturbations, (3) $f_{\rm NL} = O(1)$, and (4) the spectral index of perturbations $n_{\rm s} \approx 0.96$. Clearly, the availability of compelling data could easily confirm or refute a theory with such a large prediction potential. But the state of observational cosmology was rather poor until the early 1990s, and therefore the theory of quantum perturbations was not dismissed from the very beginning, although it contradicted almost all astrophysical data at that time. In particular, up to 1998, astronomical observations compellingly showed that dark matter in the Universe is insufficient to make the Universe Euclidean. It appeared that adiabatic, Gaussian perturbations could not explain the origin of galaxies. Therefore, most astrophysicists favored either entropy perturbations or topological defects. Moreover, the low accuracy of measurements had not allowed even dreaming about the proof of the Gaussianity of primordial perturbations, not to mention the measurement of the 4% deviation of the perturbation spectrum from the flat one, which was considered unrealistic as recently as

15 years ago. Until the early 1990s, nobody could find any CMB fluctuations or confirm its Planckian spectrum. Clearly, under these conditions, the Big Bang theory of the expanding hot Universe itself could be called into question. Moreover, in 1987, a Japanese–American group claimed a significant deviation of the CMB spectrum from the Planckian one discovered in rocket measurements. If they were right, this could be the end of the Big Bang theory.

4. Cosmology as a precision science

Unsurprisingly, in this situation the community waited impatiently for the first results of the space experiment COBE (Cosmic Background Explorer), which were published in 1992. According to the Nobel Physics Committee, these results were the 'starting point for cosmology as a precision science.'

The scientific equipment of the COBE satellite included three instruments, two of which were dedicated to the CMB studies: a high-sensitivity radiometer to measure the temperature anisotropy (differential microwave radiometer, DMR) (PI George Smoot) and a spectrophotometer to measure the CMB spectrum (Far InfraRed Absolute Spectrometer, FIRAS) (PI John Mather).

The measurement results proved to be sensational. It was established that the CMB spectrum is Planckian with a high precision and its temperature is 2.725 K (Fig. 1). Thus, the primordial nature of this radiation was undoubtedly proved.

The DMR made an even more sensational discovery. For the first time, small variations of the CMB temperature in different directions in the sky were found at a level of 0.0001 K (Fig. 2). Thus, we could finally see the seeds of galaxies in the Universe when its age was only several hundred thousand years. With this photo of the early Universe, it could be possible to reconstruct a portrait of an even younger Universe at an age of only small fractions of a second. Indeed, as noted above, on scales that later expanded to galactic ones and beyond, according to Einstein's General Relativity, after the accelerating expansion stage, the perturbations did not grow until the Universe 'aged' to 100,000 years. This demonstrates all the power of gravity, which ignores all other interactions on scales where it dominates. The seeds of galaxies 'wake up' and start developing only when the Universe is already about 100,000 years old. For that time, we already know all the relevant physics determining the evolution of perturbations.

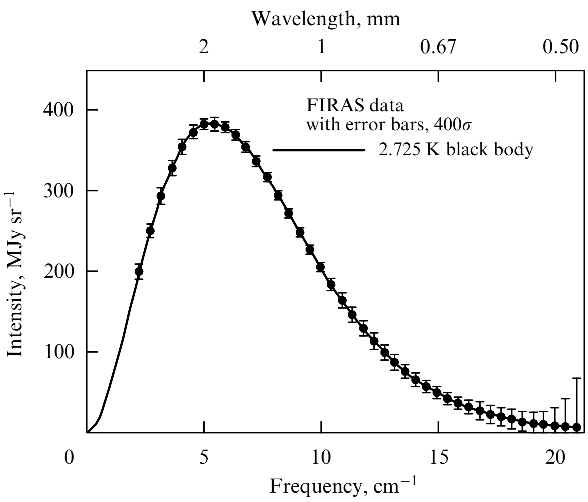

Figure 1. The CMB spectrum measured by COBE.

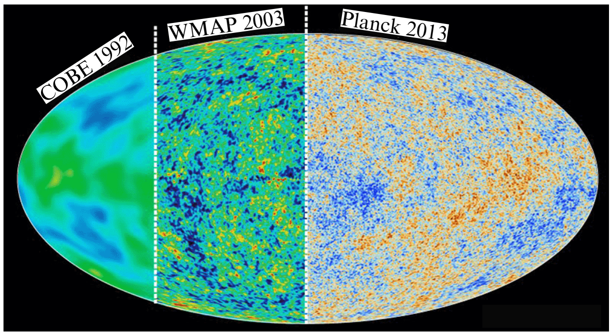

Figure 2. COBE, WMAP, and Planck maps revealing a more detailed structure of the early Universe.

Thus, the COBE results uniquely implied that in fact we live in a hot expanding Universe and can even see the galaxy seeds. Nevertheless, the obtained snapshot of the primordial perturbations was not sufficiently detailed to uniquely decide on their origin. The DMR resolution was not too high, which did not allow the perturbation structure to be captured in detail. Therefore, although the COBE results did not contradict the theory of quantum perturbations, they were also compatible with other theories, such as cosmic strings, textures, and even entropy perturbations. The next task was to improve the sensitivity and angular resolution of the CMB fluctuation measurements.

Before returning to the history of CMB observations, we briefly discuss the results obtained by extragalactic astronomy in the 1990s. Here, huge progress was achieved due to the construction of new telescopes, including the 2.4 m Hubble Space Telescope, two 10 m W Keck telescopes in Hawaii, the VLT (Very Large Telescope) in Chile consisting of four 8 m mirrors, and many others. These instruments enabled a significant improvement in our knowledge about the present state of the Universe exactly in the field that is very important for cosmology.

As early as the 1980s, it became absolutely clear that some dark matter, invisible to telescopes, should exist in the Universe. Otherwise, it was almost impossible to explain the rotational curves of galaxies and galaxy cluster dynamics.

We note that the need for such dark matter was first pointed out by Fritz Zwicky already in the 1930s. One of the big puzzles is the content of this dark matter. The assumption of its baryonic origin has contradicted the observed deuterium abundance, because if the amount of baryonic matter greatly exceeded the observed value, the deuterium would already have burned out in the early Universe. Therefore, in the 1980s, a hypothesis on the nonbaryonic nature of dark matter was put forward; it was assumed that it can consist of unknown particles undetected so far by accelerators. However, even in the mid-1980s, observations suggested that dark matter in galaxies and galaxy clusters is by far insufficient to make the Universe Euclidean (flat). This fact was in contradiction with theoretical predictions, and if it were confirmed, the theory of quantum fluctuations and the inflationary cosmology would have been rejected altogether. Fortunately, the missing matter was discovered in the form of dark antigravitating energy that homogeneously fills the Universe and therefore does not affect either the rotational curves of galaxies or the dynamics of galaxy clusters.

In 1998, two groups of researchers led by Brian Schmidt, Adam Riess, and Saul Perlmutter, using observations of distant supernovae, concluded that our Universe is currently accelerating, and hence homogeneously distributed antigravitating dark energy should dominate. Thus, the missing matter was found.

Among other astronomical observations, the Sloan Digital Sky Survey (SDSS) should be noted. In this experiment, using a 2.5 m telescope, redshifts of more than one million galaxies were measured in the 2000s. As a result, the cosmological principle stating that the Universe is homogeneous and isotropic on large scales was proved beyond any doubt. Moreover, the SDSS demonstrated that on smaller scales, the structure of the Universe resembles a web (the Cosmic Web). In particular, galaxies, by crowding, form clusters connected by filaments. The filaments, in turn, are bounded by walls, between which voids are found. Another achievement of extragalactic astronomy was the discovery in 2005 of baryon acoustic oscillations in the matter distribution in the present-day Universe, in full agreement with the results of the CMB temperature fluctuations from the early Universe measured by that time. Finally, the recent measurement of the deuterium abundance enabled CMB-independent measurements of the baryonic density in the Universe with high accuracy.

Returning to the CMB, we emphasize that unlike astronomical observations, the temperature measurements do not suffer to such an extent from uncontrolled systematic errors and directly relate to the early Universe, which was much simpler than it is nowadays. After COBE, due to colossal progress and the construction of new sensitive detectors in the millimeter and submillimeter bands, it became possible to measure the CMB temperature fluctuations from balloons and even from the ground. Of course, these experiments are limited by a relatively small part of the sky in directions that are most transparent to CMB radiation. However, the angular resolution of these experiments was at least 10 times as high as that in the COBE experiments, which enabled studies of the detailed structure of small-scale perturbations.

As noted above, inhomogeneities on galactic scales started growing when the age of the Universe was 100,000 years In particular, after entering under the cosmological horizon (the size of the causally connected region), but prior to recombination, the perturbations were given by standing sound waves. As a result, the perturbation spectrum was modulated to acquire maxima and minima.

Therefore, in the case of adiabatic perturbations, the dependence of the temperature difference between two antennas on the angular distance between them must have many maxima (referred to as acoustic peaks). The position and amplitude of these peaks depend not only on the initial perturbation spectrum but also on the matter content and geometry of the Universe. In the case of a flat Euclidean Universe, the first peak should approximately be found at an angular distance of 1° between antennas.

The first triumph of the theory was achieved in 1999 after measurements by two ground experiments, Saskatoon[3] and the Microwave Anisotropy Telescope (MAT)/TOCO (Cerro Toco, a mountain in Chile), led by Lyman Page. It was discovered that this peak is indeed at an angular scale of one degree, and therefore the Universe must be Euclidean. Thus it was established that dark energy is sufficient to ensure the flatness of the Universe. Several months later, this result was fully confirmed by the balloon experiments BOOMERANG (Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics) and MAXIMA (Millimeter Anisotropy eXperiment IMaging Array), respectively led by Paolo de Bernardis and Andrew Lange, and Paul Richards. In addition, the second and third acoustic peaks were detected, which in turn strongly supported adiabatic perturbations and served as firm proof of the existence of dark energy. Thus, in the early 2000s, the theory of quantum perturbations 'killed off competitors', but the test of finer predictions of the theory was still ahead.

During the subsequent several years, several dozen other ground-based and balloon experiments fully confirmed the BOOMERANG/MAXIMA results with improved angular resolution. However, to obtain a fully detailed picture of the early Universe, much more expensive space experiments were required.

In 1996, the National Aeronautic and Space Administration (NASA), USA, approved the space mission WMAP (Wilkinson Microwave Anisotropy Probe) headed by Charles Bennett and Lyman Page. The WMAP sensitivity was 40 times as high as that of COBE and the angular resolution was 30 times as high (see Fig. 2). The WMAP satellite was launched in June 2001 and performed measurements of the CMB temperature and polarization over nine years. Already after the first WMAP results were published in 2003, it became clear that they fully complied with the prediction of the theory of quantum perturbations. These data uniquely favored a Euclidean Universe with adiabatic Gaussian fluctuations. Moreover, in 2006 the ever increasing observational data started to point to deviations of the perturbation spectrum from a flat one, as predicted by the theory. Nevertheless, there were still many skeptics who doubted the fine predictions related to the Gaussianity and the spectral index of primordial perturbations. The final verdict was delivered by the Planck experiment, which had a 100-fold better sensitivity and fivefold better angular resolution than the WMAP experiment (see Fig. 2). Although the Planck mission was approved by the European Space Agency at about the same time as WMAP, for some reason the launch of the Planck satellite was delayed until May 2009. The project included two separate instruments: the high-frequency HFI (High Frequency Instrument) and low-frequency LFI (Low Frequency Instrument), respectively headed by Jean-Lois Puget and Nazareno Mondolesi. A significant improvement over the WMAP results was mainly obtained by the HFI. The first Planck results were published at the end of March 2013 (Figs 3, 4) (see [24] for more details). After processing the most precise CMB maps, it was established that the theoretical predictions made more than 30 years prior were fully confirmed with a very high accuracy. Notably, it turned out that with an accuracy of 0.5% (1σ) the Universe is Euclidean. The perturbations should be adiabatic at the 99% level at least. The Gaussianity of primordial fluctuations was confirmed with a maximum possible accuracy ($f_{\rm NL} = 0.8 \pm 5$). And finally, and most strikingly, the deviations from the flat spectrum were established at the 7σ level. In particular, the measured spectral index was found to be equal to 0.965 ± 0.005 (our prediction with Chibisov in 1981 was 0.96).

Along with numerous astrophysical data, for example, the detection of baryonic acoustic oscillations, direct measure-

[3] After the name of the Canadian city Saskatoon.

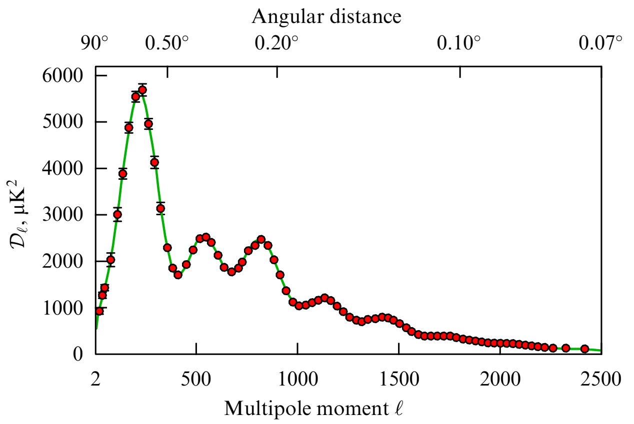

Figure 3. Temperature fluctuations $\mathcal{D}_\ell$ as a function of the angular distance between antennas. The experimental data (circles) are in very good agreement with theoretical predictions (solid curve).

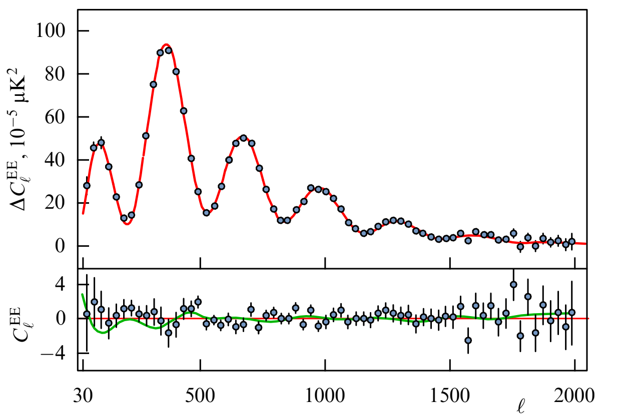

Figure 4. Planck results (circles) for the polarization correlation function $C_\ell^{\rm EE}$ and $\Delta C_\ell^{\rm EE}$, which show remarkable agreement with theoretical predictions (solid curves).

ments of primordial deuterium, and direct measurement of the Hubble constant and dark matter from supernova observations, measurements of the CMB fluctuations enabled a compelling and reliable reconstruction of the evolution of the Universe. Moreover, observational data that contradicted each other over several decades at some time proved to be in full agreement with each other.

5. Conclusion

Presently, it is firmly established that we live in a Universe where baryons constitute only 5% of the total amount of matter. The remaining matter consists of two dark components: dark matter and dark energy. The amount of dark energy is 2.5 times as high as that of dark matter. Unlike dark matter, dark energy antigravitates. Its present role is not fully clear, but in the very distant past it could well be responsible for the amplification of quantum fluctuations. Irrespective of the amplification mechanism of the initial quantum fluctuations, the theory of the quantum origin of structures in the Universe with all its nontrivial predictions is now reliably confirmed, and there are no viable alternatives. We also note that besides black holes, cosmology is the only field where the nonperturbative Einstein theory is needed. Numerous cosmological data confirm that this theory is valid in a wide range from 10^{-27} cm to 10^{28} cm.

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