Introducing the notation $1/x \equiv q$, we get

$$I_h(h) = C \int_0^{q_0} \frac{\exp(-2\phi)\,\mathrm{d}q}{\sqrt{1-qy}\,\left[\exp(-2\phi) - q^2h^2\right]^{3/2}}\,. \qquad (28)$$

This intensity distribution in h is minimal at the zero impact parameter and maximal at maximum impact parameters corresponding to the width of the wormhole neck, with this result being independent of the wavelength of the light traveling through the wormhole.

A characteristic diagram for $I_h(h)$ is shown in Fig. 3b. It corresponds to a wormhole with metric (1). Thus, the observer will see a ring of light with sharp outer edges and smeared inner edges.

With sufficiently high resolution of the observational devices, this fact can make it possible to distinguish between wormholes and black holes in, say, active galactic nuclei.

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Dark matter: from initial conditions to structure formation in the Universe

V N Lukash, E V Mikheeva

1. "Bring me that, don't know what"

We are at the verge of a discovery capable of changing the essence of our world view. We are talking about the nature of dark matter.

Recently, astronomy has taken important steps in observational justification for dark matter, and today the presence of dark matter in the Universe can be considered a firmly established fact. What makes the situation so special is that astronomers *observe* structures made of matter *unknown* to physicists. This has posed the problem of identifying the physical nature of such matter.

Modern elementary particle physics knows of no particles that have the properties of dark matter. This requires an extension of the Standard Model. But how and in what direction should we move, and what and where should we look for? The heading of this section, a quotation from a Russian fairy tale, very fittingly reflects the current situation.

Physicists are looking for the unknown particles, having only a general idea about the properties of the observed matter. But what are these properties?

The only thing we know for certain is that dark matter interacts with a luminous matter (baryons) in the gravitational way and constitutes a cold medium with a cosmological density several times higher than the baryon density. In view of such simple properties, dark matter directly affects the development of the gravitational potential of the Universe. The contrast of its density grew with time, leading to the formation of gravitationally bound systems of dark-matter halos.

It should be emphasized that this process of development of gravitational instability could be triggered in the Friedmann Universe only in the presence of primordial density perturbations, whose very existence is in no way related to dark matter but instead is caused by Big Bang physics. Hence, we face another important question of how these seed perturbations, from which the structure of dark matter developed, emerged.

We will turn our attention to the problem of generation of primordial cosmological perturbations somewhat later. Let us now return to dark matter.

Baryons are trapped by the gravitational wells of dark matter concentrations. Hence, although the particles of dark

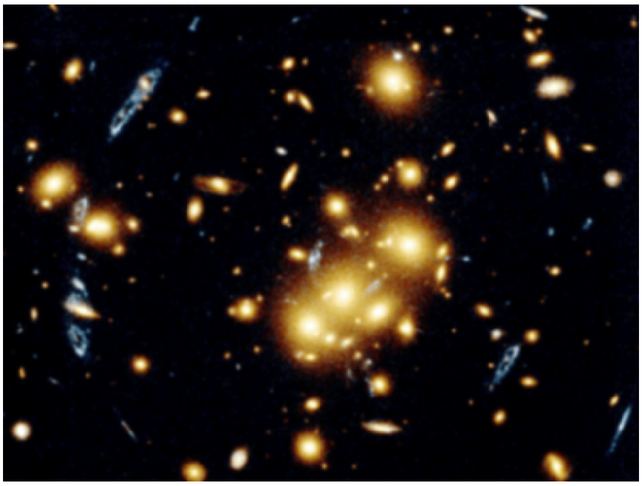

Figure 1. A region of the sky in the direction of the 0024+1654 cluster of galaxies. The picture was taken by the Hubble Space Telescope.

matter do not interact with light, there is light where there is dark matter. This remarkable property of gravitational instability has made it possible to study the amount, state, and distribution of dark matter from observational data from the radio range to the X-ray range.

An independent corroboration of our conclusions concerning the properties of dark matter and other parameters of the Universe is presented by data on the anisotropy and polarization of the cosmic microwave background (CMB), the abundance of light elements in the Universe, and the distribution of absorption lines in the spectra of distant quasars. Numerical simulations, which replaced experiments in cosmological studies, are now being widely used. Valuable information on the distribution of dark matter is contained in numerous observational data on the gravitational lensing of distant sources by nearby clusters of matter.

Figure 1 displays a region of the sky in the direction of one such cluster of dark mass ($\sim 10^{14} M_{\odot}$). We see a cluster of galaxies trapped by the gravitational field of this cluster, hot X-ray gas residing at the bottom of the gravitational potential well, and a multiple image of one of the galaxies of the background that happened to be in the line of sight of the dark halo.

Table 1 lists the average values of various cosmological parameters obtained from astronomical observations (with 10% accuracy). Obviously, the total energy density of all types of particles in the Universe is not higher than 30% of the total critical density (the neutrino contribution does not exceed a few percent). The other 70% 'belongs' to an entity that takes no part in the gravitational 'clustering' of matter. Only the cosmological constant or its generalization, i.e., the medium with negative pressure $\left(|\varepsilon + p| \ll \varepsilon\right)$ that became known as 'dark energy', exhibit such a property. Determining the nature of this dark energy is a goal in the future development of physics.

Table 1. The main cosmological parameters.

Hubble's constant	$h = 0.7$
CMB temperature	$T = 2.725$ K
Curvature of space	$\Omega_{\varkappa} = 0$
Cosmological density of baryons	$\Omega_{\rm B} = 0.05$
Cosmological density of dark matter	$\Omega_{\rm DM} = 0.23$
Cosmological density of dark energy	$\Omega_{\Lambda} = 0.7$
Tilt of density perturbations spectrum	$n_S = 0.96$

The present report is devoted to problems of physical cosmology that can be expected to be solved in the nearest future. The primary problem is to determine the initial conditions needed for the formation of dark-matter structures and the search for unknown particles themselves.

2. Early Universe and late Universe

The observed structure of the Universe is the result of the combined action of the initial conditions and the evolution of the density perturbations field. Modern observational data have allowed scientists to determine the characteristics of the density perturbations field in different epochs of its development. This has made it possible to separate information about the initial conditions and the conditions of evolution. Thus, independent studies on the physics of the early and the late Universe have been initiated.

In modern cosmology, the early Universe is understood as a stage of accelerated expansion with the subsequent transition to the hot phase of evolution. We do not know parameters of the Big Bang. There are only the upper bounds [see Eqn (12) in Section 3]. However, there exists a well-developed theory of the generation of cosmological perturbations, where we can calculate spectra of initial density perturbations of matter and primary gravitational waves as functions of the cosmological parameters.

The reasons why commonly accepted model of the early Universe is absent, stem from stability of the predictions of the inflationary Big Bang paradigm — the facts that the generated spectra are close to the flat one, the amplitude of cosmological gravitational waves is relatively small, the geometry of the visible part of the Universe is three-dimensional Euclidean, etc. All these results can be obtained within a broad class of model parameters. The key point in building up a model of the early Universe would be discovery of cosmological gravitational waves. We believe that this can be realized if the space mission *Planck* (starting in 2008) will be successful.

Our knowledge about the late Universe is drastically different. We have here rather precise model, we know the composition of matter, the laws governing the development of the structure, and the values of the cosmological parameters (see Table 1), but at the same time we have no commonly accepted theory describing the origin of the components of matter.

The known properties of the visible part of the Universe make it possible to describe its geometry in terms of the perturbation theory. The amplitude of cosmological perturbations is a small parameter (10^{-5}).

In the zeroth order, the Universe can be described by the Friedmann model specified by a single function of time — the scale factor $a(t)$. The first order is somewhat more complicated. The metric perturbations are the sum of three independent modes: the scalar mode $S(k)$, the vector mode $V(k)$, and the tensor mode $T(k)$, characterized by the spectral functions of the wave number k. The scalar mode describes cosmological density perturbations, the vector mode is responsible for the vortex motion of matter, and the tensor mode is gravitational waves. Thus, the entire geometry is described by four functions: $a(t)$, $S(k)$, $V(k)$, and $T(k)$, of which today we know only the first two (within certain ranges of definition).

The Big Bang represented a catastrophic process of rapid expansion accompanied by an intense, rapidly varying gravitational field. In the course of cosmological expansion, metric perturbations were spontaneously generated in a parametric manner from vacuum fluctuations, as any massless degrees of freedom are generated under the action of an external variable field. Analysis of the observational data favors the quantum-gravitational mechanisms of generation of the primordial perturbations. Thus, the large-scale structure of the Universe is an example of solving the problem of measurability in quantum-field theory.

Here are the main properties of the generated perturbation fields: Gaussian statistics (random distributions in space), a preferential temporal phase (the 'growing' branch of perturbations), the absence of a characteristic scale within a broad range of wavelengths, and a nonzero amplitude of gravitational waves. The last property plays a decisive role in building models of the early Universe, since, coupled most simply to the background metric, gravitational waves carry direct information about the energy scale of the Big Bang.

As the scalar perturbation mode develops, galaxies and other astronomical objects form. An important achievement in recent years [the Wilkinson Microwave Anisotropy Probe (WMAP) experiment] was the impressive refinement of our knowledge concerning the CMB anisotropy and polarization. They emerged long before galaxies were formed as a result of acting all three cosmological perturbation modes on the distribution of relic photons.

Combined analysis of the observational data on the distribution of galaxies and on the CMB anisotropy made it possible to separate the starting conditions and the evolution. Taking into account that the sum $S + V + T \approx 10^{-10}$ is fixed by the value of the CMB anisotropy, one can obtain the upper bound on the vortex and tensor perturbation modes in the Universe (their detection is only possible if the accuracy of observation becomes higher):

$$\frac{V+T}{S} < 0.2 \,. \tag{1}$$

If inequality (1) were not true, the amplitude of primordial density perturbations would be insufficient for the formation of the observed structure.

3. In the beginning was sound...

The effect of the quantum-gravitational creation of massless fields has been thoroughly studied. For instance, particles of matter can be produced in this way (e.g., see Refs [1, 2]) (although, in particular, relict photons appeared as a result of the decay of protomatter in the early Universe). The same is true of the generation of gravitational waves [3] and density perturbations [4], since these fields also belong to massless fields and their creation is not forbidden by a threshold energy condition. The problem of how vortex perturbations are generated is still awaiting a solution.

The theory of S and T perturbation modes in a Friedmann Universe is reduced to the quantum-mechanical problem of independent oscillators $q_k(\eta)$ placed in an external parametric field $\alpha(\eta)$ in the Minkowski world with a time coordinate $\eta = \int \mathrm{d}t/a$. The action integral and Lagrangian of these elementary oscillators depend on their spatial frequency $k \in (0, \infty)$:

$$S_k = \int L_k \,\mathrm{d}\eta \,, \qquad L_k = \frac{\alpha^2}{2k^3}\left(q'^2 - \omega^2 q^2\right) , \tag{2}$$

where the prime indicates a time (η) derivative, $\omega = \beta k$ is the oscillator frequency, and β is the perturbation propagation velocity expressed in units of the speed of light in vacuum (here and in what follows, $c = \hbar = 1$, and the subscript k has been dropped from the field q). In the case of the T mode, $q \equiv q_T$ is the transverse-traceless component of the metric tensor, with

$$\alpha_T^2 = \frac{a^2}{8\pi G} \,, \qquad \beta = 1 \,, \tag{3}$$

and in the case of the S mode, $q \equiv q_S$ is a linear superposition of the longitudinal gravitational potential (a perturbation of the scale factor) and the potential of the 3-velocity of the medium multiplied by the Hubble parameter [4], with

$$\alpha_S^2 = \frac{a^2\gamma}{4\pi G\beta^2} \,, \qquad \gamma = -\frac{\dot H}{H^2} \,, \qquad H = \frac{\dot a}{a} \,, \tag{4}$$

where the over-dot indicates a time (t) derivative.

As formulas (3) suggest, the field q_T is more fundamental than q_S, since it is minimally coupled to the background metric and is independent of the properties of matter (in General Relativity, the velocity of gravitational waves is equal to the speed of light). As for q_S, its coupling to the external field (4) is more complicated: it includes the derivatives of the scale factor and some characteristics of the matter (e.g., the velocity at which perturbations propagate in a medium). We know nothing about protomatter in the early Universe, there are only the general approaches to this problem.

Usually, the medium is assumed to be ideal with its energy–momentum tensor depending on the energy density ε, pressure p, and 4-velocity u^μ of matter. For the S mode, the 4-velocity is potential and can be represented by the gradient of a 4-scalar ϕ:

$$T_{\mu\nu} = (\varepsilon + p)u_\mu u_\nu - p g_{\mu\nu} \,, \qquad u_\mu = \frac{\phi_{,\,\mu}}{w} \,, \tag{5}$$

where $w^2 = \phi_{,\,\mu}\phi_{,\,\nu}\, g^{\mu\nu}$ is a normalization function, with the comma in the subscript indicating a coordinate derivative. The speed of sound appears in the 'equation of state' as a proportionality factor between the comoving perturbations of pressure and energy density of matter:

$$\delta p_{\mathrm{c}} = \beta^2\, \delta\varepsilon_{\mathrm{c}} \,, \tag{6}$$

where $\delta X_{\mathrm{c}} \equiv \delta X - v\dot X$, and $v \equiv \delta\phi/w$ is the potential of the 3-velocity of the medium.

In the linear order of the perturbation theory, the concept of an ideal medium is equivalent to the field concept where the Lagrangian density $L = L(w, \phi)$ is assigned to the matter field ϕ. In the field approach, the rate at which perturbations propagate is found from the equation [4–6]

$$\beta^{-2} = \frac{\partial \ln |\partial L/\partial w|}{\partial \ln |w|} \,, \tag{7}$$

which also corresponds to Eqn (6). In most models of the early Universe, it is assumed that $\beta \sim 1$ (in particular, at the radiation-dominated stage $\beta = 1/\sqrt{3}$).

The evolution of elementary oscillators is described by the Klein–Gordon equation

$$\bar q'' + (\omega^2 - U)\bar q = 0 \,, \tag{8}$$

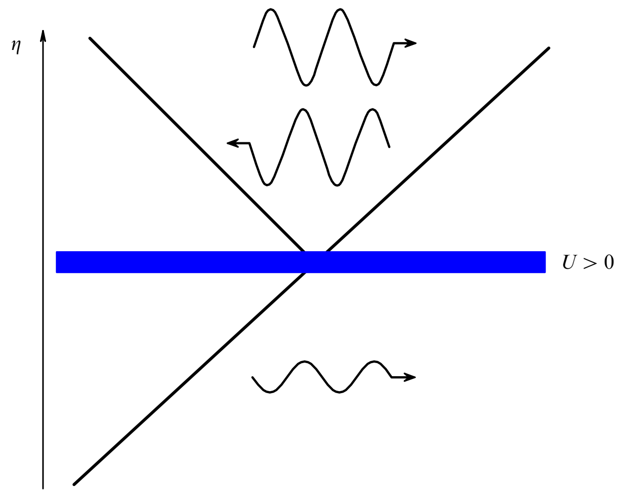

Figure 2. Illustration of the solution of Eqn (8) in the scattering problem.

where

$$\bar{q} \equiv \alpha q\,, \qquad U \equiv \frac{\alpha''}{\alpha}\,. \tag{9}$$

The solution to Eqn (8) has two asymptotic branches: the adiabatic branch ($\omega^2 > U$), where an oscillator is freely oscillates and its excitation amplitude decays ($|q| \sim (\alpha\sqrt{\beta}\,)^{-1}$), and the parametric branch ($\omega^2 < U$), where the field q is frozen ($q \to \mathrm{const}$). The latter condition means, from the viewpoint of quantum-field theory, parametric production of a pair of particles from a state with elementary excitation (Fig. 2).

Quantitatively, the spectra of the produced perturbations depend on the initial state of the oscillators:

$$T \equiv 2\langle q_T^2 \rangle\,, \qquad S \equiv \langle q_S^2 \rangle\,, \tag{10}$$

with the factor '2' in the expression for the tensor mode accounting for two polarizations of gravitational waves. The state $\langle\ \rangle$ is assumed to be the ground state, i.e., it corresponds to the minimum level of initial excitation of the oscillators. This constitutes the main hypothesis for the Big Bang theory. In the presence of an adiabatic zone, the ground (vacuum) state of elementary excitations is uniquely determining [7].

Thus, assuming that the function U increases with time and that $\beta \sim 1$, we arrive at a universally general result for the spectra $T(k)$ and $S(k)$:

$$T \approx \frac{(1-\gamma/2)H^2}{M_{\mathrm{P}}^2}\,, \qquad \frac{T}{S} \approx 4\gamma\,, \tag{11}$$

where $k = \sqrt{U} \approx aH$, and $M_{\mathrm{P}} \equiv G^{-1/2}$ is the Planck mass. From formulas (11) we see that in theory the mode T is never discriminated in relation to mode S. Everything depends on the value of the factor γ at the epoch of excitation generation.

From the observed fact that the T mode is small in our Universe [see Eqn (1) in Section 2], we obtain the upper bounds on the energy scale of the Big Bang and on the parameter γ in the early Universe:

$$H < 10^{13}\ \mathrm{GeV}\,, \qquad \gamma < 0.05\,. \tag{12}$$

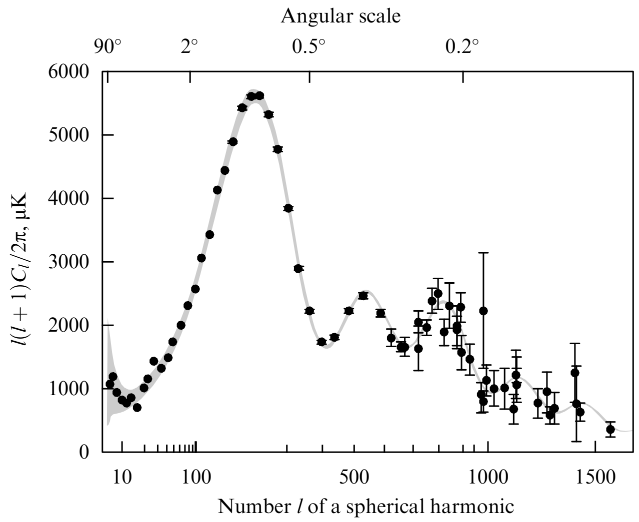

Figure 3. Manifestation of sound modulation of CMB anisotropy spectrum. [According to the data of the WMAP, ACBAR (Arcminute Cosmology Bolometer Array Receiver), BOOMERANG (Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics), CBI (Cosmic Background Imager), and VSA (Very Small Array) experiments.]

The second condition means that the Big Bang was inflationary ($\gamma < 1$).

Thus, we possess an important phase information, namely, that the fields are created in a certain phase, and only the growing branch of the perturbations is parametrically amplified. Let us explain this fact on the example of scattering problem, assuming that $U = 0$ in the *initial* (adiabatic) and *final* (radiation-dominated, $a \propto \eta$) stages of evolution (see Fig. 2).

For each of the above-mentioned asymptotics, the general solution is written in the form

$$\bar{q} = C_1 \sin\omega\eta + C_2 \cos\omega\eta\,, \tag{13}$$

where the operators $C_{1,2}$ specify the amplitudes of the 'growing' and 'decaying' evolution branches. In the vacuum state, the field's initial temporal phase is arbitrary: $\langle |C_1^{(\mathrm{in})}| \rangle = \langle |C_2^{(\mathrm{in})}| \rangle$. However, after solving the evolution equations it turns out that at the radiation-dominated stage only the growing branch of acoustic perturbations is created: $\langle |C_1^{(\mathrm{out})}| \rangle \gg \langle |C_2^{(\mathrm{out})}| \rangle$. By the instant of time when radiation decouples from matter in the recombination epoch, the radiation spectrum is modulated with a phase $k = n\pi\sqrt{3}/\eta_{\mathrm{rec}}$, where n is a natural number.

It is precisely these acoustic vibrations that are observed in the spectra of the CMB anisotropy (see Fig. 3, where the high peak corresponds to $n = 1$) and the density perturbations, which are proofs of the quantum-gravitational origin of the S mode. In the density perturbations spectrum, the acoustic modulation is suppressed by the smallness of the fraction of baryons in the total budget of matter, which makes it possible to find this fraction irrespective of other cosmological tests. The scale of baryonic oscillations is used as a standard ruler for determining the important parameters of the Universe. In view of this, it must be noted that the acuteness of the problem of degeneracy of cosmological parameters in the observational data, which for many years impeded the building up of the real model of the Universe, has finally been resolved thanks to the numerous independent and complementary observational tests.

Summarizing, we can ascertain that the problem of formation of the initial cosmological perturbations and the large-scale structure of the Universe has been solved (at least in principle). The theory of the quantum-gravitational origin of perturbations in the early Universe will receive further confirmation after the T mode is discovered, which may happen very soon. For instance, the simplest model of the Big Bang (power-law inflation on a massive scalar field) predicts the value of the T-mode amplitude only five times smaller than the S-mode amplitude [8]. Modern instruments and techniques make it possible to detect such weak signals in the CMB data on the anisotropy and polarization.

4. The dark side of matter

There are several hypotheses concerning the origin of matter, but none of them has been confirmed. We have also straightforward observational indications that the dark matter mystery is closely related to the baryon asymmetry in the Universe. However, today there is no widely accepted theory of the origin of both baryon asymmetry and dark matter.

Where is dark matter?

We know that the luminous component of matter is observed in the form of stars assembled into galaxies of various masses and in the form of X-ray gas in clusters. However, the larger part of ordinary matter (up to 90%) is in the form of rarefied intergalactic gas with a temperature of several electron-volts and in the form of MACHOs (Massive Compact Halo Object), the compact remnants from the star evolution and small-mass objects. Since these structures usually possess low luminosity, they are known as 'dark baryons'.

Several collaborations (MACHO, EROS, and some others) have investigated the amount and distribution of compact dark objects in the halo of our Galaxy by studying microlensing events. As a result of joint analysis, an important bound was obtained: no more than 20% of the entire halo mass is in MACHOs in the range from the mass of the Moon to stellar masses (Fig. 4). The remainder of the dark mass of the halo consists of particles of unknown origin.

Where else can nonbaryonic dark matter hide?

The development of high technologies in 20th-century observational astronomy gave a clear answer to this question;

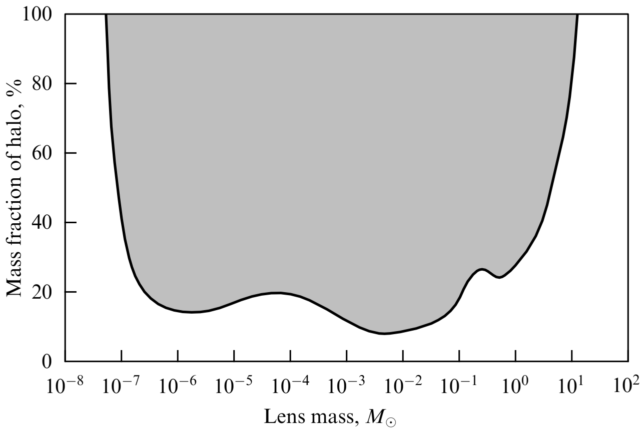

Figure 4. Upper bound on the mass fraction of the Galaxy halo in MACHOs according to EROS (Expérience pour la Recherche d'Objets Sombres) experiment.

Table 2. Candidates for particles of nonbaryonic dark matter.

Candidate	Mass
Gravitons	10^{-21} eV
Axions	10^{-5} eV
Sterile neutrinos	10 keV
Mirror matter	1 GeV
Massive particles	100 GeV
Supermassive particles	10^{13} GeV
Monopoles and defects	10^{19} GeV
Primordial black holes	$(10^{-16}-10^{-7})M_\odot$

namely, nonbaryonic dark matter is located in gravitationally bound systems (halos). The particles of dark matter are nonrelativistic and weakly interacting; they do not dissipate like baryons. Baryons radiationally cool off, precipitate, and accumulate in halo centers, achieving rotational equilibrium. Dark matter remains distributed around the visible matter of galaxies with a characteristic scale of about 200 kpc. For instance, in the Local Group, which includes the Andromeda Nebula and the Milky Way, more than half of all dark matter is concentrated in these two big galaxies.

Particles with the required properties are absent in the Standard Model of elementary particle physics. An important parameter that cannot be determined from observations due to the Equivalence principle is the mass of particles. Within the scope of various extensions of the Standard Model there are several candidates for dark matter particles. The main candidates are listed in Table 2 in ascending order of their rest masses.

The main hypothesis for massive particles, the neutralino hypothesis, is related to minimal supersymmetry. The hypothesis could be verified with the Large Hadron Collider at CERN, which should become operational in 2008. The expected mass of such particles is about 100 GeV, and their number density in our Galaxy is one particle per volume of a tea cup.

The search for dark-matter particles continues at many laboratories all over the world. What is interesting is that the neutralino hypothesis allows independent verification in underground experiments in elastic scattering and by using indirect data on the annihilation of neutralinos in the Galaxy. So far there has been only one positive response in one of the underground detectors of the DAMA (DArk MAtter) project, where for several years researchers have recorded a signal of unknown origin of the 'summer–winter' type. As yet, however, the ranges of masses and cross sections related to this experiment have not been confirmed in other experiments, which raises doubts concerning the reliability and significance of such a result.

An important property of neutralinos is the possibility of observing them indirectly by the annihilation flux in the gamma band. In the process of hierarchic clustering, such particles could have formed minihalos with a characteristic size on the order of the solar system dimension and a mass of about that of the Earth, with the remains still surviving today. It is highly probable that the Earth itself is inside such minihalos, where the particle number density increases by a factor of several dozen. This increases the probability of detecting, both directly and indirectly, dark matter in our Galaxy. The fact that there are so many different methods of searching for dark matter raises hopes, and makes it possible to believe, that the riddle of the physical nature of dark matter will soon be solved.

5. At the verge of the new physics

In our times it has become possible to independently determine the properties of the early Universe and the late Universe from observational astronomical data. We understand how the initial cosmological density perturbations emerged and how the modern structure of the Universe has developed from them. We know the values of the main cosmological parameters lying at the basement of the Standard Model of the Universe, the model has no visible rivals. However, the fundamental problems of the origin of the Big Bang and of the main components of matter still remain unresolved.

Determining the tensor mode of cosmological perturbations from observational data is the key issue in building up the model of the early Universe. Here, we are dealing with an accurate prediction of the theory that has been verified in the case of the S mode and can be experimentally verified for the T mode in the near future.

Theoretical physics, which has proposed many avenues of research and methods of searching for particles of dark matter, has exhausted itself. Now, it is experiment's turn. The current situation resembles the one just before the great discoveries: quarks, W- and Z-bosons, neutrino oscillations, and the anisotropy and polarization of CMB.

There is one question, however, that goes beyond the present report: Why is nature so benevolent and why does it open up its secrets to us?

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