proper part of the disk, and second, the chemical composition is not the primordial one but is instead enriched by the products of nucleosynthesis.

In recent years, important changes have been occurring in the theory of galaxy formation. Hot virialized gas halos of young galaxies are now 'disfavored' as sources of matter for stellar disk formation; theoreticians doubt that the gas virialization occurs in most of the collapsing halos. The formation of disks and bulges of galaxies does not necessarily have to occur via the merging of small-size subsystems only. A more and more important role in galaxy formation is probably played by cold filamentary gas flows directed to the inner part of a halo [22]. This is also a sort of flow accretion, but the accretion via gas streams that cannot occur on the entire disk and rather fuel its periphery. These cold streams pass without stopping through a hot gas halo and fall onto the disk. According to modern models [23], cold flows must dominate in low-mass (relative to the dark mass of clusters and groups of galaxies) halos at all redshifts starting from $z = 5-6$. This means that there has been no effective gas accretion from outside onto the *center* of the disk at any stage of galactic evolution. Therefore, the inside-out galaxy formation scenario in its classical formulation is now in conflict with both observations and the cosmological theory. Clearly, the time for its cardinal revision is coming.

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Dark components of the Universe

V V Burdyuzha

1. Dark energy

The multiverse, an internally growing fractal, is the new cosmological paradigm. The multiverse includes a large number of parts (universes) with different coupling constants, masses of fundamental particles, and other natural constants. Our Universe, whose age is about 14 Gyr, is one of them. During this time, the Universe has gone through a number of stages, including inflation, reheating, the radiation-dominated stage, and the matter-dominated stage, and is now in the vacuum-dominated stage. Starting from the redshift $z \sim 0.7$, the Universe is expanding with acceleration (at larger redshifts, the expansion decelerates).[1] The content of the Universe is also enigmatic. Baryons amounts to only 4% of the total density Ω_{tot}, dark matter (Ω_{DM}) contributes 23% to the total density, and the remaining 73% of the total density is due to dark energy (Ω_{DE}):

$$\Omega_{\text{tot}} = \Omega_{\text{b}} + \Omega_{\text{DM}} + \Omega_{\text{DE}} = 0.04 + 0.23 + 0.73\,,$$

$$\Omega_i = \frac{\rho_i}{\rho_{\text{cr}}}\,, \qquad \rho_{\text{cr}} = \frac{3H_0^2}{8\pi G_{\text{N}}}\,,$$

where H_0 is the present-day value of the Hubble constant and G_{N} is the Newton gravitational constant.

Unfortunately, the nature of these components remains currently unknown, and they are therefore referred to as dark components, although more than a dozen models have been proposed for each of them. Very probably, dark energy is the vacuum. In this case, the cosmological constant, Λ-term, vacuum energy, and dark energy are identical notions. But in any case, it is better to start from the fundamental Einstein equations

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = -8\pi G_{\text{N}} T_{\mu\nu}\,, \qquad G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}\,R g_{\mu\nu}\,. \tag{1}$$

Einstein introduced the cosmological constant Λ as a property of space. If the Λ term is placed in the right-hand side of the equations, then it can be treated as a form of energy, called dark energy (DE):

$$G_{\mu\nu} = -8\pi G_{\text{N}} T_{\mu\nu} + \Lambda g_{\mu\nu}\,. \tag{2}$$

The modern value of the DE density is

$$\rho_{\text{DE}} = \rho_\Lambda \sim 10^{-47}\ \text{GeV}^4 \approx 0.7 \times 10^{-29}\ \text{g cm}^{-3}\,,$$
$$\text{for}\quad H_0 = 70.5\ \text{km s}^{-1}\ \text{Mpc}^{-1}\,. \tag{3}$$

[1] Presently, the redshift is $z = 0$, while at the time of the birth of the Universe, $z = \infty$.

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In the Planck era, this energy density was

$$\rho_\Lambda \sim 2\times10^{76}\ \mathrm{GeV}^4\ (\approx 0.5\times10^{94}\ \mathrm{g\ cm}^{-3})\quad \text{for}\quad M_{\mathrm{Pl}} = 1.2\times10^{19}\ \mathrm{GeV}\,, \tag{4}$$

which is 123 orders of magnitude larger than the DE density presently observed. This unexplained difference of 123 orders of magnitude gave rise to a crisis in physics, although, of course, many ways to overcome this problem have been proposed (see [1–5]).[2]

Here, it is relevant to recall the definition of the vacuum and its properties. In classical physics, the vacuum is the world without particles, and this world is flat. In quantum physics, the vacuum includes vacuum condensates resulting from relativistic phase transitions. In geometrical physics, the vacuum is a state in which the space–time geometry is nondeformed. A more general definition of the vacuum is as follows: a stable state of quantum fields without excitations of wave modes (nonwave modes represent condensates). The vacuum equation of state is $p = -\rho$. Hence, setting $w \equiv p/\rho$, we have the following cases:

if $w = -1$, the state is called the vacuum proper;
if $w > -1$, the state is called quintessence (scalar field);
if $w < -1$, the state is called phantom energy.

The last observational data obtained by the WMAP (Wilkinson Microwave Anisotropy Probe) satellite [6] suggest $-0.14 < 1 + w < 0.12$ at 95% confidence level (CL). A more precise value of the Hubble constant $H_0 \sim 70.5\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ was also inferred from these new data.

The vacuum in the Universe (as follows from its definition) is a combination of a large number of mutually dependent vacuum subsystems, including the gravitational condensate, the Higgs condensate, and the quark–gluon condensate. Other condensates with the energy in the range $265\ \mathrm{GeV} < E < 10^{19}$ GeV are, unfortunately, poorly understood. The problem is how they are related and with what weight they contribute to the total vacuum energy, which can be defined as

$$\Lambda = \Lambda_{\mathrm{QF}} + \Lambda_{\mathrm{GVC}}\,, \tag{5}$$

where Λ_{QF} are quantum field condensates and Λ_{GVC} is the gravitational vacuum condensate — a new vacuum structure [7] including topological defects of different dimensions, such as wormholes (three-dimensional defects), micromembranes (two-dimensional defects), and point-like monopole defects. Of course, higher-dimensional microdefects are also present in this condensate. Three-dimensional microdefects (wormholes) explicitly contribute to the total vacuum energy density, i.e., renormalize the Λ term:

$$\Lambda = \Lambda_0 - \frac{\kappa\hbar^2 c_3^2}{768\pi^2}\,, \tag{6}$$

where κ is the gravitational constant in the system of units where $c = 1$ and $\hbar = 1$, and c_3 is a coefficient parameterizing the function $\mu(a)$ (see paper [7] for more details). Equation (6) gives the first indication of the presence of a compensation mechanism in the vacuum of our Universe, because three-dimensional topological defects decrease the Λ-term. As the temperature decreased, the condensates of other quantum fields also made negative contributions to the positive vacuum energy density (as the temperature was decreasing, the Universe lost its symmetry by forming condensates). The compensation hypothesis seems to have been first proposed by A D Dolgov.

We emphasize the profound meaning of the observed 'smallness' of the cosmological constant. A universe with a large negative Λ never becomes macroscopic (in order to give physical meaning to these statements, Λ-antigravity can be considered). In a universe with a large positive Λ, complex nuclear, chemical, and biological structures would be absent (because there would not be enough time for their formation).

But we continue discussing the compensation hypothesis and traces of relativistic phase transitions. Their plausible chain can be given by

$$\begin{aligned} \mathrm{P} &\underset{10^{19}\ \mathrm{GeV}}{\Rightarrow} \mathrm{D}_4 \times [\mathrm{SU}(5)]_{\mathrm{SUSY}} \\ &\underset{10^{16}\ \mathrm{GeV}}{\Rightarrow} \mathrm{D}_4 \times [\mathrm{U}(1)\times\mathrm{SU}(2)\times\mathrm{SU}(3)]_{\mathrm{SUSY}} \\ &\underset{\sim(10^5\text{–}10^{10})\ \mathrm{GeV}}{\Rightarrow} \mathrm{D}_4 \times \mathrm{U}(1)\times\mathrm{SU}(2)\times\mathrm{SU}(3) \\ &\underset{100\ \mathrm{GeV}}{\Rightarrow} \mathrm{D}_4 \times \mathrm{U}(1)\times\mathrm{SU}(3) \underset{0.15\ \mathrm{GeV}}{\Rightarrow} \mathrm{D}_4\times\mathrm{U}(1)\,, \end{aligned} \tag{7}$$

where only the last two phase transitions can be specified in detail because they are well studied (these energies can be reached by current accelerators):

$$\Lambda_{\mathrm{QF}} = \Lambda_{\mathrm{EW}} + \Lambda_{\mathrm{QCD}}\,; \qquad \rho_{\mathrm{QF}} = -\rho_{\mathrm{EW}} - \rho_{\mathrm{QCD}}\,. \tag{8}$$

The electroweak (EW) phase transition occurred at the temperature about 100 GeV and was accompanied by the appearance of the Higgs condensate, which also contributed to decreasing the vacuum energy:

$$\rho_{\mathrm{EW}} = -\frac{m_{\mathrm{H}}^2 m_{\mathrm{W}}^2}{2g^2} - \frac{1}{128\pi^2}\left(m_{\mathrm{H}}^4 + 3m_{\mathrm{Z}}^4 + 6m_{\mathrm{W}}^4 - 12m_{\mathrm{t}}^4\right). \tag{9}$$

The first term in the right-hand side of Eqn (9) is the energy density of the semiclassical Higgs condensate, the second term is the vacuum polarization by quantum fields, m_{H}, m_{Z}, m_{W}, and m_{t} are masses of the Higgs boson, Z and W bosons, and the t quark, and g is the coupling constant. The boson contribution in formula (9) is negative, while the fermion one (t quark) is positive. Because the values of all constants (except the Higgs boson mass) are known, the vacuum stability condition can be derived: in the Standard Model (SM), the mutual compensation of positive and negative contributions to the vacuum energy density is prohibited by the stability condition! Therefore, the statement about a vacuum energy decrease by symmetry breaking in the evolution of the Universe due to relativistic phase transitions is related to the vacuum stability condition and apparently bears a universal character. For the Higgs boson mass $m_{\mathrm{H}} \sim 2m_{\mathrm{W}} \sim 160$ GeV,

$$\rho_{\mathrm{EW}} \sim -(120\ \mathrm{GeV})^4\,, \tag{10}$$

and there is little doubt that the Higgs boson will be discovered with the Large Hadron Collider.

The nonperturbative quark–gluon condensate is an element of theory incorporated into the SM. Studying quantum chromodynamics (QCD) equations has shown that the phenomenon of confinement occurs if quantum correla-

[2] A fresh look at the cosmological constant problem was suggested in recent review [5].

tors of quark–gluon fields are nonzero. The quark–gluon condensate is a system of mutually correlated nonperturbative fluctuations resulting from quantum topological tunnel transitions between degenerate states of the gluon vacuum [8]. The energy density of this condensate is

$$\rho_{\mathrm{QCD}} = -\frac{b}{32}\left\langle 0\left|\frac{\alpha_{\mathrm{s}}}{\pi}\, G^a_{ik}G^{ik}_a\right|0\right\rangle , \tag{11}$$

where $b = 9 + 8T_g(m_{\mathrm{u}} + m_{\mathrm{d}} + 0.8m_{\mathrm{s}}) \approx 9.6$, $T_g = (1.5\,\mathrm{GeV})^{-1}$ is the characteristic space–time scale of fluctuations, and m_{u}, m_{d}, and m_{s} are masses of u, d, and s quarks. The principal energy parameter of the quark–gluon condensate is

$$u^4 = \left\langle 0\left|\frac{\alpha_{\mathrm{s}}}{\pi}\, G^a_{ik}G^{ik}_a\right|0\right\rangle \approx (360\ \mathrm{MeV})^4 .$$

According to the modern paradigm, the quark–gluon condensate has several phase states, in each of which fluctuations have a specific microstructure. As a result, we have

$$\rho_{\mathrm{QCD}} = -\frac{b}{32}\, u^4 \approx -(265\ \mathrm{MeV})^4 . \tag{12}$$

The quark–hadron phase transition alone suppresses more than 10 orders ($120^4/0.265^4 \sim 4\times10^{10}$) of the total vacuum energy decrease (more than 78 orders of magnitude) by vacuum condensates:

$$\left(\frac{M_{\mathrm{Pl}}}{M_{\mathrm{QCD}}}\right)^4 = \left(\frac{1.2\times10^{19}}{0.265}\right)^4 \approx 4.5\times10^{78} . \tag{13}$$

It is therefore quite plausible that the Universe lost more than 78 orders during the first 10^{-5} s of its evolution. The QCD phase transition was the last in the sequence of phase transitions and was a specific marker. The point is that the chiral $\mathrm{SU}(3)_{\mathrm{L}}\times\mathrm{SU}(3)_{\mathrm{R}}$ symmetry was not exact, and pseudo-Goldstone bosons are a physical realization of this symmetry breaking at $E \sim 265$ MeV.[3] Many years ago, D A Kirzhnits drew my attention to the fact that π-mesons are pseudo-Goldstone bosons. Therefore, π-mesons, being the lightest particles of the octet of pseudo-Goldstone states, characterize the ground state. In this case, the vacuum is the ground state. More than 40 years ago, from dimensional considerations, Zel'dovich [9] derived a formula for calculating the Λ-term (the formula was slightly modified by N S Kardashev), according to which the cosmological constant is the sum of zero oscillations of quantum fields, i.e., the vacuum energy:

$$\Lambda = 8\pi G_{\mathrm{N}}^2 m_\pi^6 h^{-4}\ [\mathrm{cm}^{-2}] , \qquad \rho_\Lambda = G_{\mathrm{N}} m_\pi^6 c^2 h^{-4}\ [\mathrm{g\ cm}^{-3}] , \tag{14}$$

and the vacuum condensate of the last phase transition can then be calculated as

$$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{\mathrm{cr}}} = \frac{\Lambda c^2}{3H_0^2} , \qquad \rho_{\mathrm{cr}} = \frac{3H_0^2}{8\pi G_{\mathrm{N}}} . \tag{15}$$

For the average π-meson mass $m_\pi = 138$ MeV and $H_0 = 70.5$ km s^{-1} Mpc^{-1}, we find $\Omega_\Lambda \approx 0.73$. The last value is almost equal to the observed dimensionless vacuum energy density $\Omega_\Lambda \approx 0.726 \pm 0.015$ obtained by the WMAP collaboration [6]. In other words, we can say that the vacuum energy at that time (10^{-5} s) was 'quenched' after the abrupt compensation by quantum field condensates.

But it remains to 'suppress' (during about 14 Gyr) almost 44 orders of magnitude to reach the present-day value of the vacuum energy (DE) density

$$\rho_{\mathrm{DE}} \sim (1.8\times10^{-12}\ \mathrm{GeV})^4 \quad \left(\left(\frac{0.15}{1.8\times10^{-12}}\right)^4 \sim 5\times10^{43}\right) . \tag{16}$$

Over this huge time period, the vacuum energy must have changed, because new quantum states had to be created in the expanding Universe at the expense of decreasing its energy. But during this period, the rate of the vacuum energy change was 10^{57} times smaller than during the quantum period of its evolution. To understand the 'recent' changes in the vacuum energy from 0.15 GeV to 1.8×10^{-12} GeV, we consider the holographic principle introduced by 't Hooft [10].[4] According to this principle, the 'physics' of a three-dimensional system can be described by a theory formulated on its two-dimensional boundary. Using the anti-de Sitter space–time, J Maldacena and E Witten showed that the description of the Universe by superstring theory corresponds to its description by quantum field theory formulated on its boundary. However, this example appears unconvincing, because our space–time is the de Sitter space–time. But we consider this problem at a greater depth, because there is a holographic limit on the number of the degrees of freedom that can exist inside a bounded surface. Bekenstein showed [11] that the entropy of a black hole is proportional to 1/4 of its horizon area expressed in Planck units. Therefore, if one bounds our Universe and wants to measure this 'boundary,' as proposed in [12], also in Planck units, then the vacuum energy density in the holographic limit is expressed by the simple formula

$$\rho_{\mathrm{DE}} = \frac{3M_{\mathrm{Pl}}^4}{8S} , \tag{17}$$

where $S \leqslant \pi R^2 M_{\mathrm{Pl}}^2$ is the entropy of the Universe. For $R = 10^{28}$ cm, $\rho_{\mathrm{DE}} \sim 10^{-57}$. In this formula, the entropy is proportional to 1/4 of the area of the 'surface' of the Universe. In fact, this derivation is called the Fischler–Susskind holographic conjecture [12].

It is also important to discuss the applicability of the holographic approach and to show how the remaining 44 orders of magnitude can be suppressed. As noted by 't Hooft [10], the entropy bound yields an upper limit on the mean energy density in the Universe. The physics here is as follows: new quantum degrees of freedom are generated as the area of the Hubble horizon increases, and their continuous creation requires some energy expenditure (see paper [12] for more details about the holographic approach in cosmology; it is noted there that general relativity (GR) is an illuminating example of the holographic theory). However, the holographic approach appears relevant as far as GR is applicable. Quantum theory in its present state is not a holographic theory. Using these 'arguments,' we make a numerical

[3] The QCD phase transition started at $E \sim 265$ MeV and ended at $E \sim 150$ MeV.

[4] All previous physical principles, including the Pauli principle, the equivalence principle, the relativity principle, and the Heisenberg uncertainty principle have led to significant progress in physics.

estimate. The holographic approach can possibly be used after a series of relativistic phase transitions, starting from the 'quenching' of the vacuum energy at $E \sim 150$ MeV, $t \sim 10^{-5}$ s, and $R \sim 3 \times 10^5$ cm (where R is the causality horizon at that time). The present-day size of the Universe is $R \sim 10^{28}$ cm, and the vacuum energy has lost around 45 orders of magnitude due to creation of new quantum states,

$$\left(\frac{10^{28}}{3 \times 10^5}\right)^2 \approx 10^{45}\,, \tag{18}$$

or even more if the causality horizon was smaller than 10^5 cm at the instant of quenching.

Summarizing the above arguments, we note that in the early Universe when the energy decreased from 10^{19} GeV to 150 MeV, quantum field condensates compensated 78 orders of magnitude of the initial vacuum energy density over the time period of only 10^{-5} s. Then in the next 14 Gyr ($\approx 4 \times 10^{17}$ s), the vacuum component lost another 45 orders of magnitude of its energy density due to the creation of new quantum states in the expanding Universe. This means that 123 orders of magnitude of the vacuum energy density were lost in ordinary physical processes.

However, we now discuss some considerations related to maverick statements that the black hole thermodynamics follow from the thermal nature of the Minkowski vacuum and the Einstein equations have a thermodynamic origin [13], i.e., these equations represent the equation of state of the Universe. The link established by Bekenstein between gravity and thermodynamics is extremely interesting because the Einstein equation is a second-order hyperbolic differential equation for the space–time metric, and thermodynamics is apparently irrelevant. But the point is that the Universe expands (with acceleration) and gradually cools down, and hence we here have a different physical situation, because nonequilibrium thermodynamics is applicable. The Klausius relation $\mathrm{d}S = \delta Q/T$ can be applied, where the entropy $\mathrm{d}S$ is equal to $1/4$ of the area of the horizon, δQ is the energy flux through the horizon, and T is the Unruh temperature seen by an accelerating observer inside the horizon [13]. The ideological foundation underlying these considerations is the statement that gravity on macroscopic scales is the manifestation of the thermodynamics of the vacuum. New quantum states are created in the Universe at the expense of the energy of the vacuum, and Eqn (17) is the Friedman equation.

Summarizing this part of the talk, we can argue that a satisfactory numerical difference between the vacuum energy density at the Planckian time and the present time could be realized if the compensation hypothesis and holographic approach are used to suppress 123 critical orders of magnitude due to phase transitions and the creation of new quantum states.

In addition, we also note that dark energy more and more 'gives way' to vacuum energy, as follows from the recent experimental results obtained by the WMAP collaboration [6] mentioned above.

2. Dark matter

The situation with dark matter (DM), another component of our Universe, with the density $\Omega_{\mathrm{DM}} \sim 0.23$, is equally intriguing. As early as 1933, Swiss astrophysicist Fritz Zwicky, who was working in the USA at a large telescope, recognized that a galaxy cluster in Coma Berenices (the Coma cluster) cannot be gravitationally bound unless an additional mass is present, which later was called dark mass. In recent decades, it has become clear that dark matter in our Universe is much more abundant than the visible matter ($\Omega_{\mathrm{stars}} \sim 0.005$) and baryonic matter ($\Omega_{\mathrm{b}} \sim 0.04$). A new field has even emerged, DM cosmology, whose main goal is to understand the nature of DM particles. Formally, this component of the Universe can have a baryonic nature. For example, it might consist of underformed 'Jupiter' stars, whose mass is too small for thermonuclear reactions to begin, or other baryonic structures, including black holes and white dwarfs. In particular, as stressed in review [14], more than half of dark matter can be baryonic. In addition, the Universe can harbor nonradiating remnants of black holes with the Planck mass (10^{-5} g), and, possibly, preonic stars with $M \sim 10^2 M_{\oplus}$ (the Earth mass is $M_{\oplus} \sim 6 \times 10^{27}$ g) [15]. In the EROS-2 experiment (from the French Expérience pour la Recherche d'Objets Sombres) [16], the masses of massive astrophysical compact halo objects (MACHOs) were measured by microlensing 25 mln stars in Magellanic Clouds: $M_{\mathrm{MACHO}} \sim (10^{-2} - 10^{-6}) M_{\odot}$ (the mass of the Sun $M_{\odot} \approx 2 \times 10^{33}$ g). Omitting the details, we note that the baryonic component must necessarily be present in dark matter because $\Omega_{\mathrm{b}} \sim 0.04$ and $\Omega_{\mathrm{stars}} \sim 0.005$.

We note that a 'mad' hypothesis was proposed in [17] that the Standard Model can have an infinite number of replicas, and then the presence of baryons in hidden replicas can naturally explain dark matter. In that model, gravity is strong already at 1 TeV energies and the number of copies of dark baryons can be enormous:

$$10^{11} \leqslant N \leqslant 10^{32}\,. \tag{19}$$

This large number of copies became 'possible' by virtue of a new permutation symmetry introduced in [17]. This also involves another interesting point: inflation occurs due to the inflaton pertaining to our copy of the SM, while reheating after inflation is mediated by a modular field that is common for all copies. Nonbaryonic dark matter must consist of stable particles or these particles must have lifetimes exceeding the age of the Universe. Such particles primarily include neutrinos, neutralinos, and axions.

Of course, there are other models for dark matter, including the hypothetical Kaluza–Klein dark matter. Such dark matter can annihilate to produce charged leptons, which could be responsible for the electron–positron asymmetry in cosmic rays observed in PAMELA (Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics) and ATIC (Advanced Thin Ionization Calorimeter) experiments [18]. Nonbaryonic particles of dark matter can be cold (CDM) or hot (HDM) [19]:

$$\Omega_{\mathrm{CDM}} \sim 0.223 \pm 0.016\,, \qquad \Omega_{\mathrm{HDM}} \sim 0.0152\,. \tag{20}$$

We recall that if these particles at the time of formation (quenching) had relativistic or nonrelativistic velocities, then they are HDM or CDM particles, respectively. For example, a light neutrino is an HDM particle.[5] The discovery of neutrino oscillations was a watershed in our understanding of the nature of the neutrino. This discovery brought the physics of neutrinos into the focus of the physics community, because it became clear that neutrinos have mass (even the industry of neutrino oscillations emerged; see, e.g., http://

[5] Neutrinos with a mass above 1 GeV are already CDM particles.

neutrinooscillation.org). The small neutrino masses confirmed theoretical expectations of the early 1980s that the so-called 'see-saw' mechanism induces both light and superheavy neutrinos; however, some 'neutrino challenges' remain for the future. They include the CP-violation amplitude in neutrino oscillations, the existence of neutrinoless β-decay (in which case the neutrino is a Majorana particle), and the absolute scale of neutrino masses. The data on neutrino oscillations are summarized in [20] at the 3σ level:

$$\Delta m^2_{2,3} = (1.4-3.3)\times 10^{-3}\ \mathrm{eV}^2\,, \qquad (21)$$
$$\Delta m^2_{1,2} = (7.2-9.1)\times 10^{-5}\ \mathrm{eV}^2\,.$$

We also mention new long-based oscillation experiments, such as MINOS (Main Injector Neutrino Oscillation Search), CNGS (CERN Neutrinos to Gran Sasso), ICARUS (Imaging Cosmic And Rare Underground Signal), and OPERA (Oscillation Project with Emulsion-tRacking Apparatus), which will 'hunt' for $\nu_\mu \to \nu_e$ oscillations [21].

Cosmological constraints are sensitive to all three neutrino mass flavors:

$$\sum_i m_i \leqslant 0.2-1.7\ \mathrm{eV}\ (95\%\ \mathrm{CL}), \qquad (22)$$

but cosmology does not provide values of mixing angles or possible CP-violations. Cosmological bounds can be obtained from the WMAP data on the CMB anisotropy, from the large-scale distribution of galaxies in the Sloan Digital Sky Survey (SDSS), from the Hubble Space Telescope (HST) observations, and from measurements of remote type-Ia supernovae. A new cosmological bound on neutrino masses was recently obtained in [23]: $m_\nu < 1.05$ eV. Experiments on the β-decay of tritium in [24] give the following limit on the electron antineutrino mass:

$$m_{\bar\nu} < 2.05\ \mathrm{eV}\,. \qquad (23)$$

The KATRIN (KArlsruhe TRItium Neutrino) collaboration promises to measure the neutrino mass with a sensitivity of 0.25 eV [25]. There are interesting prospects in the neutrinoless β-decay ($\beta\beta_{0\nu}$), in which the effective Majorana neutrino mass is

$$m_{\mathrm{M}}^{\mathrm{eff}} \leqslant 0.3-1\ \mathrm{eV}\,. \qquad (24)$$

We note that the lepton number conservation must be violated in the neutrinoless double β-decay, and therefore its detection will be a direct manifestation of supersymmetry, because the lepton number nonconservation (like the baryon number nonconservation) is a key prediction of supersymmetric (SUSY) theories.

All neutrino research groups are huge collaborations of different specialists. Neutrino fluxes from the Sun and even from supernovae are observed and measured by different methods in deep mines (Sudbury Neutrino Observatory in Canada, Baksan Neutrino Observatory in Russia, Boulby Mine Laboratory in the UK, National Laboratory Gran Sasso in Italy, Kamioka in Japan), in nuclear reactor experiments, and in secondary cosmic ray cascades. The general conclusion is that the main component of HDM,[6] neutrinos, provides a certain nonnegligible contribution to the dark matter density ($n_\nu \sim 112\ \mathrm{cm}^{-3}$ per neutrino flavor).

[6] Sterile neutrinos, as well as gravitinos, are warm dark matter.

We now consider the principle CDM components of dark matter, such as the neutralino and axion (these particles come from an extension of the Standard Model). These are more exotic particles than neutrinos, but they should not stay in this category for a long time.

The neutralino χ is a weekly interacting massive particle (WIMP) that could have originated in the early Universe if supersymmetry took place. Supersymmetry can naturally solve the dark matter problem because in most minimal SUSY models, the lightest superpartner is absolutely stable due to the conservation of a multiplicative quantum number (the R-parity). Probably, superparticles born in pairs in the early Universe rapidly decayed to form the lightest supersymmetric particles in addition to ordinary particles. They must be noncharged and not strongly interacting in order to not violate the Big Bang Nucleosynthesis (BBN). These requirements are satisfied for the neutralino, which is described by a Majorana spinor. The wave function of the neutralino is given by a superposition of wave functions of four supersymmetric particles: two gauginos and two higgsinos. If neutralinos build up the halo of our Galaxy, then their number density is [26]

$$n_\chi \sim \frac{0{,}3}{m_\chi\ \mathrm{GeV}}\ [\mathrm{GeV\ cm}^{-3}]\,. \qquad (25)$$

As noted in [14], neutralinos in the halo of our Galaxy (and, naturally, in halos of other galaxies) could form small-scale ($R \sim 10^{14}-10^{15}$ cm) hierarchical objects and even neutralino stars. Neutralinos could be observed by their decay products during annihilation. Seven (!) underground laboratories are searching out searches for the annihilation products. The neutralino annihilation signal falls in the energy range 100–200 GeV (energies available with the LHC), and the neutralino contribution to the total density of the Universe is

$$0.1 < \Omega_\chi < 0.3\,, \quad \text{if}\ \ 5\times 10^{-8} < \sigma_\chi < 5\times 10^{-10}\ \mathrm{pb} \qquad (26)$$

($1\ \mathrm{pb} \equiv 10^{-36}\ \mathrm{cm}^2$). Searches for neutralinos are being carried out by different neutrino research groups, such as SuperKamiokande, Baykal, Ananda, Baksan, and ANTARES (Astronomy with Neutrino Telescope and Abyss environmental RESearch) in the Mediterranean Sea.

The axion was postulated more than three decades ago to explain the P- and CP-symmetry conservation in strong interactions, although these symmetries are violated in the Standard Model (in the electroweak sector). Peccei and Queen [27] proposed solving the strong CP problem by introducing a new global symmetry $\mathrm{U_{PQ}}$. Then axions appear as Nambu–Goldstone bosons associated with spontaneous breaking of this symmetry. The axion has zero spin, zero electric charge, and negative internal parity. The mass of the axion is

$$m_{\mathrm{a}} \sim 6\times 10^{-6}\,\frac{10^{12}}{f_{\mathrm{a}}}\ [\mathrm{eV}]\,, \qquad (27)$$

and if the free coupling constant is $f_{\mathrm{a}} < 10^{12}$ GeV, the density of axions does not exceed the critical density in the Universe. In this case, $m_{\mathrm{a}} \sim 10^{-5}$ eV. This particle could have been formed during the QCD phase transition in the very early Universe. Axions can be detected in laboratory by stimulating their conversion into two microwave photons by a strong magnetic field [28]. The ADMX (Axion Dark Matter eXperiment) is aimed at registering relic axions. In a pilot search carried out by the ADMX collaboration, no axions were found in the mass range 1.98–2.17 μeV [29].

We note another important fact, which has no direct relation to the discussed problems, but is related to axions, more precisely, to familons [30]. If the next fundamental level of matter (preons) is discovered, the role of particle generations will be more transparent. The first particle generation composes our baryon world. The account for symmetry between generations (due to their mere existence) produces all dark matter. Therefore, particles (familons) that appear from symmetry between generations can explain structurization of dark matter and the subsequent structurization of baryons.

In a familon medium, a phase transition could occur that quenched the fractality (fractality is the prerogative of phase transitions only), and baryons would then reproduce the dark matter distribution. In that case, the fractality of the large-scale baryon structure can be naturally explained. We must also mention studies on the possible interaction of dark energy and dark matter (see [31] and the references therein), as well as $f(R)$ gravity studies (see [32] and the references therein), which are directly related to dark matter.

Other models for dark matter, which we did not discuss in detail here, include sterile (supersymmetric) neutrinos, gravitinos, axinos, light scalar particles, light Higgs bosons, Kaluza–Klein dark matter, superheavy dark matter (simpzillas), nontopological solitons (Q-balls), charged massive particles (CHAMPS), weakly interacting dark matter (SWIMPS), braneworld dark matter, heavy neutrinos of the fourth generation, and mirror particles. The list of exotic dark matter candidates was presented, for example, in the talk by J Colar at the Schramm memorial symposium in December 2005.

To conclude, we note that our main result is the explanation of the huge difference (123 orders of magnitude) between the vacuum energy density at the birth of the Universe and that at the present time, which initiated a long-lasting crisis in physics. In our paper [33], the vacuum density was calculated for redshifts ranging from $z = 0$ to $z = 10^{11}$ using the 'cosmological calculator' [34]. Apart from that, we have recognized why three particle generations are needed in our Universe. But such a 'recognition' invokes the next fundamental (preonic) level of matter. Then the first generation of particles forms the observed baryonic world, and the account of symmetry between generations yields all dark matter.

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