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Hierarchies of fundamental constants (to items Nos 16, 17, and 27 from Ginzburg's list)

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Contents

Abstract. **Current understanding of major unsolved problems in particle physics and cosmology suggests that physics is facing serious challenges and that the existing view of how the laws of Nature work may possibly (though not necessarily) be substantially extended in the near future. From this standpoint, experiments at the LHC proton collider due to start shortly at CERN are going to make a crucial impact.**

1. Introduction

The problems from Vitalii Ginzburg's list that we are going to discuss relate, on the one hand, to the physics of elementary particles (Standard Model, Grand Unification, Super-grand Unification, particle interactions at high energies, etc.) and, on the other hand, to cosmology (the problem of dark matter; I would also add here the problem of dark energy). The present stage of developing these fundamental fields of natural science is quite peculiar. Long-term efforts by scientists working in high-energy physics (in the broad sense) have established properties of elementary particles and their interactions up to energies and masses [1] of the order of 100 GeV and distances 10^{-16} cm. At the same time, the rapid advance in cosmology (observational, first and foremost) has led to an understanding of the properties of the early Universe and its subsequent evolution both qualitatively and quantitatively with good accuracy.

[1] Below, we use the system of units in which, as accepted in particle physics, the speed of light in vacuum and the Planck constant are set equal to unity: $c = \hbar = 1$. In this system, the mass (rest energy) of a proton equals about 1 GeV.

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Nevertheless, the above problems remain unsolved. Moreover, the modern understanding of these issues leads to the conclusion that fundamental physics is facing quite new questions and it appears that (possibly!) our concepts of the laws of Nature will be substantially and radically complemented in the nearest future.

Two kinds of arguments point to such a possibility. First, to interpret cosmological observations, it is necessary to invoke hypotheses going beyond known concepts of the physics of elementary particles and their interactions; moreover, even using new hypotheses, some properties of the Universe (more precisely, its observable part) cannot be explained satisfactorily but look like chance coincidences. Other arguments come from particle physics itself, where there are hierarchies — differences by several, and sometimes by many, orders of magnitude — between fundamental physical constants which are understood in the broad sense as dimensionless parameters of theory. No reliable, experimentally tested explanation of these hierarchies has been found so far, and some of them cannot be explained even using hypotheses of any degree of plausibility.

The aim of this contribution is to briefly present some of these considerations, to explain which conclusions they suggest, and to discuss to what extent these conclusions can be confirmed by future experiments. From this viewpoint, experiments at the forthcoming proton – proton LHC collider at CERN with a colliding proton energy of 7×7 TeV are going to make a crucial impact. These experiments will probe a new energy range around 1 TeV and even beyond. LHC is due to start in 2007 – 2008, so that the situation must be elucidated in the nearest future. This is another salient feature of the modern development of fundamental physics.

2. Hierarchies in particle physics

All known elementary particles and their interactions, with the exception of neutrino oscillations, are described by a theory traditionally called the Standard Model of particle physics (see, for example, the monograph [1]). This theory is fairly simple. Figure 1 shows schematically its particles

Three particle families

Leptons $\binom{e}{\nu_e}$, $\binom{\mu}{\nu_\mu}$, $\binom{\tau}{\nu_\tau}$

Quarks $\binom{u}{d}$, $\binom{c}{s}$, $\binom{t}{b}$

+ ANTIPARTICLES e^+: positron, . . .
$\bar{\nu}_e$: antineutrino, . . .
$\bar{u}$: antiquarks, . . .

+ particles responsible for interactions: photon, gluons, W-, Z-bozons, graviton + Higgs boson (not yet discovered).

Figure 1. Particles of the Standard Model.

interacting via electromagnetic (mediated by a photon), weak (mediated by W- and Z-bosons), and strong (mediated by gluons) forces. Strong interactions between quarks and gluons are described by quantum chromodynamics — a gauge theory based on the color group $SU(3)_c$, while electromagnetic and weak interactions unify into one electroweak interaction with the gauge group $SU(2)_W \times U(1)_Y$. It is important for further consideration that the theory has three gauge coupling constants α_3, α_2, and α_1 corresponding to three factors in the full gauge group $SU(3)_c \times SU(2)_W \times U(1)_Y$ (in fact, these constants are energy-dependent; see below). The electromagnetic interaction constant $\alpha = 1/137$ is the combination of α_1 and α_2.

The masses of quarks, charged leptons, and W- and Z-bosons are likely to emerge due to the Higgs mechanism. Namely, it is assumed that in addition to known fields in Nature there exists at least yet another field — scalar Higgs field that has a nonzero vacuum expectation value, the Higgs condensate, interaction with which leads to nonzero masses of particles. The situation here is in many respects similar to the appearance of the Meissner effect (the emergence of a 'mass' of magnetic field) as a result of the formation of the effective scalar field condensate in the Ginsburg–Landau model of superconductivity. In the Minimal Standard Model with one Higgs field there is only one additional particle, the Higgs boson, searching for which is one of the primary goals of the forthcoming experiments at large hadron collider (LHC) at CERN (see, for example, Ref. [2]). The vacuum expectation value of the Higgs field ϕ determines the characteristic energy and mass scale of the electroweak theory:

$$\Lambda_{EW} = \langle \phi \rangle = 247\ \text{GeV}\,. \tag{1}$$

The distinctions between masses of quarks, charged leptons, and W- and Z-bosons are due to different strengths of interactions of respective fields with the Higgs field: the mass of each particle is proportional to the corresponding dimensionless coupling constant with the Higgs field. These couplings are not equal to one another, hence different masses of the particles. In the Standard Model, these coupling constants are arbitrary parameters which are determined experimentally from measurements of particle masses (and mixing angles).

There is one more energy scale in the framework of the Standard Model. It characterizes strong interactions and is estimated as

$$\Lambda_{QCD} \approx 200\ \text{MeV}\,. \tag{2}$$

It is this scale that mainly determines the masses of particles [2] consisting of light quarks, for example, protons, neutrons, and ρ-mesons (see Ref. [3]). The scales Λ_{EW} and Λ_{QCD} in the Standard Model are independent, and their ratio could be arbitrary, in principle.

Of course, there is gravitational interaction in Nature, which is characterized by its own energy scale of the order of the Planck mass

$$M_{Pl} \approx 10^{19}\ \text{GeV}\,. \tag{3}$$

Clearly, energy scales for different interactions are distinct. This is the gauge hierarchy problem which can also be formulated as follows: Why are the strong and electroweak interaction scales fairly close to each other, while the gravitational interaction scale is so different from them?

In the Standard Model itself, there is no answer to this question: the Λ_{QCD}, Λ_{EW}, and M_{Pl} scales are completely independent. The traditional point of view on this issue is that the Standard Model is not a full theory, and the gauge hierarchies should naturally appear in a theory extending the Standard Model.

One of the most popular hypotheses explaining the small value of Λ_{QCD} with respect to M_{Pl} is the Grand Unification hypothesis. The latter assumes that at ultrahigh energies there is a unified gauge interaction which on a M_{GUT} scale not very different from M_{Pl} 'splits' into strong and electroweak interactions [the simple gauge group of a Grand Unified Theory is broken down to the group $SU(3)_c \times SU(2)_W \times U(1)_Y$)]. Such a splitting can also be caused by the Higgs mechanism but with a large vacuum expectation value of the Higgs field amounting to $\langle \Phi \rangle \sim M_{GUT}$. Of course, the field Φ should be included in the theory in addition to the Higgs field ϕ of the Standard Model.

In realistic models $M_{GUT} \sim 10^{16}$ GeV, which is indeed fairly close [3] to M_{Pl}. The gauge coupling constants are in fact not constants; they change with energy according to the renormalization group equations. At energies above M_{GUT}, there is a unified gauge coupling such that

$$\alpha_1 = \alpha_2 = \alpha_3\,, \qquad E \geqslant M_{GUT} \tag{4}$$

(assuming an appropriate definition of α_1, see the monograph [1] for more detail). For $E < M_{GUT}$, the gauge coupling constants α_1, α_2, and α_3 evolve differently as energy decreases, with equation (4) playing a role of the initial condition for the renormalization group evolution, as schematically shown in Fig. 2.

It is essential that this evolution be *logarithmic*, i.e., the gauge couplings change slowly with energy. In particular, the gauge coupling of strong interactions behaves as

$$\alpha_3(E) = \frac{\alpha_{GUT}}{1 + \hat{\beta}\,\alpha_{GUT}\,\ln\left(E/M_{GUT}\right)}\,, \tag{5}$$

where the constant $\hat{\beta}$ is determined by the content of colored particles with masses in the range $m < E$, and α_{GUT} is the

[2] The vacuum of quantum chromodynamics is characterized by quark and gluon condensates whose values are determined by the Λ_{QCD} scale. These condensates make the dominant contributions to the masses of particles consisting of light quarks.

[3] Note that there still exists the hierarchy between M_{GUT} and M_{Pl}, albeit not so dramatic as between Λ_{EW}, Λ_{QCD}, and M_{Pl}.

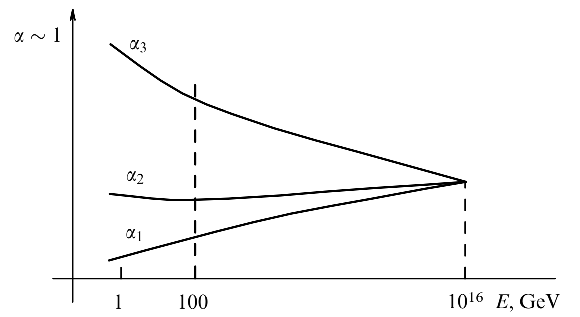

Figure 2. Behavior of gauge couplings with energy in Grand Unified Theories.

gauge coupling (common for all interactions) on the $M_{\rm GUT}$ scale, which is fairly small: $\alpha_{\rm GUT} \sim 1/20 - 1/40$, depending on the model. The constant $\hat{\beta}$ is positive, so that $\alpha_3(E)$ increases as energy decreases (and vice versa, decreases as energy increases, which corresponds to the asymptotic freedom of quantum chromodynamics). The $\Lambda_{\rm QCD}$ scale corresponds to the energy where the constant α_3 becomes of the order of unity and the quantum chromodynamics enters a strong coupling regime. Due to the logarithmic dependence in formula (5), this energy scale is *exponentially* small compared to the $M_{\rm GUT}$ scale:

$$\alpha_3(\Lambda_{\rm QCD}) \sim 1 \Longleftrightarrow \Lambda_{\rm QCD} = M_{\rm GUT} \exp\left(-\frac{\rm const}{\alpha_{\rm GUT}}\right). \quad (6)$$

The problem of hierarchy between $\Lambda_{\rm QCD}$ and $M_{\rm Pl}$ (more precisely, between $\Lambda_{\rm QCD}$ and $M_{\rm GUT}$) is elegantly solved in this mechanism.

The problem of hierarchy between $\Lambda_{\rm EW}$ and $M_{\rm Pl}$ can be solved in a similar way. In this case, the logarithmic variation with energy of the parameters in the Higgs sector is crucial. At the same time, *the relation between* $\Lambda_{\rm QCD}$ *and* $\Lambda_{\rm EW}$ *is of a random character*: the values of $\Lambda_{\rm QCD}$ and $\Lambda_{\rm EW}$ would differ exponentially without fine tuning of the parameters. Thus far, no natural mechanism providing the equality of the values of $\Lambda_{\rm QCD}$ and $\Lambda_{\rm EW}$ to within three orders of magnitude has been proposed.

The unification of gauge couplings, i.e., the fulfillment of the equality $\alpha_1 = \alpha_2 = \alpha_3$ on some $M_{\rm GUT}$ scale, is not automatic: three curves, generally, do not pass through one point. Such a unification is impossible without extending the particle content of the Standard Model. Thus, Grand Unification necessitates that the Standard Model be extended, and already at sufficiently low energies. The most popular extensions providing the gauge coupling unification include models with low-energy supersymmetry (see, for example, Refs [2, 4–6]), though there are other options such as split supersymmetry [7] or a model with additional isodoublet fermions [8]. Supersymmetric theories, unlike many other models, also provide the *stability* of the value of $\Lambda_{\rm EW}$, which is another problem of the Standard Model. This issue stands as follows. In general, there are radiative corrections to the square of the Higgs boson mass $m_{\rm H}$ and, correspondingly, to the square of the vacuum expectation value $\langle\phi\rangle$ of the Higgs field. Unlike other radiative corrections, they diverge quadratically and not logarithmically, so that radiative corrections to the electroweak scale have the following structure

$$\delta\Lambda_{\rm EW}^2 \sim \delta m_{\rm H}^2 = F(g)\,\Lambda_{\rm UV}^2\,, \quad (7)$$

where $F(g)$ is a certain combination of coupling constants of the theory, and $\Lambda_{\rm UV}$ is the ultraviolet cutoff parameter. In the Standard Model, one obtains

$$\delta m_{\rm H}^2 \approx 0.1\,\Lambda_{\rm UV}^2\,. \quad (8)$$

If one perceives the Standard Model as a full theory working up to the Planck scale and sets $\Lambda_{\rm UV} \sim M_{\rm Pl}$, the bare value of $m_{\rm H}^2$ should be fine tuned to cancel out the contributions (7) with an accuracy better than 10^{-32} to all orders of the perturbation theory (!).

This problem can be looked at from another perspective. Namely, let us suppose that the Standard Model is a part of a more fundamental theory with better ultraviolet behavior. More specifically, let us assume that in this more fundamental theory there are no quadratic ultraviolet divergences in $\delta m_{\rm H}^2$. Then, the scale of 'new physics' i.e., the mass scale of new particles, will serve as $\Lambda_{\rm UV}$. Indeed, up to these energies only the fields of the Standard Model contribute to $\delta m_{\rm H}^2$, and only at energies above $\Lambda_{\rm UV}$ are these contributions cancelled due to the 'new physics'. The estimate (8) indicates that the energy scale of the 'new physics', without assuming the fine tuning of the parameters, must be of order

$$\Lambda_{\rm UV} \sim 300\ {\rm GeV} - 1\ {\rm TeV}\,, \quad (9)$$

i.e., falls just in the LHC energy range. It is this argument that is behind the expectations that new particles and phenomena will be discovered at LHC, in addition to the Higgs boson.

Low-energy supersymmetry is one of the possible scenarios of the 'new physics'. In supersymmetric theories, quadratic divergences like those in formula (7) are cancelled out due to contributions from new particles — superpartners of the Standard Model particles. The above estimates suggest the masses of these particles to fall within the range from several hundred GeV to several TeV, which is readily accessible to LHC [2]. It should be stressed, however, that already existing experimental data substantially constrain the allowed range of parameters in the low-energy supersymmetry models. To illustrate this, in Fig. 3 we depict the whole region of theoretically admissible dimensionless parameters together with the allowed region [9] in one simple model, the so-called mSUGRA (from *minimal supergravity*). This model

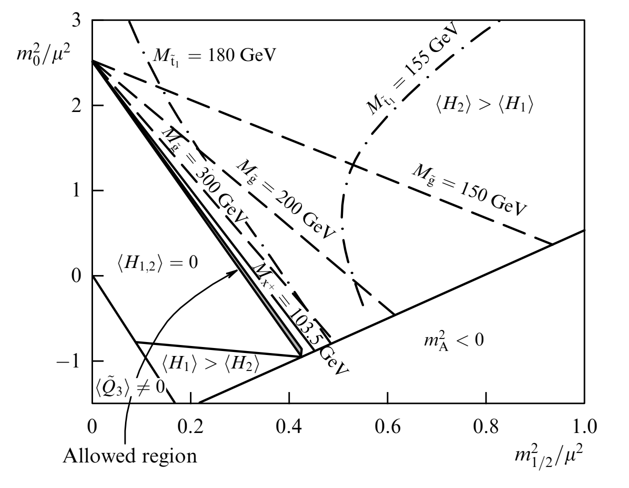

Figure 3. The allowed region of parameters [9] of the mSUGRA model. Experimental constraints excluding certain regions of parameters are shown.

has three additional parameters (with respect to the Standard Model) with the dimension of mass, namely, m_0, $m_{1/2}$, and μ. Looking at Fig. 3 makes it clear that the fact that supersymmetry has not been experimentally discovered so far is itself a problem for supersymmetric theories.[4] In this connection, intense efforts have been made recently to solve the problem of stability of the electroweak scale against radiative corrections, using ideas different from low-energy supersymmetry (see the reviews [10–12]); however, most models proposed so far cannot solve simultaneously the problem of hierarchy between $\Lambda_{\rm EW}$ and $M_{\rm Pl}$.

To conclude this section, we mention one more hierarchy problem that exists in both the Standard Model and its extensions. It has to do with the masses of known fermions — quarks and charged leptons. The mass of the heaviest fermion, the t-quark, is around 172 GeV, while the mass of the lightest, the electron, is around 0.5 MeV. Thus, we are dealing with a hierarchy[5]

$$\frac{m_{\rm e}}{m_{\rm t}} \sim 3\times 10^{-6}\,. \qquad (10)$$

In spite of numerous hypotheses, no convincing answer to the question as to the origin of this hierarchy has been found so far. Generally speaking, the values of the masses of quarks and charged leptons look fairly random; as a tendency one can note only the overall increase in these masses from one generation to another.

3. Dark matter and dark energy in the Universe

One of unexpected results obtained in the last one and a half decade or so is the recognition that known particles (protons, neutrons, nuclei, electrons, photons, and neutrinos) provide only 5% of the total energy in the present Universe. Most energy is due to dark matter (20–25%) and dark energy (70–75%) (Fig. 4). The behavior of these forms of energy is essentially different in the expanding Universe and they have totally different interpretations from the viewpoint of particle physics.

3.1 Dark matter

Dark matter is likely to consist of new, unknown particles (see the reviews [13]). These particles must be stable or have a lifetime comparable to the present age of the Universe, $t_{\rm U} \approx 14$ bln years. Such particles are absent in the Standard Model, so that the very notion of dark matter demands going beyond the Standard Model framework. Particles of dark matter share the same properties as ordinary particles with respect to gravitational interactions; they are capable of forming clumps (halos of galaxies and galaxy clusters) and producing gravitational potentials. Dark matter plays the key role in the formation of structures in the Universe — galaxies, their clusters, etc. Studies of these structures, as well as measurements of the anisotropy and polarization of the cosmic microwave background, suggest that dark matter particles were nonrelativistic already at very early stages of the cosmological evolution, this property being most likely (but not necessarily: the well-known exception here is axions) due to their sufficiently large masses. At the same time, dark matter particles have no electric charge and in general very weakly interact with matter, otherwise they would have already been detected in experiments designed to directly search for them.

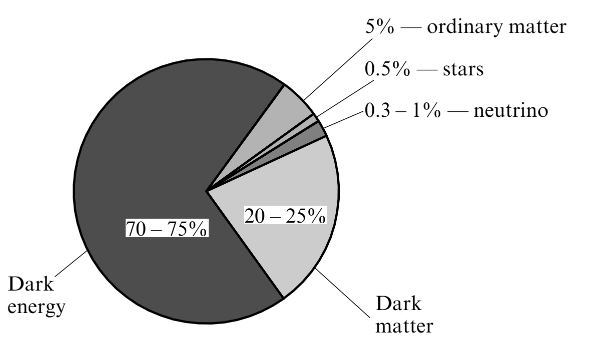

Figure 4. Energy balance in the modern Universe.

Let us consider the simplest and, hence, the most attractive mechanism of dark matter generation in the Universe. At temperatures in the early Universe comparable to the mass $m_{\rm DM}$ of dark matter particles[6], processes of pair creation and annihilation of these particles occurred intensively, so their number density was close to the equilibrium value.[7] As the temperature dropped, the number density of dark matter particles decreased due to annihilations and the expansion of the Universe. At $T \sim m_{\rm DM}/20$, the number density became so small that pair annihilations stopped, and since then the number density of dark matter particles has decreased only because of the expansion of the Universe.

The calculated mass density of dark matter in the present Universe depends very weakly (logarithmically) on $m_{\rm DM}$ and strongly (as $1/\sigma$) on the annihilation cross section. The required dark-matter mass density can be obtained if one assumes that the mass of a dark matter particle is estimated as $m_{\rm DM} \sim 10$ GeV – 1 TeV, and the strength of interaction of dark matter particles between themselves and with ordinary matter is comparable to the strength of weak interactions (pair annihilation into ordinary particles occurs with a cross section of about 10^{-35} – 10^{-36} cm^2). These masses and cross sections suggest the possibility of creating dark matter particles in proton collisions at LHC, as well as, in a certain range of parameters, of their direct and indirect registration in experiments aimed at searching for dark matter in our Galaxy. This scenario is realized in many models with low-energy supersymmetry, which indeed have stable neutral massive particles (neutralinos) as superpartners of known particles.

Of course, there are other hypothetical dark matter candidates (axions, gravitinos, supermassive particles, etc.). However, in most other scenarios the required dark-matter mass density in the Universe can be obtained only by fine

[4] This issue is called the little hierarchy problem in the literature.

[5] Fermion masses are proportional to dimensionless Yukawa coupling constants with the Higgs field, so that one can think of the hierarchy of these constants and not of the masses.

[6] Here, we use the system of units in which, in addition to $\hbar$ and c, the Boltzmann constant is set equal to unity, $k_{\rm B} = 1$. In ordinary units, we discuss temperatures for which $k_{\rm B}T \sim m_{\rm DM}c^2$.

[7] It is assumed that dark matter particles are not created and annihilated in other processes. This assumption is consistent with the requirement of their stability. Besides, if dark matter particles differ from their antiparticles (i.e., they are not absolutely neutral), an additional assumption is the absence of asymmetry in the dark matter sector, namely, it is assumed that the numbers of dark matter particles and antiparticles have been and are exactly the same.

tuning the model parameters. We stress that, in any case, generation mechanisms of dark matter and of matter–antimatter asymmetry in the Universe are quite different (except for some rather exotic scenarios like the scenario with the formation and subsequent decay of Q-balls [14]), so that *the approximate equality* (*to within one order of magnitude*) *between the ordinary matter mass density and the dark-matter mass density in the Universe appears to be accidental coincidence*. This fact is even more remarkable because dimensionless characteristics of the number density of baryons (protons and neutrons) and dark matter particles are very small: for baryons it is the ratio η_{B} of the baryon number density n_{B} to the number density n_γ of relic photons, which is independent of time (up to a factor of order unity):

$$\eta_{\mathrm{B}} \equiv \frac{n_{\mathrm{B}}}{n_\gamma} = 6 \times 10^{-10} \,. \tag{11}$$

The similar ratio η_{DM} for dark matter particles is also small; however, to within a factor of 5 in our Universe the following equality holds true:

$$\frac{\eta_{\mathrm{B}}}{\eta_{\mathrm{DM}}} \approx \frac{m_{\mathrm{DM}}}{m_{\mathrm{p}}} \,, \tag{12}$$

where m_{p} is the proton mass. As we have just noted, thus far no appealing mechanism explaining relationship (12) without the fine tuning of the parameters is known.

3.2 Dark energy

The gravitational properties of dark energy are strongly different from those of other forms of energy (see the reviews [15]). Dark energy does not concentrate in clumps, it is homogeneously spread across the Universe. The dark energy density changes very weakly or even does not change at all with time, while the number density of any particles relatively rapidly decreases due to the expansion of the Universe. The presence of dark energy leads to *accelerated* expansion of the Universe, so one can say that the dark energy experiences 'antigravity'. In the framework of general relativity this is possible if a given substance, in addition to positive energy, has negative pressure. The negative pressure also follows from the general relationship

$$\mathrm{d}E = -p\,\mathrm{d}V \,. \tag{13}$$

Indeed, if the energy density is constant or almost constant in time, then as the Universe expands the energy (in the comoving volume) increases with volume, so that the pressure must be negative and equal or almost equal in absolute value to the energy density. [8]

At the present time, possible forms of dark energy and their manifestation in cosmological observations are the subject of wide speculation. One possibility is that dark energy is a vacuum energy (or a cosmological constant, which is the same thing at least with the present understanding of the problem). Indeed, the Lorentz-invariance of a vacuum uniquely determines the form of its energy–momentum tensor (in a locally Lorentzian frame of reference):

$$T^{\mathrm{vac}}_{\mu\nu} = \varepsilon^{\mathrm{vac}}\,\eta_{\mu\nu} \,, \tag{14}$$

where $\varepsilon^{\mathrm{vac}}$ is a constant, and $\eta_{\mu\nu}$ is the Minkowski tensor. It follows from this relation that the vacuum energy $T^{\mathrm{vac}}_{00} = \varepsilon^{\mathrm{vac}}$ does not depend on time, and the pressure equals $p^{\mathrm{vac}} = -\varepsilon^{\mathrm{vac}}$. An alternative to vacuum could be a new superweak field homogeneously distributed in the Universe (more precisely, inside its observable part). An accelerated expansion of the Universe could, in principle, also be explained if the laws of gravity are modified at superlarge distances.

The problem of dark energy (it is also called the cosmological constant problem) has two aspects. First, from the particle physics viewpoint one could expect that all different interactions contribute to the vacuum energy, with the magnitudes of contributions being determined by the characteristic energy scales of these interactions. For example, the contribution due to strong interactions could be estimated on dimensional grounds [9] to be

$$\varepsilon^{\mathrm{vac}}_{\mathrm{QCD}} \sim \Lambda^4_{\mathrm{QCD}} \approx (200\ \mathrm{MeV})^4 \,. \tag{15}$$

Indeed, the vacuum of quantum chromodynamics has a very complex structure, and *a priori* there are no reasons to expect that its energy differs by many orders of magnitude from estimate (15). At the same time, the observed value of dark energy density equals

$$\varepsilon_{\mathrm{DE}} = \Lambda^4_{\mathrm{DE}} \,, \tag{16}$$

where

$$\Lambda_{\mathrm{DE}} \approx 2 \times 10^{-3}\ \mathrm{eV} \,. \tag{17}$$

It is seen that the difference between the dimensional estimate (15) and actual value amounts to 44 orders of magnitude (!). The situation worsens if we take into account contributions due to electroweak interactions and gravitational interactions themselves, which could be evaluated as Λ^4_{EW} and M^4_{Pl}, respectively. So the first aspect of the problem is as follows: it is absolutely unclear why the actual value of the cosmological constant is so small compared to the characteristic scales of energy densities in particle physics.

It should be emphasized that this aspect of the problem had been discussed long before the first observational clues for nonzero dark energy density were obtained (see the reviews [16, 17]); it would persist even in the absence of dark energy in the Universe. In particular, mechanisms were suggested that lead to relaxation of the cosmological constant to a zero or almost zero value. These mechanisms, however, look quite exotic; besides, they could be realized [18, 19] in the course of the evolution of the Universe only at stages preceding all known cosmological epochs and even the inflationary stage, which makes experimental testing of these ideas a hopeless enterprise.

The second aspect of the dark energy problem consists in the fact that in particle physics there is no such a small energy scale as $\Lambda_{\mathrm{DE}} \sim 10^{-3}$ eV. In most dark energy hypotheses for the dark energy carrier this scale has to be introduced 'by hand'; it is extremely hard, if possible at all, to relate it to known scales like Λ_{EW} or M_{Pl}. Hence, this aspect of the problem in some sense is analogous to the gauge hierarchy problem; however, unlike the latter, no solution of any degree of elegance has been found here so far.

[8] Note that in the context of general relativity equation (13) is nothing but one of the conditions of covariant conservation of energy–momentum tensor.

[9] In the system of units used we have $c = \hbar = 1$, the dimension of length is inversely proportional to energy, so that the dimension of the energy density is [(energy)^4].

4. What does this all mean?

Summarizing, we can say that in both particle physics and cosmology many fundamental facts appear at the moment to be quite contrived. On the one hand, similar parameters in the theory of elementary particles turn out to be scattered by many orders of magnitude: energy scales characterizing different interactions and dark energy provide one example; another example is given by dimensionless coupling constants determining masses of quarks and charged leptons. On the other hand, dissimilar characteristics of the Universe, for example, the densities of dark matter and ordinary matter, are found to take close values in spite of their probably different generation mechanisms in the early Universe. The problem of the cosmological constant (vacuum energy) stands apart; it has remained unresolved over many decades despite all the theoretical efforts.

Of course, the possibility that each of these facts has its own dynamical explanation is the most attractive. We briefly mentioned some of such hypotheses in Sections 2 and 3. It is remarkable that most of them require extending the known theory of particle physics and predict phenomena that will be accessible to experimental testing in the near future, at LHC first and foremost. If one accepts this point of view, one would expect the discovery of whole wild lands of 'new physics' in the nearest future.

There is, however, another possibility as well. Namely, it cannot be totally excluded that 'chance' indeed plays a role at a very fundamental level, so that the actual values of some (or even many) parameters of the theory are not in fact natural. This point of view is advocated by the *anthropic principle*, according to which the observed values of fundamental parameters ought to be consistent with the possibility of our existence (see the reviews [20, 21]). This anthropic (environmental) viewpoint is supported by the observation that there are indeed 'friendly coincidences' in Nature, for example:

— the value of the cosmological constant, if perceived as a random number, turned out to be by many orders of magnitude smaller than the characteristic value of the vacuum energy in particle physics. If the cosmological constant were higher by 2–3 orders of magnitude in absolute value than the actually observed value, stars of the solar type and planetary systems could not be formed [10] [17, 22];

— the masses of light quarks and the electromagnetic constant $\alpha = 1/137$ are such that a neutron is heavier than a proton (and hence there is hydrogen in Nature), but not too much heavier (and therefore there are many stable nuclei). Note that for fixed values of quark coupling constants with the Higgs field this requires the Higgs vacuum expectation value (the electroweak scale $\Lambda_{\rm EW}$) to be close to its actual value [8];

— primordial density perturbations in the Universe, $\delta\rho/\rho \sim 10^{-5}$, are such that galaxies form but planetary systems are not destroyed [23].

The enumeration of such 'friendly coincidences' can be continued; a rather complete list can be found in the book [24] entirely devoted to the anthropic principle.

At first glance, the anthropic principle contradicts the natural science view on the laws of nature. However, this is not the case. There is a possibility that the Universe is in fact incredibly larger than its observable part, and in different parts of the Universe, which themselves are much larger than our observable part, parameters that we think of as fundamental take different values (perhaps even physical laws, in the present understanding of this term, are also different). Such a possibility is supported, for example, by the model of 'eternal inflation' [21] or by the concept of 'landscape' in string theory [25]. According to the former model, in the Universe there is a huge (possibly infinite) number of regions with various effective ages, inherent cosmological histories, and distinct present states; some of them are still experiencing inflationary expansion, others, to the contrary, have collapsed; if fundamental parameters can be time dependent (even on time scales largely exceeding what we believe to be the age of our part of the Universe), they can indeed take different values in these regions. In the latter case, one argues for a huge number of almost degenerate vacua of string theory, which can be realized in different parts of the Universe; not only can they have different values of fundamental parameters but also they can differ by gauge groups, 'elementary' particle content, etc. Let us also mention the model of baby Universes [26], in which there is a countless number of Universes with unequal values of fundamental parameters.

If this point of view is correct, the anthropic principle simply reflects the fact that our existence is possible not in an arbitrary place in the Universe, but only where there are suitable conditions. As formulated by Brandon Carter in 1974, "our location in the Universe is necessarily privileged to the extent of being compatible with our existence as observers" (see Ref. [24]). The fact that constants we used to think of as fundamental take values which are far from being natural could be a selection effect similar to the 'unnatural' result (relative to the characteristic temperatures in the Universe) of measuring the temperature on Earth.

The difficulty in utilizing the anthropic principle to obtain specific results is that it is unknown *a priori* which parameters are fundamental, in the sense that their values are determined from anthropic considerations, and which parameters are derivative, i.e., are calculable starting from the fundamental ones. In this sense, the anthropic principle cannot be disproved. [11]

At the same time, the anthropic principle *can* be seriously supported by experiment, and quite soon. Namely, as we discussed in Section 2, the smallness of radiative corrections to the electroweak energy scale can either be provided by extreme fine fitting of the parameters or be due to the existence of new particles and new interactions on the energy scale accessible by LHC. The fine fitting of the parameters of the theory is inconsistent with the traditional view on the laws of nature but is quite admissible by the anthropic principle. So, the lack of 'new physics' at LHC energies or the discovery of new particles and new interactions which, however, are incapable of ensuring the stability of the electroweak scale against radiative corrections, would be a serious (and maybe

[10] A large positive cosmological constant causes too rapid an expansion of the Universe, so that galaxies, stars, and planets cannot be formed; in the case of a large negative cosmological constant, the Universe stops expanding before stars and planets can form and collapses back to the cosmological singularity.

[11] A purely hypothetical situation, in which the anthropic principle could be invalidated, would be the construction of a 'theory of everything' allowing for the unique and unequivocal *ab initio* calculations of *all* dimensionless quantities, including coupling constants, mass ratios of all particles, ratios like $\Lambda_{\rm DE}/M_{\rm Pl}$, etc. Interestingly, comparatively recently such a possibility was considered quite seriously in the context of superstring theory.

crucial) argument favoring the role the anthropic principle plays at the level of the structure of matter we study today.

Needless to say that such a turn would have fundamental consequences for the natural science. However, these consequences would be rather negative since they would deprive naturalness-based considerations of their predictive power, while such considerations play an increasingly important role today. [12] The experiment, as usual, has the last word, and this word is going to be said by experiments at LHC due to start already a year from now.

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[12] Waiving all naturalness requirements, the minimum model capable of describing all known phenomena in particle physics and cosmology is the model [27] in which, in addition to the Standard Model fields, there are only an inflaton and three types of right (sterile) neutrinos. The inflaton is responsible for inflation; one of the sterile neutrinos has a mass of about 10 keV and is a particle of (warm) dark matter; two other sterile neutrinos with masses around several GeV are very strongly degenerate in mass, which allows for the generation of baryon asymmetry in the Universe. Oscillations of ordinary neutrinos occur due to their interactions with sterile ones and with the Higgs field via the see-saw mechanism.