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# The basis for a new model of the universe

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## Abstract

After decades of impotence to solve the frustrating series of problems revealed by astrophysics and cosmology and after recent debacle of theories beyond the Standard Model at LHC at CERN, *theoretical physics goes through the greatest crisis in its history*. As a potential escape from the crisis we propose a new model of the universe (without dark matter, dark energy and inflation field), based only on the Standard Model and General Relativity with one additional hypothesis: *quantum vacuum fluctuations are virtual gravitational dipoles*. The major consequences of hypothesis include: (1) solution to the cosmological constant problem; (2) explication of phenomena attributed to dark matter and dark energy, respectively as *local* and *global* effects of the quantum vacuum; (3) a *cyclic* universe with cycles alternatively dominated by matter and antimatter and with each cycle beginning with a macroscopic size and the accelerated expansion; (4) there is no need for an inflation field of unknown nature in the primordial universe. It is intriguing that only one hypothesis (at least mathematically) provides the encouraging initial answers to so many different fundamental questions.

## 1. Physics at the end of 2014

Our best fundamental knowledge has two cornerstones: Einstein's General Relativity [1] and the Standard Model of Particles and Fields [2]. General Relativity is our best theory of gravitation, while, according to the Standard Model, everything is made from apparently structureless fermions (quarks and leptons) which interact through the exchange of gauge bosons (photons for electromagnetic, gluons for strong, and  $W^\pm, Z^0$  for weak interactions).

General Relativity cannot develop a model of the universe without the appropriate input; the needed input is the *matter-energy content* of the universe. As it will become clearer in Section 2, different inputs lead to different models of the universe. The only well-established content of the universe (and hence the only well-established input in general relativistic cosmological field equations) is the Standard Model matter.

The Standard Model matter might be in different states, the familiar ones (gas, liquid, solid, plasma in stars...), less familiar like quark-gluon plasma and the most counterintuitive (but omnipresent) state called quantum vacuum (briefly presented in Section 3). It is important to understand that, with the exception of some speculations concerning the primordial universe, quantum vacuum is systematically neglected in Astrophysics and Cosmology; not because we are unaware of the possible gravitational impact of the quantum vacuum, but we cannot consider it as the content of the universe, because no one knows its gravitational properties.

Before we continue, let us underline that, so far, the Standard Model is the most successful and the *best tested theory* of all time. The recent LHC experiments at CERN have been a new triumph for the Standard Model contrary to the mainstream conviction that experiments will be a triumph of supersymmetric theories (the dominant theoretical guess of physics beyond the Standard Model, for thirty years considered as the future of physics, now by empirical evidence nearly eliminated [3] as a possible physical theory).

The sophisticated astronomical observations have revealed [1] three major phenomena. First, the expansion of the universe is accelerating. Second, the gravitational field in galaxies and clusters of

galaxies is much stronger than it should be according to our theory of gravitation and the existing quantity of the Standard Model matter (in fact, only the incomplete Standard Model matter without quantum vacuum is taken into account). Third, our universe is apparently dominated by matter in spite of the strong evidence that particles and antiparticles are always created in the same quantities.

In addition to these observed but unexplained phenomena, there are two model dependant problems, one related to the Big-Bang model and the other to our model of the quantum vacuum.

The Big-Bang model *contradicts* observations without an ad hoc assumption of cosmic inflation in the primordial universe, i.e. an accelerated expansion of the early universe, within the first  $10^{-30}$  seconds, with a speed more than twenty orders of magnitude greater than the speed of light (see more in subsection 2.3).

Quantum vacuum leads to the cosmological constant problem i.e. the predicted gravitational effects of the quantum vacuum are many orders of magnitude greater than permitted by experimental evidence. In fact, the cosmological constant problem is the obstacle to considering quantum vacuum as the major component of the content of the universe.

In the time of the writing this paper (second half of 2014) these five problems are the most fundamental problems of physics, astrophysics and cosmology. They are all a surprise and mystery for contemporary physics.

The dominant opinion is that all these phenomena are signatures of new physics and completely inexplicable if the Standard Model matter is *the only content* of the universe. Following this questionable line of thinking, three mysterious components of the matter-energy content of the universe have been postulated: (1) dark energy is invoked to explain the current accelerated expansion of the universe, (2) dark matter is invoked to explain the anomalous gravitational field in galaxies and cluster of galaxies, (3) a third component (inflation field) is invoked as the dominant component in the primordial universe in order to reconcile the old Big Bang theory with observations. Even after introducing all this mysterious content of the universe, it remains unclear what the cause is of the cosmological constant problem, and, why matter dominates antimatter in our universe (the popular explanation is a hypothetical CP violation, many orders of magnitude greater than the CP violation observed experimentally). The hope was that some (if not all) of these ad hoc conjectures would be explained in the framework of supersymmetric theories (for instance, the lightest supersymmetric particle was considered as the best candidate for dark matter).

Of course, the Standard Model of Particles and Fields is not the last word in physics; one day it will be replaced by a better model. However it is still a young and powerful model and it seems reasonable to ask if the Standard Model matter (but complete, with quantum vacuum as an inherent part) can explain all five fundamental problems revealed by contemporary astrophysics and cosmology. In the present paper we propose a new model of the universe based on the hypothesis that quantum vacuum contains virtual gravitational dipoles. We argue that (at least mathematically) quantum vacuum enriched with virtual gravitational dipoles might lead to the following fundamental results:

- (a) Eliminates the cosmological constant problem
- (b) Explains phenomena attributed to dark matter and dark energy, respectively, as *local* and *global* effects of the quantum vacuum
- (c) Predicts a *cyclic* universe with cycles alternatively dominated by matter and antimatter; with each cycle beginning with a macroscopic size and the accelerated expansion. Consequently, there is an elegant explanation of the matter-antimatter asymmetry in the universe: Our universe is dominated by matter because the previous cycle of the universe was dominated by antimatter.
- (d) Eliminates the need for an inflation field in the primordial universe.

After three years of very successful experimental work at Large Hadrons Collider at CERN, and unresolved major problems coming from astrophysics and cosmology, theoretical physics is apparently in the greatest crisis in its history [3]. The experimental findings strongly confirm the Standard Model and have nearly eliminated supersymmetry as a possible physical theory. It seems inevitable that we have to face the Nightmare Scenario (i.e. no signs of new physics at LHC) and the unprecedented collapse of decades of speculative work. The current crisis is worsened by the fact that the long domination of supersymmetric theories has largely suppressed alternative thinking.

Hopefully, independent of any scientific value, our paper would help to release researchers from the chains and limits imposed by the mainstream thinking and their nearly absolute control of funds, journals and the process of decision making. When we will learn the lessons of history: the most efficient way to decelerate the advance of science is to suppress imagination and alternative thinking.

## 2. General relativistic Cosmology

Let us remember the basic points of the Standard Cosmology [1].

### 2.1 The cosmological field equations

As is well known, the cosmological principle (i.e. the statement that at any particular time the Universe is isotropic about every point) determines [1] the Friedman-Robertson-Walker metric

$$ds^2 = c^2 dt^2 - R^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2 \theta d\varphi^2) \right] \quad (1)$$

where  $k = +1$ ;  $k = -1$ ;  $k = 0$  correspond respectively to closed, open and flat Universe.

The dynamics of the above space-time geometry is entirely characterised by the scale factor  $R(t)$ . In order to determine the function  $R(t)$ , the Einstein equation  $G_{\mu\nu} = -(8\pi G / c^4) T_{\mu\nu}$  must be solved. While the Einstein tensor  $G_{\mu\nu}$  is determined by metric (1); we need a model for the energy-momentum tensor ( $T_{\mu\nu}$ ) of the content of the Universe. In view of homogeneity and isotropy of the Universe, a reasonable approximation is to assume the energy-momentum tensor of a perfect fluid; characterised at each point by its proper density  $\rho$  and the pressure  $p$  in the instantaneous rest frame. Assuming that the cosmological fluid in fact consists of several distinct components denoted by  $n$ , the final results are cosmological field equations, which may be written [1], in the form:

$$\ddot{R} = -\frac{4\pi G}{3} R \sum_n \left( \rho_n + \frac{3p_n}{c^2} \right) \quad (2)$$

$$\dot{R}^2 = \frac{8\pi G}{3} R^2 \sum_n \rho_n - kc^2 \quad (3)$$

By eliminating  $\ddot{R}$  from the cosmological field equations (2) and (3) leads to

$$\sum_n \left[ \dot{\rho}_n + 3 \frac{\dot{R}}{R} \left( \rho_n + \frac{p_n}{c^2} \right) \right] = 0 \quad (4)$$

Thus, only two of the three equations (2), (3) and (4) are independent. One may use whichever two equations are most convenient in any particular calculation.

At this point it is evident that in order to solve the cosmological field equations, we need to know what the components of the matter-energy content of the universe are, and how density ( $\rho_n$ ) and pressure ( $p_n$ ) of each component evolve with the scale factor and eventually time. But, before we focus on the open problem of the matter-energy content of the Universe, let us comment the cosmological equation (2).

The necessary condition for the accelerated expansion of the Universe ( $\ddot{R} > 0$ ) is that the term in brackets of equation (2) is negative at least for one of the components of the cosmological fluid; hence, the corresponding pressure must be negative. Because of the relation

$$p_n = - \frac{\partial U_n}{\partial V} \quad (5)$$

it is obvious that the pressure is negative *only if*  $U_n$  (the total energy of the component  $n$ ) increases with the volume (i.e. with the scale factor  $R$  of the Universe). In general if  $U_n$  increases with the size of the Universe the pressure is negative, if  $U_n$  decreases the pressure is positive; pressure is zero if and only if  $U_n$  is a constant.

Hence, the observed existence of a period of the accelerated expansion of the Universe should be considered as a hint that the quantity of some cosmological fluids may increase with the size of the Universe. By the way, the quantum vacuum of the Standard Model of Particles and Fields has a constant energy density; consequently the total energy linearly increases with the volume and the corresponding pressure is negative. While the use of the Standard Model quantum vacuum is prevented by the cosmological constant problem, it is significant that in principle, cosmological fluids with the needed qualitative behaviour are not in conflict with existing physics.

## 2.2 The matter-energy content of the Universe

### 2.2.1 Matter-energy content of the Universe according to the Standard Model

According to the Standard Model of Particles and Fields there are three components of the content of the universe, i.e. three different cosmological fluids, in the usual jargon called: radiation, pressureless matter (or dust) and quantum vacuum. These components evolve according to the power-law

$$\rho_n = \rho_{n0} \left( \frac{R_0}{R} \right)^n \quad (6)$$

where, as usually, index  $0$  denotes the present day value. The values  $n = 4$ ,  $n = 3$  and  $n = 0$  correspond respectively to radiation, matter and quantum vacuum. The corresponding equation of state, relating pressure and density is:

$$p_n = w_n \rho_n c^2 \quad (7)$$

where the equation of state-parameter  $w_n = (n - 3)/3$  is a constant. In contrast to the Standard Cosmology, later, in our theory we will be forced to consider one variable parameter  $w_v$ .

Instead of densities  $\rho_n$ , it is common practice in cosmology to work in terms of *dimensionless* quantities, usually called *density parameters* or simply *densities*, which are defined by

$$\Omega_n(t) = \frac{8\pi G}{3H^2(t)} \rho_n(t) \quad (8)$$

where  $H(t) = \dot{R}/R$  is the Hubble parameter. Consequently, instead of transformation (6) we have

$$\Omega_n(t) = \left( \frac{H_0}{H(t)} \right)^2 \left( \frac{R_0}{R} \right)^n \quad (9)$$

while equations (2) and (3) transform to

$$\ddot{R} = - \frac{RH^2}{2} \sum_n \Omega_n (1 + 3w_n) \quad (10)$$

$$\frac{kc^2}{R^2 H^2} = \Omega_{tot} - 1, \quad \Omega_{tot} \equiv \sum_n \Omega_n \quad (11)$$

The crucial point is that the  $n = 0$  component corresponding to the quantum vacuum can be interpreted as a fluid with constant density (and negative pressure, because of  $w_n = -1$ ) during the

whole history of the universe. Consequently, the gravitational effects of quantum vacuum can be described by a cosmological constant in Einstein's equation, and, as is well known, a positive cosmological constant leads to a universe with the accelerated expansion. Unfortunately, this idyllic scenario is brutally destroyed by the cosmological constant problem [4]: the predicted vacuum energy density is many orders of magnitude greater than permitted by empirical evidence. Hence, while the standard  $\Lambda$ CDM cosmology uses a cosmological fluid (named dark energy) with  $n = 0$ , because of the cosmological constant problem this dark energy *cannot* be identified with the quantum vacuum.

### 2.2.2 Matter-energy content of the non-primordial universe according to the Standard Cosmology

In brief, within the framework of the standard  $\Lambda$ CDM cosmology, the content of the Universe has the following components: fluids with  $n = 4$  and  $n = 3$  well understood by the Standard Model of Particles and Fields, and two hypothetical fluids [2] of unknown nature, dark energy with  $n = 0$  and dark matter with  $n = 3$ . Let us note that dark matter is attributed the same value  $n = 3$  as the matter component from the Standard Model; they produce the same effects globally but different effects locally (at the level of galaxies and clusters of galaxies).

The cosmological field equations (2-4), together with the content of the universe sketched out in this subsection, are a surprisingly successful model of the universe (in fact the Big Bang model without cosmic inflation). Among the other successes, this model fits the empirical data well concerning the accelerated expansion of the universe and anomalous gravitational field in galaxies and clusters of galaxies. However the price paid for this is very high, ad hoc introduction of dark matter and dark energy of unknown nature which together must represent about 95% of the content of the universe. If this is true we are obviously made from exotic matter which is less than 5% of the total content. Worse than that, the model has inherent problems and shortcomings which are the subject of the following subsection.

### 2.2.3 Content of the primordial universe

The prevailing opinion is that in the primordial universe the content was dominated by inflation field; hence a content fundamentally different from cosmological fluids described in the previous subsection (2.2.2).

Let us start with a simple definition of cosmic inflation: *Inflation is a stage of accelerated expansion of the primordial universe when gravity acts as a repulsive force* [5].

The ad hoc assumption of cosmic inflation was motivated by the fact that the old Big-Bang theory contains both, theoretical predictions well confirmed by observations and predictions in sharp conflict with observations. For instance, the old theory predicts the existence of the cosmic microwave background (CMB), but contradicts its major characteristics: high level of homogeneity and isotropy.

The key difference between the model without inflation and the model with inflation is schematically presented in Fig.1, with  $t$ ,  $R$  and  $\dot{R}$  denoting respectively the cosmic time, the scale factor of the Universe and the speed of the expansion of the universe. The old picture of a decelerated Friedmann universe is modified by inserting a stage of cosmic acceleration. Of course, in order to preserve the successful predictions of the standard Friedmann model, inflation must end sufficiently early and must possess a smooth graceful exit (roughly speaking in less than  $10^{-30}$  s) into the decelerated Friedmann stage.

The theory of cosmic inflation was born from the mathematical understanding that the decreasing functions  $\dot{R}$  cannot be reconciled with the homogeneity and isotropy revealed by the study of the CMB, while some mathematical functions with  $\dot{R}$  initially increasing and after that decreasing are in good agreement with the observed homogeneity and isotropy. This *mathematical* success can be considered as the indication that the initial accelerated expansion of the Universe really existed; however the cause of such a phenomenon remains a total mystery and we can only speculate about it.

The inflationary cosmology is based on speculation that the primordial accelerated expansion of the universe is driven by a fundamental scalar field of unknown nature (in fact in the absence of any empirical evidence, cosmologists still play with many different mathematical forms of the scalar field). According to the prevailing scenario (chaotic inflation) the creation of matter of our Universe has happened *after* inflation [5, 6] when the energy concentrated in the inflation field was converted into particle-antiparticle pairs. From this time on, the universe can be described by the usual Big-Bang theory. Let us underline how this is radically different from the theory without inflation. In the Big Bang model without inflation, the *totality* of mass of the Universe emerges from a single Planck size domain. In the theory with inflation, the *only* content of the universe during inflation is the fundamental scalar field; the mass of the universe emerges at the *end* of inflation when universe already has a *macroscopic* size. Hence the microscopic universe doesn't contain matter; matter appears only in a macroscopic universe!

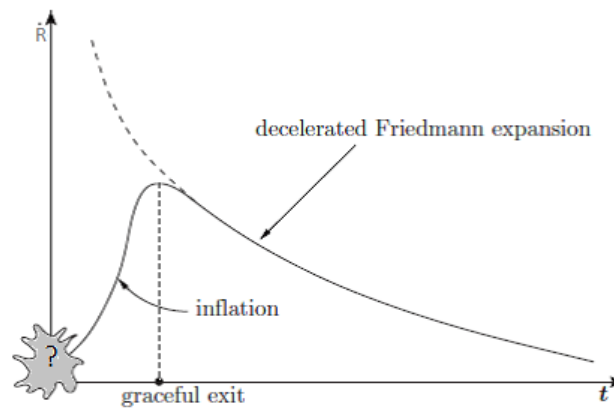


Figure 1

### 2.3. The cosmological constant problem

The nature of dark energy, invoked to explain the accelerated expansion of the Universe, is a major mystery in theoretical physics and cosmology. From the purely mathematical point of view, adding a positive cosmological constant term to the right-hand side of the Einstein equation, can account for the observed accelerated expansion. However no one knows what the physics is behind such an ad hoc introduction of the cosmological constant. In principle, the cosmological constant  $\Lambda$  may be interpreted as a cosmological fluid with a constant density  $\rho_{de}$  and negative pressure ( $p_{de} = -\rho_{de}c^2$ ) i.e.  $\Lambda = 8\pi G\rho_{de}/c^2$  but the physical nature of such a hypothetical fluid remains unknown. The most elegant and natural solution would be to identify dark energy with the energy of the quantum vacuum predicted by Quantum Field Theory (QFT); but the trouble is that QFT predicts [4] the energy density of the vacuum to be many orders of magnitude greater than the observed [7] dark energy density and the corresponding cosmological constant:

$$\rho_{de} \approx 7.1 \times 10^{-27} \text{ kg/m}^3, \quad \rho_{de}c^2 \approx 6.4 \times 10^{-10} \text{ J/m}^3 \quad (12)$$

$$\Lambda \approx 1.3 \times 10^{-52} \text{ m}^{-2} \quad (13)$$

According to QFT, summing the zero-point energies of all normal modes [4] of some field of mass  $m$  up to a wave number cut-off  $K_c \gg m$  yields a vacuum energy density (with  $\hbar = c = 1$ )

$$\langle \rho_{ve} \rangle = \int_0^{K_c} \frac{k^2 \sqrt{k^2 + m^2}}{(2\pi)^2} dk \approx \left( \frac{K_c}{2\pi} \right)^4 \quad (14)$$

or reintroducing  $\hbar$  and  $c$ , and using the corresponding mass cut-off instead of  $K_c$ :

$$\rho_{ve} = \frac{1}{16\pi^2} \left( \frac{c}{\hbar} \right)^3 M_c^4 \equiv \frac{\pi}{2} \frac{M_c}{\lambda_{Mc}^3} \quad (15)$$

where  $\lambda_{Mc}$  denotes the (non-reduced) Compton wavelength corresponding to  $M_c$ . If we take the Planck scale (i.e. the Planck mass) as a cut-off, the vacuum energy density calculated from (15) is  $10^{121}$  times greater than the observed dark energy density (12). If we only worry about zero-point energies in quantum chromodynamics (i.e. if the cut-off mass is about the mass of a pion), (15) is still  $10^{41}$  times larger than (12). Even if the Compton wavelength of an electron is taken as the cut-off, the result exceeds the observed value by nearly 30 orders of magnitude. This huge discrepancy is known as the cosmological constant problem and it is the principal obstacle in the attempt to interpret dark energy as the energy of the quantum vacuum.

The result (15) is a completely wrong estimation of the gravitational charge density of the quantum vacuum, but, if we trust quantum field theory (and we have all reasons to trust it) it must be a correct estimation of the inertial mass density. Consequently, the incredible disagreement of the result (15) with observations may be considered as a strong hint that, for some unknown reasons, the inertial mass of the quantum vacuum is many orders of magnitude greater than the gravitational charge.

### 3. The standard picture of the quantum vacuum

Before the foundation of Quantum Field Theory, the physical vacuum was a synonym for nothing. However in quantum field theory “nothing’s plenty”, as nicely said by Aitchison in his classical review [8] for non-specialists readership. More precisely, the physical (or quantum) vacuum is *the ground state* (a state of minimum energy) of the considered system of fundamental fields. The other states of the system are ‘excited’ states, containing quanta of excitation, i.e. particles. There are no particles in the vacuum (in that sense the vacuum is empty); but the vacuum is plenty of quantum vacuum fluctuations, or, in more popular wording; of short-living virtual particle-antiparticle pairs which in permanence appear and disappear (as is allowed by time-energy uncertainty relation  $\Delta E \Delta t \geq \hbar/2$ ).

Quantum vacuum should be considered as a *new state* of matter-energy, completely different from familiar states (gas, liquid, solid, plasma...) but *as real as* they are [8, 9, and 10]. Popularly speaking, quantum vacuum is an “ocean” of short living, virtual particle-antiparticle pairs (like quark-antiquark, neutrino-antineutrino and electron-positron pairs). According to our best knowledge: (1) quantum vacuum is a state with perfect *symmetry* between matter and antimatter; a particle *always* appears in pair with its antiparticle, which is totally different from mysterious matter-antimatter *asymmetry*, i.e. the fact that everything on the Earth (and apparently in the Universe) is made only from matter, with only traces of antimatter; (2) contrary to all other states of matter-energy which are composed from the long living particles (electrons and protons in stars and flowers, have existed before them and will exist after them), the quantum vacuum is a state with extremely *short living* virtual particles and antiparticles (for instance, the lifetime of a virtual electron-positron pair is only about  $10^{-21}$  seconds).

Let us briefly consider three important and illuminating phenomena in quantum electrodynamics.

The first phenomenon coming from quantum electrodynamics is known as Schwinger’s mechanism [11, 12]. A virtual electron-positron pair might be *converted* into a real one by a sufficiently strong external electric field which accelerates electrons and positrons in *opposite* directions. For a constant acceleration  $a$  (which corresponds to a constant electric field), the particle creation rate per unit volume and time, can be written as:

$$\frac{dN_{m\bar{m}}}{dt dV} = \frac{c}{\hat{\lambda}_m^4} \left( \frac{a}{a_{cr}} \right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left( -n \frac{a_{cr}}{a} \right); \quad a_{cr} \equiv \pi \frac{c^2}{\hat{\lambda}_m} \quad (16)$$

which is the famous Schwinger formula [11, 12], with  $\hat{\lambda}_m \equiv \hbar/cm$  being the reduced Compton wavelength of a particle with mass  $m$ . In simple words, a virtual pair can be converted to a real one (i.e. real particle-antiparticle pairs can be created from the quantum vacuum!), by an external field which, during their short lifetime, can separate particle and antiparticle to a distance of about one



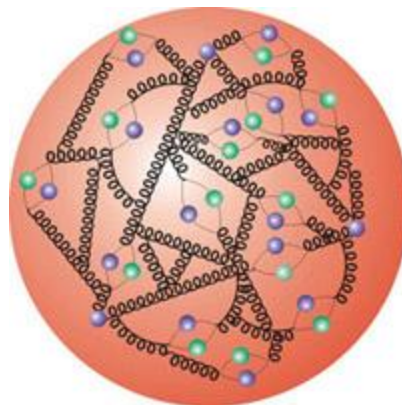
reduced Compton wavelength. While we still cannot produce a sufficiently strong electric field needed for creation of electron-positron pairs from the quantum vacuum, the analogous experiment (dynamic Casimir effect), i.e. creation of photons from the quantum vacuum was performed two years ago [10].

The second significant fact in quantum electrodynamics is: Virtual pairs of charged particles (for instance, electron-positron or quark-antiquark pairs) *behave as virtual electric dipoles*. Consequently, in an external electric field, the polarization of the quantum vacuum, analogous to the familiar polarization of a dielectric should be expected. In particular, the vacuum around an electron might be polarized. An electron attracts virtual particles with a charge of the opposite sign; hence there is a vacuum *screening* effect around the electron. What we measure at large distances is “*screened*” charge and it must be less than the “bare” charge. Thus, the observed charge of an electron  $e$ , or equivalently the fine structure constant ( $\alpha \equiv e^2/4\pi\epsilon_0\hbar c$ ) should be position dependent. Today, this theoretical prediction is a confirmed reality; for instance, at large distances  $\alpha^{-1} = 137.036$ , while at the shortest distances probed so far [9]  $\alpha^{-1} = 128.886$  (i.e. because of the quantum vacuum the electric charge of electron is about 4% greater!), which is in perfect agreement with theoretical calculations.

In brief, a sufficiently strong electric field can convert virtual pairs into real ones, while in weaker fields there is phenomenon of electric polarization of the quantum vacuum. Both phenomena are possible only because virtual pairs (of particles and antiparticles with electric charge) are virtual electric dipoles.

Third, quantum vacuum has an impact (known as Lamb shift [8]) on “orbits” of electrons in atoms! By the way, as it will become clear in sections 5 and 6 we have invented an intriguing way in which quantum vacuum can influence the orbits of astronomical bodies.

Of course, quantum vacuum is much more than these three phenomena. Just to get a better idea of the fundamental importance of the quantum vacuum, I invite you to imagine that, you can switch off and switch on, the quantum vacuum in our Universe. As we live in the Universe with quantum vacuum switched on, you firstly must switch it off. What would happen? In fact I must warn you not to do it; after switching off the quantum vacuum, you will not stay alive to switch it on again! This is not a speculation but prediction based on our best knowledge. For instance, sophisticated experiments [13] have revealed that the proton is not an elementary particle but a very complex system that in addition to three valence quarks contains virtual (or sea) quark-antiquark pairs and gluons (see Fig. 2).



**Fig. 2** Inner structure of a proton revealed at HERA

Black spirals represent gluons while purple-green particles denote virtual quark-antiquark pairs (up to 100 of these quark/anti-quark pairs are “visible” at any instant!). Note that there are three more quarks (two up, one down) than anti-quarks. These are the three valence quarks we would normally refer to when speaking of the proton. (Source: DESY in Hamburg)

In simple words, quantum vacuum significantly contributes to the structure of protons (and neutrons as well). If this contribution is switched off, protons would become quite different particles.

A radical change of constituents of atoms would perturb everything; the Universe without quantum vacuum would be a completely different place (and certainly without us). Hence, quantum vacuum is not only a strange state of matter in quantum field theory, but also the root of our existence.

## 4. Hypothesis of virtual gravitational dipoles

Let us introduce the main *working hypothesis* of this paper:

*Quantum vacuum fluctuations are virtual gravitational dipoles*

The importance of this hypothesis is clarified in the two following subsections.

### 4.1 The gravitational polarization of the quantum vacuum

Obviously, for virtual particle-antiparticle pairs, this *working hypothesis* is satisfied if the gravitational charge  $m_g$  of a particle and the gravitational charge  $\bar{m}_g$  of an antiparticle have the opposite sign (of course the corresponding inertial masses are equal  $m_i = \bar{m}_i$ ). Consequently, a virtual particle-antiparticle pair in the quantum vacuum can be considered as a gravitational dipole, with the gravitational dipole moment

$$\vec{p}_g = m_g \vec{d}; \quad |\vec{p}_g| < \frac{\hbar}{c} \quad (17)$$

Here, by definition, the vector  $\vec{d}$  is directed from the antiparticle to the particle, and has a magnitude  $d$  equal to the distance between them. The inequality in (17) follows from the fact that the size  $d$  of the virtual pair must be smaller than the reduced Compton wavelength  $\lambda_m = \hbar/mc$  (for a larger separation a virtual pair becomes real). Hence,  $|\vec{p}_g|$  must be a fraction of  $\hbar/c$ . Consequently, a gravitational polarization density  $\vec{P}_g$  (i.e. the gravitational dipole moment per unit volume) may be attributed to the quantum vacuum. The simplest possible case of the gravitational polarization of the quantum vacuum is *saturation* i.e. the case when the external gravitational field is sufficiently strong to align all dipoles along the field. If all dipoles are aligned in the same direction, the gravitational polarization density has the maximal magnitude  $P_{g \max}$  which may be written as

$$P_{g \max} = \frac{A}{\lambda_m^3} \frac{\hbar}{c} \quad (18)$$

where  $A < 1$  should be a dimensionless constant of order of unity (as a crude theoretical approximation we adopt the value  $A = 1/2\pi$  which was already proposed in previous papers [14, 15] and will be further justified at the end of the next Section). The relation (18) is a consequence of inequality (17) and the prediction of quantum field theory that the number density of the virtual gravitational dipoles has constant value proportional to  $1/\lambda_m^3$  (here,  $\lambda_m$  denotes the corresponding Compton wavelength).

The first fundamental consequence of the hypothesis is: *Without matter immersed in it*, the gravitational charge density of the physical vacuum is zero. It is analogous to the case of electric dipoles; as we have already noticed, some virtual pairs in the quantum vacuum (like quark-antiquark and electron-positron pairs) are virtual electric dipoles. In the absence of an external electromagnetic field, these dipoles are randomly oriented and consequently the electric charge density of the quantum vacuum is zero. If the virtual pairs are gravitational dipoles (i.e. if particles and antiparticles, known to have the same inertial mass have the gravitational charge of the opposite sign) an analogous statement would also be true for gravitation: in the absence of external fields, the gravitational charge density (and consequently the cosmological constant) of the quantum vacuum is zero.

This is logically the simplest candidate for the solution of the cosmological constant problem; without matter immersed in it, the quantum vacuum has a zero cosmological constant, while a small non-zero value emerges as a result of immersed matter.

Let us clarify a few points.

It is more difficult to align more massive dipoles. Hence, for a given external field, dipoles with a sufficiently big mass will stay randomly oriented and will not contribute to the gravitational polarization density. In respect to the relations (14) and (15) it means that the cut-off value ( $\kappa_c$  or  $M_c$ ) is not indeterminate (as naively considered in quantum field theory); the cut-off might depend on the external field (i.e. on the distribution of matter immersed in the physical vacuum). In quantum field theory the cut-off is introduced to avoid an infinite value of the integral (14), while the hypothesis of virtual gravitational dipoles provides a *physical reason* for a cut-off and absence of infinity.

Dipoles which are both gravitational and electric dipoles persist in their random orientations. For these reasons, the dominant contribution to the gravitational charge of the physical vacuum of the present day Universe should come from purely gravitational dipoles. For instance a good candidate might be gluon condensates.

The mean distance between two dipoles which are first neighbours is  $\lambda_m$ . The gravitational acceleration produced by a particle at the distance of its own Compton wavelength is

$$g_\lambda(m) = \frac{Gm}{\lambda_m^2} \quad (19)$$

In the absence of more accurate estimates, this acceleration can be used as a rough approximation of the external gravitational field which is needed to produce the effect of saturation for the dipoles of mass  $m$ . As an aside, the accelerations (19) corresponding to the Planck mass, a neutron and a pion are respectively:  $5.7 \times 10^{51} m/s^2$ ,  $6 \times 10^{-8} m/s^2$  and  $2.1 \times 10^{-10} m/s^2$ . For comparison: the acceleration corresponding to neutrons is about one order of magnitude greater than the current acceleration of the expansion of the Universe, while only in central parts of galaxies is the gravitational field stronger than the acceleration corresponding to a pion. Hence, the acceleration corresponding to the Planck mass is about sixty orders of magnitude greater than typical gravitational fields in the present day Universe and cannot be the cut-off in (14); the relation (19) and the observed acceleration of the expansion of the Universe suggest that the right cut-off for the present day Universe should be close to the mass  $m_\pi$  of a pion (which is roughly a typical mass in the physical vacuum of quantum chromodynamics). In the following considerations, we will use as an approximation the mass  $m_\pi$ , while in a more accurate approach it would be necessary to consider gluon condensates of quantum chromodynamics.

The acceleration (19) produced by a pion is close to the acceleration  $a_0 \approx 1.2 \times 10^{-10} m/s^2$  claimed by MOND theory to be a critical acceleration and a universal constant of nature; according to MOND for weak gravitational fields with strength smaller than  $a_0$  the Newton's law of gravitation is no longer valid but must be modified. While our approach completely opposes the MOND, the significant success of this theory in the description of galactic rotational curves signals that there is something well mimicked by  $a_0$  and modification of Newton's law. The truth might be that acceleration  $a_0$  can be considered as a critical value; in stronger fields the gravitational polarisation density has a constant maximal magnitude  $P_{g \max}$  determined by (18), while for accelerations smaller than  $a_0$ ,  $P_g(r)$  is no longer a constant but decreases with distance.

## 4.2 Gravitational version of the Schwinger mechanism

If particles and antiparticles have gravitational charge of the opposite sign, than equation (16) might be valid for gravitation as well; hence there is the gravitational version of the Schwinger

mechanism, a sufficiently strong gravitational field can convert virtual particle-antiparticle pairs to real ones.

Eq. (16) contains a sum of exponential functions with negative exponents; hence, the particle creation rate is significant only for a gravitational field  $a$  greater than the critical value  $a_{cm} = \pi c^2 / \hat{\lambda}_m$ . Let us compare the critical acceleration  $a_{cm}$  with the gravitational acceleration  $g_s = GM / R_s^2 = c^2 / 2R_s$  at the Schwarzschild radius ( $R_s = 2GM / c^2$ ) of a black hole with mass  $M$ ; the comparison leads to the conclusion  $a_{cm} \gg g_s$ , i.e. a virtual pair can be converted to a real one *only deep inside the horizon* of a black hole. Hence, the gravitational version of the Schwinger mechanism might be important in the study of black holes (see Section 10). Another case when the gravitational Schwinger mechanism is inevitable is the primordial Universe (see Section 9).

Beside these mainlines (primordial Universe and black holes) there is the following striking relation between the gravitational Schwinger mechanism and the Unruh and Hawking temperature.

Equation (16) trivially transforms to

$$\frac{dN}{dt dV} \frac{m \bar{m}}{m \bar{m}} = \frac{1}{\pi^2} \frac{a^2}{c^3} \frac{1}{\hat{\lambda}_m^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\pi \frac{c^2}{a \hat{\lambda}_m}\right) \quad (20)$$

Taking (for simplicity) only the leading term  $n = 1$ , distribution (18) has a maximum for

$$\hat{\lambda}_{\max} = \frac{\pi c^2}{2 a} \quad (21)$$

Equation (21) together with the Wien displacement law  $\hat{\lambda}_{\max} T = b$  (where  $T$  and  $b$  are respectively the absolute temperature and Wien displacement law constant) leads to

$$k_B T = C \frac{1}{2\pi} \frac{\hbar}{c} a \quad (22)$$

where  $k_B$  is the Boltzmann constant and  $C$  a dimensionless constant

$$C = \frac{2}{\pi} \frac{b k_B}{\hbar c} \approx 0.8 \quad (23)$$

Equation (22) is mathematically, but apparently not physically, essentially the same as the Unruh temperature! In fact, the Unruh temperature corresponds to  $C = 1$ , while the gravitational version of the Schwinger mechanism leads to  $C < 1$ .

Thus, considering quantum vacuum fluctuations as virtual gravitational dipoles, we have attributed a temperature  $T$  to the physical vacuum, a temperature which is proportional to the strength of the gravitational field at that point.

According to (22) the temperature of the quantum vacuum at the Schwarzschild radius of a black hole is

$$k_B T = C \frac{\hbar c^3}{8\pi GM} \quad (24)$$

which is essentially (in fact for  $C = 1$ ) the Hawking temperature of a black hole! However there is a major difference, (24) is valid only at the Schwarzschild radius, while (22) is also valid inside the horizon of a black hole.

## 5. Quantum vacuum contribution to gravitational field around a spherical body

Newton's law of gravity was the first successful description of the gravitational field around a spherical body (or, strictly speaking, around a point-like body). More accurate description comes from

Einstein's General Relativity; in particular the gravitational field of a non-rotating, electrically neutral spherical body is described by the Schwarzschild metric.

In general, Newton's theory of gravity is less accurate in description of stronger gravitational fields; in the extreme case of a black hole it is an invalid theory, but small discrepancies can already be observed within the Solar System. The most famous discrepancy within the Solar System is precession of the perihelion of Mercury: the observed value and the prediction of Newton's theory differ by about 8%, which was successfully explained by General Relativity.

Both, the Newton and Einstein theory are based on the same *wrong* hypothesis that all matter in the Universe exists in the classical (*non-quantum*) vacuum. Classical vacuum is a synonym for nothing; hence, according to our theory of gravity, all bodies exist in a *featureless* empty space which has no impact on the gravitational field. Consequently, at large scales, theories of Newton and Einstein can be a satisfactory approximation only if the quantum vacuum is a negligible source of the gravitational field.

The featureless empty space (zero gravitational effect) is one extreme. The second extreme, dismissed by empirical evidence, is the enormous gravitational effect predicted by the standard gravitational picture of the quantum vacuum in which virtual particle-antiparticle pairs are considered as two *identical gravitational monopoles*. Our hypothesis of virtual gravitational dipoles lies between these two extremes.

If the quantum vacuum "contains" the virtual gravitational dipoles, a massive body with mass  $M_b$  (a star, a black hole...), but also multi-body systems as galaxies should produce gravitational vacuum polarization, characterized with a gravitational polarization density  $\vec{P}_g$ . Hence we have a new paradigm:

A body creates around it an invisible *halo* of the *polarized quantum vacuum* which is detectable only through the produced gravitational effects

According to the current theory (considering bodies immersed in featureless empty space), *the gravitational charge* of a spherical body is a constant; hence two observers at different distances  $r_1$  and  $r_2$  from the body measure *the same* gravitational charge  $M_b$  within the corresponding spheres of radii  $r_1$  and  $r_2$ . In our theory, observers at different distances measure *different* effective gravitational charge. The effective gravitational charge of a body within a sphere of radius  $r$  is a sum of the constant gravitational charge  $M_b$  and the component  $M_v(r)$  caused by the gravitational polarization of the quantum vacuum, i.e.

$$M(r) = M_b + M_v(r) \quad (25)$$

While there is convincing evidence that the quantum vacuum exists, the current knowledge of its structure is very incomplete and does not permit development of a complete theory based on our hypothesis. Fortunately, in spite of the absence of detailed knowledge, we can make a few important conclusions.

As is well known, in a dielectric medium the spatial variation of the electric polarization generates a charge density  $\rho_b = -\nabla \cdot \vec{P}$ , known as the bound charge density. In an analogous way, the gravitational polarization of the quantum vacuum should result in a gravitational bound charge density of the vacuum

$$\rho_v = -\nabla \cdot \vec{P}_g \quad (26)$$

If we assume the spherical symmetry, equation (13) may be reduced to

$$\rho_v(r) = \frac{1}{r^2} \frac{d}{dr} (r^2 P_g(r)); \quad P_g(r) \equiv |\vec{P}_g(r)| \geq 0 \quad (27)$$

or, if we are interested in the radial gravitational charge density

$$\rho_r = 4\pi \frac{d}{dr} (r^2 P_g(r)) \quad (28)$$

It is obvious that  $P_g(r)$  must be a bounded decreasing function

$$0 \leq P_g(r) \leq P_{g \max} \quad (29)$$

According to (27) the gravitational bound charge density is zero in two cases:  $P_g(r) = 0$  and  $r^2 P_g(r) = \text{const} \dots$  The first case corresponds to the random orientation of virtual gravitational dipoles; it might appear only if at a critical distance from the body there is a phase transition from  $P_g(r) \neq 0$  to  $P_g(r) = 0$ . The second case corresponds to the decrease of  $P_g(r)$  according to the inverse square law.

Additionally, because of the anti-screening by the quantum vacuum, the gravitational charge of the body and the gravitational bound charge density of the physical vacuum must have the same sign. Consequently, according to (27),  $r^2 P_g(r)$  must increase with  $r$ , while  $P_g(r)$  cannot decrease faster than the inverse square law.

Schematically (assuming a sufficiently large distance from the other bodies) the space around a spherical body of the radius  $R_b$  can be divided in two (perhaps, not sharply separated) regions defined with a characteristic radius  $R_{p \max}$ . In the inner region ( $R_b < r < R_{p \max}$ ) the *gravitational bound charge density has a non-zero value* and consequently  $M_v(r)$  increases with  $r$  from zero to a constant value  $M_{v \max}$ . In the outer region ( $r > R_{p \max}$ ) the gravitational bound charge density is zero; hence there is no further increase of  $M_v(r)$ . Thus,  $R_{p \max}$  can serve as a rough approximation for the *maximal size of the halo* of the gravitational bound charge. However, the region of the gravitational domination of the considered body can be much smaller in the case of the proximity of other bodies; consequently the size ( $R_{halo}$ ) of the quantum vacuum halo can be significantly smaller than the maximal size ( $R_{p \max}$ ).

Here, the key point is that the size  $R_{halo}$  of a halo and the corresponding quantity of the gravitational bound charge can increase with the increases of distances between bodies. We will argue later that *locally*, a galaxy has no halo of dark matter but a halo of the gravitationally polarized quantum vacuum; the fundamental difference is that while the quantity of dark matter is a constant, the quantity of *the gravitational bound charge in each halo might increase* in a period of the expansion of the Universe. According to the paragraph containing the equation (5) it means that the gravitational bound charge which *locally might explain dark matter* globally must be described by a fluid with negative pressure and hence *globally might explain what we call dark energy*. In conclusion, what we call dark matter and dark energy must be respectively *local* and *global* effects of the gravitational polarisation of the quantum vacuum!

In the absence of the knowledge of the function  $P_g(r)$  the most robust prediction is that *the body is surrounded with a region of saturation* in which quasi-totality of virtual gravitational dipoles is aligned with the gravitational field of the body. In the region of saturation  $R_0 < r < R_{sat}$  (the value of

the characteristic radius  $R_{sat}$  would be discussed below),  $P_g(r)$  has a constant value (in fact a maximum value  $P_{g\max}$ ).

For the region of saturation, equation (27) leads to very simple expressions for the gravitational bound charge density of the quantum vacuum and for the effective gravitational charge within the sphere of radius  $r$

$$\rho_v(r) = \frac{2P_{g\max}}{r}, \quad M_v(r) = 4\pi P_{g\max} r^2, \quad r < R_{sat} \quad (30)$$

Consequently, as the result of the gravitational polarization of the quantum vacuum in the region of saturation, there is an additional constant gravitational field oriented towards the center

$$g_{v\max} = \frac{GM_v(r)}{r^2} = 4\pi GP_{g\max} \quad (31)$$

In principle, the relation (31) permits determining the maximum of the gravitational polarization density of the quantum vacuum  $P_{g\max}$ , by measuring the constant component of the acceleration  $g_{v\max}$ . The eventual measurement of  $g_{v\max}$  would be both: the first observation of the gravitational properties of the quantum vacuum and the first determination of the fundamental quantity  $P_{g\max}$ . In a preliminary pioneering study [16] astronomers have concluded that such a measurement is feasible, using a recent theoretical proposal [17] briefly presented in the next Section.

At the distance  $R_{sat}$ , the cumulative acceleration caused by the gravitational charge of the body and the gravitational bound charge density of the quantum vacuum should be of the same order of magnitude as the acceleration (19). Hence,  $R_{sat}$  can be written as

$$R_{sat} = \lambda_m \sqrt{\frac{BM_b}{m}} \quad (32)$$

where  $B$  is a dimensionless constant of the order of unity that will be estimated later to be roughly  $B \approx 1/2A \approx \pi$ . The value of  $R_{sat}$  is very big; for a planet like the Earth it is close to  $2.4 \times 10^{12} m$ , for a star as our Sun it is about  $1.4 \times 10^{15} m$ , while for  $M_b = 1.2 \times 10^{41} kg$  (what is roughly the baryonic mass of our galaxy)  $R_{sat} \approx 3.4 \times 10^{20} m \approx 11 kpc$ . As a consequence of so large region of saturation, for individual planets and stars, we cannot hope to perform tests at distances greater than  $R_{sat}$ ; however, as we will argue later, outside the region of saturation ( $r > R_{sat}$ ) the appropriate tests might be possible for galaxies.

If the phenomenon described by equation (31) exists, it is obvious that the universal acceleration  $g_{vmah}$  must be very small; otherwise it would be already revealed by the study of orbits of planets in our Solar System. Additionally, if what we call the dark matter halo in a galaxy is a halo of the gravitational bound charge, the phenomena usually attributed to dark matter appear outside of the region of saturation; hence at distances close to  $R_{sat}$  the total gravitational acceleration must be approximately equal to the characteristic empirical acceleration  $a_0$  at which “dark matter” effects become dominant

$$g_b(R_{sat}) + g_{vmah} \approx a_0 \approx 1.2 \times 10^{-10} m/s^2 \quad (33)$$

where  $g_b(R_{sat})$  denotes the part of acceleration caused by the baryonic matter. Using equations (31) and (33) together with the empirical fact that for galaxies in the region of saturation baryonic matter dominates “dark matter” (i.e. the gravitational bound charge) follows that numerically  $4\pi P_{g\max} \leq 1$  and  $g_{v\max} \leq 6.67 \times 10^{-11} m/s^2$ . Additionally, according to observations (for instance of our galaxy)

within the region of saturation determined by equation (32), the quantity of “dark matter” is roughly not less than half of the baryonic matter; consequently  $g_{v \max}$  cannot be much smaller than the established upper limit; hence we will use as approximation.

$$P_{g \max} \approx \frac{1}{4\pi} \frac{kg}{m^2} \approx 38 \frac{M_{Sun}}{pc^2} \quad (34)$$

$$g_{v \max} = 6.67 \times 10^{-11} m/s^2 \quad (35)$$

while strictly speaking these are upper bounds.

Unfortunately, in the region  $R_{sat} < r < R_{p \max}$  there is no an obvious solution and we must look for crude approximations of the function  $P_g(r)$ . An apparently reasonable common approximation for both regions,  $R_b < r < R_{sat}$  and  $R_{sat} < r < R_{p \max}$ , is obtained in Appendix B, considering quantum vacuum as an ideal system of non-interacting gravitational dipoles in an external gravitational field (analogous to polarization of a dielectric in external electric field, or a paramagnetic in an external magnetic field). We will come back to this in Section 7.

In brief, we suggest that each body is surrounded with a halo or the non-zero gravitational bound charge density; the gravitational bound charge  $M_v(r)$  increases from the lower bound (equal to zero) to an upper bound (equal to  $M_{v \max}$ ). In the region of saturation  $M_v(r)$  increases roughly as  $r^2$ , after that there is a region in which  $M_v(r)$  is nearly a linear function of  $r$ , while for  $r > R_{p \max}$ ,  $M_v(r)$  can be approximated with a constant value ( $M_{v \max}$ ). However if the other bodies are not sufficiently far, the mass of the halo ( $M_{halo}$ ) might be significantly smaller than  $M_{v \max}$ .

## 6. Astronomical tests of the gravitational effects of the quantum vacuum around dwarf planets at the periphery of Solar System

In the previous Section, we have noticed the crucial fact that the eventual existence of the region of saturation can be revealed by the study of the trans-Neptunian binaries [16, 17, 18, and 19].

The simplest problem in celestial mechanics is to determine the orbit of a point-like body in a central gravitational field. The orbit is an ellipse *fixed* with respect to the centre of gravity *if and only if* the central gravitational field has perfect spherical symmetry and the gravitational force strictly follows Newton’s inverse square law. Any departure from spherical symmetry and/or the inverse square law of gravity, leads to the precession of the perihelion (see for instance [20, 21]).

General Relativity (describing a spherically symmetric central gravitational field by Schwarzschild metric) is more accurate than Newtonian theory and it predicts a tiny precession even in the case of spherical symmetry. The general relativistic precession is well approximated by

$$\Delta \omega_{GR} = \frac{3\pi}{1 - e^2} \frac{R_s}{a} \quad (36)$$

where  $\Delta \omega_{GR}$  is the extra rotation *per orbit* in radians,  $a$  the semi-major axis of the orbit,  $e$  the eccentricity of the ellipse and  $R_s$  the Schwarzschild radius of the central body.

It is worth noting that the perihelion precession of planets predicted by classical theory (Newtonian mechanics together with the inverse square law for gravity) is close to the observed values; the largest discrepancy occurs for the Mercury (Mercury’s orbit precesses at a rate that is about 8% greater than the predicted one). The discrepancy has been explained by general relativistic correction (36) which must be added to the Newtonian result.



In brief, in the case of a central gravitational field with the exact spherical symmetry, Newtonian precession of the perihelion is zero, while the general relativistic result (36) is too small to be detected (with the current accuracy of measurements) for satellites of small central bodies like minor planets in the outer part of the Solar System.

Of course, a minor planet (which orbits around the Sun with a period  $T_{Sun}$ ) and its satellite (which orbits around the planet with a period  $T_p$ ) are not an isolated system but subject to an external gravitational field dominated by the Sun. This external gravitational field produces a Newtonian perihelion shift in the orbit of the satellite: the shift per orbit is well approximated [20, 21] with

$$\Delta \omega_N = \frac{3\pi}{2} \left( \frac{T_p}{T_{Sun}} \right)^2 \quad (37)$$

Any significant difference between observed precession and the expected value (37) must be considered as a signature of new physics. Typical value of the shift (37) for satellites of trans-Neptunian minor planets is a few tens of arc seconds per century. As we will argue, the shift caused by quantum vacuum might be greater by more than one order of magnitude.

However, *independent of any theoretical argument* it is of major importance to observe and see if there is any anomalous perihelion shift in the orbits of satellites of trans-Neptunian minor planets. With the existing infrastructure of satellites and telescopes it would be less expensive but potentially not less important than LHC experiments at CERN or detectors devoted to search for dark matter.

Now, let us assume that a satellite (with mass  $m$ ) orbiting about a minor planet (with mass  $M$ ) is subject to both Newtonian gravitational force and a tiny additional radial acceleration  $A_{qv}(r)$  caused by the presence of the quantum vacuum

$$g(r) = \frac{GM}{r^2} + A_{qv}(r) \quad (38)$$

As known from the classical celestial mechanics (see for instance the book of Murray and Dermott, 1999, page 55) in this problem characterized with spherical symmetry, the time evolution of the argument of pericentre  $\omega$  is determined by the equation

$$\frac{d\omega}{dt} = \frac{\sqrt{1-e^2}}{e} \sqrt{\frac{a}{\mu}} A_{qv}(r) \cos f \quad (39)$$

where  $\mu = G(m+M)$  and  $f$  denotes the true anomaly.

In order to integrate equation (39) it is necessary to know the function  $A_{qv}(r)$  and to express  $r$ ,  $\cos f$  and  $dt$  as functions of the eccentric anomaly  $E$ :

$$r = a(1 - e \cos E) \quad (40)$$

$$\cos f = \frac{\cos E - e}{1 - e \cos E} \quad (41)$$

$$dt = \frac{1 - e \cos E}{n} dE \quad (42)$$

where  $n = 2\pi/T$  denotes “average” angular velocity (or the mean motion) and  $T$  is the orbital period. Equations (39), (40), (41) and (42) yield the extra rotation per orbit ( $\Delta \omega_{qv}$ ) in radians.

$$\Delta \omega_{qv} = \sqrt{\frac{1-e^2}{e^2}} \frac{a^2}{\mu} \int_0^{2\pi} A_{qv}(r) (\cos E - e) dE \quad (43)$$

In the simplest but illuminating case,  $A_{qv}(r)$  has a constant value denoted by  $A_{qv}$ . In this case the perihelion shift per orbit can be written in the following way

$$\Delta \omega_{qv} = -2\pi A_{qv} \sqrt{1-e^2} \frac{a^2}{G\mu} \quad (44)$$

Hence, the internal precession (44) caused by the quantum vacuum is mixed with the precession (37) induced by the external Newtonian gravitational field dominated by the Sun. Let us note that according to equations (37) and (44) quantum vacuum might be dominant only for small systems far from the Sun.

Now, as an example let us consider the minor planet 2002 UX25; the needed data taken from Reference [22] are given in Table 1.

**Table 1:** Parameters for 2002 UX25 and its Satellite

UX25	Mass	1.25x10 <sup>20</sup> kg
	Semimajor axis	42.869 AU
	Orbital Period	280.69 years
Satellite	Semimajor axis	4770 km
	Orbital Period	8.309 days
	Eccentricity	0.17

According to Table 1 and Equation (37)

$$\Delta \omega_N \approx 3.09 \times 10^{-8} \text{ rad} \approx 0.0064 \text{ arc sec} \quad (45)$$

while  $\Delta \omega_{qv}$  depends on the choice of  $A_{qv}$  in Equation (44). As an interesting choice suggested recently let us take  $A_{qv} = 6.673 \times 10^{-11} \text{ m / s}^2$ . It leads to

$$\Delta \omega_{qv} \approx -0.23 \text{ arc sec} \quad (46)$$

Comparison of (45) and (46) shows that in this example the effect of quantum vacuum is strongly dominant (it is larger by nearly two orders of magnitude). Hence, there is potential for a clear signal of new physics.

If an anomalous perihelion precession is unambiguously revealed by the observation of the UX25 binary it would be clear signature of new physics and the beginning of a new field of astronomical observations.

Of course, while it is the best studied [16], the UX25 is not the only candidate; a number of other candidates were already suggested [18, 19]. In fact, if new physics is discovered, it is obvious that other trans-Neptunian binaries must be studied in order to distinguish between our theory and the eventual alternative explanations.

Majority of trans-Neptunian binaries are too small to be successfully studied with the present generation of space and ground based telescopes, but it would be possible with the next generation of telescopes. However, there are two interesting systems that can be and should be studied with the best currently available instrumentation. The first system Eris-Dysnomia (Table 2) is easy for observations and it might compensate the main shortcoming: the small eccentricity of the orbit of Dysnomia. The second system (Table 3) is also relatively easy for observations and of particular importance because the dwarf planet Haumea has two satellites (Hi'iaka and Namaka) what is the unique opportunity to get some insight on how the gravitational effects depend on distance; the major shortcoming is that Haumea is not a spherical body and impact of it must be carefully taken into account.

**Table 2:** Parameters for Eris and its Satellite Dysnomia

Eris	Mass	1.66x10 <sup>22</sup> kg
	Semimajor axis	67.836 AU
	Orbital Period	558.73 years
Dysnomia	Semimajor axis	37580 km
	Orbital Period	15.79 days
	Eccentricity	0.017

**Table 3:** Parameters for Haumea and its Satellites  
Hi'iaka and Namaka

Haumea	Mass	$4 \times 10^{21}$ kg
	Semimajor axis	43.166 AU
	Orbital Period	283.61 years
Hi'iaka	Semimajor axis	49880 km
	Orbital Period	49.46 days
	Eccentricity	0.05
Namaka	Semimajor axis	25657 km
	Orbital Period	18.27 days
	Eccentricity	0.25

For Eris and Dysnomia, Table 2 and equations (37) and (44) give

$$\Delta \omega_N \approx 2.82 \times 10^{-8} \text{ rad} \approx 0.0058 \text{ arc sec}; \quad \Delta \omega_{qv} \approx -0.11 \text{ arc sec} \quad (47)$$

In the same way, we have

$$\Delta \omega_N \approx 1.07 \times 10^{-6} \text{ rad} \approx 0.22 \text{ arc sec}; \quad \Delta \omega_{qv} \approx -0.81 \text{ arc sec} \quad (48)$$

for Haumea and Hi'iaka, while for Haumea and Namaka

$$\Delta \omega_N \approx 1.46 \times 10^{-7} \text{ rad} \approx 0.03 \text{ arc sec}; \quad \Delta \omega_{qv} \approx -0.21 \text{ arc sec} \quad (49)$$

A careful study of these systems (analogous to the study of UX25) is under way.

Let us end noting that, as a consequence of relations (31) and (44), the eventual measurement of  $\Delta \omega_{qv}$  directly gives directly the fundamental characteristics of the gravitational properties of the quantum vacuum

$$P_{g \max} = \frac{1}{8\pi^2 \sqrt{1-e^2}} \frac{\mu}{a^2} |\Delta \omega_{qv}|; \quad g_{v \max} = 4\pi G P_{g \max} \quad (50)$$

Of course, only astronomical observations can reveal the eventual gravitational impact of quantum vacuum, but the complementary laboratory tests are also of the fundamental importance. Hopefully, before the end of this decade, three competing experiments at CERN (ALPHA [23], AEGIS [24] and GBAR [25]) will discover if atoms of antihydrogen fall up or down.

An interesting question is what if the astronomical observations confirm the predicted anomalous precession in trans-Neptunian binaries, while laboratory tests show that antimatter falls down.

## 7. Local effects of quantum vacuum instead of dark matter

According to the *mainstream paradigm*, baryonic matter of a galaxy (in the astronomical jargon *baryonic* means the *incomplete* Standard Model matter *without* quantum vacuum taken into account) resides in a *halo of dark matter* made of unknown non-baryonic particles. A full list of the proposed dark matter particles would be longer than this section; let us mention only weakly interacting massive particles and axions. In spite of the significant efforts dark particles have never been detected. It is important to underline that the conjecture of the existence of dark matter *is not sufficient*; in order to fit the observational data for a galaxy, a particular distribution of dark matter is needed: the radial mass density of dark matter in a halo, from unknown reasons should be nearly constant

$$\rho_r = \frac{dM_{dm}(r)}{dr} \approx \text{const} . \quad (51)$$

However, according to the previous section, baryonic matter in a galaxy must be considered as a source of the gravitational polarization of the quantum vacuum. Each baryonic body (a star, a black hole, a cloud of gas...) produces the gravitational polarization of the quantum vacuum in the region in

which its gravitational field is dominant; as a consequence, the effective gravitational charge augments.

The immediate question is if the gravitational polarization of the quantum vacuum has potential to explain phenomena usually attributed to dark matter. While the detailed calculations must involve the extensive use of computers, there are simple arguments that gravitational polarization of the quantum vacuum eliminates the need for dark matter in galaxies and clusters of galaxies.

Before we continue a few topics must be clarified. Without use of computers, the simplest way to get the first insight if gravitational bound charge has potential to explain phenomena attributed to dark matter is to approximate the galaxy with a spherical body considered in Section 5. For a single spherical body, the whole mass is located in a small central part of the region of saturation; the region of saturation is roughly determined by  $R_{sat}$ , which can be calculated from (32). For a galaxy, mass is distributed both inside and outside the region of saturation; hence, in general, for a galaxy the region of baryonic mass distribution is larger than the region of saturation corresponding to the case when the whole mass is concentrated in the center. For some galaxies (for instance our Milky Way) the baryonic mass inside the region of saturation is bigger than the mass outside that region; in the usual astronomical wording we can roughly say that the radius of saturation is larger than the half-light radius. While it would be subject of a future publication, it is intuitively clear that only for such galaxies is the approximation with a spherical body reasonable. However for many galaxies of small baryonic mass (the extreme example is Segue 2 [26]) the baryonic mass inside the region of saturation is much smaller than the total baryonic mass, i.e. the half-light radius is much larger than the radius of saturation. For example, Segue 2 has three-dimensional (de-projected) half-light radius  $r_{1/2} = (46 \pm 3)pc$ , while according to (32)  $R_{sat} \approx 1.4 pc$  (corresponding to the stellar mass of about one thousands Solar masses). Once again, while details will be given in a forthcoming publication, let us underline that for Segue 2, the sphere inside the half-light radius contains large gravitational bound charge halos of individual stars; in other words the effective mass of each star is much bigger than it's baryonic mass. It is a plausible explanation of the observed fact [26] that in galaxies like Segue the ratio of "dark matter" to baryonic mater might be one order of magnitude larger than for galaxies like our Milky Way.

## 7.1 The local gravitational bound charge density

What is called the local dark matter density is an average over a small volume, typically a few hundred parsecs around the Sun. Apparently, the best estimate of the local dark matter density [27] is  $0.0075 \pm 0.0021 M_{sun} / pc^3$  (and hence an upper bound of  $0.0096 M_{sun} / pc^3$ ).

We deny the existence of dark matter and suggest that effects are caused by the gravitational bound charge density. Hence, according to the above distinction between different types of galaxies like Milky Way and Segue, let us start by noting that the central part of the majority of galaxies (including Milky Way) must be a region of saturation; consequently the gravitational bound charge density can be approximated with (23), i.e.  $\rho_v(r) = 2P_{g\ max} / r$ . Using the value (27) for  $P_{g\ max}$  and  $8kpc$  as the galactocentric distance of the Sun, the upper bound for the local gravitational bound charge density is  $0.0095 M_{sun} / pc^3$ ; in excellent agreement with the estimates of the hypothetical local dark matter density.

Let us note that with the gravitational bound charge distribution obtained in the Appendix B (see equations (B5) and (46)) instead of the upper bound we have the value  $0.0069 M_{sun} / pc^3$  in surprising agreement with the empirical value [27] of  $0.0075 \pm 0.0021 M_{sun} / pc^3$ .

## 7.2 The radial gravitational bound charge density

Of course, baryonic matter of a galaxy can be approximated by spherical body only at large radii. In order to satisfy the empirical evidence expressed by (46), in the limit  $r \gg R_{sat}$  the gravitational polarization density in equation (21) must behave as  $P_g(r) = P_{g \max} R_{sat} / r$ , which leads to

$$\rho_r \equiv \frac{dM_v(r)}{dr} = 4\pi P_{g \max} R_{sat} \quad (52)$$

For our galaxy, according to (32)  $R_{sat} \approx 11 \text{ kpc}$  and the radial gravitational bound charge density is  $5.25 \times 10^6 M_{Sun} / \text{pc}$ . With this value of the radial density, the gravitational bound charge within the  $260 \text{ kpc}$  is  $M_v(260 \text{ kpc}) \approx 1.37 \times 10^{12} M_{Sun}$ . With the added baryonic mass it is in excellent agreement with the best astronomical estimates, for instance, a very recent estimate [28] of total mass within  $260 \text{ kpc}$ :  $M_{tot}(260 \text{ kpc}) \approx 1.6 \times 10^{12} M_{Sun}$ .

## 7.3 A new model of “dark matter” distribution in galaxies

In Appendix B we have suggested (it would be too strong to say derived) the following gravitational bound charge distribution around a spherical body

$$M_v(r) = 4\pi P_{g \max} r^2 \tanh\left(\frac{R_{sat}}{r}\right), \quad r < R_{p \max} \quad (53)$$

While (53) can be only a crude approximation for a galaxy, it still might be used as a reasonable approximation because of the fact that the mass of a galactic dark matter halo is still not constrained better than a factor of two [28]. In the absence of physical understanding of the phenomenon, the distribution of (real or *effective*?) dark matter in a galaxy is usually described by empirical laws (NFW profile, Einasto profile, Burkert profile . . .) In our opinion, it is very important to include the profile (53) in forthcoming studies of dark matter halos and to reveal how well it performs in comparison with empirical profiles.

As suggested in Appendix B, the result (53) can be extended to all values of  $r$

$$M_v(r) = 4\pi P_{g \max} r^2 \tanh\left(\frac{R_{sat}}{r}\right) \tanh\left(\frac{R_{p \max}}{r}\right) \quad (54)$$

Of course, the estimates (53) and (54) should be taken with caution, as the initial toy models.

## 8. Global effects of quantum vacuum instead of dark energy

The above discussion suggests that the content of the Universe might have only two components:

1. The well-established Standard Model matter (in astrophysics and cosmology imprecisely called baryonic matter), according to equations (6) and (7), is modeled with two perfect cosmological fluids: one pressureless fluid (called matter or dust) with  $n = 3, w = 0$  and the second fluid called radiation with  $n_r = 4$  and positive pressure determined with the equation of state-parameter  $w_r = 1/3$ .
2. Quantum vacuum, which produces gravitational effects because of the non-zero gravitational bound charge density induced by the immersed baryonic matter. Such a quantum vacuum might be the true nature of what we call dark matter and dark energy.

According to the above considerations, the gravitational bound charge of the Universe ( $M_{vU}$ ) must increase with the expansion (i.e. the cosmological scale parameter  $R$ ) approaching asymptotically a constant value  $M_{v \max U}$ . An immediate consequence of equation (5) and the increase

of the gravitational bound charge is that, if modeled as a perfect fluid, the gravitational bound charge must produce a *negative pressure*. There is a period when the Universe is dominated by saturation and the corresponding gravitational bound charge approximately grows as  $R^2$ , i.e. behaves as a fluid with  $n_v \approx 1$  and the parameter  $w_v \approx -2/3$ , leading to the accelerated expansion. After the period of saturation,  $M_{vU}$  grows slower and slower becoming practically a constant in the asymptotic region. This means that gravitational bound charge evolves from a fluid with  $n_v \approx 1$  to a fluid with  $n_v \approx 3$ , while parameter  $w_v(R)$  increases from  $-2/3$  to  $0$ . In conclusion, the main feature of the fluid corresponding to the gravitational bound charge is transformation from a fluid with a negative pressure (which is source of the accelerated expansion) to a pressureless fluid (which is the source of decelerated expansion). Hence, this is completely different from the standard mainstream cosmology, the expansion of the Universe would not be eternal; expansion might convert to contraction, opening the possibility (see the next Section) for a cyclic Universe with cycles alternatively dominated by matter and antimatter.

As a toy model, let us consider the following function

$$M_{vU}(R) = M_{v \max U} \tanh \left( \frac{R}{R_{cU}} \right)^2 \quad (55)$$

where  $R_{cU}$  is a characteristic size of the scale factor of the Universe. It is evident that for  $R \ll R_{cU}$ , the function  $M_{vU}$  increases as  $R^2$ , while for  $R > R_{cU}$  it is close to the constant value  $M_{v \max U}$ . Using equations (5), (7) and (53) a simple calculation yields

$$w_v(R) = -\frac{4}{3} \frac{1}{\sinh 2 \left( \frac{R}{R_{cU}} \right)^2} \left( \frac{R}{R_{cU}} \right)^2 \quad (56)$$

Further, the solution of equation (4) in terms of density parameters (8) is

$$\Omega_v(R) = \Omega_{v0} \left( \frac{H_0}{H} \right)^2 \left( \frac{R_0}{R} \right)^3 \frac{\tanh \left[ 2 \left( \frac{R}{R_{cU}} \right)^2 \right]}{\tanh \left[ 2 \left( \frac{R_0}{R_{cU}} \right)^2 \right]} \quad (57)$$

while the cosmological equation (2) can be written as

$$\ddot{R} = -\frac{RH^2}{2} \left[ \Omega_m + \Omega_v \left( 1 - \frac{4}{\sinh 2 \left( \frac{R}{R_{cU}} \right)^2} \left( \frac{R}{R_{cU}} \right)^2 \right) \right] \quad (58)$$

The key point is that acceleration (58) changes the sign from positive to negative, roughly at  $R/R_{cU} \approx 1$ . Hence, there is a transition from the accelerated to decelerated expansion.

These equations should be considered as a first illustration how everything is radically different from the current mainstream cosmology.

A more profound consideration will be subject of a future publication.

## 9. Cyclic universe alternatively dominated by matter and antimatter

In the previous section we have argued that the current expansion of the universe might be reversed to contraction, resulting in a Big-Crunch end of our universe (or better to say, our cycle of the universe). In the present section we point out that through the gravitational version of the Schwinger mechanism, the Big-Crunch of our cycle might be a conversion of matter to antimatter, giving birth to a new cycle dominated by antimatter. This provides a striking and simple explanation of matter-antimatter asymmetry in the universe: *our universe is dominated by matter because the previous cycle was dominated by antimatter*. In addition, if a universe is always dominated by matter or antimatter, General Relativity can be used in each cycle of the universe; we are not forced to do modifications.

Today, the acceleration  $\ddot{R}$  has a small value [7] of the order of  $10^{-9} \text{ m/s}^2$ . However (and it is crucial for our arguments), in the primordial Universe  $\ddot{R}$  might be extremely big. For instance, if we limit only to the effects of pressureless matter, equations (2) and (7) lead to the following *lower bound*  $\ddot{R}_{lb}$  for acceleration

$$\ddot{R}_{lb} = -\frac{4\pi G \rho_{m0}}{3} \frac{R_0^3}{R^2} = -\frac{4\pi G \rho_{m0}}{3} \left( \frac{c}{H_0} \right)^3 \frac{1}{(\Omega_{tot} - 1)^{3/2}} \frac{1}{R^2} \quad (59)$$

The second equality in (59) is a consequence of well-known relation (11)  $c^2/H^2 R^2 = \Omega_{tot} - 1$  where the usual dimensionless parameter  $\Omega_{tot}$  (with the present-day value  $\Omega_{0tot} \approx 1.002$ ) denotes the total energy density of the Universe. For example, if  $R = 1 \text{ m}$ ,  $\ddot{R}_{lb}$  has tremendous value of the order of  $10^{45} \text{ m/s}^2$ .

Now when we know how strong the gravitational field in the primordial universe might be, let us note that according to (16) the critical accelerations for creation of electron-positron and proton-antiproton pairs are respectively  $7.4 \times 10^{29} \text{ m/s}^2$  and  $1.4 \times 10^{33} \text{ m/s}^2$ . These accelerations are much smaller than the gravitational accelerations which might exist in the primordial Universe!

It is important to understand, the Schwinger mechanism is valid *only* for an external field that has the tendency to *separate* particles and antiparticles. Hence, Eq. (16) can be used for the gravitational field, *only if*, particles and antiparticles have *gravitational charge of the opposite sign*, implying both the gravitational repulsion between matter and antimatter and the existence of virtual gravitational dipoles in the quantum vacuum. Well, why not? The theoretical debate is still open (see [29, 30] and references therein), while the existing experimental evidence does not and cannot preclude the hypothesis that the quantum vacuum contains virtual gravitational dipoles. The hypothesis can be confirmed or dismissed only by forthcoming experiments at CERN and astronomical observations. So, we continue our considerations assuming that virtual gravitational dipoles exist, and consequently that there is the gravitational version of the Schwinger's mechanism.

In the framework of contemporary physics there is no known mechanism to stop the gravitational collapse; hence, our imagined trip backward in time must end with a *singularity* as is the case in the Old Big Bang theory. As noted there is no singularity in chaotic inflation but the initial quantum vacuum fluctuation is roughly within a single Planck size domain.

However, assuming the quantum vacuum contains virtual gravitational dipoles, there is a physical mechanism preventing gravitational collapse to microscopic size. Through the gravitational version of the Schwinger mechanism *at a macroscopic size* the matter of our Universe would be converted to antimatter leading to a new cycle of the Universe dominated by antimatter.

The qualitative picture of the expected phenomena is very simple and beautiful. An extremely strong gravitational field (estimated by Eq. 59) would create a huge number of particle-antiparticle pairs from the physical vacuum; with the additional feature that matter tends to reach toward singularity while antimatter is violently ejected farther and farther from singularity. The amount of created antimatter is equal to the decrease in the mass of the collapsing matter Universe. Hence, the

quantity of matter decreases while the quantity of antimatter increases for the same amount; the final result might be conversion of nearly all matter into antimatter. If the process of conversion is very fast, it may look like a Big Bang starting with a macroscopic initial size many orders of magnitude greater than the Planck length.

The particle-antiparticle creation rate per unit volume and time can be estimated using Eq. (16). For instance, if the scale factor of the Universe is  $R = 1 m$ , Eq. (16) gives the following order of the magnitude for neutron-antineutron pairs

$$\frac{dN_{mm}}{dt dV} \approx 10^{96} \frac{\text{pairs}}{\text{sm}^3} \quad (60)$$

which corresponds to a mass of  $10^{69} \text{ kg}$  per second and cubic meter. With such an enormous conversion rate the matter of our Universe can be transformed into antimatter in a tiny fraction of second.

It is evident that during the process of conversion, the antimatter (matter) of the new cycle of the universe is subject to the *gravitational repulsion* by the matter (antimatter) of the previous cycle of the universe, which is in fact the definition of cosmic inflation. Hence there is a kind of cosmic inflation but without need for a mysterious scalar field. In addition, as the mass of the previous cycle decreases and the mass of the new cycle increases there is a natural transition from repulsion to attraction (i.e. there is no problem with the graceful exit). Everything happens as sketched in Figure 1, but at a macroscopic size, eliminating the need for an exponential expansion with more than billions of billions times faster than the speed of light.

In the current inflation scenario at a macroscopic size the energy of the hypothetical scalar field converts to an initial matter-antimatter mixture, from which somehow only matter will survive. In our scenario, instead of the energy of the scalar field, the existing matter of the Universe converts to antimatter; there is no need for fundamental scalar field and for any additional mechanism to explain the matter-antimatter asymmetry of the Universe. Of course conversion of matter to antimatter is a cataclysmic event comparable with the supposed conversion of scalar field to matter; hence the strong primordial gravitational waves (revealed by results of BICEP2 Collaboration) are inherent part of both theories.

## 9. Black holes and virtual gravitational dipoles

The Hawking radiation of a black hole (see equation (24)) is one of the most famous (unproved) theoretical predictions in the contemporary physics. However, Hawking radiation is extremely small (for instance, the Hawking temperature of the supermassive black hole in the center of our galaxy is about  $10^{-14} \text{ K}$ ) that it is safe to say that it would be never detected and confirmed. However, things are radically different if there is gravitational repulsion between matter and antimatter; black hole radiation is many orders of magnitude stronger than predicted by Hawking.

In this section, for completeness we review the arguments [31] that through the gravitational version of the Schwinger mechanism black holes made from matter radiate antineutrinos; in the case of supermassive black holes this radiation is relatively strong and might be detected with the next generation of neutrino telescopes.

While it is not the subject of the present paper, let us note that because of accretion a black hole (made from matter) might also emit positrons and antiprotons, which can be the source of the observed anomalous content of positrons and antiprotons in cosmic rays. The key point is that a tiny fraction of accreted matter might be converted to electron-positron and proton-antiproton pairs, with antiparticles being violently ejected.

Let us consider the simplest case of a Schwarzschild black hole made from matter. While it is neglected, from a mathematical point of view there are two solutions: the positive mass Schwarzschild solution

$$ds^2 = c^2 \left( 1 - \frac{2GM}{c^2 r} \right) dt^2 - \left( 1 - \frac{2GM}{c^2 r} \right)^{-1} dr^2 - r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \quad (61)$$

considered as the physical space-time metric; and the negative mass Schwarzschild solution



$$ds^2 = c^2 \left( 1 + \frac{2Gm}{c^2 r} \right) dt^2 - \left( 1 + \frac{2GM}{c^2 r} \right)^{-1} dr^2 - r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \quad (62)$$

considered and neglected as a nonphysical solution. It serves as the simplest example of a naked singularity [32] and a repulsive space-time allowed by mathematical structure of general relativity but rejected as non-physical. However, in the framework of the gravitational repulsion between matter and antimatter, both solutions may be given a physical meaning: the metric (61) is the metric “seen” by a test particle, while the metric (62) is the metric “seen” by a test antiparticle .

The major difference is that there is a horizon in the case of metric (61), while there is no horizon in the case of metric (62). In simple words, a black hole made from matter acts as a black hole with respect to matter and as a white hole with respect to antimatter.

Equations (61) and (62) are a significant example that general relativistic solutions, allow both positive and negative gravitational charge (with the inertial mass positive in both cases). Hence, while the existence of positive and negative gravitational charges is in obvious violation of the weak equivalence principle (i.e. the universality of the free fall) *it is not in conflict with solutions of general relativistic equations*. Apparently, General Relativity and the existence of gravitational charges of both signs can be reconciled with more careful statement considering universality of free fall: universality of free fall is valid for all bodies having *the same sign* of the gravitational charge.

According to the metric (62) the radial motion of a massive antiparticle is determined [1] by

$$\dot{r}^2 = c^2 \left( k^2 - 1 - \frac{GM}{r} \right) \quad (63)$$

where  $k$  is a constant of motion and dot indicates the derivative with respect to the proper time.

Differentiating (61) with respect to proper time and dividing through by  $\dot{r}$  gives

$$\ddot{r} = \frac{GM}{r^2} \quad (64)$$

Eqs. (63) and (64) have the same form as should have the corresponding Newtonian equation of motion with the assumed gravitational repulsion; however, the Schwarzschild coordinate  $r$  is not identical with the radial distance in the Newtonian theory, and dots indicate derivatives with respect to proper time rather than universal time.

For simplicity, as a toy model [31], let us consider a black hole as a ball with decreasing “radius”  $r_H < R_S \equiv 2GM/c^2$ , and let us define a critical radius  $r_{Cm} < R_S$ , as the distance at which the gravitational acceleration  $g = GM/r^2$ , produced by a Schwarzschild black hole, has the critical value  $a_{cr}(m) = \pi c^2 / \hat{\lambda}_m$ . Consequently,

$$r_{Cm} = \sqrt{\frac{\hat{\lambda}_m R_S}{2\pi}} \quad (65)$$

Hence a spherical shell with the inner radius  $r_H$  and the outer radius  $r_{Cm}$  acts as a “factory” for creation of particle–antiparticle pairs with mass  $m$ . It is evident that there is a series of decreasing critical radiuses  $r_{Cm}$ . For instance, according to (65), the critical radius  $r_{C\nu}$  corresponding to neutrinos is nearly four orders of magnitude greater than the critical radius  $r_{Ce}$  for electrons, which is about 43 times greater than the critical radius  $r_{Cn}$  for neutrons.

Integration of Eq. (16) over the shell determined by  $r_H$  and  $r_{Cm}$  (and taking  $r_{Cm} \gg r_H$  leads to the following approximation

$$\frac{dN_{m\bar{m}}}{dt} \approx \left( \frac{R_S}{\hat{\lambda}_m} \right)^2 \frac{c}{r_H} \quad (66)$$

According to (66), the particle–antiparticle creation rate per unit time depends on both mass  $M$  and radius  $r_H$ . If  $r_H$  (i.e. the size of a black hole) is very small, the conversion of matter into antimatter is very fast! Consequently, a black hole can have a very long lifetime only if the collapse to singularity is somehow prevented; long lifetime and singularity are incompatible; in a different way we know it already from the previous section.

According to a previous publication [31] the minimum value of  $r_H$  can be approximated with the critical radius  $r_{Ce}$  for electrons. Basically, the argument is that  $r_H \approx r_{Ce}$  must be point of phase transition, from a neutral to a charged black hole, what would be reflected in the change of the metric from the Schwarzschild metric to the Reissner-Nordstrom metric, what is a possible mechanism to prevent the further collapse.

Contrary to the Hawking radiation which cannot be measured, the antineutrino radiation of black holes is not very far from what can be detected with the existing facilities like Ice Cube at the South Pole; hence, hopefully it can be detected with the next generation of neutrino telescopes. For instance, the number of antineutrinos that may hit a telescope as the Ice Cube [31] during one year period is

$$N_{\bar{\nu}_A} \approx 3 \times 10^{10} / \text{year} , \quad N_{\nu_{MW}} \approx 1.4 \times 10^{12} / \text{year} \quad (67)$$

with maximal energies of

$$\varepsilon_{\nu_A} \approx 58 \text{ GeV} , \quad \varepsilon_{\nu_{MW}} \approx 10 \text{ GeV} \quad (68)$$

for antineutrinos coming respectively from supermassive black holes in the center of Andromeda and Milky Way.

## 10. Conclusions and comments

We have suggested the cornerstones, for a new model of the universe, *strictly based on the known physics* (General Relativity and the Standard Model of Particles and Fields) *complemented* with only one additional hypothesis: *Quantum vacuum fluctuations are virtual gravitational dipoles*. It is important that this hypothesis does not force us to modify the known physics! The Standard Model of Particles and Fields completely neglects gravity; hence it is obvious that whatever we assume about gravity is not in conflict with the Standard Model. Concerning General Relativity, from a purely mathematical point of view, there are solutions of general relativistic equations for both positive and negative gravitational charge (see equations (61) and (62)); if mathematical solutions for negative gravitational charge are not neglected, our hypothesis is not in conflict with General Relativity (but, as explained in Section 9, a more careful formulation of the weak equivalence principle is needed). It is quite possible that neglecting a class of mathematical solutions we do make an error which, in an analogous situation was fortunately not made by Dirac; imagine Dirac rejecting as non-physical a class of his mathematical solutions and missing the prediction of the existence of antimatter.

If homogeneity and isotropy of quantum vacuum are not broken by immersed matter, virtual gravitational dipoles are randomly oriented; consequently the gravitational charge density of the quantum vacuum is zero, what is the simplest and the most elegant candidate for the solution to the cosmological constant problem.

The matter immersed in the quantum vacuum might be the cause of the appearance of the gravitational bound charge density. We have given the initial arguments that locally (in galaxies and clusters of galaxies) the gravitational bound charge has the potential to explain phenomena usually attributed to hypothetical dark matter of unknown nature, while globally gravitational bound charge density acts as a cosmological fluid with a variable negative pressure; the magnitude of pressure decreases and approaches zero with the expansion of the universe, i.e. with the expansion of the universe the fluid converts from a fluid with negative pressure to a nearly pressureless fluid. Consequently, when it is dominant, such a fluid firstly causes the accelerated expansion, followed by the deceleration, eventually reversing the expansion to contraction.

A nice surprise (see Section 8) is that the collapse to singularity is prevented by an extremely fast conversion of virtual particle-antiparticle pairs to real ones (what we have named the gravitational version of the Schwinger mechanism). This opens the possibility of a cyclic universe with cycles alternatively dominated with matter and antimatter, what is the simplest and the most elegant candidate to explain matter-antimatter asymmetry of the universe. This superfast conversion of matter (antimatter) content of a cycle to the antimatter (matter) content of the next cycle looks similar to a Big-Bang but it is not a Big-Bang because it starts with a macroscopic size and eliminates the need for the inflation field as the dominant content of the primordial universe. Of course the conversion of the antimatter of the previous cycle to matter of our cycle is a cataclysmic beginning of our universe that might produce the primordial gravitational waves.

Proponents of supersymmetric theories have underlined many times that it would be pity if such a beautiful theory is “neglected” by nature. We can say that the theory of virtual gravitational dipoles in addition to beauty has great simplicity and suggests solutions to a wider spectrum of problems than supersymmetry.

It is premature to say that dark matter, dark energy, inflation field and a conjectured, extremely strong CP violation, are human artifices that mimic well the effects of the quantum vacuum, but it should be considered as an open possibility.

Let us end with a significant clarification. So far, the present author is the only one developing this theory. Quantum vacuum fluctuations as virtual gravitational dipoles is a radical novelty, completely different from some other approaches like proposal that non-baryonic dark matter has bipolar nature ([33, 34] and references therein), or attempts to use the anomalous gravitational properties of antimatter together with the hypothesis that we live with a symmetric matter-antimatter universe, with antimatter somehow hidden in the cosmic voids [35, 36]. Not only that, my theory and these other approaches shouldn't be confused, but in fact they exclude each other; if one of these theories is correct the others are wrong.

## Appendix A

### Coincidence or not coincidence: that is the question

For completeness in this Appendix we would like to point out the existence of a series of coincidences, improved or discovered by the present author [14, 37 and 38]. They are intriguing and might be important hints towards a new physics even in the first scenario that the theory presented in this paper is disproved by experiments and observations.

Let us start with the proportionality revealed by Dirac [39] and considered by Weinberg [40] as the most striking of all numerical “coincidences”

$$m_{\pi}^3 \sim \frac{\hbar^2}{cG} H_0 \quad (A1)$$

According to (A1), the mass of a typical elementary particle, such as the pion, does not differ too much from a mass that is “constructed” from the fundamental constants  $G, \hbar, c$  and the Hubble constant  $H_0$  (i.e. the present-day value of the Hubble parameter  $H$ ).

The attempt of writing the proportionality (A1) as an equation encounters two problems: First, the left-hand side of (A1) is about 10 times larger than the right-hand side; hence, in the case of an equality the “missing” proportionality factor on the right-hand side should come up for this order of magnitude discrepancy. The second problem is of more fundamental nature. In contemporary cosmology  $H$  is not a constant; it is a function of the age of the Universe. If we want the mass  $m_{\pi}$  in (A1) to be a constant, we must deal with the problem of a variable  $H$ . As a possible solution, Dirac [39] suggested that the ratio  $H/G$  does not vary with cosmological time. This implied that  $G$  would

also vary with time (it would, in fact, decrease). According to Dirac, the reason why the gravitational force is so weak today is thus, because the Universe is so old. This would be a beautiful theoretical explanation of the weakness of gravity. Unfortunately, Dirac's hypothesis is in conflict with observation; in particular, it provides a wrong age of the Universe [40].

A paradigm shift in consideration of (A1) was proposed recently [38]. There is evident asymmetry of the right-hand side of relation (A1); all the most fundamental physical constants ( $\hbar, c, G$ ) are included but only one isolated cosmological parameter  $H$ . It leads to the idea that the right-hand side is incomplete and that with the inclusion of other cosmological parameters it can have a value that does not change with the expansion of the universe. Of course, the way in which the right-hand side must be completed depends on the content of the universe, i.e. on the characteristics of the used cosmological fluids which determine the transformation laws (9). For instance (see for details the reference [38]) we can right respectively

$$m_{\pi}^3 = \frac{\hbar^2}{cG} H \left\{ \frac{\Omega_{\Lambda} R_0}{\sqrt{\Omega_{tot} - 1} R} \right\}, \quad m_{\pi}^3 = \frac{\hbar^2}{cG} \left\{ \frac{\Omega_v}{\sqrt{\Omega_{tot} - 1}} \right\} \quad (A2)$$

for cosmological fluids with  $n = 0$  (corresponding to the dark energy interpreted as the cosmological constant) and  $n = 1$  (corresponding to the maximum magnitude of the negative pressure in Section 9). The factor that completes Dirac's relation (A1) is put in brackets. Relations (A2) are free of problems of the original relation (A1) and even more intriguing and appealing.

Other coincidences can be found in [14 and 37]

## Appendix B

### The gravitational bound charge distribution around a spherical body

In two limits ( $r \ll R_{sat}$  and  $r \gg R_{sat}$ ), the function  $P_g(r)$  must behave as

$$P_g(r \ll R_{sat}) = P_{g \max}, \quad P_g(r \gg R_{sat}) = \frac{P_{g \max} R_{sat}}{r} \quad (B1)$$

Our understanding of the quantum vacuum is not sufficient to find function  $P_g(r)$  within the rigorous approach of quantum field theory. Fortunately, in spite of absence of detailed knowledge, we can get a crude approximation from consideration of an ideal system of non-interacting dipoles in an external gravitational field. Hence, we consider the gravitational polarization of the quantum vacuum as analogous to polarization of a dielectric in external electric field, or a paramagnetic in an external magnetic field [42]. If so, paramagnetic ideal gas, ideal gas of electric dipoles and ideal gas of gravitational dipoles are three mathematically equivalent models.

It is well established in quantum mechanics that an electric dipole in an external electric field (or a magnetic dipole in an external magnetic field) can have only a finite number  $n_e$  of different energies. In other words, the angle between the direction of the field and the direction of the dipole can have only  $n_e$  different values. The same should be true for an ideal system of non-interacting gravitational dipoles.

The simplest physical case is  $n_e = 2$  when dipoles can point only in two directions, in the direction of the field and opposite to the field; with the corresponding energy levels  $-\varepsilon$  and  $+\varepsilon$  which depend on  $r$ . In this case, the partition function for a system of  $N$  non-interacting dipoles is

$$Z = \left( e^{\varepsilon/k_B T} + e^{-\varepsilon/k_B T} \right)^N = 2^N \cosh \left( \frac{\varepsilon(r)}{k_B T} \right) \quad (B2)$$

where  $k_B$  is the Boltzmann constant and  $T$  the absolute temperature of the quantum vacuum.

From the partition function  $Z$ , it is easy to calculate the thermal average of the dipole moment and the corresponding polarization density

$$P_g(r) = P_{g \max} \tanh\left(\frac{\varepsilon(r)}{k_B T}\right) \quad (\text{B3})$$

It remains to show that

$$\frac{\varepsilon(r)}{k_B T} = \frac{R_{sat}}{r} \quad (\text{B4})$$

and then distribution

$$M_v(r) = 4\pi r^2 P_{g \max} \tanh\left(\frac{R_{sat}}{r}\right) \quad (\text{B5})$$

trivially follows from equation (31).

From purely mathematical point of view, relation (B4) follows from the demand that  $P_g(r)$  determined by equation (B3) has limits given by (B1).

Of course physical reasons are always preferable to mathematical ones. While it will be subject of a forthcoming publication, let us give an initial physical argument that  $k_B T$  and  $R_{sat}$  are inversely proportional as in equation (B4). Physically there is a competition between energy  $\varepsilon$  (favoring alignment of dipoles) and energy  $k_B T$  (favoring randomness in orientation). The mean distance between two dipoles which are the first neighbors is  $\lambda_m$ . The gravitational acceleration produced by a particle of mass  $m$  at the distance of its own Compton wavelength  $\lambda_m$  is  $Gm/\lambda_m^2$ ; in the absence of more accurate estimates, this acceleration can be used as a rough approximation of the external gravitational field which is needed to produce the effect of saturation for the dipoles of mass  $m$ . In a similar way, the energy of gravitational interaction between two particles of mass  $m$  at the distance of the corresponding Compton wavelength may be used as approximation for the energy  $k_B T$ , i.e.  $k_B T \propto Gm^2/\lambda_m$ . Hence  $k_B T$  is inversely proportional to  $\lambda_m$  and because of the direct proportionality (25) it is also inversely proportional to  $R_{sat}$ .

For completeness, let us underline that equation (B5) is a special case ( $J = 1/2$ ) of

$$M_v(r) = 4\pi r^2 P_{g \max} B_J\left(\frac{R_{sat}}{r}\right) \quad (\text{B6})$$

where  $B_J(x)$ , with  $J$  being a positive integer or half-integer, denotes Brillouin function

$$B_J(x) = \frac{2J+1}{2J} \coth\left(\frac{2J+1}{2J}x\right) - \frac{1}{2J} \coth\left(\frac{1}{2J}x\right) \quad (\text{B7})$$

Of notable interest, the Brillouin function is best known for arising in the calculation of the magnetization of an ideal paramagnet. In particular, it describes the dependency of the magnetization  $M$  on the applied magnetic field  $B$  and the total angular momentum quantum number  $J$  of the microscopic magnetic moments of the material. In the analogous way the Brillouin function describes how the electric polarization density of an ideal dielectric depends on the external electric field. Hence, it should not be a surprise if the gravitational polarisation density of the quantum vacuum can be approximated by use of a Brillouin function.

The value of  $J$  should be related to the number of degrees of freedom of the appropriate virtual constituents of the quantum vacuum. For instance, as we know from quantum field theory, a *massless* spin-1 particle (like photon or gluon) has two degrees of freedom that can be related with  $J = 1/2$ , effectively the same as if they were fermions. Of course, virtual dipoles with three degrees of freedom cannot be excluded. It is easy to show that

$$\frac{2}{3} < \frac{B_1(x)}{B_{1/2}(x)} < 1 \quad (\text{B7})$$

Since the mass of a galactic dark matter halo is not constrained better than a factor of two [42], relation (B6) indicates that the present day precision of measurements is not sufficient to distinguish between Brillouin function with  $J = 1/2$  and  $J = 1$ . However it is important to keep in mind that more precise observational findings might provide information about the number of degrees of freedom of virtual gravitational dipoles.

Let us end noting that for illustrative purposes the right-hand side of (B5) can be multiplied with  $\tanh(R_{p \text{ max}}/r)$  what leads to equation (54) in which the gravitational bound charge asymptotically approaches a maximum value.

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