The basis for a new model of the universe

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Outline

- Mass-energy content of the Universe according to the Standard Model of Particles and Fields
- Fundamental problems revealed by Astronomy that cannot be explained by the known physics
- **A surprise**

Two “wild” hypotheses

(1) quantum vacuum fluctuations are virtual gravitational dipoles

(2) Baryonic matter(more precisely the Standard Model matter) and quantum vacuum are ***the only*** *matter-energy content of the Universe*

Outline

- The major consequences of these two hypotheses 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 gravitational polarization 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

Outline

- The major consequences (continuation)
  4. There is no need for an inflation field of unknown nature in the primordial universe

Of course, it would be wrong to say that problems are solved, but it is intriguing that, at least mathematically, the conjecture that quantum vacuum fluctuations behave as gravitational dipoles, provides the encouraging initial answers to so many different fundamental questions

Mass-energy content of the Universe according to the Standard Model of Particles and Fields

Our best fundamental knowledge

- **Standard Model of Particles and Fields** *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^+, W^- and Z^o for weak interactions)
- **General Relativity** our best theory of gravitation

The States of matter in the Standard Model

The Standard Model matter might be in different states

- **the familiar states**: gas, liquid, solid, plasma in stars, quark-gluon plasma... This is what in Astrophysics and Cosmology is called *baryonic* matter – a well established part of the matter-energy content of the Universe.

- **Quantum vacuum**, a counterintuitive state but as real as the familiar states of matter-energy

"**nothing's plenty**"

Physical 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).

The mass-energy content of the Universe

According to the Standard Model of Particles and Fields the content of the Universe has two components

Baryonic matter

and

Quantum vacuum

However, 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 (remember the cosmological constant problem).

What we know about quantum vacuum

1. The Standard Model of Particles and Fields is 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. Quantum vacuum is inherent part of the Standard Model.
2. Quantum vacuum is a state with perfect *symmetry* between matter and antimatter; a particle *always* appears in pair with its antiparticle

What we know about quantum vacuum

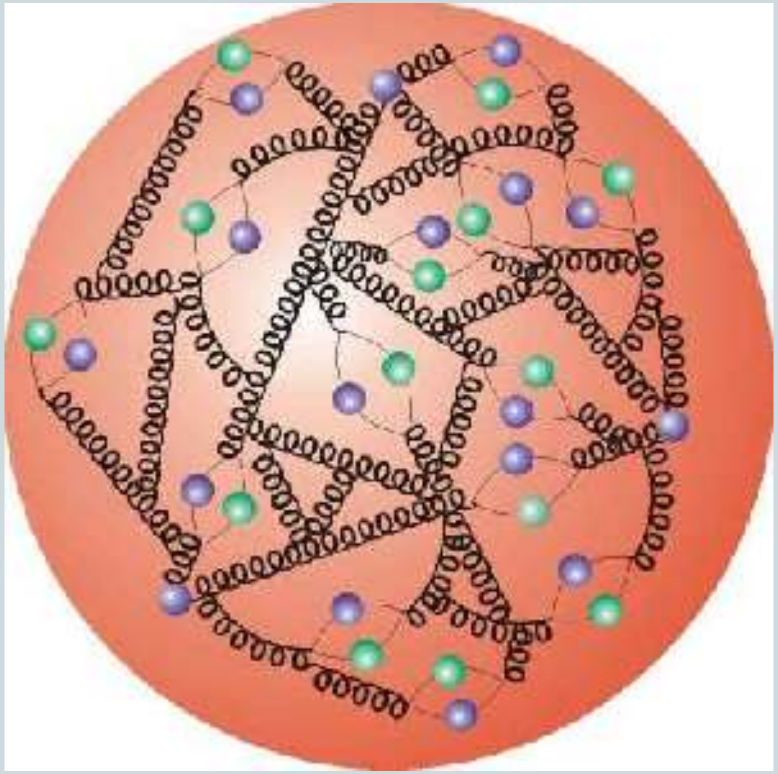
3. Contrary to all other states of matter-energy which are composed from the long living particles (electrons and protons in stars and flowers, have existed before them and will exist after them), the quantum vacuum is a state with extremely *short living* virtual particles and antiparticles (for instance, the lifetime of a virtual electron-positron pair is only about 10^{-21} seconds).

What we know about quantum vacuum

4. Quantum vacuum has measurable impact (Lamb shift) on “orbits” of electrons in atoms
5. Virtual pairs of charged particles (for instance, electron-positron or quark-antiquark pairs) *behave as virtual electric dipoles*. Consequently, in an external electric field, there is the *polarization of the quantum vacuum*, analogous to the familiar polarization of a dielectric. In particular, because of such polarization (vacuum *screening*) the observed charge of an electron , or equivalently the fine structure constant is position dependent – the measured electric charge increases with decrease of distance.

What we know about quantum vacuum

6. 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
- Switching off the quantum vacuum in the Universe would destroy protons and neutrons! Quantum vacuum is the root of our existence!

What we know about quantum vacuum

7. Quantum vacuum fluctuations might be converted into real particles; we can create something from "nothing"
   - Dynamic Casimir effect, i.e. creation of photons from the quantum vacuum was performed two years ago
   - Schwinger's mechanism: 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.

More about Schwinger's mechanism

- 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

$$\frac{dN_{m\bar{m}}}{dtdV} = \frac{c}{\lambdabar^4}\left(\frac{a}{a_{cr}}\right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\frac{a_{cr}}{a}\right), \quad a_{cr} \equiv \pi \frac{c^2}{\lambdabar_m}$$

$$\lambdabar_m = \frac{\hbar}{mc}, \textit{ the reduced Compton wavelength}$$

Fundamental problems revealed by observations that cannot be explained by the known physics

Fundamental problems revealed by observations

The sophisticated astronomical observations have revealed five major phenomena which are surprise and mystery for physics:

1. The expansion of the universe is accelerating
2. 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)

As a potential solution to these problems, mainstream invokes dark energy and dark matter

Fundamental problems revealed by observations

3. Our universe is apparently dominated by matter in spite of the strong evidence that particles and antiparticles are always created in the same quantities

   Mainstream believes that solution to this problem is a hypothetical CP violation many orders of magnitude stronger than experimentally established CP violation

Fundamental problems revealed by observations

4. The Big-Bang model *contradicts* observations (for instance the homogeneity and isotropy revealed by the study of the CMB)

In order to reconcile the Big-Bang model with the empirical evidence, the mainstream invokes ad hoc assumption of cosmic inflation (in the primordial universe) driven by a fundamental scalar field of unknown nature

Fundamental problems revealed by observations

5. Quantum vacuum (together with dominant hypothesis that gravitation is always attraction) leads to the cosmological constant problem i.e. the predicted gravitational effects of the quantum vacuum are many orders of the magnitude greater than permitted by experimental evidence. In fact, the cosmological constant problem is the obstacle to consider quantum vacuum as the major component of the content of the universe.

Reconsidering the gravitational properties of the quantum vacuum

Two "wild" hypotheses

(1)Quantum vacuum fluctuations are virtual gravitational dipoles

*(2)Baryonic matter (more precisely the Standard Model matter) and quantum vacuum are **the only** matter-energy content of the Universe*

Notes

- A virtual gravitational dipole is defined in analogy with an electric dipole: two gravitational charges of the opposite sign at a distance smaller than the corresponding reduced Compton wavelength
- We do not enter the theoretical debate if there is gravitational repulsion between matter and antimatter; we just study the consequences. While majority argues against gravitational repulsion there are also significant arguments for (Villata, 2011)

Gravitational polarization density

- Each virtual gravitational dipole may be characterized with the gravitational dipole moment $\vec{p}_g$
- The magnitude of gravitational dipole moments has a universal upper bound

$$\left|\vec{p}_g\right| \leq \frac{\hbar}{c}$$

- Gravitational polarization density $\vec{P}_g$

  i.e. the gravitational dipole moment per unit volume, *may be attributed to the quantum vacuum.*

(Hajdukovic, 2011a,b)

Gravitational bound charge density

- In a dielectric medium the spatial variation of the electric polarization generates a charge density 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 physical vacuum

$$\rho_v = -\nabla \cdot \vec{P}_g$$

- *Gravitational bound charge density* (caused by the baryonic matter immersed in the quantum vacuum) *might produce effects attributed to dark matter*.

(Hajdukovic, 2011a,b) Hajdukovic (2014a)

The gravitational polarization - saturation

- The simplest possible case of **the gravitational polarization of the quantum vacuum** is *saturation* i.e. the case when as the consequence of a sufficiently strong external gravitational field, all dipoles are aligned in the same direction; the gravitational polarization density has the maximal magnitude

$$P_{g\max} = \frac{A}{\lambda_m^3}\frac{\hbar}{c}$$

$A < 1$ is a dimensionless constant of order of unity (as a theoretical approximation we use the value $A = 1/2\pi$)
(Hajdukovic 2011a) Hajdukovic, 2014a)

The cosmological constant problem

- Quantum vacuum fluctuations are gravitational dipoles - *the simplest candidate for the solution of the cosmological constant problem*
- *Without baryonic matter immersed in it*, virtual dipoles are *randomly oriented*. Hence the corresponding gravitational polarization density, gravitational charge density and cosmological constant are equal to zero.
- a small non-zero value of the cosmological constant might emerge only as a result of the immersed matter (Hajdukovic, 2011b)

Gravitational field around a spherical body

Gravitational field around a spherical body

What is the contribution of the quantum vacuum to the gravitational field around a spherical body?

In the case of spherical symmetry the general equation for the gravitational bound charge density

$$\rho_v = -\nabla \cdot \vec{P}_g$$

reduces to

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

(Hajdukovic 2011a) (Hajdukovic, 2014a)

Gravitational field around a spherical body

- The region of saturation: a spherical shell with the inner radius R_b (the radius of the body with the baryonic mass M_b) and the outer radius R_{sat} estimated to be (Hajdukovic, 2011a, 2014a)

$$R_{sat} \approx \lambda_m \sqrt{\pi \frac{M_b}{m_\pi}}, \; m_\pi \; and \; \lambda_m \; correspond \; to \; a \; pion$$

- In the region of saturation, the gravitational bound charge density of the quantum vacuum and the effective gravitational charge within the sphere of radius r are

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

Gravitational field around a spherical body

- Important conclusion: 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

$$g_{v\max} = \frac{GM_v(r)}{r^2} = 4\pi G P_{g\max}$$

- This relation can be used to determine the maximum of the gravitational polarization density of the quantum vacuum and to test the theory (Hajdukovic, 2013a, 2014b; Gai and Vecchiato 2014)

Gravitational field around a spherical body

Region of decreasing gravitational polarization density

- 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) leads to approximation (Hajdukovic 2014c)

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

R_{ran} is a critical radius. For $r > R_{ran}$ the function $M_v(r)$ doesn't increase more with distance and has a constant value $M_{v\max}$

Summary

According to current theory, *the gravitational charge* of a spherical body is a constant; hence two observers at different distances from the body measure *the same* gravitational charge. In our theory, the effective gravitational charge of a body is a sum of the constant baryonic mass and the component caused by the gravitational polarization of the quantum vacuum, i.e.

$$M(r) = M_b + M_v(r)$$

Gravitational field around a spherical body

- Summary (continuation)

A baryonic body resides in a halo of the polarized quantum vacuum

Two observers at different distances $r < R_{ran}$ *from the body measure different gravitational charges.*

Local effects of quantum vacuum instead of dark matter in a Galaxy

Quantum vacuum and dark matter

The mainstream paradigm

- Baryonic matter of a galaxy resides in a *halo of dark matter* made of unknown non-baryonic particles

The quantum vacuum paradigm

- Baryonic matter of a galaxy resides in a *halo of the gravitationally polarized quantum vacuum*

Quantum vacuum and dark matter

Previous result: the effective gravitational charge of the quantum vacuum within the sphere of radius *r*

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

For $r >> R_{sat}$ we may use it as approximation for a galaxy

$$M_v(r) \approx 4\pi P_{g\max} R_{sat}\, r, \quad r < R_{ran}$$

$$M_v(r) \approx const, \; r > R_{ran}$$

(Hajdukovic 2013a, 2014a,c) and a paper in preparation

Quantum vacuum and dark matter

- The size and the effective gravitational charge of the polarized quantum vacuum halo of a galaxy increases if the distance from other galaxies increases.
- However, when the maximum possible size of a galactic halo is reached, the further increase of distance from the other galaxies do not change the effective gravitational charge
- From the cosmological point of view, in the period of the increase of the effective gravitational charge, it *must be modeled with a perfect fluid with non-zero pressure*, contrary to dark matter which is modeled with presureless fluid (Hajdukovic 2014, in preparation)

Quantum vacuum and dark matter

The mainstream paradigm

- Quantity of dark matter in the Universe is a *constant*; in Cosmology dark matter is modeled by a presureless fluid

The quantum vacuum paradigm

- The total effective gravitational charge of the quantum vacuum in the Universe *is not a constant*; it depends on the distribution of the baryonic matter and the size of the scale factor in the cosmological field equations.

(Hajdukovic 2014, in preparation)

Global effects of quantum vacuum instead of dark energy

Quantum Vacuum instead of dark energy

- Already shown (Hajdukovic 2011b, 2013b) that hypothesis of virtual gravitational dipoles gives the correct order of magnitude for the present day gravitational charge density of the quantum vacuum

$$\rho_{de} \propto \frac{m_\pi}{\lambda_\pi^2 R(t)}$$

R(t) is the scale factor from the cosmological field equations

Our result is essentially the wrong result (cosmological constant problem) multiplied by $\lambda_\pi / R(t)$ as it must be if we work with gravitational dipoles

Quantum Vacuum instead of dark energy

(Hajdukovic 20014, in preparation)

- If what we call dark matter is the effective gravitational charge of the quantum vacuum polarized by the immersed baryonic matter, this effective gravitational charge increases with the scale factor of the Universe R(t) before to reach a constant value.
- Hence, in the stage of increase of the effective gravitational charge it must be modeled by a perfect fluid with pressure and acts as dark energy.
- In the stage of nearly constant effective gravitational charge quantum vacuum does not produce the effect of dark energy, just attraction. The expansion might be reversed to the collapse.

Cyclic universe alternatively dominated by matter and antimatter?

Cyclic Universe?

- The current expansion of the universe might be reversed to contraction
- When the scale factor R(t) of the Universe is sufficiently small the gravitation is so strong that virtual particle-antiparticle pairs might be created through the gravitational version of the Schwinger mechanism.
- The qualitative picture of the expected phenomena, supported by calculations using the Schwinger formula and the cosmological field equations (Hajdukovic 2011b, 2014b,d) is very simple and beautiful.

Cyclic Universe

- An extremely strong gravitational field 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.

Matter-antimatter asymmetry

- 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.

Future Tests

Future Tests

Astronomical observations

(Gai and Vecchiato, 2014)

Tests at CERN

- The ALPHA Collaboration; A.E. Charman. Description and first application of a new technique to measure the gravitational mass of antihydrogen, Nat. Commun. 4 (2013) 1785. http://dx.doi.org/10.1038/ncomms2787
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Appendix- Cosmological field equations

The cosmological principle (i.e. the statement that at any particular time the Universe is isotropic about every point) determines the Friedman-Robertson-Walker metric

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

where k=+1, k=-1 and 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)*.

Appendix- Cosmological field equations

- Assuming that the cosmological fluid in fact consists of several distinct perfect fluids denoted by *n*, leads to the cosmological field equations, which may be written in the form:

$$\ddot{R} = -\frac{4\pi G}{3} R \sum_n \left(\rho_\mathrm{n} + \frac{3p_\mathrm{n}}{c^2} \right)$$

$$\dot{R}^2 = \frac{8\pi G}{3} R^2 \sum_n \rho_\mathrm{n} - kc^2$$

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