

Quantum vacuum and the gravitational repulsion between matter and antimatter: a key for the understanding of the Universe?

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- Our best physics

The Standard Model of Particles and Fields

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General Relativity

is considered as insufficient to explain the observed phenomena in Astrophysics and Cosmology.

- Contemporary Cosmology considers the physics as a very incomplete theory and as a solution invokes two mysterious forms of matter-energy (dark matter and dark energy) and two mechanisms of unknown nature, that are needed to assure the matter domination and a period of inflation in the early Universe.
- I suggest that the major unexplained phenomena in Astrophysics and Cosmology can be understood in the framework of the established physics “enriched” with the hypothesis of the gravitational repulsion between matter and antimatter; a hypothesis with the far-reaching consequences for the gravitational properties of the quantum vacuum and through it for the Universe.

Matter-antimatter asymmetry in the Universe

- It seems that our Universe is dominated by matter.
- No one knows why.
CP violation is one possible explanation, but in order to produce such a huge effect, the CP violation must be much larger than the observed one.
- Hence, the current hope that CP violation is a solution is based on another hope that there is a still unknown mechanism to assure a sufficiently large CP violation.

Dark matter

- The observed gravitational field (in galaxies and at larger scales than galaxy) is much stronger that it should be, according to the existing quantity of the baryonic* matter and the fundamental law of gravity.
- The current attempts to explain the anomalous gravitational field invoke or dark matter of unknown nature or an ad-hoc modification of the law of gravity (for instance MOND)

*In the cosmological jargon “baryonic” mean the matter made of quarks and leptons interacting through exchange of gauge bosons

Dark energy

- **The expansion of the Universe is accelerating.**
- No one knows why. Our ignorance is hidden behind the words “dark energy”.
- Mathematically, the accelerated expansion can be described by the cosmological constant term in the Einstein’s equation. But the physical origin of the cosmological constant is not known.
- The Standard Cosmological Model fits the observations, without understanding of the underlying physics.

The cosmological constant problem

- The most elegant and natural solution would be to identify dark energy with the energy of the quantum vacuum predicted by the Quantum field Theory (QFT)
- Unfortunately, the energy density of the quantum vacuum, predicted by QFT is more than 40 orders of magnitude greater than the observed dark energy density and the corresponding cosmological constant:

$$\rho_{de} \approx 7.2 \times 10^{-27} \text{ kg/m}^3; \quad \Lambda = \frac{8\pi G}{c^2} \rho_{de} \approx 1.4 \times 10^{-52} \text{ m}^{-2}$$

- This discrepancy, called the cosmological constant problem, is the principal obstacle in the attempt to interpret dark energy as the quantum vacuum energy

Inflation in the early Universe

- Without “inserting” a brief interval of inflation in the early Universe, the Big Bang Cosmology is in conflict with observations.
- Inflation is a hypothetical period of extremely rapid exponential expansion that lasted from about 10^{-35} to 10^{-32} seconds after the Big Bang, increasing the size of the Universe about 30 orders of magnitude!
- No one knows the mechanism for such a monstrous expansion, but Big Bang Cosmology doesn't work without it.

Quantum vacuum and the negative gravitational charge of antiparticles

- *Quantum vacuum (in simple words an “ocean” of virtual particle-antiparticle pairs) is a physical reality.*
- Experiments have confirmed many phenomena related to the quantum vacuum; for instance the static and dynamic Casimir effect and the dependence of the fine structure constant on the distance.
- Contrary to the reality of the quantum vacuum, the gravitational repulsion between matter and antimatter is only a hypothesis, that is already 50 years old and has never been tested.

- *The hypothesis of the gravitational repulsion between particles and antiparticles has never been combined with the well established fact of the existence of the quantum vacuum.*
- *This combination “converts” the quantum vacuum into a “fluid” of virtual gravitational dipoles. It seems that such a quantum vacuum (that interacts gravitationally with the immersed baryonic matter) can explain the phenomena usually attributed to the dark matter and dark energy and can resolve the cosmological constant problem.*

- *In addition, in a very strong gravitational field (that may exist deep inside the horizon of a black hole or in the early Universe) the virtual pairs may be converted into real ones. Such a gravitational version of the Schwinger mechanism (well known in the Quantum Electrodynamics) may be related to the problem of inflation and appearance of matter antimatter asymmetry in the early Universe.*
- As we shall see the first (simplified) theoretical calculations are in surprising agreement with the observations.
- Of course, it is too early to say that the quantum vacuum and the negative gravitational charge of antiparticles can be a solution to the most fundamental problems in Physics, Astrophysics and Cosmology, but it is a possibility that shouldn't be neglected.

- The simplest way to postulate a gravitational repulsion between matter and antimatter is

$$m_i = m_g; \quad m_i = \bar{m}_i; \quad m_g + \bar{m}_g = 0$$

where m_i and m_g denote the inertial mass and the gravitational charge.

Consequence 1: the gravitational dipoles

A virtual particle-antiparticle pair is a system with zero gravitational charge, but a non-zero gravitational dipole moment:

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

The vector \vec{d} is directed from the antiparticle to the particle, and has a magnitude equal to the distance between them. The inequality follows from the fact that the size of the virtual pair must be smaller than the reduced Compton wavelength (for larger separation a virtual pair becomes real).

Consequence 2: A small cosmological constant

The gravitational charge of the quantum vacuum is zero (in the same way as the electric charge is zero). Because of this cancelation of the gravitational charges, the quantum vacuum, if not perturbed by the gravitational field of the long-living baryonic matter, naturally has the cosmological constant equal to zero. A small non-zero cosmological constant may be result of dipole effects.

Consequence 3: The gravitational vacuum polarization as origin of phenomena attributed to dark matter

If the quantum vacuum “contains” the virtual gravitational dipoles, *the gravitational field of a body immersed in the quantum vacuum, may produce vacuum polarization*, characterized with a gravitational polarization density \vec{P}_g (i.e. the gravitational dipole moment per unit volume).

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

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

This relation allows to interpret “dark matter” as the gravitational polarization of the quantum vacuum by the baryonic matter.

Note: In the simplest case of the spherical symmetry

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

- Consequence 4: conversion of virtual pairs into real ones by a strong gravitational field

A virtual particle-antiparticle pair can be converted into a real pair, by a sufficiently strong external field that attempts to separate particle and antiparticle. In the case of a constant field the exact particle creation rate per unite volume and time was calculated by Schwinger

$$\frac{dN_{m\bar{m}}}{dt dV} = \frac{4}{\pi^2} \frac{c}{\hat{\lambda}_m^4} \left(\frac{g}{g_{cr}} \right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n\pi}{2} \frac{g_{cr}}{g} \right)$$

$$g_{cr}(m) = \frac{2c^2}{\hat{\lambda}_m}$$

$$\text{For } g \gg g_{cr} \quad \frac{dN_{m\bar{m}}}{dt dV} \approx \frac{4}{\pi^2} \frac{c}{\hat{\lambda}_m^4} \left(\frac{g}{g_{cr}} \right)^2$$

g denotes acceleration caused by an electric field in the Schwinger's case and by a gravitational field in our case; $g_{cr}(m)$ is the critical field

Two predictions based on the Schwinger mechanism

- A gravitational field sufficiently strong to create particle-antiparticle pairs, could exist only deep inside the horizon of a black hole with mass M . The significant production of pairs with a mass m is located inside the sphere with the radius

$$R_{Cm} = \frac{1}{2} \sqrt{\hat{\lambda}_m R_S} \equiv L_P \sqrt{\frac{M}{2m}}; \quad R_S = \frac{2GM}{c^2}$$

- The particle-antiparticle creation rate per unite time depends on both, mass M and radius R_H of the black hole

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

A black hole made from matter violently ejects the created antiparticles. If R_H (i.e. the size of a black hole) is very small the conversion of matter into antimatter is very fast.

$$R_{Cn} \approx 10^5 m; \frac{dN_{n\bar{n}}}{dt} > 10^{86} \text{ pairs} / s \approx 10^{59} \text{ kg} / s$$

$$\frac{dN_{M_P \bar{M}_P}}{dt} \approx 10^{136} \text{ pairs} / s \approx 10^{128} \text{ kg} / s$$

Universality of dark matter halo surface density in galaxies

- Our theoretical result: Dark matter halo in a Galaxy has a core with a radius R_c and mass M_c . The surface density has a universal value, well approximated with

$$\frac{M_c}{4\pi R_c^2} = \frac{1}{\sqrt{3}} \frac{m_\pi}{4\pi\lambda_\pi^2} \approx 70 \frac{M_\odot}{pc^2}$$

- Observations: The mean dark matter surface density within one dark halo scale-length (the radius within which the volume density profile of dark matter remains approximately flat) is constant across a wide range of galaxies. This scaling relation holds for galaxies spanning a luminosity range of 14 magnitudes and the whole Hubble sequence.

$$71_{-26}^{+41} M_\odot pc^{-2}$$

Universality of dark matter halo surface density in galaxies

- Note: There is a **core/cusp problem** for the current dark matter theory. Astrophysical observations show a core, while theory predicts a cusp distribution in the central part of the dark matter halo.
- Donato, F. et al. A constant dark matter halo surface density in galaxies. *Mon. Not. R. Astron. Soc.* 397, 1169–1176 (2009) | Article
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- Spano, M. et al. GHASP: an H kinematic survey of spiral and irregular galaxies—V. Dark matter distribution in 36 nearby spiral galaxies. *Mon. Not. R. Astron. Soc.* 383, 297–316 (2008)
- Gentile, G. et al. Universality of galactic surface densities within one dark halo scale-length. *Nature* 461, 627–628 (2009)

- Radial dark matter density

$$\rho_r \equiv \frac{dM_{dm}}{dr} = \frac{B}{\lambda_\pi} \sqrt{m_\pi M_b}; \quad \mathbf{B} \approx \frac{\sqrt{3}}{3}$$

- Tully-Fisher relation

$$V_{rot}^4 = B^2 G^2 \frac{m_\pi M_b}{\lambda_\pi^2}$$

$$m_{\pi}^3 = \frac{\hbar^2}{cG} H \left\{ \frac{\Omega_{\Lambda}}{\Omega - 1} \right\}$$

The right value of the cosmological constant

Summing the zero-point energies of all normal modes of some field of mass m up to a wave number cut-off $K_c \gg m$, QFT (Weinberg, 1989) yields a vacuum energy density (with $\hbar = c = 1$)

$$\langle \rho_{\text{ve}} \rangle = \int_0^{K_c} \frac{k^2 \sqrt{k^2 + m^2}}{(2\pi)^2} dk \approx \frac{K_c^4}{16\pi^2} \quad (1)$$

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

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

where λ_{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 Eq. (4) is 10^{121} times larger than the observed dark energy density (1). If we only worry about zero-point energies in quantum chromodynamics, Eq. (4) is still 10^{41} times larger than the Eq. (1). Even if the Compton wavelength of an electron is taken as cut-off, the result exceeds the observed value by nearly 30 orders of magnitude. This huge discrepancy is known as the cosmological constant problem (See Weinberg, 1989 for more details).

The right value of the cosmological constant

- QFT result without gravitational dipoles

Summing the zero-point energies of all normal modes of some field of mass m up to a wave number cut-off K_c , QFT (Weinberg, 1989) yields a vacuum energy density

$$\langle \rho_{ve} \rangle = \int_0^{K_c} \frac{k^2 \sqrt{k^2 + m^2}}{(2\pi)^2} dk \approx \frac{K_c^4}{16\pi^2}$$
$$\rho_{ve} = \frac{1}{16\pi^2} \left(\frac{c}{\hbar} \right)^3 M_c^4 \equiv \frac{\pi}{2} \frac{M_c}{\lambda_{Mc}^3}$$

- Considering virtual pair as dipoles

$$\rho_{ve} \approx \pi \frac{m_{\pi}}{\lambda_{\pi}^2 R} \quad R \text{ is the scale factor}$$

Very close to the observed values

$$\rho_{de} \approx 7.2 \times 10^{-27} \text{ kg/m}^3; \quad \Lambda = \frac{8\pi G}{c^2} \rho_{de} \approx 1.4 \times 10^{-52} \text{ m}^{-2}$$