Quantum vacuum as the cause of the phenomena usually attributed to dark matter

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Abstract

We show that if quantum vacuum fluctuations are virtual gravitational dipoles, then the phenomena usually attributed to hypothetical dark matter, may be considered as a consequence of the gravitational polarization of the quantum vacuum by the immersed baryonic matter; apparently, at least mathematically, the galactic halo of dark matter can be replaced by the halo of the polarized quantum vacuum. The eventual gravitational effects of the quantum vacuum "enriched" with virtual gravitational dipoles, can be revealed by the study of orbits of tiny satellites in trans-Neptunian binaries (for instance UX 25 and Eris-Dysnomia).

According to the *Standard Model of Particles and Fields* everything is made from quarks and leptons interacting through the exchange of gauge bosons. So far, the Standard Model is the most successful and the best tested theory of all time; together with General Relativity (our best theory of gravitation) it is one of the *two cornerstones* of our fundamental knowledge.

One of the greatest mysteries in contemporary physics is that *in galaxies and clusters of galaxies, the gravitational field is much stronger than it should be according to our theory of gravitation and the existing amount of the Standard Model matter* (note that astrophysicists use "baryonic matter" as a synonym for the Standard Model matter). There are two schools of thinking related to this mystery. According to the first school, *our theory of gravitation is correct*, but the content of the Universe proposed by the Standard Model is *highly incomplete*; additional sources of gravitational field are halos of hypothetical dark matter in which galaxies are immersed. For the second school the content of the Universe proposed by *the Standard Model is correct* but our theory of gravity *must be modified.*

In fact, both schools have in common the incorrect assumption that the matter of the Universe exists in the classical, non-quantum vacuum; hence, *quantum vacuum* [1] *is neglected as the content of galaxies and clusters of galaxies* (but also as the content of our Solar System). If *quantum vacuum is the source of the gravitational field*, any theory that neglects the existence of the quantum vacuum is blind to some crucial gravitational phenomena, and, as a compensation for the lost phenomena, must invoke some artificial mechanisms. The inevitable question is if dark matter and dark energy are such "artificial stuff" which only mimics the phenomena which are in fact caused by the quantum vacuum.

We point out (and it may be the emergence of a third school of thinking) that, if we adopt the working hypothesis that, by their nature, *quantum vacuum fluctuations are virtual gravitational dipoles*, the phenomena usually attributed to hypothetical dark matter, may be considered as a consequence of the gravitational polarization of the quantum vacuum [2, 3, 4, 5, 6, 7] by the immersed baryonic matter within it. An analogous result for dark energy is presented in a separate paper in these proceedings. Let us note that the simplest and the most elegant realization of this hypothesis is, if particles and antiparticles have the gravitational charge of the opposite sign; of course nature may surprise us with a different realization of the gravitational dipoles-like behavior of the quantum vacuum.

It is illuminating to remember that in quantum electrodynamics quantum vacuum behaves [1] as a fluid of virtual electric dipoles. For instance, quantum vacuum, as "ocean" of virtual electric dipoles has a tiny impact (but impact!) on the "orbits" of electrons in atoms. It is known as the Lamb shift [1]. Another important example: An electron "immersed" in the quantum vacuum produces around itself *a halo of non-random oriented virtual electric dipoles, i.e. a halo of the polarized quantum vacuum.* This halo screens the "bare" charge of an electron; what we measure is the effective electric charge which decreases [1, 8] with distance! These phenomena well established within the quantum electrodynamics make more plausible the effects of the eventual existence of virtual gravitational dipoles.

According to our hypothesis we consider a quantum vacuum fluctuation as a system of two gravitational charges of the opposite sign; consequently the total gravitational charge of a vacuum fluctuation is zero but it has a non-zero gravitational dipole moment $\mathbf{p_g}$:

$$\mathbf{p_g} = m_g \mathbf{d}, \ |\mathbf{p_g}| < \frac{\hbar}{c} \tag{1}$$

Here, m_g denotes the magnitude of the gravitational charge, while, by definition, the vector $\mathbf{d}$ is directed from the antiparticle to the particle, and has a magnitude d equal to the distance between them. The inequality in 1 follows from the fact that the size d of the virtual pair must be smaller than the reduced Compton wavelength. Consequently, the gravitational polarization density $\mathbf{P_g}$, i.e. the gravitational dipole moment per unit volume, may be attributed to the quantum vacuum. It is obvious that the magnitude of the gravitational polarization density $|\mathbf{P_g}|$ satisfies the inequality $0 \leq |\mathbf{P_g}| \leq P_{g\,max}$, where 0 corresponds to the random orientations of dipoles, while the maximal magnitude $P_{g\,max}$ corresponds to the case of saturation (when all dipoles are aligned with the external field). The most plausible theoretical estimate [2, 3, 7] is $P_{g\,max} = [0.06 \pm 0.02] kg/m^3 \approx 28.5 M_{Sun}/pc^2$. In addition, following the previous results [2, 3, 5, 7], in calculations concerning dipoles, we use the mass of a pion m_π (which is a typical mass in the physical vacuum of quantum chromodynamics).

In the limit of zero external gravitational field quantum vacuum may be considered as a fluid of randomly oriented gravitational dipoles 1; both the total gravitational charge and $\mathbf{P_g}$ are zero.

Random orientation of virtual dipoles may be broken by the immersed Standard Model matter. Massive bodies (stars, black holes...) but also multi-body systems as galaxies are surrounded by an invisible *halo* of the gravitationally polarized quantum vacuum, i.e. a region of non-random orientation of virtual gravitational dipoles 2. This halo of the polarized quantum vacuum acts as an *effective gravitational charge.* Namely, the spatial variation of the gravitational polarization density $\mathbf{P_g}$, generates a gravitational bound charge density [2, 3, 7] of the quantum vacuum

$$\rho_{q\nu} = -\nabla \cdot \mathbf{P_g} \tag{2}$$

which may explain phenomena usually attributed to dark matter.

In the simplest case of spherical symmetry, the equation 2 reduces to

$$\rho_{q\nu}(r) = \frac{1}{r^2}\frac{d}{dr}\left[r^2 P_g(r)\right]; \ P_g(r) \equiv |\mathbf{P_g}| \tag{3}$$

The most robust solution corresponds to the region of saturation (a sphere with a characteristic radius); the effective gravitational charge of the quantum vacuum is given [2, 3, 7] by

$$M_{q\nu}(r) = 4\pi P_{g\,max} r^2; \ r < R_{sat} \approx \lambda_\pi \sqrt{\pi \frac{M_b}{m_\pi}} \tag{4}$$

It is obvious that in the region of saturation, equation 4 predicts a universal surface density $M_{q\nu}(r)/4\pi r^2 = P_{g\,max}$. In fact, such a surprising surface density (the same for all galaxies!) was observed [9, 10] and presents a surprise and mystery for dark matter paradigm.

According to equation 4, in the region of saturation, the gravitational polarization of the quantum vacuum produces an additional anomalous constant gravitational field oriented towards the centre. If such acceleration exists it causes a retrograde precession of the perihelion of the satellite in a binary; the anomalous acceleration and precession per orbit in radians are respectively [4]

$$g_{q\nu} = 4\pi G P_{g\,max}, \ \triangle\omega_{q\nu} \approx -8\pi P_{g\,max} a^2/\mu \tag{5}$$

Figure 1: Randomly oriented gravitational dipoles (in absence of an external gravitational field)

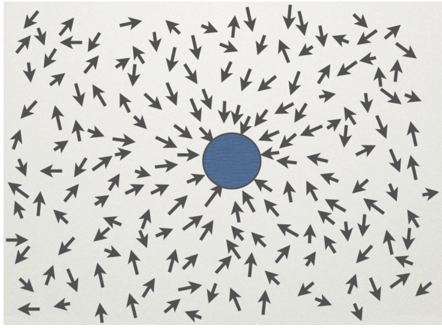

Figure 2: *Halo* of non-random oriented gravitational dipoles around a body (or a galaxy) with baryonic mass M_b

where a and μ are respectively the semi-major axis of the orbit and the total mass of the binary. Transneptunian binaries (mini planets with miniscule satellites, as for instance UX25) are the best natural laboratory [4] to test the prediction 5 that quantum vacuum causes an anomalous perihelion precession (in fact a gravitational version of the Lamb shift!). Astronomers have already started [11] the preparation of the future tests.

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 [6] to the following approximation

$$M_{q\nu}(r) = 4\pi P_{g\,max}\, r^2\, tanh\left(\frac{R_{sat}}{r}\right) \tag{6}$$

valid also for the region $r > R_{sat}$ which is the most relevant for "dark matter" phenomena.

It is encouraging that such a simplified model for a galaxy (spherical symmetry and ideal system of non-interacting gravitational dipoles) gives good results. Let us give a few examples. First, our theory of the gravitational effects of the quantum vacuum leads [2, 3, 7] to the Tully-Fisher relation which is one of the most robust empirical results, unexplained by "dark matter". Let us note that at this point (Tully-Fisher relation) MOND is more successful than "dark matter" theory. The significant success of MOND is a sign that there is something special about their acceleration $a_0 \approx 1.2 \times 10^{-10} m/s^2$. However, according to our model there is not any modification of the Newtons law, as proposed by MOND, for gravitational fields weaker than a_0. In our model, a_0 is rather a transition point, from saturation in stronger fields to non-saturated polarization in weaker fields. Second, according to observations [12] the median Milky Way mass within 260kpc is $M_{MW}(260kpc) = 1.6 \times 10^{12} M_{Sun}$ with a 90% confidence interval of $[1.0 - 2.4] \times 10^{12} M_{Sun}$, while our theoretical estimate [6, 7] is $M_{MW}(260kpc) \approx 1.45 \times 10^{12} M_{Sun}$. Third, apparently the best estimate [13] for the local dark matter density (an average over a small volume, typically a few hundred parsecs around the Sun) is $[0.0075 \pm 0.0021] M_{Sun}/pc^3$ while our theoretical estimate is $\approx 0.0069 M_{Sun}/pc^3$.

Let us end with three important notes-clarifications. First, it is obvious that gravitational field can align only quantum vacuum fluctuations which are gravitational dipoles but not electric dipoles. Second, only a weak interaction such as gravity can polarize large volumes of quantum vacuum and create large galactic halos! Namely, the gravitational acceleration produced by a pion (roughly a typical mass in the physical vacuum of quantum chromodynamics) at the distance of its Compton wavelength is $\approx 2.1 \times 10^{-10} m/s^2$. The mean distance between two dipoles which are first neighbours is one Compton wavelength; hence, the small value of this acceleration indicates that the gravitational polarization can be caused by a very weak gravitational field. Third, and the most important, there is a maximum size of the halo for each massive body, galaxy or cluster of galaxies; simply, after a characteristic size the random orientation of dipoles dominates again. A halo of the maximum size can be formed only if other bodies are sufficiently far; hence galactic halos, and consequently the effective gravitational charge of the Universe, increase with the expansion of the Universe asymptotically reaching a maximum size. The ratio of *the effective gravitational charge* and the baryonic mass of the Universe is not a constant, contrary to the ratio of the quantity of hypothetical dark matter and baryonic matter.

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