

Review

Dark Energy and Spacetime Symmetry

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Abstract: The Petrov classification of stress-energy tensors provides a model-independent definition of a vacuum by the algebraic structure of its stress-energy tensor and implies the existence of vacua whose symmetry is reduced as compared with the maximally symmetric de Sitter vacuum associated with the Einstein cosmological term. This allows to describe a vacuum in general setting by dynamical vacuum dark fluid, presented by a variable cosmological term with the reduced symmetry which makes vacuum fluid essentially anisotropic and allows it to be evolving and clustering. The relevant solutions to the Einstein equations describe regular cosmological models with time-evolving and spatially inhomogeneous vacuum dark energy, and compact vacuum objects generically related to a dark energy: regular black holes, their remnants and self-gravitating vacuum solitons with de Sitter vacuum interiors—which can be responsible for observational effects typically related to a dark matter. The mass of objects with de Sitter interior is generically related to vacuum dark energy and to breaking of space-time symmetry. In the cosmological context spacetime symmetry provides a mechanism for relaxing cosmological constant to a needed non-zero value.

Keywords: dark energy; de Sitter vacuum; spacetime symmetry; relaxing cosmological constant; dark matter; regular black hole remnants; mass and spacetime symmetry

1. Introduction

Dark Energy is described by the equation of state $p = w\rho$ with $w < -1/3$ responsible for accelerated expansion $\ddot{a} \sim -a(\rho + 3p)$. The best fit, $w = -1.06 \pm 0.06$ at 68% CL [1], corresponds to the cosmological constant λ related to the vacuum density ρ_{vac} by $\lambda = 8\pi G\rho_{vac}$.

In the Einstein equations with the cosmological constant $G_{\nu}^{\mu} + \lambda\delta_{\nu}^{\mu} = 0$; $G_{\nu}^{\mu} = -\lambda\delta_{\nu}^{\mu} = -8\pi GT_{\nu}^{\mu}$ the cosmological term corresponds to the de Sitter vacuum (false vacuum in the Standard Model)

$$T_{\nu}^{\mu} = \rho_{vac}\delta_{\nu}^{\mu}; \quad \rho_{vac} = (8\pi G)^{-1}\lambda = const, \quad (1)$$

which is able also to support the inflationary dynamics in the very early Universe. The problem is that the first inflation needs the value at the GUT level $\rho_{vac} \simeq \rho_{GUT} \simeq 5 \times 10^{77} \text{ g}\cdot\text{cm}^{-3}$, the QFT estimates the value of ρ_{vac} by $\rho_{Pl} = 5 \times 10^{93} \text{ g}\cdot\text{cm}^{-3}$ which by many orders of magnitude exceeds the observational value $\rho_{vac} \simeq 3.6 \times 10^{-30} \text{ g}\cdot\text{cm}^{-3}$, and the Einstein equations require $\rho_{vac} = const$.

Alternative models typically impose $\rho_{vac} = 0$ for some reason (still unknown) and introduce a dark energy of a non-vacuum origin which mimics λ when necessary (for a review [2–4]).

In this paper we present the time-dependent and spatially inhomogeneous vacuum dark energy which is intrinsically related to the spacetime symmetry and can be evolving and clustering.

2. Vacuum Dark Energy

2.1. Vacuum Dark Fluid

QFT does not contain an appropriate symmetry to zero out ρ_{vac} , or to reduce it to a certain non-zero value. A relevant symmetry does however exist in General Relativity. It follows from the Petrov classification for the algebraic structure of stress-energy tensors, $T_{\mu}^{\nu} = diag[\rho, -p_1, -p_2, -p_3]$, as intrinsically related to it (via the Einstein equations) the spacetime symmetry.

Eigenvectors of $T_{\mu\nu}$ form a comoving reference frame with a time-like eigenvector representing a velocity. In the Petrov classification the maximally symmetric de Sitter vacuum (1) is denoted by [(III)]—all eigenvalues equal. As a result it has an infinite set of comoving reference frames which makes impossible to fix a velocity with respect to it which is the most general intrinsic property of a vacuum. T_{μ}^{ν} with [(III)] generates the maximally symmetric de Sitter spacetime for any underlying particular model of T_{μ}^{ν} . The isotropic medium is denoted by [I(III)] and anisotropic media by [III].

A maximal symmetry [(III)] can be reduced to [5,6]

$$T_t^t = T_{\alpha}^{\alpha} \quad (p_{\alpha} = -\rho) \tag{2}$$

which represents a vacuum dark fluid invariant under the Lorentz boosts in the α -direction(s) which still makes impossible to single out a preferred comoving reference frame and thus to fix the velocity with respect to a medium specified by (2), but makes density and pressures time- and spatially-dependent. The Petrov classification suggests the following types of vacuum dark fluid [7]: [(III)]—isotropic vacuum dark fluid (de Sitter vacuum); [(II)II], [(III)I], [(II)(II)]—anisotropic vacuum dark fluids, associated with variable cosmological term [6]

$$\Lambda_{\nu}^{\mu} = (8\pi G)^{-1} T_{\nu}^{\mu}; \quad \Lambda \implies \Lambda_t^t = (8\pi G)^{-1} T_t^t. \tag{3}$$

It generates spacetimes which contain regions of the de Sitter vacuum with the restored maximal symmetry; transitions to regions with the reduced vacuum symmetry involve breaking of spacetime symmetry from the de Sitter group.

2.2. Spherically Symmetric Vacuum Dark Energy

A spherically symmetric vacuum dark fluid, defined by $T_t^t = T_r^r$ ($p_r = -\rho$) [5], generates spacetimes with the obligatory de Sitter center [8,9]. Regular spacetimes with the de Sitter center are described by the metric [6,8,9]

$$ds^2 = g(r)dt^2 - \frac{dr^2}{g(r)} - r^2 d\Omega^2; \quad g(r) = 1 - \frac{2G}{r} \mathcal{M}(r); \quad \mathcal{M}(r) = \int_0^r \rho(x)x^2 dx. \tag{4}$$

The number of the spacetime horizons is related to the number of the de Sitter vacuum scales, $N_{horizons} \leq (2N_{vacuum\ scales} - 1)$ [10].

For the case of two vacuum scales a stress-energy tensor for vacuum dark energy connects two de Sitter vacua, at the center and at infinity,

$$T_{\nu}^{\mu} (deSitter) = (8\pi G)^{-1} \Lambda \delta_{\nu}^{\mu} \iff T_{\nu}^{\mu} \implies T_{\nu}^{\mu} (deSitter) = (8\pi G)^{-1} \lambda \delta_{\nu}^{\mu}, \tag{5}$$

and the metric evolves between two de Sitter asymptotics with $\lambda < \Lambda$. Spacetime can have at most 3 horizons and describes five possible configurations shown in Figure 1: regular cosmological black hole within the mass range $M_{cr1} < M < M_{cr2}$, between the event horizon r_b and the internal Cauchy horizon r_a in the universe with the cosmological horizon r_c (Figure 1a); two double-horizon states, $r_a = r_b$ ($M = M_{cr1}$) and $r_b = r_c$ ($M = M_{cr2}$), and two one-horizon states (Figure 1b) [11].

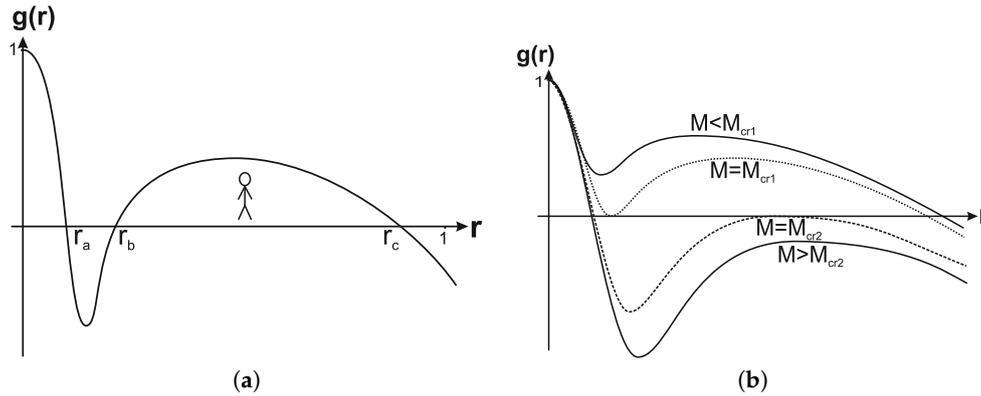


Figure 1. Typical behavior of the metric function $g(r)$ for the case of two vacuum scales.

Dependently on the coordinate mapping, solutions to the Einstein equations with the source term (5) describe cosmological models or compact objects with the de Sitter vacuum interiors.

3. Regular Cosmological Models

Lemaître class cosmological models are described by the metric ([10] and references therein)

$$ds^2 = d\tau^2 - b^2(R, \tau)dR^2 - r^2(R, \tau)d\Omega^2 = d\tau^2 - \frac{E^2(R) - g(r(R, \tau))}{E^2(R)}dR^2 - r^2(R, \tau)d\Omega^2. \quad (6)$$

Coordinates R, τ are the Lagrange (comoving) coordinates. For Lemaître observers, shown in Figure 2 for the case of the one-horizon spacetime with the same global structure as for the de Sitter spacetime (Figure 2 right), for spatially flat models with $\Omega = 1$ evolution starts with the non-singular non-simultaneous de Sitter bang at $(\tau + R) \rightarrow -\infty$ from the regular timelike surface $r(R, \tau) = 0$. It is followed by the anisotropic stage at which the expansion in the transversal direction with $\partial_\tau r > 0$ is accompanied by shrinking in the radial direction where $\partial_R |g_{RR}| < 0$ until $dg(r)/dr < 0$ [10,12].

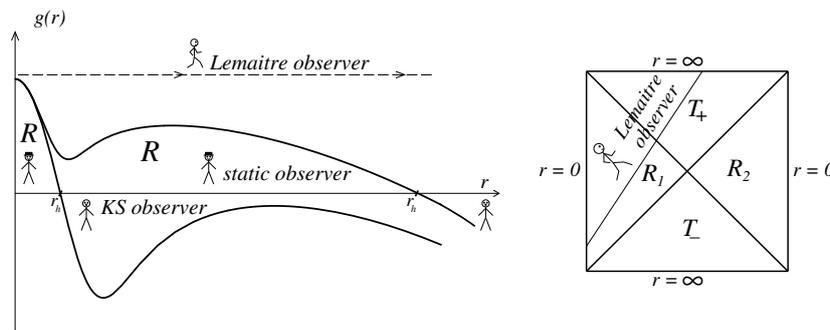


Figure 2. One-horizon spacetimes with vacuum dark fluid.

Regular models of the Kantowski-Sachs type are described by the metric $ds^2 = |g(t)|^{-1}dt^2 - |g(t)|dr^2 - t^2d\Omega^2$. These are homogeneous anisotropic T-models. Evolution starts with a null bang from the Killing horizon (r_h in Figure 2), and pre-bang information from a regular asymptotically de Sitter region behind the horizon r_h is available for KS observers (shown in Figure 2 left) [12].

More general class of regular homogeneous anisotropic T-models is described by the t -dependent metric

$$ds^2 = e^{\alpha(t)}dt^2 - e^{\beta(t)}dx^2 - e^{\gamma(t)}d\Omega^2. \quad (7)$$

Characteristic features of this class models are (i) existence of a Killing horizon; (ii) a null bang from horizon; (iii) pre-bang information available; (iv) creation of matter from anisotropic vacuum [13].

4. Spacetime Singled Out By the Holographic Principle

For the class of metrics (4) the quantum temperature of any horizon is given by [14]

$$kT_h = \frac{\hbar c}{4\pi} |g'(r_h)| \tag{8}$$

The partition function calculated as the path integral for a canonical ensemble of metrics from the class (4), which satisfy $g_{tt}g_{rr} = -1$ and are generated by source terms with $T_t^t = T_r^r$, reads [15]

$$Z(kT_h) = Z_0 \exp \left[\frac{1}{4} \left(4\pi r_h^2 \right) - \frac{1}{kT_h} \left(\frac{|g'|}{g'} \frac{r_h}{2} \right) \right] \exp \left[S(r_h) - \frac{E(r_h)}{kT_h} \right] \rightarrow S_h = \pi r_h^2; E_h = \frac{|g'|}{g'} \frac{r_h}{2}. \tag{9}$$

The specific heat of a horizon is given by [16]

$$C_h = dE_h/dT_h = \frac{2\pi r_h}{g'(r_h) + g''(r_h)r_h}. \tag{10}$$

The Holographic Principle states that the number of quantum degrees of freedom in a spatial volume is bounded from above by its surface area [17]. It is also formulated as the Conjecture: A physical system can be completely specified by data stored on its boundary [18].

Quantum evaporation proceeds with decreasing mass M [16]. In the case of one-horizon spacetime with the de Sitter global structure and two vacuum scales (initial and final) the process directed towards diminishing M starts in the state $M > M_{cr2}$ (Figure 3a). Evaporation results in the state $M = M_{cr2}$ (the Nariai solution) with the negative specific heat according to (10), which is thermodynamically unstable. There exists, however, another possibility presented by the class of one-horizon solutions with the inflection point instead of extrema (Figure 3b). In this case quantum evaporation of the cosmological horizon starts in the state $M > M_{cr}$ and goes towards the triple-horizon spacetime determined by $g(r_t) = g' = g'' = 0$, which define uniquely the final mass M_{cr} , the horizon radius r_t and the key parameter q_{cr} ($q^2 = \rho_\Lambda / \rho_\lambda = \Lambda / \lambda$) [19].

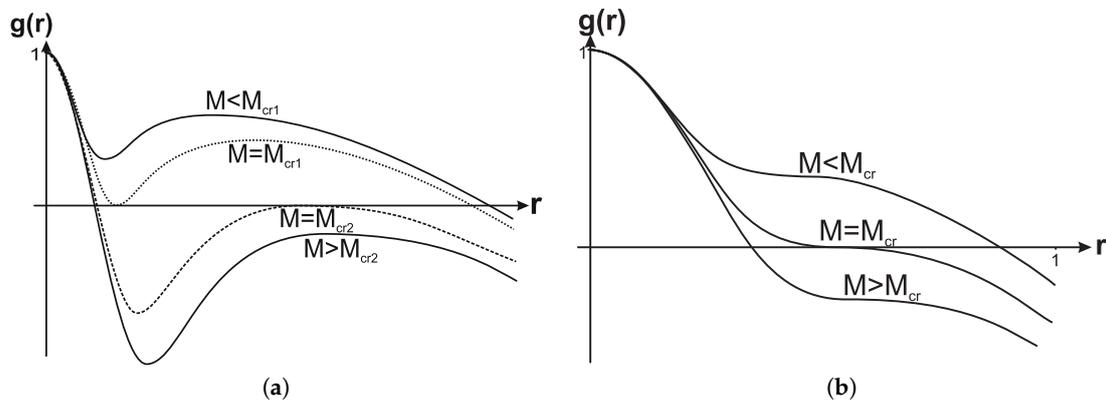


Figure 3. Two options for quantum evaporation of one-horizon spacetimes.

The triple-horizon spacetime is distinguished by quantum dynamics of the cosmological horizon as the only thermodynamically stable final product of its evaporation: Evaporation stops when $T_h = 0$ and $C_h \rightarrow \infty$. What is most important—evaporation stops with the finite non-zero value of the cosmological constant given by the finite value of q_{cr} , so that the spacetime symmetry acts as the symmetry which provides, via the Holographic Principle, the mechanism of relaxing of the cosmological constant to a certain tightly fixed non-zero value.

Choosing a density profile one can calculate the final value of ρ_Λ and compare it with that given by observations. We apply the density profile [5]

$$\rho(r) = \rho_\Lambda e^{-r^3/r_\Lambda^2 r_g}; \quad r_\Lambda^2 = \frac{3}{8\pi G \rho_\Lambda}; \quad \rho_\Lambda = \rho(r \rightarrow 0); \quad r_g = 2GM. \tag{11}$$

It describes vacuum polarization effects, which contribute all together to vacuum polarization in the gravitational field [5], in the simple semiclassical model $\rho \propto \exp(-F_{cr}/F)$, where the gravitational (tidal) force $F \propto r_g/r^3$, and the critical (de Sitter) force $F_{cr} \propto 1/r_\Lambda^2$ [8,20].

Estimate with $\rho_\Lambda = \rho_{GUT}$ and $E_{GUT} \simeq 10^{15}$ GeV, gives $r_t = 5.4 \times 10^{28}$ cm, $M_{cr} = 2.33 \times 10^{56}$ g, and $q_{cr}^2 \simeq 1.37 \times 10^{107}$. Observational value $\rho_\Lambda \simeq 3.6 \times 10^{-30}$ g·cm⁻³ corresponds to $q_{obs}^2 \simeq 1.39 \times 10^{107}$.

5. Regular Compact Objects with de Sitter Vacuum Interiors

5.1. Regular Black Holes and Vacuum Gravitational Solitons G-Lumps

The early proposals of replacing a singularity with the de Sitter vacuum were based on the hypotheses of self-regulation of geometry by vacuum polarization effects [21], of the existence of the limiting curvature [22], and of the symmetry restoration at the GUT scale in the course of the gravitational collapse [5,23]. The first solution describing regular black hole with the de Sitter interior [5] was obtained with the density profile (11). A loop quantum gravity provides arguments in favor of a regular black hole with the de Sitter interior [24–27].

During evaporation a regular black hole with three horizons (shown in Figure 1a) evolves to its extreme state with the double horizon $r_a \rightleftharpoons r_b$ (the curve $M = M_{cr1}$ in Figure 1b). Behavior of temperature of the event horizon shown in Figure 4a, is generic for black holes with the de Sitter center [16,20]. In the maximum of temperature, the specific heat $C_h = dE_h/dT_h$ (shown in Figure 4b) is broken and changes sign, i.e., the second order phase transition occurs which is followed by the quantum cooling [16,20,28]. At the double horizon temperature vanishes while specific heat becomes positive, in accordance with (10).

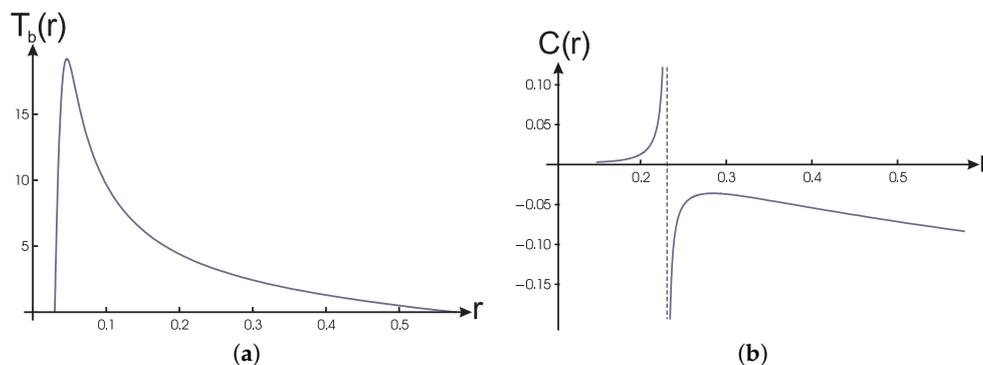


Figure 4. Temperature (a) and specific heat (b) of the black hole horizon.

Maximal temperature at the phase transition is given by $T_{tr} \simeq \alpha T_{Pl} \sqrt{\rho_\Lambda/\rho_{Pl}}$. For the density profile (11) with $\rho_\Lambda = \rho_{GUT}$ and $M_{GUT} \simeq 10^{15}$ GeV, temperature at the phase transition $T_{tr} \simeq 0.2 \times 10^{11}$ GeV [20].

Spacetime without the event horizon (the upper curve, $M < M_{cr1}$, at the Figure 1b) represents a vacuum gravitational soliton G-lump [8,20], a non-singular non-dissipative particle-like structure taking itself together by its own gravitational self-interaction. Energy of G-lump calculated in the minisuperspace model is $E_n = \hbar\omega(n + \frac{1}{2}) - \frac{G.M(r_m)}{r_m} E_{Pl}$; $\omega = \sqrt{p_\perp(r_m)\Lambda c}$, where p_\perp is the transversal pressure (normalized to ρ_Λ) at the minimum r_m of the G-lump potential [8].

Regular black holes, their remnants and self-gravitating vacuum solitons G-lumps with de Sitter vacuum interiors can be responsible for observational effects typically related to a dark matter [29].

5.2. Regular Black Hole Remnants

BH remnants are considered as a reliable source of dark matter for more than three decades [30–32]. Singular black hole remnants are plagued by the existential problem: No evident symmetry or quantum number exists which would prevent complete evaporation [18,33]. On the other hand, complete evaporation would involve a fundamental change in the spacetime structure in the transition from a spacetime with the distinguished center (distinguished by the singularity), the Schwarzschild-de Sitter spacetime $g(r)_{Schw-deS} = 1 - \frac{2GM}{r} - \frac{\lambda}{3}r^2$ (the curve 3 in Figure 5a), to the globally regular maximally symmetric de Sitter spacetime $g(r)_{deS} = 1 - \frac{\lambda}{3}r^2$ (Figure 5b) and actually would require to find an answer to the question—How to evaporate a singularity? [34].

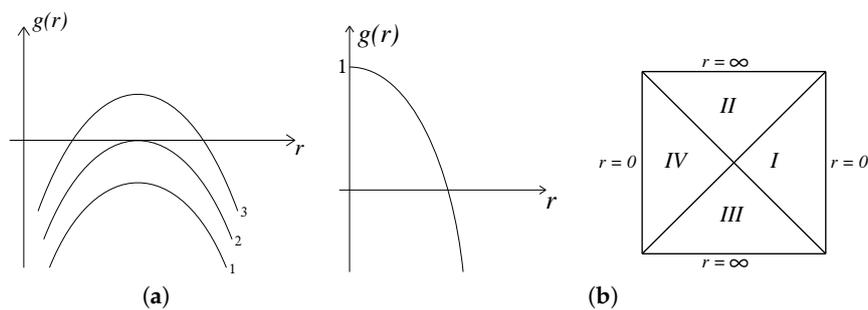


Figure 5. Evolution of the Schwarzschild-de Sitter black hole in the case of complete evaporation. (a) Schwarzschild-de Sitter metric function; (b) De Sitter metric function and global structure.

A regular black hole leaves behind a thermodynamically stable double-horizon remnant generically related to vacuum dark energy through its interior de Sitter vacuum ([16,35] and references therein). Mass of the remnant is given by $M_{remnant} \simeq \beta M_{Pl} \sqrt{\rho_{Pl}/\rho_{int}}$. For the density profile (11) with $\rho_{\Lambda} = \rho_{GUT}$ and $M_{GUT} \simeq 10^{15}$ GeV, the mass $M_{remnant} \simeq 0.3 \times 10^{11}$ GeV [20].

5.3. Graviatoms with the de Sitter Interiors

Regular primordial black holes, their remnants and G-lumps can arise during first and second (100–200 MeV [36]) inflationary stages in a quantum collapse of primordial fluctuations. Probability of tunnelling in a collapse is given by [37]

$$D \geq \exp \left[-4 \left(\frac{M}{M_{Pl}} \right)^{3/4} \left(\frac{E_{Pl}}{E_{infl}} \right) \right] \quad \text{for} \quad \frac{M}{M_{Pl}} \geq \left(\frac{E_{infl}}{E_{Pl}} \right)^4 \left(\frac{E_{Pl}}{E_{int}} \right)^8, \quad (12)$$

where E_{infl} is the scale of the inflationary vacuum. At the first inflation, $E_{infl} = E_{GUT}$, regular objects with the interior de Sitter vacuum $E_{int} = E_{GUT}$ can arise with masses $M > 10^{11}$ g. For $E_{int} = E_{Pl}$ any mass is possible, as well as for regular objects arising at the second inflationary stage, $E_{infl} = E_{QCD}$.

Regular primordial black holes, their remnants and G-lumps can capture available particles and form graviatoms ([37] and references therein) - gravitationally bound ($\alpha_G = GMm/\hbar c$) quantum systems with charged particles. Conditions of the existence of graviatoms [37] constrain the masses of captured particles by $m > 10^9$ GeV for $E_{int} = E_{GUT}$. They can be (i) GUT particles captured at the first inflation; and (ii) leptosquarks survived in galactic haloes [38].

Observational signatures of graviatoms as heavy dark matter candidates provide additional signatures for inhomogeneity of the early Universe [39]. Most promising is the oscillatory electromagnetic radiation of graviatom whose characteristic frequency depends on the scale E_{int} of the interior de Sitter vacuum [37]. For the density profile (11) $\hbar\omega = 0.678\hbar c/r_{deS} = 0.678 \times 10^{11}$ GeV $(E_{int}/E_{GUT})^2$. Detection of cosmic photons is possible up to $10^{11.5}$ GeV [40]. In graviatoms with the GUT scale interiors,

where baryon and lepton numbers are not conserved, a remnant component of graviatom can induce proton decay, which could in principle serve as an additional observational signature of graviatom for heavy dark matter searches at the IceCUBE experiment [39].

5.4. Mass and Spacetime Symmetry

Masses of objects with the de Sitter vacuum interiors are generically related to the de Sitter vacuum and to breaking of spacetime symmetry from the de Sitter group in the origin [8].

In the Standard Model de Sitter vacuum appears as the false vacuum of the Higgs field responsible for particle mass. Calculation of mass in the gravito-electroweak vortex by the Casimir formula in de Sitter space provides explanation for the observational effect known as negative mass-square difference for neutrinos [41,42]. This can also explain appearance of the minimal length scale $l = 1.57 \times 10^{-17}$ cm at the energy scale $E = 1.253$ TeV in the annihilation reaction $e^+e^- \rightarrow \gamma\gamma(\gamma)$ [43]. QED hypotheses applied in the χ^2 -test predict increasing of the total cross section. Contrary to these expectations, the fit displays a minimum with the negative fit parameter with a significance about 5σ . The scale $l_e = 1.57 \times 10^{-17}$ cm fits inside the internal de Sitter region where gravity is repulsive. The minimal length scale l_e can be thus understood as a distance at which electromagnetic attraction is balanced by the gravitational repulsion of the interior de Sitter vacuum [43].

6. Summary and Discussion

Algebraic classification of stress-energy tensors and related (via the Einstein equations) spacetime symmetry implies the possibility to introduce in general setting dynamical vacuum dark energy which can be evolving and clustering. It is presented by the class of regular spherical solutions to the Einstein equations specified by $T_i^t = T_r^r$ ($p_r = -\rho$) which generate the metrics $ds^2 = g(r)dt^2 - g(r)^{-1}dr^2 - r^2d\Omega^2$.

These metrics belong to the Kerr-Schild class and can be presented as $g_{\mu\nu} = \eta_{\mu\nu} + 2f(r)k_\mu k_\nu$, where $\eta_{\mu\nu}$ is the Minkowski metric and k_μ are principal null congruences. This is the special class of algebraically degenerated solutions to the Einstein equations. In the algebraically special Kerr-Schild geometry the Einstein equations take the linear form, $\partial_\mu T_\nu^t = 0$, and pseudotensor of gravitational energy $t_{\mu\nu} = 0$ [44]. They admit decomposition into free-falling (2 + 1)-dimensional shells with the associated conserved stress-energy tensors, each of shells can be treated as a closed system and described by a (2 + 1) Hamiltonian [45].

Regular spherical solutions of the class $T_i^t = T_r^r$ have obligatory de Sitter center, represent dynamical vacuum dark energy on the basis of spacetime symmetry, and describe, dependently on a mapping (reference frame), regular cosmological dark energy models and regular compact objects with the de Sitter vacuum interiors (black holes, their remnants and gravitational solitons).

In the case of two vacuum scales (e.g., for initial inflation and the present accelerated expansion) the Holographic Principle singles out the triple-horizon spacetime as the only thermodynamically stable product of quantum evaporation of the cosmological horizon. What is most important—the spacetime symmetry appears to be that (lacking in QFT) symmetry which provides, via the Holographic Principle, the mechanism of relaxing cosmological constant to a certain non-zero value, tightly fixed by quantum dynamics of quantum evaporation of the cosmological horizon. Choice of the density profile related to vacuum polarization effects and of the GUT scale for the first inflation gives the non-zero final value of the vacuum density in remarkable agreement with its observational value.

Regular compact objects generically related to vacuum dark energy through their de Sitter vacuum interiors, include regular black holes, their remnants and vacuum gravitational solitons G-lumps, which can be responsible for observational effects typically related to a dark matter.

Mass of objects is generically related to breaking of spacetime symmetry from the de Sitter group in the origin which is confirmed by explanation of observational effects in high energy physics.

Conflicts of Interest: The authors declare no conflict of interest.

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