Region of instability of matter as an alternative to gravitational collapse inside black holes

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Abstract – A novel suggestive treatment of black holes in a model of dynamical quantum vacuum defined by a variable energy density is introduced. In this approach, the gravitational collapse of black holes towards an event horizon and a gravitational singularity is replaced by interpreting black holes as dark compact objects, i.e. dark stars, with extremely high density, whose inner region is characterized by a modification of electromagnetic interactions that lead to a decay of matter into elementary particles and then into non-structured energy of the vacuum. Perspectives of solution of the information paradox, in this picture, are introduced.

1. Introduction

Since the original work of Penrose [1], it has been proposed that in the centre of black holes there is a gravitational singularity, where density and gravity interaction become infinite, space and time cease to exist and the laws of physics break down. Despite it is yet unclear whether singularities can even exist in nature or whether they are just an unavoidable mathematical artefact predicted by general relativity when some constraints are satisfied, the idea of gravitational singularities continues today to receive significant attention by the scientific community. Moreover, strictly connected to the concept of gravitational singularities of black holes is the existence of event horizons which, since the pionieristic work of David Finkelstein [2], have been intended as the boundaries beyond which events cannot influence an outside observer, where gravity would be so strong that the escape velocity would be equal to the speed of light. However, the concept of event horizon is problematic because it leads to two famous paradoxes, that put in evidence the conflicts existing between quantum mechanics and general relativity in the physics of black holes, i.e. the information and firewall paradoxes, which are yet waiting to receive a satisfactory solution.

In order to provide new keys of reading in order to overcome the situation of impasse regarding gravitational singularities, horizons and the related paradoxes of black holes, different alternative theories have been emerging. In these new approaches, the concept of singularity in the centre of a black hole is put in discussion. In other words, we deal with attempts to build a non-singular paradigm of black hole physics, in which black holes do not constitute the singular end state of a gravitational collapse.

As regards the development of the physics of non-singular black holes, some approaches, inspired by semiclassical or quantum gravity considerations, typically involve the embedding of effects beyond general relativity, that can be represented through an action including effective matter content that violates energy conditions [3] and/or higher-order curvature terms. Some research propose that new physics kicks in at the onset of horizon formation, such as in the gravastar proposal [4–8], where classical black holes are replaced by black hole mimickers by following a phase transition that provokes the breakdown of general relativity near any horizon. However, this kind of models present the weak point regarding the fact that spacetime curvatures at the onset of horizon formation can be made arbitrarily low for large enough masses, which implies that the existence of a universal mechanism to avoid horizon formation is unlikely [9, 10].

On the other hand, another class of models are based on the consideration that the regime where new physics appears is represented by the Planckian densities. This idea stems from the original works of Sakharov and Gliner regarding the natural emergence of a de Sitter geometry in the description of matter at such extreme densities [11, 12], that later has lead to various kind of models providing a framework for the treatment of regular black hole geometries, such as bounded curvature invariants, semiclassical effects or higher-curvature corrections [13-18].

However, despite the progresses reached by the mathematical machinery regarding the models mentioned above, we must emphasize that most of the issues of the non-singular paradigm of black hole physics have been focused on idealized situations such as static or spherically symmetric spacetimes, while dynamics remains yet unaddressed. How can one provide important contributions to the treatment of the dynamics of black holes in a context where the concept of singularity is avoided? In the paper [19], that provides a comprehensive overview of the area of research of non-singular paradigm of physics (as regards, in particular, regular black holes and black hole mimickers), and which summarizes the results shaped through a week-long workshop held at the Institute for Fundamental Physics of the Universe in Trieste in November 2024, Raul-Carballo Rubio and his coauthors conclude that the future of the non-singular paradigm of black hole physics looks healthy, and the next years will probably see critical advances in this field.

In this paper, our aim is to introduce, inside the non-singular paradigm, an alternative path to treat the dynamics of black holes, that can open compelling scenarios that are worth to be explored. In this regard, we start from a 2014 consideration of Hawking that, in the formation of a black hole, no real event horizon is formed behind which information is lost [20]. Hawking's proposal is that, somehow, the gravitational collapse generates only apparent horizons and does not continue beyond them. In this picture, therefore, there would be no black holes, in the sense of regimes from which light cannot escape to infinity and black holes should be only defined as metastable bound states of the gravitational field. Moreover, Vaz [21] developed the Hawking idea of the apparent horizon, showing that the gravitational collapse till a spacetime singularity covered by an event horizon can be replaced by the formation of essentially quantum objects, spherically symmetric shells, i.e. extremely compact "dark stars". Then, Corda has recently supported the Vaz model of quantum shells as the results of gravitational collapse, by making an estimate, on the basis of the generalized uncertainty principle, of the maximum density of these shells [22].

In this paper, by considering a model of a dynamical quantum vacuum (DQV) defined by a variable energy density, we introduce a new interpretation of black holes which goes beyond the results obtained by Vaz and Corda. In our approach, the fundamental insight lies in the fact that black holes can be seen as a particular kind of stars with high mass density where not only singularity does not exist but also the concept of gravitational collapse can be avoided, in the sense that it can be replaced by regions characterized by an instability of matter, which results in a decreasing of the electromagnetic forces, thus generating an expulsion of jets of fresh gas and electromagnetic radiation in the intergalactic space.

The structure of the paper is the following. In chapter 2, we review the foundations and fundamental features of the model of the DQV, in particular as regards the elementary geometry of the vacuum. In chapter 3, we explore in what sense the inner region of a black hole is characterized by an electromagnetic instability of matter, by taking into consideration the decay of hydrogenoid atoms and heavy quarkonium structure. In chapter 4, we analyse the decay of fermionic collective systems inside the inner region of a black hole and we show that these unstable Fermi plasma is coupled with electromagnetic radiation which is released outside, where this correlation is described by an entanglement entropy which provides a unitary evolution. In chapter 5, we show how, by considering the dissipative features of the DQV, the concept of electromagnetic collapse inside the dark star allows us to obtain results that are equivalent to the results obtained in the recent model of Corda and Vaz which invokes a gravitational collapse till the formation of a dark compact object defined by an apparent horizon and, therefore, in what sense the gravitational collapse can be replaced by an electromagnetic collapse. In chapter 6 we put in evidence how our model can open new perspectives of solution of the black hole information paradox. Finally, in chapter 7 we summarize the main results of the paper.

2. The fundamental features and informational lattice of the dynamical quantum vacuum

The foundational ideas of the DQV model developed by the authors in [23-31] can be synthesized in the following postulates:

1- The medium of space is an isotropic, granular, three-dimensional (3D) "dynamical quantum vacuum" (DQV) constituted by energetic packets having the size of Planck's scale and whose most universal physical property is the energy density.

2- In the free space, without the presence of massive particles, the quantum vacuum energy density is at its maximum and is given by equation

$$\rho_{PE} = \frac{M_{Pl}c^2}{l_P^3} = \frac{\hbar c}{l_P^4} \quad (1)$$

(M_{Pl} being Planck's mass, c the light speed, l_p Planck's length and $\hbar$ Planck's reduced constant) which defines the so-called "ground state" of the 3D quantum vacuum.

3- In the three-dimensional space, the appearance of matter derives from an opportune excited state of the 3D quantum vacuum corresponding to an opportune change of the quantum vacuum energy density. The excited state of the quantum vacuum corresponding to the appearance of a material particle of mass *m* is defined by the energy density

$$\rho_{qvE} = \rho_{pE} - \frac{mc^2}{V} \quad (2)$$

and by the change of the energy density

$$\Delta\rho_{qvE} \equiv \rho_{pE} - \rho_{qvE} = \frac{mc^2}{V} \quad (3),$$

with respect to the ground state, depending on the amount of mass m and the volume V of the particle.

In the model of the DQV, equations (2) and (3) regarding the quantum vacuum energy density and the changes of the quantum vacuum energy density in the centre of a given material objects, are valid for all scales, from the subatomic scale to the scale of supermassive black holes. In particular, as regards stellar objects, they imply that the mass m of a given stellar object can be expressed by the diminished energy density of quantum vacuum in its centre:

$m = \frac{(\rho_{pE}-\rho_{qvE})V}{c^2}$ (4)

where V is the volume of the stellar object and ρ_{qvE} is the quantum vacuum energy density in the centre of the stellar object. Moreover, we underline that gravity inside black holes obeys Newton's shell theorem, and thus its value in the centre is zero [32].

The variable quantum vacuum energy density is the fundamental element which generates the bending of light near stellar objects according to relation

$\Delta\theta \approx \frac{4G}{Rc^2} \frac{(\rho_{pE}-\rho_{qvE})V}{c^2}$ (5),

where $\rho_{pE} = 4.641266 \times 10^{\wedge}113\, Jm^{-3}$ is the quantum vacuum energy density (equal to Planck energy density) in intergalactic space, ρ_{qvE} is the quantum vacuum energy density in the centre of the stellar object, V is its volume, R is its radius, G is Newton's gravitational constant. In particular, as regards the Sun, one finds $\rho_{qvE} = 1.27 \times 10^{20}\, Jm^{-3}$ and thus

$\Delta\theta \approx \frac{4G}{Rc^2} \frac{(\rho_{EP}-\rho_{cE})V}{c^2} = \frac{4\times 6.67\times 10^{-11}}{6.96\times 10^{8}\times 9\times 10^{16}} \times \frac{1.27\times 10^{20}\times 1.412\times 10^{27}}{9\times 10^{16}} = 8.496 \times 10^{-6} \times 206264.86$

$\Delta\theta \approx$ 1.75 arc seconds (6)

in agreement with the results of general relativity [33].

The quantum vacuum energy density and at any point T at a distance $R + d$ from the centre of a given stellar object can be expressed by relation

$\rho_{TE} = \rho_{pE} - \frac{3mc^2}{4\pi(R+d)^3}$ (7), where ρ_{TE} is the energy density of DQV at point T, ρ_{pE} is the energy density of DQV in intergalactic space, m is the mass of the physical object, R is the radius of the object, and d is the distance of point T from the surface of the physical object. Instead, if the point T is inside the stellar object and d<R is the distance from the centre, the quantum vacuum energy density, by using Newton's shell theorem, can be expressed by relation

$$\rho_{TE} = \rho_{SE} - \rho_{qvE} \quad (8)$$

where ρ_{SE} is the quantum vacuum energy density on the surface of the stellar object.

Moreover, the geometric features of the background can be described by invoking the following peculiar specific form of generalized uncertainty relations, which are valid at the Planck scale:

$$\Delta x \Delta p \geq \frac{\hbar}{2}\left(1 + \beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}\right) \quad (9)$$

where β is a fluctuating dimensionless parameter which expresses the fact that here one deals with quantum vacuum fluctuations, associated with virtual particles, that fix the minimal length scale only on average and the term $\frac{\hbar}{2}\beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}$ measures the degree of violations of the Heisenberg uncertainty relations at scales that approach the Planck scale.

The generalized uncertainty relations (9) have been demonstrated to provide a suggestive unification of the quantum regime of elementary particles and the macroscopic regime of black holes, by considering a generalized Compton wavelength given by relation

$$R'_C = R'_S = \sqrt{\left(\frac{\beta \hbar c}{\Delta\rho_{qvE} V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE} V}{\hbar c}\right)^2} \quad (10).$$

The scale (5), by unifying the Compton wavelength and Schwarzschild radius, expresses the existence of a common matrix of virtual proto-particles of the vacuum (living on a variable quantum vacuum energy density) that can give rise to the real elementary particles of microphysics or black holes depending of the cases, under opportune constraints [30, 31]. In other words, one can say that the DVQ intended as the fundamental background of physical processes is constituted by a sea of virtual elementary objects living on a variable quantum vacuum energy density which are defined by the variable scale represented by the generalized Compton wavelength (5) and which encode the information regarding the sea of possibilities that can actualize under opportune constraints on the quantum vacuum energy density. These virtual elementary objects can give origin to the real elementary particles of the Standard Model under the constraint $\frac{\Delta\rho_{qvE}V}{c^2} \ll M_{Pl}$ (where the generalized Compton wavelength (5) tends to the standard value of the Compton wavelength) while can give origin to real macroscopic black holes under the constraint $\frac{\Delta\rho_{qvE}V}{c^2} \gg M_{Pl}$ (where one recovers the standard value of the Schwarzschild radius).

Moreover, in epistemological affinity with the results obtained in [34-36], we consider that these virtual elementary objects of the scale (5) are subjected to RS (reduction-state) processes of creation/annihilation, thus giving rise to a Bose ensemble and that the corresponding energy fluctuations of the DQV generate superfluid features. In this regard, we assume that these superfluid features are expressed by a dissipative hydrodynamics corresponding to elementary modes which can be described by an opportune dispersion relation of the form

$$\omega^2 = c^2\kappa^2 - \frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2V^2}\kappa^4 \quad (11).$$

In equation (11) the wave number κ is determined by the generalized Compton wavelength (10) describing the ultimate (virtual) unified matrix of the world, namely

$$\kappa = \frac{1}{\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2}} \quad (12)$$

and, therefore, the dispersion relation ruling the dissipative processes of the 3D DQV reads:

$$\omega^2 = \frac{c^2}{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2} - \frac{c^4\hbar^2}{\Delta\rho_{qvE}{}^2V^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]^2} \quad (13).$$

The elementary modes of the DQV defined by the dispersion relation (13) can be associated with a wave function whose behaviour generates the dynamics of the processes of the superfluid vacuum. This wave function satisfies a nonlinear Schrödinger-like equation of the form

$$i\hbar\frac{\partial\psi}{\partial t} = \frac{-\hbar^2}{2m}\nabla^2\psi + \nu m|\psi|^2\psi + U\psi \quad (14).$$

In equation (14), m is the mass of each virtual particle of the physical vacuum, U is the potential energy relating to the single virtual particle and ν is a viscosity coefficient having the dimensions $\frac{length^2}{time}$ which can be expressed as $\nu = \frac{a^2 k\omega}{2\pi}$ where a is the scattering length between the virtual particles, ω is the frequency of the elementary modes of the vacuum given by equation (13) and k is an adimensional parameter corresponding to the size of the condensate of virtual sub-particles of the DQV in the region of consideration (namely represents a sort of effective parameter of density of the virtual particles of the medium). The non-linearity of equation (14) emerges as a result of the interactions of the fundamental virtual particles of the 3D DQV, which give rise to states of collective organization. In this superfluid medium, the virtual particles associated to elementary energy density fluctuations continuously appear and disappear, giving rise to a total zero spin, i.e. to an organized Bose ensemble. By virtue of the dissipative features, under opportune constraints, the virtual particles of the 3D DQV can give rise to actualization processes that lead to the appearance of elementary particles of microphysics or material bodies of macrophysics. In this regard, by virtue of the properties of the generalized Compton wavelength (10) in generating the quantum domain of elementary particles or the general relativistic domain of black holes on the basis of opportune constraints, we can say that, before the actualization of the processes, the virtual geometry of the background expressed by the elementary fluctuations associated with the generalized Compton wavelength can be imagined as a sort of ensemble of grains or pixels having variable length. It is the specific fluctuations of the quantum vacuum energy density that determine, through opportune dissipative processes, the actualization of the specific physical domain, i.e. for instance microphysics defined by the standard Compton wavelength of elementary particles or macrophysics defined by the standard Schwarzschild radius of black holes.

3. About the modifications of electromagnetic interactions inside black holes: decay of hydrogenoid atoms and of quarkonium structure

In this paper, we introduce the idea that black holes can be interpreted as dark stars, as dark compact objects, with extremely high density, where the energy density of the quantum vacuum is so low that the inner region is characterized by a modification of the physical laws. In particular, we suggest that the matter of the inner region of the black hole is subjected to a change of the electromagnetic interactions with respect to what happens in the outer intergalactic space.

3.1. From the critical conditions of the quantum vacuum energy density to the diminishing of the Planck constant inside black holes

Taking account that a star can collapse into a black hole if its mass is bigger than 2,9 times of the mass of the Sun, we can compute the quantum vacuum energy density ρ_{qvE-BH} in the centre of a star of 2,9 Solar masses that corresponds to the origin of a black hole, by considering the corresponding Schwarzschild volume:

$$\rho_{qvE-BH} = \rho_{pE} - \frac{2{,}9M_{\odot}c^2}{V_{Sch}} \quad (15)$$

namely

$$\rho_{qvE-BH} = 4{,}641266 \cdot 10^{113} Jm^{-3} - \frac{2{,}9M_{\odot}c^2}{V_{Sch}} = 4{,}641266 \cdot 10^{113} Jm^{-3} - \frac{2{,}9M_{\odot}c^2}{35834\ m^3} = 4{,}641266 \cdot 10^{113} Jm^{-3} - 1{,}62 \cdot 10^{26} Jm^{-3} \quad (16).$$

The physical meaning of equation (16) lies in the fact that a black hole provokes a deformation of the geometry of space because it causes a strong diminishing of the quantum vacuum energy density with respect to the Planck energy density characterizing the outer intergalactic space. Relation (16) indeed provides the maximum value of the quantum vacuum energy density which corresponds to the generation of a black hole, i.e. if in a region of space the quantum vacuum energy density overcomes the value given by (16) a black hole cannot arise. This implies that the critical, minimum variation of the quantum vacuum energy density that could generate the actualization of a black hole is given by relation:

$$\Delta\rho_{qve-BH_{minimum}} = \frac{2{,}9M_{\odot}c^2}{V_{Sch}} = 1{,}62 \cdot 10^{26} Jm^{-3} \quad (17).$$

We can therefore say that the black holes can be defined as “excited states” of the DQV corresponding to fluctuations of the quantum vacuum energy density (with respect to the ground state defined by the Planck energy density of the outer intergalactic space) which are equal or bigger of the value given by equation (17). In other words, equation (17) defines the minimum value of the quantum vacuum energy density fluctuations in order to give rise to the formation of a black hole. A black hole is generated by the variable energy density of the DQV if and only if the following constraint is satisfied:

$$\Delta\rho_{qve-BH} \geq 1{,}62 \cdot 10^{26} Jm^{-3} \quad (18).$$

Now, according to the authors of this paper, if the constraint (18) is satisfied, the quantum vacuum energy density inside the dark stellar object is so low that matter inside the stellar object becomes unstable as a consequence of a diminishing of the electromagnetic interactions. The modifications of the electromagnetic properties induced by the extremely low energy density of the vacuum inside the dark star can be seen as a consequence of the relation of Planck constant with the energy density of the DQV.

In the intergalactic space, the Planck reduced constant can be expressed by relation

$\hbar = \frac{\rho_{pE} l_P^4}{c}$ (19) [37]

namely turns out to be an emergent dimensionful parameter which is fixed by the energy density of the ground state of the DQV, i.e. the Planck energy density. As a consequence of the emergence of the Planck reduced constant of the intergalactic space from the Planck energy density, the electric permittivity of the vacuum and the magnetic permeability of the vacuum, that – as well known – are respectively given by relations

$\varepsilon_0 = \frac{e^2}{4\pi\alpha\hbar c}$ (20),

$\mu_0 = \frac{\alpha\hbar}{\pi c e^2}$ (21),

where α is the fine reduced constant, by substituting equation (19), respectively read

$\varepsilon_0 = \frac{e^2}{4\pi\alpha\rho_{pE} l_P^4}$ (22)

and

$\mu_0 = \frac{\alpha\rho_{pE} l_P^4}{\pi c^2 e^2}$ (23),

namely can be themselves seen as properties of the vacuum that are directly associated with the ground state of the DQV defined by the Planck energy density.

Now, if in a region of space the condition on the quantum vacuum energy density (18) is satisfied, and this occurs in the inner region of the dark compact object which is generated in the dynamics of black holes, as a consequence of the strong variation of the quantum vacuum energy density, one deals with a diminishing of the Planck reduced constant, a corresponding diminishing of the magnetic permeability of the vacuum and a corresponding increasing of the electric permittivity of the vacuum.

In intergalactic space the value of reduced Planck constant is defined by equation (19). By following a fruitful insight introduced by one of the authors (AS) in [38], we consider that the diminished energy density of the vacuum in the centre of the dark compact object determines a corresponding diminishing of the value of Planck reduced constant according to relation

$$\hbar_{CBH} = \frac{\left(\rho_{pE} - \frac{Mc^2}{V}\right) l_P^4}{c} \quad (24) ,$$

where ρ_{pE} is Planck energy density of 3D DQV in intergalactic space, M is the mass of the dark compact object and V is the volume of the dark compact object.

i.e.

$$\hbar_{CBH} = \frac{(\rho_{cE}) l_P^4}{c} \quad (25)$$

where ρ_{cE} is highly diminished energy density of the vacuum in the centre of the dark compact object due to its enormous mass M and relatively small volume V which generates extremely high mass density of the dark compact object. Extremely high mass density causes extremely low energy density of the vacuum, but the sum of the energy in a given region of space remains stable. This is the so-called extension of the mass-energy equivalence principle on the vacuum expressed by the equation (2).

In this model, curvature of space is replaced by the variable energy density of the vacuum in the sense that curvature of space represents only a mathematical measure of a more fundamental variable energy density of the DQV. according to the model presented in this article, more space is curved, less vacuum is dense: increasing of the curvature of space corresponds physically to a more fundamental diminishing of the quantum vacuum energy density. Variable energy density of the vacuum (medium) carries gravity. This idea was already predicted intuitively by Issac Newton: “Doth not this aethereal medium in passing out of water, glass, crystal, and other compact and dense bodies in empty spaces, grow denser and denser by degrees, and by that means refract the rays of light not in a point, but by bending them gradually in curve lines? . . . Is not this medium much rarer within the dense bodies of the Sun, stars, planets and comets, than in the empty celestial space between them? And in passing from them to great distances, doth it not grow denser and denser perpetually, and thereby cause the gravity of those great bodies towards one another, and of their parts towards the bodies; everybody endeavouring to go from the denser parts of the medium towards the rarer?" [39] and put in a rigorous mathematical formulation in our model [28].

On the basis of the modified electromagnetic properties inside extremely dense stars because of the diminishing of the Planck constant, our model can overcome and put in discussion the results obtained in the context of Chandrasekhar's theory of black holes based on gravitational collapse. Our criticism of Chandrasekhar's model of gravitational collapse is that it lacks a proper mathematical formulation able to calculate at which gravity the pressure of mass is so great that atoms become unstable: "In Chandrasekhar's article from 1975, there is no clear mathematical description and no calculation of how the pressure caused by gravity could break the atoms. Going inside any stellar object, the vertical pressure of matter increases because of the matter's weight, but this pressure cannot break atoms. Physical pressure as a result of the weight can only break physical objects; it does not work on the atomic level. That's why Chandrasekar did not explain in his article how this pressure breaks atoms. His article is a mathematical speculation without a physical model and without quantitative calculation. What happens above the Chandrasekar limit of $1{,}44_{\odot}$ is that the diminished density of the medium changes the electromagnetic properties of the medium, which causes atoms and nuclei of the atom to decay" [38].

In the model of black holes we developed there is no event horizon and there is no gravitational singularity in its centre [40]. Astronomical observations confirm that the huge black holes in the centre of galaxies (AGN) are throwing out in intergalactic space a huge amount of energy in the form of astrophysical jets which prove that event horizon is a false idea. Black holes are massive stars which do not create holes in space, because they do not curve space, they diminish its energy density. Kerr suggests in his latest article that mathematical singularities in black holes have no correspondent physical singularities: "In conclusion, I have tried to show that whatever the Penrose and Hawking theorems prove has nothing to do with Physics breaking down and singularities appearing. Of course, it is impossible to prove that these cannot exist, but it is extremely unlikely and goes against known physics" [41]. The idea that gravity inside a black hole creates such a physical pressure of matter that this pressure breaks an atom has no basis in either theoretical or experimental physics. There is no theoretical model of how physical pressure breaks down atoms. To date, no one has experimentally broken atoms with physical pressure.

In this paper, in order to overcome the inconsistencies of Chandrasekhar's model of black holes, we propose that the fundamental reason of the instability of atoms inside black holes lies in the electromagnetic collapse of these atoms. Electromagnetic instability of atoms is valid also in Kerr's rotating black holes which because of its high angular velocity have their relativistic mass. High angular velocity of supermassive black holes in the centre of some galaxies generates their relativistic mass which increases their gravity force and could be the partial answer for the missing dark matter. Supermassive black holes also provoke a rotation of the local vacuum inside the galaxy, which causes that stars have higher orbiting velocity as it is predicted by Newton physics. This effect could also provide a mechanism able to mimic the action of dark matter [42].

Our model gives physical meaning to the concept of "frame dragging effect". Rotating stellar objects are not rotating space-time which is a model only, they rotate quantum vacuum. Lense–Thirring effect is rotation of the quantum vacuum (medium) caused by the rotation of the stellar objects that are in the medium. Einstein himself had already corrected in 1920 his 1916 idea that universal space is empty and curved, deprived of physical properties. In his historical speech in Leiden, he reintroduced medium (ether): "Recapitulating, we may say that according to the general theory of relativity space is endowed with physical qualities; in this sense, therefore, there exists an ether. According to the general theory of relativity space without ether is unthinkable" [43].

General Relativity is a mathematical model (geometrization) of gravitation. With the reintroduction of the medium and its variable energy density, general relativity is developed in physical model; curvature of space is replaced by the variable energy density of quantum vacuum [44]. NASA measured in 2014 that universal space has an Euclidean shape: ""Recent measurements (c. 2001) by a number of ground-based and balloon-based experiments, including MAT/TOCO, Boomerang, Maxima, and DASI, have shown that the brightest spots are about 1 degree across. Thus, the universe was known to be flat to within about 15% accuracy prior to the WMAP results. WMAP has confirmed this result with very high accuracy and precision. We now know (as of 2013) that the universe is flat with only a 0.4% margin of error. This suggests that the Universe is infinite in extent; however, since the Universe has a finite age, we can only observe a finite volume of the Universe" [45]. Since NASA discovery, it is obvious that curvature of space as a model to describe gravity seems incomplete. That is why we replace curvature of space with the variable energy density of the quantum vacuum.

With the introduction of the medium in physics we develop a novel model of black holes where there are no holes in space-time, there is no event horizon, and there is no gravitational singularity. Black holes are diminishing the entropy of the universe; they transform their own matter with high entropy into fresh energy in the form of astrophysical jets or winds [46].

Bekenstein–Hawking model that the black hole entropy is proportional to the area of its event horizon is a theoretical model that has no experimental confirmation. Our model replaces the Bekenstein-Hawking formulation of black hole entropy with the idea that, as a consequence of the release of astrophysical jets and winds, in black holes – and thus in the entire universe – a diminishing of entropy occurs: "The black hole model in this paper explains that winds and jets originate from the same source, specifically, the electromagnetic collapse at the centre of the black hole. The magnetic fields of black holes are dynamic and are likely the key physical factor that determines whether a black hole will produce wind or a jet" [38].

The notion of black holes curving space-time and creating holes is wrong (see Figure 1):

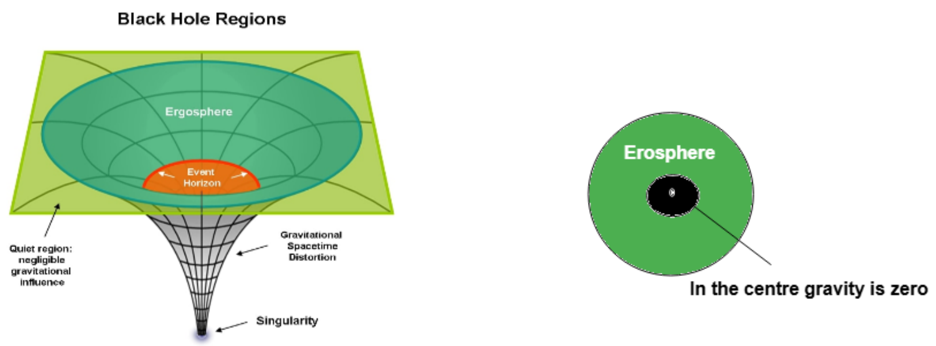

Figure 1: On the left it is wrong imagination and on the right it is adequate imagination

In summary, our model of black holes introduces indeed the following insights:

- Curvature of space and gravitational space-time distortion are not primary physical realities but exist only as mathematical artefacts associated with the variable energy density of the DQV. Universal space has Euclidean shape and black hole diminishes energy density of quantum vacuum which generates gravity force.
- There is no gravitational singularity in the centre of black holes. In black holes gravity follows Newton's Shell theorem and has zero value in the centre of every stellar object, black holes included.

- There is no event horizon that even light cannot escape. Black holes in the centre of galaxies throw in intergalactic space jets and winds of energy.
- There is no physical model developed in physics how rotating stellar object could rotate space-time that has no physical attributes. Ergosphere is not rotating space-time. Ergosphere of black hole is rotating quantum vacuum which has physical attributes.

3.2. Derivation of an effective variable Planck constant in the three-dimensional dynamical quantum vacuum

Recent research imply that Planck constant does not represent a primary physical reality but is an emergent parameter which exhibit spatial variations in the context of dense stellar objects. In particular, in Entangled Relativity, which provides a non-linear formulation of general relativity in terms of its field content without invoking the Newton gravitational constant and the Planck constant in its definition, a key result is that the Planck reduced constant is a dynamical field that varies across space and time, whose variations are not negligible in dense stellar objects [47].

In affinity with these results, in our model of 3D DQV defined by a variable energy density, we consider the possibility that Planck constant is an effective parameter whose value inside extreme dense stellar objects (like black holes) is characterized by a non-negligible diminishing. Our approach allows us to derive an effective variable value of the Planck constant which is fixed by the variable energy density by considering the insight that general relativity can be interpreted as the hydrodynamic limit of an underlying “microscopic” structure, of a 3D quantum vacuum (seen as a Bose–Einstein condensate) whose most universal physical property is its energy density and whose quantum evolution can be seen as the coherent superposition of virtual fine–grained histories [24]. In the low energy – long wavelength limit, space emerges from the microscopic 3D quantum vacuum, in which the metric and its perturbation correspond to collective variables and collective excitations. A fine–grained history which describes the 3D quantum vacuum is defined by the value of a field $\Phi(x)$ at the point x and has quantum amplitude $\Psi[\Phi]=e^{iS[\Phi]}$, where S is the classical action corresponding to the considered history. The quantum amplitude for a coarse–grained history is defined by:

$$\Psi[\omega] = \int D_F \Phi e^{iS} \omega[\Phi] \qquad (26)$$

where

$$D_F[\Phi_A, \Phi_B] \approx \Psi[\Phi_A]\Psi[\Phi_B]^* \approx e^{i(S[\Phi_A] - S[\Phi_B])} \qquad (27)$$

is the "decoherence" functional measuring the quantum interference between two virtual histories A and B, ω can be considered as a "filter" function that selects which fine–grained histories are associated to the same superposition with their relative phases. The decoherence functional for a couple of coarse–grained histories is then:

$$D_F[\omega_A, \omega_B] = \int D_F \Phi_A D_F \Phi_B e^{i(S[\Phi_A] - S[\Phi_B])} \omega[\Phi_A] \omega[\Phi_B]^* \qquad (28)$$

in which the histories Φ_A and Φ_B assume the same value at a given time instant, where decoherence indicates that the different histories contributing to the full quantum evolution can exist individually. By applying the formalism (28) to hydrodynamics variables, Einstein's stress-energy tensor can be expressed through the following operator:

$$\hat{T}_{\mu\nu}(x_A, x_B) = \Gamma_{\mu\nu} \Phi(x_A) \Phi(x_B) \qquad (29).$$

where $\Gamma_{\mu\nu}$ is a generic field operator defined at two points that leads to the "conservation law"

$$\hat{T}_{\mu\nu}^{;\nu} = 0 \qquad (30)$$

meaning that the decohered quantities, showing a classical behaviour, are the conserved ones [24].

The theory is defined by a path integral of coarse-grained histories (30) as follows

$$Z = \int [D_F g] \prod_j [D_F f_i] \, exp\left[-\frac{i}{2\epsilon^2} \int d_g^4 x \frac{\mathcal{L}_m^2(f, g, \Delta\rho_{qvE})}{R(g)}\right] \qquad (31)$$

where $\int [D_F]$ indicates the sum over all possible field configurations associated with the coarse-grained histories, R is the usual Ricci scalar, g is the metric tensor, $d_g^4 x = \sqrt{-|g|} d^4 x$, with $|g|$ the determinant of the metric g, and $\mathcal{L}_m$ is the Lagrangian density depending of the matter fields f and related to the variable quantum vacuum energy density (which provides a completion to the Standard Model Lagrangian density). In equation (31) the key parameter is ϵ^2 which is a quantum of energy squared. In our model, this parameter is directly related to the fundamental properties describing the microscopic geometry of the DQV, i.e. the variable quantum vacuum energy density and the Planck length, through relation

$$\epsilon^2 = \frac{\rho_{qvE} l_P^4}{\kappa} \quad (32).$$

In equation (32) κ is a dimensionful scalar field, which on the basis of the Euler-Lagrange equation turns out to be given by relation

$$\kappa = -\frac{R}{\mathcal{L}_m} \quad (33).$$

The field equations of classical physics in the approach based on the path integral (31) derive from extremization of the quantum phase, yielding

$$\Theta = -\frac{1}{2\epsilon^2}\int d_g^4 x \frac{\mathcal{L}_m^2(f, g, \Delta\rho_{qvE})}{R(g)} \quad (34)$$

or from the following Einstein phase

$$\Theta_{\mathrm{E}} = \frac{1}{\epsilon^2}\int d_g^4 x \frac{1}{\kappa}\left(\frac{R(g)}{2\kappa} + \mathcal{L}_m\big(f, g, \Delta\rho_{qvE}\big)\right) \quad (35).$$

Here, we observe that standard physics is recovered under the constraint that the variation of κ can be neglected, such as in our Solar System, for which equation (35) becomes

$$\Theta_{\mathrm{E}} = \frac{1}{\rho_{pE} l_P^4}\int d_g^4 x \left(\frac{R(g)}{2\kappa_0} + \mathcal{L}_m\big(f, g, \Delta\rho_{qvE}\big)\right) \quad (36)$$

where $\kappa_0 = \frac{8\pi G}{c^4}$. From equation (36), in the classical limit of the theory one has therefore

$$\kappa_0 \epsilon^2 = \hbar c \quad (37)$$

namely the parameter ϵ of the theory turns out to be related only on the reduced Planck energy

$$\epsilon = \sqrt{\frac{\hbar c}{\kappa_0}} = \frac{\rho_{pE} l_P^3}{\sqrt{8\pi}} \quad (38).$$

On the other hand, in general – for example at the cosmological scale – the Planck reduced constant varies proportionally to the parameter κ according to relation

$$\hbar' = \epsilon^2 \kappa \quad (39)$$

and, therefore, taking account of equation (32) and substituting equation (2), one obtains the final expression of the variable Planck reduced constant, which represents the core idea of our model:

$$\hbar' = \frac{\left(\rho_{pE} - \frac{mc^2}{V}\right) l_P^4}{c} \quad (40).$$

We have thus demonstrated how the effective variable Planck reduced constant defined by relation (40) turns out to be directly derived from the fundamental path integral (30) of coarse-grained histories describing the geometrodynamics of the DQV. Moreover, this treatment turns out to be compatible with the results obtained in [47].

Now, we emphasize here that the assumption of the diminished value of the Planck reduced constant inside black holes, as expressed by equation (24), and therefore the modification of the Planck constant and bounds at the Planck scale, can be directly related to the Bekenstein bound which acts as a natural ultraviolet cut-off on information/entropy density. In the picture of a variable Planck constant (and, in particular, of a diminished Planck constant inside very compact objects as dark stars), the Bekenstein bound emerges as a physical regulator for quantum field theory, becoming a "natural" cut-off which removes ultraviolet divergences, limiting the maximal information density. Because of the correspondence with the Bekenstein bound – associated with the maximum amount of information encoded in a physical system –, the diminished value of the Planck reduced constant inside black holes can be considered a potential gravitational explanation for renormalization in physics. Moreover, in the picture of the generalized uncertainty relations (9) and of the generalized Compton wavelength (10), the Bekenstein bound provides a valid constraint on entropy, even by considering scenarios where the Planck constant inside black holes is diminished, thus guaranteeing consistency between quantum information theory and general relativity inside black holes.

In order to show this in detail, we start by observing that in [48], an effective Planck reduced constant has been defined for hadronic particles where the Planck length is replaced with the charge radius r and the Planck mass with the mass m of the hadron/nuclei, i.e.

$$\hbar' = rmc \quad (41).$$

By applying equation (41) to hadronic particles and large nuclei, it has been shown that an effective variation of the Planck constant could be related to the timeless state of the universe and leads to a novel connection between gravitation and quantum field theories [49].

In the model developed in this paper, we observe that, on the basis of equations (2)-(4), relation (41) can be written as

$$\hbar' = \frac{r\Delta\rho_{qve}V}{c} \quad (42).$$

Now, the Bekenstein bound for a physical system having entropy S and energy $E = Mc^2 = \Delta\rho_{qve}V$ and radius r, is:

$$S \leq \frac{2\pi k_B r\Delta\rho_{qve}V}{\hbar c} \quad (43)$$

where k_B is the Boltzmann constant. As regards equation (43), on the basis of the symmetry between energy of the system and diminished energy density of quantum vacuum with respect to the Planck energy density, we propose that one can make the substitution $r\Delta\rho_{qve}V \rightarrow \left(\rho_{PE} - \frac{Mc^2}{V}\right) l_P^4$, thus expressing the Bekenstein bound in the following convenient form

$$S \leq 2\pi k_B \left[\frac{\left(\rho_{pE} - \frac{Mc^2}{V}\right) l_P^4}{\hbar c}\right] \quad (44)$$

where the reduced Planck constant $\hbar$ is of course given by equation (19). The Bekenstein bound (44) suggests us to define an effective Planck constant on the basis of relation

$$\hbar' = \frac{\left(\rho_{pE} - \frac{Mc^2}{V}\right) l_P^4}{c} \quad (45)$$

where r is the radius of a sphere that encloses the object into consideration and M is the mass of the object. Equation (45) implies that, for elementary particles, the modification of the reduced Planck constant determined by the quantum vacuum energy density fluctuations is negligible. However, if we consider the case of black holes, i.e. dark compact objects, the things are different: on the basis of equation (45) the extremely big value of the mass density can generate important modifications in the value of the Planck reduced constant. In other words, in the light of equation (45), we can say that, inside dark stars, the quantum vacuum energy density $\rho_{qvE-BH} = \left(\rho_{pE} - \frac{Mc^2}{V}\right)$ is so low that the bound quantity $2\pi k_B \left(\frac{\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}{\hbar c}\right)$ becomes very low with respect to elementary particles. Nonetheless, the Bekenstein bound (44) turns out to provide a good natural cutoff that is compatible with renormalization in quantum field theory. In fact, if one replaces the thermodynamic entropy with the Shannon entropy

$$S = k_B H \ln 2 \quad (46)$$

where H identifies the Shannon entropy calculated in terms of the number of bits embedded in the quantum states inside the dark star, in this way the Bekenstein bound (44) becomes:

$$k_B H \ln 2 \quad \leq 2\pi k_B \left(\frac{\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}{\hbar c}\right) \quad (47)$$

i.e.

$$H \leq \frac{2\pi}{\ln 2}\left(\frac{\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}{\hbar c}\right) \quad (48).$$

The constraint (48) represents the maximal amount of information required to perfectly describe a physical object like a dark compact object, i.e. a dark star, up to the quantum level, compatibly with the pionieristic work of Bekenstein [50]. In the light of equation (48), we can say that the effective variable reduced Planck constant (45) – and therefore the diminished value of the reduced Planck constant (24) inside dark compact objects – suggests a novel way to combine the universal Bekenstein bound with quantum field theory, through considering the effective variable reduced Planck constant $\hbar'$ for every physical object. The constraint (48) allows us to provide a new re-reading of the results obtained in [51], showing how an effective variable Planck constant inside extremely dense stellar objects is compatible with quantum field theory requirements. However, a limit of this approach lies in the introduction of a violation of the Lorentz symmetry at very high energy (a problem which is common also to other well known approaches to quantum gravity), unless the ultraviolet cut-off is extremely low, far below the Planck scale.

3.3. Electromagnetic collapse inside black holes: decay of hydrogenoid atoms and of quarkonium structure

In this work, we are interested in exploring the consequences of the diminished Planck constant inside dark compact objects (like black holes) as regards the modifications in the electromagnetic interactions. In this regard, we underline that the diminishing of the Planck reduced constant expressed by equation (24) has the consequence of generating a corresponding increasing of the dielectric permittivity of the vacuum on the basis of relation:

$$\varepsilon_{0_{BH}} = \frac{e^2}{4\pi\alpha\hbar_{BH}c} \quad (49)$$

namely

$$\varepsilon_{0_{BH}} = \frac{e^2}{4\pi\alpha\left(\rho_{pE} - \frac{Mc^2}{V}\right)l_P^4} \quad (50)$$

that can be defined as the permittivity of the vacuum in black holes.

Now, the new greater value of the permittivity of the vacuum (50) can be considered as the real origin of the diminishing of the electromagnetic interaction inside the dark star that then are responsible of an electromagnetic collapse of this region which leads the black hole to eat itself. In particular, under these constraints (24) and (49) regarding the permittivity of the vacuum and the Planck reduced constant inside black holes, for example, hydrogenoid atoms could not exist as we know them. This is due to the fact that the interaction potential which should be responsible of the formation of the hydrogenoid atoms turns out to be diminished with respect to the standard Coulomb potential and is given by relation:

$$V_{BH} = -\frac{Ze^2}{4\pi\varepsilon_{0_{BH}}r} \quad (51)$$

namely, substituting equation (25),

$$V_{BH} = -\frac{Z\alpha\left(\rho_{pE} - \frac{Mc^2}{V}\right)l_P^4}{r} \quad (52).$$

The Schrödinger equation for hydrogenoid atoms inside the region instability of matter represented by the inner region of the dark compact object defined by a variable energy density which satisfies equation (18), reads

$$\left[-\frac{\left(\rho_{pE}-\frac{Mc^2}{V}\right)^2 l_P^8}{2m_e c^2}\nabla^2-\frac{Z\alpha\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}{r}\right]\psi(\vec{r})=i\frac{\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}{c}\frac{\partial\psi(\vec{r})}{\partial t} \quad (53)$$

where m_e the mass of the electron. By solving the Schrödinger-type equation (53), the energy spectrum of the virtual hydrogenoid atoms inside the dark compact object (whose boundary defines a sort of "apparent horizon" which marks the region characterized by the electromagnetic collapse) would be as follows:

$$E_n=-\frac{m_e e^4}{2\hbar_{BH}^2 {\varepsilon_0}_{BH}^{\ 2} n^2} \quad (54)$$

i.e.

$$E_n=-\frac{8\pi^2\alpha^2 m_e c^2}{n^2} \quad (55).$$

Moreover, by decomposing the Schrödinger-type equation (29) through a Madelung transformation

$$\psi(\vec{r})=Re^{i\frac{S}{\hbar_{BH}}} \quad (56)$$

and separating into real and imaginary parts, one obtains a quantum Hamilton-Jacobi equation for the phase of the wave function and a continuity equation for the amplitude of the wave function that lead to define the modified quantum potential inside black holes of the form

$$Q_{BH}=-\frac{{\hbar_{BH}}^2}{2m_e}\left(\frac{Z}{a_0}-\frac{2}{r}\right)^2 \quad (57)$$

where

$$a_{0_{BH}}=\frac{{\hbar_{BH}}^2}{m_e e^2} \quad (58)$$

would be the counterpart of "Bohr radius" of the hydrogen atom inside the dark star. By substituting equation (25) inside equations (57) and (58), the quantum potential and the Bohr radius of hydrogen atom read

$$Q_{BH}=-\frac{\left(\rho_{pE}-\frac{Mc^2}{V}\right)^2 l_P^8}{2m_e c^2}\left(\frac{Zm_e c^2 e^2}{\left(\rho_{pE}-\frac{Mc^2}{V}\right)^2 l_P^8}-\frac{2}{r}\right)^2 \quad (59)$$

and

$$a_{0_{BH}} = \frac{\left(\rho_{pE} - \frac{Mc^2}{V}\right)^2 l_P^8}{m_e c^2 e^2} \quad (60).$$

By comparing the quantum potential (59) and the radius of the hydrogen atom (60) inside the dark star with the corresponding standard values

$$Q = -\frac{(\rho_{pE})^2 l_P^8}{2m_e c^2}\left(\frac{Zm_e c^2 e^2}{(\rho_{pE})^4 l_P^8} - \frac{2}{r}\right)^2 \quad (61)$$

$$a_0 = \frac{(\rho_{pE})^2 l_P^8}{m_e c^2 e^2} \quad (62),$$

one finds that, inside the dark star of mass M, the quantum potential and the radius are much smaller than the corresponding standard values. These results, according to the authors, are strong clues that inside the dark star of mass M the hydrogenoid atoms are unstable and cannot exist as bound states, in other words that the inner region of a black hole can be defined just as a region of instability of matter. In summary, as regards the physics of hydrogenoid atoms inside black holes, the physical meaning of the modified interaction potential, the modified quantum potential and the modified Bohr radius imply that, as a consequence of the diminishing of the Planck reduced constant with respect to the intergalactic space, these atoms cannot be stable and are subjected to processes of decay releasing free electrons and protons, that then are transformed into non-structured energy of the DQV.

Moreover, the diminished Planck constant $\hbar$ in the black holes (as well as in neutron stars) changes the Cornell potential, which provides a phenomenological description of the confined dynamics of heavy quarkonium structure [52], according to relation

$$V_c = -\frac{4\alpha_s \hbar_{BH} c}{3r} + \frac{\sigma}{\hbar_{BH} c} r \quad (63)$$

where α_s is the QCD coupling and σ is a parameter with dimension of $energy^2$. By substituting equation (24) inside equation (40), the Cornell potential inside a black hole reads:

$$V_c = -\frac{4\alpha_s\left(\rho_{pE} - \frac{Mc^2}{V}\right) l_P^4}{3r} + \frac{\sigma}{\left(\rho_{pE} - \frac{Mc^2}{V}\right) l_P^4} r \quad (64).$$

The modified Cornell potential (64) inside black holes can be considered the physical origin of the diminishing of the nuclear forces inside nuclei, that therefore has the effect to generate a decay of nuclei. The typical distance scale in the heavy quarkonium structure is directly influenced by the diminishing of the Planck reduced constant according to relation

$$a_Q = \frac{3}{2}\frac{\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}{m_Q c^2 \alpha_s} \quad (65).$$

On the basis of relation (65), the distance scale of quarkonium structure inside black holes turns out to be diminished with respect to the intergalactic space. This implies that the quarkonium cannot exist inside black holes, i.e. that is subject to a decay process that releases free quarks in the DQV and this free quarks then give rise to non-structured energy of the quantum vacuum.

Moreover, by following [53], the Cornell potential (64) inside black holes can be associated to a non-local Lagrangian

$$L(A) = -\frac{1}{4}F_{\mu\nu}\frac{\partial^2}{\partial^2-\frac{3\sigma}{2\alpha_s\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}}F^{\mu\nu} - \frac{16}{3}\pi\alpha_s\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4 J^\mu A_\mu \quad (66)$$

that provide a non-local version of Maxwell equations inside black holes

$$\frac{\partial}{\partial\lambda}\frac{\partial^2}{\partial^2-\frac{3\sigma}{2\alpha_s\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}}F^{\lambda\mu} = \frac{16}{3}\pi\alpha_s\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4 J^\mu \quad (67),$$

where

$$A^0 = -\frac{4\alpha_s\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}{3r} + \sigma r \quad (68)$$

and

$$E = -\frac{dA^0}{dr} = -\frac{4\alpha_s\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}{3r^2} - \sigma \quad (69).$$

The modified non-local versions of the Maxwell equations determined inside black holes by the diminishing of the Planck constant can be put in comparison with the corresponding field equations

$$\frac{\partial}{\partial\lambda}\frac{\partial^2}{\partial^2-\Lambda_{QCD}^2}F^{\lambda\mu} = gJ^\mu \quad (70)$$

where

$g = \frac{16}{3}\pi\alpha_s(\rho_{pE})l_P^4$ (71)

is the coupling constant and

$\Lambda_{QCD}^2 = \frac{8\pi\sigma}{g}$ (72)

is associated with the QCD energy scale ($\Lambda_{QCD} \approx 0{,}15\ GeV$). On the basis of the non-local field equations (70), equipped with relations (71) and (72), in [53] Spallucci and Smailagic have found a static solution for the metric in the Kerr-Schild gauge, which corresponds to a charged Anti deSitter metric, where one can define an effective cosmological constant

$\Lambda \equiv \frac{3g^2}{16\pi} G\Lambda_{QCD}^4$ (73)

which can be identified with a pressure of a "Cornell photon fluid" associated with the black hole at the Hawking temperature. Now, in our approach, we consider that, as a consequence of the modified Cornell potential (64) determined by the diminishing of the Planck reduced constant inside black holes, the Spallucci and Smailagic non-local version of the Maxwell equations (70) are not valid anymore inside black holes and must be replaced by the modified non-local Maxwell equations (67). The effect of the modified equations (67) lies in a breaking of the static solution for the metric in the Kerr-Schild gauge obtained by Spallucci and Smailagic in [53]. In other words, we can say that a charged black hole described by the modified Cornell potential (64) cannot correspond to static solutions for the metric, i.e. it is not in a static condition from the electromagnetic point of view, but is characterized by processes of decay of matter.

In summary, in black holes, in the light of the modified conditions represented by the modified potential of hydrogenoid atoms (52) and the modified Cornell potential (64), we can conclude that atoms decay into electrons, protons, and neutrons (see Figure 2). That is the reason why astrophysical jets generated in supermassive black holes also contain protons [32].

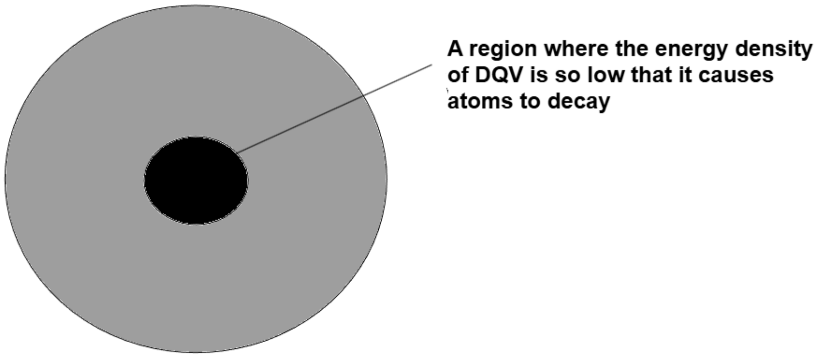

Figure 2: Low energy density of DQV in the central area of a black hole and electromagnetic decay of atoms

4. Decay of Fermi plasmas of electrons and protons inside a black hole

A recent study has suggested that, at the rim of the photon sphere of a black hole, a quantum statistics transition with a local departure from Pauli exclusion principle occurs, which provokes a decay of collective fermionic systems and, in particular, the collapse of Fermi spheres in compressed matter and that this Fermi sphere decay is accompanied with the emission of electromagnetic radiation, expelling the energy and entropy of the falling matter without unitarity violation [54]. In our model, we can provide a new re-reading to these results, in a picture where the decay of fermionic system is ultimately generated by the electromagnetic collapse occurring in the black hole.

In our approach, we consider that, in the inner region of the dark star of mass M the diminishing of the electromagnetic interactions – determined by the diminishing of the Planck reduced constant and by a corresponding increasing of the dielectric permittivity of the vacuum – induces a local decay of quantum statistics associated with the release of energy in the form of electromagnetic radiation according to a law analogous to the Fermi golden rule, and in this physical situation the particles devoid of quantum statistics generate a pure quantum state of individual particles which cannot interchange their positions. The loss of the statistics in this inner region of the dark compact star make the Fermi spheres in multi-particle systems unstable, with a consequent expulsion of the energy accumulated in the Fermi sphere of these compressed systems, which is eaten by the black hole.

The decay of the quantum statistics implies that the neutrons decompose into electrons and protons that interact with an electromagnetic radiation and neutral antineutrino, along $\beta-$ decay exponentially accelerated by large number of neutrons in a neutron star merger. Liberated charged electrons and protons interact with the modified electromagnetic field associated with the diminishing of the magnetic permeability of the vacuum and the increasing of the dielectric permittivity of the vacuum and rapidly jump onto lower quantum states emitting photons.

The dynamics of the processes of decay of fermionic systems accompanied by the loss of quantum statistics, can be mathematically described as follows. Before all, we consider that the quantum transitions of a charged particle from a stationary state $|1\rangle$ with energy E_1 to a final state $|2\rangle$ with energy E_2 that leads the particle to be expelled together with the emission of electromagnetic radiation, can be described by an interaction Hamiltonian

$$H_{int}(\tau) = \int d^3x\sqrt{-g}\,\mathcal{H}_{int} \quad (74)$$

where $\mathcal{H}_{int}(\tau) = -\sqrt{4\pi\alpha\left(\rho_{pE} - \frac{Mc^2}{V}\right) l_P^4}\,\bar{\psi}\gamma^\mu A_\mu \psi$, A_μ is the modified electromagnetic field, γ^μ are the Dirac matrices, ψ are Dirac spinors and τ is the proper time of the observer. Hence, the transition amplitude from the initial state $|1\rangle$ to the final state $|2\rangle$ of the charged fermionic system, can be derived directly as

$$f_{12} = -\frac{ic}{\left(\rho_{pE} - \frac{Mc^2}{V}\right) l_P^4} \int_{-\infty}^{\tau} d\tau' \langle 1|\hat{V}(r)|2\rangle \quad (75)$$

where $\hat{V}(r)$ is the interaction Hamiltonian (derived from (74)) which describes the coupling of the charged particle with the modified electromagnetic field associated with the diminishing of the magnetic permeability of the vacuum and the increasing of the dielectric permittivity of the vacuum. Then, by taking the limit $\tau \to \infty$, the time-integral of the phase factor leads to a Dirac delta, thus obtaining the following formula for the probability per time unit of quantum transitions of the charged fermionic particle from a stationary state $|1\rangle$ with energy E_1 to a final state $|2\rangle$ with energy E_2 that leads the particle to be expelled together with the emission of electromagnetic radiation:

$$f_{1,2} = \frac{2\pi c}{\left(\rho_{pE} - \frac{Mc^2}{V}\right) l_P^4} \left|\langle 1|\hat{V}(r)|2\rangle\right|^2 \delta\left(E_1 - E_2 - k\frac{\left(\rho_{pE} - \frac{Mc^2}{V}\right) l_P^4}{c}\omega\right) \quad (76).$$

In equation (76), $\langle 1|\hat{V}(r)|2\rangle$ is the matrix element of the operator $\hat{V}(r)$, the Dirac delta assures the energy conservation characterizing the transition and ω is the frequency of the emitted photons, that is linked with the informational lattice of the 3D DQV characterized by dissipative features on the basis of the dispersion relation (13). In this picture, relativistic electrons or protons interacting with the modified electromagnetic field of the inner region of the dark compact star can be described by a single-particle Hamiltonian of the form

$$\hat{H}_{e(p)} = \sqrt{\left(\hat{\boldsymbol{p}} \mp e\boldsymbol{A}(\boldsymbol{r},t)\right)^2 c^2 + m_{e(p)}^2 c^4} - m_{e(p)}c^2 \quad (77)$$

where

$$\boldsymbol{A}(\boldsymbol{r},t) = \boldsymbol{A_0} e^{\frac{i(\boldsymbol{q}\cdot\boldsymbol{r}-cqt)c}{\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}} \quad (78)$$

is the vector potential of the modified electromagnetic field and $\hat{\boldsymbol{p}} = -i\frac{\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}{c}\nabla$. By considering quantum transitions in the regime of linearity (which represents the domain of validity of the Fermi golden rule), the operator $\hat{V}(r)$ in equation (76) can be assumed as linear function with respect to $\boldsymbol{A}$, as follows

$$\hat{V}(r,t) = \mp \frac{ec^2\boldsymbol{A}(\boldsymbol{r},t)\cdot\hat{\boldsymbol{p}}}{\sqrt{\hat{\boldsymbol{p}}^2c^2+m_{e(p)}^2c^4}} \quad (79)$$

where $\mp$ corresponds to a proton and an electron respectively.

Now, if one considers isotropic systems with local translational symmetry, the states $|1\rangle$ and $|2\rangle$ can be taken in the form

$$|1\rangle = \frac{c^{3/2}}{(2\pi G)^{3/2}\left(\rho_{pE}-\frac{Mc^2}{V}\right)^{3/2} l_P^6} e^{\frac{i(\boldsymbol{p}_1\cdot\boldsymbol{r}-E_{p_1}t)c}{\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}} \quad (80),$$

$$|2\rangle = \frac{c^{3/2}}{(2\pi G)^{3/2}\left(\rho_{pE}-\frac{Mc^2}{V}\right)^{3/2} l_P^6} e^{\frac{i(\boldsymbol{p}_1\cdot\boldsymbol{r}-E_{p_1}t)c}{\left(\rho_{pE}-\frac{Mc^2}{V}\right)l_P^4}} \quad (81).$$

Then, the analytical calculus of the matrix element in equation (76) yields

$$\langle \boldsymbol{p}_1|\hat{V}(\boldsymbol{r})|\boldsymbol{p}_2\rangle = \mp\delta(\boldsymbol{p}_1 - \boldsymbol{p}_2 - \boldsymbol{q})\frac{ec^2\boldsymbol{A_0}\cdot\hat{\boldsymbol{p}}_2}{\sqrt{{p_2}^2c^2+m_{e(p)}^2c^4}} \quad (82)$$

that implies the following expression for the transition probability:

$$f_{1,2} = \frac{e^2 c^6 \mathcal{V}}{(2\pi)^2 \left(\rho_{pE} - \frac{Mc^2}{V}\right)^4 l_P^{16}} A_0{}^2 cos^2\theta F(p_2)\delta(\boldsymbol{p}_1 - \boldsymbol{p}_2 - \boldsymbol{q}) \quad (83)$$

with $F(p_2) = \frac{p_2^2 c^2}{p_2{}^2 c^2 + m_{e(p)}^2 c^4} < 1$ and θ is the angle between the vectors $\boldsymbol{A_0}$ and $\boldsymbol{p}_2$. By integrating equation (83), one finally obtains the probability per unit time of decay of the Fermi sphere in the inner region of the dark star:

$$f_{1,2} = (N+1)\gamma \quad (84)$$

where

$$\gamma = \frac{4\alpha m c^3 e^2}{3\left(\rho_{pE} - \frac{Mc^2}{V}\right) l_P^4 y} \int_{-1}^{1} dz \int_0^{p_F/mc} dx \frac{x^4}{x^2+1} \times \delta\left(\sqrt{x^2 + y^2 + 2xy + 1} - \sqrt{x^2+1} - 0{,}57y\right) \quad (85)$$

where $x = p_2/mc$, $y = q/mc$, $N = \frac{e^2 c \mathcal{V} E_0^2}{8\pi\alpha\omega\left(\rho_{pE} - \frac{Mc^2}{V}\right)^2 l_P^8}$ is the number of photons in the volume $\mathcal{V}$, p_F is the momentum corresponding to the Fermi level, E_0 and A_0 are the amplitudes of the modified electric field and of the vector potential of the electromagnetic radiation. In the light of the probability per unit time (84), the total number of emitted photons in the infinitesimal time duration dt is therefore

$$dN = (N+1)\gamma dt \quad (86)$$

which has solution

$$\ln N = \gamma t \quad (87)$$

and thus

$$\ln N_0 = \gamma \Delta t \quad (88)$$

where Δt is the time of the Fermi decay as a consequence of the modifications of the electromagnetic interactions and N_0 is the number of the emitted photons corresponding to the particle number in the system. In equation (88), the duration of the Fermi decay is linked with the frequency ω of the elementary modes of the DQV corresponding to the emitted photons.

The decay process of a Fermi sphere of electrons ruled by a modified electromagnetic field associated with the loss of the fermionic quantum statistics in the inner region of the dark star occurs, for example, during the collapse of an unstable neutron star. In the case of a neutron star with 2,3 solar masses, according to the results obtained in [54], the loss of the fermionic quantum statistics accelerates the spontaneous decay of a free neutron by a few orders, to the order of $\gamma' \sim 10^3\ s^{-1}$, which leads to the release of electrons and protons within ca. $ln(2.53\ \times\ 10^{57})/\gamma'\ \simeq\ 0.1\ s$ and a subsequent almost instantaneous emission of antineutrinos and of photons. The duration of the entire process of the electromagnetic collapse associated with the Fermi decay in the inner region of the dark star agrees with observations of some kind of short gamma-ray bursts that, according previous research, are assumed to be associated with the neutron star merger.

Moreover, we emphasize that the energy released in the form of electromagnetic radiation, during the electromagnetic collapse characterizing the Fermi decay, is able to explain the observed luminosity of giant quasars. While the thermal radiation from the accretion disc and the Comptonization of soft photons present weak points in explaining the radiation intensity and its spectral composition for superluminous quasars [55-59], the electromagnetic collapse associated with the decay of Fermi spheres of electrons and protons, where the rate of mass consumption per second is directly linked with the number N of emitted photons according to relation

$\mathcal{M} \approx N\left(m_p + m_e\right)$ (89),

provides an efficient mechanism for converting gravitational energy into electromagnetic radiation which can explain the observed luminosity of quasars.

We emphasize here that the decay of Fermi plasma determined by the electromagnetic collapse inside the dark star follows a unitary evolution, which is compatible with the Page curve. This is due to the fact that the fermionic degrees freedom are entangled with the electromagnetic radiation released during the process of decay. Instead of a simple thermal process, the emission of electromagnetic radiation as a consequence of the decay of Fermi plasma inside extremely dense dark stars desxcribed by the transition probability (84), can be seen as a unitary process where information is not lost. Because of the quantum entanglement between the internal fermions and the emitted radiation, which turn out to form a coupled quantum system, the information initially stored in the Fermi plasma is returned to the environment by following the process of electromagnetic collapse, in the form of the astrophysical jets and winds that are released by the dark star.

Compatibly with the ER=EPR approach originally developed by Susskind and Maldacena [60], the entanglement between the decaying Fermi plasma determined by the electromagnetic collapse inside the dark star and the electromagnetic radiation released in the astrophysical jets and winds, can be associated with an opportune entanglement entropy depending of the variable energy density at the generalized Compton wavelength and of the transition probability $f_{1,2}$ given by the final formula (84), on the basis of relation:

$$S_E = \frac{N\Delta\rho_{qvE}{}^2 V^3}{k_B \eta c^2} f_{1,2} \frac{\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]}{4G} \quad (90)$$

where k_B is the Boltzmann constant, $N = \frac{e^2 c\mathcal{V} E_0^2}{8\pi\alpha\omega\left(\rho_{pE} - \frac{Mc^2}{V}\right)^2 l_P^8}$ is the number of the photons in the volume $\mathcal{V}$ and the parameter η plays the role of an inverse temperature. The effect of the entanglement entropy (90) between the fermionic degrees inside the dark star and the electromagnetic radiation released outside is of determining a connection between the information contained in the interior region of the dark star (where an electromagnetic collapse occurs) and the modes outside the dark star. This connection can be described by considering a quantum superposition between of the form

$$\psi(\eta) = \sum_k e^{-\frac{\eta}{c^2}\frac{N\Delta\rho_{qvE}V f_{1,2}}{k_B}} |\psi_k\rangle \otimes |\psi_k\rangle \quad (91)$$

where $|\psi_k\rangle$ is the k-th energy eigenstate for a single mode outside the dark star. In other words, we can say that the interplay between the electromagnetic collapse of the Fermi plasma and the fluctuations of the variable energy density at the generalized Compton wavelength determines the generation of a sort of quantum wormholes described by an entanglement entropy that is responsible of the connection between the information contained in the interior and the modes outside the dark star and, therefore, between causally disconnected regions of the universe and their corresponding evolutions. In other words, we can say that, on the basis of the entanglement entropy (90), the surface of the dark star acts as a sort of entanglement island between the information contained in the effective interior of the dark star and the modes outside this surface, thus introducing new perspectives of explanation of the black hole information paradox, which avoid the violation of quantum mechanics' principle of unitarity.

Here, as a consequence of the entanglement between the decaying Fermi plasma inside the dark star and the emitted electromagnetic radiation (characterizing the observed astrophysical jets and winds) outside, the interior of the dark star emerges as an effective description of the outside evolution. This means that the inner region of the dark star is described by an effective theory containing a zone $0 < r < r_Z$, where r_Z is the location of the outer edge of the near black-hole region which provides the effective electromagnetic radiation released by the dark star, up to a time

$$T_{t_x} = t_x + 2\frac{r_+}{c}\ln\frac{r_+}{l_p} \quad (92)$$

where r_+ is the radius of the inner region of the dark star characterized by the electromagnetic collapse, and the time $t_x < T_{evap}$ (where T_{diss} corresponds to the time of complete dissolving of the dark star into non-structured energy of the vacuum and jets of energy) is directly fixed by a corresponding behaviour of the variable energy density of the 3D DQV and the entanglement entropy, on the basis of relation

$$t_x = \frac{\hbar\eta}{S_E} \quad (93)$$

where S_E is given by equation (90) and therefore

$$t_x = \frac{k_B\eta c^2}{N\Delta\rho_{qvE}{}^2 V^3 f_{1,2}\,\frac{\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]}{4G}} \quad (94).$$

On the basis of equations (92)-(94), the physics characterizing the interior portion of of the black hole characterized by electromagnetic collapse describes correlations between the fermionic degrees of freedom inside and the electromagnetic radiation released outside, that correspond to the time interval

$$t_x < t < T_{t_x} \quad (95).$$

Therefore, in the model of the black holes as extremely dense stars defined by an electromagnetic collapse, there is no paradox as regards the link between the interior time evolution and the exterior time evolution. There is no contradiction between interior description and exterior description. The connection between the interior and the exterior evolution of the black hole appears as a direct natural consequence of the rearrangement of correlations determined by the action of the surface delimiting the boundary of the inner region characterized by electromagnetic collapse as an entanglement island with the electromagnetic radiation released outside and transmitted by the non-local action of the resulting quantum wormholes.

In this model, the entanglement entropy (90) measuring the correlation between the decaying, unstable fermionic systems inside the dark star and the electromagnetic radiation released outside in the form of astrophysical jets and winds, has also the merit to reproduce and explain the Page curve of black holes in a direct way without requiring causal structures of standard horizons or singularity. In fact, the entanglement entropy (90) leads to re-define entropy through a formula of quantum extremal surfaces which regard the inner region characterized by electromagnetic collapse, of the following form

$$S_{rad} = min_X ext_X \left[\frac{Area\ [X]}{4G\hbar} + S_E\right] \quad (96).$$

In this equation, the appearance of information islands in the inner region of the dark star implies that the total entropy of the dark star decreases after the Page time. In this picture, in summary, because of the action of the surface of the dark star as a sort of entanglement island between the information associated with the decay of Fermi plasma in the effective interior of the dark star and the electromagnetic radiation released outside this surface, and because of the consequent formation of quantum extremal surfaces in the region of instability of matter, the generalized entropy given by equation (96) (which is directly related with the entanglement entropy of the emitted electromagnetic radiation) has the following behaviour: it begins at zero, then increases in correspondence to the processes of electromagnetic collapse inside the dark star, reaches a maximum critical value (when half of the mass of the dark star has overcome electromagnetic collapse – situation that corresponds to the usual Page time) and then decreases rapidly to zero. In other words, we can say that the decay of Fermi plasma inside the dark star generates a release of entropy from the interior to the exterior, which satisfies unitarity, in the sense that the total entanglement entropy of the emitted radiation and the remaining dark star is zero. This treatment allows us to re-read in a different (and, according to us) more general and elegant way the results regarding the Page curve obtained in the current models which adopt a semiclassical calculation of the generalized entropy by holographic correspondence with the inclusion of the bulk entropy [61-65]. The generalized entropy (96) derived from the entanglement entropy between unstable fermionic matter in the inner region of the dark star and emitted electromagnetic radiation, replaces the fine-grained entanglement entropy invoked in the model of higher-dimensional two sided eternal black hole in double holography developed in [66], given by relation

$$S_A = min_X \left[\frac{Area\ (X)}{4G\hbar} + S_{bulk}(X)\right] \quad (97)$$

where here, however, X is the quantum extremal surface that minimizes $\frac{Area\,[X]}{4G\hbar}+S_{bulk}(X)$ and is chosen among co-dimensional Ryu-Takayanagi surfaces in the bulk spacetime which is anchored on the boundary of the entangling region A.

Finally, it is interesting to observe that, in the light of its peculiar features, the processes associated with the decay of these fermionic systems inside the dark star are consistent with quantum gravity.

5. How the gravitational collapse till the formation of a dark compact star can be replaced by the electromagnetic collapse

As regards the physics of black holes, by considering a model of collapsing dust shells in the picture of a Schrödinger-like equation for the gravitational potential of a fictitious two-particle system of identical masses, in [22] Corda found that the gravitational collapse occurs till the formation of a final dark star defined by a maximum density of the shells fixed by the mass spectrum of the shells. Corda's theory, thus, replaces the gravitational singularity with the formation of a dark compact object constrained by a maximum value of the density of the collapsing shells. In our theory developed in this paper, we consider that the gravitational collapse can be replaced by the electromagnetic collapse taking place in the inner region of the dark star and, therefore, that the concept of region of instability of matter is equivalent to the physical condition of the maximum density of collapsing shells predicted by Corda's model.

In order to show this, before all, we start by expressing Corda's results regarding the processes of gravitational collapse of spherical dust shells till the formation of a dark compact object defined by an "apparent horizon" in the fundamental background of our theory, i.e. in terms of the dissipative features of the DQV associated with the virtual sub-particles of the DQV living at the virtual (variable) generalized Compton wavelength. In other words, we consider that the gravitational potential of a fictitious two-particle system of identical masses of Corda's approach can be ultimately associated with a gravitational potential describing the interaction of the spherical shells with the dissipative features of the superfluid DQV defined by a variable energy density and associated with the sea of virtual proto-particles of the vacuum living on the scale (10). The gravitational potential describing the interaction between the dust shells and the dissipative features of the DQV is the following

$$V(r) = -G\frac{vmM}{2Rc^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]^{3/2}} \quad (98)$$

where M is the mass of the dark compact object associated with the spherical massive shells and R is the radius of these shells. These dust shells have bound states of energy that can be determined by considering the gravitational potential of interaction (65). On the basis of the mathematical treatment provided by Corda in [22], in analogy to what happens in the hydrogen atom, here one can consider a Schrödinger-type equation for the potential of interaction (98) of the form

$$-\frac{\hbar^2}{2M}\left(\frac{\partial^2\Psi}{\partial r^2}+\frac{2}{r}\frac{\partial\Psi}{\partial r}\right)+V\Psi = \mathrm{E}\Psi \quad (99).$$

which is formally identical to the standard Schrödinger equation of the s states of the hydrogen atom which obeys to the Coulomb potential. By solving equation (66), one obtains the following bound states of energy of the dust shells:

$$E_n = -\frac{1}{n^2}\frac{G^2M^2v^3m^3}{2\hbar^2c^4\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]^{9/2}} \quad (100)$$

that lead to the following mass spectrum of the shells:

$$M_n = \frac{2}{n^2}\frac{G^2v^4m^4}{\hbar^2c^4\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]^{6}} \quad (101).$$

In the light of the generalized uncertainty relations (9) and the existence of the variable scale represented by the generalized Compton wavelength (10), the position of the physical quantum shells generated during the gravitational collapse till the apparent horizon cannot be exactly localized but can be defined through an average radius expressed by relation

$$\langle R_n\rangle = \frac{3}{2}\frac{M_nc^2}{\Delta\rho_{qvE}V}\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2} \quad (102).$$

The minimum value of the volume of these shells, in Planck units, can be computed as the difference between the volume of the sphere having radius $\langle R_n\rangle+\frac{1}{2}l_p$ and the volume of the sphere having radius $\langle R_n\rangle-\frac{1}{2}l_p$:

$$V_{min} = \frac{4}{3}\pi\left[\left(\langle R_n\rangle+\frac{1}{2}l_p\right)^3-\left(\langle R_n\rangle-\frac{1}{2}l_p\right)^3\right] = \frac{4}{3}\pi\left[3\langle R_n\rangle^2l_p+\frac{1}{4}l_p^3\right] = 4\pi\langle R_n\rangle^2l_p+\frac{\pi}{3}l_p^3 \quad (103).$$

Therefore, taking account of the mass spectrum (101) and the minimum value of the volume of the shells (103), one finds the following expression for the maximum value of the density of the shells:

$$\sigma_{max} = \frac{2G^2 \Delta\rho_{qvE}^4 V^4}{n^2 \hbar^2 c^4 \left(4\pi \langle R_n \rangle^2 l_p + \frac{\pi}{3} l_p^3\right)} \quad (104).$$

On the basis of equation (104), the variable energy density of the DQV and the interplay between the lattice of the (variable) scale represented by the generalized Compton wavelength (10) with the Planck length, determine a maximum value of the density of the shells generated during the gravitational collapse of the black hole, i.e. a critical, limit value of the number of these collapsing dust shells that cannot be overcome. The surface of the region corresponding to this maximum value of the density of collapsing dust shells defines an “apparent horizon” in the sense that the gravitational collapse cannot take place beyond this surface, and the region included between the centre of the black hole and this peculiar surface constitutes a “dark” quantum compact object, i.e. a “dark” star of extremely high mass and high density. The mass (101) of the shells, under the constraint (104) regarding the maximum density, can be therefore defined as the mass of the dark star generated during the gravitational collapse of the black hole. Finally, the maximum density of the shells (104) determined by an interplay with the elementary dissipative features associated with the virtual proto-particles of the vacuum leads to define a maximum energy density of the DQV given by relation

$$\rho_{qvE-max} = \frac{2G^2 \Delta\rho_{qvE}^4 V^4}{n^2 \hbar^2 c^2 \left(4\pi \langle R_n \rangle^2 l_p + \frac{\pi}{3} l_p^3\right)} \quad (105).$$

Now, we can demonstrate that the gravitational collapse of dust shells till the formation of a dark compact object is equivalent to considering an electromagnetic collapse of the inner region of the dark star, by taking account of the conservation of energy which rules the dynamics of the processes. The maximum energy density (105) determined by the collapsing dust shells of Corda’s model can be associated to the generation of a dark star whose inner region is characterized by an electromagnetic collapse in the sense that the baryonic matter corresponding to the maximum energy density (105), as a consequence of the conservation of energy, gives rise to a transition to a new kind of exotic matter – defined by a diminishing of the electromagnetic interactions – that thus provokes a release of energy outside the dark star in the form of electromagnetic radiation, i.e. astrophysical jets and winds. In this regard, we remember that, on the basis of the results obtained in [67], the collapse of baryon-like matter transitioning into a new state with the energy density emitted as electromagnetic radiation, may lead not only to well-known solutions of Einstein’s equations, such as Hayward's and Dymnikova's regular black holes [68, 69] but also to any other black hole whose metric is a solution of Einstein's equations. In affinity with these results, here we consider that the transition from the baryonic matter entangled with radiation to a new type of unstable matter characterized by a diminishing of electromagnetic interactions – during which energy is released in the form of electromagnetic radiation outside the dark star – is described by a conversion efficiency φ that can be determined by solving the following integral equation:

$\rho_{new} = \rho_r + \rho_b$ (106)

where ρ_{new} is the energy density of the (exotic) unstable matter associated with the diminished value of the Planck reduced constant (24),

$\rho_r = \rho_{0r} e^{\int f_{1,2} \frac{\varphi}{r} dr}$ (107)

is the energy density of radiation and

$\rho_b = -\rho_{0r} r^{-2\alpha-2} \int r^{1+2\alpha} \varphi e^{\int f_{1,2} \frac{\varphi}{r} dr} dr$ (108)

is the energy density of baryonic matter, which is described by the equation of state

$P = \alpha\rho$, $0 \leq \alpha \leq 1$, $\alpha \neq \frac{1}{2}$ (109).

Therefore, by introducing the parameter φ which measures the efficiency of conversion of the baryonic matter to exotic unstable matter and satisfies equation (106), we can say that the constraint (105) regarding the maximum energy density determined by the collapsing dust shells of Vaz's and Corda's model corresponds to a critical point which implies a transition of the baryonic matter inside the dark star into a new state of unstable matter subjected to electromagnetic collapse, with the release of electromagnetic energy outside in the form of astrophysical jets and winds. Moreover, on the basis of equations (107) and (108), the energy density of radiation and of baryonic matter depend of the probability $f_{1,2}$ of decay of the Fermi plasma to be expelled together with the emission of electromagnetic radiation.

In this picture, the baryonic matter makes a transition into radiation which is governed by the equation of state

$P = \frac{1}{3}\rho$ (110).

In order to evaluate the integral (106), by using the continuity equation

$\rho'_{new} + 2\rho_{new} + 2P_{new} = 0$ (111),

one arrives to the solution

$\varphi = \frac{\frac{2}{3}\alpha\rho_{new} - 2\alpha P_{new} - P'_{new} r}{f_{1,2}(\alpha\rho_{new} - P_{new})}$ (112).

Thus, one has

$$\int f_{1,2}\frac{\varphi}{r}dr = \ln|\alpha\rho_{new} - P_{new}| \quad (113)$$

and then

$$\rho_r = \rho_{0r}(\alpha\rho_{new} - P_{new}) \quad (114)$$

and

$$\rho_b = -\rho_{0r}\left(\frac{1}{3}\rho_{new} - P_{new}\right) \quad (115).$$

The total energy density of the new matter which is ruled by a diminished Planck reduced constant and is subjected to electromagnetic collapse, is therefore:

$$\rho_r + \rho_b = \rho_{0r}\left(\alpha - \frac{1}{3}\right)\rho_{new} \quad (116)$$

where the integration constant is

$$\rho_{0r} = \frac{1}{\alpha - \frac{1}{3}} \quad (117)$$

with the consequent constraint $\alpha > \frac{1}{3}$, compatibly with the results obtained in [67] as regards the physics of regular black holes (i.e. without a central singularity).

Now, the processes of transition – fixed by the conservation of energy and described by equations (106)-(117) – from the baryonic matter to unstable matter characterized by a diminishing of electromagnetic interactions, allow us to make a parallelism between the existence of the maximum energy density of collapsing dust shells (105) defining an "apparent horizon" and the maximum energy density (15) which, in our model, corresponds to the generation of a dark star characterized by an electromagnetic collapse in its inner region. Just like, in Vaz's and Corda's model, the maximum density of the collapsing dust shells (104) and their corresponding maximum energy density (105) imply the formation of surface constituting a dark compact object, in analogous way, in the model proposed in this paper, the maximum value of the quantum vacuum energy density (15) avoids the singularity in the centre of a black hole, defining a region of space characterized by a diminishing of electromagnetic interactions determined by a diminished value of the Planck constant. By considering that inside the dark star, as a consequence of the conservation of energy, there are processes of transition from baryonic matter to exotic (or unstable) matter (described by equations (106)-(117)), one can therefore say that the electromagnetic collapse inside black holes invoked by our model can be considered equivalent to Corda's and Vaz's insight regarding the formation of a dark compact object fixed by the constraint (105) regarding the maximum density of the collapsing dust shells.

In other words, on the basis of the treatment made here, according to the authors, it is legitimate to replace the concept of gravitational collapse till the formation of an apparent horizon defining the surface of a dark star with the “more elegant” view of electromagnetic collapse characterizing specific peculiar regions of space where the extremely low energy density of the vacuum generates a non-negligible variation of the Planck constant, thus provoking the decay of fermionic systems and particles into non-structured energy of the vacuum with a corresponding release of energy in the form of astrophysical jets. This equivalence between the maximum energy density of the collapsing shells defining the dark compact object of Vaz’s and Corda’s model and the maximum value of the quantum vacuum energy density which defines the region characterized by electromagnetic collapse, can thus be expressed by equating relations (105) and (15), namely

$$\frac{2G^2\Delta\rho_{qvE}^4V^4}{n^2\hbar^2c^2\left(4\pi\langle R_n\rangle^2 l_p+\frac{\pi}{3}l_p^3\right)}=\rho_{pE}-\frac{2{,}9M_{\odot}c^2}{V_{Sch}} \quad (118).$$

Equation (118) shows that the collapsing spherical shells till the formation of a dark compact object defined by the maximum density of the shells (104) is equivalent to considering the inner region of the dark star as a region of instability of matter, in the sense that the elementary fluctuations of the DVQ associated with the (virtual) proto-particles of the vacuum living on the (variable) generalized Compton wavelength act in such a way that their action mimic the generation of a sort of gravitational collapse till the formation of the dark star, directly depending of (and directly deriving from) the maximum value of the energy density which corresponds to the generation of this dark star. Equation (118), therefore, allows us to guarantee a compatibility of the model proposed in this paper with Corda’s and Vaz’s model regarding the gravitational collapse till the apparent horizon, showing in what sense the concept of diminishing of electromagnetic interactions inside black holes replaces the concept of gravitational collapse till the formation of a dark compact object.

In this way, on the basis of our model, it is possible to provide a new key of reading and physical interpretation of the formation of apparent horizons and black holes (intended as dark quantum objects). When the energy density reaches the value (16) in a region of the DQV, in this situation, the quantum vacuum energy density cannot further grow, thus implying that a dark compact object is formed whose inner region is characterized by processes of electromagnetic collapse, that determine a decay of matter into elementary particles and then into non-structured energy of quantum vacuum.

On the other hand, by virtue of the equivalence between the existence of a maximum value of the density of the shells – determined by the interaction of the shells with the dissipative features of the vacuum associated with the virtual proto-particles of the vacuum at the generalized Compton wavelength – and the maximum value of the quantum vacuum energy density originating the formation of the dark star, one can consider that, in the inner region of the dark star characterized by instability of atoms, also the entropy is characterized by a critical, maximum value that is compatible with the geometry determined by the dissipative features of the superfluid DQV and cannot further increase. In this regard, taking account the results obtained in [70], one can consider that the entropy of decaying matter is converted into that of the vacuum and, during these processes, because of the entanglement between the vacuum and the arising Hawking radiation, no firewall arises. As a consequence, because of the interaction between the virtual particles associated with the fluctuations of the 3D DQV and the black hole's apparent horizon, as well as because of the entanglement between the virtual particles of the vacuum and the arising Hawking radiation, on the basis of the results obtained in [71], the surface of the apparent horizon μ (that represents the boundary of the dark compact object that is forming and, therefore, of the region of instability of atoms) acts as a sort of coarse-grained entropy:

$$S^{coarse} = \frac{Area\,[\mu]}{4G\hbar} \quad (119).$$

In equation (119), the area of the apparent horizon can be interpreted statistically as the maximum boundary entropy that is compatible with the maximum quantum vacuum energy density (16) that can generate the dark star. Thus, if the coarse-grained entropy associated with the dark compact object, and thus of the region of instability of atoms, is constrained by the maximum quantum vacuum energy density (16) which can generate a dark star, and if the maximum density of hypothetical collapsing shells (104) is equivalent to the maximum quantum vacuum energy density (16), the area of the apparent horizon appearing in equation (119) derives from the dissipative features of the vacuum on the basis of relation

$$Area\,[\mu] = \frac{M_n \langle R_n \rangle}{\sigma_{max}} \quad (120)$$

namely

$$Area\,[\mu] = \frac{3}{2}\frac{M_n c^2}{\Delta\rho_{qvE} V}\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE} V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE} V}{\hbar c}\right)^2} \cdot$$

$$\left(9\pi \frac{{M_n}^2 c^4}{{\Delta\rho_{qvE}}^2 V^2}\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE} V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE} V}{\hbar c}\right)^2\right]{l_p}^2 + \frac{\pi}{3} l_p^3\right) \quad (121).$$

Thus, by substituting equation (121) inside equation (119) and taking account of relations (102) and (101), one finds the final expression of the coarse-grained entropy associated with the boundary of the region of instability of atoms:

$$S^{coarse} = \frac{3}{8}\frac{M_n c^2}{G\hbar\Delta\rho_{qvE}V}\sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2} \cdot$$

$$\left(9\frac{{M_n}^2c^4}{{\Delta\rho_{qvE}}^2V^2}\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right]{l_p}^2 + \frac{1}{3}l_p^3\right) \quad (122).$$

On the basis of equation (122), the maximum coarse-grained entropy associated with the formation of the apparent horizon, i.e. of the formation of the dark compact object defining the region of instability of atoms, is directly determined by the behaviour of the fluctuations of the quantum vacuum energy density that generate the dissipative features of the 3D DQV at the (variable) generalized Compton wavelength. And the impossibility of the coarse-grained entropy (122) to further increase, united with the maximum quantum vacuum energy density (16) which can generate the dark star, physically corresponds to the transition from the baryonic matter to the new exotic (unstable) matter that is associated with the modification of the electromagnetic properties in the inner region of the formed dark star, provoking therefore, the decay of matter of this region into ionized particles and, then, into non-structured energy of the DQV.

Moreover, this model provides an important lesson also as regards the paradoxes connected to the firewall of black holes. The lesson is the following. If the lattice of the DQV associated with the variable energy density corresponds to the transition from baryonic matter to unstable matter subjected to electromagnetic collapse, with the release of electromagnetic energy outside in the form of astrophysical jets and winds, there will be no firewall because, when the critical quantum vacuum energy density (16) is reached, a corresponding coarse-grained entropy given by relation (122) emerges that cannot further grow in this region. The formation of the dark compact object fixed by the critical value of the quantum vacuum energy density (16) and the maximum coarse-grained entropy (122), and the consequent processes of diminishing of electromagnetic interactions inside this region which lead to the decay of matter and the expulsion of ionized particles, can be considered as the solution of the paradoxes connected to the concepts of firewall and central singularity. In particular, we can say that, as a consequence of the dissipative features of the vacuum at the generalized Compton wavelength determined by opportune fluctuations of the variable quantum vacuum energy density, the area of the apparent horizon acts as the coarse-grained entropy (122) and this action allows us to demonstrate in a direct way the impossibility of the formation of a firewall and, in particular, to avoid the incompatibility determined by the simultaneous consideration of equivalence principle, Hawking radiation and quantum entanglement claimed in the so-called AMPS argument developed in [72, 73], therefore assuring the conservation of information in the dynamics of the black holes.

6. Perspectives about the information paradox

In the physics of black holes, a crucial problem regards the fate of the information embedded in matter that falls into a black hole. In this regard, in the literature one can find a plethora of attempts of solution. Think, for example, of Susskind's model of black hole complementarity, which implies the existence of two different complementary scenarios for objects approaching the horizon, i.e. the point of view of an outside observer and the perspective of a falling observer (who cannot communicate each other) [74-76], the Maldacena ADS/CFT Duality which, on the basis of string theory, implies that all information encoded by a black hole is reemitted with the Hawking radiation [77, 78], the Mathur fuzzball model which interprets the boundary of a black hole as a fuzzball wrapped by a bunch of superstrings [79], the black hole soft-haired model, which implies that low-energy soft photons radiate information with the evaporation of the black hole [80], the AMPS work about the existence of a firewall [72, 73], Bousso's and Penington's entanglement surfaces outside the event horizon [81], etc... However, all these theories cannot be considered satisfactory and present weak points that require further research and investigation. Today we deal yet with the problem whether the Hawking radiation carries information about matter that falls in the black hole and whether the quantum information encoded by the matter that collapsed to originate the black hole is destroyed and lost forever.

The electromagnetic collapse in the inner region of the dark star determined by the diminishing value of the Planck reduced constant, can provide new keys of re-reading of the problem of the information paradox, by introducing new perspectives of solution. The almost instantaneous decay of Fermi spheres of electrons and protons joined with the decay of quantum statistics in the inner region of the dark star, imply an energy escape along with entropy to outer space, with the result of modifying the treatment of the information paradox. In the approach developed in this paper, where the concept of black hole is replaced with the concept of a extremely dark compact star characterized, in its inner region, by an instability of matter determined by a diminishing of the electromagnetic interactions, there is no event horizon and no real paradox of loss of information. Here, the release of energy in the form of astrophysical jets which are emitted as a consequence of the electromagnetic collapse of the baryonic matter inside the dark star is in agreement with unitary evolution in quantum mechanics and, at the same time, does not imply losses of information encoded by matter falling in the black hole.

When the critical maximum energy density of the DQV (16) is reached, a diminishing of the electromagnetic interactions occur in the region into consideration, that assumes the form of a dark star which eats itself. Therefore, holes do not really exist in space and thus the term evaporation regarding the fate of these objects here does not seem appropriate. More adequate term instead of *evaporation* would be self-disintegration. Because of the electromagnetic collapse caused by the extremely low energy density of the vacuum, the black star literally breaks down its own matter and turns it into fresh energy in the form of jets and winds. This energy coming from black stars in the form of astrophysical winds and jets proves that current research on the information paradox of black stars has been flawed. There is nothing irrational in black stars that physics today cannot understand and describe. The first law of thermodynamics is preserved; dark stars are rejuvenating systems of the universe.

On the other hand, if the inner region of the dark star is a region of instability of matter as a consequence of the diminishing of electromagnetic interactions, it follows that also the matter that is attracted by the extremely dense star is subjected to the same fate of the old matter of the dark star which is already inside. In other words, we can say that the processes of electromagnetic collapse associated with the Fermi decay of electrons and protons which occur in the inner region of the dark star can be seen as the real stores, reservoirs of the information encoded by the matter that is falling inside the black hole.

In this picture, the emission of Hawking radiation can be seen itself as a consequence of the instability of matter inside the black hole generated by the diminishing of the electromagnetic interactions. Hawking radiation is not a phenomenon associated with evaporation of black holes because there are no black holes and there is no evaporation. There are simply regions of space characterized by extremely low energy density of space which causes electromagnetic instability of matter, with emission of radiation in the form of astrophysical jets, therefore assuring conservation of the information. Here, Hawking radiation can be itself seen as a part of this emitted radiation, that can be associated with the electromagnetic collapse characterizing the Fermi decay of electrons and protons inside the dark star defined by constraints (15) and (18) regarding the critical value of the quantum vacuum energy density. This consideration allows also an overcoming of the black hole soft-haired model, in the sense that the low-energy soft emitted photons which record information about matter falling into the dark star, can be seen only as a part of the processes that radiate outside information as a consequence of the electromagnetic collapse of the inner region, because all decay processes of matter occurring in the inner region of the dark star as a consequence of the diminishing of the electromagnetic interactions (and, thus, in particular, the decay dynamics of hydrogenoid atoms, quarkonium as well as fermionic systems) store the material information falling inside.

On the other hand, because of the entanglement entropy (90) which connects the fermionic degrees of freedom inside the dark star with the electromagnetic radiation emitted outside, the surface of the dark star acts as an entanglement island between the information inside the dark star and the modes outside. The entanglement between the decaying Fermi plasma inside the dark star and the emitted electromagnetic radiation (associated with the observed astrophysical jets and winds) outside, implies that there is no contradiction between interior evolution and exterior evolution. In particular, the number $N = \frac{e^2 c\mathcal{V} E_0^2}{8\pi\alpha\omega\left(\rho_{pE} - \frac{Mc^2}{V}\right)^2 l_P^8}$ of photons which are coupled with the decaying Fermi plasma inside the dark star, by virtue of the underlying activity of the proto-particles of the vacuum at the generalized Compton wavelength, can be seen as a source of entanglement islands between the information inside the dark star and the information outside the dark star. This reservoir of photons emitted during the decay of the Fermi spheres of electrons and protons in the inner region of the dark star, generates the connection between the information contained in the effective interior of the black hole and the modes outside and, therefore, between the effective interior evolution and the fundamental exterior evolution.

Finally, our model throws new light also as regards the black hole complementarity in the sense that the perspective is opened that the interior of the black star, as a consequence of the electromagnetic collapse and therefore the decay of matter into elementary particles and then into non-structured energy of the quantum vacuum, can be seen as a way of reorganizing the degrees of freedom associated to the transient phenomenon of an infalling object dissolving into the boundary of the dark star.

Recent research [82–87] has shown that an effective theory of a smooth interior, intended as a secondary concept associated with the modes in the zone describing an object falling into the black hole, can be developed from the exterior degrees of freedom. On the basis of the results obtained in [88], the paradox implied by the black hole complementarity regarding the apparent acausal influence determined, on the interior, by operators acting only on the Hawking radiation, can be avoided by considering that, as a consequence of the limited ability of an infalling observer to access complex information, the black hole interior and the Hawking radiation appear spacelike separated only in the semiclassical description and that, from the point of view of an exterior observer, the chaotic dynamics of the horizon transforms any effect to information in the Hawking radiation which cannot be accessed at the semiclassical level. In the framework provided in [88], the Hawking radiation containing information about the interior always lies in the causal future of the corresponding interior region and the interior appears causally disconnected from the radiation region only in the semiclassical description.

Now, in the approach developed in this paper, the electromagnetic collapse characterizing the interior of the black hole, leading to the decay of matter, implies that the modes outside the inner region contain any information of the effective interior as a consequence of the entanglement between the fermionic degrees of freedom inside the dark star and the emitted radiation outside. Because of the action of the photons coupled with the decaying Fermi plasma as source of entanglement between inner region and exterior region of the dark star, no operation performed on Hawking radiation, however complex, can affect the experience of an infalling observer. Therefore, by postulating that the inner region of the black star is a region of instability of matter, there is no paradox as regards the link between the interior time evolution to the black hole and the exterior time evolution. There is no contradiction between interior description and exterior description. The connection between the interior and the exterior time evolution of the black hole can be considered as a direct natural consequence of the rearrangement of correlations determined by the electromagnetic collapse determining the decay of matter inside the black star and the associated entanglement between decaying matter and emitted radiation. By following [72], this rearrangement of correlations associated with the decay of matter in the inner region of the black hole towards $r = 0$ (where a null shell of infalling particles is eaten) can be described by considering the following metric

$$ds^2 = -c^2\left(1 - \frac{2GV_{sch}\left(\rho_{pE} - \frac{M(t)c^2}{V}\right)}{c^2 r}\right)dt^2 + 2cdtdr + r^2 d\Omega^2 \quad (123)$$

where

$$M(t) = \begin{cases} 0 & for\ t < t_0 \\ M & for\ t > t_0 \end{cases} \quad (124)$$

and t_0 is the ingoing time at which the null shell is shot. For $t < t_0$, on the basis of the coordinate transformation

$$t = t' + \frac{r}{c} \quad (125),$$

the metric (123) tends to the flat space metric

$ds^2 = -c^2dt'^2 + dr^2 + r^2d\Omega^2$ (126).

The metric (126) describing the rearrangement of correlations associated with the decay of matter in the inner region of the black star implies that the trajectory of the boundary of this inner region characterized by electromagnetic collapse is

$$r = ct' + \frac{4GV_{sch}\left(\rho_{pE} - \frac{M(t)c^2}{V}\right)l_p^2}{c^2} - ct_0 \quad (127)$$

for $t_0 - \frac{4GV_{sch}\left(\rho_{pE} - \frac{M(t)c^2}{V}\right)l_p^2}{c^2} \leq t' \leq t_0 + \frac{4GV_{sch}\left(\rho_{pE} - \frac{M(t)c^2}{V}\right)l_p^2}{c^2}$ (128).

Now, the metric (126) can be converted into a metric of a “exterior” picture of the form

$$ds^2 = -\rho^2 d\tau^2 + d\rho^2 + \rho^2 cosh^2\tau d\Omega^2 \quad (129)$$

where

$$\tau = arctanh\frac{c(t'-t_*)}{r},\ \rho = \sqrt{r^2 - c^2(t'-t_*)^2} \quad (130)$$

are spherical Rindler coordinates, with

$$t_* = t_0 - \frac{4GV_{sch}\left(\rho_{pE} - \frac{M(t)c^2}{V}\right)l_p^2}{c^2} \quad (131).$$

The metric (129) is thus valid under the constraint $t < t_0$, i.e. for $\rho < \frac{4GV_{sch}\left(\rho_{pE} - \frac{M(t)c^2}{V}\right)l_p^2}{c^2}e^{-\tau}$ and $\tau \geq 0$. On the basis of the metric (129), the Rindler horizon is compatible with the trajectory of the boundary of the inner region of the dark star characterized by electromagnetic collapse, given by equation (127), which is smoothly linked with the inner region at $t = t_0$. Because of the not static features of the metric (129), observers at constant ρ follow trajectories of constant acceleration. This implies the possibility of appearance of a Unruh radiation. This result is in agreement with the prediction provided in the context of a model – similar to Vaz’s and Corda’s one – where one deals with a gravitational collapse of dust shells till an apparent horizon and the formation of a dark compact object defined by a maximum density, where the local Unruh temperature corresponds to the generalized Compton wavelength

$$\rho_s = \sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2} \quad (132).$$

For $\rho > \rho_s$ the apparent horizon can be characterized by the coarse-grained entropy

$$S_h(\tau) = \frac{\pi k_B \rho_s^2 cosh^2\tau}{l_p^2} \quad (133)$$

that corresponds with the entropy of a black hole of mass M when the apparent horizon intersects the null shell at the time

$$\tau = \ln \frac{c(t_0 - t_*)}{\rho_s} = \ln \frac{4GV_{sch}\left(\rho_{pE} - \frac{M(t)c^2}{V}\right) l_p^2}{\rho_s c^2} \quad (134).$$

Hence, by invoking the holographic principle, one can consider that the degrees of freedom associated with the boundary of the inner region of the dark star encode semiclassical information in the domain of dependence of a partial Cauchy surface bounded by the apparent horizon, predicted in the context of Corda's and Vaz's model, at time τ. In this picture, the information stored in these degrees of freedom is transmitted to the degrees of freedom of the inner region of the dark star characterized by electromagnetic collapse, when the apparent horizon is hit by the incoming null shell.

7. Conclusions

Although Roger Penrose won half of the Nobel Prize in 2020 for his contribution to the birth of the so-called singularity theorems that open new paths for mathematical general relativity, by addressing the question whether a general collapse of sufficiently heavy stars also leads to the formation of a black hole, these theorems are characterized by subtleties that are often misunderstood. Penrose's 1965 singularity theorem did not prove the existence of black holes, it neither implied the existence of a curvature singularity nor of an event horizon [1, 89]. Penrose's theorem does not say anything about the process of gravitational collapse itself, rather only what happens when a trapped surface already exists.

On the other hand, some recent research are trying to provide a solution to the singularity of black holes. For example, it has been recently demonstrated that, if one considers a Kerr space-time, in the case of an unextended spacetime, scalar curvature invariants remain finite everywhere and geodesic incompleteness does not necessarily imply the emergence of a physical singularity [90]. Another interesting study has shown how, by considering unimodular gravity in which the gravitational degrees of freedom are quantised using the Wheeler-deWitt equation and measurable differences with respect to general relativity appear only in the quantum regime, the classical singularity and horizon can be replaced by a non-singular highly quantum region where unitarity is preserved in unimodular time, in other words unitarity means globally well-defined evolution that is incompatible with the existence of singularities [91].

In this paper, we have introduced a different way of treating the physics of black holes where not only the gravitational singularities but also the gravitational collapse of black holes can be replaced by the consideration, inside a model of dynamical quantum vacuum defined by a variable energy density, of a diminishing of electromagnetic interactions inside black holes – determined by a diminishing of the Planck constant – which leads to the instability of matter. The concept of electromagnetic collapse of the inner region of black holes has been introduced, on the basis of a modified Coulomb interaction potential which leads to the decay of hydrogenoid atoms and of a modified Cornell potential which leads to the decay of quarkonium. The decay of collective fermionic systems has then been analysed.

Moreover, we have shown how the electromagnetic collapse in the inner region of the dark star can be considered equivalent to the consideration of a gravitational collapse till an apparent horizon defined by a maximum density of collapsing dust shells, thus evidencing a suggestive equivalence and compatibility with the results obtained recently by Vaz and Corda. This result, in our opinion, is an important clue as regards the legitimacy of the view introduced in this paper.

Finally, we have seen how our model has the merit of introducing novel perspectives of solution to the black hole information paradox, implying that there is no contradiction between interior description and exterior description, thus avoiding the apparent violation of causality associated with the black hole complementarity.

In summary, we can conclude that the consideration of the electromagnetic collapse in the inner region of a black hole – determined by a diminishing of the numerical value of the Planck constant – provides a compelling alternative path of construction of the physics of black holes, that open scenarios that are all to be explored. In particular, a suggestive perspective could be the possibility that the energy density of the dynamical quantum vacuum is related to dark energy. In this regard, it has been recently shown, on the basis of astronomical observations, that baryonic matter can be converted into dark energy during the collapse of extremely massive stars, i.e. non-singular black holes, to regions of energized vacuum [92]. A new image of the physical world could therefore emerge where ether, dynamical quantum vacuum, superfluid quantum space, and dark energy are all different names for the same underlying physical reality [44]. The age of physics, when the curvature of space without physical properties generates gravity, is coming to an end. A new vision is being created in which space has physical properties and interacts with matter. This vision naturally leads to the physics of black holes (black stars) that we have presented in this article. Further research will give us more results on the impact of the new model of black holes on cosmology. We hypothesize the suggestive perspective that black holes act as revitalization systems of the universe. This topic has the potential to open scenarios that are all to be explored.

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