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About Electroweak Regime, Electroweak Symmetry Breaking and Quantum Chromodynamics Condensates in a Completion of the Standard Model Based on Energy Fluctuations of a Timeless Three-Dimensional Quantum Vacuum

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Abstract. A completion of the Standard Model based on energy fluctuations of a timeless three-dimensional quantum vacuum corresponding to elementary processes of creation/annihilation of quanta is proposed which introduces interesting perspectives in the understanding of the electroweak interaction and of quantum chromodynamics. In this picture, electroweak symmetry breaking emerges dynamically via dimensional transmutation determined by the couplings associated with a singlet field depending on the changes of the energy density of the timeless three-dimensional quantum vacuum, thus removing the global minimum of the Standard Model Higgs potential. QCD condensates are vacuum properties linked with opportune elementary processes of creation/annihilation of quanta from the three-dimensional timeless quantum vacuum.

KEY WORDS: Standard Model, timeless three-dimensional quantum vacuum, fluctuations of the three-dimensional quantum vacuum, electroweak regime, electroweak symmetry breaking, quantum chromodynamics.

1 Introduction

The Standard Model of particle physics, developed since the 70s, is a theoretical framework that integrates our current knowledge of the subatomic world and its fundamental interactions. It incorporates Quantum Electrodynamics (the quantised version of Maxwell's electromagnetism) and the weak and strong interactions, and has survived unmodified for decades, describing a vast array of data over a wide range of energy scales.

Within the Standard Model, a particularly important role is occupied by symmetry groups: the strong interactions reflect invariance under the local SU(3) colour gauge group and are described by the exchange of the corresponding spin-1 gauge fields, namely eight massless gluons, while the electromagnetic and weak interactions are described by a lagrangian that, being invariant under local weak isospin and hypercharge gauge transformations, is based on the $SU(2) \otimes U(1)$ group and are transmitted by the exchange respectively of one massless photon and three massive bosons, $W^{\pm}$ and Z_0.

As regards the fermionic matter content, from the Standard Model we have learnt experimentally that there are six different quark flavours u, d, s, c, b, t, three different charged leptons e, μ, τ and their corresponding neutrinos ν_e, ν_μ and ν_τ. Inside this theory, all these particles are organized into three families, as expressed by the following relations

$$\begin{bmatrix} \nu_e & u \\ e^- & d' \end{bmatrix}, \qquad \begin{bmatrix} \nu_\mu & c \\ \mu^- & s' \end{bmatrix}, \qquad \begin{bmatrix} \nu_\tau & t \\ \tau^- & b' \end{bmatrix} \tag{1}$$

(where each quark appears in three different colours) and

$$\begin{bmatrix} \nu_l & q_u \\ l^- & q_d \end{bmatrix} \equiv \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L, \begin{pmatrix} q_u \\ q_d \end{pmatrix}_L, l_R^-, q_{uR}, q_{dR} \tag{2}$$

(where L refers to left-handed and R to right-handed fields)

plus the corresponding antiparticles. Thus, we have three nearly identical copies of the same $SU(2)_L \otimes U(1)_Y$ structure (the label Y referring to weak hypercharge fields), with masses as the only difference. The three fermionic families in equation (1) turn out to have identical properties (gauge interactions); they differ only by their mass and their flavour quantum number [1].

Inside the Standard Model, the vacuum has the effect to generate a breaking of the gauge symmetry, to activate a spontaneous symmetry breaking of the electroweak group to the electromagnetic subgroup $U(1)$ of quantum electrodynamics:

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \xrightarrow{\text{SSB}} SU(3)_C \otimes U(1)_{\text{QED}} . \tag{3}$$

As a consequence of the spontaneous symmetry breaking mechanism, the Standard Model allows masses of the weak gauge bosons to be generated by requiring in this regard the presence of a physical scalar particle in the model, the so-called Higgs boson. The spontaneous symmetry breaking generates also fermion masses and mixings. The Higgs field, which forms a condensate filling the whole universe, can be probably considered the most mysterious topic within the Standard Model. According to the Standard Model, the motion of all the existing material particles turn out to be influenced by this condensate, which can be considered the real source of their mass. It must be emphasized that the Higgs boson, a spin-0 particle produced from excitations of the Higgs field, was recently discovered, completing the particle spectrum of the Standard Model, but that does not mean the story is now over. The study of the Higgs boson's couplings is now extremely important, and is connected to a new chapter of physics that can be opportunely called "beyond the Standard Model physics".

The Standard Model has been confirmed countless times in all accelerator experiments, including the latest runs of the Large Hadron Collider (LHC). Despite this convincing body of evidence, the Standard Model has many puzzled aspects and has to face many unsolved challenges [2–4]. Although the Standard Model of strong and electroweak interactions has passed all experimental tests during the last 40 years, however many relevant questions remain unanswered and lead to the conclusion that this theory might not be the final theory of the universe. Fundamental topics which are waiting for a consistent and satisfactory explanation regard, for example, the search of the ultimate mechanism that can be considered the real origin of particles' masses, what is the origin of the difference between matter and antimatter and, above all, the nature and the origin of the dark matter (invoked to explain the formation of large-scale structures on a cosmological scale such as the rotation of galaxies) and of the dark energy (invoked to explain the accelerated expansion of the universe) and how one can unify the fundamental interactions and quantize gravity.

By using the language of quantum field theory, the Standard Model of particle physics provides a compelling description of phenomena up to the energy scales probed by present accelerators. The current accelerator technology allows us to test energies moderately above the range $\mu_{\text{SM}} = O$ (TeV) defining the Standard Model of particle physics. The current view, on the basis of the assumption that no dramatic change in physics occurs between μ_{SM} and Planck's mass m_{P}, namely that m_{P} provides the only genuine scale in quantum field theory. But if this assumption which bases our current description of particle physics is true, we have got now no compelling explanation for the mass hierarchy. Moreover, if one applies quantum corrections to the Higgs vacuum the result is a shift of the Higgs mass close to m_{P}, and this generates the so-called "fine-tuning problem" where the quadratic divergences (associated with the corrections to the Higgs mass) are not radiative corrections to fermion or gauge boson masses, these being protected by chiral and gauge symmetries [5].

The considerations above provide plausible reasons to suspect that the Standard Model breaks down at some high energy scale close to the Planck scale, where it seems necessary to replace it by a more fundamental theory and, thus, that a new physics exists between the weak scale and the Planck scale. Today, we have got indeed several proposals of extensions of the Standard Model which suggest solutions to its open questions or ideas on how to pursue model-building beyond its boundaries ($\mu > \mu_{\text{SM}}$). Most proposals add new aspects of complexity to the structure of the Standard Model under the tacit assumption that these must come into play at large energy scales. Much of this research seem to be based on the widespread belief that a new kind of physics is prone to manifest its effects in the form of hidden particles or extended symmetry groups (examples include supersymmetric partners, sterile neutrinos, axions, Kaluza-Klein particles, WIMP's, dark photons and so on [6,7]). The way towards the correct theory will be found thanks to experiments and, so far, LHC searches show no credible hint for physics beyond the Standard Model up to a center-of-mass energy of 8 TeV [8]. These preliminary results seem to suggest the possibility that an undiscovered and possibly non-trivial connection between the Standard Model and TeV phenomena exists.

More importantly, the discussion about the foundations and the challenges of the Standard Model introduces the following key question: what should be considered the principles guiding model-building efforts towards the development of a "beyond the Standard Model" physics? In contrast with many mainstream proposals on how to tackle this question, in the interesting paper *Fractal space-time as underlying structure of the Standard Model*, Ervin Goldfain argues that a satisfactory resolution to the challenges confronting the Standard Model requires further advancing the Renormalization Group, which is one of the fundamental programs built in the structure of the Standard Model whose function is to preserve self-consistency and to describe how parameters of the theory evolve with the energy scale [9]. In particular, Goldfain shows that, in virtue of the nonlinear dynamics of the Renormalization Group equations, the quantum geometry of the Standard Model may be replaced with a fractal space-time near or above the electroweak scale. Goldfain's approach shows that the fractal geometry of the background can explain the mass hierarchy problem and reproduce the emergence of the Higgs-like resonance as a condensate of gauge bosons with a vanishing topological charge. In addition, as evidenced in detail in the references [10–12], in this model the onset of space-time of low level fractality clarifies the fermion chirality and the violation of CP symmetry in weak interactions, the gauge hierarchy and cosmological constant problems as well as the possible content of non-baryonic dark matter, which may surface as low-energy condensates of gauge bosons on fractal space-time that are likely to quickly annihilate into lepton-antilepton or quark-antiquark pairs. Goldfain claims finally that in his model one can obtain an unified understanding of symmetries that operate within quantum field theory, a tantalizing connection between the symmetries of quantum field theory and the geometry of the fractal space-time, which leads also to two other fundamental unifying physical insights: the interpretation of an arbitrary spin as a topological manifestation of the fractal space-time and the equivalence of classical gravitation in ordinary space-time and field theory on fractal space-time (which suggests thus an unforeseen path to the long-sought unification of general relativity and quantum theory) [11, 13].

On the other hand, if one considers the Higgs potential and how it evolves with energy in the Standard Model, in particular its stability, one finds that it is metastable yielding to the problem that additional particles coupling to the Higgs sector change the shape of the potential drammatically. In particular, in [14] Gabrielli *et al.* found that, due to dimensional transmutation, the Standard Model Higgs potential has a global minimum at $\approx 10^{26}$ GeV, which has the consequence to invalidate the Standard Model as a phenomenologically acceptable model in this energy range. In order to solve this problem, Gabrielli and his collaborators considered a minimal extension of the Standard Model, which consists in introducing a new complex singlet scalar field coupled to the Higgs sector. This minimal extension of the Standard Model by one complex singlet field solves the wrong vacuum problem, stabilising thus the Standard Model Higgs potential, generates electroweak symmetry breaking dynamically via dimensional transmutation (induces a scale in the singlet sector via dimensional transmutation that generates the negative Standard Model Higgs mass term through the Higgs portal), provides a natural dark matter candidate for the Standard Model which is in well agreement with present dark matter measurements, and is a candidate for the inflation. Gabrielli and his co-authors write: "Compared to previous such attempts to formulate the new Standard Model, ours has less parameters as well as less new dynamical degrees of freedom. In this framework the false Standard Model vacuum is avoided due to the modification of the Standard Model Higgs boson quartic coupling Renormalization Group Equations by the singlet couplings. The electroweak scale can be generated from a classically scale invariant Lagrangian through dimensional transmutation in the scalar sector, by letting the quartic coupling of the CP-even scalar run negative close to the Electroweak scale. The Vacuum Expectation Value of this scalar then induces the Standard Model Higgs Vacuum Expectation Value through a portal coupling.".

In this paper, in order to solve the problems of the current Standard Model mentioned above (and in particular to treat the electroweak regime, to explain how the electroweak symmetry breaking occurs, as well as to throw new light on quantum chromodynamics) we propose a completion of the Standard Model based on energy fluctuations of an ultimate timeless three-dimensional (3D) quantum vacuum characterized by elementary processes of creation/annihilation of quanta. This paper is so structured. In Chapter 2 we will review the general features of the 3D timeless quantum vacuum model recently proposed by the author in [15–23]. In Chapter 3 we will show how the 3D timeless quantum vacuum model allows us to extend the Standard Model in such a way that provides a compelling description of the electroweak regime as well as of the spontaneous symmetry breaking and of the interpretation of the origin of particles' masses. Finally, in Chapter 4 we will analyse quantum chromodynamics in the picture of fundamental fluctuations of the 3D quantum vacuum, showing how QCD condensates are vacuum properties that are significantly distorted or reduced in hadrons.

2 The Ontology and the Fundamental Features of the Timeless Three-Dimensional Quantum Vacuum Model

The existence of the physical vacuum can be considered one of the most relevant predictions of modern quantum field theories, such as quantum electrodynamics, the Weinberg-Salam-Glashow theory of electroweak interactions, and the quantum chromodynamics of strong interactions. From the quantum field theories which describe the known particles and forces one can derive various contributions to the vacuum energy density characterizing this quantum medium permeating the universe. The vacuum energy density associated with these theories, which has experimentally demonstrated consequences and is thus taken to be physically real, has cosmological implications which derive directly when certain assumptions are made about the relation between general relativity and quantum field theory. On the basis of the fundamental theories, one can infer that the total vacuum energy density has at least the following three contributions,

$$\begin{pmatrix}\text{Vacuum}\\ \text{energy}\\ \text{density}\end{pmatrix} = \begin{pmatrix}\text{VACUUM}\\ \text{ZERO-POINT-ENERGY}\\ +\text{FLUCTUATIONS}\end{pmatrix} + \begin{pmatrix}\text{QCD}\\ \text{gluon-and-quark}\\ \text{condensates}\end{pmatrix} + \begin{pmatrix}\text{The}\\ \text{Higgs}\\ \text{field}\end{pmatrix} + \cdots \quad (4)$$

namely the fluctuations characterizing the zero-point field, the fluctuations characterizing the quantum chromodynamic level of subnuclear physics and the fluctuations linked with the Higgs field, and the dots represent contributions from possible existing sources outside the Standard Model (for instance, GUT's, string theories, and every other unknown contributor to the vacuum energy density). Since there is no structure within the Standard Model which suggests any relations between the terms in equation (4), here it is legitimate to assume that the total vacuum energy density ρ_{vac} is, at least, as large as any of the individual terms. In order to reconcile the vacuum energy density estimate within the Standard Model with the observational limits on the cosmological constant $|\Lambda| < 10^{-56}$ cm^{-2}, the usual programme is to "fine-tune": for example, if the vacuum energy is estimated to be at least as large as the contribution from the QED sector then Λ_0 has to cancel the vacuum energy to a precision of at least 55 orders of magnitude.

Several different indications, based either on laboratory experiments or on astronomical observations, indicate that the vacuum energy density should be non-zero. As well known, the notion of physical vacuum originated after the birth of quantum mechanics, in connection with the development of the idea of spontaneous emission of an isolated excited atom [24]. It was later found that the polarization of the electromagnetic component of the physical vacuum, the quantum electrodynamics vacuum (QED-vacuum), could manifest itself in the spatial "smearing" of the electron and a change, as a result, of the potential energy of its interaction with the nucleus, thus providing conditions for the removal of the degeneracy of the energies of the $2S1/2$ and $2P1/2$ states in the hydrogen atom – the Lamb shift [25]. It was also demonstrated that the quantum fluctuations of the electromagnetic component of the physical vacuum in regions contiguous with material objects could provoke a modification of the relativistic quantum relationships in the near-surface regions of the objects (think, for example, to the macroscopic manifestations represented by the Casimir ponderomotive effect [26, 27] and by the Josephson contact noise [28]). All these phenomena here mentioned are of electromagnetic nature: they vanish if the fine structure constant $\alpha = e^2/(\hbar c)$ (where e is the electron charge, c is the velocity of light in a vacuum, and $\hbar$ is Planck's reduced constant) tends to zero [26, 27].

The development of quantum chromodynamics [29] brought interesting results as regards the nature of the physical vacuum on high-energy scales. In particular, it emerged that at an energy density of $E_{\text{QED}} \approx 200$ MeV a phenomenon of confinement-deconfinement transition regards the nucleus where quarks are no longer bound in nucleons but form a quark-gluon plasma or quark soup. The strong interaction constant α_{S} in that case proved to be dependent on the excitation energy, with magnitude changing from $\alpha_{\text{S}} \sim 1$ at low energies to $\alpha_{\text{S}} \approx 0.3$ at energies of a few gigaelectron-volts, depending but weakly on energy thereafter [29]. In the last decade, the notion of a physical vacuum have come into wide use in cosmology [30–33] in connection with the concept of "dark energy" that accounts for 73% of the entire energy of the universe, in the context of the Friedmann equations of the general theory of relativity. The current view is that and elusive form of energy, called "dark energy", is uniformly "spilled" in the universe, its unalterable density being $\varepsilon_V = \lambda c^4/8\pi G$, where λ and G are the cosmological and the gravitational constant, respectively. Moreover, an unknown form of matter (referred to as "dark matter"), is invoked to explain the rotation curves of galaxies and the mass of galaxy clusters (as well as the anisotropies of the cosmic microwave background and distribution of galaxies on a large scale). On the other hand, it must be emphasized that, apart from the introduction of the here mentioned physically obscure entities, namely dark energy and dark matter, the inner structure of the Standard Model meets relevant problems as a consequence of the unsuccessful attempts to tie in the apparent value $\varepsilon_V \approx 0.66 \times 10^{-8}$ erg/cm^3 [34] with the parameters of the physical vacuum introduced in elementary particle physics, the quantum chromodynamics vacuum (QCD vacuum). The above discrepancies come to more than 40 orders of magnitude if the characteristic energy scale of the quantum chromodynamics vacuum is taken to be $E_{\text{QCD}} \approx 200$ MeV [30, 35, 36], with its energy density being $\varepsilon_{\text{QCD}} = E_{\text{QCD}}^4/(2\pi\hbar c)^3$, and over 120 orders of magnitude if one is orientated towards the vacuum of physical fields, wherein quantum effects and gravitational effects would manifest themselves simultaneously, with the Planck energy density

$$\rho_{\text{PE}} = \frac{m_{\text{P}} c^2}{l_{\text{P}}^3} = 4.641266 \times 10^{113} \frac{\text{Kg}}{\text{ms}^2} \tag{5}$$

(where m_{P} is Planck's mass, c is the light speed and l_{P} is Planck's length) playing the part of the characteristic energy scale.

According to the approach suggested by the author and Sorli in [15–23], the fundamental arena of the universe is a 3D isotropic quantum vacuum composed by elementary packets of energy having the size of Planck volume and whose most universal property is its energy density. The ordinary space-time we perceive derives from this 3D isotropic quantum vacuum. On the basis of the Planckian metric which defines the 3D quantum vacuum, the maximum energy density characterizing the minimum quantized space constituted by Planck's volume given by the Planck energy density (1) defines a universal property of space. In the free space, in the absence of matter, the energy density of the 3D quantum vacuum is at its maximum and is given by (1). One can say that in the presence of a material object the curvature of space increases and corresponds physically to a more fundamental diminishing of the energy density of the quantum vacuum, which, in the centre of the material object, is given by relation

$$\rho_{\mathrm{qvE}} = \rho_{\mathrm{PE}} - \frac{mc^2}{V} \, , \tag{6}$$

m and V being the mass and volume of the object. The appearance of matter corresponds to a given change of the energy density of quantum vacuum and derives from elementary processes of creation/annihilation of quanta analogous to Chiatti's and Licata's transactions [37–40]. If in Chiatti's and Licata's model the only truly existent "things" in the physical world are the events of creation and destruction (or, in other words, physical manifestation and demanifestation) of certain qualities, the fundamental physical reality is an atemporal substratum, where only the transactions between field modes take place, and the quantum-mechanical wave-function simply emerges as a statistical coverage of a great amount of elementary transitions, in analogous way in the model proposed by the author the fundamental physical reality is a timeless 3D quantum vacuum characterized by fluctuations of energy corresponding to elementary processes of creation/annihilation of quanta and the presence of a given massive particle or massive object in our level of physical reality derives from a more fundamental diminishing of the energy density of quantum vacuum associated to opportune processes of creation and annihilation of quanta.

In this model, the changes and fluctuations of the quantum vacuum energy density, through a quantized metric characterizing the underlying microscopic geometry of the 3D quantum vacuum, can be considered the origin of a curvature of space-time similar to the curvature produced by a "dark energy" density [16–20, 23]. The quantized metric of the 3D quantum vacuum condensate is linked with the changes of the quantum vacuum energy density determining the appearance of matter and the opportune fluctuations of the quantum vacuum energy density determining dark energy. Furthermore, it is associated with an underlying microscopic geometry depending of the Planck scale and allows the quantum Einstein equations of general relativity to be obtained directly: this means that the curvature of space-time characteristic of general relativity may be considered as a mathematical value which emerges from the quantized metric and thus from the changes and fluctuations of the quantum vacuum energy density. The quantized metric of the 3D quantum vacuum condensate is

$$d\hat{s}^2 = \hat{g}_{\mu\nu} dx^\mu dx^\nu \tag{7}$$

whose coefficients (in polar coordinates) are defined by equations

$$\begin{gathered} \hat{g}_{00} = -1 + \hat{h}_{00}\,, \qquad \hat{g}_{11} = 1 + \hat{h}_{11}\,, \qquad \hat{g}_{22} = r^2(1+\hat{h}_{22})\,, \\ \hat{g}_{33} = r^2 \sin^2\vartheta(1+\hat{h}_{33}), \qquad \hat{g}_{\mu\nu} = \hat{h}_{\mu\nu} \ \text{ for } \ \mu \neq \nu \end{gathered} \tag{8}$$

where multiplication of every term times the unit operator is implicit and, at the order $O\left(r^2\right)$, one has $\langle \hat{h}_{\mu\nu} \rangle = 0$ except

$$\begin{aligned} \langle \hat{h}_{00} \rangle &= \frac{8\pi G}{3} \left(\frac{\Delta\rho_{\text{qvE}}}{c^2} + \frac{35Gc^2}{2\pi\hbar^4 V} \left(\frac{V}{c^2} \Delta\rho_{\text{qvE}}^{\text{DE}} \right)^6 \right) r^2 \\ \langle \hat{h}_{11} \rangle &= \frac{8\pi G}{3} \left(-\frac{\Delta\rho_{\text{qvE}}}{2c^2} + \frac{35Gc^2}{2\pi\hbar^4 V} \left(\frac{V}{c^2} \Delta\rho_{\text{qvE}}^{\text{DE}} \right)^6 \right) r^2\,, \end{aligned} \tag{9}$$

where $\Delta\rho_{\text{qvE}}^{\text{DE}} = m_{\text{DE}} c^2/V$ is the opportune change of the quantum vacuum energy density which generates the manifestation of dark energy density of energy density $\rho_{\text{DE}} = m_{\text{DE}} c^2$. The quantized metric (7) is associated with an underlying microscopic geometry expressed by equations

$$\Delta x \geq \frac{\hbar}{2\Delta p} + \frac{\Delta p}{2\hbar} \left(2\pi^2/3\right)^{2/3} l^{2/3} l_{\text{P}}^{4/3} \tag{10}$$

(which indicates that the uncertainty in the measure of the position cannot be smaller than an elementary length proportional to Planck's length),

$$\Delta t \geq \frac{\hbar}{2\Delta E} + \frac{\Delta E T_0^2}{2\hbar} \tag{11}$$

which is the time uncertainty and

$$\Delta L \cong \frac{\left(2\pi^2/3\right)^{1/3} l^{1/3} l_{\text{P}}^{2/3} T_0 E}{2\hbar} \tag{12}$$

which indicates in what sense the curvature of a region of size L can be related to the presence of energy and momentum in it. The quantized metric (7) allows the quantum Einstein equations

$$\hat{G}_{\mu\nu} = \frac{8\pi G}{c^4} \hat{T}_{\mu\nu} \tag{13}$$

(where the quantum Einstein tensor operator $\hat{G}_{\mu\nu}$ is expressed in terms of the operators $\hat{h}_{\mu\nu}$) to be obtained directly: this means that the curvature of space-time characteristic of general relativity may be considered as a mathematical value which emerges from the quantized metric (7) and thus from the changes and fluctuations of the quantum vacuum energy density (on the basis of equations (8) and (9)) [16].

In the approach proposed by the author in [15, 17, 19, 21–23], in analogy with Chiatti's and Licata's transactional approach, the events of preparation of an initial state (creation of a particle or object from the 3D quantum vacuum) and of detection of a final state (annihilation or destruction of a particle or object from the 3D quantum vacuum) can be considered as the two only real primary physical events. These two events are connected by their common origin in the timeless background represented by the 3D quantum vacuum. These two primary extreme physical events of the 3D quantum vacuum are each corresponding to a peculiar reduction of a state vector (which are constituted of interaction vertices in which real elementary particles are created or destroyed). For this reason, they can be also called "**RS** processes" where **RS** stands for *state reduction* in analogy with the **R** processes of the Penrose terminology. Each **RS** process is a self-connection of the timeless 3D quantum vacuum. In this picture, the history of the Universe, considered at the basic level, can be seen as a whole as a complete network of **RS** processes that take place in the timeless 3D quantum vacuum.

The probability of the occurrence of a creation/destruction event for a quantum particle Q, associated with a certain diminishing of the quantum vacuum energy density, in a point event x is linked with the probability amplitudes $\psi_{Q,i}(x)$ (for creation events) and $\varphi_{Q,i}(x)$ (for destruction events) of a spinor $C = \begin{pmatrix} \psi_{Q,i} \\ \varphi_{Q,i} \end{pmatrix}$ at two components. The generic spinor $C = \begin{pmatrix} \psi_{Q,i} \\ \varphi_{Q,i} \end{pmatrix}$ satisfies a time-symmetric extension of Klein-Gordon quantum relativistic equation of the form

$$\begin{pmatrix} H & 0 \\ 0 & -H \end{pmatrix} C = 0\,, \tag{14}$$

where $H = (-\hbar^2 \partial^\mu \partial_\mu + m^2 c^2)$, $m = \dfrac{V \Delta\rho_{\text{qvE}}}{c^2}$ is the mass of the quantum particle, V being its volume. Equation (10) corresponds to the following equations:

$$\left(-\hbar^2 \partial^\mu \partial_\mu + \frac{V^2}{c^2} \left(\Delta\rho_{\text{qvE}}\right)^2\right) \psi_{Q,i}(x) = 0 \qquad \text{for creation events,} \tag{15}$$

$$\left(\hbar^2 \partial^\mu \partial_\mu - \frac{V^2}{c^2} \left(\Delta\rho_{\text{qvE}}\right)^2\right) \varphi_{Q,i}(x) = 0 \qquad \text{for destruction events,} \tag{16}$$

respectively. At the non-relativistic limit, equation (14) becomes a pair of Schrödinger-type equations

$$-\frac{\hbar^2 c^2}{2V\Delta\rho_{\text{qvE}}}\nabla^2\psi_{Q,i}(x) = i\hbar\frac{\partial}{\partial t}\psi_{Q,i}(x) \ , \tag{17}$$

$$\frac{\hbar^2 c^2}{2V\Delta\rho_{\text{qvE}}}\nabla^2\phi_{Q,i}(x) = i\hbar\frac{\partial}{\partial t}\phi^*_{Q,i}(x) \ . \tag{18}$$

In the view of a timeless 3D quantum vacuum model, the evolution of a particle of object is determined by appropriate waves of the vacuum associated with the spinor which describes the amplitude of creation or destruction events. The waves of the vacuum act in a non-local way through an appropriate quantum potential of the vacuum

$$Q_{Q,i} = \frac{\hbar^2 c^2}{V^2\left(\Delta\rho_{\text{qvE}}\right)^2}\begin{pmatrix} \dfrac{\left(\nabla^2 - \dfrac{1}{c^2}\dfrac{\partial^2}{\partial t^2}\right)|\psi_{Q,i}|}{|\psi_{Q,i}|} \\ -\dfrac{\left(\nabla^2 - \dfrac{1}{c^2}\dfrac{\partial^2}{\partial t^2}\right)|\varphi_{Q,i}|}{|\varphi_{Q,i}|} \end{pmatrix} \tag{19}$$

which becomes

$$Q_{Q,i} = -\frac{\hbar^2 c^2}{2V\Delta\rho_{\text{qvE}}}\begin{pmatrix} \dfrac{\nabla^2|\psi_{Q,i}|}{|\psi_{Q,i}|} \\ -\dfrac{\nabla^2|\phi_{Q,i}|}{|\phi_{Q,i}|} \end{pmatrix} \tag{20}$$

in the non-relativistic limit) which guides the occurring of the processes of creation or annihilation of quanta in the 3D quantum vacuum in a non-local, instantaneous manner. In virtue of the primary physical reality of the processes of creation and annihilation and of the non-local features of the quantum potential which is associated with the amplitudes of them, in the 3D quantum vacuum the duration of the processes from the creation of a particle or object till its annihilation has not a primary physical reality but exists only in the sense of numerical order. In other words, in the 3D quantum vacuum time exists merely as a mathematical parameter measuring the dynamics of a particle or object. This approach implies thus that, at a fundamental level, events run only in space and time is a mathematical emergent quantity which measures the numerical order of changes' evolution.

The 3D quantum vacuum model described by equations (14)–(19) introduces the possibility to obtain the standard quantum formalism as a particular aspect of such general theory and, on the other hand, a suggestive interpretation of gravity as a phenomenon emerging from the timeless 3D quantum vacuum [15, 17, 19, 21–23]. The presence of the quantum potential of the vacuum is in fact equivalent to a curved space-time with its metric being given by

$$\tilde{g}_{\mu\nu} = g_{\mu\nu}/\exp Q_{Q,i} \ , \tag{21}$$

which is a conformal metric, where here

$$Q_{Q,i} = \frac{\hbar^2 c^2}{V^2 \left(\Delta\rho_{\text{qvE}}\right)^2} \frac{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)_g |\psi_{Q,i}|}{|\psi_{Q,i}|} \tag{22}$$

is the quantum potential of the vacuum. In this picture, **RS** processes associated with creation events of quantum particles determine a quantum potential of the vacuum which is equivalent to the curvature of the space-time. The quantum potential of the vacuum corresponding to the generic component of the spinor of a quantum particle is tightly linked with the curvature of the space-time we perceive. In other words, one can say that **RS** processes, through the manifestation of the quantum potential of the vacuum (22), lead to the generation, in our macroscopic level of reality, of a curvature of space-time and, at the same time, the space-time metric is linked with the quantum potential of the vacuum which influences and determines the behaviour of the particles (themselves corresponding to creation events from the timeless 3D quantum vacuum). In this model, one can say that the space-time geometry sometimes looks like gravity and sometimes looks like quantum behaviours and both these features of physical geometry emerge from the **RS** processes of the 3D timeless quantum vacuum.

3 About Electroweak Theory and Electroweak Symmetry Breaking

In the Standard Model, in order to describe electroweak interactions, an opportune elaborated mathematical formalism is required, which invokes the presence of several fermionic flavours and different properties for left- and right-handed fields; moreover, the left-handed fermions should appear in doublets, and one has to include massive gauge bosons $W^{\pm}$ and Z in addition to the photon. By considering the symmetry group $SU\left(2\right)_L \otimes U\left(1\right)_Y$ where L refers to left-handed fields and Y to weak hypercharge fields, one finds that the properly normalized kinetic lagrangian may be expressed as

$$L_{\text{Kin}} = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{2} Tr\left[\tilde{W}_{\mu\nu}\tilde{W}^{\mu\nu}\right] = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}\,, \tag{23}$$

where

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu\,, \tag{24}$$

$$\tilde{W}_{\mu\nu} = -\frac{i}{g}\left[\left(\partial_\mu + ig\tilde{W}_\mu\right), \left(\partial_\nu + ig\tilde{W}_\nu\right)\right] \tag{25}$$

and thus

$$\tilde{W}_{\mu\nu} = \frac{\sigma_i}{2} W^i_{\mu\nu}\,, \qquad W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\varepsilon^{ijk} W^i_\mu W^k_\nu\,, \tag{26}$$

where σ_i are the Pauli matrices, g is the $SU(2)_L$ coupling, B_μ is the mass isosinglet (for $U(1)_Y$), $\vec{W}_\mu$ is the mass less isovector triplet (for $SU(2)_L$), as in the original Weinberg-Glashow-Salam model [41–43].

In our proposal of completion of the Standard Model inside a 3D quantum vacuum characterized by energy density fluctuations, the Abelian group $U(1)_Y$ is given by the infinite set of phase transformations on the wave function of a charged particle $C = \begin{pmatrix} \psi_{Q,i} \\ \varphi_{Q,i} \end{pmatrix}$ at two components describing the probability of the occurrence of a creation/destruction event for a quantum particle Q of a given mass $m = V\Delta\rho_{\text{qvE}}/c^2$ in a point event

$$C \to e^{ie\theta(x)}C\,. \tag{27}$$

In analogous way, the group $SU(2)_L$ of isospin is given by the set of rotations in isospin space applied to the same wave function $C = \begin{pmatrix} \psi_{Q,i} \\ \varphi_{Q,i} \end{pmatrix}$ at two components

$$C \to e^{ig\vec{\tau}\bullet\vec{\Lambda}}C\,, \tag{28}$$

where $\vec{\Lambda}$ is an arbitrary vector about which the rotation in "isospin space" takes space and g is the coupling of the isospin current $\vec{J}_\mu$ of the fermions (quarks and leptons) to $\vec{W}_\mu$.

Moreover, the most general lagrangian has also to contain interactions of the fermionic fields with the gauge bosons. In our model the fermionic fields derive from the elementary processes of creation/annihilation of quanta from the timeless 3D quantum vacuum and thus from the wave function $C = \begin{pmatrix} \psi_{Q,i} \\ \varphi_{Q,i} \end{pmatrix}$ at two components describing the probability of the occurrence of a creation/destruction event for a quantum particle Q of a given mass $m = V\Delta\rho_{\text{qvE}}/c^2$ in a point event. The interaction of the fermionic fields with the gauge bosons are in other words generated by the coupling of the wave function $C = \begin{pmatrix} \psi_{Q,i} \\ \varphi_{Q,i} \end{pmatrix}$) of the 3D quantum vacuum with the gauge bosons and can be expressed by a lagrangian term of interaction of the form

$$L_{\text{INTERACTION}} = -g\bar{C}_1\gamma^\mu\tilde{W}_\mu C_1 - g'B_\mu\sum_{j=1}^{3}y_j\bar{C}_j\gamma^\mu C_j\,, \tag{29}$$

where g is the coupling of the isospin current $\vec{J}_\mu$ of the fermions to $\vec{W}_\mu$, g' is the coupling of the hypercharge current of the same fermions to B_μ and, in the lepton sector, C_1 is the wave function of the quantum vacuum determining the appearance of left-handed electron and neutrino in the state $\psi_1 = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$,

$\psi_2 = \nu_{eR}$, $\psi_3 = e_R^-$ (and an analogous discussion can be made also for a single family of quarks).

The first term in (29) gives rise to charged-current interactions with the boson field $W_\mu = \left(W_\mu^1 + iW_\mu^2\right)/\sqrt{2}$ and its complex conjugate $\left(W_\mu^1 - iW_\mu^2\right)$, having the form

$$L_{\text{weak-charged-current}} = \frac{g}{\sqrt{2}}\left(J_\mu^- W_\mu^+ + J_\mu^+ W_\mu^-\right) , \tag{30}$$

where $J_\mu^\pm = J_\mu^{(1)} \pm iJ_\mu^{(2)}$, $J_\mu^{(1)}$ and $J_\mu^{(2)}$ being respectively the first and second component of the isospin current of the fermions, $W_\mu^\pm = \left(W_\mu^1 \pm iW_\mu^2\right)/\sqrt{2}$. The universality of the quark and lepton interactions emerges here as a direct consequence of the gauge symmetry deriving from the elementary processes of creation/annihilation characterizing the 3D quantum vacuum.

Equation (29) contains furthermore interactions with the neutral gauge fields W_μ^3 and B_μ, which lead to neutral-current terms in the lagrangian, which may be expressed as

$$L_{\text{weak-neutral-current}} = L_{\text{QED}} + L_{\text{NC}}^Z , \tag{31}$$

where

$$L_{\text{QED}} = -g\sin\theta_W A_\mu \sum_j \bar{C}_j \gamma^\mu Q_j C_j = -eA_\mu J_{em}^\mu \tag{32}$$

is the QED lagrangian,

$$g\sin\theta_W = e\,, \tag{33}$$

θ_W being the weak mixing angle, Q is the electromagnetic charge operator

$$Q_1 = \begin{pmatrix} Q_{u/\nu} & 0 \\ 0 & Q_{d/e} \end{pmatrix} , \qquad Q_2 = Q_{u/\nu}\,, \qquad Q_3 = Q_{d/e} \tag{34}$$

and

$$L_{\text{NC}}^Z = -\frac{g}{2\cos\theta_W} J_\mu^Z Z^\mu \tag{35}$$

contains the interaction of the Z boson with the neutral fermionic current

$$J_\mu^Z = \sum_j \bar{C}_j \gamma^\mu \left(\sigma_3 - 2\sin^2\theta_W Q_j\right) C_j = J_3^\mu - 2\sin^2\theta_W J_{em}^\mu\,. \tag{36}$$

Taking account of equations (23), (29), (31), (32), (35), the total lagrangian to describe electroweak interactions may be expressed in the following form:

$$\begin{aligned} L_{\text{total}} = -\frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - g\bar{C}_1 \gamma^\mu \tilde{W}_\mu C_1 \\ - g\sin\theta_W A_\mu \sum_j \bar{C}_j \gamma^\mu Q_j C_j - \frac{g}{2\cos\theta_W} J_\mu^Z Z^\mu\,. \end{aligned} \tag{37}$$

Here, in order to give masses to the intermediate carriers of the weak interaction, while in the Standard Model one invokes the existence, at a fundamental level, of a new scalar particle, namely the Higgs, which is introduced by adding to the $SU(2)_L \otimes U(1)_Y$ lagrangian describing the electroweak interactions a gauged scalar lagrangian of the form

$$L_s = (D_\mu \varphi)^+ D_\mu \varphi - \mu^2 \varphi^+ \varphi - h \left(\varphi^+ \varphi\right)^2 \quad (\text{where } \ h > 0, \ \mu^2 < 0)\,, \tag{38}$$

where

$$D^\mu \varphi = \left[\partial^\mu + ig\tilde{W}^\mu + ig' y_\varphi B^\mu\right] \varphi\,, \qquad y_\varphi = Q_\varphi - T_3 = \frac{1}{2}\,, \tag{39}$$

$$g' = g \tan \theta_W \tag{40}$$

and

$$\varphi(x) = \exp\left\{i\frac{\sigma_i}{2}\theta_i(x)\right\} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}\,, \tag{41}$$

which is characterized – on the basis of Goldstone theorem – by a infinite set of degenerate states of minimum energy, satisfying relation

$$\left|\langle 0 \left| \varphi^{(0)} \right| \rangle\right| = \sqrt{\frac{-\mu^2}{2h}} \equiv \frac{v}{\sqrt{2}}\,, \tag{42}$$

$\theta^i(x)$ and $H(x)$ being four real fields (and in this approach, one obtains in this way

$$M_Z \cos \theta_W = M_W = \frac{1}{2} v g\,, \tag{43}$$

instead in our model the Higgs particle is not a primary physical reality. As the author of this paper and Sorli have suggested in [44], one can consider the following most general potential invariant under the Standard Model gauge group

$$V = \lambda_C C^4 + \lambda_I s_I^4 + \lambda_{RI} s_I^2 s_R^2 + \lambda_R s_R^4 + \lambda_{IC} C^2 s_I^2 + \lambda_{RC} C^2 s_R^2\,, \tag{44}$$

where s_R and s_I are the real and imaginary parts of a singlet field S which is a function of the changes and fluctuations of the quantum vacuum energy density, λ_C is the coupling associated with the wave function at two components C, λ_R is the coupling associated with the real part of the singlet field S, λ_I is the coupling associated with the imaginary part of the singlet field S and one has

$$\lambda_R = \lambda_S + \lambda'_S + \lambda''_S\,, \tag{45}$$

$$\lambda_I = \lambda_S + \lambda'_S - \lambda''_S\,, \tag{46}$$

$$\lambda_{RI} = 2(\lambda_S - 3\lambda'_S)\,, \tag{47}$$

$$\lambda_{RC} = \lambda_{SC} + \lambda'_{SC}\,, \tag{48}$$

$$\lambda_{IC} = \lambda_{SC} - \lambda'_{SC}\,. \tag{49}$$

The scalar couplings λ_C, λ_R, λ_I, λ_{RI}, λ_{RC}, λ_{IC} lead to the following one-loop renormalization group equations in terms of the top Yukawa coupling y_t and the Standard Model electroweak gauge couplings g, g':

$$16\pi^2\beta_{\lambda_C} = \frac{3}{8}(3g^4 + 2g^2g'^2 + g'^4) + \frac{1}{2}(\lambda_{RC}^2 + \lambda_{IC}^2) + 24\lambda_C^2 - 3\lambda_C(3g^2 + g'^2 - 4y_t^2) - 6y_t^4\,, \tag{50}$$

$$16\pi^2\beta_{\lambda_R} = 18\lambda_R^2 + 2\lambda_{RC}^2 + \frac{1}{2}\lambda_{RI}^2\,, \tag{51}$$

$$16\pi^2\beta_{\lambda_I} = 18\lambda_I^2 + 2\lambda_{IC}^2 + \frac{1}{2}\lambda_{RI}^2\,, \tag{52}$$

$$16\pi^2\beta_{\lambda_{RI}} = 4\lambda_{IC}\lambda_{RC} + 6\lambda_{RI}(\lambda_I + \lambda_R) + 4\lambda_{RI}^2\,, \tag{53}$$

$$16\pi^2\beta_{\lambda_{RC}} = -\frac{3}{2}\lambda_{RC}(g'^2 + 3g^2 - 4y_t^2) + \lambda_{IC}\lambda_{RI} + 6\lambda_{RC}(2\lambda_C + \lambda_R) + 4\lambda_{RC}^2\,, \tag{54}$$

$$16\pi^2\beta_{\lambda_{IC}} = -\frac{3}{2}\lambda_{IC}(g'^2 + 3g^2 - 4y_t^2) + \lambda_{RC}\lambda_{RI} + 6\lambda_{IC}(2\lambda_C + \lambda_I) + 4\lambda_{IC}^2\,. \tag{55}$$

By approximating λ_R by

$$\lambda_R = \beta_{\lambda_R}\ln\frac{|s_R|}{s_0}\,, \tag{56}$$

where β_{λ_R} is the always positive beta function of λ_R, and s_0 is the scale at which λ_R becomes negative, in the basis (C, s_R) the square quantum vacuum energy density matrix for CP-even fields is given by

$$\begin{pmatrix} 2v^2\lambda_C & -\sqrt{2}v^2\sqrt{\lambda_C\,|\lambda_{RC}|} \\ -\sqrt{2}v^2\sqrt{\lambda_C\,|\lambda_{RC}|} & |\lambda_{RC}|\,v^2 + \dfrac{2\beta_{\lambda_R}\lambda_C v^2}{|\lambda_{RC}|} \end{pmatrix}, \tag{57}$$

where

$$v = \frac{s_0}{e^{1/4}}\sqrt{\frac{|\lambda_{RC}|}{2\lambda_C}}\,. \tag{58}$$

In the case of small λ_{RC} the square matrix (57) leads to the following eigenvalues for the energy density of the quantum vacuum:

$$\rho_h^2 \cong v^2\left(2\lambda_C - \frac{\lambda_{RC}^2}{\beta_{\lambda_R}}\right), \tag{59}$$

$$\rho_s^2 \cong v^2\left(2\frac{\beta_{\lambda_R}\lambda_C}{|\lambda_{RC}|} + \frac{\lambda_C^2}{\beta_{\lambda_R}} + |\lambda_{RC}|\right), \tag{60}$$

while the CP-odd quantum vacuum energy density is

$$\rho_s^2 \cong v^2 \left(2\frac{\lambda_C \lambda_{RI}}{|\lambda_{RC}|} + \frac{\lambda_{IC}}{2} \right) . \tag{61}$$

Equations (59) and (60) are valid only if $\lambda_{RC}^2/\beta_{\lambda_R} \ll 1$. If this is not true, the proper approximation is

$$\rho_h^2 \cong v^2 \left(2\lambda_C + |\lambda_{RC}| + \beta_{\lambda_R}\right) , \tag{62}$$

$$\rho_s^2 \cong v^2 \left(2\frac{\beta_{\lambda_R} \lambda_C}{|\lambda_{RC}|} + \beta_{\lambda_R} \right) , \tag{63}$$

which imply that the real singlet s_R derives from a quantum vacuum energy density which is associated to a mass lighter than the Higgs boson. On the basis of equations (59)–(63), the singlet s_R decays to Standard Model particles via more fundamental values of the quantum vacuum energy density. The approach based on equations (59)–(63) implies in this way that the mixing action of the Higgs boson in the production of the mass of Standard Model particles cannot be considered as a fundamental physical reality but derives from more fundamental entities, represented by opportune physical values of the quantum vacuum energy density, given just by equations (59)–(63). One can say also that, in this picture, at a fundamental level, the Higgs boson does not exist as physical reality: the action of the Higgs boson is only an emerging reality, it is the interplay of opportune fluctuations of the quantum vacuum energy density which indeed determines the action of the Higgs boson [44, 45]. The branching ratios of the kinematically allowed decay channels of the real part of the singlet function corresponding to opportune fluctuations of the quantum vacuum energy density are the same as for the Standard Model Higgs boson with mass corresponding to the same changes of the quantum vacuum energy density, and the production cross section is given by the Standard Model Higgs production cross section multiplied by $\sin^2\theta_{SC}$, where θ_{SC} is the mixing angle between the singlet and the wave function associated to opportune processes of creation/annihilation corresponding to those same changes of the quantum vacuum energy density, obtained by diagonalising the mass matrix (57). In analogy to the approach developed by Gabrielli *et al.* in [14], the various couplings of the scalar sector allow us to remove the global minimum of the Standard Model Higgs potential and generate the electroweak symmetry breaking minimum. In particular, here one needs to add a positive term to the beta-function of λ_C to keep it from crossing zero and, on the basis of equation (60), this can be achieved by the term $\lambda_{RC}^2 + \lambda_{IC}^2$, which is dominated by λ_{IC}. So, by choosing the initial values for the parameters at the top mass scale as follows: $\lambda_{RI} = 0.3$, $\lambda_R = -1.2 \times 10^{-3}$, $\lambda_{IC} = 0.35$, $\lambda_I = 0.01$, $\lambda_{RC} = -10^{-4}$, $\lambda_C = 0.12879$ and $m_t = 173.1$ GeV, and using beta functions at first order in the scalar couplings and second order in gauge couplings, in this picture, from the couplings of this approach a Higgs self coupling λ_H is derived which remains positive and therefore the Standard Model global minimum at 10^{26} GeV is removed, while λ_R becomes negative around $s_0 \approx 10^4$ GeV.

On the basis of equations (59)–(63) one can, therefore, say that the electroweak symmetry breaking is indeed determined by the real component of the singlet field S (while the imaginary component remains stable because of the CP-invariance of the general scalar potential (44)). The wave function of the quantum vacuum associated to the occurrence of creation/destruction events which activate the electroweak symmetry breaking can be therefore expressed in the following form:

$$C = \exp\left\{ i\frac{\sigma_i}{2}\theta_i\left(x\right)\right\} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \lambda_R + s_R(x) \end{pmatrix} . \tag{64}$$

Now, in analogy to the Standard Model, by defining the covariant derivative as

$$D^\mu C = \left[\partial^\mu + ig\tilde{W}^\mu + ig' y_\varphi B^\mu\right] C \, , \tag{65}$$

if one takes the physical unitary gauge $\theta_i(x) = 0$, by applying the electroweak symmetry breaking one obtains

$$\begin{aligned} \left(D^\mu C\right)^+ D^\mu C \xrightarrow{\theta^i 0} & \frac{1}{2}\partial_\mu s_R \partial^\mu s_R \\ & + \left(\lambda_R + s_R\right)^2 \left\{ \frac{g^2}{4} W_\mu^+ W^\mu + \frac{g^2}{8\cos^2\theta_W} Z_\mu Z^\mu \right\} . \end{aligned} \tag{66}$$

The kinetic piece of the lagrangian in the electroweak symmetry breaking regime (66) leads the vacuum expectation value of the neutral scalar to generate a quadratic term for the $W^\pm$ and the Z, and thus leads those gauge bosons to acquire masses on the basis of the following relation:

$$M_Z \cos\theta_W = M_W = \frac{75}{2\sin\theta_W} \text{ GeV} = \frac{1}{2}\lambda_R g \, . \tag{67}$$

Therefore, one finds that in the electroweak symmetry breaking regime the coupling λ_R associated with the real part of the singlet field S has the following expression:

$$\lambda_R = \frac{75}{g\sin\theta_W} \, . \tag{68}$$

The general scalar gauged potential (44) suggests therefore a new interesting manner to explain the origin of the masses of fermions as well as of the intermediate carriers of the weak force. It is sufficient to add the gauged potential (44) and the kinetic piece (66) to the total lagrangian (37) obtaining in this way a new effective lagrangian, which can be defined as "beyond Standard

Model lagrangian", which, on one hand, is invariant under gauge transformations, guarantees the renormalizability of the associated quantum field theory (as it occurs in the original Weinberg-Glashow-Salam theory [46]) and, on the other hand, allows electroweak symmetry breaking to occur dynamically via dimensional transmutation determined by the singlet couplings associated with the singlet field S which is a function of the changes and fluctuations of the energy density of the timeless 3D quantum vacuum, thus removing the global minimum of the Standard Model Higgs potential. The Vacuum Expectation Value of the scalar sector then generates the Standard Model Higgs Vacuum Expectation Value through a portal coupling. In synthesis, one can say that the effective lagrangian ("beyond Standard Model lagrangian") which determines the electroweak Symmetry Breaking dynamically via dimensional transmutation by means of the couplings associated with the singlet field S of the timeless 3D quantum vacuum is

$$\begin{aligned} L_{\text{effective}}^{\text{beyondSM}} &= -\frac{1}{4}W_{\mu\nu}^{a}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - g\bar{C}_1\gamma^\mu\tilde{W}_\mu C_1 \\ &\quad - g\sin\theta_W A_\mu \sum_j \bar{C}_j\gamma^\mu Q_j C_j - \frac{g}{2\cos\theta_W}J_\mu^Z Z^\mu \\ &+ \frac{1}{2}\partial_\mu s_R \partial^\mu s_R + (\lambda_R + s_R)^2 \left\{ \frac{g^2}{4}W_\mu^+ W^\mu + \frac{g^2}{8\cos^2\theta_W} Z_\mu Z^\mu \right\} \\ &- \left(\lambda_C C^4 + \lambda_I s_I^4 + \lambda_{RI} s_I^2 s_R^2 + \lambda_R s_R^4 + \lambda_{IC} C^2 s_I^2 + \lambda_{RC} C^2 s_R^2\right) . \end{aligned} \tag{69}$$

Moreover, in the unitary gauge this beyond Standard Model lagrangian leads to the following Yukawa-type lagrangian:

$$L_{\text{Y}} = -\frac{1}{\sqrt{2}}\left(\lambda_R + s_R\right)\left(c_1\bar{d}d + c_2\bar{u}u + c_3\bar{e}e\right) . \tag{70}$$

As a consequence, through the electroweak symmetry breaking determined dynamically via dimensional transmutation by the couplings associated with the singlet field S of the timeless 3D quantum vacuum, also the fermion masses are generated

$$m_d = c_1\frac{\lambda_R}{\sqrt{2}}, \qquad m_u = c_2\frac{\lambda_R}{\sqrt{2}}, \qquad m_e = c_3\frac{\lambda_R}{\sqrt{2}} \tag{71}$$

and thus the Yukawa-type lagrangian may be expressed as

$$L_{\text{Y}} = -\left(1 + \frac{s_R}{\lambda_R}\right)\left(m_d\bar{d}d + m_u\bar{u}u + m_e\bar{e}e\right) . \tag{72}$$

At the end of this chapter it is interesting to make some considerations about how our model is presented in a general picture with respect to the Standard

Model, what progresses it allows us to reach. The Standard Model lagrangian contains only four parameters, g, g', μ^2 and h, but it implies the necessity to introduce in an ad hoc form the Higgs field which yields a global minimum at $\approx 10^{26}$ GeV, thus determining significant problems in this energy range, in the light of Gabrielli's results [14]. Instead, in this model, in the gauge and scalar sector, the beyond Standard Model lagrangian allows us to face in a significant and coherent way different problems encountered by the Standard Model (in connection to the electroweak symmetry breaking and the possibility to remove the global minimum at energies $\approx 10^{26}$ GeV) in the picture of the same 3D timeless quantum vacuum characterized fluctuations of its energy density corresponding to elementary processes of annihilation/creation of quanta, but at the price of the introduction of several physically significant parameters, namely the couplings associated with the wave function of the quantum vacuum (but it is also worth to mention that, among these, as regards the generation of masses associated with the spontaneous symmetry breaking, practically the most fundamental parameter is indeed the coupling associated with the real component of the singlet field S).

4 About Quantum Chromodynamics in the Three-Dimensional Quantum Vacuum Model

As well known, the deep level of elementary constituents of matter represented by quarks is clearly demonstrated by the existence of a large number of mesonic and baryonic states. Quarks occur in several varieties or flavours (up, down, strange, charm, bottom, top), which are distinguished by the assignment of specific internal quantum numbers. The strong forces which link quarks are "colour forces" which are transmitted by gluons of eight different species. These forces turn out to be flavour conserving and flavour independent. In the Standard Model the description of the interaction between quarks is based on the idea that the quantum field theory which describes it – the so-called quantum chromodynamics (QCD) – takes colour as the charge associated with the strong forces [47,48].

Inside the mathematical formalism of QCD, if one assumes that mesons are quark-antiquark states, while baryons have three quark constituents, the entire hadronic spectrum can be easily classified. An important aspect of this formalism is that, in order to obtain a compatibility with the Fermi–Dirac statistics, in the treatment of mesonic and baryonic states the quantum number of colour must be considered, such that each species of quark may have 3 different colours q_α, where $\alpha = 1, 2, 3$ (red, green, blue). Baryons and mesons are then described by colour-singlet combinations. In this picture, one can avoid the existence of non-observed extra states with non-zero colour by postulating that all asymptotic states are colourless, i.e., singlets under rotations in colour space. This assumption is known as the confinement hypothesis, because it implies the fact that free quarks are unobservable: since quarks carry colour they are confined within colour-singlet bound states.

Now, in our model of a timeless 3D quantum vacuum as fundamental arena of physics, we assume that a quark field q_f^α of colour α and flavour f is determined by an opportune wave function C_f describing the probability of the occurrence of a creation/destruction event in the timeless 3D quantum vacuum characterized by flavour f. In this way, a baryon state B and a meson state M will be expressed respectively as follows:

$$B = \frac{1}{\sqrt{6}} \varepsilon^{\alpha\beta\gamma} C_f^\alpha C_f^\beta C_f^\gamma \,, \tag{73}$$

$$M = \frac{1}{\sqrt{3}} \delta^{\alpha\beta\gamma} C_f^\alpha \bar{C}_f^\beta \,. \tag{74}$$

The corresponding general lagrangian of our view of quantum chromodynamics (QCD) may be expressed as

$$L_{\mathrm{QCD}} = -\frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a + \sum_f \bar{C}_f \left(i\gamma^\mu D_\mu - \frac{1}{c^2} V_f \Delta\rho_{\mathrm{qvE}} \right) C_f \,, \tag{75}$$

where

$$D^\mu C_f = \left[\partial_\mu + i g_s \frac{\lambda_a}{2} G_a^\mu(x) \right] C_f \,, \tag{76}$$

$G_a^\mu(x)$ being the eight gluons, $\frac{1}{2}\lambda^a$ denote the generators of the fundamental representation of the $SU(3)_C$ algebra in the colour space, V_f is the volume of the region under consideration (characterized by flavour f). The Lagrangian (75) is invariant under the local $SU(3)_C$ group thanks to the eight gluons. In spite of the rich physics contained in it, the Lagrangian (75) looks very simple because of its colour symmetry properties associated with the wave function of the timeless 3D quantum vacuum. All interactions – besides an opportune wave function of the elementary processes of the 3D quantum vacuum – are linked with a single universal coupling g_s, namely the strong coupling constant. The existence of self-interactions among the gauge fields, which is a specific feature of QCD, could explain properties like asymptotic freedom (strong interactions become weaker at short distances, tending to a situation where quark behave like they were free) and confinement (namely the fact that the strong forces increase at large distances), which do not appear in QED [49]. Moreover, on the basis of equation (75) one can say that the emission of gluons by quarks and, in particular, the emission of a single gauge boson, which is the dominant process at the lowest order in g_s – and therefore the corresponding self-interactions among gauge fields – can be considered an effect of the elementary processes of creation/annihilation characterizing the timeless 3D quantum vacuum.

In the light of our current knowledge, we can say that at low energies QCD is characterized by a confined phase where chiral symmetry is spontaneously broken while at high temperature or density the quarks and gluons give place to a correlated plasma in which chiral symmetry is restored. The various phases of QCD are characterized by order (and disorder) parameters which correspond to peculiar vacuum expectation values of certain gauge invariant products of quark and gluon operators. The most relevant of these phases of QCD are the quark condensate and the gluon condensate, which in our model derive from elementary processes of creation/annihilation of quanta from the 3D quantum vacuum.

Although in some papers [50–53] it was argued that the strong interaction condensates like the quark and gluon condensate are not properties of the QCD vacuum but are instead associated with the internal dynamics of hadrons, in [54] Reinhardt and Weigel claim that the translationally invariant quark condensate is a vacuum property suggesting a model calculation for the quark condensate that strongly supports the understanding that QCD condensates are vacuum properties that are significantly distorted or reduced in hadrons.

If condensates existed only inside the hadrons, chiral symmetry would be spontaneously broken only inside the hadrons, while the exterior of hadrons would be in the chirally symmetric phase. This implies, consequently, that the corresponding Goldstone boson, the pion, which is responsible of the nuclear force between hadrons, could exist only inside other hadrons, thing that however seems to be not compatible with the experimental observations. If chiral symmetry were spontaneously broken only inside the hadrons then there would be no physical reason why this symmetry should be restored with the increasing of the density of baryons. If the condensates were indeed hadron properties, their universal character could not be sustained. Furthermore, in the light of the results of McLerran and Pisarski [55], at high density a so-called quarkyonic phase of baryonic matter exists where quarks and gluons are still confined but chiral symmetry is restored. This implies that it seems very unlikely that confinement restricts chiral symmetry breaking to the interior of hadrons.

On the other hand, in the light of currently accepted baryon models, the quark condensate is non–zero outside the baryon while it vanishes or is, at least, substantially reduced inside the hadrons, in other words chiral symmetry is spontaneously broken outside the hadrons and at least partially restored inside. By following the philosophy that is at the basis of Reinhardt's and Weigel's approach, we can show now in what sense the quark condensate is a vacuum property associated with the elementary processes of creation/annihilation of quanta and consequently that the properties of chiral symmetry outside or inside the hadrons emerge as properties of the timeless 3D quantum vacuum.

In our model of 3D timeless quantum vacuum, the QCD condensate can be obtained from the functional

$$\langle \bar{C}C \rangle = \frac{\int D[\bar{C}_f] D[C_f] \bar{C}_f C_f \exp(iA)}{\int D[\bar{C}_f] D[C_f] \exp(iA)} \ , \tag{77}$$

where $A = A[\bar{C}_f, C_f]$ expresses the underlying action of the wave function C_f describing the probability of the occurrence of a creation/destruction event in the timeless quantum vacuum characterized by flavour f. Here, by following the results of the Nambu–Jona–Lasinio (NJL) approach for the quark flavor dynamics [56–58], one can deduce from equation (77) the following lagrangian of the 3D timeless quantum vacuum in QCD regime, which contains chirally invariant scalar and pseudoscalar self–interactions:

$$L_{\mathrm{NJL}} = \bar{C}_f \left(i\partial - \frac{V\Delta\rho_{\mathrm{qvE}_0}}{c^2} \right) C_f + 2G \sum_{a=0}^{3} \left[\left(\bar{C}_f \frac{\sigma_a}{2} C_f \right)^2 + \left(\bar{C}_f \frac{\sigma_a}{2} i\gamma_5 C_f \right)^2 \right], \quad (78)$$

where G is the strength of the quark self–interaction and $\Delta\rho_{\mathrm{qvE}_0}$ represents the (small) perturbative fluctuation of the quantum vacuum energy density which determines the current quark mass matrix and here we assume two light flavours ($\bar{C}_f = \left(\bar{C}_u, \bar{C}_d\right)$, C_u being the wave function describing the creation/annihilation of quanta corresponding to the appearance of a quark u, C_d being the wave function describing the creation/annihilation of quanta corresponding to the appearance of a quark d) so that $\sigma_{1,2,3}$ are the Pauli matrices and $\sigma_0 = 1$. The physical meaning of equation (77) is that chiral symmetry associated with chirally invariant scalar and pseudoscalar self-interactions are indeed properties of the 3D quantum vacuum, in particular depend on the wave function of the vacuum and on the (small) perturbative fluctuation of the quantum vacuum energy density $\Delta\rho_{\mathrm{qvE}_0}$.

By bosonizing equation (78) through standard functional methods resulting in an effective theory for scalar (S) and pseudoscalar (P) matrix fields, equation (77) may be expressed as

$$\langle \bar{C}C \rangle = \frac{\int D[\bar{C}_f] D[C_f] \bar{C}_f C_f \exp(iA_{\mathrm{sp}})}{\int D[\bar{C}_f] D[C_f] \exp(iA_{\mathrm{sp}})}, \quad (79)$$

where

$$A_{\mathrm{sp}} = \frac{-1}{4G} \int d^4x \bar{C}_f \left[i\partial - (S + i\gamma_5 P_{\mathrm{sp}}) \right] C - \frac{1}{4G} \int d^4x \mathrm{Tr}_F \left[(S_{\mathrm{sp}} - m_0)^2 + P_{\mathrm{sp}}^2 \right] - A_0 \quad (80)$$

is the action for which the meson configuration $(S_{\mathrm{sp}}, P_{\mathrm{sp}})$ is the one that minimizes the action, Tr includes the discretized trace over flavour, colour and Dirac indices as well as spatial integration and we have considered a counterterm, A_0, such that the saddle point action (density) vanishes for the vacuum configuration of the meson fields. The gluon exchange of QCD is choreographed by the quark self-interaction, that is not linked to the colour charge of the quarks, whose effect is thus only to merely produce a factor N_C in the vacuum condensate.

The ground state of the model is obtained from the variational principle $\dfrac{\delta A_B}{\delta S, P} = 0$. By applying symmetry arguments, the ground state turns out to be flavour symmetric and homogenous, namely one has $\langle S\rangle = \dfrac{V\Delta\rho_{\mathrm{qvE}}}{c^2}1$, and $\langle P\rangle = 0$ where $\Delta\rho_{\mathrm{qvE}}$ are the fluctuations of the 3D quantum vacuum which determine the appearance of the constituent quark mass and V is the volume under consideration. The variation with respect to the scalar field S_{11} leads to the following gap-equation

$$\Delta\rho_{\mathrm{qvE}} = \frac{c^2}{V}\left(\frac{V\Delta\rho_{\mathrm{qvE}_0}}{c^2} - 2G\langle\bar{C}_u C_u\rangle_{\mathrm{qv}}\right) \tag{81}$$

that embodies the up–quark condensate associated with the 3D quantum vacuum. Taking account of Ebert's and Reinhardt's and Weigel's results [49, 54], this vacuum up-quark condensate upon proper time regularization becomes

$$\langle\bar{C}_u C_u\rangle_{\mathrm{qv}} = -\frac{N_C}{4\pi^2}\frac{V^3(\Delta\rho_{\mathrm{qvE}})^3}{c^6}\Gamma\left(-1, \frac{V^2(\Delta\rho_{\mathrm{qvE}})^2}{\Lambda^2 c^4}\right). \tag{82}$$

In equations (81)–(82), C_u is the wave function describing the probability of the occurrence of a creation/destruction event in the timeless 3D quantum vacuum characterized by flavour u, N_C is the factor which is determined by the colour charge of the quarks. Equation (82) can be considered the starting-point law which rules the behaviour of the quark condensate in 3D quantum vacuum model. Taking into account that pion properties are determined by expanding the action to quadratic order in P and that consequently there is a relation between the model parameters to the pion decay constant and the pion mass, the gap-equation (82) may be expressed as

$$\Delta\rho_{\mathrm{qvE}} = \Delta\rho_{\mathrm{qvE}_0}\left(1 + \frac{N_C}{2\pi^2 f_\pi^2(\Delta\rho^\pi_{\mathrm{qvE}})^2}\frac{V^2(\Delta\rho_{\mathrm{qvE}})^4}{c^4}\Gamma\Big(-1, \frac{V^2(\Delta\rho_{\mathrm{qvE}})^2}{\Lambda^2 c^2}\Big)\right), \tag{83}$$

where $\Delta\rho^\pi_{\mathrm{qvE}}$ are the fluctuations of the quantum vacuum which determine the appearance of the pion,

$$f_\pi^2 = \frac{V^2(\Delta\rho_{\mathrm{qvE}})^2}{c^4}\frac{N_C}{4\pi^2}\int_0^1 dx\Gamma\left(0, \frac{\frac{V^2(\Delta\rho_{\mathrm{qvE}})^2}{c^4} - x(1-x)\frac{V^2(\Delta\rho^\pi_{\mathrm{qvE}})^2}{c^4}}{\Lambda^2}\right), \tag{84}$$

and

$$\frac{V^2(\Delta\rho_{\mathrm{qvE}})^4}{c^4}f_\pi^2 = \frac{V^2\Delta\rho_{\mathrm{qvE}_0}\Delta\rho_{\mathrm{qvE}}}{Gc^4}\ . \tag{85}$$

Given a value for the change of the quantum vacuum energy density $\Delta\rho_{\mathrm{qvE}}$ and its corresponding volume, the equations (83)–(85) allow us to determine the model parameters from $f_\pi = 93$ MeV and $m_\pi \equiv V\Delta\rho^{\pi}_{\mathrm{qvE}}/c^2 = 135$ MeV.

Moreover, by describing baryons in a soliton picture, by utilizing the fruitful considerations made in [59], the energy functional may be expressed as

$$E_F = N_C\theta(\varepsilon_{\mathrm{val}})\varepsilon_{\mathrm{val}} + \frac{N_C}{4\sqrt{\pi}}\sum_\nu |\varepsilon_\nu|\,\Gamma\left(-\frac{1}{2}, \left(\frac{\varepsilon_\nu}{\Lambda}\right)^2\right), \qquad (86)$$

where ε_ν are single particle energy eigenvalues of the Dirac-type Hamiltonian

$$h = \vec{\alpha}\cdot\vec{p} + \frac{V\Delta\rho_{\mathrm{qvE}}}{c^2}\beta[\cos\Theta(r) + i\gamma_5\vec{\sigma}\cdot\hat{r}\sin\Theta(r)]\,, \qquad (87)$$

the subscript 'val' indicates valence quark contribution, $\Theta(r)$ is a chiral angle that minimizes the total energy functional of the 3D quantum vacuum

$$E[\Theta] = E_F + 4\pi f_\pi^2\frac{V^2(\Delta\rho^{\pi}_{\mathrm{qvE}})}{c^4}\int_0^\infty drr^2[1-\cos(\Theta(r))]\,. \qquad (88)$$

By computing $\dfrac{\delta E_F}{\delta\cos\Theta}$ the condensate in the soliton background turns out to be

$$\langle\bar{C}_u C_u\rangle_S = \frac{N_C}{2}\int\frac{d\Omega}{4\pi}\Big\{\theta(\varepsilon_{\mathrm{val}})\psi^{+}_{\mathrm{val}}(\vec{r})\beta\psi_{\mathrm{val}}(\vec{r}) - \frac{1}{2}\sum_\nu \mathrm{sign}(\varepsilon_\nu)\mathrm{erfc}\left(\frac{\varepsilon_\nu}{\Lambda}\right)\psi^{+}_\nu(\vec{r})\beta\psi_\nu(\vec{r})\Big\}\,. \qquad (89)$$

For a typical value of the energy density of the quantum vacuum $\Delta\rho_{\mathrm{qvE}} = \dfrac{450}{V}$ MeV (corresponding to the appearance of the constituent quark mass), the soliton is localized in the regime $r \le \dfrac{2}{V\Delta\rho_{\mathrm{qvE}}}$. Outside that regime the condensate corresponds to the meson sector. This means that the meson sector is itself produced by a peculiar behaviour of the fluctuations of the quantum vacuum energy density corresponding to the elementary RS processes of creation/annihilation of quanta. Inside the soliton regime the condensate is dominated by the valence quark contribution, providing a clue that the modification of the condensate in the in-hadron region, namely its distortion in the domain of the hadron, associated with the interactions that bind quarks to hadrons, are ultimately owed to fundamental energy fluctuations of the 3D quantum vacuum. And, in analogous way, also the constant features of the condensates in the hadronless regime is itself the consequence of the properties of the 3D quantum vacuum.

5 Conclusions

Although the Standard Model of particle physics agrees very well with experiment and indeed no clear signal of physics beyond the Standard Model has appeared so far at the LHC, many important topics remain unresolved and indicate that this theory has to be extended. The framework we have outlined in this paper based on fundamental fluctuations of a timeless three-dimensional quantum vacuum corresponding to elementary processes of creation/annihilation of quanta suggests the interesting perspective to provide a ultraviolet completion of the Standard Model (and thus to open the doors to a new formulation of GUT's) which involves gravity *ab initio* (in contrast to more conventional formulations). In this picture, electroweak symmetry breaking emerges dynamically from opportune quantum vacuum energy density fluctuations via dimensional transmutation determined by the singlet couplings associated with a singlet field depending on the changes of the energy density of the timeless three-dimensional quantum vacuum, thus avoiding the false Standard Model vacuum namely removing the global minimum of the Standard Model Higgs potential at energies $\approx 10^{26}$ GeV (which seems to invalidate the Standard Model as a phenomenologically acceptable model in this energy range). The approach of the timeless three-dimensional quantum vacuum is not based on ad hoc assumptions regarding the Higgs boson: here, the mixing action of the Higgs boson in the production of the mass of Standard Model particles cannot be considered as a fundamental physical reality but derives from more fundamental entities, represented by opportune fluctuations of the quantum vacuum energy density. A "beyond Standard Model lagrangian", characterized by different interaction terms and depending on the fluctuations of the quantum vacuum and its wave function, can be introduced which, on one hand, is invariant under gauge transformations, guaranteeing the renormalizability of the associated quantum field theory and, on the other hand, allows electroweak symmetry breaking to occur dynamically via dimensional transmutation determined by the couplings associated with the singlet field.

In quantum chromodynamics (QCD), a general lagrangian depending on the wave function of the quantum vacuum and the fluctuations of the quantum vacuum energy density can be introduced which provides a unifying treatment in which the emission of gluons by quarks and, in particular, the emission of a single gauge boson, which is the dominant process at the lowest order in the strong coupling constant, can be considered an effect of the elementary fluctuations of energy density associated to the processes of creation/annihilation characterizing the 3D quantum vacuum. Moreover, QCD condensates are strictly linked with the wave function describing the probability of the occurrence of a creation/destruction event in the timeless 3D quantum vacuum characterized by a certain flavour u, thus emerging directly as vacuum properties. The distortion of the QCD condensate inside an hadron as well as its constant feature outside the hadron regime turn out to be consequences of the elementary processes of the timeless three-dimensional quantum vacuum.

Finally, as regards future developments of the approach developed in this paper, an interesting matter concerns the possibility to find a link between the timeless three-dimensional quantum vacuum model and other proposals of completion of the Standard Model, namely supersymmetry, axions' models, extra dimensions' models, etc. In this regard, we claim that the results obtained in all these conventional current theories should emerge from special opportune behaviour of opportune (and more fundamental) fluctuations of the energy density of the timeless three-dimensional quantum vacuum and/or of opportune couplings associated with specific fields depending on the energy density of the three-dimensional quantum vacuum.

In particular, as regards the idea of supersymmetry, if in the Minimal Supersymmetric Standard Model fine-tuning within the Higgs sector is reduced as a consequence of the fact that the Higgs quartic coupling is proportional to the square of the loops involving the superpartners (of spin $1/2$) of the gauge bosons and of the Higgs bosons, namely gauginos and higgsinos, in our approach of the timeless three-dimensional quantum vacuum, since the mixing action of the Higgs boson in the production of the mass of Standard Model particles derives from more fundamental entities (represented by opportune fluctuations of the quantum vacuum energy density), we suggest that the higgsino-gaugino loops are not fundamental realities but emerge from more fundamental fluctuations of the energy density of the timeless three-dimensional quantum vacuum and/or of opportune couplings associated with specific fields depending on the energy density of the three-dimensional quantum vacuum. In other words, here the crucial perspective is opened that the Higgs quartic coupling is proportional to the square of the higgsino-gaugino loops in virtue of opportune behaviours of the energy density of the timeless three-dimensional quantum vacuum.

On the other hand, as regards alternative paths to provide a completion of the Standard Model in the picture of new ideas, Salvio [60] recently suggested a simple model which adds to the Standard Model only right-handed neutrinos and the extra fields needed to implement the axion idea (proposed by Kim, Shifman, Vainshtein and Zakharov in [61,62]). Salvio's model, on that basis, would seem to throw new light as regards the following signals of beyond Standard Model physics: small neutrino masses, dark matter, baryon asymmetry, inflation and vacuum instability, strong CP problem. Salvio emphasized also that an important extension of his model would be the inclusion of quantum gravity. However, despite some clues provided in this direction in [60, 63], inside Salvio's axion model the role of gravitational quantum effects in the stability issue of the Standard Model is still unclear. According to us, this provides a further element that motivates the search of a connection between the axion idea and the completion of the Standard Model in the timeless three-dimensional quantum vacuum here analysed – which instead has the merit to involve gravity *ab initio* – where there is the possibility to derive the axion and Salvio's extra fields as special properties corresponding to opportune (and more fundamental) fluctuations of the energy density of the timeless three-dimensional quantum vacuum.

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