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Universe 2.0: Higgs quantum gravity

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Since decades quantum gravity tries to close the gap to general relativity, but all attempts remain pure theory without empirical test. The present study now extends loop quantum gravity to a verified theory that *determines how matter causes* the space-time curvature. A recap of the 'problem of time in quantum gravity' reveals that quantum theory on principle cannot quantize time. Hence, we quantize time on a meta-level. The network links thus oscillate at the Planck frequency as an $SU(2)$ gauge field. They carry a Planck energy each, which due to background independence is not directly effective. The Higgs field propagates in the space-time lattice as a lower frequency $SU(2)$ fluctuation mode. A modified Higgs mechanism transfers energy from the space-time network to the massive particles, modifying the local space-time quanta. Linear combination of space-time quanta yields the space-time curvature due to macroscopic masses, in rotational symmetry the Schwarzschild or Kerr metric. Instead of Einstein's field equations, Higgs quantum gravity reproduces the key solutions for static or stationary mass configurations. Yet, the empirical evidence for general relativity applies. Higgs quantum gravity represents the first experimentally verified quantum gravity, and the first theory predicting the space-time curvature by mass generation from the space-time structure.

KEYWORDS

Higgs mechanism, loop quantum gravity, general relativity, space-time curvature, Schwarzschild metric, Kerr metric, Planck energy, problem of time

1 Introduction

The present study is part of the series 'Universe 2.0', which aims at new concepts clarifying a number of open issues of cosmology. The first part [1] showed that black holes in fact are black stars. The study on hand presents a new quantum gravity theory that determines the space-time curvature by mass generation. It entails a third study on the physics of hidden worlds explaining dark matter. The planned final study shall use all these concepts for a new Big Bang model yielding a plausible explanation of the inflation period and of dark energy.

The present contribution covers the quantum gravity part. The question whether gravitation is a quantum entity is as old as general relativity. In 1916 already, Einstein himself showed that according to his equations gravitational waves carrying energy should exist and suspected that quantum theory will have to modify not only Maxwell's electrodynamics, but the theory of gravitation as well [[2], p. 696].

After some failed attempts to quantize gravity, Rosenfeld [3] in 1930 presented the *canonical quantization approach* based on the Einstein-Hilbert action and using the tetrad formalism. In the same year he proposed a splitting of the metric tensor into a perturbation of the Minkowski metric [4], a procedure which more than 20 years later Gupta [5] adopted for the *covariant* quantization approach. Around 1960, Dirac [6, 7] presented a simplified

Hamiltonian form of Einstein's theory that facilitates quantization, and Feynman [8] suggested a quantization of geometry. Feynman also sketched the great difficulties in quantum gravity, namely, because of its weakness.

Facing challenges such as gravitational singularities and regarding a theory of everything, numerous scientists ever since put effort into quantum gravity. Six decades of controversial research followed, yielding a variety of ansatzes such as string theory and loop quantum gravity (LQG), with some promising results, but still awaiting a major breakthrough. The quantization of gravity thus was proposed in the very beginning of general relativity, but many decades and thousands of studies later we still are struggling for a cogent solution.

A key advance with regard to quantum gravity would be the discovery of the hypothetical gravitons. According to Rothman and Boughn [9], however, the graviton energy would be so small that it might be impossible to detect. Nevertheless, Quach [10] proposed a theory involving a gravitational Casimir effect due to the non-zero vacuum energy. Yet, experiments failed to establish it [11]. Advanced LIGO observations applied kinematic methods to gravitational waves and found that $\hbar\omega$ gravitons must be excluded [12]. Carney et al. [13] gave an overview of promising laboratory experiments to detect gravitons, but they still are in the stage of thought experiments. Bose et al. [14], for example, suggested correlation measurements of spin entanglement, and Pitelli and Perche [15] proposed a detector based on angular momentum. Yet none of these experiments have been implemented yet. The past 20 years thus yielded various suggestions for experimental arrangements but no astronomical evidence.

Hence, quantum gravity remains a mystery, even after more than a century of struggles by thousands of renowned scientists, be it from the viewpoint of quantum theory, by turning Einstein's equations into an operator form, or by astronomical evidence. Furthermore, general relativity only *describes* how masses curve the space-time. But, we know nothing about an interaction between mass and geometry.

The former approaches all suffer from the same conceptual weakness. The indications are strong that quantum theory by itself on principle cannot quantize gravitation. We need a completely different approach. The present study starts out from a fundamental irreconcilability of quantum theory and general relativity, known as the 'problem of time in quantum gravity'. Quantum theory on the one hand requires a continuous background time parameter to describe particle motion and field interactions. General relativity on the other hand postulates strict background independence and only allows for a proper time depending on the standpoint and the state of motion.

Quantum gravity must consolidate this discrepancy. We approach the 'problem of time' from a meta-level and elaborate a quantum gravity theory which is verified by observations and in addition provides a physical interrelation which *determines* how and why masses curve the space-time geometry.

2 Methods

We start out in Section 3 by introducing LQG as the basis of Higgs quantum gravity. In Section 4 we address the 'problem of time', which severely limits all associated efforts and cannot be solved by quantum theory alone. The Higgs gravity network presented in Section 5 approaches the problem from a meta-level and results in a space-time lattice oscillating as an $SU(2)$ field with an energy potential of a Planck energy per space-time quantum. Section 6 describes the modified Higgs mechanism that receives its energy from the corresponding Higgs-Planck potential, while preserving the mass generation of the standard model. In Section 7 we relate the Higgs-Planck potential to the energy potential available in the links of the Higgs gravity space-time network. The energy drain by the modified Higgs mechanism curves the local space-time quanta according to the line element associated with a single particle. Linear combination of space-time quanta yields the line element due to macroscopic masses. In spherical symmetry the Schwarzschild solution results. The discussion in Section 8 resumes the analogies used and illuminates how these findings can be transformed to the Kerr solution for rotating masses. Higgs quantum gravity combines two quantum theories to solve at one stroke two key problems of a century. It quantizes general relativity, while at the same time explaining the interrelationship of mass generation and space-time curvature.

3 Loop quantum gravity in a nutshell

Higgs quantum gravity builds on LQG, which is the only background independent ansatz for quantum gravity available to date. In the current section we briefly introduce the very basics of LQG before providing below some more details in the course of a discussion of the 'problem of time'.

Rovelli [16] summarized LQG and labelled it "a tentative, but intriguing possible formalism for describing quantum space-time". It is Lorentz invariant and has no ultraviolet divergences. We have theoretical evidence (but no solid proof) that its large distance limit is general relativity. There is a diffeomorphism-invariant LQG representation of the Maxwell-Dirac-Einstein system [16, 17]. Fermions and Yang-Mills fields couple to the spin network, as shown by Bianchi et al. [17] and Han and Rovelli [18].

On the down side, LQG like all other quantum gravity concepts remains pure theory, without empirical test, and it is far from being complete [[16], p. 18]. In the past 15 years, the promising spin foam variant of LQG emerged. Asante et al. [19] describe the spin foam by a gauge theory, which relieves from the burden of calculating node amplitudes and brings the model in the reach of simulating large networks. Numerical simulations by Dittrich [20] have shown that spin foams create dynamical effects that may be interpreted as gravitational waves. Yet, these results are limited to a small piece of spin foam and based on an interplay between the various parameters of the model. Thus, LQG is a promising concept for quantum gravity, but simulating a macroscopic space-time remains far out of reach.

The study on hand nevertheless builds on the original LQG as described by Rovelli [16]. LQG models the space-time as a quantum spin network at the Planck scale. It is an $SU(2)$ algebra formally related to quantum electrodynamics and quantum chromodynamics. Each quantum node has a metric tensor generated by the momentum operators of its links. The momentum operators behave like the one of an elementary particle with spin. The nodes are not located on a background metric but associated in an abstract graph to constitute the space-time itself. They are only localized with respect to one another and carry no vector quantum numbers such as momentum or position. The states of the LQG Hilbert space are invariant under gauge transformations $V_n \in SU(2)$,

$$\psi(U_l) \rightarrow \psi\left(V_{s_l} U_l V_{t_l}^{-1}\right), \quad (1)$$

where U_l denotes the transporter link variable and s_l and t_l the source and target nodes. The gauge transformations V_n are equivalent to those of lattice gauge theories. The measure of the LQG metric is the area gap, which corresponds to the Planck area, the area operator's lowest possible non-vanishing eigenvalue. The areas combine to polyhedral volumes. Area and volume form a complete set of commuting operators and define an orthonormal basis of the geometry. Yet, the nodes carry no length dimension.

To date, the emphasis in LQG has been put on the curvature of the graph. The study on hand instead extends the space quantization to the time dimension and by an energy balance focuses on the modification of area and volume. The correspondence limit results from area and volume of a multi-node network amounting to the sum of expected values. Linear combination leads to the Schwarzschild and Kerr solutions of general relativity. Higgs quantum gravity not only tolerates but even depends on the macroscopic measure of length being only indirectly defined, by the area gap.

4 New approach to the 'problem of time'

The 'problem of time in quantum gravity' challenges all corresponding efforts from the outset. As we will see in what follows, all former quantum gravity theories fail to solve it. A brief history of quantum gravity shall identify the fundamental conceptual conflict and its current state regarding LQG in particular. In addition, this is an opportunity to introduce LQG in some more detail.

A history of quantum gravity must briefly address the very popular string theory, an approach directly from perturbative quantum theory. Originally, string theory was a rather unsuccessful attempt for hadron physics (history see [21], e.g.). In the early seventies Fritzsch, Gell-Mann, and Leutwyler [22] developed the groundbreaking color concept of quantum chromodynamics, thus marginalizing string theory. Shortly thereafter, Scherk and Schwarz [23] and Yoneya [24] independently showed that the scalar strings vibrate in spin-2 states, as expected for the hypothetical graviton. String theory gradually revived as a quantum gravity aiming at grand unification. It formally reproduces the equations of general relativity, but its latest descendant M-theory bases on a fixed 11-dimensional background space-time [25], while general relativity indicates background independence. The 'string landscape' comprises at least $\mathcal{O}(10^{500})$ possible flux vacua, with no clear-cut selection method in sight. It requires supersymmetry, which to each fermion adds an unknown bosonic partner and *vice versa*. Collider experiments never detected any of them.

The present study aims at a strictly non-perturbative and background independent theory and thus concentrates on LQG. The latter emerges from a canonical (or Hamiltonian) quantization of general relativity, as proposed in 1967 by DeWitt [26]. He uses the ADM formalism [27], a foliation of the space-time in space-like hypersurfaces with a connecting time parameter. The foliation is well justified, because general relativity does not support an interchange of the time with space dimensions, as recently shown by the author [1]. The resulting Hamiltonian constraint yields the Wheeler-DeWitt equation $\widehat{H}(x)|\Psi\rangle = 0$. Unlike the similar Schrödinger equation, $|\Psi\rangle$ is not a normalized function on a space-like surface but contains all the information of geometry and matter of the universe. The Hamiltonian $\widehat{H}(x)$ does not determine the evolution of the system. The wavefunction of the universe appears frozen. Time becomes an unphysical gauge variable. The 'problem of time in quantum gravity' was born. It was born to stay.

Canonical quantization did not yield a significant improvement until 1986, when Ashtekar [28] presented his new set of variables, an $SU(2)$ connection and the associated orthonormal triads (dreibeins) as the conjugate momenta. "The emphasis is shifted from distances and geodesics to holonomies and Wilson loops" [[29], p.14]. This connection dynamics resembles a classical Yang-Mills gauge theory. "However, unlike the familiar Yang-Mills theory in Minkowski spacetime, now there is no metric or any other field in the background" [[30], p.6]. This was the genesis of LQG. The Gauss constraint (due to the $SU(2)$ gauge symmetry group) and the vector constraints generating the diffeomorphisms of the space-like hypersurfaces could be solved rather directly [31]. Thus, the space-like hypersurfaces could be quantized, mostly in an arbitrary number of space dimensions, including a derived measure on the Planck scale, as described by Thiemann [32, 33]. Rovelli, one of the major founders of LQG, concludes [[34], p.10]: "The space continuum 'on which' things are located and the time 'along which' evolution happens are semiclassical approximate notions in the theory."

Yet, are these continuum notions of time and space both semiclassical and approximate? The space dimensions are quantized into Planck scale bits, but the time of their evolution is continuous and "the clear-cut quantum dynamics remains open" [[31], p.8]. The scalar Hamiltonian constraint, which is related to the time parameter, remains unsolved [[35], p.12]: "There is still a large number of poorly controlled ambiguities in the definition of the Hamiltonian constraint." The 'problem of time in quantum gravity' persists. But a fully background independent theory requires radical rethinking anyway: "The theory gives up unitarity, time evolution, Poincaré invariance at the fundamental level, and the very notion that physical objects are localized in space and evolve in time" [[36], p.1302] and "there is no need to expect or to search for unitary time evolution in quantum gravity, because there is no time in which we could have unitary evolution" [[37], p.114]. Kiefer concludes [[38], p.9]: "Such constraints result from any theory that is classically reparameterization invariant, that is, a theory without background structure".

The 'problem of time in quantum gravity' originates in the interpretation of the diffeomorphism invariance as a gauge invariance. In general relativity the impact may be attenuated by concentrating on one specific solution [[36], p.1318]: "A single solution of the [general relativity] equations of motion determines a spacetime, where a notion of proper time is associated to each timelike worldline." In LQG, however, we are dealing with background independent space-time networks, with serious consequences [[34], p.21]: "In quantum gravity the notion of spacetime disappears in the same manner in which the notion of trajectory disappears in the quantum theory of a particle." Should we drop the concept of time and of the evolution of space altogether and regard it as an illusion, as Barbour suggests [39]?

The latest descendant of LQG are spin foams, its covariant counterpart. They have been introduced in detail by Perez [31]. The concept goes back to Reisenberger and Rovelli [40], who formulated a heuristic method of how to solve the Hamiltonian constraint by switching to a constrained $SU(2)$ BF topological theory. Various models emerged until about 15 years later an effective theory of spin foams could be formulated in 3 + 1 dimensions. The conceptual issues regarding the Hamiltonian constraint were addressed by defining observables not with respect to space-time points, but in terms of relations between dynamical fields [[16], p.12].

Spin foam models may be rated the most successful quantum gravity theory to date. Being 4-geometries from the start, they allow not only for space-like, but also for time-like triangles [41]. The spin networks abruptly change their node and link structure, which is interpreted as a quantization not only of space, but also of time. Yet, the price for switching to a covariant base of 'sum over spin network state histories' is considerable. The relational solution of the Hamiltonian constraint at random generates and removes links at the network nodes. The quantum networks thus represent chaotically wobbling foams. Despite some respectable achievements lately [20], we still have no solid proof that the long-distance limit is general relativity. As mentioned in Section 3, the limit of semiclassical states requires various assumptions.

The 'problem of time' may appear overcome by switching to covariant spin foams and by solving the Hamiltonian constraint in terms of dynamic relations. Time and evolution are not lost completely, but we end up in a chaotically wobbling space-time network. May this be considered a solution to the 'problem of time'? Indeed, this might be the best solution we could ever expect. Spin foam models are quantum theory and as such on principle depend on a continuous time parameter. The lowest possible eigenvalue of the area operator has been determined for the space-like hypersurfaces, by the original canonical theory. A corresponding lowest possible eigenvalue regarding time is not available and a translation between canonical LQG and spin foams is missing [[34], p.262]: "There are several gaps between the Hamiltonian loop theory and the spinfoam models."

Sixty years of efforts regarding the 'problem of time in quantum gravity' did not yield a cogent solution within quantum theory. We conclude that quantum theory can perfectly quantize space, but it cannot quantize time, because it would extinguish all regular evolution and invalidate itself. In order to solve the 'problem of time' we must rise to a meta-level, beyond the concepts of quantum theory.

5 Higgs gravity network

In the previous section we delineated the 'problem of time in quantum gravity' and concluded that a solution cannot be expected from quantum theory itself. Moreover, in quantum gravity the coupling to matter remains as descriptive as in general relativity. Spin foams are the most successful theory to date, but "the issue of the coupling of the new spin foam models to matter remains to a large extend un-explored territory" [[31], p.73]. The couplings of the spin network to fermions and Yang-Mills fields [17, 18] have been developed in canonical LQG and do not account for the strong back reaction of matter [[30], p.3]: "As is the case with classical general relativity, while requirements of background independence and general covariance do restrict the form of interactions between gravity and matter fields […], the theory would not have a built-in principle which *determines* these interactions."

The present section proposes a quantization of the time parameter, emanating from canonical LQG, but avoiding quantum theoretical methods. We aim at a quantum network, which on a semiclassical level carries a Higgs field suitable to determine the interaction between matter and the quantum space-time.

Canonical LQG quantizes the space-time by the aid of the area operator. The 3-dimensional momentum operators on $L_2[SU(2)^L]$ are the left invariant derivative operators $\vec{L}_l$ acting on the group elements $h_l \in SU(2)$ for each link l [16]. They generate the metric tensor of the quantum node. The diagonal elements of the Penrose metric operator

$$A_l^2 = \vec{L}_l \vec{L}_l \tag{2}$$

are the Casimirs of the $SU(2)$ group associated with the link l. They denote the area of the surface bounding two connected quanta of space. The lowest possible non-zero eigenvalue of Equation 2 yields the Planck area, ℓ_{P}^2, which is the scale of LQG, the area gap (for details, see [32, 33]). LQG thus quantizes the space-like hypersurfaces but lacks a quantization of the time parameter on an equal footing.

Simple triangulation of this space-like network in the classical limit yields a flat 3-dimensional Euclidian metric. Minkowski [42] extended the flat space by the product of the time t with the light speed c, $x^\mu = (ct, \boldsymbol{x})$, thus postulating his 4-dimensional space-time metric. With regard to what follows, we represent it by a line element

$$\mathrm{d}s^2 = \eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -c^2\mathrm{d}t^2 + \mathrm{d}\boldsymbol{x}^2 \tag{3}$$

with the 'mostly plus' metric $\eta_{\mu\nu} = \mathrm{diag}(-1,1,1,1)$. Because quantum theory cannot quantize time, we likewise complement the quantized space-like hypersurfaces by transposing the time differential of Equation 3 down to the smallest possible time step at the Planck scale,

$$c^2\mathrm{d}t^2\big|_{\mathrm{d}t\to t_{\mathrm{P}}} = c^2 t_{\mathrm{P}}^2 = \ell_{\mathrm{P}}^2, \tag{4}$$

where t_{P} denotes the Planck time.

Equation 4 cannot indicate any movement or evolution, because, as mentioned in Section 3, the nodes of the spin network carry no vector quantum numbers such as momentum or position. It must be a local oscillation, but it can neither be a vibration of the network nodes on an inexistent background. Equation 4 indicates a quantum field oscillation, attributed to the bosonic links l, which are associated with the group elements $h_l \in SU(2)$ and span the area gap provided by Equation 2.

Time on principle can only be metered from an arbitrary reference point, based on a stable oscillator defining the smallest measurable time interval. The Higgs gravity space-time network provides such an oscillator, a scalar $SU(2)$ field oscillating at the Planck frequency $\omega_{\mathrm{P}} = c/\ell_{\mathrm{P}} = t_{\mathrm{P}}^{-1}$, with the same gauge symmetry as the Higgs field. A quantum field equation for this oscillation does not exist, because the time differential $dt < t_P$ is undefined. Herewith, we have the space-time network equipped with densely distributed clocks. As shown in what follows, this time measure is not absolute like in the Minkowski space-time.

In the absence of matter, Higgs quantum gravity thus constitutes a flat spin lattice of fermionic nodes connected by bosonic $SU(2)$ links. The latter span the faces between space-time quanta and oscillate at the Planck frequency ω_P. The energy associated with the oscillation of the links or faces is $\hbar\omega_P = E_P$, the Planck energy, where $\hbar$ denotes the Planck constant. The enormous energy potential $E_P \approx 10^{19}$GeV per space-time quantum should not come as a surprise, because the space-time provides the energy for all matter, whose volume density may approach the Planck limit. This energy potential is not directly effective, because the links are not defined on a fixed background. They only are associated with respect to each other, forming an abstract graph, which represents the space-time itself.

The latent energy potential of the universe is exorbitant indeed and is expected to increase as the universe expands. The same is true for the pervasive Higgs field of the original Higgs mechanism. However, the observed baryonic and dark matter is enormous as well. Attributing its source to the Big Bang just shifts the problem, because we do not know where the energy for the Big Bang came from. We may conclude that all energy should have the same origin, be it latent, like the oscillation of the space-time network, observable, like baryonic matter, hidden, like dark matter, or mysterious, like dark energy. We must humbly admit that we currently have no clue regarding its source.

The Higgs quantum gravity network provides a base of measurement at the Planck limit. The light speed as the maximum propagation velocity of signals is given by the quantum space-time oscillation, $c = \ell_P\omega_P$, which according to Equation 1 invariantly translates the coupled fields along the links. The upper limit of mass concentration is a Planck mass $m_P = E_P/c^2$ per space-time quantum, that is, the Planck density $\rho_P = m_P/\ell_P^3$.

Thiemann [43] showed that the Hamiltonian of the standard model supports a representation including Higgs field insertions at the end points of open lines, that is, of the network links. We make a step forward and promote the Higgs field to a modulation of the Higgs gravity network itself. In analogy to phonons in a crystal lattice (see, e.g., [44]) the oscillation of the links or faces may be regarded as the normal mode of the entire quantum space-time, oscillating as a scalar field with an $SU(2)$ gauge symmetry. When excited by matter fields the space-time may fluctuate as propagating $SU(2)$ modes of a lower frequency. Hence, the Higgs gravity field corresponds to the $SU(2)$ normal mode oscillation of the entire space-time, while the Higgs field of the Higgs boson represents a lower frequency modulation in the oscillating lattice.

6 Higgs gravity mechanism

The Higgs gravity mechanism adheres to the original Higgs mechanism (see, e.g., [45]), while modifying the mass term. Putra and Alrizal [46] also modify the Higgs equation, adding a mass term based on their relativistic Heisenberg uncertainty principle. The relativistic action causes explicit symmetry breaking and thus results in a new type of mass generating field. A discontinuity of the inertial mass in the transition between relativistic energy and action thus generates both ordinary and dark matter. Their mechanism creates masses from the fluctuating vacuum, but they do not relate the mass generation to the space-time curvature. Putra et al. [47] on the other hand use the Ehrenfest paradox in the Bohr atomic model in relation to their generalized uncertainty principles [46]. The atom induces a quantization of the space-time curvature caused by other masses.

The present study in contrast *determines* how the masses *cause* the curvature. In Section 5 we transposed a flat Minkowski space-time down to the Planck scale and thus found that the links (or area gaps) oscillate and carry the Planck energy E_P as their energy potential. Please recall that the space-time nodes of LQG build an abstract graph representing the space-time geometry. They carry neither momentum nor position and cannot contribute to a space-time pressure. The energy potential $E_P \approx 1.2 \times 10^{19}$GeV per area gap is not related to the issue of dark energy or the cosmological constant.

The Higgs mechanism acts at the scale of the Higgs energy $v_H \approx 246\text{GeV} = \mathcal{O}(10^{-17}E_P)$. The markedly different scales indicate that the energy transfer from the Higgs gravity network to the Higgs field fluctuation mode spreads over a high number of space-time quanta, $N \gg 1$. Due to Equation 1 the excitations may invariantly translate between nodes. The Higgs field represents a lower frequency fluctuation mode of the oscillating Higgs gravity network, analogous to phonons in a crystal lattice, as discussed in Section 5.

The Higgs-Planck gravity potential V_{HP} thus is composed of the partial contributions by elementary excitations of N space-time nodes. A quantum excitation by an external field indicates a corresponding mass term, for the scalar Higgs field an explicit term μ^2. The Planck mass term μ_P^2, contributed by the links or area gaps involved, must compensate for the energy absorbed in Higgs field fluctuation mode, that is, $\mu_P^2 \to (\mu_P - \mu)^2$. Each of the N space-time nodes to the total potential contributes a partial term ρ_i, where $\sum_{i=1}^N \rho_i = 1$.

In the usual units with $\hbar = c = 1$ we find the Lagrangian for the complex scalar doublet ϕ interacting with the N space-time nodes,

$$\mathcal{L} = (\partial^\alpha\phi)^\dagger\partial_\alpha\phi - V_{HP}(\phi) \tag{5}$$

with the accumulated potential

$$\begin{aligned} V_{HP}(\phi) &= \sum_{i=1}^{N}\left[\rho_i\left\{-(\mu_P-\mu)^2+\mu^2\right\}\right]|\phi|^2+\lambda|\phi|^4 \\ &= -(\mu_P-\mu)^2|\phi|^2+\mu^2|\phi|^2+\lambda|\phi|^4 \\ &= -\left(\mu_P^2-2\mu_P\mu\right)|\phi|^2+\lambda|\phi|^4, \end{aligned} \tag{6}$$

where λ denotes the dimensionless coupling constant. The Higgs equation basically corresponds to the Klein-Gordon equation, but it has a negative mass term. The latter resembles an imaginary valued mass and turns the Higgs field ϕ into a complex valued two-component field with a sombrero-like shape, with a 'spontaneously broken gauge symmetry'. The Higgs field thus is short-ranged and acquires a 'charge', that is, a mass. Accordingly, $-(\mu_P - \mu)^2 < 0$ in Equation 6 resembles an imaginary valued energy. It replaces the corresponding negative mass term in the original Higgs equation and represents the local energy potential of the space-time lattice, whose gauge symmetry is globally broken.

Without excitation the potential $V_{\mathrm{HP}}(\phi)$ only becomes manifest as the oscillation energy in the area gaps, which provide the space-time quanta with their area and volume. The term $+\mu^2$ is the regular mass term of the Higgs field, which as an excitation of the oscillating lattice receives its mass. Figure 1 depicts a schematic of $V_{\mathrm{HP}}(\phi)$. The expected field value equivalent to the original Higgs mechanism is located at the minimum

$$\begin{aligned}\langle\phi\rangle &= \frac{v_{\mathrm{HP}}}{\sqrt{2}} = \sqrt{\frac{\mu_{\mathrm{P}}^2 - 2\mu_{\mathrm{P}}\mu}{2\lambda}} \\ &= E_{\mathrm{HP}} = \sqrt{E_{\mathrm{P}}^2 - 2E_{\mathrm{P}}m_{\mathrm{H}}} = E_{\mathrm{P}} - m_{\mathrm{H}} + \mathcal{O}\left(10^{-17}m_{\mathrm{H}}\right),\end{aligned} \tag{7}$$

where m_{H} denotes the mass of the Higgs boson. The greatest masses of the standard model are $< v_{\mathrm{H}}$. The higher order terms in Equation 7 are $\mathcal{O}(10^{-17}m_{\mathrm{H}})$. Thus, the Higgs gravity mechanism compared to the original Higgs mechanism just shifts the potential by a constant, E_{P}, which is irrelevant regarding the expansions of the electroweak theory. The standard model remains unaffected.

Similar to the original Higgs mechanism, the Higgs gravity mechanism, as represented by the equations above, is limited to low mass concentrations, $E_{\mathrm{HP}} \approx E_{\mathrm{P}}$. When the mass concentration approaches the Planck limit, that is, when the sum of all locally generated m_{H} becomes significant with respect to E_{P}, higher order effects can no longer be ignored. Such effects are expected in extremely dense stellar objects like black stars, which were discussed in the first paper of the series 'Universe 2.0' [1]. Higher order terms in the scope of the original Higgs mechanism have been analyzed by Cai and Wang [48], who show that the Higgs vacuum in fact is metastable. The implications of analogous effects in Higgs quantum gravity shall be discussed in a forthcoming study, as briefly outlined in the outlook below.

7 Higgs quantum gravity

With regard to an arbitrary coupled massive field and returning to explicit units, the excited Higgs-Planck energy from Equation 7

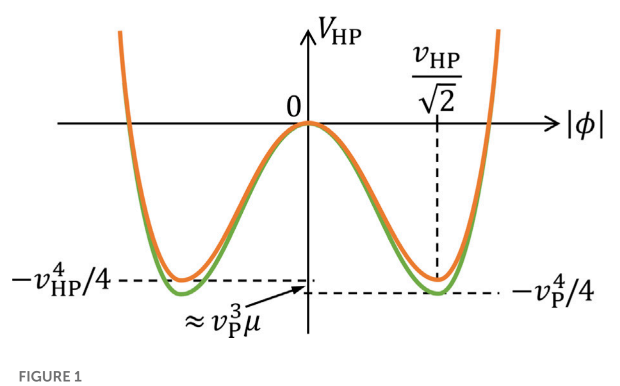

FIGURE 1
Schematic of the excited Higgs-Planck potential $V_{\mathrm{HP}}(\phi)$(orange line) and the associated vacuum potential ($\mu = 0$, green line). For visibility, the energy drop $v_{\mathrm{P}}^3\mu$is depicted many orders of magnitude too large.

relates to the vacuum Planck energy E_{P} as

$$\frac{E_{\mathrm{HP}}}{E_{\mathrm{P}}} = \frac{\ell_{\mathrm{HP}}}{\ell_{\mathrm{P}}} = \frac{t_{\mathrm{P}}}{t_{\mathrm{HP}}} = \sqrt{1 - \frac{2mc^2}{E_{\mathrm{P}}}}, \tag{8}$$

where m denotes the resulting mass of the coupled particle. The Higgs-Planck length $\ell_{\mathrm{HP}} = E_{\mathrm{HP}}G/c^4$ indicates a smaller area gap, that is, a tighter spatial base of measurement compared to the ℓ_{P} of a flat vacuum. Likewise, the Higgs-Planck time $t_{\mathrm{HP}} = \hbar/E_{\mathrm{HP}} > t_{\mathrm{P}}$ indicates an extended time scale. Referring to the Minkowski metric in Equation 3, the measured local line element due to the excitations of $N \gg 1$ network nodes is inversely proportional, extended in space and contracted in time,

$$\begin{aligned}\mathrm{d}s^2 &= -c^2\frac{t_{\mathrm{P}}^2}{t_{\mathrm{HP}}^2}\mathrm{d}t^2 + \frac{\ell_{\mathrm{P}}^2}{\ell_{\mathrm{HP}}^2}\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2 \\ &= -c^2\left(1 - \frac{r_{\mathrm{S}}}{r}\right)\mathrm{d}t^2 + \left(1 - \frac{r_{\mathrm{S}}}{r}\right)^{-1}\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2,\end{aligned} \tag{9}$$

where $r_{\mathrm{S}} = 2Gm/c^2$ denotes the particle's Schwarzschild radius and $r^2\mathrm{d}\Omega$ the surface area element of the spherically symmetric metric. The Schwarzschild line element in Equation 9 applies to a distribution of $\mathcal{O}(10^{17})$ elementary excitations. The surface area element is just included for conceptual completeness. It is not modified by mass generation. The mixed term $\mathrm{d}t\mathrm{d}r$ of the general metric is not part of the Schwarzschild coordinates and would not be modified either.

In the next steps we consider the linear combination of contracted and non-contracted area gaps of the quantum space-time, not the non-linear equations of general relativity. The metric of the space-time nodes is defined by their links, which span the area gap but provide no length. A path in the quantum space-time may be viewed as a chain of bubbles with the local area gap as their cross section. A distance $r = n\ell_{\mathrm{P}}$ combines the area gaps of all the nodes in the chain, in flat vacuum, $n\ell_{\mathrm{P}}^2 = r\ell_{\mathrm{P}}$. If some of the area gaps along the path are contracted by masses, the base of measurement of r is contracted by the corresponding sum of contractions. For the particle m in vacuum this results in

$$\frac{\sum_{k=1}^{n}\ell_{\mathrm{HP}}^2(k)}{n\ell_{\mathrm{P}}^2} = \frac{(n-1)\,\ell_{\mathrm{P}}^2 + \ell_{\mathrm{HP}}^2}{n\ell_{\mathrm{P}}^2} = 1 - \frac{r_{\mathrm{S}}}{n\ell_{\mathrm{P}}}. \tag{10}$$

The Schwarzschild line element in Equation 9 thus applies for a distance $r = n\ell_{\mathrm{P}}$. The Higgs-Planck potential in Equation 6 is a linear combination of elementary excitations of $N \gg 1$ network nodes and refers to a linear combination of masses squared. All the subsequent steps combined this sum of squared energy contributions up to the preliminary result for $\ell_{\mathrm{HP}}^2(k) \propto E_{\mathrm{HP}}^2(k)$ in Equation 10.

Most relevant for gravity are the stable nucleons that contribute the baryonic mass of the universe. The masses of fermions are explained by a Yukawa coupling of their fermionic field, ψ, to the Higgs doublet, ϕ (see, e.g., [45]). The resulting coupling term, $-g\bar{\psi}\phi\psi$, is linear in ϕ and results in a Lagrangian that is linear in the fermion masses.

In a macroscopic, static mass M confined in a volume $\mathcal{V}$, the infinitesimal volume element $\mathrm{d}\mathcal{V}(\boldsymbol{x})$ at the location $\boldsymbol{x}$ shall contain a number $k(\boldsymbol{x})\mathrm{d}\mathcal{V}(\boldsymbol{x})$ of fermions with a mass m_f each. Interactions of nucleons preserve the sum of stable masses with deviations of $\mathcal{O}(10^{-3})$. Thus, the assumption of an average, constant m_f is justified with good accuracy for cold matter or stars, for instance. The

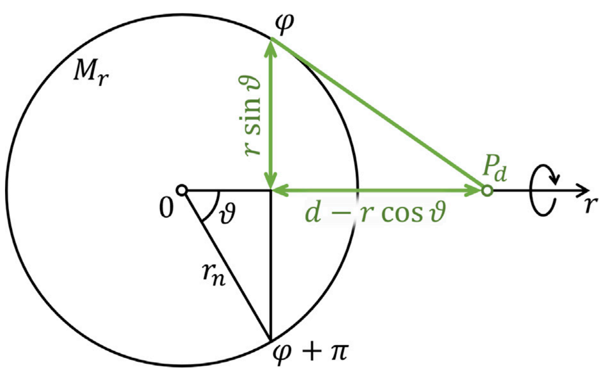

FIGURE 2
Sketch regarding the integration of a Newtonian shell with mass M_r.

area gaps, the masses, and the mass terms of the remote fermion Lagrangians are linearly associated and combined. The area gaps and their contractions in $d\mathcal{V}(\boldsymbol{x})$ both accumulate linearly, resulting in the space-time curvature caused by M.

Let, for instance, a Newtonian shell have a radius $r_n = n_r \ell_P$ and a mass $M_r = N m_f$. Let a reference point P_d be at a distance $d = n_d \ell_P \geq r_n$ from the center, $r = 0$. P_d without loss of generality may be assumed over the pole of the spherical coordinates, on the axis $\vartheta = 0$, as sketched in Figure 2.

The opposing gravitational components at φ and $\varphi + \pi$, related to $r \sin \vartheta$, compensate due to the rotational symmetry. For each fermion in the shell, the gradient towards the center is defined by the axial component of its distance, that is, by the sum of the area gaps, $n(\vartheta)\ell_P^2 = (d - r\cos\vartheta)\ell_P$. Similar to Equation 10, the total effect at the distance from the center to P_d linearly combines to

$$\frac{(n_m - N)\,\ell_P^2 + N\ell_{HP}^2}{n_m \ell_P^2} = 1 - \frac{2GM_r}{c^2 d} = -g_{tt} = g_{rr}^{-1} \tag{11}$$

$$n_m = \frac{1}{\pi \ell_P} \int_0^\pi d - r\cos\vartheta\, d\vartheta = n_d, \tag{12}$$

where g_{tt} and g_{rr} are the time and radius components of the Schwarzschild solution and n_m the mean number of area gaps. The linear combination in Equation 11 equivalent to Equation 10 leads to the Schwarzschild line element for the Newtonian shell, M_r. In the first study of the series 'Universe 2.0' [1], the author showed that the Newtonian shell theorem is valid for the relativistic case without restriction. A spherically symmetric body in general may be composed as a linear combination of concentric Newtonian shells, each of which may be represented by a point mass at $r = 0$. A point mass may represent a spherically symmetric mass distribution, regardless of radial density variations and whether the body is static or stationary.

8 Discussion and conclusions

The theory of superconductivity inspired the Higgs mechanism. The atomic fluctuation in a superconductor at low temperature results in a coupling of electrons to bosonic Cooper pairs. The Bose-Einstein condensate leads to a spontaneously broken $U(1)_{em}$ gauge symmetry, which causes a longitudinal polarization state of photons. They become massive, which explains the limited penetration depth of a magnetic field into a superconductor. The Higgs mechanism's analogy is the broken gauge symmetry.

The proposed Higgs gravity mechanism is more evident regarding both the physical context and its analogy to superconductivity. We solved the 'problem of time in quantum gravity' by transposing the Minkowski metric down to the Planck scale and thus found the Higgs gravity spin network, which represents the lattice with the globally broken gauge symmetry. The energy source for the masses is the quantum space-time itself, in analogy to the Bose-Einstein condensate. The Higgs field, that is, the Higgs boson, as a local modulation of the space-time oscillation receives its mass, in analogy to phonons in a crystal lattice.

The Higgs gravity mechanism thus transfers energy from the spin network to the massive particles. The Higgs boson represents the interaction agent. The local network nodes are left with an energy drop that amounts to the mass of the coupled particle. The area gap of the nodes, the base of their metric, contracts, while the corresponding measure of time extends, equivalent to the particle's Schwarzschild line element. Linear combination of modified area gaps yields the space-time curvature due to macroscopic masses. In spherical symmetry the Schwarzschild metric results.

Chou [49] presented a method to construct from the Schwarzschild coordinates the Kerr metric for rotating masses. He transforms the coordinates to the new symmetry and then adds the rotational energy. The kinetic energy is part of the relativistic mass and thus leads to a corresponding additional energy drop in the network nodes of the quantum space-time. This indicates that the Kerr metric may be derived equivalent to the Schwarzschild metric, by arguments of energy density.

LQG aims at explaining general relativity as a limit in the sense of the correspondence principle. Its most promising descendant, spin foam theory, still relies on additional assumptions such as the scale of the triangulation and the curvature scales around the bulk triangles, for instance. The current theory is not subject to additional assumptions.

Higgs quantum gravity combines two quantum field theories with shortcomings each. The original Higgs mechanism generates the masses from an unobservable energy field pervading the universe. LQG describes the curved space-time as a superposition with various degrees of freedom. By combining the two, the particles from the space-time receive their masses and the space-time by providing the masses its well defined curvature.

Higgs quantum gravity as presented above in the classical limit does not correspond to Einstein's equations, but it reproduces key solutions of them. The quantum space-time itself represents its gravity field, in accordance with Einstein's notion of gravitation. Higgs quantum gravity thus by a simple concept mediates between quantum theory and general relativity. Much of the experimental evidence for general relativity addresses the Schwarzschild and Kerr solutions. This includes, for instance, the perihelion precession of Mercury, the deflection of light by the sun, the gravitational redshift of light, or basic properties of gravitational lensing like the radius of the Einstein ring. All this evidence equivalently supports Higgs quantum gravity.

By its basis LQG, Higgs quantum gravity explains additional phenomena. To mention some examples, LQG reproduces the

Beckenstein-Hawking entropy and the Hawking radiation of black holes [50]. Gravitational waves, discovered by Abbott et al. [51], were successfully simulated by Dittrich [20] and are an important aspect of loop quantum cosmology [52].

Yet, Higgs quantum gravity in its current form handles static or stationary mass distributions only. Using relativistic masses should improve the predictions for objects in motion, but the Higgs gravity network at the time being does not allow for dynamic space-time effects such as gravitational waves. Due to the background independence the network nodes carry no momentum or position and cannot generate waves. They are, however, associated with one another by the oscillating links, which carry the Higgs fluctuation modes. The latter are massive and short-ranged, but the links of the Higgs gravity network may carry a different kind of long-ranged fluctuation that the present study does not cover. The relation between the Higgs energy and the Planck energy from Section 6 might allow deriving the required coupling between the associated links or area gaps.

Another open question relates to the expansion of the universe and was addressed in the concluding remarks of Section 5. Spatial expansion indicates newly created space-time quanta that carry latent energy, the source of which we do not know. The same is true, however, for all other forms of energy in the universe.

Higgs quantum gravity compared to LQG has advantages regarding simplicity. The linear combination of area gaps is much simpler and less intricate than the triangulation by Regge calculus. Nevertheless, future studies should extend the current theory based on Regge calculus, which is the standard method for discretizing general relativity. The deficit angles of 2-faces, which result in the space-time curvature, might be determined by the well-defined area differences in neighboring triangles.

The author encourages forthcoming studies to test Higgs quantum gravity versus general relativity. We should compare numerical relativity to the linear combination of area gaps, using the relativistic mass, when indicated. Lattice calculus all the way down to the Planck scale would be prohibitive regarding numerical effort, but the linear combination from the Planck scale to the semiclassical scale allows for averaging over the corresponding scale gap of a factor of $\mathcal{O}(10^{17})$, which drastically reduces the resolution. Astronomical objects of interest might be complex gravitational lenses or binary stars, including black stars.

Higgs quantum gravity is not a new form of gravity, but a new approach to the well-established form. It is the first experimentally verified quantum gravity and the first theory that determines the space-time curvature by mass generation from the space-time structure.

9 Outlook

As a next step of research, the author based on Higgs quantum gravity plans to challenge the Planck scale by a new ansatz related to the metastable electroweak vacuum of the Higgs potential [48]. Near the Planck limit, Higgs quantum gravity could allow for an escape to a separate sombrero potential representing a different oscillation mode of the space-time network. The Higgs gravity mechanism would provide masses in a similar sense as described in the present study, but excluding field interactions with the observable baryonic matter. The space-time network, however, would nevertheless be left with a curvature. This might yield a promising explanation for dark matter.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JB-M: Formal Analysis, Visualization, Project administration, Resources, Validation, Conceptualization, Methodology, Writing – review and editing, Investigation, Writing – original draft, Software.

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References

1. Böhm-Mäder J. Universe 2.0: black holes? No. black stars. *Front Phys* (2025). doi:10.3389/fphy.2025.1599363

2. Einstein A. Närungsweise Integration der Feldgleichungen der Gravitation. *Sitzungsber D. Preuss Akad D. Wiss* (1916) XXXII:688–96. doi:10.34663/9783945561317-04

3. Rosenfeld L. Zur Quantelung der Wellenfelder. *Ann Phys* (1930) 5:113–52. doi:10.34663/9783945561317-20

4. Rosenfeld L. Über die Gravitationswirkungen des Lichtes. *Z Physik* (1930) 65:589–99. doi:10.1007/BF01391161

5. Gupta SN. Quantization of Einstein's gravitational field: linear approximation. *Proc Phys Soc Section A* (1952) 65:161–9. doi:10.1088/0370-1298/65/3/301

6. Dirac PAM. The theory of gravitation in Hamiltonian form. *Prod R Soc Lond A* (1959) 246:333–43. doi:10.1098/rspa.1958.0142

7. Dirac PAM. Fixation of coordinates in the Hamiltonian theory of gravitation. *Phys Rev* (1959) 114:924–30. doi:10.1103/PhysRev.114.924

8. Feynman RP. Quantum theory of gravitation. *Acta Phys Pol* (1963) 24:697–722.

9. Rothman T, Boughn S. Can gravitons be detected? *Found Phys* (2006) 36:1801–25. doi:10.1007/s10701-006-9081-9

10. Quach JQ. Gravitational casimir effect. *Phys Rev Lett* (2015) 114:081104. doi:10.1103/PhysRevLett.118.139901

11. Norte RA, Forsch M, Wallucks A, Marinković I, Gröblacher S. Platform for measurements of the Casimir force between two superconductors. *Phys Rev Lett* (2018) 121:030405. doi:10.1103/PhysRevLett.121.030405

12. Lieu R. Exclusion of standard $\hbar\omega$ gravitons by LIGO observation. *Class Quan Gravity* (2018) 35:19LT02. doi:10.1088/1361-6382/aadb30

13. Carney D, Stamp PCE, Taylor JM. Tabletop experiments for quantum gravity: a user's manual. *Class Quan Gravity* (2019) 36:034001. doi:10.1088/1361-6382/aaf9ca

14. Bose S, Mazumdar A, Morley GW, Ulbricht H, Toroš M, Paternostro M, et al. A spin entaglement witness for quantum gravity. *Phys Rev Lett* (2017) 119:240401. doi:10.1103/PhysRevLett.119.240401

15. Pitelli JPM, Perche TR. Angular momentum based graviton detector. *Phys Rev D* (2021) 104:065016. doi:10.1103/PhysRevD.104.065016

16. Rovelli C. Loop quantum gravity: the first 25 years. *Class Quan Gravity* (2011) 28:153002. doi:10.1088/0264-9381/28/15/153002

17. Bianchi E, Han M, Rovelli C, Wieland W, Magliaro E, Perini C. Spinfoam fermions. *Class Quan Gravity* (2013) 30:235023. doi:10.1088/0264-9381/30/23/235023

18. Han M, Rovelli C. Spin-foam fermions: PCT symmetry, Dirac determinant and correlation functions. *Class Quan Gravity* (2013) 30:075007. doi:10.1088/0264-9381/30/7/075007

19. Asante SK, Dittrich B, Haggard HM. Discrete gravity dynamics from effective spin foams. *Class Quan Gravity* (2021) 38:145023. doi:10.1088/1361-6382/ac011b

20. Dittrich B. Modified graviton dynamics from spin foams: the area regge action. *Eur Phys J Plus* (2024) 139:145023. doi:10.1140/epjp/s13360-024-05432-4

21. Rickles D. *A brief history of string theory. From dual models to M-Theory the frontiers collection*. Heidelberg, Germany: Springer (2014). doi:10.1007/978-3-642-45128-7

22. Fritzsch H, Gell-Mann M, Leutwyler H. Advantages of the color octet gluon picture. *Phys Lett B* (1973) 47:365–8. doi:10.1016/0370-2693(73)90625-4

23. Scherk J, Schwarz JH. Dual models for non-hadrons. *Nucl Phys B* (1974) 81:118–44. doi:10.1016/0550-3213(74)90010-8

24. Yoneya T. Connection of dual models to electrodynamics and gravidynamics. *Progr Theor Phys* (1974) 51:1907–20. doi:10.1143/PTP.51.1907

25. Witten E. String theory dynamics in various dimensions. *Nucl Phys B* (1995) 443:85–126. doi:10.1016/0550-3213(95)00158-o

26. DeWitt BS. Quantum theory of gravity. I. The canonical theory. *Phys Rev* (1967) 160:1113–48. doi:10.1103/PhysRev.160.1113

27. Arnowitt R, Deser S, Misner CW. Dynamical structure and definition of energy in general relativity. *Phys Rev* (1959) 116:1322–30. doi:10.1103/PhysRev.116.1322

28. Ashtekar A. New variables for classical and quantum gravity. *Phys Rev Lett* (1986) 57:2244–7. doi:10.1103/PhysRevLett.57.2244

29. Ashtekar A. Gravity and the quantum. *New J Phys* (2005) 7:198. doi:10.1088/1367-2630/7/1/198

30. Ashtekar A, Pullin J *Loop quantum gravity: the first 30 years*, 4. World Scientific (2017). doi:10.1142/10445

31. Perez A. The spin-foam approach to quantum gravity. *Living Rev Relativ* (2013) 16:3. doi:10.12942/lrr-2013-3

32. Thiemann T. Introduction to modern canonical quantum general relativity (2001). doi:10.48550/arXiv.gr-qc/0110034

33. Thiemann T. *Modern canonical quantum general relativity. Cambridge monographs on mathematical physics*. Cambridge, United Kingdom: Cambridge Univ. Press (2007). doi:10.1017/CBO9780511755682

34. Rovelli C. *Quantum gravity. Cambridge Monographs on Mathematical physics*. Cambridge, United Kingdom: Cambridge Univ. Pr. (2004). doi:10.1017/CBO9780511755804

35. Ashtekar A. Loop Quantum gravity: four recent advances and a dozen frequently asked questions. In: *The eleventh marcel grossmann meeting*. World Scientific Publishing Company (2008). p. 126–47. doi:10.1142/9789812834300_0008

36. Rovelli C, Butterfield J, Earman J. Quantum gravity. In: *Philosophy of physics*. Amsterdam: Elsevier (2007). p. 1287–329. doi:10.1016/b978-044451560-5/50015-4

37. Rovelli C. *Quantum spacetime: what do we know?*. Cambridge, United Kingdom: Cambridge Univ. Pr. (2001). p. 101–22. doi:10.1017/CBO9780511612909

38. Kiefer C. Quantum gravity: general introduction and recent developments. *Ann Phys* (2005) 15:129–48. doi:10.1002/andp.200510175

39. Barbour JB. *The end of time: the next revolution in physics*. New York: Oxford University Press (1999).

40. Reisenberger MP, Rovelli C. "Sum over surfaces" form of loop quantum gravity. *Phys Rev D* (1997) 56:3490–508. doi:10.1103/PhysRevD.56.3490

41. Conrady F. Spin foams with timelike surfaces. *Class Quan Gravity* (2010) 27:155014. doi:10.1088/0264-9381/27/15/155014

42. Minkowski H. Raum und Zeit. *Phys Zeitschr* (1909) 10:104–11.

43. Thiemann T. Quantum spin dynamics (QSD) V: Quantum gravity as the natural regulator of matter quantum field theories. *Class Quan Gravity* (1998) 15:1281–314. doi:10.1088/0264-9381/15/5/012

44. Schwabl F. *Advanced quantum mechanics*. 4th ed. Springer (2008). doi:10.1007/978-3-540-85062-5

45. Zyla PA, Barnett RM, Beringer J, Dahl O, Dwyer DA, Groom DE, et al. Review of particle physics. *Prog Theor Exp Phys* (2020) 2020:083C01. doi:10.1093/ptep/ptaa104

46. Putra FA, Alrizal A. Mass–action equivalence with respect to explicit symmetry breaking. *Indian J Phys* (2022) 96:909–24. doi:10.1007/s12648-021-02041-0

47. Putra FA, Yaqubi AK, Adam RI, Wiliyanti V, Anigrahawati P. Curvature quantization based on the Ehrenfest paradox in the Bohr atomic model. *Astropart Phys* (2024) 159:102950. [Corrigendum: DOI 10.1016/j.astropartphys.2025.103137]. doi:10.1016/j.astropartphys.2024.102950

48. Cai R, Wang S. Higgs chameleon. *Phys Rev D* (2021) 103:023502. doi:10.1103/PhysRevD.103.023502

49. Chou Y. A radiating Kerr black hole and hawking radiation. *Heliyon* (2020) 6:e03336. doi:10.1016/j.heliyon.2020.e03336

50. Heidmann P, Liu H, Noui K. Semiclassical analysis of black holes in loop quantum gravity: modeling hawking radiation with volume fluctuations. *Phys Rev D* (2017) 95:044015. doi:10.1103/PhysRevD.95.044015

51. Abbott BP, Abbott R, Abbott TD, Abernathy MR, Acernese F, Ackley K, et al. Observation of gravitational waves from a binary black hole merger. *Phys Rev Lett* (2016) 116:061102. doi:10.1103/PhysRevLett.116.061102

52. Mielczarek J, Cailleteau T, Grain J, Barrau A. Inflation in loop quantum cosmology: dynamics and spectrum of gravitational waves. *Phys Rev D* (2010) 81:104049. doi:10.1103/PhysRevD.81.104049