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Newtonian Gravity of Antimatter Particles and Gravitational Foundation Underlying Field Quantization Through Quantum Spacetime Geometrization

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Abstract: By incorporating quantum mechanics into gravitational theory through the so-called spacetime geometrization procedure that consists in applying the principle of least action alongside the covariance of quantum mechanical motion equations, we present a model that describes the gravitational behavior of antimatter whose existence is fundamentally rooted in quantum mechanics. This approach is based on the fact that the equivalence of gravitational and inertial mass in General Relativity can be replaced by the condition of covariance of classical equations of motion in curved spacetime. The findings show that even if the antimatter particles rest mass assumes negative values, the Newtonian gravity of point-like antimatter matter on macroscopic scale is attractive. The work also shows that the weak Newtonian gravity includes an additional quantum term that is inversely proportional to their mass and depending by the quantum mass density distributions. $|\psi|$. The divergence of gravitational energy for infinitesimal masses may provide an explanation for the origin of field quantization in elementary particles and enforcing a discrete spectrum of elementary particle masses.

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1. Introduction

General Relativity, a form of spacetime geometrization, is derived by utilizing two fundamental conditions: the equivalence of inertial and gravitational masses, and the principle of least action [1]. On the other hand, it is also true that the equivalence of inertial and gravitational masses corresponds to imposing the covariance of the classical equations of motion in curved spacetime. In this sense the general Relativity can be conceptualized as classical spacetime geometrization consequent to the minimum action principle. If, instead of the covariance of the classical motion equation, we assume the covariance of quantum mechanical motion equations for the mass distributions $|\psi|^2$ we obtain the spacetime geometry consequent to the presence of quantum bodies.

This can be achieved by utilizing the Madelung hydrodynamic representation of quantum mechanics [2–4] that transforms the quantum equations (such as the Schrodinger or the Klein-Gordon or the Dirac ones) as a function of the field

$$\psi_{(x_\mu)} = |\psi_{(x_\mu)}| e^{-i\frac{S_{(x_\mu)}}{\hbar}} \tag{1}$$

in a system of two equations as a function of the real variables: $|\psi_{(x_\mu)}|$ and $\partial_\mu S = -p_\mu$.

This transformation for the Klein-Gordon equation (KGE)

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$$\psi_{;\mu}^{;\mu} = \left(g^{\mu\nu}\partial_\nu\psi\right)_{;\mu} = \frac{1}{\sqrt{-g}}\partial_\mu\sqrt{-g}\left(g^{\mu\nu}\partial_\nu\psi\right) = -\frac{m^2c^2}{\hbar^2}\psi \tag{2}$$

leads to [5] the motion equation

$$g_{\mu\nu}\partial^\nu S\,\partial^\mu S - \hbar^2\frac{1}{|\psi|\sqrt{-g}}\partial_\mu\sqrt{-g}\left(g^{\mu\nu}\partial_\nu|\psi|\right) - m^2c^2 = 0 \tag{3}$$

coupled to the conservation equation

$$\frac{1}{\sqrt{-g}}\frac{\partial}{\partial q^\mu}\sqrt{-g}\left(g^{\mu\nu}|\psi|^2\frac{\partial S}{\partial q^\nu}\right) = 0, \tag{4}$$

that gives rise to a classical-like description where the mass density $|\psi|^2$ owing the hydrodynamic impulse p_μ is subject to the additional non-local quantum potential interaction

$$V_{qu(|\psi|)} = -\frac{\hbar^2}{m}\frac{1}{|\psi|\sqrt{-g}}\partial_\mu\sqrt{-g}\left(g^{\mu\nu}\partial_\nu|\psi|\right) \tag{5}$$

conceptualizing (3) in the form

$$g_{\mu\nu}p^\nu p^\mu + mV_{qu} - m^2c^2 = 0 \tag{6}$$

If in the non-relativistic limit where (2) reduces to the Schrodinger equation, Eq. (3) reduces to the classical equation of motion [4]. In the quantum case, analogously to the general relativity procedure, by imposing the covariance of (3) in curved spacetime we can utilize the minimum action principle to obtain the geometry of spacetime subject to the quantum physics.
As shown in ref. [5,6] minimum action condition $\delta\mathcal{S}_{QH} = 0$ in the quantum hydrodynamic representation can be expressed as

$$\delta\mathcal{S}_{QH} = \frac{1}{c}\int\!\!\iiint|\psi|^2\sum_k\left(\left(\frac{1}{\sqrt{-g}}\left(\frac{\partial\sqrt{-g}\tilde{L}_{(k)}}{\partial g^{\mu\nu}} - \frac{\partial}{\partial q^\lambda}\frac{\partial\sqrt{-g}\tilde{L}_{(k)}}{\partial\frac{\partial g^{\mu\nu}}{\partial q^\lambda}} - \frac{\partial}{\partial|\psi|}\frac{\partial\sqrt{-g}\tilde{L}_{(k)}}{\partial\frac{\partial g^{\mu\nu}}{\partial|\psi_k|}}\right)\right)\delta g^{\mu\nu}\right)\sqrt{-g}\,d\Omega \tag{7}$$

where $\tilde{L}_{(k)}$ is the quantum hydrodynamic Lagrangian density $\tilde{L}_{(k)}$ given in ref. [2]. Furthermore, by comprehending the contribution coming from the spacetime curvature,

$$\delta\mathcal{S}_g = \frac{c^3}{16\pi G}\int\!\!\iiint\left(R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}\right)\delta g^{\mu\nu}\sqrt{-g}\,d\Omega, \tag{8}$$

the overall minimum condition

$$\delta\mathcal{S}_{QH} + \delta\mathcal{S}_g = \int\!\!\iiint\left(R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - \frac{8\pi G}{c^4}|\psi|^2\tau_{\mu\nu}\right)\delta g^{\mu\nu}\sqrt{-g}\,d\Omega = 0 \tag{9}$$

defines the quantum gravity equation (QGE) [5,6]

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - \frac{8\pi G}{c^4}|\psi|^2\tau_{\mu\nu} = 0 \tag{10}$$

where $\tau_{\mu\nu}$ in (10) is explicitly derived as a function of the quantum hydrodynamic Lagrangian density $\tilde{L}_{(k)}$ in ref. [5].

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For the particular case of interest, of the macroscopically stable state (stationary energy eigenstates [7]), $\tilde{L}_{(k)}$ reads

$$\tilde{L}_{(k)} = -c^2 \left(\partial_t S_{(k)}\right)^{-1} g_{\mu\alpha} p^{\alpha}{}_{(k)} p^{\mu}{}_{(k)} = -c^2 \left(\partial_t S_{(k)}\right)^{-1} g_{\mu\alpha} \partial^{\alpha} S_{(k)} \partial^{\mu} S_{(k)}$$
$$= -c^2 \frac{i\hbar}{2} \left(\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial t} \right)^{-1} g_{\mu\alpha} \frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q_\alpha} \frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q_\nu} . \tag{11}$$

Therefore, as shown in ref. [5], in the macroscopic weak gravity limit (10) acquires the form

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} \left(T_{(k)\mu\nu} - \Lambda_Q g_{\mu\nu} \right) \tag{12}$$

where the energy tensor density $T_{(k)\mu\nu}$ reads

$$T_{(k)\mu\nu} = |\psi_k|^2 c^2 \left(\frac{\partial S_{(k)}}{\partial t} \right)^{-1} \left(\frac{\partial S_{(k)}}{\partial q^\mu} \frac{\partial S_{(k)}}{\partial q^\nu} - \left(g_{\alpha\beta} \frac{\partial S_{(k)}}{\partial q_\beta} \frac{\partial S_{(k)}}{\partial q_\alpha} \right) g_{\mu\nu} \right)$$
$$= -|\psi_k|^2 c^2 \frac{\hbar}{2i} \left(\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial t} \right)^{-1} \left(\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q^\mu} \frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q^\nu} - \left(g_{\alpha\beta} \frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q_\beta} \frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q_\alpha} \right) g_{\mu\nu} \right) . \tag{13}$$

where $g_{\nu\mu}$ is the metric tensor, where $g = |g_{\nu\mu}|^{-1}$ and where

$$ln \frac{\psi_k}{\psi_k{}^*} = -\frac{2i}{\hbar} S_{(k)} \tag{14}$$

Furthermore, by defining $\psi_{+k} = \psi_k$ and $\psi_{-k} = \psi_k{}^*$ the wavefunction of the particle and antiparticle. respectively, it follows that $S_- = -S_+$ and

$$T_{(k)\pm\mu\nu} = \mp |\psi_k|^2 c^2 \frac{\hbar}{2i} \left(\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial t} \right)^{-1} \left(\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q^\mu} \frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q^\nu} - \left(g_{\alpha\beta} \frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q_\beta} \frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q_\alpha} \right) g_{\mu\nu} \right) . \tag{15}$$

Moreover, by utilizing, in the low curvature limit (Newtonian gravity), the KGE expression

$$\frac{\partial S}{\partial q^\mu} \frac{\partial S}{\partial q_\mu} = p_\mu p^\mu = \left(\frac{E^2}{c^2} - p^2 \right) = m^2 c^2 \left(1 - \frac{V_{qu}}{mc^2} \right) \tag{16}$$

(15) reads

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$$T_{(k)\pm\mu\nu} = \mp|\psi_k|^2 m^2c^4 \frac{\hbar}{2i}\left(\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial t}\right)^{-1}\left(\begin{array}{l}\frac{1}{m^2c^2}\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q^\mu}\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q^\nu}\\ -\left(1-\frac{V_{qu}}{mc^2}\right)g_{\mu\nu}\end{array}\right). \quad (17)$$

It is interesting to note the quantum nature of Eqs. (13,17) in the presence of not-null off-diagonal terms, as pointed out by the non-commutative field theory [8].

Given the physical description of antimatter provided by quantum mechanics, the gravity equation (10) naturally incorporates it into gravitational theory. Consequently, performing the (non-relativistic) weak gravity limit of (10) yields the Newtonian forces for both matter and antimatter. To derive the macroscopic Newtonian gravity of matter and antimatter, it is necessary to disregard the quantum contributions performing the limit $\hbar \to 0$ from which we have [5]

$$lim_{\hbar\to 0}\Lambda_Q = 0 \quad (18)$$

and

$$lim_{\hbar\to 0}V_{qu} = 0\,. \quad (19)$$

Moreover, we have to impose the conditions for the establishing of low energy non-relativistic limit [7]

$$\gamma \cong 1\ . \quad (20)$$

leading to the identity

$$\frac{2i}{\hbar}\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial t} = \frac{\partial S_+}{\partial t} = -E = -\gamma mc^2 \cong -mc^2 \quad (21)$$

and

$$\frac{\partial S_-}{\partial t} = E = \gamma mc^2 \cong mc^2 \quad (22)$$

that introduce into (17) leads to

$$\begin{aligned} T_{(k)\pm\mu\nu} &= |\psi_{\pm k}|^2 mc^2\left(\frac{1}{m^2c^2}\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q^\mu}\frac{\partial\, ln[\frac{\psi_k}{\psi_k{}^*}]}{\partial q^\nu} - g_{\mu\nu}\right)\\ &= |\psi_{\pm k}|^2 mc^2\left(\left(\frac{1}{mc}\right)^2 p_\mu p_\nu - g_{\mu\nu}\right)\\ &= |\psi_{\pm k}|^2 mc^2\left(u_\mu u_\nu - g_{\mu\nu}\right) \end{aligned} \quad (23)$$

where $u_\mu = \frac{p_\mu}{mc}$ is the velocity field.

Therefore, from (23) the weak gravity limit of QGE reads

$$R_{\pm\nu\mu} - \frac{1}{2}g_{\nu\mu}R_{\pm\alpha}{}^{\alpha} = \frac{8\pi G}{c^2}m|\psi_{\pm(k)}|^2\left(u_\mu u_\nu\right) \quad (24)$$

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leading to the trace identity

$$R_{\pm\alpha}{}^{\alpha} - \frac{1}{2}\delta_{\alpha}{}^{\alpha} R_{\pm\alpha}{}^{\alpha} = -R_{\pm\alpha}{}^{\alpha} = \frac{8\pi G}{c^2} m\,|\psi_{\pm}|^2\, u_{\alpha}u^{\alpha}\,. \tag{25}$$

Thus, in the particles reference system where

$$u_{\mu} = (1,0,0,0), \tag{26}$$

it follows that

$$R_{\pm 0}{}^{0} = \frac{8\pi G}{c^2} m\,|\psi_{\pm}|^2 \tag{27}$$

2. The Antimatter Newtonian Field

Given the Newtonian gravitational potential ϕ, as a function of the component g_{00} of the metric tensor [9]

$$\frac{2\phi}{c^2} = g_{00} - 1, \tag{28}$$

whose trace, at zero order, reads

$$g_{\alpha\alpha} \cong -2, \tag{29}$$

leading to the identity

$$R_0{}^{0} = \frac{4\pi G}{c^2} m\,|\psi|^2 = R_{00} = \frac{\partial \Gamma^{\alpha}{}_{00}}{\partial q^{\alpha}} \approx -\frac{1}{2}\partial_{\alpha}\left(g_{\gamma\gamma}\partial_{\alpha} g_{00}\right) = \frac{1}{c^2}\partial_{\alpha}\partial_{\alpha}\phi \tag{30}$$

it follows that

$$\partial_{\alpha}\partial_{\alpha}\phi_{\pm} = 4\pi G m\,|\psi_{\pm}|^2\,. \tag{31}$$

Therefore, given that $m\,|\psi_{-}|^2 = m\,|\psi^*|^2$ and, thence,

$$m\,|\psi_{+}|^2 = m\,|\psi|^2 = m\,|\psi^*|^2 \tag{32}$$

it follows that the antiparticle mass density is equal to that of the particle mass density and the Newtonian gravity of antimatter is equal to that of matter.

3. Newtonian Gravity at Short Distance Between Two Quantum Bodies

The results (29-32) are valid as far as the wave function localization produces a mass distribution that is satisfactory well described for distance much larger than the quantum mass density distribution of particles respect the scale of the problem (for instance by the Dirac's delta typical of the classical macroscopic approach). On very short distance, when the physical length of the problem is of order of the quantum body mass distribution, the gravitational interaction is influenced by the effective form of the quantum mass density distribution $|\psi|^2$.

Here we consider the case of quantum bodies (sufficiently large) to be described by continuous fields. Furthermore, the gravity interaction is derived by assuming the particle densities are very much lighter than the Planck mass in a cube of Planck length side, so that (at zero order of approximation) the spacetime can be assumed Minkowskian. Then, the gravitational force is derived by the first order curvature produced by such mass distributions.

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Therefore, we are in the position to derive the gravitational potential of a particles as deriving by the curvature induced by its mass distributions $|\psi|^2$ through the gravity equation

$$R_{\nu\mu}-\frac{1}{2}g_{\nu\mu}R_{\alpha}^{\ \alpha}=\frac{8\pi G}{c^4}\frac{mc^2|\psi|^2}{\gamma}\begin{pmatrix}\left(\sqrt{1-\frac{V_{qu}}{mc^2}}-1\right)g_{\mu\nu}-\Lambda_Q g_{\mu\nu}\\+\sqrt{1-\frac{V_{qu}}{mc^2}}^{-1}\left(\frac{\hbar}{2mc}\right)^2\partial_\mu ln[\frac{\psi}{\psi^*}]\partial^\lambda ln[\frac{\psi}{\psi^*}]g_{\lambda\nu}\end{pmatrix}.$$

$$=\frac{8\pi G}{c^4}\frac{mc^2|\psi|^2}{\gamma}\begin{pmatrix}\left(\sqrt{1-\frac{V_{qu}}{mc^2}}-1\right)g_{\mu\nu}-\Lambda_Q g_{\mu\nu}\\+\sqrt{1-\frac{V_{qu}}{mc^2}}^{-1}\left(\frac{\hbar}{2mc}\right)^2 p_\mu p^\lambda g_{\lambda\nu}\end{pmatrix} \quad (33)$$

Here, for sake of completeness, we also re-consider the contribution that can come from the quantum pressure term $-\Lambda_Q g_{\mu\nu}$ where the cosmological-like term Λ_Q, given in ref. [5], reduces to a small constant in quasi-Minkowskian spacetime approximation [10]. Therefore, Equation (33) for the non-relativistic case, where $\frac{V_{qu}}{mc^2}\ll 1$, leads to

$$R_{\nu\mu}-\frac{1}{2}g_{\nu\mu}R_{\alpha}^{\ \alpha}=\frac{8\pi G}{c^4}\frac{mc^2|\psi|^2}{\gamma}\begin{pmatrix}-\left(\frac{V_{qu}}{2mc^2}+\Lambda_Q\right)g_{\mu\nu}\\+\left(1+\frac{V_{qu}}{2mc^2}\right)u_\mu u_\nu\end{pmatrix}. \quad (34)$$

Furthermore, by using the identity

$$-\left(\frac{V_{qu}}{2mc^2}+\Lambda_Q\right)\left(\delta_\alpha^\alpha-u_\alpha u^\alpha\right)=-3\left(\frac{V_{qu}}{2mc^2}+\Lambda_Q\right) \quad (35)$$

it follows that

$$-R_{\alpha}^{\ \alpha}=\frac{8\pi G}{c^4}mc^2|\psi|^2\left(1-3\left(\frac{V_{qu}}{2mc^2}+\Lambda_Q\right)\right) \quad (36)$$

leading to the gravitational potential

$$\partial_r\phi=\frac{Gm}{(r-R)^2}\int_0^V|\psi|^2\left(1-3\left(\frac{V_{qu}}{2mc^2}+\Lambda_Q\right)\right)d^3V \quad (37)$$

where, we can recognize the classical and quantum parts that read, respectively,

$$\partial_r\phi_{Class}=\frac{Gm}{\left(r-R_j\right)^2}\left(\int_0^{(r-R)}\int_{-\pi/2}^{\pi/2}\int_0^{2\pi}|\psi|_{(r-R,\vartheta,\varphi)}^2(r-R)^2 d(r-R)\cos\vartheta d\vartheta d\varphi\right) \quad (38)$$

$$\partial_r\phi_Q=\frac{3}{2}\frac{\hbar^2}{mc^2}\frac{G}{\left(r-R_j\right)^2}\left(\int_0^{(r-R)}\int_{-\pi/2}^{\pi/2}\int_0^{2\pi}|\psi|_{(r-R,\vartheta,\varphi)}(r-R)^2\left(\partial_\mu\partial^\mu|\psi|+2mc^2|\psi|\Lambda_Q\right)d(r-R)\cos\vartheta d\vartheta d\varphi\right). \quad (39)$$

It is worth noting that the quantum contribution (39) becomes larger smaller the particle mass m leading to the asymptotic expression for infinitesimal mass

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$$lim_{m\to 0}\partial_r\phi_Q \approx \frac{3}{2}\frac{\hbar^2}{mc^2}\frac{G}{\left(r-R_j\right)^2}\left(\int_0^{(r-R)}\int_{-\pi/2}^{\pi/2}\int_0^{2\pi}|\psi|_{(r-R,\vartheta,\varphi)}\left(r-R\right)^2\partial_\mu\partial^\mu|\psi|\,d\left(r-R\right)cos\,\vartheta d\vartheta d\varphi\right). \quad (40)$$

From (40) it is important to highlight that, to prevent gravitational energies from diverging, the mass of particles cannot decrease continuously to zero but must be quantized with minimum values. This implies the existence of elementary particles with discrete mass values and the necessity of quantizing their fields, pointing to a gravitational constraint that drives field quantization. Furthermore, this hypothesis supports the notion that only fields require quantization, while gravity itself, as defined by the left side of gravitational equation (10), becomes indirectly a quantum operator through the equivalence to the quantized fields on the right side of (10) [11].

4. Discussion

Quantizing particle masses to avoid gravitational divergences is a compelling topic in theoretical physics, with ongoing research exploring its implications. Some nonlinear field theories propose that gravity could play a pivotal role in the formation of elementary particles, suggesting the existence of regular solitonic solutions that can be interpreted as particles with discrete masses [12].The stability and discreteness of masses might be a consequence of intrinsic gravitational constraints.

Despite this, quantum gravity remains a non-renormalizable theory, meaning that it cannot fully eliminate divergences to yield finite results, in contrast to renormalizable frameworks like the Standard Model. The Higgs field, while providing mass to elementary particles such as quarks, electrons, neutrinos, and the W and Z bosons, has no direct connection to the gravitational field.

However, certain models suggest that quantum effects in gravity might influence the discretization of black hole masses, implying the existence of a minimum mass required for their formation [13].

The quantum contribution of the gravitational field, arising from quantum potential energy, is characterized by a term $\frac{\hbar^2}{m}$ inversely proportional to the particle mass that is also present into the quantum potential expression in (5) that, for weak Newtonian gravity, takes the form:

$$V_{qu(|\psi|)} = -\frac{\hbar^2}{m}\frac{1}{|\psi|}\partial^\mu\partial_\mu|\psi| \quad (41)$$

This term diverges as the particle mass approaches zero. However, it can remain constant if we increase the delocalization of the particle state, thereby reducing the spatial density term $\partial^\mu\partial_\mu|\psi|$. Moreover, since particle delocalization can extend up to the maximum elemental spacetime cell, corresponding to the lowest possible gravitational curvature and tied to a minimum critical value of the cosmological constant [14], below this critical value, the presence of a smaller mass density would cause spacetime to collapse into a polymeric-like, non-metric state.

Thus, in physical spacetime, particles with vanishing rest mass are not permissible, while the presence of discrete mass particle in spacetime stabilizes it in the metric physical state.

If elementary particles with continuously decreasing mass were possible, the universe's outer regions could become infinite, making possible additional large discrete spacetime cells at will (with practically null mass inside). Conversely, if only particles with finite mass, resulting in cells of minimum curvature, can exist, the external horizon of the universe could assume a finite extension. Beyond this horizon, the void spacetime would collapse into a polymeric phase lacking metric structure.

Similar principles are observed in black hole physics, where a critical density is linked to horizon formation. Analogously, the critical cosmological constant Λ_Q value, connected to mass

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discretization, might define a boundary separating the metric spacetime from its non-metric counterpart.

5. Conclusion

By employing the quantum spacetime geometrization, which describes gravity in spacetime with quantum bodies, the weak gravity limit of the Newtonian potential for antimatter is theoretically demonstrated to be identical to that of matter, even when the mass and energy of antimatter assume negative values. The theory also reveals additional weak gravity contributions that arise directly from the quantum nature of spacetime, exhibiting dependence on the quantum mass density distributions. $|\psi|^2$.

The quantum contribution to gravity, stemming from the energy of the quantum potential, reveals that a continuous spectrum of mass in elementary particles approaching zero would lead to a diverging gravitational potential energy, thereby justifying the fields quantization and enforcing a discrete spectrum of elementary particle masses. The emergence of discrete masses driven by gravitational principles has profound implications for the nature of our universe. It aligns with the concept of a fundamentally quantized reality, where discreteness is an intrinsic and necessary property, shaping time, space, matter, their origins, their extent, and their ultimate end.

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