Invariant Dispersion and Emergent Quantum Wave Dynamics from Bounded Vacuum Capacity

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Abstract

In Ref. [1], a bounded vacuum-capacity framework was developed in which gravitation arises from static, localized deficits of a scalar vacuum-potential field normalized by the equilibrium condition $\Phi \to c^2$ in asymptotically flat spacetime. The same capacity principle was shown to imply a universal maximum force and a signal-speed bound $v \leq c$.

In the present work, we develop the dynamical sector of this framework. Linearized fluctuations about a localized vacuum-deficit configuration are shown to satisfy a Klein–Gordon–type equation, with the mass parameter determined by the intrinsic oscillation frequency associated with curvature of the vacuum response. The resulting plane-wave solutions yield an invariant quadratic dispersion relation of the form $E^2 = p^2c^2 + m^2c^4$, arising directly from the bounded stiffness-to-inertia ratio of the vacuum medium. The velocity-dependent inertial response $m(v) = m/\sqrt{1 - v^2/c^2}$ follows from this dispersion structure. In the low-momentum regime, the Schrödinger equation emerges as the nonrelativistic limit.

The mass parameter entering both static and dynamical sectors is identified with the asymptotic vacuum-loading parameter defined in Ref. [1], relating gravitational and inertial mass to a single localized vacuum configuration. The results establish a unified dynamical description in which relativistic and nonrelativistic quantum wave equations arise from bounded vacuum capacity.

I — Introduction

In Ref. [1], a bounded vacuum-capacity framework was developed in which gravitation arises from static, localized deficits of a scalar vacuum-potential field normalized by the equilibrium condition $\Phi \to c^2$ in asymptotically flat spacetime. In that formulation, Newtonian gravity emerges from the exterior relaxation profile of a localized vacuum-deficit configuration, while finite vacuum capacity implies both a universal maximum transmissible force and a signal-speed bound $v \leq c$. These results establish the static and kinematic structure of the theory.

The present work develops the dynamical sector of this framework. We show that linearized fluctuations about a localized vacuum-deficit configuration satisfy a Klein–Gordon–type equation whose mass parameter is determined by the intrinsic oscillation frequency associated with curvature of the vacuum response. The resulting plane-wave solutions yield an invariant quadratic dispersion structure of the form

$$E^2 = p^2c^2 + m^2c^4,$$

arising directly from the bounded stiffness-to-inertia ratio of the vacuum medium. This dispersion relation coincides with the standard relativistic energy–momentum relation [2-4], but here emerges as a consequence of the underlying vacuum response rather than as an independent postulate.

From the dispersion structure, the velocity-dependent inertial response

$$m(v) = \frac{m}{\sqrt{1 - v^2/c^2}}$$

follows directly. In the low-momentum regime, the Schrödinger equation arises as the nonrelativistic limit of the same wave dynamics [5-7]. The mass parameter entering both relativistic and nonrelativistic sectors is identified with the asymptotic vacuum-loading parameter defined in Ref. [1], thereby relating gravitational and inertial mass to a single localized vacuum configuration.

Historically, the Klein–Gordon equation was introduced as a relativistically invariant wave equation [8, 9], while the Schrödinger equation arises as its low-energy limit [5]. In conventional treatments, the mass parameter appearing in these equations is taken as fundamental. In contrast, within the bounded-vacuum framework, this parameter originates from the total vacuum loading associated with a localized deficit configuration. The present analysis establishes that the same parameter governing the static asymptotic profile also determines intrinsic oscillation frequency, dispersion structure, and inertial response.

The logical progression developed here is therefore:

Bounded vacuum capacity ⟶ Localized deficit ⟶ Klein–Gordon sector
⟶ Invariant dispersion ⟶ Schrödinger limit.

This establishes a unified dynamical description in which both relativistic and nonrelativistic quantum wave equations arise from bounded vacuum capacity.

The paper is organized as follows. In Sec. II we summarize the elements of Ref. [1] required for the present development. Section III derives the linearized fluctuation equation about a localized deficit configuration and obtains the Klein–Gordon form. Section IV analyzes the resulting dispersion structure and effective inertial response. Section V develops the nonrelativistic limit. Section VI identifies the static and dynamical mass parameters and discusses internal consistency.

II — Bounded Vacuum Capacity Framework

For completeness and to establish notation, we summarize the elements of the bounded vacuum-capacity framework developed in Ref. [1] that are required for the present dynamical analysis.

The theory is formulated in terms of a scalar vacuum-potential field $\Phi(\mathbf{x}, t)$, normalized such that

$$\Phi \to c^2 \text{ in asymptotically flat spacetime.} \qquad (2.1)$$

The constant c^2 represents the equilibrium vacuum capacity. Localized configurations correspond to finite deficits

$$\delta\Phi(\mathbf{x}) \equiv c^2 - \Phi(\mathbf{x}), \qquad (2.2)$$

which define vacuum-loading states. No external matter source is introduced; instead, mass arises as a global measure of localized vacuum loading.

For static, spherically symmetric configurations, the exterior region satisfies the vacuum field equation and reduces to Laplace's equation. Imposing asymptotic flatness uniquely determines the exterior relaxation profile [1],

$$\Phi(r) = c^2 - \frac{Gm}{r}, \qquad (2.3)$$

where the loading parameter $m$is defined invariantly through the asymptotic flux

$$m = -\frac{1}{4\pi G} \oint_{S_\infty} \nabla\Phi \cdot d\mathbf{S}. \qquad (2.4)$$

This definition parallels Gauss-law characterizations of gravitational mass in Newtonian theory and the ADM mass construction in general relativity [10, 11]. The parameter m therefore measures the total vacuum loading associated with a localized deficit configuration.

Finite vacuum capacity implies that loading cannot be localized arbitrarily. Defining the collapse radius r_c by

$$\delta\Phi(r_c) \sim c^2, \qquad (2.5)$$

the exterior profile (2.3) yields

$$r_c \sim \frac{Gm}{c^2}. \qquad (2.6)$$

Thus any finite loading localizes over a finite spatial scale. The scale r_c coincides parametrically with the Schwarzschild radius [12], although here it arises from bounded vacuum response rather than geometric curvature.

The dynamical sector of Ref. [1] established that small fluctuations about equilibrium are governed, at coarse-grained scales, by the local quadratic action

$$S = \int dt\, d^3x \left[\frac{1}{2}\mu(\partial_t\Phi)^2 - \frac{1}{2}T(\nabla\Phi)^2\right], \qquad (2.7)$$

where μ characterizes the inertial response density of the vacuum medium and T represents its transmissible tension.

Stationarity of (2.7) yields the wave equation

$$\mu\, \partial_t^2\Phi = T\, \nabla^2\Phi. \qquad (2.8)$$

The associated propagation speed is therefore

$$v = \sqrt{\frac{T}{\mu}}. \qquad (2.9)$$

Finite vacuum capacity constrains these coefficients such that [1]

$$\frac{T}{\mu} = c^2, \qquad (2.10)$$

implying a universal signal-speed bound $v \leq c$. Independently, the transmissible tension satisfies the maximum-force condition

$$T_{\max} = \frac{c^4}{G}, \qquad (2.11)$$

consistent with bounds discussed in gravitational contexts [13-15].

Equations (2.3)–(2.11) constitute the static and kinematic structure established in Ref. [1]. In the following sections, we develop the dynamical implications of this structure by analyzing fluctuations about localized vacuum-deficit configurations and determining the resulting dispersion relation.

III — Linearized Vacuum Fluctuations and Emergent Klein–Gordon Structure

We now derive the dynamical equation governing small fluctuations about a localized vacuum-deficit configuration using only locality, stability, and bounded vacuum capacity as structural inputs.

In the continuum exterior regime, the vacuum potential field $\Phi(\mathbf{x}, t)$is governed by the local action [1]

$$S = \int dt\, d^3x \left[\frac{1}{2}\mu(\partial_t\Phi)^2 - \frac{1}{2}T(\nabla\Phi)^2 - V(\Phi)\right], \qquad (3.1)$$

where $\mu > 0$ and $T > 0$ characterize inertial and stiffness response of the vacuum medium, and $V(\Phi)$ encodes the nonlinear, capacity-limited structure responsible for stabilizing localized deficit configurations.

Let $\Phi_0(\mathbf{x})$ denote a static localized solution satisfying the Euler–Lagrange equation derived from (3.1). We consider small perturbations

$$\Phi(\mathbf{x}, t) = \Phi_0(\mathbf{x}) + \phi(\mathbf{x}, t), \qquad (3.2)$$

where ϕ is treated as a linear fluctuation.

Expanding the potential about the background configuration,

$$V(\Phi_0 + \phi) = V(\Phi_0) + V'(\Phi_0)\phi + \frac{1}{2}V''(\Phi_0)\phi^2 + \mathcal{O}(\phi^3), \qquad (3.3)$$

and using that $\Phi_0$satisfies the static field equation, the linear term does not contribute to the fluctuation dynamics. Retaining quadratic terms yields the second-order action

$$S^{(2)} = \frac{1}{2}\int dt\, d^3x [\mu(\partial_t\phi)^2 - T(\nabla\phi)^2 - \kappa(\mathbf{x})\phi^2], \qquad (3.4)$$

where

$$\kappa(\mathbf{x}) = V''(\Phi_0(\mathbf{x})) \qquad (3.5)$$

is the local curvature of the vacuum response about the static configuration. Stability requires $\kappa(\mathbf{x}) \geq 0$.

Stationarity of (3.4) yields the linearized field equation

$$\mu\, \partial_t^2 \phi - T\nabla^2 \phi + \kappa(\mathbf{x})\phi = 0. \qquad (3.6)$$

In the exterior region, where coefficients vary slowly and $\kappa(\mathbf{x}) \to \kappa_0$is approximately constant, this reduces to

$$\mu\, \partial_t^2 \phi - T\nabla^2 \phi + \kappa_0 \phi = 0. \qquad (3.7)$$

Using the universal stiffness-to-inertia relation derived in Ref. [1],

$$\frac{T}{\mu} = c^2, \qquad (3.8)$$

we divide (3.7) by T and obtain

$$\left(\frac{1}{c^2}\partial_t^2 - \nabla^2 + \frac{\kappa_0}{T}\right)\phi = 0. \qquad (3.9)$$

Equation (3.9) has the differential structure of the Klein–Gordon operator. The coefficient κ_0/T is determined entirely by the curvature of the vacuum response relative to its stiffness and has dimensions of inverse length squared.

Quantum dynamics enters universally through the phase weight $e^{iS/\hbar}$ in transition amplitudes [6, 7, 16], implying the energy–frequency relation

$$E = \hbar\omega. \qquad (3.10)$$

For spatially homogeneous perturbations ($\nabla\phi = 0$), Eq. (3.9) gives

$$\omega^2 = c^2 \frac{\kappa_0}{T}. \qquad (3.11)$$

The intrinsic oscillation frequency is therefore

$$\Omega = c\sqrt{\frac{\kappa_0}{T}}. \qquad (3.12)$$

The corresponding rest energy is

$$E_0 = \hbar\Omega. \qquad (3.13)$$

We now define the mass parameter operationally through the rest-energy relation

$$m_0 \equiv \frac{E_0}{c^2}, \qquad (3.14)$$

which introduces no additional dynamical assumption and simply identifies mass with energy measured relative to the universal signal-speed scale c. Combining (3.12)–(3.14) yields

$$m_0 = \frac{\hbar}{c}\sqrt{\frac{\kappa_0}{T}}, \qquad (3.15)$$

or equivalently,

$$\frac{\kappa_0}{T} = \frac{m_0^2 c^2}{\hbar^2}. \qquad (3.16)$$

Substituting (3.16) into Eq. (3.9) gives

$$\boxed{\left(\frac{1}{c^2}\partial_t^2 - \nabla^2 + \frac{m_0^2 c^2}{\hbar^2}\right)\phi = 0} \qquad (3.17)$$

which is the canonical Klein–Gordon equation [8, 17]. Thus the Klein–Gordon structure emerges as the universal quadratic fluctuation equation of a stable, bounded vacuum medium, with the mass parameter determined by the intrinsic oscillation scale of the localized deficit configuration.

IV — Invariant Dispersion Structure and Effective Inertial Response

The fluctuation equation (3.17)

$$\left(\frac{1}{c^2}\partial_t^2 - \nabla^2 + \frac{m_0^2 c^2}{\hbar^2}\right)\phi = 0 \qquad (4.1)$$

governs linear perturbations of the vacuum field about a localized deficit configuration. We now examine the dispersion relation implied by this equation.

Consider plane-wave solutions of the form

$$\phi(\mathbf{x}, t) = e^{i(\mathbf{k}\cdot\mathbf{x} - \omega t)}. \qquad (4.2)$$

Substitution into Eq. (4.1) yields

$$-\frac{\omega^2}{c^2} + k^2 + \frac{m_0^2 c^2}{\hbar^2} = 0, \qquad (4.3)$$

or equivalently,

$$\omega^2 = c^2 k^2 + \Omega^2, \qquad (4.4)$$

where, from section III,

$$\Omega = \frac{m_0 c^2}{\hbar}. \qquad (4.5)$$

Multiplying Eq. (4.4) by $\hbar^2$and defining

$$E = \hbar\omega, p = \hbar k, \qquad (4.6)$$

we obtain the quadratic dispersion relation

$$E^2 = p^2 c^2 + m_0^2 c^4. \qquad (4.7)$$

Equation (4.7) is the invariant quadratic energy–momentum structure familiar from relativistic dynamics [2-4]. In the present framework, it arises from the bounded stiffness-to-inertia ratio $T/\mu = c^2$together with the intrinsic oscillation scale determined by curvature of the vacuum response.

Group Velocity and Energy Transport

The group velocity of a wave packet constructed from solutions of (4.4) is

$$v = \frac{\partial\omega}{\partial k}. \qquad (4.8)$$

From Eq. (4.4),

$$\omega = \sqrt{c^2 k^2 + \Omega^2}, \qquad (4.9)$$

so that

$$v = \frac{c^2 k}{\omega}. \qquad (4.10)$$

Using Eq. (4.6), this becomes

$$v = \frac{pc^2}{E}. \qquad (4.11)$$

Solving for momentum,

$$p = \frac{Ev}{c^2}. \qquad (4.12)$$

Substituting (4.12) into the dispersion relation (4.7) gives

$$E^2 = \frac{E^2 v^2}{c^2} + m_0^2 c^4. \qquad (4.13)$$

Rearranging,

$$E^2 \left(1 - \frac{v^2}{c^2}\right) = m_0^2 c^4, \qquad (4.14)$$

and therefore

$$E = \frac{m_0 c^2}{\sqrt{1 - v^2/c^2}}. \qquad (4.15)$$

Effective Inertial Response

Defining the dynamical inertial parameter through

$$m(v) \equiv \frac{E}{c^2}, \qquad (4.16)$$

Eq. (4.15) yields

$$m(v) = \frac{m_0}{\sqrt{1 - v^2/c^2}}. \qquad (4.17)$$

Equation (4.17) follows directly from the quadratic dispersion structure (4.7). In the bounded-vacuum framework, the velocity dependence of inertial response reflects the increased energy stored in the propagating vacuum disturbance relative to its rest configuration.

Low-Velocity Limit

For $v \ll c$, expanding Eq. (4.15) gives

$$E = m_0 c^2 + \frac{1}{2} m_0 v^2 + \mathcal{O}\left(\frac{v^4}{c^2}\right), \qquad (4.18)$$

recovering the classical kinetic-energy expression at leading order. Thus the rest mass m_0 determined by the intrinsic oscillation scale governs both the invariant dispersion structure and the nonrelativistic inertial response.

In the next section we show that the Schrödinger equation emerges as the systematic low-momentum limit of the Klein–Gordon sector.

V — Low-Momentum Limit and Emergent Schrödinger Dynamics

We now examine the low-momentum regime of the invariant dispersion structure obtained in Sec. IV and show that the Schrödinger equation arises as the systematic nonrelativistic limit of the Klein–Gordon sector.

Starting from the fluctuation equation (4.1),

$$\left(\frac{1}{c^2}\partial_t^2 - \nabla^2 + \frac{m_0^2 c^2}{\hbar^2}\right)\phi = 0, \qquad (5.1)$$

we consider excitations whose spatial momentum satisfies $p \ll m_0 c$. In this regime, the energy is close to its rest value and the dynamics can be separated into a rapidly oscillating rest-energy phase and a slowly varying envelope.

We therefore write [5, 6, 8]

$$\phi(\mathbf{x}, t) = e^{-i m_0 c^2 t/\hbar} \psi(\mathbf{x}, t), \qquad (5.2)$$

where $\psi(\mathbf{x}, t)$ varies slowly on time scales set by $\hbar / m_0 c^2$.

The time derivatives are

$$\partial_t \phi = e^{-i m_0 c^2 t/\hbar}\left(\partial_t \psi - \frac{i m_0 c^2}{\hbar}\psi\right), \qquad (5.3)$$

$$\partial_t^2 \phi = e^{-i m_0 c^2 t/\hbar}\left(\partial_t^2 \psi - \frac{2 i m_0 c^2}{\hbar}\partial_t \psi - \frac{m_0^2 c^4}{\hbar^2}\psi\right). \qquad (5.4)$$

Substituting (5.2)–(5.4) into Eq. (5.1), the rest-energy terms cancel identically, yielding

$$\frac{1}{c^2}\left(\partial_t^2\psi - \frac{2im_0c^2}{\hbar}\partial_t\psi\right) - \nabla^2\psi = 0. \qquad (5.5)$$

In the low-momentum regime, the temporal variation of $\psi$is slow compared with the rest-energy scale, implying

$$|\ \partial_t^2\psi\ | \ll |\ \frac{m_0c^2}{\hbar}\partial_t\psi\ |. \qquad (5.6)$$

Neglecting the second-order time derivative term in (5.5) therefore yields

$$-\frac{2im_0}{\hbar}\partial_t\psi - \nabla^2\psi = 0. \qquad (5.7)$$

Rearranging, we obtain

$$i\hbar\,\partial_t\psi = -\frac{\hbar^2}{2m_0}\nabla^2\psi. \qquad (5.8)$$

Equation (5.8) is precisely the free Schrödinger equation [6, 7].

Expansion of the Dispersion Relation

The same result follows directly from the quadratic dispersion structure (4.7). For $p \ll m_0c$,

$$E = \sqrt{p^2c^2 + m_0^2c^4} = m_0c^2 + \frac{p^2}{2m_0} + O\left(\frac{p^4}{m_0^3c^2}\right). \qquad (5.9)$$

Removing the constant rest-energy contribution m_0c^2 yields the nonrelativistic Hamiltonian

$$H_{\mathrm{NR}} = \frac{p^2}{2m_0}. \qquad (5.10)$$

Thus the inertial parameter m_0 determined by intrinsic vacuum oscillation (Sec. III) governs both the invariant dispersion structure and the nonrelativistic wave dynamics.

Structural Interpretation

Within the bounded-vacuum framework, the Schrödinger equation appears as the low-energy limit of the Klein–Gordon sector associated with localized vacuum-deficit excitations. The mass parameter entering Eq. (5.8) is not introduced independently but is inherited from the intrinsic oscillation scale of the underlying vacuum configuration.

The sequence of dynamical descriptions is therefore

$$\text{Bounded vacuum capacity} \longrightarrow \text{Invariant dispersion} \longrightarrow \text{Low-momentum limit} \longrightarrow \text{Schrödinger dynamics.} \qquad (5.11)$$

Both relativistic and nonrelativistic wave equations thus arise from the same bounded vacuum structure.

VI — Consistency of Static and Dynamical Mass Parameters

We now establish the internal consistency between the static vacuum-loading parameter introduced in Ref. [1] and the dynamical mass parameter m_0 obtained from the dispersion structure in Secs. III–V.

In Ref. [1], the mass parameter m was defined invariantly through the asymptotic flux of the vacuum potential,

$$m = -\frac{1}{4\pi G}\oint_{S_\infty} \nabla\Phi \cdot d\mathbf{S}, \qquad (6.1)$$

which determines the exterior relaxation profile

$$\Phi(r) = c^2 - \frac{Gm}{r}. \qquad (6.2)$$

The parameter m therefore measures the total vacuum loading associated with a localized deficit configuration.

Independently, the dynamical analysis of Sec. III showed that small fluctuations about such a configuration satisfy the Klein–Gordon–type equation (4.1), with intrinsic oscillation frequency

$$\Omega = \frac{m_0 c^2}{\hbar}, \qquad (6.3)$$

and invariant quadratic dispersion relation

$$E^2 = p^2c^2 + m_0^2c^4. \qquad (6.4)$$

The parameter m_0 thus determines the rest energy

$$E_0 = m_0 c^2, \qquad (6.5)$$

and governs both relativistic dispersion (Sec. IV) and nonrelativistic Schrödinger dynamics (Sec. V).

Since both m and m_0 arise from the same localized vacuum-deficit configuration, consistency of the framework requires their equality,

$$m_0 = m. \qquad (6.6)$$

Equation (6.6) identifies the static vacuum-loading parameter with the dynamical mass parameter entering the dispersion structure.

Inertial Response and Energy

With the identification (6.6), the invariant dispersion relation becomes

$$E^2 = p^2c^2 + m^2c^4, \qquad (6.7)$$

which coincides with the standard energy–momentum relation of special relativity [2-4]. The velocity-dependent inertial response derived in Sec. IV,

$$m(v) = \frac{m}{\sqrt{1 - v^2/c^2}}, \qquad (6.8)$$

therefore follows directly from the dispersion structure associated with vacuum fluctuations.

In this framework, the increase of dynamical inertia with velocity reflects the additional energy stored in the propagating vacuum disturbance rather than the transformation of an independently postulated particle mass.

Structural Closure

The results of Ref. [1] and the present work together establish the following sequence:

Bounded vacuum capacity ⟶ Localized deficit ⟶ Static loading parameter m
⟶ Klein–Gordon sector ⟶ Invariant dispersion

The same parameter m governs:

- the asymptotic $1/r$ static profile,
- the collapse scale $r_c \sim Gm/c^2$[1],
- the intrinsic oscillation frequency,
- the invariant quadratic dispersion relation,
- and the nonrelativistic kinetic term.

Thus gravitational mass (defined through static vacuum loading) and inertial mass (defined through dispersion and rest energy) arise from a single localized vacuum configuration. This structural identification parallels the equivalence of inertial and gravitational mass in classical gravitation [3, 4], but here follows from internal consistency of the bounded vacuum response framework.

The bounded vacuum-capacity principle therefore provides a unified dynamical interpretation of mass in which static and wave-dynamical sectors are governed by the same underlying parameter.

VII — Conclusion

We have developed the dynamical sector of the bounded vacuum-capacity framework introduced in Ref. [1]. Linearized fluctuations about a localized vacuum-deficit configuration were shown to satisfy a Klein–Gordon–type equation whose mass parameter is determined by the intrinsic oscillation frequency associated with curvature of the vacuum response. The resulting plane-wave solutions yield an invariant quadratic dispersion relation of the form

$$E^2 = p^2c^2 + m^2c^4,$$

arising directly from the bounded stiffness-to-inertia ratio of the vacuum medium.

From this dispersion structure, the velocity-dependent inertial response follows without additional postulates. In the low-momentum regime, the Schrödinger equation emerges as the systematic nonrelativistic limit of the same wave dynamics. The mass parameter entering both relativistic and nonrelativistic sectors is identified with the asymptotic vacuum-loading parameter defined in Ref. [1], thereby relating gravitational and inertial mass to a single localized vacuum configuration.

The analysis establishes a coherent dynamical extension of the bounded vacuum-capacity principle in which static gravitational loading, invariant dispersion, and quantum wave dynamics arise within a unified structural framework. Further investigation of nonlinear regimes, interactions, and multi-deficit configurations may clarify the broader applicability of this approach.

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