Geometric Emergence and Scalar Breathing Modes in Vacuum Scalar-Field Gravity

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Abstract

We present a gravitational framework rooted in a cosmic vacuum scalar field ϕ, where the energy relation $E = m\phi$ and the field equation $\Box(\phi^2) = 0$ define the dynamics. In static spherically symmetric configurations, the Schwarzschild metric emerges geometrically, recovering the classical tests of general relativity. For rotating sources, the non-commutativity of Lorentz transformations along different directions naturally incorporates angular momentum, yielding the Kerr metric in the weak-field limit and reproducing frame-dragging effects relevant to astrophysical black holes such as Sgr A* and M87*. Linear perturbations $\delta\phi$ propagate as massless waves and source purely transverse breathing modes in gravitational waves without longitudinal components, offering a polarization signature distinct from general relativity and general scalar-tensor theories. In unequal-mass binary systems, these modes may give rise to scalar dipole radiation, providing observational targets for future space-borne detectors (LISA, TianQin, Taiji) and pulsar timing arrays. On cosmological scales, the background field $\phi_0(t)$ evolves consistently with dark energy dynamics, while the coupling of gravity exclusively to spatial gradients of ϕ decouples vacuum energy from gravitational sources, offering a new perspective on the cosmological constant problem. This framework unifies the description of local gravity, rotating compact objects, gravitational-wave polarization, and cosmic expansion, with testable predictions across multiple astrophysical and cosmological windows.

Full Text

Preamble

Geometric Emergence and Scalar Breathing Modes in Vacuum Scalar-Field Gravity

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1 Introduction

1.1 Background and Motivation

Since its inception, General Relativity (GR) has achieved unprecedented experimental success across scales from the solar system to cosmology [?]. However, GR still faces several fundamental theoretical challenges: the physical origin of the equivalence principle lacks a deep mechanistic explanation; there exists a staggering discrepancy, spanning many orders of magnitude, between the vacuum energy density predicted by quantum field theory and the observed cosmological constant [?]; and the unification of gravity with quantum theory remains an unfinished endeavor.

Concurrently, the rapid advancements in cosmology and gravitational-wave astronomy in recent years offer new opportunities to test gravitational theories. Indications that the dark energy equation of state parameter may evolve over time [?], along with the detection of a nanohertz gravitational-wave background by pulsar timing arrays [?, ?], suggest the necessity of exploring gravitational frameworks beyond GR.

This paper systematically investigates, within a class of gravitational theories based on a cosmic vacuum scalar field, the emergence of geometry in static spherically symmetric gravitational fields, the description of rotating sources, the polarization characteristics of scalar gravitational waves, and the implications on cosmological scales. The core assumption of this framework is the existence of a classical scalar field ϕ associated with the cosmic vacuum structure, with particles coupling to ϕ via the energy relation $E = m\phi$, while gravitational and inertial effects both originate from gradients of this scalar field.

1.2 Comparison with Related Theoretical Work

To highlight the distinctive features of the present model, we compare it with several important gravitational theories across four dimensions:

1. **Theoretical Construction Logic: Geometry First vs. Field-Theoretic Emergence.** GR adopts a geometry-first approach where matter curves the metric. Our model adopts a field-theoretic emergence logic. It posits a fundamental vacuum scalar field ϕ, with particles coupled to it via the action $S = -m\int \phi d\tau$. We demonstrate that this coupling is dynamically equivalent to particles moving along geodesics in an emergent metric $g_{\mu\nu}[\phi]$.
2. **Source of Degrees of Freedom.** GR' s degrees of freedom are the two tensor polarization modes. Scalar-tensor theories [?] introduce an additional scalar degree of freedom, typically leading to both longitudinal and breathing modes. In vacuum, the present model possesses a single real scalar field ϕ as its degree of freedom, which generates only purely transverse breathing modes.
3. **Coupling to Matter.** In our model, matter particles couple directly to the ϕ field through $S = -m\int \phi d\tau$. This links a particle' s energy scale E to the local value of ϕ, ensuring the automatic equality of inertial and gravitational masses.
4. **Handling the Cosmological Constant.** Our model offers a distinct approach: gravity arises solely from spatial gradients $\nabla\phi$, while a homogeneous background value $\phi_0(t)$ generates no gravitational acceleration. This achieves a partial decoupling of gravity from vacuum energy.

1.3 Main Contributions and Structure of This Paper

Building upon previous work, this paper further develops the vacuum scalar field theory of gravity. The main contributions include: 1. Establishing an action principle for the scalar field and deriving the vacuum dynamical equation

$\Box(\phi^2) = 0$. 2. Rigorously deriving the Schwarzschild metric for static spherically symmetric fields. 3. Analyzing rotating sources and the recovery of the weak-field Kerr metric. 4. Investigating the polarization of scalar gravitational waves, showing they exhibit only a purely transverse breathing mode.

2 Vacuum Scalar Field Framework and the Equivalence Principle

The core assumption is the existence of a classical scalar field ϕ associated with the cosmic vacuum. On cosmological scales, it defines a preferred global reference frame S_0 where its background value is $\phi_0 = c^2$.

2.1 Field-Theoretic Derivation and a Mechanistic Interpretation of Inertial Forces

Consider a test particle with rest mass m, whose motion is described by the action:

$$S = -m \int \phi d\tau$$

where $d\tau = \sqrt{\eta_{\mu\nu} dx^\mu dx^\nu}$ is the proper time in the background Minkowski spacetime. Varying $\delta S = 0$ yields the covariant equation of motion:

$$m\phi \frac{du_\mu}{d\tau} + m\frac{d\phi}{d\tau} u_\mu = m\partial_\mu \phi$$

In the Newtonian limit (weak-field, low-velocity), the spatial component simplifies to:

$$\mathbf{a} = -\frac{1}{c^2} \nabla \phi$$

This establishes the physical basis for gravity: the spatial gradient of ϕ directly gives the gravitational acceleration. Inertial forces arise from the effective field gradient induced by the particle' s own acceleration, providing a mechanistic explanation for the equivalence principle.

3 Schwarzschild Metric from Vacuum Scalar Field Dynamics

3.1 Action for the Scalar Field

Based on the geometric emergence principle and effective field theory, we treat $\psi \equiv \phi^2$ as the fundamental field. The simplest action in source-free regions is:

$$S_\phi = \int d^4x \mathcal{L}_\phi = \int d^4x \left[-\frac{1}{2} \partial_\mu(\phi^2) \partial^\mu(\phi^2) \right]$$

Varying this action yields the fundamental dynamical equation:

$$\Box(\phi^2) = 0$$

3.2 Static Spherically Symmetric Solution

For a static spherically symmetric body of mass M, the vacuum solution to $\nabla^2(\phi^2) = 0$ with the boundary condition $\lim_{r\to\infty} \phi(r) = c^2$ is:

$$\phi(r) = c^2\sqrt{1 - \frac{2GM}{c^2 r}}$$

3.3 Derivation of the Metric Components

From energy conservation $mc^2 = m\gamma(r)\phi(r)$ and the geometric emergence principle, we derive the time and spatial components of the metric:

$$g_{00}(r) = \left(\frac{\phi(r)}{c^2}\right)^2 = 1 - \frac{2GM}{c^2 r}$$

$$g_{rr}(r) = -\left(1 - \frac{2GM}{c^2 r}\right)^{-1}$$

This results in the complete Schwarzschild metric:

$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right)c^2 dt^2 - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 - r^2 d\Omega^2$$

3.6 Rotating Sources and the Kerr Metric

When the mass source carries angular momentum, rotation leads to the non-commutativity of Lorentz transformations. The vacuum field is extended to a matrix-valued scalar field $\Phi = \phi \cdot U$, where $U \in \mathrm{Spin}(1,3)$. In the weak-field linear approximation, the linearized Einstein equations derived from the Einstein-Hilbert action yield the metric cross-term consistent with the Kerr metric:

$$g_{0\phi} = -\frac{2GJ\sin^2\theta}{c^3 r}$$

4 Testable Predictions and Observational Prospects

4.1 Breathing Modes in Scalar Gravitational Waves

Linearizing $\phi = c^2 + \delta\phi$ leads to the wave equation $\Box\delta\phi = 0$. The resulting metric perturbation $h_{\mu\nu}$ exhibits a purely transverse breathing mode. For a wave propagating in the z-direction, the polarization tensor is:

$$e_{\mu\nu} = \mathrm{diag}(1, 1, 0)$$

This signature is distinct from GR (tensor modes only) and general scalar-tensor theories (which often include longitudinal modes).

4.4 Vacuum Energy Decoupling and Dark Energy

Gravity arises solely from spatial gradients $\nabla\phi$. A spatially uniform cosmological background $\phi_0(t)$ does not contribute to gravitational acceleration, potentially decoupling the large vacuum energy density predicted by QFT from observable gravity. The evolution of $\phi_0(t)$ via $\Box(\phi^2) = 0$ may yield a time-dependent effective dark energy equation of state, consistent with recent DESI observations [**?**].

5 Conclusion

This framework unifies local gravity, rotating compact objects, and cosmic expansion through a vacuum scalar field ϕ. By deriving the Schwarzschild and Kerr metrics from first principles, it maintains consistency with classical tests while offering new predictions for gravitational wave polarization and the cosmological constant problem.

Appendix A: Lorentz Transformations in Static Spherically Symmetric Fields

The Lorentz factor $\gamma(r) = c^2/\phi(r)$ ensures consistency between time dilation and energy conservation. Expanding $\gamma(r)$ for $r \gg 2GM/c^2$ recovers the post-Newtonian corrections of GR:

$$\gamma(r) = 1 + \frac{GM}{c^2 r} + \frac{3}{2}\left(\frac{GM}{c^2 r}\right)^2 + \ldots$$

Appendix B: Electromagnetic Interactions and the Standard Model

By extending ϕ to a complex field $\Phi = \phi e^{i\theta}$, electromagnetic interactions emerge from the non-integrability of the phase θ. This framework can be further extended to $SU(2)$ and $SU(3)$ to incorporate weak and strong interactions, where mass scales are proportional to the vacuum expectation value $\langle\phi\rangle = c^2$.

Note: Figure translations are in progress. See original paper for figures.