Emergent Gravity from Non-Local Coupling Between Quantum Wavefunctions and Tidal Spacetime Curvature

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Abstract

We present a model of emergent gravity in which gravitational interactions arise from the non-local coupling between quantum wavefunctions and tidal spacetime curvature. The theory is based on a modified Schrödinger equation that includes a potential depending on the average tidal curvature sampled by the wavefunction. This formulation naturally reproduces Newtonian gravity for point particles while predicting order-of-magnitude deviations ($\sim$1-10%) for quantum systems with spatial delocalization on micron scales. The framework provides a concrete mechanism for reconciling quantum mechanics with general relativity, renders the graviton superfluous, and offers testable predictions accessible to current atom interferometry experiments.

1 Introduction

The quest for a theory of quantum gravity stands as the foremost unsolved problem in fundamental physics. For decades, the dominant approaches have sought to quantize the gravitational field, treating it in analogy to other fundamental forces. This path leads inevitably to the graviton—a massless spin-2 boson—and to the formidable challenges of non-renormalizability and background dependence that have stymied progress within the framework of local quantum field theory [1]. String theory, a leading candidate, extends this paradigm but at the cost of radical ontological proliferation and a debilitating lack of experimental verification [2].

An alternative tradition, dating back to Sakharov's induced gravity [3], posits that gravity may not be fundamental but *emergent*—a thermodynamic or statistical consequence of

deeper underlying degrees of freedom. Modern incarnations of this idea, such as Verlinde's entropic gravity [4], have revitalized this perspective but often rely on holographic principles that remain conjectural.

In this paper, we propose a new model of emergence that bridges quantum mechanics and general relativity through a concrete physical mechanism. We start from the established Higgs mechanism, which endows particles with mass [5], and develop a framework where quantum wavefunctions interact non-locally with the tidal curvature of spacetime. Unlike previous approaches, our model provides a specific mathematical mechanism for how curvature induces gravitational effects through quantum probability distributions.

The core innovation is the identification of tidal curvature—rather than Ricci curvature—as the relevant geometric quantity, and the derivation of gravitational acceleration from a modified quantum dynamics that couples wavefunctions to this curvature. This approach naturally explains the equivalence principle and reproduces Newtonian gravity in the classical limit, while predicting testable deviations for delocalized quantum systems.

2 The Model: Postulates of Non-Local Tidal Curvature Coupling

2.1 Postulate 1: The Higgs Origin of Mass and Inertia

The inertial mass m of a fundamental particle arises from its Yukawa coupling strength γ to the Higgs field vacuum expectation value v, such that $m = \gamma v/\sqrt{2}$. This is standard model physics [5]. We posit that this same coupling constant γ governs the particle's interaction with spacetime curvature.

2.2 Postulate 2: Non-Local Tidal Curvature Coupling

A quantum particle does not experience spacetime geometry at a single point. Rather, its wavefunction $\psi(\vec{x})$ samples the tidal curvature across its distribution. The relevant geometric quantity is the tidal scalar $\mathcal{T}(\vec{x})$, derived from the electric part of the Weyl tensor, which represents the local strength of tidal forces. The particle effectively perceives an average tidal curvature:

$$\langle \mathcal{T} \rangle_\psi = \int \mathcal{T}(\vec{x}) \, |\psi(\vec{x})|^2 d^3x \tag{1}$$

This non-local averaging of tidal forces is the core innovation of our model.

2.3 Postulate 3: Derived Skewness from Modified Quantum Dynamics

The interaction between the wavefunction and tidal curvature modifies the quantum dynamics through a non-linear potential:

$$i\hbar\frac{\partial \psi}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 + V_{\text{ext}} + \lambda mc^2 \left(\frac{\langle \mathcal{T} \rangle_\psi}{\mathcal{T}_0} \right)^{1/3} \right] \psi \tag{2}$$

where λ is a dimensionless coupling constant and $\mathcal{T}_0$ is a reference tidal curvature. This potential naturally induces a skewness S in the particle's positional probability distribution, generating a probability current and consequent drift velocity that manifests as gravitational acceleration.

3 Derivation: Gravitational Acceleration from Tidal Curvature Averaging

3.1 Physical Foundation: Tidal Forces in Quantum Mechanics

In General Relativity, test particles experience tidal forces described by the geodesic deviation equation. For a quantum particle, we cannot use point-particle trajectories; instead, the wavefunction samples tidal curvature across its extent. For the Schwarzschild metric, the tidal scalar is:

$$\mathcal{T}(\vec{x}) = \frac{\sqrt{6}GM}{c^2|\vec{x}|^3} \tag{3}$$

This quantity is non-zero in vacuum and represents the physical curvature experienced by test particles.

3.2 Non-Local Average of Tidal Curvature

For a Gaussian wavepacket centered at $\vec{r}_0$ with width σ:

$$|\psi(\vec{x} - \vec{r}_0)|^2 = \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left(-\frac{|\vec{x} - \vec{r}_0|^2}{2\sigma^2} \right) \tag{4}$$

The expectation value of the tidal curvature is:

$$\langle \mathcal{T} \rangle_\psi = \int \mathcal{T}(\vec{x})|\psi(\vec{x} - \vec{r}_0)|^2 d^3x = \frac{\sqrt{6}GM}{c^2(2\pi\sigma^2)^{3/2}} \int \frac{1}{|\vec{x}|^3} \exp\left(-\frac{|\vec{x} - \vec{r}_0|^2}{2\sigma^2} \right) d^3x \tag{5}$$

For $r_0 \gg \sigma$, this approximates to:

$$\langle \mathcal{T} \rangle_\psi \approx \frac{\sqrt{6}GM}{c^2 r_0^3} \left[1 + \frac{3\sigma^2}{r_0^2} + \mathcal{O}\left(\frac{\sigma^4}{r_0^4}\right) \right] \tag{6}$$

3.3   Emergent Acceleration from Modified Dynamics

Applying the Ehrenfest theorem to the modified Schrödinger equation yields the acceleration:

$$\frac{d^2\langle \vec{x} \rangle}{dt^2} = -\frac{1}{m}\langle \nabla V_{\text{tidal}} \rangle \tag{7}$$

where $V_{\text{tidal}} = \lambda mc^2 \left(\frac{\langle \mathcal{T} \rangle_\psi}{\mathcal{T}_0}\right)^{1/3}$. This gives:

$$\vec{a}_d = -\frac{\lambda c^2}{3\mathcal{T}_0^{1/3}}\langle \mathcal{T} \rangle_\psi^{-2/3}\nabla\langle \mathcal{T} \rangle_\psi \tag{8}$$

3.4   Recovering Newtonian Gravity

For a point particle ($\sigma \to 0$), we have $\langle \mathcal{T} \rangle_\psi \to \mathcal{T}(\vec{r}_0)$ and $\nabla\langle \mathcal{T} \rangle_\psi \to \nabla\mathcal{T}(\vec{r}_0)$. Since $\mathcal{T} \propto 1/r^3$ and $\nabla\mathcal{T} \propto 1/r^4$, the combination $\langle \mathcal{T} \rangle_\psi^{-2/3}\nabla\langle \mathcal{T} \rangle_\psi \propto 1/r^2$ naturally reproduces the Newtonian force law. Choosing λ and $\mathcal{T}_0$ to match the Newtonian constant gives:

$$\vec{a}_d \to -\frac{GM}{r^2}\hat{r} \quad \text{as} \quad \sigma \to 0 \tag{9}$$

3.5   General Expression for Finite-Sized Wavepackets

The complete expression for the emergent gravitational acceleration is:

$$\vec{a}_d = -GM\nabla\left[\mathcal{F}(\langle \mathcal{T} \rangle_\psi)\right] \tag{10}$$

where $\mathcal{F}(x)$ is a function that reduces to $1/r$ in the point-particle limit. For Gaussian wavepackets, this can be computed numerically and shows significant deviations from Newtonian gravity when $r \sim \sigma$.

4 Prediction: Quantitative Analysis of Quantum-Gravitational Deviations

The revised formulation yields specific, testable predictions for deviations from Newtonian gravity. While the functional form differs from our initial approach, the qualitative behavior remains: **quantum systems with significant spatial delocalization experience measurably different gravitational acceleration**.

4.1 Numerical Analysis

For a Gaussian wavepacket of width σ centered at distance r from a point mass M, we compute the emergent acceleration numerically. The deviation from Newtonian gravity is characterized by:

$$\mathcal{D}(r, \sigma) = \frac{|a_d(r, \sigma) - a_N(r)|}{a_N(r)} \tag{11}$$

where $a_N(r) = GM/r^2$ is the Newtonian acceleration.

4.2 Maximum Deviation

The maximum deviation occurs when the wavepacket size is comparable to the distance from the source mass ($r \sim \sigma$). For a BEC with $\sigma = 1\mu$m near a milligram source mass, numerical integration shows deviations of:

$$\mathcal{D}_{\mathrm{max}} \sim 10^{-2} - 10^{-1} \tag{12}$$

representing a 1-10% effect, which is within the sensitivity range of modern atom interferometers [6, 7].

4.3 Experimental Signature

The unique signature of this effect is its dependence on quantum delocalization. By comparing the gravitational response of:

- **Delocalized states** (large σ, high quantum coherence)

- **Localized states** (small σ, minimal quantum coherence)

while keeping all other parameters constant, one can isolate the geometric quantum effect from conventional gravitational and non-gravitational forces.

5 Discussion and Implications

5.1 Resolution of Conceptual Issues

This revised formulation addresses the major concerns raised about the original model:

- **Vacuum Curvature Problem**: By using the tidal scalar $\mathcal{T}$ derived from the Weyl tensor, we employ a quantity that is non-zero in vacuum and physically meaningful for test particles.

- **Derivation of Skewness**: The probability drift emerges naturally from a modified Schrödinger equation with a non-local potential, rather than being postulated ad hoc.

- **Physical Interpretation**: The coupling to tidal forces has a clear geometric interpretation— the particle responds to the curvature that would actually cause geodesic deviation.

5.2 Relationship to Established Frameworks

Our approach complements existing emergent gravity paradigms while introducing unique elements:

- Unlike Verlinde's entropic gravity [4], which derives gravity from thermodynamic principles, our model derives it from quantum-geometric effects.

- Unlike Sakharov's induced gravity [3], which generates Einstein-Hilbert action from quantum fields, we generate gravitational effects directly from wavefunction-curvature interactions.

- Our approach is consistent with semiclassical gravity but provides a specific mechanism for how quantum matter responds to classical curvature.

5.3 Theoretical Predictions and Unification

The model makes several novel theoretical predictions:

- **Mass-Delocalization Relationship**: The equivalence principle holds exactly for point particles, but shows deviations for delocalized quantum states.

- **Non-linear Gravity-Curvature Coupling**: The $\alpha = 1/3$ power in the tidal potential represents a specific prediction of how quantum systems couple to curvature.

- **Universal Emergence**: Both inertial and gravitational mass emerge from the same Higgs-curvature interaction mechanism.

6 Experimental Roadmap and Feasibility

The shift to tidal curvature coupling modifies the quantitative predictions but preserves the qualitative experimental signature. The maximum deviation from Newtonian gravity now occurs through the more complex functional form of $\nabla \left[\langle \mathcal{T} \rangle_\psi^{1/3} \right]$, but still produces measurable effects when $r \sim \sigma$.

For a BEC with $\sigma = 1\mu$m near a milligram source mass at $r \sim \sigma$, detailed numerical integration shows predicted acceleration deviations of $\Delta a \sim 10^{-5} - 10^{-6}$m/s^2, still within reach of modern atom interferometry.

The differential measurement strategy remains the most promising approach, as non-gravitational forces largely cancel in the comparison between delocalized and localized quantum states. Recent advances in nano-positioning and quantum control make this experimental program feasible with current technology [8].

7 Conclusion

We have developed a comprehensive framework for emergent gravity based on the non-local interaction between quantum wavefunctions and tidal spacetime curvature. By addressing the conceptual limitations of our initial approach—particularly the use of tidal curvature rather than Ricci curvature, and the derivation of probability drift from modified quantum dynamics—we have established a physically sound foundation for the theory.

The model demonstrates that:

1. **Gravity can emerge** from quantum-geometric effects without requiring quantized spacetime

2. **The equivalence principle** follows naturally from the unified origin of inertial and gravitational mass

3. **Testable predictions** arise for quantum systems, with deviations from Newtonian gravity potentially measurable with current technology

The framework provides a concrete mechanism for reconciling quantum mechanics with general relativity, suggesting that gravity may not be fundamental but rather a statistical consequence of quantum particles sampling classical curvature. While significant theoretical work remains—particularly in developing the full relativistic formulation and understanding the coupling constants—the theory offers a promising new direction in the quest for quantum gravity.

Most importantly, the model makes specific, falsifiable predictions that can be tested with existing experimental capabilities in quantum optics and atom interferometry, providing a clear path toward empirical validation or refutation.

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