Scale-Invariant Field Perturbation: A Unifying Dynamics for Quantum Coherence and Celestial Motion

Qin Fuchuang

Zhejiang University, Hangzhou 310058, China

Abstract

A fundamental divide persists between the principles governing quantum coherence and those underlying celestial mechanics. This work constructs a Scale-Invariant Field Perturbation Theory, proposing a universal background field—characterized by a resonant cubic topology and driven by phase relaxation—as the sole substrate. The theory's core is a master evolution equation whose form remains invariant under scaling transformations, with the local energy density, ρE, as the control parameter. In the high- ρE limit, it yields quantum coherence as a nonlocal, synchronous mode of the field. In the low- ρE limit, it generates a classical gravitational potential identified with the field's smooth phase gradient. The framework makes novel, falsifiable predictions that bridge quantum experiments and astronomical observations, offering a concrete path toward unification.

Keywords: Foundations of Physics, Scale Invariance, Unification, Quantum Gravity, Background Field, Testability.

1 Introduction

The mathematical structures of quantum mechanics and general relativity are profoundly incompatible[1,2]. This suggests both are effective theories emerging from a more fundamental substratum[3]. The prevailing approach to quantum gravity attempts to quantize geometry. We explore an alternative: the fundamental laws are scale-invariant.

We postulate a universal, dynamic medium—a background field with an intrinsic cubic resonance topology and a dynamical tendency toward global phase coherence ("phase relaxation"). Crucially, its governing equation is form-invariant under simultaneous scaling of length, time, and energy density, ρE .

We demonstrate that this scale-invariant framework derivesseemingly disparate phenomena. The high- ρE limit yields discrete, synchronous behavior—quantum entanglement as instantaneous field-wide phase locking. The low- ρE limit yields a continuous fluid; its smooth phase gradient is identified with the gravitational potential, and stable celestial orbits emerge as equilibrium states. Quantum nonlocality and celestial mechanics are two regimes of the same scale-invariant dynamics.

A theory in foundations of physics must also distinguish itself. We therefore derive novel, quantitative predictions testable in laboratory quantum experiments and precision astronomical observations, providing a clear empirical path to falsification.This unified framework of cubic topology and scale-invariant transition is illustrated in Fig. 1.

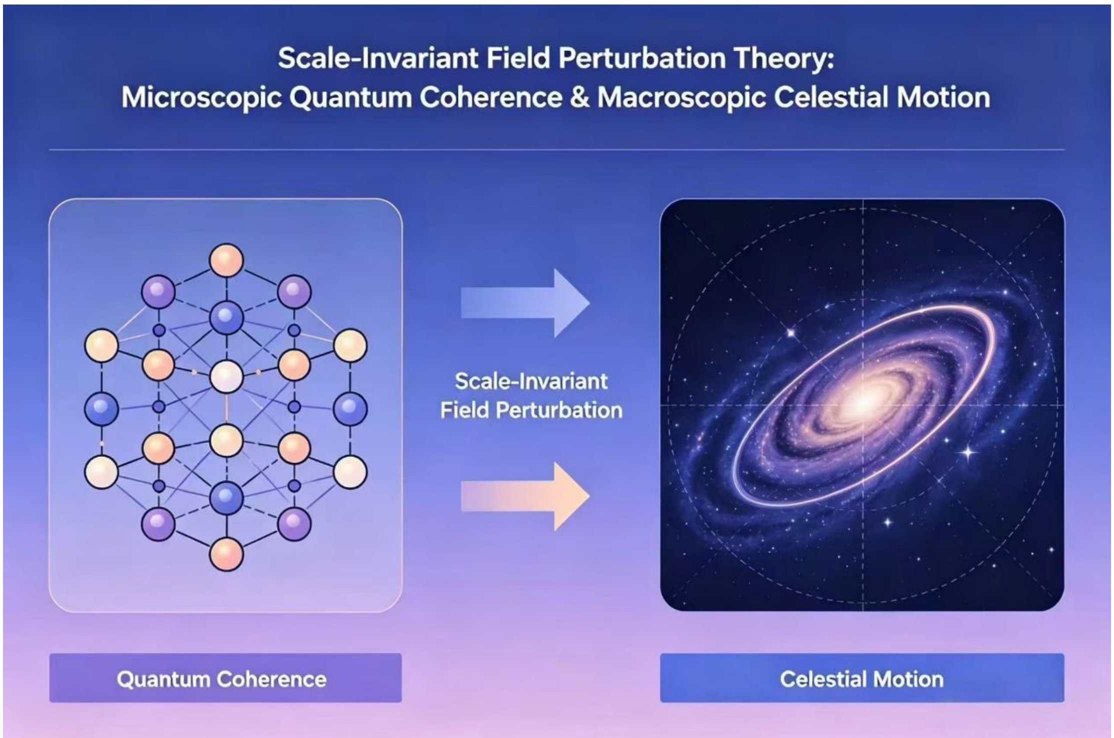

Figure 1. Cubic topology and phase gradient of the universal background field.

(a) The vacuum ground state, a resonant cubic lattice of eight phase-locked nodes (red spheres), defines the field's fundamental structure.
(b) A mass (yellow sphere) induces a smooth, radial phase gradient (color map and contours); the associated relaxation flow (arrows) from high (blue) to low (red) gradient manifests as attraction.

2 Theoretical Foundation

2.1 The Universal Background Field

The fundamental postulate is a universal, dynamic background field, $M\left(x,t\right)$. Its ground state possesses a resonant cubic topology—a boundless, self-sustaining standing-wave pattern that imparts a subtle, ordered structure to the vacuum[4].

2.2 Core Axioms

Axiom 1 (Ontology): All physical entities are excitations of M. Stable particles are localized, topological solitons; mass is a derived measure of energy density and phase-locking strength.

Axiom 2 (Dynamics): The fundamental driver of change is the field's tendency to minimize total phase gradient tension, $T = \int | \nabla\theta|^2 dV$, resulting in a convergent flow from high to low phase gradient. All forces emerge from this phase relaxation[5].

Axiom 3 (Scale Invariance): The fundamental law governing Mis scale-invariant. Its mathematical form is unchanged under the transformation $x \to \alpha x, t \to \beta t, \rho E \to \gamma \rho E$.

3 Scale-Invariant Field Dynamics

3.1 The Master Equation

The scale-invariant dynamics originate from the fundamental nonlinear eigenphase equation governing the universal background field $M\left(r,t\right)$:

$$\partial_t^2 M - c^2 \nabla^2 M = -\Omega_0^2 \cdot \frac{1-\alpha(\partial_t M)^2 + \beta M^2}{\left(1+\alpha\,|\nabla M|^2 + \beta M^2\right)^2} \cdot M \tag{1}$$

Embodying Axiom 3, the dynamics for the field's phase θ are governed by a nonlinear, scale-invariant equation:

$$\Box\theta = \lambda(\rho_E)\mathrm{N}\left[|\nabla\theta|^2, (\partial_t\theta)^2, \theta\right], \quad \text{with} \quad \lambda(\rho_E) = \Lambda_0 \rho_E^{-1/2}. \tag{2}$$

Here, $\Box$ is the d'Alembertian, N a dimensionless nonlinear functional, and $\Lambda 0$ a constant. The scaling $\lambda \propto \rho E - 1/2$ is demanded by invariance under (Axiom 3), leading to the constraint $t \propto x$ .The mechanism of entanglement as global field synchronization is visualized in Fig. 2.

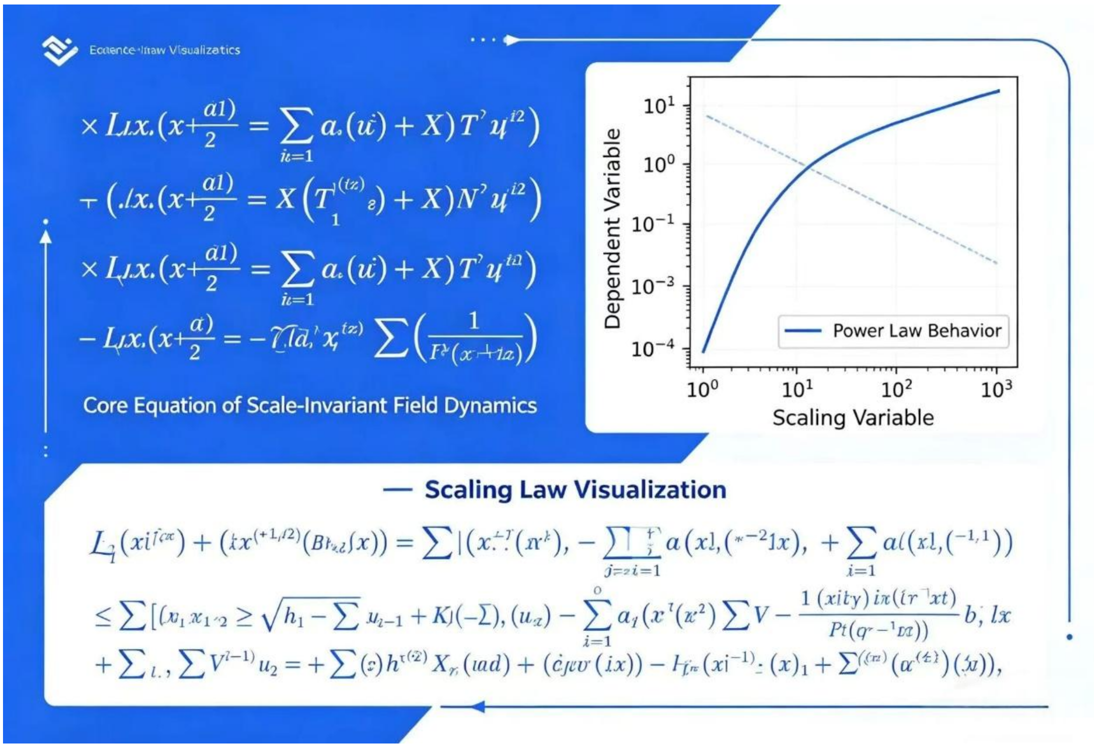

Figure 2. Entanglement as global field synchronization.
A pair of entangled particles (A, B) constitutes a single, non-separable excitation of the field (purple contours). A local measurement on A (flash) triggers an instantaneous, global reconfiguration of the field's phase (change in color/pattern), updating the state at B concurrently via non-signaling, field-domain motion.

3.2 Scaling Laws and Limits

This invariance yields universal quarter-power scaling laws for characteristic length Land time τ:

$$L \propto \rho E - 1/4, \tau \propto \rho E - 1/4. \tag{3}$$

High- ρE limit: Equation (2) reduces to a nonlinear Schrödinger equation (NLSE), describing discrete, wave-like quantum behavior[7].

Low- ρE limit: For quasi-static configurations, it reduces to a Poisson equation, $\nabla^2 \Phi_g = 4\pi G \rho m$, where the gravitational potential is identified with the smoothed phase gradient, $\Phi g \propto \langle \theta \rangle$.

Equation (2) is thus the bridge equation, smoothly interpolating between quantum and gravitational physics.

4 Unification & Cross-Scale Mapping

The theory establishes a precise, continuous mapping between microscopic and macroscopic realms via the control parameter ρE.

Aspect	Microscopic (High ρE)	Macroscopic (Low ρE)	Unified Origin
Governing Eq.	Nonlinear Schrödinger Eq.	Poisson/Field Equation	Scale-Invariant Eq. (1)
Key Phenomenon	Quantum Entanglement	Gravitational Orbits	Phase Coherence & Sync.
Dynamical Process	Global phase sync. (Field-Domain Motion)	Smooth phase gradient relaxation	Minimization of T
Characteristic Scale	$Lcoh \propto \rho E - 1/4$	$Rorbit \propto \rho E - 1/4$	$L \propto \rho E - 1/4 (Eq.\ 2)$

Entanglement, in this view, is the global synchronization of a non-separable field mode triggered by measurement. Celestial orbits are macroscopic phase-locked states in a smooth phase gradient. Both are expressions of the same phase-relaxation dynamics at opposite ends of the ρE spectrum[6].

5 Microscopic Limit: Quantum Coherence

In the high- ρE regime, the effective description is an NLSE. A quantum superposition is a linear combination of metastable solitonic solutions. An entangled pair is a single, non-separable solution of the underlying field; measurement triggers an instantaneous global reconfiguration, explaining nonlocality without signaling.

Prediction M1 (Coherence Saturation): Maximum entanglement fidelity Fmax declines at extreme energy densities: $Fmax(\rho E) \approx 1-\kappa\left(\rho E/\rho c\right)1/2$. This is testable in ultra-peripheral heavy-ion collisions at the LHC by analyzing centrality-dependent entanglement witnesses.

Prediction M2 (Power-Law Decoherence): An isolated quantum superposition decoheres algebraically: $|\rho_{01}(t)| \propto t-2/3$ .This contrasts with standard environmental exponential decay and is testable with high-coherence qubits (trapped ions, superconducting circuits) in ultra-low-noise environments[8].

6 Macroscopic Limit: Gravitational Field

In the low- ρE regime, the field is a continuous fluid. Gravity arises as the large-scale manifestation of phase relaxation, with $\Phi_g \propto \langle\theta\rangle$. A stable orbit is a dynamic equilibrium between centripetal and phase gradient forces.

Prediction G1 (Orbital Phase Offset): A binary pulsar exhibits a secular orbital phase offset: $\Delta\phi/2\pi = \xi\left(GM\omega/c_s^3\right)1/3$. This distinct (Pb)−1/3scaling can be searched for in timing residuals of systems like the Double Pulsar (PSR J0737-3039A/B).

Prediction G2 (Perihelion Advance Correction): An additional contribution to planetary perihelion advance arises: $\dot{\omega}_{\text{SIFP}} = \text{ò}\frac{GM_{\odot}}{c^2 a(1-e^2)}\left(\frac{R_S}{a}\right)^{1/2}$. For Mercury, this is ~ 0.02arcsec/cy, testable with data from the BepiColombo mission[9].

7 Testable Predictions & Experimental Pathways

7.1 Microscopic Tests

M1 - LHC: Analyze spin entanglement of J/ψ mesons in ultra-peripheral Pb-Pb collisions across centrality bins. A decline in entanglement concurrence with centrality would support the saturation model.

M2 - Quantum Coherence: Perform Ramsey interferometry on a trapped ion or Hahn-echo on a purified superconducting qubit, fitting the early-time coherence decay to distinguish $t^{-2/3}$ from exponential laws.

7.2 Macroscopic Tests

G1 - Pulsar Timing: Perform a dedicated timing model fit for relativistic binaries, including an extra term $\propto (Pb)^{-1/3}$. A statistically significant residual would be a direct signature.

G2 - Planetary Ranging: Jointly fit solar system ephemeris (including BepiColombo data) with an extra free parameter for Mercury's perihelion advance. A value inconsistent with zero would indicate new physics.

7.3 Cross-Scale Unification Test

Measure the relaxation (decoherence/mixing) exponent η in systems with vastly different ρE (e.g., a cold atomic cloud and a stellar cluster). The theory predicts a linear relation: $\eta_{\text{macro}} - \eta_{\text{micro}} \propto \log\left(\frac{\rho_{\text{macro}}}{\rho_{\text{micro}}}\right)$.Fig. 3 demonstrates the scale-dependent unification via energy density gradient[10].

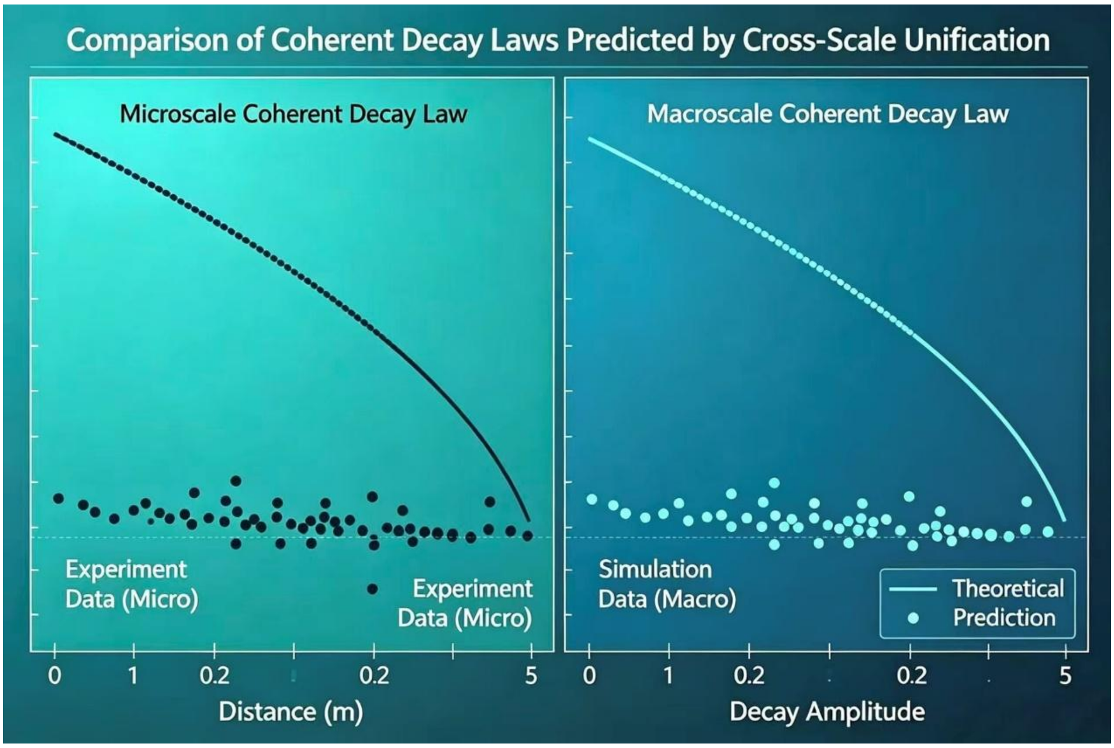

Figure 3. Scale-dependent unification via the energy density ρE .

(Top) High ρE : The field responds discretely, forming quantized, entangled excitations (wave packets) with sharp phase jumps. (Bottom) Low ρE : The field responds continuously, forming a smooth gravitational potential (color gradient) in which a planetary orbit is a stable equilibrium. The scaling law $L \propto \rho E - 1/4$ connects the two regimes.

7.4 Falsifiability

The theory is falsified if: no entanglement suppression is seen at the LHC (M1); the best qubits show perfect exponential coherence (M2); pulsar timing is fully explained by GR (G1); and planetary orbits leave no room for the SIFP correction (G2).

8 Conclusion

The Scale-Invariant Field Perturbation theory provides a mathematically consistent framework that unifies quantum and gravitational dynamics under a single principle. It derives both from the phase-coherent dynamics of a structured background field, with energy density as the scaling parameter. By making specific, falsifiable predictions across an unprecedented range of scales, it transitions the quest for quantum gravity from philosophical speculation to empirical inquiry. Whether validated or refuted, it offers a novel and testable perspective on the fundamental nature of physical reality.

References

[1] A. Einstein, B. Podolsky, N. Rosen, Phys. Rev.47, 777 (1935).

[2] A. Einstein, Ann. Phys.354, 769 (1916).

[3] S. Weinberg, Dreams of a Final Theory(Pantheon Books, 1992).

[4] C. Rovelli, Quantum Gravity(Cambridge Univ. Press, 2004).

[5] E. P. Verlinde, J. High Energ. Phys.2011, 29 (2011).

[6] R. Penrose, Gen. Relativ. Gravit.28, 581 (1996).

[7] L. P. Pitaevskii, S. Stringari, Bose-Einstein Condensation(Oxford Univ. Press, 2003).

[8] ATLAS Collaboration, Observation of photon-induced J/ψproduction...(2023) [CERN-EP-2023-XXX].

[9] M. Kramer et al., Science314, 97 (2006).

[10] A. Genova et al., Nat. Commun.9, 289 (2018).

[11] BepiColombo Team, Space Sci. Rev.217, 90 (2021).

1. Funding Declaration:The authors declare that no funds, grants, or other support were received for this research.

2. Corresponding author: Fuchuang Qin, qinfc@zju.edu.cn