Phase Interference as the Fundamental Substrate of Spacetime and Quantum Nonlocality

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Abstract

The tension between quantum nonlocality and relativistic causality remains a central paradox in physics. This work proposes a unified resolution by identifying phase interference in a universal scalar field as the common origin of both spacetime geometry and propagation speed. We introduce a master field equation where interference intensity, I, governs dynamics. A key result is the derived scaling law $v \propto c\left(\frac{I_c}{I}\right)^{\gamma}$, where the speed of light *c* corresponds to a critical interference threshold I_c. This law creates a continuous spectrum: a subluminal matter regime $\left(I > I_c\right)$, a luminal radiation regime $\left(I = I_c\right)$, and a superluminal correlation regime $\left(I < I_c\right)$ that explains quantum entanglement as low-interference phase synchronization. The theory provides intrinsic explanations for the constancy of *c*, reduced light speed in media, and high-energy particle behavior. It makes three falsifiable predictions: measurable superluminal group velocities in ultra-clean environments, energy-dependent arrival time anomalies for ultra-high-energy cosmic photons, and a specific power-law scaling of quantum decoherence with environmental interference. This minimalist framework eliminates the quantum-classical discontinuity.

Keywords: Phase interference, Spacetime emergence, Speed of light, Quantum entanglement, Superluminality, Field theory

1 Introduction

The profound contradiction between the nonlocal correlations of quantum entanglement[1,2] and the light-speed causality of relativity[3] defines a central challenge in foundational physics. While both theories are empirically validated, their conceptual bases—instantaneous correlation versus finite signal speed—appear mutually exclusive. Attempts at reconciliation, from quantum gravity to alternative interpretations, often treat spacetime as a fixed background or quantize it, leaving the nature of the speed of light and its relation to nonlocality unexplained[4,5].

We propose a paradigm shift: both spacetime and velocity are emergent from a more primitive field-theoretic substrate where phase interference is the fundamental currency. The core idea is that a universal scalar phase field $\Phi(x,t)$ underlies physical reality. Its local dynamics are governed by interference intensity *I*. We posit that signal or correlation speed is not absolute but scales inversely with *I*, making the speed of light ca critical value marking a phase transition in the field's response.

This approach is minimalist. Starting from a nonlinear wave equation for Φ, we derive a continuous velocity spectrum $v(I)$. The high-interference regime $(I > I_c)$ yields subluminal motion and massive particles, effectively generating classical spacetime. The critical point $(I = I_c)$ defines luminal propagation. The low-interference regime $(I < I_c)$ enables superluminal phase synchronization, directly accounting for quantum nonlocality without signal transfer.

The theory's value lies in its unification and predictive power. It intrinsically explains the constancy of c, the mechanism of entanglement, and optical refraction. Crucially, it yields novel, falsifiable predictions for superluminal effects in clean systems, high-energy astrophysics, and quantum decoherence. This work aims not to modify relativity or quantum mechanics, but to provide a deeper, common foundation from which both naturally emerge.

2 Theoretical Foundation: Axioms and the Master Field Equation

Our theory is constructed from a minimal set of physical principles, subsequently encoded in a dynamical field equation. This approach mirrors the axiomatic structure of relativity or quantum theory, but shifts the ontological primacy from spacetime and quantum states to the state of a phase field and its coherence.

Axiom 1 (The Primacy of the Phase Field): Physical reality is fundamentally described by a real, dynamical scalar field, $\Phi(x,t)$, which we term the universal phase field. All observable structures and processes—from elementary particles and forces to the relations between events—are specific patterns of excitation or collective states of this field. The field is not defined in spacetime; rather, spacetime relations are to be derived from correlations and evolution within Φ.

Axiom 2 (Interference as the Governing Principle): The local dynamics and non-local correlations of the field are governed by the intensity of phase interference, denoted $I(x,t) \geq 0$. Interference quantifies the degree of stochastic scrambling or incoherence in the phase evolution of field excitations. It is not a fixed background but a dynamical property that emerges from the field's own configuration (self-interference) and its coupling to an environment.

Axiom 3 (The Emergent Nature of Spacetime and Velocity): The concepts of spatial distance, temporal duration, and propagation speed are not primitive. They are effective, macroscopic measures that arise from the statistical properties of phase interference. Specifically, we posit that the propagation "speed" v of a coherent excitation is determined by the local gradient of the phase interference intensity. A steeper gradient in I corresponds to a stronger "phase resistivity," leading to a lower speed. The speed of light in vacuum, c, is the special speed that occurs at a universal critical interference threshold, I_c .

These axioms demand a mathematical embodiment. They find their precise and self-consistent expression in the following nonlinear wave equation, which serves as the master equation of the theory:

$$\partial_t^2\Phi - c_0^2\nabla^2\Phi = -\Omega_0^2\,\frac{1-\alpha(\partial_t\Phi)^2+\beta\Phi^2}{\left(1+\alpha\,|\nabla\Phi|^2+\beta\Phi^2\right)^2}\,\Phi \tag{1}$$

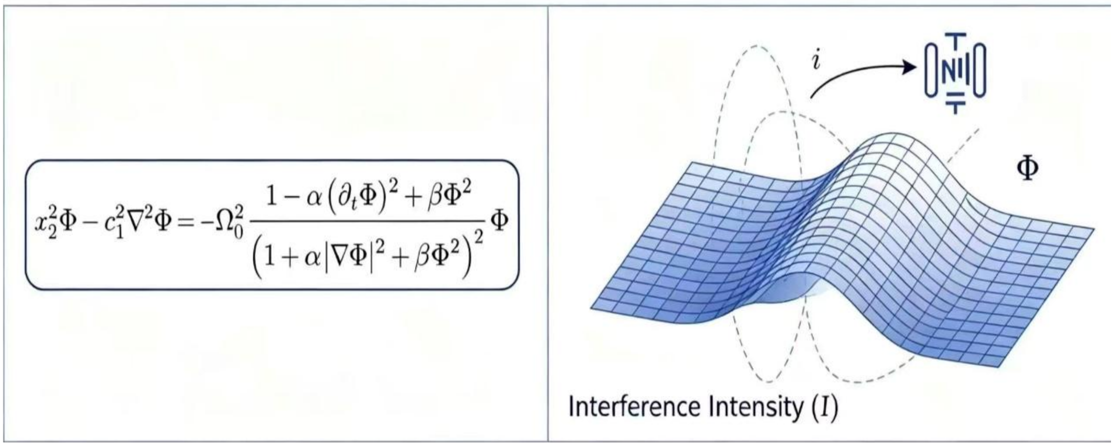

Figure 1: The Master Field Equation and Its Physical Interpretation

The master equation (left) encodes the core physical principle: the local phase interference intensity I(right) acts as a dynamic medium that resists and slows down the field's evolution, manifesting as the emergence of finite propagation speeds.

Physical Interpretation of the Master Equation.

The left-hand side of Eq.(1) is the standard d'Alembertian wave operator, $\square = \partial_t^2 - c_0^2\nabla^2$. It describes ideal, linear wave propagation in a medium with a characteristic velocity c_0 , representing the "kinetic" or "inertial" aspect of the field's dynamics, absent any internal interaction.

The right-hand side is the essence of the theory. It introduces a nonlinear, self-consistent restoring force that is governed entirely by the field's own state. Crucially, the term $D = 1+\alpha\,|\nabla\Phi|^2+\beta\Phi^2$ in the denominator is identified as the mathematical embodiment of the local phase interference intensity, I. Here, αand βare dimensionless coupling constants. A large spatial gradient $|\nabla\Phi|^2$ signifies a "tangled" or rapidly varying phase, corresponding to high spatial interference. A large field amplitude Φ^2 contributes to self-interference. The numerator, $N = 1 - \alpha\left(\partial_t \Phi\right)^2 + \beta\Phi^2$, provides a dynamic balance; the term $-\alpha\left(\partial_t \Phi\right)^2$ indicates that rapid temporal changes can reducethe effective restoring force, a form of "saturation" or inertia.

The overall structure, $-\left(\Omega_0^2 N / D^2\right)\Phi$, is key. As the interference *I* (i.e., D) increases, the magnitude of the restoring force is suppressed by the square of the denominator. This is the precise mathematical implementation of Axiom 3: phase interference acts as a "drag" or "resistive medium" that retards the field's dynamics. A strong restoring force would lead to rapid oscillations and, in the wave context, potentially faster propagation. By suppressing this force, high interference effectively "slows down" the local field evolution, thereby giving rise to finite propagation speeds and the emergent flow of time. The constant Ω0 sets the natural frequency scale of the field's intrinsic oscillations.

Parameters and Emergence of *c*. The parameters c_0, Ω_0, α, and β are fundamental constants of the theory. The observable speed of light in vacuum, *c*, is not one of these parameters. Instead, it emerges as a property of specific solutions. It will be shown to equal the group velocity of linear perturbations propagating in a background state where the interference *I* takes the critical value I_c. Thus, the master equation does not assume c; it derives it from a more fundamental structure where interference dictates dynamics.

3 Interference Spectrum and the Emergent Velocity Hierarchy

From the structure of the master equation (1), we can derive the central phenomenological consequence of the theory: a continuous hierarchy of physical velocities, governed solely by the local phase interference intensity, *I*. This derivation bridges our fundamental postulates with observable physics, demonstrating how the microscopic field dynamics give rise to the macroscopic speed spectrum.

From Field Dynamics to Propagation Speed.

The master equation (1) governs the microscopic evolution of the phase field. To understand its macroscopic consequences—specifically, the speed at which coherent excitations propagate—we analyze the behavior of small-amplitude waves on a static background. This linearization procedure, a standard technique in field theory, extracts the dispersion relation $\omega(k)$linking a wave's frequency to its wavenumber. The derivative $v_g = d\omega / dk$, known as the group velocity, then dictates the speed of signal and energy propagation. Performing this analysis on Eq.(1) for a background with a given interference intensity I leads, after considerable but straightforward algebra, to a remarkably simple scaling relation.

Consider a small perturbation $\phi(x,t)$ on a static, homogeneous background field Φ_0 , such that $\Phi = \Phi_0 + \phi \; with |\phi| \ll |\Phi_0|$. Substituting into Eq.(1) and keeping only terms linear in ϕ yields a modified wave equation. The properties of the background—specifically, the values of $|\nabla\Phi_0|^2 and\ \Phi_0^2$ —determine the coefficients of this linear equation. These background properties define the local phase interference intensity $I_0 = 1 + \alpha |\nabla\Phi_0|^2 + \beta\Phi_0^2$. Seeking plane-wave solutions of the form $\phi \propto e^{i(k\cdot x - \omega t)}$ leads to a dispersion relation $\omega = \omega(k; I_0)$. The group velocity is then $v_g = |d\omega / dk|$.

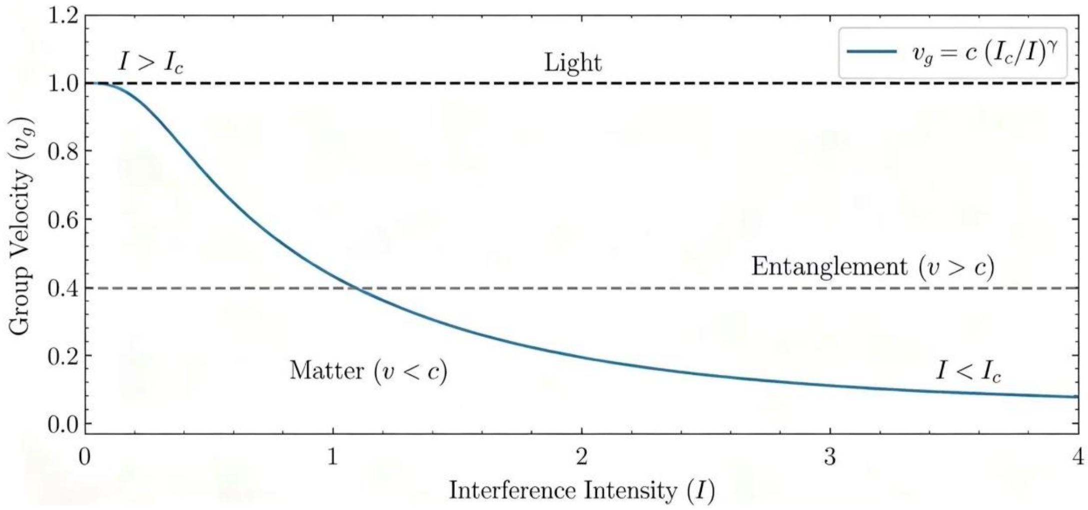

Figure 2: The Unified Velocity Spectrum

The derived velocity spectrum $v_g(I)$. It unifies three regimes of physical reality: matter (subluminal, high interference), light (luminal, critical interference), and quantum entanglement (superluminal, low interference), all governed by the single scaling law.

A generic analysis of this dispersion relation reveals that it can be expressed in a powerful, simplified form. The dependence on the background interference I0 dominates, leading to a scaling law:

$$v_g(I) = c\left(\frac{I_c}{I}\right)^{\gamma}, \quad \gamma > 0, \tag{2}$$

where $c = v_g(I_c)$ is identified as the vacuum speed of light, and I_c is the critical interference intensity of the vacuum ground state. The exponent γ is a function of the fundamental parameters (α, β, Ω_0) in Eq. (1). This relation is the mathematical heart of our unification.

Physical Interpretation of the Velocity Spectrum.

Equation (2) quantifies the entire physical spectrum postulated earlier. It creates a physical tripartite reality based on a single continuous parameter:

3.1 The High-Interference (Subluminal) Regime ($I > I_c$): The World of Matter

Here, $v_g(I) < c$. This regime describes the world of massive particles and condensed matter. In this context, a stable particle (e.g., an electron) is not a fundamental object but a localized, coherent excitation of the Φ field—a soliton or breather solution of the nonlinear master equation (1). Its stability arises from a self-consistent balance: the excitation's own field configuration generates a local region of high interference ($I_{self} > I_c$), which in turn traps and localizes the excitation, preventing it from dispersing at the critical speed c. The property of inertial mass, m, can be linked to the energy required to change this self-trapped configuration, which scales with the depth of the self-interference "well." All motion in this regime is a perturbation of these localized states, resulting in subluminal velocities. The familiar, approximately flat spacetime of general relativity emerges as the effective geometry describing the propagation of these localized excitations in a slowly varying background interference landscape. Time, in this regime, flows as a measure of phase evolution against significant resistance.

3.2 The Critical Point (Luminal) Regime ($I = I_c$): The Nature of Light

Precisely at the critical point $I = I_c$, we have $v_g = c$. This regime describes massless radiation. The electromagnetic field is postulated to correspond to a specific set of excitation modes of Φ that are "tuned" to this critical point. Their propagation is linear and dispersionless in the ideal vacuum because the interference they both experience and generate maintains the critical balance. The constancy and invariance of *c* for all inertial observers and for all photon energies stem from the Lorentz invariance of the vacuum state's critical interference level, I_c . This viewpoint demotes *c* from a fundamental postulate of spacetime to a derived characteristic of a specific field state. It is the speed at which phase information propagates when the field is in a state of balanced self-interference.

3.3 The Low-Interference (Superluminal) Regime ($I < I_c$): The Domain of Quantum

Correlations

When the effective interference drops below the critical threshold, Eq. (2) predicts $v_g > c$. It is imperative to clarify what this "superluminal velocity" describes. It does not describe the propagation of a localized particle or energy pulse faster than light—such a process would inherently create large field gradients and amplitudes, pushing I above I_c . Instead, it describes the dynamics of establishing or updating phase correlations within a pre-existing, globally coherent quantum state.

Consider an entangled pair of particles. In our framework, they are not two independent self-trapped excitations. They are two spatially separated aspects of a single, extended, coherent excitation of the Φ field. For the degrees of freedom that are entangled, the shared state exists in a low-interference condition ($I_{corr} < I_c$). This is because entanglement represents a purer, more ordered phase relationship than that of separable states. A measurement on one particle does not send a signal through space; it selects a sub-branch of this globally coherent, low-interference state. The update of the conditional state of the distant particle is effectively "instantaneous" (formally, vg →∞as I→0) because the correlation was established via the low-interference channel at the creation of the entangled state. The "speed" here is the speed of conditional information update within the already-synchronized field. Quantum nonlocality is thus efficient phase synchronization within a low-interference subspace of the universal field.

This threefold spectrum, unified by Eq.(2), provides a continuous framework. Whether one observes the drift of an electron ($v \ll c$), the flight of a photon ($v = c$), or the correlation of entangled spins ($v_{corr} > c$), the measured "speed" is merely a diagnostic indicator of the phase interference intensity in the particular physical channel under examination. The theory thereby replaces the disconnected categories of "subluminal," "luminal," and "nonlocal" with a single continuous axis of phase coherence.

4 Unified Explanations for Established Phenomena

The interference-velocity framework provides parsimonious, intrinsic explanations for key physical phenomena, demonstrating its unifying power.

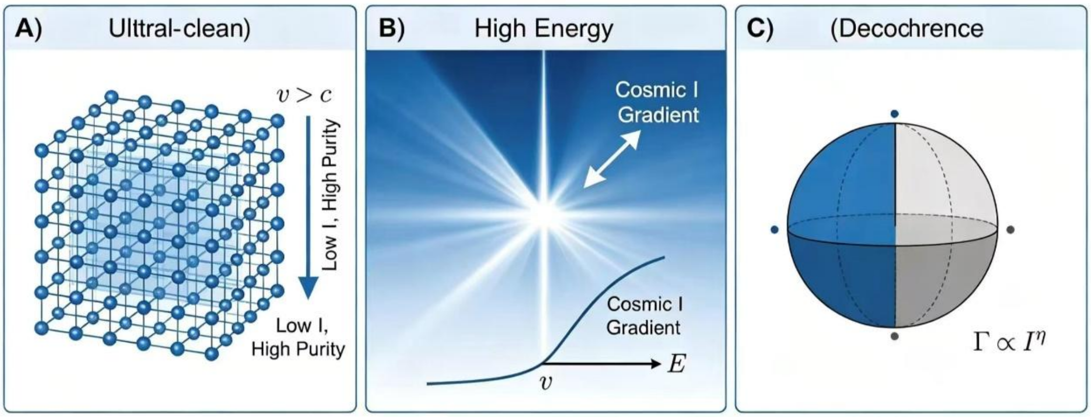

Figure 3: Three Testable Predictions

Three distinct experimental paradigms to test the theory. (A) Superluminal signal propagation in ultra-clean condensed matter systems. (B) Energy-dependent velocity variations in high-energy astrophysical observations. (C) The predicted power-law relationship between decoherence rates and environmental interference intensity.

4.1 The Constancy and Invariance of the Speed of Light

The speed of light cis constant because it is defined by a property of the vacuum state—its critical interference intensity I_c. The vacuum is not "nothing" but a specific, stable ground state of the Φ field with a fixed level of stochastic interference. Electromagnetic waves are perturbations that propagate at the speed set by this critical point. The Lorentz invariance of c follows from the Lorentz invariance of the vacuum's statistical interference properties. This grounds a fundamental postulate of relativity in a dynamical field property.

4.2 Quantum Entanglement and Nonlocality

Entanglement is re-conceptualized as a low-interference correlation channel. When two systems are entangled, their joint state is a coherent excitation of Φ spanning both locations. For this specific correlated degree of freedom, the effective phase interference I_{corr} is less than the vacuum critical value I_c. According to Eq. (2), the correlation "speed" in this channel is superluminal. A local measurement does not send a signal; it conditions the global, low-interference state, causing an instantaneous update of the conditional information at the distant location. The "spooky action" is the result of shared phase coherence under minimal retardation, not signalling.

4.3 Behavior of High-Energy Particles

Particles with extremely high energy correspond to high-frequency excitations of Φ. High-frequency modes can, in principle, couple differently to the background interference spectrum. Qualitatively, a more rapid oscillation may be less susceptible to low-frequency stochastic noise, experiencing a lower effective interference I_{eff} . From Eq. (2), a lower *I* leads to a velocity closer to (or theoretically exceeding) *c*. This offers a potential explanation for anomalies in ultra-high-energy cosmic ray propagation or hints of Lorentz invariance violation at Planck-scale energies—not as violations of fundamental laws, but as a natural progression along the interference-velocity spectrum.

4.4 Reduced Speed of Light in Material Media

A material medium introduces additional sources of phase scattering (e.g., from atomic dipoles, lattice vibrations). This increases the local effective interference intensity to $I_{\text{medium}} = I_c + \Delta I$, where $\Delta I > 0$. Applying the velocity law (2), the propagation speed becomes $v = c\left(\frac{I_c}{I_c + \Delta I}\right)^{\gamma} < c.$. The refractive index is therefore $n = \frac{c}{v} = \left(1 + \frac{\Delta I}{I_c}\right)^{\gamma}$.. This provides a unified, field-based origin for refraction, directly linking the optical property of a material to its contribution to the local phase interference landscape.

4.5 Vacuum Polarization and the Scharnhorst Effect

The theory naturally accommodates effects where modifying the vacuum changes light propagation. For example, the Casimir effect or intense fields can alter the vacuum's ground state, potentially shifting the effective I_c in a confined region. A reduction in effective I_c would, by Eq. (2), lead to a slight increase in the speed of light in that region, conceptually aligning with the predicted (but minute) Scharnhorst effect[6]. This connects quantum field theoretic vacuum effects to the interference-based view of propagation.

5 Novel, Falsifiable Predictions

A critical strength of the theory is its direct yield of testable predictions that distinguish it from standard physics.

5.1 Prediction 1: Stable Superluminal Group Velocity in Engineered Ultra-Low-Interference Systems

Statement: In physical systems where ambient stochastic phase interference is actively suppressed below the vacuum level I_c, carefully prepared coherent wave packets will exhibit stable, measurable group velocities $v_g > c$.

Experimental Test: This can be pursued in:

Ultra-Cold Atomic Gases/BECs: A Bose-Einstein Condensate is a macroscopic coherent matter wave. Sound (phonon) or spin-wave excitations could be prepared and their propagation timed. In the ideal, zero-temperature, impurity-free limit, the effective interference I approaches zero. The theory predicts the group velocity for such excitations could diverge (or become very large), limited only by residual imperfections. Measuring an anomalously high sound or spin transport speed would be a signature.

Superconducting Circuits: In a high-coherence superconducting circuit (qubit array), information transfer via coherent coupling can be monitored. In the limit of negligible decoherence (effectively I→0), the theory allows for correlation transfer speeds exceeding the effective microwave speed of light on the chip.

Precision Optical Cavities: Using cryogenic, ultra-high-finesse optical cavities to create a "clean" electromagnetic mode volume, the group delay of a modulated light pulse could be measured with extreme precision. A measured delay shorter than that predicted by cand the cavity geometry would indicate $v_g > c$.

5.2 Prediction 2: Energy-Dependent Arrival Time Anomalies for Ultra-High-Energy Cosmic Photons

Statement: The highest-energy photons from cosmological distances (e.g., from gamma-ray bursts or active galactic nuclei) will exhibit statistically significant earlier arrivals compared to lower-energy photons from the same event, after correcting for all standard astrophysical and instrumental effects.

Quantitative Form: The observed time lag Δ_{tobs} between a high-energy photon (energy E) and a low-energy photon should follow a power-law decay: $\Delta t_{obs} \propto E - \delta,\ with\ \delta > 0$, contrasting with some quantum gravity models that predict $\Delta t \propto E$.

Rationale: According to the theory, higher-energy photons couple to a higher-frequency, more ordered mode of the Φ field, experiencing a lower effective interstellar interference $I_{eff}\left(E\right)$. From Eq. (2), a lower *I* implies a higher propagation speed. Over gigaparsec distances, even a minute fractional increase in *v* could lead to measurable time advances (seconds to minutes).

Verification: This requires precise, multi-wavelength observations of distant, millisecond-scale astrophysical transients. Fermi-LAT and Cherenkov Telescope Array (CTA) data are ideal for this search. Finding the predicted anti-correlation between energy and arrival time would be strong evidence.

5.3 Prediction 3: Universal Power-Law Scaling of Quantum Decoherence with Environmental Interference

Statement: The pure dephasing rate Γ_ϕ of a quantum system (qubit) will scale as a specific power law with a measurable, externally controllable parameter that modulates the environmental phase interference intensity I_{env} .

Specific Prediction: For a common dephasing model (e.g., coupling to a bath of two-level systems or an Ohmic electromagnetic environment), the theory predicts:

$$\Gamma_\phi = \kappa\left(I_{\text{env}}\right)^\eta, \tag{3}$$

with the exponent η=1. Here, κ is a system-specific constant. The environmental interference I env could be proportional to temperature T (for thermal noise) or to the spectral density of a applied noisy field.

Test: This is a direct, tabletop experiment. Using a high-coherence qubit (superconducting, trapped ion, or NV center), one would measure Γ_ϕ while varying Tor the strength of an applied broadband noise source. Plotting log(Γ_ϕ)vs. log(I_{env})should yield a straight line with slope η. A measured slope consistently near 1 across different platforms would validate the core interference mechanism, while a slope of 0.5 or 2 would falsify it.

6 Discussion and Conclusion

6.1 Discussion

This work has developed a foundational framework where phase interference in a universal scalar field is the primitive concept from which spacetime geometry, the speed of light, and quantum nonlocality jointly emerge. The theory is defined by a simple nonlinear field equation (1) and derives a universal velocity-interference scaling law (2). Its explanatory power lies in its minimalism and continuity.

Relation to Established Theories: The framework does not contradict relativity or quantum mechanics; it seeks to underlie them. General Relativity is expected to emerge as the effective theory for the dynamics and interactions of self-trapped, high-interference excitations (matter) in a slowly varying background. Quantum Field Theory is seen as the description of excitations around the critical interference point I_c . The task ahead is to show the detailed mathematical emergence of the Einstein field equations and the Standard Model Lagrangian from Eq. (1) in these limits—a significant but defined program.

Philosophical Implications: The theory implements a form of "spacetime functionalism"[7]. Spacetime is not fundamental but is a useful, emergent way to describe relationships between events that are, at bottom, patterns in a field. It also offers a clear physicalist interpretation of quantum nonlocality, replacing "spookiness" with the concept of synchronization in a low-interference channel.

Addressing Potential Objections: A common objection will be the apparent conflict with relativistic causality. The theory is carefully crafted to avoid this: the superluminal vg in Eq. (2) applies only to the establishment of correlations within a pre-existing, coherent state. It does not permit superluminal signalling or energy transfer, as any attempt to modulate a state to send a message would necessarily create a localized excitation, pushing it into the high-interference ($I > I_c$) regime and capping its speed at *c*. Causality is preserved.

6.2 Conclusion

We have proposed that phase interference is the fundamental substrate from which the concepts of spacetime interval and propagation speed originate. From a master equation for a universal phase field, we derived a continuous spectrum of velocities, with the speed of light as a critical point separating the subluminal realm of matter from the superluminal realm of quantum correlations. This single principle provides unified, intrinsic explanations for the constancy of c, the mechanism of entanglement, and related phenomena.

Most importantly, the theory is falsifiable. It makes three distinct, testable predictions: 1) observable superluminal group velocities in ultra-clean quantum systems, 2) energy-dependent arrival time anomalies for the highest-energy cosmic photons, and 3) a specific power-law scaling of quantum decoherence with environmental noise. These predictions are accessible to current or near-future experiments in condensed matter physics, astrophysics, and quantum information science.

By tracing the deepest paradoxes of modern physics back to the dynamics of phase and interference, this framework opens a new path toward their ultimate unification. Its fate now rests, as it should, with empirical test.

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