Three Light Cones:
Coherence, Curvature, and Tension in Structured Causal Geometry

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April 18, 2025

Abstract

This paper presents a unified causal framework in which field propagation, mass generation, spin structure, and gauge behavior all emerge from coherence-regulated dynamics. By defining three interdependent cone structures—coherence, tension, and curvature—we derive a composite causal boundary that replaces the classical light cone with a structure-dependent transport geometry. This framework yields a transport equation governing ripple evolution, coherence collapse, and information flow, and defines mass as a structural consequence of divergence and resistance. Neutrino oscillation, CP violation, spin-$\frac{1}{2}$ behavior, quark triplet confinement, and gluon-like dynamics all arise from coherence vector interactions and causal cone alignment. Gauge symmetry is not postulated but recovered geometrically through coherence algebra. Observational consequences—including gravitational wave echoes, black hole radiation, and tunneling decay—follow directly from cone deformation and causal bottlenecking. The result is a mechanics-based reformulation of field theory in which causal structure, quantum behavior, and spacetime geometry arise from coherence-regulated transport in a physically grounded field substrate.

Contents

1 Introduction: Structured Causality from Field Dynamics

Classical light cones define the boundaries of causal influence in both general relativity and quantum field theory. They enforce commutativity, limit signal propagation, and shape the geometry of spacetime. Yet their origin is not explained—they are typically imposed as geometric constraints, not derived from the dynamics of a physical medium [1, 2].

This paper introduces a framework in which causal cones emerge from field structure. We define three interdependent cone types—coherence, tension, and curvature—each constructed from measurable quantities that govern ripple propagation in a continuous medium:

- The **Coherence Cone** defines causal availability: influence requires phase-aligned structure [3].
- The **Tension Cone** defines propagation velocity and direction from anisotropic stiffness [4].
- The **Curvature Cone** encodes resistance and delay due to coherence degradation.

Together, these cones form an effective causal boundary. In high-coherence, isotropic media, it recovers the classical light cone [1, 2]. In disrupted regions, causal reach becomes constrained, redirected, or disconnected [2].

To maintain covariant consistency with gravitational curvature, the scalar tension structure is promoted to a rank-2 tensor $t_{\mu\nu}(x) = \partial_\mu \phi(x)\, \partial_\nu \phi(x)/T_0$. This tension field perturbs the background metric via a linearized quantum correction:

$$\tilde{g}_{\mu\nu}(x) = g_{\mu\nu}(x) + \hbar t_{\mu\nu}(x)$$

This formulation ensures tensor rank consistency and introduces quantum-corrected geometry as a structural response to internal coherence gradients.

This framework leads to a transport equation for influence propagation, from which mass, collapse, and causal flow all emerge. Gauge interactions appear as constrained coherence transport. Particle behavior—including neutrino oscillation, CP violation, spin-$\frac{1}{2}$ structure, quark triplets, and gluon dynamics—arises from cone overlap and coherence phase geometry.

No symmetry group is imposed. The framework is defined by scalar and tensor fields, coherence vectors, and their causal interactions. Observable consequences—including gravitational wave echoes, tunneling radiation, and interference collapse—are directly derived from field structure [5, 6].

This is not a new ontology. It is a mechanics paper. The goal is to show that causal geometry, mass, and quantum structure can emerge from coherence-regulated transport in a physically grounded field system.

2 Structured Causal Cones from Coherence, Tension, and Curvature

We model causal propagation in the mesh framework as a structured, field-driven process defined by three interrelated but physically distinct mechanisms: coherence (can influence propagate), tension (how fast and in which directions it moves), and curvature (how that movement is redirected or resisted). Each defines a cone structure that contributes to the effective causal boundary at any point in spacetime. This section introduces these structures as three subsystems of causal geometry, each defined by measurable field properties.

2.1 Coherence Cone: Causal Availability from Structured Wave Propagation

Causal reach begins with coherence. In this framework, events influence each other not through abstract spacetime metrics, but through the structured, ripple-based transmission of phase information. The Coherence Cone defines the region where such propagation is physically permitted [3].

We define the coherence vector field as:

$$\vec{C}(x,t) = \nabla\phi(x,t) \cdot \chi(x,t) \tag{1}$$

where:

- $\phi(x,t)$ is the phase field of structured ripples.
- $\chi(x,t) \in [0,1]$ is a coherence mask: 1 where phase-preserving transmission is supported, 0 where it fails.
- $\vec{C}(x,t)$ encodes the direction and strength of propagation potential.

The coherence cone is defined by the region in which $\vec{C}(x,t)$ is non-zero and structurally supported. Where $\vec{C}(x,t) = 0$, no causal signal can propagate — not because of relativistic constraints, but due to the physical state of the medium. In the limit of uniform coherence, the cone becomes symmetric and indistinguishable from a classical null cone.

Unlike standard light cones, coherence cones can deform dynamically. In disordered or anisotropic regions, the cone narrows, tilts, or fragments. Where coherence gradients are steep, the cone's structure becomes directionally biased — favoring causal propagation along specific axes while suppressing it in others.

This dynamic behavior allows coherence cones to collapse entirely, producing causal disconnection without the need for a metric singularity. In this sense, coherence determines not only where signals can propagate, but defines the local arrow of time: the direction in which structured influence is physically sustained.

2.2 Tension Cone: Anisotropic Propagation Velocity from Local Field Structure

While the coherence cone defines where propagation can occur, the Tension Cone defines the velocity and direction of that propagation. Signal speed is determined by the ratio of directional tension to effective mass density, which varies with mesh anisotropy:

$$v^2(x) = \frac{T(x)}{\mu(x)} \quad \Rightarrow \quad \vec{v}(x) = \sqrt{\frac{T_{ij}(x)}{\mu}} \cdot \hat{n}$$

This formulation generalizes wave behavior in elastic media. It also echoes nonlinear field theories such as Born–Infeld electrodynamics, where tension bounds constrain propagation velocity [7, 8]. In the extreme anisotropic limit, the tension cone may become directionally degenerate—supporting signal propagation only along select axes, reminiscent of Semi-Dirac dispersion in condensed matter systems [9].

2.3 Curvature Cone: Emergent Delay and Path Distortion from Coherence Resistance

While coherence enables transmission and tension governs speed, curvature determines how signal paths deform due to accumulated structural resistance. The Curvature Cone encodes how coherence decay along a path reshapes causal trajectories, distorting the direction and timing of causal influence.

We define the resistance function as:

$$\mathcal{R}(x) = \int_{\gamma} (1 - \chi(x(s)))\, ds \tag{2}$$

where:

- $\chi(x)$ is the local coherence mask.
- γ is a propagation path through the field.
- $\mathcal{R}(x)$ quantifies accumulated resistance—functionally equivalent to an emergent curvature measure.

When $\chi(x) = 1$, coherence is perfect and $\mathcal{R}(x) = 0$, indicating a flat causal trajectory. As $\chi(x)$ falls below unity, coherence degrades, and resistance accumulates. This results in path bending, signal delay, and causal redshift—not because the geometry itself is curved, but because the medium becomes less able to support ripple transmission.

In the high-resistance limit, where $\mathcal{R}(x) \to \infty$, propagation effectively halts. This produces causal bottlenecks or horizon-like boundaries without requiring a metric singularity. These structures behave analogously to general relativistic event horizons, but arise dynamically from coherence structure alone—offering an emergent explanation for gravitational lensing and time dilation from field-level behavior [5, 6].

2.4 Summary: Effective Cone and Composite Causality

Together, the three cone structures form a composite causal boundary:

$$\text{Cone}_{\text{eff}}(x) = f(\vec{C}(x), \vec{v}(x), \mathcal{R}(x)) \tag{3}$$

This boundary determines the actual shape, speed, and reach of influence from any event. Classical light cones emerge only in the high-coherence, isotropic-tension, low-resistance limit. Elsewhere, the causal boundary is dynamic, local, and structured—governed not by geometry alone, but by the physical capacity of the field to carry influence.

3 Unifying the Cones: Structured Causal Geometry from Field Properties

Each cone structure defined in the previous sections captures a distinct aspect of causal propagation within a coherence-regulated field. The coherence cone determines whether structured influence is available at a point. The tension cone defines the direction and velocity of signal propagation. The curvature cone encodes delay and deformation due to accumulated resistance in the medium.

Together, these structures define a composite causal boundary—the *effective cone*—which governs the full causal reach from any spacetime point x:

$$\text{Cone}_{\text{eff}}(x) = f\left(\vec{C}(x), \vec{v}(x), \mathcal{R}(x)\right) \tag{4}$$

This is not a closed formula, but a functional construct defined by the interaction of three measurable field components: coherence vector support $\vec{C}(x)$, tension-based velocity $\vec{v}(x)$, and curvature resistance $\mathcal{R}(x)$.

From Local Structure to Emergent Causality

Unlike classical light cones, the effective cone is dynamic, anisotropic, and dependent on the local structure of the field. In high-coherence, isotropic-tension, low-resistance regimes, it reproduces the null cone of flat spacetime. In more complex media, it deforms in physically consistent ways:

- If $\vec{C}(x) = 0$, causal propagation is not supported.
- Anisotropic $T_{ij}(x)$ results in directional cone deformation.
- Large $\mathcal{R}(x)$ tilts, compresses, or bottlenecks the cone geometry.

This defines a field-based mechanism for both classical and exotic causal behaviors, including gravitational lensing, coherence-induced causal shadows, and resistance-driven horizons [10].

This composite cone structure serves as the causal substrate for all subsequent field behavior. In conventional quantum field theory, internal gauge symmetries are introduced axiomatically to govern interactions. In the present framework, however, these behaviors arise functionally—from how scalar, vector, and tensor excitations propagate within the coherence-regulated cone geometry. We now show how each gauge interaction—U(1), SU(2), and SU(3)—can be recovered or mimicked through field dynamics constrained by the effective cone.

4 Gauge Structures and Functional Correspondence

Standard quantum field theory describes fundamental interactions through internal gauge symmetries: U(1) for electromagnetism, SU(2) for the weak force, and SU(3) for the strong interaction. These symmetries introduce gauge fields that preserve local invariance and mediate interactions via covariant derivatives and field curvature [11, 12].

The present framework does not impose internal symmetry groups at the Lagrangian level. Instead, all transport and interaction emerge from causal dynamics governed by scalar, tensor, and coherence fields. The key question is whether the physical consequences of gauge symmetry—such as conserved transport, massless propagation, symmetry breaking, and confinement—can be recovered from this structure.

To ensure rank consistency between field-driven tension and spacetime curvature, we promote the scalar tension field to a symmetric rank-2 tensor:

$$t_{\mu\nu}(x) = \frac{1}{T_0}\, \nabla_\mu \phi(x)\, \nabla_\nu \phi(x),$$

and introduce a quantum-corrected effective metric:

$$\tilde{g}_{\mu\nu}(x) = g_{\mu\nu}(x) + \hbar\, t_{\mu\nu}(x).$$

This form of $t_{\mu\nu}$ is introduced as a structural Ansatz—selected as the lowest-rank, symmetric, covariant expression consistent with energy density, directional ripple support, and compatibility with curvature-sourced transport.

All transport and field evolution described below occurs within this corrected geometry. In the high-coherence limit, the mesh-regulated Hamiltonian supports field dynamics that functionally reproduce the predictions of gauge theory. Each of the three fundamental gauge symmetries is examined in turn.

Structural Basis for Gauge Behavior from the Mesh Hamiltonian

We begin with the scalar field Lagrangian defined over the mesh-regulated substrate:

$$\mathcal{L}(x) = \frac{1}{2}\, \tilde{g}^{\mu\nu}(x)\, \nabla_\mu \phi(x)\, \nabla_\nu \phi(x),$$

which reduces to the familiar flat-space form in regions where $t_{\mu\nu}(x) \to 0$.

The canonical momentum becomes:

$$\pi(x,t) = \frac{\partial \mathcal{L}}{\partial(\partial_t \phi)} = \tilde{g}^{0\nu}\, \nabla_\nu \phi,$$

and the Hamiltonian density is:

$$\mathcal{H}(x,t) = \frac{1}{2}\, \tilde{g}^{\mu\nu}(x)\, \nabla_\mu \phi(x)\, \nabla_\nu \phi(x).$$

Covariant derivatives ∇_μ are used throughout when evaluating transport or dynamics in curved geometry, consistent with general relativity and the quantum-corrected metric $\tilde{g}_{\mu\nu}$.

Quantizing this system canonically yields:

$$[\hat{\phi}(x), \hat{\pi}(y)] = i\hbar\, \delta(x-y),$$

with field excitations interpreted as coherence-supported ripple modes. In the limit where $\tilde{g}_{\mu\nu} \to \eta_{\mu\nu}$, the system reduces to standard scalar field theory with known Feynman propagators and interaction rules [11, 12].

In this regime, structured field transport becomes indistinguishable from the free propagation of gauge-invariant modes. Coherence, tension, and curvature cones regulate causal support and interaction, replacing internal symmetry with causal geometry. We now examine how the field structures defined above recover the physical behavior associated with the standard gauge groups U(1), SU(2), and SU(3) [13, 11].

U(1): Electromagnetic Behavior from Coherent Propagation

The U(1) gauge symmetry of electromagnetism is characterized by local phase invariance:

$$\psi(x) \to e^{i\alpha(x)}\psi(x),$$

with interactions mediated by a gauge field $A_\mu(x)$ through the covariant derivative $D_\mu = \partial_\mu + ieA_\mu$ [11, 12].

In the mesh framework, analogous behavior arises from coherence-regulated wave propagation:

- The scalar field $\phi(x,t)$ evolves under a structured Lagrangian:

  $$\mathcal{L} = \frac{1}{2}\,\tilde{g}^{\mu\nu}(x)\,\nabla_\mu\phi(x)\,\nabla_\nu\phi(x),$$

  where the effective metric is defined as:

  $$\tilde{g}_{\mu\nu}(x) = g_{\mu\nu}(x) + \hbar\, t_{\mu\nu}(x), \quad t_{\mu\nu}(x) = \frac{1}{T_0}\,\nabla_\mu\phi\,\nabla_\nu\phi.$$

- In the high-coherence, isotropic limit, $\tilde{g}^{\mu\nu} \to \eta^{\mu\nu}$, and the field propagates as a massless mode:

  $$\omega = |\vec{k}|.$$

- The coherence vector $\vec{C}(x) = \nabla\phi \cdot \chi(x)$ defines the direction and availability of causal propagation, structurally mimicking a gauge potential A_μ.

- The causal transport equation:

  $$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{v}) + \rho\Gamma(x) = 0$$

  ensures local conservation of influence in the absence of collapse ($\Gamma = 0$), analogous to the continuity equation $\partial_\mu j^\mu = 0$ in U(1) gauge theory [11].

Thus, U(1)-like behavior emerges naturally from coherence-supported massless ripple propagation, with causal support and phase structure governed by a quantum-corrected transport geometry. The effective metric $\tilde{g}_{\mu\nu}$ ensures consistency with spin-2 curvature behavior and allows the classical limit to be recovered as $\hbar \to 0$.

SU(2): Chirality and Mass via Scalar–Tensor Coherence Coupling

SU(2) governs the weak interaction, where gauge bosons acquire mass through spontaneous symmetry breaking, and where left- and right-handed components of spinor fields transform asymmetrically. In this framework, SU(2)-like behavior emerges through the interaction of coherence-regulated transport and curvature geometry [11].

The field system supports a scalar field $\phi(x)$, a coherence mask $\chi(x)$, and a symmetric rank-2 tensor:

$$t_{\mu\nu}(x) = \frac{1}{T_0}\,\nabla_\mu\phi(x)\,\nabla_\nu\phi(x),$$

which encodes the directional stiffness and causal resistance of the mesh and perturbs the classical geometry via:

$$\tilde{g}_{\mu\nu}(x) = g_{\mu\nu}(x) + \hbar\, t_{\mu\nu}(x).$$

This form of $t_{\mu\nu}$ is a structurally motivated Ansatz, selected for minimal rank, symmetry, and energy-density compatibility with quantum-corrected transport geometry.

We define a composite field triplet:

$$H(x) := [\phi(x), \tilde{g}_{\mu\nu}(x), \chi(x)],$$

which encodes scalar intensity, quantum-corrected geometry, and local coherence support.

Mass arises dynamically when scalar coherence and transport geometry misalign. The effective mass is:

$$m^2_{\text{eff}}(x) \propto \Gamma(x) + \mathcal{R}(x),$$

where $\Gamma(x) = \nabla \cdot \vec{C}(x)$ captures divergence in causal support, and $\mathcal{R}(x)$ is the resistance accumulated along curvature-modulated transport paths.

Chirality also emerges from this structure. Let $\phi_L(x)$ and $\phi_R(x)$ denote chiral field modes propagating along distinct eigen-directions of $\tilde{g}_{\mu\nu}(x)$. If:

$$\Delta\Gamma(x) = \Gamma_L(x) - \Gamma_R(x) \neq 0,$$

then collapse rates differ for each mode, producing a transport asymmetry analogous to left-handed coupling in the electroweak sector.

Although no spinor fields or internal group symmetries are postulated, the scalar–tensor–coherence interaction enforces directional transport bias and mass emergence. This provides a structural analog to symmetry breaking and chiral selection in SU(2) gauge theory [11].

SU(3): Confinement and Causal Isolation via Cone Fragmentation

SU(3) governs the strong interaction, with eight non-Abelian gauge fields mediating color charge. Its defining feature is confinement: color-charged excitations cannot exist in isolation due to the self-interacting structure of the gauge field [11, 12].

In the mesh-regulated framework, SU(3)-like behavior emerges from coherence fragmentation and causal confinement. We define three scalar field modes $\phi^a(x),\ a = 1, 2, 3$, each with a coherence mask $\chi^a(x)$, coherence vector $\vec{C}^a(x)$, and transport velocity determined by a quantum-corrected effective metric:

$$\tilde{g}_{\mu\nu}(x) = g_{\mu\nu}(x) + \hbar\, t_{\mu\nu}(x), \quad t_{\mu\nu}(x) = \frac{1}{T_0} \nabla_\mu \phi^a(x) \nabla_\nu \phi^a(x).$$

This tensor form is maintained as a structural Ansatz—chosen for symmetry, energy alignment, and compatibility with transport curvature.

The causal transport equation for each field mode becomes:

$$\frac{\partial \rho^a}{\partial t} + \nabla \cdot (\rho^a \vec{v}^a) + \rho^a \Gamma^a(x) = 0,$$

where $\vec{v}^a$ reflects transport direction derived from $\tilde{g}_{\mu\nu}$.

An effective non-Abelian structure is introduced through a coherence-based commutator:

$$[\vec{C}^a, \vec{C}^b] := f^{abc} \vec{C}^c,$$

with structure coefficients defined by coherence gradient interference:

$$f^{abc}(x) \propto \epsilon^{\mu\nu} \left(\partial_\mu \chi^a \, \partial_\nu \chi^b \right).$$

In regions of degraded coherence or high anisotropy, cone overlap fails and directional transport becomes structurally disconnected. The field modes cannot propagate independently unless all three coherence vectors are simultaneously supported:

$$\mathcal{I}(x) = \left\{ x \mid \bigcap_{a=1}^{3} \vec{C}^a(x) \neq 0 \right\}.$$

This structurally reproduces color confinement: transport only persists within coherence-bound domains, and isolated excitations collapse causally. Interaction occurs only when coherence support across all three modes is geometrically aligned—mimicking the necessity of color-neutral combinations in QCD [11].

Although no explicit SU(3) symmetry is assumed, the coherence structure enforces a triplet transport constraint, a nonlinear curvature field, and non-observability of isolated field modes. These features functionally realize SU(3) confinement through causal geometry and quantum-corrected transport dynamics [11, 12].

Toward SU(N): Coherence-Algebra from Field Interaction

While no internal symmetry algebra is assumed, the mesh structure supports the formation of multiple coherence-regulated scalar modes with directionally constrained propagation. We define a set of N scalar fields $\phi^a(x)$ (with $a = 1, ..., N$), each governed by the causal transport equation:

$$\frac{\partial \rho^a}{\partial t} + \nabla \cdot (\rho^a \vec{v}^a) + \rho^a \Gamma^a(x) = 0,$$

where $\vec{v}^a$ is the local transport velocity derived from a quantum-corrected metric $\tilde{g}_{\mu\nu}$, and $\vec{C}^a(x)$ is the coherence vector for mode a. Each field contributes to the effective transport geometry through:

$$t^a_{\mu\nu}(x) = \frac{1}{T_0} \nabla_\mu \phi^a(x) \nabla_\nu \phi^a(x), \quad \tilde{g}_{\mu\nu}(x) = g_{\mu\nu}(x) + \hbar \sum_{a=1}^{N} t^a_{\mu\nu}(x).$$

This tensor form is preserved as a structural Ansatz—selected for symmetry, curvature compatibility, and transport alignment.

We define an effective commutator:

$$[\vec{C}^a, \vec{C}^b] := f^{abc} \vec{C}^c,$$

with structure coefficients induced by coherence misalignment:

$$f^{abc}(x) \propto \epsilon^{\mu\nu} \left(\partial_\mu \chi^a \partial_\nu \chi^b \right),$$

producing interference-induced curvature terms in the evolution of ϕ^c. This defines an SU(N)-like algebra over local coherence gradients—one rooted in transport geometry and causal support, rather than imposed internal symmetry [11, 12].

Higgs-Like Structure from Scalar–Tensor Misalignment

In electroweak theory, mass arises from coupling between gauge fields and a scalar Higgs doublet. Here, we define an effective Higgs-like structure as a composite of scalar, coherence, and quantum-corrected geometry:

$$H(x) := [\phi(x),\ \tilde{g}_{\mu\nu}(x),\ \chi(x)]\,,$$

where $\phi(x)$ encodes ripple tension, $\tilde{g}_{\mu\nu}(x) = g_{\mu\nu} + \hbar t_{\mu\nu}(x)$ represents coherence-modulated geometry, and $\chi(x)$ tracks local coherence availability.

The tensor $t_{\mu\nu}(x)$ is defined structurally as:

$$t_{\mu\nu}(x) = \frac{1}{T_0}\,\nabla_\mu\phi(x)\,\nabla_\nu\phi(x),$$

maintained as an Ansatz for symmetry, energy alignment, and compatibility with rank-2 curvature sourcing.

When scalar and tensor components are aligned, transport remains coherent and massless. When misaligned, causal support collapses and effective mass emerges:

$$m^2_{\text{eff}}(x) \propto \Gamma(x) + \mathcal{R}(x),$$

where $\Gamma(x) = \nabla \cdot \vec{C}(x)$ is the coherence divergence and $\mathcal{R}(x)$ is the resistance accumulated along transport paths. This reproduces the core features of symmetry breaking—mass generation, directional bias, and coherence sensitivity—without invoking an explicit Higgs field [11, 12].

Outlook

The structural correspondence between coherence-regulated field dynamics and gauge-theoretic behavior suggests a pathway toward geometrically embedded unification. U(1)-like behavior emerges from massless ripple propagation in high-coherence regions. SU(3)-like confinement arises from cone fragmentation and causal isolation. SU(2)-type transport asymmetry and mass generation appear when scalar and tensor structures align or misalign coherently within $\tilde{g}_{\mu\nu}$.

Although no internal symmetry group is postulated, the effective behavior of gauge interactions is recovered as a function of coherence structure, tension geometry, and resistance gradients. These effects arise from structural Ansätze—such as the form of $t_{\mu\nu}$—rather than from imposed symmetry groups, but reproduce key features of gauge behavior through transport geometry. Whether full gauge symmetry can be embedded formally—through internal coherence phase spaces, structured field multiplets, or Lie-algebra-preserving cone transformations—remains an open and promising direction for future development [11, 12].

5 Causal Transport as a Structured Field Equation

To model the flow of influence within the mesh, we define a causal influence field $\rho(x,t)$ governed by the structural properties of coherence, tension, and resistance.

We propose the transport equation:

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{v}) + \rho\,\Gamma(x) = 0$$

where:

- $\vec{v}(x)$ is the tension-based propagation vector.
- $\Gamma(x)$ is a local decay term derived from the divergence of coherence:

$$\Gamma(x) = \nabla\cdot\vec{C}(x)$$

- The domain of influence is defined by the effective cone:

$$\text{Cone}_{\text{eff}}(x) = \{x \mid \vec{C}(x) \neq 0,\, v(x) > 0,\, \mathcal{R}(x) < \infty\}$$

This equation defines the causal dynamics of structured propagation in a field-theoretic setting, with collapse and constraint emerging from internal coherence degradation.

Causality Without Predefined Geometry

The Mesh Model thus reverses the standard picture: causal structure is not imposed by geometry—it creates it. The classical light cone is no longer an axiom of the spacetime manifold, but an emergent limit of ripple-based propagation in a structured field [1].

This unification bridges the gap between general relativity and quantum field behavior. GR's causal invariance arises in the limit of stable, high-tension, high-coherence mesh regions. QFT's field locality emerges from directional coherence patterns bounded by the tension cone [14]. And deviations from either—such as gravitational wave echoes, jet anisotropies, or black hole horizon dynamics—can now be seen as structural deformations of the effective cone [5, 6].

We define the effective propagation speed v_{eff} across a coherence-regulated path γ as the harmonic mean of local velocity along the path:

$$v_{\text{eff}} = \left(\int_\gamma \frac{1}{v(x)}\, ds \right)^{-1} L$$

where:

- $v(x) = \sqrt{T(x)/\mu(x)}$ is the local signal speed from the tension cone,
- $L = \int_\gamma ds$ is the proper path length.

This expression accounts for mesh-induced anisotropy and tension modulation along the signal path.

Toward a Structured Causal Geometry

What emerges from this synthesis is not a replacement for relativistic geometry, but a deeper scaffolding that can explain where its causal features come from. The effective cone unites:

- $\vec{C}(x)$: the availability of coherence (can information propagate?)
- $\vec{v}(x)$: the tension-governed velocity structure (how fast and where?)
- $\mathcal{R}(x)$: the accumulated curvature resistance (how distorted or delayed?)

These three together give a complete causal fingerprint for any region of the mesh.

In the sections that follow, we explore how this structured causality constrains entropy flow and information propagation, and how it leads to observable predictions.

5.1 Causal Influence as Mesh-Based Ripple Propagation

The scalar field $\phi(x,t)$ defined in the mesh framework represents structured ripple dynamics across a coherence-regulated substrate. Its propagation is governed by the local tension tensor and coherence profile, leading to an anisotropic wave equation:

$$\frac{\partial^2 \phi}{\partial t^2} - \nabla \cdot \left(v^2(x) \nabla \phi \right) = 0$$

where $v^2(x) = T_{ij}(x)/\mu(x)$. We define the causal influence field $\rho(x,t)$ as the structured ripple intensity:

$$\rho(x,t) = \frac{1}{2} \left[\left(\frac{\partial \phi}{\partial t} \right)^2 + v^2(x)(\nabla \phi)^2 \right]$$

This field evolves under a transport equation derived from mesh structure:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}(x)) + \rho\, \Gamma(x) = 0$$

Here:

- $\vec{v}(x)$ is the local mesh-based propagation vector.
- $\Gamma(x) = \nabla \cdot \vec{C}(x)$ represents coherence divergence (loss of structural support).

This formulation describes how structured influence propagates, attenuates, and collapses within the causal geometry of the mesh. It integrates coherence, tension, and resistance into a unified expression of causal evolution.

5.2 Causal Geometry in the Double Slit Configuration

To illustrate how the structured causal framework constrains interference and collapse, we apply the cone formalism to the classic double slit setup. We analyze this configuration not as a quantum abstraction, but as a ripple-propagating system constrained by coherence, tension, and resistance—each embedded in the mesh field structure [11, 12].

Let $\phi_L(x,t)$ and $\phi_R(x,t)$ denote scalar field solutions emanating from the left and right slits, respectively. The total field at a point on the screen is:

$$\phi(x,t) = \phi_L(x,t) + \phi_R(x,t)$$

We define the causal influence field associated with this structure as:

$$\rho(x,t) = \frac{1}{2} \left[\left(\frac{\partial \phi}{\partial t} \right)^2 + v^2(x)(\nabla \phi)^2 \right]$$

which evolves under the transport equation derived from mesh-based propagation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}(x)) + \rho\, \Gamma(x) = 0$$

where:

- $\vec{v}(x)$ is the local signal velocity vector from the tension cone.

- $\Gamma(x) = \nabla \cdot \vec{C}(x)$ is the coherence divergence (collapse rate).
- $\vec{C}(x) = \nabla\phi \cdot \chi(x)$ is the coherence vector field [3].

We now define the interference-permitted region $\mathcal{I}(x)$ as the set of points where the coherence vectors from both slits overlap constructively and resistance remains finite:

$$\mathcal{I}(x) = \left\{ x \mid \vec{C}_L(x) \cdot \vec{C}_R(x) > 0 \quad \text{and} \quad \mathcal{R}(x) < \infty \right\}$$

Outside this region, causal disconnection or saturation occurs, and interference collapses geometrically. The resistance term is defined pathwise by:

$$\mathcal{R}(x) = \int_{\gamma_x} (1 - \chi(x(s)))\, ds$$

where γ_x is a field-supported path from slit to detector point x.

This construction imposes physical boundaries on interference visibility. Fringes appear only where coherence cones overlap, propagation velocity supports phase alignment, and resistance does not suppress structured influence. Collapse is not treated as an axiomatic measurement event, but as the terminal result of failed causal propagation.

The structured field $\phi(x,t)$ describing ripple propagation through the slit system evolves under the mesh-derived wave equation:

$$\frac{\partial^2 \phi}{\partial t^2} - \nabla \cdot \left(v^2(x) \nabla \phi \right) = 0$$

This equation governs the left- and right-slit fields ϕ_L, ϕ_R, and their superposition. The local signal velocity $v(x)$ is determined by the mesh tension tensor via $v^2(x) = T_{ij}(x)/\mu(x)$.

Interference only persists in regions where the coherence field supports stable wave propagation. Collapse and decoherence occur where $v(x) \to 0$ or $\Gamma(x)$ becomes large. The resulting interference zone is not assumed—it's a domain of well-supported solutions to the structured field equation.

This application unifies the causal geometry defined in this work with interference behavior derived in previous field-theoretic formulations. It provides a pathway toward modeling collapse not as a discrete event, but as a dynamically constrained boundary of causal flow in structured spacetime [15].

6 Entropy and Information Boundaries

Causal boundaries constrain not only whether influence can propagate, but also how much structured information can be transmitted through a region. In the coherence-regulated field framework, entropy flow is governed by the structure and divergence of the coherence vector $\vec{C}(x)$. Where coherence flow bottlenecks, information transport is similarly constrained [14].

This section introduces a structural formulation of entropy bounds, inspired by the Bousso bound [16, 17], but derived directly from the behavior of the coherence field. The divergence of $\vec{C}(x)$ defines effective information flux through a causal surface, and its integrability limits determine the structural capacity for entropy transport.

Divergence of Coherence and Information Flux

Let $\vec{C}(x)$ denote the local coherence vector field as defined in Section 2. The divergence $\nabla \cdot \vec{C}(x)$ quantifies the rate at which coherent ripple influence expands or contracts within a region. Positive divergence indicates coherence outflow; negative divergence indicates structural collapse.

The maximum entropy flux through a surface Σ is bounded by the divergence of $\vec{C}(x)$ across that surface:

$$S_{\max} \leq \frac{1}{4} \int_{\Sigma} \left| \nabla \cdot \vec{C}(x) \right| dA \tag{5}$$

where:

- Σ is a codimension-one surface bounding a region of the coherence-regulated field.
- $\vec{C}(x)$ is the local causal availability vector field.
- The integrand represents the net structural support for entropy-carrying ripple propagation.

This bound constrains entropy transport not by geometric assumptions, but by the field's internal ability to support coherent signal flow. In regions where $\vec{C}(x)$ collapses, entropy flux is suppressed. This formulation yields a structural equivalent to holographic bounds, with coherence divergence replacing surface area or geodesic focusing as the limiting mechanism.

Bousso Bound as a Structural Limit

In general relativity, the Bousso bound constrains the entropy flux through a surface based on its area and the convergence of null rays orthogonal to it [16]. In the coherence-regulated framework, this geometric focusing condition is replaced by the divergence of the coherence vector field $\vec{C}(x)$.

This substitution reframes entropy transport as a structural constraint: causal information flow is limited by the coherence structure of the field, not by spacetime geometry. Surfaces where $\nabla \cdot \vec{C}(x)$ is minimized define entropy bottlenecks. The entropy bound becomes:

$$S_{\max} \leq \frac{1}{4} \int_{\Sigma} \left| \nabla \cdot \vec{C}(x) \right| dA$$

This result provides a physically grounded, testable formulation of entropy limits arising from field dynamics rather than geometric axioms.

Holography as a Structural Effect

Where coherence collapses sharply—such as across vacuum gradients or regions of discontinuous tension—entropy flow becomes restricted to lower-dimensional subspaces. This reproduces holographic behavior: entropy scaling with surface area rather than volume.

In this formulation, holography arises as a structural outcome of field coherence limits. The transition from volume-based to surface-based entropy encoding is governed by local properties of $\vec{C}(x)$ and its divergence, rather than a universal principle.

This model predicts that holographic behavior may vary in strength and orientation based on coherence anisotropy. Such variation, if observed in gravitational wave echoes or near-horizon dynamics, could serve as an indirect probe of coherence geometry in extreme field configurations.

The next section explores how these structural constraints influence observable astrophysical signals.

7 Mass, Collapse, and Coherence Phases: From Gauge Behavior to Darkness

Dark Matter as a Coherence-Isolated Field Phase

The scalar–tensor–coherence framework developed in this work provides a structural mechanism for mass generation through misalignment between scalar ripple propagation and curvature-induced resistance. In this model, mass is not a fixed property of the field, but a consequence of causal structure:

$$m_{\text{eff}}^2(x) \propto \Gamma(x) + \mathcal{R}(x),$$

where $\Gamma(x) = \nabla \cdot \vec{C}(x)$ is the divergence of the coherence vector, and $\mathcal{R}(x)$ is the integrated resistance to causal transport.

In regions where scalar–tensor alignment is strong and coherence is high, the field supports massless propagation and standard quantum behavior. But when coherence is low or fragmented—and curvature structure introduces significant resistance—field excitations become causally isolated and acquire effective mass. These excitations:

- Gravitate through mass induced by coherence collapse and resistance accumulation,
- Do not emit, absorb, or scatter—since causal transport is suppressed ($\vec{C}(x) \to 0$),
- Remain stable over long timescales due to confinement within disconnected cone geometry.

These properties match the defining traits of dark matter: gravitational mass, non-interaction with luminous fields, and long-term structural stability. In this framework, dark matter is not a separate particle species or externally coupled field—it is a **phase of the causal field** in which coherence fails but geometric structure persists.

This suggests that dark matter may be understood as a structural sector of the scalar–tensor field: a domain where causal geometry exists, but is disconnected from the coherence cones required for observable interaction. Gravitational lensing, structure formation, and halo distributions may offer indirect access to these coherence-isolated regions [18, 19].

Dark Energy as a High-Coherence Background Phase

While mass and interaction arise from coherence fragmentation and scalar–tensor misalignment, a contrasting phase emerges when coherence remains uniformly high, resistance is minimal, and causal structure remains unconstrained.

In such regions, the scalar field retains full coherence support ($\chi(x) \approx 1$) but does not collapse or localize. The resistance integral $\mathcal{R}(x)$ remains near zero, and cone geometry expands freely without gravitational binding. This defines a phase where ripple propagation is sustained, but structure cannot condense.

This coherence-dominated regime exhibits the key features associated with dark energy:

- Persistent expansion driven by field tension, unopposed by curvature or collapse,
- Uniform, non-clumping behavior across space,
- A negative-pressure-like effect due to coherence-driven volumetric expansion,
- Absence of causal fragmentation or confinement.

In this view, dark energy is not a constant or exotic scalar field, but a **high-coherence background phase** of the same causal system that gives rise to both matter and dark matter. Matter arises from coherence fragmentation and structural confinement; dark matter from causal isolation; and dark energy from coherence without collapse [18, 19].

Neutrino Transport, Oscillation, and Coherence Structure

While mass and confinement arise from scalar–tensor misalignment and coherence collapse, neutrino behavior presents a more subtle structure: one in which mass is present but minimal, chirality is asymmetric, and propagation occurs through overlapping yet flavor-specific causal channels. This section shows how neutrino oscillation, chiral suppression, and potential CP violation emerge as direct consequences of coherence geometry, without requiring externally imposed flavor symmetry or mixing matrices [11, 12].

We define each neutrino flavor $\nu_a(x)$ as a scalar coherence mode $\phi^a(x)$ with its own transport geometry:

$$m_a^2(x) = \Gamma^a(x) + \mathcal{R}^a(x)$$

where:

- $\Gamma^a(x) = \nabla \cdot \vec{C}^a(x)$ is the local divergence of flavor-specific coherence flow,
- $\mathcal{R}^a(x) = \int_{\gamma_a} (1 - \chi^a(x(s)))\, ds$ is the accumulated resistance along a flavor-constrained path.

This structural mass term varies between modes and sets the baseline for oscillation.

We describe flavor superposition as a field rotation:

$$\phi^a(x,t) = \sum_b U^{ab}(x)\psi^b(x,t)$$

with $U^{ab}(x)$ defined by cone overlap and coherence alignment across modes. The evolution of each mode is governed by:

$$i\frac{\partial}{\partial t}\phi^a(x,t) = \left[-\nabla \cdot (v^a(x)\nabla) + m_a^2(x)\right]\phi^a(x,t)$$

Oscillation arises as coherence-induced phase beating between propagating eigenmodes, regulated by local geometry [15].

Let $\phi_L^a(x)$ and $\phi_R^a(x)$ denote left- and right-handed components of a neutrino mode. Their causal stability is governed by:

$$\Gamma_L^a(x) = \nabla \cdot \vec{C}_L^a(x), \quad \Gamma_R^a(x) = \nabla \cdot \vec{C}_R^a(x)$$

We define the chiral asymmetry:

$$\Delta\Gamma^a(x) = \Gamma_L^a(x) - \Gamma_R^a(x)$$

When $\Delta\Gamma^a \gg 0$, right-handed components collapse more rapidly, leaving only left-handed propagation in observable channels.

Each coherence field may carry an intrinsic phase $\delta_a(x)$:

$$\vec{C}^a(x) = |\vec{C}^a(x)|e^{i\delta_a(x)}$$

We define the geometric interference between flavors:

$$\mathcal{I}^{ab}(x) = \mathrm{Re}\left[\vec{C}^a(x) \cdot \vec{C}^{b*}(x)\right] = |\vec{C}^a||\vec{C}^b| \cos(\delta_a - \delta_b)$$

Nonzero $\delta_a - \delta_b$ produces phase asymmetries in oscillation rates—offering a structural mechanism for CP violation [15].

Sterile Neutrinos as Coherence-Isolated Phases

The causal framework developed in previous sections describes how mass and isolation arise from coherence collapse and cone disconnection. In this structure, we identify sterile neutrinos as a distinct field phase: one that exhibits internal coherence and effective mass but lacks causal support within the observable mesh.

We define the sterile neutrino mode $\phi_s(x)$ as:

$$\vec{C}^s(x) \approx 0, \quad \mathcal{R}^s(x) \gg 1$$

This state does not emit, absorb, or scatter—since it is causally disconnected—but may still couple gravitationally. It mirrors the same confinement mechanism discussed in Section 7 for dark matter and in the SU(3) formulation as coherence cone fragmentation.

Oscillation into such a state is still permitted structurally, via local interference between coherence channels:

$$\phi^a(x) = \sum_b U^{ab}(x)\psi^b(x) + U^{as}(x)\phi_s(x)$$

Here, $U^{as}(x)$ arises from the geometry of local cone overlap—even when one mode is causally limited. This offers a field-based realization of sterile neutrinos as **non-radiating, coherence-confined excitations** that may transition into or out of observable neutrino states through mesh-level interference [15].

Spin-$\frac{1}{2}$ Behavior from Coherence Phase Geometry

In the coherence-regulated framework, causal propagation is governed not only by the presence of phase-aligned structure, but by how that structure is geometrically wound. In this section, we show how spin-$\frac{1}{2}$ behavior—specifically, the double-valued phase structure of fermions—emerges naturally from the topology of coherence flow in the field [11, 12].

Topological Phase Wrapping and Field Sign Reversal

We begin with the coherence vector:

$$\vec{C}(x) = \nabla\phi(x) \cdot \chi(x)$$

and consider a coherence phase field with winding behavior:

$$\phi(x) = \frac{\theta(x)}{2}, \quad \theta \in [0, 2\pi)$$

A full 2π rotation in θ corresponds to a π shift in ϕ, so that:

$$\Psi(x) \propto e^{i\phi(x)} = e^{i\theta(x)/2}$$

This defines a double-valued field structure: under a closed loop around a vortex, the field acquires a sign flip:

$$\oint_\gamma \nabla\theta \cdot d\ell = 2\pi \quad \Rightarrow \quad \Psi(x) \to -\Psi(x)$$

This is the hallmark of spin-$\frac{1}{2}$ behavior.

Spinor Construction from Coherence Modes

We define a local two-component coherence structure:

$$\Psi(x) = \begin{bmatrix} \phi_1(x) \\ \phi_2(x) \end{bmatrix}$$

where ϕ_1 and ϕ_2 are orthogonal field modes related by a transport-induced rotation. Local coherence flow acts on this object via a phase-driven SU(2)-like operator:

$$\Psi(x) \mapsto e^{i\vec{\alpha}(x)\cdot\vec{\sigma}/2}\Psi(x)$$

with $\vec{\sigma}$ as effective coherence rotation generators, constructed from directional coherence gradients or curvature-aligned phase flows [11].

This structure reproduces the transformation properties of spin-$\frac{1}{2}$ fields: under a 2π rotation, the field acquires a minus sign:

$$e^{i\pi\vec{n}\cdot\vec{\sigma}} = -\mathbb{I}$$

Angular Momentum and Quantized Circulation

The mesh coherence structure also admits a circulation-based angular momentum density:

$$S_k = \frac{1}{2}\int d^3x\, \epsilon_{ijk}\, \rho(x)\, (x_i\partial_j\theta(x) - x_j\partial_i\theta(x))$$

Here, $\rho(x)$ is the ripple energy density, and $\theta(x)$ is the coherence phase. The integrand quantifies the winding of causal phase flow around a spatial axis, yielding a quantized spin measure when integrated around a localized structure.

This provides a structural foundation for spin quantization: a topologically protected coherence twist that imposes a discrete angular momentum spectrum, even in the absence of imposed symmetry [15].

Summary

In this framework, spin-$\frac{1}{2}$ behavior emerges from a double-valued coherence phase geometry and two-mode ripple structure. The sign reversal under 2π rotation is not imposed—it is a topological consequence of coherence alignment and transport around causal loops. This offers a non-algebraic, field-structural origin for half-integer spin in the same language that governs mass, transport, and flavor dynamics [11, 12].

Coherence Triplets and Quark Behavior from Cone Geometry

The Mesh Model framework supports spin, mass, confinement, and gauge-like transport through field-coherence dynamics. In this section, we extend the causal and geometric formalism to model quark-like structures: spin-$\frac{1}{2}$ excitations confined in triplets, exhibiting fractional charge, non-Abelian interaction structure, and color-neutrality constraints.

1. Fractional Charge from Coherence Winding

Let each quark-like excitation be defined by a coherence phase field $\theta^a(x)$ associated with flavor $a \in \{1, 2, 3\}$. The physical field is taken to be:

$$\phi^a(x) = \frac{\theta^a(x)}{k_a}, \quad k_a \in \mathbb{Z}^+$$

We define the effective topological charge of the mode as:

$$Q^a = \frac{1}{2\pi} \oint_\gamma \nabla\theta^a(x) \cdot d\ell = \frac{n_a}{k_a}, \quad n_a \in \mathbb{Z}$$

For $k_a = 3$, this yields allowed fractional charges:

$$Q^a \in \left\{ \pm\frac{1}{3}, \pm\frac{2}{3}, \pm 1, ... \right\}$$

This defines charge as a **winding density per mode**. Total observable charge is the sum over coherence contributions:

$$Q_{\text{total}} = \sum_a Q^a$$

2. Color Singlet Constraint via Cone Neutrality

Each mode has an associated coherence vector $\vec{C}^a(x)$. We define the total color vector:

$$\Psi_{\text{color}}(x) = \sum_{a=1}^{3} \vec{C}^a(x)$$

The color singlet condition requires that the composite state supports propagation only when:

$$\Psi_{\text{color}}(x) = 0 \quad \text{(color neutrality)}$$

This ensures that only color-neutral combinations form bound states, reproducing confinement of non-singlet configurations.

3. Confinement Potential from Coherence Resistance

Define the resistance to causal propagation between coherence modes as:

$$\mathcal{R}_{ab}(r) = \int_0^r (1 - \chi^a(x))\, dx$$

Let this represent the effective interaction cost between a quark of type a and b. The total pairwise potential becomes:

$$V_{ab}(r) \propto \mathcal{R}_{ab}(r) \quad \Rightarrow \quad V(r) \to \infty \text{ as } \chi \to 0$$

This reproduces confinement: as separation increases and coherence support drops, the energy cost of separation diverges.

4. Bound State Energy Functional

Let the total composite field be:

$$\phi(x) = \phi^1(x) + \phi^2(x) + \phi^3(x)$$

Define the ripple energy density for each flavor as:

$$\rho^a(x) = \frac{1}{2}\left[(\partial_t\phi^a)^2 + v^2(x)(\nabla\phi^a)^2\right]$$

The total system energy is:

$$E[\phi] = \int d^3x \left(\sum_{a=1}^{3} \rho^a(x) + \sum_{a<b} \left|\vec{C}^a(x)\cdot\vec{C}^b(x)\right|\right)$$

The cross terms represent coupling energy due to cone overlap. The minimum-energy configuration satisfies:

$$\vec{C}^1(x) + \vec{C}^2(x) + \vec{C}^3(x) = 0, \quad \Gamma^a(x) = 0$$

which ensures cone alignment, color neutrality, and coherence preservation.

5. Gluon-Like Interaction Terms from Coherence Commutators

We define an effective field strength tensor:

$$\mathcal{F}^{ab}_{\mu\nu}(x) = \partial_\mu C^a_\nu - \partial_\nu C^a_\mu + f^{abc} C^b_\mu C^c_\nu$$

Where:

$$f^{abc}(x) \propto \epsilon^{\mu\nu}\left(\partial_\mu\chi^b\partial_\nu\chi^c\right)$$

This structure mirrors non-Abelian gauge field dynamics, with curvature induced by coherence misalignment. These interference-driven corrections regulate coherence flow across overlapping cone regions.

Summary

The Mesh Model supports a structural realization of quark-like behavior. Fractional charge arises from mode winding, confinement from rising resistance, and color singlet propagation from cone alignment constraints. A composite triplet state behaves as a coherence-bound hadron, with gluon-like curvature encoded in commutators between coherence vectors. No symmetry group is imposed—yet SU(3)-like dynamics emerge geometrically from causal transport.

Gluon Field Dynamics from Coherence Curvature

The preceding section established that quark-like excitations arise as coherence-phase modes confined within color-neutral triplet combinations. These excitations interact through coherence cone overlap and are constrained by a causal structure that enforces SU(3)-like transport behavior. We now extend this framework to describe the fields that mediate these interactions. These fields—structured through coherence curvature—serve as the Mesh Model analog of gluons.

1. Coherence Curvature as Field Strength

We begin with the coherence vector field $C^a_\mu(x)$ associated with flavor or color label a. The effective field strength tensor is defined as:

$$\mathcal{F}^{ab}_{\mu\nu}(x) = \partial_\mu C^a_\nu(x) - \partial_\nu C^a_\mu(x) + f^{abc} C^b_\mu(x) C^c_\nu(x)$$

Here:

- The first two terms represent curvature in the transport geometry,
- The third term captures non-Abelian interference structure, where:

  $$f^{abc}(x) \propto \epsilon^{\rho\sigma} \left(\partial_\rho \chi^b(x) \partial_\sigma \chi^c(x) \right)$$

  represents structural misalignment between coherence masks.

2. Gluon Field Definition and Propagation

We define the gluon-like field as the deviation of the coherence vector from a pure scalar gradient:

$$G^a_\mu(x) = C^a_\mu(x) - \partial_\mu \phi^a(x)$$

This defines the gluon as a vector field arising from curvature in phase transport—i.e., a failure of the coherence vector to remain purely gradient-aligned.

This field satisfies a generalized evolution equation of the Yang–Mills type:

$$\nabla^\mu \mathcal{F}^{ab}_{\mu\nu}(x) + f^{abc} G^{c\mu}(x) \mathcal{F}^{bd}_{\mu\nu}(x) = J^b_\nu(x)$$

where $J^b_\nu(x)$ is a coherence current generated by phase flow in quark-like modes.

3. Coherence Current as Source Term

The interaction between quark coherence modes $\phi^a(x)$ induces a field-aligned current:

$$J^a_\nu(x) = \phi^b(x) \partial_\nu \phi^c(x) f^{abc}(x)$$

This term structurally matches the color current in non-Abelian gauge theory. It ensures that changes in the coherence phase of bound triplets generate a back-reaction in the gluon field.

4. Dynamic Feedback and Self-Interaction

The presence of $f^{abc} G^b_\mu G^c_\nu$ in $\mathcal{F}^{ab}_{\mu\nu}$ introduces gluon self-interactions. These terms are not assumed—they emerge from the curvature of overlapping coherence vectors. This reproduces the nonlinear dynamics of gluon fields within SU(3)-like geometry.

5. Interpretation and Summary

The Mesh Model does not introduce gluons as elementary gauge bosons. Instead, gluons emerge as coherence curvature fields that mediate interactions between color modes. Their field strength tensor arises from structural interference in cone transport. Their propagation follows from causal coherence constraints. Their self-interaction is a consequence of overlapping phase gradients.

This structure reproduces the full behavior of gluon dynamics—nonlinearity, self-coupling, and triplet connectivity—without postulating gauge symmetry. Gluons in this framework are the dynamic agents of mesh coherence regulation, responsible for quark binding, confinement, and triplet-level propagation across causal domains.

8 Observational Predictions

The value of a physical framework lies not only in its internal coherence, but in its ability to produce measurable consequences. The causal structure defined by coherence, tension, and curvature cones offers new avenues for interpreting and predicting astrophysical phenomena. This section outlines several domains where the effects of structured causality may become observable.

Gravitational Wave Echoes and Cone Reflections

In coherence-regulated field systems, black holes do not terminate in singularities or event horizons, but in stable quantum cores surrounded by steep coherence gradients [10]. These gradients form partially reflective barriers to ripple propagation—delaying or redirecting signal energy.

This structure gives rise to predicted *gravitational wave echoes* following black hole mergers. Unlike standard ringdowns in general relativity, where signals dampen quickly, coherence gradients in the causal field framework allow for secondary signals delayed by curvature-induced reflections within the vacuum boundary layer [5, 6].

Echo delay scales with the resistance integral $\mathcal{R}(x)$ accumulated along a round-trip causal path from the core to the vacuum shell:

$$\Delta t_{\text{echo}} \approx \frac{2}{v_{\text{eff}}} \int_{\gamma} (1 - \chi(x))\, ds$$

where:

- $\chi(x)$ is the local coherence mask.
- γ is the round-trip causal path.
- v_{eff} is the effective propagation speed, defined by:

$$v_{\text{eff}} = \left(\int_{\gamma} \frac{1}{v(x)}\, ds \right)^{-1} L$$

with L the proper path length.

This structure connects directly to observable features:

- Steep coherence gradients $\rightarrow$ larger $\mathcal{R}(x)$ $\rightarrow$ longer delay times.
- Tension anisotropy $\rightarrow$ directional variation in echo amplitudes.
- Coherence divergence $\Gamma(x)$ $\rightarrow$ localized damping and echo profile modulation.

Detecting such echoes—and analyzing their delay, shape, and angular structure—may provide indirect access to the geometry, resistance profile, and anisotropy of the underlying cone system near collapsed quantum cores. These observations would serve as testable signatures of coherence-regulated causal geometry.

Black Hole Radiation via Coherence Tunneling

In field systems constrained by coherence-regulated transport, black hole radiation arises not from event horizons and pair production, but from ripple tunneling across structured resistance barriers [10]. A ripple approaching a steep vacuum gradient may escape by tunneling through a high-resistance boundary defined by $\mathcal{R}(x)$.

The tunneling rate is given by:

$$\Gamma \sim \exp\left(-\frac{\Delta\mathcal{R}}{\hbar}\right) \tag{6}$$

where $\Delta\mathcal{R}$ is the resistance difference across the vacuum shell.

This process preserves unitarity and emits radiation without invoking geometric singularities. In the high-mass limit, the emitted spectrum approximates the thermal profile predicted by Hawking radiation [2]. Observable deviations from perfect thermality—particularly spectrum shifts or anisotropies—could provide empirical tests of resistance-mediated tunneling.

Jet Alignment and Anisotropic Tension Cones

In rotating or shear-driven systems, anisotropy in the tension cone structure constrains ripple propagation to preferred spatial channels. These anisotropic pathways arise naturally in regions where $T_{ij}(x)$ exhibits directional bias, producing coherent escape routes aligned with maximal-tension axes [20].

This mechanism offers a structural explanation for the observed alignment of relativistic jets in active galactic nuclei and compact binaries. Rather than attributing jet collimation solely to ergospheres or magnetic fields, this approach links jet structure to the directional propagation capacity of the tension cone.

Testable predictions include:

- Jet orientation correlates with maximal-tension directions in rotating systems.
- Coherent ripple propagation favors escape along anisotropic tension channels.

These predictions can be evaluated by comparing jet structures with spin geometry and inferred tension anisotropy from lensing and accretion disk alignment data.

Quasinormal Modes and Horizon Deformation

The vibrational response of compact objects—quasinormal modes (QNMs)—is sensitive to the causal structure surrounding the emission region. In coherence-regulated field systems, collapsing configurations that form steep vacuum gradients without true horizons will exhibit QNMs that deviate from general relativity predictions [10].

Observable signatures include:

- Lengthened damping times, as signal propagation is delayed by increased curvature cone resistance $\mathcal{R}(x)$.
- Mode frequency shifts, resulting from anisotropic wave speeds in tension-deformed regions.

Precision QNM measurements from detectors such as LIGO, Virgo, and the next generation of gravitational wave observatories may provide constraints on cone structure near compact cores.

Pathways to Empirical Constraint

The predictive mechanisms introduced in this framework rely on the interaction of coherence, tension, and curvature fields. Each cone structure emerges from field-regulated dynamics and produces testable signatures in observational data.

While the field definitions are physically grounded, their specific thresholds and parametric forms require empirical calibration. As gravitational wave astronomy, high-resolution imaging, and compact object spectroscopy advance, the ability to constrain and map cone geometry will improve.

This work provides a structural framework. Its alignment with data will determine its future viability.

Structural Analog of Field Decay

In standard quantum field theory, particle decay is modeled via perturbative interaction amplitudes derived from Feynman diagrams. In the structured causal framework, decay arises when coherence becomes unstable and causal propagation diverges. The decay rate is structurally defined by the divergence of the coherence vector:

$$\Gamma(x) = \nabla \cdot \vec{C}(x)$$

This produces a decay probability:

$$P(t) = 1 - e^{-\int \Gamma(x(t))dt}$$

This formulation mirrors standard exponential decay but grounds the rate in structural failure, not coupling parameters. The decay process corresponds to ripple propagation splitting across multiple causal pathways, initiated by structural thresholds rather than perturbative vertices.

These observational predictions point toward a testable causal geometry shaped by coherence, tension, and resistance. But the same structures that govern black hole echoes and wave tunneling also determine how matter, interaction, and isolation arise within the field itself. In what follows, we examine how coherence collapse and scalar–tensor misalignment give rise to mass, causal confinement, and non-interacting field phases—revealing the structural basis for phenomena traditionally attributed to dark matter and dark energy.

9 Mathematical Framework

This section summarizes the key mathematical structures used to define and unify the three cone types—coherence, tension, and curvature. These expressions represent a transition from geometric postulates to physically grounded field dynamics. They offer a substrate from which classical causal behavior emerges as a limiting case [21, 14].

1. Coherence Vector Field

The coherence vector field describes the structured flow of ripple-based influence:

$$\vec{C}(x,t) = \nabla\phi(x,t) \cdot \chi(x,t) \tag{7}$$

Where:

- $\phi(x,t)$ is the ripple phase field (analogous to a potential or phase gradient).

- $\chi(x,t) \in [0,1]$ is a coherence mask—1 where propagation is fully supported, 0 where coherence fails.
- $\vec{C}(x,t)$ defines the local causal direction and strength of influence.

The coherence cone is defined by the region where $\vec{C}(x,t)$ is non-zero and structurally supported.

2. Tension-Dependent Signal Speed

Local signal propagation speed is derived from the tension tensor field:

$$v^2(x) = \frac{T(x)}{\mu(x)} \quad \Rightarrow \quad \vec{v}(x) = \sqrt{\frac{T_{ij}(x)}{\mu}} \cdot \hat{n} \tag{8}$$

Where:

- $T_{ij}(x)$ is the directional tension tensor at point x.
- μ is the effective mass density of the mesh medium.
- $\hat{n}$ is the intended propagation direction.
- $\vec{v}(x)$ defines the local anisotropic ripple velocity.

This structure generalizes classical field propagation in elastic media and shares conceptual roots with Born–Infeld theory, where tension limits and signal propagation constraints naturally arise [22, 8].

3. Accumulated Curvature Resistance

Curvature is defined as an integral measure of coherence decay across a path γ:

$$\mathcal{R}(x) = \int_\gamma (1 - \chi(x(s)))\ ds \tag{9}$$

Where:

- γ is a path (typically along $\vec{C}$).
- $\chi(x)$ is the coherence mask along that path.
- $\mathcal{R}(x)$ quantifies the total resistance to coherent propagation.

This accumulated resistance deforms propagation paths and mimics gravitational curvature in the limit [10].

4. Unified Effective Cone Function

The effective causal cone combines the above structures into a single functional description:

$$\mathrm{Cone}_{\mathrm{effective}}(x) = f\left(\vec{C}(x), \vec{v}(x), \mathcal{R}(x)\right) \tag{10}$$

This is a generalized causal boundary—shaped by local coherence, propagation speed, and resistance. It replaces geometric null cones with a physically emergent causal frontier [21].

5. Entropy Bound from Coherence Divergence

Information flow is bounded by the divergence of coherence vectors:

$$S_{\max} \leq \frac{1}{4} \int_{\Sigma} \left| \nabla \cdot \vec{C}(x) \right| \, dA \tag{11}$$

Where:

- Σ is a surface bounding the causal region.
- $\nabla \cdot \vec{C}$ quantifies the bottleneck in coherence flow.

This structurally reproduces the Bousso bound [16, 17], traditionally defined in terms of null expansion, but here derived from ripple-capable structure.

6. Horizonless Tunneling Radiation

Black hole radiation is modeled here as tunneling through a coherence-regulated causal barrier. Rather than invoking an event horizon, this mechanism arises from quantum-limited transport across a steep coherence gradient embedded in a corrected geometric background.

We define the quantum-corrected metric as:

$$\tilde{g}_{\mu\nu}(x) = g_{\mu\nu}(x) + \hbar t_{\mu\nu}(x), \quad t_{\mu\nu}(x) = \frac{1}{T_0} \nabla_\mu \phi(x) \nabla_\nu \phi(x)$$

The tunneling rate across a resistance gradient becomes:

$$\Gamma \sim \exp\left(-\frac{\Delta \mathcal{R}}{\hbar}\right) \tag{12}$$

where $\Delta\mathcal{R}$ is the resistance difference across a causal boundary defined by deformed cone structure in the $\tilde{g}_{\mu\nu}$ background. This replaces Hawking's geometric horizon formalism with a mechanism rooted in coherence-regulated transport and causal cone geometry [10, 2].

Observable Quantities Derived from Structured Cone Geometry

We summarize below the key observable quantities derived from the causal cone framework, along with their structural origin and associated equations.

Observable	Governing Equation	Structural Origin
Echo delay time Δt_{echo}	$\Delta t_{\text{echo}} \approx \frac{2}{v_{\text{eff}}} \int_\gamma (1 - \chi(x))\, ds$	Curvature cone resistance $\mathcal{R}(x)$
Effective propagation speed v_{eff}	$v_{\text{eff}} = \left(\int_\gamma \frac{1}{v(x)}\, ds \right)^{-1} L$	Tension cone: anisotropic $t_{\mu\nu}(x)$
Tunneling rate Γ	$\Gamma \sim \exp(-\Delta\mathcal{R}/\hbar)$	Quantum-corrected resistance gradient via $\tilde{g}_{\mu\nu}(x)$
Entropy bound $S_{\max}$	$S_{\max} \leq \frac{1}{4} \int_\Sigma \lvert \nabla \cdot \vec{C} \rvert \, dA$	Divergence of coherence vector field
Interference region $\mathcal{I}(x)$	$\mathcal{I}(x) = \left\{ x \mid \vec{C}_L \cdot \vec{C}_R > 0,\ \mathcal{R}(x) < \infty \right\}$	Cone overlap and coherence structure

7. Mass from Coherence Collapse and Resistance

Mass emerges in this framework as a structural response to coherence failure and curvature-induced delay. The effective mass of a field excitation is defined as:

$$m_{\text{eff}}^2(x) \propto \Gamma(x) + \mathcal{R}(x) \tag{13}$$

Where:

- $\Gamma(x) = \nabla \cdot \vec{C}(x)$ is the coherence divergence (rate of causal collapse),
- $\mathcal{R}(x)$ is the integrated resistance along a transport path.

This structural mass term governs causal inertia and confinement, replacing symmetry-breaking potentials with phase-alignment thresholds in scalar–tensor geometry.

8. Commutation Structure from Coherence Misalignment

An effective SU(N)-like algebra emerges from the interference between coherence gradients:

$$[\vec{C}^a, \vec{C}^b] := f^{abc}\vec{C}^c \tag{14}$$

With structure coefficients defined geometrically:

$$f^{abc}(x) \propto \epsilon^{\mu\nu} \left(\partial_\mu \chi^a \, \partial_\nu \chi^b\right) \tag{15}$$

This defines a curvature-like transport structure between scalar modes $\phi^a(x)$, where coherence misalignment induces structural interference terms analogous to non-Abelian gauge curvature.

Summary

These equations establish a physically structured foundation for causal dynamics. They eliminate the need to postulate spacetime curvature, gauge symmetry, or particle mass at the outset. Instead, these features emerge from coherence-regulated interactions within a structured field substrate. Geometry arises from ripple propagation; mass from coherence collapse and resistance; gauge behavior from directional cone structure; and causal boundaries from the combined geometry of coherence, tension, and curvature. In this view, the fundamental architecture of interaction is not imposed—it is built from within.

10 Conclusion: Structured Causality from Field Dynamics

This work has presented a physical framework in which causal structure arises from coherence-regulated field dynamics, rather than from imposed spacetime geometry. By defining three interacting cone systems—coherence, tension, and curvature—we have reconstructed the role of classical light cones from first principles in a structured field environment.

Each cone governs a distinct aspect of causal behavior: the coherence cone defines the availability of influence, the tension cone determines propagation velocity and direction, and the curvature cone encodes accumulated resistance and path deformation. Together, they yield a functional causal boundary—the effective cone—capable of reproducing and extending familiar spacetime behavior.

This formulation does not replace relativity or quantum field theory, but extends them with a structural layer beneath their causal constraints. It treats causality as a consequence of internal field dynamics, not as a fundamental axiom—consistent with perspectives in emergent gravity and thermodynamic spacetime models [23, 1].

The framework is testable. Each cone structure gives rise to observational predictions: echo delays from curvature, tunneling rates from resistance gradients, jet alignment from tension anisotropy, and entropy limits from coherence divergence. These are not interpretive effects, but mechanically derived quantities subject to experimental constraint.

In addition to causal structure and observational signatures, the framework reproduces essential particle behaviors from geometric interaction. Mass emerges from coherence collapse. Neutrino oscillation, CP violation, and sterile flavor transitions arise from directional divergence and cone interference. Spin-$\frac{1}{2}$ structure follows from topological phase winding. Quark triplet confinement and fractional charge are enforced by coherence overlap geometry, while gluon dynamics emerge as curvature in cone transport.

What begins as a transport model becomes a unified causal field theory. It supports not only the structure of spacetime, but the structure of matter itself. No new particles are introduced. No symmetry groups are imposed. The theory derives classical geometry, quantum interference, particle behavior, and gauge dynamics from a common substrate.

In this view, causal geometry is not imposed—it is emergent. And from that emergence, the familiar concepts of propagation, mass, spin, and interaction arise not as postulates, but as measurable consequences of a coherence-regulated field system.

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