Dynamical Evolution of the Informational Stiffness Field: Wave Propagation in Curved Spacetime

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1. Introduction

Informational Field Theory in Strong Curvature (IFT-SC) defined the static informational-stiffness field,

$$\sigma(x) = \sigma_{\mathrm{matter}}(x) + \sigma_{\mathrm{grav}}(K(x))$$

where curvature enters through the Kretschmann scalar and determines how recursion behaves near strong gravitational fields.

That treatment was stationary. It did not describe how σ changes in time or whether disturbances in σ propagate.

This paper develops the dynamical structure.

Small perturbations of the field evolve as Informational Wave Solutions (IWS), governed by the linearized deviation

$$\sigma(x,t) = \sigma_0(x) + \delta\sigma(x,t), \qquad |\delta\sigma| \ll \sigma_0$$

The aim is to show:

1. δσ propagates as a scalar field on curved spacetime.
2. Curvature influences propagation through the covariant operator, not through any modification of geometry.
3. Local temperature determines damping through the URT efficiency law.
4. Approaching the freeze region suppresses propagation.
5. These waves generate small modulations of recursion efficiency, relevant for future studies.

The resulting framework completes the stiffness-field description.

Unified Recursion Theory (URT) established the proportionality law and recursion operators. **Informational Field Theory in Strong Curvature (IFT-SC)** identified how strong curvature shapes the static σ profile.

This paper extends the theory by providing the differential structure needed to understand how informational disturbances evolve and how they encode observable signatures without altering spacetime geometry.

2. Field Foundations

The informational-stiffness field introduced in *IFT-SC* provides the background structure for the present analysis. The stationary field is

$$\sigma_0(x) = \sigma_{\mathrm{matter}}(x) + k_B T_P \frac{K(x)}{K_{\mathrm{crit}}}$$

Here K(x) is the Kretschmann scalar of the underlying spacetime, and $K_{crit} = \ell_P^{-4}$.

This background field is static unless the matter distribution or curvature profile changes.

Nothing in the URT framework modifies the geometry; σ_0 responds to it.

To describe dynamical effects, we consider small, time-dependent perturbations around this background:

$$\sigma(x,t) = \sigma_0(x) + \delta\sigma(x,t), \qquad |\delta\sigma| \ll \sigma_0$$

Only δσ propagates.

The background σ_0 encodes the quasi-static response of stiffness to curvature and matter, consistent with IFT-SC.

Because σ is a scalar field, locality and covariance restrict the admissible second-order linear operator governing its dynamics.

Following the structural constraints of the *URT Core Framework*—which introduce no geometric degrees of freedom—the only consistent propagation operator is the covariant d'Alembertian acting on δσ:

$$\Box_g \, \delta\sigma - m_{\mathrm{eff}}^2(x) \, \delta\sigma = 0$$

The effective mass term reflects curvature-induced structure.

Minimal coupling corresponds to

$$m_{\text{eff}}^2(x) = 0$$

so curvature influences propagation through the operator □g alone, not through a potential term.

This choice is the least presumptive and complies with the constraint that URT introduces no new geometric physics.

The resulting equation defines the basic propagation mechanics for informational wave solutions.

The next section derives the corresponding evolution law and explains how curvature shapes the motion of δσ without modifying the underlying metric.

3. Linearized Dynamics of the Perturbation Field

Informational-stiffness dynamics arise from small deviations around the stationary background defined in *Informational Field Theory in Strong Curvature (IFT-SC)*.

We consider the expansion

$$\sigma(x,t) = \sigma_0(x) + \delta\sigma(x,t), \qquad |\delta\sigma| \ll \sigma_0$$

Only δσ is dynamical; σ_0 encodes the quasi-static curvature response.

Because σ is a scalar quantity and URT introduces no geometric fields, the propagation operator must satisfy locality, covariance, and scalar transformation rules.

These constraints restrict the admissible second-order operator to the covariant d'Alembertian.

Thus the perturbation satisfies

$$\Box_g \, \delta\sigma - m_{\text{eff}}^2(x) \, \delta\sigma = 0$$

The term $m_{eff}^2(x)$ represents any curvature-induced potential allowed by the background geometry.

To remain consistent with the *URT Core Framework*—which forbids introducing new degrees of freedom—we adopt the minimal coupling case:

$$m_{\text{eff}}^2(x) = 0$$

Curvature therefore influences propagation only through the metric appearing in $\square_g$.

No backreaction occurs; δσ does not modify the geometry.

This yields the final propagation equation:

$$\square_g \, \delta\sigma(x,t) = 0$$

The result is the cleanest and most constrained form consistent with URT: a massless scalar wave evolving on a fixed spacetime background.

This formulation introduces no new operators, no geometric corrections, and no additional parameters.

It is the unique linear-dynamical law compatible with the informational interpretation defined by the preceding papers.

The next section analyzes how curvature shapes the evolution implied by this equation while remaining fully consistent with general relativity.

4. Curvature-Driven Propagation Structure

The propagation of δσ occurs on a fixed spacetime background.

No geometric backreaction is allowed, consistent with both the *URT* and *(IFT-SC)*.

Curvature influences δσ only through the operator $\square_g$ in the wave equation:

$$\square_g \, \delta\sigma(x,t) = 0$$

Because the covariant d'Alembertian contains derivatives contracted with the metric $g_{\mu\nu}$, curvature affects wave evolution indirectly through:

1. **redshift effects** in the time-derivative structure,
2. **spatial stretching and compression** in the gradient terms, and

3. **effective potential barriers** arising from angular-momentum decomposition in curved backgrounds.

These influences do not constitute new physics.

They reflect the geometric structure already present in the background spacetime.

To illustrate the mechanism, consider the general decomposition of the operator:

$$\Box_g \, \delta\sigma = g^{\mu\nu} \nabla_\mu \nabla_\nu \delta\sigma$$

The metric coefficients $g^{\mu\nu}(x)$ encode curvature.

As a result:

- regions of high redshift slow the coordinate-time propagation of $\delta\sigma$,
- radial derivatives acquire curvature-dependent prefactors,
- angular modes accumulate potential barriers similar to those appearing for scalar waves in general relativity.

Nothing in this structure introduces a geometric field sourced by $\delta\sigma$; the stiffness perturbation evolves passively on the fixed spacetime.

This separation is essential for consistency across the URT framework.

σ responds to curvature but does not generate it.

$\delta\sigma$ therefore has the same causal structure as any minimally coupled scalar disturbance on a curved background.

Curvature shapes the evolution of informational waves without altering the geometry or violating general relativity.

The next section shows how thermodynamic structure from the URT Core Framework introduces damping through the recursion-efficiency factor.

5. Thermodynamic Damping and Recursion Inefficiency

The *URT Core Framework* establishes the universal recursion-efficiency law:

$$\lambda(x) = \lambda_0 \exp\left[-\frac{\sigma(x)}{k_B T_{\mathrm{loc}}(x)}\right] \lambda_t(x)$$

This efficiency governs the amplitude retained by irreversible updates under the compressive branch.

When $\lambda < 1$, recursion loses amplitude locally.

For perturbations of the stiffness field, this loss manifests as **damping** of $\delta\sigma$.

To describe this effect, we introduce a local damping coefficient,

$$\Gamma(x) = \Gamma_0 \left[1 - \lambda(x)\right]$$

where Γ_0 sets the maximal damping scale.

This form follows directly from the interpretive rule: when recursion is perfectly efficient ($\lambda = 1$), no amplitude is lost; when recursion is suppressed ($\lambda \rightarrow 0$), damping reaches Γ_0.

The resulting evolution equation for the perturbation becomes

$$\Box_g \, \delta\sigma + \Gamma(x) \, \partial_t \delta\sigma = 0$$

This is the unique thermodynamically consistent extension of the propagation equation.

It introduces no new operators and maintains full compatibility with general relativity: damping arises from recursion inefficiency, not from geometric interaction.

Two regimes follow directly:

1. Low-stiffness regime (σ≪kBTloc\sigma \ll k_B T_{\mathrm{loc}}σ≪kBTloc)

   $$\Gamma(x) \rightarrow 0$$

   so waves propagate freely aside from geometric effects.

2. Strong-curvature regime ($\sigma \gg k_B T_{\mathrm{loc}}$)

   $$\lambda(x) \ll 1 \quad \Rightarrow \quad \Gamma(x) \approx \Gamma_0$$

   giving overdamped evolution and rapid suppression of δσ\delta\sigmaδσ.

These limits align precisely with the freeze behavior established in *Informational Field Theory in Strong Curvature*:

regions where $\sigma \gg k_B T_{loc}$ cannot support informational dynamics.

The next section studies explicit solutions of the damped wave equation in representative geometries.

6. Solutions in Representative Geometries

The dynamics of $\delta\sigma$ depend on the curvature profile and the local damping structure.

Here we examine the principal geometries relevant to later applications: flat spacetime, the exterior region of a compact object, the near-horizon zone, and the strong-curvature interior where freeze occurs.

6.1 Minkowski Spacetime

In flat spacetime, $g_{\mu\nu}$ is constant and T_{loc} is uniform, giving $\Gamma = 0$.

The wave equation reduces to

$$\partial_t^2 \delta\sigma - \nabla^2 \delta\sigma = 0$$

Solutions are undamped traveling waves.

This regime sets the reference behavior against which curvature and damping effects are measured.

6.2 Schwarzschild Geometry

For a spherically symmetric compact object, curvature and redshift modify the propagation operator.

The equation becomes

$$\Box_{\mathrm{Sch}}\, \delta\sigma + \Gamma(r)\, \partial_t \delta\sigma = 0$$

Three effects dominate:

- **redshift:** coordinate-time derivatives slow as g_{tt} decreases,

- **geometric stretching:** spatial derivatives acquire curvature-dependent prefactors,
- **inward suppression:** the curvature barrier reduces the amplitude of inward-propagating modes.

These effects are geometric and introduce no backreaction.

6.3 Near-Horizon Behavior

The horizon region is characterized by finite curvature and divergent local temperature:

- $K(r_s)$ remains finite,
- $T_{loc}(r) \rightarrow \infty$ as $r \rightarrow r_s$.

Thus,

$$\frac{\sigma(r)}{k_B T_{\mathrm{loc}}(r)} \rightarrow 0$$

and the efficiency approaches its upper limit,

$$\lambda(r_s) \rightarrow \lambda_0$$

Therefore:

- **ISWs do not freeze at the horizon**,
- they experience redshift and energy loss,
- but the damping term remains small.

This matches the predictions of *Informational Field Theory in Strong Curvature* and preserves full compatibility with general relativity.

6.4 Strong-Curvature Interior (Freeze Region)

Deep inside the compact object, the behavior reverses:

- curvature grows rapidly with decreasing radius,
- local temperature decreases away from the horizon,
- stiffness increases through the relation $\sigma_{grav} \propto K$.

As a result,

$$\frac{\sigma(r)}{k_B T_{\mathrm{loc}}(r)} \gg 1$$

and recursion becomes inefficient,

$$\lambda(r) \to 0 \quad \Rightarrow \quad \Gamma(r) \approx \Gamma_0$$

In this overdamped limit, the perturbation is extinguished:

$$\delta\sigma \to 0$$

Propagation ceases inside this region, which corresponds exactly to the freeze surface identified in *Informational Field Theory in Strong Curvature*.

This ensures that informational dynamics halt before curvature diverges.

This constitutes operational freeze, defined by $\sigma(r) \gg k_B\, T_{loc}(r)$, where recursion inefficiency ($\lambda \to 0$) rather than hard geometric constraints halts propagation.

7. Causal and Operational Structure of Informational Waves

The propagation of $\delta\sigma$ defines the causal structure for informational disturbances.

Because the evolution equation

$$\Box_g \, \delta\sigma + \Gamma(x) \, \partial_t \delta\sigma = 0$$

is hyperbolic for all $\Gamma(x) \geq 0$, $\delta\sigma$ signals propagate within the causal cones of the spacetime metric.

No superluminal or acausal behavior is permitted.

This ensures consistency with the URT principle that the stiffness field responds to curvature but never modifies it.

7.1 Causal Cones and Propagation Limits

In regions where damping is weak ($\Gamma \approx 0$), $\delta\sigma$ propagates at the characteristic speed set by the metric.

As stiffness increases, recursion efficiency decreases, and the effective propagation rate slows.

Operationally:

$$\Gamma(x)\uparrow \quad \Rightarrow \quad \text{propagation speed decreases}$$

This is the informational analogue of characteristic-velocity reduction.

It arises from recursion inefficiency, not from modified geometry.

7.2 No Superluminal Updates

The recursion update cadence Δt_0 imposed by the *URT Core Framework* restricts allowable transitions between informational states.

If propagation attempts to exceed the geometric limit, update cost increases through σ, forcing λ downward:

$$\lambda(x) = \lambda_0 \exp\left[-\frac{\sigma(x)}{k_B T_{\text{loc}}(x)}\right]$$

Large stiffness suppresses the update entirely.

Thus the dynamics enforce causal propagation: informational waves cannot outrun the metric's causal cones.

7.3 Freeze Surfaces as Informational Barriers

When the freeze condition from IFT-SC is reached,

$$\sigma(x) \gg k_B T_{\text{loc}}(x)$$

efficiency collapses,

$$\lambda(x) \to 0$$

and the damping term reaches its maximum.

For δσ,

$$\delta\sigma \to 0$$

meaning no informational disturbance can propagate across the freeze surface.

This boundary is not geometric and does not modify spacetime structure.

It is an operational barrier determined by recursion cost.

Beyond this point the informational state becomes static, matching the finite-depth structure developed in IFT-SC.

7.4 Consistency With GR Causality

Because the propagation operator is $\Box_g$ and not a modified geometric operator, the causal cones of $\delta\sigma$ coincide with those of the background spacetime.

All limits on propagation—including slowing and freeze—stem from thermodynamic recursion constraints, not geometric alteration.

The next section identifies observational signatures generated by δσ\delta\sigmaδσ propagation, including measurable modulations of recursion efficiency.

8. Observable Signatures of Informational Waves

Informational stiffness waves ($\delta\sigma$) do not modify geometry and therefore produce subtle but measurable consequences.

Their observational signatures arise from two mechanisms:

1. **local modulation of recursion efficiency**, and
2. **damping effects accumulated along propagation paths in curved spacetime**.

Both mechanisms are fully determined by the *URT Core Framework* and the stiffness–curvature relation defined in *Informational Field Theory in Strong Curvature (IFT-SC)*.

8.1 Amplitude Suppression Near Compact Objects

In regions of increasing stiffness, the damping coefficient $\Gamma(x)$ grows and suppresses the amplitude of propagating waves.

The integrated effect along a trajectory is

$$\frac{A_{\text{obs}}}{A_{\text{emit}}} \approx \exp\left[-\int \Gamma(x)\,dt\right]$$

where $\Gamma(x) = \Gamma_0\,[1-\lambda(x)]$.

This produces frequency-dependent filtering near compact objects, with deeper suppression in regions where $\sigma(x) \gg k_B T_{loc}(x)$.

8.2 Modulations of Recursion Efficiency (δλ/λ)

Because $\lambda(x)$ depends exponentially on $\sigma(x)$,

$$\lambda(x) = \lambda_0 \exp\left[-\frac{\sigma(x)}{k_B T_{\text{loc}}(x)}\right]$$

a small perturbation $\delta\sigma$ produces a fractional modulation

$$\frac{\delta\lambda}{\lambda} = -\frac{\delta\sigma}{k_B T_{\text{loc}}}$$

This is the primary observable signature of informational waves.

It provides a direct experimental route for detecting stiffness fluctuations in high-coherence laboratory systems or astrophysical environments.

8.3 Scattering by Gravitational Waves (Geometric Only)

Because $\delta\sigma$ propagates via $\Box_g$, gravitational waves modify their trajectories only through geometric distortion of the metric:

- small phase shifts,
- weak amplitude modulation,
- no backreaction.

The stiffness field does not couple to gravitational-wave strain beyond the curvature encoded already in $g_{\mu\nu}$.

8.4 Early-Universe Damping

In epochs where curvature approached a significant fraction of K_{crit} while temperature remained high, the ratio $\sigma/(k_B T_{loc})$ could take intermediate values.

For example, with $K \approx 0.1K_{crit}$ and $T_{loc} \approx T_P$,

$$\lambda \approx \lambda_0 \exp(-0.1)$$

implying

$$\lambda \approx 0.7$$

so informational waves would be partially damped but not frozen.

This identifies a possible early-universe signature of the stiffness field without invoking new physics.

8.5 Constraints From High-Coherence Systems

Modern interferometric platforms can detect phase or amplitude modulations at levels compatible with the predicted $\delta\lambda/\lambda$ effects.

Although such signals are expected to be small, they are falsifiable predictions of URT.

9. Summary

This paper developed the dynamical structure of the informational-stiffness field defined in *Informational Field Theory in Strong Curvature (IFT-SC)*.

The analysis extends the static framework by introducing time-dependent perturbations of the form

$$\sigma(x,t) = \sigma_0(x) + \delta\sigma(x,t), \qquad |\delta\sigma| \ll \sigma_0$$

and deriving the unique covariant propagation law compatible with the *URT Core Framework*:

$$\Box_g \, \delta\sigma(x,t) = 0$$

Curvature enters through the spacetime metric, shaping propagation by redshift, geometric stretching, and potential barriers.

No geometric backreaction occurs; the metric remains purely that of general relativity.

The informational field responds to curvature but does not generate it.

Thermodynamic constraints from the recursion-efficiency law introduce damping via

$$\Gamma(x) = \Gamma_0[1 - \lambda(x)]$$

producing the full evolution equation

$$\Box_g \, \delta\sigma + \Gamma(x) \, \partial_t \delta\sigma = 0$$

In low-curvature regions, waves propagate freely.

Near horizons, redshift dominates but freeze does *not* occur because local temperature diverges.

Deep in the interior, where stiffness overwhelms thermal capacity, $\lambda \to 0$ and $\delta\sigma$ is extinguished.

This reproduces the freeze surface established in IFT-SC and provides the dynamic confirmation of finite informational depth.

Informational waves generate observable consequences through fractional efficiency modulations $\delta\lambda/\lambda$, geometric scattering, and curvature-dependent damping.

These signatures appear in laboratory and astrophysical contexts, providing clear, falsifiable predictions.

This dynamical framework is foundational for subsequent developments in the URT program.

Future work uses $\delta\sigma$ evolution to describe informational flow around evaporating compact objects and forms the basis for the dissolution of the black hole information paradox.

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