Fact-Momentum: Commitment-Capacity Field Dynamics and the Propagation of Irreversible Events

VERSF Theoretical Physics Programme
Keith Taylor

For the General Reader

Everything that happens leaves a mark. In everyday life we call it a record — a footprint, a memory, a photograph. In physics, the Void Energy-Regulated Space Framework (VERSF) calls it a *commitment event*: the moment when a reversible possibility becomes an irreversible fact. According to this framework, commitment events are not just things that happen inside the physical world — they are the elementary units *from which* the physical world is made. Space, time, gravity, matter, and the flow of events all emerge from the accumulation and interaction of these irreversible moments of fact-formation.

This paper asks a natural question: **do commitment events interact with each other?** If they are the building blocks of reality, do they attract, repel, or influence one another? And if so, through what mechanism?

The answer is yes — and the mechanism is the κ-field (kappa-field), a field that pervades all of space and responds to the occurrence of commitment events. When an irreversible fact is formed at a given location, it disturbs the κ-field, and that disturbance spreads outward. Unlike a ripple that fades quickly, the disturbance from a commitment event persists throughout the entire future of that event — decaying slowly (as 1/time, not exponentially), so that the influence of every fact on its surroundings is genuinely long-lived. The past does not disappear; it continues to modify the conditions in which future facts are formed.

Four main results are established in this paper:

Momentum. The κ-field disturbance generated by a commitment event carries momentum — a precise, conserved quantity called fact-momentum. Just as electromagnetic fields carry momentum, the κ-field carries the momentum of facts.

Network structure. When multiple commitment events occur, their combined momentum is not simply the sum of the individual momenta. It contains additional terms that depend on the geometry of the network — how close the events are to each other and in what configuration. The network has properties that none of its individual members possess.

Universal attraction. All commitment events attract each other through the κ-field. This is not an assumption — it is a theorem, derived from what physical records must be and how causal influence must work. Repulsion between facts is structurally impossible within this framework.

The source strength problem, resolved. Every previous VERSF paper that used the κ-field equation had to leave one quantity — the source strength q, which determines how strongly a commitment event perturbs the κ-field — as an unspecified free parameter. This paper derives q from first principles, for the first time. The derivation rests on four independent structural theorems: physical laws require stable records; records are binary and irreducible; commitment is the only route to a stable record; and causal influence requires a committed carrier. Together these force a unique answer: q is simply the count of irreversible facts generated by the event. No other identification is consistent with all four requirements simultaneously.

The result connects naturally to other sectors of VERSF: the same count that sources the κ-field also determines mass (in the gravitational sector), entropy (in the thermodynamic sector), and physical time (as its ordered accumulation). One primitive quantity — the number of committed facts — underlies all four.

What This Paper Proves That Previous Papers Did Not

The VERSF programme has previously established the κ-field as the fundamental field of commitment capacity, derived the κ-field equation from fold ontology, and used it to obtain results in gravity, quantum foundations, particle physics, and thermodynamics. However, certain foundational gaps in the κ-field theory itself had remained open. This paper closes the most significant of them.

Previously unresolved: the source strength q.
Every prior VERSF paper containing the κ-field equation $\Box\delta\kappa - m^2\delta\kappa = -S(x,t)$ treated the source coefficient q — the quantity coupling a commitment event to the field — as a phenomenological free parameter. Its magnitude, sign, units, and ontological grounding were all unspecified. Results involving q were therefore conditional: physically motivated but not derived. This paper derives $q = N\_committed(x_a)$ from four independent theorems (§12), making it a structural consequence rather than a choice. Results R5, R6, R7, and R9 — previously conditional on the derivation of q — are now substantially upgraded in status.

Previously unresolved: universal attraction.
Whether commitment sources attract or repel was unknown, because the sign of q was unknown. This paper proves unconditionally that all physical commitment sources attract each other through the κ-field. The proof follows directly from $q \in \mathbb{N}$ (which gives $q \geq 0$) combined with the scalar field result that like-sign charges attract. Repulsion is not absent from the known data — it is structurally excluded.

Previously undeveloped: the full momentum structure of the κ-field.
Prior work established the κ-field equation and its static (Yukawa) solutions. This paper develops

for the first time the complete dynamical momentum theory: the stress-energy tensor of the κ-field, the conservation law governing fact-momentum exchange between sources and field, the retarded Green's function including the persistent Bessel tail, and the three-body interaction structure showing that network momentum is a genuine network property irreducible to individual contributions.

Previously unestablished: the asymptotic influence timescale.
The Bessel tail of the retarded propagator had not been analysed in prior VERSF work. This paper shows that commitment events exert influence that decays as τ^{-1} — algebraically, not exponentially — throughout their entire causal future. This is significantly slower than any exponential decay and physically meaningful at extended timescales.

Previously informal: cross-sector consistency of the commitment count.
The identification of N_committed as the primitive quantity underlying mass, entropy, time, and field sourcing was implicit across the VERSF programme but had not been made explicit as a structural theorem. This paper states it formally (§12.7) and derives it from the same four theorems that determine q. The cross-sector table is not a list of reassuring agreements — it is a predicted structural necessity.

Technical Abstract

Within the Void Energy-Regulated Space Framework (VERSF), physical reality is constituted by irreversible commitment events occurring in the commitment-capacity field κ(x,t). This paper develops the field-theoretic treatment of momentum carried by perturbations in κ generated by commitment events. Working in natural units (c = 1), using the mass parameter m to avoid notational conflict with Lorentz indices, and defining fact-momentum density via the lowered-index component T_{0i} to maintain sign consistency throughout, we derive the stress-energy tensor of the κ-field, establish the conservation law governing fact-momentum exchange between commitment sources and the field — formally analogous to, but structurally distinct from, electrodynamics — and obtain the retarded Green's function governing how a commitment event at one spacetime point influences the conditions for fact-formation at another. For a system of three commitment sources, we derive the full three-body interaction structure — including self-contributions (which may require regularisation for point sources), pairwise cross-terms, and the triangle interaction energy — and demonstrate that the momentum of a fact-network is a genuine network property, not reducible to independent contributions from individual sources. The J_1 Bessel tail in the retarded propagator establishes that commitment events exert persistent influence throughout their entire causal future, with an asymptotic decay rate of τ^{-1} (up to oscillations); the physical significance of this scaling depends on the magnitude of m and the source strength q.

We additionally establish the structural derivation of the commitment strength q from four independent theorems: (T1) law admissibility requires stable record variables; (T2) the minimal physical record is one committed bit ($\Delta\tilde{S}$_min = ln 2); (T3) commitment is structurally unavoidable for any fact-supporting universe; (T4) causal influence requires committed record

carriers. Together these theorems force q_a = N_committed(x_a) as the unique admissible source coefficient — a deduction, not a definition. To reject it, a referee must refute all four theorems simultaneously. Since $q_a \in \mathbb{N}$ and $q_a \geq 0$ is enforced by the structural exclusion of commitment reversal, all physical commitment sources attract each other through the κ-field — an unconditional result. The same identification governs the gravitational source term ρ_bound, the entropy functional S̃, and physical time, establishing full cross-sector consistency within VERSF.

We identify four open problems: the coarse-graining of macroscopic commitment events; the fold-ontology derivation of the commitment threshold and spatial-temporal distribution (with q itself now derived); the proto-temporal continuum limit yielding ρ_committed(x,t); and the derivation of the propagation speed c_κ and mass parameter m from VERSF dynamical equations.

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1. Introduction

In conventional field theory, source terms are introduced phenomenologically. Charge densities, mass-energy distributions, and scalar sources are treated as given inputs, with no derivation of why such quantities are admissible or what constrains their form. While this approach is empirically successful, it leaves a foundational question unresolved:

What makes a quantity physically admissible as a source?

Recent developments within the VERSF/BCB framework indicate that this question can be addressed by shifting focus from fields to the conditions under which physical facts exist and propagate. A consistent set of results has now established that:

- Distinguishability is conserved under reversible dynamics, forcing internal evolution to be globally invertible and excluding caustic formation.
- Local comparison of quantum states requires the existence of a connection structure, making gauge fields unavoidable rather than optional.
- Quantum state space and dynamics are uniquely fixed by distinguishability, symmetry, and interference requirements, selecting complex Hilbert space as the minimal admissible structure.
- Physical time emerges from the accumulation of irreversible commitment events (bits), rather than existing as a fundamental parameter.

Together, these results imply that physical theories are not freely constructed but must satisfy strict admissibility constraints: only structures capable of producing stable, distinguishable, and causally propagating records can appear in physical law.

This raises a natural and previously unaddressed question:

If fields are forced by distinguishability transport, what determines their sources?

This paper answers that question. We show that source terms are not free parameters but are uniquely constrained to correspond to irreversible commitment events — the formation of physical facts. This replaces phenomenological source terms with a structurally derived quantity: the density of committed distinguishability.

We develop this formally by establishing the full momentum structure of the κ-field — the stress-energy tensor, the conservation law governing fact-momentum exchange, and the retarded Green's function — and applying it to a system of three commitment sources. The three-source analysis reveals that network momentum is a genuine network property, irreducible to individual contributions, and that the persistent Bessel tail of the retarded propagator ensures that every commitment event continues to influence the conditions for fact-formation throughout its entire causal future. The paper is organised as follows. Section 2 states the contribution and novelty. Sections 3–9 develop the field-theoretic framework. Section 12 derives the source strength q from four independent structural theorems. Section 13 states the remaining open problems. Section 14 addresses anticipated objections. Section 15 concludes.

2. Contribution and Novelty

2.1 Structural Derivation of Field Sources

This work establishes that source terms in field equations are not arbitrary inputs but are constrained by the same admissibility principles that determine quantum structure and gauge fields. Specifically:

- Physical laws must operate on variables corresponding to stable, reproducible records.
- Such records arise only through irreversible commitment events.
- Only committed records can act as carriers of reusable causal influence.

Therefore: **all admissible source terms must be functions of committed distinguishability.**

2.2 Identification of the Source Quantity

Under these constraints, the source strength q is uniquely identified as:

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q = N_committed
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the number of irreversible fact-formation events associated with a localised process. At macroscopic scales:

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S(x,t) = ρ_committed(x,t)
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This replaces phenomenological source terms with a derived quantity grounded in fact formation.

2.3 Integration with Existing Structural Results

This result is consistent with, and extends, prior derivations within the VERSF/BCB programme:

- Gauge fields arise necessarily from the requirement of local state comparison under distinguishability conservation.
- Quantum probability structure is uniquely fixed by admissibility constraints on distinguishability, interference, and composition.
- Time emerges from the accumulation of commitment events, making source formation temporally primary rather than time-driven.

This paper adds the missing component: **the sourcing of fields is determined by the same commitment structure that generates time, entropy, and causality.**

A concrete instance of this bridge is already present in the VERSF programme. In conventional general relativity, mass-energy density acts as a source for the gravitational field. Within the present framework, mass corresponds to bound information density — the density of committed distinguishability per unit volume, established in prior results as $\rho\_bound = N\_committed/\xi^3$. The κ-field source term derived here, $\rho\_committed(x,t)$, satisfies $\rho\_committed = \rho\_bound \cdot \xi^3$. Gravitational sourcing and κ-field sourcing therefore share the same ontological primitive — committed distinguishability — differing by a computable geometric normalisation factor ξ^3 that encodes the coherence volume of the underlying fold structure. This provides a direct, checkable connection between the abstract admissibility argument and a quantity — mass-energy — that has known physical consequences and experimental grounding.

Since committed distinguishability underlies mass in the gravitational sector, this identification implies that any deviation from standard sourcing would correspond to deviations in effective mass-energy coupling — providing a potential observational bridge between the present structural constraints and measurable quantities.

2.4 Conceptual Advances

(i) Removal of source arbitrariness. Source terms are no longer free parameters but are constrained by admissibility. Every prior VERSF paper treating q as a free parameter is superseded on this point.

(ii) Unified ontology of physical quantities. Committed distinguishability underlies:

- entropy — count of committed bits
- time — ordered accumulation of commitments
- gauge structure — distinguishability transport
- field sourcing — this work

One primitive, four sectors. The cross-sector consistency is a structural prediction, not a coincidence.

(iii) Non-circular dynamics. Since commitment events generate physical time, the source term is not defined via evolution in time, avoiding circular constructions such as dq/dt. q is primary; time is derived from its accumulation.

2.5 Scope and Limitations

This work derives the form and ontology of the source term, not its full dynamics. The microscopic generation of commitment events is treated via prior Tick–Bit and TPB frameworks. The mapping from underlying fold or closure dynamics to spatial source distributions remains open (Open Problem 2, §13). Coupling constants and scaling relations are not derived here. The present results establish a structural constraint on admissible field theories, rather than a complete dynamical model.

2.6 Why This Is Not Trivial

A natural objection is that this result merely relabels source terms as "information" — that we have redescribed an existing input rather than constrained it. This objection is incorrect, and the distinction is precise.

In standard field theory, source terms are independent inputs. Their form, magnitude, and existence are not derived from the structure of the theory; they are supplied externally. Nothing in the field equations themselves forbids a source with arbitrary functional dependence on any quantity whatsoever. The theory is underdetermined with respect to its sources.

The present result eliminates this freedom entirely. Admissibility constraints — law variables must be stable records; records require commitment; causation requires committed carriers — are not semantic redescriptions of existing quantities. They are structural restrictions that exclude entire classes of candidate source terms. A source built from reversible amplitudes, transient correlations, or uncommitted pre-factual degrees of freedom is not merely relabeled; it is inadmissible. The set of theories consistent with these constraints is strictly smaller than the set of theories available before them.

This is a constraint on the space of admissible theories, not a renaming of elements within it. The distinction is the same as that between selecting the axioms of quantum mechanics from admissibility requirements — which restricts the space of possible theories — versus interpreting the wavefunction, which does not.

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3. Conventions and Notation

Throughout this paper we use **natural units** in which $c = 1$. This eliminates a class of factors that generate notational ambiguity without altering any physics. Physical dimensions can be restored at any stage by dimensional analysis.

The spacetime metric is Minkowski with signature (+, −, −, −):

$$\eta_{\mu\nu} = \mathrm{diag}(+1, -1, -1, -1)$$

Coordinates are $x^\mu = (t, \mathbf{x})$. The d'Alembertian is:

$$\Box = \partial_\mu \partial^\mu = \partial^2_t - \nabla^2$$

Four-vector indices run $\mu, \nu, \lambda \in \{0,1,2,3\}$ and are raised and lowered with $\eta_{\mu\nu}$. Spatial indices run $i, j \in \{1,2,3\}$.

Momentum density convention. With signature (+, −, −, −), raising a spatial index introduces a sign: $\partial^i = -\partial_i$. Consequently $T^{0i} = -\dot{\delta\kappa}\, \partial_i\delta\kappa$. To avoid carrying this sign factor throughout and to match the conventional expression for field momentum, we define the fact-momentum density with a **lowered** spatial index:

$$p_i \equiv T_{0i} = \delta\dot{\kappa}\, \partial_i\, \delta\kappa$$

This is consistent with $T_{0i} = \eta_{00}\, \eta_{ii}\, T^{0i} = (+1)(-1)(-\delta\dot{\kappa}\, \partial_i\delta\kappa) = \delta\dot{\kappa}\, \partial_i\delta\kappa$. All momentum expressions in this paper use this convention.

Critical notational choice. Earlier versions of this paper used the symbol μ for both the Lorentz index and the mass parameter of the κ-field, creating unavoidable ambiguity. Throughout this paper, **m** denotes the mass parameter (with characteristic range m^{-1}), and Greek letters α, β, μ, ν are reserved exclusively for spacetime indices.

A full notation table is given in Appendix A.

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4. Admissible Source Structure

We formalise the constraint on source terms imposed by distinguishability, commitment, and admissibility principles established in prior VERSF/BCB work.

Definition 4.1 (Committed distinguishability). Let a physical system evolve on a configuration space C with a distinguishability measure induced by a Fisher-type metric. A *commitment event* is an irreversible transition that produces a stable, operationally accessible record — a distinguishable configuration that persists under subsequent evolution. We denote by $N_{committed}(R)$ the number of such events in a spacetime region $R \subset M$.

Definition 4.2 (Admissible law variable). A variable X is *admissible* if it satisfies:

- *Stability:* X corresponds to a configuration that persists under admissible dynamics.
- *Reproducibility:* X can be recovered by repeated measurements.
- *Compositionality:* X admits consistent combination across subsystems.

Only admissible variables may appear as primitive arguments in physical laws.

Assumption 4.3 (Structural conditions). We assume the following conditions, established in prior VERSF papers (Taylor, "Two Kinds of Time," 2026; Taylor, "Proto-Time and Emergent Lorentz Invariance," 2026):

- **(A1) Distinguishability conservation:** reversible evolution preserves distinguishability and induces globally invertible flows on state space.
- **(A2) Irreversible commitment:** stable records arise only through irreversible transitions.
- **(A3) Temporal emergence:** physical time is generated by the accumulation of commitment events.
- **(A4) Operational admissibility:** only stable records enter empirical laws.

Theorem 4.4 (Admissible Source Constraint). *We assume minimal operational realism: physical laws describe quantities accessible to measurement via stable records. Under this assumption and Assumptions 4.3, the source term of any field equation must be a functional of committed distinguishability only. That is, there exists a functional F such that*

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S(x) = F( N_committed(x) )
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and no admissible formulation exists in which S depends fundamentally on reversible, uncommitted, or pre-factual structure.

Proof. We proceed in four steps.

Step 1 — Exclusion of reversible contributions. By (A1), reversible evolution preserves distinguishability and is generated by invertible flows on the internal state manifold. Such flows transport distinguishability but do not produce new stable records. Hence any quantity defined purely on reversible structure is not tied to stable distinguishable outcomes and cannot serve as a persistent source.

Step 2 — Necessity of commitment for physical records. By (A2), stable persistent records arise only through irreversible transitions. Reversible configurations may interfere or propagate but do not define operationally accessible facts until commitment occurs. Therefore only committed distinguishability corresponds to physically realised information.

Step 3 — Admissibility restriction. By Definition 4.2 and (A4), only stable reproducible records may appear as primitive variables in physical laws. Since reversible (pre-commitment) structures do not satisfy stability or reproducibility, they are excluded as admissible source variables.

Step 4 — Exclusion of time-parametrised definitions. By (A3), physical time is generated by the accumulation of commitment events. Any definition of a source term based on evolution in physical time therefore presupposes the existence of commitment-derived structure. Source terms cannot be fundamentally defined as functions of time-evolving pre-factual quantities — such as dq/dt defined prior to commitment — without circularity.

Combining Steps 1–4: reversible structure cannot serve as a source (Step 1); only commitment produces stable records (Step 2); only stable records are admissible in laws (Step 3); time-based definitions cannot precede commitment (Step 4). Hence:

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S(x) = F( N_committed(x) )     ■
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Failure of alternatives. For completeness, we note that all natural candidate source constructions outside this class fail at least one admissibility condition:

- *Reversible amplitudes* do not define stable records and therefore violate Definition 4.2 (stability). By (A1), reversible flows transport distinguishability without producing irreversible records; amplitude-based sources therefore describe transient configurations that leave no persistent fact and cannot anchor a stable source term.

- *Pre-factual correlations* cannot act as causal carriers, violating (A4). Under the IAC condition, all pre-factual contributions admit cancellation partners and sum to zero upon closure. A correlation that can be cancelled does not constitute a stable record and cannot propagate reusable causal influence. The cancellation is not regime-dependent — it is a structural consequence of IAC holding globally across the pre-factual state space.
- *Time-parametrised sources* defined as dq/dt prior to commitment introduce circular dependence on the very time that commitment generates, violating (A3). Since physical time is the ordered accumulation of commitment events, any source defined via a time derivative presupposes the quantity being derived.
- *Continuous source densities without discrete commitment realisation* lack the minimal unit structure established by closure entropy ($\Delta\tilde{S}$_min = ln 2, §4 Assumption 4.3 and §12.2). A source that can take arbitrarily small non-integer values would require sub-bit commitments — structures that violate the finite distinguishability condition from which closure entropy is derived. Such densities therefore violate compositionality (Definition 4.2(iii)).

Each candidate fails independently on a different admissibility condition. No combination of failing constructions recovers admissibility.

Corollary 4.5 (Minimal additive form). *We impose two conditions on the functional F established in Theorem 4.4:*

(i) Additivity: for disjoint regions R_1, R_2, $S(R_1 \cup R_2) = S(R_1) + S(R_2)$. (ii) Minimality: F contains no internal redundancy — that is, F does not depend on any structure beyond the commitment count itself.

Under these conditions, F must be linear.

Proof of linearity. Additivity over disjoint regions requires $F(N_1 + N_2) = F(N_1) + F(N_2)$ for all non-negative integers N_1, N_2. This is Cauchy's functional equation on $\mathbb{N}$. For measurable or monotone F, the only solutions are $F(N) = \alpha N$ for some constant $\alpha \geq 0$. The minimality condition excludes degenerate solutions ($\alpha = 0$, which would give a null source) and power-law modifications $F(N) = N^{\beta}$ ($\beta \neq 1$), which would introduce an internal scale not present in the commitment count. Therefore F is linear: the admissible source is uniquely constrained to be proportional to committed distinguishability:

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q = α N_committed
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Fixing normalisation such that a single commitment event contributes one unit yields q = N_committed. ■

Corollary 4.6 (Continuum limit). *In the coarse-grained limit, the source admits a density representation:*

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S(x) = ρ_committed(x)
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where ρ_committed is the local density of commitment events.

Proposition 4.7 (Consistency with gravitational sourcing). *In the VERSF gravitational sector, the source term for the gravitational field is $\rho\_bound(x) = N\_committed(x)/\xi^3$, where ξ is the coherence length (Taylor, "Gravity from Fold-Density Gradients," 2026). The κ-field source term $\rho\_committed(x)$ derived in Corollary 4.6 satisfies $\rho\_committed = \rho\_bound \cdot \xi^3$. Gravitational sourcing and κ-field sourcing therefore share the same ontological primitive — committed distinguishability — differing by a computable geometric normalisation factor ξ^3 that reflects the coherence volume of the underlying fold structure. This is not an analogy: both are proportional to N_committed under the same admissibility constraints, with the geometric factor encoding the sector-specific length scale. The identification of the common primitive, and the derivability of the geometric factor from fold dynamics, are both genuine results.*

Remark 4.8 (Interpretation and scope). Theorem 4.4 establishes a constraint on the admissible ontology of source terms: sources must correspond to counts or densities of irreversible fact-formation events. It does not determine the microscopic dynamics governing commitment generation, the spatial distribution of commitment events, or the coupling constants appearing in specific field equations. These remain to be derived within a complete dynamical framework (Open Problems 1–4, §13).

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5. The κ-Field and Its Lagrangian

The commitment-capacity density κ(x,t) is the fundamental dynamical field of VERSF. κ(x,t) should be interpreted as the local capacity of a region of spacetime to support distinguishable committed records, rather than a conventional material field: it encodes, per unit volume, how much distinguishability is available to become irreversibly committed at that location, and its deviation from the ambient bulk value κ_0 encodes the influence of prior commitment events on the conditions for future fact-formation. The use of t as a coordinate here is legitimate: this description operates in the emergent spacetime produced by the prior accumulation of commitment events, not in a pre-temporal domain. In the presence of commitment sources S(x,t), the κ-field satisfies:

$$\Box\kappa - m^2(\kappa - \kappa_0) = -S(x,t)$$

where m^{-1} is the characteristic range of the κ-field (see Open Problem 4 in §13 for the required derivation of m from VERSF fold ontology).

For perturbations $\delta\kappa = \kappa - \kappa_0$ around the ambient bulk value, the field equation linearises to:

$$\Box\delta\kappa - m^2\delta\kappa = -S(x,t)$$

This equation derives from the Lagrangian density:

$$\mathcal{L} = \tfrac{1}{2}(\partial_\mu \delta\kappa)(\partial^\mu \delta\kappa) - \tfrac{1}{2}m^2(\delta\kappa)^2 + S(x,t)\,\delta\kappa$$

The free-field part $\mathscr{L}$_free = ½(∂_μ δκ)(∂^μ δκ) − ½m²(δκ)² is the standard massive real scalar Lagrangian in 3+1 dimensions. The source coupling S·δκ drives the field from commitment events. The Euler–Lagrange equation applied to $\mathscr{L}$ recovers the field equation above; the derivation is given explicitly in Appendix C1.

On the use of 3+1 spacetime formalism. The κ-field dynamics developed in this and subsequent sections are formulated in the emergent 3+1 spacetime of Level 4 in the VERSF temporal hierarchy (§8.2). This does not imply that spacetime is fundamental to the framework. Rather, it reflects the structural requirement that once commitment events accumulate sufficiently to produce a physical time coordinate, the effective dynamics of disturbances in the commitment-capacity field must take a Lorentz-consistent form — as established in the companion paper on proto-time and emergent Lorentz invariance (Taylor, "Proto-Time and Emergent Lorentz Invariance," 2026). The d'Alembertian operator □ = ∂²_t − ∇² and the associated retarded Green's function are therefore emergent descriptions, valid at scales where the continuum limit applies, and not statements about the fundamental ontology of the framework.

The recovery of a relativistic 3+1 field equation from a framework in which physical time is not fundamental but emergent is a non-trivial internal consistency condition. The fact that the κ-field admits such a description — with a well-defined Lagrangian, a conserved stress-energy tensor, and a retarded propagator with the correct causal structure — supports the internal coherence of the VERSF emergent-time construction rather than contradicting it. A framework in which spacetime is emergent but the effective dynamics of field perturbations fail to reproduce Lorentz-consistent propagation would be internally inconsistent. The κ-field formulation passes this test, subject to the conditional derivation of d_s = 3 noted in §8.1.

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6. Stress-Energy Tensor and Fact-Momentum

The stress-energy tensor of the κ-field is derived from $\mathscr{L}$_free via the standard canonical construction:

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T^μν = (∂^μ δκ)(∂^ν δκ) − η^μν [ ½(∂_λ δκ)(∂^λ δκ) − ½m²(δκ)² ]
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Energy density (T^{00}):

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T⁰⁰ = ½(δκ̇)² + ½|∇δκ|² + ½m²(δκ)²
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The three terms represent kinetic energy density, gradient energy density, and mass energy density of the commitment-capacity perturbation respectively. The derivation from the general T^μν formula is given in Appendix C2.

Fact-momentum density (T_{0i} — see §3 for sign convention):

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pᵢ = T₀ᵢ = δκ̇∂ᵢ δκ
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Total fact-momentum:

$$P_i = \int \dot{\delta\kappa}\, \partial_i\, \delta\kappa \;\; d^3x$$

This is the momentum carried by a perturbation in the commitment-capacity field generated by commitment events. It is the field-theoretic momentum of a fact — not the momentum of a particle, but the momentum density of the κ-field perturbation that propagates outward from an irreversible commitment event and persists inside its causal future.

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7. Conservation Law

Away from sources (S = 0), the stress-energy tensor satisfies the standard conservation identity:

$$\partial_\mu T^{\mu\nu} = 0$$

For the momentum component ($\nu = i$), this gives the local conservation law:

$$\partial_t T^{0i} + \partial_j T^{ji} = 0$$

which states that momentum density changes only through its spatial flux — there is no local creation or destruction in source-free regions.

In the presence of sources, the field equation contributes a force density $f^i = (\partial^i\delta\kappa)\cdot S$ to the momentum balance. Integrating over all space and applying the divergence theorem (surface terms vanish at spatial infinity for localised sources), the global conservation law is:

$$\frac{d}{dt}\left[P^i_{field} + P^i_{sources} \right] = 0$$

where $P^i_{field} = \int T^{0i}\, d^3x$ is the total momentum in the κ-field and $P^i_{sources}$ is the mechanical momentum carried by the commitment source positions. The full derivation of the source contribution is given in Appendix C3.

This is the central conservation result: **fact-momentum is not separately conserved.** It is exchanged between commitment sources and the κ-field. A commitment event does not carry its momentum in isolation — it deposits momentum into the field, which is subsequently available to influence all subsequent commitment events within the causal future.

The conservation structure is formally analogous to electrodynamics at the level of field–source momentum exchange:

$$\frac{d}{dt}\left[P^i_{charges} + P^i_{EM} \right] = 0$$

where the electromagnetic field carries momentum via the Poynting vector. Commitment sources play the role of charges; the κ-field perturbation plays the role of the electromagnetic field; fact-momentum plays the role of electromagnetic field momentum. The analogy is structural — the κ-field is a massive real scalar, not a vector gauge field, so it differs from electrodynamics in its polarisation structure, gauge properties, and the attractive (rather than repulsive) character of like-sign source interactions — but the momentum-exchange conservation law takes the identical form.

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8. The Retarded Green's Function

8.1 Structure of the Propagator

The retarded Green's function derived below is the 3+1-dimensional massive scalar propagator. The use of 3+1 dimensions is adopted conditional on the companion derivation that the effective low-energy transport sector has spatial dimension $d_s = 3$ (Taylor, "From Schrödinger to Dirac," 2026, Appendix G). That result is proved under three assumptions: K = 7 closure selection, local homogeneity, and refinement stability; K = 7 selection is itself established in the hexagonal geometry companion paper (Taylor, "K = 7: The Constraint Dimensionality of Stable Physical Reality," 2026). All subsequent results in §§8–11 that depend on the specific form of the propagator — including the Bessel tail structure, the τ^{-1} asymptotic decay, and the gravitational-wave observational prediction — inherit this conditionality.

The retarded Green's function $G_{ret}(x,t)$ for the massive scalar field equation $\square G - m^2G = -\delta^4(x)$ in 3+1 dimensions is:

$$G_{ret}(x,t) = \theta(t) \cdot \delta(t - r) / (4\pi r) - \theta(t) \cdot \theta(t - r) \cdot m J_1(m\sqrt{t^2 - r^2}) / (4\pi\sqrt{t^2 - r^2})$$

where $r = |\mathbf{x}|$, θ is the Heaviside step function, and J_1 is the Bessel function of the first kind of order one. Natural units c = 1 are in force throughout.

The full field perturbation generated by a point commitment source $S(x,t) = q\, \delta^4(x - x_0)$ at spacetime position $x_0 = (t_0, \mathbf{x}_0)$ is:

$$\delta\kappa(x,t) = q \cdot G_{ret}(x - x_0,\ t - t_0)$$

8.2 The Tail Term and Persistent Influence

The retarded Green's function has two physically distinct parts:

The sharp wavefront — the $\delta(t - r)$ term. A commitment event generates a signal propagating outward at speed $c_\kappa = 1$ (natural units). This is the leading edge of fact-influence: the earliest moment at which a commitment at x_0, t_0 can influence conditions at x, t.

The Bessel tail — the J_1 term. This term is nonzero for all $t > r$ — throughout the entire interior of the causal future of x_0. It does not vanish after the wavefront passes. A commitment event at x_0, t_0 continues to perturb the κ-field at every subsequent point within its causal future.

This is a direct consequence of the massive nature of the κ-field. In the massless limit $m \to 0$, the tail term vanishes and influence is confined to the null cone — the field has no memory. The mass term $m \neq 0$ gives the κ-field a finite range but also generates persistent influence inside the light cone via the Bessel tail. This is the massive scalar analogue of the Huygens–Fresnel principle: in 3+1 dimensions, massless fields propagate cleanly on the light cone, while massive fields fill the interior.

Physical interpretation: a commitment event does not merely signal its occurrence and cease. It continues to modify the conditions for fact-formation throughout its entire causal future. The past does not disappear — it persists as a residual modification of the κ-field in which all subsequent facts are formed.

On the use of τ when commitment constitutes time. A natural concern arises here: if physical time is itself constituted by the accumulation of commitment events, in what sense can the Bessel tail "decay as τ^{-1}"? Does describing the tail in terms of τ presuppose the very structure that commitment generates?

The resolution requires holding the VERSF temporal hierarchy precisely. As established in the companion papers on proto-time and emergent Lorentz invariance (Taylor, "Two Kinds of Time," 2026; Taylor, "Proto-Time and Emergent Lorentz Invariance," 2026), the VERSF framework has four distinct levels:

Level 1 — Proto-time s. A global, non-observable ordering parameter $s \in \mathbb{R}$ for the unitary evolution of the universal wavefunction, formalised as $i\hbar\, \partial|\Psi(s)\rangle/\partial s = \hat{H}|\Psi(s)\rangle$. Proto-time is a mathematical bookkeeping structure, not a physical temporal background: no internal clock yields s as a measurement outcome, and it has no conjugate observable in any local subsystem's algebra.

Level 2 — Ticks. Local, reversible micro-events embedded in proto-time, arising from the accumulation of quantum distinguishability in the TPB framework. Each tick event is assigned a proto-time label s.

Level 3 — Bits (commitment events). Threshold crossings in which a candidate tick first crosses the irreversibility threshold, producing a stable physical record. Each commitment event occurs at a specific proto-time value s^* — it has a proto-time label — but this label does not make s^* a measurable physical time. The proto-time of a commitment event is a position in the mathematical ordering structure, not a location in any observable temporal background.

Level 4 — Physical time t. The accumulated density of commitment events: $t(s) = \int_0^s \lambda(s')\, ds'$, where $\lambda(s) = \Sigma(s)/(k_B \ln 2)$ is the commitment density. This is what clocks measure. Physical time is local, irreversible, and generated by commitment events — it does not exist independently of them.

Commitment events therefore DO have proto-time labels. What they are not located in is *physical time*, which they themselves constitute. The relationship is: a commitment event fires at proto-time s^*; the physical time coordinate $t_0 = t(s^*) = \int_0^{s^*} \lambda(s')\, ds'$ is assigned to it retrospectively by the accumulated count of prior commitment events; and the emergent spacetime point (t_0, $\mathbf{x}_0$) is the coordinate at which the κ-field perturbation is generated.

The τ^{-1} decay of the Bessel tail is a statement at Level 4. It describes how the κ-field perturbation propagates and attenuates in the emergent physical time coordinate $\tau = t - t_0$ — not in proto-time. The sourcing (a Bit fires at proto-time s*) and the propagation (a field perturbation decays algebraically in emergent physical time) are distinct steps at different levels of the hierarchy. No circularity arises between them.

In the static Yukawa limit (time-independent sources), the Green's function reduces to:

```
G_Yukawa(r) = e^(-mr) / (4πr)
```

This is the field generated by a single static commitment source at the origin — exponentially suppressed at large distances with characteristic range m^{-1}, but nonzero at all finite r.

8.3 Asymptotic Decay Rate of the Bessel Tail

For large argument z, the Bessel function satisfies:

```
J₁(z) ~ √(2/πz) · cos(z − 3π/4)     (z → ∞)
```

At fixed spatial separation r and large proper time $\tau = t - t_0 \gg r$, the argument of J_1 grows as mτ, giving:

```
G_tail ~ [m^½ / (4π)] · cos(mτ − 3π/4) / τ     (τ → ∞)
```

The Bessel tail therefore decays as $\boldsymbol{\tau^{-1}}$ asymptotically, up to oscillations. This is considerably slower than the exponential suppression one might naively expect from a massive field. The magnitude of this influence is parametrically controlled by the mass scale m and the source strength q, and may become negligible at large separations despite its non-vanishing character. The slow algebraic decay nonetheless preserves the structural claim of §10.2: commitment events exert long-range persistent influence not merely as a formal mathematical residue, but at a magnitude that remains non-zero throughout the entire causal future. The physical significance in any specific system depends on the magnitude of m and the source strength q; the τ^{-1} scaling establishes the slowness of decay but not the absolute amplitude, which remains parametric pending the resolution of Open Problems 2 and 4 in §13.

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9. Three Commitment Sources

9.1 Field Superposition

Consider three commitment events with strengths q_1, q_2, q_3 at spacetime positions x_1, x_2, x_3. The total source term is:

$$S(x,t) = q_1\, \delta^4(x - x_1) + q_2\, \delta^4(x - x_2) + q_3\, \delta^4(x - x_3)$$

By linearity of the field equation, the total perturbation is:

$$\delta\kappa(x,t) = q_1 G(x - x_1) + q_2 G(x - x_2) + q_3 G(x - x_3) \equiv \delta\kappa_1 + \delta\kappa_2 + \delta\kappa_3$$

9.2 Momentum Decomposition

Substituting the superposed field into the momentum density $p_i = \delta\dot{\kappa}\, \partial_i \delta\kappa$:

$$p_i = (\delta\dot{\kappa}_1 + \delta\dot{\kappa}_2 + \delta\dot{\kappa}_3)(\partial_i\delta\kappa_1 + \partial_i\delta\kappa_2 + \partial_i\delta\kappa_3)$$

Expanding yields nine terms, naturally grouped as:

Self-terms (diagonal):

$$p^{aa}_i = \delta\dot{\kappa}_a \cdot \partial_i\delta\kappa_a \quad (a = 1, 2, 3)$$

Each self-term is the momentum density that source a would carry in isolation.

Pairwise cross-terms (off-diagonal):

$$p^{ab}_i = \delta\dot{\kappa}_a \cdot \partial_i\delta\kappa_b + \delta\dot{\kappa}_b \cdot \partial_i\delta\kappa_a \quad (a \neq b)$$

These are the interaction momentum densities — the momentum flowing between commitment sources through the shared κ-field perturbation.

Total momentum:

$$P_i = \int \left[\Sigma_a\, p^{aa}_i + \Sigma_{a<b}\, p^{ab}_i \right] d^3x$$

9.3 Three-Body Interaction Energy

In the static Yukawa limit, the pairwise interaction energy of the three-source system is:

$$E_{int} = -(1/4\pi) \cdot \left[q_1q_2\, e^{(-mr_{12})}/r_{12} + q_1q_3\, e^{(-mr_{13})}/r_{13} + q_2q_3\, e^{(-mr_{23})}/r_{23} \right]$$

where $r_{ab} = |x_a - x_b|$ is the separation between sources a and b. The Yukawa force on source 1 from sources 2 and 3 is:

$$F^i_1 = - \Sigma_{b\neq 1}\; q_1 q_b \cdot (1 + mr_{1b})\, e^{(-mr_{1b})} / (4\pi r^2_{1b}) \cdot \hat{n}^i_{1b}$$

where $\hat{n}_{ab}$ is the unit vector from b to a. The derivation of the force law from the Yukawa potential is given in Appendix C4.

Note that E_int contains no term factoring as $q_1 q_2 q_3$ — there is no genuine three-body force at pairwise order in the Yukawa potential. Three-body forces arise at the next perturbative order through nonlinear corrections to the field equation.

9.4 The Triangle Structure

Define the edge weights of the three-source fact-network:

$$W_{ab} = q_a\, q_b\, e^{(-mr_{ab})} / r_{ab}$$

The interaction energy is a weighted sum over the edges of the triangle:

$$E_{int} = -(1/4\pi)\, \Sigma_{\{a<b\}}\, W_{ab}$$

Although E_int decomposes into pairwise terms, the system is genuinely networked: the momentum flowing between sources 1 and 2 depends on r_{12}, which is constrained by the triangle geometry formed with source 3. Any perturbation to source 3 modifies the geometry and alters the conditions under which the 1–2 interaction occurs. The network is not the sum of its parts at the level of momentum exchange, even though the static interaction energy is pairwise-additive at leading order.

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10. Derived Results

10.1 Centre of Commitment

Define the commitment-weighted centre of the three-source system:

$$X^i_c = (q_1 x^i_1 + q_2 x^i_2 + q_3 x^i_3) / (q_1 + q_2 + q_3)$$

This definition is exact. The conservation result — that the weighted centre moves at constant velocity in the absence of external sources — requires the additional assumption that q_a acts as the inertial mass of source a, i.e. $q_a\, \ddot{x}^i_a = F^i_a$. This identification is consistent with the counting definition of §12 and the gravitational ρ_bound analogy, but is not yet derived from VERSF fold dynamics. The full derivation is given in Appendix C5.

Subject to that assumption, Newton's third law applied to the Yukawa force gives:

$$d/dt\ \ \Sigma_a\, q_a\, \dot{x}^i_a = 0$$

so the weighted centre of a fact-network moves at constant velocity. An isolated fact-network has **inertia**: it continues in the direction established by its initial configuration of commitment events.

10.2 Momentum as a Network Property

The total fact-momentum is:

$$P^i_{total} = \Sigma_a P^{aa}_i + \Sigma_{a<b} P^{ab}_i$$

The formal decomposition contains self-contributions P^{aa}, whose physical interpretation requires regularisation: point-source self-energies in scalar field theory are generically divergent. Three regularisation approaches are available within the VERSF framework — finite-size source modelling (replacing point sources with extended distributions over a coherence volume ξ^3), a VERSF-native ultraviolet cutoff set by the coherence length ξ (below which the point-source approximation breaks down), or dimensional regularisation (if the divergence is mild). The appropriate scheme depends on the fold-ontology derivation of ξ, which remains open. This issue is deferred to a companion paper on the microscopic commitment structure; the present results treat self-contributions as formal placeholders whose physical content requires that derivation. The cross-terms P^{ab} ($a \neq b$), free of self-energy divergences, carry the genuinely relational content of the network momentum and are unaffected by this caveat. A fact-network has additional interaction momentum that cannot be attributed to any single node. **The network is not the sum of its parts.**

10.3 Persistent Influence

From §8.2 and §8.3, the retarded Green's function guarantees:

$$\delta\kappa(x,t) \neq 0 \quad \text{for all} \quad t > t_0 + |x - x_0|$$

(natural units). The perturbation decays asymptotically as τ^{-1} (up to oscillations), not exponentially. It is never identically zero for finite m and finite r.

The conditions in which any future commitment event occurs are therefore shaped by every prior commitment event within its causal past. The past is not erased. It persists as a residual modification of κ — slower than exponential, oscillatory, but present throughout the entire causal future of any commitment event.

This long-tailed persistence is analogous in structure to known power-law memory effects in non-Markovian systems, but arises here at the fundamental level from the field dynamics of the κ-field rather than from coarse-grained statistical behaviour. It is not an emergent or approximate feature; it is an exact consequence of the massive scalar propagator in 3+1 dimensions.

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11. Observational Tests: Late-Time Horizon Memory in Gravitational-Wave Data

11.1 Motivation

The κ-field framework predicts that irreversible commitment events generate perturbations that persist throughout their causal future, with asymptotic decay that is algebraic rather than exponential (§10.3, Result R4):

$$\delta\kappa(\tau) \sim \cos(m\tau + \varphi) / \tau \quad (\tau \to \infty)$$

This implies that physical systems subject to large irreversible events should not exhibit purely exponential relaxation. Instead, their return to equilibrium should contain a long-lived residual component reflecting persistent κ-field memory.

Black hole mergers provide a natural environment in which to test this prediction: they are among the most energetic irreversible events in the observable universe, they produce a well-defined post-event relaxation phase (ringdown), and high-quality observational data is publicly available.

Coupling to gravitational-wave strain — phenomenological status. The κ-field is a massive real scalar field; gravitational waves are spin-2 tensor perturbations. A first-principles derivation of the coupling between δκ and the observable strain h(t) is not provided in this paper — that derivation requires the full VERSF treatment of how the κ-field couples to metric perturbations, which is reserved for companion work on the gravitational sector (Taylor, "Gravity from Fold-Density Gradients," 2026). The observational test proposed in §§11.2–11.8 should therefore be understood as a *phenomenological proposal*: if the κ-field couples to the gravitational sector (which the cross-sector consistency of §12.7 strongly motivates), then the algebraic tail of δκ should imprint on h(t) with the functional form derived from Result R4. The prediction is the functional form and the discrimination criterion; the coupling amplitude A_κ is a free parameter until the gravitational coupling is derived from first principles. This status is stated at the outset so that the observational test and the underlying field-theoretic framework can be evaluated independently.

11.2 Standard Ringdown Model

In general relativity, the post-merger gravitational-wave signal is modelled as a superposition of damped quasinormal modes:

$$h_{GR}(t) = \Sigma_n A_n e^{-\gamma_n t} \cos(\omega_n t + \varphi_n)$$

where γ_n are the damping rates and ω_n are the mode frequencies. This model predicts purely exponential decay of the signal amplitude at late times. The quasinormal-mode spectrum is fully determined by the final black hole mass and spin, with no residual memory.

11.3 κ-Field Correction: Persistent Memory Tail

Under the κ-field framework, the total observable signal takes the form:

$$h(t) = h_{GR}(t) + \Delta h_\kappa(t)$$

with the correction term:

$$\Delta h_\kappa(t) \approx A_\kappa \cos(mt + \varphi_\kappa) / t^p \qquad (p \approx 1)$$

where A_κ is a model-dependent amplitude, m is the κ-field mass parameter (Open Problem 4, §13), and p = 1 corresponds to the asymptotic tail derived from the retarded propagator in §10.3. This correction term arises directly from the Bessel tail of the Green's function and represents a persistent memory of prior commitment events. It is not a new postulate; it is a consequence of Result R4 applied to the post-merger spacetime region.

11.4 Toy Model: Minimal Relaxation with κ-Memory Tail

Before examining actual gravitational-wave data, it is instructive to establish the qualitative behaviour of the κ-field prediction in a controlled setting. We present a minimal toy model that isolates the essential physics — the competition between exponential damping and algebraic memory — without committing to the full parameter structure of a black hole merger.

The model. All time coordinates in this section are emergent physical time at Level 4 of the VERSF temporal hierarchy (§8.2) — the smooth coordinate $t(s) = \int_0^s \lambda(s')\, ds'$ accumulated from prior commitment events. The merger event is, at Level 3, a large localised Bit: a threshold crossing that occurs at a specific proto-time value s* and contributes to the physical time accumulation. The κ-field perturbation it generates is then described in the emergent physical time $t(s^*) = t_0$ and propagates in the already-constituted emergent spacetime. All subsequent propagation, decay, and measurement — including τ, γ, and O(t) — are quantities in emergent physical time. No circularity arises: sourcing is at Level 3 (proto-time label s*); propagation is at Level 4 (physical time t).

Define a post-event observable O(t). The complete minimal κ-memory relaxation model is:

$$\text{(Eq. 11.1)} \quad O(t) = A\, e^{-\gamma t} \cos(\omega t + \varphi) \;+\; B \cos(mt + \varphi_\kappa) / (1 + t/t_0)$$

where the first term is the standard damped-oscillation component $O_{std}(t)$ and the second is the κ-memory tail $O_\kappa(t)$. Equation 11.1 is the central object of the toy model — it is a concrete, parameter-defined prediction whose two terms have qualitatively distinct late-time behaviour.

Three-regime behaviour. The model exhibits qualitatively distinct behaviour across three temporal regimes:

Early times ($\gamma t \lesssim 1$): $O_{std}(t)$ dominates. If $B \ll A$, the κ contribution is negligible and the observable follows standard damped-oscillation behaviour. Standard physics is fully preserved in this regime.

Intermediate times ($\gamma t \sim \ln(A/B)$): The exponential $e^{-\gamma t}$ has decayed by a factor of order B/A, bringing $O_{std}(t)$ and $O_\kappa(t)$ to comparable amplitude. This is the crossover regime.

Late times ($\gamma t \gg \ln(A/B)$): The exponential decays faster than the power law for any finite γ. Regardless of how small B is, $O_\kappa(t)$ eventually dominates. The observable no longer approaches zero exponentially but settles onto an algebraically decaying residual.

This is the essential physical point: **even a very small κ-tail produces a qualitatively distinct late-time signature**. The departure from pure exponential decay is not a matter of parameter tuning — it is a structural consequence of the algebraic tail existing at all.

Crossover time. The crossover time t_* is defined implicitly by:

$$A e^{-\gamma t_*} \sim B / (1 + t_*/t_0)$$

For $t_* \gg t_0$ (late crossover), this gives:

$$\gamma t_* \sim \ln(A/B) + \ln(t_*/t_0)$$

The logarithmic term on the right ensures that even the logarithmic correction to the crossover grows slowly, so for modest A/B ratios (say, 10^2–10^4) and physically reasonable γ and t_0, the crossover occurs at a finite and computable time. The key point is that t_* is finite for any $B > 0$ — no matter how small the κ coupling, there is always a late-time epoch at which the algebraic tail dominates. Detectability in practice requires the crossover time t_* to lie within the observational window before the signal is buried by noise, placing a joint constraint on the ratio B/A and the damping scale γ: larger γ shortens the quasinormal-mode window, making the κ-tail accessible at earlier times even for smaller B.

Enhanced convolution model. For a more physical picture that mirrors the κ-field mechanism directly, define an effective response function:

$$R(t) = e^{-\gamma t} + \varepsilon \cos(mt) / (1 + t/t_0)$$

where $\varepsilon = B/A$ is the relative κ-coupling. The observed signal for a source burst J(t) is then:

$$O(t) = \int_0^t R(t - t') J(t') dt'$$

with a localised source burst:

$$J(t) = J_0 \exp(-(t - t_b)^2 / 2\sigma^2)$$

This convolution formulation is closer to the physical picture: an irreversible commitment event (the merger) produces a localised burst, and the κ-field responds with both a damped component (the quasinormal modes) and a persistent algebraic tail (the Bessel memory). The convolution smooths the source and removes the $t = 0$ singularity naturally, while preserving the asymptotic τ^{-1} behaviour at late times $t \gg t_b + \sigma$.

The toy models establish the qualitative signature to be searched for in §11.7. Whether the amplitude ε is large enough to be detectable in current data depends on the undetermined parameters m and q (Open Problem 4), but the functional form of the signature — algebraic rather than exponential approach to zero — is robust across all values of these parameters. Equation (11.1) provides the explicit fitting form used in the analysis procedure of §11.7.

Equation (11.1) therefore demonstrates the central physical prediction of the κ-field framework: exponential relaxation is only transient, while algebraic decay is asymptotically unavoidable.

11.5 The Testable Prediction

The key observational distinction is between the two models:

Model	Late-time behaviour
Standard GR (quasinormal modes only)	Exponential decay: e^(−γt)
κ-field augmented	Power-law residual: 1/t

The testable prediction is therefore: at sufficiently late times after merger, the gravitational-wave signal should deviate from pure exponential decay and exhibit a residual power-law tail consistent with τ^{-1} scaling. The late-time segment is the discriminating regime — the quasinormal-mode contribution dominates early, while the κ-field tail dominates asymptotically.

We emphasise that the κ-field contribution does not replace the standard quasinormal-mode description, but appears as a subleading correction at late times. The prediction is not a qualitative alteration of the ringdown phase, but a specific deviation in its asymptotic decay structure — the distinction between a purely exponential approach to equilibrium and one with a residual algebraic tail. Standard GR ringdown physics is fully retained in the h_GR(t) term; the κ-field adds only a late-time residual whose amplitude A_κ depends on the (currently undetermined) parameters m and q. The two descriptions are therefore not in competition: Model B is a proper extension of Model A, reducible to it in the limit A_κ → 0.

11.6 Public Data Sources

This prediction can be tested using publicly available gravitational-wave data from the LIGO Open Science Center (LOSC) and the Gravitational Wave Transient Catalogs (GWTC-1, GWTC-2, GWTC-3). Representative events with well-resolved ringdown phases include GW150914 (the first detected merger), GW170814, and GW170817. Event selection for this analysis should prioritise signal-to-noise ratio in the post-merger window; events with short or poorly-resolved ringdowns are less suitable regardless of their scientific interest for other purposes. These datasets provide time-domain strain data h(t) with sufficient temporal resolution to analyse post-merger relaxation.

11.7 Proposed Analysis Procedure

A minimal test proceeds as follows.

Step 1 — Signal isolation. Extract the ringdown phase of the waveform following peak amplitude, discarding the inspiral and merger portions.

Step 2 — Model fitting. Fit the data to two competing models:

Model A (standard GR):

$$h(t) = \Sigma_n A_n e^{(-\gamma_n t)} \cos(\omega_n t + \varphi_n)$$

Model B (κ-augmented):

$$h(t) = \Sigma_n A_n e^{(-\gamma_n t)} \cos(\omega_n t + \varphi_n) + A_\kappa \cos(mt + \varphi_\kappa) / t^p$$

Step 3 — Model comparison. Evaluate whether inclusion of the power-law term improves late-time fit quality, reduces systematic residuals at late times, and produces consistent scaling exponent p across independent events. Consistency of $p \approx 1$ across multiple events would be the strongest signature.

11.8 Interpretation

Detection of a statistically significant power-law tail in post-merger data would support the existence of a persistent memory component beyond standard quasinormal-mode damping, consistent with the κ-field prediction. Absence of such a tail within experimental sensitivity constrains the magnitude A_κ and the scale m, providing upper bounds on the κ-field parameters that can be compared with the values required by VERSF fold dynamics once Open Problems 2 and 4 are resolved.

The test is falsifiable in both directions: a positive detection would be evidence for the framework; a tight null result would constrain or exclude the κ-field memory effect at the accessible amplitude range.

11.9 Limitations

Several limitations must be noted explicitly.

Signal-to-noise constraints. Late-time gravitational-wave data is typically noise-dominated. Extracting a weak power-law tail against instrumental noise requires careful spectral characterisation and may not be feasible for current detector sensitivity at the required amplitude.

Parameter dependence. The amplitude A_κ of the κ-field contribution depends on the currently undetermined parameters m and the coupling strength q (Open Problem 4). Without these derived values, only the functional form — τ^{-1} — is predicted, not the absolute magnitude.

Non-uniqueness of power-law tails. Algebraic late-time behaviour can arise in other contexts, including gravitational-wave tails from memory effects and Price-law decay of fields outside black holes. Discrimination from these alternatives requires the specific signature of Eq. 11.1: a phase-coherent oscillatory tail $\cos(mt + \varphi_\kappa)/t$, rather than the monotonic or broadband power-law decay expected from standard gravitational-wave tails. Price-law tails are monotonic and non-oscillatory; gravitational-wave memory is a step-function offset rather than a decaying oscillation. The κ-field prediction is structurally distinct from both: it is oscillatory with a characteristic frequency m, phase-coherent across the duration of the signal, and should produce consistent phase and frequency across independent merger events if the κ-field mass parameter m is universal.

Status. This section proposes a testable prediction from the framework, not a confirmed detection. The analysis described in §11.7 has not yet been performed on the LIGO data.

11.10 Summary

The κ-field framework predicts a persistent, algebraically decaying memory component following irreversible events, arising from the Bessel tail of the massive scalar retarded propagator. Gravitational-wave ringdown data provides a direct observational arena in which to test this prediction. The key empirical question is whether post-merger relaxation follows purely exponential decay or exhibits a residual τ^{-1} tail consistent with κ-field memory. The prediction is falsifiable, the data is public, and the analysis is well-defined.

12. Commitment Strength q: A Multi-Theorem Structural Derivation

The κ-field equation introduces a source term of the form:

$$S(x,t) = \Sigma_a \, q_a \, \delta^4(x - x_a)$$

In standard field theory, such source coefficients are introduced phenomenologically. Within the VERSF framework, the form of q is not free. It is the unique conclusion of four independent structural theorems. To reject the identification q_a = N_committed(x_a), a referee must refute all four simultaneously.

12.1 Law Admissibility Forces Record Variables

Any empirically meaningful theory must support repeatable outcomes. Repeatable outcomes require physical records: without a stable record of what occurred, no outcome can be compared across trials and no law can have empirical content. Therefore:

Repeatable experiments ⟹ physical records.
Any theory lacking a record primitive cannot support empirical content.

Theorem 1: All variables appearing in physical laws must correspond to stable physical records.

Within the VERSF admissibility framework, this requirement is not an external philosophical constraint but a derived structural result, established in the admissibility and law-closure papers (Taylor, "On the Structural Status of PAR and Compositional Completeness," 2026). Physically meaningful variables must correspond to stable committed records; uncommitted or pre-factual quantities are inadmissible as primitive law variables. This constrains the source term of any VERSF field equation to represent committed distinguishability — not amplitude, not potential, not any pre-factual degree of freedom.

A source term in a field equation is a variable of that field law. It must therefore correspond to a stable record. Any source variable that is transient, reversible, or observer-incomparable violates the empirical admissibility of the law itself.

12.2 Records Are Binary and Irreducible

The minimal physical record is a single committed distinction between two stable states. This follows from the closure entropy structure: the admissible entropy functional is uniquely $\tilde{S}(N) = \ln N$, with minimal irreversible refinement:

$$\Delta\tilde{S}_{min} = \ln 2$$

corresponding to one binary commitment event. No sub-bit record can be physically stabilised. No non-integer number of bits is consistent with the closure entropy structure.

Theorem 2: The minimal admissible unit of physical sourcing = 1 committed bit.

12.3 Commitment Is Structurally Unavoidable

From the inevitability programme within VERSF:

Irreversible commitment is required for any fact-supporting universe.
Stable records imply coarse-graining and irreversibility.

A record that can be undone is not a record in the empirically meaningful sense — it cannot stably carry information across time and into comparative experimental trials. Reversible distinctions therefore cannot serve as record primitives.

Theorem 3: Records = committed distinctions. Commitment is not a modelling choice; it is the structural prerequisite for records to exist at all.

12.4 Causation Requires Commitment-Carrying Variables

From the causal structure analysis within VERSF:

Reusable causal influence requires a stable record carrier.
Amplitude propagation alone cannot define causal ancestry.

A source term in a field equation must carry causal influence — it is precisely the term that determines what the field does at future spacetime points. Amplitudes that have not committed to a definite record cannot propagate reusable causal influence: they interfere, cancel, and leave no stable ancestry. Only committed records can act as physical sources of influence.

Theorem 4: Only committed records can appear as physical sources of causal influence.

12.5 All Admissible Variables Reduce to Commitment Count

Theorems 1–4 combine without remainder:

- Laws require stable records (T1).
- Records require commitment (T3).
- The primitive unit of a committed record is one bit (T2).
- Physical sources of influence must be committed records (T4).

Therefore:

All admissible physical variables must be functions of N_committed.

This is not a definition. It is the unique conclusion of four independent structural results. Any admissible source term must count committed distinctions. No other functional form survives the conjunction of T1–T4.

12.6 Definition of q

Applying §12.5 to the κ-field source coefficient:

$$q_a = N\_committed(x_a) \quad \in \mathbb{N}$$

q is the count of committed distinctions (facts) associated with a localised process. This is not a definition — it is the unique conclusion of T1–T4. As established in the VERSF admissibility papers (Taylor, "On the Structural Status of PAR and Compositional Completeness," 2026), any source term in a physically meaningful field law must represent committed distinguishability; the present derivation identifies N_committed as the precise measure of that quantity. Any other identification of q would require either an inadmissible law variable or a violation of closure entropy structure. At the continuum level:

$$S(x,t) = \rho\_committed(x,t)$$

where ρ_committed is the local density of committed bits, obtained by coarse-graining over proto-temporal ordering (see §12.8).

Sign. Since q_a = N_committed ∈ ℕ, we have $q_a \geq 0$ for all physical commitment events. A negative q would require destroying committed distinctions — reversing irreversible records — which is excluded by Theorem 3: commitment is structurally unavoidable and its products cannot be undone within the pre-factual domain. Combined with the scalar field result that like-sign charges attract (§10.3):

All physical commitment sources attract each other through the κ-field.

This is unconditional within the admissible class of commitment-sourced interactions. Repulsion is excluded within this class — not by empirical observation but by the same structural theorems that determine q: a negative source would require reversing irreversible committed records, which violates Theorem 3.

12.7 Structural Consistency Across the Framework

The same identification — commitment count — governs every sector of the VERSF programme:

Gravity:

```
ρ_bound(x) = N_committed(x) / ξ³
```

Mass = committed distinguishability density.

Entropy:

```
S = k_B ln 2 · N_committed
```

Entropy = ledger of committed bits.

Time:

```
τ = ordered accumulation of commitment events
```

Time = ordering of facts.

Field sourcing (this paper):

```
q = N_committed
```

Source = local fact density.

This cross-sector consistency is not coincidental. It is a predicted consequence of deriving all four quantities from the same multi-theorem foundation. Any framework that requires different primitives for mass, entropy, time, and field sourcing is either over-parameterised or internally inconsistent. VERSF requires one.

12.8 Absence of a Physical-Time Rate Law

The commitment density $\lambda(s) = dN\_committed/ds$ is a well-defined quantity in proto-time — it is the rate of commitment events per unit proto-time s, equal to $\Sigma(s)/(k\_B \ln 2)$ as derived in the companion proto-time papers (Taylor, "Two Kinds of Time," 2026; Taylor, "Proto-Time and Emergent Lorentz Invariance," 2026). There is nothing circular about expressing the commitment rate in proto-time.

What is circular is a rate equation dq/dt in *physical time* t. Physical time accumulates as $t(s) = \int_0^s \lambda(s')\, ds' = \int_0^s (dN\_committed/ds)\, ds'$. Treating dq/dt as primitive therefore requires physical time t to exist as a parameter — but t is itself the integral of the commitment rate in proto-time. A rate dq/dt where $t = \int(dq/ds)\, ds$ uses the integral of the numerator as the denominator, which is circular.

The proto-time description $\lambda(s) = dq/ds$ is primary and free of this circularity. Physical time $dt = \lambda(s)\, ds$ is derived from it. The passage from the discrete commitment count q to the smooth source density ρ_committed(x,t) is a coarse-graining over proto-time — replacing the sum over discrete proto-time labels s* with a smooth density in the emergent coordinate t(s). This is not a differentiation of q in physical time; it is the Level 4 continuum limit of the Level 3 commitment count, constructed using the four-level hierarchy of §8.2.

12.9 Final Form of the κ-Field Equation

With q fully derived from Theorems 1–4:

$$\Box\delta\kappa - m^2\delta\kappa = -\rho\_committed(x,t)$$

This is a field of commitment capacity sourced by irreversible fact formation. The source term is anchored in the same structural layer as ρ_bound, S̃, and τ. All four are commitment counts. All four are derived from the same theorems. None is postulated.

12.10 Remaining Open Derivation

The identification q = N_committed is fully derived. What remains open is the spatial-temporal distribution of commitment events — not what q is, but where and when the commitment events occur:

- The fold-ontology derivation of the threshold conditions under which a coherence cell commits.
- The emergence of ρ_committed(x,t) from microscopic fold interactions.
- The proto-temporal coarse-graining procedure yielding a smooth classical source density.

These are questions about the distribution of q. They do not affect its identification.

13. Open Problems and Required Derivations

The results of §§7–12 are derived within the established VERSF κ-field framework and are internally consistent with the field equation, the Lagrangian, and the propagator structure. Section 12 has substantially resolved the previously open question of the origin, definition, and sign of q. The following problems remain open.

Open Problem 1 — The macroscopic commitment event.

VERSF defines commitment events at the quantum substrate level: an irreversible state change of the void substrate that produces a distinguishable, stable fact. The extension to macroscopic systems requires a precise coarse-graining procedure. What constitutes a macroscopic commitment event? The natural candidate is a density of microscopic commitment events above a threshold that produces an irreversible macroscopic state change distinguishable by an external observer. This threshold must be derived from VERSF fold ontology, not assumed.

Distinction from Open Problem 2. OP1 is an observational-level question: given that microscopic commitment events exist and occur with some distribution, at what density or combination do they constitute a single macroscopic fact? This is a coarse-graining question about the relationship between the microscopic and macroscopic descriptions. OP2, by contrast, is a dynamical-level question: what fold dynamics generate the microscopic commitment events themselves, and what is their spatial distribution? OP1 presupposes OP2 in the sense that a resolved OP2 would provide the microscopic event distribution that OP1 must coarse-grain — but the two problems are otherwise logically independent and could be addressed in either order.

Open Problem 2 — Fold-ontology derivation of commitment threshold and distribution.

Section 12 establishes $q_a = N\_committed(x_a) \in \mathbb{N}$ as the unique admissible source structure by a law-admissibility argument: any admissible law variable must be a stable record; stable records arise only from fold-level commitment; the primitive unit is one bit; admissibility eliminates all non-committed contributions. The identification of q is therefore fully derived and no longer open. What remains is the detailed mapping between microscopic fold dynamics and the spatial-temporal distribution of commitment events: the threshold conditions under which a coherence cell commits; the emergence of ρ_committed(x,t) from microscopic fold interactions; and the proto-temporal coarse-graining procedure yielding a smooth classical source density. These determine how commitment events are distributed, not what they are.

Open Problem 3 — The continuum limit.

The three-source analysis treats commitment events as point sources. In macroscopic systems, commitment events occur at high density and must be treated as a continuum distribution. The continuum limit requires showing that the classical κ-field source term $S(x,t) = \int q(x') \delta^4(x - x') d^4x'$ emerges correctly from the density of microscopic commitment events as that density becomes large. With q now defined as a commitment count, this passage is analogous to the derivation of charge density from discrete charges in electrostatics — but grounded in VERSF fold ontology. The discreteness of q at the primitive level ($q \in \mathbb{N}$) provides a firmer starting point than was previously available.

Open Problem 4 — Derivation of m and c_κ from VERSF dynamics.

The propagation speed c_κ (taken as c, in natural units $c_\kappa = 1$) and the mass parameter m have been introduced as phenomenological inputs to the field equation. Neither is derived from the underlying VERSF fold ontology. What sets the scale of m? Is it related to the ambient κ_0, to the critical fold-density threshold, or to some characteristic length of the void substrate? Until m is derived, the Yukawa range m^{-1}, the Bessel tail structure, and all results depending on them are parametric rather than predictive. The derivation of c_κ is a prerequisite for the derivation of m, since both enter the dispersion relation of κ-field perturbations.

Until these four problems are resolved — noting that Open Problem 2 is substantially narrowed by §12 — the results of this paper apply at the level of discrete quantum commitment events. Extension to macroscopic systems, while physically motivated and mathematically natural, is not yet fully derived.

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14. Pre-Emptive Response to Potential Objections

The present work introduces a structural constraint on admissible source terms and proposes an observable consequence in late-time relaxation behaviour. Given the foundational scope of the framework, several natural objections arise. We address the most likely concerns explicitly.

14.1 "This is a reinterpretation, not a new result"

A potential criticism is that the identification $q = N_{committed}$ merely redescribes existing source terms in informational language without adding physical content.

This is not the case. In standard field theory, source terms are independent inputs: their existence, form, and magnitude are not constrained by the structure of the theory itself. Nothing prevents the introduction of arbitrary source functions built from any mathematical quantity whatsoever.

In contrast, the present work derives a restriction on admissible source terms. Under the assumptions of distinguishability conservation, irreversible commitment, and operational admissibility (§4), large classes of candidate source constructions are excluded: reversible amplitudes do not define stable records; pre-factual correlations do not survive closure; time-parametrised rates presuppose the temporal structure being derived; continuous densities without discrete commitment violate finite distinguishability. The result reduces the space of admissible theories. It is a constraint on theory construction, not a reinterpretation of existing variables.

14.2 "Admissibility is philosophical rather than physical"

The requirement that law variables correspond to stable records may appear philosophical rather than physical. However, this condition follows directly from empirical consistency: physical laws must support repeatable outcomes; repeatability requires stable records; without stable records, no comparison across experiments is possible. This is a minimal operational requirement, not an additional philosophical assumption. It is the same level of constraint used in operational reconstructions of quantum theory, where measurement outcomes must correspond to physically accessible states.

14.3 "The κ-field is an ad hoc addition"

A common concern with scalar-field extensions is that they introduce new degrees of freedom without necessity. In the present framework, the κ-field is not introduced phenomenologically. It is defined as the local capacity of a region of spacetime to support distinguishable committed records (§5). This interpretation is consistent with the sourcing of the field by commitment events, the propagation of disturbances via a retarded Green's function, the conservation of fact-momentum, and the cross-sector identification with entropy, mass, and time (§12.7). The field therefore arises from the same structural layer as the admissibility constraints. More precisely: just as the VERSF programme establishes that gauge fields are unavoidable rather than optional — forced by the requirement of local state comparison under distinguishability conservation (§1, §2.3) — the κ-field is forced by the requirement that commitment events source the field consistently with the same admissibility conditions. Both are structural necessities of the framework, not phenomenological additions to it.

14.4 "The prediction is too weak or unobservable"

The κ-field correction appears as a subleading contribution at late times:

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Δh_κ(t) ~ cos(mt + φ) / t
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Its amplitude depends on currently undetermined parameters (Open Problem 4, §13), and may be small relative to detector sensitivity. Two points are relevant. First, the prediction concerns functional form, not magnitude: the distinction between exponential and algebraic decay is qualitative and does not depend on parameter tuning. Second, even a very small κ-contribution produces a qualitatively distinct asymptotic regime, demonstrated in the toy model of §11.4, in which exponential relaxation cannot fully erase the residual tail. The prediction is therefore falsifiable in principle, even if current data limits the accessible parameter range.

14.5 "Power-law tails already exist in general relativity"

It is well known that gravitational-wave signals can exhibit late-time power-law behaviour (Price-law tails). The κ-field prediction is structurally distinct in three ways.

Oscillatory structure. The κ-tail has the form $\cos(mt + \varphi)/t$, whereas standard GR tails are typically monotonic or broadband.

Phase coherence. The κ-tail is phase-coherent over time, with a fixed frequency m, while standard tails lack a single coherent oscillation frequency.

Universality across events. If m is a universal parameter of the κ-field, the same frequency and phase structure should appear across independent merger events — unlike geometry-dependent GR tails, which depend on the specific final black hole parameters.

Detection therefore requires identifying this specific phase-coherent oscillatory structure, not merely the presence of power-law decay. §11.9 addresses this discrimination requirement in detail.

14.6 "The framework lacks a complete dynamical derivation"

It is correct that several elements remain open: the derivation of the mass parameter m, the microscopic distribution of commitment events, the continuum limit, and the macroscopic definition of commitment events. These are explicitly identified as Open Problems in §13. The present paper does not claim a complete dynamical theory. Its contribution is to derive the admissible ontology of source terms and the resulting asymptotic behaviour of field perturbations. This is analogous to early stages of other successful programmes, where structural constraints precede full dynamical closure.

14.7 "No existing anomaly is explained"

The absence of a previously identified anomaly may be viewed as a weakness. However, the present work is not framed as an explanation of existing anomalies. It is a predictive framework: it identifies a previously unconstrained aspect of field theory (source admissibility); it derives a new observable consequence (late-time algebraic memory); and it specifies a concrete test using publicly available data (§11). The value of the result lies in its testability, not in post-hoc explanation.

14.8 Summary and Refutation Condition

The central claim of this work can be stated precisely: under minimal operational assumptions, admissible field sources must correspond to committed distinguishability, and this implies a persistent algebraic memory in post-event relaxation.

The prediction is specific (oscillatory 1/t tail), testable (gravitational-wave ringdown using public LIGO data), and falsifiable. The refutation condition is:

Absence of a phase-coherent oscillatory algebraic tail — of the form $\cos(mt + \varphi)/t$ with consistent frequency m across independent merger events — in late-time gravitational-wave ringdown data at sufficient sensitivity would falsify the κ-field memory prediction within the accessible parameter range.

This establishes the work as a constraint-based extension of field theory with a specific empirical signature, not a reinterpretative or unfalsifiable proposal.

Results Status

Result	Status
Spatial dimension $d_s = 3$ (propagator input)	Conditional — proved under K = 7 selection, local homogeneity, and refinement stability (Taylor, "From Schrödinger to Dirac," 2026, Appendix G); K = 7 selection established in Taylor, "K = 7," 2026
κ-field dynamics and Lagrangian	Derived
Stress-energy tensor and fact-momentum	Derived
Conservation law (fact-momentum exchange)	Derived
Retarded propagator and Bessel tail	Derived
Asymptotic τ^{-1} decay rate	Derived
Three-body interaction and network momentum	Derived
Admissible source constraint: $S = F(N_{committed})$	Derived (Theorem 4.4)
q uniquely constrained to committed distinguishability	Structurally derived (Corollary 4.5)
Normalisation: $q = N_{committed}$	Fixed by unit convention
Universal attraction (within admissible class)	Derived (given $q \geq 0$ from Theorem 3)
Cross-sector consistency (gravity, entropy, time, field)	Derived (Proposition 4.7, §12.7)
Distribution of commitment events (spatial-temporal)	Open (OP2)

Result	Status
Mass parameter m and propagation speed c_κ	Open (OP4)
Continuum limit from discrete commitments	Open (OP3)
Macroscopic commitment event definition	Open (OP1)

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15. Conclusion

This paper has established two things that were not previously established in the VERSF programme, and connected them.

The field-theoretic structure of fact-momentum. Working from the κ-field Lagrangian, we derived the complete dynamical momentum theory: the stress-energy tensor, the fact-momentum conservation law, the retarded Green's function, and the three-body interaction structure. The retarded propagator has two distinct parts: a sharp wavefront at $r = t$ and a Bessel tail throughout the causal future that decays algebraically as τ^{-1} — not exponentially. This is an exact result, not an approximation, and it implies that every commitment event continues to modify the conditions for fact-formation throughout its entire causal future. The momentum of a fact-network is a genuine network property: it includes pairwise cross-terms that depend on network geometry and cannot be attributed to individual nodes. The self-contributions require regularisation (deferred to companion work); the cross-terms are well-defined and unconditional.

The structural derivation of q. Every prior VERSF paper using the κ-field equation treated the source strength q as a free parameter. This paper derives it from four independent structural theorems — law admissibility forces record variables (T1); records are binary and irreducible (T2); commitment is structurally unavoidable (T3); causal influence requires committed carriers (T4) — and from Theorem 4.4 and Corollary 4.5, which establish that F must be linear under additivity and minimality. The result $q = N_{committed}$ is not a definition: it is the unique conclusion of T1–T4. Since $q \in \mathbb{N}$ implies $q \geq 0$ and like-sign scalar charges attract, all physical commitment sources attract each other within the κ-field — unconditionally within the admissible class. The same identification governs the gravitational source term ρ_{bound} (up to a geometric normalisation ξ^3), the entropy functional $\tilde{S}$, and physical time, establishing that committed distinguishability is a single primitive underlying four distinct physical sectors.

What remains open. Four open problems are stated in §13: the coarse-graining of macroscopic commitment events (OP1), the fold-ontology derivation of the commitment threshold and spatial distribution (OP2), the continuum limit (OP3), and the derivation of m and c_κ (OP4). The observational prediction of §11 — a τ^{-1} power-law tail in gravitational-wave ringdown data, distinguishable from standard quasinormal-mode exponential decay — provides a natural empirical test of the persistent-influence result (R4) using public LIGO data.

The full inventory of derived results, their status, and their conditionality is given in Appendix B.

The κ-field framework therefore predicts that physical systems are not perfectly forgetful: irreversible events leave a persistent, algebraically decaying imprint that modifies future dynamics in a measurable way.

Appendix A — Notation

Symbol	Definition
$\kappa(x,t)$	Commitment-capacity density
κ_0	Ambient bulk commitment-capacity density
$\delta\kappa$	Perturbation: $\kappa - \kappa_0$
$\delta\dot{\kappa}$	Time derivative of $\delta\kappa$
$\rho_f(x)$	Fold density = $\kappa(x)/\kappa_0$
$\rho_{committed}$	Continuum density of committed bits (coarse-grained q)
ρ_{bound}	Gravitational source density = $N_{committed}/\xi^3$
m	Mass parameter of κ-field; characteristic range m^{-1}
c_κ	κ-field signal propagation speed (set to c = 1 in natural units)
$\Box$	d'Alembertian: $\partial^2_t - \nabla^2$ (natural units)
∂_μ	Partial derivative (coordinate derivative, μ = 0,1,2,3); coincides with covariant derivative on flat Minkowski spacetime
$\eta_{\mu\nu}$	Minkowski metric: diag(+1,−1,−1,−1)
S(x,t)	Commitment source density
q_a	Commitment strength of source a = $N_{committed}(x_a) \in \mathbb{N}$; derived from four independent theorems: (T1) law admissibility requires record variables, (T2) minimal record = 1 bit, (T3) commitment is structurally unavoidable, (T4) causal influence requires committed carriers (§12)
G_{ret}	Retarded Green's function
$T^{\mu\nu}$	Stress-energy tensor of κ-field
p_i	Fact-momentum density: $T_{0i} = \delta\dot{\kappa}\, \partial_i \delta\kappa$ (lowered spatial index; see §3)
P_i	Total fact-momentum: $\int p_i\, d^3x$
P^{aa}_i	Self-momentum of source a (formal; may require regularisation for point sources)
P^{ab}_i	Interaction momentum between sources a and b
W_{ab}	Edge weight: $q_a q_b e^{(-mr_{ab})}/r_{ab}$
E_{int}	Total pairwise interaction energy
r_{ab}	Separation $\lVert x_a - x_b \rVert$
$\hat{n}_{ab}$	Unit vector from b to a
X^i_c	Commitment-weighted centre
ξ	Coherence length (fold ontology)
$\tilde{S}(N)$	Closure entropy functional: ln N

Symbol	Definition
$\Delta\tilde{S}_{min}$	Minimal closure entropy increment: ln 2
J_1	Bessel function of the first kind, order 1
θ(t)	Heaviside step function
ℕ	Natural numbers {0,1,2,...}
ℂ	Complex numbers

Appendix B — Summary of Derived Results

Label	Result	Status
R1	Fact-momentum density: $p_i = T_{0i} = \dot{\delta\kappa}\, \partial_i\delta\kappa$ (lowered index; sign consistent with (+,−,−,−) metric)	Derived from $T^{\mu\nu}$ via §3 convention
R2	Conservation: $d/dt[P_{facts} + P_{field}] = 0$	Derived from $\partial_\mu T^{\mu\nu} = 0$, including source contribution (Appendix C3)
R3	Sharp wavefront at r = t (natural units)	From δ(t−r) term in G_{ret}
R4	Persistent tail: δκ ≠ 0 for all t > r; asymptotic decay τ^{-1} (up to oscillations); absolute amplitude depends on m and q	From J_1 Bessel term; asymptotics from $J_1(z) \sim \sqrt{2/\pi z}$
R5	Pairwise interaction energy: $E_{int} = -(1/4\pi) \Sigma_{a<b}\, q_a q_b\, e^{-mr_{ab}}/r_{ab}$	q derived from fold + closure structure (§12); residual conditionality on fold-threshold derivation (OP2)
R6	Force on source 1: $F^i_1 = -\Sigma_{b\neq 1}\, q_1 q_b\, (1+mr_{1b})\, e^{-mr_{1b}} / (4\pi r^2_{1b})\, \hat{n}^i_{1b}$	q derived (§12)
R7	Centre of commitment: $d/dt\, \Sigma_a\, q_a\, \dot{x}^i_a = 0$	Requires q as inertial mass — consistent with counting definition and ρ_{bound} analogy; derivation from fold dynamics pending (OP2)
R8	Momentum as network property: $P_{total} = \Sigma_a P^{aa} + \Sigma_{a<b} P^{ab}$	Self-terms formal (point-source regularisation required); cross-terms unconditional
R9	Universal attraction: all commitment sources attract	$q_a = N_{committed} \in \mathbb{N}$ (four-theorem derivation, §12) ⟹ $q_a \geq 0$ (commitment reversal excluded by T3) ⟹ all pairs attract; **unconditional**

Appendix C — Mathematical Derivations

C1. Euler–Lagrange Equation from $\mathscr{L}$

Applying the Euler–Lagrange equation to $\mathscr{L} = ½(\partial_\mu\delta\kappa)(\partial^\mu\delta\kappa) - ½m^2(\delta\kappa)^2 + S\cdot\delta\kappa$:

$$\partial_\mu (\partial\mathcal{L} / \partial(\partial_\mu\delta\kappa)) - \partial\mathcal{L}/\partial(\delta\kappa) = 0$$

$$\partial_\mu(\partial^\mu\delta\kappa) + m^2\delta\kappa - S = 0$$

$$\Box\delta\kappa - m^2\delta\kappa = -S$$

confirming the field equation of §5.

C2. Stress-Energy Tensor Derivation

From $T^{\mu\nu} = [\partial\mathcal{L}/\partial(\partial_\mu\delta\kappa)]\, \partial^\nu\delta\kappa - \eta^{\mu\nu}\, \mathcal{L}_{free}$:

$$T^{\mu\nu} = (\partial^\mu\delta\kappa)(\partial^\nu\delta\kappa) - \eta^{\mu\nu} \left[\tfrac{1}{2}(\partial_\lambda\delta\kappa)(\partial^\lambda\delta\kappa) - \tfrac{1}{2}m^2(\delta\kappa)^2 \right]$$

Setting $\mu = \nu = 0$, using $\eta^{00} = +1$ and $\partial_\lambda\delta\kappa\, \partial^\lambda\delta\kappa = (\dot{\delta\kappa})^2 - |\nabla\delta\kappa|^2$:

$$T^{00} = (\dot{\delta\kappa})^2 - \tfrac{1}{2}[(\dot{\delta\kappa})^2 - |\nabla\delta\kappa|^2] + \tfrac{1}{2}m^2(\delta\kappa)^2$$
$$= \tfrac{1}{2}(\dot{\delta\kappa})^2 + \tfrac{1}{2}|\nabla\delta\kappa|^2 + \tfrac{1}{2}m^2(\delta\kappa)^2$$

Setting $\mu = 0$, $\nu = i$ (spatial), using $\eta^{0i} = 0$:

$$T^{0i} = (\partial^0\delta\kappa)(\partial^i\delta\kappa) = \dot{\delta\kappa} \cdot (-\partial_i\delta\kappa) = -\dot{\delta\kappa}\,\partial_i\delta\kappa$$

Lowering both indices:

$$T_{0i} = \eta_{00}\, \eta_{ii}\, T^{0i} = (+1)(-1)(-\dot{\delta\kappa}\,\partial_i\delta\kappa) = \dot{\delta\kappa}\,\partial_i\delta\kappa$$

The fact-momentum density is therefore $p_i = T_{0i} = \dot{\delta\kappa}\, \partial_i\delta\kappa$, consistent with §3. There is no sign ambiguity: the lowered-index definition absorbs the metric factors exactly.

C3. Conservation Law: Full Derivation Including Source Contribution

For the free field ($S = 0$), $\partial_\mu T^{\mu\nu} = 0$ follows from the Euler–Lagrange equation in the standard way. For the momentum component:

$$\partial_t T^{0i} + \partial_j T^{ji} = 0$$

Integrating over all space:

$$d/dt \int T^{0i}\, d^3x = -\oint T^{ji}\, dA_j \rightarrow 0$$

for localised fields (surface terms vanish). This gives $dP^i_{field}/dt = 0$ in the source-free case.

In the presence of sources $S \neq 0$, computing $\partial_\mu T^{\mu i}$ using the field equation yields:

$$\partial_\mu T^{\mu i} = (\partial^i \delta\kappa)\, S = f^i$$

where f^i is the force density exerted on the κ-field by the sources. Integrating:

$$dP^i_{field}/dt = -\int f^i\, d^3x = -dP^i_{sources}/dt$$

Momentum flows between field and sources; the total is conserved. Result R2 follows.

C4. Yukawa Force Derivation

From $G_{Yukawa}(r) = e^{(-mr)}/(4\pi r)$, the force on source a from source b is:

$$F^i_a = -q_a q_b \cdot \partial/\partial x^i_a [G(x_a - x_b)]$$

Computing the radial gradient:

$$\partial/\partial r [e^{(-mr)}/(4\pi r)] = -(1 + mr) e^{(-mr)} / (4\pi r^2)$$

Therefore:

$$F^i_a = -q_a q_b \cdot (1 + mr_{ab}) e^{(-mr_{ab})} / (4\pi r^2_{ab}) \cdot \hat{n}^i_{ab}$$

The factor $(1 + mr)$ arises because the gradient acts on both the Yukawa exponential and the Coulomb-like $1/r$ prefactor. In the limit $m \to 0$ the force reduces to the Coulomb-analogue form $\propto 1/r^2$.

C5. Centre of Commitment Conservation

Assumption (to be derived from fold dynamics). We treat q_a as the inertial mass of commitment source a, so that the equation of motion is:

$$q_a \ddot{x}^i_a = F^i_a$$

This identification is consistent with the counting definition of §12 and the gravitational ρ_{bound} analogy; its derivation from VERSF fold dynamics is left to future work (Open Problem 2).

Subject to this assumption, the total force in the absence of external sources is:

$$\Sigma_a F^i_a = \Sigma_{\{a\neq b\}} F^i_{ab} = 0$$

by Newton's third law: $F^i_{ab} = -F^i_{ba}$ follows from $G(x_a-x_b) = G(x_b-x_a)$ and $\hat{n}_{ab} = -\hat{n}_{ba}$. Therefore:

$$d^2/dt^2 \; \Sigma_a q_a x^i_a = \Sigma_a q_a \ddot{x}^i_a = \Sigma_a F^i_a = 0$$

giving $\Sigma_a q_a \dot{x}^i_a$ = constant, establishing R7.