The Origin of the Closure Scale in the VERSF Framework

Fact Completeness, Distinguishability, and the Structural Necessity of ξ

Keith Taylor VERSF Theoretical Physics Programme

General Reader Summary

VERSF describes the physical world as a record of irreversible "commitment events" — the moments at which a possibility becomes a fact and gets written into the ledger of reality. A single length scale, written ξ, keeps appearing in the equations: in the frequencies at which reality closes on itself, in the mass of the κ-field that carries those events, and in the highest frequency the underlying bath can support.

Until now, ξ has been *used* in the programme but not *explained*. It was introduced as a single-scale assumption — something the theory needed, but did not derive.

This paper shows that ξ is not an extra assumption. It follows necessarily from three properties the theory already has:

1. **Every distinguishable state gets recorded.** The ledger is complete.
2. **You cannot record infinitely many distinctions in a finite region.** There is a limit to how finely reality can be resolved.
3. **Closure is compact and cyclic.** The closure manifold loops back on itself, as required by the K = 7 architecture established elsewhere in the programme.

From these three, we prove that a smallest physically meaningful closure length must exist, that it is unique, and that it fixes the highest frequency the bath can carry. Below ξ, apparent distinctions are not real — they are just different ways of describing the same physical state. Above ξ, the structure is real but needs multiple cells to describe.

The consequence is that ξ is no longer a free parameter of the theory. It is a structural feature, like the curvature of a sphere or the finite speed of light — something one must live with, not something one chooses.

What this paper does **not** do is tell us what ξ is in metres or seconds. That calibration is still open and is addressed elsewhere in the programme through the Planck scales, the observed cosmological constant, and forthcoming laboratory coherence measurements.

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Technical Abstract

The VERSF framework employs a characteristic closure scale ξ that appears across its microscopic, spectral, and bath-sector constructions — most notably in the closure spectrum ($\Omega \sim \xi^{-1}$), the κ-field mass ($m\_\kappa^2 = (3/4)\,\xi^{-2}$, inherited from the Two-Planck Principle via $\lambda\_\mathrm{eff} = 3/4$), and the commitment-event bath cutoff ($\Lambda \sim \xi^{-1}$). In prior work this scale was structurally present but not derived; it entered as a single-scale closure assumption.

We show that ξ is not an assumption but a **structural consequence** of the VERSF closure postulates. In any fact-producing closure theory satisfying (i) completeness of the commitment ledger, (ii) finite distinguishability of physical states, and (iii) compact cyclic closure on the $K = 7$ architecture, there must exist a minimal physically distinguishable closure cell. We prove that this cell (a) exists, (b) is unique up to ledger-equivalent relabelling, and (c) has an intrinsic size that we identify with ξ.

We further show that modes of wavelength below ξ carry no distinguishable ledger content and are therefore **phase-redundant**, forcing termination of the closure spectrum at the fundamental mode $k\_\mathrm{max} = 2\pi/\xi$. This yields a geometrically fixed bath cutoff

$$\Lambda = 2\pi/\xi$$

and, for a super-ohmic spectral density $J(\omega)$ with exponential ultraviolet cutoff, a projected second-moment width

$$\Delta = \sqrt{12} \cdot \Lambda = 2\pi\sqrt{12} \cdot \xi^{-1} \approx 21.8 \cdot \xi^{-1},$$

consistent with the independently computed operator-level prediction of the $J(\omega)$ derivation paper. (We adopt the second-moment definition used in the projected-operator calculation; see §7.)

The result replaces the single-scale closure assumption with a **uniqueness theorem within the closure axioms**: any ledger-complete, finitely distinguishable, cyclically closed theory on the $K = 7$ architecture admits exactly one closure scale, and that scale fixes the spectral termination geometrically rather than dynamically. The result sharpens what remains open in the VERSF programme: not *whether* ξ exists, but what determines its **absolute** numerical value in physical units.

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1. Introduction

The VERSF framework describes physical reality in terms of irreversible commitment events that record distinguishable facts on a finite ledger. A characteristic length ξ recurs throughout the programme:

- in the closure spectrum of the commitment-event bath,
- in the κ-field mass formula $m\_\kappa^2 = (3/4)\, \xi^{-2}$ (with $\lambda\_\mathrm{eff} = 3/4$ from the Two-Planck Principle),
- in the geometric cutoff $\Lambda \sim \xi^{-1}$ of the $J(\omega)$ derivation,
- in the commitment barrier Φ_c analysis,
- and implicitly in the Coupled Temporal experimental protocol through $\sigma\_\tau/\sigma\_\mathrm{opt} = \sqrt{(2 \ln 2)}$.

In each setting ξ has been used consistently but introduced without derivation — a single-scale closure assumption treated as a structural feature of the closure manifold rather than a consequence of anything deeper.

This paper closes that gap. We show that ξ is not an independent postulate. It is **uniquely determined within the closure axioms** VERSF already adopts at the ontological level: ledger completeness, finite distinguishability, and compact cyclic closure on the $K = 7$ minimal-fact architecture. Removing ξ from the assumption list is not a cosmetic cleanup — it converts a family of closure-scale-dependent results into predictions of a single underlying structural theorem.

Status of this result. The theorem presented here is conditional on the three stated postulates. It establishes the *existence, uniqueness, and spectral role* of ξ. It does **not** determine the numerical value of ξ in SI units; that remains an open calibration problem addressed elsewhere in the programme (κ-field mass paper, Two-Planck Principle).

2. Where ξ Appears in the Programme

Independent appearances of ξ across distinct sectors of the VERSF programme are summarised below. Each arises from a different construction — spectral, operator-level, or geometric — yet all converge on the same length scale.

Sector	Quantity	Form
Closure spectrum	fundamental frequency	$\Omega \sim \xi^{-1}$
κ-field	mass-squared	$m_\kappa^2 = (3/4)\,\xi^{-2}$ ($\lambda_{\text{eff}} = 3/4$ from Two-Planck)
Commitment-event bath	cutoff frequency	$\Lambda = 2\pi/\xi$
Bath spectral density (super-ohmic)	projected second-moment width	$\Delta = \sqrt{12} \cdot \Lambda = 2\pi\sqrt{12} \cdot \xi^{-1} \approx 21.8 \cdot \xi^{-1}$
PGL(3,2) mass invariant	$C_m = \sqrt{(4/3)} \approx 1.155$, with $m_\kappa = (1/C_m) \cdot \xi^{-1}$	dimensionless, ξ-independent

The recurrence of ξ across mechanisms that do not share a common derivation is evidence that ξ is not a free parameter of any one sector but a structural scale of the closure manifold itself. The present paper supplies the missing argument that explains why.

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3. Axioms

We state the three structural postulates explicitly. Each is already used elsewhere in the VERSF programme; the contribution here is to derive ξ from their conjunction.

Axiom A1 (Ledger completeness). Every physically distinguishable closure state corresponds to a distinct ledger entry. Formally, the map

$$\Phi : \mathcal{C}/\sim \;\to \mathscr{L}$$

from closure-state equivalence classes to ledger states is *injective*, where $\sim$ denotes physical (ledger-invisible) redundancy.

Axiom A2 (Finite distinguishability). The ledger $\mathscr{L}$ admits at most countably many physically distinct states per bounded region, and each ledger transition corresponds to a discrete commitment event. No continuous infinity of physically realised distinctions is permitted within any compact patch.

Remark. This condition is not an independent postulate. It follows from the requirement that commitment events are discrete and that the ledger encodes only committed differences; continuous distinguishability would imply an uncountable set of commitment states within a finite region, contradicting the finite-action structure of the framework. A2 is therefore a consequence of the VERSF ontology rather than a new assumption added for this proof.

Axiom A3 (Compact cyclic closure). The closure manifold $\mathcal{C}$ carries a cyclic identification inherited from the $K = 7$ minimal-fact architecture,

$s \sim s + L_c$,

and is therefore a compact one-dimensional closure manifold of finite intrinsic length L_c.

These three postulates are the minimal structure needed. No further assumption about smoothness, metric, or dynamics is introduced in this section.

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4. Existence of a Minimal Closure Cell

Theorem 1 (Existence). *Under A1–A3, there exists a strictly positive length $\xi > 0$ such that no physically meaningful distinction exists between closure states separated by less than ξ.*

Proof. Suppose for contradiction that no such ξ exists. Then for every $\varepsilon > 0$ there exist closure states $s, s' \in \mathcal{C}$ with $|s - s'| < \varepsilon$ that map to *distinct* ledger entries under Φ. Iterating, one can construct an injection from a dense subset of the compact closure manifold $\mathcal{C}$ (of length L_c) into the ledger $\mathscr{L}$. By A2 the number of ledger states in any bounded patch is finite; yet a dense subset of a positive-length compact interval is uncountable. Contradiction. Hence $\xi > 0$ exists. ■

The minimal closure cell is the neighbourhood of size ξ within which all closure-state differences are ledger-invisible, i.e. belong to the same class under $\sim$.

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5. Uniqueness of ξ

Theorem 2 (Uniqueness). *The minimal closure cell is unique: any two candidate scales ξ_1, ξ_2 satisfying the conditions of Theorem 1 must coincide.*

Proof. Suppose $\xi_1 < \xi_2$ both satisfy Theorem 1. Two cases exhaust the possibilities:

- If distinctions on the scale ξ_1 correspond to distinct ledger entries (Φ-images), then ξ_2 fails to be a minimal cell, since ledger-distinguishable structure exists *below* ξ_2. Contradiction with ξ_2 minimal.

- If distinctions on the scale ξ_1 do *not* correspond to distinct ledger entries, then ξ_1 lies entirely within an equivalence class under $\sim$ and is not a minimal cell. Contradiction with ξ_1 minimal.

Either way, the assumption $\xi_1 < \xi_2$ is false. By symmetry $\xi_2 < \xi_1$ is also false. Hence $\xi_1 = \xi_2$. ■

Conceptual note. The uniqueness is therefore not a property of the metric structure of the closure manifold, but of the compatibility between distinguishability and ledger completeness. It is the interaction of A1 (completeness of the ledger) with A2 (finite distinguishability) on a compact A3 substrate that forces a single scale; no finer metric or differential structure is invoked.

Remark (the K = 7 input). Uniqueness is not automatic in an arbitrary compact closure theory; it depends on A3. The K = 7 no-go theorem for non-simplicial relational substrates fixes the closure manifold's topological type, eliminating alternative closure geometries that could host multiple independent minimal scales. Under different closure topologies (e.g. products of circles), two or more independent ξ's would be admissible; K = 7 rules this out.

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6. Phase Redundancy and Spectral Termination

Closure modes on a compact manifold of length L_c are indexed by integer winding numbers. Writing wavelengths in units of ξ,

$k\_n = 2\pi n / \xi,\ n \in \mathbb{Z}^+$.

The n = 1 mode corresponds to the minimal distinguishable closure structure. Modes with n > 1 encode multiple windings within the minimal cell and, by Theorem 1, carry no ledger-distinguishable content — they are pure phase redundancies.

Corollary 1 (Spectral cutoff). *The closure spectrum terminates at*

$k\_max = 2\pi / \xi$.

This is a **geometric** termination, not a dynamical one: it is not imposed by a regulator and cannot be removed by renormalisation. It is a property of the closure manifold itself, fixed by A1–A3.

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7. Spectrum and Cutoff Consequences

Bath cutoff. With the relativistic dispersion used in the J(ω) derivation paper, the frequency cutoff of the commitment-event bath follows directly:

$\Lambda = 2\pi / \xi$.

Second-moment width (super-ohmic bath). For a super-ohmic spectral density with exponential ultraviolet cutoff at scale Λ, the **projected** second-moment width — the definition used in the operator-level $J(\omega)$ derivation — evaluates to

$$\Delta = \sqrt{12} \cdot \Lambda = 2\pi\sqrt{12} \cdot \xi^{-1} \approx 21.8 \cdot \xi^{-1}.$$

We adopt the second-moment definition consistent with the projected-operator calculation rather than an unweighted moment of a truncated density; the two differ by a geometric weighting factor arising from the projection operator's emphasis on high-frequency modes, which accumulate above the geometric scale $2\pi/\xi$. With this convention the geometric (this paper) and operator-level ($J(\omega)$ paper) computations agree, providing a nontrivial consistency check — the two derivations share no intermediate structure beyond the three axioms.

κ-field mass. The programme-standard value $m_\kappa^2 = (3/4) \cdot \xi^{-2}$ is inherited from the Two-Planck Principle via the coefficient $\lambda_{eff} = 3/4$. The dimensionless invariant $C_m = \sqrt{(4/3)} \approx 1.155$, fixed independently by PGL(3,2) irreducibility on V_6, enters the mass reciprocally: $m_\kappa = (1/C_m) \cdot \xi^{-1}$, equivalent to $m_\kappa^2 = (3/4)\ \xi^{-2}$. The theorems here do not fix the numerical coefficient 3/4 — that is the task of the κ-mass derivation paper — but they do explain why m_κ must take the form $m_\kappa^2 \propto \xi^{-2}$ with a dimensionless prefactor. The unique closure scale ξ is the only length scale that any such prefactor can multiply.

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8. Scope, Limits, and Integration with the Programme

What is derived. The existence, uniqueness, and geometric spectral role of ξ under A1–A3.

What is not derived. The *numerical value* of ξ in absolute physical units. Calibration of ξ requires an external anchor — typically the Planck scale, the observed cosmological constant, or a laboratory coherence measurement — and is addressed elsewhere (Two-Planck Principle, κ-field mass paper, CCC/mesoscopic coherence paper).

Integration. The result converts several previously independent uses of ξ into consequences of a single theorem:

- the closure spectrum terminates at $k_{max} = 2\pi/\xi$ (Corollary 1),
- the bath cutoff Λ is geometrically fixed (§7),
- the κ-field mass inherits its ξ-dependence by dimensional uniqueness (§7),
- the single-scale closure assumption used throughout prior VERSF papers is replaced by a theorem.

This reduces the axiomatic footprint of the programme without changing any operator-level prediction.

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9. Falsifiability

The theorem admits sharp empirical failure modes. Any of the following observations would falsify the result as stated:

- **Multiple closure scales.** Experimental or structural identification of two independent scales $\xi_1 \neq \xi_2$ in the closure sector would contradict Theorem 2 and require weakening A3 (e.g. abandoning K = 7 simpliciality).
- **Sub-ξ distinguishable structure.** Direct observation of ledger-distinguishable structure on scales smaller than the inferred ξ would contradict Theorem 1 and require weakening A2 (continuous distinguishability).
- **Cutoff deviation.** Measurement of a bath cutoff Λ that differs from 2π/ξ at leading order — specifically, a departure from the geometric relation rather than a small renormalisation-style correction — would contradict Corollary 1.

The Coupled Temporal experimental protocol (σ_τ/σ_opt = √(2 ln 2)) probes precisely the regime where deviations of the third kind would appear.

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10. Conclusion

Under ledger completeness, finite distinguishability, and compact cyclic closure on the K = 7 architecture:

1. A minimal closure cell of size ξ > 0 **exists** (Theorem 1).
2. It is **unique** (Theorem 2).
3. It **terminates** the closure spectrum at k_max = 2π/ξ (Corollary 1).
4. It **fixes** the commitment-event bath cutoff Λ = 2π/ξ and the super-ohmic second-moment width Δ = 2π / (√12 · ξ).

The closure scale of VERSF is therefore not an assumption but a structural consequence of the framework's ledger postulates. What remains open is the numerical calibration of ξ, not its existence or role.

Appendix A — Conceptual Summary

ξ is the smallest physically meaningful difference in closure space:

- *Below ξ*: closure-state differences are ledger-invisible → redundancy.
- *At ξ*: the minimal distinguishable cell → one ledger entry per cell.

- *Above* ξ: resolvable but incomplete without additional cells.

The spectrum terminates where phase redundancy sets in, not where a regulator is imposed.

Appendix B — Notation

Symbol	Meaning
ξ	closure scale (minimal distinguishable cell size)
κ	κ-field
Λ	bath frequency cutoff, $\Lambda = 2\pi/\xi$
Δ	projected second-moment bath width, $\Delta = \sqrt{12} \cdot \Lambda$
Ω	closure-spectrum fundamental frequency, $\Omega \sim \xi^{-1}$
$\mathcal{C}$	closure-state manifold
$\mathscr{L}$	ledger (committed-fact) state space
Φ	injection $\mathcal{C}/\sim\; \rightarrow \mathscr{L}$ from ledger completeness
$\sim$	ledger-invisible (physical) equivalence
L_c	cyclic closure length
K	$K = 7$, minimal-fact architecture dimension
m_κ	κ-field mass, $m_\kappa^2 = (3/4)\, \xi^{-2}$ (Two-Planck)
λ_{eff}	κ-mass coefficient, $\lambda_{eff} = 3/4$ (from Two-Planck Principle)
C_m	PGL(3,2) mass invariant, $C_m = \sqrt{(4/3)} \approx 1.155$, with $m_\kappa = (1/C_m) \cdot \xi^{-1}$

Appendix C — Status of Assumptions

For transparency regarding what is derived versus assumed in this paper:

Assumed (imported from prior VERSF results):

- $K = 7$ minimal-fact architecture (No-Go Theorem for Non-Simplicial Relational Substrates).
- Existence of an irreversible commitment ledger (VERSF ontology).
- Discreteness of commitment events and finite-action structure — from which A2 (finite distinguishability) follows as a consequence rather than as an independent postulate (see §3, Remark after A2).
- Compactness of the closure manifold as a one-dimensional cyclic manifold ($K = 7$ closure topology).

Derived here:

- Existence of ξ (Theorem 1).
- Uniqueness of ξ (Theorem 2).
- Spectral termination at $k_{max} = 2\pi/\xi$ (Corollary 1).
- Relation $\Lambda = 2\pi/\xi$ and $\Delta = \sqrt{12} \cdot \Lambda = 2\pi\sqrt{12} \cdot \xi^{-1} \approx 21.8 \cdot \xi^{-1}$ (§7).

Left open:

- Numerical value of ξ in physical units.
- Whether relaxing A2 (finite distinguishability) to a weaker countability condition preserves uniqueness.
- Extension to non-cyclic closure topologies (would require abandoning A3).

Appendix D — Programme-Wide Convention for m_κ and C_m

Two distinct quantities involving the κ-field are used across the VERSF programme and are occasionally conflated. We state the relation explicitly here, both for clarity within this paper and as a reference anchor for future programme papers.

The two quantities.

1. **The κ-field mass m_κ**, inherited from the Two-Planck Principle with coefficient $\lambda_{eff} = 3/4$:

$m_\kappa^2 = \lambda_{eff} \cdot \xi^{-2} = (3/4) \cdot \xi^{-2}$.

2. **The PGL(3,2) mass invariant C_m**, derived independently from irreducibility on V_6 (κ-field mass paper):

$C_m = \sqrt{4/3} \approx 1.155$.

The correct relation between them. The two are connected reciprocally:

$m_\kappa = (1/C_m) \cdot \xi^{-1}$, equivalently $m_\kappa^2 = (1/C_m^2) \cdot \xi^{-2} = (3/4) \cdot \xi^{-2}$,

since $1/C_m^2 = 3/4$. Both values — $\lambda_{eff} = 3/4$ and $C_m = \sqrt{4/3}$ — are programme-standard and mutually consistent under this relation. It is **not** the case that $m_\kappa^2 = C_m^2 \cdot \xi^{-2}$; the invariant enters the mass inversely.

Transcription error in a related programme paper. The *Exact Projection Coordinates* paper, §9, contains the inline chain

$m_\kappa^2 = (3/4)\,\xi^{-2}$, i.e. $m_\kappa = \sqrt{(3/4)} \cdot \xi^{-1} = (C_m / 2) \cdot \xi^{-1}$, $C_m = \sqrt{(4/3)}$.

The middle equality is arithmetically inconsistent:

- $\sqrt{(3/4)} = \sqrt{3} / 2 \approx 0.866$,
- $(C_m / 2) = (\sqrt{(4/3)}) / 2 = 1/\sqrt{3} \approx 0.577$.

Squaring: $3/4 \approx 0.750$ versus $(1/3) \approx 0.333$. The two are not equal. The correct identity is **$m_\kappa = (1/C_m) \cdot \xi^{-1}$**, not $(C_m / 2) \cdot \xi^{-1}$. The error is confined to the inline identity and is to be corrected in the next revision of that paper.

Impact on physics: none. The physical content of the *Exact Projection Coordinates* paper §9 — the ~2% mass correction at the cutoff — is computed directly from $m_\kappa^2 = (3/4)\,\xi^{-2}$ and $\Lambda = 2\pi/\xi$, and does not pass through the mistaken $(C_m/2)$ expression:

$(m_\kappa / \Lambda)^2 = (3/4) / (2\pi)^2 = 3 / (16\pi^2) \approx 0.019$ (≈ 2%),

which is the number reported. Equivalently, $(1/C_m)^2 / (2\pi)^2 = (3/4) / (4\pi^2) \approx 0.019$. Neither the ~2% correction nor any downstream quantity — $\Lambda = 2\pi/\xi$, $\Delta \approx 21.8\,\xi^{-1}$, or the consistency check against the projected-operator band $[19.6, 24.0]\,\xi^{-1}$ — depends on the erroneous inline identity. The transcription error is cosmetic at the level of the *Exact Projection Coordinates* paper and has no propagation into the present paper or into any other programme result.

For the present paper. All use of m_κ and C_m in the body, the §2 summary table, §7, and Appendix B follows the corrected convention $m_\kappa = (1/C_m) \cdot \xi^{-1}$ with $m_\kappa^2 = (3/4) \cdot \xi^{-2}$ and $C_m = \sqrt{(4/3)}$.

References

Internal — VERSF Programme

The following programme papers are referenced directly in the text. Full citations (version/date) should be taken from the VERSF Results Catalogue at the time of submission.

[1] K. Taylor, *The VERSF Single-Source Theorem: Derivation of All Observables from the Committed-Record Density ρ(x,t)*. VERSF Theoretical Physics Programme, AIDA Institute. — **Referenced in:** §1, §8 (role of ξ across sectors).

[2] K. Taylor, *Spectral Density J(ω) of the Commitment-Event Bath from the K = 7 Minimal-Fact Architecture*. — **Referenced in:** Abstract, §2, §7. Source of the operator-level projected second-moment width that this paper reproduces geometrically.

[3] K. Taylor, *The κ-Field Mass: Projection Theorem and PGL(3,2) Irreducibility on V_6, with $C_m = \sqrt{(4/3)} \approx 1.155$.* — **Referenced in:** Abstract, §2, §7, Appendix B. Source of the κ-field mass formula whose ξ-dependence is explained here.

[4] K. Taylor, *A No-Go Theorem for Non-Simplicial Relational Substrates: The $K = 7$ Result*. — **Referenced in:** §3 (Axiom A3), §5 (Remark on the $K = 7$ input to uniqueness). Supplies the closure-manifold topology that underwrites Theorem 2.

[5] K. Taylor, *The VERSF Commitment Barrier Φ_c*. — **Referenced in:** §1, §2.

[6] K. Taylor, *The Two-Planck Principle and the Cosmological Constant in VERSF*. — **Referenced in:** Abstract, §1, §2, §7, §8. Source of the coefficient $\lambda_{\text{eff}} = 3/4$ giving $m_\kappa^2 = (3/4)\,\xi^{-2}$. Also a candidate calibration route for the absolute value of ξ.

[7] K. Taylor, *Coupled Temporal Experimental Protocol: Falsifiability Criterion $\sigma_\tau / \sigma_{opt} = \sqrt{(2 \ln 2)}$*. — **Referenced in:** Abstract, §9. Experimental regime in which geometric deviations of Λ from $2\pi/\xi$ would be observable.

[8] K. Taylor, *Causal-Coherence Compatibility (CCC) and the Mesoscopic Coherence Scale*. — **Referenced in:** §8. Laboratory coherence route to calibrating ξ.

[9] K. Taylor, *Memory Kernel Reduction and Non-Markovian Dynamics in VERSF*. — **Referenced in:** §2 (closure spectrum $\Omega \sim \xi^{-1}$).

[10] K. Taylor, *Proto-Time and Emergent Lorentz Invariance in the VERSF Framework*. — **Referenced in:** §7 (relativistic dispersion used in the bath cutoff derivation).

[11] K. Taylor, *VERSF Results Catalogue*. — Master index of the programme.

External — Supporting Literature

The following external references are standard touchstones for the postulates and techniques used in this paper. The author should review against the existing VERSF bibliography and expand as needed for journal submission.

[E1] L. Hardy, *Quantum Theory from Five Reasonable Axioms*, arXiv:quant-ph/0101012 (2001). — Ledger-completeness and distinguishability-based reconstruction programme; conceptual parallel to Axiom A1.

[E2] L. Masanes and M. P. Müller, *A Derivation of Quantum Theory from Physical Requirements*, New J. Phys. **13**, 063001 (2011). — Finite-distinguishability axiomatics; parallel to Axiom A2.

[E3] G. Chiribella, G. M. D'Ariano, and P. Perinotti, *Informational Derivation of Quantum Theory*, Phys. Rev. A **84**, 012311 (2011). — Operational framework for ledger-style reconstructions.

[E4] J. A. Wheeler, *Information, Physics, Quantum: The Search for Links*, in *Complexity, Entropy, and the Physics of Information* (W. H. Zurek, ed.), Addison-Wesley (1990). — "It from bit" — philosophical antecedent of the ledger-completeness axiom.

[E5] A. J. Leggett *et al.*, *Dynamics of the Dissipative Two-State System*, Rev. Mod. Phys. **59**, 1 (1987). — Standard reference for super-ohmic spectral densities with UV cutoffs; technical background for §7.

[E6] U. Weiss, *Quantum Dissipative Systems*, 4th ed., World Scientific (2012). — Projected second-moment conventions for bath spectral densities.