

# Chronotopic Metric Theory IV: Coherence Causality Geometry and Emergent Lorentz Structure

Matěj Rada

Email: MatejRada@email.cz

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**Abstract**—Chronotopic Metric Theory (CTMT) is a pre-geometric, kernel-based framework in which metric structure, gauge redundancy, and effective quantum dynamics emerge from information-theoretic curvature and coherence constraints rather than being postulated. Building on CTMT-III, where Fisher information geometry was shown to be the unique curvature compatible with kernel distinguishability and where Standard Model gauge structure and low-dimensional geometry arise as rigidity fixed points of the Coherence–Redundancy Stabilization Criterion (CRSC), the present work develops the causal sector of CTMT.

We introduce *coherence causality geometry*, in which causal admissibility is defined by monotonicity of coherence proper time induced by Fisher curvature and transport kernels. We show that coherence-preserving transport necessarily obeys a partial ordering constraint, derive a Fisher-induced effective line element with Lorentzian signature in the rigid regime, and define *coherence cones*, *hazard cones*, and *causal horizons* as stability-limited analogues of light cones and event horizons.

Within this unified framework, linear quantum dynamics, mesoscopic nonlinear behavior, and macroscopic decoherence appear as distinct rigidity regimes of a single causality structure, resolving the tension between microscopic reversibility and macroscopic irreversibility without introducing additional postulates. Lorentz-like causal structure is shown to be a consequence of coherence geometry and information-theoretic stability rather than a fundamental assumption.

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## I. OVERVIEW

CTMT begins with a minimal kernel seed  $\mathcal{K}$ , without presupposing metric structure, dimensionality, gauge groups, or Hilbert spaces. CTMT-I/II established reconstruction procedures and coherence geometry; CTMT-III showed that Fisher curvature is the unique curvature compatible with kernel distinguishability and that the Coherence–Redundancy Stabilization Criterion (CRSC) enforces low-dimensional geometry and Standard Model gauge structure in the rigid regime.

In this fourth part we address the causal sector:

- 1) How does causality arise from pre-geometric kernel dynamics?
- 2) How are causal cones, Lorentz-like signatures, and horizon-like structures enforced by coherence geometry?
- 3) How are microscopic linear quantum dynamics, mesoscopic nonlinear behavior, and macroscopic decoherence unified by a single causality machinery?

The core result is that *causality in CTMT is more primitive than quantum linearity*: it is encoded in coherence-time ordering induced by Fisher curvature and transport kernels. Rigidity amplifies this into the linear, Lorentz-compatible

causal structure observed in quantum field theory, but is not required for causal admissibility itself.

## II. FOUNDATIONS AND RELATION TO EXISTING WORK

CTMT is not introduced as a replacement for existing physical theories, but as a pre-geometric inference framework whose rigid limits reproduce known structures. Several components of CTMT connect directly to established lines of research:

- **Information geometry:** Fisher information metrics and curvature as measures of distinguishability are well established [1], [2]. CTMT differs in treating Fisher curvature not as an auxiliary structure on a statistical model, but as the primary generator of effective geometry.
- **Emergent spacetime and causality:** Prior approaches derive spacetime or causal structure from entanglement, order relations, or quantum channels [3], [4]. CTMT instead derives causality from coherence-preserving transport constraints on kernel dynamics.
- **Open quantum systems and decoherence:** The distinction between coherent, mesoscopic, and decoherent regimes parallels known behavior in open-system dynamics [5], but CTMT provides a unified geometric explanation via rigidity rather than environment-specific modeling.
- **Relativity and Lorentz structure:** Unlike axiomatic relativity, CTMT does not assume Lorentz invariance. Instead, Lorentzian signature emerges from positivity and rank structure of Fisher curvature, similar in spirit to thermodynamic or entropic gravity approaches [6], but derived here from kernel coherence constraints.

This positioning clarifies that CTMT extends, rather than contradicts, existing theoretical frameworks, while providing a deeper unifying structure.

## III. STRUCTURAL ENERGY-KERNEL LAW AND TRANSPORT GEOMETRY

We recall the structural energy-kernel law in CTMT, which expresses observable influence at spacetime label  $(\mathbf{x}, t)$  as transported structured energy:

$$p(\mathbf{x}, t) = \int_{\Omega_\epsilon} \int_V \int_\epsilon \mathcal{T}(\mathbf{x}, t; \mathbf{x}', t'; \epsilon) \cdot \mathcal{S}(\mathbf{x}', t'; \epsilon) d^3x' dt' d\epsilon. \quad (1)$$

Here:

- $\mathcal{S}(\mathbf{x}', t'; \epsilon)$  is a source density (structured energy, modulation, or information) at scale  $\epsilon$ ,
- $\mathcal{T}(\mathbf{x}, t; \mathbf{x}', t'; \epsilon)$  is the transport kernel encoding medium constraints and coherence geometry,
- $\epsilon$  is an internal coherence/resolution parameter, integrated over a domain  $\Omega_\epsilon$ .

Equation (1) defines *transport geometry*: the geometry of how structured influence propagates through the reconstruction layer induced by the kernel. In CTMT-IV we refine this to *causality geometry* by imposing coherence-time ordering constraints on the support of  $\mathcal{T}$ .

## IV. COHERENCE PROPER TIME AND CANONICAL CAUSALITY CONSTRAINT

### A. Coherence proper time

We define coherence proper time  $\tau$  as a monotonic parameter along kernel trajectories that preserve or increase Fisher distinguishability. This definition is operational rather than kinematic:  $\tau$  is not assumed to coincide with coordinate time, nor is it required to be globally integrable.

In the rigid regime,  $\tau$  aligns with reconstructed coordinate time, but this alignment is a consequence of stability, not an axiom.

### B. Canonical causality constraint

We now formulate causality as an admissibility condition on  $\mathcal{T}$ .

**Definition IV.1** (Coherence causality). A transport kernel  $\mathcal{T}$  is *coherently causal* if for all  $(\mathbf{x}, t; \mathbf{x}', t'; \epsilon)$  with  $\mathcal{T}(\mathbf{x}, t; \mathbf{x}', t'; \epsilon) \neq 0$  one has

$$\mathcal{T}(\mathbf{x}, t; \mathbf{x}', t'; \epsilon) \neq 0 \Rightarrow \tau(\mathbf{x}, t) \geq \tau(\mathbf{x}', t'). \quad (2)$$

Thus, influence can only be transported along non-decreasing coherence proper time. This replaces coordinate-time ordering with *behavioral-time ordering*. In the rigid quantum regime,  $\tau$  and  $t$  are aligned, and (2) reduces effectively to standard causal ordering.

**Proposition IV.2** (Causality without rigidity). *Coherence causality (2) does not require full rigidity of the Fisher spectrum. Nonlinear, nonunitary kernel evolution can still be coherently causal as long as  $\tau$  is non-decreasing along the support of  $\mathcal{T}$ .*

This formalizes the central CTMT insight: *causality is more primitive than quantum linearity*. Quantum mechanics is the rigid limit of a more general coherently causal dynamics.

## V. FISHER-INDUCED CAUSAL METRIC AND LORENTZ STRUCTURE

### A. Projected Fisher tensor and effective line element

Let  $F$  be the Fisher curvature tensor on the reconstruction manifold. From CTMT-III, CRSC enforces a low-rank, low-dimensional stable spectrum in the rigid regime. Let  $F_{\parallel}$  denote the projection of  $F$  along dominant coherence directions (longitudinal) and  $F_{\perp}$  the projection onto orthogonal directions (transverse).

We define an effective line element:

$$d\tau^2 = \frac{1}{\lambda_{\max}(F_{\parallel})} dt^2 - \frac{1}{\lambda_{\min}(F_{\perp})} d\ell^2, \quad (3)$$

where:

- $\lambda_{\max}(F_{\parallel})$  is the largest eigenvalue of the longitudinal Fisher block (strongest temporal sensitivity),
- $\lambda_{\min}(F_{\perp})$  is the smallest eigenvalue of the transverse block (weakest spatial sensitivity),
- $d\ell^2$  is an induced spatial line element along stable coherence directions.

In the rigid limit where CRSC enforces a stable low-rank Fisher spectrum, this construction coincides with the emergence of an effective pseudo-Riemannian metric. Outside this limit, Eq. (3) should be interpreted as a causal ordering functional rather than a spacetime metric.

**Proposition V.1** (Lorentzian sign structure). *If  $F_{\parallel}$  and  $F_{\perp}$  are positive semidefinite with  $\lambda_{\max}(F_{\parallel}) > 0$  and  $\lambda_{\min}(F_{\perp}) > 0$ , then the effective line element (3) has Lorentzian signature  $(+, -, \dots, -)$  along the stable coherence subspace.*

*Proof.* The coefficients in front of  $dt^2$  and  $d\ell^2$  in (3) are strictly positive and negative, respectively, so the quadratic form has exactly one positive and the remaining negative signs along the stable subspace.  $\square$

Thus, *Lorentz signature is forced* by the positivity of Fisher curvature and the separation into longitudinal and transverse coherence directions. No a priori metric or spacetime manifold is assumed.

### B. Coherence cones and hazard cones

Hazard cones are structurally analogous to decoherence cones in open quantum systems and to effective causal domains in dissipative field theories, but are derived here from coherence stability rather than environmental coupling.

Equation (3) defines a *coherence cone*: the set of displacements  $(dt, d\ell)$  for which  $d\tau^2 \geq 0$ . This region bounds admissible transport of distinguishability.

To make this structure operational, we introduce a characteristic causal speed scale and a hazard cone.

**Definition V.2** (Causal speed scale). Let  $v_{\text{sync}}$  be a synchronization velocity set by the medium and  $\gamma$  a rigidity factor (dimensionless) measuring proximity to the rigid quantum regime. Let  $\chi_F$  be a Fisher-curvature susceptibility (sensitivity of dynamics to curvature). Define a causal speed scale

$$L_{\text{causal}} \lesssim \frac{v_{\text{sync}}}{\gamma} \frac{1}{\chi_F}. \quad (4)$$

This scale characterizes the maximal coherent propagation rate of structured influence along admissible directions. In high rigidity (large  $\gamma$ , small  $\chi_F$ ),  $L_{\text{causal}}$  approaches a constant reminiscent of the speed of light.

**Definition V.3** (Hazard cone). The *hazard cone* at  $(\mathbf{x}, t)$  is the region in label space where transport by  $\mathcal{T}$  is permitted but coherence loss is significant enough that causal interpretation becomes fragile. It is determined by

$$0 \leq d\tau^2 < \delta_{\tau}^2, \quad (5)$$

for some threshold  $\delta_{\tau}$  beyond which collapse geometry becomes dominant.

Coherence cones define admissible transport (CTMT's analogue of light cones); hazard cones delineate regions where transport is formally causal but practically at risk of decoherence-driven collapse.

## VI. COLLAPSE GEOMETRY AND CAUSAL HORIZONS

### A. Collapse-preceded causality failure

CTMT distinguishes between:

- *coherence causality*: ordering in  $\tau$  enforced by (2),
- *collapse geometry*: the dynamics of curvature loss and rank collapse in  $F$ .

Causality “failures” (in the sense of breakdown of a smooth causal description) occur not via superluminal transport but via *collapse preceding propagation*. Influence attempts to traverse hazard cones but coherence decays before a stable trajectory can be maintained.

### B. Causal horizon from modulation and collapse

Let  $\Xi_F$  denote a curvature gradient invariant (e.g., a norm of  $\nabla F$  projected along stable directions). Consider the time-integrated norm of the transport kernel:

$$R_{\text{causal}}(\mathbf{x}, t) = \frac{\int_{t' < t} \|\mathcal{T}(\mathbf{x}, t; \mathbf{x}', t')\| dt'}{\int_{t' > t} \|\mathcal{T}(\mathbf{x}, t; \mathbf{x}', t')\| dt'}. \quad (6)$$

**Definition VI.1** (Causal horizon). The *causal horizon* at  $(\mathbf{x}, t)$  is the locus where  $R_{\text{causal}}$  exceeds a critical value  $R_*$ , beyond which forward influence is exponentially suppressed by collapse:

$$R_{\text{causal}}(\mathbf{x}, t) \gg R_* \Rightarrow \text{future-directed transport decoheres before influence accumulates.} \quad (7)$$

Beyond the causal horizon, transport is still formally constrained by (2), but effective influence cannot accumulate: the system behaves as if a horizon blocks further coherent propagation.

## VII. RIGIDITY REGIMES: MICRO, MESO, MACRO

We now connect coherence causality geometry with the observed behavior of physical systems across scales.

### A. Microscopic regime: rigid quantum mechanics

In the microscopic regime with high rigidity:

- the Fisher spectrum is sharply peaked along a small number of stable directions,
- $\gamma$  is large and  $\chi_F$  is small in (4),
- $d\tau^2$  aligns closely with  $dt^2 - c^{-2}d\ell^2$  for some constant  $c$ ,
- transport kernels  $\mathcal{T}$  linearize to unitary propagators.

This regime corresponds to standard quantum mechanics and relativistic quantum field theory:

- coherence cones  $\approx$  light cones,
- hazard cones are narrow; collapse is rare within coherence cones,
- causal horizons are effectively pushed to large scales.

### B. Mesoscopic regime: nonlinear, contextual behavior

In mesoscopic systems:

- rigidity is moderate; Fisher spectrum is still structured but less sharply separated,
- $\gamma$  is finite and  $\chi_F$  non-negligible,
- $d\tau^2$  retains Lorentzian sign structure but the coherence cone deforms,
- transport kernels  $\mathcal{T}$  exhibit nonlinear dependence on sources.

Phenomenologically, this regime includes:

- contextual effects,
- measurement-like collapse phenomena,
- significant hazard cones: influence can approach the boundary of coherence, where collapse geometry dominates.

Despite nonlinearity and collapse, coherence causality remains valid: there are no true causal paradoxes, only breakdowns of smooth coherent propagation.

### C. Macroscopic regime: decoherence and effective classicality

At macroscopic scales:

- rigidity is low; Fisher curvature is weak and dominated by collapse dynamics,
- coherence cones shrink; hazard cones effectively cover the accessible region,
- causal horizons become local: influence decays rapidly with propagation distance and time.

The resulting behavior is:

- effective irreversibility,
- classical stochastic dynamics,
- no observable quantum coherence over large scales.

Again, coherence causality is not violated; rather, the ability to sustain coherent trajectories within the causal cones is lost.

## VIII. CORRESPONDENCE AND STAND-ALONE CAUSALITY

### A. Quantum correspondence

CTMT-IV establishes a *causality correspondence principle*:

In the limit of high rigidity and stable Fisher spectrum, coherence causality reduces to standard relativistic quantum causality: linear unitary evolution within light cones and no superluminal signaling.

This confirms that quantum mechanics and relativistic field theory appear as rigidity fixed points of coherence causality geometry.

### B. Mesoscopic and macroscopic correspondence

Similarly, in low-rigidity regimes CTMT recovers:

- mesoscopic nonlinear and contextual behavior with preserved causal ordering,
- macroscopic decoherence and effective classical stochasticity, again without causal pathologies.

Thus, *the same causality machinery* continuously connects:

- micro: rigid, linear QM,
- meso: nonlinear, collapse-dominated,

- macro: decoherent, classical.

No separate axioms for micro vs. macro causality are needed; everything arises from transport geometry constrained by Fisher-induced coherence proper time.

## IX. DISCUSSION AND OUTLOOK

CTMT-IV completes the causal sector of CTMT by showing that:

- causality is a consequence of coherence geometry, not an independent kinematic postulate,
- Lorentzian signature emerges from Fisher curvature projections, with no assumed spacetime metric,
- hazard cones and causal horizons arise from the interplay of modulation and collapse geometries,
- rigid quantum mechanics, mesoscopic nonlinearity, and macroscopic decoherence are regimes of a single coherently causal framework.

Future work can extend this causality geometry to:

- explicit reconstruction of relativistic quantum field theories as rigid fixed points,
- quantitative predictions for mesoscopic interferometry in low-rigidity regimes,
- gravitational analogues where Fisher curvature gradients mimic effective gravitational potentials in the causal line element (3).

In this sense, CTMT-IV shows that coherence geometry not only explains the emergence of quantum structure but also *forces* the Lorentzian causal scaffolding that has guided physics for over a century.

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