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Locality and Reality in Special Relativity: A Timelike-Boundary Reading

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Abstract

This manuscript develops a timelike-boundary reading of locality and reality within the established Lorentzian causal structure of special relativity and the standard record language of quantum measurement. The central object is a timelike boundary equipped with a boundary observer field and observer-adapted cuts. Such a cut is treated as the local comparison surface on which selected quantities are read relative to a coarse-grained reference structure. A local record appears when a boundary-relative deviation becomes resolvable on that cut. The framework separates two roles that are often compressed into one event statement. Lorentzian geometry supplies causal admissibility: it determines which prior data or contextual contributions may be relevant for a candidate event. The boundary comparison supplies record content: it identifies the deviation that becomes locally manifest. Thus the causal cone constrains the admissible domain, but it does not by itself provide a microscopic route or a measurement record. The proposed reading therefore assigns locality to cut-local record formation under Lorentzian causal admissibility. Reality is associated with stable, record-accessible deviations rather than with direct exposure of the underlying reference structure. The result is a compact assignment framework in which causal structure, reference structure, resolved deviation, and local record formation are organized on the same timelike boundary without replacing the established mathematical content of special relativity or quantum mechanics.

Keywords: special relativity; locality; timelike boundaries; Lorentzian geometry; causal admissibility; observer-adapted cuts; boundary-relative deviation; local records

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1. Introduction

Special relativity supplies the local causal structure of physical events. A candidate event is embedded in a Lorentzian light-cone structure that determines which prior data can be causally admissible. Quantum measurement language, by contrast, assigns local records in selected measurement channels. These two descriptions are usually used together, but they do not assign the same role to locality. The causal cone fixes admissibility; it does not by itself specify what becomes a local record.

The present manuscript develops a timelike-boundary reading of this interface. The aim is not to modify special relativity or to replace the standard quantum-mechanical record language. The aim is to make explicit the surface on which local record content can be assigned. The proposed surface is an observer-adapted cut of a timelike boundary. On such a cut, selected quantities can be compared with a coarse-grained reference structure, and a local record appears when a boundary-relative deviation becomes resolvable.

The motivation comes from the timelike thin-shell framework developed in earlier gravitational and thermodynamic boundary settings. In that framework, a finite-radius timelike shell is treated as a boundary system with proper time, area, quasilocal variables, and finite response channels [1]. The later cut-level formulation isolated the corresponding local Lorentzian boundary geometry: a timelike boundary Σ, a tangent observer field u^a, and observer-adapted cuts C_{τ_Σ} on which reference structures, resolved deviations, and response variables can be assigned together [2]. A complementary balance framework described how a coarse-grained reference sector can be registered at a timelike shell through storage, release, and pressure–area response channels [3].

These earlier constructions are classical boundary constructions. Their coarse-grained reference sector is introduced before any measurement language is added. In this sense, the boundary framework can be developed as a gravitational and thermodynamic comparison structure without first postulating quantum measurement outcomes. The present manuscript asks how such a cut-level structure can be read when the established local causal geometry of special relativity and the standard language of measurement records are placed on the same boundary surface.

The central object is therefore a timelike boundary equipped with a boundary observer field and observer-adapted cuts,

$$\Sigma, \qquad u^a, \qquad C_{\tau_\Sigma} \subset \Sigma. \tag{1}$$

The cut C_{τ_Σ} is the local comparison surface. A selected boundary channel q_Σ is read relative to a coarse-grained reference structure R_Σ. The corresponding channel-specific comparison object is written as

$$q_\Sigma^{\mathrm{ref}}(B) = \Pi_q[R_\Sigma](B), \tag{2}$$

and the boundary-relative deviation is

$$D_{R_\Sigma}[q](B) = q_\Sigma(B) - q_\Sigma^{\mathrm{ref}}(B). \tag{3}$$

A local record is formed when this deviation becomes resolvable in the selected channel and is compatible with the Lorentzian causal structure of the candidate event.

The assignment structure studied in this manuscript is

$$\text{Lorentzian admissibility} \; + \; \text{resolved boundary-relative deviation} \; \longrightarrow \; \text{local record}. \tag{4}$$

This equation is the core statement of the paper. Lorentzian geometry supplies the admissible causal domain. The observer-adapted cut supplies the comparison surface. The reference structure supplies the comparison level. The resolved deviation supplies the local record.

This separation also clarifies the role of the coarse-grained reference structure. A reference structure is not displayed by a single record. It is the comparison structure relative to which a record becomes meaningful. In the simplest statistical illustration, a single value q_i is not the expectation value μ; it is a record whose deviation from the reference level may be written as $D_i = q_i - \mu$. This elementary distinction is used below in boundary language. The reference structure organizes possible records, while record-accessible content is carried by resolved deviations from it.

The guiding question of the manuscript can now be stated as follows: Can the established Lorentzian causal structure of special relativity and the standard record language of quantum measurement be read in a timelike-boundary language in which local measurement content is assigned to a resolved deviation on an observer-adapted cut?

The answer developed below is deliberately limited. The manuscript does not derive the Born rule, does not supply a new microscopic dynamics, and does not reconstruct Bell-violating correlations. It formulates the cut-level assignment structure on which such later statistical, thermodynamic, or quantum-theoretic closures would have to be built. In particular, the thermodynamic reading suggested later treats information as appearing when a distinction becomes resolvable on the cut; this interpretation is developed only after the causal and reference-level structures have been fixed.

The paper is organized as follows. Section 2 recalls the special-relativistic causal structure used as the admissibility framework. Section 3 introduces observer-adapted cuts as local comparison surfaces. Section 4 formulates the reference assignment and boundary-relative deviation map. Section 5 defines local event closure as the combination of causal admissibility and cut-level resolution. Section 6 relates the construction to record and eigenvalue language. Section 7 discusses the cut-level interface, Bell-type constraints, thermodynamic interpretation, and open questions. Appendix E collects the

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reference notation, while the remaining appendices provide illustrative bookkeeping, thermodynamic, and interferometric examples.

2. Special Relativity as Local Lorentzian Causal Geometry

Special relativity supplies the local Lorentzian causal structure used throughout this manuscript. It fixes observer-dependent coordinate assignments, invariant light cones, spacelike separation, and proper time along timelike worldlines. These structures provide the established causal stage on which the timelike-boundary reading is formulated.

The point of comparison is the assignment of local record content. In the standard special-relativistic description, a candidate event B is localized in spacetime and equipped with a Lorentzian causal cone. In the timelike-boundary reading, this localization is retained, while the content of a local record is assigned relative to an observer-adapted cut of a timelike boundary. The causal structure determines admissibility; the cut supplies the comparison surface on which a boundary-relative deviation can become resolvable.

Thus the distinction is not between two causal geometries. It is a distinction between Lorentzian localization and cut-local record assignment. Special relativity fixes the admissible causal domain. The timelike-boundary reading adds the boundary surface on which selected quantities are compared with reference structures and can become local records.

2.1. Events, Observers, and Light Cones

For a candidate event B, the causal past $J^-(B)$ specifies the domain from which prior data can be Lorentz-admissible for the local reading of B. If A is a candidate prior datum or preparation event, causal admissibility is expressed as

$$A \in J^-(B). \tag{5}$$

Equation (5) fixes the causal status of A relative to B. It identifies A as belonging to the Lorentz-allowed past of B. The equation therefore supplies the admissible causal domain for a later local closure at B.

Events outside both the causal past and the causal future of B are spacelike separated from B. They are not causally ordered with respect to B, and they cannot serve as Lorentz-admissible prior data for a local closure at B. This is the precise causal content of spacelike separation: no Lorentz-admissible local causal ordering connects the two events.

The light cone is therefore used here as an admissibility structure. It restricts the class of prior events and contextual contributions that may enter a consistent local reading of B. The local record itself requires an additional ingredient: a selected boundary quantity must become resolvably different from its reference structure on the relevant observer-adapted cut.

Figure 1 summarizes this comparison. Panel (a) shows the standard special-relativistic causal structure around B. Panel (b) shows the corresponding timelike-boundary reading. The same Lorentzian structure is retained, while the timelike boundary Σ and its observer-adapted cuts provide the local comparison surfaces on which record content may later be assigned.

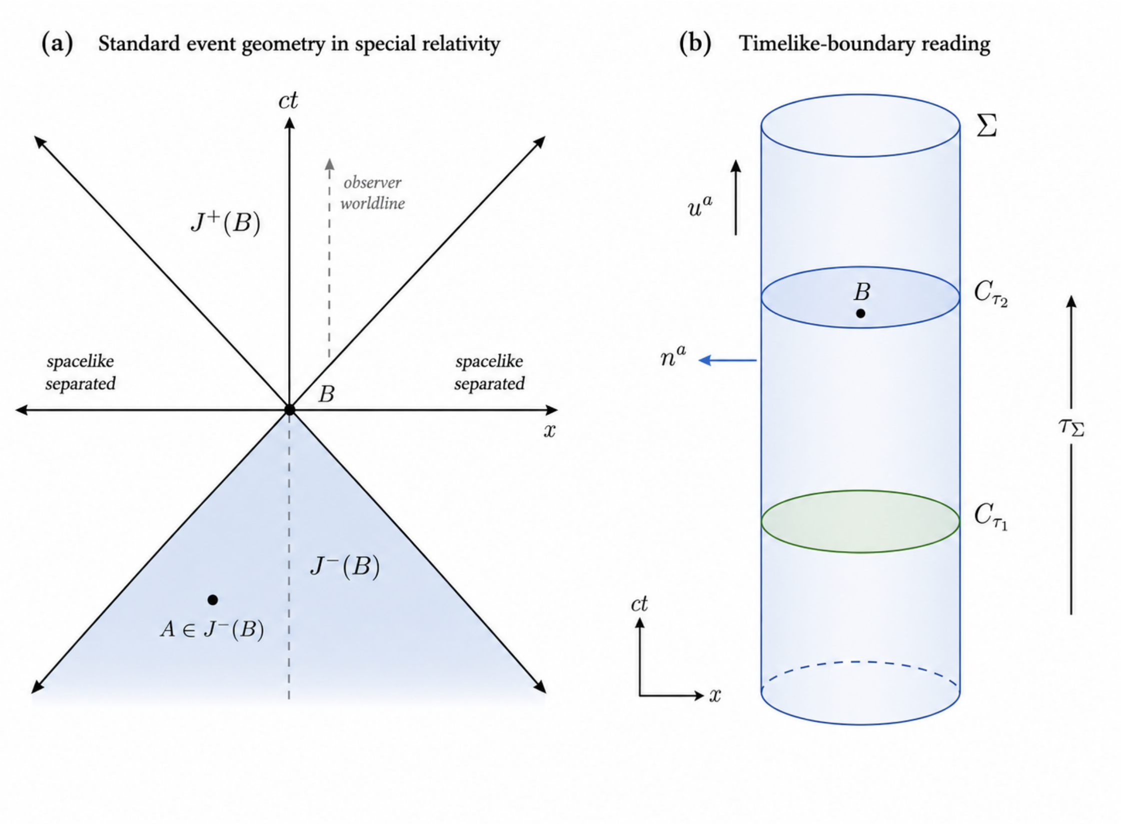

Figure 1. Special-relativistic causal structure and its timelike-boundary reading. Panel (a) shows the light-cone structure around a candidate event B in a Minkowski diagram with coordinates (x, ct). The causal past $J^-(B)$ restricts the class of prior events and contextual contributions that can be reconstructed as Lorentz-admissible for the local reading of B. Regions outside the light cone are spacelike separated from B. Panel (b) shows the corresponding timelike-boundary reading. The local Lorentzian structure is retained, while record assignment is made relative to a timelike boundary Σ, equipped with observer field u^a, spacelike normal n^a, boundary proper time τ_Σ, and observer-adapted cuts C_{τ_1} and C_{τ_2}.

The comparison in Figure 1 fixes the role of the boundary language at this stage. The causal cone supplies admissible ordering. The timelike boundary supplies the cut on which local comparison can be made. The assignment of record content is thereby placed on a definite observer-adapted surface.

2.2. Causal Admissibility and Reconstructed Prior Structure

The light cone constrains the prior structure that may be reconstructed for a candidate event B. Such reconstructed prior structures are Lorentz-constrained, but they are not yet local record content. The term “history” is used here in this retrodictive sense: it denotes an admissible reconstruction of prior structure, not an observed particle path.

This distinction is compatible with standard amplitude-based language. In the standard language one may speak of path contributions or reconstructed histories. In the present boundary reading, these contributions belong to the contextual comparison structure relative to which the candidate event B is read. The local object of the construction is the resolved record at B.

Thus the causal cone restricts which prior data and contextual contributions may be admissible for the reading of B. The cut-local record arises only after this admissible structure is combined with a resolvable boundary-relative deviation at B.

This distinction is illustrated in Figure 2. The dashed curves inside $J^-(B)$ are schematic retrodictive reconstruction lines. Their role is to visualize admissible prior structure within the causal past of B. The figure therefore separates causal admissibility from local record formation.

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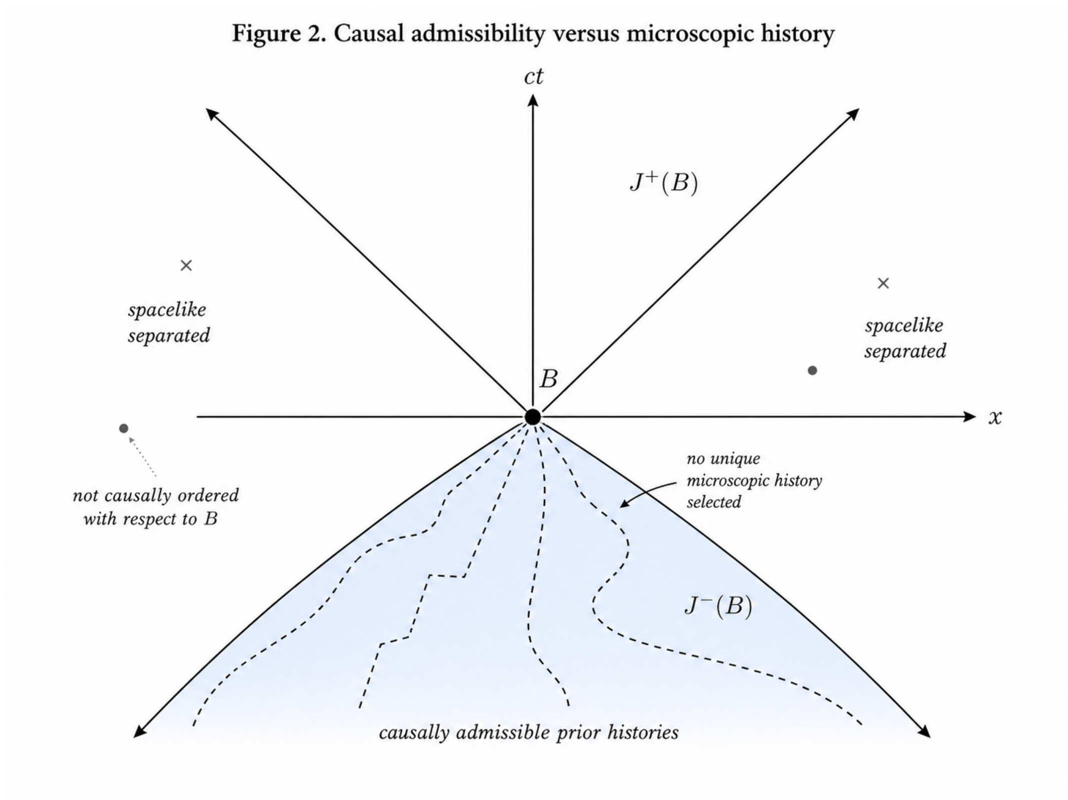

Figure 2. Causal admissibility and reconstructed prior structure. A candidate event B is shown in a Minkowski diagram with coordinates (x, ct). The causal past $J^-(B)$ defines the domain from which prior data or contextual contributions may be reconstructed as Lorentz-admissible for local closure at B. The dashed curves inside $J^-(B)$ are schematic retrodictive reconstruction lines. They represent admissible prior structure in the causal past, not observed particle trajectories. The light cone therefore restricts prior structure, while the local record is supplied later by cut-level resolution.

This formulation will be used throughout the manuscript. Causality is treated as the condition that fixes the admissible prior domain. The boundary construction adds the second ingredient: a selected quantity must differ from its reference structure by an amount that can be locally resolved. Only then does an admissible structure become local record content.

2.3. Proper Time and Observer-Adapted Cuts

The invariant time associated with a timelike observer is the proper time along the observer's worldline. In the timelike-boundary reading, the corresponding role is played by the proper-time direction of a boundary observer field. The basic geometric objects are

$$\Sigma, \qquad u^a, \qquad C_{\tau_\Sigma} \subset \Sigma. \tag{6}$$

Here Σ is the timelike boundary, u^a is a future-directed unit timelike observer field tangent to Σ, and C_{τ_Σ} is the spacelike cut selected by the boundary proper time τ_Σ. The cut is the local comparison surface associated with the boundary observer. It is the surface on which boundary quantities can be assigned, compared with reference structures, and tested for local resolution.

In a local frame adapted to the boundary observer, the intrinsic line element of the timelike boundary takes the form

$$ds_\Sigma^2 = -c^2 d\tau_\Sigma^2 + \sigma_{AB} dy^A dy^B. \tag{7}$$

The first term identifies the proper-time direction on the boundary. The second term is the positive spatial metric on the observer-adapted cut. Thus τ_Σ orders the local cuts, while σ_{AB} supplies the spatial geometry on which cut-local comparison can be made.

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This ordering is geometric. A clock-like sequence requires more than a proper-time parameter: it requires distinguishable updates on successive cuts. In the main text, τ_Σ is used only as the proper-time parameter that orders the observer-adapted cuts. The distinction between geometric proper time, clock time, and observable updating is deferred to Appendix A.

3. Observer-Adapted Cuts as Local Comparison Surfaces

The previous section fixed the special-relativistic causal structure used in the manuscript. The causal cone determines which prior data and contextual contributions may be Lorentz-admissible for a candidate event B. The present section introduces the complementary geometric object: the observer-adapted cut on which boundary quantities are compared with a reference structure.

In the timelike-boundary reading, the cut is the local comparison surface within a timelike boundary. This use follows the standard hypersurface language of Lorentzian geometry: the timelike boundary carries an intrinsic Lorentzian metric, while observer-adapted cuts provide spacelike sections on which boundary data can be evaluated [4,5]. The cut is therefore the surface on which a boundary observer assigns selected quantities, relates them to a coarse-grained reference structure, and identifies departures from that structure.

The geometry of admissibility remains Lorentzian. The comparison that supplies local record content is cut-local. Thus the causal cone fixes the admissible domain, while the observer-adapted cut fixes the surface on which comparison becomes possible.

3.1. Cut-Local Comparison

The observer-adapted cut C_{τ_Σ} is selected by the boundary proper time τ_Σ and by the observer field u^a. Locality is therefore used here in a cut-local sense: a selected local value and its reference structure are compared on the same boundary cut.

The point B labels the idealized location of a candidate record. The comparison that gives this record its content, however, is supported by the cut containing B. The cut supplies the local surface on which the reference structure and the corresponding departure become comparable.

For a pointlike idealization one may write $\mathcal{D}_\Sigma[q](B)$. Operationally, any actual record has finite resolution. It is therefore natural to associate the record with a small comparison patch

$$U_B \subset C_{\tau_\Sigma}, \tag{8}$$

centered at the idealized event location B. The point B labels the candidate record; the patch U_B represents the local support on which the comparison is made.

A finite-resolution version of the departure may then be written schematically as

$$\mathcal{D}_q(U_B) = \int_{U_B} \left\| \Delta_q(q_\Sigma, \mathcal{R}_\Sigma) \right\|_q \, dA_\Sigma. \tag{9}$$

Equation (9) is not used as an additional dynamical postulate. It records the operational point that local comparison is accessed with finite resolution. The point notation $\mathcal{D}_\Sigma[q](B)$ used below is the idealized limit of this cut-local comparison.

Figure 3 should be read as a comparison diagram. The boundary provides the observer-adapted surface on which a candidate event can acquire record content through a reference–deviation comparison. The local object of the construction is the resolved record at B.

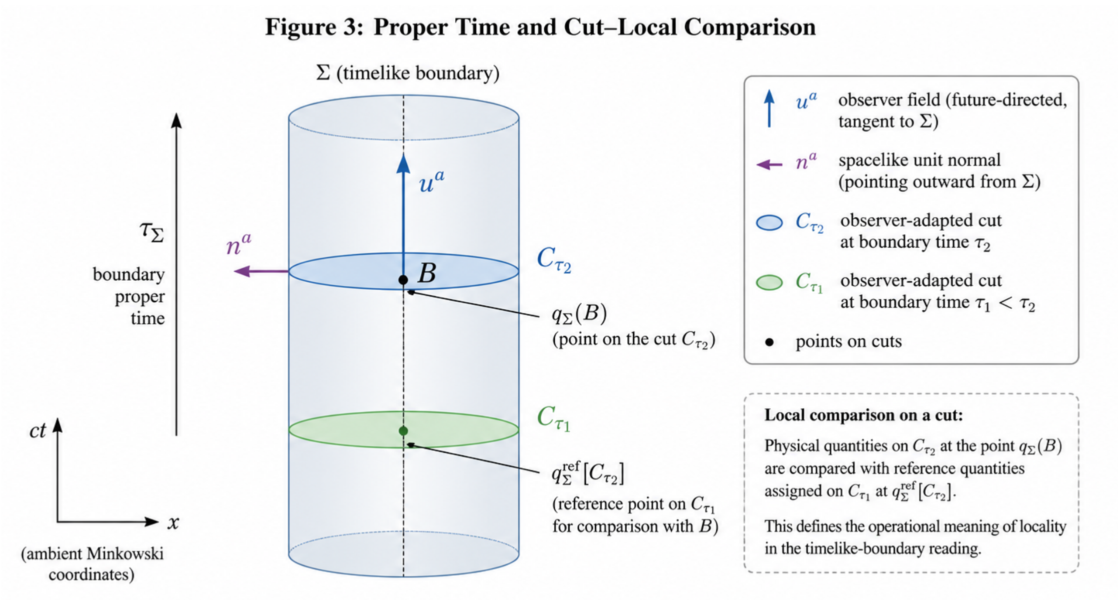

Figure 3. Proper time along a timelike boundary and cut-local comparison. The timelike boundary Σ is equipped with a future-directed observer field u^a tangent to Σ and a spacelike outward normal n^a. The boundary proper time τ_Σ orders observer-adapted cuts of Σ. A candidate boundary event B lies on one such cut. The cut is the local support on which selected boundary quantities are assigned and later compared with coarse-grained reference structures.

3.2. Selected Boundary Quantities

On each observer-adapted cut, a set of boundary quantities is selected,

$$Q_\Sigma = \{q_1, q_2, \ldots\}. \tag{10}$$

The elements of Q_Σ are the channels through which local information can be assigned on the cut. They may be scalar, vectorial, tensorial, or other effective boundary quantities, depending on the realization of the framework. In a classical boundary realization, such channels may be supplied by projections of a quasilocal boundary stress tensor, as in the Brown–York construction on timelike boundaries [5–7]. The present manuscript does not require this specific realization. The role of Q_Σ here is operational: it specifies what is being compared locally.

A selected quantity is a channel of comparison. A record-like value arises only after the selected quantity is related to a reference structure and the corresponding departure becomes locally resolvable. This separates three levels:

$$\text{selected channel} \quad \neq \quad \text{reference structure} \quad \neq \quad \text{local record}. \tag{11}$$

The selected channel specifies what is being compared. The reference structure specifies the comparison level. The local record appears when a departure from that reference structure becomes resolvable in the selected channel.

3.3. Coarse-Grained Reference Structure

Let $\mathcal{R}_\Sigma$ denote the coarse-grained reference structure assigned to the observer-adapted cut. For a selected boundary quantity q_Σ, a chosen closure may induce a channel-specific comparison object,

$$q_\Sigma^{\mathrm{ref}}(B) := \Pi_q[\mathcal{R}_\Sigma](B), \tag{12}$$

where Π_q denotes the projection or channel representation of the reference structure in the selected quantity.

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The reference structure may be represented by a stationary profile, an equilibrium assignment, a smoothed cut-level field, a statistical distribution, or another closure prescription for the boundary system. The channel-specific object $q_\Sigma^{\mathrm{ref}}(B)$ is the representation of that structure in the selected channel. It is the comparison object relative to which the local departure will be defined.

This point is important because the reference structure is deliberately weaker than a complete microscopic or thermodynamic closure. It is the current comparison structure of the cut-level description. It need not be identified with a final ground state unless an additional closure supplies such an identification. A single record may be read relative to this structure, but it displays only the channel value and its departure from the reference level.

The reference structure therefore belongs to the comparison scheme. It organizes how selected quantities are read on the cut, while local record-accessible content is carried by departures from it. The next section introduces the corresponding deviation map.

4. Reference Assignment and Visible Deviation

The previous section introduced the observer-adapted cut as the local comparison surface. The next step is to specify what is compared on that surface. The central operation of the manuscript is the separation between a coarse-grained reference structure and a boundary-relative deviation defined with respect to it.

A measurement record gives a visible value in a selected channel. In the present reading, this value is organized by comparison with the reference structure assigned to the cut. The reference structure supplies the comparison scheme; the record-accessible content is carried by the departure from that structure.

This distinction is familiar from coarse-grained and statistical descriptions, where ensemble-level structures and individual records have different operational roles [8–10]. It is also analogous to the distinction between proper-time ordering and clock-like updating: proper time can order cuts, while a clock requires recordable differences between cuts. This point is discussed separately in Appendix A.

The purpose of the present section is therefore to formulate the cut-level operation by which a selected boundary quantity becomes locally meaningful: reference assignment followed by visible deviation.

4.1. Deviation Map

For a selected boundary quantity q_Σ, the boundary-relative deviation is defined relative to the reference structure $\mathcal{R}_\Sigma$,

$$\mathcal{D}_\Sigma[q](B) := \Delta_q(q_\Sigma(B), \mathcal{R}_\Sigma). \tag{13}$$

Here Δ_q denotes the departure operation appropriate to the selected channel. In additive representations, where the reference structure induces the channel-specific comparison object of Eq. (12), this reduces to

$$\mathcal{D}_\Sigma[q](B) = q_\Sigma(B) - q_\Sigma^{\mathrm{ref}}(B). \tag{14}$$

The notation is pointlike for simplicity. Operationally, it may be understood as the idealized limit of a comparison on a finite patch $U_B \subset C_{\tau_\Sigma}$.

The measurable content is carried by the departure from the reference structure. The deviation is the quantity that can become event-capable once it satisfies the resolution condition introduced in the next section. The deviation map therefore states how a local value is read relative to the selected reference structure in a specified channel.

4.2. Equality, Non-Equality, and Event-Capable Deviation

Equality with the reference structure means

$$\mathcal{D}_\Sigma[q](B) = 0. \tag{15}$$

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In the selected channel, this means that no locally visible departure from the reference structure is present at B.

Non-equality means

$$\mathcal{D}_\Sigma[q](B) \neq 0. \tag{16}$$

This is the first event-capable structure of the reading. A local record requires a departure from the reference structure. However, non-equality alone is not yet a measurement outcome. The departure must also satisfy a resolution condition on the cut.

At this stage, non-equality is therefore candidate event content. The next section adds the required resolution condition. Only then can a boundary-relative departure become a local record.

4.3. Statistical Analogy: Gaussian Reference Closure

A simple statistical analogy for the reference–deviation split is provided by a Gaussian closure,

$$p_{\mathrm{ref}}(q) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(q-\mu)^2}{2\sigma^2}\right]. \tag{17}$$

Here the reference structure is represented by a distribution. The expectation value μ is a derived object of that structure. A single local record gives a value q_i, and the corresponding departure in this additive representation is

$$D_i = q_i - \mu. \tag{18}$$

The signed mean deviation can vanish,

$$\langle D \rangle = 0, \tag{19}$$

while the variance remains nonzero,

$$\langle D^2 \rangle = \sigma^2. \tag{20}$$

This example is used as a statistical analogy for the reference–deviation split. It is not a measurement model, and it does not identify quantum eigenvalues with fluctuations around a classical mean. Its role is to make explicit the mathematical distinction between an ensemble-level reference structure and an individual record. The reference structure organizes possible departures, while individual records display particular values in the selected channel [8,11].

For the Gaussian closure in Eq. (17), the mean absolute departure is

$$\langle |D| \rangle = \sigma\sqrt{\frac{2}{\pi}}. \tag{21}$$

Thus, the absence of a signed mean departure does not imply the absence of measurable structure. It only means that positive and negative departures cancel in the signed average. The reference structure remains the comparison structure, while the visible statistical content is carried by the distribution of departures.

4.4. Reference Structure and Manifestation

The relevant distinction is between a comparison structure assigned by the coarse-grained reference scheme and visible deviations from it. The comparison structure determines how departures are evaluated. The observable structure is carried by departures that become locally resolvable.

In this sense, measurement is the manifestation of a boundary-relative deviation as a local record. What becomes manifest is the resolved departure from the reference structure on the cut. The reference structure remains the comparison structure relative to which this departure becomes meaningful.

The word manifestation is used operationally. It denotes the formation of a local record on an observer-adapted cut. A value is manifest when it is resolved on that cut and can enter the causal

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record associated with the candidate event. This language is close in spirit to record-based descriptions of measurement, where a stable record is distinguished from the unresolved pre-record structure [9,10].

Thus, the reference structure belongs to the comparison scheme, while the manifest record belongs to the local event structure.

5. Local Event Closure

The preceding section introduced visible deviation as the record-capable departure from a coarse-grained reference structure. The present section adds the closure condition. A local record requires two ingredients: the deviation must be resolvable in the selected boundary channel, and the candidate record must be compatible with the Lorentzian causal structure of the candidate event.

Local event closure denotes this combined condition. The causal part follows the standard Lorentzian ordering of events. The record part is supplied by local resolution on the observer-adapted cut [4,5]. Thus closure is not introduced as an additional dynamical law; it names the point at which an admissible boundary-relative departure becomes a local record.

5.1. Resolution Condition

A boundary-relative deviation becomes local event content when it is resolvable in the selected channel. This is represented by the condition

$$\|\mathcal{D}_\Sigma[q](B)\|_q \geq \epsilon_q. \tag{22}$$

Here $\|\cdot\|_q$ denotes a positive resolution measure appropriate to the selected channel q, and ϵ_q denotes the corresponding resolution scale. The notation is intentionally general. Scalar, vectorial, spin-like, and tensorial quantities may require different resolution criteria.

The condition in Eq. (22) concerns the departure from the reference structure in the selected channel. It states that the departure has become sufficiently resolved to contribute local event content on the cut.

There are therefore three distinct cases:

$$\mathcal{D}_\Sigma[q](B) = 0, \qquad \text{no departure from the reference structure,} \tag{23}$$

$$0 < \|\mathcal{D}_\Sigma[q](B)\|_q < \epsilon_q, \qquad \text{unresolved departure,} \tag{24}$$

$$\|\mathcal{D}_\Sigma[q](B)\|_q \geq \epsilon_q, \qquad \text{resolved departure.} \tag{25}$$

Only the third case is event-capable in the sense used here. The second case may still belong to the unresolved comparison structure, but it has not yet become a local record.

5.2. Causality and Local Closure

Resolution alone is not sufficient. A resolved departure must also be situated within the Lorentzian causal structure of the candidate event. The minimal local closure condition is therefore

$$A \in J^-(B), \qquad \|\mathcal{D}_\Sigma[q](B)\|_q \geq \epsilon_q. \tag{26}$$

The first condition supplies causal admissibility. It states that prior data or a contextual contribution represented by A can be Lorentz-admissible for the local closure at B. The second condition supplies record-capable content. It states that a boundary-relative departure from the reference structure has become resolvable on the cut containing B.

The operational core of the reading is therefore:

$$\text{causal admissibility} \;+\; \text{resolved boundary-relative deviation} \;\longrightarrow\; \text{local event content.} \tag{27}$$

The causal cone determines which prior data or contextual contributions may be relevant for the local reading of B. The deviation supplies the content that can become manifest at B. Local event closure requires both ingredients.

5.3. Measurement as Boundary Closure

In the boundary reading, a measurement record is the result of local closure on an observer-adapted cut. In schematic form,

$$\text{measurement record} \quad \Longleftrightarrow \quad \text{causally admissible resolved deviation at } B. \tag{28}$$

For a selected quantity q_Σ, the numerical record can be written, in an additive representation, as

$$q_\Sigma(B) = q_\Sigma^{\text{ref}}(B) + \mathcal{D}_\Sigma[q](B). \tag{29}$$

The record is the local value $q_\Sigma(B)$. The split into a channel-specific reference representation and a deviation is the boundary reading of that record. The reference structure supplies the comparison scheme; the resolved deviation supplies the manifest event content.

A measurement record is therefore formed when a departure from the reference structure becomes resolvable in a causally admissible setting. The observer-adapted cut is the local surface on which this closure is assigned.

5.4. Closure Without a Unique Microscopic Route

The closure condition also clarifies the status of reconstructed prior structure. The condition $A \in J^-(B)$ identifies A as belonging to the Lorentz-admissible prior domain of B. More than one reconstructed prior structure may be compatible with this condition.

In the boundary reading, this is handled by assigning record content at the cut. The local record is the resolved deviation that becomes manifest at B. The prior structure supplies admissible context for the closure, while the record itself is localized at the candidate event.

Thus, the closure rule can be summarized schematically as

$$\text{admissible prior structure} \; + \; \text{resolved deviation at } B \; \longrightarrow \; \text{local event record}. \tag{30}$$

This equation is not a dynamical evolution law. Its role is to keep separate the ingredients used throughout the manuscript: causal admissibility, reference-relative deviation, and local measurement content. The contribution is contextual; the record is local.

5.5. Amplitude Contributions and Manifest Records

The closure condition also provides a way to read standard amplitude language within the present framework. In the usual path-integral notation, an amplitude between a preparation context A and a detection event B may be written formally as

$$\mathcal{A}(A \to B) = \int \mathcal{D}\gamma \, \exp\!\left(\frac{i}{\hbar} S[\gamma]\right). \tag{31}$$

This notation belongs to the standard amplitude formalism [12,13]. It is used here as a point of comparison.

The contributions γ in Eq. (31) belong to the amplitude structure. In the semiclassical limit, a classical route may be reconstructed as a stable constructive approximation. The boundary reading assigns the local record at B instead to the resolved deviation that satisfies the closure condition.

The causal past of B restricts which prior data and contextual contributions may be reconstructed as Lorentz-admissible. Additional contextual contributions, such as external fields, apertures, detector settings, absorbing objects, or environmental records, may enter the experimental comparison structure. They shape the reference structure relative to which a resolved deviation at B can become manifest.

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Thus, the relevant distinction is

$$\text{amplitude contribution} \quad \neq \quad \text{particle trajectory} \quad \neq \quad \text{local event record.} \tag{32}$$

What becomes manifest at B is the boundary-local record. In the terminology of this section, the record is the resolved deviation that satisfies the local closure condition. The reconstructed prior structure is constrained by manifest records, but it is not itself the manifest record.

This distinction is compatible with record-based and decoherence-oriented descriptions of measurement, in which stable records are separated from unresolved pre-record structure [9,10]. The present manuscript does not require adopting a specific decoherence model; it uses only the operational distinction between contextual contributions and local records.

6. Measurement Records and Eigenvalue Language

The previous sections described local measurement content as the manifestation of a boundary-relative deviation. This section relates that language to the standard quantum-mechanical terminology of eigenvalues. The purpose is to specify how an already assigned measurement outcome can be read in the present boundary language.

In standard quantum mechanics, an eigenvalue is the numerical value associated with an idealized projective measurement outcome in a selected channel [14–16]. More general measurement schemes may be represented by POVMs or other operational descriptions; these are not reconstructed here. The present discussion is limited to the idealized eigenvalue language as a point of comparison.

In the timelike-boundary reading, the same numerical outcome is read as a local record whose content is a resolved deviation relative to a reference structure. The quantum-mechanical operator, spectrum, and probability rule are taken from the standard formalism. The boundary language specifies how the resulting record is organized once it has been assigned.

6.1. Eigenvalue as Resolved Record

In standard quantum language, an idealized measurement of an observable $\hat{Q}$ is associated with the eigenvalue equation

$$\hat{Q}\psi_i = q_i\psi_i. \tag{33}$$

The number q_i is the value assigned to the measurement outcome in that idealized channel. In the boundary reading, this value is the manifest local record on the cut.

For comparison with the reference–deviation language, the assigned record may be written, in an additive representation, as

$$q_i = q_\Sigma^{\mathrm{ref}} + D_i, \tag{34}$$

where D_i denotes the resolved deviation associated with the record.

Equation (34) is not a spectral postulate. The operator, the measurement channel, the eigenvalue structure, and the probability assignment are taken from standard quantum mechanics. The equation states how an already assigned outcome is expressed in the reference–deviation language.

The measurement record is q_i. The split into a channel-specific reference representation and a deviation is the boundary reading of that record. The reference structure supplies the comparison scheme; the resolved deviation supplies the manifest event content.

Thus, in the present reading,

$$\text{eigenvalue} \quad \longleftrightarrow \quad \text{stable manifest record in a selected measurement channel.} \tag{35}$$

This statement preserves the operational role of eigenvalues in quantum mechanics and assigns the resulting record a boundary-local interpretation.

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6.2. Repeatability and Record Stability

The ideal eigenvalue equation is also connected with repeatability in an idealized projective measurement channel. In the standard projection picture, if a first ideal measurement yields q_i and prepares or stabilizes the corresponding eigenstate, an immediate repetition of the same measurement returns the same eigenvalue in the ideal limit [15,16].

In the boundary reading, this repeatability is interpreted as stability of the resolved record relative to the chosen reference structure and measurement channel. The repeated outcome shows that the same resolved deviation channel can remain stable across successive local closures.

Schematically, for repeated records $B_1, B_2, \ldots$ in the same channel,

$$q_\Sigma(B_n) = q_\Sigma^{\mathrm{ref}}(B_n) + D_i \qquad \text{within the selected resolution scale.} \tag{36}$$

The same record value can therefore manifest repeatedly as a stable resolved deviation in the selected channel.

This provides the boundary-language analogue of an ideal eigenstate: stability of the manifest record under repeated closure in the same channel.

6.3. Measurement and Reference Structure

The distinction between q_i, q_Σ^{ref}, and D_i is central. A measurement record gives a manifest value in a selected channel. The channel-specific reference representation may be reconstructed or calibrated only through an additional statistical, operational, or boundary closure.

This parallels the statistical reference example discussed above. A single record gives q_i. A reference representation may be inferred from an ensemble of records or fixed by an external calibration procedure. The individual record is the manifest value read relative to that structure.

This distinction also fixes the relation to hidden-outcome language. The reference structure is a comparison structure; it is not a store of pre-assigned outcomes for possible measurements. In particular, it does not play the role of a Bell-type hidden-outcome variable. The visible content is the resolved deviation in the selected channel.

6.4. Macroscopic Stability

A macroscopic object is represented as a highly stabilized, redundantly recorded, and causally continued structure of local records. Its persistence is not created by a single measurement event. A measurement adds a new local record to a structure that is already stabilized through many prior and ongoing interactions.

This statement is consistent with standard decoherence-oriented and record-based accounts of macroscopic stability, in which environmental monitoring and redundant records help explain the persistence of classical patterns without requiring direct access to an underlying reference structure [9,10]. The present manuscript does not require a specific decoherence model; it uses only the operational distinction between stable records and unresolved reference structure.

In boundary language, a macroscopic object corresponds to a robust pattern of resolved deviations. These deviations are repeatedly supported across many cuts, channels, and environmental records. Their stability is the persistence of a manifest pattern relative to the reference structure.

Thus,

$$\text{macroscopic object} \quad \longleftrightarrow \quad \text{stable, redundant pattern of resolved deviations.} \tag{37}$$

A measurement of such an object adds a new local record to an already stabilized pattern.

7. Discussion: The Cut-Level Interface

The manuscript has developed a timelike-boundary reading of local measurement at the level of special-relativistic causal structure. The central contribution is a cut-level organization of notions that are often used together but not always separated explicitly: causal admissibility, contextual contribution, reference structure, visible deviation, manifestation, and local measurement record.

Special relativity and quantum mechanics provide the established reference framework. The timelike-boundary reading keeps their standard mathematical roles in place and identifies a shared interface at which their local readings can be organized together. This interface is the observer-adapted cut of a timelike boundary.

7.1. The Shared Interface

The central object of the manuscript is the observer-adapted cut on a timelike boundary. This cut supplies the local surface on which Lorentzian admissibility, reference structure, resolved deviation, and local record formation can be assigned within one boundary language.

The resulting structure can be summarized as

$$\begin{aligned} &\text{Lorentzian admissibility } + \text{experimental comparison structure} \\ &\quad + \text{observer-adapted boundary cut } \longrightarrow \text{ manifest local deviation.} \end{aligned} \tag{38}$$

The importance of this summary is the location of the interface. The causal cone fixes the admissible domain of prior data and contextual contributions. The experimental comparison structure specifies which channel is being probed. The observer-adapted cut supplies the local surface on which the reference structure and the boundary-relative deviation are compared. A local record appears when this deviation becomes resolvable on the cut.

In this sense, the contribution of the boundary language is an assignment claim. It specifies where, in the present reading, the content of a local measurement record is assigned: on the observer-adapted cut, as a resolved deviation relative to the corresponding reference structure.

7.2. Standard Structures and Boundary Assignment

The re-reading concerns the assignment of local measurement content, not the Lorentzian causal structure or the operational use of quantum measurement outcomes. The light cone retains its role as the structure of causal admissibility. The amplitude formalism retains its role in the standard quantum description. The eigenvalue language retains its role as the idealized language of projective measurement outcomes.

The boundary reading adds a local assignment surface. In the standard special-relativistic description, a candidate event B is localized in spacetime and equipped with a causal cone. In the timelike-boundary reading, the same local Lorentzian structure is retained, while the assignment of record content is made relative to an observer-adapted cut. The cut supplies the local comparison surface on which a selected quantity can be read relative to a reference structure.

The key point is the separation between reference structure and visible deviation. The reference structure is the comparison structure assigned by the coarse-grained boundary reading. The measurable content is carried by deviations from it. A local record appears when such a deviation becomes resolvable on the cut and causally admissible for the candidate event.

7.3. Bell-Type Constraints and the Scope of the Reading

Bell-type constraints provide a central consistency test for any language that uses locality and record formation. The timelike-boundary reading must therefore be compared with what Bell-type results exclude [17–19].

Bell-type no-go results constrain models in which measurement outcomes are represented as pre-existing separable local values, typically through functions of local settings and a hidden state,

$$A = A(a, \lambda), \qquad B = B(b, \lambda). \tag{39}$$

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The timelike-boundary reading assigns a different role to the reference structure. The reference structure is a comparison structure for local records. It is not used as a store of outcomes for possible measurement settings. Record content appears when a boundary-relative deviation becomes resolvable on the observer-adapted cut.

Thus, the relevant distinction is

$$\text{pre-existing local outcome assignment} \quad \neq \quad \text{cut-local record formation.} \tag{40}$$

The first structure is the one constrained by Bell-type arguments under the usual assumptions. The second is the structure used here. The locality claimed in the present reading is therefore cut-locality of record formation under Lorentzian causal admissibility, rather than classical Bell-locality of pre-assigned outcomes.

The interface-level conclusion is

$$\text{local reality in this reading} = \text{cut-local manifest records} \quad (\text{not Bell-local hidden outcomes}). \tag{41}$$

This fixes the scope of the Bell comparison. The boundary reading is not formulated as a classical local hidden-variable model. At the same time, the present manuscript does not derive Bell-violating quantum correlations. A quantitative Bell analysis would require additional structure: the selected boundary quantities, the preparation procedure, the measurement settings, and a statistical rule for correlations between resolved deviations. Whether the interface language can be extended into such a quantitative correlation framework remains an open problem.

7.4. Entropic and Thermodynamic Orientation

The construction developed in the main text does not require an entropy postulate. Local event closure was formulated in terms of causal admissibility and resolution of a boundary-relative deviation. The boundary language nevertheless raises a natural thermodynamic question: if observation is possible only through distinguishable local records, what information scale should be associated with the first such distinction?

A minimal binary distinction would suggest an information increment of order

$$\Delta S \sim k_B \ln 2. \tag{42}$$

This expression is not used here as a threshold condition. It is a possible interpretive scale for a future thermodynamic reading of local records. In the language of the Appendix, it would concern the first distinguishable update along an already defined proper-time ordering, not the existence of proper time itself. This connects at the level of orientation with information thermodynamics and the thermodynamic cost of distinguishability [20,21].

In a gravitational setting, area laws such as

$$S_{\mathrm{BH}} = \frac{k_B A}{4\ell_P^2} \tag{43}$$

show that entropy, information, and boundary area can be closely related [22,23]. The present manuscript does not assign Bekenstein–Hawking entropy to a general timelike boundary cut. It notes that a later gravitational extension would have to specify whether, and how, cut-local record formation is associated with an area-like measure.

7.5. Macroscopic Fluctuations and Reference Profiles

The same reference–deviation distinction can also be read in a classical thermodynamic setting. A macroscopic object is not free of microscopic activity. In a standard statistical description, thermal

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fluctuations, Brownian motion, and molecular impacts produce distributions of local quantities rather than one perfectly sharp microscopic value [24–27].

In the usual kinetic reading, such behavior is described through random microscopic exchanges, coarse-graining, and statistical relaxation. The present boundary language suggests a complementary organization. A Gaussian, Boltzmann, or otherwise chosen statistical closure may be treated as an effective reference profile of a locally equilibrated coarse-grained system. Relative to such a profile, non-Gaussian features, persistent tails, skewness, localized excesses, or other structured departures can be read as deviations from the current reference structure.

This is an interpretive translation of the same reference–deviation logic. The reference profile is a representation of the coarse-grained reference structure in a chosen closure. A local or mesoscopic departure from that profile can become record-like when it is resolved in an appropriate channel.

Schematically, for a macroscopic fluctuation variable q, one may write

$$p(q) = p_{\mathrm{ref}}(q) + \delta p(q), \tag{44}$$

where $p_{\mathrm{ref}}(q)$ denotes the chosen coarse-grained reference profile and $\delta p(q)$ denotes the visible departure from it. The profile is the representation of the reference structure in that statistical closure.

In this sense, relaxation can be described as a reduction or redistribution of resolved departures from the reference profile. The statement does not identify the reference profile with an absolute ground state. It identifies it with the current comparison structure supplied by the chosen thermodynamic or statistical closure.

Thus the thermodynamic reading mirrors the local measurement reading:

$$\text{reference profile} \quad \neq \quad \text{local record}, \qquad \text{resolved departure} \quad \longrightarrow \quad \text{visible structure}. \tag{45}$$

This perspective may be useful when macroscopic stability is discussed together with local records. A macroscopic object can be treated as a robust pattern of resolved deviations, while its thermal background is organized by a coarse-grained reference distribution. The observable object is then the stable pattern of departures that persists relative to that profile.

7.6. Relation to Open Questions

The entropic and thermodynamic readings introduced above are interpretive extensions of the assignment framework. They point toward questions that require further structure: which boundary quantities are selected, which reference profile is used, what closure fixes the statistical rule, and how deviations are correlated across cuts.

For this reason, the thermodynamic reading should be understood as a bridge to open questions rather than as a completed result. The main result of the present manuscript remains the local assignment structure:

$$\text{Lorentzian admissibility} \ + \ \text{resolved boundary-relative deviation} \ \longrightarrow \ \text{local record}. \tag{46}$$

This structure identifies the shared cut-level interface developed in the manuscript. Lorentzian geometry supplies admissibility, the observer-adapted cut supplies the comparison surface, the reference structure supplies the comparison structure, and the resolved deviation supplies the local record. Later statistical, thermodynamic, gravitational, or quantum-theoretic closures would have to specify the corresponding dynamics, probabilities, and correlations.

8. Conclusions

This manuscript developed a timelike-boundary reading of locality and reality within the established Lorentzian causal structure of special relativity. In this reading, local reality is not assigned to a hidden route, to a directly exposed reference state, or to a pre-existing list of outcomes. It is assigned to the formation of a resolved record on an observer-adapted boundary cut.

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The manuscript therefore addresses two linked questions. The first is how locality can be understood when a causal cone constrains admissible prior structure but does not select a unique microscopic route. The second is how reality can be associated with local facts without identifying those facts with direct access to an underlying reference structure. The answer proposed here is the timelike-boundary assignment: Lorentzian admissibility supplies the causal domain, while a resolved boundary-relative deviation supplies the local record.

In this formulation, the timelike boundary is a local comparison surface. A selected channel is read relative to a coarse-grained reference structure on an observer-adapted cut. The reference structure itself is not what becomes visible as a local fact. What becomes visible is the deviation from it, once that deviation satisfies the relevant resolution condition on the cut. Thus the local record marks the point at which an admissible contextual structure becomes fixed as record-accessible content.

Mathematical anchor.

Many physical readings are organized around a compact mathematical anchor. In general relativity this role is played by the Einstein field equations, $G_{ab} = 8\pi G T_{ab}/c^4$. In special relativity it is the Lorentzian interval, $ds^2 = -c^2 dt^2 + d\mathbf{x}^2$. In unitary quantum mechanics, and therefore also in many-worlds readings, it is the Schrödinger equation, $i\hbar\partial_t\psi = \hat{H}\psi$. The present timelike-boundary reading uses a compact statistical anchor: a reference profile together with its record-level deviations. In the Gaussian illustration,

$$p_{\mathrm{ref}}(q) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(q-\mu)^2}{2\sigma^2}\right], \qquad D_i = q_i - \mu. \tag{47}$$

This expression is not introduced as a new dynamical law. Its role is to condense the reference–deviation logic into a minimal mathematical form. A single record gives q_i, not the reference profile itself. The reference profile, or its channel representation μ, organizes the comparison, while the record-accessible content is carried by the resolved deviation from it. In this restricted sense, the Gaussian reference closure functions as the mathematical anchor of the timelike-boundary reading.

The reference horizon.

The same distinction motivates the notion of a reference horizon. The term does not denote a physical event horizon, a null surface, or a second spacetime region. It denotes the boundary of single-record access to the reference structure. Local records become manifest on the record-accessible cut, while the reference structure remains the non-record comparison level. A single measurement can display a resolved deviation from the reference structure, but it cannot display the reference structure itself as a local fact.

The resulting locality is therefore cut-local rather than route-local. The prior structure may be contextual, amplitude-like, or retrodictively reconstructed, but the record itself is local. It appears at the candidate event when the boundary-relative deviation becomes resolvable on the observer-adapted cut. Causality constrains admissibility; resolution supplies local factual content.

The corresponding reading of reality is also record-based. A macroscopic or measurement-like fact is not the exposure of the reference structure itself. It is a stable, record-accessible pattern of resolved deviations relative to that structure. In this sense, reality belongs to what has become locally fixed on the cut, while the reference structure remains the non-record comparison level that makes such fixation meaningful.

The perturbative image is reversed.

In the thermodynamic reading suggested here, the usual perturbative image is reversed. The smooth reference profile is not an ordered background that is later disturbed by entropy. It is the coarse-grained profile in which, under the chosen closure, no cut-resolvable distinction is available. Information appears only when a difference becomes resolvable on the cut. The visible structure is therefore not the reference profile itself, but the departure from it that has become distinguishable.

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The future stands wide open.

In the corresponding wave reading, the particle-like wave is not a memory of a hidden route through the past. It is a probability-weighted openness toward possible future interactions. The local record marks what has become fixed; the wave indicates what may still happen. In this restricted sense, the boundary reading keeps the future open while assigning reality to those local records that have become causally admissible and operationally fixed.

The result is a controlled assignment framework. Lorentzian causal structure fixes the admissible domain, the observer-adapted cut supplies the comparison surface, the reference structure supplies the comparison level, and the resolved deviation supplies the local record. Further statistical, thermodynamic, gravitational, or quantum-theoretic closures are required to turn this assignment structure into a predictive theory. The present work provides the conceptual interface on which such closures can be formulated.

9. Open Questions and Outlook

The present manuscript remains at the level of special-relativistic event geometry and boundary-local measurement. Its main result is a controlled assignment reading of local event formation: Lorentzian causal structure supplies admissibility, while event content is supplied by a resolved boundary-relative deviation on an observer-adapted cut.

Several questions remain open.

First, the present reading has not derived standard quantum probabilities. It identifies where a local record is assigned and distinguishes this record from both a microscopic route and a direct exposure of the reference structure. It does not derive the Born rule, nor does it provide a new statistical law for the distribution of resolved deviations [14–16,28]. A future extension would have to specify which boundary quantities are selected, how the reference structure is fixed, and which statistical rule connects unresolved comparison structure with observed record frequencies.

Second, the Bell comparison remains incomplete at the quantitative level. The reading is not formulated as a classical local hidden-variable model with pre-existing separable outcomes. However, reproducing Bell-violating quantum correlations would require an explicit statistical rule for correlations between resolved deviations under different measurement settings [17–19]. The present manuscript therefore makes only a compatibility statement: the reference structure is not used as a Bell-type hidden store of outcomes. It does not claim to reconstruct the full quantum correlation structure.

Third, the operational status of the reference structure requires further development. In the present manuscript, the reference structure is the current comparison structure of the cut-level description. It is not itself a local record and need not be identified with a final ground state. Future work must specify which closure fixes this reference structure in a given physical realization. In a statistical setting it may be supplied by an ensemble or coarse-grained distribution; in a thermodynamic setting by an equilibrium or near-equilibrium profile; in a boundary-gravitational setting by a macroscopic reference sector.

Fourth, the possible thermodynamic reading of record formation remains open. The discussion above suggested that a Gaussian, Boltzmann, or other statistical closure may serve as an effective reference profile for a locally equilibrated coarse-grained system, while structured departures may be read as resolved departures from that profile. This is only an interpretive orientation. It does not replace the standard kinetic or statistical description of fluctuations, Brownian motion, and relaxation [24–27]. A future thermodynamic formulation would have to state which variables define the reference profile, which deviations are record-like, and how relaxation reduces or redistributes resolved departures.

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Fifth, the relation between record formation and a minimal information scale remains to be clarified. A future thermodynamic extension may ask whether the first distinguishable update along proper time carries an information scale of order

$$\Delta S \sim k_B \ln 2. \tag{48}$$

In the present manuscript, this expression is not used as a threshold condition. It is only identified as a possible scale for future work. The relevant issue is not the existence of proper time itself, but the appearance of a distinguishable update that can function as a local record. This connects the boundary reading only at the level of orientation with information thermodynamics and the cost of distinguishability [20,21].

Sixth, the relation to gravitational boundary area remains to be developed. Area laws such as

$$S_{\rm BH} = \frac{k_B A}{4\ell_P^2} \tag{49}$$

show that entropy, information, and boundary area can be closely related in gravitational settings [22,23]. The present manuscript does not assign Bekenstein–Hawking entropy to a general timelike boundary cut. A later gravitational extension would have to specify whether, and how, cut-local record formation is associated with an area-like measure. This issue is naturally connected with finite-radius timelike boundary variables, quasilocal stress, and area-response terms in gravitational boundary frameworks [5,6].

Seventh, the status of unresolved non-event structure remains open. In the present manuscript, unresolved structure is used only as comparison background for manifestation. It is not treated as a hidden list of outcomes and not as a set of observed microscopic routes. Whether such structure should be developed thermodynamically, gravitationally, statistically, or as a metastable reference sector requires additional assumptions. A particularly important question is whether a state that appears as a local reference structure is a final ground state or only a metastable comparison structure relative to the currently available resolution channels.

Finally, the relation to established accounts of macroscopic record stability should be made more explicit in future work. Decoherence-oriented and record-based descriptions explain why certain macroscopic patterns become stable and redundantly accessible without requiring direct access to an underlying microscopic state [9,10]. The present boundary reading is compatible with that orientation, but it does not derive a decoherence model. It only provides the assignment language in which a stable macroscopic object can be read as a robust pattern of resolved deviations across cuts, channels, and environmental records.

These issues belong to later work. The main result of the present manuscript is therefore deliberately limited:

$$\text{Lorentzian admissibility} \;+\; \text{resolved boundary-relative deviation} \;\longrightarrow\; \text{local record.} \tag{50}$$

The open task is to determine which statistical, thermodynamic, and gravitational closures can turn this assignment structure into a predictive framework.

Appendix A. Proper Time, Clock Time, and Boundary Updating

Special relativity defines proper time along a timelike worldline by the Lorentzian interval. In the timelike-boundary reading, the corresponding proper-time ordering is carried by the boundary observer field u^a. Locally, the intrinsic boundary line element is

$$ds_\Sigma^2 = -c^2 d\tau_\Sigma^2 + \sigma_{AB} dy^A dy^B. \tag{A1}$$

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Here τ_Σ orders the observer-adapted cuts of the timelike boundary, while σ_{AB} is the positive spatial metric on each cut. This is the standard local Lorentzian separation between a timelike direction and spacelike cut geometry [4,5].

The distinction used in the main text is between geometric proper time and operational clock time. Proper time orders the possible comparison cuts. Clock time requires distinguishable updates on such cuts. Thus a timelike boundary may possess a proper-time ordering without already carrying a clock-like sequence of displayed readings.

In boundary language, a clock-like process requires a sequence of locally distinguishable records on successive observer-adapted cuts,

$$C_{\tau_1}, \quad C_{\tau_2}, \quad C_{\tau_3}, \ldots . \tag{A2}$$

The ordering of the cuts is geometric. The ticks are supplied only when successive cuts carry resolved differences in at least one selected channel. In this sense, proper time orders the cuts, while resolved updates provide the operational ticks.

Such an update sequence may be represented abstractly by resolved boundary-relative deviations,

$$\mathcal{D}_\Sigma[q](B_n) = q_\Sigma(B_n) - q_\Sigma^{\mathrm{ref}}(B_n), \qquad B_n \in C_{\tau_n}, \tag{A3}$$

together with the corresponding resolution condition

$$\|\mathcal{D}_\Sigma[q](B_n)\|_q \geq \epsilon_q. \tag{A4}$$

Equation (A3) is not a universal model of physical clocks. It states the minimal boundary-language requirement for clock-like updating: successive cuts must carry distinguishable local records in at least one selected channel.

This also clarifies the role of the reference structure. The reference structure may belong to the proper-time ordered comparison scheme, but it is not itself displayed as a clock reading. The channel-specific reference representation $q_\Sigma^{\mathrm{ref}}(B_n)$ supplies the comparison object on the cut. Operationally visible updating appears only through the resolved deviation from that representation.

Without such resolved deviations, the boundary still has proper-time ordering, but no operational tick sequence. Local event closure therefore requires a resolved deviation on a cut; it does not require that the boundary itself already functions as a clock. Proper time supplies the ordering of possible updates, while boundary-relative deviations supply the recordable differences by which updates become observable.

A later thermodynamic extension may ask whether the first distinguishable update along proper time carries an information scale of order

$$\Delta S \sim k_B \ln 2. \tag{A5}$$

This question is not part of the core construction. It is an orientation toward information thermodynamics, where distinguishability and record formation may carry thermodynamic cost [20,21]. The core construction requires only the distinction between geometric proper time, operational clock time, and observable boundary updating.

Appendix B. Interferometric Example: Context Change and Local Record

This appendix gives a simple interferometric example of the reference–deviation language used in the main text. The example is only illustrative. It is not introduced as a new analysis of interferometry or as a derivation of interaction-free measurement. Its purpose is to clarify how a change in the experimental context can become visible as a local detector record without being read as an observed particle route.

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Consider a two-output interferometer tuned such that one detector channel is dark in the reference configuration. Let B_{dark} denote the candidate detector event at this dark output. In the ideal reference configuration, destructive interference defines the detector-channel reference condition

$$q_{\Sigma}^{\text{ref}}(B_{\text{dark}}) \simeq 0. \tag{A6}$$

This condition should not be read as the absence of physical structure. It is the local expression of the cancellation structure of the interferometric setup in the selected detector channel. Destructive interference therefore does not mean that information has been destroyed. It means that, relative to the reference configuration, no resolved local departure is produced in the dark detector channel,

$$\mathcal{D}_{\Sigma}[q](B_{\text{dark}}) \simeq 0. \tag{A7}$$

Now suppose that an absorbing object is inserted into one branch of the interferometer. In the usual language, this is the setting underlying interaction-free or "bomb-tester" measurements [29,30]. In the present boundary reading, the object is not first interpreted as revealing which route a particle has taken. Instead, the object changes the experimental comparison structure relative to which the detector event B_{dark} is read.

In runs in which no absorption record is formed at the object, the object still belongs to the experimental context. It changes the amplitude structure of the setup and thereby changes the reference-relative condition at the dark detector channel. A click at the formerly dark detector is therefore read as a local resolved deviation,

$$\mathcal{D}_{\Sigma}[q](B_{\text{dark}}) = q_{\Sigma}(B_{\text{dark}}) - q_{\Sigma}^{\text{ref}}(B_{\text{dark}}), \qquad \|\mathcal{D}_{\Sigma}[q](B_{\text{dark}})\|_q \geq \epsilon_q. \tag{A8}$$

The local record is the detector event at B_{dark}. The object is not itself the site of a local absorption record in such a run. Its role is contextual: it changes the comparison structure from which the deviation at B_{dark} is read.

Thus the example separates three notions:

$$\text{object in the experimental context} \quad \neq \quad \text{observed particle route} \quad \neq \quad \text{local detector record.} \tag{A9}$$

The detector record is local and manifest. The statement that the object was present in the interferometer is a retrodictive inference from the changed comparison structure. It is not the observation of a microscopic route.

In the language of the main text, the interferometer example therefore realizes the general closure pattern

$$\begin{aligned} &\text{Lorentz-admissible context } + \text{changed comparison structure} \\ &\quad + \text{resolved detector deviation at } B_{\text{dark}} \\ &\longrightarrow \text{local record.} \end{aligned} \tag{A10}$$

This reading is consistent with the complementarity point that visibility of interference and which-way information cannot be freely combined in one and the same experimental arrangement [31]. The boundary reading does not change that result. It only assigns the manifest event content to the local detector record and treats the object as part of the context that changes the reference structure.

Appendix C. Context Contributions and Retrodictive Reconstruction

This appendix records how standard amplitude language is used as a point of comparison for the timelike-boundary reading. Amplitude contributions are treated as context contributions to the comparison structure relative to which a local record becomes manifest. The local object of the construction remains the record at B, while the prior structure is reconstructed retrodictively within the Lorentz-admissible domain.

The core closure condition of the manuscript is

$$A \in J^{-}(B), \qquad \left\| D_{R_\Sigma}[q](B) \right\|_q \geq \epsilon_q. \tag{A11}$$

The first condition fixes causal admissibility. The second condition fixes local resolution on the observer-adapted cut. The appendix adds only the bookkeeping language for prior context contributions.

Appendix C.1. Standard Amplitude Contributions

In the standard path-integral formulation, an amplitude between a preparation context A and a detection event B is written schematically as

$$\mathcal{A}(A \to B) = \int_{\gamma: A \to B} \mathcal{D}\gamma \, \exp\!\left(\frac{i}{\hbar} S[\gamma]\right). \tag{A12}$$

This is standard amplitude language [12,13]. It is used here as a reference formulation.

The contributions γ in Eq. (A12) belong to the amplitude structure. They encode phase contributions to the transition amplitude. In the semiclassical limit, the stationary-action condition

$$\delta S[\gamma_{\mathrm{cl}}] = 0 \tag{A13}$$

selects the stable constructive approximation that can be read as the classical route. In the present boundary reading, this route is a reconstruction from the phase structure, while the manifest local object is the record at B.

Appendix C.2. Context Contributions to the Comparison Structure

In the boundary reading, B is the manifestation point of a local record on an observer-adapted cut. The amplitude contributions belong to the experimental and causal comparison context relative to which a resolved deviation at B is read.

The translation used here is therefore

$$\text{standard amplitude contribution} \quad \longrightarrow \quad \text{context contribution to the comparison structure.} \tag{A14}$$

The contribution is contextual; the record is local.

A schematic record-conditioned amplitude may be written as

$$\mathcal{A}(R_B \mid \mathcal{C}_B) = \int_{\gamma \in \Gamma(\mathcal{C}_B \to U_B)} \mathcal{D}\gamma \, \exp\!\left(\frac{i}{\hbar} S[\gamma; \mathcal{C}_B]\right) \chi_{R_B}[\gamma; \mathcal{C}_B]. \tag{A15}$$

Here $U_B \subset C_{\tau_\Sigma}$ is the local comparison patch around B, $\mathcal{C}_B$ is the Lorentz-admissible context relevant for B, and χ_{R_B} is a schematic compatibility filter for the manifest record.

Equation (A15) is a bookkeeping expression. It states that reconstructed context contributions are conditioned by the manifest record and by the Lorentz-admissible causal context. It does not add a new dynamical law to the standard amplitude formalism.

Appendix C.3. Manifest Records and Retrodictive Reconstruction

Let R_B denote the manifest local record at the candidate event B,

$$R_B = \big(B,\, q_\Sigma(B),\, D_{R_\Sigma}[q](B)\big). \tag{A16}$$

The record R_B is local and manifest on the cut. The prior structure relevant for it is reconstructed from the manifest record, the experimental context, and Lorentzian causal admissibility.

In the idealized case in which the context reduces to a sharply prepared record R_A, the usual transition language $A \to B$ is recovered. In a more general context, external fields, apertures, walls,

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detector settings, absorbing objects, and environmental records can contribute to the amplitude structure. These contributions shape the comparison structure relative to which the detector event B is read.

This may be expressed schematically by a retrodictive distribution

$$P(A \mid R_B, \mathcal{C}_B). \tag{A17}$$

In an idealized preparation, this distribution may be sharply peaked around a prepared record A_0. In a less controlled context, context contributions broaden the distribution and make the inferred prior origin less sharp.

Thus, retrodictive reconstruction is record-conditioned. The manifest object is the local record at B, while the prior structure is the Lorentz-admissible context reconstructed relative to that record.

Appendix D. Symbolic Reference–Deviation Bookkeeping

This appendix records a symbolic bookkeeping device for the reference–deviation split used in the main text. The notation is interpretive. It is not part of the core construction and is not required for the local closure condition. Its role is to provide a compact mnemonic for the relation between a coarse-grained pre-record structure, a reference branch, and a record-capable deviation.

The symbols below should be read as orientation labels. They do not define a metric signature, a second spacetime geometry, or a microscopic spin model. They display, in a compressed form, the distinction between an unresolved comparison structure, a reference side, and a deviation side that may become manifest on an observer-adapted cut.

Appendix D.1. Thermodynamic Reading of the Symbolic States

The symbolic notation may be read through a restricted thermodynamic mnemonic. In this reading, aligned symbolic configurations represent ordered low-entropy branches, while mixed symbolic configurations represent unresolved high-entropy comparison regimes.

The useful spin-like ordering mnemonic has three idealized roles:

$$(+,+,+,+)_{\uparrow}, \qquad (\pm,\pm,\pm,\pm)_{\text{mix}}, \qquad (-,-,-,-)_{\downarrow}. \tag{A18}$$

The first and third symbols denote ordered branches. In this simplified reading, $(+,+,+,+)_{\uparrow}$ represents an upper-oriented ordered branch, while $(-,-,-,-)_{\downarrow}$ represents a lower-oriented ordered branch. Both are low-entropy configurations in the coarse-grained sense: only a comparatively small class of microscopic or contextual arrangements is compatible with a fully aligned symbolic orientation.

By contrast,

$$(\pm,\pm,\pm,\pm)_{\text{mix}} \tag{A19}$$

denotes an unresolved mixed-orientation structure. It represents the coarse-grained situation in which several symbolic orientations remain open relative to the chosen comparison structure. In the mnemonic, this is the high-entropy configuration, because many unresolved arrangements are compatible with the same coarse-grained description.

This can be stated schematically by assigning a coarse-grained multiplicity Ω_{cg} to the symbolic state,

$$S_{\text{cg}} = k_B \ln \Omega_{\text{cg}}. \tag{A20}$$

The ordered branches have comparatively small multiplicity,

$$\Omega_{\text{cg}}[(+,+,+,+)_{\uparrow}] \ll \Omega_{\text{cg}}[(\pm,\pm,\pm,\pm)_{\text{mix}}], \qquad \Omega_{\text{cg}}[(-,-,-,-)_{\downarrow}] \ll \Omega_{\text{cg}}[(\pm,\pm,\pm,\pm)_{\text{mix}}]. \tag{A21}$$

Thus the mixed symbolic structure carries the largest coarse-grained entropy in this mnemonic, while the aligned branches carry lower coarse-grained entropy.

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A local transition from a mixed regime to an ordered branch does not violate thermodynamic bookkeeping. The entropy discussed here is the entropy of the selected coarse-grained symbolic sector. A decrease of this sector entropy is admissible when boundary response, exterior channels, or unresolved degrees of freedom carry the compensating entropy or dissipated energy. In a finite-response boundary system, this is the role of storage, release, and response channels: resolved local ordering does not exhaust the full thermodynamic bookkeeping.

The same mnemonic gives a controlled way to discuss false-vacuum-like and true-vacuum-like language. An ordered branch may be stable relative to the presently available comparison structure. If a lower reference branch becomes available, the same ordered branch can be read as metastable. The symbolic transition may then be written as

$$\begin{aligned} (-,-,-,-)_{\text{false}} &\longrightarrow (-,\pm,\pm,\pm)_{\text{trans}} \\ &\longrightarrow (-,-,-,-)_{\text{true}}. \end{aligned} \tag{A22}$$

The initial and final symbols have the same formal orientation pattern, but they denote different reference branches. The label "false" denotes an ordered branch that is stable only relative to the original comparison structure. The label "true" denotes the lower reference branch selected by the later closure.

The intermediate symbol

$$(-,\pm,\pm,\pm)_{\text{trans}} \tag{A23}$$

denotes the transition regime. The first sign is kept fixed as the reference orientation of the comparison, while the remaining signs denote unresolved branch content. This is the finite-response part of the mnemonic: if the transition is not instantaneous, the system does not pass directly from one ordered branch to another. It passes through an unresolved comparison regime in which the old ordered branch is no longer sufficient, while the lower reference branch has not yet become the effective comparison structure for a local record.

In a symmetry-breaking-like reading, the fixed first sign plays the role of a selected orientation of the comparison structure. The analogy is structural. No specific Higgs-sector dynamics, vacuum-decay mechanism, or microscopic transition model is assumed. The point is only that an effective-potential-like picture can be represented symbolically: a metastable ordered branch, an unresolved transition regime, and a lower ordered reference branch can be distinguished within the same cut-level language.

The schematic picture is therefore

$$\begin{aligned} \text{ordered metastable branch} &\longrightarrow \text{unresolved high-entropy transition regime} \\ &\longrightarrow \text{ordered lower reference branch.} \end{aligned} \tag{A24}$$

In this thermodynamic reading, the boundary does not display the reference structure as a local record. It supplies the cut-local comparison surface on which non-equality between the metastable coarse-grained structure and the reference orientation can become record-accessible. The record-accessible content is the resolved deviation from the reference structure.

The analogy is intentionally restricted. It states only that a coarse-grained reference structure, an unresolved transition regime, and a resolved deviation can be organized in a thermodynamically admissible way. The core manuscript requires only causal admissibility, cut-local comparison, and resolved deviation. The present subsection adds the thermodynamic intuition that the unresolved symbolic middle state may carry maximal coarse-grained entropy, while aligned reference branches may represent low-entropy ordered states within the chosen closure.

Appendix D.2. Coarse-Grained Pre-Record Structure

Before a local record is formed, the relevant comparison structure may be represented symbolically as a coarse-grained pre-record structure,

$$\mathrm{GC}_{\mathrm{pre}} \sim (-,\pm,\pm,\pm). \tag{A25}$$

The notation in Eq. (A25) is not a spacetime signature and does not define a Lorentzian or Euclidean sector. The fixed sign marks an orientation of comparison. The $\pm$ entries denote open or not-yet-separated comparison channels.

A possible statistical representation of this pre-record structure is

$$R_\Sigma(B) \sim \int_{\mathcal{I}_B} \rho_{\mathrm{GC}}(\xi)\, \mathcal{R}_\Sigma(B;\xi)\, d\xi. \tag{A26}$$

The index ξ labels non-manifest context contributions that may shape the reference structure assigned on the cut. It is a bookkeeping index for unresolved comparison content.

A channel-specific comparison object is obtained by projection,

$$q_\Sigma^{\mathrm{ref}}(B) = \Pi_q[R_\Sigma](B). \tag{A27}$$

Equations (A26) and (A27) state that the reference structure may depend on non-manifest context structure while the local record is carried by a resolved channel-specific deviation.

Appendix D.3. Symbolic GC–TTS–QM Reading

The symbolic relation between the coarse-grained pre-record structure, the timelike boundary, and the reference–deviation split may be written as

$$(-,\pm,\pm,\pm)_{\mathrm{GC}} \xleftrightarrow{\text{boundary reading}} \{(-,-,-,-)_{\mathrm{ref}} \leftrightarrow (-,+,+,+)_{\mathrm{dev}}\}. \tag{A28}$$

Equation (A28) is a symbolic map of roles. It is not a transition law.

The left side denotes a coarse-grained pre-record comparison structure. The middle term denotes the timelike boundary as the Lorentzian surface on which local comparison can be organized. The right side denotes the measurement-side reading: a reference branch and a visible deviation are separated on the cut.

The pair

$$(-,-,-,-)_{\mathrm{ref}} \leftrightarrow (-,+,+,+)_{\mathrm{dev}} \tag{A29}$$

does not describe two observed spacetime signatures. It denotes the reference–deviation split. The first term represents the reference structure: a comparison side that is not itself a local record. The second term represents the deviation side: the part that may become manifest as event content when the local closure condition is satisfied.

The three plus signs in $(-,+,+,+)_{\mathrm{dev}}$ should not be read as spatial axes or numerical components. They are a mnemonic for the open deviation side: the possibility channels that remain future-open until a local record is formed. In this sense, the symbol points to what may still become record-accessible, not to an already selected local outcome.

In the notation of the main text, the same statement is

$$q_\Sigma(B) = q_\Sigma^{\mathrm{ref}}(B) + D_{R_\Sigma}[q](B), \qquad \left\| D_{R_\Sigma}[q](B) \right\|_q \geq \epsilon_q. \tag{A30}$$

Thus, the symbolic expression in Eq. (A28) is a compact mnemonic for the comparison structure written explicitly in Eq. (A30). It adds no independent closure condition beyond the reference assignment, boundary-relative deviation, and local resolution condition used in the main text.

Appendix E. Notation for the Reference–Deviation Structure

This appendix summarizes the notation used for the cut-level reference–deviation structure. The purpose is to keep distinct the roles of observer-adapted cut, selected channel, reference structure, channel-specific comparison object, boundary-relative deviation, and local record.

Symbol or term	Meaning in this manuscript	Operational role
C_{τ_Σ}	observer-adapted comparison cut of the timelike boundary	supplies the local surface on which comparison is made
Q_Σ	selected set of boundary channels	specifies which quantities can be compared locally
$\mathcal{R}_\Sigma$	coarse-grained reference structure assigned to the cut	supplies the comparison structure, but is not itself displayed by a single record
$\Pi_q[\mathcal{R}_\Sigma]$	channel-specific representation or projection of the reference structure	gives the comparison object in the selected channel q
$q_\Sigma^{\mathrm{ref}}(B)$	channel-specific comparison object at the candidate event B	enters the deviation map as the reference representation in channel q
$\Delta_q(q_\Sigma, \mathcal{R}_\Sigma)$	channel-dependent departure operation	defines how departure from the reference structure is evaluated
$\mathcal{D}_\Sigma[q](B)$	boundary-relative deviation in channel q	carries the record-capable content when resolved on the cut
ϵ_q	resolution scale of channel q	sets the threshold for local record formation in that channel
R_B	manifest local record at B	denotes the locally resolved record after causal admissibility and resolution are satisfied
$U_B \subset C_{\tau_\Sigma}$	finite comparison patch around the idealized event location B	represents the finite support of an operational comparison
$\mathcal{C}_B$	Lorentz-admissible context relevant for B	collects prior data and contextual contributions used in retrodictive reconstruction

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