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

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Abstract

Timelike boundaries provide a natural setting for organizing causal admissibility, reference structure, visible deviation, and local measurement content on the same Lorentzian surface. This manuscript develops a timelike–boundary reading of local measurement using the established language of special relativity and quantum mechanics as the reference framework. The central object is a timelike boundary equipped with a boundary observer field and observer–adapted cuts. Lorentzian geometry supplies the admissible causal domain of a candidate event. The boundary cut supplies 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 analysis deliberately focuses on the shared interface rather than on the full individual dynamics of general relativity or quantum mechanics. The common structure considered here is the cut–level assignment of causal admissibility, reference structure, resolved deviation, and local record formation. The key distinction is between causal admissibility and measurement content. The causal cone constrains which prior data or contextual contributions may be relevant for a candidate event; it does not by itself supply the local record. The reference structure is specified internally by the boundary reading and is accessed in local records only through locally resolved deviations from it. Thus measurement does not expose the reference structure directly, but records a deviation relative to it. The resulting framework identifies the observer–adapted cut on a timelike boundary as a potential interface where Lorentzian causal geometry and quantum–mechanical record language can be organized together without replacing the established content of either theory.

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

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1. Introduction

Timelike boundaries provide a geometric surface on which causal structure, observer–dependent localization, reference assignments, and local records can be organized together. The present manuscript examines how this timelike–boundary language can be placed within the established descriptions of special relativity and quantum measurement. The established descriptions form the reference framework against which the TTS geometry is read.

The finite–radius TTS setting used here builds on the timelike thin–shell framework developed previously in gravitational–collapse and thermodynamic boundary–response settings [1]. In that setting, a timelike shell acts as a finite–radius interface with proper time, area, macroscopic response, and boundary thermodynamic interpretation. The present manuscript does not redevelop the gravitational shell dynamics. It extracts the local cut–level reading suggested by this framework and applies it to the assignment of local measurement content.

The guiding idea is that a timelike boundary can serve as a local comparison surface. Once an observer field u^a tangent to the boundary is fixed, the boundary proper time τ_Σ selects observer–adapted cuts C_{τ_Σ}. On such cuts, selected boundary quantities can be compared with a coarse–grained

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reference structure. A local record appears when a boundary–relative deviation becomes resolvable on the cut and is compatible with the Lorentzian causal structure of the candidate event.

The manuscript therefore focuses on the shared interface between three structures:

$$\text{Lorentzian causal admissibility}, \qquad \text{cut–local comparison}, \qquad \text{local record formation}. \tag{1}$$

Special relativity supplies the local causal geometry. Standard quantum measurement language supplies the notion of a record or outcome in a selected measurement channel. The timelike–boundary reading supplies the comparison surface on which a selected quantity can be read relative to a reference structure. The resulting assignment structure is

$$\text{Lorentzian admissibility} \;+\; \text{resolved boundary–relative deviation} \;\longrightarrow\; \text{local record}. \tag{2}$$

This is the central claim of the manuscript. It is an assignment claim, not a new dynamical law. The Lorentzian event geometry is retained. The standard quantum–mechanical probability rule is not replaced. The contribution is the cut–level reading of where local measurement content is assigned: not to a hidden value, not to an individual microscopic route, and not to the reference structure itself, but to a manifest resolved deviation on an observer–adapted cut.

Clarifying note on reference terminology.

The word reference is used in two related but distinct senses. The established descriptions of special relativity and quantum mechanics form the external reference framework of the manuscript. Inside the timelike-boundary reading, the reference structure R_Σ denotes the coarse-grained comparison structure assigned to an observer-adapted cut. To avoid confusing these two uses, the internal notation is summarized in Appendix E.

Thus, the internal reference structure R_Σ is part of the comparison scheme, but it is not itself a local causal record. A selected channel q_Σ is read relative to R_Σ, and only a resolvable departure from that structure can become local event content. In compressed notation,

$$R_\Sigma \xrightarrow{\;\Pi_q\;} q_\Sigma^{\mathrm{ref}}(B) \xrightarrow{\;\Delta_q\;} D_{R_\Sigma}[q](B) \xrightarrow{\;\|\cdot\|_q \geq \epsilon_q\;} R_B. \tag{3}$$

Here R_B denotes the manifest local record at B. The sequence in Eq. (3) is not a dynamical evolution law. It is a notation map: reference structure, channel-specific comparison object, boundary-relative deviation, and manifest record are distinct roles in the cut-level reading.

Statistical illustration.

Even in the elementary statistical case, a reference mean is not displayed by a single record. If a distribution $p(q)$ has expectation value

$$\mu = \mathbb{E}[q], \tag{4}$$

then one measurement gives a record q_i, not the reference mean itself. A finite sequence of records provides only an estimator,

$$\bar{q}_N = \frac{1}{N}\sum_{i=1}^{N} q_i, \tag{5}$$

which may approach μ only under the assumptions of the chosen statistical closure. The same distinction is used below in boundary language: the reference structure belongs to the comparison scheme, while local information enters the record only as a resolved departure from that structure.

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Structural horizon analogy.

The analogy with a horizon is only structural. An event horizon separates causal domains while not being identical with either open domain. Similarly, the reference structure is not one further local record inside the event structure. It marks the comparison structure relative to which local records become meaningful. The timelike boundary used in this manuscript is not a null event horizon; the analogy concerns only the separation between record-accessible information and non-record reference structure.

In this sense, the TTS geometry is used as a comparison language. The cut is not introduced as a second spacetime or as a replacement for the event structure of special relativity. It is the local surface on which comparison becomes possible. The reference structure is not treated as a hidden measurement value. It is the coarse-grained comparison structure relative to which selected boundary quantities are read. The observable content is carried by visible deviations from that reference structure.

This framing also fixes the relation to Bell-type constraints. The manuscript does not claim to reproduce Bell-violating correlations. It clarifies the interface-level position of the boundary reading: the reference structure is not a Bell-type hidden variable carrying pre-existing separable outcomes. Locality is used in the restricted sense of cut-local record formation under Lorentzian causal admissibility. A record becomes local when a boundary-relative deviation becomes manifest on the cut.

The guiding question of the manuscript can therefore be stated as follows: Can the established event geometry of special relativity and the standard measurement language of quantum mechanics be read in a timelike-boundary language in which local measurement content is assigned not to a hidden value or to an individual microscopic route, but to a manifest resolved deviation on an observer-adapted cut?

2. Special Relativity as Local Event Geometry

Special relativity supplies the local Lorentzian stage used throughout this manuscript: observer-dependent coordinate assignments, invariant light cones, spacelike separation, and proper time along timelike worldlines. This structure is taken as part of the established reference framework. The timelike-boundary reading does not modify the causal geometry of special relativity.

The point of comparison is more specific. In the standard event-geometric language, an event B is a localized spacetime event equipped with a Lorentzian causal cone. In the timelike-boundary reading, the same local Lorentzian structure is retained, while the assignment of measurement content is made relative to an observer-adapted boundary cut. The geometric localization of B is not replaced. What is re-read is the place where measurement content is assigned: it is assigned when a boundary-relative deviation becomes resolvable on the relevant cut.

Thus, the distinction is not between two different causal geometries. It is a distinction between geometric localization and local event content. Special relativity fixes the admissible causal structure. The timelike-boundary reading adds a language for the cut-local assignment of measurement content.

2.1. Events, Observers, and Light Cones

For a candidate event B, the causal past $J^-(B)$ specifies the set of events 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

$$A \in J^-(B). \tag{6}$$

Equation (6) is an admissibility statement. It says that A lies in the Lorentz-allowed past of B. It does not say that a resolved microscopic process connecting A and B has been observed, nor does it select a unique intervening history.

Events outside both the causal past and causal future of B are spacelike separated from B. They are not causally ordered with respect to B. In the present reading, this means that they cannot serve as Lorentz-admissible prior data for a local closure at B. This statement is stronger and more precise

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than saying that a signal would have to travel faster than light. Spacelike separation means that no Lorentz-admissible local causal ordering connects the two events.

The light cone is therefore used here as a causal admissibility structure. It restricts the class of prior events and contextual contributions that can be reconstructed as Lorentz-admissible for the local reading of B. It does not provide a completed microscopic story of what happened before B. This distinction is central for the timelike-boundary reading: causal admissibility is not yet local event content.

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

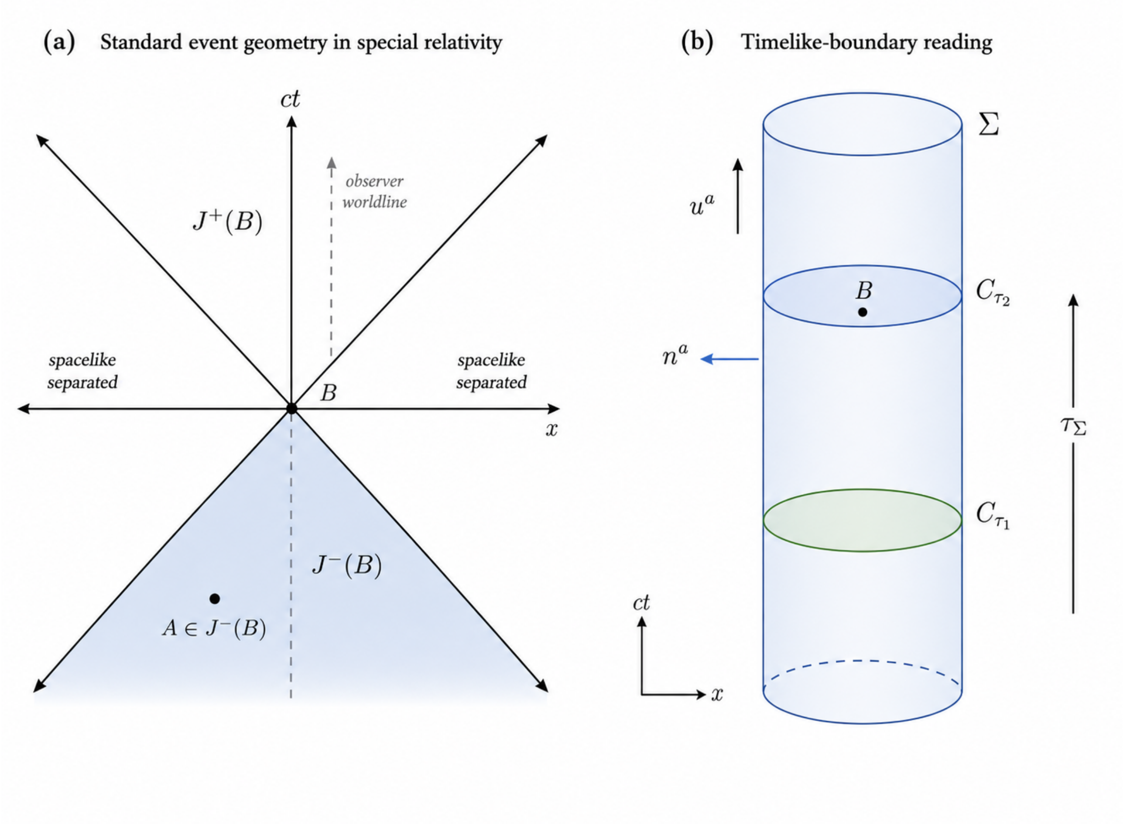

Figure 1. Standard event geometry and its timelike-boundary reading. Panel (a) shows the special-relativistic light-cone structure around a candidate event B in a Minkowski diagram with coordinates (x, ct). The causal past $J^-(B)$ restricts the class of prior events and contextual contributions that can be reconstructed as Lorentz-admissible for the local reading of B; it does not determine a unique microscopic history. 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 the assignment of measurement content 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 limited 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 geometry is not replaced; the location at which measurement content is assigned is made explicit.

2.2. Causal Admissibility and Reconstructed Prior Structure

The light cone does not select a unique microscopic history for a candidate event B. It only restricts the prior structure that may be reconstructed as Lorentz-admissible for B. In this sense, reconstructed

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histories are not arbitrary: they are Lorentz-constrained. At the same time, they are not yet local event content.

Terminological note.

The term "history" is used here only for retrodictive reconstruction. It does not denote an observed particle path. The local object of the construction is the candidate record at B; the prior structure specifies only what may be Lorentz-admissible for its local closure.

This distinction is compatible with standard amplitude-based language, but the translation into the boundary reading is specific. In the standard language one may speak of path contributions or reconstructed histories. In the present reading, these are not particle routes from A to B. They are contextual contributions to the comparison structure relative to which the candidate event B is read. The local object of the construction is the resolved record at B, not an intervening microscopic path.

Thus, the causal cone restricts which prior data and contextual contributions may be admissible for the reading of B. It does not select one microscopic route to B, and it does not by itself supply the event content at B.

This distinction is illustrated in Figure 2. The dashed curves inside $J^-(B)$ are schematic retrodictive reconstruction lines. They are not observed particle trajectories. The point of the figure is only that the causal cone restricts what may consistently enter the local reading of B; it does not select one microscopic route to B.

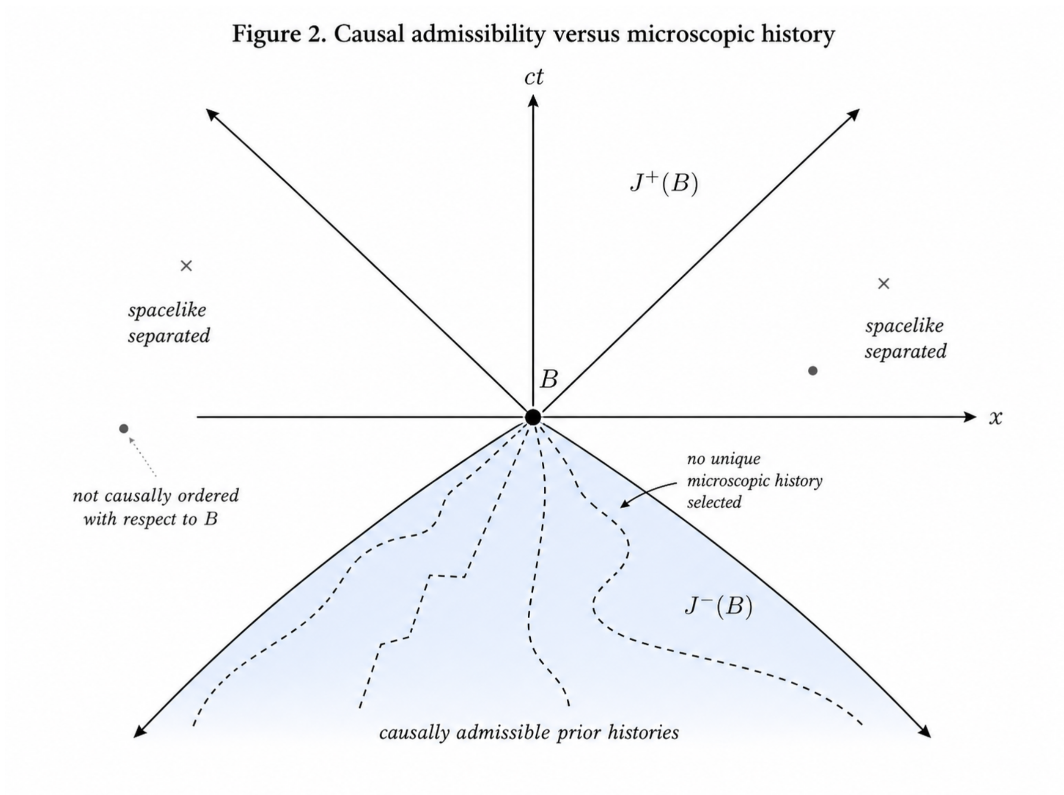

Figure 2. Causal admissibility versus reconstructed prior structure. A candidate event B is shown in a Minkowski diagram with coordinates (x, ct). The causal past $J^-(B)$ defines the domain from which prior data or contextual contributions may be reconstructed as Lorentz-admissible for the local closure at B. The dashed curves inside $J^-(B)$ are schematic retrodictive reconstruction lines. They do not represent observed particle trajectories and should not be read as literal Feynman paths. The light cone therefore restricts admissible prior structure, but it does not select a unique microscopic route to B.

The formulation will be used throughout the manuscript. Causality is treated as a condition of admissibility, not as a record of a completed microscopic path. The boundary construction later adds a

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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 event 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 analogous role is played by the proper-time direction of a boundary observer field. The basic geometric objects are

$$\Sigma, \qquad u^a, \qquad C_{\tau_\Sigma} \subset \Sigma. \tag{7}$$

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 relative to the boundary observer field. It is the surface on which boundary quantities can later 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

$$ds_\Sigma^2 = -c^2 d\tau_\Sigma^2 + \sigma_{AB} dy^A dy^B. \tag{8}$$

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. This ordering is geometric; it is not yet a clock-like sequence of resolved updates.

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 used special relativity as the reference framework for local event geometry. The causal cone fixes which prior data and contextual contributions may be Lorentz-admissible for a candidate event B. It does not, by itself, specify the surface on which a boundary quantity is compared with a reference structure. This is the role of the observer-adapted cut.

In the timelike-boundary reading, the cut is not introduced as a new causal geometry. It is introduced as a local comparison surface within a timelike boundary. This use is consistent with 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 [2,3]. The cut is therefore the surface on which a boundary observer can assign selected quantities, specify a coarse-grained reference structure, and identify departures from that structure.

Thus, the cut does not replace the spacetime event structure of special relativity. It makes explicit the local surface on which measurement content is read relative to a reference structure. The geometry of admissibility remains Lorentzian; the comparison that supplies event content is cut-local.

> The cut does not define a new causal geometry; it defines the local 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. In this manuscript, locality is therefore used in a cut-local sense: a local value and its reference structure are compared on the same boundary cut structure.

This is the first point at which the boundary reading differs from a purely event-point description. In the standard special-relativistic picture, an event can be localized as a point B. In the boundary reading, the point B is retained as the idealized location of a candidate record, but the comparison that gives this record its content is supported by the cut containing B. The cut supplies the local surface on which reference structure and departure become comparable.

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

$$U_B \subset C_{\tau_\Sigma}, \tag{9}$$

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

$$\mathcal{D}_q(U_B) = \int_{U_B} \left\| \Delta_q(q_\Sigma, \mathcal{R}_\Sigma) \right\|_q dA_\Sigma. \tag{10}$$

Equation (10) is not used as an additional dynamical postulate. It records only the operational point that local comparison is never accessed as an infinitely sharp mathematical point. The point notation $\mathcal{D}_\Sigma[q](B)$ used below is the idealized limit of this cut-local comparison.

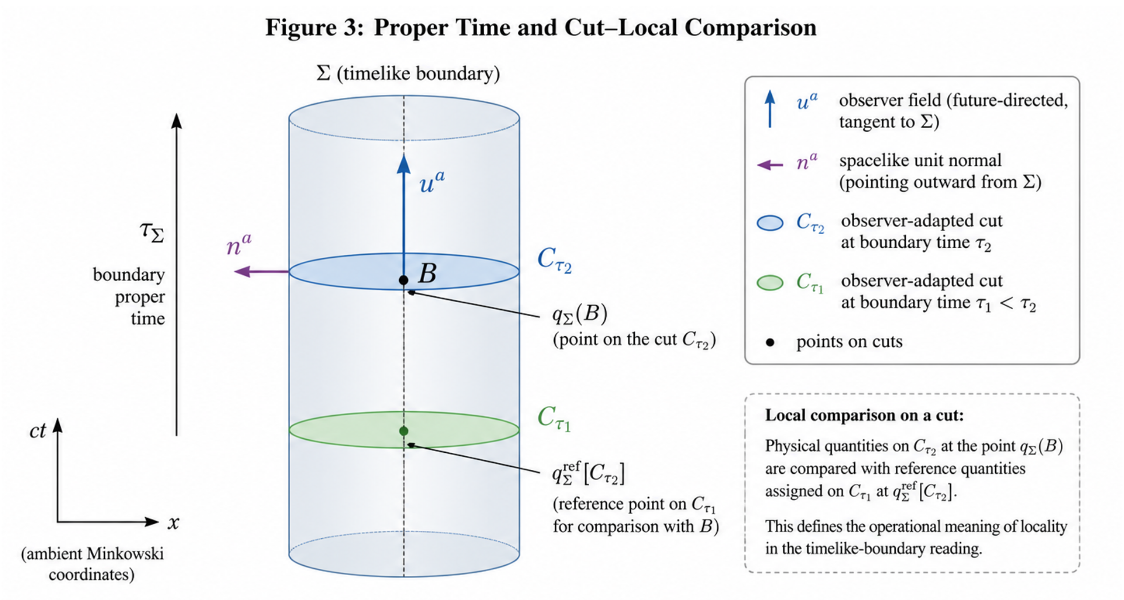

Figure 3. Proper time along a timelike boundary and cut-local comparison. The timelike boundary Σ is equipped with a future-directed observer field u^a tangent to Σ and a spacelike outward normal n^a. The boundary proper time τ_Σ orders observer-adapted cuts of Σ. A candidate boundary event B lies on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

Figure 3 should therefore be read as a comparison diagram. The boundary does not add a second spacetime to the special-relativistic event. It provides the observer-adapted surface on which the event can acquire measurement content through a later reference–deviation comparison. The local object is the resolved record at B, not an intermediate microscopic route to B.

3.2. Selected Boundary Quantities

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

$$Q_\Sigma = \{q_1, q_2, \ldots\}. \tag{11}$$

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

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by projections of a quasilocal boundary stress tensor, as in the Brown–York construction on timelike boundaries [3–5]. 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 therefore not yet a measurement outcome. It is a possible channel of comparison. A record-like value arises only after the selected quantity is read relative to a reference structure and the corresponding departure becomes locally resolvable.

This separates three levels:

$$\text{selected channel} \quad \neq \quad \text{reference structure} \quad \neq \quad \text{local record.} \tag{12}$$

The selected channel specifies what is being read. The reference structure specifies relative to what it is being read. The local record appears only when a departure from that reference structure becomes resolvable. Thus the selected channel is not a hidden value and not a particle path. It is the cut-local channel in which a possible deviation may later become manifest.

3.3. Coarse-Grained Reference Structure

Let $\mathcal{R}_\Sigma$ denote the coarse-grained reference structure assigned to the observer-adapted cut. This reference structure is not itself a local record and is not directly measured. For a selected boundary quantity q_Σ, a chosen closure may induce a channel-specific comparison object,

$$q_\Sigma^{\mathrm{ref}}(B) := \Pi_q[\mathcal{R}_\Sigma](B), \tag{13}$$

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

This notation replaces the overly literal idea that the reference state itself is a measurable value. 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. A channel-specific comparison object is only the representation of that structure in the selected channel.

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 does not display the structure itself as an event.

> The reference structure is part of the comparison scheme, but it is not itself a local event record.

The reference structure should therefore not be confused with a hidden measurement value. It is not a pre-existing local outcome waiting to be revealed. It is the structure relative to which visible departures become meaningful. 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 from it.

This separation should be read relative to established measurement language. A measurement record gives a visible value in a selected channel. It does not give direct access to the reference structure itself. The reference structure fixes the comparison scheme; the visible record is read relative to that structure.

Thus, the reference structure is not a hidden measurement value and not a pre-existing local outcome. It is the current comparison structure relative to which a local departure can become meaningful. This use is compatible with the general role of coarse-grained descriptions in statistical

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and quantum measurement contexts, where the resolved record is distinguished from the unresolved background or ensemble-level structure [6–8].

4.1. Deviation Map

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

$$\mathcal{D}_\Sigma[q](B) := \Delta_q(q_\Sigma(B), \mathcal{R}_\Sigma). \tag{14}$$

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. (13), this reduces to

$$\mathcal{D}_\Sigma[q](B) = q_\Sigma(B) - q_\Sigma^{\mathrm{ref}}(B). \tag{15}$$

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 central distinction can be stated as follows:

> A measurement does not access the reference structure directly. It resolves a visible deviation relative to that reference structure.

The measurable content is therefore not the reference structure as such, but the departure from it. The deviation carries the possible event content. In this sense, the deviation map is not a hidden-variable map. It does not assign pre-existing outcomes to unperformed measurements. It only states how a resolved local value is read relative to the selected reference structure.

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

Equality with the reference structure means

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

This does not mean that the reference structure has been measured as a local event. It means only that no locally visible departure from the reference structure is present in the selected channel at B.

Non-equality means

$$\mathcal{D}_\Sigma[q](B) \neq 0. \tag{17}$$

In the present reading, non-equality is the first event-capable structure. A local event record cannot be built from the reference structure alone. It requires a departure from that structure. However, non-equality by itself is not yet a measurement outcome. The departure must also satisfy a resolution condition on the cut.

At this stage, non-equality should therefore be read only as 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,

$$p_{\mathrm{ref}}(q) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(q-\mu)^2}{2\sigma^2}\right]. \tag{18}$$

Here the reference structure is represented by a distribution. The expectation value μ is only one derived object of that structure. It is not displayed by a single event. A single local record gives a value q_i, and the corresponding departure in this additive representation is

$$D_i = q_i - \mu. \tag{19}$$

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The signed mean deviation can vanish,

$$\langle D \rangle = 0, \tag{20}$$

while the variance remains nonzero,

$$\langle D^2 \rangle = \sigma^2. \tag{21}$$

This is only 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. The point is more limited: a reference structure can organize visible departures without itself appearing as a single local record. This distinction is standard in coarse-grained and statistical descriptions, where ensemble-level quantities and individual records have different operational roles [6,9].

For the Gaussian closure in Eq. (18), the mean absolute departure is

$$\langle |D| \rangle = \sigma \sqrt{\frac{2}{\pi}}. \tag{22}$$

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 a comparison structure, while the visible statistical content is carried by the distribution of departures.

4.4. Reference Structure and Manifestation

The distinction introduced here should not be understood as a distinction between hidden and visible measurement values. Such a wording would suggest that the reference structure stores a value that is later uncovered by a measurement. This is not the intended reading.

The relevant opposition is between a comparison structure assigned by the coarse-grained reference scheme and visible deviations from it. The comparison structure is not itself a local record. It marks the structure relative to which departures are evaluated. The observable structure is carried by departures that become locally resolvable.

In this sense, measurement is not the uncovering of a concealed local value. It is the manifestation of a boundary-relative deviation as a local record. What becomes manifest is not the reference structure itself, but a departure from it that has become locally resolvable on the cut.

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 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 [7,8].

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

5. Local Event Closure

The preceding section introduced manifestation as the formation of a local record from a boundary-relative deviation. The present section states the two conditions required for such a record. First, the deviation must be resolvable in the selected boundary channel. Second, the candidate record must be compatible with the Lorentzian causal structure of the candidate event.

Local event closure is the name used here for this combined condition. It is not introduced as a new dynamical law. It is a boundary-language for the point at which a reference-relative departure becomes a local record. The causal part of the condition follows the standard Lorentzian ordering of events, while the record part is supplied by local resolution on the observer-adapted cut [2,3].

5.1. Resolution Condition

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

$$\|\mathcal{D}_\Sigma[q](B)\|_q \geq \epsilon_q. \tag{23}$$

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, or tensorial quantities need not share the same resolution criterion.

The condition (23) should not be read as direct access to the reference structure. It says only that the departure from the reference structure has become resolved enough to form local event content in the selected channel.

There are therefore three distinct cases:

$$\mathcal{D}_\Sigma[q](B) = 0, \qquad \text{no departure from the reference structure,} \tag{24}$$

$$0 < \|\mathcal{D}_\Sigma[q](B)\|_q < \epsilon_q, \qquad \text{unresolved departure,} \tag{25}$$

$$\|\mathcal{D}_\Sigma[q](B)\|_q \geq \epsilon_q, \qquad \text{resolved departure.} \tag{26}$$

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 does not yet appear as a local record.

5.2. Causality and Local Closure

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

$$A \in J^-(B), \qquad \|\mathcal{D}_\Sigma[q](B)\|_q \geq \epsilon_q. \tag{27}$$

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 event content. It states that a boundary-relative departure from the reference structure has become resolvable on the cut containing B.

Hence,

Causality supplies admissibility; deviation supplies event content.

This sentence is the operational core of the present reading. The causal cone does not by itself produce a measurement record. It restricts which prior data or contextual contributions may be relevant for the local reading of B. The deviation does not by itself define a causal relation. It supplies the content that can become manifest at B. Local event closure requires both.

This is the sense in which causal structure and measurement content are kept distinct in the present reading.

5.3. Measurement as Boundary Closure

A measurement record is not identified with the reference structure and not with a microscopic route to the event. It is the result of a local closure process on the boundary cut. In schematic form,

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

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

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

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Equation (29) should not be read as two separately observed terms. 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 fixes the comparison scheme; the resolved deviation supplies the manifest event content.

This is the point at which the boundary reading differs from a picture in which a measurement merely uncovers a pre-existing local value. A measurement record is formed when a departure from the reference structure becomes resolvable in a causally admissible setting.

5.4. Closure Without a Unique Microscopic Route

The closure condition also clarifies the status of reconstructed microscopic structure. The condition $A \in J^-(B)$ does not identify a unique route from A to B. It only states that prior data, preparation conditions, or contextual contributions lie within the Lorentz-admissible domain of B. More than one reconstructed prior structure may be compatible with this condition.

In the boundary reading, the absence of a unique microscopic route is not a defect. It is precisely why event content is assigned at the cut rather than to a pre-selected route. The local record is not the route itself. It is the resolved deviation that becomes manifest at B.

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 three 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 clarifies how standard amplitude language is read in 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 [10,11]. It is used here only as a point of comparison.

The paths γ in Eq. (31) should not be read as observed particle trajectories. They are phase contributions to an amplitude. In the semiclassical limit, a classical route may be reconstructed as a stable constructive approximation, but this reconstructed route is not itself the local record.

In the timelike-boundary reading, the point B is read as the local manifestation point of a record on a boundary cut. The causal past of B restricts which prior data and contextual contributions may be reconstructed as Lorentz-admissible, but it does not select a unique microscopic route to B. Additional contextual contributions, such as external fields, apertures, detector settings, absorbing objects, or environmental records, may enter the experimental comparison structure. Their role is not to define a particle route. They shape the reference structure relative to which a resolved deviation at B can become manifest.

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 not an individual path, but a 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.

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This distinction is compatible with record-based and decoherence-oriented descriptions of measurement, in which stable records are separated from unresolved pre-record structure [7,8]. 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 not to replace the eigenvalue formalism. 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 [12–14]. 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 the value of a local record whose event 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 only specifies how the manifest record is interpreted after 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 not interpreted as direct access to the reference structure. It is interpreted as 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 only states how an already assigned outcome is read in the reference–deviation language.

It should also not be read as saying that the two terms on the right-hand side are separately observed. 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 fixes 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 does not alter the operational role of eigenvalues in quantum mechanics. It only assigns the resulting record a boundary-local interpretation.

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 [13,14].

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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 does not expose the reference structure itself. It 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 point is not that the reference structure is directly displayed. The point is that the same record value can manifest repeatedly as a stable resolved deviation in the selected channel.

This provides the boundary-language analogue of an ideal eigenstate: not direct exposure of the reference structure, but stability of the manifest record under repeated closure in the same channel.

6.3. Measurement Does Not Reveal the 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. It does not directly reveal the coarse-grained reference structure. A channel-specific reference representation may be reconstructed or calibrated only through an additional statistical, operational, or boundary closure. It is not itself displayed by a single event.

This parallels the statistical reference example discussed above, but only at the level of analogy. 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 not the reference structure itself; it is the manifest value read relative to that structure.

This avoids a hidden-outcome interpretation. The reference structure is not a pre-stored local measurement value. It is the comparison background relative to which the visible deviation is defined. In particular, the reference structure does not assign outcomes to unperformed measurements. It is therefore distinct from a Bell-type hidden-outcome variable.

6.4. Macroscopic Stability

The framework does not imply that macroscopic objects disappear when unmeasured. 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 [7,8]. 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 therefore not equivalent to direct access to an underlying reference structure. It is the persistence of a manifest pattern relative to that structure.

Thus,

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

A measurement of such an object does not bring the object into existence. It adds a new local record to an already stabilized pattern.

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7. Discussion: The Cut-Level Interface

The manuscript has developed a timelike-boundary reading of local measurement at the level of special-relativistic event geometry. The central aim was not to add a new microscopic mechanism, but to separate notions that are often compressed into a single statement: causal admissibility, amplitude contribution, reference structure, visible deviation, manifestation, and local measurement record.

The established descriptions of special relativity and quantum mechanics form the reference framework. The boundary reading is tested against them. Its value does not lie in changing their mathematical content, but in identifying a shared cut-level interface at which their local readings can be organized together.

7.1. The Shared Interface

The central object of the manuscript is not an individual particle route, a hidden state, or a new spacetime sector. It 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

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

The importance of this summary is the location of the interface. The causal cone and the amplitude/context structure do not by themselves supply the local record. The record is assigned on the cut when a boundary-relative deviation becomes resolvable. Conversely, the cut does not replace the causal cone or the standard quantum record language. It provides the surface on which their local roles can be compared.

In this sense, the contribution of the boundary language is an assignment claim. It does not introduce a new gravitational field equation or a new quantum probability rule. It specifies where, in the present reading, the content of a local measurement record is assigned.

7.2. What Remains Standard and What Is Re-Read

Several elements remain standard. The Lorentzian light cone is not modified. The standard amplitude formalism is not replaced. The operational use of eigenvalues is not changed. Bell-type constraints are not dismissed.

The re-reading concerns the assignment of local measurement content. In the standard event-geometric language, 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 measurement 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 that the reference structure is not itself a local event record. It is the comparison structure assigned by the coarse-grained boundary reading. The measurable content is carried by visible 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 as a Consistency Gate

Bell-type constraints provide the central consistency test for any language that uses locality and record formation. The present reading therefore cannot be judged only by its own terminology. It must be compared with what Bell-type results exclude [15–17].

The relevant point is that 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,

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

The timelike-boundary reading does not introduce the reference structure in this role. The reference structure is not a hidden store of outcomes for possible measurement settings. It supplies the comparison background relative to which visible deviations become meaningful.

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. A record becomes local only when a boundary-relative deviation becomes manifest on the cut.

In this sense, the reading does not look for a hidden passage around Bell's theorem. It avoids introducing the specific hidden-outcome structure that Bell excludes. The locality claimed here is not classical Bell-locality of pre-assigned outcomes. It is cut-locality of record formation under Lorentzian causal admissibility.

The interface-level conclusion is therefore

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

The equation fixes the position of the boundary reading with respect to Bell-type constraints. Local records are manifest on observer-adapted cuts, but they are not assumed to have existed beforehand as separable local outcomes. A quantitative reconstruction of Bell-violating correlations would require an additional statistical rule for correlations between resolved deviations.

7.4. What the Bell Comparison Does and Does Not Show

The Bell comparison shows that the boundary reading is not formulated as a classical local hidden-variable model. The reference structure is not identified with a Bell variable λ that stores outcomes for all possible settings. The local record is not uncovered from such a store. It is formed as a manifest deviation on the cut.

The comparison does not show that the boundary reading reproduces quantum Bell 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.

The appropriate conclusion is therefore modest. The reading is not excluded at the level of its basic language by treating the reference structure as a hidden outcome, because it does not do so. Whether the interface language can be extended into a quantitative correlation framework remains an open problem.

7.5. Possible Entropic Reading of Boundary Records

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. Nevertheless, the boundary language naturally raises a 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 only 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 only at the level of orientation with information thermodynamics and the thermodynamic cost of distinguishability [18,19].

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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 [20,21]. The present manuscript does not assign Bekenstein–Hawking entropy to a general timelike boundary cut. It only notes that a later gravitational extension would have to specify whether, and how, cut-local record formation is associated with an area-like measure.

7.6. Macroscopic Fluctuations and Reference Profiles

The same reference–deviation distinction can also be read in a more classical thermodynamic setting. A macroscopic object is not free of microscopic activity. In a standard statistical description, thermal fluctuations, Brownian motion, and molecular impacts produce distributions of local quantities rather than one perfectly sharp microscopic value [22–25].

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 interpretation. 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 not introduced as a new law of statistical mechanics. It is an interpretive translation of the same reference–deviation logic. The reference profile is not a single local record; it 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 only 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 not the reference state itself; it is the representation of the reference structure in that statistical closure.

In this sense, a system may be said to adapt to its "underlying" reference state only in a restricted, coarse-grained sense: relaxation reduces the resolved departure 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, but its thermal background can still be organized by a coarse-grained reference distribution. The observable object is then not the reference profile itself; it is the stable pattern of departures that persists relative to that profile.

7.7. Relation to Open Questions

The entropic and thermodynamic readings introduced above are interpretive orientations, not additional postulates of the present manuscript. 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.

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

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

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.

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.

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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.

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 [12–14,26]. 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 [15–17]. 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

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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 [22–25]. 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.

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 [18,19].

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

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

show that entropy, information, and boundary area can be closely related in gravitational settings [20,21]. 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 [3,4].

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 [7,8]. 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.

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10. Appendix

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, this proper-time ordering is inherited by the boundary observer field u^a. Locally, the intrinsic boundary line element is

$$ds_\Sigma^2 = -c^2 d\tau_\Sigma^2 + \sigma_{AB} dy^A dy^B. \tag{A51}$$

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 [2,3].

The present reading distinguishes geometric proper time from operational clock time. A timelike boundary may possess a proper-time ordering without itself carrying a clock-like ticker. A clock does not merely possess a timelike worldline; it produces distinguishable updates along that worldline. In boundary language, a clock-like process requires a sequence of locally distinguishable records on successive observer-adapted cuts,

$$C_{\tau_1}, \quad C_{\tau_2}, \quad C_{\tau_3}, \ldots. \tag{A52}$$

Proper time orders the cuts; resolved updates provide ticks.

Thus, τ_Σ is a geometric ordering parameter, not yet an operational clock. Clock time requires a recordable update structure. Such a ticker may be represented abstractly by a sequence of resolved boundary-relative deviations,

$$\mathcal{D}_\Sigma[q](B_n) = q_\Sigma(B_n) - q_\Sigma^{\text{ref}}(B_n), \qquad B_n \in C_{\tau_n}, \tag{A53}$$

together with the corresponding resolution condition

$$\|\mathcal{D}_\Sigma[q](B_n)\|_q \geq \epsilon_q. \tag{A54}$$

Equation (A53) should not be read as a universal model of physical clocks. It only states the minimal boundary-language requirement for a clock-like process: successive cuts must carry distinguishable local records in at least one selected channel. Without such resolved updates, the boundary still has proper time, but no operational tick sequence.

This distinction is useful for the main text. Local event closure 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. The updates become observable only when boundary-relative deviations are locally resolved.

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

$$\Delta S \sim k_B \ln 2. \tag{A55}$$

This question is not part of the core construction. It is only an orientation toward information thermodynamics, where distinguishability and record formation may carry thermodynamic cost [18,19]. 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.

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

$$q_\Sigma^{\rm ref}(B_{\rm dark}) \simeq 0. \tag{A56}$$

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,

$$\mathcal{D}_\Sigma[q](B_{\rm dark}) \simeq 0. \tag{A57}$$

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 [27,28]. 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 $B_{\rm dark}$ 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,

$$\mathcal{D}_\Sigma[q](B_{\rm dark}) = q_\Sigma(B_{\rm dark}) - q_\Sigma^{\rm ref}(B_{\rm dark}), \qquad \|\mathcal{D}_\Sigma[q](B_{\rm dark})\|_q \geq \epsilon_q. \tag{A58}$$

The local record is the detector event at $B_{\rm dark}$. 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 $B_{\rm dark}$ is read.

Thus the example separates three notions:

$$\text{object in the experimental context} \quad \neq \quad \text{observed particle route} \quad \neq \quad \text{local detector record}. \tag{A59}$$

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

$$\begin{aligned} &\text{Lorentz-admissible context } + \text{changed comparison structure} \\ &\quad + \text{resolved detector deviation at } B_{\rm dark} \\ &\longrightarrow \text{local record.} \end{aligned} \tag{A60}$$

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 [29]. 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 boundary reading. The purpose is limited. Amplitude contributions are not interpreted as observed

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particle routes. They are treated as context contributions to the comparison structure relative to which a local record becomes manifest.

The core construction of the manuscript remains

$$A \in J^{-}(B), \qquad \left\| D_{R_\Sigma}[q](B) \right\|_q \geq \epsilon_q. \tag{A61}$$

The local object is always the manifest record at B, not a microscopic route to B.

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

$$\mathcal{A}(A \to B) = \int_{\gamma: A \to B} \mathcal{D}\gamma \, \exp\!\left(\frac{i}{\hbar} S[\gamma]\right). \tag{A62}$$

This is standard amplitude language [10,11]. It is used here only as a point of comparison.

The paths γ in Eq. (A62) should not be read as observed particle trajectories. They are phase contributions to an amplitude. In the semiclassical limit, the stationary-action condition

$$\delta S[\gamma_{\mathrm{cl}}] = 0 \tag{A63}$$

selects the stable constructive approximation that can be read as the classical route. This does not imply that all paths are physically traversed. It means that the phase structure admits a classical reconstruction.

Appendix C.2 Context Contributions to the Comparison Structure

In the boundary reading, the point B is the manifestation point of a local record on an observer-adapted cut. The amplitude contributions are not the manifest object. They belong to the experimental and causal comparison context relative to which a resolved deviation at B is read.

Thus, the translation used here is

$$\text{standard amplitude contribution} \quad \longrightarrow \quad \text{context contribution to the comparison structure.} \tag{A64}$$

The contribution is contextual; the record is local.

A schematic record-conditioned amplitude may be written as

$$\mathcal{A}(R_B \mid \mathcal{C}_B) = \int_{\gamma \in \Gamma(\mathcal{C}_B \to U_B)} \mathcal{D}\gamma \, \exp\!\left(\frac{i}{\hbar} S[\gamma; \mathcal{C}_B]\right) \chi_{R_B}[\gamma; \mathcal{C}_B]. \tag{A65}$$

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 (A65) is not a new dynamical law. It only states that reconstructed context contributions must be compatible with the manifest record and with the causal context.

Appendix C.3 Manifest Records and Retrodictive Reconstruction

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

$$R_B = \big(B,\, q_\Sigma(B),\, D_{R_\Sigma}[q](B)\big). \tag{A66}$$

The record R_B is local and manifest on the cut. The prior structure relevant for it is not directly manifest as a microscopic route. It is a retrodictive reconstruction constrained by the manifest record, the experimental context, and Lorentzian causal admissibility.

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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, detector settings, absorbing objects, and environmental records can contribute to the amplitude structure. They do not thereby become observed particle routes. They shape the comparison structure relative to which the detector event B is read.

This may be expressed schematically by a retrodictive distribution

$$P(A \mid R_B, \mathcal{C}_B). \tag{A67}$$

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, context contributions do not hide a pre-existing route. They make the assignment of a unique route inappropriate. What is manifest is not a microscopic path, but the local record at B.

Appendix D Symbolic Reference–Deviation Bookkeeping

This appendix records a symbolic bookkeeping device that may help visualize the reference–deviation split used in the main text. The notation is interpretive. It was neither part of the core design nor a necessary model representation. Rather, it is a highly simplified educational aid.

The symbols below should be read as mnemonic orientation labels. They do not enumerate hidden outcomes and they do not assign values to unperformed measurements. Their only purpose is to display, in a compact form, the difference between a non-manifest comparison structure, a reference side, and a manifest deviation side.

Appendix D.1 Thermodynamic Reading of the Symbolic States

The symbolic notation used in this appendix may also be read through a deliberately simplified thermodynamic mnemonic. This reading is not a metric signature, not a second spacetime geometry, and not a microscopic spin model. The signs are symbolic orientation labels for coarse-grained comparison states.

The useful thermodynamic picture is a spin-like ordering mnemonic with three idealized roles:

$$(+,+,+,+)_{\uparrow}, \qquad (\pm,\pm,\pm,\pm)_{\text{mix}}, \qquad (-,-,-,-)_{\downarrow}. \tag{A68}$$

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 small class of microscopic or contextual arrangements is compatible with a fully aligned symbolic orientation.

By contrast,

$$(\pm,\pm,\pm,\pm)_{\text{mix}} \tag{A69}$$

denotes an unresolved mixed-orientation structure. It represents the coarse-grained situation in which several symbolic orientations remain open relative to the chosen reference 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,

$$S_{\text{cg}} = k_B \ln \Omega_{\text{cg}}. \tag{A70}$$

The ordered branches have comparatively small multiplicity,

$$\Omega_{\text{cg}}[(+,+,+,+)_{\uparrow}] \ll \Omega_{\text{cg}}[(\pm,\pm,\pm,\pm)_{\text{mix}}], \qquad \Omega_{\text{cg}}[(-,-,-,-)_{\downarrow}] \ll \Omega_{\text{cg}}[(\pm,\pm,\pm,\pm)_{\text{mix}}]. \tag{A71}$$

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

This does not mean that the transition from a mixed state to an ordered state violates thermodynamics. The entropy discussed here is the entropy of the selected coarse-grained symbolic sector. A local decrease of this sector entropy is thermodynamically admissible when the boundary, exterior channels, or unresolved degrees of freedom carry the compensating entropy or dissipated energy. In a finite-response boundary system, this is exactly the role of storage, release, and response channels: the resolved local ordering need not be the whole thermodynamic bookkeeping.

The same mnemonic gives a cautious way to discuss false-vacuum-like and true-vacuum-like language. An ordered lower branch may appear stable relative to the presently available comparison structure. It is then true-vacuum-like only within that closure. If a still lower comparison structure becomes available, the same ordered branch can become metastable. In that case the transition may be represented symbolically as

$$(-,-,-,-)_{\text{false}} \longrightarrow (-,\pm,\pm,\pm)_{\text{trans}} \longrightarrow (-,-,-,-)_{\text{true}}. \tag{A72}$$

The initial and final symbols have the same formal orientation pattern, but they do not denote the same thermodynamic reference level. The labels "false" and "true" specify their role relative to the effective comparison structure: the false branch is a metastable local minimum, whereas the true branch is the lower reference branch selected by the later closure.

The intermediate symbol

$$(-,\pm,\pm,\pm)_{\text{trans}} \tag{A73}$$

denotes the transition regime. The first sign is kept fixed only as a 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 cannot occur instantaneously, the system does not jump directly from one ordered reference branch to another. It passes through an unresolved comparison regime in which the old ordered branch is no longer sufficient, while the new ordered branch has not yet become a resolved reference structure.

In this thermodynamic reading, the boundary does not reveal the reference structure directly. It provides the cut-local comparison surface on which non-equality between the metastable coarse-grained structure and the reference direction can become visible. The record-accessible content is not the reference structure itself, but the resolved deviation from it.

The schematic picture is therefore

$$\begin{aligned}\text{ordered metastable branch} &\longrightarrow \text{unresolved high-entropy transition regime} \\ &\longrightarrow \text{ordered lower reference branch.}\end{aligned} \tag{A74}$$

The analogy is intentionally restricted. It does not claim a microscopic derivation of vacuum decay, symmetry breaking, or quantum measurement. 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 the 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,

$$\mathrm{GC}_{\text{pre}} \sim (-,\pm,\pm,\pm). \tag{A75}$$

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The notation in Eq. (A75) is not a spacetime signature. It is not a metric and does not define a Lorentzian or Euclidean sector. The fixed sign marks only an orientation of comparison. The $\pm$ entries denote open or not-yet-separated comparison channels. They are not hidden measurement values.

A possible statistical representation of this pre-record structure is

$$R_\Sigma(B) \sim \int_{\mathcal{I}_B} \rho_{\mathrm{GC}}(\xi)\, \mathcal{R}_\Sigma(B;\xi)\, d\xi. \tag{A76}$$

The index ξ does not hide an outcome and does not label an observed microscopic route. It labels non-manifest context contributions that may shape the reference structure assigned on the cut.

A channel-specific comparison object is obtained by projection,

$$q_\Sigma^{\mathrm{ref}}(B) = \Pi_q[R_\Sigma](B). \tag{A77}$$

Equations (A76) and (A77) are bookkeeping expressions. They only state that the reference structure may depend on non-manifest context structure without turning that context into a list of pre-existing outcomes.

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

$$(-,\pm,\pm,\pm)_{\mathrm{GC}} \xleftrightarrow{\text{boundary reading}} \{(-,-,-,-)_{\mathrm{ref}} \leftrightarrow (-,+,+,+)_{\mathrm{dev}}\}. \tag{A78}$$

Equation (A78) is not a transition law. It is a symbolic map of roles.

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 structure and a visible deviation are separated on the cut.

The pair

$$(-,-,-,-)_{\mathrm{ref}} \leftrightarrow (-,+,+,+)_{\mathrm{dev}} \tag{A79}$$

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 as numerical components. They are a mnemonic for the open deviation side: the sum of 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 a hidden state already carrying a definite outcome.

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

$$q_\Sigma(B) = q_\Sigma^{\mathrm{ref}}(B) + D_{R_\Sigma}[q](B), \qquad \left\| D_{R_\Sigma}[q](B) \right\|_q \geq \epsilon_q. \tag{A80}$$

Thus, the symbolic expression in Eq. (A80) is not an additional law. It is a compact mnemonic for the same comparison structure.

Appendix E Notation for the Reference–Deviation Structure

This appendix summarizes the notation used for the cut-level reference–deviation structure. The purpose is only to keep the roles of reference structure, comparison object, deviation, and local record distinct.

Symbol or term	Meaning in this manuscript	Not to be confused with
C_{τ_Σ}	observer-adapted comparison cut	a second spacetime or a horizon
Q_Σ	selected boundary channels	measurement outcomes
R_Σ	coarse-grained reference structure on the cut	a directly measured local value
$\Pi_q[R_\Sigma]$	reading of R_Σ in channel q	a microscopic state reconstruction
$q_\Sigma^{\mathrm{ref}}(B)$	channel-specific comparison object	a hidden outcome stored at B
$\Delta_q(q_\Sigma, R_\Sigma)$	channel-dependent departure operation	a dynamical law
$D_{R_\Sigma}[q](B)$	boundary-relative deviation	a pre-existing measurement result
ϵ_q	resolution scale of channel q	a universal quantum threshold
R_B	manifest local record at B	a microscopic route to B

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