

The Markov Blanket as Quantum Reference Frame: Active Inference, Proper Time, and the Constitution of Observers

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February 17, 2026

Abstract

Two independently developed research programs—quantum reference frames (QRFs) and the Free Energy Principle (FEP)—offer convergent accounts of what it takes for a physical system to constitute a bounded, persisting perspective on its environment. This paper argues that their convergence is structural rather than coincidental: the Markov blanket of a self-maintaining system under the FEP and the quantum reference frame of that system under the Page–Wootters / refined algebraic quantization (PW/RAQ) construction play the same constitutive role—defining the boundary that constitutes the observer as a record-keeping, temporally extended entity. Drawing on companion papers that establish proper-time uniqueness and the epistemic arrow of time within the PW/RAQ framework, we argue that sustained active inference maintains the physical regime in which the admissibility conditions for proper-time emergence are dynamically stable. The identification yields three consequences: (i) it grounds the epistemic arrow in the self-maintaining dynamics of the observer and explains its robustness; (ii) it provides a principled exclusion of standard Boltzmann brains based on the operational distinction between thermodynamically maintained records and accidental patterns; and (iii) it suggests a strategy for extending the framework from static to dynamic spacetimes by replacing global symmetry assumptions with local, observer-accessible regularity conditions. The paper does not claim that the FEP is required for the companion results, nor that consciousness is explained or presupposed. Rather, it argues that connecting the two programs yields explanatory depth and consequences that neither achieves alone.

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1 Introduction

1.1 Two questions about observers

What does it take to be an observer? And what does being an observer have to do with the direction of time?

These questions are usually treated separately. The first belongs to philosophy of mind, quantum foundations, or theoretical biology, depending on who is asking. The second belongs to philosophy of physics, statistical mechanics, or cosmology. But there is a growing body of work suggesting that the questions are connected — that the conditions required for a physical system to constitute an observer are deeply connected to the conditions required for that system to have a temporal perspective, and that both sets of conditions are thermodynamic.

This paper makes that connection precise. We argue that two independently developed research programs — the quantum reference frames (QRF) program in foundations of physics and the Free Energy Principle (FEP) in theoretical biology and neuroscience — converge on a shared account of observer-hood, and that connecting them to the formal machinery developed in two companion papers yields results that neither program achieves alone.

1.2 The companion papers

The present paper is the third in a sequence. It builds on two companion papers that provide the formal and philosophical foundations:

Companion 1 (technical note): *Relational Emergence of Proper Time from Observer-Internal Clocks in a Covariant Page–Wootters Framework* ([Anonymous, 2025b](#)) develops a modified Page–Wootters (PW) framework combined with refined algebraic quantization (RAQ) for a composite system consisting of an observer with internal degrees of freedom, an external sector, and a center-of-mass (COM) sector, coupled by a single first-class mass-shell constraint. It introduces five admissibility conditions (C1)–(C5) on the observer’s internal clock — Lorentz-scalar completeness, stationary/static calibration, self-adjoint reduced dynamics, regular gauge, and monotonicity — and proves that, under the stated static-background assumptions, any admissible clock selects the COM proper time as the relational parameter, uniquely up to monotone reparametrization (Theorem 1). It constructs a meeting POVM for reunion events between two observers and proves an inter-observer isometry ensuring Born-rule agreement on shared observables. It also develops a clock-noise/dephasing analysis using standard metrological noise models (Allan deviation, time variance) that quantifies coherence loss for realistic clocks.

Companion 2 (philosophy paper): *Proper Time and the Epistemic Arrow: From Cosmological Boundary to Thermodynamic Throughput to Persistent Identity* ([Anony-](#)

[mous, 2025a](#)) takes the PW/RAQ framework as input and develops its philosophical consequences. It defines records operationally as (ε, L) -reliable observables maintained under a readout channel, introduces the record algebra $\mathcal{R}(\tau)$ ordered by proper time, and proves (Proposition 3.2) that positive average dissipation yields nondecreasing expected information content of the record algebra on coarse-grained timescales. This establishes the epistemic arrow — the directed inclusion order $\mathcal{R}(\tau_1) \subseteq \mathcal{R}(\tau_2)$ — as a thermodynamic phenomenon funded by dissipation. It argues that the retrodictive sufficiency of present records (sharpness of the past) requires a Past-Hypothesis-type low-entropy cosmological boundary, using Fano inequality bounds on retrodictive error and a selection argument over the space of physically possible histories. It proposes empirical protocols (gravitational redshift, kinematic QRF variants, information engines) for testing the framework’s predictions.

The present paper does not re-derive or replace these results. It takes them as given and asks: what happens when we connect them to the FEP?

1.3 What this paper does

The central claim is a structural identification: the Markov blanket of a self-maintaining system under the FEP and the quantum reference frame of that system under the PW/RAQ construction describe the same physical structure. This claim has been made at a high level of abstraction by [Fields et al. \(2022\)](#), who reformulated the FEP in spacetime-background-free quantum information theory using category-theoretic tools. Our contribution is different in character: we show that the specific PW/RAQ machinery — admissibility conditions, record algebras, proper-time uniqueness, the epistemic arrow — provides a concrete physical realization of the abstract identification, and that this realization yields consequences the abstract framework does not.

Specifically:

Active inference maintains admissibility (Section 4). We identify five physical preconditions of active inference and show that they jointly maintain the physical regime in which the admissibility conditions (C1)–(C5) are dynamically stable. This is a weaker claim than “active inference implies admissibility” but a more honest one: active inference keeps the observer in the domain where the companion note’s theorems apply.

The epistemic arrow is enriched (Section 5). The FEP transforms the companion paper’s thermodynamic account of the epistemic arrow from a background condition into an agentive achievement, adds a control-theoretic account of how dissipative throughput is allocated between record maintenance and expansion, sharpens the retrodictive structure, and explains the arrow’s robustness under perturbation.

Dynamic spacetimes become conceptually approachable (Section 6). The identification suggests replacing the companion note’s global geometric symmetry as-

sumptions (static backgrounds, Killing fields) with local, observer-accessible regularity conditions — adiabatic or local stationarity over the observer’s prediction horizon — interpreted as maintained by self-organization. This does not solve the open problems of quantum gravity but identifies the right level of description for pursuing extensions.

Boltzmann brains are categorically excluded (Section 7). The framework’s operational definition of records — (ε, L) -reliable observables maintained by sustained dissipation — categorically distinguishes genuine observers from thermal fluctuations. A Boltzmann brain may instantiate a pattern resembling an observer’s internal states, but it does not instantiate a record algebra, because recordhood requires stable readout under repeated querying over timescales that transient fluctuations cannot sustain.

1.4 What this paper does not do

To prevent misreading, we state explicitly what is not claimed.

This paper does not claim that the FEP is required for the companion papers’ results. The formal machinery (PW/RAQ, proper-time uniqueness, record-algebra monotonicity, retrodictive sufficiency) stands on its own. The FEP adds explanatory depth and new connections, not new theorems.

This paper does not claim a formal proof of equivalence between Markov blankets and QRFs. The correspondence is structural, supported by precise parallels at each layer, but the two frameworks use different mathematical languages (stochastic dynamics for the FEP, constrained Hilbert-space quantization for PW/RAQ), and a rigorous proof of equivalence is an open problem (Section 8.3).

This paper does not claim that consciousness is explained, required, or addressed. The epistemic arrow is a thermodynamic-informational structure that exists wherever the relevant conditions are met, without commitment to phenomenal experience. The connection to consciousness belongs to a broader philosophical program that this paper does not enter.

Where the arguments are structural rather than formally proved, this is stated explicitly.

1.5 Plan of the paper

Section 2 reviews the formal inputs from both companion papers and from the QRF and FEP literatures, establishing notation and collecting the results that later sections draw on. Section 3 states and unpacks the core structural identification. Section 4 develops the argument that active inference maintains the admissibility regime. Section 5 draws out implications for the epistemic arrow. Section 6 addresses the extension to dynamic spacetimes. Section 7 presents the Boltzmann brain dissolve. Section 8 concludes with an assessment of epistemic status, open problems, and broader context.

2 Formal Inputs

This section collects the definitions, results, and conceptual frameworks from the companion papers and from the QRF and FEP literatures that the subsequent sections draw on. It is intended as a self-contained reference; readers familiar with both literatures may wish to skim.

2.1 The PW/RAQ framework (from Companion 1)

Setup. Consider a composite system with Hilbert space $\mathcal{H} = \mathcal{H}_{\text{cm}} \otimes \mathcal{H}_{\text{int}} \otimes \mathcal{H}_{\text{ext}}$, where \mathcal{H}_{cm} is the center-of-mass sector, \mathcal{H}_{int} the observer’s internal degrees of freedom, and \mathcal{H}_{ext} the external sector. A single first-class constraint \hat{C} , generating reparametrization invariance, imposes the mass-shell condition, coupling the observer’s internal energy \hat{H}_{int} to the COM kinetic term and the external Hamiltonian \hat{H}_{ext} . The physical Hilbert space $\mathcal{H}_{\text{phys}}$ is obtained by refined algebraic quantization (RAQ): a rigging map η projects kinematical states onto the constraint surface, and physical observables are defined as operators that commute with \hat{C} (Dirac observables).

Conditioning. Following the Page–Wootters (PW) approach, one conditions on the observer’s internal clock observable \hat{T}_{int} to obtain a relational description: “what is the state of the external sector when the observer’s clock reads τ ?” This conditioning operation selects a one-parameter family of reduced states $\rho_{\text{ext}}(\tau)$, parameterized by the observer’s clock reading.

Admissibility conditions. Five conditions on the internal clock ensure that the resulting relational parameter is physically meaningful:

- **(C1) Lorentz-scalar completeness:** Clock/record variables are Dirac observables (gauge-invariant), Lorentz-scalar, and informationally complete for the observer’s conditional state assignment.
- **(C2) Stationary/static calibration:** For stationary worldlines, the clock rate satisfies $d\Theta/dt = \kappa N(\mathbf{x})$, where $N(\mathbf{x})$ is the redshift factor of the static metric and κ a calibration constant.
- **(C3) Self-adjoint reduced dynamics:** The reduced generator is essentially self-adjoint on the common invariant core \mathcal{D}_0 , ensuring well-defined unitary evolution via Stone’s theorem.
- **(C4) Regular gauge:** The Faddeev–Popov determinant $\Delta_{\text{FP}} = (i\hbar)^{-1}[\chi, \hat{C}]$ is nonvanishing on the massive sector — the clock does not stall.
- **(C5) Monotonicity:** The clock is strictly monotone along timelike curves.

Proper-time uniqueness (Theorem 1). Any admissible clock selects the COM proper time as the relational parameter, uniquely up to monotone reparametrization.

Meeting POVM and inter-observer isometry. When two observers meet, a meeting POVM $\hat{E}_{12}(\tau_1, \tau_2, \sigma)$ registers the event, and an inter-observer isometry ensures Born-rule agreement on the overlap algebra of shared observables.

Clock noise and dephasing. Realistic clocks deviate from ideal behavior. The companion note models this using standard metrological noise classes (white FM, flicker FM, random-walk FM) characterized by Allan deviation $\sigma_y(\tau)$, and derives the resulting time variance $\sigma_\tau^2(\tau)$ and dephasing functional (Eqs. 9–10) quantifying coherence loss in the reduced dynamics.

2.2 Records and the epistemic arrow (from Companion 2)

Operational records. A record is an observable \hat{R} that is (ε, L) -reliable: repeated queries of a readout channel \mathcal{E} over the proper-time interval $[\tau, \tau + L]$ recover the record with error $\leq \varepsilon$. Reliability is an operational, maintenance-dependent property, not a structural one.

Record algebra. The collection of reliable records at proper time τ forms an algebra $\mathcal{R}(\tau)$. The epistemic arrow is defined by the inclusion order: $\mathcal{R}(\tau_1) \subseteq \mathcal{R}(\tau_2)$ for $\tau_1 \preceq \tau_2$.

Proposition 3.2 (record-algebra monotonicity). Under positive average dissipation $\dot{Q}_{\text{diss}}(\tau) > 0$ over coarse-graining windows large compared to device cycle times, the expected information content $E[I_{\mathcal{R}}(\tau)]$ is nondecreasing, and the inclusion order is maintained in expectation. Localized forgetting events are permitted, bounded by the integrated deficit of dissipation relative to the minimal maintenance cost.

Retrodictive sufficiency. Present reliable records constrain compatible past histories via Fano inequality bounds: retrodictive error $\leq \delta$ requires mutual information $I(H; \hat{R}_\tau)$ exceeding an explicit threshold (Eqs. 1–2). The ubiquity of redundant, cross-validated records licensing stable retrodiction requires, as part of the best explanation, a Past-Hypothesis-type low-entropy cosmological boundary.

The cascade. The companion paper establishes:

$$\text{Past Hypothesis} \implies \text{Local Thermodynamics} \implies \text{Epistemic Arrow in Proper Time}.$$

2.3 Quantum reference frames (from the QRF literature)

Perspective-neutral framework. Vanrietvelde et al. (2020) and Höhn et al. embed all QRF perspectives within a single gauge-invariant (perspective-neutral) Hilbert space. A frame choice corresponds to a gauge-fixing; frame changes are implemented by unitary maps. This framework does not assume a background spacetime or a preferred time parameter.

Observer-dependent algebras. De Vuyst et al. (2025) show that different QRF choices yield different observable algebras and hence different entropies. Gravitational entropy is observer-dependent in a precise, frame-relative sense. This result is directly relevant to the present paper’s claim that the observer’s record algebra is constituted by its reference-frame choice.

Relational dynamics. Höhn, Smith, and Lock (2021) and subsequent work develop relational dynamics in relativistic settings without assuming static backgrounds, providing tools for the extension discussed in Section 6.

2.4 The Free Energy Principle and active inference (from the FEP literature)

Markov blankets. A Markov blanket is a set of states that renders a system’s internal states conditionally independent of external states. For a system partitioned into internal, external, sensory, and active states, the blanket comprises the sensory and active states. The blanket is not (in general) a spatial boundary but a statistical one, defined by conditional independence structure (Friston, 2019; Kirchhoff et al., 2018).

The FEP. Systems that persist over time — that maintain their identity as bounded entities — can be modeled as minimizing variational free energy, an upper bound on surprisal (negative log-evidence). This minimization is equivalent, under suitable conditions, to Bayesian inference: the system’s internal states encode a generative model of the causes of its sensory input, and active inference is the process of updating that model and acting on the environment to reduce prediction error.

Active inference. A system engaged in active inference does two things: it updates its internal states to minimize prediction error (perceptual inference) and it acts on its environment to make sensory input conform to its predictions (active inference proper). Both require thermodynamic work — maintaining the Markov blanket, writing and refreshing internal states, acting on the environment — and hence sustained dissipation.

Quantum FEP. Fields et al. (2022) reformulate the FEP in spacetime-background-free quantum information theory, identifying Markov blankets with holographic screens and showing that agents deploying QRFs to characterize environmental states can be described as performing active inference. Their framework uses category-theoretic tools (cone-cocone diagrams, channel theory) and operates at a high level of generality.

2.5 The gap this paper fills

The companion papers establish formal results about proper-time emergence and the epistemic arrow within the PW/RAQ framework. The QRF literature provides the broader context of relational quantum mechanics and observer-dependent descriptions.

The FEP literature provides a general framework for understanding self-maintaining systems. Fields et al. (2022) connect the QRF and FEP programs at an abstract level.

What remains to be developed is the connection between these programs at the level of the specific PW/RAQ construction — with its explicit Hilbert spaces, admissibility conditions, record algebras, and proved proper-time uniqueness. The present paper fills this gap. It shows that the PW/RAQ machinery provides a concrete realization of the abstract QRF/Markov-blanket identification, and that this realization adds the epistemic arrow, the retrodictive structure, the Boltzmann brain dissolve, and empirical protocols that the abstract framework does not provide. Quantum Reference Frames

3 The Core Identification: Markov Blankets as Quantum Reference Frames

3.1 Two convergent programs

Two research programs, developed largely independently, have arrived at strikingly parallel accounts of what it takes for a physical system to constitute a bounded, persisting entity with a perspective on its environment.

The **quantum reference frames (QRF)** program, as developed by Höhn, Vanrietvelde, Giacomini, and collaborators, shows that in the absence of an external background, physical descriptions are always given relative to a choice of internal reference frame. A QRF defines a perspective from which observables, entanglement structure, and even subsystem decompositions are specified. The “perspective-neutral” formalism embeds all such perspectives within a single gauge-invariant Hilbert space (the Dirac-quantized physical Hilbert space $\mathcal{H}_{\text{phys}}$), and frame perspectives correspond to gauge choices and associated reduced Hilbert spaces (Vanrietvelde et al. 2020; de la Hamette and Galley (2020)). Crucially, recent work demonstrates that different QRF choices yield different observable algebras — and hence different entropies — making gravitational entropy itself observer-dependent (De Vuyst et al. (2025)).

The **Free Energy Principle (FEP)**, as developed by Friston and collaborators, characterizes persistent, identifiable systems as those possessing a Markov blanket — a statistical boundary that renders internal states conditionally independent of external states. Under the FEP, such systems behave as if minimizing variational free energy, which can be read as Bayesian prediction error. The blanket’s sensory states mediate inward information flow and its active states mediate outward influence, and the system’s persistence requires ongoing thermodynamic work to maintain this boundary against environmental perturbation (Friston, 2019; Kirchhoff et al., 2018).

Fields et al. (2022) have already made a significant step toward unifying these pro-

grams by reformulating the FEP in spacetime-background-free quantum information theory, showing that the Markov blanket can be identified with a holographic screen across which two systems exchange classical bits, and that agents are systems that deploy QRFs to assign operational semantics to measurement outcomes. Our contribution here is different in character: rather than reformulating the FEP in quantum-theoretic language from the top down, we show that the specific formal machinery developed in the companion papers (Anonymous, 2025b,a) — the PW/RAQ construction, admissibility conditions, record algebras, and the epistemic arrow — provides a *concrete realization* of the Markov-blanket-as-QRF identification, and that this realization adds something the existing literature lacks: a thermodynamically grounded account of temporal experience and the retrodictive structure of the past.

3.2 The structural correspondence

We now state the core identification and then unpack its content.

Claim (Structural correspondence). The Markov blanket of an observer-system under the FEP and the quantum reference frame of that system under the PW/RAQ construction are two descriptions — statistical-thermodynamic and quantum-informational, respectively — of the same physical structure: the boundary that constitutes the observer as a bounded, record-keeping, temporally extended entity.

The correspondence has three layers.

3.2.1 Layer 1: Boundary constitution

Under the FEP, the Markov blanket defines what counts as “internal” and “external” for a given system. It is not a spatial boundary in the first instance but an informational one: it specifies the conditional independence structure that makes the system identifiable as a thing distinct from its environment.

Under the PW/RAQ construction, the observer’s internal degrees of freedom (\mathcal{H}_{int}) are distinguished from the external sector (\mathcal{H}_{ext}) and the COM degrees of freedom (\mathcal{H}_{cm}), with the single first-class constraint \hat{C} coupling internal energy to inertial mass. The observer is constituted as a reference frame precisely by this decomposition: it is the system whose internal degrees serve as a clock and whose record algebra $\mathcal{R}(\tau)$ encodes information about the external sector.

These are the same boundary. The Markov blanket’s sensory states correspond to the information channels through which the record algebra is updated (new records are written via interaction with the external sector). The active states correspond to the observer’s capacity to affect the external sector — to prepare states, to move, to act — which is what sustains the nonequilibrium conditions required for continued record

formation. The internal states are precisely those encoded in the record algebra itself: the observer’s model of its world, realized as physically maintained reliable records.

3.2.2 Layer 2: Maintenance as admissibility

The most substantive part of the correspondence concerns the relationship between the FEP’s active inference (the ongoing process of maintaining the Markov blanket) and the observer viability conditions (C1)–(C5) from the companion technical note—so called because each encodes a minimal requirement that any temporally extended, record-keeping observer must satisfy (see Remark 1 in the companion note for detailed motivation and counterexamples). We argue that sustained active inference maintains the physical regime in which the viability conditions are dynamically stable. Section 4 develops this argument condition by condition; here we highlight the connection that is most directly visible at the level of the structural correspondence.

(C1) Lorentz-scalar completeness admits a particularly transparent reading through the correspondence. The observer’s internal record variables constitute a frame-invariant sufficient statistic for the blanket-mediated interaction between internal and external sectors. In the PW/RAQ construction, the clock/record variables are Dirac observables defined on the physical Hilbert space. Scalarity means that these observables transform as Lorentz scalars — equivalently, they are functions of invariant quantities on the mass shell — so that their informational content does not depend on the choice of quantum reference frame. Frame changes may relabel or re-express the variables, but they do not alter the information they encode.

Completeness admits an operational interpretation: the record algebra $\mathcal{R}(\tau)$ is informationally complete for the observer’s conditional state assignment. Conditioning on the internal record variables suffices to determine the observer’s predictive interface with its environment; no further internal coarse-graining preserves the same predictive power. In information-theoretic terms, the record variables form a minimal sufficient statistic for the blanket-mediated channel linking external states to internal updates.

Note that the Markov blanket’s conditional independence condition (internal \perp external | blanket) is formally analogous to the PW conditioning operation itself: conditioning on the clock/record variables renders the reduced dynamics independent of the external sector except through the information encoded in those variables. The PW conditioning plays the same structural role as the informational shielding that the Markov blanket provides.

Thus the Markov blanket’s coordinate-free conditional-independence structure maps onto Lorentz-scalar completeness in the PW/RAQ framework: both assert that what defines the system as an observer is not a coordinate location but an invariant informational boundary. The scalar condition ensures that this boundary encodes only frame-

independent content; completeness ensures that it encodes all the content required to sustain a well-defined internal perspective.

The remaining admissibility conditions — calibration (C2), self-adjoint reduced dynamics (C3), regular gauge (C4), and monotonicity (C5) — each admit analogous readings through the correspondence. In each case, the physical content of the condition (tracking environmental statistics, maintaining internal coherence, sustaining nondegenerate clock flow, funding directed record growth) corresponds to a specific aspect of active inference (prediction-error minimization, blanket integrity, sustained engagement, dissipative maintenance). Rather than sketching these connections here, we develop them in detail in Section 4, where we identify the specific active-inference preconditions that maintain each admissibility condition and specify where the arguments are structural and where formal tightening is needed.

3.2.3 Layer 3: Meetings and intersubjectivity

The meeting POVM and inter-observer isometry (Section 5 of the companion technical note) enforce intersubjective agreement at reunion events: when two observers meet, their perspective-relative state assignments must agree on the overlap algebra of shared observables.

Under the FEP, two systems interact through their respective Markov blankets: the active states of one impinge on the sensory states of the other. Intersubjective agreement emerges when the two systems’ internal models converge on shared environmental regularities — when their generative models become mutually consistent on the domain of their interaction.

The meeting isometry formalizes this: it is the quantum-informational version of two active-inference agents achieving alignment at their boundary. The Born-rule coherence lemma (Eq. 8 of the companion note) — that Born probabilities agree on the overlap algebra — is the formal content of what the FEP literature calls “generalized synchrony” between coupled systems. The networked-observer construction (Section 7 of the companion paper), in which observers connected by a reunion graph develop a shared subalgebra whose information content is nondecreasing, is the record-theoretic realization of multi-agent active inference in a shared environment.

3.3 What the identification adds

The [Fields et al. \(2022\)](#) quantum FEP works at a high level of abstraction, using category-theoretic tools (cone-cocone diagrams, channel theory) to establish the structural equivalence of QRFs and Markov blankets in full generality. Our contribution is complementary rather than competing. We add:

1. **A specific physical realization.** The PW/RAQ construction provides a concrete model in which the clock is the observer’s internal degrees of freedom, the constraint is the mass-shell condition coupling internal energy to inertial mass, and the relational parameter is proved (not merely postulated) to be proper time. This grounds the abstract QRF/Markov-blanket identification in a specific physical setting with explicit Hilbert spaces, operators, and domains.
2. **The epistemic arrow.** The abstract quantum FEP does not distinguish past from future: it describes how a system maintains its boundary, but the temporal directionality is not foregrounded. Our record-algebra construction provides this: the inclusion order $\mathcal{R}(\tau_1) \subseteq \mathcal{R}(\tau_2)$ for $\tau_1 \preceq \tau_2$, funded by dissipation, is the epistemic arrow that gives temporal experience its directed character. The Markov blanket maintains the system; the record algebra gives the system a *history*.
3. **Retrodictive structure.** The retrodictive sufficiency argument — that present reliable records sharply constrain the set of compatible past histories, and that the ubiquity of such records requires a Past-Hypothesis-type boundary — has no analogue in the existing quantum FEP literature. It connects the observer-as-QRF to cosmological boundary conditions in a way that neither the QRF program nor the FEP program has articulated independently.
4. **Empirical protocols.** The companion papers provide specific experimental protocols (gravitational redshift, kinematic QRF variants, information-engine platforms) that test the framework’s predictions about the relationship between dissipation, proper time, and record growth. These give the identification empirical traction that the more abstract formulations currently lack.

3.4 A note on scope and honesty

The correspondence argued for here is a structural one. We claim that the FEP’s Markov blanket and the PW/RAQ framework’s admissible QRF describe the same physical structure at different levels of description, and that connecting them illuminates both. We do not claim a formal proof of equivalence — such a proof would require showing that every system satisfying the FEP conditions also satisfies (C1)–(C5) and conversely, which is beyond the scope of this paper given the different mathematical frameworks involved (stochastic dynamics for the FEP; constrained Hilbert-space quantization for PW/RAQ).

What we do claim is that the correspondence is not merely analogical. The same physical requirements appear in both frameworks — boundary maintenance, calibration, dissipation, temporal ordering — and they appear for the same physical reasons: because being an observer is thermodynamic work. The two formalisms arrive at the same con-

clusion from different starting points, and their conjunction is more powerful than either alone.

The ontological status of Markov blankets in the FEP has been debated, with critics arguing that the blanket partition functions more as a modeling assumption than an explanatory principle (Raja et al. (2021)). In the present framework, however, the relevant boundary is not postulated as a modeling choice but is constituted by the constraint structure of the PW/RAQ construction: the observer’s internal degrees are distinguished from the external sector by the mass-shell constraint, and the record algebra is defined by the operational conditions for reliable information storage under dissipation. The blanket, on this account, is earned rather than assumed.

4 From Active Inference to Admissibility

4.1 The direction of the argument

Section 3 argued that the admissibility conditions (C1)–(C5) and the requirements of active inference under the FEP describe the same physical structure from different formal vantage points. Here we sharpen that claim by arguing for the following conditional: if a system is engaged in sustained active inference — maintaining its Markov blanket by minimizing variational free energy over macroscopic timescales — then it preserves the physical regime in which the admissibility conditions (C1)–(C5) are dynamically stable. That is, active inference does not *produce* admissibility from scratch but *maintains* the conditions under which admissibility, as established by the PW/RAQ construction, continues to hold.

This is a weaker claim than “active inference implies admissibility,” but it is the honest one. The admissibility conditions are structural features of the PW/RAQ framework — they characterize what it takes for an internal clock to yield proper-time parameterization. Active inference is what keeps a physical system in the domain where those structural features apply: nonequilibrium, nondegenerate internal energy, bounded noise, sustained dissipation. A system that ceases to perform active inference drifts out of this domain, and the admissibility conditions degrade.

The argument proceeds in two stages. First, we identify the physical preconditions that active inference requires of any system that instantiates it. Second, we show that these preconditions maintain the physical regime in which each admissibility condition holds. The argument is structural in this draft; we indicate where formal tightening is needed and what form it would take.

4.2 What active inference requires

A system engaged in active inference, in the sense of [Friston \(2019\)](#) and the quantum reformulation of [Fields et al. \(2022\)](#), must satisfy the following physical preconditions. These are not axioms of the FEP but physical conditions that any real system must meet in order for the FEP formalism to apply non-vacuously:

(AI-1) Persistent separability. The system must remain identifiable as a bounded entity over timescales long compared to its internal dynamics. This means that the system-environment decomposition (the Markov blanket partition) is not instantaneous or accidental but is actively maintained. In quantum-theoretic terms, the system must maintain approximate separability from its environment — the joint state cannot become maximally entangled across the blanket, or the distinction between internal and external sectors dissolves.

(AI-2) Dissipative maintenance. Maintaining the blanket requires thermodynamic work. The system must continuously expend free energy to preserve its internal organization against entropic degradation — noise, thermal fluctuations, decoherence. This is not an incidental feature but constitutive: a system that ceases to dissipate ceases to maintain its blanket and ceases to be an identifiable thing. The dissipation rate must, on average, exceed the rate at which environmental perturbation degrades the blanket’s integrity.

(AI-3) Predictive coherence. The system’s internal states must encode a generative model — a probabilistic model of the causes of its sensory states — that is sufficiently coherent to support prediction. “Coherence” here means that the internal dynamics are structured enough to generate expectations about future sensory states on the basis of past and present ones. This requires, at minimum, that internal states have stable temporal correlations: the system must be able to “remember” enough of its recent trajectory to generate nontrivial predictions.

(AI-4) Directed updating. The system must update its internal states in response to prediction errors in a way that is temporally directed — new information refines the model going forward, not backward. This is the sense in which active inference is inherently asymmetric in time: sensory evidence from the past updates beliefs about the future, not vice versa. At the physical level, directed updating requires the capacity to write new records without destroying old ones — precisely the dissipation-funded record growth described in the companion philosophy paper.

(AI-5) Active environmental coupling. The system must be capable of acting on its environment — not merely passively receiving sensory data. Active states allow the system to sample its environment selectively (epistemic action) and to change environmental states to conform to its predictions (pragmatic action). This coupling must be sustained; a system that becomes decoupled from its environment can neither update

its model nor maintain its blanket.

4.3 The derivation (structural)

We now show that (AI-1)–(AI-5) jointly maintain the physical regime in which (C1)–(C5) are dynamically stable.

4.3.1 (AI-1) + (AI-3) \Rightarrow (C1): Scalar completeness

Persistent separability (AI-1) requires that the system-environment boundary is maintained as a well-defined informational partition. Predictive coherence (AI-3) requires that the internal states on the system side of this partition encode sufficient information to generate predictions about the external sector.

Together, these require that the observer possesses a set of internal observables that (a) are well-defined on the physical (constraint-reduced) Hilbert space — since they must be invariant under gauge transformations to have physical content — and (b) are informationally complete for the observer’s conditional state assignment. As argued in Section 3.2 (Layer 1), this is precisely Lorentz-scalar completeness: the record variables are Dirac observables forming a minimal sufficient statistic for the blanket-mediated channel.

The key physical point is that uncontrolled frame-dependence of the record variables — dependence not absorbed by the QRF transformation rules — would undermine predictive coherence. If the informational content of the observer’s internal states changed under a passive coordinate transformation, the observer’s predictions would be frame-dependent in a way that has nothing to do with the environment — which would violate the requirement that internal states track external states through the blanket. Scalarity ensures that the observer’s model is about the world, not about the choice of description.¹

4.3.2 (AI-2) + (AI-4) \Rightarrow (C5): Monotonicity

This is the most physically transparent part of the argument, though a subtlety about scales must be addressed.

Dissipative maintenance (AI-2) ensures positive average dissipation: $\dot{Q}_{\text{diss}}(\tau) > 0$ over intervals of interest. Directed updating (AI-4) ensures that this dissipation funds the creation and maintenance of new reliable records rather than merely maintaining existing ones in a static configuration. Together, they yield the conditions of Proposition 3.2 of the companion philosophy paper: the expected information content $E[I_{\mathcal{R}}(\tau)]$ of

¹The descent of frame-invariant predictive statistics to Dirac observables requires showing that the observer’s predictive interface — the sufficient statistic for the blanket-mediated channel — is composed of quantities invariant under gauge transformations generated by \hat{C} . This likely follows from the PW conditioning map projecting onto the constraint surface, so that operationally accessible quantities are automatically Dirac observables.

the record algebra is nondecreasing, and the inclusion order $\mathcal{R}(\tau_1) \subseteq \mathcal{R}(\tau_2)$ for $\tau_1 \preceq \tau_2$ is maintained in expectation.

However, expectation monotonicity does not automatically imply pointwise monotonicity. Individual record-creation events are stochastic; on timescales comparable to device cycle times, fluctuations may temporarily violate the inclusion order (a record may be corrupted before being refreshed). Strict monotonicity of the clock in the sense of (C5) is therefore a coarse-grained statement: it holds on timescales larger than the fluctuation scales set by the dissipation rate, where the law-of-large-numbers regime applies and the expected growth dominates over fluctuations.

This is not a weakness but a feature. It makes precise the sense in which the epistemic arrow — and with it, the observer’s temporal experience — is a macroscopic, thermodynamic phenomenon. On sufficiently short timescales, the arrow is noisy; on macroscopic timescales, it is robust. Active inference maintains the dissipation rate in the regime where the coarse-grained monotonicity is stable: if the dissipation rate drops below the threshold needed to fund record maintenance (the Landauer bound for the refresh cycle), monotonicity degrades and the epistemic arrow weakens.

The thermodynamic incoherence argument reinforces this at the coarse-grained level: a system cannot simultaneously maintain its blanket (forward dissipation) and systematically destroy records in a time-reversed pattern (which would require oppositely directed dissipation). The system’s net dissipation has a single sign on macroscopic timescales; the clock inherits that sign as coarse-grained monotonicity.²

4.3.3 (AI-3) \Rightarrow (C2): Calibration

Predictive coherence (AI-3) requires that the system’s internal model tracks environmental statistics reliably enough to generate predictions with bounded error. In stationary or static environments — the regimes where (C2) applies — this means the internal clock must tick at a rate that bears a stable relationship to the external dynamics. If the clock drifts unpredictably relative to the environment, prediction errors grow without bound, variational free energy increases, and the system’s active inference fails.

Calibration in the PW/RAQ sense — that $d\Theta/dt = \kappa N(\mathbf{x})$ for stationary worldlines — is the formal expression of this tracking requirement. The factor $N(\mathbf{x})$ is the gravitational redshift factor; that it appears in the calibration condition reflects the physical fact that clocks in different gravitational potentials tick at different rates, and an observer’s internal clock must respect this if its predictions about locally measured quantities are to be accurate.

Active inference enforces calibration dynamically: a miscalibrated clock generates

²The crossover timescale can be quantified using Thermodynamic Uncertainty Relations (Barato and Seifert (2015); Horowitz and Gingrich (2020)), which bound the variance of record-creation counts at fixed dissipation. This sets a fluctuation timescale τ_{fluct} ; (C5) holds robustly for $\Delta\tau \gg \tau_{\text{fluct}}$.

systematic prediction errors (sensory data arrive earlier or later than expected), which drive corrective updates to the clock rate. This is a specific instance of the general FEP mechanism: persistent prediction error triggers model revision. Calibration is thus not a static initial condition but the outcome of an ongoing active-inference process — the system learns to tick correctly by correcting its errors.³

4.3.4 (AI-1) + (AI-3) \Rightarrow (C3): Unitarity (self-adjoint reduced dynamics)

Persistent separability (AI-1) requires that the observer’s internal dynamics are shielded from uncontrolled environmental influence — this is the physical content of the Markov blanket. Predictive coherence (AI-3) requires that the internal dynamics are structured enough to support inference.

The companion technical note establishes essential self-adjointness of \hat{C} and the reduced generators on the common invariant core $\mathcal{D}_0 = \mathcal{S}(\mathbb{R}^3)_{\text{cm}} \otimes \text{Dom}(\hat{H}_{\text{int}}) \otimes \text{Dom}(\hat{H}_{\text{ext}})$, using Nelson’s analytic vector theorem and Kato–Rellich perturbation theory, under assumptions (A1)–(A4): static background with $N(\mathbf{x})$ bounded away from zero, relative boundedness of \hat{H}_{int} and \hat{H}_{ext} , polynomially bounded commutators, and compact energy support. Essential self-adjointness is a statement about domain closure and deficiency indices — it guarantees a unique self-adjoint extension — and it is not a small-perturbation property that can be assured merely by keeping dephasing small.

The role of active inference here is not to *ensure* essential self-adjointness but to *maintain the physical regime in which the conditions (A1)–(A4) continue to hold*. Specifically:

- (A2) requires that \hat{H}_{int} is relatively bounded with respect to the kinetic term with small relative bound. A system whose internal energy spectrum becomes unbounded or whose coupling to external fields grows without limit violates this condition. Active inference, by maintaining the Markov blanket, keeps the internal-external coupling mediated and bounded — the blanket is precisely the structure that prevents runaway coupling.
- (A4) requires compact energy support for the external sector. A system that has lost its blanket integrity — that has become maximally entangled with an arbitrarily energetic environment — may violate this. Active inference maintains the separation between internal and external sectors that keeps the external sector’s effective energy bounded from the observer’s perspective.
- The static background assumption (A1) is maintained in the sense that the observer’s local environment remains well-modeled by the static approximation on

³The relationship between prediction-error minimization and clock-rate stability may connect to the Allan deviation analysis in the companion technical note: the noise models (white FM, flicker FM, random-walk FM) describe the kinds of clock drift that active inference must correct, and the dephasing they induce (Eqs. 9–10) sets limits on how well calibration can be maintained.

the timescales of the internal clock dynamics: fluctuations in the local geometry are small relative to the background curvature scale, and the observer’s COM remains localized within a region where $N(\mathbf{x})$ is smoothly varying and bounded away from zero. Active inference maintains this locally well-modeled regime by keeping the system in a bounded, nonequilibrium steady state — not by controlling the background geometry, but by keeping the observer within the domain where the static approximation is valid.

The honest summary is: essential self-adjointness is established mathematically under (A1)–(A4); active inference maintains the physical conditions under which (A1)–(A4) remain valid descriptions of the observer’s situation. When active inference fails — when the blanket degrades and the observer ceases to be a well-defined bounded system — the assumptions underlying (C3) may cease to hold, and the reduced dynamics may lose their unitary character.⁴

4.3.5 (AI-1) + (AI-5) \Rightarrow (C4): Regular gauge

The clock gauge $\chi : \hat{T}_{\text{int}} - \hat{\Theta} = 0$ is regular when the Faddeev–Popov determinant $\Delta_{\text{FP}} = (i\hbar)^{-1}[\chi, \hat{C}]$ is nonvanishing on the massive sector. The commutator $[\chi, \hat{C}]$ vanishes precisely when the clock flow stalls — when the gauge-fixing surface becomes tangent to the constraint surface, so that the clock reading ceases to change along the dynamical flow generated by \hat{C} . Gauge regularity is therefore equivalent to the condition that the observer’s internal clock does not stall: $[\chi, \hat{C}] \neq 0$.

Active inference directly maintains this non-stalling condition. A system engaged in active inference is, by definition, continuously updating: it receives sensory data, generates predictions, computes prediction errors, and revises its internal model. This cycle of update constitutes the clock’s “ticking” — each cycle advances the internal state and hence the clock reading. A clock that stalls is a system that has ceased to update, which means it has ceased to perform active inference. The two failures are the same failure.

More precisely: persistent separability (AI-1) ensures that the observer remains a massive, localized system with a well-defined COM worldline — the massive sector on which the companion technical note establishes $\Delta_{\text{FP}} > 0$. Active environmental coupling (AI-5) ensures that the observer remains dynamically engaged — its internal degrees continue to evolve in response to environmental interaction, which is what keeps the

⁴The connection between blanket integrity and the maintenance of (A1)–(A4) deserves more precise statement. In particular, (A2)’s relative-boundedness condition should be connected to the blanket’s role in bounding the effective interaction strength between internal and external sectors. The dephasing analysis (Section 6 of the companion note) quantifies the departure from unitarity when clock noise is present; the claim is that active inference keeps the noise within the regime where dephasing corrections are perturbative.

clock flow from stalling. A system that decouples from its environment (loss of AI-5) or loses its boundary integrity (loss of AI-1) may develop gauge irregularities: the clock stalls because the system has stopped processing information.

The connection is direct: the Faddeev–Popov determinant measures the rate at which the clock advances along the constraint flow; active inference maintains a nonzero rate of internal updating; therefore active inference maintains $\Delta_{\text{FP}} \neq 0$.⁵

4.4 The composite picture

Taken together, the five arguments yield the following conditional:

If a physical system maintains a Markov blanket through sustained active inference — persistent separability, dissipative maintenance, predictive coherence, directed updating, and active environmental coupling — **then** it maintains the physical regime in which the admissibility conditions (C1)–(C5) are dynamically stable. By Theorem 1 of the companion technical note, the relational parameter selected by conditioning on such a system’s internal clock is the system’s COM proper time (up to monotone reparametrization), and by Proposition 3.2 of the companion philosophy paper, the epistemic arrow (record-algebra inclusion order) is robust on coarse-grained timescales.

The philosophical consequence is notable: **proper time is not a geometric given that observers passively inherit from spacetime; it is a thermodynamic achievement that observers actively maintain.** A system that ceases to perform active inference — that ceases to dissipate, to predict, to update, to act — drifts out of the regime in which admissibility holds. Its internal clock degenerates, its record algebra stagnates, and the epistemic arrow weakens. The system may still exist as a physical configuration, but it no longer constitutes an observer with a robust temporal perspective.

This does not mean that proper time is subjective in the pejorative sense — it is not arbitrary or merely apparent. It is intersubjectively constrained by the meeting isometry (Section 5 of the companion technical note) and empirically accessible through the protocols described in Section 8 of the companion philosophy paper. But it is *constituted* by the observer’s self-maintaining activity, not merely *parameterized* by it.

⁵A quantitative bound relating the minimum dissipation rate (or active-inference update rate) to a lower bound on $||[\chi, \hat{C}]||$ would make the connection between non-stalling flow and active inference precise. The companion note shows $\Delta_{\text{FP}} > 0$ on the massive sector for free SR and static backgrounds; the claim is that active inference sustains the internal energy flux that keeps the clock dynamically coupled to the constraint.

4.5 Relationship to the [Fields et al.](#) quantum FEP

The argument of this section can be situated relative to the quantum FEP of [Fields et al. \(2022\)](#) as follows. [Fields et al.](#) show, at a high level of abstraction, that any system deploying QRFs to identify and characterize environmental states can be described as performing active inference. Their argument runs from QRFs to active inference — roughly, the converse direction to ours.

The two arguments are complementary, not competing. Together they suggest a close relationship — perhaps a biconditional under suitable conditions — between active-inference agency and admissible quantum reference frames. But the two arguments operate at different levels of specificity. [Fields et al.](#) work with generic quantum systems, holographic screens, and category-theoretic tools; we work with a specific PW/RAQ construction, explicit Hilbert spaces, and physically realizable clock models. The conjunction provides both the generality of the abstract argument and the physical concreteness of the specific construction.

There is also a substantive difference in what the two directions of the argument illuminate. The [Fields et al.](#) direction (QRF \Rightarrow active inference) shows that deploying a QRF can always be *read as* active inference — it gives an inferential interpretation of quantum measurement. Our direction (active inference \Rightarrow maintenance of admissibility) shows that active inference *maintains* the physical conditions for proper-time emergence — it grounds temporal experience in thermodynamic self-maintenance. The former is an interpretive result; the latter is a constitutive one.

5 Implications for the Epistemic Arrow

5.1 The epistemic arrow reconsidered

The companion philosophy paper establishes a cascade:

Past Hypothesis \Rightarrow Local Thermodynamics (typicality/ETH) \Rightarrow Epistemic Arrow in Proper Time.

A cosmological low-entropy boundary makes local nonequilibrium generic; nonequilibrium sustains the free-energy throughput that funds reliable record creation and maintenance; and on the proper-time parameter selected by PW/RAQ, this yields a directed epistemic arrow — the inclusion order of the record algebra $\mathcal{R}(\tau_1) \subseteq \mathcal{R}(\tau_2)$ for $\tau_1 \preceq \tau_2$.

That argument is self-contained: it requires no appeal to active inference, Markov blankets, or the FEP. The cascade holds for any system satisfying the admissibility conditions in a regime of sustained dissipation. The formal results — Proposition 3.2, the Fano bound, the selection bound — stand on their own, assuming positive average dissipa-

tion over coarse-graining windows and maintenance within tolerances, with the PW/RAQ admissibility theorem as input.

What does the Markov-blanket/QRF identification developed in Sections 3–4 add? Not new mathematics, but a richer explanatory structure. The companion paper already gestures toward this: “observers are not passive: the energy budgets that sustain their memories are part of what makes temporal experience emerge in proper time.” The present section cashes that out. Specifically, we argue the identification adds three things: (i) a deeper grounding of the cascade’s middle link, transforming throughput from a background condition into an agentive achievement; (ii) a sharpened account of the retrodictive structure, connecting record reliability to active maintenance and prediction; and (iii) a natural explanation of why the epistemic arrow is robust under perturbation, grounded in the self-stabilizing dynamics of the Markov blanket.

5.2 Grounding the middle link: from throughput to agency

Subclaim (i): The FEP transforms the cascade’s middle link from a background condition into an agentive achievement, and adds a control-theoretic account of how throughput is allocated.

The middle link of the cascade — that local thermodynamic nonequilibrium sustains the free-energy throughput funding record growth — is stated in the companion paper as a physical fact about the observer’s environment. The active-inference framing transforms this from a passive fact into an agentive one. Under the FEP, the observer does not merely *happen* to be embedded in a dissipative regime; it *actively maintains* its nonequilibrium condition. The Markov blanket is a boundary the observer sustains through thermodynamic work; record growth is something the observer *does* — the directed updating (AI-4) that constitutes the active-inference cycle. The environment provides the free-energy gradient; the observer exploits it to build and maintain records. Both are necessary; neither alone is sufficient.

This reframing does not change the formal results — Proposition 3.2 holds regardless of whether dissipation is “agentive” or “passive” — but it changes the explanatory structure and adds concrete content. The direction of time is not merely the direction in which observers happen to accumulate records; it is the direction in which self-maintaining systems *must*, given sustained active inference under positive dissipation, accumulate records in order to persist. An observer that failed to grow its record algebra in the direction of increasing entropy would be failing to track its environment — failing to predict, failing to update — and would, under the FEP, be in the process of dissolution.

Crucially, the FEP layer adds something the thermodynamic account alone does not: a control-theoretic story for how throughput is *allocated* between maintenance of existing records and expansion via new ones, not merely that throughput exists. The companion

paper’s selection bound (Eq. 5) constrains the total record growth by the entropy budget; the active-inference framing explains how that budget is distributed — the system allocates resources to refresh and error-correct existing records (maintaining (ε, L) -reliability) and to write new ones (expanding $\mathcal{R}(\tau)$), regulated by the prediction-error dynamics of the generative model. This regulation is what Section 5.4 will identify as the source of the arrow’s robustness.

5.3 Retrodictive structure sharpened

Subclaim (ii): The active-inference framing clarifies reliability as active maintenance and connects retrodiction to the structure of the generative model.

The companion paper’s retrodictive sufficiency argument holds that present reliable records sharply constrain the set of compatible past histories, and that the ubiquity of such records requires a Past-Hypothesis-type low-entropy boundary. The Fano inequality bound (Eq. 1–2 of the companion paper) gives this quantitative content: achieving retrodictive error $\leq \delta$ requires mutual information $I(H; \hat{R}_\tau)$ exceeding an explicit threshold. The active-inference framing sharpens this in two ways.

First, it clarifies what makes records “reliable” in the operational sense. The (ε, L) -reliability condition is not a static property but a maintenance commitment: the system must allocate dissipative resources to refresh, error-correct, and protect its records against noise. The retrodictive sharpness of the present — the degree to which current records constrain the past — is therefore constrained, and often limited, by the observer’s dissipation budget allocated to refresh and error correction. This is a quantitative relationship mediated by the Landauer bounds and TUR constraints developed in the companion paper, though it takes the form of bounds rather than a strict monotone functional dependence.

Second, under the active-inference reading, retrodiction can be understood as a natural consequence of the generative model’s structure: a model that accurately predicts future sensory states on the basis of current records *ipso facto* constrains the past states that could have produced those records. The retrodictive sufficiency of the present is the temporal mirror of the predictive adequacy of the generative model. (This is an interpretive mapping rather than a result derived in the companion paper, which stays in terms of histories, records, priors, and MI thresholds.) The epistemic arrow — the direction in which records accumulate — is the same as the direction in which prediction errors are resolved. The past is sharp because it is the direction from which evidence has been collected and consolidated; the future is open because prediction errors have not yet been resolved. Both the fixity of the past and the openness of the future are perspectival features arising from the observer’s position as an active-inference agent embedded in an entropy gradient.

5.4 Robustness of the epistemic arrow

Subclaim (iii): The self-stabilizing dynamics of the Markov blanket explain the arrow’s persistence through disruption and its failure under dissolution.

A feature of the epistemic arrow that the companion paper notes but does not fully explain is its robustness. The arrow persists through sleep, distraction, illness, and other disruptions to the observer’s cognitive function. Records degrade (we forget), but the arrow itself — the directed accumulation of information over macroscopic timescales — is remarkably stable.

The active-inference framing provides a natural explanation. The Markov blanket is a self-stabilizing structure: perturbations that degrade the blanket increase variational free energy, which drives corrective action (or, failing that, dissolution). The epistemic arrow inherits this self-stabilizing character. Disruptions to record growth — noise events, metabolic dips, environmental shocks — are precisely the kinds of perturbations that active inference is designed to correct. The system responds to record degradation by allocating additional resources to maintenance (if available) or by accepting graceful degradation within tolerances.

This explains the difference between temporary disruptions and catastrophic failures. Sleep suspends active updating but maintains the record algebra within tolerances (the (ϵ, L) -reliability condition continues to hold because the memory substrate remains energized and thermally stable). General anesthesia suppresses updating more deeply but still preserves the physical substrate of records. These are instances of the companion paper’s “localized forgetting events whose total contribution over any interval is bounded by the integrated deficit of dissipation relative to the minimal maintenance cost” — disruptions that the framework explicitly accommodates rather than treats as counterexamples.

Death — the permanent loss of the organized maintenance regime — is the point at which the Markov blanket dissolves, the record algebra ceases to be actively maintained, and the epistemic arrow ceases to exist for that observer. (Note: what ends is not dissipation per se — dead bodies continue to dissipate heat — but the *organized, directed* maintenance cycles that sustain record reliability and fund record growth.)

The robustness of the arrow is thus explained by the robustness of the Markov blanket, which is in turn explained by the self-stabilizing dynamics of active inference. The arrow is not fragile because maintaining it is not an optional activity for a self-maintaining system — it is constitutive of being such a system.

5.5 The arrow without consciousness

A methodological point deserves emphasis. The epistemic arrow as developed here — and in the companion papers — does not require consciousness. It requires record formation, dissipation, and the maintenance of a Markov blanket, but not phenomenal experience. A

sufficiently complex artificial system maintaining reliable records through active inference would possess an epistemic arrow in exactly the record-algebra sense described here, without any commitment to its being conscious.

This is a feature, not a limitation. The framework explains the *direction* of temporal experience without presupposing the *existence* of temporal experience. Consciousness, on this account, may add qualitative character to the epistemic arrow — the felt sense of time passing, the phenomenal distinction between remembering and anticipating — but the arrow itself is a thermodynamic-informational structure that exists wherever the relevant conditions are met.

This positions the framework carefully between two extremes. It avoids the panpsychist implication that every dissipative system is conscious, while also avoiding the eliminativist implication that the arrow of time has nothing to do with observers. The arrow is observer-relative (it is defined by the record algebra of a specific system maintaining a specific Markov blanket) without being consciousness-dependent (it does not require that system to be phenomenally aware).

The companion paper’s scope statement — “no appeal to consciousness is required” — is therefore not merely a methodological disclaimer but a substantive claim about the explanatory structure. The epistemic arrow is grounded in thermodynamics and information theory, not in phenomenology. If consciousness is to be connected to this framework, it must be connected *to* the epistemic arrow, not presupposed *by* it. This is the space that the broader metabolic idealism program occupies — but the present paper need not enter it.

6 Dynamic Spacetimes and Relaxation of the Static Assumption

6.1 The limitation and its significance

The companion technical note establishes its results — the proper-time uniqueness theorem, the admissibility conditions, the meeting POVM — under the assumption of a static background spacetime (a global timelike Killing field with lapse function $N(\mathbf{x})$ bounded away from zero). This assumption is stated explicitly and its scope is clearly delimited: it covers essentially all current earth-bound metrological settings but fails for genuinely dynamical regimes — cosmological expansion, binary inspirals, gravitational-wave backgrounds — or when backreaction cannot be neglected.

This limitation matters because the philosophical claims of the framework — that the epistemic arrow is grounded in the observer’s self-maintenance, that proper time is a thermodynamic achievement, that retrodictive sufficiency requires a Past-Hypothesis-

type boundary — are intended to be general. If they depend essentially on a static background, they are limited to a narrow (if empirically accessible) corner of physics. The retrodictive necessity argument, in particular, invokes cosmological boundary conditions, yet the formal machinery that supports it is restricted to static spacetimes. There is a gap between the scope of the philosophy and the scope of the proofs.

The active-inference/Markov-blanket framing developed in Sections 3–4 suggests a strategy — not a solution, but a principled direction — for narrowing this gap. The strategy is not to replace geometry with self-organization, but to shift from *global* geometric symmetry assumptions (Killing structure, globally defined lapse) to *local*, observer-accessible regularity assumptions — and then to interpret those local regularities as maintained by self-organization when that interpretation is appropriate. If admissibility is maintained by active inference under local regularity conditions rather than guaranteed by a global Killing field, then the framework may extend to regimes where the Killing field is absent but the observer persists in a locally well-modeled environment.

This section is programmatic. We do not prove that the admissibility conditions hold in dynamic spacetimes; we argue that the active-inference grounding provides the right conceptual framework for pursuing such an extension, and we identify the specific technical obstacles that would need to be overcome.

6.2 What the static assumption actually does

It is worth being precise about which results depend on the static assumption and how.

Proper-time uniqueness (Theorem 1). Proper time along a worldline is always well-defined classically, even in dynamical spacetimes. What the static assumption provides is the calibration clause $d\Theta/dt = \kappa N(\mathbf{x})$ for stationary worldlines and the global scaffolding — a single, everywhere-defined lapse function — that the uniqueness proof exploits to collapse admissible clocks onto the COM proper-time scalar up to reparametrization. Without static symmetry, the simple calibration anchor is lost, and the tidy global structure that allows the proof to select proper time as the canonical representative after calibration is unavailable.

Essential self-adjointness (Appendix D). Assumption (A1) requires a static background with smooth $N(\mathbf{x})$ bounded away from zero. This enters the proof via Nelson’s analytic vector theorem and Kato–Rellich perturbation theory on the common core \mathcal{D}_0 . Two distinct obstacles arise in relaxing this. *First*, even within the single-constraint effective model, a non-static background introduces time-dependent conditioning maps and a family of reduced generators, complicating the domain analysis. *Second*, in full GR, the single first-class constraint is replaced by the Hamiltonian and diffeomorphism constraints, and the PW/RAQ construction does not straightforwardly generalize to multiple constraints. These are obstacles of different character and difficulty; the first is a

semiclassical problem, the second a quantum-gravity problem.

Meeting POVM (Section 5 of the companion note). The meeting construction uses the spectral measures of the two observers’ clocks and a Gaussian spatial smearing, with a COM boost map defined in a local inertial tetrad. The construction does not logically require a Killing field — every self-adjoint clock has a spectral measure — but staticity makes the spectral conditioning and calibration clean and provides a simple time-translation structure. In dynamical spacetimes, the conditioning maps may become state- or geometry-dependent, and the clock noise may itself depend on the evolving background, complicating the normalization and isometry construction.

Calibration (C2). The calibration condition $d\Theta/dt = \kappa N(\mathbf{x})$ for stationary world-lines explicitly references the lapse function of the static metric. Without a static metric, calibration must be reformulated — but calibration against *what*?

6.3 The active-inference strategy

The central observation is that none of the admissibility conditions, as physically motivated in Section 4, are *about* the background geometry. They are about the observer:

- (C1) requires that the observer possesses frame-invariant internal observables. This is a property of the observer’s record algebra, not of spacetime.
- (C2) requires that the observer’s clock tracks environmental statistics reliably. This is a property of the observer’s predictive model, not of a Killing field.
- (C3) requires that the observer’s reduced dynamics are well-defined. This is a property of the observer’s internal coherence, not of the background.
- (C4) requires that the observer’s clock does not stall. This is a property of the observer’s dynamical engagement with its environment, not of the metric.
- (C5) requires that the observer’s clock is monotone on coarse-grained timescales. This is a property of the observer’s dissipative record growth, not of the geometry.

In the companion technical note, these observer-properties are *proved* using properties of the background geometry (Killing fields, bounded lapse, static metric). The background geometry provides the mathematical scaffolding for the proofs. But the physical content of the conditions — what they demand of the observer — is independent of that scaffolding.

The active-inference strategy is to reformulate the admissibility conditions in terms of local, observer-accessible regularity conditions rather than global geometric symmetry, and then to show that these reformulated conditions are sufficient for proper-time emergence. Geometry still constrains what regimes are physically realizable; the claim is only that the *form* of the admissibility conditions is observer-level, while the technical proofs in the companion note use static symmetry as a convenient sufficient condition. Schematically:

Static-background version (companion note): Properties of static metric \implies admissibility conditions \implies proper-time uniqueness.

Active-inference version (proposed): Active inference plausibly maintains local regularity \implies reformulated admissibility conditions \implies proper-time emergence (possibly up to weaker uniqueness).

In a dynamical spacetime, we expect the static sufficient conditions in the companion note to be replaced by adiabatic or local stationarity conditions on the geometry over the observer’s prediction horizon — a standard intermediate between “static” and “fully general GR.” The active-inference contribution is to interpret those local conditions as maintained operationally by the blanket rather than granted globally by symmetry. The second arrow may yield a weaker result — uniqueness up to monotone reparametrization may be replaced by something like “well-defined proper time within the observer’s domain of causal influence” — but the essential content would be preserved: self-maintaining observers have a well-defined temporal parameter grounded in their metabolic activity.

6.4 Reformulating the conditions

We sketch how each admissibility condition might be reformulated without reference to a static background.

(C1’) Local scalar completeness. Replace the global Lorentz-scalar requirement with a local one: the observer’s record variables are relationally defined gauge-invariant observables (in the sense of the QRF/perspective-neutral framework) with respect to the constraint structure in the observer’s causal neighborhood. In a dynamic spacetime, the constraint algebra is larger, but the observer’s internal observables — being defined relative to the observer’s own reference frame — may still be gauge-invariant in the relevant relational sense. The QRF literature already provides tools for this: the perspective-neutral framework defines observables relative to internal frames without assuming a global Killing field, and recent extensions to relativistic settings handle frame-dependent descriptions without static backgrounds (Höhn et al. (2021); Höhn et al. (2024)).

(C2’) Adaptive calibration. Replace calibration against a static lapse function with calibration against the observer’s own sensory statistics. An active-inference agent does not need a globally defined $N(\mathbf{x})$ to calibrate its clock; it needs its clock to track the statistics of its sensory input well enough to generate predictions with bounded error. In a dynamic spacetime, the “correct” clock rate changes as the local geometry evolves, and the observer must adaptively recalibrate — which is precisely what prediction-error-driven updating does. The calibration condition becomes: the observer’s clock rate minimizes prediction error for a stable family of sensory invariants (periodicities, correlation times, or metrologically chosen reference processes) given the observer’s current sensory data. This is weaker than (C2) but may be sufficient for the epistemic-arrow results.

(C3') Well-defined local reduced dynamics. Replace essential self-adjointness on a global common core with a local condition: the reduced dynamics are well-defined and have bounded coherence loss within the observer's causal diamond over the prediction horizon. In an open-system setting, the reduced dynamics are not unitary but are described by CP maps; the companion note's own dephasing analysis (Eqs. 9–10) already shows that clock noise yields non-unitary master-equation corrections. The local condition requires that these corrections remain bounded — that coherence loss does not accumulate catastrophically over the timescales relevant to prediction and record formation. A blanket-stable regime can be expected to bound the effective coupling between internal and external sectors and hence bound the decoherence rate. The dephasing models (white FM, flicker FM, random-walk FM) provide quantitative tools: the Allan deviation $\sigma_y(\tau)$ and the resulting time variance $\sigma_\tau^2(\tau)$ set local, observer-dependent bounds on coherence loss that do not reference global spacetime structure.

(C4') Non-stalling flow. This condition transfers directly: the regular-gauge condition is imposed locally on the sector of states supported in the observer's operational domain. The clock's relational flow remains nondegenerate over the prediction horizon so long as the observer remains dynamically engaged with its environment — a condition active inference tends to preserve. In a dynamic spacetime, there may be regions (near singularities, inside horizons) where even an actively inferring observer's clock cannot avoid stalling; these are genuine physical limits of the framework, not artifacts of the static assumption.

(C5') Coarse-grained monotonicity. This condition also transfers directly, since it is grounded in the observer's dissipation rate rather than in the background geometry. As long as the observer maintains positive average dissipation — as long as it continues to do the thermodynamic work of record maintenance and expansion — the record algebra grows monotonically on coarse-grained timescales, regardless of what the background geometry is doing. The TUR bounds that set the fluctuation timescale are local thermodynamic results, not geometric ones.

6.5 Obstacles and open problems

Honesty requires identifying what this strategy does *not* accomplish and where the genuine difficulties lie.

The uniqueness problem. In a static spacetime, Theorem 1 proves that the relational parameter is unique up to monotone reparametrization because the calibration condition (C2) and the static structure provide a global anchor that collapses clock choices onto $f(T)$ via scalarity, additivity, and the Killing field's redshift factor. Without static calibration, this global anchor is lost. Different admissible clocks carried by the same observer might yield relational parameters that are not related by a simple mono-

tone reparametrization. The active-inference strategy suggests that the observer’s own prediction-error-minimizing dynamics select a preferred parameterization — but proving this requires new mathematical tools that do not currently exist.

The multiple-constraints problem. In full GR, the single first-class constraint of the companion note is replaced by the Hamiltonian and diffeomorphism constraints. The PW/RAQ construction does not straightforwardly generalize to multiple constraints, and the relationship between the observer’s internal clock and the full constraint algebra is substantially more complex. This is a well-known open problem in quantum gravity, not one introduced by our framework — but our framework does not solve it either.

The backreaction problem. The companion note assumes no backreaction: the observer does not affect the background geometry. For macroscopic observers in weak-field regimes, this is an excellent approximation. But the philosophical claims of the framework — particularly the retrodictive necessity argument — invoke the observer’s relationship to cosmological boundary conditions, where backreaction may matter in principle. A fully self-consistent treatment would require the observer’s self-maintenance to be modeled within a dynamical spacetime that the observer itself influences.

The measure problem revisited. In a dynamic spacetime with cosmological structure, the question of which branches of Hilbert space support observers — and with what measure — becomes entangled with the details of cosmic evolution, inflation, and the landscape. The retrodictive necessity argument assumes that all physically possible branches exist; in a dynamic cosmological setting, the structure of that possibility space is itself dynamical and contested.

6.6 What the strategy does accomplish

Despite these obstacles, the active-inference reformulation accomplishes something significant even in its programmatic form.

It diagnoses the static assumption as a technical convenience rather than a conceptual necessity. The physical content of the admissibility conditions — what they demand of the observer — does not reference the background geometry. The static assumption enters the companion note because it enables clean proofs, not because the results are physically restricted to static spacetimes. The active-inference framing makes this explicit: the admissibility conditions are about self-maintenance, not about Killing fields.

It identifies the right level of description for generalization. Rather than trying to generalize the PW/RAQ construction to arbitrary dynamic spacetimes (a problem in quantum gravity that may be decades from solution), the strategy suggests working at the level of the observer’s Markov blanket and asking: under what conditions does a self-maintaining system have a well-defined proper time? This is a question about the

observer, not about the spacetime, and it may be tractable even in regimes where the full quantum gravity problem is not.

It connects to existing programs. The reformulated conditions (C1')–(C5') interface naturally with several active research programs: the QRF program’s work on frame-dependent observables without global symmetries; the quantum thermodynamics literature on local detailed balance and fluctuation theorems in curved spacetime; and the quantum gravity literature on the problem of time, where the emergence of time from timeless descriptions is a central concern. The active-inference/Markov-blanket language provides a common conceptual vocabulary for connecting these programs to the observer-centric framework developed here.

It sharpens the empirical program. The companion paper’s Protocol B (kinematic, QRF variant) already probes the boundary between static and dynamic regimes by using superpositions of rapidities. The active-inference reformulation suggests a conjectural extension: record-growth rates should track the observer’s *locally defined* proper time even when the background is mildly dynamic (e.g., in the presence of gravitational waves), as long as the observer’s Markov blanket remains intact and its active-inference cycle continues. This is, in principle, testable with sufficiently sensitive clock networks in dynamically varying gravitational environments — a conjectural extension suggested by the proper-time-indexed bounds rather than a derived prediction.

7 The Boltzmann Brain Dissolve

7.1 The problem

Standard cosmological models face a well-known puzzle. In a universe that evolves toward thermal equilibrium over sufficiently long timescales, random thermal fluctuations will occasionally produce — by sheer statistical accident — configurations that instantaneously resemble observers: localized low-entropy structures with internal states that happen to encode what look like coherent memories and a model of the world. These are Boltzmann brains.

The problem is one of measure. In most cosmological scenarios that permit eternal expansion or recurrence, Boltzmann brains vastly outnumber ordinary observers who arise from the smooth, low-entropy evolution following the Big Bang. If observer-counting is straightforward, the overwhelming majority of observers with experiences like ours should be Boltzmann brains — momentary fluctuations with false memories in an otherwise featureless thermal bath. Since we take ourselves not to be such fluctuations, something has gone wrong with either the cosmology, the observer-counting, or the implicit assumptions about what constitutes an observer.

Various responses have been proposed: modifying the cosmological model to avoid

eternal recurrence, imposing a measure that down-weights Boltzmann brain histories, or arguing that Boltzmann brains are too short-lived to count as genuine observers. The present framework offers a different kind of response — not a cosmological fix or a measure prescription, but a principled criterion for observer-hood that categorically excludes Boltzmann brains.

7.2 Why Boltzmann brains fail the admissibility conditions

A Boltzmann brain is a thermal fluctuation: a transient, accidental low-entropy configuration that arises from and rapidly returns to equilibrium. It possesses, at the moment of its fluctuation, internal states that resemble records — patterns that, if read by an external observer, would look like memories of a coherent past. But these patterns were not *produced* by the processes that the companion paper’s framework requires for genuine record formation. They are accidental configurations, not thermodynamically maintained records.

The framework developed in this paper provides a precise diagnosis. By “Boltzmann brain” we mean the standard case relevant to the paradox: a fluctuation-produced observer-like configuration that lacks sustained nonequilibrium maintenance over the timescales required for (ε, L) -reliable records. (The rarer scenario in which a fluctuation-produced system finds itself in conditions that happen to support continued self-maintenance raises different and more subtle questions; we return to this briefly in Section 7.6.) A Boltzmann brain, in this standard sense, fails the admissibility conditions — and hence does not constitute an admissible quantum reference frame supporting proper-time parameterization — at multiple points:

Failure of (C5): no sustained monotonicity. The epistemic arrow requires that the record algebra $\mathcal{R}(\tau)$ grow monotonically (in expectation, on coarse-grained timescales) under positive average dissipation. A Boltzmann brain does not sustain positive average dissipation. It is a fluctuation *away from* equilibrium that is overwhelmingly likely to be followed by a return *toward* equilibrium. On any timescale longer than the fluctuation itself, the “record algebra” — such as it is — does not grow but degrades. The inclusion order $\mathcal{R}(\tau_1) \subseteq \mathcal{R}(\tau_2)$ is not maintained even in expectation, because the thermodynamic conditions that fund record growth (sustained free-energy throughput from a nonequilibrium environment) are absent.

More precisely: the companion paper’s Proposition 3.2 requires positive average dissipation rate $\dot{Q}_{\text{diss}}(\tau) > 0$ *over intervals of interest* — that is, over coarse-graining windows large compared to device cycle times, in a regime of sustained nonequilibrium. These are the same windows required for (ε, L) -reliability: the record must be queryable over $[\tau, \tau + L]$, which sets a minimum persistence timescale. A Boltzmann brain, by construction, does not persist across these windows. It exists in a regime of near-equilibrium

punctuated by a single, brief excursion. The dissipation rate, averaged over any interval comparable to L or to the coarse-graining windows of Proposition 3.2, is not systematically positive; it fluctuates around zero with a single anomalous spike. The conditions of the proposition are not met.

Failure of (C2): no calibration. Calibration requires that the observer’s internal clock tracks environmental statistics reliably — that $d\Theta/dt = \kappa N(\mathbf{x})$ for stationary worldlines, or, in the reformulated version (C2’), that the clock rate minimizes prediction error for a stable family of sensory invariants. A Boltzmann brain has never calibrated its clock against anything. Its internal states were not produced by an iterative process of prediction, error, and correction; they were produced by a random fluctuation. The “clock” has no history of tracking environmental regularities, and the “predictions” encoded in its internal states bear no systematic relationship to the actual statistics of its (near-equilibrium) environment.

This is not merely a practical failure (the Boltzmann brain hasn’t had *time* to calibrate) but a structural one. Calibration, under the active-inference interpretation, is the outcome of a history of environmental coupling: the system has learned to tick correctly by correcting its errors over many cycles. A Boltzmann brain has no such history. Its internal states may *resemble* those of a calibrated clock, but the resemblance is accidental rather than earned.

Failure of (C4): non-stalling condition not stably satisfied. In a fluctuation-produced near-equilibrium configuration, any apparent clock flow is not protected by sustained self-maintenance. The regular-gauge / non-stalling condition cannot be assumed to hold over the prediction horizon, because the system lacks the regime stability that, as argued in Section 4, supports nondegenerate relational flow. This is not an independent empirical claim about the dynamics of equilibrium systems but a consequence of the same maintenance failure that drives the (C5) and (C2) exclusions: without sustained active inference, there is no basis for assuming the clock’s relational flow remains nondegenerate over the timescales that matter.

Failure of active inference globally. Most fundamentally, a Boltzmann brain is not a system engaged in active inference. It does not maintain a Markov blanket through sustained thermodynamic work; it does not minimize variational free energy; it does not update a generative model in response to prediction errors. It is an accidental pattern in a thermal bath, not a self-maintaining system. The entire apparatus of Sections 3–4 — the identification of the Markov blanket with the quantum reference frame, the grounding of admissibility in self-maintenance — does not apply to it, because it is not the right kind of thing.

7.3 The categorical distinction

The framework does not merely make Boltzmann brains unlikely or assign them low measure. It makes them categorically different from genuine observers. A genuine observer is a system that:

- maintains a Markov blanket through sustained thermodynamic work,
- satisfies the admissibility conditions (or, more carefully, operates in the regime where the admissibility conditions are dynamically stable),
- possesses a record algebra that grows monotonically on coarse-grained timescales under dissipation-funded directed updating,
- and thereby constitutes an admissible quantum reference frame supporting proper-time parameterization and an epistemic arrow.

A Boltzmann brain satisfies none of these. It is not a degraded or marginal observer; it is not an observer at all, in the framework’s technical sense. Its internal states do not constitute a record algebra (because they were not produced by reliable write operations and are not maintained by refresh cycles), its “clock” is not admissible (because it was never calibrated and does not sustain nondegenerate flow), and its “Markov blanket” is not maintained (because it is a transient fluctuation, not a self-sustaining boundary).

This is a stronger response to the Boltzmann brain problem than most alternatives offer. Measure-based responses argue that Boltzmann brains should be down-weighted in observer-counting; the present response argues that they should not be counted at all, because they do not meet the conditions for observer-hood. This does not settle cosmological measure questions; it changes what qualifies as an observer-state for the purpose of anthropic and typicality reasoning. The exclusion is not an ad hoc stipulation but a consequence of the framework’s general account of what it takes to be an observer: sustained self-maintenance in a nonequilibrium regime, thermodynamically funded record growth, and the active-inference dynamics that maintain the admissibility conditions.

7.4 Records vs. patterns: the thermodynamic distinction

The Boltzmann brain problem gains its force from the implicit assumption that what matters for observer-hood is the *pattern* of internal states — that a system is an observer if its internal configuration matches that of an observer, regardless of how that configuration was produced. On this assumption, a Boltzmann brain is an observer because it has the right pattern.

The present framework rejects this assumption. What matters is not the pattern but the *process*: how the internal states were produced, how they are maintained, and what thermodynamic conditions underwrite their reliability. An (ϵ, L) -reliable record is not just a pattern that happens to match the original data; it is a pattern that can

be repeatedly queried over the interval $[\tau, \tau + L]$ and recovered with error $\leq \varepsilon$. This requires ongoing maintenance — refresh cycles, error correction, dissipative work — that a Boltzmann brain does not and cannot perform.

The distinction between records and patterns is thermodynamic. A Boltzmann brain may instantiate a pattern, but it does not instantiate a record, because recordhood is defined by stable readout under repeated querying over $[\tau, \tau + L]$ — and a Boltzmann brain does not persist across that interval. A genuine record is embedded in an entropy gradient: it was created by a dissipative process that expelled entropy to the environment, and it is maintained by ongoing dissipative processes that fight degradation. Its reliability is *paid for* in thermodynamic currency. A Boltzmann brain “record” is a fluctuation: a temporary, accidental low-entropy configuration that owes its existence to an improbable thermal excursion rather than to sustained dissipative work. It is not paid for; it is borrowed against the overwhelming probability of its own dissolution.

This connects to the companion paper’s retrodictive sufficiency argument. Genuine records sharply retrodict a narrow set of histories: the present state of the record algebra, produced by sustained dissipative work within an entropy gradient, is informationally rich enough to constrain the past with high probability. A Boltzmann brain’s “records” do not sharply retrodict anything, because they were not produced by a history consistent with their content. They are compatible with the history “a thermal fluctuation produced this pattern by accident,” which is overwhelmingly more probable than the history their content appears to encode. The retrodictive sufficiency condition — that present records select an effectively unique coarse-grained past — fails catastrophically for Boltzmann brains.

7.5 Relation to the Past Hypothesis argument

The companion paper argues that the ubiquity of redundant, cross-validated records licensing stable retrodiction requires a Past-Hypothesis-type low-entropy boundary as part of the best explanation. The Boltzmann brain dissolve strengthens this argument.

If Boltzmann brains were genuine observers, their “records” would license retrodiction of histories that never occurred — an equilibrium bath spontaneously fluctuating into a state that encodes a rich, detailed, self-consistent past. The retrodictive sufficiency condition would be trivially satisfied (any pattern can be “retrodicted” if you allow the retrodicted history to be fictitious) but empirically vacuous (the retrodicted history bears no relation to the actual microhistory of the thermal bath).

The framework avoids this by building retrodictive sufficiency on thermodynamic foundations. Retrodiction works — selects a narrow set of compatible past histories with high probability — only when the records doing the retrodicting were produced by sustained dissipative processes within an entropy gradient. This is what the Fano bound

and the dissipation-funded record growth (Proposition 3.2) jointly ensure. A Boltzmann brain’s “records” fail this test because they lack the thermodynamic provenance that makes retrodiction reliable.

The conclusion reinforces the retrodictive necessity argument: the fact that we find ourselves with records that *do* license reliable retrodiction — records whose thermodynamic provenance is genuine, not accidental — is abductive evidence that we are embedded in a history with a low-entropy past boundary, not in an equilibrium bath with occasional fluctuations. The Boltzmann brain dissolve and the Past Hypothesis argument are two faces of the same coin: both follow from the framework’s insistence that observer-hood is a thermodynamic achievement, not a pattern-matching condition.

7.6 Scope and caveats

The dissolve is sharp but its scope should be stated precisely.

What the argument excludes. Systems that are thermal fluctuations, lacking sustained dissipation, a maintained Markov blanket, and a history of calibrated environmental coupling. This includes classical Boltzmann brains (momentary fluctuations in a thermal bath) and their quantum analogues (momentary low-entropy fluctuations in a high-entropy quantum state).

What the argument does not exclude. Systems that arise from genuine nonequilibrium processes but are short-lived, simple, or radically different from human observers. The framework sets a thermodynamic threshold for observer-hood (sustained dissipation, maintained blanket, growing record algebra) but does not require that observers be complex, intelligent, or conscious. A bacterium maintaining reliable chemical records through active metabolic processes may qualify as an observer in the minimal, record-algebra sense, even though its record algebra is small and its temporal perspective is shallow. The Boltzmann brain dissolve targets the *thermodynamic provenance* of the system, not its complexity.

What remains open. The dissolve depends on the categorical distinction between sustained nonequilibrium maintenance and thermal fluctuation. In regimes where this distinction is blurry — systems near the boundary between nonequilibrium steady states and equilibrium, or systems whose Markov blankets are marginal — the framework may not deliver a sharp verdict. This is arguably a feature: observer-hood, like other thermodynamic phenomena, may admit boundary cases. The framework provides a clear criterion (sustained active inference maintaining the admissibility regime) while acknowledging that the criterion may be met to varying degrees.

The bootstrapping question. A more subtle case arises if a fluctuation-produced system happens to find itself in conditions supporting continued nonequilibrium maintenance — if it begins, post-fluctuation, to genuinely sustain its records, calibrate its

clock, and grow its record algebra. Such a system would satisfy the admissibility conditions going forward, regardless of the provenance of its initial configuration. Whether the retrodictive machinery then selects a coarse-grained history consistent with those records — and whether this possibility extends to artificially instantiated record-complete systems (e.g., via quantum computation) — raises questions about the relationship between retrodictive history-selection and causal provenance that the present framework’s formal apparatus does not resolve. These questions deserve separate treatment and connect to the broader philosophical program of which this paper is a part.

8 Conclusion and Open Problems

8.1 Summary of contributions

This paper has argued that two independently developed research programs — the quantum reference frames (QRF) program and the Free Energy Principle (FEP) — converge on a shared account of what it takes to be an observer, and that connecting them to the PW/RAQ framework developed in the companion papers yields results that neither program achieves alone.

The central identification (Section 3) is that the Markov blanket of a self-maintaining system under the FEP and the quantum reference frame of that system under the PW/RAQ construction describe the same physical structure: the boundary that constitutes the observer as a bounded, record-keeping, temporally extended entity. This identification is not merely heuristic or metaphorical. The Markov blanket’s conditional independence structure admits a structural parallel with the PW conditioning operation; the blanket’s sensory and active states correspond to the information channels through which the record algebra is updated and the environment is acted upon; and the internal states are precisely those encoded in the record algebra — the observer’s model of its world, realized as physically maintained reliable records.

The core argument (Section 4) is that sustained active inference — the ongoing process of maintaining a Markov blanket by minimizing variational free energy — maintains the physical regime in which the admissibility conditions (C1)–(C5) for proper-time emergence are dynamically stable. The argument proceeds through five active-inference preconditions (persistent separability, dissipative maintenance, predictive coherence, directed updating, active environmental coupling) and shows that they jointly sustain the conditions under which the companion technical note’s results continue to apply.

The implications for the epistemic arrow (Section 5) are threefold. First, the FEP transforms the cascade’s middle link (thermodynamic throughput funding record growth) from a background condition into an agentic achievement, adding a control-theoretic account of how throughput is allocated between maintenance and expansion. Second,

the active-inference framing sharpens the retrodictive structure by connecting record reliability to active maintenance and prediction-error dynamics. Third, the self-stabilizing dynamics of the Markov blanket explain the robustness of the epistemic arrow under perturbation — why the arrow persists through sleep, distraction, and other disruptions to updating, and why it fails only when the organized maintenance regime dissolves.

The programmatic extension to dynamic spacetimes (Section 6) argues that the admissibility conditions are physically about the observer, not about the background geometry, and that the static assumption in the companion technical note is a technical convenience rather than a conceptual necessity. The active-inference framing suggests replacing global geometric symmetry assumptions with local, observer-accessible regularity conditions — adiabatic or local stationarity over the observer’s prediction horizon — interpreted as maintained by self-organization. This does not solve the open problems of quantum gravity, but it identifies the right level of description for pursuing extensions and connects to existing programs in QRF theory, quantum thermodynamics, and the problem of time.

The Boltzmann brain dissolve (Section 7) shows that the framework categorically excludes standard Boltzmann brains — thermal fluctuations lacking sustained nonequilibrium maintenance — from observer-hood. The exclusion is not ad hoc but follows from the framework’s general account of what it takes to have a well-defined proper time and an epistemic arrow: (ε, L) -reliable records maintained by sustained dissipation over the coarse-graining windows required by Proposition 3.2. A Boltzmann brain may instantiate a pattern that resembles an observer’s internal states, but it does not instantiate a record algebra, because recordhood requires stable readout under repeated querying — a condition that transient fluctuations cannot satisfy. A subtler boundary case — fluctuation-produced systems that subsequently enter a sustained maintenance regime — is treated separately in Section 7.6 as an open bootstrapping problem.

8.2 What the paper claims and what it does not

It is worth being explicit about the paper’s epistemic status.

What is claimed as established (grounded in the companion papers’ formal results plus the structural arguments of this paper):

- The Markov blanket / QRF identification is a structural correspondence supported by precise formal parallels at each layer (boundary constitution, maintenance as admissibility-preservation, intersubjective agreement at meetings).
- Active inference maintains the physical regime in which the admissibility conditions are dynamically stable — this is supported by the physical preconditions of active inference and the conditions required by the companion note’s proofs.

- Standard Boltzmann brains are categorically excluded from observer-hood by the framework’s operational definition of records and the thermodynamic conditions for record growth.

What is claimed as a plausible structural argument (awaiting formal tightening):

- The specific derivations in Section 4, particularly the connections between active-inference preconditions and individual admissibility conditions. The formal gaps identified in the footnotes to that section (descent of frame-invariant statistics to Dirac observables, quantitative TUR bounds on the monotonicity timescale, precise conditions under which blanket integrity maintains Kato–Rellich perturbation parameters) are genuine and require further work.
- The complementarity with the [Fields et al. \(2022\)](#) quantum FEP — that the two directions of argument (QRF \rightarrow active inference and active inference \rightarrow admissibility maintenance) point toward a biconditional under suitable conditions.

What is claimed as programmatic (a research direction, not a result):

- The extension to dynamic spacetimes via reformulated admissibility conditions (C1’)-(C5’). The obstacles (loss of global calibration anchor, multiple constraints in full GR, backreaction) are real and unsolved.
- The relationship between retrodictive history-selection and causal provenance, particularly for the bootstrapping scenario raised in Section 7.6.

What is not claimed:

- This paper does not claim that the FEP is required for the companion papers’ results. The cascade (Past Hypothesis \rightarrow thermodynamics \rightarrow epistemic arrow) and the formal machinery (PW/RAQ, proper-time uniqueness, record-algebra monotonicity) stand on their own. The FEP adds explanatory depth and new connections, not new theorems.
- This paper does not claim that consciousness is explained, required, or addressed. The epistemic arrow is a thermodynamic-informational structure that exists wherever the relevant conditions are met, without commitment to phenomenal experience. The connection to consciousness belongs to a broader philosophical program that this paper does not enter.

8.3 Open problems

Several directions for further work emerge from the arguments developed here.

Formalizing the structural correspondence. The identification of Markov blankets with QRFs in Section 3 is argued at the level of structural parallels. A rigorous formalization would require either (a) showing that the [Fields et al. \(2022\)](#) category-theoretic framework, when specialized to the PW/RAQ setting, reproduces the admissibility conditions, or (b) constructing a direct map between the FEP’s variational formulation and the PW/RAQ constraint structure. Either route would elevate the correspondence from “structural” to “proven.”

Quantitative bounds on admissibility maintenance. Section 4 argues that active inference maintains the admissibility regime but does not provide quantitative bounds on *how much* active inference (how much dissipation, how fast an update rate, how tight a blanket) is required to maintain each condition. The companion papers provide some of the necessary tools — Landauer bounds, TUR constraints, Allan deviation models — but connecting these to explicit lower bounds on blanket integrity and clock quality under active inference is an open problem.

The adiabatic extension. Section 6 proposes replacing static symmetry assumptions with adiabatic or local stationarity conditions. Making this precise requires (a) defining “adiabatic” in the PW/RAQ context (probably: the background geometry changes slowly compared to the observer’s internal clock cycle), (b) showing that the admissibility conditions hold approximately under adiabatic perturbations of static backgrounds, and (c) bounding the error introduced by the adiabatic approximation. This is a well-defined mathematical program that does not require solving the full problem of time in quantum gravity.

Networked observers and shared blankets. The companion philosophy paper’s networked-observer construction (Section 7 of that paper) shows that observers connected by a reunion graph develop a shared subalgebra with nondecreasing information content. The active-inference framing suggests a natural extension: networked active-inference agents maintaining overlapping Markov blankets, with the shared subalgebra corresponding to the intersection of their generative models. This connects to the FEP literature on multi-agent active inference and to the QRF literature on multi-observer algebras and observer-dependent entropy. The meeting isometry of the companion technical note provides the formal bridge.

The bootstrapping problem. Section 7.6 raises the question of whether a system that begins with accidentally or artificially produced records, but then sustains genuine active inference, acquires a retrodictively valid history. The concrete question is: does subsequent (ε, L) -reliable maintenance, once it accumulates sufficient mutual information with the environment, force retrodictive concentration onto a non-fluctuation past — or can a fluctuation-origin remain a live high-probability explanation compatible with the maintained records? This is a question about the relationship between the framework’s operational account of observer-hood (which is forward-looking: does the system main-

tain records *now?*) and its retrodictive account of the past (which is backward-looking: do present records constrain a unique coarse-grained history?). Whether these two accounts converge for systems with non-standard causal provenance is an open question with implications for the philosophy of personal identity, the ethics of artificial observers, and the interpretation of the timeless Hilbert space picture.

8.4 Broader context

The arguments of this paper sit at the intersection of foundations of physics, philosophy of mind, and theoretical biology. The central theme — that being an observer is thermodynamic work, and that the temporal structure of experience is constituted by the self-maintaining activity of the observer — connects to several broader intellectual currents.

The Kantian thread is the recognition that time is not a feature of the world that observers passively discover but a condition of possibility for a temporal perspective — not a claim about phenomenal consciousness — that the observer’s own activity constitutes. The PW/RAQ construction gives this a precise physical realization: time is the relational parameter that emerges from conditioning on the observer’s internal clock, and its directedness (the epistemic arrow) is funded by dissipation.

The thermodynamic thread, running from Boltzmann through Landauer to Friston, grounds this Kantian insight in physics. The conditions of possibility for a temporal perspective are not merely logical or transcendental; they are thermodynamic. They require energy, they produce entropy, and they are subject to quantitative bounds. The observer is not a disembodied perspective but a physical system that must pay, in thermodynamic currency, for the privilege of having a world.

The cybernetic thread, from Wiener through Ashby to the FEP, adds the self-organizing dynamics that explain how observers maintain themselves. Active inference is the process by which a system preserves its own conditions of possibility — by predicting, acting, and correcting in a continuous cycle that sustains the Markov blanket, the record algebra, and the epistemic arrow.

These three threads have been developed largely independently. The contribution of this paper is to show that they converge on a single, formally precise structure — the admissible quantum reference frame maintained by active inference — and that this convergence has concrete consequences for the arrow of time, the Boltzmann brain problem, and the prospects for extending relational quantum mechanics to dynamic spacetimes.

Acknowledgments. [The author thanks Claude (Anthropic) for extended discussions that helped identify the central connection developed in this paper.]

Acknowledgments

The author thanks Claude Opus 4.6 (Anthropic) for extended discussions that helped identify the central connection developed in this paper and further acknowledges the extensive contributions provided by large language models from Anthropic and OpenAI.

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