The Pre-Entropic and Entropic Domains

An Alignment-Regulated Boundary Framework for Quantum Measurement, Irreversibility and Emergent Gravitational Response

---

General Reader Summary

Quantum theory is superbly accurate, yet it contains a famous gap. Before a measurement, a system can hold several possibilities at once, woven together in a delicate pattern. After a measurement, exactly one result exists on record. Standard textbooks bridge that gap by adding a special rule by hand.

This paper proposes that the bridge is a real physical process. A quantum system changes character when it couples to a boundary — an apparatus or environment — that is capable of writing permanent records. Before that coupling becomes effective, change is reversible and nothing is permanently written; we call this the pre-entropic regime. Once the boundary engages, possibilities are converted into records, and that conversion is irreversible; we call this the entropic regime.

What decides when the boundary engages? We propose a measurable quantity called alignment: how well the internal rhythm of the quantum state matches the reference rhythm supplied by the apparatus itself. Alignment is not a property of the state alone — it is a relationship between state and instrument, like the fit between a key and a particular lock. When the fit is good, record-forming events become more frequent; which outcome gets recorded still follows the usual quantum statistics.

The same picture offers a sharper account of time. Reversible change merely orders events, like pages in a book; the felt direction of time — the difference between a past that is written and a future that is not — comes from record formation itself. And the medium that writes records may, near a delicate tipping point, respond to matter over enormous distances in exactly the pattern of Newtonian gravity, though the full relativistic story remains open work.

The proposal stands or falls on one clean experiment: two quantum states that are identical in every standard respect, differing only in how they are phased against a fixed apparatus reference, should lose their quantum character at different rates. If they do not, the mechanism is wrong. Either answer teaches us something.

Table of Contents

---

1. Purpose and Scientific Status

The purpose of this framework is to investigate whether quantum measurement, irreversible record formation and the macroscopic arrow of time can be described as different aspects of one boundary-regulated process, and whether the medium responsible could additionally support long-range gravitational response.

The framework is presented at three sharply separated levels.

Level 1 — kinematical. Alignment is defined as an operationally measurable relation between a quantum state and an apparatus (a rank-one effect expectation). This level is theorem-grade: definitions, bounds and the Born-flux uniqueness theorem are exact.

Level 2 — dynamical. A local boundary controller converts alignment into a state-dependent rate of dephasing and stochastic outcome registration. This level is a well-posed effective open-system theory with named parameters and direct falsifiers.

Level 3 — emergent and gravitational. The boundary controller is investigated as a medium whose near-critical static response reproduces the Newtonian Poisson equation. This level is a research programme: the Newtonian limit is derived from an assumed free energy; the relativistic spin-two completion is open.

The terms *pre-entropic* and *entropic* do not denote two substances or two universes. They denote two dynamical regimes of one physical system:

- a **pre-entropic state** is one for which irreversible boundary coupling is absent or negligible — amplitudes and relative phases evolve coherently and no durable classical record has yet been produced;
- an **entropic state** is one for which information is being transferred into stable records, heat, and inaccessible environmental degrees of freedom.

The stronger ontological claim — that geometry itself arises from this transition — must be earned by a successful relativistic completion and is treated throughout as a hypothesis, not a result.

---

2. Quantum States, Apparatuses and Operational Alignment

2.1 State representation

Let the state of a finite-dimensional quantum system be a density operator

$\rho \geq 0$, Tr $\rho = 1$.

For a pure state,

$\rho = |\psi\rangle\langle\psi|$, $|\psi\rangle = \Sigma_{i=1}^{n} \sqrt{p_i}\, e^{i\varphi_i}\, |i\rangle$, $p_i \geq 0$, $\Sigma_i\, p_i = 1$.

The weights p_i determine outcome statistics in the basis $\{|i\rangle\}$; the phase differences $\varphi_i - \varphi_j$ determine interference.

A real apparatus contributes more than a basis. An interferometric or quantum-control apparatus also supplies **physical reference phases** through its local oscillators, drive pulses, cavity modes or interaction Hamiltonian. Alignment must therefore be defined relative to both a basis and a physical phase reference.

2.2 Apparatus reference state and the alignment functional

For apparatus basis $\mathfrak{B} = \{|i\rangle\}_{i=1}^{n}$ and phase reference $\theta = (\theta_1, \ldots, \theta_n)$, define the apparatus reference state

$|u_{\mathfrak{B},\theta}\rangle = (1/\sqrt{n})\, \Sigma_i\, e^{i\theta_i}\, |i\rangle$

and the alignment projector

$Q_{\mathfrak{B},\theta} = |u_{\mathfrak{B},\theta}\rangle\langle u_{\mathfrak{B},\theta}|$.

Definition 2.1 (operational alignment).

$\boldsymbol{A_{\mathfrak{B},\theta}(\rho) = \mathrm{Tr}(\rho\, Q_{\mathfrak{B},\theta})}$.

2.3 Elementary properties

Because Q is a rank-one projector (an effect with $0 \leq Q \leq \mathbb{1}$),

$0 \leq A_{\mathfrak{B},\theta}(\rho) \leq 1$,

and A is linear in ρ, basis-covariant, and continuous. For a pure state,

$A = (1/n)\, |\Sigma_i \sqrt{p_i}\, e^{i(\varphi_i - \theta_i)}|^2 = (1/n)\, [\, 1 + 2\, \Sigma_{i<j} \sqrt{(p_i p_j)}\, \cos(\varphi_i - \varphi_j - \theta_i + \theta_j)\,]$.

Alignment is therefore a **coherent matching functional**: it is maximal when the state's phase pattern locks to the apparatus reference, and it depends only on gauge-invariant phase *differences* measured against the reference.

Three cautions are structural, not incidental:

1. A is **not** purity, classicality or entanglement. A fully coherent state can have low alignment relative to one apparatus and high alignment relative to another. This is not a defect: relative phase is physically meaningful only relative to a reference.
2. A is **relational**: it transforms covariantly when the reference is rotated, $A_{\mathfrak{B},\theta+\delta\theta}(\rho) = A_{\mathfrak{B},\theta}(U_{\delta\theta}\,\rho\,U_{\delta\theta}^\dagger)$ with $U_{\delta\theta} = \Sigma_i e^{-i\delta\theta_i}|i\rangle\langle i|$. This covariance is itself testable (§14.2).
3. A is **linear** in ρ. All nonlinearity in the framework enters through the controller (§5), never through the kinematics.

2.4 Intrinsic alignment capacity

The greatest alignment obtainable by varying the reference is

$$A_{max}(\rho) = \max_{|u\rangle} \langle u|\rho|u\rangle = \lambda_{max}(\rho),$$

the largest eigenvalue of ρ. Hence

$$A_{\mathfrak{B},\theta}(\rho) \leq A_{max}(\rho),$$

with $A_{max} = 1$ for pure states and $A_{max} = 1/n$ for the maximally mixed state $\rho = \mathbb{1}/n$. The two quantities have distinct meanings: $A_{\mathfrak{B},\theta}$ measures fit to a *particular* boundary; A_{max} measures the state's maximum possible concentration along any single direction.

2.5 Operational measurability of A

Since $A = \mathrm{Tr}(\rho Q)$ is the expectation of a rank-one effect, it is measurable by standard means: project onto $|u\rangle$ (a Ramsey-type rotation into the reference frame followed by a population readout), or estimate it by a SWAP-test against an ancilla prepared in $|u\rangle$. No tomography of ρ is required to measure A itself, although tomography is required to certify the matched-state controls of §14.1.

---

3. Boundary Flux and the Born Rule

The Born rule should not be claimed to follow from conservation (normalization) alone: normalization is necessary but does not fix the functional dependence on the state. A stronger and exact result can nevertheless be established.

3.1 The flux axioms

Let $p_i = \mathrm{Tr}(\rho P_i)$ with $P_i = |i\rangle\langle i|$, and suppose the boundary assigns to each channel an outcome flux F_i subject to:

- **(B1) Positivity.** $F_i \geq 0$.
- **(B2) Normalization.** $\Sigma_i F_i = 1$.
- **(B3) Permutation covariance.** Relabelling physically equivalent channels relabels fluxes without changing the functional law.
- **(B4) Non-contextuality.** The flux of channel i depends on its own weight p_i, not on how the same effect is embedded in a larger measurement.
- **(B5) Coarse-graining consistency.** Merging two exclusive channels adds their fluxes: the merged channel with weight $p_i + p_j$ receives flux $F_i + F_j$.
- **(B6) Continuity.** The flux depends continuously on the state.

3.2 The uniqueness theorem

Theorem 3.1 (Born flux uniqueness). Under (B1)–(B6), the unique flux law is

$$\mathbf{F_i = Tr(\rho P_i) = p_i.}$$

Proof. By (B3)–(B4) there is a single continuous function $f \geq 0$ with $F_i = f(p_i)/\Sigma_j f(p_j)$. Coarse-graining (B5) applied inside the normalized family forces the Cauchy additivity equation

$$f(x + y) = f(x) + f(y), \quad x, y \geq 0, \; x + y \leq 1.$$

Additivity determines f on the dyadic rationals as $f(x) = f(1)\cdot x$; continuity (B6) extends this to all of [0,1]; positivity fixes $k = f(1) > 0$ up to the overall constant, which cancels in the ratio:

$$F_i = k\, p_i / (k\, \Sigma_j\, p_j) = p_i. \; \blacksquare$$

For a pure state, $F_i = |\langle i|\psi\rangle|^2 = |c_i|^2$.

The division of labour is exact and limited: **conservation supplies normalization; additivity, non-contextuality, symmetry and continuity force linearity in p_i.** Neither ingredient suffices alone.

3.3 Scope, dimension two, and the POVM extension

Two scope remarks strengthen the claim rather than weaken it.

First, Gleason's original theorem fails in Hilbert dimension 2 for projective measures; the effect-algebra (POVM) generalization of Busch and of Caves–Fuchs–Manne–Renes repairs this, and Theorem 3.1 is precisely of that effect-additive type. For general effects E the corresponding statement is

$F(E) = \mathrm{Tr}(\rho E)$,

the unique non-contextual, additive, continuous probability assignment on quantum effects — valid in every finite dimension, including $n = 2$.

Second, within this framework the Born rule is the unique boundary-flux law compatible with the stated consistency requirements. That is a strong result, and it is the honest one: it does not require the exaggerated claim that normalization by itself determines quantum probability.

---

4. Pre-Entropic (Relational) Dynamics

4.1 Relational parameter

Let τ denote an ordering parameter along a trajectory in state space. "Ordering" means τ labels the sequence of configurations; it does not yet carry an irreversible thermodynamic arrow. Unitary dynamics read

$$i\hbar\, d|\psi\rangle/d\tau = H|\psi\rangle.$$

Under a reparametrization $\tau \to f(\tau)$ the Hamiltonian may be rescaled so that the physical trajectory is unchanged. Before an irreversible clock is introduced, what is physical is the ordered path through state space, not an absolute flow rate.

4.2 Amplitude–phase equations

Write $H_{ij} = |H_{ij}|\, e^{i\vartheta_{ij}}$ with Hermiticity $H_{ji} = H_{ij}^*$, and $c_i = \sqrt{p_i}\, e^{i\varphi_i}$. The Schrödinger equation is equivalent to the coupled real system

$$dp_i/d\tau = (2/\hbar)\, \Sigma_j\, |H_{ij}|\, \sqrt{(p_i p_j)}\, \sin(\vartheta_{ij} + \varphi_j - \varphi_i),$$

$$d\varphi_i/d\tau = -(1/\hbar)\, \Sigma_j\, |H_{ij}|\, \sqrt{(p_j/p_i)}\, \cos(\vartheta_{ij} + \varphi_j - \varphi_i).$$

Hermiticity makes the sine kernel antisymmetric under (i,j) exchange, whence

$$\Sigma_i\, dp_i/d\tau = 0$$

identically: probability conservation is automatic, not imposed.

Structural consequence. This formulation removes any need to introduce independent K- and J-matrices with separately chosen symmetry assignments. Wherever such matrices appear as notation, they must be *derived* as the real and imaginary parts of one Hermitian generator; independent choices generically violate conservation.

5. The Boundary Controller

5.1 Why a separate controller is needed

A threshold cannot simply be inserted into the density-matrix equation without identifying what physically undergoes the transition. We therefore introduce a local boundary variable $a(\tau)$: a coarse-grained order parameter of the measurement interface, apparatus or environment. Operational alignment A drives the controller, but the two are distinct objects — one is a functional of the state, the other a physical degree of freedom of the boundary.

This separation carries the framework's causal hygiene. The fundamental dynamics remain **linear** on the full system ⊗ controller ⊗ bath space; the state-dependent reduced equation of §6 is an effective mean-field/adiabatic description. A phenomenological nonlinearity is thereby prevented from masquerading as a fundamental modification of quantum mechanics before its causal consistency is established (§10.2).

5.2 Controller dynamics

A general stochastic controller equation is

$$\tau_a \, da/d\tau = -\partial U(a; A)/\partial a + \xi(\tau),$$

with τ_a the boundary response scale, U an effective boundary potential and ξ microscopic noise. A minimal form is

$$U(a; A) = U_0(a) + (\kappa/2)(a - A)^2,$$

where U_0 may possess a rapid crossover or bistable region; alignment then biases the boundary toward or away from its active phase. In the **fast-controller limit** $\tau_a \to 0$,

$$a(\tau) \approx a^\star(A(\rho)),$$

and the reduced quantum equation acquires a rate that depends directly on the state. The finite-τ_a corrections are themselves observable (lag, relaxation, hysteresis — §14.4), so the controller is not an unfalsifiable intermediary.

5.3 Smooth activation law

Define the softplus regularization

$$g_\delta(x) = \delta \ln(1 + e^{x/\delta}), \quad g_\delta(x) \to \max(x, 0) \text{ as } \delta \to 0^+.$$

The active boundary rate is

$$\boldsymbol{\gamma(a) = \gamma_{bg} + \gamma_0 [g_\delta(a - a_c)]^\nu}, \quad \gamma_{bg} \geq 0,\ \gamma_0 > 0,\ \delta > 0,$$

with a_c the crossover location, δ the crossover width, and ν an **empirical response exponent**. A square-root onset corresponds to $\nu = \frac{1}{2}$, and may be *fitted* if data support it; no value of ν is asserted from an incomplete renormalization-group calculation. The smooth form avoids singular derivatives and, together with §6.1, guarantees well-posed coupled evolution.

---

6. Alignment-Regulated Open-System Dynamics

6.1 The master equation and well-posedness

Let $P_i = |i\rangle\langle i|$ be the pointer projectors and define the dephasing generator

$$\mathcal{D}_{\mathfrak{B}}[\rho] = \Sigma_i \left(P_i \rho P_i - \tfrac{1}{2}\{P_i, \rho\} \right) = \Delta_{\mathfrak{B}}(\rho) - \rho,$$

where $\Delta_{\mathfrak{B}}(\rho) = \Sigma_i P_i \rho P_i$ is the pinching (full dephasing) channel. The alignment-regulated master equation is

$$\boldsymbol{d\rho/d\tau = -(i/\hbar)[H, \rho] + \gamma(a)\, \mathcal{D}_{\mathfrak{B}}[\rho].}$$

Theorem 6.1 (well-posedness and structure). For any bounded, smooth, nonnegative rate trajectory $\gamma(a(\tau))$:

1. $\mathrm{Tr}\,\rho$ and Hermiticity are preserved;
2. the dissipator is of GKSL form at every instant, so the propagator is a two-parameter family of completely positive trace-preserving maps;
3. in finite dimensions the coupled (ρ, a) system has a unique global solution.

In the pointer basis,

$$d\rho_{ij}/d\tau = -(i/\hbar)[H, \rho]_{ij} - \gamma(a)\, \rho_{ij}\ (i \neq j), \quad d\rho_{ii}/d\tau\, |_{diss} = 0,$$

and for $H = 0$ the coherences decay with the accumulated dose:

$$\rho_{ij}(\tau) = \rho_{ij}(0) \cdot \exp\left(-\int_0^\tau \gamma(a(s))\, ds \right).$$

The boundary removes coherence; it never redistributes Born weights.

6.2 Entropy production: exact closed form

The dephasing channel is unital, $\mathcal{D}_{\mathfrak{B}}[\mathbb{1}] = 0$, and cannot decrease von Neumann entropy $S_{vN}(\rho) = -k_B \mathrm{Tr}(\rho \ln \rho)$. The dissipative entropy-production rate is

$$dS\_vN/d\tau |\_diss = \gamma(a)\, \sigma\_\mathfrak{B}(\rho),\ \sigma\_\mathfrak{B}(\rho) = -k\_B\ \mathrm{Tr}[\mathcal{D}\_\mathfrak{B}(\rho) \ln \rho].$$

Lemma 6.2 (Jeffreys form of the entropy production). With $\Delta\rho \equiv \Delta\_\mathfrak{B}(\rho)$,

$$\boldsymbol{\sigma\_\mathfrak{B}(\rho) = k\_B\ [\ D(\Delta\rho \parallel \rho) + D(\rho \parallel \Delta\rho)\ ],}$$

the symmetrized (Jeffreys) relative entropy between the state and its pointer pinching, where $D(\sigma\|\rho) = \mathrm{Tr}\ \sigma(\ln \sigma - \ln \rho)$.

Proof. Write $\sigma\_\mathfrak{B}/k\_B = -\mathrm{Tr}[(\Delta\rho - \rho) \ln \rho] = -\mathrm{Tr}(\Delta\rho \ln \rho) + \mathrm{Tr}(\rho \ln \rho)$. The first term is $-\mathrm{Tr}(\Delta\rho \ln \rho) = D(\Delta\rho\|\rho) - \mathrm{Tr}(\Delta\rho \ln \Delta\rho) = D(\Delta\rho\|\rho) + S(\Delta\rho)/k\_B$, and the second is $\mathrm{Tr}(\rho \ln \rho) = -S(\rho)/k\_B$, so $\sigma\_\mathfrak{B}/k\_B = D(\Delta\rho\|\rho) + [S(\Delta\rho) - S(\rho)]/k\_B$. Since $\ln \Delta\rho$ is diagonal in the pointer basis and the pinching is self-adjoint, $\mathrm{Tr}(\rho \ln \Delta\rho) = \mathrm{Tr}(\Delta\rho \ln \Delta\rho)$, whence $[S(\Delta\rho) - S(\rho)]/k\_B = D(\rho\|\Delta\rho)$ — the relative entropy of coherence. Summing the two pieces gives the Jeffreys form. ■

Consequences:

- $\sigma\_\mathfrak{B}(\rho) \geq 0$, with **equality iff $\boldsymbol{\rho = \Delta\rho}$**, i.e. iff the state carries no pointer-basis coherence. Entropy production is *exactly* the erasure of coherence, no more and no less.
- The second summand $k\_B\ D(\rho\|\Delta\rho)$ is the standard relative entropy of coherence; the boundary's thermodynamic cost is pinned to a recognized coherence monotone.
- No universal effective temperature is introduced. A relation $\dot{Q} = T\ \dot{S}$ requires a specified bath, detailed balance and a definition of heat flow — additional physical structure, not a consequence of Lindblad form.

6.3 Energy exchange

With $E = \mathrm{Tr}(\rho H)$,

$$dE/d\tau = \gamma(a)\ \mathrm{Tr}[H\ \mathcal{D}\_\mathfrak{B}(\rho)].$$

If $[H, P_i] = 0$ for all i, dephasing is exactly energy conserving. If the pointer basis does not commute with H, energy is exchanged with apparatus and environment, and a complete thermodynamic treatment must include the controller and bath energetics.

---

7. Measurement and Definite Outcomes

The unconditional master equation describes the ensemble: it explains decoherence but not which individual result is recorded. Single outcomes are represented by a quantum-trajectory unravelling.

7.1 Quantum-jump unravelling

Define jump operators

$J_i(a) = \sqrt{\gamma(a)} \cdot P_i$.

During $d\tau$, the probability that channel i registers an event is

$\Pr(i \text{ in } d\tau) = \mathrm{Tr}(J_i^\dagger J_i \rho)\, d\tau = \gamma(a)\, \mathrm{Tr}(P_i \rho)\, d\tau$,

and the total event probability is

$\Pr(\text{any event in } d\tau) = \gamma(a)\, d\tau$.

After outcome i the conditional state is

$\rho \longrightarrow P_i \rho P_i / \mathrm{Tr}(P_i \rho)$.

This is the operational meaning of "actualization" in the effective theory: a stochastic boundary event creates a definite record and updates the conditioned state.

7.2 Rate–statistics separation theorem

Theorem 7.1 (rate–statistics separation). In the alignment-regulated unravelling, alignment controls *when* events happen; the Born rule controls *what* happens:

$\Pr(i \mid \text{event}) = \gamma(a)\, \mathrm{Tr}(P_i\rho) / [\ \gamma(a)\, \Sigma_j\, \mathrm{Tr}(P_j\rho)\ ] = \mathbf{Tr(P_i\ \rho)}$,

because the common factor $\gamma(a)$ cancels and $\Sigma_j\, \mathrm{Tr}(P_j\rho) = 1$. ■

This exact factorization is the framework's central structural feature. It permits a state-dependent total event rate — the new physics — while protecting Born statistics — the established physics — without fine tuning.

7.3 Entropy-weighted deviations (non-minimal extension)

One could generalize to $J_i = \sqrt{(\gamma(a)\, e^{-\Delta S_i/k_B})}\, P_i$, giving

$\Pr(i \mid \text{event}) = p_i\, e^{-\Delta S_i/k_B} / \Sigma_j\, p_j\, e^{-\Delta S_j/k_B}$.

This predicts Born-rule deviations and is already tightly constrained experimentally. The **minimal framework** assumes equal thermodynamic prefactors for equivalent channels, so exact Born statistics are recovered; the extension is recorded only as a labelled, testable departure, not as part of the theory.

8. Entropic Time

The framework distinguishes three concepts:

1. **relational order**, represented by τ;
2. **reversible dynamical evolution**, generated by H;
3. **irreversible clock time**, produced through records and entropy generation.

The pre-entropic regime may possess relational change without an arrow. The entropic regime produces stable distinctions between records already created and outcomes not yet registered.

Let $\sigma_{tot}(\tau)$ be the total entropy-production rate of system, controller, apparatus and environment. Define the irreversible clock

$$T_{irr}(\tau) = t\star \int_0^\tau [\sigma_{tot}(s)/\sigma\star]\, ds, \quad dT_{irr}/d\tau = t\star\, \sigma_{tot}/\sigma\star \geq 0,$$

with calibration constants $t\star$, $\sigma\star$. When dynamics are effectively reversible, $\sigma_{tot} \approx 0$ and the irreversible clock advances negligibly even while the state changes relationally. When boundary events write records, $\sigma_{tot} > 0$ and T_{irr} advances monotonically.

The claim is therefore *not* that unitary systems lack sequence. The claim is that the experimentally observed arrow is supplied by irreversible record formation:

relational change orders events; entropy distinguishes past from future.

---

9. Two-Level Worked Example

9.1 Alignment of the phase family

Consider

$$|\psi_\theta\rangle = \sqrt{p}\,|0\rangle + e^{i\theta}\sqrt{(1-p)}\,|1\rangle, \quad |u\rangle = (|0\rangle + |1\rangle)/\sqrt{2}.$$

Then

$$A(\theta) = |\langle u|\psi_\theta\rangle|^2 = \tfrac{1}{2}\left[\, 1 + 2\sqrt{(p(1-p))} \cos\theta \,\right],$$

and for $p = \tfrac{1}{2}$,

$\mathbf{A(\theta) = (1 + \cos\theta)/2}$**:** $A(0) = 1$, $A(\pi/2) = \tfrac{1}{2}$, $A(\pi) = 0$.

All three states have identical populations and identical coherence magnitude; they differ only in phase relative to the apparatus.

9.2 The primary prediction

Let ρ have populations ½, ½ and coherence $z = \rho_{01}$, with $H = 0$. Dephasing gives $dz/d\tau = -\gamma(a) z$. For a fast controller, $a \approx A(\rho)$, and the initial coherence-decay rate is

$$\mathbf{R(\theta) \equiv -(d/d\tau) \ln|z| |_{\tau=0} = \gamma((1 + \cos \theta)/2).}$$

A standard phase-covariant dephasing model predicts a rate depending on coherence magnitude and the noise spectrum but **not** on θ after apparatus settings are correctly transformed. The alignment-regulated model predicts systematic θ-dependence relative to a physically fixed boundary phase. The distinction is falsifiable (§14.1).

9.3 Self-quenching: a closed autonomous flow

For this configuration the alignment is $A = ½ + \mathrm{Re}\, z$, and $d(\mathrm{Re}\, z)/d\tau = -\gamma(A)(A - ½)$. The fast-controller dynamics therefore close on A itself:

$$\mathbf{dA/d\tau = -\gamma(A) (A - ½).}$$

This single autonomous equation makes the "valve" intuition exact:

- for aligned initial data (A near 1) the rate $\gamma(A)$ is large and A is driven down;
- as coherence is erased, $A \to ½$, the drive $(A - ½)$ vanishes, and if $\gamma_{bg} = 0$ with $a_c > ½$ the flow can even freeze before reaching ½;
- measurement is therefore **self-quenching**: high alignment → boundary activation → loss of alignment → rate reduction.

Measurement is not unlimited decoherence; it is a boundary event that consumes the very quantity that triggered it.

---

10. Composite Systems and Entanglement

10.1 Local and collective alignment

For subsystems A and B with local reference projectors $Q_A = |u_A\rangle\langle u_A|$, $Q_B = |u_B\rangle\langle u_B|$:

$\mathcal{A}_A = \mathrm{Tr}[\rho_{AB} (Q_A \otimes \mathbb{1})]$, $\mathcal{A}_B = \mathrm{Tr}[\rho_{AB} (\mathbb{1} \otimes Q_B)]$, $\mathcal{A}_{AB} = \mathrm{Tr}[\rho_{AB} (Q_A \otimes Q_B)]$,

with connected correlator

$C_{AB} = \mathcal{A}_{AB} - \mathcal{A}_A \mathcal{A}_B$.

C_{AB} measures phase correlation relative to the chosen references; it can be nonzero for quantum *or* classical correlations, and is deliberately **not** presented as an entanglement measure.

For a Bell-like subspace, with $|\Phi_{\theta_0}\rangle = (|00\rangle + e^{i\theta_0}|11\rangle)/\sqrt{2}$ and $Q_\Phi = |\Phi_{\theta_0}\rangle\langle\Phi_{\theta_0}|$, the state $|\Phi_\theta\rangle = (|00\rangle + e^{i\theta}|11\rangle)/\sqrt{2}$ has collective alignment

$\mathcal{A}_\Phi = (1 + \cos(\theta - \theta_0))/2$,

so a collective boundary controller with rate $\gamma_{AB}(\mathcal{A}_\Phi)$ predicts **phase-sensitive collective decoherence** for Bell and GHZ states (§14.5).

10.2 No-signalling proposition

State-dependent nonlinear evolution can create signalling pathologies if applied carelessly to entangled systems. The framework therefore imposes a strict locality rule and proves its adequacy at the effective level.

Locality rule. A controller acting in region A may depend only on locally accessible fields and the reduced state $\rho_A = \mathrm{Tr}_B\, \rho_{AB}$. A collective alignment term is admissible only when the subsystems interact with a common apparatus or common environment inside the relevant causal domain.

Proposition 10.1 (no superluminal signalling at the effective level). Under the locality rule, no local operation performed by a distant agent B alters the statistics of A's boundary events.

Proof sketch. For fixed controller value a, the generator of §6.1 acting on A is linear and trace preserving; B's local CPTP operations leave ρ_A invariant by ordinary quantum no-signalling. Since a depends on the state only through ρ_A, both the local rate $\gamma(a(\rho_A))$ and the local event statistics $\gamma\, \mathrm{Tr}(P_i\, \rho_A)$ are unchanged by anything B does. Nonlinearity in ρ_A alone cannot transmit a signal that ρ_A does not carry. ■

Fundamental-level requirement. The combined system–controller–bath evolution must be linear and completely positive; the nonlinear rate law is an effective reduced description, never a licence for nonlocal deterministic modification of quantum mechanics. Failure to construct such a linear dilation is itself a falsifier (F4, §16).

---

11. Tunnelling in the Pre-Entropic Regime

Quantum tunnelling requires no claim that space "disappears" inside a barrier. The defensible formulation is: tunnelling is predominantly coherent, and is therefore especially sensitive to any boundary mechanism that converts phase information into records.

With $H = P^2/2m + V(X)$, position-sensitive boundary coupling may be represented by

$$d\rho/d\tau = -(i/\hbar)[H, \rho] - (\gamma(a)/2)\,[X, [X, \rho]],$$

and the transmission probability after τ_f is $T = \mathrm{Tr}(P_R\, \rho(\tau_f))$, with P_R projecting on the transmitted region.

The prediction is **not** a replacement of WKB. The standard factor

$$T_{WKB} \sim \exp\left[-(2/\hbar) \int_{x_1}^{x_2} \sqrt{2m(V(x) - E)}\, dx \right]$$

remains intact; the framework contributes a **separately calculable open-system correction** whose size depends on the alignment-controlled rate $\gamma(a)$. Two experiments with identical mass, barrier and conventional noise, but different apparatus-relative alignment, may exhibit different transmission or traversal-coherence statistics. No undefined "logarithmic alignment integral" replaces the dimensionless WKB action.

---

12. Emergent Gravitational Response

12.1 What gravity cannot be identified with

Gravitational mass cannot be equated with the instantaneous rate of entropy production: a cold, stationary, highly isolated object still gravitates. Any viable source must reduce, in ordinary conditions, to mass-energy density rather than ongoing dissipation. The connection to the entropic boundary must therefore enter through the **equilibrium properties of the boundary medium** — its free energy, stiffness, susceptibility and critical modes — not through its current dissipative activity.

12.2 Boundary order parameter in space

Let $a(x)$ be the static long-wavelength boundary order parameter and $\rho_m(x)$ the nonrelativistic mass density. Take the effective free energy

$$\mathbf{F[a; \rho_m] = \int d^3x \left[(\kappa_a/2)|\nabla a|^2 + (m_a^2/2)(a - a_0)^2 - g_a (a - a_0)\, \rho_m \right],}$$

with stiffness $\kappa_a > 0$, potential curvature m_a^2, vacuum value a_0 and matter coupling g_a. Variation gives the screened response equation

$$\mathbf{(\nabla^2 - \ell_a^{-2})(a - a_0) = -(g_a/\kappa_a)\, \rho_m, \quad \ell_a^2 = \kappa_a/m_a^2.}$$

The correlation length ℓ_a sets the range of the force; a point mass sources the Yukawa profile

$$\Phi(r) = -(G_{eff} M / r)\, e^{-r/\ell_a}.$$

12.3 Critical limit and the Poisson equation

Near a continuous critical point $m_a^2 \to 0$, so $\ell_a \to \infty$ and

$$\nabla^2(a - a_0) = -(g_a/\kappa_a)\,\rho_m.$$

Defining the Newtonian potential $\Phi = -q_a\,(a - a_0)$,

$$\boldsymbol{\nabla^2\Phi = 4\pi G_{eff}\,\rho_m,\quad G_{eff} = q_a\,g_a / (4\pi\,\kappa_a),}$$

and for a point mass $\Phi(r) = -G_{eff}\,M/r$. A long-range inverse-square force thus arises from a boundary mode whose susceptibility diverges near criticality. This is the corrected mathematical content behind the intuition that gravity is related to a near-critical boundary response — and it replaces any earlier dimensional matching.

12.4 Derivation ledger: established vs open

Established (from the assumed free energy):

- a critical boundary mode generates a $1/r$ potential;
- G_{eff} is a ratio of couplings to boundary stiffness;
- departure from criticality produces a finite range e^{-r/ℓ_a} — an immediate falsifier against inverse-square tests;
- composition-dependent coupling would produce fifth-force signatures — a second immediate falsifier.

Not derived:

- universal coupling of all matter through ρ_m (and hence through stress-energy);
- the correct coupling of antimatter, radiation and binding energy;
- the equivalence principle from microscopic dynamics;
- gravitational light bending;
- the tensor structure of gravitational waves;
- the nonlinear Einstein equations.

12.5 Relativistic completion criterion

A scalar long-range mode cannot reproduce all observations attributed to general relativity. The sharpest single obstruction: a scalar coupled to the trace $T^\mu{}_\mu$ does not deflect light, because the electromagnetic stress tensor is traceless — yet light bending is observed at the full relativistic value. A successful completion must therefore produce an effective **massless spin-two** mode $h_{\mu\nu}$ with universal coupling to stress-energy,

$$S_{int} = (\kappa_g/2) \int d^4x\, h_{\mu\nu}\, T^{\mu\nu},$$

whose kinetic term carries the gauge redundancy of the massless Fierz–Pauli field, and whose consistent nonlinear self-coupling recovers an Einstein-like geometric theory or an observationally equivalent alternative. The boundary framework may supply the microscopic origin of the stiffness and susceptibility of this collective tensor mode; that construction is open.

The gravity claim, stated precisely: **the framework supplies a candidate thermodynamic boundary medium whose critical long-wavelength response reproduces Newtonian gravity; deriving the universal relativistic spin-two sector remains a central unsolved task.** That claim is ambitious, meaningful and defensible.

---

13. Cosmological Extension

A covariant boundary order parameter may be represented at effective level by

$$S_a = \int d^4x \sqrt{-g} \left[-(Z_a/2)\, g^{\mu\nu}\, \partial_\mu a\, \partial_\nu a - V(a) \right].$$

For a homogeneous background $a = a(t)$,

$$\rho_a = (Z_a/2)\, \dot{a}^2 + V(a), \quad p_a = (Z_a/2)\, \dot{a}^2 - V(a),$$

so a slowly varying field contributes an approximately vacuum-like component $p_a \approx -\rho_a$.

No numerical prediction for the expansion rate or the vacuum-energy scale follows until $V(a)$, Z_a, the matter coupling and initial conditions are derived or measured. The cosmological programme is therefore, in order: derive the covariant boundary action; determine stable backgrounds; compute perturbations and their propagation speed; confront expansion, structure-growth and gravitational-wave data; rule out ghosts, instabilities and prohibited fifth forces.

Standard of honesty: expressions that generate the observed cosmological scale only by inserting the observed value into another formula are not predictions and must not be presented as such.

---

14. Experimental Programme

14.1 Primary test: phase-dependent decoherence

Prepare the family $|\psi_\theta\rangle = (|0\rangle + e^{i\theta}|1\rangle)/\sqrt{2}$ — identical populations, purity and coherence magnitude across θ. Fix the physical apparatus reference phase and measure the initial decay rate

$$R(\theta) = -(d/d\tau) \ln|\rho_{01}(\tau)|\,\big|_{\tau=0}.$$

- **Alignment-regulated prediction:** $R(\theta) = \gamma\left((1 + \cos\theta)/2 \right)$.

- **Phase-covariant null hypothesis:** $R(\theta)$ = constant.

The decisive control requirement: changing θ must not inadvertently change pulse errors, populations, detuning, noise exposure or preparation fidelity. A valid run therefore requires full state tomography of the prepared family and independent calibration of the apparatus reference.

14.2 Reference-rotation test

Rotate the physical apparatus reference by θ_0. The model predicts a rigid shift of the response curve:

$R(\theta; \theta_0) = \gamma[\ (1 + \cos(\theta - \theta_0))/2\ ]$.

A phase dependence that stays fixed in the laboratory frame while the physical reference is rotated would contradict the relational definition of alignment (§2.3, property 2).

14.3 Threshold-shape test

Fit $\gamma(a) = \gamma_{bg} + \gamma_0[g_\delta(a - a_c)]^\nu$ on one dataset; the parameters (γ_{bg}, γ_0, a_c, δ, ν) must then *predict* independent datasets, protocols and platforms. A threshold law that changes arbitrarily between runs has no explanatory value.

14.4 Controller-memory test

If τ_a is finite, the same instantaneous alignment can yield different rates depending on recent history, per $\tau_a \dot{a} = -\partial_a U(a; A)$: lag, relaxation, possibly hysteresis. Prepare the same final state by fast and slow ramps; a difference in early event rate indicates controller memory. A null result bounds τ_a and favours the fast-controller limit — either outcome constrains the theory.

14.5 Collective-state test

Prepare $|\Phi_\theta\rangle = (|00\rangle + e^{i\theta}|11\rangle)/\sqrt{2}$, vary θ against a fixed collective reference, and measure the decay of $\langle 00|\rho|11\rangle$. Collective alignment predicts phase-dependent decay; calibrated local independent noise predicts none.

---

15. Premise Ledger

- **P1 (Operational alignment).** The apparatus supplies a basis and physical reference phases; alignment is the rank-one effect expectation $A = \mathrm{Tr}(\rho Q_{\mathfrak{B},\theta})$.
- **P2 (Flux axioms).** Boundary outcome flux satisfies positivity, normalization, permutation covariance, non-contextuality, coarse-graining additivity and continuity (B1–B6).

- **P3 (Boundary controller).** A local order parameter a with potential U(a; A) and response time τ_a mediates between alignment and dissipation; the fast-controller limit gives $a \approx a^\star(A)$.
- **P4 (Activation law).** $\gamma(a) = \gamma_{bg} + \gamma_0[g_\delta(a - a_c)]^\nu$ with ν empirical; no RG derivation of ν is claimed.
- **P5 (GKSL dissipation).** The entropic coupling is pointer-basis dephasing of Lindblad form with rate γ(a); jumps $J_i = \sqrt{\gamma}\, P_i$ describe single events.
- **P6 (Minimality).** Equivalent channels have equal thermodynamic prefactors, so conditional statistics are exactly Born (Theorem 7.1); entropy-weighted deviations are excluded from the minimal theory.
- **P7 (Locality/dilation).** Controllers depend only on locally accessible fields and reduced states; the fundamental system–controller–bath dynamics are linear and completely positive.
- **P8 (Entropic clock).** Irreversible time is the calibrated integral of total entropy production; relational order is prior to and distinct from it.
- **P9 (Boundary free energy).** The static gravitational sector is governed by the quadratic free energy of §12.2 with matter coupling $g_a \rho_m$; criticality $m_a^2 \to 0$ is assumed available.
- **P10 (Hypothesis status of Level 3).** Universal coupling, the equivalence principle and the spin-two sector are hypotheses to be earned, not premises silently promoted to results.

---

16. Falsifier Register

- **F1 (Rate flatness).** Accurately matched states with different operational alignment show no rate difference beyond uncertainty across increasingly precise platforms → the mechanism (P3–P5) is eliminated. [§14.1]
- **F2 (Reference decoupling).** An apparent phase dependence fails to follow the physical reference under rotation → the relational definition (P1) is contradicted. [§14.2]
- **F3 (Parameter irreproducibility).** Fitted (γ_{bg}, γ_0, a_c, δ, ν) do not transfer between protocols, sizes or datasets → the activation law (P4) loses explanatory content. [§14.3]
- **F4 (Dilation failure).** The effective state-dependent dynamics cannot be embedded in any local linear system–controller–bath model without superluminal signalling → P7 fails and the framework is inadmissible as physics. [§10.2]
- **F5 (Gravitational range/composition).** The boundary mode predicts a finite range, composition dependence or scalar radiation incompatible with inverse-square and equivalence-principle tests → the Level-3 medium (P9) is excluded. [§12.4]
- **F6 (Spin-two failure).** The microscopic theory fails to generate universal stress-energy coupling or a viable massless spin-two sector → the gravitational extension is restricted to a non-universal, sub-relativistic curiosity. [§12.5]
- **F7 (Controller-memory contradiction).** Observed hysteresis/lag inconsistent with any (τ_a, U) within the controller class → P3 as formulated fails. [§14.4]
- **F8 (Collective-phase null).** No collective phase dependence for Bell/GHZ decay under a fixed collective reference, after calibration → collective controllers are excluded; only local alignment survives. [§14.5]

Failure of the gravity extension (F5, F6) would **not** automatically disprove the alignment-regulated measurement model (P1–P8): the modules are independently testable and must be independently scored.

---

17. Honest Limitations

1. The controller potential $U_0(a)$ is not derived from a microscopic Hamiltonian.
2. The activation parameters a_c, δ, ν, γ_0 are not calculated from first principles.
3. Universality of those parameters across quantum platforms is not established.
4. The effective reduced dynamics are nonlinear and must be justified as the reduction of a local linear theory; §10.2 proves effective-level safety, not the existence of the dilation.
5. The framework does not replace standard quantum field theory.
6. It does not derive general relativity; the Newtonian construction assumes coupling to mass density and therefore does not derive the equivalence principle — it shows what must be true for a critical boundary response to resemble gravity.

These limitations do not make the framework empty. They define, exactly, the work required to turn it from a well-posed effective hypothesis into a deeper theory.

---

18. Conclusion

The central proposal is that quantum measurement should be treated neither as an undefined observer action nor as environmental decay at a fixed rate, but as a boundary process in which three structures interact:

1. **quantum phase geometry**, evolving reversibly in the pre-entropic regime;
2. **a physical apparatus reference**, against which alignment $A = \mathrm{Tr}(\rho Q)$ is defined and measured;
3. **an irreversible boundary controller**, converting alignment into an event rate $\gamma = \gamma(a)$.

The resulting quantum jumps create definite records with conditional probabilities $\Pr(i) = \mathrm{Tr}(P_i\rho)$ — the unique flux law under (B1)–(B6) — while the total event rate carries the new physics. Entropy production accompanies the conversion of coherent alternatives into stable records, and equals exactly the Jeffreys divergence between the state and its pointer pinching: the thermodynamic cost of measurement *is* the erasure of coherence. This supplies the irreversible component of experienced time without denying reversible relational change.

The gravitational extension takes its clearest form when gravity is associated not with ongoing entropy production but with the equilibrium response of a near-critical boundary medium, whose order parameter obeys $\nabla^2\Phi = 4\pi G_{eff}\,\rho$ in the critical limit. The relativistic spin-two completion remains open, and the light-bending obstruction to any purely scalar version is stated rather than hidden.

The framework's immediate scientific value lies in one sharp question:

Does the rate at which quantum coherence becomes an irreversible record depend on phase alignment relative to a physical measurement boundary?

That question can be answered experimentally. A positive result would reveal a previously unrecognized state–apparatus variable in quantum measurement. A negative result would decisively constrain or eliminate the proposed mechanism. Either outcome advances the problem.