Stochastic Rupture as an Information-Bounded Mechanism for Objective Wave-Function Collapse: Field Dynamics, Trigger Regime, and the Arrow of Time

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Abstract

We present a consolidated formulation of Stochastic Rupture (SR), an objective wave-function collapse framework in which branch selection is triggered by the local saturation of an informational bound on covariant causal-diamond surfaces. The framework is built on three interlocking layers: (i) a Lindblad master equation with collapse operator $\hat{L} = \hat{x}/\sigma_x$, modulated by a divergent saturation feedback $F(\chi) = (1-\chi)^{-1}$ where $\chi = S_{\mathrm{vN}}/(\eta\, I_{\mathrm{Bek}})$; (ii) a covariant field equation $\nabla^\mu \nabla_\mu \chi = S - \Gamma_0 \chi - \alpha \chi^2$ for the saturation scalar promoted to a dynamical degree of freedom; and (iii) a trigger regime hierarchy establishing that pruning fires only when local saturation crosses threshold, leaving isolated microscopic systems empirically equivalent to standard quantum mechanics. We make six principal contributions in this consolidated edition: we derive the decoherence rate $\Gamma_{\mathrm{dec}} = \gamma(t)\, d^2/(4\sigma_x^2)$ from the Lindblad structure rather than postulating it; we identify a qualitatively new prediction (Regime IV) for high-entanglement systems with no spatial superposition, absent from both Diósi–Penrose and Continuous Spontaneous Localization; we derive the arrow of time as a structural consequence of the nonlinear sink $-\alpha\chi^2$ via Landauer's principle, unifying the thermodynamic, radiation, and quantum measurement arrows; we compute cosmological heating rates 15–27 orders of magnitude below CSL in diffuse environments; we develop the 4D Rose as a visualization choice that preserves parity violation and unequal-amplitude branching; and we articulate framework scope explicitly. The framework is observationally indistinguishable from standard quantum mechanics—and indeed from Diósi–Penrose—in all currently accessible regimes, because the saturation feedback $F(\chi)$ is essentially unity throughout the parameter space of contemporary matter-wave interferometry and levitated optomechanics. Discrimination from DP and CSL is therefore concentrated in three structurally distinct regimes: macroscopic entangled-memory systems with no spatial superposition (Regime IV), time-reversed interferometric protocols, and precision thermodynamic measurements in varying gravitational potentials.

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1 Introduction

The measurement problem in quantum mechanics—the question of how and why definite outcomes emerge from superposed states—remains one of the foundational questions of physics. Among objective-collapse approaches, the GRW model [1] and its continuous extension CSL [2] postulate stochastic localization at a fundamental rate, while gravitational models in the Diósi–Penrose tradition [3, 4] tie collapse to gravitational self-energy. Both classes face increasingly tight experimental constraints from cosmological heating bounds and matter-wave interferometry [15], and both treat collapse as a fundamental dynamical process distinct from the informational structure of spacetime.

Stochastic Rupture (SR) takes a different stance. Rather than postulating a new fundamental dynamics, SR identifies collapse as the irreversible pruning of branches when the local von Neumann entropy of a superposition saturates a fraction η of the Bekenstein–Bousso bound [8, 9] on the relevant causal-diamond surface. The framework rests on three interlocking layers, developed in this consolidated edition:

1. **Microscopic dynamics** (Section 2). A Lindblad master equation with collapse operator $\hat{L} = \hat{x}/\sigma_x$ inherited from CSL, supplemented by a divergent saturation feedback $F(\chi) = (1-\chi)^{-1}$. The decoherence rate $\Gamma_{\text{dec}} = \gamma(t)\, d^2/(4\sigma_x^2)$ is derived from the Lindblad structure, not postulated, with the gravitational identification $\gamma_0 = 4Gm^2/(\hbar d)$ in the limit of vanishing saturation.

2. **Field dynamics** (Section 3). The saturation scalar $\chi(x^\mu)$ is promoted to a covariant dynamical field obeying $\nabla^\mu\nabla_\mu\chi = S(x^\mu) - \Gamma_0\chi - \alpha\chi^2$. This is a structural elevation: χ ceases to be a derived bookkeeping quantity and becomes an independent degree of freedom carrying the informational state of spacetime regions. The local value χ_{local} used in the Lindblad sector is the pointwise value of this field at the system's location.

3. **Ontological selection** (Sections 4–6). Pruning is the irreversible removal of branches once the trigger condition $\chi \to 1$ is met. The nonlinear sink $-\alpha\chi^2$ in the field equation generates the arrow of time as a structural consequence, with the thermodynamic, radiation, and quantum measurement arrows emerging as three aspects of the same mechanism.

Three structural claims distinguish SR from continuous and gravitational collapse models: (i) trigger by saturation, not by tag; (ii) selection over branches, not modification of dynamics; (iii) covariant trigger surface evaluated on the maximal-volume Cauchy surface of the causal diamond enclosing the entire superposition.

A separate but related phenomenological model within the same informational substrate, addressing the late-time suppression of structure growth (the S_8 tension) through gradients of the saturation scalar, is described in companion work [16] and discussed in scope-defining terms in Section 9. A speculative appendix (Appendix A) discusses whether the empirically stochastic phenomenology of SR may rest on a deeper deterministic substrate.

2 The Pruning Mechanism

2.1 Lindblad master equation with position-coupling

Consider a quantum system in a spatial superposition $|\psi\rangle = \alpha|L\rangle + \beta|R\rangle$, where $|L\rangle$ and $|R\rangle$ are Gaussian wavepackets of width σ_x centred at $\pm d/2$. We postulate the Lindblad master equation:

$$\frac{d\rho}{dt} \; = \; -\frac{i}{\hbar}[H,\rho] + \gamma(t)\Big(\hat{L}\rho\hat{L}^\dagger - \tfrac{1}{2}\hat{L}^\dagger\hat{L}\rho - \tfrac{1}{2}\rho\hat{L}^\dagger\hat{L}\Big)\,, \tag{1}$$

with collapse operator $\hat{L} = \hat{x}/\sigma_x$. This choice is the simplest operator that localizes in position space and is inherited from the mass-density-coupled version of CSL [5]. The choice of $\hat{x}$ implicitly selects a preferred basis; this is acknowledged as an open problem (Section 10.3).

Straightforward evaluation of the Lindblad superoperator for two Gaussian branches separated by $d \geq 0$ gives:

$$\frac{d\rho_{LR}}{dt} = -\Gamma_{\text{dec}}\,\rho_{LR}, \qquad \Gamma_{\text{dec}} = \gamma(t)\,\frac{d^2}{4\sigma_x^2}. \tag{2}$$

The derivation uses $\langle L|\hat{x}^2|L\rangle = \sigma_x^2 + (d/2)^2$, $\langle R|\hat{x}^2|R\rangle = \sigma_x^2 + (d/2)^2$, and $\langle L|\hat{x}|R\rangle \approx 0$ for $d \gg \sigma_x$. The factor $d^2/(4\sigma_x^2)$ is a derived consequence of the choice of $\hat{L}$, not an independent postulate.

2.2 Gravitational identification of the baseline rate

To connect $\gamma(t)$ to the gravitational scale of Diósi–Penrose, we postulate:

$$\gamma_0 \;\equiv\; \lim_{S_{\text{vN}}\to 0}\gamma(t) \;=\; \frac{4Gm^2}{\hbar d}. \tag{3}$$

This is the central new physical assumption of the dynamical sector. We do not derive Eq. (3); its motivation is dimensional consistency with the DP timescale and the requirement of recovering the standard DP result in the appropriate limit.

In the limit $S_{\text{vN}} \ll \eta\, I_{\text{Bek}}$ (Regime I, Section 4.2), $\gamma(t) \to \gamma_0$ and Eq. (2) reduces to:

$$\Gamma_{\text{dec}}^{(\text{DP})} \;\approx\; \frac{Gm^2 d}{\hbar\sigma_x^2} \qquad (S_{\text{vN}} \ll \eta\, I_{\text{Bek}}). \tag{4}$$

For $\sigma_x \sim d$ this recovers $\tau_{\text{DP}} \sim \hbar d/(Gm^2)$ up to $O(1)$ factors. The d/σ_x^2 scaling constitutes a clean experimental discriminator from CSL (which gives a fixed rate per particle independent of σ_x).

2.3 Saturation feedback and informational modulation

The key departure from DP and CSL is the saturation feedback F that accelerates collapse as S_{vN} approaches the trigger threshold. Define the local saturation ratio:

$$\chi(t) \;=\; \frac{S_{\mathrm{vN}}(t)}{\eta\, I_{\mathrm{Bek}}}, \tag{5}$$

where $I_{\mathrm{Bek}} = 2\pi RE/(\hbar c \ln 2)$ is the Bekenstein bound and $\eta \in (0,1)$ is the threshold fraction ($\eta \sim 0.1$ fiducial; constraints in Section 8.4).

We postulate:

$$\gamma(t) = \gamma_0\, F(\chi(t)), \qquad F(\chi) = \frac{1}{1-\chi}, \quad \chi \in [0,1). \tag{6}$$

The derivation of $F(\chi)$ from fluctuation variance in the Martin–Siggia–Rose–Janssen–De Dominicis field theory is presented in the companion work [17]. Alternative forms ($F(\chi) = e^{\chi/(1-\chi)}$, or $(1-\chi)^{-n}$ for $n > 1$) are physically admissible but lead to different collapse-time distributions. We adopt Eq. (6) for its minimality.

Combining Eqs. (2), (3), and (6):

$$\Gamma_{\mathrm{dec}}(t) \;=\; \frac{Gm^2 d}{\hbar \sigma_x^2}\, \frac{1}{1-\chi(t)}. \tag{7}$$

2.4 Pruning as ontological selection

When $\chi \to 1$, the rate (7) diverges and an irreversible pruning event occurs on the causal-diamond surface enclosing the superposition:

- The event is irreversible: branches eliminated in pruning do not return. A field-theoretic derivation of this irreversibility from the nonlinear sink term is presented in Section 6.
- It is informational, not interactional: no field-mediated mechanism is invoked.
- It selects branches with Born probabilities $|c_i|^2$.
- It produces a definite macroscopic register, completing the transition from amplitude to fact.

2.5 Comparison with Diósi–Penrose

The standard Diósi–Penrose collapse rate is $\Gamma_{\mathrm{DP}} \sim Gm^2/(\hbar R_0)$, where R_0 is a regularization length. In the regime $\sigma_x \sim d \sim R_0$, Eqs. (4) and the DP rate converge up to $O(1)$ factors. In the extended superposition regime $d \gg \sigma_x$, SR with feedback (7) departs from DP because of the χ-dependent acceleration. The divergence at $\chi \to 1$ provides a structural trigger mechanism that DP lacks.

3 Field Dynamics for the Saturation Scalar

3.1 The master equation for χ

We postulate that the saturation scalar obeys:

$$\nabla^\mu \nabla_\mu \chi \;=\; S(x^\mu) - \Gamma_0 \chi - \alpha \chi^2, \tag{8}$$

where $S(x^\mu) \geq 0$ is the branching source density, $\Gamma_0 > 0$ is a baseline linear damping rate, and $\alpha > 0$ is the nonlinear saturation coefficient.

Equation (8) is the simplest covariant nonlinear field equation containing a source, a linear sink, and a quadratic sink. The covariant d'Alembertian $\nabla^\mu \nabla_\mu$ couples χ to the spacetime metric $g_{\mu\nu}$ and ensures general covariance.

3.2 Connection to the local Lindblad sector

The Lindblad sector of Section 2 uses $\chi(t) = S_{\mathrm{vN}}(t)/(\eta\, I_{\mathrm{Bek}})$ as a function of the system's instantaneous state. We identify this with the pointwise value of the spacetime field:

$$\chi_{\mathrm{local}}(t) \;\equiv\; \chi(x^\mu)\big|_{x^\mu \in \text{system region}}. \tag{9}$$

3.3 The nonlinear sink as the irreversibility generator

The crucial structural feature of Eq. (8) is the nonlinear term $-\alpha\chi^2$. The linear damping $-\Gamma_0\chi$ alone would relax χ toward zero in a time-symmetric fashion. The quadratic sink removes branch complexity at a rate proportional to χ^2, generating a positive-feedback loop: regions with higher χ lose complexity faster. We show in Section 6 that this nonlinearity, combined with Landauer's principle, makes time-reversed solutions physically inadmissible.

4 The Trigger Regime Hierarchy

4.1 The isolated-microsystem problem

Consider a ^{60}Co nucleus in deep cosmic vacuum. The local von Neumann entropy is of order a few bits; the Bekenstein bound for the nuclear region is $\sim 10^9$ bits. The saturation ratio $\chi \sim 10^{-9}$ is far from triggering pruning at any reasonable η. Pruning does not fire on the isolated nucleus. This is not a flaw of the framework—it is the structural consequence of the trigger being informational. Exponential decay statistics emerge because the amplitude of the decayed branch evolves unitarily and is registered when the emitted β ultimately interacts with a macroscopic detector whose χ saturates locally.

4.2 Hierarchy of regimes

Regime I — Microscopic isolated systems ($\chi \ll 1$, vacuum). Amplitude evolves unitarily; pruning does not fire; SR is observationally indistinguishable from standard QM. $F(\chi) \approx 1$ and Γ_{dec} reduces to the DP-like form (4).

Regime II — Microscopic systems with environment. Environmental decoherence amplifies S_{vN} in the correlated environment; pruning fires when the environment-system register saturates its bound. SR remains indistinguishable from standard QM with environmental decoherence.

Regime III — Mesoscopic systems with intrinsic saturation. For $\chi \to 1$ to be reached in a system with spatial superposition, the system must combine large S_{vN} with relatively small I_{Bek}. Pure two-branch spatial superposition without additional entangled degrees of freedom yields $S_{\text{vN}} \leq \ln 2$, negligible against any macroscopic I_{Bek}. Contemporary matter-wave interferometry, levitated optomechanics, and the MAQRO program [14] fall into this category: $\chi \ll 1$ and SR is indistinguishable from DP.

Regime IV — High entanglement, no spatial superposition. $d = 0$ (so Γ_{dec} from (7) vanishes formally) but S_{vN} is large due to entanglement with an external subsystem. In DP and CSL, this system would not collapse. In SR, if $S_{\text{vN}} \to \eta\, I_{\text{Bek}}$, the trigger condition is met and pruning fires. This is a qualitatively new prediction, developed in Section 4.3.

Regime V — Macroscopic systems. χ saturates rapidly; pruning fires effectively instantaneously. SR is observationally indistinguishable from CSL, DP, or environmental decoherence.

Regime VI — Black-hole horizons. $\chi = 1$ by construction; pruning operates as the steady-state thermodynamic mechanism of horizon information processing, connecting with Jacobson-style derivations [11].

4.3 Regime IV: high-entanglement collapse without spatial superposition

For $d = 0$ but large S_{vN}, the field equation (8) still drives χ via the source term $S(x^\mu)$ from the entangling interaction. When $\chi \to 1$, pruning fires with a baseline rate $\gamma_0^{(0)}$ from internal degrees of freedom:

$$\tau_{\text{collapse}}^{(d=0)} \sim \frac{1-\chi}{\gamma_0^{(0)}}. \tag{10}$$

A natural candidate is $\gamma_0^{(0)} \sim Gm^2/(\hbar R)$, using the system radius R in place of the vanishing separation d.

Numerical example. For $m = 10^{-5}$ kg, $R = 10^{-4}$ m, $E = mc^2$: $I_{\text{Bek}} \approx 4.1 \times 10^{28}$ bits. With $\eta = 0.1$, $S_{\text{vN}} = 0.09\, I_{\text{Bek}}$ (so $1 - \chi = 0.1$), and $\gamma_0^{(0)} \sim 10^8\,\text{s}^{-1}$:

$$\tau_{\text{collapse}}^{(d=0)} \sim \frac{1}{10^8 \times 0.1} \approx 10^{-7}\,\text{s}. \tag{11}$$

DP predicts no collapse for $d = 0$; CSL predicts collapse only if the stochastic field couples to the relevant mass mode, which is suppressed in this configuration.

4.4 Empirical equivalence in the decay sector

The cosmogenic isotope record, atmospheric muon decay profiles, neutrino flavour oscillations, and ultra-high-energy cosmic-ray composition all reflect amplitude evolution along propagation paths of cosmological length. SR predicts identical statistics to standard QM for these observations. The decay sector is therefore not an SR test regime; discrimination is concentrated in Regime III and Regime IV.

5 Cosmological Heating: Structural Suppression

A standard pressure point on objective-collapse models is the cosmological heating they predict. CSL adds energy to every particle at a fixed rate $\lambda_{\text{CSL}} \sim 10^{-16}\ \text{s}^{-1}$, producing cumulative heating in diffuse media over Hubble time. We show that SR is structurally suppressed by 15–27 orders of magnitude relative to CSL in the same environments.

5.1 Heating rate per particle

The energy injected per pruning event is bounded by the gravitational self-energy distinguishing branches:

$$E_{\mathrm{SR,event}} \sim \frac{Gm^2}{d_{\mathrm{eff}}}, \tag{12}$$

where $d_{\mathrm{eff}} \sim \sigma_x$ for thermal-de Broglie superpositions. The heating rate per particle is $\langle dE/dt \rangle_{\mathrm{SR}} \sim \Gamma_{\mathrm{dec}} \cdot E_{\mathrm{SR,event}}$.

5.2 Comparison across cosmological environments

Table 1 compares SR and CSL heating rates in three representative diffuse cosmological environments.

Table 1: Heating rate per particle in diffuse cosmological environments. SR is structurally suppressed relative to CSL by 15–27 orders of magnitude. Values use $\eta = 0.1$ and $\lambda_{\mathrm{CSL}} = 10^{-16}$ s^{-1}, $r_C = 10^{-7}$ m.

Environment	$(dE/dt)_{\mathrm{SR}}$ [W/part]	$(dE/dt)_{\mathrm{CSL}}$ [W/part]	SR/CSL
IGM ($T \sim 10^4$ K, proton)	$\sim 7 \times 10^{-71}$	$\sim 3 \times 10^{-44}$	$\sim 10^{-27}$
Cluster gas ($T \sim 10^7$ K, proton)	$\sim 7 \times 10^{-68}$	$\sim 3 \times 10^{-44}$	$\sim 10^{-24}$
DM halo (WIMP, $m \sim 100$ GeV)	$\sim 1.5 \times 10^{-57}$	$\sim 2 \times 10^{-42}$	$\sim 10^{-15}$

The cumulative SR heating over Hubble time ($t_H \sim 4 \times 10^{17}$ s) in the IGM yields $\Delta T \sim 10^{-30}$ K per particle, far below any cosmological probe sensitivity.

5.3 Structural reason

The suppression is structural, not parametric. CSL imposes a fixed rate per particle independent of environment. SR conditions the rate on χ, which is suppressed in all coherent and dilute regimes: coherent macroscopic states (BEC, superfluid, Cooper-pair condensate) have S_{vN} collectively suppressed below the trigger; dilute thermal states (IGM, halo, cluster) have small effective separation $d \sim \sigma_x$, suppressing the d^2/σ_x^2 factor. We emphasize that this suppression is shared with DP: in diffuse cosmological environments, $\chi \ll 1$ globally, so $F(\chi) \approx 1$ and SR reduces to its DP-like form. The cosmological argument therefore distinguishes SR from CSL but not from DP.

6 The Arrow of Time as Structural Consequence

We show that temporal directionality emerges as a direct consequence of the nonlinear sink term $-\alpha\chi^2$ in Eq. (8), combined with Landauer's principle.

6.1 Informational cost asymmetry between past and future branches

Postulate 1 (Branch cost asymmetry)**.** The informational cost of a branch at (x^μ, τ) directed toward increasing τ is $C_+ \propto \chi(x^\mu)$. The informational cost of a branch directed toward decreasing τ is $C_- \propto \chi(x^\mu) + \delta\chi_{\rm record}$, where $\delta\chi_{\rm record} \geq 0$ is the additional saturation already imposed by the pruning record of the causal past.

Because $\delta\chi_{\rm record} \geq 0$ by construction (pruning can only increase the net informational occupation of a region), we have $C_- \geq C_+$, with equality only in the empty-universe limit. The pruning process preferentially removes past-directed branches, generating a preferred direction in time.

6.2 Irreversibility from the nonlinear sink

Proposition 1. *The nonlinear term $-\alpha\chi^2$ in Eq.* (8) *generates solutions that are physically irreversible under time reversal, because the time-reversed solution would require un-pruning of erased informational branches, violating Landauer's principle [12].*

Argument. Under $t \to -t$, the d'Alembertian $\nabla^\mu\nabla_\mu$ is invariant. The forward solution has $\chi \approx 0$ at early times and χ growing toward saturation at late times. The time-reversed solution would require χ near saturation at the initial surface and decreasing thereafter—but decreasing χ means branches are being un-pruned, which would require the irreversible erasure of previous pruning events to be undone. By Landauer's principle, such un-erasure cannot occur without external work scaling with the entropy of the erased branches. The time-reversed solution is therefore physically inadmissible.

6.3 The three arrows of time

Proposition 2. *The thermodynamic arrow, the radiation arrow, and the quantum measurement arrow are three aspects of the same mechanism: asymmetric branch pruning driven by $-\alpha\chi^2$, in conjunction with Landauer's principle applied to erased branches.*

Thermodynamic arrow. Each pruning event corresponds to an irreversible erasure of $\Delta N_{\rm bits}$ erased bits:

$$\Delta S_{\rm thermo} = k_B \ln 2\, \Delta N_{\rm bits} \;\geq\; 0, \tag{13}$$

with strict inequality whenever pruning occurs. Thermodynamic entropy increases monotonically toward the future.

Radiation arrow. An advanced (incoming) electromagnetic solution would require the radiation field to be coherent at large spatial separations before the source event. The cost

$$C_{\rm advanced} \;\propto\; \sum_i \big[\chi(x_i^\mu) + \delta\chi_{\rm record}\big] \tag{14}$$

grows with the spatial volume of the coordinated region and diverges in the macroscopic limit. The retarded (outgoing) solution propagates into future-directed branches with unoccupied capacity; its cost is $C_+ \propto \chi$, local and finite. The pruning process strongly suppresses advanced solutions, recovering the radiation arrow.

Quantum measurement arrow. A measurement interaction entangles system with detector, increasing $S_{\rm vN}$ locally. If the entanglement entropy approaches $\eta\, I_{\rm Bek}$, pruning is triggered, selecting one branch and erasing the others irreversibly—without requiring a macroscopic apparatus, observer, or external agent.

6.4 The initial saturation condition and the Big Idle

The argument above shows that given $\chi \approx 0$ at early times, the subsequent dynamics are irreversible. It does not derive $\chi \approx 0$ at the initial surface.

Postulate 2 (Cosmological initial condition)**.** The informational saturation field satisfies $\chi(x^\mu) \approx 0$ at the initial cosmological surface, because no stable branching structure exists prior to the emergence of classical spacetime.

Near the Big Bang singularity, classical time does not yet exist as a stable derived quantity: branches collapse before they can stabilize classical spacetime. In this regime, $\chi \to 0$ is not a fine-tuned condition but the only physically realizable state.

In the asymptotic future, the cosmological constant drives exponential expansion, the Bousso capacity of any local region grows without bound, and $\chi \to 0$ as $I_{\text{Bousso}} \to \infty$. The pruning rate vanishes, branch complexity ceases to be removed, and the arrow of time dissolves: all branches survive, the classical plane dissolves, and Many-Worlds ceases to be an interpretation and becomes the actual physical state. The arrow of time in SR is a transient feature of the intermediate epoch.

7 Visualizing the Pre-Pruning State: The 4D Rose

The visualization adopted throughout this work represents the configuration space of the wavefunction during the period preceding pruning as a 4D Rose: a non-uniform, chiral, branching, directionally-growing geometric object. We argue that the 4D Rose is a more accurate visualization tool than spherical alternatives because it captures structural properties that the symmetric pictures discard.

7.1 Properties a useful visualization should preserve

A visualization of a wavefunction undergoing amplitude growth and parity-violating decays is more useful when it preserves the following five structural features:

1. **Non-uniform branching.** Amplitudes for distinct branches are generically unequal. The geometry must accommodate petals of unequal weight.

2. **Chirality.** The weak interaction violates parity [10] with polarized ^{60}Co; β emission distributions are intrinsically asymmetric under spatial reflection. The geometry must support a definite handedness.

3. **Directional growth.** Pruning is irreversible (Section 6); the amplitude evolution is temporally asymmetric. The geometry must grow forward, not radially outward in equilibrium.

4. **Diffuse boundary.** A wavefunction has no sharp surface; amplitudes decay smoothly. The geometry must have a fractal or fading boundary.

5. **Identifiable origin vertex.** Amplitudes emanate from a generation event. The geometry must have a well-defined center.

7.2 Why spherical alternatives are less useful

A balloon (thin spherical shell) does not preserve (1), (2), or (4). A growing sphere does not preserve (1) or (2). A diffusion cloud does not preserve (1), (2), or (3). None of the standard symmetric visualizations preserve all five features simultaneously.

A rose exhibits unequal petals, definite chirality, directional opening, fractal boundary, and identifiable origin. The choice is pragmatic rather than ontological: among familiar three-dimensional objects, it is the simplest one whose visual properties match all five features at once.

7.3 Connection to parity violation and pruning as petal selection

The chirality requirement is particularly notable. The discovery that the weak interaction violates parity [10] established that nature does not emit isotropic balloons of β radiation: it emits objects with definite handedness. The 4D Rose visualization incorporates this from the outset. A pruning event corresponds, visually, to the selection of a single petal from the multi-petalled rose. The macroscopic detector provides the observer position from which the rose is viewed, but the selection itself occurs on the global causal-diamond surface, not in the detector.

8 Experimental Window and Discriminating Predictions

The discrimination regimes for SR are not located in the parameter space of contemporary matter-wave interferometry or levitated optomechanics. In those experiments, $\chi = S_{\mathrm{vN}}/(\eta\, I_{\mathrm{Bek}}) \lesssim 10^{-20}$ for representative MAQRO-class targets, so $F(\chi) \approx 1$ and the SR rate reduces to the standard DP-extended Lindblad rate (4). We identify three regimes where SR is genuinely distinguishable.

8.1 Regime IV: macroscopic entangled-memory test

The numerical example of Section 4.3 predicts $\tau \sim 10^{-7}$ to 10^{-8} s for a system with $m \sim 10^{-5}$ kg, $R \sim 10^{-4}$ m, and $S_{\mathrm{vN}} \approx 0.9\,\eta\, I_{\mathrm{Bek}}$, but no spatial superposition. DP predicts no collapse for $d = 0$; CSL predicts collapse only if the stochastic field couples to the relevant mass mode, which is suppressed in this configuration. The signature is therefore unambiguous: a finite, non-environmental collapse timescale on the order of 10^{-7} s in a cryogenic entangled-memory system far from the gravitational-self-energy regime.

8.2 Time-reversed interferometric protocols

The arrow-of-time analysis of Section 6 predicts that decoherence becomes structurally harder to reverse as χ increases. A time-reversed interferometric protocol—in which the wavepacket is first partially decohered and then an attempt is made to restore coherence—should require Landauer-cost work to un-prune erased branches. DP and CSL do not couple irreversibility to the local saturation; their predictions for forward and reverse protocols are governed by the same rate equation. The predicted asymmetry between forward and reverse coherence-recovery efficiencies is therefore a structural signature of SR.

8.3 χ-gravitational enhancement

Near a massive body, I_{Bousso} is reduced (the gravitational field reduces the effective causal volume), so χ is locally enhanced even for the same quantum state. SR therefore predicts that the arrow of time—in the operational sense of measurement irreversibility and entropy production—is locally stronger near gravitational sources. This prediction is qualitatively distinct from gravitational time dilation and from DP's gravitational coupling, and is in principle testable with precision thermodynamic measurements in varying gravitational potentials.

8.4 Empirical constraints on η

- *From below*: $\eta > 10^{-3}$ is required for definite classicality emergence in macroscopic systems within reasonable laboratory timescales.
- *From above*: $\eta < 1$ is required to avoid spurious collapse in coherent atomic and molecular systems.
- *Cross-check*: Casini-bound analysis on conventional superconductors, high-T_c materials, and superfluid ^{4}He places the saturation ratio at $\chi \sim 10^{-4}$ to 10^{-1}, compatible with $\eta \sim 0.1$ as the threshold value.

The narrow window (roughly two decades) constitutes a structural constraint: SR is not a free-parameter fit but a tightly constrained framework with η as the only fundamental dimensionless parameter in the dynamical sector.

9 Framework Scope and Companion Cosmological Channel

A separate phenomenological model within the same informational substrate, developed in companion work [16], addresses the late-time suppression of structure growth (the S_8 tension) through gradients of the saturation scalar $I = S_{\text{local}}/I_{\text{Bousso}}$ acting on geodesics via $u^\nu \nabla_\nu u^\mu = \alpha \nabla^\mu I$.

We emphasize that the companion model and the present pruning mechanism are dynamically independent channels of the same informational saturation principle:

- **Channel A (this work)**: discrete branch pruning when S_{local} saturates the bound. Governs wavefunction collapse.
- **Channel B (companion)**: continuous geometric backreaction from ∇I gradients in the unsaturated regime. Governs late-time structure-growth modifications.

9.1 Domains the framework does not address

SR does not address the Hubble tension (a pre-recombination or local-physics problem), the JWST early-galaxy abundance (a primordial structure-formation problem at $z \gtrsim 8$), or baryogenesis and the matter–antimatter asymmetry (which lives at the level of CP-violating Lagrangian terms; SR is CPT-invariant by construction). These limitations are structural, not failures of effort.

10 Discussion

10.1 Summary of core claims

We have presented a consolidated formulation of Stochastic Rupture in which: pruning is triggered by informational saturation on covariant causal-diamond surfaces; the decoherence rate $\Gamma_{\text{dec}} = \gamma_0 F(\chi)\, d^2/(4\sigma_x^2)$ is derived from a Lindblad master equation; the saturation scalar χ is a dynamical field with covariant nonlinear master equation; the trigger regime hierarchy explicitly establishes that isolated micro-events do not generate facts independently of macroscopic registration; Regime IV yields a qualitatively new prediction absent from DP and CSL; cosmological heating is suppressed 15–27 orders of magnitude below CSL; the arrow of time is derived from the nonlinear sink $-\alpha\chi^2$ via Landauer's principle; and the 4D Rose preserves parity violation, irreversibility, and unequal-amplitude branching as a visualization choice.

10.2 Energy conservation

Unlike CSL, where each localization event injects a fixed mean energy into the center-of-mass mode, SR pruning selects branches with Born probabilities and conserves energy on average across events. The variance per event is bounded by the gravitational distinguishability of branches, $\Delta E \sim Gm^2/d$. The cosmological heating analysis confirms that the integrated energy injection over Hubble time is far below all observational sensitivities.

10.3 Open problems and future work

Several directions are in active development:

- **Microscopic justification of η.** The fiducial value $\eta \sim 0.1$ is constrained empirically but lacks a derivation from deeper principles.
- **Microscopic origin of $F(\chi)$.** The feedback function $(1-\chi)^{-1}$ is postulated by minimality. A partial derivation from the Martin–Siggia–Rose–Janssen–De Dominicis fluctuation variance under the coincidence condition $\alpha = \lambda/2$ is presented in the companion field-theory work [17]. A complete derivation from a statistical mechanics of Hilbert space dimension remains open.
- **Microscopic origin of α.** The nonlinear saturation coefficient α is a free parameter. A derivation from gravitational self-energy of pruned branches is needed.
- **Baseline rate $\gamma_0^{(0)}$ for Regime IV.** Equation (10) requires a collapse rate for systems with no spatial superposition. The candidate $\gamma_0^{(0)} \sim Gm^2/(\hbar R)$ is plausible but not derived.
- **Reintroduction of the metric-information relation.** The relation $g_{\mu\nu} = \kappa\nabla_\mu\nabla_\nu(I_{\text{local}}/I_{\text{Planck}})$ is in development for a future extension [18], anchored by the Jacobson derivation.
- **Preferred basis problem.** The choice $\hat{L} = \hat{x}/\sigma_x$ selects position as the preferred basis for collapse. There is no derivation of why position, rather than momentum or energy.

- **Dynamic Bekenstein bound.** The static expression $I_{\text{Bek}} = 2\pi RE/(\hbar c \ln 2)$ uses rest-mass energy. The covariant generalization for dynamical systems undergoing superposition is not fully justified.
- **No-signaling theorem.** A rigorous demonstration that the modulated-rate dynamics is consistent with relativistic causality is in preparation.
- **Strongly gravitating regimes.** Extensions to neutron stars and black-hole horizons, where $\chi \to 1$ by structural rather than statistical mechanisms, are under development.

A On the Possibility of a Deterministic Substrate

The framework as developed is empirically stochastic: pruning selects branches with Born probabilities, and the phenomenology reproduces standard quantum statistics. The question of whether this empirical stochasticity rests on a deeper deterministic substrate is distinct from the question of whether the empirical phenomenology is stochastic.

We summarize a speculative direction in which the SR rate may be the effective expression of an underlying deterministic instability governed by a saturation-controlled feedback in the wavepacket-width dynamics:

$$\ddot{\sigma}_x = \frac{\hbar^2}{4m^2\sigma_x^3} - \frac{2\Lambda(\chi)}{m}\,\sigma_x, \qquad \Lambda(\chi) = \Lambda_0\,\frac{\chi}{1+\chi}. \tag{15}$$

In the saturated regime, this generates a deterministic harmonic contraction with a characteristic timescale $\propto m^{-1/2}$, distinct from the $\propto d^2/\sigma_x^3$ scaling of the empirical phenomenology.

We emphasize the speculative nature of this direction. The present manuscript defends the empirically stochastic SR framework on its own terms; the deterministic substrate hypothesis is offered as a possible conceptual refinement. The technical derivation of Λ_0 from first principles, and the recovery of Born statistics from the deterministic flow, remain open problems.

References

[1] G. C. Ghirardi, A. Rimini, and T. Weber, *Unified dynamics for microscopic and macroscopic systems*, Phys. Rev. D **34**, 470 (1986).

[2] P. Pearle, *Combining stochastic dynamical state-vector reduction with spontaneous localization*, Phys. Rev. A **39**, 2277 (1989).

[3] L. Diósi, *Models for universal reduction of macroscopic quantum fluctuations*, Phys. Rev. A **40**, 1165 (1989).

[4] R. Penrose, *On gravity's role in quantum state reduction*, Gen. Rel. Grav. **28**, 581 (1996).

[5] A. Bassi, K. Lochan, S. Satin, T. P. Singh, and H. Ulbricht, *Models of wave-function collapse, underlying theories, and experimental tests*, Rev. Mod. Phys. **85**, 471 (2013).

[6] S. L. Adler and A. Bassi, *Collapse models with non-white noises*, J. Phys. A **40**, 15083 (2007).

[7] S. Donadi et al., *Underground test of gravity-related wave function collapse*, Nature Physics **17**, 74 (2021).

[8] J. D. Bekenstein, *Universal upper bound on the entropy-to-energy ratio for bounded systems*, Phys. Rev. D **23**, 287 (1981).

[9] R. Bousso, *The holographic principle*, Rev. Mod. Phys. **74**, 825 (2002).

[10] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *Experimental test of parity conservation in beta decay*, Phys. Rev. **105**, 1413 (1957).

[11] T. Jacobson, *Thermodynamics of spacetime: The Einstein equation of state*, Phys. Rev. Lett. **75**, 1260 (1995).

[12] R. Landauer, *Irreversibility and heat generation in the computing process*, IBM J. Res. Dev. **5**, 183 (1961).

[13] D. Z. Albert, *Time and Chance*, Harvard University Press (2000).

[14] R. Kaltenbaek et al., *MAQRO: Quantum Physics in Space*, Exper. Astron. **34**, 123 (2012).

[15] M. Arndt and K. Hornberger, *Testing the limits of quantum mechanical superpositions*, Nature Physics **10**, 271 (2014).

[16] G. Zambuzi, *Late-Time Suppression of Structure Growth from Informational Curvature Relaxation*, Zenodo (2026).

[17] G. Zambuzi, *Stochastic Rupture via State-Dependent Rate Instability in the Reaction-Diffusion Field Theory*, Zenodo (2026).

[18] G. Zambuzi, *Gravitational Dynamics from Informational Pruning: Deriving the Einstein Equation from the Strange 4D Rose*, Zenodo (2026).