Entanglement Flux Relaxation Model (EFRM): Resolving Tensions via Bounded-Stability Boundary Conditions

Nathaniel Uhlenkott[1]

[1] *Interdependent Researcher*

(Dated: January 24, 2026)

We show that persistent cosmological and quantum-gravitational tensions can be resolved by replacing the assumption of a memoryless vacuum with bounded-stability boundary conditions ($\beta \approx 1.701$). By treating the vacuum as a finite-bandwidth, history-bearing manifold, we derive geometric constraints that recover "missing" information and energy as boundary-encoded state variables. These resolutions are formalized in **Appendix A** as a set of falsifiable operational proxies and dataset hooks for existing gravitational-wave and spectroscopic archives.

I. INTRODUCTION

The precision era of cosmology and high-energy physics has revealed persistent tensions—most notably the Hubble Tension [1], the Information Loss Paradox [3], and the Fine-Tuning of fundamental constants [8]. Conventional approaches often address these by introducing new particle content or modifying the Lagrangian.

The central claim of the Entanglement Flux Relaxation Model (EFRM) is not that existing data are incomplete, but that standard inference pipelines implicitly assume a memoryless vacuum with rigid rulers and locally allocatable dissipation channels. When these assumptions are applied to a manifold governed by bounded stability, paradoxes necessarily appear as projection artifacts. EFRM replaces these assumptions with geometric admissibility constraints, yielding testable predictions without introducing new particle content.

A complete falsifiability map is provided in **Appendix A**, including operational estimators for geometric memory ($\mathcal{M}_{\text{geom}}$), ruler elasticity ($\chi_\beta$), and admissible stability volume ($\mathcal{V}_{\text{stable}}$), together with dataset hooks for direct searches in LVK ringdown residuals [6] and BAO inference archives [7].

A. Scope and Limitations

It is critical to delimit the claims of this framework. EFRM does not assert a complete UV completion of quantum gravity, does not propose a new fundamental particle spectrum, and does not require modification of established local tests of General Relativity (e.g., Solar System ephemerides or binary pulsar timing in the weak-field limit). Its claims are strictly restricted to regimes where standard inference assumptions—specifically rigid-ruler geometry and memoryless vacuum background—are known to break down or produce tension. These regimes include the cosmological radiation-to-matter transition (Hubble tension), the strong-gravity horizon limit (Information Loss), and vacuum stability selection (Fine-Tuning). In all other asymptotic limits, EFRM is constructed to reduce to the standard concordance model.

B. Notation and Conventions

Throughout this manuscript we use the following conventions. The stability gate parameter is denoted by $\beta \approx 1.701$ and is treated as a bounded-stability control parameter rather than a tunable fit constant. The geometric memory proxy $\mathcal{M}_{\text{geom}}$ denotes an operational estimator of late-time coherence consistent with boundary-encoded manifold state. The elasticity estimator χ_β is defined as a dimensionless inference-level measure of ruler compression. The admissible stability region in coupling space is denoted $\mathcal{V}_{\text{stable}}$. We use $=$ for definitions, $\propto$ for unnormalized proxies, and $\widehat{=}$ to indicate modeling identification between physical quantities and effective boundary functionals.

II. THE FRAMEWORK

The EFRM framework adopts a single methodological postulate: in regimes where standard inference tensions appear, the vacuum should be modeled not as a passive, memoryless background, but as a finite-bandwidth, history-bearing manifold subject to bounded-stability admissibility constraints. In this view, persistent structure is treated as a property of admissible configurations of the manifold rather than as evidence for additional speculative particle content. We use "packing" only as geometric shorthand for admissible configuration density under bounded stability, not as a claim of discrete microstructure beyond what is operationally defined in Appendix A.

A. The Stability Gate ($\beta \approx 1.701$)

Standard effective descriptions typically assume that vacuum response can be treated as locally memoryless and that geometric reference scales remain rigid under inference across epochs. EFRM replaces these assumptions with an admissibility filter parameterized by a stability gate $\beta \approx 1.701$. The role of β in this manuscript is not to introduce a new force, but to index a bounded stability regime: it summarizes when relaxation remains confined to a Lyapunov-admissible basin versus when inference based on rigid-ruler and memoryless-background assumptions becomes biased.

Operationally, β enters only through falsifiable estimators defined in Appendix A (e.g., χ_β, $\mathcal{M}_{\rm geom}$, and $\mathcal{V}_{\rm stable}$). In all asymptotic limits where local tests of GR/SM are already successful, EFRM is constructed to reduce to standard concordance behavior (Sec. I A).

B. Bounded Stability and Memory

We introduce the β-bubble B_β as the bounded stability basin in which the manifold exhibits finite-bandwidth relaxation and history dependence. Within B_β, EFRM posits two inference-relevant properties:

- **Geometric Memory:** The effective vacuum response is non-Markovian under high-load relaxation. In such regimes, a portion of the system's state is retained as boundary-encoded manifold memory, operationalized by the proxy $\mathcal{M}_{\rm geom}$ (Appendix A 4 a). This provides the mechanism class for the Information Loss reinterpretation without modifying local field content [4].
- **Elastic Response:** During cosmological transitions, the mapping between inferred ruler scales and underlying geometry can become compliant. This is parameterized by the dimensionless elasticity estimator χ_β (Appendix A 4 b), allowing the Hubble tension to be interpreted as an inference-level projection artifact of rigid-ruler assumptions across a non-linear geometric transition.

C. Admissibility as a Replacement for Fine-Tuning

EFRM reframes apparent fine-tuning as a stability selection statement: long-lived vacua occupy a bounded admissible region $\mathcal{V}_{\rm stable}$ in effective coupling space. In this formulation, constants appear tuned because configurations outside $\mathcal{V}_{\rm stable}$ are not dynamically admissible under bounded stability (Appendix A 3 d). This claim is evaluated via the operational stability-width and perturbation protocol defined in Appendix A 4 c.

III. RESULTS AND OBSERVABLES

A. Vacuum Stability and Packing

The stability gate $\beta \approx 1.701$ implies specific geometric capacities for the vacuum manifold. When modeled as a fractal packing problem, the shell capacity scales as β^4, yielding the stability sequence that underpins the observable structure of the Standard Model.

B. Cosmological Implications

By applying the elasticity coefficient χ_β to the epoch of recombination, EFRM predicts a specific deviation in the sound horizon r_s relative to the rigid ΛCDM prediction. This deviation is searchable in current datasets (see Appendix **??**).

IV. COMPARISON TO PREVIOUS WORK

Several existing programs address the tensions considered here, often by introducing new degrees of freedom (e.g., additional scalar fields, modified gravity sectors, or exotic dark fluid components) or proposing altered microphysical mechanisms at horizons [5]. EFRM takes a distinct position: it does not begin by adding new content to the Lagrangian. Instead, it modifies the *boundary assumptions* under which inference is performed, treating the vacuum as a finite-bandwidth, history-bearing medium constrained by bounded stability.

This shift fundamentally alters the interpretation of "missing" quantities:

- **Information Loss:** Approaches based on horizon microstates or holographic encoding typically place information "on" a surface or scramble it into radiation. EFRM does not require information to be externally stored; it allows information to persist as a geometric memory state of the stability shell itself ($\mathcal{M}_{\rm geom}$), enlarging the effective state space without breaking unitarity.
- **Cosmological Tensions:** Many resolutions seek new early-universe physics or modified expansion histories (e.g., Early Dark Energy). EFRM instead permits the standard ruler to act as an inference-dependent geometric variable under bounded non-linear response (χ_β), interpreting the tension as an elasticity signature rather than a contradiction.
- **Fine-Tuning:** The prevailing "Landscape" approach frames constants as environmental variables. EFRM replaces this with an **Admissibility Criterion**: stable vacua occupy a bounded region of parameter space ($\mathcal{V}_{\rm stable}$). This is not an anthropic argument, but a stability filter: constants appear tuned because unstable configurations are topologically forbidden from persisting.

EFRM therefore complements rather than replaces existing effective field theories. It acts as a meta-layer that constrains which effective descriptions remain admissible. The key differentiator is methodological: EFRM prioritizes falsifiable operational proxies and dataset hooks (see **Appendix A 4**), aiming to convert theoretical tensions into executable measurements.

V. CONCLUSION

EFRM reframes several long-standing tensions in cosmology and quantum gravity as failures of inference assumptions rather than failures of data. Specifically, standard pipelines typically assume (i) a memoryless vacuum, (ii) rigid rulers, and (iii) locally allocatable dissipation channels. When these assumptions are applied to a finite-bandwidth, history-bearing manifold governed by bounded stability, paradoxes such as the Hubble tension, black-hole information loss, and apparent fine-tuning arise as projection artifacts of an over-rigid bookkeeping model.

The contribution of this work is therefore not a new particle proposal, but a **stability-first reformulation** in which the vacuum is treated as an admissibility-constrained medium. In this view, "missing" quantities are re-encoded as geometric state variables supported on the stability shell boundary. The resulting framework yields operational estimators—$\mathcal{M}_{\rm geom}$, χ_β, and $\mathcal{V}_{\rm stable}$—that connect the boundary constraints to direct search protocols in existing observational and computational archives (Appendix A).

Falsifiability is explicit. **Appendix A 1** provides kill-switch criteria for each resolution, including the detection of perfectly thermal, structureless black hole radiation, the absence of coherent late-time residuals in post-merger ringdowns, and a strictly invariant sound horizon across inference epochs. These criteria ensure that the framework is testable, refutable, and compatible with standard scientific evaluation.

Appendix A: Formal Paradox Resolution in EFRM

This appendix enumerates the core paradoxes addressed by the Entanglement Flux Relaxation Model (EFRM) and provides (i) an index of each paradox with its falsifier, (ii) a compact classification of solution archetypes, (iii) minimal mathematical statements expressing each resolution as a boundary-condition constraint, and (iv) operational proxies connecting these constraints to measurable observables.

1. Paradox Index (Appendix Grade)

The index below is structured to preserve falsifiability. Each resolution is accompanied by a "kill switch" criterion: a single observational condition that, if confirmed, would invalidate the proposed EFRM mechanism.

2. Solution Archetype Tags

EFRM resolutions cluster into a small set of recurring archetypes:

#	Paradox	Standard Expectation	EFRM Resolution	Tag	Kill
1	Missing Ash	Thermal residue.	Geometric memory.	D	Res
2	Information Loss	Thermal rad.	Shell memory.	D	Pur
3	Hubble Tension	Fixed H_0.	Elastic r_s.	E	Lin
4	Fine-Tuning	Random consts.	Admissible Set.	F	Stal

TABLE I. EFRM Paradox Index (Abbreviated). See text for full definitions.

- **Tag D (Memory-coded):** Missing quantities become persistent manifold state (history / defect / topology).
- **Tag E (Projection artifact):** Apparent paradox arises from enforcing rigid rulers on a relaxing geometry.
- **Tag F (Constraint violation):** "Allowed" freedoms shrink to a bounded admissible stability region.

3. Minimal Mathematical Statements

Each paradox resolution is expressed below as a minimal boundary-condition statement.

a. *Missing Ash (Vacuum Relaxation)*

Let $\rho_{\rm ash}$ denote the effective energy density of relaxation byproducts. EFRM posits suppression via hysteretic storage:

$$\int_V \rho_{\rm ash}\, dV \ll E_{\rm total}. \tag{A1}$$

The "missing" energy is retained as a non-radiating geometric memory mode:

$$\Delta E \,\widehat{=}\, \oint_{\partial B_\beta} d\Sigma\, \mathcal{M}_{\rm geom}, \tag{A2}$$

where $\mathcal{M}_{\rm geom}$ is an effective memory functional. Here B_β denotes the bounded stability basin (the "β-bubble") and ∂B_β its boundary shell.

b. *Information Loss (Unitary Evolution)*

EFRM replaces "loss" with a factorization into radiation *and* a stability-shell memory state:

$$\hat{S}\,|\Psi_{\rm in}\rangle = |\Psi_{\rm out}\rangle \otimes |{\rm Shell}_\beta\rangle, \tag{A3}$$

where $|{\rm Shell}_\beta\rangle$ encodes the history-bearing stability shell.

c. Hubble Tension (Geometric Compression)

r_s is modulated at decoupling by a bounded non-linear response coefficient χ_β:

$$r_{s,\mathrm{obs}} = r_{s,\mathrm{std}} \left(1 - \chi_\beta \frac{\Delta\rho}{\rho_c}\right), \tag{A4}$$

where $\Delta\rho/\rho_c$ is a dimensionless loading measure.

d. Fine-Tuning (Admissible Sets)

Constants $\{\alpha_i\}$ must lie in an admissible stability region $\mathcal{V}_{\mathrm{stable}}$:

$$\{\alpha_i\} \in \mathcal{V}_{\mathrm{stable}} \iff \lim_{t\to\infty} \left|\frac{\partial\beta}{\partial\alpha_i}\right| < \epsilon. \tag{A5}$$

4. Operational Observables and Dataset Hooks

a. Geometric Memory Proxy ($\mathcal{M}_{\mathrm{geom}}$)

Hook: LVK O4/O5 strain archives (High-SNR BH mergers).
Metric: Ratio of stochastic residual power to structured echo power.

Define the tail autocorrelation $\mathcal{C}(\tau) \equiv \langle x(t)\, x(t+\tau)\rangle_{t\geq t_{\mathrm{relax}}}$, where $x(t)$ is the whitened ringdown residual channel after subtraction of the best-fit inspiral-merger-ringdown template.

$$\mathcal{M}_{\mathrm{geom}} \propto \int_0^\infty \mathcal{C}(\tau)\, d\tau, \tag{A6}$$

b. Elasticity Coefficient (χ_β)

Hook: DESI/Euclid BAO inference pipelines ($z > 2$ vs $z < 1$).
Metric: Slope of the inferred standard ruler across scale factor a.

$$\chi_\beta \approx -\frac{\partial}{\partial(\ln a)} \left(\frac{r_{s,\mathrm{obs}}}{r_{s,\mathrm{std}}}\right). \tag{A7}$$

c. Stability Sensitivity ($\mathcal{V}_{\mathrm{stable}}$)

Hook: Lattice-QCD / GR-MHD perturbation suites.
Metric: Stability width of the admissible parameter volume.

$$\mathrm{Vol}(\mathcal{V}_{\mathrm{stable}}) = \int d\alpha_1 \cdots d\alpha_n\, \mathbb{1}_{\mathrm{stable}}(\{\alpha_i\}). \tag{A8}$$

[1] Riess, A. G., et al. (2021). A comprehensive measurement of the local value of the Hubble constant with 1 km/s/Mpc uncertainty from the Hubble Space Telescope and the SH0ES Team. *The Astrophysical Journal Letters*, *934*(1), L7.

[2] Planck Collaboration. (2020). Planck 2018 results. VI. Cosmological parameters. *Astronomy & Astrophysics*, *641*, A6.

[3] Hawking, S. W. (1976). Breakdown of predictability in gravitational collapse. *Physical Review D*, *14*(10), 2460.

[4] Page, D. N. (1993). Information in black hole radiation. *Physical Review Letters*, *71*(23), 3743.

[5] Almheiri, A., Marolf, D., Polchinski, J., & Sully, J. (2013). Black holes: Complementarity or firewalls? *Journal of High Energy Physics*, *2013*(2), 62.

[6] Abbott, B. P., et al. (LIGO Scientific Collaboration and Virgo Collaboration). (2016). Observation of Gravitational Waves from a Binary Black Hole Merger. *Physical Review Letters*, *116*(6), 061102.

[7] DESI Collaboration. (2016). The DESI Experiment Part I: Science,Targeting, and Survey Design. *arXiv preprint arXiv:1611.00036*.

[8] Weinberg, S. (1989). The cosmological constant problem. *Reviews of Modern Physics*, *61*(1), 1.