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On the Black Hole Information Loss Paradox under a Novel Phenomenological Model of Quantum Measurements

Aman Chawla

REAL Institute, Gurugram and IIT Delhi, New Delhi, India
Email: editor@realinstitute.live

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Abstract

In this paper, the authors propose a phenomenological framework for addressing the black hole information loss paradox using the Gravity Branch Model (GBM) of quantum measurements. In this approach, quantum measurement branching is dynamically constrained by local spacetime curvature, producing effective selection of semiclassically consistent trajectories. We develop Schrödinger-like and master equation formulations for the GBM, apply it to a detector of Hawking radiation, and examine how gravitationally suppressed branch proliferation modifies the apparent information content. Our analysis suggests that information loss in black holes can be reinterpreted as curvature-induced pruning of quantum measurement branches, rather than fundamental nonunitarity, with experimentally constrained coupling strengths ensuring consistency with laboratory observations.

Keywords

Black Holes, Information Loss, Quantum Measurements, Page Curve, Entropy, Schrodinger Equation

1. Introduction and Overview

The black hole information loss paradox [1] arises from the apparent tension between quantum unitary evolution and the semiclassical description of black hole evaporation. In standard treatments, Hawking radiation emerges as a thermal flux, leading to mixed states for distant observers and suggesting a breakdown of information conservation. Numerous approaches, including the holographic principle, firewalls, and black hole complementarity, have been proposed [2] [3], yet a fully consistent microscopic understanding remains elusive.

In this work, we examine the paradox through the lens of the Gravity Branch Model (GBM) of quantum measurements, recently introduced in a phenomenological context. The GBM recognizes that quantum measurements, if extended over finite durations, generate a branching structure in Hilbert space. Each branch corresponds to a potential measurement outcome, but spacetime curvature provides a natural dynamical constraint on branch proliferation. The essential idea is that gravitational interactions penalize large deviations from a semiclassically consistent reference branch, effectively pruning branches that would otherwise produce incompatible stress-energy distributions. This framework unifies three key ingredients: 1) quantum measurement dynamics, 2) local spacetime curvature, and 3) branching paths, which collectively enable a reinterpretation of apparent information loss.

Here, we apply the GBM to black hole evaporation, considering a model detector placed at varying distances from a Schwarzschild black hole. We analyze how curvature-dependent suppression of measurement branches affects the evolution of the detector's reduced state and discuss implications for the apparent loss of information. Our approach bridges phenomenological laboratory constraints on GBM coupling strengths with astrophysical regimes of strong curvature.

2. Methods

2.1. Development and Reasoning behind the Gravity Branch Model

The Gravity Branch Model (GBM) arises from the observation that quantum measurements, if extended over finite durations, generate a *tree of possible outcomes* in Hilbert space. Each branch represents a potential result of a measurement event.

2.1.1. Discrete Measurement Branching

Consider a system with an initial state $\left|\Psi_0\right\rangle$. A projective measurement with finite duration ΔT generates an interpolated evolution from the pre-measurement state $\left|\Psi_{\text{pre}}\right\rangle$ to a post-measurement state $\left|\Psi_{\text{post}}\right\rangle$:

$$\left|\Psi(t)\right\rangle = \left(1 - f(t)\right)\left|\Psi_{\text{pre}}\right\rangle + f(t)\left|\Psi_{\text{post}}\right\rangle,\quad 0 \le t \le \Delta T, \tag{1}$$

where $f(0) = 0$, $f(\Delta T) = 1$ is a smooth function (e.g., sigmoid or linear). Repeated measurements at intermediate times $t_2, t_4, \cdots$ generate a *branching tree*, with each new measurement interpolating from the current branch to its post-measurement endpoint.

2.1.2. Schrödinger-Like Evolution for Measurement Paths

Analogous to Feynman's path integral construction for unitary evolution, we propose a Schrödinger-like equation for measurement branches:

$$i\hbar \frac{\mathrm{d}}{\mathrm{d}t}\left|\Psi_{\text{branch}}(t)\right\rangle = \hat{H}_0\left|\Psi_{\text{branch}}(t)\right\rangle - i\hbar\Gamma G \cdot \left(\left|\Psi_{\text{branch}}(t)\right\rangle - \left|\Psi_{\text{ref}}(t)\right\rangle\right), \tag{2}$$

where:

- $\hat{H}_0$ is the system Hamiltonian,
- G quantifies deviation from a *reference branch* $|\Psi_{\text{ref}}\rangle$ which, for example, can be defined as the cluster mean of the tree's branches,
- Γ is a phenomenological rate controlling branch suppression.

2.1.3. Incorporating Gravity

We posit that local spacetime curvature R constrains branch excursions. The gravitationally weighted suppression is encoded via:

$$\Gamma \to \Lambda(R),\ \Lambda(R) = \xi_0 \left(\frac{R}{R_P}\right)^{\beta}, \tag{3}$$

where R_P is the Planck-scale curvature, ξ_0 is a laboratory-bounded coupling, and β controls curvature scaling. Branches implying large local deviations from semiclassical spacetime geometry acquire a larger $\Lambda(R)$, causing them to decay faster.

2.1.4. Reduced Density Matrix Evolution

Tracing over inaccessible degrees of freedom (e.g., the infalling Hawking partner modes) gives the detector density matrix:

$$\frac{\mathrm{d}\rho_{\text{det}}}{\mathrm{d}t} = -\frac{i}{\hbar}\left[\hat{H}_{\text{det}}, \rho_{\text{det}}\right] + \mathcal{D}_{\text{meas}}\left[\rho_{\text{det}}\right] - \Lambda(R)\mathcal{G}\left[\rho_{\text{det}}\right], \tag{4}$$

where $\mathcal{D}_{\text{meas}}$ represents standard measurement-induced decoherence, and $\mathcal{G}$ encodes gravitational suppression of off-reference branches.

2.1.5. Summary of Key Steps

1) Start from a discrete measurement event with smooth interpolation from pre- to post-measurement states.

2) Allow repeated measurements at intermediate times, generating a branching tree of potential outcomes.

3) Introduce a Schrödinger-like evolution equation for each branch, with a non-unitary damping term proportional to deviation from a reference branch.

4) Assign a gravitationally dependent coupling $\Lambda(R)$ to penalize branches incompatible with the local spacetime curvature.

5) Trace over inaccessible modes to obtain a reduced density matrix for the observable subsystem, revealing curvature-dependent decoherence.

This framework forms the basis of the GBM, providing a natural connection between quantum measurements, branching dynamics, and gravitational constraints, and allowing reinterpretation of apparent information loss in black hole evaporation scenarios.

2.2. Details of the Gravity Branch Model

The GBM (see **Figure 1**) introduces a Schrödinger-like evolution for a quantum system subjected to measurements in a curved background. Let $|\Psi(t)\rangle$ denote the pure state of the system plus apparatus. The effective evolution is

$$i\hbar \frac{\mathrm{d}}{\mathrm{d}t}\left|\Psi(t)\right\rangle = \hat{H}_0\left|\Psi(t)\right\rangle - i\hbar\Lambda(R)G\cdot\left(\left|\Psi(t)\right\rangle - \left|\Psi_{\mathrm{ref}}(t)\right\rangle\right), \tag{5}$$

where $\hat{H}_0$ is the unitary Hamiltonian, R is the local curvature, $\Lambda(R)$ is a curvature-dependent coupling strength, G is a positive-definite operator[1] encoding deviations from the reference. The non-Hermitian term implements gravitational suppression of incompatible branches.

A natural choice for G is the gravitational self-energy kernel associated with the mass-density operator $\hat{\rho}(\boldsymbol{r})$:

$$G = \frac{G_N}{\hbar}\iint \mathrm{d}^3r\,\mathrm{d}^3r' \frac{\left(\hat{\rho}(\boldsymbol{r}) - \rho_{\mathrm{ref}}(\boldsymbol{r})\right)\left(\hat{\rho}(\boldsymbol{r}') - \rho_{\mathrm{ref}}(\boldsymbol{r}')\right)}{\left|\boldsymbol{r}-\boldsymbol{r}'\right|}, \tag{6}$$

where $\rho_{\mathrm{ref}}(\boldsymbol{r})$ is the reference mass distribution, typically chosen[2] to minimize the effective gravitational energy of the branch ensemble. The choice of G made here effectively couples the gravitational and quantum degrees of freedom.

For ensemble-level or unconditioned descriptions, we derive a density-matrix evolution of Lindblad form:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\frac{i}{\hbar}\left[\hat{H}_0, \rho\right] + \sum_f \left(L_f \rho L_f^{\dagger} - \frac{1}{2}\left\{L_f^{\dagger} L_f, \rho\right\}\right), \tag{7}$$

where $L_f = \sqrt{\gamma}\int \mathrm{d}^3r\, f(\boldsymbol{r})\hat{\rho}(\boldsymbol{r})$ are gravitationally weighted Lindblad operators, and $\gamma \sim \Lambda(R)G_N/\hbar$ sets the suppression rate. This formalism ensures positivity and allows computation of decoherence effects while retaining compatibility with laboratory constraints.

Gravity as a Branch-Selection Mechanism. Standard decoherence theory, as formulated by Joos and Zeh (1985), explains the suppression of interference between components of a quantum superposition through entanglement with environmental degrees of freedom. While this dynamically drives the density matrix toward a diagonal, quasi-classical form, it does not provide a physical mechanism that selects a unique outcome; many decohered branches persist in parallel. By contrast, in a curvature-dependent framework, gravitational back-reaction constrains the set of physically admissible branches (via pruning or non-unitary damping). Quantum histories that imply incompatible stress–energy distributions induce large curvature discrepancies, which in turn amplify a non-unitary suppression term proportional to $\Lambda(R)$, effectively pruning dynamically unstable branches. Only trajectories consistent with smooth semiclassical spacetime survive as long-lived pointer states, while others rapidly decay. Thus gravity functions not merely as an environment producing decoherence, but as an active dynamical selection rule, enforcing internal consistency of geometry and yielding a single robust classical outcome.

Resolution of the Symmetry Objection. A central critique of gravity-based branch pruning models is the claim that the selection of a reference branch ψ_{ref}

[1] G was introduced in Equation (3).

[2] possibilities for the reference include cluster mean where the mean is taken over the branch ensemble; if the minimum is not a branch then the branch closest to the minimum can be considered.

implicitly breaks symmetry by arbitrarily privileging a particular outcome. This concern can be resolved by defining ψ_{ref} not as an externally imposed choice, but as the consensus representative of a cluster of post-measurement candidate states. Let $\{\psi_i\}$ denote the decohered branches compatible with the macroscopic measurement context. We define the reference branch as the geometric median (or Fréchet mean) within this set,

$$\psi_{\text{ref}} = \arg\min_{\psi \in \{\psi_i\}} \sum_j d\left(\psi, \psi_j\right),$$

where $d(\cdot,\cdot)$ is a Hilbert-space metric such as the Fubini–Study distance or curvature-weighted trace distance. This construction preserves symmetry initially and yields spontaneous symmetry breaking only through dynamical stability: the surviving branch is the one most consistent with all others and with smooth semiclassical geometry. In this sense gravity enforces collective self-consistency rather than arbitrary selection, providing a principled mechanism for physical outcome uniqueness.

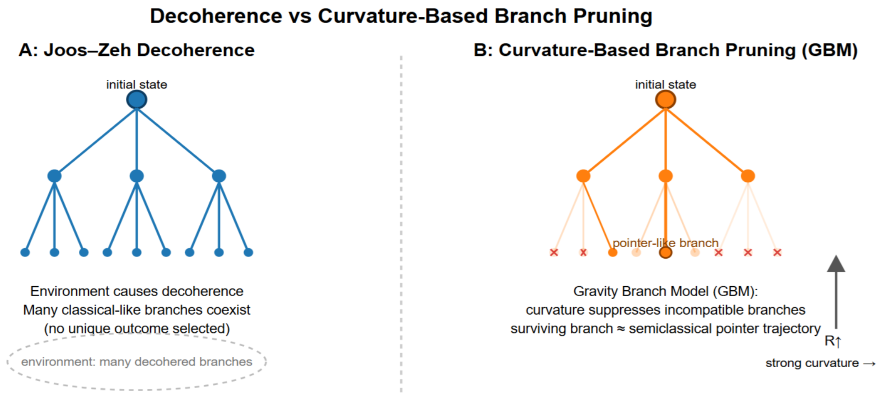

Figure 1. Comparison of standard Joos–Zeh decoherence (left), which suppresses interference but leaves many classical-like branches coexisting, versus curvature-based branch pruning (right), where gravitational back-reaction suppresses dynamically inconsistent branches and selects a stable pointer-like trajectory.

2.3. Application to Hawking Radiation Detection

Consider a Schwarzschild black hole of mass M with Schwarzschild radius $r_s = 2GM/c^2$. Hawking radiation arises from entangled pairs of modes near the horizon. The outgoing mode a_ω is detected by a measurement apparatus at radius r_d, while the infalling partner b_ω falls behind the horizon. The initial state of a single frequency mode is

$$\left|\Psi_\omega\right\rangle = \sum_{n=0}^{\infty} \mathrm{e}^{-\pi\omega n/\kappa} \left|n\right\rangle_a \left|n\right\rangle_b, \tag{8}$$

with $\kappa = c^4/(4GM)$ the surface gravity.

The detector-field system obeys the GBM evolution:

$$i\hbar \frac{\mathrm{d}}{\mathrm{d}t}\left|\Psi(t)\right\rangle = \left(\hat{H}_{\text{rad}} + \hat{H}_{\text{det}} + \hat{H}_{\text{int}}\right)\left|\Psi(t)\right\rangle - i\hbar\Lambda(R_d)G\left(\left|\Psi(t)\right\rangle - \left|\Psi_{\text{ref}}(t)\right\rangle\right), \tag{9}$$

where $\hat{H}_{\text{int}}$ describes local photon detection. The curvature at the detector is estimated from the Kretschmann scalar:

$$R_d \sim \frac{48G^2M^2}{c^4 r_d^6}. \tag{10}$$

2.4. Curvature-Dependent Coupling

We adopt a phenomenological scaling for $\Lambda(R)$:

$$\Lambda(R_d) = \xi_0 \left(\frac{R_d}{R_P}\right)^{\beta}, \tag{11}$$

with $R_P = c^3/\hbar G$ the Planck curvature, ξ_0 bounded by laboratory experiments, and β a dimensionless exponent controlling the growth with curvature. Typical bounds from mesoscopic interferometry set $\xi_0 \lesssim 10^{-12}$ - 10^{-15}, ensuring negligible effects in low-curvature settings.

2.5. Reduced Density Matrix for the Detector

Tracing over radiation modes yields a reduced detector density matrix:

$$\frac{\mathrm{d}\rho_{\text{det}}}{\mathrm{d}t} = -\frac{i}{\hbar}\left[\hat{H}_{\text{det}}, \rho_{\text{det}}\right] + \mathcal{D}_{\text{Hawking}}\left[\rho_{\text{det}}\right] - \Lambda(R_d)\mathcal{G}\left[\rho_{\text{det}}\right], \tag{12}$$

where $\mathcal{D}_{\text{Hawking}}$ represents the standard open-system interaction with the thermal Hawking bath, and $\mathcal{G}$ encodes gravitationally induced damping of off-reference branches.

3. Results

3.1. Branching Dynamics and Curvature Suppression

The GBM formalism predicts that each photon detection spawns potential branches corresponding to distinct detector outcomes. The gravitational term suppresses branches whose implied mass-energy distributions would significantly alter local curvature. Near a stellar-mass black hole, the curvature at the detector can be large enough that $\Lambda(R_d)$ approaches order unity, producing rapid pruning of incompatible branches.

Numerical estimates for two-mode toy models indicate that the damping timescale $\tau_{\text{grav}} \sim 1/\Lambda(R_d)\langle G\rangle$ can vary from milliseconds near the horizon to effectively infinite at laboratory distances. This demonstrates that GBM provides a distance-dependent transition from standard quantum branching to gravitationally constrained, effectively classical trajectories.

3.2. Entropy and Information Flow

The von Neumann entropy of the detector's reduced state, $S(\rho_{\text{det}}) = -\text{Tr}(\rho_{\text{det}} \ln \rho_{\text{det}})$, quantifies apparent information loss. Under GBM evolution, curvature-dependent pruning reduces the effective branch multiplicity, limiting entropy growth for detectors near strong curvature. Far from the black hole, GBM reduces to standard quantum measurements, yielding thermal-like entropy consistent with Hawking predictions.

3.3. Comparing GBM's Entropy Predictions and the Page Curve

The Page curve describes the time evolution of the von Neumann entropy of Hawking radiation under unitary black hole evaporation. In its standard form, the entropy of the radiation subsystem,

$$S_{\text{rad}}(t) = -\text{Tr}\rho_{\text{rad}}(t)\log\rho_{\text{rad}}(t), \tag{13}$$

initially increases as radiation is emitted and entangled with the remaining black hole, reaches a maximum at the Page time, and then decreases back to zero as the system purifies.

In contrast, the Gravity Branch Model (GBM) introduces a non-unitary correction to Schrodinger evolution:

$$i\hbar\frac{\mathrm{d}}{\mathrm{d}t}|\Psi(t)\rangle = \hat{H}_0|\Psi(t)\rangle - i\hbar\Lambda(R)G\cdot(|\Psi(t)\rangle - |\Psi_{\text{ref}}(t)\rangle), \tag{14}$$

where $\Lambda(R)$ modulates the strength of gravitational pruning, and G encodes the gravitational self-energy of deviations from a reference branch.

To compare entropy evolution, we expand the state $|\Psi(t)\rangle$ in a joint system basis:

$$|\Psi(t)\rangle = \sum_{i=1}^{N(t)} c_i(t)|i\rangle_{\text{BH}} \otimes |i\rangle_{\text{rad}}. \tag{15}$$

Under GBM, the branch weights acquire a curvature-dependent suppression:

$$|c_i(t)|^2 \propto |c_i^{\text{U}}(t)|^2 \exp[-2K_i(t)], \tag{16}$$

where

$$K_i(t) = \int_0^t \mathrm{d}\tau\,\Lambda(R(\tau))g_i(\tau), \tag{17}$$

and

$$g_i(\tau) = \frac{G_N}{\hbar}\iint \mathrm{d}^3r\mathrm{d}^3r'\frac{\Delta\rho_i(\boldsymbol{r}\tau)\Delta\rho_i(\boldsymbol{r}'\tau)}{|\boldsymbol{r}-\boldsymbol{r}'|}. \tag{18}$$

Assuming approximate orthogonality of branches[3], the reduced radiation density matrix becomes diagonal:

$$\rho_{\text{rad}}(t) \approx \sum_i p_i(t)|i\rangle\langle i|, \tag{19}$$

with

$$p_i(t) = \frac{\lambda_i^{\text{U}}(t)\mathrm{e}^{-2K_i(t)}}{\sum_j \lambda_j^{\text{U}}(t)\mathrm{e}^{-2K_j(t)}}. \tag{20}$$

The GBM entropy is therefore

[3]GBM dynamically damps incompatible branches.

$$S_{\text{GBM}}(t) = -\sum_i p_i(t)\log p_i(t). \tag{21}$$

For comparison, the unitary Page curve assumes approximately uniform weights at early times:

$$\lambda_i^{\text{U}}(t) \approx \frac{1}{N(t)},\ S_{\text{U}}(t) \approx \log N(t) \tag{22}$$

and a clear distinction emerges from the proposed model, which can serve as the foundation for testability.

3.4. Compatibility with Laboratory Bounds

By setting ξ_0 consistent with interferometry experiments, the GBM coupling does not produce detectable deviations from quantum superpositions in low-curvature environments. The formalism therefore reconciles terrestrial constraints with potential strong-gravity effects near black holes, providing a self-consistent framework for extrapolating laboratory-based bounds to astrophysical scenarios.

4. Limitations

While the Gravity Branch Model offers a novel phenomenological framework for addressing aspects of the black hole information paradox, several significant limitations must be acknowledged.

4.1. Measurement-Gravity Coupling

The central mechanism linking spacetime curvature to quantum measurement branching in Equstion (2) is introduced phenomenologically rather than derived from first principles. The fundamental question of *why* local curvature should constrain measurement outcomes—and *how* gravitational fields acquire knowledge of quantum branching structures—remains unaddressed. A complete theory would require derivation from an underlying quantum gravity framework or demonstration that such coupling emerges naturally in appropriate limits. The theory of Nonlocal Unification [4] can possibly be applied in this context.

4.2. Coupling Strength Extrapolation

The phenomenological coupling $\xi_0 \lesssim 10^{-12}$ - 10^{-15} is bounded by terrestrial experiments, while black hole applications require extrapolation across ~60 orders of magnitude in curvature. The functional form $\Lambda(R) = \xi_0 (R/R_P)^\beta$ with free exponent β allows enormous flexibility. Without theoretical constraints on β or higher-order corrections, predictions in the strong-curvature regime remain underconstrained.

4.3. Physical Consistency

4.3.1. Back-Reaction and Self-Consistency

The formalism treats spacetime curvature R as a fixed background affecting quantum evolution. However, the quantum state itself sources curvature through the stress-energy tensor. A fully consistent treatment requires showing that gravitationally suppressed branches remain compatible with Einstein's equations, or demonstrating that back-reaction corrections are negligible in relevant regimes.

4.3.2. Causality and Locality

The suppression mechanism must respect causal structure. If branch pruning affects spacelike-separated measurement events, this could enable superluminal signaling. The formalism should include explicit demonstration that causal propagation is preserved, particularly when $\Lambda(R)$ varies significantly across a spatial region.

4.4. Astrophysical Signatures

Direct detection of Hawking radiation from astrophysical black holes remains far beyond current capabilities. The framework could explore indirect signatures: modifications to gravitational wave emission from binary mergers, effects on accretion disk physics, or imprints on primordial black hole evaporation in the early universe.

4.5. Scope and Generality

The present analysis is restricted to:

- Schwarzschild (non-rotating, uncharged) black holes
- Two-mode toy models of Hawking radiation
- Static detector configurations
- Weak-coupling approximations in the reduced dynamics

Extensions to Kerr black holes, charged (Reissner-Nordström) solutions, dynamical detectors with back-reaction, and strong-coupling regimes are necessary for a comprehensive study.

5. Brief Discussion and Future Work

Despite these limitations, the GBM provides a concrete, parameterized framework for exploring gravitational constraints on quantum measurements. Its phenomenological character allows experimental constraints while maintaining sufficient flexibility for theoretical development. The identification of these limitations serves as a roadmap for transforming the present proposal into a comprehensive, testable theory.

5.1. Interpretation of Information Loss

In GBM, apparent black hole information loss arises from gravitationally constrained branch proliferation rather than fundamental nonunitarity. The pruning mechanism ensures that only branches compatible with semiclassical spacetime geometry remain significant, while branches leading to inconsistent stress-energy profiles are suppressed. This perspective naturally unifies quantum measurement theory with gravitational considerations, offering a concrete mechanism for reconciling Hawking radiation with semiclassical consistency.

5.2. Predictions and Observables

The framework predicts a distance-dependent suppression of quantum superpositions in detectors of Hawking radiation. Near the horizon, branch pruning can significantly reduce observable interference effects, while far away, standard quantum behavior is recovered. Although direct detection of Hawking photons remains beyond current technology, analogous systems (e.g., analog gravity or condensed-matter setups) may allow experimental probes of GBM-like damping effects.

5.3. Relation to Previous Work

The GBM extends previous phenomenological collapse models [5] [6] by incorporating measurement branching explicitly and linking the suppression strength to local spacetime curvature. Unlike continuous measurement formalisms [7], GBM maintains discrete measurement events, enabling a clear mapping between measurement trees and gravitationally constrained evolution. It offers a concrete, parameterized bridge between laboratory constraints on mass-dependent collapse rates and astrophysical black hole physics.

5.4. Future Directions

Several avenues remain open:

- **Many-mode Hawking radiation:** Extending the two-mode toy models to full field-theoretic treatments, allowing quantitative calculation of entropy evolution for realistic black holes.
- **Detector dynamics:** Incorporating fully dynamical detectors, including finite-time interactions and backreaction, to refine predictions of branch selection.
- **Curvature-dependent couplings:** Exploring functional forms of $\Lambda(R)$ consistent with both terrestrial and astrophysical constraints, including potential nonlinear dependencies on the Kretschmann scalar.
- **Numerical simulations:** Developing stochastic Schrödinger or density-matrix simulations of measurement trees under GBM evolution to assess the robustness of entropy reduction and information preservation.
- **Experimental analogues:** Investigating laboratory analogues of GBM, such as optomechanical or Bose-Einstein condensate setups with effective gravitational-like couplings, to test the phenomenological predictions.

6. Conclusion

We have formulated a Gravity Branch Model of quantum measurements applicable to black hole evaporation scenarios. By introducing curvature-dependent suppression of measurement branches, GBM provides a framework in which apparent information loss is reinterpreted as gravitationally enforced selection of semiclassically consistent trajectories. The approach bridges laboratory constraints on quantum collapse models with astrophysical settings, offering a unifying picture that preserves global unitarity while reproducing effective thermal behavior for distant observers. Future work will explore detailed multi-mode simulations, field-theoretic extensions, and potential experimental probes.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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