

Quantum Simulation of Horizon Memory Combs: A Finite-Memory Framework for Unitarizing Black Hole Evaporation

1 Introduction

The reconciliation of general relativity with quantum mechanics remains the premier challenge in fundamental physics, most acutely manifested in the black hole information paradox. The semiclassical analysis of black hole evaporation, first articulated by Hawking, predicts a thermal radiation spectrum that depends solely on macroscopic quantities—mass, charge, and angular momentum—thereby implying a non-unitary evolution that transforms pure initial states into mixed thermal states. This violation of unitarity, known as the information loss problem, suggests a breakdown in our understanding of either quantum dynamics or the equivalence principle.

To resolve this paradox within a unitary framework, the entanglement entropy of the Hawking radiation must follow the Page curve: rising initially as the black hole evaporates and builds entanglement with the radiation field, but eventually turning over and decreasing to zero as the black hole disappears, ensuring the final state of the radiation is pure. Standard semiclassical derivations, which implicitly assume a Markovian (memoryless) emission process, yield a monotonically increasing entropy curve—the so-called “Information Lock”—that leads to a catastrophic loss of information or the formation of pathological remnants.

Recent theoretical advances have proposed the Horizon Memory Comb (HMC) framework as a solution that preserves semiclassical spacetime structure outside the horizon while enforcing unitarity through non-Markovian dynamics. The HMC postulates that the black hole horizon functions as a finite-capacity quantum memory, physically identified with gravitational edge modes or “soft hair,” which mediates entanglement between the interior and the asymptotic radiation. Unlike proposals that require macroscopic non-locality or high-energy firewalls, the HMC achieves information recovery through “gentle,” causally retarded interactions governed by a quantum comb—a sequential quantum channel with memory.

This research report details the theoretical architecture and algorithmic implementation required to simulate the HMC framework on a gate-based quantum computer. While classical simulations using Process-Tensor Matrix Product Operators (PT-MPO) have validated the entropic bounds of the HMC, a quantum simulation offers a native platform to explore the complexity of the scrambling dynamics and the multipartite entanglement structure of the evaporation process. By mapping the HMC’s axioms—specifically the Area-Memory Correspondence, Fast Scrambling, and Adiabatic Dilution—to a quantum circuit model, we provide a falsifiable, operational definitions of unitary evaporation. We derive the explicit unitaries required to simulate the shrinking memory code subspace, present a complete Qiskit implementation of the “Minimal Comb” circuit, and analyze the observable signatures of non-Markovianity, such as $g^{(2)}$ intensity sidebands, that distinguish this model from thermal Hawking radiation.

2 Theoretical Architecture of the Horizon Memory Comb

The Horizon Memory Comb framework reconstructs the black hole evaporation process not as a sequence of independent, memoryless events, but as a structured quantum process with finite memory depth. This section dissects the foundational axioms and derived properties that govern the HMC, establishing the physical constraints that our quantum simulation must satisfy.

2.1 Foundational Axioms and the Assumption Ladder

The HMC is constructed upon a hierarchy of assumptions, distinguishing between unconditional results derived from standard Quantum Field Theory (QFT) in curved spacetime and conditional results dependent on holographic conjectures. This "Assumption Ladder" is critical for demarcating the regime of validity for our simulation.

Axiom 1: Semiclassical Exterior and Hadamard Structure. The framework assumes that the spacetime region exterior to the stretched horizon is globally hyperbolic and that the quantum state maintains the Hadamard property throughout the evaporation process. The Hadamard condition is a rigorous criterion for the short-distance singularity structure of the two-point correlation functions, ensuring that the renormalized stress-energy tensor $\langle T_{\mu\nu} \rangle_{ren}$ is well-defined and finite. This axiom is the bedrock of the "No-Firewall" condition; it implies that any deviations from the vacuum state near the horizon must be energetically "gentle" to avoid macroscopic back-reaction that would destroy the horizon geometry. In our simulation, this constrains the energy density of the emitted radiation and the strength of the coupling between the memory and the radiation field.

Axiom 2: Locality and Finite Memory (l_{mem}). Contrary to models that invoke instantaneous non-locality, the HMC posits that dynamics are spatially local and that the coarse-grained evolution exhibits a finite memory depth, denoted as l_{mem} . This depth corresponds to the thermal mixing time of the horizon fluid. Information entering the memory (via infalling matter or backflow) influences outgoing radiation only for a duration proportional to l_{mem} , after which correlations decay exponentially. This axiom allows us to truncate the infinite history of the black hole into a manageable "sliding window" for simulation, making the computation tractable on finite-resource quantum hardware.

Axiom 3: Fast Scrambling and Quantum Chaos. The internal dynamics of the horizon memory are assumed to be chaotic, specifically acting as a "fast scrambler". In the strongest form (conditional on holographic conjectures C1-C3), the dynamics form an approximate unitary 2-design on a timescale $t_{scr} \sim \beta \log S_{BH}$. This implies that the unitary evolution U_{scr} randomizes quantum information over the memory register so thoroughly that no local measurement can distinguish the state from a Haar-random state. We utilize this property to justify using random quantum circuits or parameterized quantum circuits (PQCs) with high expressibility in our simulation kernel.

Axiom 4: Adiabaticity. The evaporation is treated as an adiabatic process where the fractional mass loss rate is small compared to the internal dynamical timescales ($\dot{M}/M \ll 1/t_{scr}$). This allows for the definition of quasi-stationary emission windows where the thermodynamic parameters (temperature T_H , entropy S_{BH}) are approximately constant. This axiom validates the use of discrete time steps in our quantum circuit, where parameters are updated between steps to reflect the slow evolution of the background geometry.

2.2 The Area-Memory Correspondence (P0)

A pivotal derived property of the HMC is the Area-Memory Correspondence (Theorem 18 in the source text), which quantifies the information capacity of the horizon. The theorem states that the horizon supports a quantum memory register, H_{mem} , whose effective dimension d_{mem} is bounded by the exponential of the Bekenstein-Hawking entropy:

$$\log d_{mem}(u) = S_{BH}(u) + S_0 + O\left(\frac{A(u)}{l_p^2}\right) \quad (1)$$

where $S_{BH}(u) = A(u)/4G\hbar$. This correspondence provides a geometric interpretation of the memory: it is not an arbitrary auxiliary system but is physically identified with the gravitational edge modes—degrees of freedom localized at the boundary of the spacetime region (the stretched horizon) that arise from the breaking of diffeomorphism invariance.

In the context of quantum simulation, this property dictates the size of the qubit register allocated to the memory. Crucially, because the black hole area $A(u)$ decreases during evaporation (due to energy conservation and the Stefan-Boltzmann law), the dimension of the memory register d_{mem} must strictly decrease over time. This presents a fundamental challenge for unitary simulation: how to reduce the

dimension of a quantum system without measuring it or tracing it out (which introduces mixedness). The HMC resolves this via the principle of Unitary Dilution (P4), described below.

The constant S_0 in the Area-Memory relation collects scheme-dependent zero-mode contributions and is generally of order $O(\log S_{BH})$. For the purposes of our simulation, this term contributes to the error budget of the Page curve but does not alter the fundamental turnover dynamics. The correspondence implies that the "Information Lock" of Markovian models is broken because the capacity of the channel carrying information from the past to the future (the memory) eventually becomes the bottleneck, forcing information to leak into the radiation field.

2.3 The Role of the Auxiliary System E_n

To implement the shrinking memory dimension unitarily, the HMC introduces an auxiliary output system E_n at each step. The total outgoing system is defined as the tensor product of the primary Hawking radiation R_n (detectable hard quanta) and this auxiliary system:

$$O_n = R_n \otimes E_n \quad (2)$$

The physical interpretation of E_n is of paramount importance for the consistency of the theory. It is identified with the "soft sector" at future null infinity (\mathcal{I}^+)—specifically, the soft gravitons and BMS supertranslation/rotation edge modes required to restore the factorization of the S-matrix. Standard infrared factorizations (Kulish-Faddeev) suggest that hard scattering processes are always accompanied by soft emissions. In the HMC, E_n captures the "shedding" of the gravitational dressing associated with the information leaving the black hole.

From an operational standpoint within the simulation, E_n functions as a trash bin for the entropy associated with the code space reduction. However, strict bounds derived from Quantum Energy Inequalities (Lemma 6 in [Source]) and weak coupling arguments (Theorem 69 in [Source]) ensure that the energy flux carried by E_n is parametrically small:

$$\Phi_E^{(E)}(u) \leq C_{IR}\omega_{cut}\Xi_R(u, u) \quad (3)$$

where ω_{cut} is the infrared cutoff. This implies that while E_n is necessary for formal unitarity, the operationally accessible entropy $S(R_{\leq n})$ tracks the theoretical total entropy $S(O_{\leq n})$ within a negligible error margin. Our simulation will explicitly track $S(R)$ to verify that the purification is visible in the hard radiation sector alone, a critical feature for experimental verifiability.

2.4 The qTPE Route to Scrambling

A significant theoretical advancement in the HMC framework is the derivation of scrambling properties without relying on full AdS/CFT duality. The source material delineates a "primary qTPE route" (Theorem 63 in [Source]), which utilizes Quantum Tensor Product Expanders (qTPEs). This approach relies only on QFT-level hypotheses (R1-R3): KMS analyticity, Eikonal/Regge bounds on scattering, and finite-speed operator growth.

The qTPE condition is weaker than the assumption of a unitary t-design but sufficient to guarantee decoupling. It states that the second moment of the operator ensemble ν approximates the Haar average with a spectral gap γ :

$$\left\| M_\nu^{(2)} - \Pi_{Haar} \right\|_{2 \rightarrow 2} \leq 1 - \gamma \quad (4)$$

This gap γ is related to the Lyapunov exponent λ_L of the chaotic dynamics. The HMC establishes that for 4D Einstein-Hilbert dynamics, the chaotic scattering near the horizon generates a sufficient gap to ensure that information is rapidly delocalized. In our quantum simulation, we model this by applying random unitary circuits that are known to converge to 2-designs (and thus form qTPEs) with a depth that scales logarithmically with the number of qubits, $\text{Depth} \propto \log N$. This explicitly links the circuit depth of our simulation to the scrambling time t_{scr} of the black hole.

Table 1 summarizes the hierarchy of assumptions and their role in the simulation architecture:

3 The Comb Page Theorem and Decoupling Dynamics

The theoretical core of the HMC simulation is the Comb Page Theorem, which provides the analytical prediction for the entropy curve we aim to reproduce. It extends Page's original argument to the case

Tier	Level	Assumptions	Role in Simulation
Tier 1	QFT Backbone	KMS Analyticity, Regge Bounds, Finite v_B	Defines the memory depth l_{mem} and ensures unitarity
Tier 2	Operational	Adiabaticity (A4), Area-Memory (P0)	Defines the qubit count scaling and the unitarity
Tier 3	Holographic	MSS Saturation, ETH, Ramp	Justifies the random unitary ansatz for scrambling

Table 1: Hierarchy of assumptions and their role in the simulation architecture.

of a channel with memory, proving that unitarity is restored up to small corrections governed by the memory characteristics.

3.1 Derivation via Decoupling

The theorem is derived using one-shot decoupling techniques applied to the process tensor. The radiation state at step n is obtained by tracing out the interior and memory systems. The distance of the radiation state from the maximally mixed state (which represents thermal noise) is bounded by the decoupling condition. The theorem states that decoupling—and thus the purification of early radiation by late radiation—sets in once the accumulated radiation entropy exceeds the remaining black hole entropy.

The Comb Page Theorem (Theorem 36/41 in [Source]) asserts:

$$S(O_{\leq n}) = \min \left\{ \sum_{k=1}^n s_k, S_{BH}(u_n) + S(I_0, M_0) \right\} \pm \delta_{Page}(n) \quad (5)$$

Here, the error term $\delta_{Page}(n)$ is not merely a hand-waved correction but a rigorous error budget derived from the HMC axioms:

$$\delta_{Page}(n) \leq C \left(\epsilon_{spec} + \epsilon_2 + e^{-n/\tau_{mix}} + e^{-r/\xi} \right) + (c_0 + c_1 \log S_{BH}) \quad (6)$$

This error budget is critical for validating our simulation results. Each term corresponds to a specific physical parameter that can be tuned in the quantum circuit:

- ϵ_{spec} (Greybody Spectral Error): Represents the mismatch between the discrete qubit swap operation and the continuous greybody spectrum of a real black hole. In the simulation, this is controlled by the coupling angle θ in the emission unitary.
- ϵ_2 (Scrambling Error): Quantifies how close the scrambling unitary U_{scr} is to a perfect 2-design. This is controlled by the depth of the scrambling circuit. Shallow circuits will yield a large ϵ_2 , causing deviations from the Page curve and a failure to fully purify the radiation (simulating a "remnant" or incomplete evaporation).
- $e^{-n/\tau_{mix}}$ (Mixing Error): Reflects the finite memory depth. If the simulation window (memory depth) is too short compared to the correlation time, this error dominates, and the non-Markovian correlations are lost.
- $c_0 + c_1 \log S_{BH}$: Represents the irreducible contribution from the edge modes and continuity bounds (Alicki-Fannes).

3.2 The "Min" Formula Mechanics

The "min" function in the Page theorem represents a competition between two entanglement surfaces (in the holographic language) or two capacities (in the channel language).

Early Phase ($n < n_{Page}$): The memory M is large. The channel capacity from the interior to the radiation is limited by the dimension of the radiation emitted so far. The radiation is maximally entangled with the memory, so $S(R)$ grows linearly with n .

Late Phase ($n > n_{Page}$): The memory M has shrunk significantly. The capacity is now limited by the dimension of M . The strong scrambling dynamics (P2) ensure that the memory is maximally entangled with the early radiation. Therefore, any new radiation emitted, which is entangled with M , effectively becomes entangled with the early radiation. This "entanglement swapping" reduces the total entropy of the radiation subsystem $R_{\leq n}$, causing the curve to turn over.

The HMC provides the mechanism for this turnover: the finite memory M acts as the bridge. In a Markovian model, M is effectively reset or infinite, so this bridge never forces the saturation of the capacity, and the entropy grows indefinitely.

4 Quantum Circuit Mapping and Algorithms

Translating the continuum HMC formalism into a discrete gate-model quantum simulation requires a precise mapping of Hilbert spaces and operators. We adopt the "Minimal Comb" architecture referenced in Appendix N of the source text, expanded here for implementation on NISQ (Noisy Intermediate-Scale Quantum) devices.

4.1 Discretization and Qubit Allocation

We map the continuous time coordinate u to discrete steps k , with width $\Delta u \sim \kappa^{-1}$ (the inverse surface gravity). The Hilbert space is partitioned into three logical registers:

Memory Register (M): Represents the active degrees of freedom on the stretched horizon.

- **Implementation:** A fixed set of q_M qubits.
- **Dynamics:** The effective dimension d_{mem} is managed not by adding/removing qubits physically, but by restricting the "active" subspace or by varying the coupling to the radiation.
- **Physical Analogue:** Edge modes of the gravitational field.

Interior Register (I): Represents the infalling partners of the Hawking pairs and the initial collapsing matter.

- **Implementation:** A fixed set of q_I qubits.
- **Dynamics:** Entangled with M during the initial "collapse" phase. In standard HMC, I does not interact directly with R ; all interactions are mediated by M .

Radiation Register (R): Represents the asymptotic Hawking radiation.

- **Implementation:** A dynamically growing register, where a new qubit R_k is initialized in the state $|0\rangle$ at each time step k .
- **Dynamics:** Once emitted, R_k does not participate in further gates (no re-scattering), preserving the causality of the asymptotic observer.

4.2 The Step Unitary and Dilation (P4)

The evolution at step k is governed by a unitary $U_{step}^{(k)}$ acting on $M \otimes I \otimes R_k$. This unitary is decomposed into scrambling and emission sub-routines.

A. The Scrambling Operator (U_{scr}) To satisfy Axiom 3 (Fast Scrambling), we apply a unitary that mixes information across the Memory and Interior registers.

$$U_{scr}^{(k)} : H_M \otimes H_I \rightarrow H_M \otimes H_I \quad (7)$$

On a quantum processor, we implement this as a "hardware-efficient ansatz": a layered sequence of single-qubit rotations (R_y, R_z) and entangling gates (CNOT or CZ).

Depth Condition: To approximate a 2-design (Property P2), the depth D of this circuit must scale as $O(\log(q_M + q_I))$. In our simulation code, we provide the option to use exact random unitaries (via `unitary_group`) for ideal validation, or parameterized circuits for hardware execution.

B. The Emission Operator (U_{emit}) This operator realizes the "read" head of the comb, extracting information from the memory to the radiation. It implicitly implements the Stinespring dilation (P4) that shrinks the memory's information content.

$$U_{emit}^{(k)} : H_M \otimes H_{R_k} \rightarrow H_M \otimes H_{R_k} \quad (8)$$

We model this interaction as a partial SWAP operation between a specific qubit in the Memory register (the "edge" qubit) and the fresh Radiation qubit R_k .

$$U_{emit}(\theta) = \exp\left(-i\frac{\theta}{2}(X_M X_R + Y_M Y_R)\right) \quad (9)$$

Coupling Strength θ : This parameter controls the evaporation rate. $\theta = \pi/2$ corresponds to a full SWAP (maximal evaporation), while small θ corresponds to the adiabatic regime (A4) where information leaks slowly. This models the greybody factors $\Gamma(\omega)$ of the black hole.

4.3 Simulating Memory Shrinkage

In a physical black hole, d_{mem} shrinks as e^{-k} . In a fixed-qubit simulation, we simulate this effect by changing the entropic flow.

- **Early Time:** The scrambling U_{scr} creates entanglement between I and M . The emission U_{emit} is weak. The entropy of the "black hole" ($M + I$) effectively stays high or grows.
- **Evaporation:** The emission U_{emit} removes entanglement from M and transfers it to R .
- **Endgame:** We can simulate the vanishing area by gradually turning off the scrambling on subsets of M qubits or by forcibly swapping them out to an auxiliary "dump" register E , although for the Page curve turnover, the partial swap dynamics on a finite register are sufficient to observe the effect.

4.4 Observables and Measurement

The primary observable is the Von Neumann entropy of the accumulated radiation, $S(R_{\leq n})$.

$$S(R_{\leq n}) = -\text{Tr}(\rho_{R_{\leq n}} \log \rho_{R_{\leq n}}) \quad (10)$$

Calculating this requires access to the reduced density matrix $\rho_{R_{\leq n}}$.

- **Tomography:** For small systems ($n < 6$), full state tomography is feasible.
- **Shadow Estimation:** For larger systems, we can use classical shadow tomography to estimate non-linear functionals like Renyi entropies $S_2 = -\log \text{Tr}(\rho^2)$ as a proxy for Von Neumann entropy.
- **Simulation Mode:** In the provided Python code, we use statevector simulation to compute the entropy exactly, providing a noise-free baseline for theoretical validation.

5 Implementation and Algorithmic Strategy

The implementation strategy focuses on scalability and verification. We utilize the Qiskit SDK to construct the quantum circuits. The core logic is encapsulated in a `BlackHoleComb` class (see Appendix for code).

5.1 Process-Tensor vs. Gate-Based Simulation

It is crucial to distinguish between the classical PT-MPO simulation mentioned in the source text and the gate-based simulation proposed here.

- **PT-MPO (Classical):** Uses tensor network contraction to simulate the process tensor $\Upsilon_{n:0}$. Scaling is limited by the bond dimension χ , which governs the amount of entanglement the simulation can handle. It is excellent for checking asymptotic bounds ($N \rightarrow \infty$).
- **Gate-Based (Quantum):** Physically realizes the entanglement. Scaling is limited by qubit count and coherence time. This method is uniquely suited to probe the complexity of the scrambling unitary and to detect non-classical correlations like $g^{(2)}$ sidebands without truncation approximations.

5.2 Algorithmic Protocol

The simulation proceeds in the following steps:

1. **Initialization:** Prepare $|0\rangle^{\otimes(q_M+q_I)}$.
2. **Formation:** Apply an initial scrambling layer to create the "black hole" state with volume-law entanglement between M and I .
3. **Evaporation Loop ($k = 1 \dots N$):**
 - Allocate radiation qubit R_k .
 - Apply U_{scr} to $M \oplus I$.
 - Apply U_{emit} between M_{edge} and R_k .
 - (Optional) Apply a "reset" or swap to an auxiliary E_k if simulating explicit soft hair loss.
4. **Analysis:** Compute $S(R_{\leq k})$ at each step.

5.3 Noise Mitigation Strategies

To run this on actual hardware (e.g., IBM Quantum), error mitigation is essential because noise generally increases entropy, artificially straightening the Page curve and masking the turnover (the "thermal death" of the simulation).

- **Zero-Noise Extrapolation (ZNE):** We scale the noise by inserting identity gates (e.g., UU^\dagger) and extrapolating the measured entropy to the zero-noise limit.
- **Symmetry Protection:** The evaporation process should conserve total angular momentum or charge if modeled. We can post-select runs that violate these conservation laws.
- **Purification:** We assume the global state is pure ($S_{total} = 0$). We can filter the measured density matrix to find the closest pure state, removing incoherent noise contributions.

6 Predictions, Validation, and Experimental Signatures

The simulation is designed to test specific falsifiable predictions of the HMC.

6.1 The Page Curve Turnover

The most immediate validation is the reconstruction of the Page curve.

- **Prediction:** $S(R_{\leq n})$ should rise linearly until $n \approx (q_M + q_I)/2$ (the Page time), then decrease to zero.
- **Failure Mode:** If the scrambling is insufficient (ϵ_2 is large), the curve will flatten but not return to zero, indicating a "remnant" scenario where information remains locked in the hole.
- **Verification:** The provided code calculates this explicitly. A successful run confirms that the unitary dilation mechanism (P4) coupled with scrambling (P2) is sufficient to restore unitarity.

6.2 Non-Markovian $g^{(2)}$ Sidebands

A distinguishing feature of the HMC is the prediction of temporal correlations in the radiation flux, absent in thermal Hawking radiation.

- **Observable:** The second-order intensity correlation function $g^{(2)}(\tau) = \langle I(t)I(t+\tau) \rangle / \langle I \rangle^2$.
- **Prediction:** In a memoryless thermal source, $g^{(2)}(\tau) = 2$ (bunching) with no time structure. The HMC predicts sidebands: oscillatory deviations from the thermal baseline at time lags τ corresponding to multiples of the memory depth l_{mem} .
- **Mechanism:** These correlations arise because the radiation at step t and step $t + l_{mem}$ interacted with the same distinct packet of information as it cycled through the scrambled memory register.
- **Significance:** Observation of these sidebands in an analogue experiment or quantum simulation would be a "smoking gun" for finite-memory horizons, falsifying the Markovian hypothesis.

6.3 Gravitational Wave Echoes and Analogue Gravity

The HMC framework extends beyond qubit simulation to phenomenological predictions for gravitational wave astronomy.

- **Ringdown Echoes:** The finite memory structure modifies the black hole ringdown. The HMC predicts "echoes" in the gravitational waveform following a merger, with a time delay $\Delta t_{echo} \sim \tau_{mem} \sim \beta \log S_{BH}$.
- **Analogue Gravity:** The simulation logic maps directly to Bose-Einstein Condensates (BECs) simulating acoustic black holes. The "Radiation" qubits map to phonons, and the "Memory" to the condensate density fluctuations at the horizon. The $g^{(2)}$ sidebands predicted here are directly measurable in phonon coincidence counting experiments.

6.4 Resource Scaling and Feasibility

For a minimal demonstration ($q_M = 2, q_I = 2, N = 8$), the total qubit requirement is 12. This is well within the limits of current superconducting processors (e.g., IBM Eagle/Heron). The circuit depth is dominated by the N scrambling layers. If each scrambler has depth d , total depth is $N \times d$. With $N = 12$ and $d \approx 5$, the total depth ≈ 60 is approaching the coherence limit, making error mitigation critical.

7 Discussion and Future Directions

We have presented a comprehensive framework for simulating the Horizon Memory Comb on quantum computers. By translating the abstract axioms of the HMC—area-memory correspondence, fast scrambling, and adiabatic dilation—into concrete quantum circuits, we have provided a tool to explore the non-perturbative dynamics of black hole evaporation.

The results of the simulation (using the provided code) are expected to confirm that a finite-memory mechanism can unitarize evaporation without requiring firewalls, provided the "gentleness" constraints (P3) are met. The error analysis highlights that the fidelity of the Page curve recovery depends critically on the scrambling rate (ϵ_2) and the adiabaticity of the emission.

Future Directions:

- **Beyond Adiabaticity:** Extending the simulation to model violent non-adiabatic events, such as black hole mergers, by introducing time-dependent couplings $\theta(t)$ and memory sizes.
- **Charged/Rotating Black Holes:** Introducing symmetries (U(1) charge) into the scrambling unitaries to simulate the evaporation of Reissner-Nordström or Kerr black holes, verifying the universality of the memory kernel (Theorem 88 in [Source]).
- **Kernel Tomography:** Using quantum machine learning to reconstruct the effective memory kernel $\Xi_R(\omega)$ from the simulated radiation data, testing whether it satisfies the Kramers-Kronig relations required by causality.

This work bridges the gap between abstract quantum gravity conjectures and experimental quantum information science, offering a pathway to test the fundamental laws of the universe on the processors of today.