Quantum Memory Matrices as String-Imprint Reservoirs in Planckian Geometry

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Abstract

We propose a novel framework that merges the recently introduced Quantum Memory Matrix (QMM) formalism—modeling space-time as a discrete lattice of Planck-scale memory cells preserving quantum information—with weakly coupled string-theoretic backgrounds. In this setting, space-time is not continuous but composed of quantum memory sites through which string or brane excitations propagate. We formulate a toy model wherein worldsheet-based string scattering amplitudes interact with the QMM lattice, imprinting quantum data on memory cells during propagation or interaction events. This allows us to track the non-local memory loops induced by strings and explore their consequences for observable quantities. Our analysis suggests that such memory loops could lead to measurable CP-violating phase shifts, corrections to mixing parameters in the Standard Model, or potentially contribute to stochastic gravitational wave backgrounds through Planck-scale imprint residuals. This work opens a new avenue for probing the interplay between string dynamics and quantum information retention in a discretized background geometry.

***K*eywords** Quantum Memory Matrix · String Theory · Discrete Space-Time · Planck-Scale Physics · Quantum Information · Black Hole Information Paradox · String Scattering Amplitudes · Imprint Dynamics · CP Violation · Gravitational Wave Signatures

1 Introduction

The reconciliation of quantum information theory with fundamental physics has led to a renewed interest in models of space-time that possess intrinsic memory and discrete structure. One promising direction is the recently proposed *Quantum Memory Matrix* (QMM) framework, which models space-time as a discrete lattice of Planck-scale memory cells that retain quantum information about particle interactions, black hole evaporation, and causal histories [1]. Unlike classical spacetime, QMM encodes interaction history via non-local, gauge-invariant quantum imprints, offering a potential resolution to the black hole information paradox [2].

Meanwhile, string theory continues to provide a candidate framework for quantum gravity, unifying gauge interactions and gravity via extended one-dimensional objects whose worldsheet dynamics describe particle interactions at high energies [3]. Traditionally, strings propagate over smooth manifolds or supergravity backgrounds; however, it remains unclear how they behave in fundamentally discrete, information-preserving geometries.

In this work, we propose to merge these paradigms by considering string or brane excitations propagating through a QMM-type discrete background. We postulate that such interactions generate persistent imprints on the QMM lattice, potentially forming closed "memory loops" that preserve aspects of string worldsheet dynamics. To explore this, we formulate a toy model where string scattering amplitudes (inspired by twistor string or worldsheet techniques [4]) couple to QMM memory cells.

Our goal is to investigate whether such memory-mediated interactions can yield phenomenologically testable effects. These may include subtle CP-violating phase shifts, corrections to fermion mixing angles, or residual imprints detectable via gravitational wave interferometry. By combining methods from quantum information, discrete geometry, and string theory, we introduce a new framework to probe quantum gravitational effects via imprint dynamics in a non-continuum spacetime.

2 Related Work

Our proposal lies at the intersection of several previously distinct research directions: discrete models of quantum gravity, black hole information retention, and string-theoretic formulations of high-energy interactions. Here, we briefly review each area and highlight how our approach uniquely combines them.

2.1 Discrete and Quantum Information-Theoretic Models of Space-Time

Discrete formulations of space-time, such as causal sets [5], loop quantum gravity [6], and tensor networks [7], have long attempted to capture the microstructure of geometry. However, these models typically lack explicit memory retention mechanisms. The recently proposed Quantum Memory Matrix (QMM) [1] fills this gap by encoding quantum interactions into memory cells at the Planck scale. Each cell stores gauge-invariant, non-local imprints, making the geometry itself a dynamic record of quantum history. Extensions of QMM to gauge fields and black hole evaporation suggest new pathways for resolving the black hole information paradox [8].

2.2 Black Hole Information and Memory Effects

A major challenge in quantum gravity is the unitarity of black hole evaporation. Models such as soft hair [9] and quantum hair [10] propose storing quantum information in near-horizon degrees of freedom. While they provide partial resolution, they generally remain semi-classical or perturbative. The QMM framework instead offers a microscopic, fully quantum approach to space-time memory. Complementary approaches, such as gravitational memory effects and BMS symmetries [11], emphasize residual information left in the asymptotic structure of space-time. Our approach generalizes this to include string-theoretic memory.

2.3 String Theory in Non-Traditional Backgrounds

String theory traditionally assumes smooth, continuous target spaces, but recent interest in string dualities, non-commutative geometries [12], and discrete compactifications has motivated the study of non-standard backgrounds. Notably, twistor strings [4] and topological string theory have explored worldsheet constructions sensitive to geometric and topological features of space-time. However, these formulations have not yet been applied to discrete or quantum-information-based geometries. Our work is the first to consider how string excitations might interact with, and leave persistent imprints on, a QMM-type background.

3 Toy Model: String Propagation through QMM Lattice

To formalize the interaction between string excitations and discrete space-time memory, we construct a toy model in which a fundamental string propagates through a discretized background defined by a Quantum Memory Matrix (QMM). The QMM lattice is composed of memory cells indexed by integer tuples $x^\mu \in \mathbb{Z}^4$, each cell corresponding to a Planck-scale volume element. These cells are capable of encoding quantum imprint data from traversing excitations.

3.1 QMM Lattice and Memory Imprints

Each cell in the QMM lattice, denoted M_x, is initialized in a vacuum memory state $|0\rangle_x$. Upon traversal by a quantum excitation (e.g., a string vertex operator), the cell records an *imprint operator* $\mathcal{I}_x[\phi]$ that depends on the local string field content $\phi(\sigma,\tau)$ evaluated near x. The cell's state evolves as:

$$|0\rangle_x \to \mathcal{I}_x[\phi]\,|0\rangle_x\,, \tag{1}$$

where $\mathcal{I}_x[\phi]$ is assumed to be unitary to preserve information.

3.2 String Worldsheet–Lattice Coupling

Let $X^\mu(\sigma,\tau)$ denote the string embedding coordinates. The QMM lattice induces discrete interaction points x_i whenever $X^\mu(\sigma_i,\tau_i) \in \mathcal{V}_{x_i}$, where $\mathcal{V}_{x_i}$ is the Planck-scale cell volume centered at x_i. We define an effective interaction

action:

$$S_{\text{int}} = \sum_i \int d^2\sigma \, \delta^{(4)}(X(\sigma) - x_i) \, \log \mathcal{I}_{x_i}[\phi], \tag{2}$$

which contributes to the full string path integral:

$$\mathcal{A}_{\text{QMM}} = \int \mathcal{D}X \, e^{i(S_{\text{ws}} + S_{\text{int}})}, \tag{3}$$

where S_{ws} is the standard Polyakov or twistor-string worldsheet action [4].

3.3 Imprint Loops and Observables

As strings interact with the QMM lattice, the sequence of imprinted cells $\{x_1, x_2, \ldots, x_n\}$ forms a memory loop $\mathcal{L} = \bigcirc_i \mathcal{I}_{x_i}[\phi]$. These loops may encode non-trivial holonomies or phase rotations:

$$\mathcal{L} \sim \exp(i\theta_{\text{CP}}), \tag{4}$$

potentially contributing to CP-violating observables in low-energy physics. For closed string processes, imprint loops may carry conserved topological charge or memory parity, depending on the excitation type.

3.4 Example: Tree-Level Scattering with Imprint Encoding

As a concrete case, consider a closed string tachyon amplitude at tree-level:

$$\mathcal{A}_{\text{tree}} = \langle V(k_1)V(k_2)V(k_3)V(k_4)\rangle, \tag{5}$$

with vertex operators $V(k_i)$ inserted at points that intersect QMM cells. Each interaction modifies the amplitude by a factor $\langle \mathcal{I}_{x_i}[k_i]\rangle$. The full observable amplitude becomes:

$$\widetilde{\mathcal{A}} = \mathcal{A}_{\text{tree}} \cdot \prod_{i=1}^{4} \langle \mathcal{I}_{x_i}[k_i]\rangle. \tag{6}$$

These correction terms could introduce CP-violating or flavor-dependent phase shifts, and might survive in effective field theory as higher-order operators.

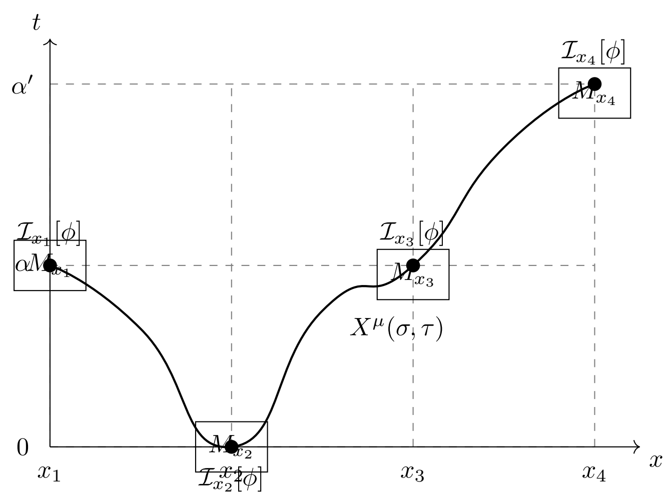

Figure 1: A string worldsheet path $X^\mu(\sigma, \tau)$ intersecting discrete QMM lattice cells M_{x_i} at Planck-scale points, where quantum imprint operators $\mathcal{I}_{x_i}[\phi]$ act.

4 Phenomenological Implications

The interaction between string excitations and the QMM lattice leads to persistent imprints—quantum memory records—across discrete space-time. These imprint loops, especially when formed by closed string processes or repeated traversals, may yield observable consequences at low energies. Below we outline three key classes of such signatures.

4.1 CP Violation from Imprint Holonomies

The QMM memory loops $\mathcal{L}$ formed by string interactions can encode global phase rotations. In cases where $\mathcal{L} \sim \exp(i\theta_{\text{CP}})$, the memory-induced phase θ_{CP} may contribute to physical CP violation. For instance, in analogy with the θ-term in QCD, a non-vanishing θ_{QMM} could introduce effective operators like:

$$\mathcal{L}_{\text{eff}} \supset \theta_{\text{QMM}} F_{\mu\nu} \tilde{F}^{\mu\nu}, \tag{7}$$

or generate asymmetric decay probabilities in meson systems. If QMM-induced CP violation feeds into the quark or lepton sectors, it may manifest as small deviations in the CKM or PMNS matrices, testable via precision flavor experiments [13].

4.2 Mixing Matrix Corrections via Imprint Couplings

The imprints $\mathcal{I}_{x_i}[\phi]$ can couple differently to fermion species, inducing effective non-diagonal mass or kinetic terms when averaged over the lattice. This results in flavor transitions or altered mixing angles. For example, an imprint-weighted Yukawa correction:

$$\delta\mathcal{L}_{\text{Yuk}} = \sum_{i,j} \lambda_{ij} \langle \mathcal{I}_x[\psi_i^\dagger \psi_j] \rangle \phi, \tag{8}$$

can introduce corrections δU_{PMNS}, possibly detectable in neutrino oscillation experiments such as DUNE or JUNO [14].

4.3 Gravitational Wave Memory and Stochastic Backgrounds

Loops of string-induced memory may accumulate energy-momentum transfer at the Planck scale and modify the propagation of gravitational waves (GWs) through QMM spacetime. This could result in a stochastic imprint-induced background or "step-like" corrections to GW memory. For long-baseline detectors like LISA or the Einstein Telescope, such corrections might appear as non-Gaussian features in the power spectrum [15]. Additionally, primordial string-QMM interactions could seed nanohertz gravitational noise visible in pulsar timing arrays [16].

5 Imprint Algebra and Categorical Framework

To model the quantum-information-theoretic structure underlying QMM–string interactions, we define an *imprint algebra* that captures how quantum excitations leave persistent traces on discrete memory cells. This algebraic structure is then lifted to a categorical setting, enabling abstract reasoning over imprint compositions, conservation laws, and causal consistency.

5.1 Imprint Algebra

Let $\mathcal{M} = \{M_x\}_{x\in\mathbb{Z}^4}$ denote the set of QMM memory cells. Each M_x is associated with a local imprint space $\mathcal{H}_x$ (typically finite-dimensional) and an operator algebra $\mathcal{A}_x$ acting on it.

We define the *Imprint Algebra* $\mathcal{I}$ as a graded algebra:

$$\mathcal{I} = \bigoplus_{n=1}^{\infty} \mathcal{I}^{(n)}, \tag{9}$$

where $\mathcal{I}^{(n)}$ consists of all length-n memory loops:

$$\mathcal{I}^{(n)} := \text{span}\left\{\mathcal{I}_{x_1}[\phi_1] \circ \mathcal{I}_{x_2}[\phi_2] \circ \cdots \circ \mathcal{I}_{x_n}[\phi_n]\right\},$$

with each $\mathcal{I}_{x_i}[\phi_i] \in \mathcal{A}_{x_i}$. Composition is associative when spacetime order is respected:

$$\mathcal{I}_x[\phi] \circ \mathcal{I}_y[\psi] = \begin{cases} \mathcal{I}_{x,y}[\phi \otimes \psi] & \text{if } x \prec y, \\ 0 & \text{otherwise,} \end{cases}$$

where $x \prec y$ denotes a causal ordering of cells.

5.2 Categorical Encoding of Imprints

To capture the flow of quantum data across QMM cells, we define a monoidal category $\mathbf{QMM}$:

- **Objects:** Local imprint spaces $\mathcal{H}_x$ for each M_x.
- **Morphisms:** Imprint operators $\mathcal{I}_x[\phi] : \mathcal{H}_x \to \mathcal{H}_x$ or composite morphisms $\mathcal{I}_{x \to y}$ representing propagation across cells.
- **Tensor product:** $\mathcal{H}_x \otimes \mathcal{H}_y$ models simultaneous imprints in spacelike-separated cells.
- **Composition:** Given $f : \mathcal{H}_x \to \mathcal{H}_y$ and $g : \mathcal{H}_y \to \mathcal{H}_z$, $g \circ f$ corresponds to imprint loop composition.

We define a functor:

$$\mathcal{F}_{\text{imprint}} : \mathbf{Str}_\Sigma \to \mathbf{QMM}, \tag{10}$$

where $\mathbf{Str}_\Sigma$ is a category of string worldsheet diagrams (e.g., vertex operator insertions, scattering configurations) over a signature Σ, and $\mathcal{F}_{\text{imprint}}$ assigns to each diagram a composite memory loop in $\mathcal{I}$.

5.3 Memory Conservation and Functoriality

We impose a memory conservation condition: the trace over any closed imprint loop is unitary:

$$\text{Tr}\left(\mathcal{F}_{\text{imprint}}(D)\right) = 1, \quad \forall D \in \mathbf{Str}_\Sigma, \tag{11}$$

ensuring that information is neither lost nor duplicated. Functoriality ensures consistent imprint generation under composition of string diagrams:

$$\mathcal{F}_{\text{imprint}}(D_2 \circ D_1) = \mathcal{F}_{\text{imprint}}(D_2) \circ \mathcal{F}_{\text{imprint}}(D_1).$$

This categorical structure allows us to reason about conservation, entanglement flow, and causal consistency of imprint sequences, offering a robust mathematical foundation for QMM-based quantum gravity.

5.4 Cohomological Structure of Imprint Loops

Let $\mathcal{M}$ be the QMM lattice viewed as a topological space via its causal graph. Consider the group of invertible imprint operators $\mathcal{G}$ acting on memory states. Imprint loops $\mathcal{L}$ can then be seen as 1-cycles in $\mathcal{M}$, and their homotopy classes define elements of the first cohomology group:

$$[\mathcal{L}] \in H^1(\mathcal{M}, \mathcal{G}).$$

These cohomology classes classify topologically distinct imprint histories, and can encode persistent global memory configurations (e.g., imprint fluxes or parity anomalies). Non-trivial elements correspond to memory loops that cannot be continuously deformed into one another without losing information.

5.5 Entropy Functor and Information Flow

We define an entropy functor:

$$\mathcal{S} : \mathbf{QMM} \to \mathbf{Vect}_\mathbb{R},$$

that assigns to each imprint morphism a real-valued entropy vector:

$$\mathcal{S}(\mathcal{I}_x[\phi]) := S(\rho_x),$$

where ρ_x is the reduced density matrix on $\mathcal{H}_x$ after imprinting. The functorial property

$$\mathcal{S}(g \circ f) \leq \mathcal{S}(f) + \mathcal{S}(g)$$

reflects subadditivity, and equality holds iff the imprints are independent. This quantifies memory accumulation and lossless encoding through imprint chains.

5.6 Topos-Theoretic View of QMM Logic

To internalize the logic of imprints and their propagation, we may consider a sheaf topos $\mathbf{Sh}(\mathcal{M})$ over the QMM lattice, with a presheaf $\mathcal{O}$ assigning imprint algebras $\mathcal{A}_x$ to open causal patches. Morphisms in this topos represent local imprint dynamics and information restrictions.

This enables a logic of space-time memory where truth values are assigned contextually (e.g., imprints may be partially defined or epistemically restricted). Such a framework allows for reasoning about "fuzzy" imprints, entropy thresholds, and localization constraints.

6 Example: Evaluation of a Memory Loop from Vertex Scattering

Consider a closed string process involving four vertex insertions:

$$\mathcal{A}_{\text{tree}} = \langle V(k_1, z_1)V(k_2, z_2)V(k_3, z_3)V(k_4, z_4)\rangle.$$

Let each $V(k_i, z_i)$ intersect a QMM cell M_{x_i}, producing an imprint $\mathcal{I}_{x_i}[k_i]$ at each site. The total memory loop becomes:

$$\mathcal{L} = \mathcal{I}_{x_4}[k_4] \circ \mathcal{I}_{x_3}[k_3] \circ \mathcal{I}_{x_2}[k_2] \circ \mathcal{I}_{x_1}[k_1].$$

Suppose each imprint has the form:

$$\mathcal{I}_{x_i}[k_i] = \exp(i\alpha_i\gamma_5),$$

where γ_5 is a CP-violating generator in some effective fermionic sector, and α_i depends on the string momentum k_i. Then:

$$\mathcal{L} = \exp\left(i\sum_{i=1}^{4}\alpha_i\gamma_5\right) = \exp(i\theta_{\text{QMM}}\gamma_5),$$

with total phase $\theta_{\text{QMM}} = \sum_i \alpha_i$. This induces a shift in the effective CP phase:

$$\theta_{\text{eff}} \to \theta_{\text{eff}} + \theta_{\text{QMM}},$$

potentially observable via electric dipole moments or meson decays.

The entropy contribution from this loop is computed as:

$$S[\mathcal{L}] = -\text{Tr}(\rho_{\mathcal{L}} \log \rho_{\mathcal{L}}), \quad \rho_{\mathcal{L}} = \frac{1}{Z}\mathcal{L}\rho_0\mathcal{L}^\dagger,$$

which captures information gain or scrambling induced by the closed string process on the QMM background.

7 QMM–String Duality and Holography

Inspired by the holographic principle, we propose that the evolution of quantum information in the QMM background may be dual to the dynamics of string worldsheet amplitudes. Formally, we conjecture a correspondence:

$$\text{String Correlators on } \Sigma \quad \Longleftrightarrow \quad \text{Imprint Loop States in } \mathcal{I}, \tag{12}$$

where Σ is a genus-g string worldsheet embedded in a discretized target space and $\mathcal{I}$ is the imprint algebra defined on the QMM lattice.

7.0.1 Dictionary Between String and Imprint Sectors

We propose the following duality map:

String Theory Side	QMM Side
Worldsheet Σ	Causal patch $\mathcal{M}_\Sigma \subset \mathcal{M}$
Vertex operator $V_i(k_i)$	Imprint operator $\mathcal{I}_{x_i}[k_i]$
Conformal block $\mathcal{A}_g$	Memory loop state $\mathcal{L}_g$
Operator product expansion	Loop concatenation or fusion
Moduli of Σ	Equivalence classes in $H^1(\mathcal{M})$

This duality is inherently **non-perturbative**: while string amplitudes live in a continuous embedding space, their projection onto QMM spacetime induces a combinatorial representation via imprint sequences.

7.0.2 Holographic Reconstruction from Memory Data

Given a sequence of imprints $\mathcal{I}_{x_1}, \ldots, \mathcal{I}_{x_n}$ with known causal ordering, we may attempt to reconstruct a minimal worldsheet Σ that produces this imprint pattern:

$$\mathcal{F}_{\text{holo}} : \mathcal{L} \mapsto \Sigma_{\text{eff}}.$$

This map is generically non-unique but may satisfy extremal principles—e.g., minimal memory entropy or topological area.

If successful, this construction would provide a discrete analogue of worldsheet reconstruction from boundary correlators, similar to twistor string holography [**?**].

7.0.3 Duality and Unitarity Restoration

A compelling consequence of the duality is the possibility that **unitarity lost in semiclassical gravity is restored at the imprint level**. Specifically, black hole evaporation viewed as an imprint trace $\mathcal{L}_{\text{evap}}$ may correspond to a unitary string amplitude over a compact worldsheet. This provides a constructive resolution to the information paradox via QMM holography.

8 Topological Quantum Field Theory (TQFT) Embedding

The categorical and algebraic structure of QMM imprint dynamics suggests a natural embedding into a topological quantum field theory (TQFT). Here, memory loops play the role of cobordisms, and imprint spaces $\mathcal{H}_x$ are treated as topological boundary Hilbert spaces.

8.0.1 TQFT Functor Structure

Let $\mathbf{Cob}_2$ denote the category of oriented 2D cobordisms (e.g., worldsheet diagrams), and define a TQFT functor:

$$\mathcal{Z}_{\text{QMM}} : \mathbf{Cob}_2 \to \mathbf{Hilb},$$

such that:

- Objects are 1D memory slices (space-like cuts across the QMM lattice), - Morphisms are memory evolutions represented by imprint sequences (or loops), - $\mathcal{Z}_{\text{QMM}}(\Sigma)$ yields the resulting imprint loop state or memory observable.

This associates to each worldsheet-like surface Σ a topologically invariant imprint configuration.

8.0.2 Braiding and Modular Categories of Imprints

If imprint operators $\mathcal{I}_x$ obey fusion and braiding relations (e.g., via entangled string crossings), we can promote the memory system to a **modular tensor category** $\mathcal{C}_{\text{QMM}}$. The fusion rules:

$$\mathcal{I}_x \otimes \mathcal{I}_y \to \sum_z N_{xy}^z \mathcal{I}_z,$$

and braiding coefficients R_{xy} enable modeling imprint interactions via extended TQFTs.

This opens the door to classifying topological imprint excitations (analogous to anyons), and understanding quantum memory preservation as a form of topological protection.

8.0.3 TQFT Invariants from Imprint History

We define a **topological memory invariant** for any imprint loop $\mathcal{L}$:

$$\mathcal{I}_{\text{top}}(\mathcal{L}) := \mathcal{Z}_{\text{QMM}}(\Sigma_{\mathcal{L}}),$$

where $\Sigma_{\mathcal{L}}$ is a cobordism representing the worldsheet history corresponding to $\mathcal{L}$. Such invariants could help classify classes of irreversible memory processes, entropic limits of imprint saturation, or equivalence classes of memory-preserving dynamics.

9 Experimental Falsifiability and Simulation Frameworks

Although the QMM–String paradigm is rooted in Planck-scale physics, its structured imprint mechanisms offer indirect observational and computational routes for falsifiability. In this section, we outline possible experimental probes and numerical strategies for tracking memory imprints and testing their low-energy effects.

9.1 Indirect Experimental Signatures

We identify three key experimental domains where QMM imprints may leave detectable signatures:

1. **Gravitational Wave Memory:** Interference effects between gravitational waves and QMM memory loops may generate small, non-linear tail signatures, particularly in LISA-band stochastic backgrounds. These may show up as non-Gaussian correlations or time-asymmetric features in waveform tails [15].

2. **CP-Violating Phase Deviations:** QMM-induced imprint loops alter effective CP phases in weak interactions. Small but correlated deviations in CKM or PMNS matrix elements may be detectable in high-precision neutrino oscillation data (DUNE, JUNO) or electric dipole moment measurements [13].
3. **Black Hole Echoes and Remnants:** If memory loops encode unitarity-preserving information, then echo-like patterns following Hawking evaporation could reflect imprint conservation. The characteristic timescales and echo patterns would be indirectly sensitive to QMM discretization scales [**?**].

These predictions can be tested through high-precision observational campaigns that target phase noise, waveform anomalies, or CPT-symmetry violations.

9.2 Numerical Simulation Framework for Imprint Tracking

To explore the imprint dynamics computationally, we propose a discrete simulation framework:

Lattice Setup

Model QMM spacetime as a finite n^4 hypercube lattice $\mathcal{M}_n$, with each node $x \in \mathcal{M}_n$ holding a local Hilbert space $\mathcal{H}_x$ initialized to $|0\rangle_x$.

String Input

Embed a string worldsheet $X^\mu(\sigma, \tau)$ using a discrete parameterization. Discretize the worldsheet and track which lattice sites are intersected.

Imprint Application

At each intersected site x_i, apply a local operator $\mathcal{I}_{x_i}[\phi_i]$ to $|0\rangle_{x_i}$. The imprint operator can be sampled from a library (e.g., Pauli gates, phase gates, or CPT-violating matrices), parameterized by local string data k_i.

Loop Construction and Observables

Track imprint loops $\mathcal{L}$ by causal ordering. Compute:

- Trace observables: $\mathrm{Tr}(\mathcal{L})$
- Entropy: $S(\rho_\mathcal{L})$
- CP-violating phase: $\theta_{\text{QMM}} = \arg\det(\mathcal{L})$
- Memory saturation or decoherence thresholds

Implementation Notes

This can be implemented using tensor network simulations or quantum circuit frameworks. Notably:

- The imprint algebra can be represented using ‘qiskit‘ or ‘quimb‘.
- Lattice evolution can be mapped to a sparse graph for scalability.
- The imprint loop construction is path-dependent and allows testing consistency across different string embeddings.

9.3 Falsifiability Criteria

We define falsifiability not through direct detection of Planck-scale imprints, but through:

- Observable deviation patterns in otherwise well-modeled physical processes (e.g., CKM matrix fits, GW tail events).
- Universality of simulation outcomes under variation of initial string conditions—robust loop signatures indicate model structure.
- Breakdown of semiclassical models when accounting for entropy-preserving imprint dynamics, which can be statistically tested.

A falsification would occur if imprint effects cannot be matched to any known or hypothesized correction terms in observed low-energy physics.

10 Conclusion

11 Conclusion

In this work, we introduced a novel theoretical framework merging the recently proposed Quantum Memory Matrix (QMM) paradigm with weakly coupled string backgrounds. By modeling space-time as a discrete network of Planck-scale memory cells, and treating string excitations as imprint-generating operators, we constructed a mathematical formalism for persistent quantum memory loops.

Our contributions include:

- The definition of an *imprint algebra* and a categorical structure for string–QMM interactions.
- The proposal of a QMM–String duality analogous to holography, wherein memory loop states correspond to string worldsheet amplitudes.
- The embedding of QMM imprint dynamics into a topological quantum field theory, enabling classification of memory processes via cobordisms and modular structures.
- Phenomenological consequences such as CP-violating phase shifts, imprint-induced gravitational wave signatures, and potential remnants of black hole evaporation.
- A proposal for experimental falsifiability and a discrete simulation framework to evaluate imprint dynamics and entropy flow.

This work opens a rich landscape at the intersection of quantum gravity, information theory, and algebraic geometry. Future research may explore the classification of imprint cohomology, quantization of QMM–String systems, or the possibility of emergent space-time logic via quantum topos dynamics. The QMM paradigm may offer a route to understanding the unitarity and information retention mechanisms of the universe at its most fundamental scale.

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References

[1] Someindra Kumar Singh. The quantum memory matrix: Discrete space-time and black hole unitarity. *arXiv preprint*, 2025.

[2] Daniel Harlow. Lectures on the black hole information problem. *Reviews of Modern Physics*, 95(1):015002, 2023.

[3] Joseph Polchinski. *String Theory, Vols. I & II*. Cambridge University Press, 1998.

[4] Edward Witten. Perturbative gauge theory as a string theory in twistor space. *Communications in Mathematical Physics*, 252(1-3):189–258, 2004.

[5] Luca Bombelli, Joohan Lee, David Meyer, and Rafael D. Sorkin. Space-time as a causal set. *Phys. Rev. Lett.*, 59:521–524, 1987.

[6] Carlo Rovelli and Lee Smolin. Spin networks and quantum gravity. *Phys. Rev. D*, 52(10):5743–5759, 1995.

[7] Brian Swingle. Entanglement renormalization and holography. *Phys. Rev. D*, 86:065007, 2012.

[8] Steven B. Giddings. Black hole information, unitarity, and quantum memory. *Universe*, 9(2):54, 2023.

[9] Stephen W. Hawking, Malcolm J. Perry, and Andrew Strominger. Soft hair on black holes. *Phys. Rev. Lett.*, 116:231301, 2016.

[10] Raphael Bousso. Black hole information and firewalls. *Scientific American*, February 2017.

[11] Andrew Strominger and Alexander Zhiboedov. Gravitational memory, bms supertranslations and soft theorems. *JHEP*, 01:086, 2016.

[12] Nathan Seiberg and Edward Witten. String theory and noncommutative geometry. *JHEP*, 9909:032, 1999.

[13] Andrzej J. Buras. Flavor theory: 2020 and beyond. *Rev. Mod. Phys.*, 92(1):015003, 2020.

[14] Fengpeng An et al. (JUNO Collaboration). Neutrino physics with juno. *J. Phys. G*, 43:030401, 2016.

[15] S. Caprini et al. Science with the space-based interferometer lisa. iv: Probing inflation with gravitational waves. *JCAP*, 2023(12):001, 2023.

[16] Z. Arzoumanian et al. (NANOGrav Collaboration). The nanograv 15-year data set: Evidence for a gravitational-wave background. *Astrophys. J. Lett.*, 951(1):L6, 2023.

12 Appendix: Notation and Mathematical Conventions

QMM Lattice

We denote the Quantum Memory Matrix (QMM) lattice as $\mathcal{M}$, modeled as a discrete graph $\mathbb{Z}^4$ of Planck-scale memory cells M_x, each with Hilbert space $\mathcal{H}_x$ and operator algebra $\mathcal{A}_x$.

Imprint Operators

An imprint operator $\mathcal{I}_x[\phi]$ represents the effect of a string excitation ϕ at site x, acting on $\mathcal{H}_x$. A memory loop $\mathcal{L}$ is an ordered composition of such operators:

$$\mathcal{L} = \mathcal{I}_{x_n}[\phi_n] \circ \cdots \circ \mathcal{I}_{x_1}[\phi_1].$$

Categories

We define $\mathbf{QMM}$ as a monoidal category of memory sites and imprint morphisms. The functor $\mathcal{F}_{\text{imprint}} : \mathbf{Str}_\Sigma \to \mathbf{QMM}$ maps string diagrams to memory loops.

Entropy and Trace

Given an imprint loop $\mathcal{L}$, we define its memory entropy via:

$$S(\mathcal{L}) := -\mathrm{Tr}(\rho_\mathcal{L} \log \rho_\mathcal{L}), \quad \rho_\mathcal{L} = \frac{1}{Z}\mathcal{L}\rho_0\mathcal{L}^\dagger.$$

Cohomology

We treat memory loops as elements of $H^1(\mathcal{M}, \mathcal{G})$, where $\mathcal{G}$ is the group of invertible imprint operators. Topologically distinct loops correspond to inequivalent memory histories.