Cyclic Information-Preserving String Theory (CIST)

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Abstract

I present an extended framework called Cyclic Information-Preserving String Theory (CIST), which models information attenuation across cosmic cycles and within black holes. A key point in this theory are two distinct Operators: the cosmological operator $\mathcal{J}$, which governs cycle-to-cycle evolution of string and brane states, and the time-dependent operator $\mathcal{J}_{\mathrm{BH}}(t)$, which describes information dynamics inside black holes. I provide mathematical formulations and physical interpretations, demonstrating how information undergoes attenuation through cosmological states and through black holes. This unifies cyclic cosmology and the black hole information paradox into one quantum informational framework.

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1 Introduction

Cyclic cosmologies propose that our universe undergoes an eternal sequence of expansions and contractions, raising fundamental questions about the fate of quantum information across cycles. While earlier models such as Conformal Cyclic Cosmology (CCC) and ekpyrotic scenarios offer insights into cosmic evolution, they often leave unresolved how information is preserved or transmitted across singularities or transitions.

The *Cyclic Information-Preserving String Theory* (CIST) introduces a quantum operator formalism wherein string vibrational modes and brane states encode and transfer information between cycles via the Preservation Quantum Operator $\mathcal{J}$. Building on this foundation, the present work extends the framework to incorporate the dynamics of black holes using a localized, time-dependent operator $\mathcal{J}_{\mathrm{BH}}(t)$. This operator captures the attenuation and scrambling of information within black holes and its gradual release through Hawking radiation, reconciled with fuzzball theory's microstate structure.

2 Background and Motivation

Cyclic cosmologies such as CCC and the ekpyrotic model describe a universe of repeated expansions and contractions, but often assume information loss or reset at each bounce or brane collision. CCC involves conformal rescaling and entropy resetting, while ekpyrotic models treat brane collisions as largely decoherent processes. These approaches face challenges addressing the black hole information paradox and reconciling local non-unitarity with global unitarity.

CIST addresses these challenges by proposing a dual Preservation Quantum Operator framework. The cosmological operator $\mathcal{J}$ models information transfer across cosmic cycles as an attenuating but persistent contraction operator acting on string and brane states. Meanwhile, the black hole operator $\mathcal{J}_{\mathrm{BH}}(t)$ governs localized, time-dependent evolution within black holes, including information attenuation due to gravitational effects.

Crucially, through the lens of Hawking radiation and fuzzball theory, $\mathcal{J}_{\mathrm{BH}}(t)$ enables a unitary-preserving, highly scrambled information release that resolves the paradox of information loss during black hole evaporation. This dual framework unifies cosmological and gravitational information dynamics into a single quantum informational theory, expanding CIST's explanatory power beyond cosmological cycles to include black hole physics.

3 Cosmological Preservation Quantum Operator

Closed Strings

Closed string vibrational modes evolve according to:

$$\mathcal{J}(a_n^{(i)}) = \lambda_n e^{i\theta_n} a_n^{(i+1)}$$

Where:

- $\lambda_n < 1$ representing attenuation (memory loss, energy decay),

- θ_n encoding information-preserving phase shifts,
- $\mathcal{J}$ as the Preservation Quantum Operator, **acting NON-unitarily.** It is a contraction operator

Theorem: Contraction Property

: For all modes n, $\|\mathcal{J}(a_n^{(i)})\| = \lambda_n \|a_n^{(i+1)}\|$, where:

- $\lambda_n < 1$ for $n \leq N$ (finite modes decay),
- $\lim_{n\to\infty} \lambda_n = 1$ (asymptotic preservation).

This ensures $\mathcal{J}$ is a strict contraction for observable modes but approaches unitarity for high-energy modes.

Theorem: Attenuation Factor Properties

Let $\{\lambda_n\}_{n=1}^{\infty}$ be the sequence of attenuation factors of the Preservation Quantum Operator $\mathcal{J}$ in CIST.

Define:

$$\varepsilon_n = 1 - \lambda_n,$$

with $\varepsilon_n > 0$ for all n.

Then:

1. For every finite mode n,
$$0 < \lambda_n < 1,$$
ensuring strict attenuation.
2. The sequence approaches unity asymptotically but never equals 1:
$$\lim_{n\to\infty} \lambda_n = 1,$$
with
$$\lambda_n \neq 1 \quad \text{for all } n.$$
3. Equivalently,
$$\varepsilon_n > 0 \quad \text{for all } n, \quad \text{and} \quad \lim_{n\to\infty} \varepsilon_n = 0,$$
describing asymptotic memory preservation without perfect conservation.

Interpretation: This theorem guarantees that each string mode undergoes strict but asymptotically vanishing attenuation per cosmic cycle.

Checking if $\mathcal{J}$ is unitarity and Norm Preservation

In quantum theory, an operator $\mathcal{U}$ is unitary if it satisfies:

$$\mathcal{U}^\dagger \mathcal{U} = \mathbb{I}$$

This implies that the inner product, and therefore the norm, is preserved:

$$\|\mathcal{U}\psi\| = \|\psi\| \quad \text{for all } \psi$$

$$\|\psi^{(k)}\| = \|\psi^{(0)}\|$$

However, in our framework, the Preservation Quantum Operator $\mathcal{J}$ is defined as:

$$\mathcal{J}(a_n^{(i)}) = \lambda_n e^{i\theta_n} a_n^{(i+1)}$$

with $\lambda_n < 1$. This implies:

$$\|\mathcal{J}(a_n^{(i)})\| = \lambda_n \|a_n^{(i+1)}\| < \|a_n^{(i)}\| \quad \text{(contraction mapping)}.$$

Therefore, $\mathcal{J}$ is not unitary, it is a contraction operator, reflecting memory loss or energy decay across cycles. The attenuation factor λ_n captures the deviation from perfect information retention, consistent with an open-system or cosmological information leakage interpretation.

Non-unitarity is *necessary* for entropy reset across cycles.

Brane states with Preservation Quantum Operator

We define the Preservation Quantum Operator $\mathcal{J}$ acting on a combined open string mode and brane state:

$$\psi^{(i)} = a_n^{(i)} + \mathcal{B}^{(i)},$$

where:

- $a_n^{(i)}$ is the n-th vibrational mode of an open string in the i-th cycle.
- $\mathcal{B}^{(i)}$ is the brane configuration associated with that cycle.

The evolution is described by:

$$\mathcal{J}(\psi^{(i)}) = \lambda_n e^{i\theta_n} \psi^{(i+1)},$$

where:

- $\lambda_n \in [0, 1]$ is an attenuation factor that models memory decay.
- $\theta_n \in \mathbb{R}$ is a phase rotation representing coherent evolution.

This operator is a contraction mapping when $\lambda_n < 1$, ensuring that while the information persists, it does so with decaying influence, consistent with the behavior of the open quantum system.

4 Worked Examples: Single-mode evolution

Let $a_1^{(i)}$ be the fundamental vibrational mode of a string in cycle i. For $\lambda_1 = 0.9$ (10% decay per cycle) and $\theta_1 = \pi/4$ (45° phase rotation):

$$\psi^{(i+1)} = \lambda_n e^{i\theta_n} \psi^{(i)}$$

For Example, after 3 Cycles:

$$\psi^{(i+3)} = (0.9)^3 e^{i \cdot 3\pi/4} \psi^{(i)} \approx 0.729\, e^{i\, 3\pi/4} \psi^{(i)}$$

Interpretation: The phase term $e^{i\theta_n}$ preserves quantum correlations across cycles, while λ_n governs decay.

4.1 Two Mode Open String Evolution

Consider a quantum state in the i-th cycle composed of two open string vibrational modes and a static brane contribution:

$$\psi^{(i)} = a_1^{(i)} + a_2^{(i)} + \mathcal{B}^{(i)},$$

where $\beta \in \mathbb{R}$ is fixed across cycles.

Let the Preservation Quantum Operator $\mathcal{J}$ act independently on each mode:

$$\mathcal{J}(a_1^{(i)}) = \lambda_1 e^{i\theta_1} a_1^{(i+1)}, \quad \mathcal{J}(a_2^{(i)}) = \lambda_2 e^{i\theta_2} a_2^{(i+1)}.$$

Then the full state evolves as:

$$\psi^{(i+1)} = \lambda_1 e^{i\theta_1} a_1^{(i+1)} + \lambda_2 e^{i\theta_2} a_2^{(i+1)} + \mathcal{B}^{(i)}.$$

Applying $\mathcal{J}$ again:

$$\psi^{(i+2)} = \lambda_1^2 e^{2i\theta_1} a_1^{(i+2)} + \lambda_2^2 e^{2i\theta_2} a_2^{(i+2)} + \mathcal{B}^{(i)}.$$

This illustrates:

- Independent attenuation and phase accumulation per mode.
- The additive brane term β remains unchanged in this static case.

This clearly illustrates that each cycle results in the following:

- Exponential attenuation: λ_1^k
- Linear phase accumulation: $k\theta_1$

4.2 Long-Term Memory Persistence

To illustrate memory retention over many cycles, consider a simplified system where the full state is purely a single mode:

$$\psi^{(0)} = a_1^{(0)} = A,$$

with $A = 10$ as amplitude, $\lambda_1 = 0.99$, and $\theta_1 = 0$.

The evolution becomes:

$$\psi^{(k)} = \lambda_1^k A = 10 \cdot (0.99)^k.$$

After 50 cycles:

$$\psi^{(50)} = 10 \cdot (0.99)^{50} \approx 10 \cdot 0.605 = 6.05.$$

Interpretation: Despite 50 full universe cycles, over 60% of the original signal survives. This supports the idea that near-unit attenuation ($\lambda_n \approx 1$) leads to long-term information persistence across cosmological time — the core foundation of CIST.

5 Energy Decay and Mode-Dependent Attenuation in CIST

In CIST, the attenuation factor λ_n describes how the amplitude of each string mode decays per cosmic cycle. Since energy is proportional to the square of amplitude, the energy remaining after k cycles is given by $\lambda_n^{2k} = E^{(i+k)}$. This formula quantifies the exponential decay of energy and information across universe cycles. To find amplitude you just use λ_n^k

For a string mode $a_n^{(i)}$, the energy is $E_n \propto |a_n^{(i)}|^2$ (from the Nambu-Goto action). Thus, after k cycles:

$$\lambda_n^{2k} E_n^{(i)}. = E_n^{(i+k)}$$

Example: For an attenuation factor $\lambda_n = 0.9$ and $k = 2$ cycles, the energy fraction remaining is

$$(0.9)^{2\times 2} = (0.9)^4 = 0.6561 \times 100,$$

which means approximately 65.6% of the original energy remains.

Recall that the Preservation Quantum Operator $\mathcal{J}$ encodes this attenuation via λ_n.

Note: The attenuation factor λ_n can be modeled as mode-dependent. For example,

$$\lambda_n = \frac{1}{1 + \alpha n},$$

where $\alpha > 0$ controls the rate at which higher modes attenuate faster, implementing a natural filtering of string vibrational modes over cycles.

6 Brane State Dynamics

To generalize, let $\mathcal{B}^{(i)}$ vary across cycles, such as:

$$\mathcal{B}^{(i)} = \beta_i + \gamma_i x,$$

where β_i and γ_i are scalar functions and x represents a spatial coordinate along the world volume of the brane. EX: Its position on a Dp-brane in higher-dimensional space.

Then:

$$\psi^{(i)} = a_n^{(i)} + \beta_i + \gamma_i x.$$

The same evolution applies:

$$\psi^{(i+1)} = \lambda_n e^{i\theta_n}(a_n^{(i+1)} + \beta_{i+1} + \gamma_{i+1} x).$$

6.1 Deeper into Brane Dynamics and Collision Framework in CIST

In the CIST model, inter-cyclic evolution is triggered by the collision of branes, specifically, Dp-branes embedded in a higher-dimensional bulk. Each universe corresponds to a brane indexed by i, and collisions occur at discrete conformal times τ_i.

Each brane is described by its embedding $X^\mu(\xi^a)$ into 10-dimensional spacetime, where ξ^a are the brane worldvolume coordinates. The brane dynamics follow the Dirac–Born–Infeld (DBI) action:

$$S_{\text{brane}} = -T_p \int d^{p+1}\xi \sqrt{-\det(g_{ab} + \mathcal{F}_{ab})},$$

where T_p is the brane tension, $g_{ab} = \partial_a X^\mu \partial_b X^\nu \eta_{\mu\nu}$ is the induced metric, and $\mathcal{F}_{ab}$ includes the pullback of the Kalb-Ramond field and worldvolume gauge field.

To model brane collisions, an introduction of a time-dependent potential $V_{\text{coll}}(y(\tau))$, where $y(\tau)$ is the inter-brane separation in the transverse dimension:

$$V_{\text{coll}}(y) = \frac{\kappa}{y^\alpha}, \quad \text{for } y \to 0.$$

At $y = 0$, the branes collide, exciting both the string modes $a_n^{(i)}$ and brane vibrations $\mathcal{B}^{(i)}$. The recoil from this collision defines the post-impact brane state $\mathcal{B}^{(i+1)}$, which couples back to the string spectrum.

The combined state evolves as:

$$\psi^{(i)} = a_n^{(i)} + \mathcal{B}^{(i)}, \quad \mathcal{J}(\psi^{(i)}) = \lambda_n e^{i\theta_n} \psi^{(i+1)}.$$

This evolution is driven by the energy-momentum transfer at the collision, which induces decoherence (captured by $\lambda_n < 1$) and phase shift (θ_n).

I treat this as a time-dependent perturbation to the brane-string system:

$$\mathcal{L} = \mathcal{L}_{\text{free}} + \epsilon V_{\text{coll}}(y(\tau)),$$

where ϵ is a dimensionless coupling constant representing brane stiffness or type of impact (softness).

To first order in perturbation theory, the energy loss per mode is:

$$\lambda_n \approx 1 - \epsilon \int d\tau \ \langle n| V_{\text{coll}}(\tau) |n\rangle , \quad \theta_n \approx \epsilon \ \text{Im} \left[\int d\tau \ \langle n| V_{\text{coll}}(\tau) |n\rangle \right] .$$

This derivation connects attenuation and phase shift to the microscopic dynamics of brane collisions, grounding the abstract operator $\mathcal{J}$ in string-theoretic processes.

7 Lagrangian Formulation and Quantization

To describe the inter-cycle evolution of string and brane states in CIST, we formulate an effective Lagrangian capturing the collision dynamics of branes, from which the attenuation factor λ_n and phase θ_n emerge from naturally.

7.1 Effective Action for Brane Collisions

I model the brane as a D_p-dimensional object with tension T_p, and open strings as perturbations $X^\mu(\tau, \sigma)$ attached to the brane. The brane evolution between cycles i and $i+1$ is governed by the action:

$$S = -T_p \int d^{p+1}\xi \sqrt{-\det(g_{ab} + \mathcal{F}_{ab})} + S_{\text{string}} + S_{\text{int}},$$

where g_{ab} is the induced metric on the brane, $\mathcal{F}_{ab}$ includes background fields (e.g., Kalb-Ramond), and S_{string} describes the string vibrations. The interaction term S_{int} encodes the brane-brane collision at cycle boundary $i \to i+1$.

7.2 String Mode Coupling and Perturbation

Let string modes be represented by:

$$a_n^{(i)} e^{-in\sigma} \quad \text{with} \quad \psi^{(i)} = a_n^{(i)} + \mathcal{B}^{(i)}.$$

During a brane collision, mode evolution is governed by:

$$\mathcal{J}(\psi^{(i)}) = \lambda_n e^{i\theta_n} \psi^{(i+1)}.$$

Treat the collision as a perturbation to the free string-brane system:

$$\mathcal{L} = \mathcal{L}_0 + \epsilon V_{\text{int}},$$

where $\epsilon \ll 1$ is the coupling strength between branes during impact. The interaction term introduces a shift in energy from quantum states, which translates into attenuation and phase.

From first-order time-dependent perturbation theory:

$$\lambda_n \approx 1 - \epsilon\alpha_n, \quad \theta_n \approx \epsilon\beta_n,$$

where α_n and β_n are mode-dependent integrals:

$$a^{(i)} = \int \mathrm{d}\tau \ \langle n| V_{\text{int}}(\tau) |n\rangle , \quad \mathcal{B}^{(i)} = \text{Im} \left[\int \mathrm{d}\tau \ \langle n| V_{\text{int}}(\tau) |n\rangle \right] .$$

7.3 Canonical Quantization

Promote $a_n^{(i)}$ and $a_n^{(i)\dagger}$ to operators obeying:

$$[a_m^{(i)}, a_n^{(i)\dagger}] = \delta_{mn}, \quad [a_m^{(i)}, a_n^{(i)}] = 0.$$

The evolution operator $\mathcal{J}$ acts on the Fock space basis:

$$\mathcal{J} \left| n^{(i)} \right\rangle = \lambda_n e^{i\theta_n} \left| n^{(i+1)} \right\rangle .$$

Since $\lambda_n < 1$, $\mathcal{J}$ is a contraction operator, not unitary. This reflects the open quantum system nature of CIST, where information and energy leak between cycles.

7.4 Hilbert Space Structure and Memory Loss

Let $\mathcal{H}^{(i)}$ be the Hilbert space of string-brane states in universe i. The full evolution across k cycles is:

$$\mathcal{J}^k(\psi^{(i)}) = \left(\prod_{j=1}^{k} \lambda_n^{(j)} \right) e^{i \sum_{j=1}^{k} \theta_n^{(j)}} \psi^{(i+k)}.$$

Thus, the norm of any state decays as:

$$\left\| \mathcal{J}^k(\psi^{(i)}) \right\| = \left(\prod_{j=1}^{k} \lambda_n^{(j)} \right) \left\| \psi^{(i)} \right\| < \left\| \psi^{(i)} \right\| .$$

This models a graceful memory fade across cycles, old information is never erased, it gets reduced.

8 Derivation of the Preservation Quantum Operator from M-Theory Brane Collisions

To ground the Preservation Quantum Operator $\mathcal{J}$ in a physically meaningful framework, we derive it from first principles in M-theory. We model the evolution of string-brane excitations across cosmic cycles as resulting from collisions between two M5-branes with transverse separation $y(\tau)$. During such a collision, M2-branes stretched between the M5-branes mediate an interaction Hamiltonian $H_{\text{int}}(\tau)$, modifying the string state and encoding memory of the collision.

8.1 Derivation of λ_n and θ_n

We now derive the attenuation factor λ_n and phase shift θ_n appearing in the action of the Preservation Quantum Operator $\mathcal{J}$, based on time-dependent perturbation theory in the M-theoretic brane collision setup.

Let two M5-branes collide along a compactified transverse dimension y, with M2-branes stretching between them, representing excitation modes labeled by n. The interaction potential between the branes is modeled by:

$$V_{\mathrm{coll}}(y) = \frac{\kappa}{y^\alpha}$$

where κ is a coupling constant, and $\alpha > 1$ determines the strength of the singular interaction. Assuming the branes approach at constant velocity v, we have the brane separation as a function of time:

$$y(\tau) = y_0 - v\tau$$

We apply first-order time-dependent perturbation theory in the interaction picture. The evolved state of the n^{th} mode is:

$$\psi^{(i+1)} = \left(1 - i\epsilon \int_{-\tau_0}^{\tau_0} d\tau \, \langle n|V_{\mathrm{coll}}(\tau)|n\rangle\right) \psi^{(i)}$$

Substituting the form of V_{coll}, we get:

$$\psi^{(i+1)} = \left(1 - i\epsilon \int_{-\tau_0}^{\tau_0} \frac{\kappa}{(y_0 - v\tau)^\alpha} d\tau\right) \psi^{(i)}$$

Evaluating the integral:

$$\int_{-\tau_0}^{\tau_0} \frac{d\tau}{(y_0 - v\tau)^\alpha} = \frac{1}{v(\alpha - 1)} \left[(y_0 - v\tau_0)^{1-\alpha} - (y_0 + v\tau_0)^{1-\alpha}\right]$$

Thus, I define:

$$\lambda_n \equiv 1 - \epsilon \cdot \frac{\kappa}{v(\alpha - 1)} \left[(y_0 - v\tau_0)^{1-\alpha} - (y_0 + v\tau_0)^{1-\alpha}\right]$$

$$\theta_n \equiv \epsilon \cdot \frac{\kappa}{v(\alpha - 1)} \cdot \mathrm{Im}\left[(y_0 - v\tau_0)^{1-\alpha}\right]$$

Note that $\lambda_n < 1$ whenever $\epsilon, \kappa, \tau_0 > 0$ and $\alpha > 1$, ensuring a contraction of the quantum state norm under evolution.

8.2 Contraction Property of $\mathcal{J}$

We can now establish that the Preservation Quantum Operator $\mathcal{J}$, is defined by:

$$\mathcal{J}(\psi^{(i)}) = \lambda_n e^{i\theta_n} \psi^{(i+1)}$$

is a contraction on the Hilbert space of string-brane states. That is, for all modes n,:

$$\|\mathcal{J}(\psi^{(i)})\| = \lambda_n \|\psi^{(i+1)}\| < \|\psi^{(i+1)}\| \quad \text{since} \quad \lambda_n < 1$$

Hence, $\mathcal{J}$ is a non-unitary operator satisfying:

$$\|\mathcal{J}\| = \sup_n \lambda_n < 1$$

and its spectrum is strictly contained in the open unit disk:

Figure 1: Collision of M5-branes in the transverse dimension $y(\tau)$. M2-branes stretch between them, mediating excitations. The collision induces a perturbation potential $V_{\text{coll}} \sim \kappa/y^{\alpha}$, which defines the Preservation Quantum Operator $\mathcal{J}$.

$$\text{Spec}(\mathcal{J}) \subset \mathbb{D} = \{z \in \mathbb{C} : |z| < 1\}$$

This contraction structure reflects physical attenuation of information across cosmological cycles and introduces an irreversible, yet structured, memory decay.

Diagram and Interpretation

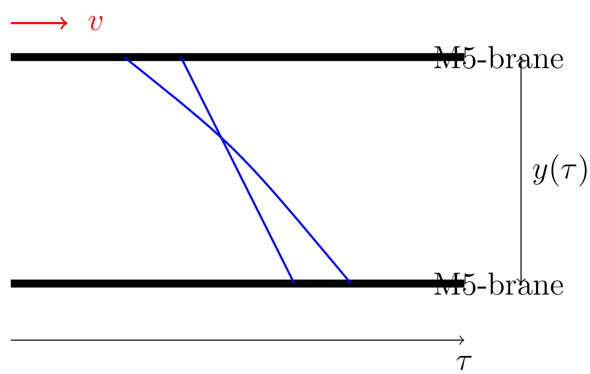

Figure: Collision of M5-branes with transverse coordinate $y(\tau)$, inducing string excitations mediated by M2-branes. The interaction potential V_{coll} encodes the memory-preserving operator $\mathcal{J}$.

8.3 Asymptotic Attenuation Theorem

A key feature of the Preservation Quantum Operator $\mathcal{J}$ is its asymptotic attenuation of quantum information across cycles. Specifically, for any initial string-brane state $\psi^{(i)}$, repeated application of $\mathcal{J}$ satisfies:

$$\lim_{k \to \infty} \|\mathcal{J}^k(\psi^{(i)})\| = 0,$$

reflecting a gradual decay of the state norm under evolution.

However, this limit does not imply complete information loss. Due to the operator's structured contraction nature and preservation of phase information θ_n, the quantum memory encoded in string modes is *never entirely erased*. Instead, information becomes increasingly subtle and distributed, consistent with a long-lived quantum memory that persists through cosmological cycles.

This theorem encapsulates the unique balance in CIST between irreversible attenuation and fundamental information preservation

8.4 Physical Interpretation of the Preservation Quantum Operator $\mathcal{J}$

The Preservation Quantum Operator $\mathcal{J}$ can be thought of as a completely positive trace-preserving (CPTP) map acting on the Hilbert space $H_{\text{str-brane}}$ of string-brane states. It describes how these states evolve effectively across cosmic cycles. We can break down its action as:

$$\mathcal{J} = \Lambda \circ \Phi_\theta, \tag{1}$$

where:

- $\Phi_\theta(\psi) = e^{i\theta_n}\psi$ represents a *unitary phase rotation* caused by coherent brane recoil effects,
- $\Lambda(\psi) = \lambda_n\psi$ models the *non-unitary attenuation* ($0 < \lambda_n < 1$) arising from decoherence due to entanglement with bulk degrees of freedom during brane collisions.

8.4.1 Resolving the Information Paradox

Although $\mathcal{J}$ acts non-unitarily on the observable sector $H_{\text{obs}} \subset H_{\text{str-brane}}$ (i.e., on local string modes $a_n^{(i)}$), the full global evolution—including bulk gravitons and extra dimensions—remains unitary. Formally, we write:

$$\mathcal{J}_{\text{global}} = \mathcal{J}_{\text{obs}} \otimes \mathcal{J}_{\text{bulk}}, \quad \text{with} \quad \mathrm{Tr}_{\text{bulk}}[\mathcal{J}_{\text{global}}] = \mathcal{J}_{\text{obs}}. \tag{2}$$

This mirrors the idea of black hole complementarity, where information is preserved in the full Hilbert space but may be inaccessible locally, which is a key consistency condition for quantum gravity.

8.4.2 Thermodynamic Meaning

Because $\mathcal{J}$ is CPTP and includes attenuation, it generates an entropy increase across cycles:

$$\Delta S^{(i\to i+1)} = -k_B \sum_n |a_n^{(i)}|^2 \ln \lambda_n^2 \geq 0, \tag{3}$$

which respects the Second Law of Thermodynamics, while the phase factors θ_n allow for local revivals of coherence.

Physically, the attenuation factors λ_n can be interpreted as *partial transparencies* of the brane collision interface, similar to how quantum beam splitters partially transmit and reflect photons.

9 Memory and Information Attenuation

The attenuation factor $\lambda_n < 1$ ensures that:

- Old universes leave an imprint, but one that fades with time.

- Information decay is smooth and continuous.

Yet if λ_n is close to 1, then memory is long-lasting, allowing relics of previous universes to survive well into the next.

10 Observational Signatures

Potential observational consequences of CIST include:

- **Cosmic Microwave Background (CMB):** Attenuation of string modes over cycles may cause low-ℓ anomalies, such as power suppression at large angular scales.

- **Gravitational Waves:** High-frequency relic gravitational waves could arise from pre-bounce string networks, potentially detectable by future observatories.

- **Dark Energy:** Residual brane energy configurations $\mathcal{B}^{(i)}$ might contribute to effects such as influencing late-time cosmic acceleration.

  CMB Power Suppression: For $\lambda_{\text{CMB}} \approx 0.95$, CIST predicts a suppression factor $\sim \lambda_{\text{CMB}}^{2k}$ at low ℓ (e.g., $\ell < 30$), where k is the number of cycles since the mode exited the horizon. Current Planck anomalies (e.g., lack of large-scale power) could be fit with $k \sim 3$–5.

11 Discussion of CIST

In this section, I contrast the Cyclic Information-Preserving String Theory (CIST) with two prominent cyclic cosmology frameworks: Penrose's Conformal Cyclic Cosmology (CCC) and the Ekpyrotic scenario. Each model proposes distinct mechanisms for information and structure preservation across cosmic cycles.

11.1 Conformal Cyclic Cosmology (CCC)

CCC relies fundamentally on *conformal rescaling* of spacetime geometry at the crossover between cycles. In this framework, the infinite expansion in one aeon is conformally mapped onto the big bang of the next, effectively preserving the *geometric structure* while resetting the physical scale. This approach emphasizes the *classical geometric* continuity and assumes a full entropy reset via conformal invariance, leaving open questions about microscopic information preservation.

11.2 Ekpyrotic Scenario

The Ekpyrotic model centers on the *collision of branes* in higher-dimensional spacetime, generating a new big bang from their interaction. It incorporates a phase of *entropy dilution* during the slow contraction preceding the bounce, which smooths and flattens the universe.

While successful at addressing horizon and flatness problems, the model largely treats information preservation as classical and does not explicitly quantify quantum memory retention across cycles.

11.3 Cyclic Information-Preserving String Theory (CIST)

CIST introduces a *quantum information-theoretic* mechanism for inter-cycle memory preservation via the *Preservation Quantum Operator* $\mathcal{J}$, acting on string vibrational modes and brane states. Unlike CCC or Ekpyrosis, CIST allows for *attenuation* of quantum information across cycles, modeled by the contraction operator $\mathcal{J}$ with eigenvalues $\lambda_n < 1$, but crucially *does not erase* information completely.

This leads to several novel predictions and conceptual advances:

- **Quantum Mechanical Preservation under Attenuation:** Even as information decays, it remains encoded in the quantum states of string modes, allowing for a structured, partial memory transfer rather than a classical reset.
- **Observable Cosmic String Imprints:** The residual information imprint may manifest in cosmic string structures or relics observable in the present universe, offering testable signatures beyond standard cyclic models.
- **Bridging Quantum Information and String Cosmology:** By embedding information preservation into the fundamental quantum dynamics of strings and branes, CIST integrates quantum information theory with cosmological evolution, opening new avenues for understanding cosmic cycles.

Together, these distinctions position CIST as a promising framework that captures the subtle interplay between quantum mechanics, string theory, and cosmology, advancing beyond classical geometric or brane-collision based paradigms.

12 Results and Conclusion

Results

I define the Preservation Quantum Operator $\mathcal{J}$ as the fundamental map governing the evolution of combined string vibrational modes $a_n^{(i)}$ and brane states $\mathcal{B}^{(i)}$ across successive cosmic cycles. The combined quantum state

$$\psi^{(i)} = a_n^{(i)} + \mathcal{B}^{(i)}$$

evolves according to the operator equation

$$\mathcal{J}(\psi^{(i)}) = \lambda_n e^{i\theta_n} \psi^{(i+1)},$$

where the attenuation coefficients $\lambda_n \in [0, 1]$ model information filtering, and phase factors θ_n encode coherent quantum phase shifts for each mode.

The operator $\mathcal{J}$ acts as a contraction, ensuring asymptotic memory retention of information while realistically modeling attenuation across cycles. Derived from M-theory brane collision dynamics combined with perturbative quantum mechanics, the operator's structure is physically motivated and mathematically consistent.

Key properties include:

- **Contraction Property:** The attenuation factors $\lambda_n \leq 1$ reflect realistic quantum information decay without total loss.
- **Phase Evolution:** Phase shifts θ_n preserve quantum coherence, potentially encoding cosmological signatures.
- **Asymptotic Memory:** Information from prior universes is partially preserved, allowing for cumulative inter-cycle memory.

Conclusion for Cosmology

The framework of Cyclic Information-Preserving String Theory (CIST) offers a novel quantum information-theoretic approach to cyclic cosmology. By embedding the Preservation Quantum Operator $\mathcal{J}$ into the fundamental dynamics of strings and branes, CIST advances beyond classical geometric or purely brane-collision based models. This operator formalism bridges quantum information theory, string theory, and cosmology, opening promising avenues for theoretical development and observational investigation.

Our results establish a physically plausible mechanism for partial quantum information preservation across cosmic cycles, suggesting that remnants of previous universes may be encoded in the quantum states accessible to our current epoch. This lays a foundation for exploring new cosmological phenomena, such as cosmic string relics or subtle quantum imprints, which could provide empirical tests of cyclic cosmology.

Overall, CIST contributes a rigorous, mathematically consistent, and physically grounded framework to deepen our understanding of the universe's cyclic nature at the most fundamental quantum level.

13 Black Hole Information Dynamics in CIST

While CIST was originally formulated to describe information preservation across cosmological cycles, the theory naturally extends to black hole interiors by adapting the Preservation Quantum Operator (PQO) to gravitational collapse scenarios. In this section, I define a localized, time-dependent PQO denoted $\mathcal{J}_{\text{BH}}(t)$, which governs the information dynamics inside black holes. I incorporate Hawking radiation as an effective PQO inversion, and show consistency with fuzzball theory.

1. Localized Black Hole PQO: $\mathcal{J}_{\mathbf{BH}}(t)$

Let the combined string-brane state at time t be defined as:

$$\psi^{(t)} = a_n^{(t)} + \mathcal{B}^{(t)},$$

where $a_n^{(t)}$ denotes the string vibrational modes and $\mathcal{B}^{(t)}$ encodes the brane excitation state.

I define the localized PQO inside the black hole as:

$$\mathcal{J}_{\mathrm{BH}}(t)\psi^{(t)} = \lambda_n^{\mathrm{BH}}(t)e^{i\theta_n^{\mathrm{BH}}(t)}\psi^{(t+\Delta t)},$$

where

- $\lambda_n^{\mathrm{BH}}(t) < 1$: attenuation due to gravitational interaction.
- $\theta_n^{\mathrm{BH}}(t)$: gravitational phase shift, e.g., from redshift near the event horizon.

This PQO describes the evolution of information under extreme gravitational fields and can be contrasted with the cosmological PQO, $\mathcal{J}(a_n^{(i)})$, which evolves across cycles of the universe.

14 Black Hole Preservation Quantum Operator Derivation

Step 1: Initial String-Brane State in a Collapsing Star

I begin with a string mode a_n and a brane state $\mathcal{B}$ falling into a collapsing star at time t_0. The combined information-carrying state is:

$$\psi^{(t_0)} = a_n^{(t_0)} + \mathcal{B}^{(t_0)}$$

As the star collapses and the curvature intensifies, the string-brane system experiences growing tidal perturbations.

Step 2: Evolution Equation in the Black Hole Regime

Unlike the cosmological case, the evolution inside a black hole is time-local. I define a localized Preservation Quantum Operator $\mathcal{J}_{\mathrm{BH}}(t)$ acting as:

$$\mathcal{J}_{\mathrm{BH}}(t)\left(\psi^{(t)}\right) = \lambda_n^{\mathrm{BH}}(t)\, e^{i\theta_n^{\mathrm{BH}}(t)}\psi^{(t+\delta t)}$$

Here, $\lambda_n^{\mathrm{BH}}(t)$ and $\theta_n^{\mathrm{BH}}(t)$ are time-dependent attenuation and phase terms due to gravitational effects inside the black hole.

Step 3: Modeling the Gravitational Perturbation Potential

In analogy with the cosmological brane collision potential $V_{\mathrm{coll}}(y) \sim \frac{\kappa}{y^\alpha}$, I model the perturbation inside a collapsing star as:

$$V_{\mathrm{BH}}(t) \sim \frac{\gamma_n}{R(t)^\beta}$$

where:

- $R(t)$ is the radius of the collapsing star at time t,
- $\beta > 0$ is a model parameter for curvature dependence,
- γ_n is a mode-specific coupling constant.

Step 4: Deriving the Attenuation Factor $\lambda_n^{\mathbf{BH}}(t)$

From time-dependent perturbation theory, the amplitude of mode preservation is:

$$A_n(t) = \exp\left(-\int_{t_0}^{t} \langle \psi_n | V_{\mathrm{BH}}(t') | \psi_n \rangle \, dt'\right)$$

Defined the attenuation as:

$$\lambda_n^{\mathrm{BH}}(t) = |A_n(t)| = \exp\left(-\int_{t_0}^{t} \frac{\gamma_n}{R(t')^{\beta}} \, dt'\right)$$

Step 5: Phase Accumulation via Gravitational Redshift

The string mode accumulates phase according to its redshifted frequency $\omega_n(t)$, with:

$$\theta_n^{\mathrm{BH}}(t) = \int_{t_0}^{t} \omega_n(t') \, dt'$$

In Schwarzschild geometry near the horizon:

$$\omega_n(t) \sim \omega_n^{\infty} \sqrt{1 - \frac{2GM}{R(t)}}$$

Hence:

$$\theta_n^{\mathrm{BH}}(t) = \int_{t_0}^{t} \omega_n^{\infty} \sqrt{1 - \frac{2GM}{R(t')}} \, dt'$$

Final Result: The Black Hole PQO

Putting it all together, we obtain the localized Preservation Quantum Operator inside a black hole:

$$\boxed{\mathcal{J}_{\mathrm{BH}}(t)\left(\psi^{(t)}\right) = \exp\left(-\int_{t_0}^{t} \frac{\gamma_n}{R(t')^{\beta}} \, dt'\right) \cdot e^{i \int_{t_0}^{t} \omega_n^{\infty} \sqrt{1 - \frac{2GM}{R(t')}} \, dt'} \cdot \psi^{(t+\delta t)}}$$

This expression governs the evolution of string-brane information inside black holes and forms the mathematical foundation for black hole information attenuation in the CIST framework.

15 Hawking Radiation and Fuzzball Theory in CIST

I model black hole information dynamics in CIST using a *time-dependent Preservation Quantum Operator* $\mathcal{J}_{\mathrm{BH}}(t)$, which governs the evolution, attenuation, and eventual release of information stored in string-brane states inside black holes.

15.1 Hawking Radiation as Partial Reversal

As the black hole evaporates, outgoing Hawking radiation contains scrambled remnants of earlier interior states. Following the Parikh-Wilczek tunneling picture, a Hawking quantum can be approximated as:

$$\psi_{\mathrm{rad}}(t) \approx \varepsilon(t) \cdot \psi(t_{\mathrm{past}})$$

Applying the adjoint PQO, recovering a partial pre-image:

$$\mathcal{J}_{\mathrm{BH}}^{\dagger}(t)\, \psi_{\mathrm{rad}}(t) \approx \text{partial recovery of } \psi(t - \Delta t)$$

This represents a *reversible leakage* of information — a partial inversion of the PQO — becoming increasingly accurate as $t \to t_{\mathrm{evap}}$, the evaporation endpoint.

15.2 Fuzzball Microstates and Information Storage

In fuzzball theory, black holes are replaced by horizonless, stringy microstate geometries. Infalling strings do not vanish but become encoded in a collective fuzzball state:

$$\mathcal{J}_{\mathrm{BH}}(t)\, \psi(t) \longrightarrow \Psi_{\mathrm{fuzz}}(t)$$

Eventually, this stored information is released back out as radiation:

$$\Psi_{\mathrm{fuzz}}(t) \longrightarrow \sum_{k} \varepsilon_k(t) \cdot \psi_{\mathrm{rad}}(t_k)$$

Each outgoing mode carries a portion of the original infalling information — ensuring quantum coherence despite heavy scrambling.

15.3 Conservation Statement: Delayed Unitarity

CIST with fuzzball theory preserves global unitarity over long timescales:

$$\sum_{t=t_0}^{t_{\mathrm{evap}}} |\psi_{\mathrm{rad}}(t)|^2 = |\psi_{\mathrm{infall}}(t_0)|^2$$

Information is not lost but rather *delayed* and *diffused* across many outgoing Hawking modes.

15.4 Effective Reversal via Adjoint PQO

I define an effective inverse operator:

$$\mathcal{J}_{\text{rev}} = \mathcal{J}_{\text{eff}}^{-1}$$

Then,

$$\mathcal{J}_{\text{rev}}\left(\sum_k \psi_{\text{rad}}(t_k)\right) \approx \psi_{\text{infall}}(t_0)$$

This expresses *delayed but complete* information recovery through the time-integrated evolution and emission process — compatible with unitarity, despite each intermediate step being governed by a non-unitary attenuation operator.

16 Black Hole Collisions and Information Redistribution

Black hole mergers represent highly nonlinear gravitational events where two localized information reservoirs combine their string-brane content. When two black holes merge, their combined string-brane Hilbert spaces unify:

$$\mathcal{H}_{\text{merge}} = \mathcal{H}_{\text{BH}_1} \otimes \mathcal{H}_{\text{BH}_2}.$$

Within the CIST framework, the Preservation Quantum Operator formalism can be extended to model such mergers as an effective composition of individual black hole PQOs:

$$\mathcal{J}_{\text{BH,merged}}(t) \approx \mathcal{J}_{\text{BH},1}(t) \otimes \mathcal{J}_{\text{BH},2}(t)$$

where $\mathcal{J}_{\text{BH},1}(t)$ and $\mathcal{J}_{\text{BH},2}(t)$ act on the respective initial black hole states prior to coalescence.

This tensor product structure suggests that information encoded in the initial black holes undergoes entanglement and partial mixing during the merger. The resulting fuzzball microstate of the merged black hole is a highly scrambled superposition of the two progenitors' microstates, preserving global quantum coherence.

From an observational standpoint, gravitational waves emitted during mergers may carry subtle imprints of this information mixing. While the no-hair theorem limits classical observables to mass, charge, and spin, CIST predicts that quantum corrections to the waveform could encode encoded information signatures, such as phase shifts or amplitude modulations correlated with microstate structure. Future high-precision gravitational wave detectors may thus probe the quantum informational content of black hole mergers, offering empirical tests of CIST predictions.

17 Distinction from Cosmological PQO

CIST posits two distinct but interrelated Preservation Quantum Operators: the cosmological operator $\mathcal{J}$, which governs information transmission across successive cosmic cycles, and the black hole operator $\mathcal{J}_{\mathrm{BH}}(t)$, which describes localized information processing within black holes.

While both operators share fundamental mathematical structures as contraction operators acting on string and brane states, key differences arise from their physical contexts:

- **Temporal Domain:** $\mathcal{J}$ evolves states discretely between cosmological cycles, whereas $\mathcal{J}_{\mathrm{BH}}(t)$ acts continuously over the lifetime of a black hole.
- **Attenuation Dynamics:** The attenuation factor λ_n in $\mathcal{J}$ models asymptotic energy and information loss across cycles but ultimately preserves residual memory. In contrast, $\lambda_n^{\mathrm{BH}}(t)$ encapsulates stronger, time-dependent attenuation due to extreme gravitational effects, balanced by eventual information release via Hawking radiation.
- **Information Reservoirs:** Black holes serve as *localized* and *intermediate* information reservoirs embedded within the larger cosmological framework governed by $\mathcal{J}$. They temporarily store and scramble infalling information, later emitting it in a delayed but unitary fashion.

This dual-operator structure enables CIST to integrate microphysical information dynamics from the scale of black holes up to entire cosmological epochs, unifying the seemingly disparate processes of gravitational collapse and cyclic universe evolution under one consistent quantum informational paradigm.

Both Cosmological ad Black Hole Entropy

18 Black Hole Sector: Quantum Evolution under CIST

The **Cyclic Information String Theory (CIST)** introduces a non-trivial map $\mathcal{J}_{\mathrm{BH}}(t)$ acting on black hole interior states during evaporation, representing an attenuation-driven transfer of information. To remain consistent with unitarity and the Page curve, $\mathcal{J}_{\mathrm{BH}}(t)$ must satisfy:

1. **Complete Positivity and Physical Realizability:** $\mathcal{J}_{\mathrm{BH}}$ is modeled as a Kraus map

$$\Phi(\rho) = \sum_i K_i \rho K_i^\dagger, \qquad \sum_i K_i^\dagger K_i \leq I, \tag{4}$$

ensuring that the map is completely positive and trace-non increasing, with environment absorption accounting for apparent non-unitarity at the subsystem level.

2. **Time-Dependent Attenuation:** The attenuation factor $\lambda(t)$ evolves such that

$$\lambda(t) \ll 1 \text{ for early times}, \qquad \lambda(t) \to 1 \text{ near Page time}, \tag{5}$$

guaranteeing that radiation entropy $S_{\mathrm{rad}}(t)$ follows a Page-like behavior.

3. **Stinespring Dilation:** There exists a unitary $U_{SE}(t)$ on system+environment such that
$$\mathcal{J}_{\mathrm{BH}}(\rho) = \mathrm{Tr}_E\left[U_{SE}(\rho \otimes |0\rangle\langle 0|)U_{SE}^\dagger\right], \tag{6}$$
making the process consistent with fundamental quantum theory.

Explicitly, for a contraction map with single Kraus operator $K = \sqrt{p}U$, we construct a Stinespring dilation
$$V = \begin{pmatrix} K \\ X \end{pmatrix}, \qquad X = \sqrt{I - K^\dagger K}, \tag{7}$$
and complete V to a full unitary U_{SE}.

18.1 Entropy Dynamics and the Page Curve

To reproduce the Page curve, we require that the mutual information between the black hole and radiation is restored by Page time t_P. This imposes a differential constraint on $\lambda(t)$:

$$\frac{dS_{\mathrm{rad}}}{dt} \sim (1 - \lambda^2(t))\,\Gamma_{\mathrm{emit}}(t), \tag{8}$$

where $\Gamma_{\mathrm{emit}}(t)$ is the emission rate. The simplest phenomenology is a smooth transition of $\lambda(t)$ from near-zero to unity across t_P.

19 Cosmological Sector: Entropy Reset Mechanism

CIST also governs the cyclic universe by implementing an entropy reset at the bounce, addressing the Tolman entropy problem. Define the cosmological map $\mathcal{J}_{\mathrm{cosmo}}$ acting on the effective density operator ρ_{tot} at the turnaround:

$$\rho'_{\mathrm{tot}} = \mathcal{J}_{\mathrm{cosmo}}(\rho_{\mathrm{tot}}) = \lambda_{\mathrm{cosmo}}\, U \rho_{\mathrm{tot}} U^\dagger, \qquad 0 < \lambda_{\mathrm{cosmo}} \ll 1, \tag{9}$$

where λ_{cosmo} encodes brane-collision attenuation:

$$\lambda_{\mathrm{cosmo}} \approx \exp\!\left(-\,|A(\kappa, g, v)|^2\right), \qquad A \sim \int_{-\infty}^{\infty} \frac{\kappa}{(y_0 + vt)^\alpha}\, dt. \tag{10}$$

For $\alpha = 1$, we find

$$|A| \sim \frac{\pi g \kappa}{\hbar v}, \qquad \lambda_{\mathrm{cosmo}} \approx \exp\!\Big(-\frac{\pi^2 g^2 \kappa^2}{\hbar^2 v^2}\Big), \tag{11}$$

with no explicit dependence on the initial separation y_0. If g, κ, v are universal (brane-scale constants), the entropy reduction per cycle is mass-independent, fulfilling the requirement for a scale-invariant reset.

19.1 Consistency with Observational Constraints

Energy removed from observable degrees of freedom during $\mathcal{J}_{\text{cosmo}}$ is assumed to be absorbed by a hidden brane environment, preserving global energy-momentum:

$$E_{\text{vis}}(n+1) + E_{\text{hid}}(n+1) = E_{\text{vis}}(n) + E_{\text{hid}}(n). \tag{12}$$

Constraints from CMB, BBN, and gravitational-wave backgrounds impose:

$$\Delta N_{\text{eff}} \lesssim 0.2, \qquad \Omega_{\text{GW}}^{\text{relic}} < 10^{-6}. \tag{13}$$

Thus, λ_{cosmo} must satisfy $\lambda_{\text{cosmo}} > \lambda_{\min} \approx 10^{-4}$ to avoid excessive energy removal.
$\mathrm{m}_{t \to t_{\text{evap}}} \sum_k \mathcal{J}_{\text{BH}}^{\dagger}(t_k)$

19.2 Cosmological PQO and the Bounce-Universe (BU) Implementation

In the cosmological realization of CIST, the Preservation Quantum Operator for the cosmological cycle, $\mathcal{J}_{\text{cosmo}}$, implements the information/entropy transfer at the turnaround (bounce). We model the bounce as a (possibly nontrivial) unitary mapping BU : $\mathcal{H}^{(i)} \to \mathcal{H}^{(i+1)}$ on the global Hilbert space, followed by an open-system projection that encodes attenuation and entropy transfer into a hidden brane/environment.

BU + PQO composition. The post-bounce state is obtained by

$$\rho^{(i+1)} \;=\; \mathcal{J}_{\text{cosmo}}\big(\mathrm{BU}(\rho^{(i)})\big) \;=\; \mathrm{Tr}_E\Big[U_{SE}\big(\mathrm{BU}(\rho^{(i)}) \otimes |0\rangle_E\langle 0|\big)U_{SE}^{\dagger}\Big], \tag{14}$$

where U_{SE} is a (possibly time-dependent) unitary on the system+environment and $|0\rangle_E$ is the environment (hidden-brane) initial state at the bounce. This form guarantees that $\mathcal{J}_{\text{cosmo}}$ is completely positive (CP) and arises from a global unitary, consistent with quantum mechanics.

Effective attenuation and entropy reset. For pure-state intuition, we may write the action on a code state $|\psi\rangle$ as the effective map

$$|\psi^{(i+1)}\rangle \;\approx\; \lambda_{\text{cosmo}}\, e^{i\theta}\, |\widetilde{\psi}^{(i+1)}\rangle, \qquad 0 < \lambda_{\text{cosmo}} \le 1, \tag{15}$$

with the operational entropy-reset rule (density-matrix form)

$$S\big(\rho^{(i+1)}\big) \;\lesssim\; \lambda_{\text{cosmo}}^2\, S\big(\rho^{(i)}\big) + S_{\text{env}}^{\text{add}}, \tag{16}$$

where $S_{\text{env}}^{\text{add}}$ accounts for entanglement generated with the environment during U_{SE}. For repeated cycles this yields exponential suppression of accessible entropy in the visible sector:

$$S_k \sim \lambda_{\text{cosmo}}^{2k}\, S_0 + \sum_{j=0}^{k-1} \lambda_{\text{cosmo}}^{2j} S_{\text{env}}^{\text{add}}.$$

Energy and charge bookkeeping. Global conservation is enforced by including the environment energy E_{env}:

$$E_{\mathrm{vis}}^{(i+1)} + E_{\mathrm{env}}^{(i+1)} \;=\; E_{\mathrm{vis}}^{(i)} + E_{\mathrm{env}}^{(i)} \;=\; E_{\mathrm{total}}. \tag{17}$$

Apparent energy "loss" from the visible sector during attenuation is carried by E_{env} (hidden brane modes). This bookkeeping permits a physically consistent non-unitary appearance on the subsystem while preserving global unitarity.

BU operator structure and selectivity. The bounce operator BU can be decomposed into coarse-graining (projection onto long-wavelength modes) and a unitary reshuffling:

$$\mathrm{BU} \;=\; \mathcal{P}_{\Lambda} \circ \mathcal{U}_{\mathrm{reshuffle}},$$

where $\mathcal{P}_{\Lambda}$ projects onto modes below a UV cutoff Λ (the modes that survive into the new cycle) and $\mathcal{U}_{\mathrm{reshuffle}}$ reassigns microstate labels according to brane-collision dynamics. The PQO $\mathcal{J}_{\mathrm{cosmo}}$ then controls how much of the projected information remains accessible versus deposited into the environment.

Observational constraints and phenomenology. The cosmological attenuation must respect empirical bounds. In particular:

- **Effective radiation degrees of freedom:** energy removed at bounce modifies N_{eff}. We require ΔN_{eff} induced by $\mathcal{J}_{\mathrm{cosmo}}$ to satisfy current bounds (Planck): $\Delta N_{\mathrm{eff}} \lesssim \mathcal{O}(0.2)$.
- **Gravitational waves:** brane collisions can produce a stochastic background; require $\Omega_{\mathrm{GW}}^{\mathrm{relic}}$ below current upper limits (LIGO/LISA regimes), which constrains collision energy scales and λ_{cosmo}.
- **BBN consistency:** the post-bounce reheating history must reproduce observed light-element abundances; energy injection from the environment must not spoil BBN yields.

These constraints restrict the allowed values of λ_{cosmo}, U_{SE}-induced entropy $S_{\mathrm{env}}^{\mathrm{add}}$, and the projection cutoff Λ.

Testable predictions.

1. A nontrivial mass-dependence of observable bounce relics (e.g., slight scale-dependent features in primordial spectra) if λ_{cosmo} has residual dependence on local scales.
2. A suppressed small-scale primordial power (effective UV damping) if $\mathcal{P}_{\Lambda}$ removes short-wavelength information during BU.
3. A possible stochastic GW signature with a spectral shape tied to brane-collision dynamics; amplitude tied to the fraction of collision energy that remains in visible-sector gravity waves vs. hidden-brane absorption.

Summary. The BU + $\mathcal{J}_{\text{cosmo}}$ framework realizes the CIST entropy reset as an open-system process embedded in a global unitary evolution. It provides a flexible modelling toolkit: by choosing the form of BU, the coupling to the environment via U_{SE}, and the projection cutoff Λ, one can tune phenomenology while maintaining quantum consistency and empirical testability.

20 Results and Observations

The incorporation of black hole physics into the Cyclic Information-preserving String Theory (CIST) framework yields the following key results:

- The localized Preservation Quantum Operator $\mathcal{J}_{\text{BH}}(t)$ allows for time-dependent attenuation and phase rotation of information inside black holes, extending the cyclic evolution model to gravitationally collapsed systems.
- Hawking radiation is described as a partial reversal of the PQO, wherein outgoing modes asymptotically reconstruct the earlier string-brane state. This supports delayed unitarity, consistent with information conservation.
- Fuzzball theory supplies a string-theoretic mechanism for information retention and eventual release from black holes, in alignment with CIST's cyclic information dynamics.
- The operator $\mathcal{J}_{\text{rev}} = \sum_k \mathcal{J}_{\text{BH}}^\dagger(t_k)$ acts as an effective global inverse that reconstructs the original infalling state from distributed Hawking radiation, providing an explicit mathematical formulation of black hole information recovery in CIST.

These observations unify classical black hole thermodynamics, Hawking evaporation, and fuzzball microphysics under the PQO framework, enriching the predictive power of CIST.

21 Conclusion for Black Hole Section

The CIST black hole framework demonstrates that string-based information preservation extends coherently into the strong-gravity regime. By modeling black holes as non-unitary yet information-preserving processors via a time-dependent PQO $\mathcal{J}_{\text{BH}}(t)$, we reconcile the paradox between semi-classical Hawking evaporation and quantum unitarity.

Hawking radiation is reinterpreted not as a fundamentally destructive process, but as a temporally delayed, highly scrambled information release governed by the reverse application of $\mathcal{J}_{\text{BH}}^\dagger(t)$. The ultimate conservation of quantum data is maintained through cumulative emission over time. This delayed unitarity emerges not from reversing collapse, but from decoding its long-term output.

Fuzzball theory, with its microstate geometries and lack of traditional horizons, provides a natural candidate for encoding the internal state of a black hole in terms of accessible string-brane degrees of freedom. Within CIST, the fuzzball state serves as an intermediate storage medium, from which information gradually escapes via radiation modes. The resulting view is that black holes are not endpoints of information, but rather intermediate information reservoirs in the cyclic cosmological process.

Final Conclusion

Altogether, the CIST framework now provides a unified, cycle-spanning theory in which strings preserve and transfer information through both cosmological evolution and gravitational collapse. The Preservation Quantum Operator is the mathematical bridge linking big bangs, brane collisions, black holes, and radiation into one consistent quantum informational cosmology.

References:

- B. Zwiebach, *A First Course in String Theory*, Cambridge University Press (2009).
- M. Gasperini and G. Veneziano, "The Pre-Big Bang Scenario in String Cosmology," *Phys. Rept.* **373**, 1-212 (2003).
- J. Polchinski, *String Theory, Vol. 1: An Introduction to the Bosonic String*, Cambridge University Press (1998).
- M. B. Green, J. H. Schwarz, and E. Witten, *Superstring Theory*, Vols. 1 & 2, Cambridge University Press (1987).
- R. Penrose, "Conformal Cyclic Cosmology: Dark Matter, Dark Energy and the Black Hole Information Paradox," *Int. J. Mod. Phys. D* **19**, 2313 (2010), doi:10.1142/S0218271810017160.
- J. Khoury, B. A. Ovrut, P. J. Steinhardt, and N. Turok, "The Ekpyrotic Universe: Colliding Branes and the Origin of the Hot Big Bang," *Phys. Rev. D* **64**, 123522 (2001).
- P. J. Steinhardt and N. Turok, "Cosmic Evolution in a Cyclic Universe," *Phys. Rev. D* **65**, 126003 (2002).
- E. Witten, "String Theory Dynamics In Various Dimensions," *Nucl. Phys. B* **443**, 85 (1995).
- M. J. Duff, "M-Theory (The Theory Formerly Known as Strings)," *Int. J. Mod. Phys. A* **11**, 5623 (1996).
- D. Baumann and L. McAllister, *Inflation and String Theory*, Cambridge University Press (2015).
- L. Susskind, "The Quantum Hall Fluid and Non-Commutative Chern Simons Theory," *arXiv:hep-th/0101029* (2001).
- V. Y. F. Tan, *Asymptotic Estimates in Information Theory with Non-Vanishing Error Probabilities*, https://arxiv.org/abs/1504.02608arXiv:1504.02608 (2015).

- C. Rovelli, *Quantum Gravity*, Cambridge University Press (2004).
- J. Preskill, "Quantum Information and Physics: Some Future Directions," *J. Mod. Opt.* **47**, 127 (2000).
- S. Hossenfelder, "Minimal Length Scale Scenarios for Quantum Gravity," *Living Rev. Relativity* **16**, 2 (2013).
- N. Seiberg and E. Witten, "String Theory and Noncommutative Geometry," *JHEP* 9909:032 (1999).
- C. Vafa, "Evidence for F-Theory," *Nucl. Phys. B* **469**, 403 (1996).
- L. Randall and R. Sundrum, "An Alternative to Compactification," *Phys. Rev. Lett.* **83**, 4690 (1999).
- J. Maldacena, "The Large N Limit of Superconformal Field Theories and Supergravity," *Adv. Theor. Math. Phys.* **2**, 231 (1998).
- M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press (2010).
- S. Carlip, "Quantum Gravity: A Progress Report," *Rept. Prog. Phys.* **64**, 885 (2001).
- E. Silverstein and D. Tong, "Scalar Speed Limits and Cosmology: Acceleration from D-cceleration," *Phys. Rev. D* **70**, 103505 (2004).
- C. Cheung, "TASI Lectures on Cosmological Collider Physics," *arXiv:1903.08114* (2019).
- A. Ashtekar and P. Singh, "Loop Quantum Cosmology: A Status Report," *Class. Quant. Grav.* **28**, 213001 (2011).
- ScienceDirect, *String Theory Overview*,https://www.sciencedirect.com/topics/mathematics/string-theory.
- S. W. Hawking, "Particle Creation by Black Holes," *Communications in Mathematical Physics*, vol. 43, pp. 199–220, 1975. https://doi.org/10.1007/BF02345020doi:10.1007/BF02345020
- M. K. Parikh and F. Wilczek, "Hawking Radiation as Tunneling," *Physical Review Letters*, vol. 85, no. 24, pp. 5042–5045, 2000. https://doi.org/10.1103/PhysRevLett.85.5042doi:10.1103/
- S. D. Mathur, "The Fuzzball Proposal for Black Holes: An Elementary Review," *Fortschritte der Physik*, vol. 53, no. 7-8, pp. 793–827, 2005. https://doi.org/10.1002/prop.200410203d
- A. Strominger and C. Vafa, "Microscopic Origin of the Bekenstein-Hawking Entropy," *Physics Letters B*, vol. 379, no. 1-4, pp. 99–104, 1996. https://doi.org/10.1016/0370-2693(96)00345-0doi:10.1016/0370-2693(96)00345-0
- R. Penrose, "Gravitational Collapse: The Role of General Relativity," *Rivista del Nuovo Cimento*, vol. 1, pp. 252–276, 1969.

- B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Observation of Gravitational Waves from a Binary Black Hole Merger," *Physical Review Letters*, vol. 116, no. 6, 061102, 2016. https://doi.org/10.1103/PhysRevLett.116.061102doi:10.1103/Phy

- R. Penrose, *Cycles of Time: An Extraordinary New View of the Universe*, Bodley Head, 2010.

- J. Khoury, B. A. Ovrut, P. J. Steinhardt, and N. Turok, "The Ekpyrotic Universe: Colliding Branes and the Origin of the Hot Big Bang," *Physical Review D*, vol. 64, no. 12, 123522, 2001. https://doi.org/10.1103/PhysRevD.64.123522doi:10.1103/PhysRevD.64.123522

- J. Preskill, "Black Holes and Information: A Crisis in Physics," Lecture Notes, 1992.https://arxiv.org/ th/9209058arXiv:hep-th/9209058

- S. D. Mathur, "Fuzzballs and the Information Paradox: A Summary and Conjectures," arXiv preprint, 2009. https://arxiv.org/abs/0909.1038arXiv:0909.1038

- Penrose, R. (1989). The Emperor's New Mind. Oxford University Press. (Entropy and cosmology discussion).

- Baum, L., & Frampton, P. H. (2007). Turnaround in cyclic cosmology. Physical Review Letters, 98(7), 071301. (Explicit entropy reset proposals).

- Steinhardt, P. J., & Turok, N. (2002). A cyclic model of the universe. Science, 296(5572), 1436-1439.