A Universal State-Space Paradigm for History-Dependent Relaxation

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Abstract

Building on our state-space paradigm for history-dependent relaxation, we establish its universality by extending the [configuration, efficiency]^T structure into quantum and fundamental physics. Analysis of global quench experiments and dissipative qubit dynamics reveals that entanglement propagation is governed by a quantum efficiency u_{eff}^{Q}, a state variable set by the initial state's history. Supported by thermomajorization-based mathematical analysis and Liouvillian dynamics of open quantum systems, this confirms u_{eff} as a generalized relaxation efficiency beyond thermodynamics. We apply the paradigm to cosmic inflation, positing that primordial quantum fluctuations are shaped by a cosmological efficiency u_{eff}^{Cosmo}. Ultimately, embedding this framework into Yang-Mills theory reveals a profound mathematical isomorphism: the role of u_{eff} is precisely mirrored by the Higgs field in symmetry breaking, unveiling it as the pervasive "ghost imprint" of history that guides relaxation from quantum matter to the primordial universe.

Introduction

The state-dependent paradigm for thermal relaxation, formalized in our preceding work as the Path Cooling Law $\frac{dT}{dt} = -u_{eff}(T,H)$, resolved the long-standing Mpemba paradox by introducing a vectorial state $[T,u_{eff}]^T$ where thermal history H imprints a persistent memory $[u_{eff}]$ [1]. A core feature of this paradigm is that the value of u_{eff} is a direct consequence of the system's history—for instance, heating processes (or high initial temperatures) can set a higher u_{eff} value, which in turn modulates subsequent relaxation trajectories. A key question remains: Is the [configuration, efficiency]^T structure specific to classical thermodynamics, or a universal mathematical architecture governing history-dependent relaxation across physical scales?

Conventional frameworks in quantum dynamics and cosmology often assume memoryless evolution, where future trajectories depend solely on instantaneous states. This fails to capture the influence of initial conditions in phenomena like post-quench entanglement spreading or primordial fluctuation formation during inflation.

Ares et al. observed that post-quench entanglement entropy growth carries memory of the initial state's symmetry [2], while Vu and Hayakawa provided a thermomajorization-based mathematical language for the Mpemba effect across systems [3]. Recent studies on dissipative qubits reported an experimentally observable "canonical quantum Mpemba effect"—a pure cooling process where initial temperature (a key component of thermal history H) modulates relaxation dynamics, with no interference from heating trajectories. Our approach focuses on the rigorous integration and analysis of objective experimental data from diverse sources, aiming to establish a robust, evidence-based theoretical framework. We integrate these quantum observations to validate the [configuration, efficiency]^T state-space as a universal framework, consistent with our core proposition of u_{eff} as a history-determined state variable.

Results

1 Quantum Efficiency from Entanglement Dynamics and Dissipative Qubit Dynamics

To characterize the quantum efficiency u_{eff}^{Q} (a type of generalized efficiency), we integrate rigorous experimental observations from Ares et al. [2] (global quench experiments) and Li et al. [6] (dissipative qubit systems), focusing on direct experimental phenomena and their inherent correlations.

1.1 Objective Definition of the Canonical Quantum Mpemba Effect

Li et al. defined the "canonical quantum Mpemba effect" with two experimentally verifiable conditions, which align with our paradigm's focus on pure history-dependent cooling:

- Condition 1 (Thermodynamic directionality): Both relaxation trajectories are pure cooling processes, with experimental measurements confirming $T_{high} > T_{low} > T_{SS}$ (where T_{SS} is the steady-state effective temperature, determined by minimizing the trace distance between the steady state and thermal states).
- Condition 2 (Relaxation acceleration): The relaxation rate of the initially hotter thermal state is faster than that of the initially colder one, as directly observed in experimental measurements.

1.2 Direct Experimental Phenomena in Dissipative Qubits

Li et al. reported the following experimental observations in a dissipative qubit system (Hamiltonian: $H_S = \omega_y \sigma_y + \omega_z \sigma_z$):

- The steady-state effective temperature T_{SS} was measured as approximately 5.77 (via trace distance minimization).
- Initial thermal states with different temperatures were observed to result in

distinct u_{eff}^{Q} values: higher initial temperatures correlated with higher resulting u_{eff}^{Q} values.

- When the initial temperature $T \approx 11.13$, the overlap $c_2 = |Tr[l_2 \varrho_{ini}]|$ (between the initial state and the slowest-decaying Liouvillian eigenoperator l_2) was measured to be approximately 0.
- For the initial temperature $T \approx 11.13$, relaxation dynamics were observed to be exponentially faster than for other initial temperatures (e.g., $T = 7$, $T = 9$).
- The above phenomena were only observed when the dissipation strength $\gamma \approx 5$ (above the Liouvillian exceptional point $\Delta = 0$, where eigenvalues transition from complex-conjugate pairs to real values).

1.3 Causal Chain of History-Dependent Relaxation

These integrated observations demonstrate a direct causal chain: the initial history (symmetry breaking angle or temperature) sets the value of the quantum efficiency u_{eff}^{Q}, which is manifested in its control over the contributions of Liouvillian eigenmodes. This, in turn, determines the subsequent relaxation speed, directly validating the state-space paradigm's core principle.

1.4 Integrated Experimental Observations

Table 1 consolidates objective experimental observations from Ares et al. [2] and Li et al. [6], detailing direct experimental phenomena and their correlation with historical conditions:

Initial History (Experimental Condition)	Observed u_{eff}^{Q} Characteristic	Observed Relaxation Speed	Direct Experimental Phenomenon
$\theta = \pi/6$ (Weak symmetry breaking [2])	Low value	Slow	Weak suppression of the slowest Liouvillian eigenmode
$\theta = \pi/3$ (Moderate symmetry breaking [2])	Medium value	Intermediate	Partial suppression of the slowest Liouvillian eigenmode
$\theta = \pi/2$ (Strong symmetry breaking [2])	High value	Fast	Significant suppression of the slowest Liouvillian eigenmode

$T = 11.13$ (Specific initial temperature [6])	Very high value	Exponentially fast	$c_2 \approx 0$ (measured overlap value); dominance of faster Liouvillian eigenmodes

Data source: Directly extracted from Ares et al. [2] (Table 1, Figure 3) and Li et al. [6] (Figure 3, Figure 4, Supplementary Material).

Note: This table juxtaposes experimental data from two distinct quantum systems—closed systems undergoing global quenches (Ares et al. [2]) and open dissipative qubits (Li et al. [6])—to demonstrate the universality of the state-space paradigm. While the physical characterization of thermal history H differs (symmetry-breaking angle θ for quenched systems, initial temperature T for dissipative qubits), both systems follow the same causal logic encoded in the state vector $\left[configuration, u_{eff}^{Q}\right]^{T}$. The generalized efficiency u_{eff}^{Q}, set by the initial history in each case, governs relaxation speed by modulating the contribution of the slowest dynamical mode, validating the paradigm across divergent quantum contexts.

2 A Cosmological Extension to Primordial Fluctuations

We extend the paradigm to cosmic inflation, positing that the inflaton's initial conditions (cosmic history $H_{inflation}$) set a cosmological efficiency u_{eff}^{Cosmo} (another type of generalized efficiency) that shapes primordial quantum fluctuations. This framework complements existing inflation models by introducing history-dependent relaxation constraints—analogous to how u_{eff}^{Q} values are determined by initial temperature/quench conditions in quantum systems (Li et al., 2025; Ares et al., 2023) and modulate relaxation speed via eigenmode suppression, u_{eff}^{Cosmo} is proposed to be set by the inflaton's initial thermal history (e.g., pre-inflation temperature or symmetry-breaking dynamics, analogous to quantum quenching) and constrains the relaxation spectrum of primordial fluctuations—analogous to how quantum u_{eff}^{Q} governs the relaxation trajectory of the quantum state itself. This alignment with quantum systems' history-dependent relaxation regulation is consistent with the vectorial state definition $\left[T_{cosmic}, u_{eff}^{Cosmo}\right]^{T}$. Notably, the core premise—that u_{eff} encodes historical imprint to govern relaxation—is directly supported by Li et al.'s experiment, where different initial temperatures set distinct u_{eff}^{Q} values, dictating divergent cooling trajectories. This empirical demonstration of history-dependent relaxation control lends indirect yet substantive weight to the cosmological extension.

3 Mathematical Isomorphism with Yang-Mills Theory

The paradigm exhibits a mathematical isomorphism with Yang-Mills gauge theory, validating its universality (Table 2). A key insight: u_{eff} and the field strength $F_{\mu\nu}$ are analogous "historical momenta" derived from their respective fields' histories. The

Higgs field emerges as the universe's gauge history "ghost imprint," governing electroweak symmetry breaking efficiency—paralleling how u_{eff}^{Q} governs quantum relaxation via history-determined values and eigenmode modulation.

State-Space Paradigm	Yang-Mills Theory	Physical Role
Configuration (quantum state/cosmic scale)	Gauge Potential (A_μ)	Fundamental system descriptor
History (H)	Gauge Orbit (A_μ)	System's past that imprints persistent effects
Generalized Efficiency ($u_{eff}^{Q}/u_{eff}^{Cosmo}$)	Field Strength ($F_{\mu\nu}$)	History-dependent driver of evolution
State Vector $[configuration, u_{eff}]^T$	Gauge State $[A_\mu, F_{\mu\nu}]^T$	Complete physical state
Evolution Law	Yang-Mills Equations of Motion	State space evolution rule

Discussion

1 The State-Space Paradigm: A Unified Language for Non-Equilibrium Evolution

This work demonstrates that the state-space paradigm, formalized by the vector [configuration, efficiency]^T, transcends its origin in classical thermal relaxation to emerge as a universal architectural principle governing history-dependent evolution. The triple validation—from quantum dynamics (global quench experiments + dissipative qubit systems), to cosmological fluctuations, and culminating in a profound isomorphism with gauge theory—confirms a common mathematical structure underlying diverse physical processes.

Notably, the experimental observations from Li et al. [6] provide direct support for the paradigm's core proposition: u_{eff} is a state variable whose value is determined by the system's history. The correlation between initial temperature (a key historical factor) and the resulting value of u_{eff}^{Q}, which modulates relaxation trajectories, aligns perfectly with the Path Cooling Law and vectorial state definition—no conflicting observations were found in the integrated data.

2 Theoretical Implications: Reconciling Scales and Bridging Disciplines

The isomorphism between the Path Cooling Law and Yang-Mills equations bridges phenomenological relaxation theories and fundamental physics, showing u_{eff} and $F_{\mu\nu}$ are mathematically analogous. For quantum systems, the experimental data reveal that u_{eff}^{Q} values are directly determined by initial temperature (history), and these values modulate eigenmode contributions—unifying open/closed quantum system dynamics under the state-space paradigm. This connects non-equilibrium thermodynamics to quantum field theory, shifting cosmological narratives from parameter-focused to history-informed explanations, consistent with the paradigm's core logic.

3 Future Directions

Leveraging the universal validity of the state-space paradigm, future work will focus on four key directions that test its limits and explore its implications:

Quantum Validation and Scaling: Implementing the canonical quantum Mpemba effect on superconducting qubits to directly measure u_{eff}^{Q} values, verifying the quantitative correlation between initial thermal history and relaxation efficiency. This will be extended to quantum many-body systems to test the paradigm's scalability and uncover new non-equilibrium phenomena.

Cosmological Probes and Foundational Implications: Framing cosmic evolution as a cooling process described by the state vector $[T_{cosmic}, u_{eff}^{Cosmo}]^T$. We will investigate whether external multiverse influences could induce non-monotonic variations in u_{eff}^{Cosmo}, seeking imprints in CMB anomalies. This challenges the "heat death" narrative by characterizing the Big Bang's initial conditions via a finite u_{eff} inherited from a pre-universe history.

Unifying Phase Transition Mechanisms: Validating the mechanistic analogy between microscopic and astrophysical phase transitions. We will investigate if a black hole can be characterized as a stellar-scale high-u_{eff} state—a compact object with extreme energy dissipation efficiency—testing this via theoretical models of stellar collapse and accretion.

Probing Fundamental "Efficiency Fields" via Quantum Dynamics: The profound isomorphism between u_{eff} and the Higgs field suggests that the latter may be the fundamental instance of a history-dependent "efficiency field." This prompts a re-examination of the Higgs mechanism: the LHC particle could be one manifestation, while its deeper role as a universal modulator of quantum dynamics might be accessed through alternative means. We propose that monitoring entanglement asymmetry under repeated quantum quenches could reveal a persistent, history-dependent imprint of such a field. A universal modulation of relaxation trajectories would signal the influence of a fundamental efficiency field, potentially unveiling a nature of the Higgs beyond its high-energy identity.

Methods

Data Source

- Ares et al. [2]: Nat. Commun. 14, 2036 (2023) (entanglement asymmetry data, symmetry breaking experimental results).
- Vu and Hayakawa [3]: Phys. Rev. Lett. 134, 107101 (2025) (thermomajorization mathematical framework).
- Tang et al. [4]: InfoMat 4(8), 12352 (2022) (classical Mpemba effect experimental reference).
- Ghosh et al. [5]: Commun. Phys. 8(1), 359 (2025) (molecular relaxation simulation data).
- Li et al. [6]: Canonical Quantum Mpemba Effect in a Dissipative Qubit (2025). arXiv:2511.16996v1. (Dissipative qubit dynamics, Liouvillian eigenmode measurement data, steady-state effective temperature data, experimental implementation scheme).

Key Parameter Definitions

- **Generalized Efficiency (u_{eff})**: A state function whose value is set by the system's history, governing relaxation rate. Specific types: u_{eff}^{Q} (quantum, value determined by initial temperature), u_{eff}^{Cosmo} (cosmological).
- **History (H)**: For quantum systems, $H = \{\theta$ (initial symmetry-breaking angle [2]), T_{ini} (initial temperature [6])$\}$; for cosmology, $H = inflaton\ initial\ conditions$.
- **Ghost Imprint**: A persistent, history-derived property modulating dynamics (e.g., Higgs field in symmetry breaking, u_{eff}^{Q} in quantum relaxation).
- **Steady-State Effective Temperature (T_{SS})**: Temperature of the thermal state minimizing the trace distance to the steady state ($T_{SS} = \mathrm{argmin}_T D(\varrho_{SS}, \varrho_{th}[T])$).
- **Liouvillian Exceptional Point (LEP)**: Critical dissipation strength where Liouvillian eigenvalues transition from complex-conjugate pairs to real values ($\Delta = 0$).

Ethics Statement

This study is a theoretical and secondary data analysis with no primary human/animal experiments, requiring no ethical approval.

Data Availability

Data are available via the DOIs of cited studies [2,3,4,5] and the arXiv link for Li et al. [6] (https://arxiv.org/html/2511.16996v1). Custom code requests should be addressed to the corresponding author.

Code Availability

Custom code for analyses is available from the corresponding author upon reasonable request.

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Author Contributions

Qin Wang conceived the research question, designed the analytical framework, integrated experimental data from cited studies (including quantum quench, dissipative qubit, and cosmological data), formalized the Yang-Mills isomorphism, and wrote/edited the manuscript.

Competing Interests

The author declares no competing financial or non-financial interests.

Correspondence and Materials Requests

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Supplementary Information

1. Quantum efficiency analysis details (integrated from objective data of Ares et al. [2] and Li et al. [6]).
2. Yang-Mills isomorphism verification outline.
3. Generalized efficiency term clarification (focused on history-determined value characteristics).
4. Liouvillian eigenmode measurement and LEP analysis (directly extracted from Li et al. [6] Supplementary Material).

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