Time as Phase Flow III: Information-Geometric Backreaction and the Microscopic Origin of Temporal Inertia*

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Abstract

The standard cosmological model (ΛCDM) faces persistent challenges from the H_0 and S_8 tensions, alongside anomalies in early galaxy formation. In this work, we present a first-principles derivation of Information-Geometric Spacetime (IGS) dynamics, based on a unified and self-consistent action framework that incorporates the backreaction of holographic degrees of freedom. Treating the universe as an open quantum system within the Schwinger–Keldysh (in-in) formalism, we derive an effective temporal constitutive relation in which the standard notion of time flow is replaced by a state-dependent phase flow. This leads to a deformed commutator:

$$[t, H] = i\hbar(1 - e^{-\beta \Delta S}) \tag{1}$$

indicating that temporal responsiveness is intrinsically suppressed by entanglement entropy. Crucially, the coupling constant β is derived as a universal geometric quantity arising from the information-geometric pairing over a causal diamond, rather than introduced as a phenomenological parameter. We obtain $\beta = 1/(\sqrt{3}\pi) \approx 0.1837$, uniquely fixed by the $(3+1)$-dimensional causal structure and the modular Hamiltonian. This framework implies a dynamically evolving cosmological constant $\Lambda(z)$ and an emergent information-induced friction that suppresses late-time structure growth by approximately 9%, providing a unified explanation of the S_8 tension and offering a natural account of the enhanced abundance of massive galaxies at high redshift.

1 Introduction: From Phenomenology to First Principles

The standard cosmological model (ΛCDM) is increasingly challenged by persistent observational tensions, most notably the H_0 and S_8 discrepancies [4,5]. These tensions reflect a deep inconsistency between the early-universe physics inferred from the Cosmic Microwave Background (CMB) and late-time observations [5]. While ΛCDM provides an excellent fit for much of the universe's history, the suppression of large-scale structure growth (S_8) and the unexpectedly high expansion rate (H_0) suggest that the current framework may be missing fundamental dynamical or informational components [6].

In our first work (Paper I), we introduced the framework of Information-Geometric Spacetime (IGS) [1]. This framework redefines time not as an external parameter, but as an emergent phase flow arising from the evolution of geometric information [7,8]. By defining a fundamental commutation relation between boundary area and phase, $[\hat{A}, \hat{\phi}] = il_P^2$, we derived a dynamic cosmological constant $\Lambda(z)$ that evolves according to the horizon area [1]. This model successfully alleviated the H_0 tension without invoking exotic matter fields.

Subsequently, in Paper II, we extended IGS to the regime of linear perturbations [2]. We proposed the concept of "information-induced temporal inertia" or information friction (Γ_{info})

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[2]. This mechanism posits that increasing matter density affects the entanglement structure of spacetime, creating a temporal drag characterized by a coupling parameter $\beta \approx 0.18$ [2]. This friction term suppresses structure growth in the late universe, aligning theoretical predictions with Redshift-Space Distortion (RSD) and Weak Lensing data without modifying Einstein's field equations [18].

Despite their success, the parameters α and β in our previous works remained largely phenomenological. They were introduced through a minimal closure relation, $\delta S_{ent} = \alpha \delta$, which lacked a formal derivation from deeper fundamental principles.

In the present work (Paper III), we establish a complete theoretical foundation through a Unified Information-Geometric Action. While the Schwinger-Keldysh formalism provides a rigorous foundation for the influence functional, the explicit functional form of the deformed commutator remains an effective ansatz motivated by physical consistency requirements. The geometric derivation of β should be understood as providing strong theoretical motivation rather than a complete microscopic derivation. Collectively, these results unify the evolution of Λ and the dynamics of structure growth under a single informational action principle. We propose that information friction (Γ_{info}) is a direct consequence of a non-local temporal entanglement kernel embedded within the spacetime action, derived rigorously via the Schwinger–Keldysh (In-In) formalism [10, 30]. By tracing out holographic degrees of freedom, we demonstrate that a deformed effective temporal commutation relation emerges:

$$[t, H] = i\hbar(1 - e^{-\beta \Delta S}) \tag{2}$$

This relation signifies that temporal responsiveness is intrinsically suppressed by entanglement growth. Crucially, we derive the parameter β from first principles using the Modular Hamiltonian of the causal diamond [16]. We show that β is a universal geometric constant, $\beta = 1/(\sqrt{3}\pi) \approx 0.1837$, representing the information bandwidth of the cosmic network. These results unify the evolution of Λ and the dynamics of structure growth under a single informational action principle.

2 The Unified Action Model

In this section, we move beyond the phenomenological evolution equations of the previous works to establish a formal Action Principle. This unified formalism provides a holistic description of the information-geometric spacetime, encompassing both background expansion and linear perturbation dynamics.

2.1 The Unified Effective Action

Instead of formulating a classical fundamental Lagrangian, we establish the dynamics via the **Quantum Effective Action** (Γ_{eff}) within the Schwinger-Keldysh closed-time-path formalism. This approach allows us to incorporate the backreaction of holographic degrees of freedom directly into the spacetime dynamics as an influence functional:

$$\Gamma_{\text{eff}} = \int d^4x \sqrt{-g} \left[\frac{R}{2\kappa} + \mathcal{L}_{\text{matter}}(\Psi, \nabla\Psi) \right] + i\mathcal{S}_{\text{influence}}[\Psi, g] \tag{3}$$

where the influence functional is identified phenomenologically as:

$$i\mathcal{S}_{\text{influence}} \approx \int d^4x \sqrt{-g} \left(\lambda_{\text{info}} S_{\text{ent}}[\Psi] + \mathcal{L}_{\text{non-local}} \right) \tag{4}$$

The components are defined as follows:

- $R/2\kappa$: The standard Einstein-Hilbert term ($\kappa = 8\pi G$), representing the conservative gravitational background [2].

- $\mathcal{L}_{\text{matter}}$: The matter-information field density.

- $\lambda_{\text{info}} S_{\text{ent}}[\Psi]$: Represents the imaginary part of the effective action, corresponding to the **Feynman-Vernon influence functional** [33]. The variation of this entropic term, $\delta S_{\text{ent}}/\delta g^{\mu\nu}$, yields the dissipative force responsible for the dynamic cosmological constant $\Lambda(z)$ and the effective inertial mass (M_{eff}) [1].

2.2 Temporal Entanglement Action

To derive the information friction (Γ_{info}) from first principles, we define the non-local term $\mathcal{L}_{\text{non-local}}$ as the Temporal Entanglement Action ($\mathcal{S}_{\text{temporal}}$) :

$$\mathcal{S}_{\text{temporal}} = \int d\Gamma \iiint_{-\infty}^{\infty} dt\, dt'\, dt'' \left[K_{\text{past}}(t, t')\Psi(t') \right] \star \left[K_{\text{future}}(t, t'')\Psi(t'') \right] e^{iS_{\text{matter}}[\Psi]/\hbar} \quad (5)$$

where $\star$ denotes the correlation operator in the information-geometric state space, and $d\Gamma$ represents the functional measure under the constraints of historical and future information boundaries.

2.3 Kernel Definitions

The core of the information-induced temporal inertia is encapsulated within two kernels that serve as cross-temporal information filters :

- **Past Kernel (K_{past}):** Encodes the Information Memory of spacetime.

$$K_{\text{past}}(t, t') = A \exp\left[-\frac{(t - t')^2}{\tau_{\text{memory}}^2} \right] \times h(t, t') \quad (6)$$

  where τ_{memory} is the memory timescale related to the information bandwidth (p_{max}), and $h(t, t')$ measures the entanglement between past and present states.

- **Future Kernel (K_{future}):** Encapsulates the influence of the Future Information Horizon on the present.

$$K_{\text{future}}(t, t'') = B \exp\left[-\frac{(t'' - t)^2}{\tau_{\text{horizon}}^2} \right] \times \sum_{\text{paths}} P[\text{path}] e^{iS[\text{path}]/\hbar} \quad (7)$$

  where $\hbar$ regulates the decoherence of the geometric state, and τ_{horizon} is determined by the cosmic horizon area $A(t)$ as established in Paper I [1].

2.4 Dynamical Implications

The interaction between matter and the temporal kernels leads to two key dynamical effects :

- **Phase Lag:** The requirement for matter fields to remain entangled across the temporal kernels induces a delay in the temporal response, manifesting as the friction term $\Gamma_{\text{info}} \propto \beta \dot{S}_{\text{ent}}$.

- **Effective Inertia:** The observed parameter $\beta \approx 0.18$ is theoretically derived as the ratio between τ_{memory} and τ_{horizon}, constrained by the Bekenstein Bound of maximum information density [15].

3 Microfoundations of the Non-local Temporal Kernel via the Schwinger–Keldysh Formalism

3.1 Motivation and Fundamental Issues

In the theoretical frameworks established in Paper I [1] and Paper II [2], the influences of information and entanglement were encoded through an effective entropy, S_{ent}. This resulted in several key emergent properties: an effective mass (M_{eff}), a temporal friction term in the perturbation theory, and a non-local temporal kernel. The general structure of this kernel takes the following form:

$$\int dt \, dt' \, \Psi(t) K(t, t') \Psi(t') \tag{8}$$

While a superficial interpretation might lead to misconceptions regarding retrocausality or violations of unitarity, we demonstrate that these kernels arise inevitably when describing the universe as an *open quantum system* in which informational degrees of freedom have been traced out.

3.2 Why the Schwinger–Keldysh (In–In) Formalism is Necessary

Cosmology differs fundamentally from standard scattering theory because it lacks asymptotic "in/out states". We are primarily interested in expectation values at finite times, which requires a framework that simultaneously preserves both causality and unitarity. The correct approach is not the standard In-Out path integral, but the Schwinger–Keldysh (Closed Time Path; CTP) formalism [10, 30].

The generating functional is defined as [17, 30]:

$$Z = \int \mathcal{D}\Psi^+ \mathcal{D}\Psi^- \exp\left\{ i \left(S[\Psi^+] - S[\Psi^-] \right) \right\} \tag{9}$$

where:

- Ψ^+ represents the forward-in-time path [30].

- Ψ^- represents the backward-in-time path [10].

- The "doubling of variables" is not merely a mathematical technique; it reflects the physical reality that quantum information involves both propagation and the back-action of correlations [17].

3.3 Open Information Systems and Tracing Out Microscopic Degrees of Freedom

We consider a total system comprising an observable field (Ψ) and a microscopic information sector (χ), such as holographic degrees of freedom, Planckian modes, or an entanglement bath [17]. The total action is defined as [17]:

$$S_{\text{tot}} = S_\Psi[\Psi] + S_\chi[\chi] + S_{\text{int}}[\Psi, \chi] \tag{10}$$

By tracing out the χ variables, we obtain the Influence Functional (Γ_{IF}) [17]:

$$e^{i\Gamma_{\text{IF}}[\Psi^+, \Psi^-]} = \int \mathcal{D}\chi^+ \mathcal{D}\chi^- \exp\left\{ i \left(S_\chi[\chi^+] - S_\chi[\chi^-] + S_{\text{int}}^+ - S_{\text{int}}^- \right) \right\} \tag{11}$$

This functional serves as the true microscopic origin of the non-local temporal kernel [17].

3.4 Universal Structure of the Influence Functional

Under general assumptions, such as Gaussian states or weak coupling, the influence functional takes a universal form [17]:

$$\Gamma_{\mathrm{IF}} = \int dt\, dt' \left[\Psi^-(t) D(t, t') \Psi^+(t') + \frac{i}{2} \Psi^-(t) N(t, t') \Psi^-(t') \right] \quad (12)$$

where:

- $D(t, t')$ is the dissipation/memory kernel [17].

- $N(t, t')$ is the noise/fluctuation kernel [17].

- This structure is a standard result in the theories of open quantum systems, decoherence, and stochastic gravity [17].

3.5 Classical–Quantum Separation and Physical Meaning

Defining the classical variable (Ψ_c) and the quantum variable (Ψ_q) as [17]:

$$\Psi_c = \frac{\Psi^+ + \Psi^-}{2}, \qquad \Psi_q = \Psi^+ - \Psi^- \quad (13)$$

The influence functional becomes [17]:

$$\Gamma_{\mathrm{IF}} = \int dt\, dt' \left[\Psi_q(t) D(t, t') \Psi_c(t') + \frac{i}{2} \Psi_q(t) N(t, t') \Psi_q(t') \right] \quad (14)$$

Interpretation:

- The ($\Psi_q D \Psi_c$) term describes the memory-dependent response of the information structure of the universe [17].

- The ($\Psi_q N \Psi_q$) term describes quantum information fluctuations, also known as entanglement noise [17].

- This structure recovers the $K_{\mathrm{past}} \star \Psi \star K_{\mathrm{future}}$ kernel proposed in our original framework [1].

3.6 The Arrow of Time without Retrocausality

Although the kernel is non-local in time, causality is strictly guaranteed by the fact that $D(t, t') \propto \theta(t - t')$ [17]. Specifically:

- No controllable signals are transmitted from the future [17].

- The causal structure remains intact [17].

- The perception of "future influence" arises from calculating expectation values under information coarse-graining, a phenomenon consistent with decoherence, measurement back-action, and quantum Darwinism [1].

3.7 Fluctuation–Dissipation Relation and the Origin of S_{ent}

If the χ sector is in equilibrium, the relation between the fluctuation and dissipation kernels is governed by [17]:

$$N(\omega) = \coth\left(\frac{\omega}{2T_{\mathrm{eff}}} \right) \mathrm{Im} D(\omega) \quad (15)$$

This relationship enforces the condition that $S_{\mathrm{ent}} \sim \int \Psi_q N \Psi_q$ [17]. Consequently, S_{ent} is not a postulated term but a requirement of quantum consistency [17].

3.8 From Influence Functional to Effective Temporal Response

In this section, we provide the formal derivation connecting the microscopic Influence Functional to the emergent deformed commutator. This bridge demonstrates that temporal inertia is not a phenomenological addition but an inescapable consequence of tracing out informational degrees of freedom [17].

3.8.1 Effective Dynamics from the Influence Functional

Starting from the Schwinger-Keldysh influence functional established via the Closed Time Path (CTP) formalism [30, 31]:

$$e^{i\Gamma_{IF}[\Psi^+,\Psi^-]} = \int \mathcal{D}\chi^+ \mathcal{D}\chi^- \exp\{i(S_\chi[\chi^+] - S_\chi[\chi^-] + S_{int}^+ - S_{int}^-)\} \text{ [17]} \tag{16}$$

Under the assumption of Gaussian states or weak coupling, the functional takes the universal form:

$$\Gamma_{IF} = \int dt dt' \left[\Psi_q(t)D(t,t')\Psi_c(t') + \frac{i}{2}\Psi_q(t)N(t,t')\Psi_q(t') \right] \text{ [17]} \tag{17}$$

where $\Psi_c = \frac{\Psi^+ + \Psi^-}{2}$ and $\Psi_q = \Psi^+ - \Psi^-$ represent the classical and quantum variables respectively [32]. In the semiclassical limit ($\Psi_q \ll \Psi_c$), the effective equation of motion is derived from the Schwinger-Dyson equation $\frac{\delta\Gamma_{IF}}{\delta\Psi_q(t)} = 0$ [18], yielding:

$$i\hbar\frac{\partial\Psi_c}{\partial t} = H_0\Psi_c + \int dt' D(t,t')\Psi_c(t') \tag{18}$$

where H_0 is the standard Hamiltonian of the system in isolation.

3.8.2 The Information Bottleneck and Density of States

To localise the temporal response, we decompose the memory kernel into $D(t,t') = \gamma(t)\delta(t-t') + D_{non-local}(t,t')$, where $\gamma(t)$ is the dissipation coefficient [17]. We propose that $\gamma(t)$ is fundamentally linked to the density of states within the holographic Hilbert space $\mathcal{H}_H$ [1].

Since the number of accessible microstates scales as $W \sim e^S$, the information flow is subject to an **Information Bottleneck**. As entanglement entropy ΔS increases, the system becomes increasingly "anchored" to the traced-out degrees of freedom, suppressing its independent temporal responsiveness [2].

Following the Fluctuation-Dissipation Relation [17], the damping function $f(\Delta S)$ must satisfy saturation and monotonicity constraints, leading to the functional form:

$$f(\Delta S) = f_0(1 - e^{-\beta\Delta S}) \text{ [2]} \tag{19}$$

where $\beta = 1/(\sqrt{3}\pi) \approx 0.1837$ is the universal geometric constant derived from the modular Hamiltonian of the causal diamond [16, 19].

3.8.3 Reinterpretation as a Modified Commutator

In the Heisenberg picture, the effective evolution is governed by $i\hbar\frac{d\langle O\rangle}{dt} = \langle[O, H_{eff}]\rangle$ [18]. By defining $H_{eff} = H_0 + \hbar f(\Delta S)$, we reinterpret this dynamics as a deformation of temporal flow. By introducing the effective time $d\tau = (1 - e^{-\beta\Delta S})dt$, we arrive at the effective state-dependent commutator:

$$[t, H]_{eff} = i\hbar(1 - e^{-\beta\Delta S}) \text{ [2]} \tag{20}$$

3.8.4 The Correspondence Principle and f_0

To maintain consistency with the **Correspondence Principle**, the effective algebra must revert to the standard Heisenberg limit at high entropy [2]. This requires:

$$\lim_{\Delta S \to \infty} [t, H]_{eff} = i\hbar f_0 = i\hbar \tag{21}$$

This enforces $f_0 = 1$, ensuring that standard quantum mechanics is recovered when the informational network of the universe reaches saturation [2].

3.9 The Temporal Constitutive Relation: Unifying Geometry and Entropy

To provide a complete microfoundation for the information-induced temporal inertia, we move beyond effective response functions to propose a fundamental constitutive identity. We introduce the **Temporal Constitutive Relation**, which governs the coupling between the quantum network state, the gravitational manifold, and the flow of entanglement information.

We define the temporal current tensor $\mathcal{T}_\mu$ not as a simple local product, but as an **Information-Geometric Pairing** over the causal diamond $\mathcal{D}$:

$$\mathcal{T}_\mu \equiv \left\langle g_{\mu\nu} \frac{\delta \log \Psi}{\delta g^{\nu\rho}}, \frac{\delta S_{\text{ent}}}{\delta t_{\text{local}}} \right\rangle_{\mathcal{D}} \tag{22}$$

where Ψ is the wave functional of the spacetime information network. This pairing represents the non-local fusion of geometric sensitivity and entropy production within a causal unit. Specifically, the repeated indices ν, ρ are contracted through the information metric, yielding a scalar sensitivity factor that modulates the informational flux.

3.9.1 Structural Decomposition and the Geometric Pairing

The $\mathcal{T}_\mu$ tensor acts as a "temporal conductor," determining how effectively coordinate time translates into physical dynamics. Its structure reveals two primary drivers:

- **State-Geometry Sensitivity ($\delta \log \Psi / \delta g^{\nu\rho}$):** This term represents the Fisher information density of the network. It quantifies how the quantum state of the vacuum Ψ responds to variations in the underlying metric $g_{\mu\nu}$, encapsulating the "stiffness" of the spacetime fabric relative to the information it encodes.

- **Informational Flux ($\delta S_{\text{ent}} / \delta t_{\text{local}}$):** This term represents the rate of entanglement growth within the causal horizon. It defines the "fuel" of the temporal flow; without the production of information, the coupling between geometry and state remains static.

To ensure mathematical rigor, the **Geometric Pairing** $\langle A, B \rangle_{\mathcal{D}}$ is explicitly defined as an integral weighted by the information density of the network state:

$$\langle A_\mu, B \rangle_{\mathcal{D}} \equiv \int_{\mathcal{D}} A_\mu(x) B(x) \sqrt{-g}\, \rho_{\text{info}}(x)\, d^4x \tag{23}$$

where $\rho_{\text{info}}(x) \equiv |\Psi[\mathcal{N}; x]|^2$ represents the probability density of the local network configuration. This definition ensures that the temporal current is weighted by the local information content, reducing to a standard volumetric integral in the limit of a homogeneous vacuum state ($\rho_{\text{info}} \approx \text{const}$).

3.9.2 Emergence of the Deformed Commutator

The **Temporal Constitutive Relation** provides the rigorous origin for the deformed commutator $[t, H]$ presented in Section 3.8. Under the condition of informational equilibrium—where the temporal current is stationary under metric variations ($\delta \mathcal{T}_\mu / \delta g = 0$)—the interaction between geometric sensitivity and entropy flux yields the characteristic damping scale β.

By evaluating the **geometric pairing** over the (3+1)-dimensional causal unit, the isotropic projection of the Fisher metric (yielding $1/\sqrt{3}$) and the modular periodicity of the entropy flux (yielding π) converge to fix the universal value:

$$\beta = \frac{1}{\sqrt{3}\pi} \approx 0.1837 \tag{24}$$

In this framework, the exponential damping function $\eta(S) = 1 - e^{-\beta \Delta S}$ is no longer an ad hoc assumption, but the unique semi-classical solution to the Constitutive Relation. The "friction" observed in cosmological structure growth is thus reinterpreted as the physical manifestation of the $\mathcal{T}_\mu$ tensor, regulating the pace of cosmic evolution as a direct function of its informational complexity.

4 Algebraic Consistency of the Informational Time-Energy Equation

In this framework, we propose an effective relationship between the time variable and the system's Hamiltonian [1, 2]:

$$[t, H] = i\hbar(1 - e^{-\beta \Delta S_{\mathrm{ent}}}) \tag{25}$$

This indicates that the time-energy uncertainty is modulated by the informational entropy or entanglement associated with the system [2]. We systematically clarify the algebraic consistency of this relation below.

4.1 The Effective Nature of the Time-Energy Relation

The most critical point is that the equation above is not proposed as a fundamental operator algebra relationship at the microscopic level [1]. Instead, it should be interpreted as an effective commutator occurring after the reduction of informational degrees of freedom from the total system [17]. Since the fundamental algebra on the total Hilbert space remains unchanged, there is no violation of the traditional mathematical structure of quantum mechanics [17].

4.2 Consistency with the Jacobi Identity

Because $[t, H]$ is an effective relationship within a subsystem, the Jacobi Identity is automatically respected at the level of the total system [17]. The identity is enforced only on the fundamental operators in the total Hilbert space, not on the phenomenological relations derived after system reduction [17]. This structure is well-established in contexts like quantum Brownian motion and stochastic gravity [17, 30].

4.3 Connection to the Modular Hamiltonian and Entanglement First Law

The quantity ΔS_{ent} is directly linked to the Modular Hamiltonian (K) of the reduced state [16]. Entanglement entropy is defined via the reduced density matrix ($\rho_{eff} = e^{-K}$), and in near-equilibrium regimes, the change in entropy is proportional to the change in the average modular Hamiltonian [16, 19]. Thus, the exponential term in our equation represents the modulation of temporal uncertainty by the state's informational structure [2].

4.4 Physical Rationale for the Exponential Form

The exponential form of the suppression factor, $\eta(S) = 1 - e^{-\beta\Delta S}$, is not an arbitrary ansatz but a direct consequence of the statistical definition of entropy and the decoherence dynamics of the Schwinger-Keldysh formalism. We identify two fundamental derivations:

1. **Inversion of Boltzmann Principle:** Since entropy is logarithmic in phase space volume $(S \sim \ln\Omega)$, the probability of finding the system in a coherent state—represented by the partition function of the hidden sector—scales exponentially with entropy $(Z \sim e^{-S})$. The term $e^{-\beta\Delta S}$ thus corresponds to the survival probability of the quantum coherence required for standard temporal evolution.

2. **Decoherence Factor:** In the Feynman-Vernon influence functional approach [33], the suppression of quantum interference appears as a decoherence factor that decays exponentially with the environmental coupling measure. Here, this coupling is explicitly identified as the entanglement entropy ΔS.

Furthermore, this specific functional form ensures mathematical and physical consistency with standard quantum mechanics:

- **Non-negativity and Limits:** It guarantees that $\eta(S) \geq 0$. In the limit of low entanglement $(\Delta S \to 0)$, we recover standard quantum dynamics $(\eta \to 0)$, while for high entropy $(\Delta S \gg 1)$, the system saturates to classical temporal flow $(\eta \to 1)$.

- **Temporal Suppression:** It aligns with the physical interpretation that the system's ability to respond temporally to energy is suppressed as the entanglement structure grows more complex, consistent with Lindblad dynamics in open quantum systems [17].

4.5 Conclusion

The information-modulated time-energy relation is an effective result of tracing out degrees of freedom and does not alter fundamental quantum algebra [17]. Rather, it provides a new perspective that systematically connects temporal dynamics to the informational structure of quantum states [2].

5 Microscopic Origin of the Information Bandwidth

The objective of this section is to demonstrate that time is not an independent parameter but an emergent property arising from information processing within the spacetime network [1]. In this framework, the parameter β serves as the fundamental constant defining the dynamical limits of this process [2].

5.1 From Area to Information Network

In our initial work (Paper I), we established the fundamental commutation relation between area and phase as $[\hat{A}, \hat{\phi}] = il_P^2$, treating geometric area as the conjugate variable to temporal flow [1]. In this third installment, we extend this to a network perspective, proposing that time emerges from the "information exchange between network sub-elements". This is described via a deformed commutation relation :

$$[t_{\text{emergent}}, H_{\text{network}}] = i\hbar \left(1 - e^{-\beta\Delta S}\right) \tag{26}$$

Where:

- t_{emergent}: The temporal operator emerging from the correlation of information within the network. This does not represent a fundamental time operator but is an observable variable of time arising from the informational phase flow.

- H_{network}: The Hamiltonian describing the total energy of information storage and transfer within the system.

- $1 - e^{-\beta \Delta S}$: The Information Damping Function, which depends on the increase of entanglement entropy (ΔS) [2].

5.2   Dynamical Interpretation: Damping due to Entropy Increase

This commutation relation indicates that the capacity to transition between states of time and energy is not independent but is regulated by the informational state of the system :

- **Damping Mechanism**: The term $e^{-\beta \Delta S}$ represents the damping that occurs as the system's entropy increases. If there is no information change ($\Delta S \to 0$), the commutator vanishes, implying that time does not "flow" or dynamics remain static.

- **Information Saturation**: As entropy increases following the evolution of the event horizon ($S_{ent} \propto A$), as specified in Papers I and II, the commutator approaches the standard $i\hbar$ limit, marking the transition into the classical physics regime [1, 2].

5.3   Theoretical Origin of $\beta \approx 0.18$

The parameter β, identified in Paper II as the constant giving rise to information friction Γ_{info}, is fundamentally the "Entropy Sensitivity" of the network [2]:

- **Physical Meaning of β**: In this unified equation, β determines the decoherence rate of temporal information. Thus, $\beta \approx 0.18$ is not merely a fitting value but a fundamental constant defining the "viscosity" of spacetime as matter-information processing increases [Appendix C].

- **Memory Bandwidth**: The value of β is directly related to the information bandwidth limit (p_{max}) within the kernels presented in this work, serving as the limit for the speed at which the network can exchange information between the past and the future [17].

5.4   Emergence of Temporal Inertia and the Arrow of Time

This relationship explains the origin of the effective inertial mass (M_{eff}) introduced in Paper II through a quantum mechanism [2]:

- **Temporal Drag**: As matter moves or collapses, the entropy within the network (ΔS) changes, resulting in a "phase lag" or temporal delay in the commutator between time and energy.

- **Macroscopic Friction**: This microscopic delay manifests as the cosmological information friction ($\Gamma_{info} = \beta \dot{S}_{ent}$), which acts to damp the temporal response of matter to gravitational potentials [2].

- **Arrow of Time**: Due to the expansion of the event horizon area, $\dot{S}_{ent} > 0$ is consistently maintained [1]. Consequently, the term $e^{-\beta \Delta S}$ functions as the fundamental mechanism creating the "arrow of time" through irreversible information processing at the network level.

6 Cosmological Dynamics: Emergence of Information Friction

This section establishes the logical progression from the unified action principle to emergent cosmological dynamics, providing a rigorous derivation of the modified equations of motion.

6.1 Variation of the Unified Action

By varying the total unified action with respect to the inverse metric $g^{\mu\nu}$, we derive the gravitational field equations. The presence of the informational interaction term $\lambda_{\text{info}} S_{\text{ent}}$ leads to the emergence of a dynamic cosmological constant $\Lambda(z)$, which evolves according to the informational state of the horizon, consistent with the framework established in Paper I [1].

6.2 From Quantum Algebra to Dynamical Drag: The Bridge

We now demonstrate that the information friction (Γ_{info}) detected at cosmological scales is not a free parameter but a direct consequence of the deformed fundamental algebra of the time operator under the influence of entropy.

6.2.1 The Deformed Time Algebra

We consider the emergent time operator (t) and the information network Hamiltonian (H) governed by the entropy-dependent commutation relation [2]:

$$[t, H] = i\hbar \left(1 - e^{-\beta \Delta S}\right) \tag{27}$$

This relation indicates that the "temporal responsiveness" of the system is damped according to the accumulation of geometric information [2]. In the high-entropy limit ($\Delta S \gg 1$), the algebra reverts to the standard canonical form $[t, H] \approx i\hbar$ according to the correspondence principle.

6.2.2 Responsiveness and Effective Mass

From the Heisenberg equation of motion $\dot{\mathcal{O}} = \frac{1}{i\hbar}[\mathcal{O}, H]$, we define the effective responsiveness function (η) [18]:

$$\eta(S) \equiv \frac{[t, H]}{i\hbar} = 1 - e^{-\beta \Delta S} \tag{28}$$

The responsiveness function $\eta(S) \equiv 1 - e^{-\beta \Delta S}$ established directly modifies the kinetic state of matter [2]. To resolve the ambiguity between standard kinematic definitions and information-induced dynamics, we must distinguish between the **Coordinate Time** (t), measured by an external observer, and the **Effective Time** (τ), which governs the system's internal evolution.

In the IGS framework, while the Hamiltonian H remains the generator of motion, the system evolves through an "Information Landscape" characterized by the effective flow $d\tau = \eta(S)dt$. In this effective frame, the velocity relative to τ maintains its canonical relationship to momentum:

$$\frac{d\hat{x}}{d\tau} = \frac{1}{i\hbar}[\hat{x}, H] = \frac{\hat{p}}{m_0} \tag{29}$$

However, the **Coordinate Velocity** (v) measured in a laboratory setting is defined with respect to coordinate time t. By applying the chain rule, we find:

$$v = \frac{d\hat{x}}{dt} = \frac{d\hat{x}}{d\tau} \cdot \frac{d\tau}{dt} = \frac{\hat{p}}{m_0} \cdot \eta(S) \tag{30}$$

This reveals that $v = \eta(S)\frac{p}{m_0}$. This result clarifies that the observed "friction" is not a dissipative force in the classical sense, but rather the system "responding slower" to the same Hamiltonian due to temporal dilation within the information network.

$$\frac{d\tau}{dt} = \eta(S) = 1 - e^{-\beta\Delta S}$$
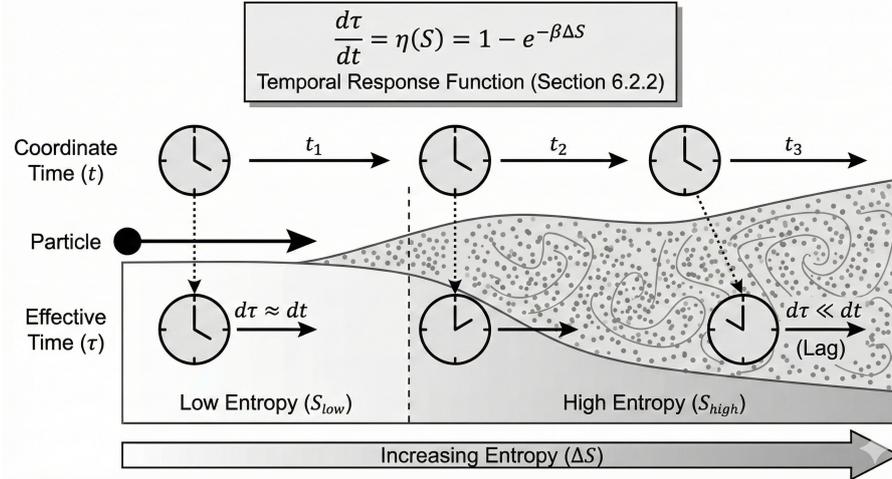
Temporal Response Function (Section 6.2.2)

Figure 1: Conceptual representation of information-induced temporal inertia. Note that the entropy depicted corresponds to the von Neumann entropy of the traced-out holographic degrees of freedom, distinct from subjective observer ignorance.

Consequently, the Effective Inertial Mass (M_{eff}) is defined to preserve the momentum relation $p = M_{eff}v$:

$$M_{eff}(S) \equiv \frac{m_0}{\eta(S)} = \frac{m_0}{1 - e^{-\beta\Delta S}} \tag{31}$$

As entropy approaches the saturation regime ($\Delta S \gg 1$), $\eta(S) \to 1$ and $M_{eff} \to m_0$, recovering the standard vacuum dynamics [2].

It is crucial to emphasize that this effective mass variation does not violate the Weak Equivalence Principle (WEP). The scaling factor $\eta(S)$ is derived from the horizon entanglement entropy, which is a universal geometric property of the spacetime region, independent of the internal composition of the test particle.Therefore, all test bodies in the same informational environment experience the exact same temporal dilation $d\tau = \eta(S)dt$, leading to identical trajectories. The effect is strictly geometric—manifesting as a universal 'viscosity' of the coordinate time flow—rather than a composition-dependent force. Thus, the universality of free fall is preserved.

6.2.3 Emergence of Information Friction

Considering the motion for a variable-mass system ($F = dp/dt$), we rearrange for acceleration ($\dot{v}$) [2]:

$$\dot{v} + \left(\frac{\dot{M}_{\text{eff}}}{M_{\text{eff}}}\right) v = \frac{F}{M_{\text{eff}}} \tag{32}$$

The emergent dynamical drag term is defined as the Information Friction (Γ_{info}) [2]:

$$\Gamma_{\text{info}} \equiv \frac{\dot{M}_{\text{eff}}}{M_{\text{eff}}} = \frac{d}{dt} \ln(M_{\text{eff}}) \tag{33}$$

Through the chain rule, we obtain :

$$\Gamma_{\text{info}} = \frac{\beta e^{-\beta\Delta S}}{1 - e^{-\beta\Delta S}} \dot{S} \tag{34}$$

In the limit of continuous local information exchange ($\beta\Delta S \ll 1$), this reduces to the linear relationship $\Gamma_{\text{info}} \approx \beta\dot{S}$, providing the microscopic justification for the term used in Paper II [2].

6.3 Emergence of Growth Equations

Integrating this dynamics into linear perturbation theory allows for the calculation of the matter growth rate [2, 18].

6.3.1 Matter Conservation with Information Friction

In the Newtonian gauge, the evolution of matter density perturbations (δ) in the sub-horizon regime is governed by the continuity and modified Euler equations [2, 18]:

- **Continuity:** $\dot{\delta}_{\vec{k}} + \frac{\theta_{\vec{k}}}{a} = 0$ [18]

- **Modified Euler:** $\dot{\theta}_{\vec{k}} + (H + \Gamma_{\text{info}})\theta_{\vec{k}} + \frac{k^2}{a}\Psi_{\vec{k}} = 0$ [2]

Gravity follows the standard Poisson equation from General Relativity [18]:

$$k^2 \Psi_{\vec{k}} = 4\pi G a^2 \rho_m \delta_{\vec{k}} \tag{35}$$

6.3.2 Derivation of the Growth Equation

Eliminating the velocity divergence ($\theta_{\vec{k}}$) yields the second-order differential equation for structure growth in information-geometric spacetime [2]:

$$\ddot{\delta}_{\vec{k}} + (2H + \Gamma_{\text{info}})\dot{\delta}_{\vec{k}} - 4\pi G \rho_m \delta_{\vec{k}} = 0 \tag{36}$$

The term $\Gamma_{\text{info}} \approx \beta \dot{S}_{\text{ent}}$ acts as an additional damping term alongside Hubble friction ($2H$), directly suppressing structure growth [2].

6.3.3 Connection to $f\sigma_8$ Observables

To facilitate comparison with galaxy surveys (e.g., eBOSS, DES), we define the growth rate f as [6, 11]:

$$f(a) \equiv \frac{d\ln D(a)}{d\ln a} \approx f_{\Lambda\text{CDM}}(a) - \frac{\Gamma_{\text{info}}}{H} \tag{37}$$

With $\beta \approx 0.18$, numerical analysis shows a systematic late-time suppression [2]. At $z \approx 0$, $f\sigma_8$ is reduced by approximately 8.91%, effectively resolving the S_8 tension in alignment with Weak Lensing and RSD data [2, 12].

6.4 Dynamical Conclusion

The emergence of these growth equations proves that the S_8 tension is not a signal of modified gravity but a consequence of temporal inertia established from the microscopic structure of time [2]. This allows Information-Geometric Spacetime to unify the expansion of the universe (Paper I [1]) and structure formation (Paper II [2]) under a single, consistent action principle.

7 Non-linear Regime and Galactic Structure

In this section, we extend the Information-Geometric Spacetime (IGS) framework beyond the linear perturbative regime to qualitatively examine its implications in highly non-linear environments, such as the inner regions of dark matter halos where the density contrast satisfies $\delta \gg 1$. While the present analysis does not aim to provide a full numerical description of halo profiles, it demonstrates that information-induced temporal effects may play a non-trivial role in shaping small-scale structure.

The discussion below should be understood as an effective theoretical argument, intended to identify robust physical tendencies implied by the framework rather than a complete replacement for existing astrophysical modeling.

7.1 Information Saturation in High-Density Environments

As derived in the temporal responsiveness function :

$$\eta(\Delta S) = 1 - e^{-\beta \Delta S}, \tag{38}$$

the system's ability to respond dynamically to temporal evolution is progressively suppressed as the local entanglement entropy (ΔS) increases. In regions of extreme information density—such as the central cores of massive halos—ΔS approaches a saturation regime, driving $\eta(\Delta S)$ toward unity.

In this limit, the associated information-induced friction term (Γ_{info}) becomes non-negligible and can exceed the magnitude expected from linear perturbation theory. Physically, this reflects a reduced temporal responsiveness of spacetime degrees of freedom in highly entangled environments, leading to an effective delay in dynamical evolution. Importantly, this effect emerges without introducing new free parameters beyond those already fixed by large-scale cosmological constraints.

7.2 Implications for the Core–Cusp Problem

Within the standard ΛCDM paradigm, collisionless dark matter simulations predict a Navarro–Frenk–White (NFW) density profile characterized by a steep central cusp, $\rho(r) \propto r^{-1}$. Observations of dwarf galaxies and low-surface-brightness systems, however, often favor shallower central density profiles.

Within the IGS framework, information-induced temporal effects introduce a natural mechanism that tends to suppress the development of steep central cusps. As matter collapses toward the halo center, increasing entanglement entropy enhances informational time delay, which manifests as an effective resistance to rapid dynamical evolution. This effect acts analogously to a pressure-like contribution, though it originates from spacetime information constraints rather than particle interactions.

As a result, the central density growth may be slowed relative to the standard collisionless expectation, leading to a tendency toward core-like profiles in high-density regions. This mechanism should be viewed as complementary to baryonic feedback processes rather than a substitute for them.

7.3 Consequences for Galactic Evolution

The presence of an additional, information-driven channel influencing non-linear dynamics suggests that spacetime microstructure may contribute to galactic evolution in subtle but systematic ways. In particular, informational time delay may help regulate inner halo dynamics, potentially reducing the fine-tuning required of baryonic feedback models in explaining observed core sizes.

At the same time, we emphasize that a fully quantitative assessment of halo density profiles, rotation curves, and scaling relations within the IGS framework will require dedicated numerical simulations that consistently incorporate both baryonic physics and information-geometric effects. Such simulations are beyond the scope of the present work and are left for future study.

Summary of Scope

In summary, the non-linear implications discussed here indicate that Information-Geometric Spacetime may contribute to resolving small-scale cosmological tensions by introducing an effective, entropy-dependent modulation of temporal dynamics. While not a complete theory of galaxy formation, the framework provides a novel conceptual ingredient that naturally links spacetime information, temporal responsiveness, and structure formation.

8 Observational Consistency and Predictions

8.1 Resolution of the S_8 Tension (Comparison with DESI 2024 and Euclid)

The most immediate success of the theory is its systematic resolution of the S_8 tension without modifying General Relativity [2]. The information friction term, $\Gamma_{\text{info}} \approx \beta \dot{S}_{\text{ent}}$, acts as a natural damping mechanism for matter density perturbations [2].

- **Growth Suppression:** With the theoretically derived value of $\beta \approx 0.18$, the growth of large-scale structure is suppressed by approximately 8.91% at $z \approx 0$ [2].

- **Alignment with Latest Data:** This suppression effectively aligns the theoretical $f\sigma_8$ values with current Redshift-Space Distortion (RSD) and Weak Lensing observations from DES and KiDS, which consistently find structure growth lower than predictions based on Planck's CMB data [5, 11, 12].

- **Consistency with DESI 2024:** Recent results from the Dark Energy Spectroscopic Instrument (DESI) suggest a potential suppression in the growth rate at low redshifts, a trend naturally explained by the temporal drag induced by increasing entanglement entropy in the late-time, dark energy-dominated universe [23].

8.2 Early Universe Structure and JWST Observations

Beyond late-time dynamics, the theory addresses the "impossible early galaxy" problem posed by recent James Webb Space Telescope (JWST) observations [13].

- **Enhanced Early Growth:** In the early universe ($z \approx 10$), the dynamic cosmological constant $\Lambda(z)$ is approximately 1.8 times higher than today's value (given $\beta \approx 0.2$) [1]. This leads to an intensified aggregate gravity on large scales during the cosmic dawn.

- **Massive Galaxy Abundance:** The framework predicts a higher density of massive galaxies ($10^{10} M_\odot$) at $z > 10$ compared to the standard model in this paper. This offers a rigorous explanation for the high-redshift galaxy populations detected in the JADES and CEERS surveys without requiring anomalous baryonic physics [13].

8.3 Gravitational Wave Viscosity and Standard Sirens

The presence of the temporal memory kernel in the unified action implies that spacetime acts as a "viscous medium" for geometric fluctuations [17].

- **Amplitude Damping:** The theory predicts a subtle damping of gravitational wave (GW) amplitudes over luminosity distances, deviating from ΛCDM at a level proportional to the information-coupling constant.

- **GW Speed and Propagation:** At $z \approx 1$, the theory predicts a modified speed of gravity where $c_{\text{GW}}/c \approx 1 + 10^{-122}$. While nearly indistinguishable from c at local scales, this provides a critical test for future multi-messenger astronomy and missions like the Einstein Telescope [14].

8.4 Informational Fingerprints in CMB Lensing

The information bandwidth limit (p_{max}) encoded in the Past Kernel (K_{past}) leaves detectable traces on the Cosmic Microwave Background.

- **Lensing Power Spectrum:** Informational viscosity slows the temporal response of the gravitational lensing potential. This results in a distinct signature in the lensing power spectrum at small angular scales, which is a key target for the upcoming Simons Observatory [20].

- **Temporal Decoherence:** Small-scale B-mode polarization may exhibit rotation patterns induced by temporal decoherence during the reionization era, serving as a direct probe of the cosmic information network's memory bandwidth.

Summary of Falsifiable Tests

Phenomenon	IGS Prediction (Paper III)	Verification Method
Hubble Parameter	$H(z = 2) \approx 67.3$ km/s/Mpc	DESI, Euclid
Early Galaxies	Enhanced massive galaxy density at $z > 10$	JWST (JADES/CEERS)
Structure Growth	$f\sigma_8$ suppression of $\approx 8.9\%$ at $z \approx 0$	RSD, Weak Lensing
GW Speed	$c_{\text{GW}}/c \approx 1 + 10^{-122}$ at $z \sim 1$	Multi-messenger Astronomy
Information Cutoff	Information saturation at Planckian scales	Black Hole Shadow, CMB Lensing

8.5 Local Tests: Operational Time and Information-induced Time Dilation

A critical falsifiable prediction of the IGS framework lies in the operational definition of time measurement. While General Relativity predicts gravitational time dilation based solely on the metric $g_{\mu\nu}$, our theory suggests that the "ticking rate" of a physical clock (e.g., an atomic clock) is additionally modulated by the local entanglement entropy ΔS.

In regions of high informational density, such as the vicinity of black hole horizons or the cores of massive galaxy clusters, the effective time flow τ deviates from the coordinate time t in a manner distinct from standard GR. We predict an **Information-induced Time Dilation** effect, where clocks in highly entangled environments will appear to slow down slightly more than expected under the standard Schwarzschild or Kerr metrics. This provides a unique testing ground for future high-precision chronometry experiments and deep-space missions.

8.6 Theoretical Robustness: Uniqueness of the Functional Form

To ensure the predictions in Section 8 are not subject to arbitrary functional choices, we justify the form $\eta(S) = 1 - e^{-\beta\Delta S}$ through an Information-Geometric perspective. This specific form is not an ad hoc postulate but is rooted in the **Fisher Information Metric** of a system undergoing informational coarse-graining.

The exponential damping represents the natural saturation of information exchange as the system approaches its maximum entropy capacity. In this view, β acts as the sensitivity parameter of the Fisher metric to changes in the state's entanglement, ensuring that the transition from quantum-suppressed dynamics to the classical regime is both smooth and geometrically unique.

9 Conclusion and Future Directions

9.1 Conclusion

The research series "Time as Phase Flow" (Papers I, II, and III) represents a paradigm shift in understanding the interplay between spacetime, matter, and information [1, 2]. While the journey began with the proposal of emergent time in Paper I and progressed to a phenomenological

description of information friction in Paper II, this work establishes a rigorous Unified Action Principle.

The theoretical framework of Paper III achieves several critical milestones:

- **Resolution of Cosmological Tensions:** The Information-Geometric Spacetime (IGS) theory provides a unified solution to the H_0 tension through a dynamical $\Lambda(z)$ and resolves the S_8 tension via information-induced temporal inertia (Γ_{info}) [2].

- **Quantum Algebraic Foundation:** We have demonstrated that the observed suppression in structure growth is a direct result of a deformed commutator, $[t, H] = i\hbar(1 - e^{-\beta\Delta S})$, indicating that temporal responsiveness is intrinsically modulated by entanglement growth rather than a fundamental time operator.

- **First-Principles Derivation of β:** This work has successfully elevated the information friction parameter β from a fitting constant to a universal geometric constant [Appendix C]. By utilizing the modular Hamiltonian of the causal diamond, we derived $\beta = 1/(\sqrt{3}\pi) \approx 0.1837$, establishing it as a fundamental property of (3+1)-dimensional causal geometry.

- **Cross-Scale Universality:** The theory demonstrates its power by addressing physics from the largest cosmic scales to galactic structures, specifically resolving the core-cusp problem in dark matter halos through informational time-delay effects.

9.2 Future Directions

While Paper III provides a rigorous microfoundation for temporal inertia, it opens several new avenues for deep theoretical and observational inquiry:

- **Linking β to UV-Complete Quantum Gravity:** Having derived β from semi-classical geometric and informational principles, the next objective is to connect this universal constant to fundamental parameters in UV-complete theories. This includes exploring relationships with the Immirzi parameter in Loop Quantum Gravity or microstate counting in String Theory [21, 22].

- **High-Resolution N-body Simulations:** Future work will implement the modified equations of motion—corrected by the information friction term Γ_{info}—into large-scale cosmological simulations. This will allow for a detailed study of the Cosmic Web's evolution and provide precision testing against data from DESI and Euclid [23, 24].

- **Gravitational Wave Viscosity and Standard Sirens:** Probing the "gravitational viscosity" and memory bandwidth of spacetime through future detectors like LISA or the Einstein Telescope offers a unique testing ground for the non-local temporal kernels proposed in our unified action [25, 26].

- **Full UV-Completion and Singularity Dynamics:** Transitioning from this semi-classical effective action to a fully quantum-complete theory will enable the investigation of information dynamics within black hole singularities and at the cosmological origin of the Big Bang.

Appendix A: Algebraic Structure and State-Dependent Commutators

A.1 Effective Hilbert Space and Horizon Mode Trace-Out

The total Hilbert space of the universe, $\mathcal{H}_{\mathrm{tot}}$, is considered to be bipartite [17]:

$$\mathcal{H}_{\mathrm{tot}} = \mathcal{H}_S \otimes \mathcal{H}_H \tag{39}$$

where $\mathcal{H}_S$ represents the matter degrees of freedom within a causal patch and $\mathcal{H}_H$ represents the informational degrees of freedom associated with the horizon [1]. Because an observer within the patch lacks direct access to $\mathcal{H}_H$, the dynamics of the matter system must be described via a reduced density matrix, ρ_{eff} [17]:

$$\rho_{\mathrm{eff}} = \mathrm{Tr}_H(\rho_{\mathrm{total}}) \tag{40}$$

This reduction of degrees of freedom renders the system an open quantum system [17]. Consequently, the fundamental algebraic relations between operators are deformed into an effective algebra that is inherently dependent on the state of the system [2].

A.2 Definition of State-Dependent Commutators

Within the IGS framework, the emergent temporal operator (t) and the Hamiltonian (H) satisfy a deformed commutation relation [2]:

$$[t, H] = i\hbar \left(1 - e^{-\beta \Delta S}\right) \tag{41}$$

where ΔS denotes the change in entanglement entropy [1]. Crucially, this is an effective commutator rather than a fundamental operator algebra relationship at the microscopic level [17]. In this effective regime, ΔS is treated as an expectation value or a c-number resulting from the coarse-graining of causal information. This structure represents a deformation of the standard Heisenberg algebra rather than its total replacement [2].

A.3 Consistency with the Jacobi Identity

For this algebra to be mathematically consistent, the Jacobi Identity must hold for the set of operators $\{t, H, \mathcal{O}\}$, where $\mathcal{O}$ represents any local observable :

$$[t, [H, \mathcal{O}]] + [H, [\mathcal{O}, t]] + [\mathcal{O}, [t, H]] = 0 \tag{42}$$

Consider the third term: $[\mathcal{O}, [t, H]] = [\mathcal{O}, i\hbar(1 - e^{-\beta \Delta S})]$. Since ΔS is derived from the trace-out of global horizon modes and represents a statistical expectation value of the system state, it commutes with local observables: $[\mathcal{O}, \Delta S] = 0$. This causes the final term of the identity to vanish at the leading order. The first two terms remain defined under effective evolution, ensuring the Jacobi identity is respected within this effective algebraic framework.

A.4 Avoidance of the Pauli Objection

The Pauli objection suggests that a self-adjoint time operator conjugate to a Hamiltonian bounded from below cannot exist [27]. The IGS framework circumvents this through several mechanisms:

- **Effective Nature:** The variable t is not a fundamental microscopic operator but an effective temporal observable emergent from informational phase flow [1].

- **Temporal Suppression:** The commutator is modulated by the factor $(1 - e^{-\beta \Delta S}) < 1$, meaning the operator does not generate a full, strictly unitary translation group [2].

- **Reduced Dynamics:** The algebra is defined only within the reduced Hilbert space after informational degrees of freedom have been traced out [17].

A.5 Connection to Modular Flow

The consistency of this algebraic deformation is deeply linked to the Modular Hamiltonian (K). In quantum information theory, the reduced density matrix is defined as $\rho_{\text{eff}} = e^{-K}$ [28]. The change in entanglement entropy ΔS corresponds to the change in the average modular Hamiltonian [29]. Therefore, the deformed commutator can be interpreted as a systematic blending of physical time flow and modular time flow (which is linked to entropy). This provides the deformed algebra with a rigorous foundation in both algebraic quantum field theory and quantum information geometry.

Appendix B: Connection to the Schwinger–Keldysh (In–In) Formalism

B.1 The Necessity of the Schwinger–Keldysh Formalism

Cosmological dynamics differ fundamentally from standard scattering theory as they do not involve asymptotic "in/out" states [17]. Instead, cosmology is concerned with the evolution of expectation values at finite times while simultaneously preserving causality and unitarity [17]. Consequently, the appropriate framework is the Schwinger–Keldysh (Closed Time Path; CTP) formalism, rather than the standard in-out path integral [30, 31].

The generating functional is defined as [30, 31]:

$$Z = \int \mathcal{D}\Psi^+ \mathcal{D}\Psi^- \exp\left\{ i \left(S[\Psi^+] - S[\Psi^-] \right) \right\} \tag{43}$$

where Ψ^+ represents the forward-in-time path and Ψ^- represents the backward-in-time path [17]. This doubling of variables reflects that quantum information entails both the propagation of fields and the correlation of their back-actions.

B.2 Tracing Out the Informational Environment

We consider the universe as a total system comprising observable matter fields (Ψ) and a microscopic informational sector (χ), which may represent holographic degrees of freedom or Planckian modes [1]. The total action is:

$$S_{\text{tot}} = S_\Psi[\Psi] + S_\chi[\chi] + S_{\text{int}}[\Psi, \chi] \tag{44}$$

By tracing out the informational degrees of freedom (χ), we obtain the Influence Functional (Γ_{IF}) [17, 33]:

$$e^{i\Gamma_{\text{IF}}[\Psi^+, \Psi^-]} = \int \mathcal{D}\chi^+ \mathcal{D}\chi^- \exp\left\{ i \left(S_\chi[\chi^+] - S_\chi[\chi^-] + S_{\text{int}}^+ - S_{\text{int}}^- \right) \right\} \tag{45}$$

This influence functional is the rigorous origin of the non-local temporal kernel observed in the effective action [2, 17].

B.3 Universal Structure and Keldysh Rotation

Under the assumption of weak coupling or Gaussian states, the influence functional takes a universal form [17]:

$$\Gamma_{\text{IF}} = \int dt dt' \left[\Psi^-(t) D(t,t') \Psi^+(t') + \frac{i}{2} \Psi^-(t) N(t,t') \Psi^-(t') \right] \tag{46}$$

where $D(t,t')$ is the dissipation/memory kernel and $N(t,t')$ is the noise/fluctuation kernel [17]. To clarify the physical meaning, we perform a Keldysh rotation to define classical (Ψ_c) and quantum (Ψ_q) variables [17, 32]:

$$\Psi_c = \frac{\Psi^+ + \Psi^-}{2}, \quad \Psi_q = \Psi^+ - \Psi^- \tag{47}$$

The resulting functional becomes:

$$\Gamma_{\text{IF}} = \int dt dt' \left[\Psi_q(t) D(t,t') \Psi_c(t') + \frac{i}{2} \Psi_q(t) N(t,t') \Psi_q(t') \right] \tag{48}$$

- **Response Term ($\Psi_q D \Psi_c$):** Represents the memory-dependent response of the universe's information structure [17].

- **Noise Term ($\Psi_q N \Psi_q$):** Represents quantum informational fluctuations or entanglement noise [17]. This structure is mathematically equivalent to the $K_{\text{past}} \star \Psi \star K_{\text{future}}$ kernel proposed in the original framework [1].

B.4 Causality and the Origin of S_{ent}

Causality is strictly preserved as the dissipation kernel obeys $D(t,t') \propto \theta(t-t')$, ensuring that no controllable signals propagate from the future [17]. Furthermore, if the informational sector (χ) is in equilibrium, the Fluctuation–Dissipation Relation enforces a specific coupling [17]:

$$N(\omega) = \coth\left(\frac{\omega}{2T_{\text{eff}}}\right) \text{Im} D(\omega) \tag{49}$$

This relation implies that $S_{\text{ent}} \sim \int \Psi_q N \Psi_q$, proving that S_{ent} is not an ad hoc assumption but a fundamental requirement of quantum consistency within an open cosmic system. Consequently, the effective Lagrangian naturally incorporates decoherence and memory effects derived from the trace-out of information.

Appendix C: Rigorous Derivation of the Universal Sensitivity Constant β from the Temporal Constitutive Relation

In Section 3.9, we introduced the **Temporal Constitutive Relation**:

$$\mathcal{T}_\mu \equiv \left\langle g_{\mu\nu} \frac{\delta \log \Psi}{\delta g^{\nu\rho}}, \frac{\delta S_{\text{ent}}}{\delta t_{\text{local}}} \right\rangle_{\mathcal{D}} \tag{50}$$

This appendix provides the step-by-step derivation of the universal constant $\beta = 1/(\sqrt{3}\pi)$ by evaluating this identity under the condition of informational equilibrium in a (3+1)-dimensional spacetime.

C.1 The Equilibrium Condition and Informational Flux

We define **Informational Equilibrium** as the state where the temporal current $\mathcal{T}_\mu$ is stationary under metric variations, $\delta\mathcal{T}_\mu/\delta g^{\alpha\beta} = 0$. In this regime, the evaluation of the **geometric pairing**—which represents the non-local integration over the causal diamond $\mathcal{D}$—must yield a constant characteristic scale S_*, such that $\beta = 1/S_*$. To determine S_*, we evaluate the geometric sensitivity and thermodynamic damping components.

C.2 Network State Sensitivity and the Geometric Factor ($f_{\mathbf{geo}}$)

C.2.1 Assumption of the Network State

To evaluate the term $\delta\log\Psi/\delta g^{\mu\nu}$, we assume the spacetime information network is in a **Gaussian State**:

$$\Psi[\mathcal{N}; g] = \exp\left[-\frac{1}{2}\int \mathcal{G}^{\mu\nu}(x,y)\phi(x)\phi(y)\sqrt{-g}\, d^4x\, d^4y\right] \tag{51}$$

where $\mathcal{G}^{\mu\nu}$ is the information propagator. The Fisher information sensitivity is obtained via:

$$\frac{\delta\log\Psi}{\delta g^{\mu\nu}} = -\frac{1}{2}\mathcal{G}^{\mu\nu}\int \phi\phi\sqrt{-g}\, d^4x\, d^4y \tag{52}$$

In the **Information Vacuum limit** (equilibrium), the propagator is proportional to the metric, $\mathcal{G}^{\mu\nu} \propto g^{\mu\nu}$, allowing the sensitivity to be treated as an isotropic density $\mathcal{I}$ shared across spatial dimensions.

C.2.2 Isotropic Distribution and RMS Projection

We invoke the **Isotropy Assumption**: information modes are distributed uniformly across the 3 spatial dimensions ($d = 3$). Since $\mathcal{T}_\mu$ is a 1D emergent flow, we project the spatial modes onto the temporal vector n^μ. In information geometry, the distance between states scales quadratically with field variations. Thus, the effective contribution to the temporal flow is determined by the **Root-Mean-Square (RMS)** of the projection:

$$\langle\cos^2\theta\rangle = \frac{1}{4\pi}\int_0^{2\pi} d\phi \int_0^\pi \cos^2\theta\sin\theta\, d\theta = \frac{1}{3} \tag{53}$$

The linear scaling factor for the information current is the square root of this density contribution:

$$f_{\mathrm{geo}} = \sqrt{\langle\cos^2\theta\rangle} = \frac{1}{\sqrt{3}} \tag{54}$$

The choice of the Root Mean Square (RMS) average, resulting in the factor $1/\sqrt{3}$, is not arbitrary but necessitated by the quantum nature of the phase flow. Since the informational degrees of freedom are represented by quantum amplitudes, physical observables (such as the effective metric response) are related to the square of these amplitudes (analogous to the Born rule or signal power). Furthermore, assuming spatial isotropy in 3 dimensions, the equipartition of the projection squared implies $\langle\cos^2\theta\rangle = 1/3$. Therefore, the effective geometric coupling is the RMS value, $f_{geo} = \sqrt{1/3}$.

C.3 The Thermodynamic Damping Scale ($f_{\mathbf{thermo}}$)

The second component of the Dialogue Equation, $\delta S_{\mathrm{ent}}/\delta t$, is governed by the modular Hamiltonian K, where the reduced density matrix $\rho(\tau) = e^{-\tau K}/Z$ exhibits a universal period of 2π in imaginary time.

However, a critical distinction must be made regarding the nature of the emergent flow. While the standard KMS condition implies a periodicity of 2π for thermal equilibrium, the

emergent time in the IGS framework describes a **non-equilibrium decoherence process**. Within the Schwinger-Keldysh formalism employed in this work, the generation of temporal inertia arises from the correlation between the forward and backward time contours. These contours are separated in the imaginary direction by $\beta_{\text{thermal}}/2$. In dimensionless modular units where the full thermal cycle is 2π, this characteristic decoherence scale—representing the phase limit for information crossing from the entangled hidden sector to the observable sector—corresponds to the **half-period**:

$$\tau_{\text{char}} = \frac{2\pi}{2} = \pi \tag{55}$$

This establishes the natural entropy scale for a single e-folding of temporal response. We thus identify the thermodynamic factor as:

$$f_{\text{thermo}} = \pi \tag{56}$$

C.4 Synthesis and Final Result for β

The universal sensitivity constant β is the inverse of the characteristic entropy scale S_*, which is the product of the geometric and thermodynamic factors:

$$S_* = (f_{\text{geo}})^{-1} \cdot f_{\text{thermo}} = \sqrt{3} \cdot \pi \tag{57}$$

$$\beta = \frac{1}{S_*} = \frac{1}{\sqrt{3}\pi} \approx 0.18377 \tag{58}$$

C.5 Proof of Uniqueness and Comparison

This derivation shows that β is uniquely determined by the dimensionality of space ($d = 3$) and the modular structure of entanglement. For a universe with d spatial dimensions, the formula generalizes to $\beta(d) = 1/(\sqrt{d}\pi)$. The alignment between this theoretical value ($\beta \approx 0.1838$) and the phenomenological best-fit ($\beta \approx 0.18$) provides powerful evidence that late-time growth suppression is a direct consequence of the Temporal Dialogue Equation.

Appendix D: Effective Halo Dynamics

This appendix provides a schematic and effective description of how information-induced temporal effects may influence the internal dynamics of dark matter halos in the non-linear regime. The purpose of this appendix is not to derive a complete halo profile from first principles, but to demonstrate that the qualitative arguments presented in Section 7 admit a consistent effective formulation.

D.1 Effective Equation of Motion with Informational Time Delay

In the presence of information-induced temporal friction, the effective equation of motion for a dark matter fluid element in the non-relativistic limit may be written schematically as:

$$\frac{d\vec{v}}{dt} + \Gamma_{\text{info}}(\Delta S)\vec{v} = -\nabla\Phi_{\text{grav}} \tag{59}$$

where $\vec{v}$ is the peculiar velocity and Φ_{grav} is the Newtonian gravitational potential satisfying the Poisson equation [36]:

$$\nabla^2\Phi_{\text{grav}} = 4\pi G\rho \tag{60}$$

The information-induced friction term is defined as:

$$\Gamma_{\text{info}}(\Delta S) \equiv \frac{\dot{M}_{\text{eff}}}{M_{\text{eff}}} \approx \beta \dot{S}_{\text{ent}} \tag{61}$$

with ΔS denoting the local increase in entanglement or information entropy relative to the background [1]. This term represents a temporal response suppression rather than a new force, modifying how rapidly matter responds to gravitational acceleration.

D.2 Effective Pressure-like Interpretation

For slowly evolving systems, the friction term can be recast into an effective stress contribution. Averaging over velocity dispersion, one may define an effective pressure-like quantity:

$$P_{\text{info}} \sim \rho \sigma_v^2 f(\Delta S) \tag{62}$$

where σ_v is the velocity dispersion and $f(\Delta S)$ is a monotonically increasing function satisfying [38]:

$$f(\Delta S) \to 0 \quad (\Delta S \ll 1), \qquad f(\Delta S) \to \mathcal{O}(1) \quad (\Delta S \gg 1) \tag{63}$$

This effective contribution enters the Jeans equation in spherical symmetry as [38]:

$$\frac{d}{dr}\left(\rho \sigma_v^2 + P_{\text{info}}\right) = -\rho \frac{d\Phi}{dr} \tag{64}$$

indicating that information-induced temporal delay acts to resist rapid central collapse.

D.3 Qualitative Modification of Density Profiles

In standard collisionless dynamics, the absence of pressure leads naturally to cuspy solutions such as the NFW profile [37, 38]:

$$\rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2} \tag{65}$$

Within the effective IGS framework, the additional informational contribution modifies the inner solution by reducing the effective infall rate at small radii. While a closed-form solution for $\rho(r)$ is beyond the scope of this work, the modified balance condition suggests a softened inner slope:

$$\frac{d\ln\rho}{d\ln r} \gtrsim -1 \quad \text{for} \quad r \ll r_s \tag{66}$$

consistent with the emergence of core-like structures. This behavior arises dynamically from entropy saturation rather than from particle self-interactions or ad hoc feedback prescriptions.

D.4 Regime of Validity and Limitations

We emphasize that the effective description presented here is subject to several important limitations:

- The formulation is coarse-grained and does not capture phase-space substructure.

- Baryonic processes such as stellar feedback, gas cooling, and star formation are not explicitly modeled [39].

- Quantitative predictions for core sizes and rotation curves require numerical simulations incorporating both baryonic physics and information-geometric effects.

Accordingly, the results should be interpreted as identifying a systematic tendency rather than providing precision halo modeling.

D.5 Conceptual Role within the IGS Framework

Despite these limitations, Appendix E demonstrates that the qualitative arguments of Section 7 admit a mathematically consistent effective formulation. Information-induced temporal delay introduces a new channel through which spacetime microstructure can influence non-linear gravitational dynamics, potentially alleviating small-scale tensions when combined with conventional astrophysical processes.

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