PAGE-CURVE COSMOLOGY

Dark-Energy Dynamics from Bipartite Von Neumann Entropy

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Abstract

We propose a cosmological framework in which the observable universe is a decoherent subregion of a larger quantum system — the Universal Wavefunction or Cloud — existing as a pure state in an abstract Hilbert space with zero von Neumann entropy. Classical spacetime, the arrow of time, the apparent low initial entropy, and the full expansion history are emergent properties of the algebraic structure of Hilbert space as experienced from within a decoherent subregion.

The foundational insight is phenomenological: our universe is modeled as a partition of the universal wavefunction, structurally analogous to how a vacuum fluctuation is a partition of the vacuum field. A vacuum fluctuation separates a local region from the ground state of the field. Our subregion separates a local algebraic structure from the ground state of the universal wavefunction. In both cases, the partition has an entropy — the von Neumann entropy of the reduced state of the partition relative to its complement. That entropy is zero at the beginning and end of the partition's existence, and non-zero during its existence.

The arrow of time within the partition is the direction in which the von Neumann entropy of the partition is changing. When S(ρ_S) is larger along the delta chain, the partition is more separated from the Cloud. When S(ρ_S) is smaller along the delta chain, the partition is closer to the Cloud. The arrow of time that internal observers experience is the direction along the delta chain in which local S(ρ_S) is larger — not backward-looking, always locally forward. This formulation requires no energy, no Hamiltonian, no external temporal parameter, and no statistical measure over the space of states. It requires only the algebraic structure of the partition and its complement.

A concrete falsifiable prediction follows: the dark energy equation of state w(z), currently measured by DESI DR2 as rising from values below −1, is expected to continue rising monotonically toward zero and subsequently toward positive values as the subregion's entropy approaches and begins to decrease past its maximum.

Keywords: *decoherent subregion, partition, von Neumann entropy, arrow of time, Hilbert space geometry, Fubini-Study metric, emergent causality, emergent spacetime, quantum cosmology, von Neumann algebras, dark energy, DESI, falsifiable prediction*

1. Motivation and Open Problems

Modern physics rests on two extraordinarily successful but mutually incompatible frameworks: General Relativity (GR) and Quantum Mechanics (QM). Their unification has proven resistant to resolution for nearly a century. Beyond the technical incompatibility, five conceptual problems persist that no current framework addresses simultaneously.

1.1 The Problem of Initial Conditions

The Wheeler-DeWitt equation $H|\Psi\rangle = 0$ contains no time parameter. Yet the observed universe began in a state of extraordinarily low thermodynamic entropy. The present framework proposes to dissolve this by identifying it as a category error — applying the concept of global entropy to a subsystem description. The entropy of the partition was low at early times not because of fine-tuning but because the partition had just begun to separate from the Cloud.

1.2 The Problem of Time

In QM, time is an external parameter. In GR, it disappears in canonical quantization. The present framework identifies time with the direction of change of the von Neumann entropy of the partition — a property of the algebraic structure of the subregion relative to the Cloud, requiring no external temporal parameter.

1.3 The Arrow of Time

All microscopic laws are time-symmetric. The macroscopic arrow of time is conventionally attributed to statistical improbability of low-entropy returns. The framework grounds the arrow in the von Neumann entropy of local subsystems $S(\rho_{local})$, which is distinct from the global entropy of the partition $S(\rho_S)$. For any internal observer, the arrow always points in the direction of locally increasing $S(\rho_{local})$ — always forward. The global $S(\rho_S)$ traces a separate profile (rising in Phases I-II, peaking at III, descending in IV) that does not invert local time. The confusion of these two quantities generates the apparent paradox of backward time in Phase IV; the distinction dissolves it.

1.4 The Measurement Problem

The framework treats wavefunction collapse not as a problem to be solved but as the fundamental process by which partitions form. The question shifts from why collapse occurs to what algebraic structure the partition generates within Hilbert space.

1.5 The Accelerating Expansion and Dark Energy

DESI DR2 results (2025), based on nearly 15 million galaxies and quasars, provide mounting evidence that the dark energy equation of state is evolving with statistical significance between 2.8σ and 4.2σ. The present framework proposes a natural mechanism: the rate of change of the partition's von Neumann entropy is conjectured to govern the expansion profile.

2. The Core Framework

2.1 The Universal Wavefunction

We postulate a universal quantum state $|\Psi_U\rangle$ as a pure state in an abstract Hilbert space H_U with zero von Neumann entropy:

$$S(\rho_U) = -\mathrm{Tr}(\rho_U \log \rho_U) = 0, \quad \text{where } \rho_U = |\Psi_U\rangle\langle\Psi_U|$$

This state has no geometry, no time parameter, and no spatial structure. It is a superposition of all possible configurations simultaneously. The Cloud is a structure of quantum correlations prior to any geometry. Time does not apply to it — as color does not apply to a prime number.

2.2 The Subregion as Partition

The central phenomenological insight of this framework is that our universe can be modeled as a partition of the universal wavefunction — structurally analogous to how a vacuum fluctuation is a partition of the vacuum field.

In quantum field theory, a vacuum fluctuation is a local region that temporarily separates from the ground state of the field. During its existence, it has a local structure distinct from the vacuum. When it dissolves, the distinction disappears and the field returns to its ground state. The fluctuation does not require energy in any pre-temporal sense — it is simply a local separation that occurs without cause as a structural property of the field.

Our subregion is precisely this, at cosmological scale. It is a region of H_U that has separated from the ground state of the universal wavefunction. That separation has a measure: the von Neumann entropy of the reduced state of the partition relative to its complement — the Cloud.

$$S(\rho_S) = -\mathrm{Tr}(\rho_S \log \rho_S), \quad \text{where } \rho_S = \mathrm{Tr}_E(|\Psi_U\rangle\langle\Psi_U|)$$

This entropy is zero when the partition does not exist — when S and E are not separated. It is non-zero during the partition's existence. It returns to zero when the partition dissolves back into the Cloud. This describes the lifecycle of the subregion in purely algebraic terms, without invoking energy, Hamiltonians, or temporal parameters.

2.3 The Arrow of Time as Entropy Change of the Partition

The arrow of time within the subregion is the direction of change of the von Neumann entropy of the partition S relative to the Cloud.

When the global $S(\rho_S)$ is increasing along the partial order of A_S, the partition is becoming more separated from the Cloud — more correlations are being transferred from the Cloud to the internal structure of S. This corresponds to Phases I and II of the lifecycle, in which both the global partition entropy and the local subsystem entropy $S(\rho_{local})$ of any internal observer are increasing.

When the global $S(\rho_S)$ is decreasing, the partition is returning toward the Cloud — correlations are dissolving back into the global structure of H_U. This is Phase IV recoherence. Critically: this does not mean that the arrow of time inverts for internal observers. Local subsystem entropy $S(\rho_{local})$ for any embedded observer continues to increase throughout, because local subsystems remain entangled with their local complements within the partition. What internal observers experience is normal forward time accompanied by anomalous dissolution of large-scale partition structure — not time running backward.

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When S(ρ_S) = 0, the partition does not exist. There is no before or
after. There is no observer to ask the question.
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This formulation has no circular elements:

- It requires no energy — von Neumann entropy is a purely algebraic property of the density matrix.
- It requires no Hamiltonian — no dynamical generator is needed to define entropy.
- It requires no external temporal parameter — the direction of entropy change is a property of the partition structure, not of a background clock.
- It requires no statistical measure over the space of states — it is a property of this specific partition relative to this specific complement.

The partition emerges when the algebraic structure of a region of H_U satisfies internal closure — when the subalgebra A_S is a von Neumann factor. This is proposed as the condition defining the subregion. It is not imposed from outside but is a structural property of certain configurations of H_U that exist as components of the superposition $|\Psi_U\rangle$.

2.4 The Delta as Geometric Difference

Within the partition, individual differences between states are measured by the Fubini-Study distance:

$$dFS(|\psi\rangle, |\varphi\rangle) = \arccos|\langle\psi|\varphi\rangle|$$

A single delta has no intrinsic direction — Fubini-Study distance is symmetric. The direction of time is not a property of individual deltas but of whether the accumulated effect of many deltas increases or decreases

$S(\rho_S)$. The delta is the microscopic unit. The entropy of the partition is the macroscopic direction. These are two levels of description that are consistent without either presupposing the other.

2.5 The Threshold as Structural Condition

The threshold separating transient configurations from self-sustaining subregions is proposed to correspond to the condition under which a subalgebra A_S of H_U becomes a von Neumann factor — internally closed, with trivial center.

Below the threshold: no stable partition exists. Any separation from the Cloud immediately dissolves — $S(\rho_S)$ returns to zero without generating internal structure. This is the analog of a transient vacuum fluctuation.

Above the threshold: a stable partition exists. The von Neumann entropy of the partition grows from zero, reaches a maximum, and eventually returns to zero as the partition dissolves. Internal observers within the partition experience this growth and subsequent decrease as the arrow of time.

The question of why this specific partition exists rather than another is not a causal question. $|\Psi_U\rangle$ contains all configurations simultaneously. Those that satisfy the factor condition exist as components of the superposition — not selected, simply present as structural features of H_U.

2.6 Entropy as the Complete Description

The apparent low entropy initial condition of the universe is dissolved by this formulation. At the beginning of the partition, $S(\rho_S)$ was small because the partition had just formed — only a small separation from the Cloud existed. As correlations transferred from the Cloud to the internal structure of S, the entropy grew. No fine-tuned initial condition is required. The entropy was low because the partition was young, not because of any special coincidence.

The Penrose problem's thermodynamic component is dissolved completely. The gravitational component — why the initial configuration had the specific geometric structure it had — is identified as a question about which configurations of H_U satisfy the factor condition. That remains open and is stated as such.

3. The Expansion of the Universe as Entropy Growth of the Partition

The framework interprets the expansion of the universe as the growth of the von Neumann entropy of the partition. As the partition becomes more separated from the Cloud — as more correlations transfer from the global structure to the internal structure of S — the partition grows. Within the framework, this growth is identified with what internal observers measure as cosmic expansion.

3.1 The Four Phases

Phase I — Maximum Entropy Growth Rate: The partition is newly formed and separating from the Cloud most rapidly. The rate of increase of $S(\rho_S)$ is at its maximum. The equation of state is most negative ($w \ll -1$). This corresponds to the inflationary epoch — rapid separation from the Cloud generates rapid internal structure.

Phase II — Moderating Growth Rate: The rate of entropy growth decreases as the internal structure of the partition approaches a local maximum of separation from the Cloud. The equation of state rises toward $w = -1$.

Phase III — Entropy Inflection: The rate of entropy growth crosses an inflection point. The partition has reached its maximum separation from the Cloud and begins the transition toward return. The equation of state crosses $w = -1$. This is the phantom crossing observed by DESI DR2.

Phase IV — Global Entropy Decrease and Recoherence: $S(\rho_S)$ is now decreasing — the partition is returning toward the Cloud. This decrease is consistent with the Page Curve theorem: for a pure bipartite quantum system with finite-dimensional Hilbert space and dynamics generating maximal entanglement, entanglement entropy is expected to decrease back toward zero once the midpoint of information transfer is crossed. The universal wavefunction $|\Psi_U\rangle$ is pure by postulate, making this decrease a mathematical consequence of the bipartite structure, not an additional postulate. Local observers do not experience time as reversed. $S(\rho_{local})$ for any embedded observer continues to increase, because local subsystems remain entangled with their local complements within the partition. What local observers experience is the anomalous dissolution of large-scale partition structure: cosmological correlations dissolving without local catastrophe. The local arrow of time remains well-defined and forward-directed throughout Phase IV. Only the global entropic profile of the partition is changing.

3.2 DESI DR2 as Observational Context

DESI DR2 (March 2025) fits the expansion history using:

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w(z) = w0 + wa × z/(1+z)
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DESI DR2 combined with CMB and supernova data finds consistent preference for $w0 > -1$ and $wa < 0$ with statistical significance between 2.8σ and 4.2σ. The best-fit solution indicates w was below −1 in the past and is currently above −1, crossing the phantom divide at approximately $z \approx 0.5$. This is precisely the signature of Phase III — the inflection point where entropy growth transitions toward entropy decrease.

3.3 The Central Falsifiable Prediction

> **THE PREDICTION:**
>
> If the universe is a partition of |Ψ_U⟩ whose von Neumann entropy is now past its maximum and beginning to decrease, then w(z) is expected to continue rising monotonically toward zero and subsequently toward positive values. This rise should not plateau, reverse, or stabilize at any negative value.
>
> This prediction is in direct conflict with: (a) ΛCDM, where $w = -1$ permanently; (b) quintessence models where w stabilizes between −1 and 0; (c) phantom energy models where w remains below −1. Testable by DESI full survey (~2026), Euclid, Vera Rubin Observatory, and Nancy Grace Roman Space Telescope.

3.4 Phase IV: The Phenomenology of Recoherence

Phase IV is phenomenologically distinct from classical gravitational recollapse in three respects:

First — the driving mechanism is entropic, not gravitational. Recoherence proceeds as S(ρ_S) decreases — as the partition's separation from the Cloud diminishes. This is not driven by matter-energy content.

Second — the dissolution is scale-dependent. The global von Neumann entropy of the partition decreases first at cosmological scales. Local partition structure — within galaxies, within laboratories — maintains its separation from the Cloud throughout. Local time remains well-defined.

Third — the endpoint is S(ρ_S) = 0. The partition ceases to exist as a distinct algebraic structure. No geometry remains because geometry was an emergent property of the partition's internal structure.

3.5 Conservation

The total von Neumann entropy of |Ψ_U⟩ remains zero throughout. The entropy S(ρ_S) observed within the partition is entanglement entropy — correlations transferred from the Cloud to the internal structure of

S. When the partition dissolves, those correlations return to the global structure of H_U. The accounting closes because it is a property of the algebraic structure, not of any dynamical process.

4. Black Holes as Local Recoherence Events

Black holes within the framework are regions where the local partition structure has reached maximum separation from the Cloud — maximum local von Neumann entropy — and is undergoing local recoherence. This is interpreted within the framework as the same process operating at the global lifecycle of the subregion, manifesting at accessible scales.

4.1 Deduction from Partition Structure

Consider a region of the subregion where local correlations have become so dense that no further separation from the Cloud is possible locally — the local von Neumann entropy has saturated. That saturation defines the horizon: the boundary beyond which no further entropy growth can propagate outward. Time dilation near the horizon follows directly: if time is entropy growth of the partition, and that growth rate decreases near saturation, then time runs more slowly near the horizon.

4.2 Singularity as Local S(ρ_S) = 0

At the center of a black hole, the local partition structure has dissolved — the local von Neumann entropy has returned to zero. This is locally what Phase IV is globally. The classical description breaks down not because of mathematical failure but because the local partition no longer exists as a distinct algebraic structure.

Black holes are observable laboratories for the recoherence mechanism — demonstrating locally what the universe undergoes globally at cosmological timescales.

4.3 Hawking Radiation and Holography

The horizon is a gradient in local entropy growth rate. At such gradients, the Hilbert space geometry generates pairs of configurations — one falling into the saturated interior, one propagating outward. This is Hawking radiation at temperature $T \propto 1/M$.

The Bekenstein-Hawking entropy $S = A/4$ is structurally expected: the local entropy of a saturated region is encoded at its boundary — the interface between the saturated interior and the unsaturated exterior. Area-scaling is a consequence of boundary encoding in the partition structure.

5. The Nature of Time

5.1 Time as Entropy Direction of the Partition

Time in the framework has a single clean definition: the direction of change of the von Neumann entropy of the partition S relative to the Cloud.

This definition requires no external parameter. It requires no energy. It requires no Hamiltonian. It requires only the algebraic structure of the partition — which is defined by the von Neumann factor condition — and its complement. Both exist as properties of H_U without temporal structure.

For any internal observer, time flows in the direction within the partial order of A_S along which $S(\rho_{local})$ increases. $S(\rho_{local})$ is always increasing for any physically embedded observer, because local subsystems are always gaining entanglement with their local complements. The global $S(\rho_S)$ traces a different profile — ascending through Phases I and II, inflecting at Phase III, descending through Phase IV. These are two distinct quantities. The confusion of one for the other generates the apparent paradox of time flowing backward in Phase IV. That paradox dissolves when the distinction is maintained. When $S(\rho_S) = 0$: time does not apply. The Lorentzian interval $ds^2 = c^2dt^2 - dx^2$ is the continuum approximation of this directional entropy structure in the limit where the discrete delta steps are invisible at classical scales.

5.2 The Wheeler-DeWitt Equation

The Wheeler-DeWitt equation $H|\Psi\rangle = 0$ states that the universal wavefunction has no external time dependence. This is correct. What it does not preclude is the existence of internal entropy structures within configurations of $|\Psi_U\rangle$ — partitions whose von Neumann entropy changes relative to their complement — that constitute temporal experience for internal observers. The Cloud is timeless. The partition has time. These refer to different levels of the algebraic structure.

5.3 The Arrow

The arrow of time is not a fundamental asymmetry in the laws of physics. It is a property of whether the partition is separating from or returning toward the Cloud. In Phases I and II, the partition is separating — entropy grows, the arrow is unambiguous. In Phase III, the rate transitions. In Phase IV, the partition is returning — entropy decreases, the cosmological arrow reverses while local arrows remain defined. This is the geometric reformulation of Boltzmann's insight: the arrow is a property of the state of the partition, not of the laws governing it.

6. Epistemological Limits of Internal Observers

6.1 The Internal Observer Problem

All physical observers are internal to the partition. Any measurement transfers correlations within the partition — it is an internal rearrangement of the structure of S. The total structure of H_U is inaccessible not because of distance but because the algebraic structure of S does not contain the global structure of H_U as a reference. The partition defines its own horizon of knowability by its own algebraic structure.

6.2 What Can Be Known

The partition leaves structural imprints accessible from within: the values of physical constants as properties of the local partition structure, the correlations at the boundary between S and E, and the direction of entropy change as the measurable arrow of time. The evolution of w(z) toward positive values is indirect evidence that the partition's entropy has passed its maximum — a structural consequence that is not predicted by any framework that does not posit a partition structure underlying the observable universe.

6.3 The Stability Illusion

Any observer within a partition experiences it as permanent. The interior has its own consistent entropy structure from the first separation onward. There is no internal signal distinguishing a partition that has existed for a short time from one that has existed for a long time — both are experienced from within as simply the world. The perceived permanence of the universe is exactly what the partition structure predicts.

6.4 The Structural Condition

|Ψ_U⟩ is a superposition of all configurations simultaneously. Some configurations satisfy the von Neumann factor condition — they generate self-consistent internal partition structures and support internal observers. Some do not. Both exist as components of the superposition. The question of why this partition exists is structurally equivalent to asking why a quantum state has the amplitude it has. There is no mechanism. There is only the algebraic structure of H_U.

Recent work by Witten, Chandrasekaran, and collaborators (2022-2023) demonstrates that the algebra of observables in de Sitter space is a Type II_1 von Neumann factor — precisely the algebraic structure the framework identifies as the condition for a self-sustaining partition. This convergence from independent directions is not coincidental.

7. Connections to Existing Frameworks

7.1 Causal Set Theory

The delta in the present framework is a single step in a causal set ordering. The contribution here is grounding the causal ordering in the von Neumann entropy structure of the partition — the ordering is defined by which configurations increase the partition's entropy.

7.2 Page-Wootters Mechanism

Page and Wootters (1983) demonstrated that time emerges from a static universal wavefunction through entanglement. The present framework implements this: the von Neumann entropy of the partition relative to its complement is the entanglement that constitutes temporal experience.

7.3 Boltzmann

Boltzmann argued that the arrow of time is a property of states, not laws. The present framework makes this precise: the arrow is the direction of change of the von Neumann entropy of the partition. The second law is recovered as a consequence of the partition structure, not as an independent postulate.

7.4 Space from Hilbert Space

Cao and Carroll (2016) showed that spatial geometry emerges from the entanglement structure of Hilbert space. The present framework extends this: the Fubini-Study metric generates geometric structure, and the von Neumann entropy of the partition provides the directional structure that gives time its arrow. Geometry and time direction arise from the same algebraic foundation.

7.5 ER = EPR

Two factor subalgebras of $|\Psi\_U\rangle$ sharing entanglement through the global Hilbert space structure would, from within each partition, appear geometrically connected. Wormholes are the classical-geometric signature of shared partition boundary structure between subregions.

8. Open Questions and Honest Limitations

8.1 The Quantitative Connection and Phenomenological Ansatz

The framework does not yet provide a quantitative derivation connecting the rate of change of $S(\rho_S)$ to the Hubble parameter $H(z)$ or the dark energy equation of state $w(z)$. The precise derivation requires a formal definition of the partition as an algebraic structure in H_U and a derivation of the emergent Lorentzian metric from the entropy structure. This is the primary mathematical open problem of the framework.

In the absence of that derivation, the following phenomenological Ansatz is proposed explicitly as a conjecture, not a derived result.

The macroscopic evolution of the dark energy equation of state $w(z)$ inherits the topological structure of the entropy saturation curve of the partition. As $S(\rho_S)$ approaches its maximum — the point at which the partition has transferred the maximum possible correlations from the Cloud to its internal structure — the modular flow $K_{\rho S}$ can no longer generate new internal structure at the same rate. This saturation manifests macroscopically as a deviation of $w(z)$ away from −1 and toward zero and subsequently positive values. The Phase III inflection in the partition entropy corresponds to the phantom crossing observed in $w(z)$.

This Ansatz is explicitly conjectural. It proposes that the microscopic saturation of modular flow and the macroscopic behavior of $w(z)$ share the same topological profile. What it does not provide — and what requires the full derivation of $F[\rho_S]$ — is a prediction of the specific redshift of the crossing, the rate of rise of $w(z)$, or its eventual positive value.

8.2 Why This Partition Rather Than Another

The framework identifies the relevant configurations as those satisfying the von Neumann factor condition. What it does not explain is why this specific partition — with this specific entropy profile — exists rather than another. This is the geometric reformulation of the Penrose problem. It is identified precisely as an open problem, not resolved.

8.3 The Phantom Crossing

The framework predicts an entropy inflection at the Phase III transition corresponding to the phantom crossing of w. DESI shows a crossing at $z \approx 0.5$. The qualitative agreement is encouraging but the framework does not yet predict the redshift of the crossing. Until the quantitative connection between $S(\rho_S)$ and $H(z)$ is established, this remains a post-hoc consistency rather than a quantitative prediction.

8.4 The Measure Problem

The framework identifies factor subalgebras of H_U as the relevant configurations. Defining a well-behaved measure on this set — which would constitute a genuine probability for partitions of this type — is technically non-trivial and remains open.

8.5 The Poincaré Recurrence and Genericity Objections

Two structural objections to the application of the Page curve in this framework require explicit treatment. They are distinct in nature and admit different responses. Conflating them leads to confusion about what the framework does and does not claim.

The Genericity Objection

The Page curve in its standard derivation assumes that the relevant state is generic — that the bipartite system explores its Hilbert space without fine-tuned structure. One might object that the universe, with its precise symmetries (Lorentz invariance, gauge symmetries $SU(3)\times SU(2)\times U(1)$, conservation laws), is far from a generic system, and therefore the Page curve argument does not apply.

This objection conflates two levels of description. The symmetries of the observable universe — Lorentz invariance, gauge structure, conservation laws — are *internal* properties of the partition S. They govern how degrees of freedom within S relate to one another. They are not, in general, constraints on the *correlation between S and its complement E* in $|\Psi_U\rangle$.

The entropy $S(\rho_S) = -\mathrm{Tr}(\rho_S \log \rho_S)$ where $\rho_S = \mathrm{Tr}_E(|\Psi_U\rangle\langle\Psi_U|)$ depends exclusively on how S and E are entangled globally in $|\Psi_U\rangle$, not on the internal dynamics of S. The question of whether $S(\rho_S)$ follows a Page-like profile is therefore a question about the structure of $|\Psi_U\rangle$ as a bipartite state, not about the equations of motion internal to the partition.

The postulate that $|\Psi_U\rangle$ contains all configurations simultaneously — that it is a superposition without preferred structure at the global level — is the condition that provides the relevant genericity. Under this postulate, the correlations between S and E are not fine-tuned by the internal symmetries of S; they are properties of the global superposition. The genericity required for the Page argument operates at the level of the S-E bipartition, not at the level of the internal Hamiltonian of S.

A residual technical question remains: Page-like structure does not follow from existence of all configurations alone; it requires at minimum a notion of typicality over the relevant branches of $|\Psi_U\rangle$. The precise measure on the space of configurations satisfying the von Neumann factor condition is the open problem identified in §8.4. Within the framework's postulates, the genericity objection does not apply to $S(\rho_S)$ as defined, but the full technical resolution awaits the measure problem.

The Poincaré Recurrence Objection

The standard Page curve for a macroscopic system completes on the Poincaré recurrence timescale, which for the observable universe is of order $T_P \sim e^{S_{BH}} \sim e^{10^{123}}$ years. The objection is then: if the Page curve governs $S(\rho_S)$, why is the partition currently at its inflection point after only $\sim 1.4 \times 10^{10}$ years, rather than after a time incomparably larger?

This objection, while serious, rests on a category that the present framework does not admit: an external time parameter with respect to which recurrence is measured. The Poincaré recurrence theorem is a statement about the evolution of a system in a background temporal parameter — the system returns to a neighborhood of its initial state after some external duration T_P. But in the present framework, there is no external time. The Cloud has no temporal structure. Time is defined internally to the partition as the direction of change of $S(\rho_S)$. The question "how many external years does the Page curve take?" has no referent in the framework, in the same way that the question "what happened before the partition existed?" has no referent.

This dissolution is partial, not complete. It removes the Poincaré timescale as a relevant comparator, but it does not itself explain what determines the intrinsic temporal scale of the partition — why the partition's lifecycle, measured in its own internal units, has the duration that it does. The vacuum-fluctuation analogy is relevant here: a vacuum fluctuation does not persist for the recurrence time of the quantum field; its duration is determined by the energy scale of the fluctuation itself, not by the recurrence properties of the background field. Analogously, the intrinsic timescale of the partition is proposed to be a property of the partition's own algebraic structure — its separation energy from the Cloud — rather than a recurrence property of $|\Psi_U\rangle$.

However, this analogy does not by itself determine the quantitative value of that intrinsic scale — it does not explain why the partition's internal duration, in its own units, corresponds to the ~13.8 Gyr we observe rather than some other value. The vacuum-fluctuation analogy motivates a finite intrinsic lifecycle of the partition, but *the quantitative origin of the partition's intrinsic timescale is not derived here and remains an open problem of the framework.* This problem is not the same as the Poincaré recurrence problem — the former is a question about an internal scale, the latter about an external one — but it is equally unresolved. Its resolution is expected to be linked to the derivation of $F[\rho_S]$ identified in §8.1 as the primary mathematical open problem.

Summary. The genericity objection is answered within the framework's ontology: the relevant genericity is a property of the S-E correlation structure in $|\Psi_U\rangle$, not of the internal dynamics of S, and the two levels must not be conflated. The Poincaré recurrence objection is dissolved as a category error — it presupposes an external temporal parameter that the framework does not posit — but the underlying question about the intrinsic timescale of the partition is genuine and remains open, identified here as a distinct sub-problem within the broader challenge of §8.1.

9. Core Conceptual Theorems

This section consolidates the logical structure of the framework into a sequence of conditional statements. The intent is to make explicit which results follow from established physics, which require the framework's central postulate, and which are direct consequences of the chain. Theorem 3 is the framework's central physical postulate. Theorems 1, 2, 4, and 5 follow from it together with standard properties of bipartite quantum systems.

Theorem 1 — Page Structure of Subregion Entropy

If *(A) the universal quantum state is pure, and (B) the observable universe corresponds to a bipartite subregion S of that state,*

then *the von Neumann entropy S(ρ_S) is expected to exhibit a Page-like structure under standard assumptions of generic dynamics: it begins at zero, increases to a maximum, and returns to zero.*

This is a direct consequence of the Page Curve theorem (Page, 1993) applied to a pure bipartite system. It is established physics, not a new claim of the framework.

Theorem 2 — Existence of a Unique Entropic Turning Point

If *(C) the entropy of the subregion follows a Page-like curve without additional structure or external driving,*

then *there exists a unique point at which dS(ρ_S)/dλ = 0, and the sign of dS/dλ changes exactly once.*

This follows from the smoothness and unimodal structure of the Page curve under condition (C). The assumption of no additional driving is non-trivial but reasonable for a pure bipartite system.

Theorem 3 — Entropic Control of Effective Cosmological Dynamics (Postulate)

If *(D) the effective cosmological dynamics of the subregion are governed by the rate of change of its entanglement entropy,*

then *the sign of dS/dλ determines the dynamical regime of the expansion.*

This is the central physical postulate of the framework. It is introduced as a postulate, not as a derived result. Its mathematical justification — the explicit functional form of g_μν^eff = F[ρ_S] — is the primary open problem identified in Section 8.1. The remaining theorems follow from this postulate together with the structural results above.

Theorem 4 — Unique Phantom Crossing

If *(A)–(D) hold,*

then *the effective equation of state w(z) is expected to exhibit a single transition across $w = -1$ corresponding to the entropic turning point:*

$dS/d\lambda > 0 \Rightarrow w < -1$ *(effective phantom regime)*

$dS/d\lambda = 0 \Rightarrow w = -1$

$dS/d\lambda < 0 \Rightarrow w > -1$

No additional crossings are generically allowed. The single phantom crossing observed by DESI DR2 at approximately $z \approx 0.5$ is consistent with this structure.

Theorem 5 — Monotonic Late-Time Evolution

If *(A)–(D) hold and no additional structure modifies the entropy flow,*

then *the post-transition evolution of w(z) is expected to be monotonic and is not expected to asymptotically stabilize at a constant negative value.*

This is the strongest distinguishing prediction of the framework. ΛCDM, quintessence models, and phantom energy models all predict either a constant w or stabilization at a negative value. The framework predicts continued monotonic evolution toward zero and beyond.

Honesty Statement

Theorem 3 is introduced as a physical postulate. Theorems 1 and 2 follow from established results about bipartite pure quantum systems. Theorems 4 and 5 follow logically from Theorems 1–3 together with standard properties of cosmological dynamics. The framework is therefore a postulate (Theorem 3) and its logical consequences. Whether the postulate is physically correct is the empirical question that w(z) measurements will eventually answer.

10. Summary of Testable Predictions

Prediction 1 — Monotonic Rise of w(z) [Primary Test]

w(z) is expected to rise monotonically toward zero and then toward positive values. It is not expected to plateau, oscillate, or reverse. Testable by DESI full survey (~2026), Euclid, Vera Rubin Observatory, Nancy Grace Roman Space Telescope.

Prediction 2 — Phase IV Signature

If Phase IV recoherence begins, it is expected to manifest as dissolution of large-scale correlations — anomalous loss of CMB structure, galaxy distribution coherence — without local catastrophe. Phenomenologically distinct from classical recollapse.

Prediction 3 — Entropy Scaling with Area

The entanglement entropy of cosmological regions is expected to scale with boundary area rather than volume in regimes where partition-Cloud entanglement dominates.

Prediction 4 — Uniformity of Physical Constants

Physical constants are proposed to be properties of the local partition structure. They are expected to be uniform within the partition. Statistically significant internal variation would constitute evidence against the framework.

Prediction 5 — No Pre-Big-Bang Signatures

The framework predicts no physically meaningful pre-Big-Bang state accessible from within the partition. Claimed pre-Big-Bang CMB signatures would be reinterpreted within the framework as boundary effects of the initial partition formation.

11. Conclusion

We have presented a cosmological framework built on a single phenomenological insight: our universe is modeled as a partition of the universal wavefunction, structurally analogous to how a vacuum fluctuation is a partition of the vacuum field. From this insight, without invoking energy, Hamiltonians, external temporal parameters, or statistical measures over the space of states, the framework generates: the algebraic condition for partition existence — the von Neumann factor condition; the arrow of time as the direction of change of the partition's entropy; the emergent Lorentzian metric as a continuum approximation; the dissolution of the initial entropy fine-tuning problem; the lifecycle of the universe as entropy growth followed by entropy decrease; black holes as local recoherence events where the partition structure saturates; the holographic principle as boundary encoding of the partition structure; and a principled epistemological limit on what can be known from within a partition.

The central advance of this version over all previous versions is the elimination of every hidden temporal or energetic presupposition from the arrow of time. Previous versions sought the arrow in energy differentials, statistical measures, or causal precedence relations — all of which presupposed, implicitly or explicitly, something temporal or dynamical. This version grounds the arrow in the von Neumann entropy of the partition itself: a purely algebraic quantity that exists without time, without energy, without external structure. The direction of time is simply whether the partition is separating from or returning toward the Cloud.

The framework's primary falsifiable prediction remains the monotonic rise of $w(z)$ toward positive values — in direct conflict with all current standard cosmological models. The DESI DR2 results are consistent with Phase III — the entropy inflection that marks the transition from growing to decreasing partition structure. Whether w continues rising will constitute a definitive observational test.

What remains is the mathematical formalization: a precise definition of the partition entropy as an algebraic structure in H_U and a quantitative derivation connecting $S(\rho_S)$ to $H(z)$. These problems are difficult and well-posed. Their resolution will determine whether the framework becomes a physical theory or remains a philosophical proposal. Both outcomes have value.

"The universe is a partition of the silence. It separated without cause, grew by accumulating the distance between itself and what it left, and is — by its own measurements — beginning to return. Time is the name we give to that distance. What we call the future is simply less of it remaining."

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