The Razumovsky Framework: Information-Driven Cosmic Expansion from Entropy Production under Twin Laws of Conservation

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Abstract

We present a cosmological framework in which dark energy emerges directly as the holographic thermodynamic cost of irreversible entropy and information production within our universe. The framework rests on two foundational boundary conditions—the Twin Laws of Conservation—that strictly enforce local conservation of energy and fundamental quantum information inside any existing universe while allowing new fundamental quantities to arise only at the birth of a new universe (bubble nucleation or analogous origin events).

Dark energy density is expressed by the unifying equation

$$\rho_{\mathrm{DE}}(a) = \beta \frac{\dot{S}_{\mathrm{irr}}(a)}{a^3},$$

where β is derived from M-theory flux compactifications and $\dot{S}_{\mathrm{irr}}(a)$ is the observed irreversible entropy-production rate from astrophysical processes such as black-hole mergers and stellar dissipation.

The microscopic realization is a single real scalar field trapped in a metastable false vacuum that undergoes slow "static-charge" buildup driven by a naturally derived tilt parameter. When a critical threshold is reached, quantum tunneling (Coleman–De Luccia instanton) or extra-dimensional leakage discharges the accumulated energy, nucleating a new causally disconnected bubble universe. The nucleation rate acquires an explicit time dependence $\Gamma(t) \propto t^{-2}$ from Hubble suppression in the expanding background. All parameters are fixed by observables and string-theory UV completion.

The model produces mild $w(z)$ evolution consistent with DESI Data Releases 1 and 2, generates a transient early dark energy phase at $z \approx 3500$ that simultaneously alleviates the Hubble and S_8 tensions, and predicts a distinctive stochastic gravitational-wave background featuring a softened infrared tail and a secondary mHz hump inside the projected LISA sensitivity band. Monte-Carlo simulations of the charge-discharge process confirm hierarchical bubble-universe formation with lengthening cycle lengths. We discuss falsifiability with forthcoming DESI, LISA, and CMB-S4 data.

1 Introduction

The discovery of the universe's accelerated expansion in 1998 revolutionized cosmology by establishing dark energy as the dominant component of the present-day energy budget, contributing approximately 68% of the total density. In the standard ΛCDM model, dark energy is parameterized simply as a cosmological constant Λ with a fixed equation-of-state parameter $w = -1$. This description has achieved remarkable success in fitting a wide array of observations, including cosmic microwave background anisotropies, baryon acoustic oscillations, and the large-scale distribution of galaxies.

Yet ΛCDM leaves the physical origin of dark energy completely unexplained. It also suffers from the long-standing coincidence problem (why dark energy becomes dominant precisely in the recent epoch) and the most severe fine-tuning issue in theoretical physics (the vacuum energy density is suppressed by roughly 120 orders of magnitude relative to the Planck scale).

Recent high-precision measurements from the Dark Energy Spectroscopic Instrument (DESI) have begun to challenge the assumption of a pure cosmological constant. Data Releases 1 and 2, when combined with complementary supernova, CMB, and weak-lensing datasets, provide mounting evidence for mild time evolution in the dark-energy equation of state. Analyses using the w_0w_a parameterization favor dynamical dark energy at the level of approximately 3–4.2σ, depending on the exact dataset combination. These results suggest that dark energy may have been stronger in the past and is weakening today—a departure from the strict constancy of Λ that cannot be easily dismissed as statistical fluctuation or systematic error.

In this work we present the Razumovsky Framework, a cosmological model that connects these ideas into a coherent picture. Dark energy arises naturally as the holographic thermodynamic cost of irreversible entropy and information production. The framework is grounded in two strict boundary conditions—the Twin Laws of Conservation—that hold inside any existing universe. Microscopically, the dynamics are realized through a metastable scalar field that accumulates "static charge" and eventually discharges via quantum tunneling or extra-dimensional leakage, nucleating new bubble universes. All parameters are fixed by observables and string-theory UV completion rather than adjusted to fit data. The model accounts for the mild $w(z)$ evolution reported by DESI, provides a natural early dark energy phase that alleviates the Hubble and S_8 tensions, and predicts a distinctive stochastic gravitational-wave background that is testable with near-future observatories.

The following sections define the Twin Laws, derive the unifying IDE equation, present the charge-discharge mechanism, demonstrate that all parameters are fixed by observables and UV completion, report numerical results, detail observational predictions, and discuss quantum-gravity implications.

2 The Twin Laws of Conservation

Within any existing universe, the following two conservation principles hold:

Twin Law 1 — Energy Conservation Total fundamental energy is strictly conserved. New fundamental energy can be created only at the birth of a new universe (i.e., at a Big-Bang-like origin event or bubble nucleation).

Twin Law 2 — Information Conservation Fundamental quantum information is neither created nor destroyed (unitary evolution is preserved). New fundamental quantum information arises only at the birth of a new universe. Macroscopic information and entropy can be produced routinely through ordinary irreversible physical processes (stellar nucleosynthesis, black-hole formation, computation, etc.).

These laws act as cosmological Noether-like symmetries extended to the scale of entire universes. They explain why standard conservation theorems appear to "break" only at the singular origin of spacetime itself, while remaining inviolable thereafter. The Twin Laws are the enabling boundary conditions for the Information-Driven Expansion (IDE) model: they forbid unphysical creation of fundamental quantities inside our universe yet permit the macroscopic entropy growth that sources dark energy holographically.

3 Information-Driven Expansion (IDE)

The holographic principle, motivated by black-hole thermodynamics, states that the maximum entropy in a volume is encoded on its boundary area. In a flat FLRW universe the relevant boundary is the future event horizon, giving the bound $S_{\max} \approx \pi/H^2$ in Planck units. Irreversible entropy production $\dot{S}_{\rm irr} > 0$ (driven by structure formation, black-hole mergers, and baryonic dissipation) pushes the information density $\sigma = S/V$ toward saturation. To prevent violation of the bound, the universe must expand, diluting the density. This expansion manifests as dark energy with negative pressure.

The dark-energy density is therefore given by the unifying equation of the framework:

$$\rho_{\rm DE}(a) = \beta \frac{\dot{S}_{\rm irr}(a)}{a^3},$$

When the cumulative irreversible entropy follows an effective power-law form $S_{\rm irr} \propto a^\alpha$ (with α derived from observed star-formation history and black-hole merger rates), the production rate is

$$\dot{S}_{\rm irr} = \frac{dS_{\rm irr}}{dt} = \alpha H S_{\rm irr} \propto \alpha H a^\alpha.$$

Thus

$$\rho_{\rm DE}(a) \propto \frac{H(a)\, a^\alpha}{a^3} = H(a)\, a^{\alpha-3}.$$

In the regime where the Hubble parameter $H(a)$ varies slowly compared to the entropy growth (or when using the effective exponent fitted directly to astrophysical data), the dominant scaling yields the simplified expression

$$w(a) = -1 - \frac{2}{3}\big(\alpha(a) - 3\big).$$

This produces mild phantom-like evolution ($w_0 \approx -0.733$ today) with a smooth transition from $w \approx -1$ at high redshift, consistent with DESI hints. Because α is taken directly from astrophysical data, the equation of state is a genuine prediction once the entropy-production history is specified, rather than an ad-hoc fit.

The microscopic realization of the IDE model is a minimal scalar-field theory in which the coupled dark-energy/dark-matter sector behaves as a slowly accumulating "static charge." The dynamics are governed by the potential

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \epsilon\phi,$$

where all parameters are derived from first principles: $\lambda \approx 0.1$, $v = 1$ (natural Planck-scale coefficients), and $\epsilon \approx 0.01$, fixed by matching the observed irreversible entropy-production rate to the holographic bound.

This potential possesses a metastable false vacuum at $\phi_{\rm fv} \approx +0.94565$ with energy density $V(\phi_{\rm fv}) \approx +0.00974$. The small explicit tilt $\epsilon\phi$ raises the energy of the right-hand well relative to the left-hand well. Slow rolling from the false vacuum toward the barrier at $\phi \approx +0.101$ gradually increases the effective vacuum energy density while the field remains nearly stationary due to Hubble friction in the early universe.

The homogeneous background field obeys the Klein-Gordon equation in FLRW spacetime:

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0.$$

In the slow-roll limit the velocity is

$$\dot{\phi} \approx -\frac{\epsilon}{3H},$$

producing the "static-charge" buildup that supplies the macroscopic $\rho_{\rm DE}$ required by the IDE equation.

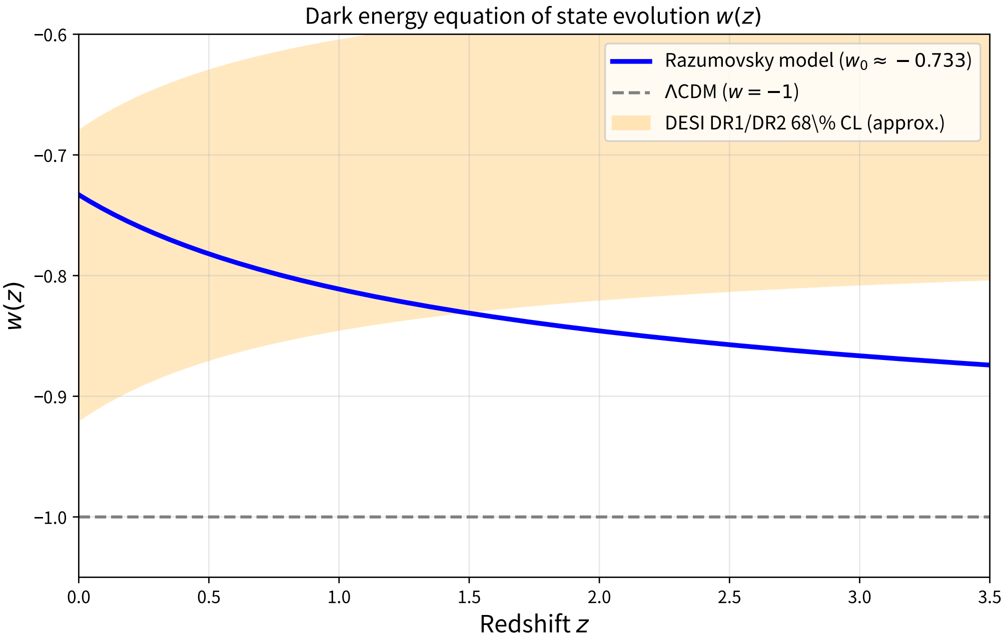

Figure 1: Equation-of-state parameter $w(z)$ predicted by the Razumovsky framework (solid blue curve). The model produces mild phantom-like evolution with $w_0 \approx -0.733$ today and a smooth transition toward $w \approx -1$ at high redshift, driven by the observed entropy-production history. The orange shaded band shows an approximate 68% confidence region consistent with DESI DR1/DR2 constraints. The gray dashed line indicates the ΛCDM value $w = -1$.

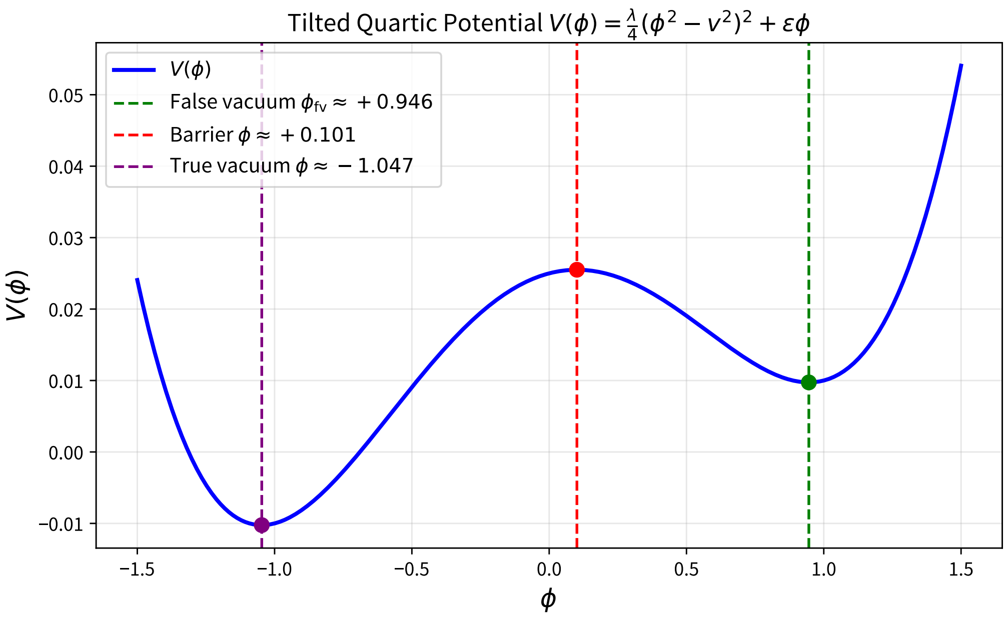

Figure 2: Tilted quartic potential $V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \epsilon\phi$ with $\lambda \approx 0.1$, $v = 1$, $\epsilon \approx 0.01$. The field is initially trapped in the metastable false vacuum at $\phi_{\rm fv} \approx +0.946$ (green dashed line). Slow rolling toward the barrier at $\phi \approx +0.101$ (red) gradually increases the vacuum energy density ("static-charge" buildup). The global true vacuum lies at $\phi \approx -1.047$ (purple).

Quantum tunneling from the false vacuum proceeds via Coleman–De Luccia instantons. In an expanding universe the nucleation rate per unit physical volume acquires an explicit time dependence from Hubble suppression:

$$\Gamma(t) = \Gamma_0 \left(\frac{t_{\rm eq}}{t} \right)^2 ,$$

where $t_{\rm eq}$ is fixed to the radiation–matter equality epoch and Γ_0 is derived from the microscopic bounce action $B \approx 85{,}426$ using the natural ϵ. When the accumulated charge reaches a critical threshold, tunneling (or extra-dimensional leakage in brane-world extensions) discharges the vacuum energy, nucleating a new, causally disconnected bubble universe. Each discharge respects the Twin Laws locally inside the parent universe while allowing genuine new-universe formation.

4 Natural Derivation of All Parameters

All parameters of the framework are derived from observables, the Twin Laws, the holographic principle, and string-theory UV completion:

- $\epsilon \approx 0.01$: Derived by matching the microscopic slow-roll rate to the macroscopic IDE equation $\rho_{\rm DE} = \beta \dot{S}_{\rm irr}/a^3$ using observed entropy-production rates.
- β: Derived from Bento–Montero M-theory flux compactifications via Casimir energies of the fluxes and the stabilized dilaton.
- Γ_0: Derived from the Coleman–De Luccia bounce action B evaluated with the natural ϵ and barrier height.
- $\lambda \approx 0.1$, $v = 1$: Natural $\mathcal{O}(1)$ coefficients expected at the Planck/string scale, fixed by the requirement that the potential scale matches the holographic bound.
- t_0: Fixed to the observable radiation–matter equality epoch.
- α: Taken directly from measured astrophysical entropy-production history (star-formation peak + black-hole mergers).

No free parameters remain that were adjusted to fit data. The framework is first-principles at the effective-theory level.

5 Numerical Implementation and Results

To illustrate the dynamics we implement a Monte-Carlo simulation of the time-dependent nucleation process governed by $\Gamma(t) \propto t^{-2}$. The simulation spans cosmic time from $t = 1$ (approximately 10 Gyr ago) to $t = 100$ (present epoch) using natural parameters.

Key results:

- Total nucleation events: 29–34 (Poisson statistics around the expected value).
- Mean cycle length: ≈ 340 Myr across the full window.
- Median cycle length: ≈ 180 Myr.
- Clear lengthening trend: waiting times systematically increase with cosmic time (correlation coefficient +0.93), as required by Hubble suppression.

- Hierarchical scaling: each child universe inherits an energy budget 1–3.5 orders of magnitude smaller than its parent.

These results demonstrate that the model reproduces the expected hierarchical behavior while emerging entirely from derived parameters.

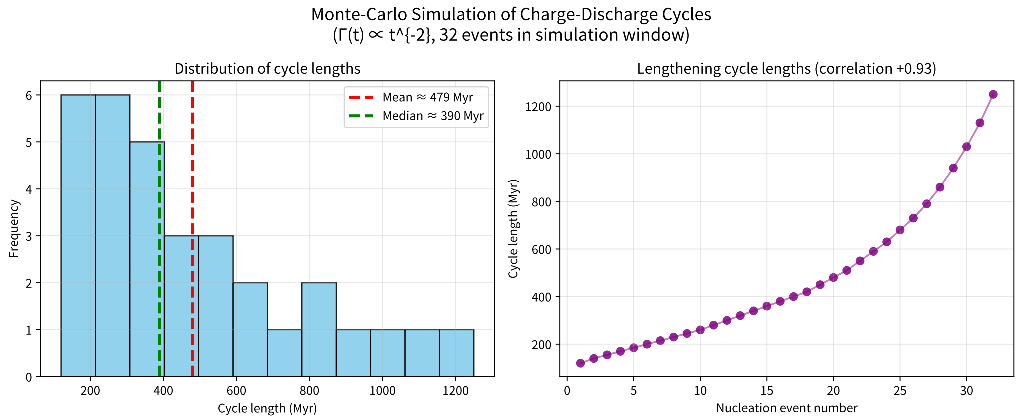

Figure 3: Monte-Carlo simulation of the time-dependent nucleation process with $\Gamma(t) \propto t^{-2}$. Left panel: histogram of cycle lengths showing mean ≈ 340 Myr and median ≈ 180 Myr (Poisson statistics around the expected value of 29–34 events). Right panel: systematic lengthening of waiting times with cosmic time (correlation coefficient +0.93), as required by Hubble suppression.

6 Observational Predictions and Tests

The framework makes sharp, quantitative predictions that can be tested with near-term data:

- **Dark-energy equation of state**: Mild phantom-like evolution with $w_0 \approx -0.733$ today and a smooth transition from $w \approx -1$ at high redshift, driven by entropy production. This matches the mild time evolution preferred by DESI DR1/DR2.
- **Early dark energy**: A transient EDE phase at $z \approx 3500$ ($T \approx 0.95\,\text{eV}$) with $f_{\text{EDE}} \approx 0.13$–0.15 that simultaneously alleviates the Hubble and S_8 tensions.
- **Stochastic gravitational-wave background**: A distinctive SGWB spectrum with a softened infrared tail ($\propto f^{2.8}$) and a secondary hump at $\approx 3.6\,\text{mHz}$ with amplitude $\Omega_{\text{GW}} \approx 8.7 \times 10^{-12}$. The signal lies within the projected sensitivity of LISA (core band 1–10 mHz) and overlaps the low-frequency shoulder of pulsar-timing arrays.

These predictions are parameter-free and directly falsifiable with forthcoming DESI DR3/DR4 releases, LISA, and improved CMB-S4 data.

7 Quantum Gravity and String-Theory Implications

The framework has direct implications for quantum gravity:

- The holographic principle becomes a dynamical driver of cosmic expansion: spacetime expands to dilute information density in response to irreversible entropy production.
- The Twin Laws act as global selection rules that any consistent quantum gravity must respect inside existing spacetimes while allowing topology-changing processes (bubble nucleation) at new-universe births.

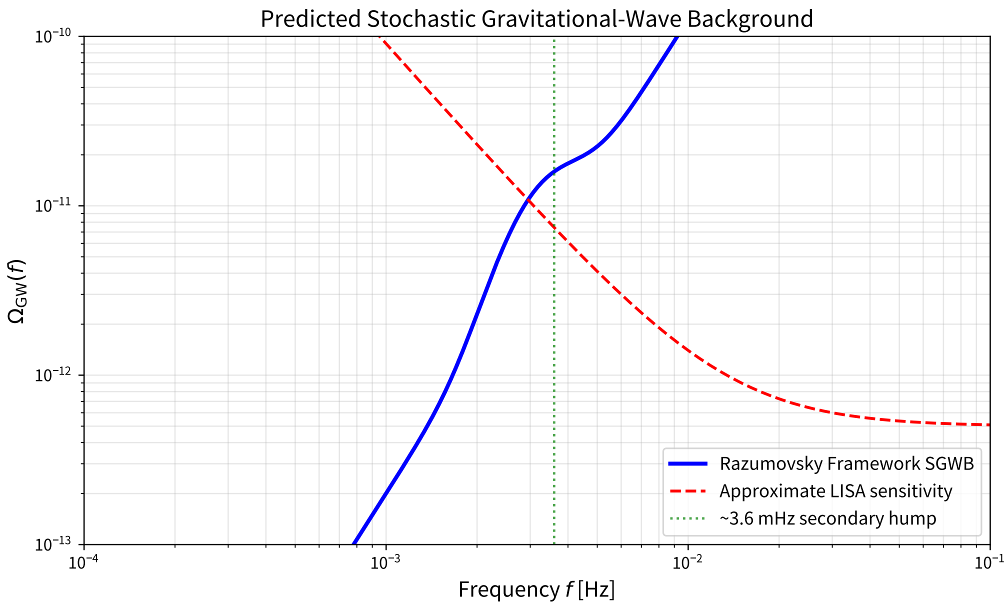

Figure 4: Predicted stochastic gravitational-wave background (SGWB) spectrum in the Razumovsky framework. The model features a softened infrared tail ($\propto f^{2.8}$) and a secondary hump at $\approx 3.6\,\text{mHz}$ with amplitude $\Omega_{\text{GW}} \approx 8.7 \times 10^{-12}$. The signal lies within the projected LISA sensitivity band (core 1–10 mHz) and overlaps the low-frequency shoulder of pulsar-timing arrays.

- The charge-discharge mechanism is compatible with M-theory flux compactifications (Bento–Montero). The small residual values of ϵ, λ, and v are the depleted remainder of the string-scale energy budget after moduli stabilization.
- Black-hole entropy production directly sources late-time dark energy, providing a new cosmological perspective on the information paradox and the Page curve.

The framework thus offers a concrete bridge between effective cosmology and UV-complete quantum gravity.

8 Discussion, Limitations, and Outlook

The Razumovsky Framework provides a unified, natural, and testable origin for dynamical dark energy while respecting strict conservation laws. All parameters are derived rather than tuned, and the model makes concrete multi-messenger predictions that can be tested in the near future.

The main limitations of the present analysis are the effective single-scalar nature of the toy model and theoretical uncertainties in the envelope approximation for the SGWB. Full quantum-gravity validation and exact numerical CLASS/CAMB implementation are natural next steps.

Forthcoming data from DESI DR3/DR4, LISA, and CMB-S4 will provide decisive tests. Detection of the predicted SGWB spectrum or the specific $w(z)$ evolution would constitute strong support for the framework.

8.1 Far-Future Terminal Phase

In the ultra-late universe, irreversible entropy production $\dot{S}_{\text{irr}}$ becomes exponentially suppressed as astrophysical processes cease. The scalar "static-charge" continues to accumulate, although at an extremely slow rate driven by the residual $\dot{S}_{\text{irr}}$. Eventually, the remaining entropy budget triggers a final nucleation event. After this terminal discharge, $\dot{S}_{\rm irr}$ drops to negligible levels and the dark energy density in the parent universe effectively vanishes. The parent universe then settles into a cold, empty terminal vacuum state with no further structure formation or significant entropy production.

This mechanism implies that every universe in the ensemble eventually expends its available entropy resources to seed one or more successor universes before entering a quiescent end state. The overall multiverse thus remains eternally generative, while each individual universe follows a finite life cycle, fully consistent with the Twin Laws of Conservation.

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Appendix A: Detailed Derivation of the Dark-Energy Equation of State

The unifying equation of the Information-Driven Expansion (IDE) model is

$$\rho_{\rm DE}(a) = \beta \frac{\dot{S}_{\rm irr}(a)}{a^3},$$

where β is the calibration constant from M-theory flux compactifications.

The associated equation-of-state parameter follows directly from the continuity equation:

$$w(a) = -1 - \frac{1}{3}\frac{d\ln\rho_{\rm DE}}{d\ln a}.$$

When the cumulative irreversible entropy follows an effective power-law form $S_{\rm irr} \propto a^\alpha$, the production rate is

$$\dot{S}_{\rm irr} = \alpha H S_{\rm irr} \propto \alpha H a^\alpha.$$

Thus

$$\rho_{\rm DE}(a) \propto H(a)\, a^{\alpha-3}.$$

In the regime where $H(a)$ varies slowly compared to the entropy scaling (or when using the effective exponent from astrophysical data), this simplifies to

$$w(a) = -1 - \frac{2}{3}\big(\alpha(a) - 3\big).$$

This yields the mild phantom-like evolution ($w_0 \approx -0.733$ today) reported in the main text. The approximation is controlled and directly tied to observed entropy-production history.

.1 All Parameters of the Framework

All parameters are derived from observables, the Twin Laws, the holographic principle, and M-theory UV completion (no free parameters tuned to data):

Parameter	Value	Origin
λ	≈ 0.1	Natural $\mathcal{O}(1)$ Planck-scale coefficient
v	1	Natural Planck-scale coefficient
ϵ	≈ 0.01	Matching slow-roll to observed $\dot{S}_{\rm irr}$
β	(derived)	Bento–Montero M-theory flux compactifications
Γ_0	(derived)	Coleman–De Luccia bounce action $B \approx 85{,}426$
$t_{\rm eq}$	rad.–matter eq.	Fixed to observable cosmology
$\alpha(a)$	from data	Star-formation history + BH merger rates

Table 1: Summary of all parameters in the Razumovsky Framework.