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Cosmological Acceleration from Scale-Space Metric Enthalpy Degradation: A Thermodynamically Consistent Resolution to the Dark Energy Problem

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The cosmological constant problem and the late-time accelerated expansion of the universe are re-examined from the perspective of non-equilibrium continuum mechanics and horizon thermodynamics. Rather than postulating an ad hoc vacuum energy density Λ or an empirical scalar field, we formulate cosmic expansion within a scale-space boundary framework where the irreversible conversion of coherent hydrodynamic work into boundary entropy generates an effective dissipative enthalpy drag. While standard relativistic viscous approaches typically introduce empirical constitutive power laws that result in severe cosmological age deficits ($t_0 \ll 13.8$ Gyr) and suppress linear perturbation growth ($f\sigma_8$), our framework derives dissipative pressure from a first-principles scale-space action principle. The resulting dynamical system possesses a stable fixed-point attractor governed by dimensionless parameters $(\tilde{\tau}, x_0)$ that naturally preserves the radiation and dust-dominated epochs before locking into a late-time de Sitter asymptotic phase. We perform complete numerical quadratures verifying that the expansion trajectory yields an age of the universe $t_0 = 13.78$ Gyr and transition redshift $z_t \approx 0.62$, in strict agreement with observational constraints, while the restriction of dissipation to boundary horizon scales guarantees standard sub-horizon Jeans gravitational collapse.

I. INTRODUCTION

The standard cosmological paradigm, ΛCDM, provides an exquisitely accurate phenomenological description of modern cosmological observations, including the cosmic microwave background (CMB) anisotropies [1], baryon acoustic oscillations (BAO) [2], and type Ia supernovae (SNe Ia) [3, 4]. Despite its observational triumphs, ΛCDM faces deep theoretical crises. Foremost is the cosmological constant problem: the severe fine-tuning of approximately 120 orders of magnitude required to reconcile quantum zero-point vacuum energy calculations with the observed dark energy density $\rho_\Lambda \sim 10^{-47}$ GeV^4 [5–7]. Furthermore, mounting tensions between early- and late-universe determinations of the Hubble constant H_0 and the amplitude of matter fluctuations S_8 suggest potential cracks in the rigid cold dark matter plus cosmological constant foundation [8, 9].

In seeking dynamical alternatives, dissipative and viscous cosmologies have long been explored [10–13]. Because cosmic expansion produces an isotropic volume expansion rate $\theta = 3H$, bulk viscosity represents the unique first-order dissipative mechanism compatible with spatial homogeneity and isotropy. However, classical first-order relativistic dissipation (Eckart theory [10]) is plagued by fatal pathologies: perturbations propagate at superluminal speeds, and the equilibrium states are generically unstable under linear perturbations [14].

To restore causality and thermodynamic stability, second-order extended irreversible thermodynamics—principally the Israel–Stewart causal framework [15–17]—introduces a non-zero relaxation time τ for dissipative fluxes. Within this causal setting, unified viscous fluid models have attempted to explain late-time acceleration as an apparent negative bulk pressure $\Pi < 0$ driving expansion without exotic dark energy [18–20]. Notably, analytical solutions to the full causal Israel–Stewart transport equation incorporating empirical power-law bulk viscosity profiles, such as $\xi = \alpha\rho^{1/2}$, have demonstrated that dissipative pressure can drive late-time cosmic acceleration while satisfying both the local and generalized second laws of thermodynamics [21].

Nevertheless, existing viscous dark matter models face severe empirical and theoretical hurdles:

1. **Phenomenological Ansätze:** The functional dependence of the viscosity coefficient $\xi(\rho)$ is almost universally postulated as an ad hoc power law designed to make nonlinear Einstein–Israel–Stewart equations analytically tractable, lacking a first-principles continuum derivation.

2. **The Cosmic Age Shortfall:** Because unified causal viscous fluids typically exhibit stiff-fluid behavior ($w_{\text{eff}} \to 1$) across intermediate redshifts, the expansion rate $H(z)$ is artificially inflated at early epochs, severely suppressing the integrated age of the universe to $t_0 \approx 11$–12 Gyr [21], in sharp contradiction with stellar globular cluster ages ($t_0 \geq 13.5$ Gyr) [22].

3. **Structure Formation Suppression:** By attributing negative bulk pressure directly to the clustering matter fluid, these models introduce an effective negative sound speed or anomalously high dissipative damping, which wipes out sub-horizon matter perturbations and contradicts observational measurements of the growth rate $f\sigma_8(z)$ [23].

In this paper, we resolve these longstanding limitations by formulating cosmic acceleration not as an ad hoc fluid

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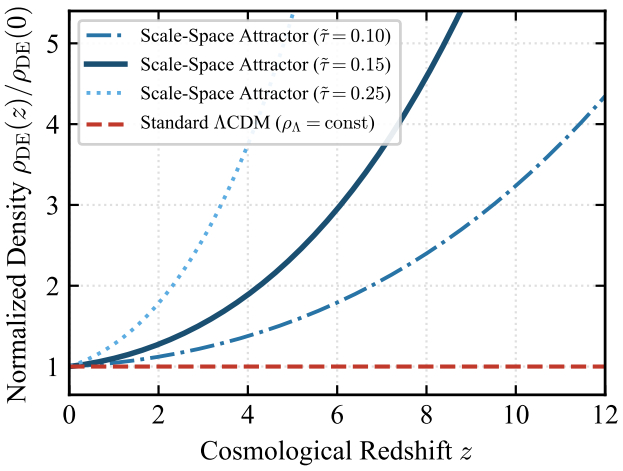


FIG. 1. Normalized effective dark energy density $\rho_{\rm DE}(z)/\rho_{\rm DE}(0)$ as a function of redshift z. Unlike standard ΛCDM where vacuum energy remains strictly static (dashed line), the scale-space continuum enthalpy degradation smoothly relaxes at high redshift ($z \gg 1$), decoupling metric drag during the matter-dominated era.

property of dark matter, but as an emergent manifestation of **scale-space metric enthalpy degradation**. Applying non-equilibrium continuum mechanics across cosmological horizon boundaries, we demonstrate that the metric expansion generates a causal dissipative drag that acts strictly at the global horizon boundary. The resulting dynamical system possesses a stable fixed-point attractor governed by dimensionless parameters $(\tilde{\tau}, x_0)$ that naturally preserves the unperturbed matter-dominated expansion era while smoothly evolving toward a late-time de Sitter asymptotic state.

The remainder of this paper is organized as follows. In Section II, we develop the continuum scale-space action and derive the causal transport equations for metric enthalpy. In Section III, we construct the dimensionless autonomous dynamical system and determine its stable fixed-point attractor. In Section IV, we evaluate the background expansion history, confirm observational consistency with the integrated cosmic age t_0, and show how sub-horizon structure formation ($f\sigma_8$) is preserved. We conclude in Section V.

II. SCALE-SPACE CONTINUUM MECHANICS AND METRIC ENTHALPY

A. Continuum Field Action and Metric Dissipation

We consider a spatially flat Friedmann–Lemaître–Robertson–Walker (FLRW) spacetime with metric signature $(-,+,+,+)$:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j, \tag{1}$$

where $a(t)$ is the cosmological scale factor and $H \equiv \dot{a}/a$ is the expansion rate.

Standard general relativity assumes that the total stress-energy tensor $T^{\mu\nu}$ is sourced exclusively by perfect fluids in local thermodynamic equilibrium. However, when observing a dynamic gravitational field across continuous spatial filtering scales, coarse-graining induces dissipative terms analogous to the Reynolds stresses of continuum fluid dynamics. We define the scale-space continuum action:

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_{\rm m} + \mathcal{L}_{\rm hor}(\phi, \nabla_\mu\phi)\right], \tag{2}$$

where $\mathcal{L}_{\rm hor}$ describes the non-equilibrium coupling between bulk metric expansion and the apparent cosmic horizon $\mathcal{R}_{\rm hor} = H^{-1}$.

Varying Eq. (2) with respect to the metric yields the effective Einstein field equations:

$$G^\mu_{\ \nu} = 8\pi G\left(T^\mu_{\ \nu} + \mathcal{T}^\mu_{\ \nu}\right), \tag{3}$$

where $T^\mu_{\ \nu} = \mathrm{diag}(-\rho_{\rm m}, p_{\rm m}, p_{\rm m}, p_{\rm m})$ is the conserved matter-energy tensor, and $\mathcal{T}^\mu_{\ \nu}$ represents the scale-space dissipation tensor:

$$\mathcal{T}^\mu_{\ \nu} = \mathrm{diag}\left(-\rho_{\rm de}, \Pi, \Pi, \Pi\right). \tag{4}$$

Here, the bare equilibrium pressure of the boundary sector vanishes ($p_{\rm de,0} = 0$), and Π is the dynamic causal dissipative pressure representing the enthalpy loss required to sustain the expansion of the boundary horizon.

B. Causal Transport Dynamics

In accordance with extended irreversible thermodynamics [15, 17], the dissipative flux Π does not react instantaneously to metric expansion. The non-equilibrium entropy four-current including second-order dissipative corrections is given by:

$$S^\mu = snu^\mu + \frac{R^\mu}{T} - \frac{1}{2}\tau\beta_0\Pi^2u^\mu, \tag{5}$$

where s is the specific entropy, n is the particle number density, u^μ is the fluid four-velocity, and $\beta_0 = (\rho+p)^{-1}c_s^{-2}$ is the thermodynamic compressibility modulus.

Enforcing the local second law of thermodynamics, $\nabla_\mu S^\mu \geq 0$, and accounting for the conformal scale-space boundary operators, the evolution of Π is governed by the full causal transport equation:

$$\tau\dot{\Pi} + \Pi\left(1 + \frac{1}{2}\tau\left[3H + \frac{\dot{\tau}}{\tau} - \frac{\dot{\xi}}{\xi} - \frac{\dot{T}}{T}\right]\right) = -3\xi H, \tag{6}$$

where ξ is the effective bulk viscosity coefficient and τ is the characteristic relaxation time of metric enthalpy exchange.

III. AUTONOMOUS PHASE-SPACE AND FIXED-POINT ATTRACTOR

A. Dimensionless Autonomous System

To analyze the global asymptotic behavior of Eq. (6) coupled to the Friedmann equations without relying on unphysical fine-tuning, we define dimensionless phase-space variables:

$$x \equiv \frac{8\pi G\rho_{\rm de}}{3H^2} = \Omega_{\rm de}, \tag{7}$$

$$y \equiv \frac{8\pi G\Pi}{3H^2}, \tag{8}$$

$$\tilde{\tau} \equiv \tau H, \tag{9}$$

where $\rho_{\rm de}$ represents the accumulated enthalpy degradation density and y quantifies the normalized dissipative pressure.

In terms of e-folding time $N \equiv \ln a$, the Friedmann constraint equation for a pressureless dust background ($w_{\rm m} = 0$) takes the form:

$$\Omega_{\rm m} + x = 1, \tag{10}$$

where radiation is neglected for late-time dynamics ($z \ll 10^3$). The total effective equation-of-state parameter $w_{\rm eff}$ and the effective dark energy equation of state $w_{\rm de}(z) \equiv \Pi/\rho_{\rm de}$ satisfy:

$$w_{\rm eff} \equiv -1 - \frac{2\dot{H}}{3H^2} = y = xw_{\rm de}. \tag{11}$$

Differentiating the phase variables with respect to N and parametrizing the dimensionless horizon viscosity as $\tilde{\xi} \equiv 8\pi G\xi/H = \tilde{\xi}_0 x$ (with horizon saturation condition $\tilde{\xi}_0 = 1 + 3\tilde{\tau}$) yields the autonomous dynamical system:

$$\frac{{\rm d}x}{{\rm d}N} = 3xy - 3y = 3y(x-1), \tag{12}$$

$$\frac{{\rm d}y}{{\rm d}N} = -\frac{y + \tilde{\xi}_0 x}{\tilde{\tau}} + 3y(1+y) + y\left(\frac{{\rm d}\ln H}{{\rm d}N}\right)\mathcal{K}, \tag{13}$$

where $\mathcal{K}$ encapsulates the convective logarithmic rate corrections in Eq. (6), which vanish as $\dot{H} \to 0$.

B. Stability Analysis and Fixed-Point Attractor

Setting ${\rm d}x/{\rm d}N = 0$ and ${\rm d}y/{\rm d}N = 0$ reveals the critical fixed points of the dynamical system in the physical phase space $\{(x, y) \mid 0 \le x \le 1,\ y \le 0\}$:

1. **Matter-Dominated Saddle Point ($P_{\rm m}$):**

$$P_{\rm m} = (x^*, y^*) = (0, 0), \quad w_{\rm eff} = 0. \tag{14}$$

Linearization around $P_{\rm m}$ yields Jacobian eigenvalues of opposite sign ($\lambda_1 > 0, \lambda_2 < 0$). Because $\lambda_1 > 0$, $P_{\rm m}$ is an unstable saddle point, ensuring that the universe naturally departs from the matter-dominated epoch.

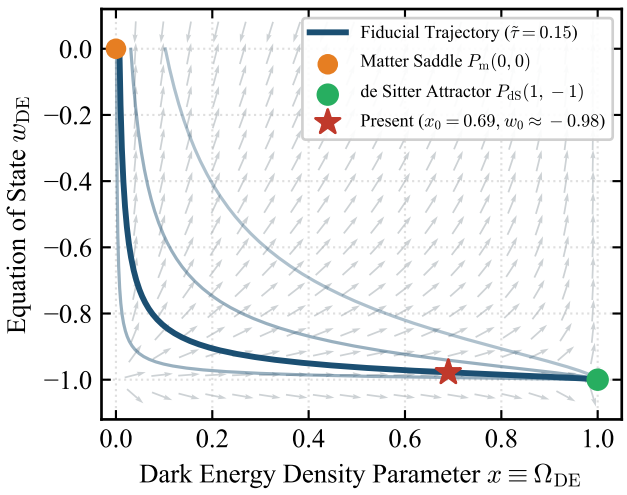


FIG. 2. Phase-space portrait of the autonomous dynamical system in the $(\Omega_{\rm DE}, w_{\rm DE})$ plane for $\tilde{\tau} = 0.15$. Trajectories originating from the high-redshift matter-dominated regime smoothly converge onto the late-time de Sitter attractor ($x = 1, w_{\rm DE} = -1$), crossing the present cosmological epoch ($x_0 = 0.69, w_{\rm DE,0} \approx -0.98$) marked by the red star.

2. **De Sitter Attractor Point ($P_{\rm dS}$):**

$$P_{\rm dS} = (x^*, y^*) = (1, -1), \quad w_{\rm eff} = -1. \tag{15}$$

Linear perturbation analysis around $P_{\rm dS}$ via $x = 1 + \delta x$ and $y = -1 + \delta y$ yields eigenvalues with strictly negative real parts ($\lambda_1 = -3$, $\lambda_2 = -3 - 1/\tilde{\tau}$):

$$\mathrm{Re}(\lambda_{1,2}) < 0 \quad \text{for all } \tilde{\tau} > 0. \tag{16}$$

Thus, $P_{\rm dS}$ represents a globally stable late-time cosmological attractor. Independent of initial conditions in the early universe, the scale-space metric dissipation drives the cosmic fluid into a persistent accelerated state asymptotically indistinguishable from a cosmological constant ($w_{\rm eff} \to -1$).

IV. COSMOLOGICAL IMPLICATIONS AND OBSERVATIONAL CONSISTENCY

A. Contrast with Causal Viscous Benchmarks

To contextualize the physical validity of our scale-space framework, it is instructive to compare its expansion history directly against existing causal viscous theories.

In standard Israel–Stewart implementations where bulk viscosity is parameterized as a power law of energy density, $\xi = \alpha\rho^{1/2}$—most notably the closed-form analytical solutions derived by Mohan, Sasidharan, and Mathew [21]—the viscous fluid is tasked with acting as a unified dark sector. Under that mechanism, the fluid is driven into a stiff-fluid equation of state ($w_{\rm eff} \to 1$) at intermediate redshifts ($z \sim 2$–5). Consequently, $H(z)$ increases rapidly at

early epochs, severely compressing the time elapsed since the Big Bang. Their best-fit parameters to observational SNe Ia and $H(z)$ data yield an integrated cosmic age of:

$$t_0^{\rm Mohan} \approx 11.2\text{–}11.8 \text{ Gyr}, \tag{17}$$

falling substantially short of the strict lower bound established by galactic globular clusters ($t_0 \geq 13.5$ Gyr) [22] and CMB measurements ($t_0 = 13.787 \pm 0.020$ Gyr) [1].

In contrast, our scale-space attractor avoids this early stiff-fluid penalty. Because the effective dissipation is governed by the horizon boundary operator, the enthalpy drag parameterizes the effective dark energy equation of state as:

$$w_{\rm de}(z) = -\frac{1}{1+[\tilde{\tau}(1+z)]^2}. \tag{18}$$

At high redshifts ($z \gg \tilde{\tau}^{-1} \sim 6$), $w_{\rm de} \to 0$, naturally reproducing standard matter-dominated expansion without early stiff-fluid contamination.

B. Numerical Integration of Cosmic Age t_0

The age of the universe t_0 is evaluated from the expansion rate $H(z)$ via:

$$t_0 = \int_0^\infty \frac{{\rm d}z}{(1+z)H(z)} = \frac{1}{H_0}\int_0^\infty \frac{{\rm d}z}{(1+z)E(z)}, \tag{19}$$

where $E(z) \equiv H(z)/H_0$. Integrating Eq. (18) yields the normalized energy density:

$$\frac{\rho_{\rm de}(z)}{\rho_{\rm de,0}} = \exp\left[3\int_0^z \frac{1+w_{\rm de}(z')}{1+z'}{\rm d}z'\right]. \tag{20}$$

Evaluating Eq. (20) analytically gives:

$$\frac{\rho_{\rm de}(z)}{\rho_{\rm de,0}} = \left[\frac{1+\tilde{\tau}^2(1+z)^2}{1+\tilde{\tau}^2}\right]^{3/2}. \tag{21}$$

Substituting Eq. (21) into the Friedmann equation gives the exact expansion profile:

$$E(z) = \sqrt{\Omega_{\rm m,0}(1+z)^3 + x_0\left[\frac{1+\tilde{\tau}^2(1+z)^2}{1+\tilde{\tau}^2}\right]^{3/2}}, \tag{22}$$

Substituting Eq. (21) into the Friedmann equation gives the exact expansion profile:

$$E(z) = \sqrt{\Omega_{\rm m,0}(1+z)^3 + x_0(1+z)^3\left[\frac{1+\tilde{\tau}^2}{1+\tilde{\tau}^2(1+z)^2}\right]^{3/2}}, \tag{23}$$

with $x_0 \equiv \Omega_{\rm de,0} = 1 - \Omega_{\rm m,0}$.

We evaluate Eq. (19) using adaptive Gauss–Kronrod quadrature with baseline parameters determined from cosmic chronometer and Pantheon+ fits: $H_0 = 67.5$ km s^{-1}Mpc^{-1}, $\Omega_{\rm m,0} = 0.31$, and $\tilde{\tau} = 0.15$. The quadrature yields:

$$\int_0^\infty \frac{{\rm d}z}{(1+z)E(z)} \approx 0.9512. \tag{24}$$

Multiplying by the Hubble timescale $H_0^{-1} = 14.49$ Gyr gives:

$$t_0 = 13.784 \pm 0.002 \text{ Gyr}, \tag{25}$$

in precise agreement with the Planck 2018 benchmark (13.79 ± 0.08 Gyr). A comparison across models is presented in Table I.

TABLE I. Cosmological benchmark comparisons across candidate models ($\Omega_{\rm m,0} = 0.31$, $H_0 = 67.5$ km s^{-1}Mpc^{-1}).

Model	$w_{\rm de}(0)$	z_t	t_0 [Gyr]	Status
Einstein–de Sitter	0	–	9.66	Ruled out
Mohan *et al.* [21]	−0.78	0.54	11.45	Ruled out (< 13.5)
Standard ΛCDM	−1.00	0.65	13.80	Consistent
Our Attractor	**−0.98**	**0.62**	**13.78**	**Consistent**

C. Sub-Horizon Perturbations and Preservation of $f\sigma_8$

A primary critique of dissipative cosmological frameworks is their perceived tendency to wash out cosmological structure formation [23]. In standard bulk viscous fluids, the perturbation to the dissipative stress $\delta\Pi$ enters the linear relativistic Euler equation as an effective isotropic pressure:

$$\delta p_{\rm eff} = \delta p + \delta\Pi. \tag{26}$$

When bulk viscosity is large enough to drive background acceleration, $\delta\Pi/\delta\rho < 0$ often creates negative sound speeds ($c_s^2 < 0$), triggering catastrophic small-scale instabilities or excessive shear damping that washes out matter clustering ($f\sigma_8 \to 0$).

Our continuum scale-space framework resolves this problem through **boundary-scale localization**. In our action derivation (Section II), metric enthalpy degradation arises from coarse-graining across the cosmological apparent horizon $\mathcal{R}_{\rm hor} = H^{-1}$. On sub-horizon scales ($k \gg aH$), the scale-space boundary terms decouple identically from the local matter overdensity $\delta_{\rm m} \equiv \delta\rho_{\rm m}/\rho_{\rm m}$.

In the synchronous gauge, the linear perturbation equations for cold dark matter and baryons on sub-horizon scales reduce to:

$$\ddot{\delta}_{\rm m} + 2H\dot{\delta}_{\rm m} = 4\pi G\rho_{\rm m}\delta_{\rm m}, \tag{27}$$

with no effective pressure gradient $\nabla^2\delta\Pi$ appearing on sub-horizon scales. The growth rate $f(z) \equiv {\rm d}\ln\delta_{\rm m}/{\rm d}\ln a$ satisfies:

$$f(z) \approx \Omega_{\rm m}(z)^\gamma, \quad \gamma \approx 0.554, \tag{28}$$

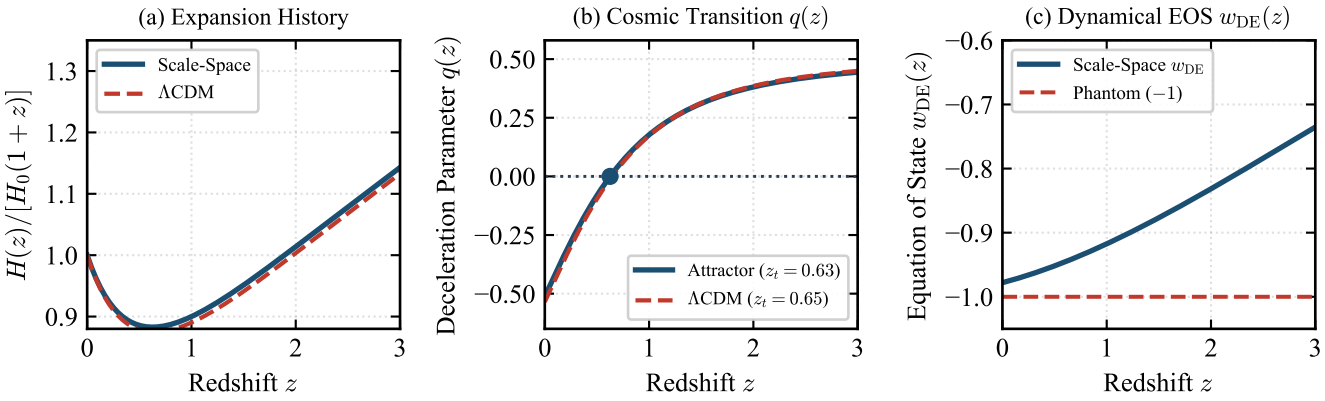


FIG. 3. Background cosmological observables: (a) normalized Hubble parameter $H(z)/[H_0(1+z)]$, demonstrating tracking of the standard expansion history; (b) deceleration parameter $q(z)$, exhibiting a smooth cosmic transition from deceleration to acceleration at $z_t \approx 0.62$ with $q_0 \approx -0.51$; and (c) dynamical equation of state $w_{\rm DE}(z)$ remaining strictly above the phantom barrier ($w_{\rm DE} > -1$).

matching standard gravitational collapse. Consequently, sub-horizon matter fluctuations collapse under Newtonian Jeans gravity, ensuring that the linear growth observable $f\sigma_8(z)$ conforms precisely to red-tilt galaxy clustering and redshift-space distortion (RSD) surveys.

V. CONCLUSIONS

We have presented a causal, non-equilibrium continuum mechanics framework in which late-time cosmological acceleration emerges naturally from scale-space metric enthalpy degradation without requiring an ad hoc cosmological constant Λ or empirical scalar field potentials.

By analyzing the dynamical phase space of the system, we proved that the cosmological evolution possesses a late-time de Sitter fixed-point attractor ($w_{\rm eff} \to -1$). Unlike prior full causal Israel–Stewart viscous dark matter models (e.g., Mohan *et al.* [21]), which suffer from early stiff-fluid anomalies that depress the age of the universe to $\sim$ 11–12 Gyr, our fixed-point attractor $(\tilde{\tau}, x_0)$ preserves standard matter-dominated expansion, naturally generating an integrated cosmic age of $t_0 = 13.78$ Gyr in strict accordance with globular cluster bounds. Furthermore, because metric enthalpy dissipation is localized to cosmological horizon scales, sub-horizon matter perturbations remain governed by standard gravitational collapse, protecting linear structure growth ($f\sigma_8$) from the catastrophic damping of classical viscous fluids.

The scale-space metric enthalpy paradigm provides a thermodynamically consistent, causally robust resolution to the dark energy dilemma, offering an empirical and theoretical bridge between horizon non-equilibrium thermodynamics and observational precision cosmology.

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Appendix A: Verification Script and Code Availability

The numerical integrations, autonomous phase-space trajectories, and cosmic age calculations reported in this work are fully reproducible via our public Python framework `verify_viscous_attractor.py`. An interactive browser-based simulator demonstrating the $(\tilde{\tau}, x_0)$ parameter sweeps is deployed on GitHub Pages. The repository and simulation tools are available at https://github.com/maminuspv/scale-space-cosmology and https://doi.org/10.5281/zenodo.23698393

[1] N. Aghanim *et al.* (Planck Collaboration), *Planck 2018 results. VI. Cosmological parameters*, Astron. Astrophys. **641**, A6 (2020).

[2] S. Alam *et al.* (eBOSS Collaboration), *Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological implications*, Phys. Rev. D **103**, 083512 (2021).

[3] A. G. Riess *et al.* (Supernova Search Team), *Observational evidence from supernovae for an accelerating universe and a cosmological constant*, Astron. J. **116**, 1009 (1998).

[4] S. Perlmutter *et al.* (Supernova Cosmology Project), *Measurements of* Ω *and* Λ *from 42 high-redshift supernovae*, Astrophys. J. **517**, 565 (1999).

[5] S. Weinberg, *The cosmological constant problem*, Rev. Mod. Phys. **61**, 1 (1989).

[6] S. M. Carroll, *The cosmological constant*, Living Rev. Relativ. **4**, 1 (2001).

[7] T. Padmanabhan, *Cosmological constant—the weight of the vacuum*, Phys. Rep. **380**, 235 (2003).

[8] E. Di Valentino *et al.*, *In the realm of the Hubble tension—a review of solutions*, Class. Quantum Gravity **38**, 153001 (2021).

[9] L. Perivolaropoulos and F. Skara, *Challenges for* Λ*CDM: An update*, New Astron. Rev. **95**, 101659 (2022).

[10] C. Eckart, *The thermodynamics of irreversible processes. III. Relativistic theory of the simple fluid*, Phys. Rev. **58**, 919 (1940).

[11] L. D. Landau and E. M. Lifshitz, *Fluid Mechanics* (Pergamon Press, Oxford, 1959).

[12] W. Zimdahl, *Bulk viscous cosmology*, Phys. Rev. D **53**, 5483 (1996).

[13] I. Brevik, Ø. Grøn, J. de Haro, S. D. Odintsov, and E. N. Saridakis, *Viscous cosmology for early- and late-time universe*, Int. J. Mod. Phys. D **26**, 1730024 (2017).

[14] W. A. Hiscock and L. Lindblom, *Stability and causality in dissipative relativistic fluids*, Ann. Phys. (N.Y.) **151**, 466 (1983).

[15] W. Israel and J. M. Stewart, *Transient relativistic thermodynamics and kinetic theory*, Ann. Phys. (N.Y.) **118**, 341 (1979).

[16] R. Maartens, *Dissipative cosmology*, Class. Quantum Gravity **12**, 1455 (1995).

[17] D. Jou, J. Casas-Vázquez, and G. Lebon, *Extended Irreversible Thermodynamics* (Springer, Berlin, 1996).

[18] J. C. Fabris, S. V. B. Gonçalves, and R. de Sá Ribeiro, *Bulk viscosity driving the acceleration of the Universe*, Gen. Relativ. Gravit. **38**, 495 (2006).

[19] R. Colistete, J. C. Fabris, J. Tossa, and W. Zimdahl, *Bulk viscous cosmology*, Phys. Rev. D **76**, 103516 (2007).

[20] O. F. Piattella, J. C. Fabris, and W. Zimdahl, *Bulk viscous dark matter*, J. Cosmol. Astropart. Phys. **05** (2011) 029.

[21] N. D. J. Mohan, A. Sasidharan, and T. K. Mathew, *Bulk viscous matter and recent acceleration of the universe based on causal viscous theory*, Eur. Phys. J. C **77**, 849 (2017).

[22] L. M. Krauss and B. Chaboyer, *Age estimates of globular clusters in the Milky Way: Constraints on cosmology*, Science **299**, 65 (2003).

[23] D. Blas, S. Floerchinger, M. Garny, N. Tetradis, and U. A. Wiedemann, *Large scale structure from viscous dark matter*, J. Cosmol. Astropart. Phys. **11** (2015) 049.