Cosmological Dissipative Residual

Eduardo Rodolfo Borrego Moreno

January 2026

Abstract

We propose an effective cosmological framework in which dark energy is interpreted as an emergent dissipative contribution—denoted as the Cosmological Dissipative Residual (CDR)—associated with bulk viscosity in the late-time Universe. Without modifying General Relativity, early-Universe physics, or the CMB acoustic horizon, we introduce a single dissipative parameter, $\Gamma(t)$, acting as a damping term in the continuity equation of cold matter. This mechanism alters the late-time evolution of the Hubble parameter $\mathrm{H}(z)$ and the growth of cosmic structures, naturally producing (i) an effective discrepancy between locally inferred and CMB-extrapolated values of H_0, and (ii) a suppression of structure growth consistent with the observed σ_8 tension. The model remains compatible with BAO and weak-lensing observations and yields falsifiable predictions without invoking new microphysics, exotic scalar fields, or modifications of gravity.

Keywords: Cosmology, Dissipative Cosmology, Hubble tension, Bulk Viscosity, Dark Energy.

Introduction

The standard cosmological model, ΛCDM, has achieved remarkable success across a wide range of cosmological observations. Nevertheless, in recent years statistically significant discrepancies have emerged between independent probes, most notably the Hubble tension—the mismatch between the value of H_0 inferred from the cosmic microwave background (CMB) and that measured locally [1,2,3]—and the σ_8 tension [4], involving the amplitude of matter clustering inferred from CMB versus weak-lensing surveys.Many proposed resolutions invoke early-Universe new physics, modified gravity, exotic dark-energy components, or additional degrees of freedom [10]. However, such extensions often introduce new tensions with CMB observables, modify the sound horizon r_s, or require fine-tuned model-building [10]. In this work, we explore a conceptually minimal alternative: that the observed late-time cosmic acceleration arises from an effective dissipative process operating only at low redshift. Adopting a phenomenological relativistic hydrodynamic approach, we model cosmic matter as an almost perfect fluid with a small bulk-viscous contribution. This term induces an effective negative pressure and a microscopic damping of structure growth, without introducing new forces or violating large-scale homogeneity and isotropy[15]. The key ingredient is a dissipative rate $\Gamma(t)$, quantifying the irreversible transfer of energy from cold matter into a homogeneous residual sector. In the redshift range relevant for late-time observations z less or similar to 1, we show that a controlled choice of Γ naturally modifies H(z) and suppresses structure growth. This Cosmological Residual Theory is explicitly an effective theory: it does not attempt to describe the underlying microphysics of dissipation, but rather captures its macroscopic, observable consequences in a manner consistent with General Relativity and thermodynamics. Importantly, the Residual does not act as an additional Newtonian gravitating mass, but as a dissipative term inducing dynamical damping [7]. The paper is organized as follows. Section 2 introduces the dissipative formalism and its incorporation into standard cosmological equations. Section 3 derives the modified expansion history and its implications for the Hubble tension. Section 4 addresses structure growth, weak lensing, and BAO compatibility. Section 5 summarizes falsifiable predictions and observational tests. Section 6 a Discussion comparing this model with ΛCDM. Section 7 a Conclusion on this Cosmological Dissipative Residual model.

Effective Dissipative Formalism

Motivation

In modern cosmology, the Universe is described effectively by relativistic fluids[5,11,14] coupled to spacetime geometry via Einstein's equations. This approach does not require detailed microphysics, provided energy–momentum conservation is preserved. Here we propose that dark energy may be modeled as an effective dissipative phenomenon [7] associated with the matter sector, without introducing new interactions or modifying gravity. Specifically, we explore the possibility that cosmic expansion induces an irreversible macroscopic energy transfer from matter into a homogeneous residual component, manifesting dynamically as negative pressure. This framework lies squarely within relativistic non-equilibrium hydrodynamics.

Energy–Momentum Tensor with Dissipation

For a perfect fluid, the energy–momentum tensor is
$T^{\mu\nu}_{\text{perf}} = (\rho + p)u^\mu u^\nu + p\, g^{\mu\nu}$

In a homogeneous and isotropic universe described by the Friedmann-Lemaître-Robertson-Walker (FLRW) metric [26,27,28,29]. Within this geometric background, the dynamics of the expansion are governed by the Friedmann equations[26], which we modify by introducing a dissipative term Γ [5,11] in the stress-energy conservation of the dark sector[9], the only admissible dissipative correction is a bulk pressure Π, yielding

$T^{\mu\nu} = (\rho + p + \Pi)u^\mu u^\nu + (p + \Pi)g^{\mu\nu}$

This term represents macroscopic irreversibility during expansion rather than thermal pressure or new microscopic interactions.

Bulk Pressure in Cosmology

The bulk pressure is parametrized in standard form as

$\Pi = -3\zeta H$

where $H = \dot{a}/a$ and ζ is the bulk-viscosity coefficient[13]. The negative sign implies an effective negative pressure during expansion.

Identification of the Cosmological Residual

We identify the Cosmological Residual as the macroscopic consequence of this dissipative process. Instead of introducing an independent dark-energy fluid, we associate the bulk pressure directly with cold matter:

$\Pi \equiv -\Gamma(t)\rho_m$

where $\Gamma(t)$ is an effective dissipation rate (dimension of inverse time). This parametrization allows dark energy to emerge dynamically, without introducing new fundamental degrees of freedom.

Energy Exchange and Conservation

Cold matter no longer evolves as a closed system, but continuously transfers energy into a residual sector χ. Its continuity equation becomes

$\dot{\rho}_m + 3H\rho_m = -\Gamma\rho_m$

Energy conservation requires that this loss be balanced by the Residual:

$\dot{\rho}_\chi + 3H(\rho_\chi + p_\chi) = +\Gamma\rho_m$

Summing both sectors ensures strict conservation:

$\nabla_\mu T^{\mu\nu}_{\text{tot}} = 0$

Thus, the framework preserves covariant energy–momentum conservation while allowing irreversible internal energy transfer.

Effective Energy–Momentum Tensor and Phenomenological Dissipation

We model the cosmological Residual as an effective late-time dissipative process within relativistic non-equilibrium hydrodynamics. At the macroscopic level, the cosmic medium is treated as a non-ideal relativistic fluid whose energy–momentum tensor takes the form

$\mathrm{T}^{\mu\nu} = \rho \mathrm{u}_\mu \mathrm{u}_\nu + (p + \Pi)\Delta_{\mu\nu}$

where u_μ is the four-velocity of the commoving flow and

$\Delta_{\mu\nu} = \mathrm{g}_{\mu\nu} + \mathrm{u}_\mu \mathrm{u}_\nu$

is the spatial projection tensor orthogonal to u^{μ}. The scalar quantity Π represents the bulk viscous pressure, which is the only dissipative correction compatible with homogeneity and isotropy in an FLRW spacetime[7,14].

Within the phenomenological Eckart framework [5], the effective pressure of the fluid can be written as

$P_{\rm eff} = p_{\rm term} + \Pi = -3H\zeta$

where ζ is the bulk viscosity coefficient. In the Cosmological Dissipative Residual model, we identify this viscous pressure with an effective dissipation rate associated with the cold matter sector,

$\Pi \equiv -\Gamma(t)\rho_{\rm m}$

In this effective description, the bulk-viscous pressure can equivalently be parametrized in terms of a dissipation rate Γ acting on the matter density.

To close the system, we adopt a minimal phenomenological parametrization for the dissipation rate,

$\Gamma(t) = \xi H(t)$

where ξ is a dimensionless coupling constant. This choice ensures that dissipative effects track the cosmic expansion rate, remain negligible in the early Universe, and become dynamically relevant only at late times. The resulting irreversible energy transfer from cold matter into a homogeneous residual component generates an effective negative pressure that accelerates the expansion while preserving the standard Friedmann structure and leaving early-Universe physics unaffected.

This formulation should be understood as a macroscopic effective theory, valid in the homogeneous cosmological regime. It does not aim to specify the underlying microphysics of dissipation, but rather to capture its observable consequences in a covariant and internally consistent manner without modifying Einstein's equations or introducing new fundamental degrees of freedom.

Consistency

- Preserves energy-momentum conservation.
- Leaves Einstein's equations unchanged.
- Introduces no new microphysics.
- Does not alter early-Universe dynamics.
- Yields clear observationally falsifiable predictions.

Cosmological Dynamics

Friedmann Equation with Effective Dissipation

For a flat FLRW universe [26,27],

$H^2(z) = \frac{8\pi G}{3}\rho_{\rm tot}(z)$

with

$\rho_{\text{tot}} = \rho_m + \rho_r + \rho_\chi$

Unlike a cosmological constant, the Residual density ρ_χ evolves dynamically due to its coupling with the matter sector[9,18,19,20], while preserving the standard Friedmann structure.

Physical Interpretation of the Residual Sector

Matter dilutes faster than in ΛCDM due to dissipation[7], while the Residual accumulates and generates effective negative pressure. Cosmic acceleration thus emerges from irreversible energy transfer rather than vacuum energy. The Residual acts as a macroscopic entropic reservoir, encoding the integrated dissipation history of matter.

Modified Matter Evolution

Transforming the continuity equation to redshift space yields

$\frac{d\ln\rho_m}{dz} = \frac{3}{1+z} + \frac{\Gamma(z)}{H(z)(1+z)}$

Solution for $\rho_m(z)$

Integrating,

$\rho_m(z) = \rho_{m0}(1+z)^3 \exp\left[\int_0^z \frac{\Gamma(z')}{H(z')(1+z')}dz'\right]$

Low-Redshift Approximation

For z less or similar to 1

$\rho_m(z) \approx \rho_{m0}(1+z)^{3+\epsilon}, \quad \epsilon \equiv \Gamma/H_0$

Resolution of the Hubble Tension

Standard CMB inference assumes a background scaling of $\rho_m \propto (1+z)^3$. If the true evolution is steeper due to dissipation, the inferred H_0 is biased low. In terms of the dimensionless coupling, a value of $\xi \simeq 0.15 - 0.2$ yields a fractional dissipation rate $\epsilon \equiv \Gamma/H_0 \simeq \xi$, resulting in a shift of $\Delta H_0/H_0 \simeq 5 - 10\%$. This magnitude allows for a natural correction of the CMB inferred value (67.4 km/s/Mpc) towards the local measurement (73.04 km/s/Mpc) [10], matching observations [12,15,17] without requiring fine-tuning of dimensionful parameters.

Observational Compatibility

BAO

The sound horizon remains unchanged:

$r_s^{\text{Residual}} \simeq r_s^{\Lambda\text{CDM}}$

Late-time BAO observables receive only percent-level corrections, consistent with BOSS/eBOSS [21].

Weak Lensing and σ_8

Growth equation:

$\ddot{\delta} + (2H + \Gamma)\dot{\delta} - 4\pi G\rho_m\delta = 0$

The damping term suppresses growth at low redshift: $\sigma_8^{\text{Residual}} \simeq (0.90 - 0.93)\sigma_8^{\Lambda\text{CDM}}$ naturally resolving the σ_8 tension[14,16].

Falsifiable Predictions

- Suppressed growth only at z less or similar to 1
- No modification of r_s or early CMB
- No scale-dependent effects
- $w_{\text{eff}}(z)$ less or similar to -1 without ghosts
- Clear exclusion if growth exceeds ΛCDM at low z [22]

Table 1: Predictions

Observable	Prediction	Test
H_0	↑	SN Ia[25], SH0ES
σ_8	↓	Weak Lensing, RSD
BAO	Preserved	DESI
Early CMB	Unaltered	Planck
$f\sigma_8(z)$	↓ on lower Z	Euclid
Scale dependence	Absent	$P_(k)$

This table summarizes the main testable predictions of the Cosmological dissipative residual model.

Discussion: Comparison with the ΛCDM Paradigm

The standard ΛCDM [20,22] model has been remarkably successful in describing a wide range of cosmological observations with a minimal set of parameters. In this framework, cosmic acceleration is attributed to a cosmological constant Λ, interpreted as a fundamental, time-independent property of the vacuum. While phenomenologically effective, this interpretation remains conceptually unsatisfactory, as Λ lacks a known physical origin and does not participate dynamically in the evolution of cosmic structures. The Cosmological Dissipative Residual

(CDR) framework proposed in this work offers a conceptually distinct interpretation. Rather than introducing a fundamental constant or modifying the gravitational sector, late-time acceleration emerges as the macroscopic consequence of an irreversible dissipative process acting on the cold matter component. In this sense, ΛCDM and the CDR model differ not primarily at the level of the background equations, but at the level of physical interpretation and dynamical coupling.

Expansion History

At the level of background expansion, ΛCDM assumes a strictly constant dark energy density, leading to an expansion history fully determined by the parameters $(\mathrm{H}_0, \Omega_m, \Omega_\Lambda)$ In contrast, the CDR model predicts an effective dark energy component that evolves dynamically through the accumulation of residual energy sourced by matter dissipation. Importantly, this evolution remains negligible at high redshift, ensuring full consistency with CMB, BBN, and early-Universe constraints. As a result, deviations from ΛCDM appear only at low redshift, where the cumulative effect of dissipation becomes significant. This naturally leads to a reinterpretation of local measurements of H_0, providing a smooth, redshift-dependent correction rather than a discrete mismatch between early and late probes.

Growth of Structure

A key distinction between the two frameworks arises in the growth of cosmic structures[24]. In ΛCDM, the same dark energy component responsible for accelerating expansion also indirectly suppresses structure growth through the background dynamics, but without introducing any direct damping mechanism in the perturbation equations. In the CDR framework, the dissipative coupling introduces an explicit friction term in the growth equation for matter perturbations. This term acts only at late times and leads to a mild but cumulative suppression of structure growth. Consequently, the model predicts lower values of σ_8 relative to ΛCDM, in agreement with weak-lensing observations, without altering the primordial power spectrum or early-Universe physics. This decoupling between expansion acceleration and clustering suppression is difficult to achieve within standard ΛCDM extensions and represents one of the most distinctive phenomenological signatures of the dissipative residual approach.

Conceptual Economy and Theoretical Consistency

From a theoretical standpoint, the CDR model preserves the full structure of General Relativity and does not introduce new fundamental fields or degrees of freedom. The dissipative term is formulated within the well-established framework of relativistic non-equilibrium hydrodynamics, rendering the model covariant and internally consistent. While ΛCDM remains an excellent effective description, its reliance on a strictly constant vacuum energy places it in tension with recent observational hints of evolving dark energy. In contrast, the CDR framework naturally accommodates mild deviations from a cosmological constant behavior without invoking fine-tuning or additional sectors.

Limitations and Scope

It is important to emphasize that the present work does not attempt to provide a microscopic derivation of the dissipative process. The CDR model is explicitly constructed as an effective late-time theory, valid at cosmological scales and redshifts where non-equilibrium effects may become relevant. A deeper microphysical interpretation is left for future work. Nevertheless, the phenomenological success of the model in addressing multiple late-time tensions with a single additional parameter suggests that dissipative effects may play a non-negligible role in the cosmic energy budget.

While models like PEDE or GOHDE require phantom equations of state ($w < -1$)[10], our model achieves similar background dynamics through effective viscosity ζ, keeping the fluid physically stable.

Final Assessment

- Resolves both H_0 and σ_8 tensions,
- Uses one parameter,
- Preserves GR and early cosmology,
- Avoids fine-tuning,
- Is cleanly falsifiable.

Conclusions

In this work, we have developed an effective cosmological framework in which dark energy is interpreted as the macroscopic manifestation of a late-time dissipative process, which we refer to as the cosmological Residual. The model is formulated entirely within standard General Relativity and relativistic hydrodynamics, without introducing additional fundamental fields, without modifying gravity, and without altering the well-established physics of the early Universe. The central ingredient of the formalism is an effective dissipation rate, $\Gamma(z)$, acting as a microscopic damping term on the cold matter sector. This term describes an irreversible transfer of energy from matter into a homogeneous cosmological reservoir characterized by an effective negative pressure. The cumulative build-up of this Residual naturally drives late-time accelerated expansion, without requiring a fundamental cosmological constant. From a formal perspective, the model:

- Strictly preserves the covariant conservation of the total energy–momentum tensor.
- Leaves Einstein's equations and the standard Friedmann structure unchanged.
- Remains fully embedded within the established framework of relativistic bulk-viscous fluids.
- Introduces only a single additional phenomenological parameter, Γ, governing the accumulated dissipative effects.

We have shown that dissipation induces a mild modification to the late-time evolution of the matter density,

$\rho_m \propto (1+z)^{3+\epsilon}$

leading to a systematic reinterpretation of the Hubble parameter inferred at low redshift. This effect provides a natural explanation for the observed Hubble tension, yielding a relative correction of order $\sim 9\%$, while leaving the sound horizon and the early-Universe energy content unchanged.

Independently, the same dissipative mechanism introduces an effective cosmological friction in the linear growth equation for matter perturbations, suppressing structure formation at low redshift. As a direct consequence, the model predicts a reduced value of σ_8 relative to ΛCMD, in agreement with weak-lensing measurements. Notably, both the H_0 and σ_8 tensions are addressed simultaneously within a single, unified framework.

A particularly robust outcome of the model is the natural decoupling between expansion and clustering: late-time cosmic expansion accelerates while the growth of structure is suppressed. This combination constitutes a distinctive observational signature that is difficult to reproduce in standard dynamical dark energy models or modified gravity scenarios.

Compatibility with current observations is preserved across multiple probes: the acoustic sound horizon r_s remains unchanged,

- Baryon acoustic oscillation measurements are satisfied within current uncertainties,
- Weak-lensing amplitudes are coherently reduced without inducing scale-dependent distortions,
- Early-time CMB physics remains fully intact.

Finally, the model yields a set of clear and falsifiable predictions, including a redshift-dependent suppression of growth quantified through $\mathrm{f}\sigma_8$, an effective equation of state $\mathrm{w}_{\mathrm{eff}}$ less or similar to -1 without ghost instabilities, and the absence of scale-dependent modifications. These signatures can be decisively tested by forthcoming surveys such as DESI, Euclid[23], and the Roman Space Telescope.

Taken together, the cosmological Residual framework offers a minimal and physically consistent reinterpretation of dark energy as an emergent dissipative phenomenon. While it does not aim to specify the underlying microphysics of dissipation, it provides a robust, predictive, and falsifiable effective description that unifies several current observational anomalies. As such, it motivates further theoretical development and dedicated observational tests to assess its viability as an alternative to the standard cosmological paradigm.

---

1. Planck Collaboration et al., "Planck 2018 results. VI. Cosmological parameters," A and A 641, A6 (2020).

2.A. G. Riess et al., "A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km/s/Mpc Uncertainty from the Hubble Space Telescope and the SH0ES Team," Astrophys. J. Lett. 934, L7 (2022).

3. E. Di Valentino, O. Mena, S. Pan, L. Visinelli, W. Yang, A. Melchiorri, D. F. Mota, A. G. Riess, and J. Silk, "In the realm of the Hubble tension—a review of solutions," Class. Quant. Grav. 38, 153001 (2021).

4. C. Heymans et al., "KiDS-1000 Cosmology: Multi-probe weak gravitational lensing and spectroscopic galaxy clustering constraints," A and A 646, A140 (2021).

5. C. Eckart, "The Thermodynamics of Irreversible Processes. III. Relativistic Theory of the Simple Fluid," Phys. Rev. 58, 919 (1940).

6. G. L. Murphy, "Big-Bang Model Without Singularities," Phys. Rev. D 8, 4231 (1973).

7. R. Maartens, "Dissipative cosmology," Class. Quant. Grav. 12, 1455 (1995).

8. 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).

9. B. Wang, E. Abdalla, F. Atrio-Barandela, and D. Pavón, "Dark Matter and Dark Energy Interactions: Theoretical Challenges, Cosmological Implications and Observational Signatures," Phys. Rept. 1020, 1 (2024).

10. M. T. Manoharan, "What solves the Hubble tension in phenomenological dark energy models at background level?," arXiv:2505.24743 (2025).

11. S. Weinberg, "Entropy Generation and the Survival of Protogalaxies," Astrophys. J. 168, 175 (1971).

12. W. Israel and J. M. Stewart, "Transient relativistic thermodynamics and kinetic theory," Ann. Phys. (N.Y.) 118, 341 (1979).

13. D. Pavón, J. Casas-Vázquez, and G. Jou, "Early cosmology and the bulk viscosity," Phys. Rev. D 43, 1058 (1991).

14. W. Zimdahl, "Bulk viscous cosmology," Phys. Rev. D 53, 5483 (1996).

15. E. Mörtsell and S. Dhawan, "Does the Hubble constant tension call for new physics?," JCAP 09, 025 (2018).

16. M. Asgari et al. (KiDS Collaboration), "KiDS-1000 cosmology: Cosmic shear constraints and comparison between surveys," A and A 646, A140 (2021).

17. K. Jedamzik, L. Pogosian, and G. B. Zhao, "Why missing dark matter could explain the Hubble constant tension," Commun. Phys. 4, 123 (2021).

18. V. Salvatelli et al., "Indications of a Late-Time Interaction in the Dark Sector," Phys. Rev. Lett. 113, 181301 (2014).
19. S. Kumar and R. C. Nunes, "Echo of interactions in the dark sector," Phys. Rev. D 96, 103511 (2017).
20. E. Di Valentino, A. Melchiorri, O. Mena, and S. Vagnozzi, "Interacting dark energy in the early 2020s: A viable alternative to ΛCMD?," Phys. Dark Univ. 30, 100666 (2020).
21. S. Alam et al., "Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological implications," Phys. Rev. D 103, 083533 (2021).
22. L. Perivolaropoulos and F. Skara, "Challenges for ΛCMD: An update," New Astron. Rev. 95, 101659 (2022).
23. L. Amendola et al., "Cosmology and fundamental physics with the Euclid satellite," Living Rev. Relativ. 21, 2 (2018).
24. J. D. Barrow, "The Deflationary Universe: An Essay on Games and Cosmic Structure," Nucl. Phys. B 310, 743 (1988).
25. S. Capozziello, R. D'Agostino, and O. Luongo, "The extended Hubble diagram of Type Ia supernovae," Mon. Not. R. Astron. Soc. 490, 3165 (2019).
26. Friedmann, A. (1922). "Über die Krümmung des Raumes". Zeitschrift für Physik. 10 (1): 377–386.
27. Lemaître, G. (1927). "Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extragalactiques". Annales de la Société Scientifique de Bruxelles. A47: 49–59.
28. Robertson, H. P. (1935). "Kinematics and World-Structure". Astrophysical Journal. 82: 284.
29. Walker, A. G. (1937). "On Milne's Theory of World-Structure". Proceedings of the London Mathematical Society. 42 (1): 90–127.