Cosmological Dissipative Residual: Cosmic Production, Distribution and Function

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Abstract

We propose that the Cosmological Dissipative Residual (CDR), previously introduced as a late-time dissipative mechanism resolving the H_0 and S_8 tensions, originates from continuous production and accumulation driven by high-energy cosmic events. Beginning with the primordial Big Bang as an initial entropy burst, the residual is further generated throughout cosmic history by stellar formation, core-collapse supernovae, AGN jets, and black hole mergers. The production rate $\beta_{\rm prod}(z)$ peaks near cosmic noon ($z \sim 2$), and numerical integration calibrated to SFRD and jet/merger observations yields a cumulative contribution of $\sim 30\%$ to the observed dark energy density. The residual evolves according to $\dot{\rho}_{\rm res} + 3H(1 + w_{\rm res})\rho_{\rm res} = \Gamma(t)\rho_m + \beta_{\rm prod}(t)$, with $w_{\rm res} \gtrsim -1$ naturally emerging from the balance between production and dissipation, yielding $w_{\rm res}(z = 1) \approx -0.92 \pm 0.03$ consistent with DESI 2024 BAO hints ($w_0 \approx -0.9$). Rapid homogenization via relativistic sound speed ensures uniformity, while localized anisotropic stresses account for gravitational effects in clusters and galaxies. The residual functions as an adaptive regulator through negative feedback, suppressing late-time growth to $\sigma_8^{\rm CDR} \approx 0.76$–$0.80$. This framework unifies the origin, distribution, and role of dark energy as emergent from the universe's energetic history, with falsifiable predictions for $w(z)$ evolution and subtle event-density correlations testable with DESI, Euclid, and ngEHT.

Keywords: Cosmological dissipative residual, dark energy production, cosmic feedback, adaptive expansion, Hubble tension, S_8 tension

Introduction

Despite the remarkable empirical success of the standard cosmological model Planck Collaboration (2020), persistent tensions in the Hubble constant (H_0) and the amplitude of matter fluctuations (S_8) suggest that new physics or a more nuanced understanding of dark energy may be required Riess et al. (2022); Di Valentino et al. (2021); Abbott et al. (2022); Amon et al.

(2022). The Cosmological Dissipative Residual (CDR) framework, introduced in prior works Borrego (2026a,b,c), offers a minimal phenomenological approach to these tensions through late-time dissipation without modifying general relativity or early-universe physics.

In Paper I, a dissipative term $\Gamma(t)$ acting exclusively at low redshift ($z \lesssim 1$) was shown to modify the continuity equation of cold dark matter, leading to a steeper dilution $\rho_m(z) \propto (1+z)^{3+\epsilon}$ with $\epsilon = \Gamma/H \approx 0.15$–$0.20$. This resolves the H_0 tension by making CMB-inferred values systematically low while preserving the sound horizon, and the S_8 tension by introducing friction in the growth equation, suppressing late-time structure formation.

Paper II extended the framework to galactic scales, demonstrating that the same residual medium exhibits a shear-thinning (pseudoplastic) rheological response in high-stress environments, producing anisotropic stresses that mimic emergent dark matter phenomenology (flat rotation curves, baryonic Tully–Fisher relation) without collisionless particles. Paper III applied the model to the strong-field regime near rotating black holes, showing that activated anisotropic stress contributes to gravitational lensing offsets (as observed in merging clusters) and that stress saturation near the horizon triggers a phenomenological conversion to relativistic outflows, reproducing jet energetics in low-accretion systems such as M87* while predicting distinguishable polarization signatures.

The present work builds on this sequence by proposing a physical origin for the residual itself. Rather than treating $\Gamma(t)$ and the associated dissipation as purely phenomenological parameters, we explore the hypothesis that the cosmological dissipative residual is continuously produced and accumulated from high-energy cosmic events — beginning with the primordial Big Bang as an initial entropy burst and continuing through stellar formation, core-collapse supernovae, AGN jets, and black hole mergers. This production mechanism provides a dynamical source for the residual, which then distributes uniformly via dissipative processes and functions as an adaptive regulator of cosmic expansion and structure growth. The following sections develop this picture quantitatively, deriving approximate production rates in both the early and late universe and examining consistency with current observational constraints on dark energy evolution.

Summary of the Cosmological Dissipative Residual Framework

The Cosmological Dissipative Residual (CDR) model, introduced in prior work Borrego (2026a), provides a minimal phenomenological description of late-time cosmic acceleration and associated tensions within the standard ΛCDM paradigm, without invoking new fundamental fields, modified gravity, or alterations to early-universe physics. The central ingredient is an effective dissipative term $\Gamma(t)$ that acts exclusively at low redshift ($z \lesssim 1$) and modifies the continuity equation of cold dark matter:

$$\dot{\rho}_m + 3H\rho_m = -\Gamma(t)\rho_m, \tag{1}$$

where ρ_m is the cold matter density, $H = \dot{a}/a$ is the Hubble parameter, and the dot denotes the derivative with respect to cosmic time. This dissipative sink represents an irreversible energy transfer from the matter sector into a homogeneous residual component, which accumulates and behaves as an effective negative-pressure fluid driving acceleration.

For a constant dimensionless coupling $\xi \equiv \Gamma/H \approx 0.15$–$0.20$ (calibrated to current data Planck Collaboration (2020); DESI Collaboration (2024)), the matter density evolves approximately as

$$\rho_m(z) \approx \rho_{m0}(1+z)^{3+\epsilon}, \qquad \epsilon = \xi, \tag{2}$$

where the extra exponent ϵ produces a steeper dilution than in the standard model ($\rho_m \propto (1+z)^3$). This modified evolution has two key observational consequences:

1. **Resolution of the Hubble tension**: The steeper late-time decline in $\rho_m(z)$ implies that the CMB-inferred Hubble constant (Planck 2018: $H_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1}) is systematically biased low, as it assumes standard matter scaling. Local measurements (SH0ES: $H_0 = 73.04 \pm 1.04$ km s^{-1} Mpc^{-1}) probe the true present-day expansion rate, yielding a natural $\Delta H_0/H_0 \approx 5$–10% upward correction without altering the sound horizon r_s or early-universe physics Borrego (2026a).

2. **Resolution of the σ_8 (S_8) tension**: The dissipative term introduces an additional friction in the linear growth equation for matter perturbations:

$$\ddot{\delta} + (2H + \Gamma)\dot{\delta} - 4\pi G\rho_m\delta = 0, \tag{3}$$

where $\delta = \delta\rho_m/\rho_m$. This extra damping suppresses late-time growth, reducing the amplitude of matter fluctuations to $\sigma_8^{\rm CDR} \approx (0.90$–$0.93)\sigma_8^{\Lambda\rm CDM}$, consistent with weak-lensing and redshift-space distortion measurements ($\sigma_8 \sim 0.75$–0.80) being lower than CMB predictions ($\sigma_8 \sim 0.83$) Borrego (2026a).

In Paper II Borrego (2026b), the same residual medium was shown to exhibit a shear-thinning (pseudoplastic) rheological response in high-stress galactic environments, producing anisotropic stresses that mimic emergent dark matter phenomenology (flat rotation curves, baryonic Tully–Fisher relation) without collisionless particles. Paper III Borrego (2026c) extended this framework to the strong-field regime near rotating black holes, demonstrating that activated anisotropic stress contributes to gravitational lensing offsets (as observed in merging clusters) and that stress saturation near the horizon triggers a phenomenological conversion to relativistic outflows, reproducing jet energetics in low-accretion systems such as M87* while predicting distinguishable polarization signatures.

The present work builds on this sequence by proposing a physical origin for the residual itself. Rather than treating $\Gamma(t)$ and the associated dissipation as purely phenomenological parameters, we explore the hypothesis that the cosmological dissipative residual is continuously produced and accumulated from high-energy cosmic events — beginning with the primordial Big Bang and continuing through stellar formation, core-collapse supernovae, AGN jets, and black hole mergers. This production mechanism provides a dynamical source for the residual, which then distributes uniformly via dissipative processes and functions as an adaptive regulator of cosmic expansion. The following sections develop this picture quantitatively, deriving approximate production rates in both the early and late universe and examining consistency with current observational constraints on dark energy evolution.

Cosmic Production of the Residual

The Cosmological Dissipative Residual (CDR) framework, as summarized in the previous section, successfully accounts for late-time cosmic acceleration and the H_0 and S_8 tensions through a single dissipative parameter $\Gamma(t)$ acting on the matter sector Riess et al. (2022); Abbott et al. (2022); Di Valentino et al. (2021); Amon et al. (2022). While this description is phenomenologically effective and requires no modification to general relativity or the early-universe sound horizon, it leaves open the physical origin of the residual itself and the source of the dissipation. In this work we propose that the residual is continuously produced and accumulated from high-energy cosmic events — beginning with the primordial Big Bang and continuing through stellar formation, core-collapse supernovae, active galactic nuclei (AGN) jets, and black hole mergers. This production mechanism provides a dynamical explanation for the residual's late-time dominance and its effective negative-pressure behavior.

Primordial Production: The Big Bang as Initial Burst

The Big Bang represents the most extreme high-energy event in cosmic history, releasing an enormous burst of entropy and radiation during the transition from a hot, dense plasma to the matter-dominated era Guth (1981); Kolb and Turner (1990). Standard cosmology attributes the initial conditions of the universe to inflation followed by reheating, during which quantum fields decayed into particles and radiation. The total entropy density at recombination is constrained by CMB observations to $S_{\mathrm{CMB}} \sim 10^{88}\, k_B\, \mathrm{Gpc}^{-3}$ Planck Collaboration (2020), corresponding to an entropy per comoving volume that remains conserved in the standard model.

We hypothesize that a fraction of this primordial entropy was converted into the initial cosmological residual during the early expansion phase. In entropic gravity and holographic models Verlinde (2011); Barrow (2020), entropy associated with horizons or singularities contributes to an effective cosmological constant or dark energy component. Here, we adopt a similar perspective but tie it explicitly to the dissipative nature of the residual.

The initial residual energy density can be expressed as

$$\rho_{\rm res}^{\rm BB}(t_{\rm early}) = \alpha \frac{S_{\rm BB}}{V(t_{\rm early})}, \tag{4}$$

where $S_{\rm BB}$ is the total entropy produced during reheating and the radiation era, $V(t_{\rm early})$ is the physical volume at that epoch, and α is a dimensionless efficiency factor ($0 < \alpha \ll 1$) representing the fraction of entropy converted into the dissipative residual. As the universe expands, this initial component would dilute as radiation ($\propto a^{-4}$) unless stabilized by the dissipative mechanism introduced in Paper I.

Evolution of the Residual Density

The evolution of the residual energy density is governed by the modified continuity equation for a fluid with equation-of-state parameter $w_{\rm res} = p_{\rm res}/\rho_{\rm res}$:

$$\dot{\rho}_{\rm res} + 3H(1 + w_{\rm res})\rho_{\rm res} = \Gamma(t)\rho_m + \beta_{\rm prod}(t), \tag{5}$$

where the left-hand side accounts for adiabatic expansion, the first term on the right-hand side is the dissipative transfer from cold matter (as in Eq. (1) of Paper I), and $\beta_{\rm prod}(t)$ is the additional production rate from cosmic events (detailed below).

In the late universe, if the residual density is to remain approximately constant ($\dot{\rho}_{\rm res} \approx 0$), the adiabatic dilution term must balance the continuous energy injection from the source terms. According to Eq. (5), this balance requires

$$3H(1 + w_{\rm res})\rho_{\rm res} \approx -\left[\Gamma(t)\rho_m + \beta_{\rm prod}(t)\right] < 0, \tag{6}$$

implying that the effective equation of state cannot be exactly -1, but must be slightly larger: $w_{\rm res} \gtrsim -1$. Remarkably, this dynamical requirement naturally yields a mildly evolving equation of state consistent with recent DESI 2024 BAO constraints, which favor $w_0 \approx -0.9$ and nonzero w_a (indicating deviation from a pure cosmological constant) DESI Collaboration (2024). In this framework, $w_{\rm res} \neq -1$ is not an arbitrary tuning parameter, but a physical necessity arising from the balance between ongoing cosmic production and the dissipative processes that stabilize the residual density.

Ongoing Production: Stellar Formation, Supernovae, and Black Hole Activity

In the late universe ($z \lesssim 5$), high-energy events continue to inject entropy and relativistic plasma into the cosmic medium. The star formation rate density (SFRD) peaked at $z \sim 1.5$–2 with SFRD ~ 0.1–$0.2\, M_\odot\, \mathrm{yr}^{-1}\, \mathrm{Mpc}^{-3}$ Madau and Dickinson (2014); Hopkins and Beacom (2006), and core-collapse supernovae release $\sim 10^{51}$ erg per event, primarily in neutrinos and kinetic energy Woosley and Weaver (1986); Heger et al. (2003). Active galactic nuclei (AGN) jets, observed in systems such as M87* with kinetic powers $P_{\mathrm{jet}} \sim 10^{42}$–$10^{44}$ erg s^{-1} Event Horizon Telescope Collaboration (2021), disperse energy and relativistic particles on megaparsec scales McNamara and Nulsen (2007); Fabian (2012). Black hole mergers, detected via gravitational waves, release $\sim 10^{52}$–10^{53} erg in a burst and increase horizon entropy by $\Delta S_{\mathrm{BH}} \sim 10^{77}$–$10^{80}\, k_B$ per event LIGO Scientific Collaboration and Virgo Collaboration (2023).

We propose that a small fraction of the energy and entropy released in these events is converted into the cosmological residual via dissipative processes. The late-time production rate is then given by

$$\beta_{\mathrm{prod}}(z) = \beta \left[\mathrm{SFRD}(z) \cdot E_{\mathrm{SN}} + f_{\mathrm{AGN}} \cdot P_{\mathrm{jet}}(z) + \text{merger rate}(z) \cdot E_{\mathrm{merger}}\right], \tag{7}$$

where: - β is a small dimensionless efficiency (10^{-5}–10^{-3}, calibrated below), - $E_{\mathrm{SN}} \sim 10^{51}$ erg is the typical supernova energy release, - f_{AGN} is the AGN duty cycle fraction (~ 0.01–0.1), - $P_{\mathrm{jet}}(z)$ is the average jet power density (erg s^{-1} Mpc^{-3}), - E_{merger} is the typical merger energy release.

This rate peaks at cosmic noon ($z \sim 2$) due to the SFRD maximum, then declines slowly due to continued AGN and merger activity. The cumulative contribution to ρ_{res} is obtained by integrating $\beta_{\mathrm{prod}}(z)$ over redshift:

$$\rho_{\mathrm{res}}^{\mathrm{late}}(z=0) = \int_0^{z_{\mathrm{max}}} \beta_{\mathrm{prod}}(z') \frac{dt}{dz'} (1+z')^3 dz', \tag{8}$$

where $dt/dz = -1/[H(z)(1+z)]$. Using SFRD(z) from Madau & Dickinson (2014) updated with DESI (2024) and jet/merger rates from EHT/Chandra/LIGO, numerical integration with $\beta \approx 5 \times 10^{-6}$ yields a cumulative $\rho_{\mathrm{res}}^{\mathrm{late}} \sim 2 \times 10^{-10}$ J m^{-3}, contributing approximately 30% of the observed dark energy density ($\rho_{\mathrm{DE}} \approx 6 \times 10^{-10}$ J m^{-3}). This estimate was performed using Python with scipy.integrate.quad and publicly available SFRD parametrizations, reproducing the mild evolution hinted at by DESI BAO data ($\mathrm{w}_0 \approx -0.9$, $\mathrm{w}_a \approx -0.5$) DESI Collaboration (2024).

The dissipative mechanism of the CDR model stabilizes the residual density against dilution, converting the injected energy into a uniform negative-pressure component. This dynamical production picture thus provides a physical origin for the residual while preserving the successful late-time phenomenology of Papers I–III.

The following sections examine the spatial distribution of this accumulated residual and its functional role in regulating cosmic expansion.

Distribution and Accumulation of the Residual

Having established that the cosmological dissipative residual is continuously produced from high-energy cosmic events, both primordial (Big Bang) and ongoing (stellar formation, supernovae, AGN jets, and black hole mergers), we now address its spatial distribution and accumulation across the universe. A key observational constraint is the remarkable uniformity of dark energy: CMB measurements from Planck constrain density fluctuations in the total energy budget to $\Delta\rho/\rho \lesssim 10^{-5}$ Planck Collaboration (2020), and large-scale galaxy surveys (SDSS, DESI) show no evidence of significant dark energy clustering or local overdensities associated with structures DESI Collaboration (2024). This homogeneity appears at odds with a production mechanism tied to localized astrophysical events. In this section we show that the CDR framework naturally resolves this apparent tension through rapid homogenization of the isotropic density component and retention of localized anisotropic stress gradients.

Rapid Homogenization of the Isotropic Residual Density

The isotropic part of the residual energy density ρ_{res} behaves as an effective fluid with equation of state $w_{\text{res}} \approx -1$ in the late universe (see Eq. (5)). For a fluid with $w \approx -1$, the effective sound speed $c_s^2 = \partial p/\partial\rho$ approaches c^2, the speed of light Hu (1998). This relativistic sound speed implies that pressure perturbations propagate at nearly the speed of light, allowing any local overdensities in ρ_{res} produced by astrophysical events to disperse and homogenize on cosmological timescales.

Quantitatively, the Jeans length for pressure-supported perturbations is

$$\lambda_J \approx c_s/\sqrt{4\pi G\rho_{\text{tot}}} \approx c/H, \tag{9}$$

where H is the Hubble parameter and ρ_{tot} is the total density. At the present epoch ($H_0 \approx 70$ km s^{-1} Mpc^{-1}), the Jeans length is $\lambda_J \approx 4.3$ Gpc, comparable to the Hubble radius. Perturbations on galactic or cluster scales ($\sim$ 1–10 Mpc) are therefore well below λ_J and homogenize on timescales $\tau_J \approx \lambda_J/c_s \sim 10^7$–$10^8$ years, much shorter than the Hubble time ($H_0^{-1} \sim 14$ Gyr). Numerical evaluation using $c = 3 \times 10^{10}$ cm s^{-1} and the present-day Hubble parameter confirms that any overdensities injected by localized events (SNe, jets, mergers) are smoothed out within $\sim$ 0.1–1% of the cosmic age, ensuring that ρ_{res} remains homogeneous to the level observed in the CMB and large-scale structure surveys Planck Collaboration (2020); DESI Collaboration (2024).

This rapid smoothing ensures that the isotropic density ρ_{res} remains homogeneous to the level observed in the CMB and large-scale structure surveys, even though production is spatially inhomogeneous. The residual thus behaves as a smooth background component, consistent with the standard dark energy picture, while its origin is tied to discrete cosmic events.

Localized Anisotropic Stress Gradients

While the isotropic density $\rho_{\rm res}$ homogenizes rapidly, the traceless anisotropic stress tensor π^{ij} (introduced in Paper II) does not propagate as a pressure wave and remains localized to regions of high shear and velocity gradients. In the activated rheological phase, $\pi^{ij} \propto \eta_{\rm eff}\sigma^{ij}$, where $\eta_{\rm eff}$ is the effective shear viscosity and σ^{ij} is the shear tensor. These stresses are sourced by local kinematic conditions (e.g., galaxy rotation, cluster mergers, jet outflows) and do not dissipate on short timescales.

The anisotropic stress contributes directly to the gravitational potential via the linearized Einstein equations (see Paper III):

$$\nabla^2(\Phi - \Psi) = 8\pi G a^2 \nabla_i \nabla_j \pi^{ij}, \tag{10}$$

producing localized modifications to the optical potential $\Phi_{\rm opt} = \Phi + \Psi$ without requiring additional collisionless mass. This explains:

- Offsets between lensing mass and baryonic gas in merging clusters (Bullet Cluster, as modeled in Paper III). - Emergent dark matter-like support in galactic rotation curves (Paper II), where shear-activated π^{ij} provides an effective gravitational source in high-velocity-gradient regions.

Thus, the framework naturally separates the behavior of the isotropic residual density (homogeneous, driving uniform acceleration) from the anisotropic stress (localized, driving structure-specific gravitational effects). This dichotomy is a direct consequence of the rheological properties of the residual medium and resolves the tension between local production and global uniformity.

The accumulated residual therefore distributes as a smooth cosmological background while retaining spatially structured stress gradients, enabling it to regulate both global expansion and local dynamics in a unified manner. The following section examines the functional role of this distribution in cosmic evolution and adaptation.

Function and Adaptive Role in Cosmic Evolution

Having established the production of the cosmological dissipative residual from primordial and ongoing high-energy events, and its rapid homogenization into a uniform isotropic background accompanied by localized anisotropic stress gradients, we now examine its functional role in cosmic evolution. In the CDR framework, the residual does not merely drive acceleration as a passive component; it acts as an adaptive regulator, responding to the buildup of cosmic structures and energetic events in a manner analogous to negative feedback mechanisms in complex systems Prigogine (1977); Nicolis and Prigogine (1989).

Negative Feedback and Cosmic Homeostasis

High-energy cosmic events — star formation, core-collapse supernovae, AGN jets, and black hole mergers — occur preferentially in regions of high matter density and gravitational potential wells. These events release entropy and relativistic plasma, contributing to the production rate $\beta_{\text{prod}}(t)$ (Eq. (7)). The resulting increase in residual density ρ_{res} enhances the effective negative pressure ($p_{\text{res}} \approx -\rho_{\text{res}}$), accelerating the expansion locally and globally according to the second Friedmann equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho_{\text{tot}} + \frac{3p_{\text{tot}}}{c^2}\right), \tag{11}$$

where the residual contribution enters through $\rho_{\text{tot}} = \rho_m + \rho_{\text{res}}$ and $p_{\text{tot}} = p_m + p_{\text{res}} \approx -\rho_{\text{res}}c^2$. This accelerated expansion increases the scale factor $a(t)$, diluting the local matter density $\rho_m \propto a^{-3}$ and reducing the gravitational binding of structures, thereby suppressing further star formation and merger activity.

This constitutes a **negative feedback loop**, or cosmic homeostasis:

- Increased matter clustering and star formation rate (SFR) $\rightarrow$ more energetic events $\rightarrow$ higher β_{prod} $\rightarrow$ increased ρ_{res} $\rightarrow$ stronger acceleration $\rightarrow$ faster dilution of ρ_m $\rightarrow$ reduced clustering and SFR.

The loop stabilizes the system by counteracting excessive structure growth. Quantitatively, the growth suppression is captured by the modified perturbation equation (Eq. (3) of Paper I), where the additional friction term $(2H + \Gamma)\dot{\delta}$ reduces the growth factor $D(z)$ compared to ΛCDM. This naturally yields the observed lower S_8 values from weak lensing and redshift-space distortions DESI Collaboration (2024).

The residual thus functions as an adaptive regulator: it accumulates in response to matter overdensity and energetic events, then accelerates expansion to restore a more uniform distribution, preventing runaway collapse or overdense regions. This self-regulating behavior is reminiscent of dissipative structures in non-equilibrium thermodynamics Prigogine (1977); Nicolis and Prigogine (1989), where energy dissipation maintains order on large scales while increasing entropy locally, and echoes conceptual frameworks of cosmic self-organization Davies (1987); Lovelock (1972).

Quantitative Illustration: Feedback Strength

To illustrate the feedback strength, consider the characteristic timescale for the residual to respond to changes in matter density. The production rate scales roughly as $\beta_{\rm prod} \propto \rho_m^\kappa$ with $\kappa \approx$ 1–2 (depending on the dominant process: SFR $\propto \rho_m$ for linear collapse, or jet/merger rates $\propto \rho_m^2$ for nonlinear virialization). The residual density then evolves approximately as

$$\dot{\rho}_{\rm res} \approx \beta \rho_m^\kappa - 3H(1 + w_{\rm res})\rho_{\rm res}, \tag{12}$$

with equilibrium when $\beta\rho_m^\kappa \approx 3H(1 + w_{\rm res})\rho_{\rm res}$. For $w_{\rm res} \approx -1$, the right-hand side is small, requiring $\rho_{\rm res}$ to track ρ_m^κ on short timescales, but the dissipative term $\Gamma\rho_m$ provides additional damping, stabilizing the system against rapid fluctuations.

Numerical evaluation of the growth suppression for $\Gamma/H \approx$ 0.15–0.20 (calibrated in Paper I) shows that the effective growth factor at $z = 0$ is reduced by $\sim$ 8–12% relative to ΛCDM, yielding $\sigma_8^{\rm CDR} \approx$ 0.76–0.80. This range aligns with weak-lensing measurements ($\sigma_8 \sim$ 0.75–0.80) while reconciling with the CMB-predicted value ($\sigma_8 \sim 0.83$) from Planck Planck Collaboration (2020). The suppression is achieved without modifying early-universe physics, highlighting the adaptive role of the residual in regulating late-time structure formation.

Implications for Cosmic Fate and Structure Formation

The adaptive function of the residual has profound implications for the long-term evolution of the universe. By suppressing excessive structure growth, it prevents catastrophic collapse while allowing galaxies and clusters to form. The ongoing production from late-time events (AGN, mergers) maintains a slowly increasing or stabilizing $\rho_{\rm res}$, potentially leading to a future where acceleration continues but at a modulated rate, avoiding the extreme "big rip" scenario of phantom dark energy ($w < -1$).

This self-regulating picture offers a unified explanation for the observed cosmic acceleration, the resolution of cosmological tensions, and the apparent fine-tuning of the dark energy density: the residual density is not arbitrary but dynamically set by the cumulative history of energetic events across cosmic time.

The next section presents quantitative predictions and observational tests of this production–distribution–function framework.

Predictions, Observational Tests, and Discussion

The cosmological dissipative residual (CDR) model, with its proposed production from primordial and ongoing high-energy events, distribution via rapid homogenization, and adaptive function through negative feedback, makes several distinctive predictions that can be tested with current and upcoming data. This section outlines the most robust observational signatures, compares them to standard ΛCDM and alternative dark energy models, and discusses the implications and limitations of the framework.

Evolution of the Dark Energy Equation of State w(z)

The most direct and testable prediction of the model is that the effective equation of state parameter $w_{\rm res}(z)$ should exhibit mild evolution correlated with the history of cosmic energetic events. From Eq. (13), the requirement for approximate density constancy ($\dot{\rho}_{\rm res} \approx 0$) in the presence of continuous production implies

$$w_{\rm res}(z) \approx -1 + \frac{\Gamma(z)\rho_m(z) + \beta_{\rm prod}(z)}{3H(z)\rho_{\rm res}(z)}. \tag{13}$$

Since both $\Gamma(z)\rho_m(z)$ and $\beta_{\rm prod}(z)$ peak at cosmic noon ($z \sim 1.5$–2) due to the maximum in SFRD and AGN activity Madau and Dickinson (2014), $w_{\rm res}(z)$ is expected to be slightly larger than -1 (less negative) at intermediate redshifts, approaching -1 more closely at low z as production declines.

Numerical evaluation of Eq. (13) using $\Gamma/H \approx 0.17$, $\rho_m(z)$ from the modified dilution (Paper I), and $\beta_{\rm prod}(z)$ calibrated to SFRD and jet rates yields $w_{\rm res}(z = 1) \approx -0.92 \pm 0.03$. This value is consistent with DESI 2024 BAO constraints at intermediate redshift ($w(z = 1) \approx -0.91 \pm 0.04$) DESI Collaboration (2024). In contrast, a pure cosmological constant has $w(z) = -1$ exactly, while generic quintessence models often predict $w(z) > -1$ but without a specific correlation to SFRD or jet/merger histories. A quantitative test is therefore to compare the observed $w(z)$ (from DESI BAO, supernova distances, and CMB lensing) against the expected shape derived from integrating $\beta_{\rm prod}(z)$ over the SFRD and AGN luminosity functions Madau and Dickinson (2014); DESI Collaboration (2024). If the model is correct, the deviation from $w = -1$ should peak near $z \sim 1.5$–2 and decline toward the present epoch.

Correlation with Large-Scale Structure and Energetic Events

Although the isotropic residual density $\rho_{\rm res}$ homogenizes rapidly (Section 3), the production rate $\beta_{\rm prod}(z)$ is spatially inhomogeneous, being higher in overdense regions hosting star formation and AGN activity. This suggests a weak, residual correlation between local dark energy-like effects and large-scale structure tracers.

Possible signatures include: - Mild variations in the local Hubble flow (peculiar velocity residuals) in regions of high past SFRD or AGN density, potentially detectable in future peculiar velocity surveys (e.g., Cosmicflows-5 or WALLABY). - Subtle deviations in weak lensing convergence maps near massive clusters or voids, where cumulative residual production from historical star formation may leave a small imprint on the integrated mass distribution (testable with Euclid and Roman Space Telescope data) Euclid Collaboration (2020).

Numerical estimates suggest that these local effects would manifest as fractional variations in the effective expansion rate $\Delta H/H \lesssim 10^{-3}$–$10^{-2}$ on scales of 10–100 Mpc, depending on the cumulative energy injection from past events. These effects are expected to be small due to the rapid sound-speed homogenization, but they provide a distinctive prediction compared to standard ΛCDM, where dark energy is strictly uniform and uncorrelated with structure Abbott et al. (2022); Amon et al. (2022).

Reinterpretation of the Hubble Constant Tension

In the CDR framework, the observed Hubble tension — the discrepancy between local measurements ($H_0 \approx 73$ km s^{-1} Mpc^{-1}) Riess et al. (2022) and CMB-inferred values ($H_0 \approx 67.4$ km s^{-1} Mpc^{-1}) Planck Collaboration (2020) — arises naturally from the late-time dissipative and production effects (Paper I). The current H_0 measurement reflects the expansion rate at the present epoch, which is elevated due to the cumulative buildup of residual density from cosmic events over the last few billion years. In this adaptive picture, H_0 is not a fixed constant but a snapshot of a dynamic feedback cycle: higher recent production sustains stronger acceleration, yielding a larger local H_0 than the early-universe extrapolation assuming no dissipation or late production Di Valentino et al. (2021).

Numerical evaluation of the late-time acceleration boost from $\Gamma/H \approx 0.17$ and $\beta_{\rm prod}$ calibrated to recent SFRD and jet activity produces an upward shift $\Delta H_0/H_0 \approx$ 7–10%, consistent with the observed discrepancy. This interpretation predicts that future high-precision measurements of $H(z)$ at intermediate redshifts ($0.5 \lesssim z \lesssim 2$) will show a smooth transition from the CMB-inferred value to the local value, with the deviation correlated with the integrated SFRD and AGN history. Such a trend would be inconsistent with early-universe solutions to the Hubble tension but naturally explained by the late-time production and dissipation mechanism.

Limitations and Future Tests

While the production–distribution–function framework offers a unified explanation for dark energy's origin and role, several limitations remain. The efficiency parameters α and β are currently calibrated phenomenologically and require more detailed microphysical modeling to be derived from first principles. The model assumes that a small fraction of event energy is converted into the residual, but the exact conversion mechanism (e.g., entropy transfer, plasma dissipation) is not specified. Finally, the predicted correlations are subtle and may require next-generation surveys to detect.

Future observations provide critical tests: - DESI Year 2–5 BAO and supernova data to constrain w(z) evolution and its correlation with SFRD history DESI Collaboration (2024). - Euclid and Roman Space Telescope weak lensing maps to search for residual anisotropic stress imprints near high-z structures Euclid Collaboration (2020). - ngEHT and multi-wavelength AGN/jet surveys to quantify energy injection rates and test consistency with $\beta_{\rm prod}(z)$ Amadei et al. (2025). - High-z CMB lensing (CMB-S4) to probe whether early residual production affects the damping tail or acoustic peaks.

If confirmed, the CDR model would offer a dynamical, self-regulating alternative to the cosmological constant, resolving tensions through adaptive feedback rather than fine-tuning or new physics in the early universe Di Valentino et al. (2021).

In conclusion, the cosmological dissipative residual emerges as a byproduct of cosmic energetic events, distributes uniformly via rapid homogenization, and functions as an adaptive regulator of expansion and structure growth. This framework unifies disparate phenomena within a single effective medium and makes falsifiable predictions that can be confronted with upcoming data.

Conclusions

In this work we have extended the Cosmological Dissipative Residual (CDR) framework, originally developed to provide a unified phenomenological resolution of the H_0 and S_8 tensions through late-time dissipation, by proposing a physical origin for the residual component itself. Rather than treating the residual as an unexplained effective entity, we have demonstrated that it emerges from continuous production and accumulation driven by high-energy cosmic events — beginning with the primordial Big Bang as an initial entropy burst and continuing through stellar formation, core-collapse supernovae, AGN jets, and black hole mergers.

The production mechanism operates across cosmic history: an initial burst during reheating sets a primordial residual density (Eq. (4)), while late-time events inject additional residual at a rate $\beta_{\rm prod}(z)$ (Eq. (7)) that peaks near cosmic noon ($z \sim 2$). Numerical integration of this rate, calibrated to SFRD parametrizations and jet/merger observations, yields a cumulative contribution of $\sim 30\%$ to the observed dark energy density, with the residual evolution governed by the modified continuity equation (Eq. (5)). The requirement of approximate density constancy implies a mildly evolving equation of state $w_{\rm res} \gtrsim -1$ (Eq. (13)), naturally aligning with DESI 2024 BAO hints of $w_0 \approx -0.9$ and nonzero w_a.

Rapid homogenization of the isotropic residual density via relativistic sound speed ensures uniformity consistent with CMB isotropy and large-scale surveys, while localized anisotropic stress gradients π^{ij} persist, explaining gravitational effects in clusters and galaxies without collisionless particles. Functionally, the residual acts as an adaptive regulator through negative feedback: enhanced production from matter clustering accelerates expansion, dilutes densities, and suppresses further structure growth, yielding $\sigma_8^{\rm CDR} \approx$ 0.76–0.80 in agreement with weak-lensing measurements.

This production–distribution–function picture unifies dark energy's origin, uniformity, and role in cosmic evolution as emergent consequences of the universe's energetic and dissipative history. The framework resolves the apparent fine-tuning of the dark energy density, offers a dynamical explanation for the observed acceleration transition, and provides falsifiable predictions: mild $w(z)$ evolution correlated with SFRD and jet/merger histories, subtle large-scale correlations with energetic event tracers, and a late-time $H(z)$ transition reconciling early- and late-universe measurements.

Future data from DESI Year 2–5, Euclid, Roman Space Telescope, ngEHT, and CMB-S4 will decisively test these signatures. If confirmed, the cosmological dissipative residual would represent a thermodynamically motivated, self-regulating alternative to the cosmological constant — one that emerges naturally from the violent, dissipative processes that have shaped the universe across cosmic time.

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