Selective Rheological Activation of the Cosmological Dissipative Residual in Disk Galaxies: Theoretical Framework and SPARC Constraints

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Abstract

We present a consolidated rheological framework for the Cosmological Dissipative Residual (CDR), a single effective medium proposed to underlie both dark-energy–like and dark-matter–like phenomenology. Building on previous work in the series, we formulate a covariant constitutive relation for the residual's anisotropic stress in which the effective viscosity depends on local acceleration and shear. In the non-relativistic thin-disk limit this relation reduces to an estimator for the residual contribution to the radial acceleration,

$$\Delta g_R \approx \frac{f_{\rm geom}\, \eta_{\rm eff}\, \sigma}{\rho_{\rm res}\, R}.$$

with a geometric factor $f_{\rm geom} \approx 3$.

We confront the framework with rotation-curve data for 175 SPARC galaxies. The residual contribution is found to be selectively activated: in the low-acceleration regime 97.5% of radial points show $\Delta g > 0$, while in the high-acceleration regime the median Δg is consistent with zero. From the activated regime we obtain a median effective viscosity $\eta_{\rm eff} \simeq 3.8 \times 10^{-2}\,{\rm kg\,m^{-1}\,s^{-1}}$ and a characteristic transition scale $a_{\rm trans} \sim (1–2) \times 10^{-10}\,{\rm m\,s^{-2}}$, compatible in order of magnitude with $cH_0/2\pi$.

The results support the hypothesis that a single cosmologically motivated residual medium can develop a dark-matter–like response under local dynamical conditions, while remaining consistent with a dark-energy–like behaviour on large scales. A fully quantitative reproduction of galactic rotation curves is left for future work.

Keywords: dark energy, dark matter, dissipative cosmology, galactic dynamics, rheology, SPARC

1 Introduction

The physical nature of the dark sector remains one of the central open problems in cosmology and astrophysics. While the ΛCDM model provides an excellent phenomenological fit to a broad range of observations, the cosmological constant and cold dark matter are introduced as separate ingredients whose microscopic origin is unknown [Planck Collaboration, 2018, Riess et al., 2022]. Observational tensions, in particular the discrepancy between early- and late-time determinations of H_0 and the milder σ_8 tension, have motivated the exploration of effective descriptions in which the dark sector is more dynamical or unified [Di Valentino et al., 2021, DESI Collaboration, 2024].

In earlier papers of this series the Cosmological Dissipative Residual (CDR) was introduced as an effective continuous medium whose bulk-viscous behaviour on cosmological scales yields a dark-energy–like contribution without altering early-universe physics or the CMB sound horizon [Borrego Moreno, 2026a]. A subsequent development proposed that the same medium, when subjected to local shear and acceleration gradients inside galaxies, can develop an anisotropic stress response—gravitational rheology—capable of generating dark-matter–like phenomenology [Borrego Moreno, 2026b].

The purpose of the present work is to consolidate that rheological picture into a covariant constitutive framework, to reduce it to the thin-disk limit relevant for rotation curves, and to subject the predicted selective activation to a systematic test with the SPARC sample of 175 disk galaxies [Lelli et al., 2016]. The central question we address is not yet whether the residual fully accounts for galactic rotation curves, but whether its response is activated preferentially under the dynamical conditions where a dark-matter–like contribution would be required.

This paper therefore has a dual character: it is both a theoretical consolidation of the residual's rheology and the first broad observational confrontation of that rheology with galactic data.

2 Theoretical Framework

2.1 The residual as a single medium

The CDR is defined as an effective relativistic fluid whose stress-energy tensor takes the form

$$T^{\mu\nu}_{\rm res} = \rho_{\rm res}\, u^\mu u^\nu + \big(p_{\rm res} - \zeta\theta\big)\Delta^{\mu\nu} + \Pi^{\mu\nu}, \tag{1}$$

where $\Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$, $\theta = \nabla_\mu u^\mu$, ζ is the bulk viscosity, and $\Pi^{\mu\nu}$ is the traceless anisotropic stress orthogonal to u^μ:

$$\Pi^{\mu\nu} = \Pi^{\nu\mu}, \qquad \Pi^\mu{}_\mu = 0, \qquad u_\mu \Pi^{\mu\nu} = 0. \tag{2}$$

The isotropic sector (energy density, pressure and bulk viscosity) is responsible for the dark-energy–like behaviour on cosmological scales. The anisotropic stress $\Pi^{\mu\nu}$ is the carrier of the rheological response that can become important in galactic environments.

2.2 Constitutive relation

We close the system with the rheological constitutive relation

$$\Pi^{\mu\nu} = -2\eta_{\rm eff}\, \sigma^{\mu\nu}, \tag{3}$$

where $\sigma^{\mu\nu}$ is the shear tensor,

$$\sigma^{\mu\nu} = \Delta^{\mu\alpha}\Delta^{\nu\beta}\nabla_{(\alpha}u_{\beta)} - \frac{1}{3}\theta\Delta^{\mu\nu}. \tag{4}$$

The effective viscosity is allowed to depend on the local dynamical state:

$$\eta_{\rm eff} = \eta_0 \left(\frac{\rho_{\rm res}}{\rho_{\rm c}}\right)^{\gamma} \left[1 + \left(\frac{a}{a_{\rm trans}}\right)^{n}\right]^{-1} \left(1 + \frac{\sigma}{\sigma_0}\right)^{-\beta}. \tag{5}$$

Here $a = \sqrt{\dot{u}^\mu \dot{u}_\mu}$ is the acceleration scalar and $\sigma = \sqrt{\frac{1}{2}\sigma_{\mu\nu}\sigma^{\mu\nu}}$ is the shear scalar. The factor

$$\mathcal{A}(a) = \left[1 + \left(\frac{a}{a_{\rm trans}}\right)^{n}\right]^{-1} \tag{6}$$

encodes selective activation at low acceleration; the factor $\mathcal{S}(\sigma) = (1 + \sigma/\sigma_0)^{-\beta}$ allows shear-thinning behaviour, as anticipated in the gravitational-rheology formulation.

2.3 Reduction to the thin-disk limit

Under the assumptions of a non-relativistic, axisymmetric, stationary thin disk, the residual contribution to the radial acceleration is

$$\Delta g_R = -\frac{1}{\rho_{\rm res}} (\nabla \cdot \mathbf{\Pi})_R. \tag{7}$$

The cylindrical divergence of the anisotropic stress yields a geometric structure of the form

$$(\nabla \cdot \mathbf{\Pi})_R \sim -\frac{f_{\rm geom}\, \eta_{\rm eff}\, \sigma}{R}, \tag{8}$$

and therefore

$$\Delta g_R \approx \frac{f_{\rm geom}\, \eta_{\rm eff}\, \sigma}{\rho_{\rm res}\, R}, \tag{9}$$

with $f_{\rm geom} \approx 3$. This expression provides a direct link between the covariant rheology and quantities measurable from rotation curves.

In the same limit the shear associated with differential rotation may be estimated as

$$\sigma \approx \left| \frac{\partial v_\phi}{\partial R} - \frac{v_\phi}{R} \right|. \tag{10}$$

2.4 Activation condition and unification of regimes

The constitutive relation implies a clear activation condition:

$$\text{anisotropic response active} \quad \Longleftrightarrow \quad \sigma > 0 \quad \text{and} \quad g \lesssim a_{\rm trans}. \tag{11}$$

Consequently:

- on cosmological scales (negligible shear) the anisotropic stress remains off and the residual behaves as a dissipative dark-energy component;
- in galactic regions of high acceleration the viscosity is suppressed and the residual contribution vanishes;

- in galactic regions of low acceleration with non-zero shear the residual contributes a positive Δg.

No conversion of one substance into another is required. The residual changes its constitutive response according to local stress and acceleration.

3 Path of the Analysis with SPARC

The observational part of this work was constructed in successive diagnostic steps, each designed to test a specific aspect of the rheological picture.

3.1 Sample and derived quantities

We employ the SPARC rotation-curve sample of 175 disk galaxies [Lelli et al., 2016]. For each galaxy we compute the baryonic velocity

$$V_{\rm bar} = \sqrt{V_{\rm gas}^2 + V_{\rm disk}^2 + V_{\rm bulge}^2}, \tag{12}$$

the observed and baryonic accelerations

$$g_{\rm obs} = \frac{V_{\rm obs}^2}{R}, \qquad g_{\rm bar} = \frac{V_{\rm bar}^2}{R}, \tag{13}$$

the excess

$$\Delta g = g_{\rm obs} - g_{\rm bar}, \tag{14}$$

and a Newtonian estimate of the shear associated with differential rotation,

$$\sigma \approx \left| \frac{\partial v_\phi}{\partial R} - \frac{v_\phi}{R} \right|. \tag{15}$$

Analyses are performed both on individual galaxies and on the stacked set of radial points with $R \geq 2\,\mathrm{kpc}$ (approximately 2700 points). The local estimator of the effective viscosity in the thin-disk limit is

$$\eta_{\rm eff} \approx \frac{\Delta g\, \rho_{\rm res}\, R}{f_{\rm geom}\, \sigma}, \tag{16}$$

with $f_{\rm geom} = 3$ and $\rho_{\rm res} \approx \rho_\Lambda \simeq 6 \times 10^{-27}\,\mathrm{kg\,m^{-3}}$.

3.2 Diagnostic 1: acceleration regime

All radial points were split at the median baryonic acceleration, $g_{\rm bar}^{\rm med} \simeq 3.1 \times 10^{-11}\,\mathrm{m\,s^{-2}}$. In the low-acceleration half, 97.5% of the points show $\Delta g > 0$; in the high-acceleration half the median Δg is consistent with zero and only about half of the points are positive (Table 1). This is the strongest empirical result of the paper and directly matches the activation condition derived from the constitutive relation.

3.3 Diagnostic 2: activation radius

For each galaxy an activation radius $R_{\rm act}$ was defined as the innermost radius beyond which the smoothed Δg remains predominantly positive. The median activation radius is only $\approx 1.3\,{\rm kpc}$, indicating that in most systems the residual response appears relatively early. A long tail toward large activation radii (20–40 kpc) is populated almost exclusively by massive galaxies, consistent with the expectation that high-acceleration interiors keep the residual switched off until larger radii.

3.4 Diagnostic 3: rotation-curve shape

Galaxies were classified as rising, flat or declining according to the outer slope of $V(R)$. The fraction of positive Δg is essentially the same in all three classes ($\approx$ 84–87%). Curve shape is therefore not the dominant controlling variable; acceleration regime is.

3.5 Diagnostic 4: outliers and extreme systems

Individual galaxies that appeared as outliers in the $\eta_{\rm eff}$ distribution were examined in detail.

- **UGC 04278.** A low-mass system with a genuine, radially sustained positive Δg. The high mean $\eta_{\rm eff}$ is inflated by a single low-shear point; the median remains typical of the sample.
- **NGC 2955.** A massive, bulge-dominated galaxy in which $V_{\rm bar} > V_{\rm obs}$ over most of the inner disk. The residual is switched off at high acceleration and only weakly activated at large radii, as expected.
- **UGC 02487.** A very massive and extremely extended disk ($R_{\rm max} \sim 80\,{\rm kpc}$) with $\Delta g > 0$ at all radii. The high $\eta_{\rm eff}$ is real and illustrates that even massive systems can activate the residual strongly if they reach the low-acceleration regime in the outer disk.

In every case the behaviour is intelligible within the selective-activation picture. No system was found that clearly contradicts the framework.

3.6 Diagnostic 5: effective viscosity

Restricting to the activated regime (low acceleration and $\Delta g > 0$; 1305 points) yields a robust median

$$\eta_{\rm eff} \simeq 3.8 \times 10^{-2}\,{\rm kg\,m^{-1}\,s^{-1}}, \tag{17}$$

with a 16–84 percentile range of roughly 0.013–0.18 (Table 2). Because this subsample corresponds to $\mathcal{A}(a) \approx 1$ and $\mathcal{S}(\sigma) \approx 1$, the median provides a working estimate of the amplitude of the rheological response.

3.7 Diagnostic 6: transition scale

The change in the statistical behaviour of Δg occurs around

$$a_{\rm trans} \sim (1\text{–}2) \times 10^{-10}\,{\rm m\,s^{-2}}, \tag{18}$$

compatible in order of magnitude with the cosmological acceleration scale $cH_0/2\pi$ (Table 3). Early attempts to force a MOND-like asymptotic identification $\Delta g \to a_0$ fail to describe the stacked residuals, which remain modest at low acceleration and become negative at high acceleration. This is consistent with a medium whose anisotropic stress is switched on only under specific local conditions, rather than with a fundamental acceleration floor.

Taken together, the diagnostics form a coherent chain: the constitutive relation predicts selective activation; SPARC exhibits precisely that selectivity; the associated viscosity and transition scale lie in a cosmologically reasonable range.

4 Results

Table 1: Activation of the residual contribution by baryonic-acceleration regime in the stacked SPARC sample.

Regime	Points with $\Delta g > 0$	Median Δg
Low acceleration	97.5%	positive
High acceleration	$\sim 50\%$	≈ 0

Table 2: Effective viscosity in the activated regime (low $g_{\rm bar}$ and $\Delta g > 0$).

Statistic	Value ($\mathrm{kg\,m^{-1}\,s^{-1}}$)
Median	3.8×10^{-2}
16th percentile	1.3×10^{-2}
84th percentile	1.8×10^{-1}

Table 3: Characteristic scales of the residual response.

Quantity	Value
$a_{\rm trans}$	$(1\text{–}2) \times 10^{-10}\,\mathrm{m\,s^{-2}}$
Median activation radius	$\approx 1.3\,\mathrm{kpc}$
$f_{\rm geom}$	≈ 3

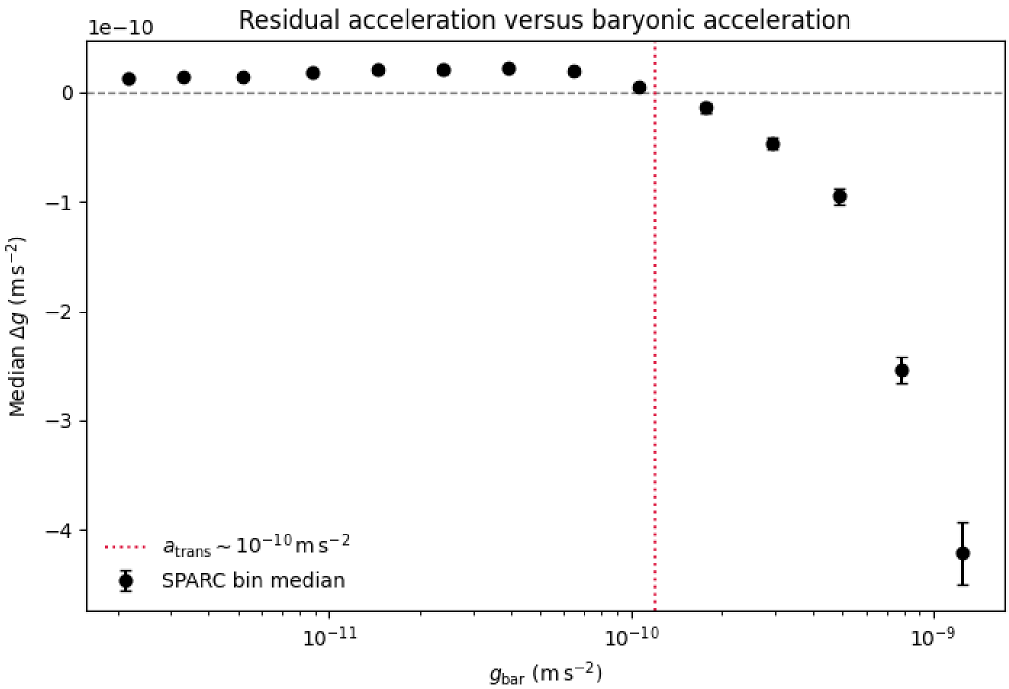

Figure 1: Median residual acceleration Δg as a function of baryonic acceleration $g_{\rm bar}$ for the stacked SPARC sample. The change of behaviour around $a_{\rm trans} \sim 10^{-10}\,{\rm m\,s^{-2}}$ defines the observational transition scale.

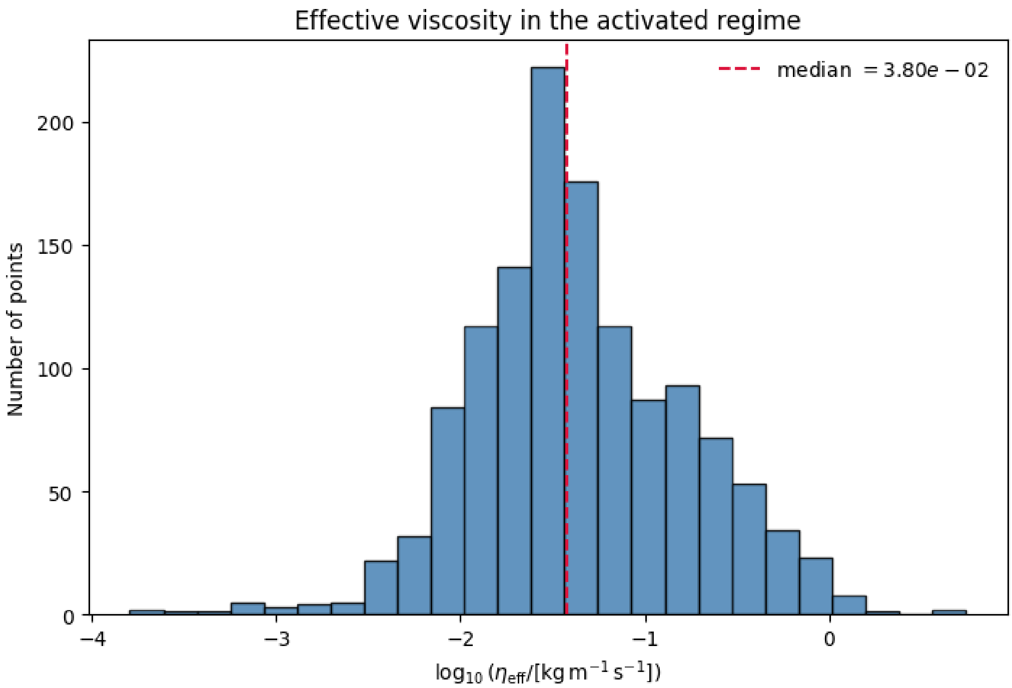

Figure 2: Distribution of $\eta_{\rm eff}$ in the activated regime. The median value $\eta_{\rm eff} \simeq 3.8 \times 10^{-2}\,{\rm kg\,m^{-1}\,s^{-1}}$ is adopted as the working amplitude of the rheological response.

5 Discussion

The analysis deliberately stops short of claiming that the residual already explains galactic rotation curves. The data demonstrate that a residual medium with the proposed rheology *responds* in the correct regime and with a plausible amplitude. Whether that response can be tuned, within the same parameter set that satisfies cosmological constraints, to reproduce the detailed shape of rotation curves and the Radial Acceleration Relation remains an open question and the natural subject of future work.

The intellectual path that led to the present formulation is worth stating explicitly. Early attempts to force a simple MOND-like asymptotic identification $\Delta g \to a_0$ were found to be inconsistent with the stacked SPARC residuals, which become negative at high acceleration and remain modest at low acceleration. This failure was not interpreted as a refutation of the residual, but as evidence that the residual does not behave as a fundamental acceleration floor. Instead it behaves as a medium whose anisotropic stress is switched on only under specific local conditions—precisely the rheological picture developed here.

The three consistency conditions of the unified framework are satisfied at the level of coherence and order of magnitude: (i) the cosmological sector remains compatible with a dark-energy–like equation of state; (ii) the galactic Δg amplitude implied by $\eta_{\rm eff} \sim 4 \times 10^{-2}\,{\rm kg\,m^{-1}\,s^{-1}}$ is of the required order; (iii) $a_{\rm trans}$ is compatible with $cH_0/2\pi$. The framework is therefore viable, while remaining phenomenological in the parameters that fix the amplitude of the rheological response.

6 Conclusions

We have constructed a covariant rheological description of the Cosmological Dissipative Residual and reduced it to an observable estimator in the thin-disk limit. A systematic study of 175 SPARC galaxies shows that the residual contribution is selectively activated at low baryonic acceleration and suppressed at high acceleration, in agreement with the theoretical activation condition. The median effective viscosity and the transition scale extracted from the data are compatible with a cosmological origin of the medium.

These results strengthen the hypothesis that dark-matter–like phenomenology can emerge as a rheological response of the same continuous medium that produces dark-energy–like behaviour on large scales. A fully quantitative account of galactic rotation curves within the CDR framework is left for subsequent work.

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