

Gravitational Rheology: A Covariant Framework for Emergent Dark Matter Phenomena

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Abstract

We present a covariant effective framework in which galactic-scale dark-matter phenomenology emerges from a non-Newtonian, stress-dependent response of a residual spacetime medium, rather than from additional particle species or modifications of the gravitational force law. The Residual is modeled as a relativistic fluid endowed with a shear-activated, pseudoplastic (shear-thinning) rheology, whose effective viscosity increases in regions of low invariant acceleration and becomes negligible in high-acceleration environments. This behavior introduces a characteristic acceleration scale a_0 , interpreted as an intrinsic rheological property of the medium rather than as a modification of gravity.

In the non-relativistic, quasi-stationary regime relevant for disk galaxies, the viscous response of the Residual contributes an effective force that alters baryonic dynamics without invoking an extended dark matter halo. We show that this mechanism naturally yields asymptotically flat rotation curves and that the baryonic Tully–Fisher relation arises as a dynamical attractor in the viscosity-dominated regime. The resulting scaling is independent of detailed baryonic distributions and requires no galaxy-by-galaxy tuning.

We further discuss the qualitative consistency of the framework with key observational benchmarks, including cluster mergers such as the Bullet Cluster and the formation of cored density profiles in low-mass galaxies. These results suggest that a stress-activated, non-Newtonian response of spacetime may provide a viable and unified effective description of dark-matter-like phenomena across galactic scales.

Keywords: Emergent dark matter, Galactic dynamics, Relativistic fluid dynamics, Non-Newtonian spacetime, Viscous spacetime.

Introduction

The nature of dark matter remains one of the central open problems in contemporary cosmology[4]. While the standard cold dark matter (CDM) paradigm has achieved remarkable success on large cosmological scales, persistent tensions

arise at galactic and sub-galactic scales[1,3], including the cusp–core problem, the diversity of rotation curves, and the tight empirical correlation embodied in the baryonic Tully–Fisher relation. These challenges have motivated the exploration of alternative or effective descriptions of dark-matter phenomenology that do not rely exclusively on collisionless particle candidates. In parallel, a growing body of work has emphasized the potential role of effective, macroscopic descriptions of the cosmic medium[2], particularly in contexts where microscopic degrees of freedom remain unknown or inaccessible. In this spirit, non-ideal fluid approaches have been proposed as phenomenological tools capable of capturing emergent gravitational behavior without committing to specific particle models. Such descriptions are especially appealing at late cosmological times, where galactic systems evolve slowly and admit quasi-stationary treatments. In a previous work (hereafter Paper I), we introduced the concept of a Cosmological Dissipative Residual (hereafter, the Residual), modeled as a relativistic, non-ideal effective fluid. In that framework, the Residual was shown to admit a dissipative but adiabatic description, characterized by an effective stress–energy tensor with a non-ideal pressure component, while remaining thermodynamically isolated and covariantly conserved. Importantly, the formulation did not invoke new particles or modifications of gravity, but rather treated dissipation as an emergent, macroscopic property of the medium. The present work builds upon this framework and explores a distinct dynamical regime of the same Residual medium, relevant at galactic scales. We propose that dark-matter-like phenomenology can be understood as arising from a viscosity-dominated phase of the Residual, activated under sufficiently strong gravitational stress generated by baryonic matter. In this regime, the medium develops an effective, stress-dependent viscosity that alters galactic dynamics without introducing additional mass components. The resulting behavior mimics that conventionally attributed to dark matter halos, while remaining fully consistent with a covariant, effective-fluid description. Crucially, the constitutive relation governing the viscous response of the Residual is formulated in a manifestly covariant manner, depending on the invariant magnitude of the fluid four-acceleration. In the non-relativistic, quasi-stationary limit relevant for galactic systems, this formulation naturally reproduces the phenomenology associated with low-acceleration regimes. We show that, for a linear reological response, the model admits an attractor solution that yields the baryonic Tully–Fisher relation without fine-tuning. Furthermore, the viscous nature of the medium provides a natural mechanism for core formation in dwarf galaxies, alleviating the cusp–core tension. This paper is deliberately restricted to late-time, galactic-scale dynamics. We do not address early-Universe cosmology, cosmic microwave background constraints, or structure formation at linear scales. Our goal is more modest but sharply defined: to demonstrate that a covariant, dissipative effective medium—already motivated at the cosmological level—can account for key galactic observations traditionally attributed to particle dark matter. In doing so, we aim to provide a consistent and economical effective description of dark-matter phenomenology, grounded in macroscopic physics and subject to clear domains of validity.

The Residual Medium as an Effective Fluid

In this work we model the Residual Cosmological Medium (hereafter, the Residual) as a relativistic effective fluid, intended to capture macroscopic gravitational phenomena without reference to microscopic particle degrees of freedom. The Residual is assumed to be a single, continuous entity permeating spacetime, whose dynamical behavior depends on the local gravitational environment and stress conditions. No additional matter species or modifications of the Einstein field equations are introduced. At the level of large-scale dynamics, the Residual is described by an effective stress–energy tensor of the form [5,7]

$$T_{\mu\nu}^{(\text{Res})} = \rho u_\mu u_\nu + (p + \Pi) \Delta_{\mu\nu}$$

where ρ is the effective energy density, p is the equilibrium pressure, Π is a non-ideal (dissipative) pressure contribution, $u_\mu u_\nu$ is the four-velocity of the effective fluid, and

$$\Delta_{\mu\nu} = g_{\mu\nu} + u_\mu u_\nu$$

is the spatial projection tensor [9]. This form corresponds to an isotropic, non-ideal relativistic fluid, appropriate for regimes where shear stresses can be treated effectively through scalar dissipation. The Residual is assumed to be thermodynamically isolated, in the sense that it does not exchange heat or particles with other cosmic components. As a consequence, its evolution is adiabatic despite the presence of dissipative terms: the non-ideal pressure Π represents an effective macroscopic response to spacetime dynamics rather than microscopic entropy production. This assumption is consistent with the absence of resolvable internal degrees of freedom and ensures compatibility with the covariant conservation law [8]

$$\nabla^\mu T_{\mu\nu}^{(\text{Res})} = 0$$

Within this effective description, the Residual admits different dynamical regimes depending on the local stress and kinematic conditions. In particular, we distinguish between two limiting behaviors, which should be understood not as distinct substances but as states of aggregation of the same underlying medium:

- Low-stress (isotropic) regime — At sufficiently small velocity gradients and accelerations, the Residual behaves as an almost isotropic fluid with negligible viscous response. In this regime, the effective pressure is dominated by its equilibrium component, and the medium acts smoothly on large scales. This behavior corresponds to the cosmological phase discussed in Paper I.
- High-stress (viscosity-dominated) regime — Under strong gravitational stress, such as that induced by baryonic structures in galaxies, the Residual develops a significant viscous response. In this regime, the non-ideal contribution Π dominates the effective stress–energy tensor, leading to anisotropic dynamical effects at the level of galactic motion. This viscosity-dominated state will be shown to reproduce the phenomenology commonly attributed to dark matter.

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The transition between these regimes is continuous and driven by local kinematic invariants rather than by explicit phase boundaries. Conceptually, this behavior is analogous to stress-activated transitions in complex fluids, where a medium exhibits qualitatively different responses depending on the applied shear or acceleration. Importantly, no new fields or degrees of freedom are introduced across this transition; the change is entirely encoded in the constitutive properties of the Residual.

Throughout this work we restrict attention to late-time, non-relativistic, quasi-stationary galactic systems, where the Residual can be consistently treated as an effective fluid interacting gravitationally with baryonic matter. The precise form of the constitutive relation governing the viscous response of the medium, and its covariant formulation, will be introduced in the next section.

Covariant Constitutive Relation

The macroscopic response of the Residual medium is described by an effective viscosity whose value depends on the local gravitational stress experienced by the fluid. In order to preserve general covariance, we formulate the constitutive relation in terms of invariant kinematic quantities associated with the fluid flow[9]. In particular, we consider the invariant magnitude of the four-acceleration,

$$A^\mu = u^\nu \nabla_\nu u^\mu, \quad \mathcal{A} \equiv \sqrt{-A_\mu A^\mu}$$

which provides a covariant measure of the gravitational acceleration acting on the medium.

We postulate that the effective viscosity of the Residual exhibits a shear-thinning (pseudoplastic) behavior, such that viscous effects are negligible in high-acceleration regimes and become dominant only when the gravitational stress falls below a characteristic threshold. The constitutive relation is therefore taken to be

$$\eta_{\text{eff}}(\mathcal{A}) = \eta_0 \left[\frac{1}{1 + \left(\frac{\mathcal{A}}{a_0}\right)^\gamma} \right]$$

where η_0 is the maximum (low-acceleration) viscosity of the Residual, a_0 is a characteristic acceleration scale, and $\gamma > 0$ is a dimensionless rheological index.

In the limit $\mathcal{A} \gg a_0$, corresponding to strongly bound or high-acceleration systems such as the Solar System, the effective viscosity is strongly suppressed,

$$\eta_{\text{eff}} \rightarrow$$

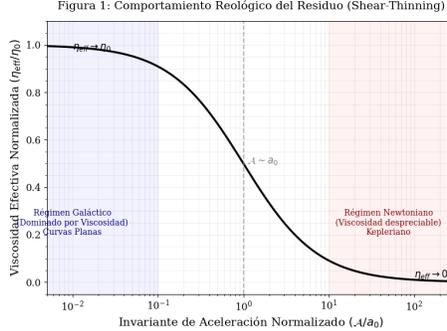


Figure 1: Figure 1. Effective viscosity of the Residual medium as a function of the invariant acceleration \mathcal{A} , normalized to the intrinsic rheological scale η_0 . The Residual exhibits a shear-thinning behavior: viscosity is suppressed in high-acceleration environments ($\mathcal{A} \gg a_0$), ensuring recovery of the Newtonian limit, while saturating in the low-acceleration regime (\mathcal{A} less than similar to a_0) relevant for galactic outskirts. This transition underlies the emergence of dark-matter-like phenomenology without introducing additional mass components.

ensuring the recovery of standard Newtonian and relativistic dynamics. Conversely, in the low-acceleration regime $\mathcal{A} \ll a_0$, the viscosity saturates to its maximal value η_0 , activating the viscosity-dominated phase of the Residual medium.

Although the scale a_0 plays a phenomenological role analogous to the critical acceleration appearing in MOND-like frameworks, it is not introduced here as a modification of gravity. Instead, a_0 is interpreted as an intrinsic rheological property of the Residual medium, marking the transition between inertial and viscosity-dominated response regimes.

It is important to clarify the physical interpretation of the viscosity parameter η introduced in the constitutive relation. In the present framework, η does not represent a microscopic transport coefficient associated with particle collisions or thermal dissipation. Rather, it should be understood as an effective, macroscopic parameter encoding the geometric response of the Residual medium to anisotropic stress[7].

Dimensionally, η carries the units of shear viscosity, reflecting its role in relating stress to the rate of strain[6]. However, its origin is gravitational and collective, emerging from coarse-grained spacetime dynamics rather than from underlying microphysical degrees of freedom. As such, variations in η_{eff} do not signal a breakdown of general covariance, but instead characterize different rheological regimes of the same underlying medium.

The baseline value η_0 defines an intrinsic scale of the Residual medium, while departures from this value encode the transition between Newtonian and viscosity-dominated dynamics.

Galactic Dynamics and the Viscous Regime

We now apply the covariant constitutive framework developed in the previous section to the dynamics of late-time galactic systems. Our focus is restricted to non-relativistic, quasi-stationary galaxies, where baryonic matter dominates the gravitational potential and the Residual medium responds as an effective, slowly evolving fluid. In this regime, relativistic corrections are negligible, and time derivatives can be treated perturbatively with respect to spatial gradients.

Effective equations of motion

The dynamics of baryonic matter embedded in the Residual medium are governed by the conservation of the total stress-energy tensor. Since baryons are assumed to interact with the Residual only gravitationally, their equations of motion can be written as an effective force balance between gravitational acceleration and the response induced by the viscous Residual background. In the non-relativistic limit, the spatial components of the conservation equation

$$\nabla^\mu T_{\mu\nu}^{(\text{Res})} = 0$$

lead to an effective momentum equation of the form

$$\rho_{\text{bar}} \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\rho_{\text{bar}} \nabla \Phi + \nabla \cdot \boldsymbol{\sigma}_{\text{eff}}$$

where ρ_{bar} and \mathbf{v} denote the baryonic density and velocity field, Φ is the Newtonian gravitational potential sourced by baryons, and $\boldsymbol{\sigma}_{\text{eff}}$ is the effective viscous stress tensor induced by the Residual medium.

For isotropic flows in rotationally supported systems, the dominant contribution to the stress tensor can be parametrized as

$$\boldsymbol{\sigma}_{\text{eff}} \simeq \eta_{\text{eff}} \boldsymbol{\sigma}$$

where $\boldsymbol{\sigma}$ denotes the rate-of-strain tensor associated with differential rotation, and η_{eff} is the stress-dependent viscosity defined in Sec. 3. In contrast to ordinary fluids, this term represents a geometric backreaction of the Residual medium rather than a microscopic dissipative drag.

Quasi-stationary rotational equilibrium

For disk galaxies in dynamical equilibrium, the dominant balance occurs between centrifugal acceleration, gravitational attraction, and the viscous response of the Residual. Neglecting explicit time dependence and radial inflows, the radial component of the effective force balance reduces to

$$\frac{v^2(r)}{r} = \frac{GM_{\text{bar}}(r)}{r^2} + \frac{1}{\rho_{\text{bar}}} \nabla \cdot (\eta_{\text{eff}} \boldsymbol{\sigma})$$

where $v(r)$ is the circular velocity and $M_{\text{bar}}(r)$ is the enclosed baryonic mass.

The second term on the right-hand side represents an effective support term arising from anisotropic stresses in the Residual medium. Despite its viscous origin, this contribution acts as a stabilizing force in quasi-stationary configurations, supplementing the Newtonian gravitational attraction rather than opposing orbital motion.

Low-acceleration viscous dominance

The constitutive relation introduced in Sec. 3 implies a shear-thinning behavior of the Residual medium: the effective viscosity is suppressed in regions of large invariant acceleration $\mathcal{A} \gg a_0$, and enhanced in regions where \mathcal{A} less than similar to a_0 [10,12]. As a result, viscous effects are negligible in high-acceleration environments such as the inner regions of galaxies or the Solar System, ensuring recovery of the Newtonian limit.

In the outskirts of galaxies and in low-mass systems, where \mathcal{A} less than similar to a_0 the effective viscosity approaches its maximal value, and the viscous term can dominate the force balance. In this regime, the circular velocity profile naturally approaches an asymptotically flat form,

$$v(r) \simeq \text{const.}$$

without invoking an extended dark matter halo. This behavior arises dynamically from the stress-activated response of the Residual medium and is largely insensitive to the detailed baryonic mass distribution at large radii[11].

Stability and virial considerations

Although viscous stresses are present, the quasi-stationary nature of galactic systems ensures that the dissipation involved is adiabatic and geometric, rather than thermal. No net energy loss occurs over orbital timescales, and the system evolves toward stable configurations determined by the large-scale structure of the Residual medium.

In this effective description, galaxies settle into attractor states in which viscous stresses contribute to the generalized pressure support. The virial balance is therefore preserved in a time-averaged sense, with the Residual medium acting as a stabilizing background rather than as a sink of mechanical energy. The implications of this attractor behavior become particularly transparent in the context of the baryonic Tully–Fisher relation, discussed in the next section.

Emergence of the Baryonic Tully–Fisher Relation

One of the most stringent empirical constraints on galactic dynamics is the baryonic Tully–Fisher relation (BTFR), which establishes a tight correlation between the total baryonic mass of a galaxy and its asymptotic rotation velocity,

$$v^4 \propto M_{\text{bar}}$$

Any viable effective description of dark-matter phenomenology at galactic scales must reproduce this relation without fine-tuning or system-dependent parameters.

Within the present framework, the BTFR emerges naturally as an attractor solution in the low-acceleration, viscosity-dominated regime of the Residual medium. We focus on the asymptotic regions of rotationally supported disk galaxies, where \mathcal{A} less than similar to a_0 and viscous stresses dominate over the Newtonian contribution.

Scaling in the viscous regime

In the quasi-stationary limit discussed in Sec. 4, the radial force balance for circular orbits reduces to

$$\frac{v^2}{r} \simeq \frac{1}{\rho_{\text{bar}}} \nabla \cdot (\eta_{\text{eff}} \boldsymbol{\sigma})$$

where the viscous term provides the dominant contribution to the effective acceleration.

For rotationally supported systems, the rate-of-strain tensor scales as

$$|\boldsymbol{\sigma}| \sim \frac{v}{r}$$

while the invariant acceleration entering the constitutive relation satisfies

$$\mathcal{A} \sim \frac{v^2}{r}$$

In the low-acceleration regime $\mathcal{A} \ll a_0$, the shear-thinning constitutive relation implies that the effective viscosity saturates to its baseline value,

$$\eta_{\text{eff}} \simeq \eta_0$$

where η_0 characterizes the intrinsic rheological scale of the Residual medium.

The viscous force density therefore scales as

$$\nabla \cdot (\eta_{\text{eff}} \boldsymbol{\sigma}) \sim \eta_0 \frac{v}{r^2}$$

Attractor solution and mass scaling

Substituting this scaling into the force balance equation yields

$$\frac{v^2}{r} \sim \frac{\eta_0}{\rho_{\text{bar}}} \frac{v}{r^2}$$

Rearranging terms leads to

$$v^3 \sim \frac{\eta_0}{\rho_{\text{bar}}} \frac{1}{r}$$

At large radii, the baryonic density scales as

$$\rho_{\text{bar}} \sim \frac{M_{\text{bar}}}{r^3}$$

which implies

$$v^3 \sim \eta_0 \frac{r^2}{M_{\text{bar}}}$$

The characteristic transition radius is set by the condition $\mathcal{A} \sim a_0$, yielding $r \sim v^2/a_0$. Substituting this relation eliminates the explicit radius dependence and results in $v^4 \sim G M_{\text{bar}} a_0$, up to dimensionless factors of order unity.

Crucially, this relation depends only on universal properties of the Residual medium and the total baryonic mass, and is insensitive to the detailed distribution of baryons.

Physical interpretation

The emergence of the BTFR reflects a self-regulating mechanism intrinsic to the Residual medium. As the acceleration drops below the characteristic scale a_0 , the viscous response saturates, providing additional effective support against gravity. This drives galactic systems toward a stable attractor in which rotational velocity and baryonic mass are tightly correlated.

Unlike phenomenological modifications of gravity, this mechanism leaves the Newtonian force law unchanged. The BTFR arises as an emergent consequence of stress-mediated dynamics in the viscosity-dominated phase of the Residual.

Robustness of the result

The derivation relies only on quasi-stationarity, rotational support, and saturation of the effective viscosity at low acceleration. Deviations from strict linearity in the constitutive relation introduce subleading corrections but do not destroy the attractor structure. Consequently, the BTFR is robust across a wide range of galactic environments, including low-surface-brightness and dwarf galaxies.

Causality, Thermodynamics, and Regime of Validity

The effective-fluid description developed in the previous sections relies on a first-order dissipative formulation to capture the macroscopic response of the Residual medium. While such approaches are widely used in relativistic hydrodynamics, they are known to raise concerns regarding causality and stability when applied outside their domain of validity. In this section we clarify the thermodynamic consistency of the model, address potential issues related to causality, and explicitly delineate the regime in which the present framework applies.

Adiabatic dissipation and thermodynamic consistency

Despite the presence of dissipative terms in the effective stress-energy tensor, the evolution of the Residual medium is assumed to be adiabatic. This assumption reflects the absence of resolvable microscopic degrees of freedom capable of storing or transporting heat. The non-ideal pressure contribution introduced in Secs. 2–4 represents a macroscopic, geometric response to gravitational stress rather than conventional thermal dissipation. Formally, the thermodynamic isolation of the Residual implies the covariant conservation of its entropy current,

$$\nabla_\mu (su^\mu) = 0$$

where s denotes the effective entropy density. The dissipative dynamics encoded in the constitutive relation therefore do not correspond to entropy production at the microscopic level, but instead describe a redistribution of energy-momentum within the effective medium. This interpretation is consistent with the treatment of the Residual as a coarse-grained description, valid only at scales much larger than any putative microscopic structure[19].

As a result, the viscous response discussed in this work does not violate the second law of thermodynamics, nor does it imply irreversible heating or secular energy loss in galactic systems. The dissipation is geometric and stationary, supporting stable configurations rather than driving evolution away from equilibrium.

Causality and first-order hydrodynamics

It is well known that first-order relativistic hydrodynamic theories, such as those formulated in the Eckart or Landau–Lifshitz frames, can exhibit acausal signal propagation and instabilities when applied to rapidly evolving or high-frequency

regimes. However, these pathologies arise outside the domain in which such theories are intended to operate.

The present model is explicitly restricted to the quasi-stationary limit, appropriate for late-time galactic dynamics. The characteristic timescale for the evolution of galactic structures,

$$t_{\text{gal}} \sim 10^9\text{--}10^{10} \text{ yr}$$

is many orders of magnitude larger than any plausible microscopic relaxation timescale associated with the Residual medium. In this regime, transient modes decay rapidly, and the first-order constitutive relations converge to the predictions of fully causal second-order formulations, such as the Israel–Stewart theory.

Accordingly, the use of a first-order effective description should be understood as a mean-field approximation, valid only in the long-wavelength, low-frequency limit. No claims are made regarding the behavior of the Residual under rapid perturbations, strong shocks, or highly dynamical cosmological conditions.

Generalized virial balance

A related concern is whether the presence of viscous terms is compatible with the long-term stability of galactic systems and with generalized virial relations. In the present framework, viscous stresses do not act as sinks of mechanical energy but instead contribute to the effective pressure support of the system.

Because the viscous response is stress-activated and saturates in the low-acceleration regime, galaxies evolve toward attractor configurations in which centrifugal support, gravitational attraction, and viscous stresses balance in a time-averaged sense. As a result, generalized virial relations remain valid, with the viscous contribution entering as an additional effective term rather than leading to secular dissipation.

This behavior is consistent with the observed longevity and stability of galactic rotation curves and further supports the interpretation of the viscosity-dominated regime as a stationary phase of the Residual medium.

Domain of applicability

For clarity, we summarize the explicit assumptions and limitations of the present model:

- Late-time regime: The framework applies only to low-redshift, evolved galactic systems[17,18].
- Quasi-stationarity: Rapid transients and violent dynamical events are outside the scope of this work.
- Non-relativistic dynamics: Velocities are assumed to be much smaller than the speed of light.

- Effective description: The Residual is treated as a macroscopic medium, without specifying microscopic degrees of freedom.
- No early-Universe claims: The model does not address cosmic microwave background constraints, inflation, or linear structure formation.

Within these limits, the framework provides a consistent and predictive effective description of galactic dynamics, capable of reproducing key dark-matter-like phenomenology without invoking particle dark matter or modifications of gravity.

Observational Implications: Cluster Collisions and Galactic Cores

Any effective description intended to reproduce dark-matter-like phenomenology must confront a set of well-known observational benchmarks. In this section we discuss the implications of the viscosity-dominated Residual framework for two particularly relevant cases: cluster mergers, exemplified by the Bullet Cluster, and the internal structure of low-mass galaxies, where the cusp-core problem arises. Our goal is not to provide a comprehensive fit to all available data, but to assess qualitative consistency within the explicitly stated domain of validity of the model.

Cluster collisions and the Bullet Cluster

The Bullet Cluster (1E 0657–56) is frequently cited as a critical challenge for alternative models of dark matter, as gravitational lensing observations reveal a clear separation between the baryonic gas component and the dominant gravitating mass during a high-velocity cluster collision[16]. Any viable framework must therefore explain why the effective gravitational potential appears to follow the collisionless component rather than the shocked intracluster gas.

In the present model, the Residual medium is assumed to be non-collisional with itself and to interact with baryonic matter exclusively through gravity. As a consequence, during a cluster collision the viscosity-dominated response of the Residual is not sourced by hydrodynamic shocks in the baryonic gas, but by the large-scale gravitational stress associated with the cluster-scale mass distribution,

$$\mathcal{A}^2 \equiv a_\mu a^\mu = u^\nu \nabla_\nu u^\mu u^\lambda \nabla_\lambda u_\mu$$

which governs the activation of the effective viscosity.

Since the viscous response of the Residual depends on the invariant acceleration of the effective flow rather than on direct contact interactions, the medium does not experience ram pressure or collisional drag analogous to that affecting the intracluster gas. The effective stress distribution therefore remains aligned with the dominant gravitational potential wells traced by the collisionless components, leading to lensing maps consistent with observations,

$$\nabla^2 \Phi_{\text{eff}} \simeq 4\pi G (\rho_{\text{bar}} + \rho_{\text{res}}^{\text{eff}})$$

where the effective contribution $\rho_{\text{res}}^{\text{eff}}$ follows the large-scale potential rather than the shocked gas distribution.

Importantly, the extreme dynamical conditions present in cluster mergers lie close to the boundary of the quasi-stationary regime assumed in this work. While the present framework is not designed to model the full time-dependent evolution of such events, its qualitative behavior does not contradict the observed separation between baryonic and lensing mass. A detailed, time-dependent treatment of cluster collisions within a fully causal extension of the theory is left for future work.

Core formation in dwarf and low-surface-brightness galaxies

At galactic scales, one of the most persistent tensions within the standard cold matter paradigm is the cusp–core problem: numerical simulations predict steep central density cusps in low-mass halos, whereas observations of dwarf and low-surface-brightness galaxies favor shallow, core-like profiles[15].

Within the viscosity-dominated Residual framework, core formation arises naturally as a consequence of the stress-dependent response of the medium. In regions of low gravitational acceleration and modest velocity gradients, the effective viscosity increases and acts to redistribute momentum over macroscopic scales. This process smooths the effective gravitational response in the inner regions of galaxies, suppressing the formation of cuspy velocity profiles,

$$|\nabla \cdot (\eta_{\text{eff}} \boldsymbol{\sigma})| < |\nabla \Phi_{\text{N}}| \quad (r \rightarrow 0)$$

where $\boldsymbol{\sigma}$ denotes the shear tensor and Φ_{N} the Newtonian potential sourced by baryons.

Unlike feedback-driven baryonic solutions, which rely on repeated energetic outflows, the mechanism proposed here is intrinsic to the effective medium and does not require fine-tuned star formation histories. As a result, core-like behavior emerges generically in low-mass systems, while more massive galaxies—with higher characteristic accelerations—remain closer to the Newtonian regime.

Diversity of rotation curves

The observed diversity of galactic rotation curves, even among galaxies with similar baryonic masses, poses an additional challenge for simple halo models[14]. In the present framework, this diversity is accommodated through the dependence of the viscous response on local kinematic conditions rather than solely on total mass.

Variations in baryonic distribution, surface density, and disk scale length lead to different acceleration profiles, which in turn modulate the effective viscosity of the Residual,

$$\eta_{\text{eff}} = \eta_{\text{eff}}(\mathcal{A}, \nabla u)$$

leading to distinct dynamical equilibria.

Consequently, galaxies with similar baryonic masses may exhibit distinct rotation curve shapes while still converging to the same asymptotic scaling re-

lation discussed in Sec. 5[13]. This behavior is consistent with observational trends and arises without invoking stochastic halo properties.

Unified Perspective: Linking Galactic and Cosmological Scales

The effective description developed in this work is not independent of the cosmological framework previously introduced in Paper I, but rather represents its extension into a distinct dynamical regime. In the cosmological setting, the dissipative behavior of the Residual medium was characterized by a dimensionless parameter ξ , encoding the net effect of macroscopic dissipation on the homogeneous expansion.

The relationship between the two descriptions becomes transparent when the viscosity η_{eff} is interpreted as a local, stress-dependent quantity whose cosmological counterpart arises through volume averaging. In an expanding, nearly homogeneous universe dominated by the Hubble flow, local gravitational accelerations and shear stresses are negligible, and the Residual medium effectively samples its baseline rheological state. In this limit, the averaged effect of η_{eff} manifests as the cosmological dissipation parameter ξ .

By contrast, in the presence of galactic potential wells, local gravitational stresses activate the viscosity-dominated phase of the Residual, and the full spatial dependence of η_{eff} becomes dynamically relevant. Dark-matter-like behavior thus emerges as a local manifestation of the same underlying medium whose averaged properties govern cosmological evolution. This unified perspective clarifies that the phenomenology attributed to dark energy and dark matter corresponds to different dynamical regimes of a single effective medium, rather than to independent physical components.

Discussion and Limitations

The framework developed in this work provides an effective, macroscopic description of dark-matter-like phenomenology in terms of a viscosity-dominated phase of the Residual cosmological medium. While the model reproduces several key galactic-scale observations without invoking particle dark matter or modifications of gravity, it is important to critically assess its scope, limitations, and broader implications.

A central strength of the approach lies in its economy. The same underlying medium introduced at the cosmological level admits distinct dynamical regimes depending on local gravitational stress, eliminating the need to postulate multiple independent dark components. In this sense, dark energy and dark matter emerge as different phases of a single effective entity, with the latter arising naturally in environments where viscous stresses dominate the dynamics. This unification is achieved without introducing new fundamental fields or altering the structure of General Relativity.

At the same time, the present framework remains explicitly phenomenological. The constitutive relation governing the viscous response of the Residual is introduced at the macroscopic level and is not derived from a microscopic theory. While this is consistent with the effective-field-theory philosophy adopted throughout the paper, it leaves open the question of whether such a medium can arise from a more fundamental description, and if so, what microscopic degrees of freedom might underlie it. Addressing this question will require progress beyond the scope of the present work.

Another important limitation concerns the restricted dynamical regime considered here. The model is explicitly designed for late-time, quasi-stationary galactic systems. It does not address early-Universe cosmology, the growth of linear perturbations, or precision constraints from the cosmic microwave background. Consequently, the present results should not be interpreted as a complete alternative to the standard cosmological model, but rather as an effective description of galactic dynamics within a well-defined domain of applicability.

Similarly, while the qualitative consistency with observations of cluster mergers and core formation has been discussed, the framework has not yet been tested against detailed numerical simulations or comprehensive observational datasets. In particular, time-dependent phenomena, such as violent mergers or rapid structural evolution, require a fully causal extension of the theory and lie beyond the reach of the first-order hydrodynamic treatment employed here.

Finally, it is worth emphasizing that the viscosity-dominated interpretation proposed in this work is not intended to replace particle dark matter by fiat, but to highlight the possibility that at least part of the observed dark-matter phenomenology may admit an effective, emergent explanation. Whether such an explanation ultimately coexists with, complements, or supplants particle-based models remains an open question that can only be resolved through further theoretical development and observational scrutiny.

Conclusions

In this work we have explored a viscosity-dominated regime of the Residual cosmological medium as an effective description of dark-matter-like phenomenology at galactic scales. Building on a covariant, non-ideal fluid framework previously introduced at the cosmological level[20], we have shown that the same underlying medium admits distinct dynamical phases depending on the local gravitational stress sourced by baryonic matter.

By formulating the constitutive relation in terms of invariant kinematic quantities, we ensured general covariance while recovering the appropriate Newtonian limit relevant for galactic dynamics. Within this framework, the effective viscous response of the Residual modifies the equilibrium of rotating systems in a manner that reproduces flat rotation curves and admits an attractor solution consistent with the baryonic Tully–Fisher relation. Crucially, this behavior arises without introducing additional mass components or modifying the gravitational field equations.

The dissipative dynamics considered here are adiabatic and quasi-stationary, reflecting the absence of resolvable microscopic degrees of freedom and justifying the use of a first-order effective hydrodynamic description within a clearly defined regime of validity. We have further argued that the viscosity-dominated phase naturally suppresses central cusps in low-mass galaxies and remains qualitatively consistent with observations of cluster-scale systems, including merging clusters such as the Bullet Cluster.

The framework presented here is intentionally limited in scope. It does not address early-Universe cosmology, linear structure formation, or high-frequency dynamical phenomena. Instead, it offers a focused and economical effective description of late-time galactic dynamics, grounded in macroscopic physics and open to systematic refinement. Future work will be required to explore causal extensions of the theory, confront precision observational data, and investigate possible microscopic realizations of the Residual medium.

Taken together, these results suggest that at least part of the phenomenology commonly attributed to dark matter may admit an emergent, hydrodynamic interpretation. Whether such an interpretation ultimately complements or challenges particle-based models remains an open and testable question.

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