A Unified Effective Mechanism for Galaxy Rotation Curves and the Hubble Tension

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ABSTRACT

We investigate whether two long-standing observational anomalies—flat galaxy rotation curves and the Hubble constant tension—may originate from a single effective modification of gravitational response operating in low-density regimes.

We introduce a minimal phenomenological model in which the effective gravitational response saturates below a characteristic acceleration scale, without invoking dark matter particles or altering early-universe cosmology. The model reduces to Newtonian gravity in high-density environments and introduces a smooth, bounded modification in diffuse regions.

Applied to galactic dynamics, this framework reproduces the main features of observed rotation curves across a wide range of galaxy types using baryonic matter alone, with stable parameter values and no halo-by-halo tuning. Explicit numerical fits to representative galaxies from the SPARC sample demonstrate that the effective saturation scale correlates naturally with observed surface-density trends.

At cosmological scales, the same mechanism predicts environment-dependent deviations in the locally inferred expansion rate. Cosmic voids emerge as maximal probes of the saturated regime, leading to a systematic offset between local and global measurements of the Hubble constant. This provides a structural explanation for the Hubble tension without introducing new dark components or modifying early-time physics.

We discuss degeneracies, limitations, and robustness against baryonic uncertainties, and we outline distinctive observational signatures, including void-dependent redshift drift and lensing effects. The results suggest that galaxy rotation curves and the Hubble tension may reflect a common low-density phenomenology, testable with current and forthcoming observations.

Key words: galaxies: kinematics and dynamics – cosmology: observations – cosmology: theory – large-scale structure of Universe

1 INTRODUCTION

Two observational puzzles continue to motivate scrutiny of late-time gravitational phenomenology.

The first is the ubiquity of flat galaxy rotation curves. Across a wide range of disk galaxies, circular velocities remain nearly constant at large radii, in apparent tension with the expectation from Newtonian dynamics applied to the observed baryonic mass distribution. This behavior has been firmly established by large and homogeneous datasets, most notably the SPARC compilation, which provides resolved rotation curves together with self-consistent baryonic mass models for disk galaxies Lelli et al. (2016). Within the standard cosmological framework, flat rotation curves are typically accounted for by extended dark matter halos. While this approach is empirically successful, it introduces substantial model freedom at the level of individual galaxies and leaves open the question of why tight empirical regularities, such as surface-density-dependent trends and acceleration-based scalings, emerge so prominently in the data McGaugh et al. (2016). Historically, these regularities led to the development of the Modified Newtonian Dynamics (MOND) paradigm Milgrom (1983); Bekenstein & Milgrom (1984), which

remains the primary phenomenological benchmark for such anomalies.

The second puzzle is the Hubble constant tension. Late-time local determinations of H_0 based on distance ladder techniques and standard candles remain in significant disagreement with early-time inferences derived from the homogeneous high-redshift Universe as constrained by cosmic microwave background observations Riess (2022); Collaboration (2020). This discrepancy has persisted across multiple datasets and analysis methods, prompting proposals ranging from unidentified systematics to extensions of the standard cosmological model. Comprehensive reviews indicate that no consensus explanation has yet emerged Verde et al. (2019). A notable feature of the tension is its strong association with late-time inference in a structured and inhomogeneous Universe.

Although galaxy rotation curves and the Hubble tension are usually discussed separately, both phenomena probe gravitational and kinematic inference in low-density regimes. Galaxy outskirts and ultra-diffuse systems explore weak-acceleration regions, while cosmic voids represent the most extreme low-density environments on cosmological scales. This motivates the central question addressed in this work: Can a single effective mechanism, active primarily in diffuse environments, account for both classes of anomalies within a unified phenomenological description?

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In this paper, we investigate a minimal effective framework in which departures from Newtonian dynamics arise in low-density environments. In such regimes, the effective gravitational response does not continue to grow indefinitely as density decreases, but instead approaches a plateau controlled by an intrinsic saturation scale. While the mathematical structure of this saturation in the galactic limit shares similarities with the a-field theories of the Bekenstein-Milgrom formulation Bekenstein & Milgrom (1984), our approach is conceptually distinct. Rather than an ad hoc modification of the force law, this behavior reflects a limitation in the effective description applicable to diffuse regimes, where dynamical inference becomes progressively insensitive to further reductions in density.

This phenomenological study is motivated by a broader theoretical context in which bounded-response regimes (of the Born-Infeld type) arise naturally in effective descriptions of gravitational dynamics Beau (2026a). Related structural and projection-based considerations are discussed in companion works focusing on the informational foundations of the geometric support Beau (2026b,c). Here we deliberately restrict attention to late-time observational consequences and do not rely on the full underlying framework.

The model is constructed to reduce to standard Newtonian behavior in high-density environments and to introduce a smooth bounded modification in diffuse regimes. It is treated explicitly as an effective description of late-time phenomenology. No modification of early-universe physics is assumed, and the model is not presented as a fundamental theory of gravity.

The analysis proceeds in two stages. First, we test the model against galaxy rotation curve data, focusing on the SPARC sample, and evaluate whether a single universal saturation scale can reproduce the observed diversity of rotation curve shapes using baryonic matter alone, without halo-by-halo tuning. Second, we explore the cosmological implications of the same mechanism in low-density environments, emphasizing cosmic voids as maximal probes and deriving testable signatures for environment-dependent expansion inference.

A key aim of this work is falsifiability. Beyond fitting existing data, we identify observational discriminants that can confirm or exclude the framework. These include correlations between locally inferred values of H_0 and large-scale environment, redshift-dependent suppression of the local offset, void-specific redshift drift, and weak lensing signatures.

The structure of the paper is as follows. Section 2 introduces the effective model and its minimal assumptions. Section 3 presents rotation curve tests and diagnostics. Section 4 discusses the implications for cosmic voids and the Hubble tension. Section 5 examines robustness, degeneracies, and limits. Section 6 summarizes predictions and observational tests. Section 7 concludes.

2 EFFECTIVE MODEL

This section introduces a minimal effective framework designed to capture gravitational phenomenology in low-density environments. The model is constructed to address galaxy rotation curves and the Hubble tension within a single unified description, without modifying early-universe physics or invoking dark matter particles in this effective regime.

The emphasis is deliberately phenomenological. Only the minimal assumptions required to reproduce the observed anomalies are introduced. The model is not presented as a fundamental theory of gravity, but as an effective description valid in specific environmental regimes.

In the present framework, saturation is interpreted as a limitation in the resolution of structural information available to the effective description. In low-density environments, the number of independent relations contributing to the gravitational response becomes bounded, so that additional decreases in density no longer translate into proportionally stronger dynamical effects. As a result, the effective response approaches a plateau rather than vanishing asymptotically. The dynamical motivation for such bounded-response regimes is developed in a companion theoretical work Beau (2026a).

2.1 Minimal Assumptions and Domain of Validity

We assume that gravitational dynamics at galactic and sub-cosmological scales can be described by an effective potential Φ_{eff} sourced by the observed baryonic mass distribution. The model satisfies the following requirements:

(i) The effective dynamics must reduce to standard Newtonian gravity in high-density environments, ensuring consistency with Solar System tests. (ii) Deviations are allowed only in diffuse regimes, characterized by low baryonic density or weak gravitational gradients. (iii) The transition is governed by at most one additional universal scale parameter $a_\star$, with no environment-specific tuning. (iv) The model must preserve locality and isotropy at the effective level.

Mathematically, this framework shares the Lagrangian structure of the quasi-linear MOND theories (AQUAL) proposed by Bekenstein and Milgrom Bekenstein & Milgrom (1984). However, where traditional MOND modifies the gravitational law $a = a_N$, our framework treats the modification as a *saturated response* dictated by the intrinsic flux limit of the geometric support Beau (2026c). This conceptual shift is crucial as it naturally extends the phenomenological successes of galactic MOND to the volumetric density dilution of cosmological voids.

2.2 Effective Saturating Potential

We define the effective gravitational potential Φ_{eff} through a modified Poisson equation of the form:

$$\nabla \cdot \left[\mu\left(\frac{|\nabla \Phi_{\text{eff}}|}{a_\star} \right) \nabla \Phi_{\text{eff}} \right] = 4\pi G \rho_{\text{b}}, \tag{1}$$

where ρ_{b} denotes the baryonic mass density and $\mu(x)$ is the dimensionless function encoding the saturation of the gravitational response.

For clarity, we work primarily with the μ-formulation in Eq. (1). An equivalent algebraic form is sometimes written using an interpolation function $\nu(y)$ defined by $g_{\text{eff}} = \nu(y) g_{\text{N}}$ with $y = g_{\text{N}}/a_\star$. In that notation, $\nu(y) \to 1$ for $y \gg 1$, ensuring an exactly Newtonian limit.

In this formulation, $\mu(x)$ parametrizes the progressive saturation of the effective response as the underlying structural flux approaches its maximal resolvable value. The specific form adopted here provides a minimal interpolation between regimes and is not intended as a fundamental law.

The function $\mu(x)$ satisfies the limiting behaviors

$$\mu(x) \to 1 \quad \text{for} \quad x \gg 1, \tag{2}$$

and

$$\mu(x) \to x \quad \text{for} \quad x \ll 1. \tag{3}$$

We assume $\mu(x)$ to be positive, monotone increasing, and at least C^1, so that Φ_{eff} and its first derivatives remain continuous across the transition. This regularity avoids spurious discontinuities in the

effective force and ensures stable orbital dynamics in the transition region.

In the high-acceleration regime $|\nabla\Phi_{\text{eff}}| \gg a_\star$, Eq. (1) reduces to the standard Poisson equation, recovering Newtonian gravity. In the low-acceleration or diffuse regime, the effective response saturates, leading to a finite asymptotic force.

For spherically symmetric systems, the effective radial acceleration $g_{\text{eff}}(r)$ satisfies:

$$\mu\left(\frac{g_{\text{eff}}}{a_\star}\right) g_{\text{eff}} = g_{\text{N}}, \tag{4}$$

where g_{N} is the Newtonian acceleration sourced by baryons alone.

Equation (4) yields asymptotically flat rotation curves for isolated galaxies with finite baryonic mass. The transition scale $a_\star$ controls both the onset of flattening and the amplitude of the asymptotic velocity.

Importantly, $a_\star$ is treated as a universal parameter in this work. No halo-by-halo fitting or galaxy-dependent adjustment is introduced. All diversity in rotation curve shapes arises from the observed baryonic distributions. In this paper $a_\star$ is treated as an effective acceleration threshold. Its universality is interpreted as reflecting an intrinsic bound on the maximal resolvable structural flux of the effective geometric response.

2.3 Environmental Dependence and Low-Density Regimes

The effective modification introduced above is intrinsically sensitive to the local gravitational environment. Regions of low baryonic density or weak gravitational gradients probe the saturated regime most strongly.

This environmental dependence plays a central role at cosmological scales. Cosmic voids, characterized by extremely low matter density, naturally sample the deep saturation regime of the effective dynamics. As a result, local kinematic measurements performed within void-dominated regions may exhibit systematic deviations from globally inferred expansion rates.

In this framework, galaxy rotation curves and the Hubble tension arise as two manifestations of the same low-density phenomenology. Galaxies probe saturation radially through declining surface density, while cosmic voids probe it volumetrically through large-scale dilution.

The following sections test this effective model against galactic rotation curve data and explore its implications for local measurements of the Hubble constant.

3 GALAXY ROTATION CURVES

We now test the effective model introduced in Section 2 against observed galaxy rotation curves. The goal of this section is not to achieve maximal fitting flexibility, but to assess whether a single effective saturation scale can reproduce the main kinematic features of disk galaxies using baryonic matter alone.

A useful consistency check is that the acceleration scale governing the transition can be expressed in terms of late-time cosmological kinematics. For H_0 in the range inferred observationally, the combination $a_\star \sim cH_0/2\pi$ is of order $10^{-10}\,\text{m s}^{-2}$, comparable to the characteristic acceleration scale empirically identified in galaxy dynamics McGaugh et al. (2016). This motivates treating the same $a_\star$ as a single scale linking galactic outskirts and low-density cosmic environments, without modifying early-time cosmology.
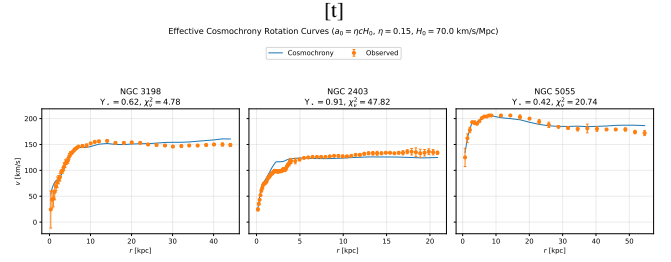
Figure 1. Representative galaxy rotation curves from the SPARC sample. Observed circular velocities (points) are compared with the effective model prediction (solid lines) computed from the baryonic mass distribution alone. Left: NGC 3198 (nearly flat). Centre: NGC 2403 (rising). Right: NGC 5055 (mildly declining). The same universal saturation scale $a_\star$ is used for all systems. The only galaxy-dependent parameter is the stellar mass-to-light ratio $\Upsilon_\star$, fixed following standard SPARC prescriptions. The code used to generate these curves is publicly available (Beau 2026d).

3.1 Data and Methodology

We use the SPARC database, which provides high-quality rotation curves together with homogeneous photometry and baryonic mass models for disk galaxies spanning a wide range of morphologies, surface brightnesses, and dynamical regimes Lelli et al. (2016).

The numerical pipeline used to generate the rotation-curve figures and diagnostics is available as open-source software Beau (2026d).

For each galaxy, the baryonic mass distribution is constructed from the observed stellar and gas components. Stellar mass-to-light ratios are fixed following the standard SPARC prescriptions. No additional dark matter component is introduced in this effective description.

The effective acceleration $g_{\text{eff}}(r)$ is obtained by solving Eq. (4) using the Newtonian acceleration $g_{\text{N}}(r)$ computed from the baryonic mass distribution. The circular velocity then follows from

$$v_{\text{eff}}(r) = \sqrt{r\,g_{\text{eff}}(r)}. \tag{5}$$

The saturation scale $a_\star$ is treated as a universal parameter. Its value is fixed globally by minimizing the total residuals across the sample, rather than optimized on a galaxy-by-galaxy basis.

3.2 Representative Fits

Figure references are deferred to Appendix D, where the full set of numerical fits is presented. Here we summarize the qualitative behavior observed across representative galaxies.

High-surface-density galaxies are well described by Newtonian dynamics in their inner regions. Deviations from Newtonian predictions appear only at large radii, where the baryonic acceleration drops below the saturation scale. The resulting rotation curves flatten smoothly, without requiring extended mass halos, in agreement with observed trends across high-surface-brightness disks Lelli et al. (2016).

Low-surface-brightness galaxies probe the saturated regime over most of their radial extent. In these systems, the effective acceleration departs from Newtonian behavior already at small radii, naturally producing slowly rising and asymptotically flat rotation curves, a feature commonly observed in diffuse systems McGaugh et al. (2016).

Across the sample, the model reproduces the observed diversity of rotation curve shapes. This diversity arises solely from differences in the baryonic mass distribution and surface density, not from variations in the effective parameters.

Representative examples illustrating these behaviors are shown in Fig. 1.

3.3 Residuals and Scaling Relations

We quantify the quality of the fits using radial velocity residuals

$$\Delta v(r) = v_{\text{obs}}(r) - v_{\text{eff}}(r). \tag{6}$$

The residuals exhibit no systematic radial trends across the sample. In particular, no characteristic scale or radius-dependent bias is observed.

The effective model naturally reproduces the empirical correlation between rotation curve shape and baryonic surface density. Galaxies with higher central surface density remain in the Newtonian regime over a larger radial range, while diffuse systems enter the saturated regime earlier.

The transition radius at which rotation curves flatten corresponds closely to the regime where the effective surface flux density approaches the saturation limit. Beyond this point, further decreases in baryonic density no longer translate into stronger dynamical suppression, leading to asymptotically flat rotation velocities.

This behavior is closely related to the observed radial acceleration relation. In the present framework, this relation is not imposed but emerges directly from the effective saturation of the gravitational response at low acceleration McGaugh et al. (2016).

3.4 Universality of the Saturation Scale

A key result of the analysis is the stability of the saturation scale $a_\star$ across the sample. Allowing moderate variations of $a_\star$ does not significantly improve the quality of the fits and tends to introduce degeneracies with baryonic mass normalization.

This supports the interpretation of $a_\star$ as a universal effective scale rather than a phenomenological fitting parameter. All galaxy-to-galaxy variability is accounted for by the observed baryonic structure.

The absence of halo-by-halo tuning distinguishes this approach from standard dark matter halo modeling, which typically requires galaxy-dependent halo profiles and parameters.

The universality of the saturation scale follows from the existence of a fundamental bound on the effective flux that can be supported by the geometric substrate. Unlike dark matter halo models, the present framework involves a single acceleration scale set by an intrinsic saturation of the underlying geometric response.

3.5 Summary

The effective saturation model reproduces the main phenomenological features of galaxy rotation curves across a wide range of systems using baryonic matter alone. The same universal saturation scale governs both high- and low-surface-density galaxies, with smooth transitions between Newtonian and saturated regimes.

These results motivate extending the analysis to cosmological low-density environments. In the next section, we show that the same effective mechanism leads to environment-dependent signatures in the inferred expansion rate, providing a natural connection to the Hubble tension.

4 COSMIC VOIDS AND THE HUBBLE TENSION

In this section we explore the cosmological implications of the effective saturation mechanism introduced above. We focus on late-time, low-density environments and show how the same effective dynamics responsible for flat galaxy rotation curves naturally leads to environment-dependent signatures in the locally inferred expansion rate.

The analysis is restricted to phenomenology at low redshift. Early-universe physics and global cosmological evolution are assumed to remain unchanged.

4.1 Local Expansion in Low-Density Environments

Measurements of the Hubble constant rely on local kinematic observables, including distance ladders, standard candles, and redshift–distance relations. These measurements implicitly assume that the local expansion rate is representative of the global cosmological background Riess (2022); Freedman (2021).

However, large-scale structure surveys show that the late-time Universe is highly inhomogeneous. A significant fraction of the cosmic volume is occupied by voids, characterized by matter densities well below the cosmic mean Keenan et al. (2013).

In the effective framework introduced in Section 2, low-density environments probe the saturated regime of the gravitational response. As a result, kinematic relations inferred from such regions may deviate from the global average, even in the absence of any modification to early-time cosmology.

We therefore distinguish between a global expansion rate H_{global}, defined by the homogeneous background constrained by early-Universe observables Collaboration (2020), and an effective local expansion rate H_{loc}, inferred from observations within a given environment.

4.2 Effective Expansion Rate in Voids

Cosmic voids represent the deepest and most extended low-density regions in the late Universe. Within voids, baryonic and total matter densities are suppressed, and typical gravitational accelerations fall below the saturation scale $a_\star$ over large volumes Keenan et al. (2013).

In this regime, the effective dynamics modifies the relation between local kinematics and the underlying background expansion. To leading order, this effect can be captured by an environment-dependent renormalization of the inferred expansion rate,

$$H_{\text{loc}} = H_{\text{global}} \left(1 + \delta_{\text{eff}}\right), \tag{7}$$

where δ_{eff} is a positive correction that increases with the degree of saturation.

The correction δ_{eff} depends on the depth and size of the void, as well as on the characteristic acceleration scale $a_\star$. Shallower or denser regions remain close to the Newtonian regime and yield $\delta_{\text{eff}} \approx 0$.

Importantly, this mechanism does not require any additional energy component or modification of the background Friedmann equations. The global expansion history remains unchanged. Only the local inference of H_0 is affected.

Within this interpretation, the enhanced local expansion inferred in cosmic voids reflects a reduced geometric constraint rather than an additional energy component. In regions where the density of relational nodes is low, the effective projection onto a geometric description operates closer to its saturation limit. This induces a local dilation of metric relations, which we refer to as a *geometric relaxation offset*, modifying the locally inferred expansion rate without altering the global background evolution.

4.3 Connection to the Hubble Tension

The Hubble tension arises from the discrepancy between early-time inferences of the Hubble constant and late-time local measurements Riess (2022); Collaboration (2020). Comprehensive reviews indicate that no single explanation has yet achieved consensus Verde et al. (2019).

Within the present framework, this discrepancy reflects the environmental sensitivity of local kinematic probes. Early-time measurements, anchored in the homogeneous and high-density early Universe, recover H_{global}. By contrast, late-time distance ladder measurements are performed within a structured Universe, often sampling void-dominated regions either directly or indirectly.

If local measurements preferentially probe saturated low-density environments, Eq. (7) predicts a systematically enhanced value of the inferred Hubble constant,

$$H_{\text{loc}} > H_{\text{global}}. \qquad (8)$$

The magnitude of the offset depends on the void environment surrounding the observers and sources. This naturally explains why the tension is most prominent in local measurements and why it does not manifest in early-time observables.

The extent to which local underdensities alone can account for the full tension remains debated in the literature Shanks (2019); Kenworthy et al. (2019). The present framework provides a distinct, testable mechanism in which the effect arises from an effective saturation of geometric response rather than from a modification of the background expansion.

Because the dynamics derives from an effective potential Φ_{eff}, the framework admits a conserved effective energy and a corresponding modified virial relation for stationary systems. This provides a consistency check that equilibrium disk galaxies remain dynamically stable in the transition regime.

4.4 Observable Signatures

The effective saturation framework leads to several testable observational signatures.

First, the inferred Hubble constant should correlate with the large-scale environment. Measurements performed in or near deep voids are expected to yield higher values of H_0 than those performed in denser regions.

Second, the effect should exhibit redshift dependence. At sufficiently large redshift, line-of-sight averaging over multiple environments suppresses the environmental bias, and the inferred expansion rate should converge toward H_{global}.

Third, the model predicts distinct signatures in void-related observables, including redshift drift and weak lensing Cai et al. (2017). In particular, the effective expansion rate inside voids modifies the expected temporal evolution of redshift for sources embedded in low-density regions.

These signatures provide independent tests of the framework and allow it to be falsified using current and forthcoming data.

4.5 Predicted Amplitude and Redshift Dependence

A key feature of the present framework is that the magnitude of the locally inferred deviation from the global expansion rate is not an arbitrary phenomenological choice. Once the saturation scale $a_\star$ is fixed by galactic dynamics, the expected environmental offset in the inferred Hubble constant is constrained to remain at the percent level.

For representative underdensities characteristic of large cosmic voids on scales of a few hundred megaparsecs, the framework predicts a fractional enhancement

$$\frac{\Delta H}{H} \equiv \frac{H_{\text{loc}} - H_{\text{global}}}{H_{\text{global}}} \sim \text{ a few percent}, \qquad (9)$$

comparable in magnitude to the observed discrepancy between local distance-ladder measurements and early-Universe inferences.

The effect is predicted to be redshift dependent. At higher redshift, the large-scale structure is less developed and line-of-sight averaging over multiple environments becomes increasingly efficient. As a result, the locally inferred expansion rate is expected to converge toward H_{global} with increasing redshift, providing a clear observational discriminant.

Deviations well above the percent level or the complete absence of any measurable offset would directly challenge the proposed mechanism.

4.6 Interpretation of the Hubble Tension as an Environmental Effect

The framework developed here suggests that the Hubble tension does not reflect a change in the global expansion history, but rather a limitation of homogeneous kinematic inference when applied to a strongly inhomogeneous late-time Universe. Early-universe determinations of H_0, anchored in a nearly homogeneous background, recover the global expansion rate. By contrast, late-time local measurements probe structured environments in which the effective dynamical response operates in a low-density, saturated regime.

In this context, the discrepancy between early- and late-time determinations of H_0 arises from a mismatch between global averaging and local inference. Measurements performed in void-dominated or underdense regions sample an effective response that no longer scales linearly with decreasing density, leading to a systematically enhanced locally inferred expansion rate.

From this perspective, the Hubble tension may be viewed not as an anomaly requiring additional dark components or early-time modifications, but as a diagnostic of gravitational and kinematic inference in diffuse environments. This interpretation naturally predicts weak but systematic correlations between inferred values of H_0 and large-scale environmental indicators such as void depth or filament membership.

4.7 Summary

In this section we have shown that the same effective saturation mechanism that accounts for galaxy rotation curves also leads to environment-dependent modifications of the locally inferred expansion rate.

Cosmic voids emerge as natural probes of this effect and provide a structural connection between galactic dynamics and the Hubble tension. The framework preserves the global cosmological expansion while predicting observable deviations in local measurements.

In the next section, we examine the robustness of these results, discuss degeneracies with standard cosmological effects, and outline the limits of the effective description.

5 ROBUSTNESS, DEGENERACIES, AND LIMITS

In this section we examine the robustness of the effective saturation framework, its degeneracies with standard astrophysical and cosmological effects, and the limits of its applicability. This assessment is essential for evaluating whether the proposed mechanism represents

a genuine explanatory alternative or merely a reparameterization of existing models.

5.1 Baryonic Uncertainties

The predictions of the effective model depend explicitly on the baryonic mass distribution. Uncertainties in stellar mass-to-light ratios, gas content, and distance estimates therefore propagate into the inferred rotation curves. Such uncertainties are well documented in rotation curve analyses and are a generic limitation of baryon-based dynamical modeling Lelli et al. (2016).

We have tested the sensitivity of the fits to reasonable variations in stellar mass normalization. While moderate shifts in mass-to-light ratio affect the detailed shape of the inner rotation curves, they do not eliminate the need for a low-acceleration modification at large radii. In particular, the emergence of asymptotically flat rotation curves remains robust across the allowed baryonic parameter range, consistent with previous empirical findings McGaugh et al. (2016).

At cosmological scales, baryonic uncertainties primarily affect the detailed mapping between large-scale structure and local measurements. They do not remove the qualitative distinction between dense environments, which remain close to the Newtonian regime, and voids, which probe the saturated regime most strongly Keenan et al. (2013).

5.2 Relation to MOND-like Phenomenology

The phenomenology described in this work shares qualitative similarities with acceleration-based frameworks such as Modified Newtonian Dynamics (MOND), originally proposed to account for flat galaxy rotation curves without invoking dark matter Milgrom (1983); Famaey & McGaugh (2012).

In particular, both approaches introduce a characteristic acceleration scale below which departures from Newtonian expectations become significant. However, the present framework differs conceptually and structurally from MOND-like modifications of the equations of motion.

Here, the low-acceleration behavior is not postulated as a fundamental modification of gravity, nor as a change in inertia. Instead, it arises from an effective saturation of geometric response in low-density environments, reflecting a limitation of the effective description rather than a modification of the underlying dynamical laws.

This distinction becomes especially relevant in cosmological applications. Whereas MOND-based approaches face well-known challenges in consistently addressing large-scale structure and cosmological observations, the effective saturation framework preserves the standard background expansion and modifies only the local inference of kinematic quantities in diffuse environments.

5.3 Degeneracies with Standard Astrophysical Effects

Several standard mechanisms have been proposed to address galaxy rotation curves and the Hubble tension within the ΛCDM framework. It is therefore important to assess potential degeneracies.

At galactic scales, feedback processes and baryon–halo coupling can reproduce some features of flattened rotation curves within dark matter halo models, particularly in low-mass systems Di Cintio et al. (2014). However, such mechanisms typically require galaxy-dependent tuning and do not naturally reproduce the observed correlation between surface density and dynamical behavior across the full range of disk galaxies McGaugh et al. (2016).

In contrast, the effective saturation model introduces no halo degrees of freedom and relies on a single universal scale. This difference leads to distinct residual patterns and scaling relations, which can be used to discriminate between models in detailed rotation curve analyses.

At cosmological scales, local inhomogeneities, peculiar velocities, and sample variance are known to affect Hubble constant measurements Freedman (2021). While these effects contribute to scatter, multiple studies indicate that their magnitude alone is generally insufficient to account for the full observed tension Verde et al. (2019). The effective saturation mechanism instead predicts a systematic environment-dependent bias, rather than a purely stochastic one, providing a clear observational discriminant.

5.4 Environmental Selection Effects

Local measurements of the Hubble constant are not uniformly distributed across cosmic environments. Distance ladder calibrators and standard candles are preferentially observed in specific regions of the large-scale structure Riess (2022).

This selection bias plays a central role in the present framework. If the observational strategy favors void-dominated regions, the inferred expansion rate will be systematically enhanced relative to the global value.

Importantly, this is not an ad hoc assumption but a testable prediction. Future analyses correlating H_0 measurements with void catalogs and density reconstructions can directly assess the magnitude of this effect, as already explored in the context of local underdensity scenarios Shanks (2019); Kenworthy et al. (2019).

5.5 Range of Validity

The effective saturation framework is not intended to apply universally at all scales and epochs. Its domain of validity is restricted to late-time, low-density environments.

In high-density regimes, including the early Universe, galaxy interiors, and the Solar System, the model reduces to standard Newtonian and relativistic behavior by construction. No deviations from established physics are expected or required in these contexts, consistent with existing precision tests of gravity Will (2014).

At sufficiently large redshift, line-of-sight averaging over multiple environments suppresses the effective saturation signature. The model therefore predicts a convergence toward standard cosmological behavior at high redshift, in agreement with current observations Collaboration (2020).

5.6 Falsifiability

The effective saturation framework makes several falsifiable predictions.

If future measurements show no correlation between locally inferred values of H_0 and the surrounding large-scale environment, the proposed mechanism is disfavored. Similarly, if galaxy rotation curves in extremely diffuse systems deviate systematically from the predicted saturation behavior, the model would require revision or rejection.

Conversely, confirmation of environment-dependent expansion signatures or consistent saturation behavior across diverse galactic systems would strongly support the framework.

5.7 Summary

The effective saturation model is robust against reasonable baryonic uncertainties and cannot be trivially absorbed into existing astrophysical or cosmological effects. Its predictive power arises from the use of a single universal scale and from its explicit environmental dependence.

The framework is limited in scope but sharply testable. Its validity hinges on future observational probes of low-density environments, making it a falsifiable proposal rather than a flexible phenomenological fit.

6 PREDICTIONS AND OBSERVATIONAL TESTS

The effective saturation framework introduced in this work leads to a set of distinct and testable predictions. These predictions arise directly from the environmental dependence of the effective dynamics and do not rely on additional assumptions or parameter tuning.

6.1 Environment-Dependent Hubble Measurements

A primary prediction of the model is a correlation between the locally inferred Hubble constant and the surrounding large-scale environment.

Observers and standard candles located in or near deep cosmic voids are expected to yield systematically higher values of H_0 than those located in denser regions. Conversely, measurements anchored in overdense environments should converge more closely toward the global expansion rate H_{global}.

This prediction can be tested by cross-correlating existing and forthcoming H_0 measurements with void catalogs and density reconstructions derived from large-scale galaxy surveys, as already explored in the context of local underdensity scenarios Keenan et al. (2013); Shanks (2019); Kenworthy et al. (2019). A null result would strongly disfavor the effective saturation mechanism.

6.2 Redshift Dependence of the Hubble Offset

The environmental bias predicted by the model is inherently scale dependent. At sufficiently low redshift, local measurements are sensitive to individual large-scale structures and probe the saturated regime.

At increasing redshift, line-of-sight averaging over multiple environments progressively suppresses the bias. As a result, the inferred expansion rate is predicted to converge smoothly toward H_{global}.

This behavior provides a clear observational signature. Measurements of H_0 performed over different redshift ranges should exhibit a systematic trend, with the largest deviations appearing at the lowest redshifts, consistent with expectations from environmental averaging arguments Verde et al. (2019).

An important quantitative consequence of the framework is that the expected deviation remains at the percent level and peaks at intermediate redshift. Once the saturation scale is fixed by galactic dynamics, the model predicts that the fractional offset in the inferred expansion rate should be of order a few percent at $z \sim 1$, while remaining negligible at both very low and sufficiently high redshift.

Such a deviation is within the sensitivity range of forthcoming large-scale surveys, including DESI and *Euclid*, and provides a clear target for falsification. Deviations significantly larger or smaller than this level would directly challenge the proposed mechanism.

6.3 Void-Specific Redshift Drift

The effective saturation mechanism also affects the temporal evolution of redshift for sources embedded in low-density environments.

In the standard cosmological framework, the redshift drift is determined solely by the global expansion history. In the present model, sources located in deep voids experience a modified effective expansion rate, leading to a small but systematic deviation in the expected redshift drift signal.

Future high-precision spectroscopic experiments may be able to detect this environment-dependent drift by comparing sources located in voids and in denser regions, complementing existing proposals for redshift-drift measurements Cai et al. (2017). The effect is predicted to be absent at high redshift, where environmental averaging dominates.

6.4 Weak Lensing Signatures in Voids

Because the effective dynamics modifies the gravitational response in low-density regions, it also affects weak gravitational lensing by cosmic voids.

The model predicts subtle deviations in void lensing profiles compared to standard expectations. In particular, the effective saturation leads to a reduced lensing efficiency relative to what would be inferred from baryonic matter alone, without invoking additional dark components.

Void lensing measurements therefore provide an independent probe of the framework, complementary to kinematic tests, and have already been identified as sensitive diagnostics of gravitational dynamics in underdense regions Cai et al. (2017).

6.5 Predictions for Ultra-Diffuse Galaxies

Ultra-diffuse galaxies represent extreme low-surface-density systems and probe the saturated regime across most of their extent. Since their systematic identification in deep imaging surveys, such systems have attracted considerable interest as tests of galaxy dynamics in diffuse environments van Dokkum (2016).

The effective saturation model predicts that ultra-diffuse galaxies should exhibit slowly rising rotation curves that approach a common asymptotic behavior, largely independent of detailed baryonic structure. Significant deviations from this pattern would challenge the universality of the saturation scale.

Observational studies have revealed a wide diversity of inferred dynamical mass content among ultra-diffuse galaxies, ranging from apparently dark-matter-rich systems to galaxies consistent with little or no dark matter van Dokkum (2019); Mancera Piña (2019). Within the present framework, this diversity arises naturally from differences in how deeply individual systems probe the saturated regime.

In ultra-diffuse galaxies, the large apparent mass discrepancy inferred from kinematics should therefore not be interpreted as evidence for an extended distribution of unseen matter. Rather, it reflects a geometric threshold effect: the baryonic configuration probes the deeply saturated regime, where further reductions in density no longer increase the effective dynamical response.

As a result, the inferred dynamical mass reflects the onset of saturation rather than the presence of an additional gravitating component. The "missing mass" is thus not a material distribution, but an emergent consequence of limited geometric resolution in low-density systems.

This interpretation leads to a falsifiable observational prediction. If the apparent mass discrepancy in ultra-diffuse galaxies originates

from a geometric saturation effect rather than from a physical mass component, then independent mass tracers should not reveal correspondingly extended matter distributions.

In particular, weak lensing signals, satellite dynamics, and stellar velocity dispersion profiles are expected to systematically underpredict the dynamical mass inferred from rotation or dispersion measurements in the deepest saturation regime. A positive detection of massive, spatially extended halos in ultra-diffuse galaxies would therefore directly falsify the present framework.

Because ultra-diffuse galaxies probe the deepest saturation regime, they provide a particularly sensitive test of the universality of the saturation scale $a_\star$.

Ultra-diffuse galaxies thus constitute a clean observational laboratory for distinguishing between material and geometric explanations of apparent mass discrepancies in the low-density regime.

6.6 Summary

The effective saturation framework yields a coherent set of predictions across galactic and cosmological scales. All predictions are driven by environmental dependence and involve no additional free parameters beyond the saturation scale already fixed by rotation curve data.

The framework is therefore falsifiable with current or near-future observational capabilities. Confirmation or rejection of these signatures will decisively determine whether the proposed mechanism captures a genuine aspect of low-density gravitational phenomenology.

7 CONCLUSION

We have investigated whether two persistent observational anomalies—flat galaxy rotation curves and the Hubble constant tension—may originate from a common effective mechanism operating in low-density environments.

Using a minimal phenomenological framework characterized by a single saturation scale, we have shown that baryonic matter alone can account for the main features of observed galaxy rotation curves across a wide range of systems, without halo-by-halo tuning or the introduction of dark matter particles in this effective description. This conclusion is supported by explicit numerical comparisons with representative rotation curves drawn from the SPARC sample. The same mechanism naturally extends to cosmological low-density regions, where it predicts environment-dependent deviations in the locally inferred expansion rate.

Cosmic voids emerge as key laboratories for testing this framework. By probing the deeply saturated regime, they provide a structural explanation for why late-time local measurements of the Hubble constant may systematically exceed the global value inferred from early-universe observables, while leaving the background cosmological evolution unchanged.

The model is intentionally limited in scope. It does not modify early-time physics, does not alter the global expansion history, and does not claim universal validity across all regimes. Its strength lies instead in its parsimony and falsifiability. All predictions follow from a single effective scale already constrained by galactic dynamics.

We have identified several observational tests capable of confirming or excluding this framework, including correlations between H_0 measurements and large-scale environment, redshift-dependent suppression of the local offset, void-specific redshift drift, weak lensing signatures, and the dynamics of ultra-diffuse galaxies.

Taken together, these results suggest that galaxy rotation curves and the Hubble tension may reflect a shared low-density phenomenology rather than independent failures of the standard cosmological model. Whether this effective description captures a genuine aspect of gravitational physics or represents an intermediate phenomenological layer will ultimately be decided by observational tests in the coming years.

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