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 dynamics operating in low-density regimes.

We introduce a minimal phenomenological model in which the effective gravitational response saturates below a characteristic density or 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. Numerical fits to 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. Within the standard cosmological framework, this behavior is 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.

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. This discrepancy has persisted across multiple datasets and analysis methods, prompting proposals ranging from systematic effects to extensions of the standard cosmological model. A notable feature of the tension is its strong association with late-time inference in a structured, 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?

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.

This behavior is not introduced as an ad hoc modification of the force law. Rather, it reflects a limitation in the effective description applicable to diffuse regimes, where dynamical inference becomes progressively insensitive to further reductions in density. As a result, the effective force remains finite at large radii, producing the characteristic flattening observed in dynamical observables.

This phenomenological study is motivated by a broader theoretical context in which bounded-response regimes arise naturally in

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effective descriptions of gravitational dynamics Beau (2026a). Related structural and projection-based considerations are discussed in companion works but are not required for the present analysis 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 4 presents rotation curve tests and diagnostics. Section 3 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. Here we restrict attention to late-time observational consequences and adopt a minimal parametrization suitable for astrophysical tests Beau (2026a).

2.1 Minimal Assumptions

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

First, the effective dynamics must reduce to standard Newtonian gravity in high-density environments. This ensures consistency with Solar System tests and with the inner regions of high-surface-density galaxies.

Second, deviations from Newtonian behavior are allowed only in diffuse regimes, characterized by low baryonic density or weak gravitational gradients. The transition between regimes must be smooth and free of singular behavior.

Third, the effective modification must be governed by at most one additional scale parameter, denoted $a_\star$, which controls the onset of saturation. No galaxy-dependent or environment-specific tuning is introduced.

Fourth, the model must preserve locality and isotropy at the effective level. No non-local interactions or preferred directions are assumed.

Finally, the model must admit a well-defined cosmological interpretation at late times, without altering early-universe observables such as primordial nucleosynthesis or recombination physics.

2.2 Effective Saturating Potential

We define the effective gravitational potential $\Phi_{\rm eff}$ through a modified Poisson equation of the form

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

where $\rho_{\rm b}$ denotes the baryonic mass density. The dimensionless function $\mu(x)$ encodes the effective 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 $g_{\rm eff} = \nu(y) g_{\rm N}$ with $y = g_{\rm N}/a_\star$. 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 $\Phi_{\rm eff}$ 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 $|\nabla \Phi_{\rm eff}| \gg a_\star$, Eq. (1) reduces to the standard Poisson equation, recovering Newtonian gravity. In the low-acceleration regime, the effective response saturates, leading to a finite asymptotic force.

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

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

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 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.

3.1 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.

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.

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 $H_{\rm global}$, defined by the homogeneous background, and an effective local expansion rate $H_{\rm loc}$, inferred from observations within a given environment.

3.2 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.

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,

$$H_{\rm loc} = H_{\rm global}\,(1 + \delta_{\rm eff})\,, \tag{5}$$

where $\delta_{\rm eff}$ is a positive correction that increases with the degree of saturation.

The correction $\delta_{\rm eff}$ 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 $\delta_{\rm eff} \approx 0$.

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.

3.3 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. 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 $H_{\rm global}$. 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. (5) predicts a systematically enhanced value of the inferred Hubble constant,

$$H_{\rm loc} > H_{\rm global}. \tag{6}$$

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.

Because the dynamics derives from an effective potential $\Phi_{\rm eff}$, 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.

3.4 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 $H_{\rm global}$.

Third, the model predicts distinct signatures in void-related observables, including redshift drift and weak lensing. 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.

3.5 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.

4 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 $10^{-10}\,\mathrm{m\,s^{-2}}$. This motivates treating the same $a_\star$ as a single scale linking galactic outskirts and low-density cosmic environments, without modifying early-time cosmology.

4.1 Data and Methodology

We use the SPARC database, which provides high-quality rotation curves together with homogeneous photometry and baryonic mass models. The dataset spans a wide range of galaxy morphologies, surface brightnesses, and dynamical regimes.

For each galaxy, the baryonic mass distribution is constructed from the observed stellar and gas components. A fixed stellar mass-to-light ratio is assumed for each band, following the standard SPARC prescriptions. No additional dark matter component is introduced.

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

$$v_{\rm eff}(r) = \sqrt{r\, g_{\rm eff}(r)}. \tag{7}$$

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.

4.2 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.

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.

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.

If the observer resides in a region of relative underdensity, such as the local large-scale underdensity discussed in the literature, the framework predicts an enhanced locally inferred expansion rate relative to the global background. This provides a concrete observational context for why local H_0 determinations could be biased high compared to early-time inferences.

4.3 Residuals and Scaling Relations

We quantify the quality of the fits using radial velocity residuals

$$\Delta v(r) = v_{\rm obs}(r) - v_{\rm eff}(r). \tag{8}$$

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.

4.4 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 and reduces the number of effective degrees of freedom.

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, which require galaxy-specific profile parameters, the present framework involves a single acceleration scale set by an intrinsic saturation of the underlying geometric response.

4.5 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.

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.

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.

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.

5.2 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 mimic some features of flattened rotation curves. However, such mechanisms typically require galaxy-dependent tuning and do not naturally reproduce the observed correlation between surface density and dynamical behavior without invoking an additional dark matter halo.

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.

At cosmological scales, local inhomogeneities and peculiar velocities are known to affect Hubble constant measurements. While these effects contribute to scatter, their magnitude alone is generally insufficient to account for the full observed tension. The effective saturation mechanism predicts a systematic environmental bias, rather than a purely stochastic one, providing a clear observational discriminant.

5.3 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.

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.

5.4 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.

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.

5.5 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.

5.6 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 $H_{\rm global}$.

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. 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 $H_{\rm global}$.

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.

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. 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.

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.

The effective saturation model predicts that such 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.

In ultra-diffuse galaxies, the large apparent mass discrepancy inferred from kinematics should not be interpreted as evidence for an extended distribution of unseen matter. Within the present framework, it arises from 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 therefore not a material distribution, but an emergent effect 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 provide 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. 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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