Emergent Gravitational Response from Structural Constraints:
A Toy Model with Observational Signatures in Galaxy Rotation Curves

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Abstract

We propose a toy framework in which the effective gravitational response emerges from structural constraints on accessible information, encoded through an inferred compressibility profile $\kappa(r)$.

Using SPARC rotation curve data, we reconstruct $\kappa(r)$ profiles and show that they do not follow a universal functional form. Instead, they organize into a small number of distinct morphological classes.

In particular, a subset of galaxies exhibits clean transition profiles characterized by a well-defined radial scale separating a baryon-dominated inner regime from an outer regime of enhanced dynamical discrepancy. Other systems display more complex or globally discrepant behaviour.

These findings suggest that the observed mass discrepancy may reflect structured dynamical regimes rather than a universal modification or an additional matter component. The framework provides a phenomenological bridge between baryonic structure and emergent gravitational response, and yields testable predictions for galaxy dynamics and cluster-scale systems.

1 Introduction

The nature of gravity at galactic and cluster scales remains an open problem. Observations such as galaxy rotation curves [4] and cluster collisions [1] are typically interpreted within the ΛCDM paradigm [2].

Alternative approaches such as MOND [5] modify gravitational laws. In this work, we explore a different route: a phenomenological framework in which the effective gravitational response depends on structural organization and information accessibility.

The present approach is not proposed as a fundamental replacement for existing paradigms. Rather, it is intended as a phenomenological model capable of identifying structured signatures in observational data and of motivating more detailed theoretical development.

2 Conceptual Framework

We define an informational density

$$\mathcal{I}(x) = \rho_{\text{bary}}(x)\chi(x),$$

where $\chi(x)$ encodes structural organization, such as density gradients, local compactness, or morphological transitions.

We define a compressibility field

$$\kappa(x) \in [0, 1],$$

which may be interpreted as an effective order parameter encoding the degree of local information accessibility.

The effective source is

$$R(x) = (1 - \kappa(x))\mathcal{I}(x).$$

The gravitational potential satisfies the effective closure

$$\nabla^2\Phi = 4\pi G\rho_{\text{bary}}(1 + \xi(1 - \kappa)\chi).$$

This relation should be interpreted as a phenomenological closure rather than a fundamental field equation. The central idea is that dynamical discrepancy may be linked not only to the amount of baryonic matter, but also to how that matter is structurally organized.

3 Toy Model and Observational Proxy

At the phenomenological level, an operational proxy for the compressibility profile is

$$\kappa(r) = \frac{V_{\text{bar}}^2(r)}{V_{\text{obs}}^2(r)},$$

where

$$V_{\text{bar}}^2(r) = V_{\text{gas}}^2(r) + \Upsilon_d V_{\text{disk}}^2(r) + \Upsilon_b V_{\text{bul}}^2(r).$$

This immediately implies

$$V_{\mathrm{obs}}^2(r) = \frac{V_{\mathrm{bar}}^2(r)}{\kappa(r)},$$

so that departures of κ from unity encode the observed dynamical discrepancy.

When $\kappa(r) \approx 1$, the observed dynamics is close to baryonic expectations. When $\kappa(r) < 1$, the observed velocity exceeds the baryonic prediction.

4 SPARC-Based Reconstruction

Using the SPARC dataset [3], we reconstruct $\kappa(r)$ for a large sample of galaxies and study the radial structure of the resulting profiles.

A first empirical finding is that the most significant changes in $\kappa(r)$ often occur close to structural transitions in the baryonic distribution. This motivates the interpretation that the relevant observable may not be a universal correction law, but the presence of regime transitions in the inferred compressibility profile.

We also tested several simple functional hypotheses for $\kappa(r)$:

- single sigmoid transitions in radius,
- local structural models of the form $\kappa = \kappa(S)$,
- non-local structural models based on kernelized proxies.

These simple closed-form models generally failed to capture the observed diversity of profiles across the SPARC sample. This suggests that $\kappa(r)$ is not well described by a single universal function of radius or of basic structural proxies.

5 Bullet-Cluster-like Toy Models

Cluster collisions provide a critical test for any framework that aims to explain gravitational discrepancy without introducing an explicit dark matter component.

We consider a toy picture in which gas becomes diffuse while compact structures remain localized. The mechanism is:

1. gas spreads and is spatially diluted,
2. compact structures remain coherent,
3. the compact sector is structurally amplified,

4. the gas contribution is diluted by broad mediation.

This leads to the qualitative condition

$$\frac{J_{\text{off}}}{J_{\text{center}}} > 1,$$

that is, off-center peaks in the effective response can dominate over the central gaseous contribution.

We do not claim quantitative agreement with observed lensing maps; this remains a qualitative proof-of-principle rather than a quantitative model.

6 Morphology of Compressibility Profiles

The inferred compressibility profiles $\kappa(r)$ do not follow a single universal functional form across the SPARC sample. Instead, they organize into a small number of distinct morphological classes.

We identify three dominant regimes, together with a residual quasi-baryonic class:

- **Quasi-baryonic profiles:** characterized by $\kappa \approx 1$ across most radii, indicating minimal dynamical discrepancy.
- **Clean transition profiles:** exhibiting a well-defined transition from $\kappa \approx 1$ in the inner region to significantly lower values in the outer region.
- **Complex profiles:** showing multiple transitions or non-monotonic behaviour.
- **Strong discrepancy profiles:** characterized by low κ values across most radii.

Representative examples of these classes are shown in Fig. 1.

These classes show clear correlations with baryonic structure, including gas dominance in outer regions and inner baryonic concentration. This indicates that the radial structure of the discrepancy is organized rather than stochastic. Clean-transition systems tend to exhibit a strongly baryon-dominated inner region, while complex profiles are associated with systems displaying more intricate structural features. Strong-discrepancy systems show a higher gas fraction in outer regions.

This suggests that $\kappa(r)$ encodes global dynamical organization rather than being a simple function of local structure.

7 Predictions and Falsifiability

The framework leads to several qualitative predictions:

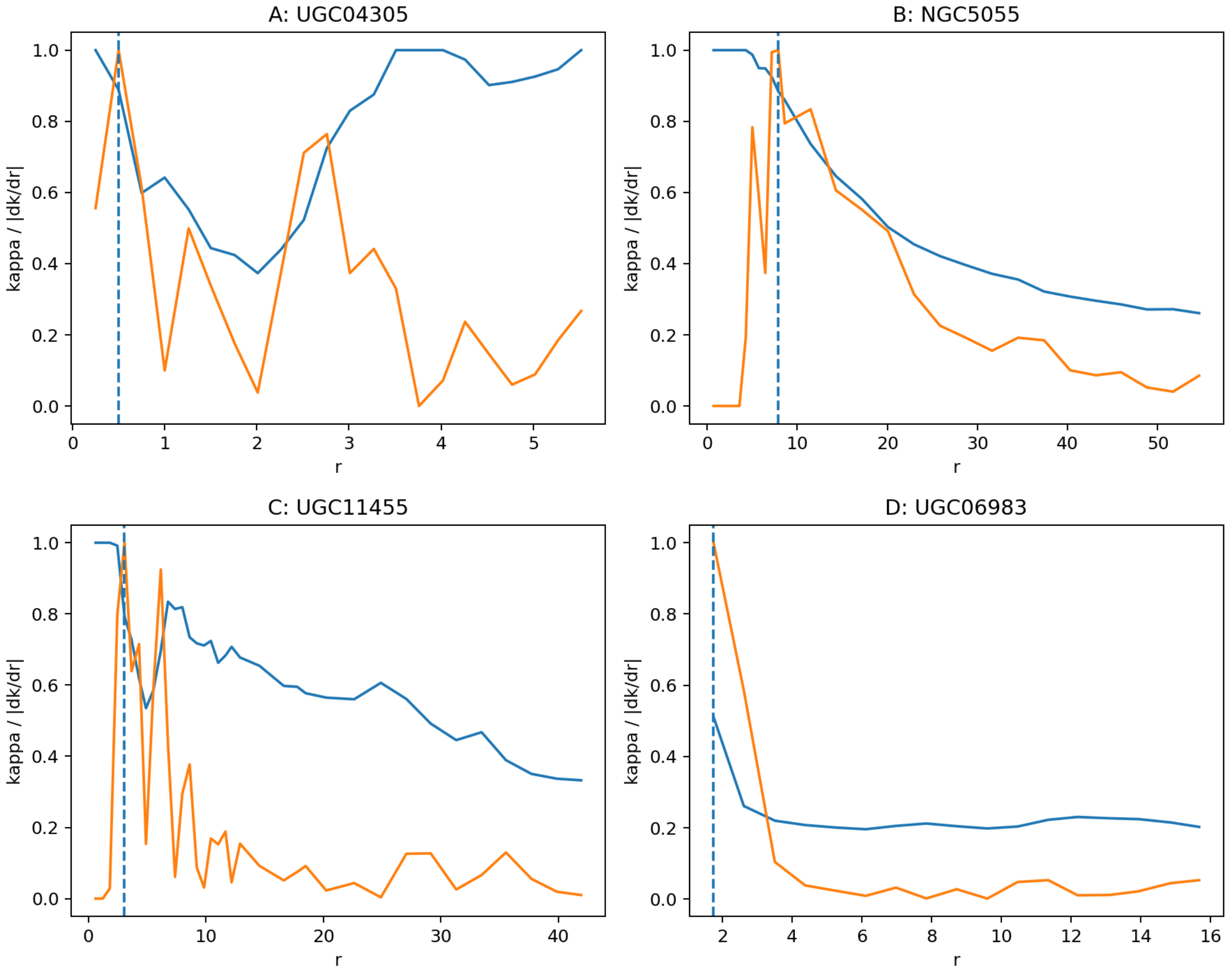

Figure 1: Representative examples of inferred compressibility-profile classes. The blue curves show $\kappa(r)$, while the orange curves show the normalized gradient $|d\kappa/dr|$ (rescaled for visualization purposes). Dashed vertical lines indicate dominant transition radii.

- dynamical discrepancy should correlate with structural transitions rather than solely with total baryonic mass;
- clean-transition profiles should correspond to systems with a well-defined baryon-dominated inner region;
- complex profiles should be associated with richer internal structure or multi-component dynamics;
- cluster-scale offsets should depend on structural differentiation between diffuse and compact baryonic sectors;
- the observed discrepancy need not follow a universal functional form across all systems.

These predictions make the framework empirically distinguishable from models based purely on additional mass components or on a universal modification law.

8 Discussion

A key observational result is that the inferred compressibility profiles do not appear random. Instead, they organize into a small number of morphological classes with plausible physical interpretation.

This is significant because the previous tests indicate that simple universal laws for $\kappa(r)$ fail, whereas a classification-based view reveals structured behaviour. In this sense, the most robust result is not yet a closed-form law, but the existence of observationally meaningful regime structure.

This suggests that classification-based approaches may provide a more robust empirical entry point than direct functional modelling.

This provides a concrete observational pathway to distinguish the framework from models based purely on additional mass components. If the classes of $\kappa(r)$ can be shown to correlate robustly with independently measured baryonic properties, the framework would gain a much stronger empirical basis.

9 Conclusions

We have proposed a toy framework in which the effective gravitational response is encoded in an inferred compressibility profile $\kappa(r)$.

Analysis of SPARC rotation curves shows that $\kappa(r)$ profiles do not follow a universal law, but instead organize into a small number of morphological classes.

This suggests that the observed dynamical discrepancy may reflect structured regimes rather than a universal modification or an additional matter component.

This highlights the possibility that gravitational phenomenology at galactic scales reflects transitions between structurally defined dynamical regimes.

Key observational result. The existence of distinct compressibility-profile classes indicates that galaxy dynamics may be governed by transitions between structurally defined regimes.

If confirmed by further observational and theoretical work, this would point toward a structurally mediated component in gravitational phenomena.

References

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