

Galactic Rotational Dynamics as Evidence for Dark Matter and Alternative Gravitational Theories

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Introduction

Observations of galactic rotation curves show that stars at large distances from galactic centres orbit at nearly constant velocities, directly contradicting predictions from Newtonian gravity based solely on visible matter. According to classical theory, such galaxies should be gravitationally unstable and should have torn themselves apart ages ago. This persistent discrepancy has led to the proposal of dark matter, a non-luminous component providing additional gravitational mass. This constitutes a clearly defined and unresolved problem within contemporary astrophysics, centred on the inconsistency between theoretical gravitational predictions and empirical astronomical observations. This problem motivates the research thematic of galactic rotational dynamics within astrophysics and cosmology, which integrates observational astronomy with gravitational theory.

Within the discipline of astrophysics, this problem is not only significant but foundational, as it directly challenges the completeness of existing gravitational frameworks and the interpretation of observable mass in the universe. Furthermore, its resolution necessitates an explicitly interdisciplinary approach, drawing upon cosmology for large-scale structure formation, particle physics for the nature of dark matter candidates, and theoretical physics for potential modifications to gravitational laws. Thus, the investigation of galactic rotational dynamics serves as a prerequisite for developing a coherent and unified understanding of the universe across multiple scientific domains.

This study argues that no single framework fully resolves this discrepancy, and adopts a comparative approach. This investigation is systematically developed through three primary sections: (i) a review of observational evidence establishing the rotation curve anomaly, (ii) a critical comparison of explanatory frameworks including dark matter models and modified gravity theories, and (iii) an evaluation of the limitations and implications of each framework. Accordingly, the manuscript develops a review of observational evidence, a critical comparison of dark matter and modified gravity models, and an evaluation of their respective limitations (Parbin & Goswami, 2023).

Background and Significance

One of the most significant challenges in contemporary astrophysics arises from the observation of galactic rotation curves, where the orbital speeds of stars and gas remain nearly constant far from the galactic centre rather than declining as predicted by Newtonian mechanics. In a standard Newtonian framework, the visible, luminous matter in a galaxy should produce a ‘Keplerian’ decline in rotational velocity with increasing radius; instead, the observed curve remains flat, indicating the presence of additional gravitational influence that cannot be accounted for by baryonic matter alone. This discrepancy can be quantitatively expressed through mass-to-light ratios (M/L), where observational data for spiral galaxies typically yield values ranging from $M/L \approx 10$ to 100 in solar units, significantly exceeding the expected range of $M/L \approx 1-5$ based on luminous stellar populations alone. Such a disparity indicates that visible matter accounts for only a small fraction of the total gravitational mass, thereby providing a measurable and concrete representation of the theoretical–observational gap (Binney & Tremaine, 2008; Sofue & Rubin, 2001). This discrepancy is one of the primary lines of evidence for an unseen component of mass in the universe commonly referred to as dark matter (Votatera, 2024).

The importance of resolving this problem extends beyond galaxy dynamics to the broader structure and evolution of the universe. Dark matter is inferred to dominate the matter content of galaxies and clusters and is a fundamental ingredient in the ‘ Λ Cold Dark Matter (Λ CDM) cosmological model’, which successfully explains large-scale structure, cosmic microwave background anisotropies, and the

growth of cosmic web filaments. Without dark matter, conventional gravitational theory would fail to account for the stability of galaxies, the dynamics of clusters, and lensing phenomena where light is bent by mass that cannot be seen. Recent observational studies further show that the fraction of dark matter within galactic radii often exceeds visible mass, and that rotation curves remain flat even at very large radii, reinforcing the need for additional explanation (Kuncewicz, 2025; Sharma et al., 2025).

Therefore, the research thematic of galactic rotational dynamics is formally defined as the investigation of how the distribution of both baryonic and non-baryonic matter governs orbital motion under gravitational interaction, and whether this interaction is best described by the introduction of unseen mass components or by modifications to established gravitational laws. This thematic directly addresses the identified problem and establishes the conceptual scope of the study within the discipline.

Within this context, the abstracted research theme is galactic rotational dynamics, i.e., the study of how the distribution of mass, both visible and invisible, governs the orbital motion of stars and gas. Investigating these dynamics involves testing whether the extra gravitation arises from an unseen matter component or whether the laws of gravity themselves need modification under low-acceleration regimes, such as those proposed by Modified Newtonian Dynamics (MOND) and other theories.

Literature Review

This research thematic studies how stars move within galaxies and what this motion reveals about gravity. Scientists have observed that stars far from the centre of galaxies move much faster than expected if only visible matter is considered. According to known laws of gravity, such galaxies should not remain stable. To explain this, scientists propose the existence of dark matter, an invisible substance that adds extra gravity. A key feature of this thematic is the study of galactic rotation curves, which show that star speeds remain almost constant across a galaxy. Within the literature, this phenomenon is consistently identified as a persistent and unresolved discrepancy between theoretical predictions and observational evidence, thereby establishing the central research gap. Another important aspect is the comparison between multiple explanatory frameworks; however, their detailed evaluation is reserved for the analytical discussion section to maintain the distinction between review and argument. By examining these possibilities, this thematic helps scientists understand whether unseen matter or changes in gravity better explain how galaxies stay together.

This research is grounded in astrophysics because it investigates the motion and gravitational behaviour of galaxies using physical laws and astronomical observations. Peer-reviewed astrophysical studies show that galactic rotation curves, measured through Doppler shifts in stellar and gas spectra, remain flat at large radii, contradicting predictions from visible matter alone. Additional astrophysical evidence from gravitational lensing, galaxy cluster dynamics, and cosmic microwave background analyses supports the presence of non-luminous mass or modified gravity. Since these phenomena are studied using observational astronomy, theoretical physics, and cosmological models, astrophysics is the most appropriate discipline for this research (Rubin et al., 1980; Zwicky, 1937).

This thematic emerged gradually within the discipline of astrophysics as astronomers attempted to understand how mass governs the motion of celestial systems. Its roots can be traced back to the late eighteenth century, when Michell (1767, 1784) first proposed that not all massive objects in the universe need be luminous. A second major moment occurred in the early twentieth century with Kapteyn (1922) and Oort (1926), who identified discrepancies between visible mass and gravitational effects in the Milky Way.

The thematic became central to cosmology in 1933, when Zwicky studied the Coma Cluster and found that galaxies were moving too rapidly to be gravitationally bound by visible matter alone. A major observational breakthrough followed when Freeman (1970) theoretically predicted flat rotation curves, later confirmed by Rubin et al. (1980). These studies established that orbital velocities remain nearly

constant with increasing galactic radius, contradicting Newtonian predictions based solely on baryonic matter.

Contemporary observational studies published in leading journals such as *The Astrophysical Journal* and *Monthly Notices of the Royal Astronomical Society* further confirm that flat rotation curves persist across diverse galaxy types, thereby consolidating the discrepancy as a robust empirical phenomenon rather than an observational anomaly (Sofue & Rubin, 2001; de Blok, 2010). This establishes a clearly defined and well-supported research gap that necessitates theoretical explanation.

Research Question

To what extent can the persistent flatness of galactic rotation curves be more comprehensively explained by the dark matter paradigm than by modified gravity theories or baryonic reinterpretations of mass distribution, when evaluated across both galactic and cosmological scales?

Argument

The contemporary debate on galactic rotational dynamics is structured around three primary explanatory frameworks: the dark matter paradigm, modified gravity theories, and baryonic reinterpretations of mass distribution (Feng, 2020). Observations of galaxy rotation curves show that orbital velocities remain nearly constant at large radii, contradicting predictions of Newtonian gravity based solely on visible matter. Each framework attempts to resolve this discrepancy through fundamentally different assumptions about mass and gravity.

Within the standard cosmological model (Λ CDM), dark matter is treated as a fundamental component of the Universe. Galaxies are embedded in massive halos of non-baryonic matter whose gravitational influence explains flat rotation curves and supports large-scale structure formation. This framework is strongly supported by multiple independent observations, particularly gravitational lensing phenomena such as the Bullet Cluster, where the spatial separation between visible baryonic matter and gravitational mass provides compelling evidence for non-luminous matter (Clowe et al., 2006). Furthermore, cosmological analyses of dark energy and matter evolution reinforce the necessity of non-baryonic components in accurately modelling the large-scale universe (Giarè et al., 2025).

However, despite its large-scale success, the Λ CDM model faces notable challenges at smaller scales, collectively referred to as the “Small-Scale Crisis.” One of the most significant issues is the cusp–core problem, where simulations predict steep central density cusps in dark matter halos, whereas observations of dwarf and low-surface-brightness galaxies suggest flatter core-like distributions (de Blok, 2010). Additional theoretical investigations suggest that uncertainties in halo structure and baryonic feedback processes may contribute to these discrepancies, indicating that the model may require refinement rather than complete replacement (Ferreras, 2025a).

In contrast, Modified Newtonian Dynamics (MOND), proposed by Milgrom (1983), rejects the need for unseen matter at galactic scales and instead modifies gravitational laws under low-acceleration conditions. A major strength of MOND lies in its ability to naturally reproduce the Tully–Fisher relation, an empirical correlation between the baryonic mass of a galaxy and its rotational velocity. This relation emerges directly from MOND’s formulation without requiring additional parameters, providing strong predictive success at galactic scales (McGaugh et al., 2016). More broadly, modified gravity frameworks have been developed to address limitations of general relativity in low-acceleration regimes, highlighting the possibility that gravitational theory itself may be incomplete (Lobo, 2008).

This creates a significant evidentiary contrast within the debate. The Tully–Fisher relation strongly supports modified gravity frameworks, whereas gravitational lensing observations, particularly those involving the Bullet Cluster, provide strong support for the existence of dark matter. This contrast highlights that no single framework currently explains all observed phenomena consistently across different scales.

A third perspective is introduced by Feng (2020), who challenges both paradigms by arguing that galactic mass distributions can be derived directly from observed rotation curves using Newtonian mechanics. According to this approach, the apparent “missing mass” problem arises from oversimplified assumptions, particularly constant mass-to-light ratios. Feng suggests that variable mass-to-light ratios and the presence of faint baryonic matter, such as cold gas and dust, can account for observed dynamics without invoking either dark matter or modified gravity. This interpretation aligns with broader discussions on methodological limitations in astrophysical inference, where theoretical conclusions may depend strongly on underlying modelling assumptions (Montgomery, 2014).

Despite these competing explanations, each framework exhibits limitations. Dark matter models rely on indirect detection and remain experimentally unconfirmed despite extensive searches. Modified gravity theories, while successful at galactic scales, struggle to account for cosmological observations such as the cosmic microwave background and galaxy cluster dynamics. Similarly, baryonic reinterpretation models depend heavily on assumptions about mass distribution and are sensitive to observational uncertainties. Philosophical critiques of cosmological inference further suggest that such competing models may remain underdetermined by available evidence, complicating efforts to identify a single definitive explanation (Wolf, 2023).

Further theoretical developments suggest additional complexity. Some modified gravity models can be mathematically reformulated to include effective mass terms, making them observationally similar to dark matter frameworks (Calmet & Kuntz, 2017). At the same time, alternative relativistic treatments of galactic dynamics within general relativity have been explored, indicating that rotation curve behaviour may emerge from more complex spacetime geometries than traditionally assumed (Ciotti, 2022). This overlap blurs the distinction between competing theories and suggests that the debate reflects deeper uncertainties in the fundamental relationship between gravity and mass.

A critical criterion for evaluating these frameworks is their consistency across different astrophysical scales. Dark matter models provide a unified explanation across galactic and cosmological scales but face discrepancies at smaller scales. Modified gravity models offer precise fits at galactic scales but lack universality across larger structures. The baryonic reinterpretation approach simplifies the problem but depends on assumptions that remain difficult to verify observationally. Some alternative models attempting to unify cosmic mass distributions across scales highlight the difficulty of constructing a single framework that remains consistent from galactic to cosmological regimes (Seshavatharam & Lakshminarayana, 2021).

Conclusion

The persistent flatness and diversity of galactic rotation curves indicate that no single approach works equally well in all contexts. Modified gravity theories provide elegant and accurate descriptions at the scale of individual galaxies, while dark matter-based frameworks offer greater consistency when extended to varied galactic environments and cosmological scales. When the full body of observational evidence is considered, including gravitational lensing and large-scale structure, dark matter models provide a more robust and transferable explanatory framework (Sharma et al., 2025).

At the same time, the baryonic reinterpretation proposed by Feng (2020) offers an important methodological critique by highlighting the role of assumptions such as constant mass-to-light ratios in shaping the “missing mass” problem. While this perspective provides valuable insight into potential observational and modelling limitations at galactic scales, its explanatory scope remains significantly constrained. In particular, baryonic-only models struggle to account for cosmological-scale phenomena, most notably the anisotropies observed in the Cosmic Microwave Background (CMB), which are accurately described within the Λ CDM framework and require a substantial non-baryonic matter component. The inability of such models to reproduce these large-scale anisotropies represents

a critical limitation, as it prevents them from offering a unified explanation across both galactic and cosmological domains.

Therefore, while alternative frameworks, including modified gravity and baryonic reinterpretations, contribute meaningfully to refining our understanding of galactic dynamics, current evidence indicates that dark matter remains the most comprehensive explanatory model. However, the persistence of small-scale discrepancies and the absence of direct detection suggest that the problem is not yet fully resolved. Continued investigation integrating observational astrophysics, theoretical physics, and cosmology is essential to achieving a more complete understanding of the fundamental nature of mass and gravity in the universe.

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