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Theoretical Foundations of the Domination of Dark Matter over Celestial Motion

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Abstract:

Recent advances in the study of celestial motion and classification have deepened people's understanding of the theoretical foundations governing astrophysical structures, particularly within the framework of general relativity and dark matter. This paper systematically explores how the motion of celestial objects is influenced by the geometry of spacetime and the gravitational effects of non-luminous matter in a dark matter-dominated universe. By analyzing key observational evidence—such as galactic rotation curves, gravitational lensing, and the formation of large-scale structures—the essential role of dark matter in maintaining galactic stability, regulating star formation, and driving cosmic evolution is established. Furthermore, the strengths and limitations of the prevailing ΛCDM model and alternative theories such as Modified Newtonian Dynamics (MOND) are critically compared. Although modified gravity offers an intriguing alternative, dark matter remains the most compelling component capable of consistently explaining a wide range of astrophysical phenomena. The integration of general relativity and dark matter into celestial classification not only enriches people's understanding of cosmic architecture but also provides a foundational direction for future empirical and theoretical investigations.

Keywords: Dark matter; gravitational lensing; ΛCDM model; Modified Newtonian Dynamics

1. Introduction

Many scientists are engaged in exploring the theoretical foundations that govern the motion and classification of celestial objects within the modern cosmological framework [1]. This pursuit is motivated by persistent gaps in people's understanding of gravitational dynamics at astrophysical scales, where observations consistently deviate from the predictions of classical mechanics and general relativity when only baryonic matter is considered. Recent decades have witnessed accumulating evidence—from anomalous galactic rotation curves to unexpected gravitational lensing effects—suggesting the presence of non-luminous mass. These anomalies have spurred extensive research into dark matter, reshaping contemporary cosmological models and classification criteria for celestial bodies [2].

This introduction begins by re-examining conventional schemes of celestial classification through the lens of general relativity, in which the curvature of spacetime dictates gravitational motion. It emphasizes the essential role of dark matter in accounting for observed astrophysical phenomena that cannot be explained by visible matter alone. The core principles of general relativity are first outlined, along with its major predictions, highlighting a key discrepancy resolved by dark matter: the unexpectedly flat rotation curves of galaxies. Subsequently, central observational evidence for dark matter is reviewed—including galactic rotation curves, gravitational lensing, and the formation of large-scale cosmic structures. The analysis then investigates the mechanisms by which dark matter influences celestial motion and concludes with a comparative assessment of the leading theoretical frameworks, evaluating their strengths and limitations in light of critical empirical evidence. This structured progression lays the foundation for understanding people's relativistic and dark-matter-dominated universe.

2. Theoretical Foundations

2.1 Classification of Celestial Objects: A Relativistic Context

Celestial objects—natural physical entities residing beyond Earth's atmosphere—serve as fundamental probes for exploring gravitational dynamics across the universe. Their classification, traditionally rooted in properties such as physical composition, luminosity, and orbital characteristics, takes on deeper significance within the framework of general relativity, where spacetime curvature governs motion. Moreover, dark matter's gravitational influence is evident in the kinematics and structure of celestial objects, making their classification functional as well as descriptive. For example, the flat rotation curves of spiral galaxies, velocity dispersions in ellipticals, and the dynamics of globular clusters all indicate dark matter's presence. Similarly, galactic disk stability, tidal streams, and gravitational lensing highlight its role in governing cosmic evolution. Thus, modern classification must incorporate these dynamical aspects within a dark matter-dominated framework to capture astrophysical significance [3].

Key categories include stars, luminous spheres of plasma sustained by nuclear fusion. Their trajectories deviate from Newtonian predictions under strong gravitational fields, requiring relativistic treatments, while their orbital velocities often signal the presence of dark matter halos. Compact Objects, including white dwarfs, neutron stars, and black holes. These high-density remnants produce extreme spacetime curvature, offering natural laboratories for strong-field gravity. Phenomena such as orbital decay in binary pulsars, accurately described by general relativity, also provide constraints on dark matter density. And vast ensembles of stars, gas, and dark matter, called galaxies. Their rotation curves, gravitational lensing signatures, and large-scale dynamics cannot be explained without dark matter, establishing them as key components in the relativistic story of structure formation. Each category responds uniquely to the geometry of spacetime and the distribution of unseen mass, making a relativistic classification essential for a physically coherent understanding of the universe.

2.2 General Relativity

Einstein's general theory of relativity, published in 1915, represents one of the most profound shifts in people's understanding of the physical universe. It reimagines gravity through the language of geometry: the presence of mass and energy curves spacetime, and this curvature dictates how objects move. The core of the theory is encapsulated in the Einstein field equations:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{1}$$

where $G_{\mu\nu}$ represents the Einstein tensor encoding the curvature of spacetime, $T_{\mu\nu}$ is the stress-energy tensor describing the distribution of mass and energy, $g_{\mu\nu}$ is the metric tensor, and Λ denotes the cosmological constant. In this framework, celestial objects follow paths of extremal proper time in curved spacetime rather than moving under a Newton-like force [4].

When applied to galaxies, general relativity combined with Newtonian limits predicts that stellar orbital speeds $v(r)$ should decline with distance from the galactic center, following a Keplerian drop-off:

$$v(r) = \sqrt{GM(r)/r} \tag{2}$$

where $M(r)$ is the mass enclosed within radius r, implying beyond the visible disk $v(r) \propto 1/\sqrt{r}$. However, astrophysical observations of rotation curves in spiral galaxies consistently show that $v(r)$ remains approximately constant at large distances, which remarkably contradicts theoretical expectations, see Fig. 1. This flatness in the rotation curve implies that either people's understanding of gravity requires modification on galactic scales, or there exists additional unseen mass—dark matter—contribut-

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ing to $M(r)$ [5]. The inferred mass profile means that $M(r) \propto r$, considering a halo of dark matter encompassing the galaxy. This discrepancy between prediction and observation remains one of the most compelling mysteries in modern cosmology.

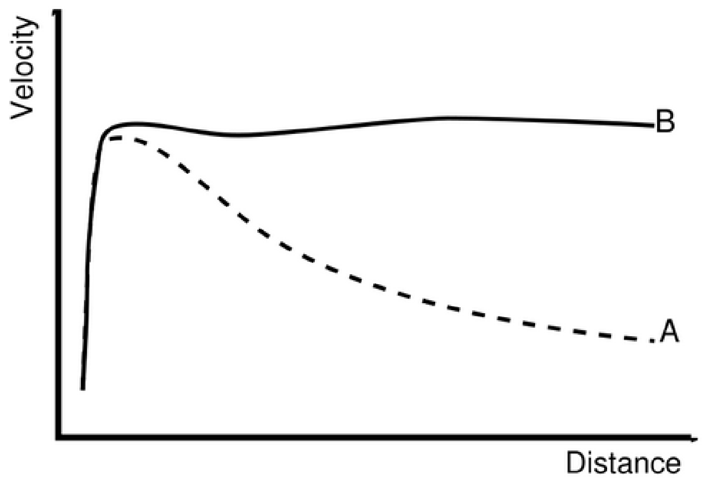

Fig. 1 The dashed curve A: the rotation curve of a spiral galaxy as predicted by Keplerian laws. The solid curve B: the observed rotation curve of a typical spiral galaxy. Adopted from Ref. [5].

2.3 Dark Matter: Concept and Observational Evidence

Dark matter is non-luminous, non-electromagnetically interacting material detectable only through gravitational effects. Conmprising~26.8% of the universe's mass-energy, its existence is supported by three key lines of evidence: galactic rotation curve anomalies, gravitational lensing and large-scale structure formation.

The most profound is galactic rotation curve anomalies. Observations show flat rotation curves in spiral galaxies—outer stars orbit at near-constant speeds, independent of distance from the center. This contradicts predictions based on visible mass alone, implying additional gravitational pull from unseen matter. The earliest identification of the „missing mass" problem dates back to Fritz Zwicky's 1933 study of the Coma Cluster. The subsequent work of Vera Rubin and W. Kent Ford in the 1970s–1980s provided robust evidence for flat rotation curves in spiral galaxies. A study by A. Del Popolo and M. Le Delliou in 2022, examines the rotation curves of galaxies with maximum velocities (V_{max}) ranging from 30 to 250 km/s, finding significantly greater diversity in their inner profiles than predicted by the ΛCDM model [6]. The observed scatter exceeds the predictions of dark matter-only simulations. Using a semi-analytical approach that incorporates baryonic physics, the authors demonstrate that this variety can be reproduced without invoking non-standard dark matter forms, as suggested by others. The model successfully accounts for both extreme outliers like the slowly-rising, large-core galaxy IC 2574 and cusp-like systems such as UGC 5721. The study concludes that properly modeling baryonic effects is essential before considering modifications to the standard cosmological model.

Another evidence is gravitational lensing. Massive galaxy clusters bend light from background objects, distorting their images. The observed lensing strength often exceeds predictions from visible matter, indicating substantial dark matter contributions [7]. Using the massive merging galaxy cluster MACSJ0025.4-1222, some researchers studied the nature of dark matter in 2008. Similar to the Bullet Cluster, this system is ideal for isolating dark matter and testing theories like CDM vs. self-interacting dark matter (SIDM). The multiwavelength analysis shows the hot X-ray gas is clearly displaced from the galaxy distributions. Both strong and weak gravitational lensing confirm the two subclusters have similar mass and reveal that the total mass is offset from the baryonic gas ($>4\sigma$) but aligned with the galaxies. The mass fractions in gas and stars are consistent with typical clusters, confirming dark matter dominates the gravity. Under the assumption of a head-on scattering scenario, the analysis places an upper limit on the dark matter self-interaction cross-section of $\sigma / m < 4$ cm²/g—a result consistent with, and thereby providing support for, the collisionless dark matter paradigm.

Large-scale structure formation also supports the existence of dark matter. The cosmic web of galaxies requires gravitational scaffolding for early collapse. Dark matter, unaffected by radiation pressure, seeded this structure before ordinary matter coalesced. For example, Ganeshaiah et al. mentions that dark matter halos serve as the nodes of structure formation [8], while the filamentary structures (or the cosmic web) connect these nodes through a process of non-spherically symmetric gravitational collapse, providing the earliest gravitational scaffolding for the accumulation of visible matter such as galaxies. Dark matter's properties include gravitational interaction, electromagnetic neutrality, and halo-like distribution around galaxies. Its stability over cosmic timescales and non-relativistic behavior further distinguishes it from known particles.

3. Mechanism Analysis

3.1 Mechanisms: How Dark Matter Governs Celestial Motion

In general relativity, dark matter indirectly governs the motion of celestial objects by modifying the geometry of spacetime. Dark matter halos play a foundational role in structuring galactic dynamics through their interaction with the fabric of spacetime. By contributing dominantly to the total mass of a galaxy, these halos extend and deepen the surrounding spacetime curvature, effectively flattening the gravitational potential wells [9]. As a result, stars located in the outer galactic regions can maintain unexpectedly high orbital velocities without escaping the system.

Moreover, the movement of dark matter—especially in rotating halos—induces frame-dragging effects analogous to those near spinning black holes. This drags local spacetime and contributes to the redistribution of angular momentum among gas clouds and stellar populations. Such a mechanism offers a compelling explanation for the observed velocity dispersion in pressure-supported structures, including elliptical galaxies [10].

Over cosmological timescales, dark matter halos constitute a fundamental element in the formation and evolution of galaxies. These extensive, invisible structures act as gravitational anchors, stabilizing galactic systems against a range of external disruptions. Numerical simulations and kinematic observations consistently demonstrate that galaxies residing within such halos exhibit markedly higher resilience to tidal disturbances—whether from galactic interactions or the dense environments of clusters—greatly reducing mass loss through stripping. Dark matter halos also play a vital role in regulating star formation over cosmic time. By gravitationally binding incoming gas clouds, they prevent the escape of material that would otherwise be expelled by feedback or environmental processes. Observations across multiple wavelengths—particularly in the infrared and radio—support this picture, revealing sustained gas reservoirs in systems like those mapped in the Hubble Ultra Deep Field. Such gas retention underpins continuous star formation, supplying the cold material necessary for the birth of new stellar populations [11].

Through these mechanisms, dark matter halos not only shield galaxies from external threats but also establish conditions conducive to long-term star formation, thereby shaping the life story of galaxies across billions of years.

3.2 Competing Theoretical Frameworks

There are two dominant models may explain dark matter's effects. The leading framework of modern cosmology, ΛCDM (Standard Cosmology) puts forward the existence of two key components, cold dark matter particles and dark energy. Cold dark matter is hypothesized to form massive, diffuse structures called halos, which exert additional gravitational pull. This extra gravity is crucial for explaining two major cosmological observations: the flat rotation curves of galaxies (where stars in the outer regions move faster than expected from visible matter alone) and the large-scale structure of the universe, such as the formation of galaxy clusters and filaments. Though ΛCDM has gained widespread acceptance and aligns with a range of data—from cosmic microwave background radiation to galaxy surveys—it is not without challenges. A primary issue is the lack of direct detection of the proposed CDM particles, despite extensive experimental efforts. Additionally, there are discrepancies in its predictions regarding dwarf galaxies, such as the number and distribution of these small satellite galaxies around larger ones, which do not always match observational findings.

Alternative theories, such as Modified Newtonian Dynamics (MOND), take a different approach by modifying the laws of gravity themselves rather than invoking dark matter. MOND suggests that Newtonian dynamics need adjustment at very low accelerations (typical of the outer regions of galaxies) effectively enhancing gravitational strength in these regimes. This modification eliminates the need for dark matter to explain galaxy rotation curves, as the adjusted gravity accounts for the observed motion of stars [12]. However, modified gravity theories face significant hurdles when confronted with other cosmological phenomena. A notable example is the Bullet Cluster collision, a cosmic event where two galaxy clusters merged. In this collision, the visible matter—primarily hot X-ray-emitting gas—slowed down due to electromagnetic interactions (like friction) between the gas particles of the two clusters. In contrast, the centers of gravitational attraction, which would be dominated by dark matter in

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the ΛCDM model, continued moving unimpeded, separate from the visible gas. Modified gravity struggles to account for this separation, as it ties gravity directly to visible matter, making it hard to explain how gravitational centers could detach from the decelerating visible gas. The comparison of ΛCDM and MOND is shown in Table 1.

Table 1. Comparison chart of ΛCDM and MOND

Theories	ΛCDM	MOND
Main Idea	Postulates the existence of cold, collisionless dark matter particles that provide the missing gravitational force.	Modifies Newton's second law at very low accelerations, making gravity stronger without unseen matter.
Explanation for Galactic Rotation Curves	The flat curve is due to the gravitational pull of an extensive, invisible dark matter halo surrounding the galaxy.	The modified force law naturally predicts flat rotation curves without any dark matter.
Explanation for the Bullet Cluster Evidence	Collisionless dark matter and stars pass through, while the dissipative gas lags behind. The mass (via lensing) and galaxies are co-located, separate from the gas.	Since gravity is tied directly to visible mass, it cannot easily explain why the gravitational potential (from lensing) is separated from the bulk of the visible matter (X-ray gas).
Key Advantages	Provides a successful, unified framework for a vast range of phenomena: CMB, large-scale structure, BBN, and cluster collisions.	Elegantly explains the rotation curves of a wide variety of individual galaxies with a single new constant.
Key Weakness and Challenges	No direct detection of DM particles yet. Faces potential issues on galactic scales (e.g., „missing satellites" and „cusp-core" problems).	Struggles to explain cluster dynamics, the cosmic microwave background, and large-scale structure without eventually invoking some form of dark matter.

The Bullet Cluster evidence strongly supports ΛCDM, as the clear spatial separation between the visible matter (the slowed X-ray gas) and the gravitational centers (detected via gravitational lensing) directly implies the presence of non-baryonic dark matter. This dark matter, being collisionless and not interacting electromagnetically, would not slow down during the cluster merger, thus maintaining its position as the gravitational center while the visible matter lagged behind—consistent with the ΛCDM framework. A study investigates a massive galaxy cluster merger at $z = 0.586$, similar to the Bullet Cluster. Using Chandra X-ray data and gravitational lensing (from HST and Keck observations), the authors demonstrate a significant spatial displacement between the peak of X-ray-emitting baryonic gas and the total mass centroid inferred from lensing [13]. This study found that the center of mass of the dark matter halo aligns perfectly with the visible galaxies at its core. This alignment is a key piece of evidence for the existence of collisionless dark matter. The researchers also measured how strongly dark matter particles might interact with each other, and found the probability is extremely low. These results strongly support the standard model of dark matter, where particles move through each other without colliding. At the same time, this evidence challenges alternative theories of gravity that try to explain cosmic phenomena without dark matter, as they struggle to account for this precise alignment.

4. Conclusion

Celestial bodies are usually classified by their physical properties—like size, composition, and brightness. However, a deeper understanding of their behavior requires looking beyond the visible to examine how they move and interact in the universe. Their motion is not only shaped by Newton's laws but also governed by the curvature of spacetime, as predicted by general relativity, and by the gravitational pull of dark matter—an invisible substance that fills the cosmos. There is strong evidence supporting the existence of dark matter. For example, spiral galaxies rotate in such a way that stars move at nearly the same speed regardless of how far they are from the center. This flat rotation curve suggests there is much more mass than people can see. Similarly, in collisions between galaxy clusters like the Bullet Cluster, researchers observed that gravitational lensing does not align with the visible matter, meaning something unseen—dark matter—must be responsible. Other ideas, such as Modified Newtonian Dynamics, have tried to explain these phenomena without dark matter. But so far, they cannot fully account for all the observations across different scales. That is why most scientists regard dark matter as a key part of the understanding of how the universe formed and evolved.

References

[1] Kahil ME. Dark Matter: the Problem of Motion. Gravit Cosmol. 2019, 25(3):256-263.
[2] Zhang M, Müller J, Biskupek L. Test of the equivalence principle for galaxy's dark matter by lunar laser ranging. Celest Mech Dyn Astron. 2020, 132(4):23.
[3] Bertone G, ed. Particle Dark Matter: Observations, Models and Searches. Cambridge University Press; 2010.
[4] Sanders RH. The Dark Matter Problem: A Historical Perspective. Cambridge University Press, 2010.
[5] Chinese Academy of Sciences. Chinese scientists achieve breakthrough in quantum communication research. February 28, 2014. https://www.cas.cn/ky/kyjz/201402/t20140228_4043378.shtml.
[6] Del Popolo A, Le Delliou M. Barions and ΛCDM Model Problems. Astron Rep. 2022, 66(2):102-115.
[7] Boveia A, Doglioni C, Lowette S. Dark matter models and direct detection. J Phys G Nucl Partic Phys. 2020, 47(9):090501.
[8] Ganeshaiah Veena P, Cautun M, van de Weygaert R, et al. The length and curvature of cosmic filaments. Mon Not R Astron Soc. 2021, 503(3):3525-3546.
[9] Bradač M, Allen SW, Treu T, et al. Revealing the properties of dark matter in the merging cluster MACS J0025.4-1222. Astrophys J. 2008, 687(2):959-967.
[10] Eckert D, Ettori S, Pointecouteau E, et al. The X-ray view of the Abell 3391/95 galaxy cluster system. Astron Astrophys. 2021, 647:A41.
[11] Wang HY, Li J, Chen X, Zhang T, Zhou Y. Clustering of diffuse dwarf galaxies and dark halo assembly bias. Nature. 2025, 624(7990):112-117.
[12] Rubin VC, Ford WK Jr. Rotation of the Andromeda nebula from a spectroscopic survey of emission regions. Astrophys J. 1970, 159:379-403.
[13] Duckworth C, Tooby-Smith H, Smith R, et al. The poorly constrained cluster-to-cluster variation in the stellar initial mass function: a critical review with insights from the E-MOSAICS simulation. Mon Not R Astron Soc. 2023, 518(2):2345-2368.