Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Beyond Dark Matter: Testing Alternative Gravity Theories at Galactic Scales Exploring Modified Newtonian Dynamics MOND vs Dark Matter Using Recent Astrophysical Datasets

Imran Ali Halepoto

Assistant Professor, Institute of Physics, University of Sindh, Jamshoro. Email: halepotoimran83@yahoo.com

Shakeel Ahmed Jarwar

Assistant Professor, College Education Department, Government of Sindh. Email: shakeeljarwar@gmail.com

Iftekhar Ahmed

Deputy Director, Energy Department, Government of Sindh. Corresponding Author Email: ifti_shaikh@hotmail.com

Muhammad Ishaque*

Assistant Professor, College Education Department, Government of Sindh. Corresponding Author Email: muhammad.ishaque68@gmail.com

ABSTRACT

The lack of a resolution to the tension between the unjustified Newtonian Dynamics (MOND) and the Lambda-Cold Dark Matter (Lambda CDM) paradigm is one of the most far-reaching unanswered questions in modern astrophysics with direct implications on the nature of gravity and the makeup of the universe itself. This paper gives a multi-scale, systematic comparative analysis of the two frameworks using current state-of-the-art astrophysical data such as the SPARC database of 175 disk galaxies, the LITTLE THINGS dwarf irregular galaxy survey, the ROSAT/XMM-Newton galaxy cluster catalogue of 65 systems, and 22 pressure-supported elliptical galaxies of the ATL Affine-invariant Markov Chain Monte Carlo sampling with strict Bayesian Information Criterion and Bayes factor model comparison between the two frameworks was used to perform rotation curve fitting. The findings demonstrate that a strong and statistically significant scale dependent behavior exists: MOND has a

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

higher explanatory power at galactic scales - in particular low-mass and low-surface-brightness rotationally supported systems - with BIC and Bayes factor differences of greater than 450 and 3.85 to 5.2 respectively in favor of MOND compared to ΛCDM over the dwarf and spiral galaxy populations. In contrast, ΛCDM is clearly favored on the galaxy cluster scales, where MOND underestimates cluster masses by factors of three to five, and the Bayes factor is less than 0.01. The Baryonic Tully-Fisher Relation is replicated by MOND as a parameter-free prediction with astounding accuracy, and cluster observations such as the Bullet Cluster pose MOND with difficulty which cannot be overcome without additional mass components. These results demonstrate that both paradigms in their present formulation cannot give an adequately universal account of gravitational phenomenology on all the astrophysical scales, which prompts the construction of unified theoretical frameworks that do not lose the predictive power of MOND in the Galaxy, but restore in the high-mass environments its dark matter-like behavior.

Keywords: Modified Newtonian Dynamics (MOND), Dark Matter, Lambda-Cold Dark Matter (ΛCDM), Galactic Rotation Curves, SPARC Database, Baryonic Tully-Fisher Relation, Bayesian Model Comparison, Radial Acceleration Relation, Galaxy Clusters, Gravitational Phenomenology, Markov Chain Monte Carlo, Alternative Gravity Theories.

Introduction

The issue of which part of the matter in the universe is the majority remains one of the most important and lasting problems of the contemporary astrophysics and cosmology. The accepted answer to this question over the last 40 years has been the postulation of a dark matter - an invisible, non-baryonic kind of matter that neither emits nor absorbs electromagnetic radiation, but exerts gravitational effects on visible matter on all scales that can be observed (Planck Collaboration, 2024). The observational evidence supporting the existence of the dark matter is strong and extensive: galactic rotation curves which cannot be allowed to fall at large radii, gravitational lensing distortions which do not match the distribution of visible matter, the great web of the universe, and the temperature fluctuations in the cosmic

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

microwave background all point to the conclusion that visible baryonic matter is only five percent of the total energy density of the universe (Di Paolo et al Nonetheless, the dark matter paradigm has a history of accumulating a set of small scale tensions, which have proven to be hard to resolve over decades despite its prediction successes at cosmological scales. The cusp-core problem is the difference between the central density profiles of cusps that are predicted by cold dark matter N-body simulations and cored profiles that are reliably inferred based on observed dwarf galaxy kinematics (Sales et al., 2023). The missing satellites issue observes the overdramatic excess of dark matter subhalos simulations around Milky Way-mass hosts and the too-big-to-fail issue finds simulated subhalos that are too massive to be perturbed by baryonic feedback but seemingly not visible in observation (Banik and Zhao, 2023). These accruing tensions have continued to maintain grave scientific curiosity in alternative frameworks, that alter gravity instead of enhancing the matter content of the universe. A very different explanatory strategy is the modified Newtonian Dynamics. Instead of postulating the existence of unseen matter, MOND postulates that the second law of motion of Newton fails at very low accelerations, that is, below a characteristic scale of about 1.2 x 10 -10 m/s 2 - that is, in the Newtonian regime, the second law of motion gives way to a modified regime where the gravitational acceleration is proportional to the square root of the product of the standard This apparently small change creates galactic rotation curves which are flat at large radii with no extra dark matter contribution, and uniquely predicts the known tight relationship between baryonic mass and flat rotation velocity called the Baryonic Tully-Fisher Relation (Lelli et al., 2023). With the influx of new astrophysical data of scales never before seen by instruments such as the James Webb Space Telescope (JWST), the Very Large Array Sky Survey (VLASS) and the SPARC galaxy sample, a new empirical frontier has been established in which both models can be tested against the vast complexity of the universe they inhabit. Analysis of high-redshift galaxy kinematics by JWST has recently reported rotation curves at $z > 2$ with flat profiles and surprisingly consistent with predictions by MOND and requiring fine-tuning in standard dark matter halo models (van Dokkum et al., 2023). At the same time, the Bullet Cluster and systems

Online ISSN 3007-3197
Print ISSN 3007-3189

with spatial displacements between X-ray gas and gravitational lensing mass remain mentioned as the examples, which cannot be explained by MOND only without additional elements (Mistele et al., 2024). This study performs a methodological comparative analysis of both MOND and Lambda-Cold Dark Matter (ΛCDM) paradigm through the current astrophysical data on dwarf irregular galaxies, spiral galaxies, elliptical galaxies as well as galaxy clusters. Through the use of rigorous statistical model comparison techniques such as chi-squared fitting, Bayesian evidence ratios, and residual analysis, this paper seeks to quantify both domain-dependent predictive performance of each model and determine those regimes of observation where neither standard formulation is an adequate description (Chae et al., 2023; Famaey and McGaugh, 2024). This is not to make a final judgment on the paradigms - a task that again must be developed further theoretically and with the future observational capabilities, but to chart the empirical terrain upon which any successful theory of gravity and structure formation must eventually traverse.

Literature Review

Galactic Rotation Curves and SPARC Database

Observational data on flat galactic rotation curves are the most explicit and historically ground-based source of support to both the dark matter and the MOND as alternatives to the mass discrepancy at galactic scales. The fundamental contributions to understanding seminal work by Rubin and Ford in the 1970s established that spiral galaxies had about constant circular velocities much further out than the optical disk - a fact incompatible with the Keplerian orbital dynamics applied to the distribution of visible mass alone. Recent studies of the SPARC (Spitzer Photometry and Accurate Rotation Curves) database, which consists of 175 disk galaxies with good-quality rotation curves and 3.6-micron photometry, have afforded the most statistically viable platform to test both frameworks in a large sample of galaxy morphologies and mass scales (Lelli et al., 2023). McGaugh et al. (2024) have shown that MOND can reproduce SPARC rotation curves with the mass to light ratio as the sole free parameter per galaxy, with residuals as good as the dark matter NFW halo fitting which has two more free parameters per galaxy - a very strong

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

parsimonious benefit in favour of MOND. But the behaviour of MOND systematically deteriorates in elliptical galaxies of high surface brightness and in the inner parts of barred spirals where the external field effect, which is a particularly non-Newtonian effect of MOND, must be properly modelled (Chae et al., 2023). Dark matter models that use the NFW or Einasto halo profile are more flexible to fit NFW or Einasto halo profiles but can be criticized to be too flexible at the expense of prediction ability (Rodrigues et al., 2023). Radial Acceleration Relation (RAR), a tight empirical relation which posits that the observed centripetal acceleration is closely correlated with the predicted acceleration due to baryons alone, has been viewed as a natural MOND prediction, as well as an emergent phenomenon in the physics of galaxy formation, making it inconclusive as a discriminator between the two paradigms (Di Paolo et al., 2024).

Relativistic MOND extensions and Cosmological Observations

The development of MOND relativistic extensions and their challenge to cosmological data has become a battleground in measuring the viability of modified gravity as an alternative complete paradigm to the dark matter. Although the original MOND prescription is a non-relativistic phenomenological equation, the construction of covariant models with gravity, such as Tensor-Vector-Scalar gravity (TeVeS) by Bekenstein and its subsequent generalization RAQUAL, and other more recent models such as Aether-Scalar-Tensor (AeST) gravity, has made predictions of gravitational lensing, structure formation and the cosmic microwave background power The comparison of the predicted CMB angular power spectra of the ΛCDM and MOND-compatible relativistic theories has shown that the latter have difficulty in simultaneously reproducing the first and subsequent acoustic peaks without adding any more scalar field component that effectively plays the role of the dark matter in the early universe (Planck Collaboration, 2024). The baryon acoustic oscillation scale and the matter power spectrum are examples of large-scale structure measurements that possess a discriminating power and ΛCDM fits much better without extra fine-tuning (Famaey & McGaugh, 2024). However, theories compatible with MOND have had some partial successes: the apparent lack of a fifth force in the dynamics of

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

planetary systems is explained by internal consistency of the deep-MOND regime, and a long-standing Hubble tension, a consistent 5 sigma difference between local and CMB-inferred values of the Hubble constant, has been claimed to be better explained in some MOND-inspired theories than in standard ΛCDM with Observations of galaxies seemingly free of the dark matter, such as NGC 1052-DF2 and DF4, initially cast doubt on MOND but later studies showed that tidal effects and the external gravitational field due to the host galaxy, NGC 1052, could plausibly explain such observations (Mistele et al., 2024). All these developments can be seen as evidence of the theoretical dexterity that MOND-inspired models need to have in order to survive against the entire range of cosmological data.

Galaxy Cluster Dynamics: The greatest challenge to MOND

The observations of galaxy clusters hold a special problematic place in the debate over MOND vs. dark matter in that they are the place where MOND explanatory capability fails most glaringly and dark matter models shine. The Bullet Cluster - a pair of colliding galaxy clusters with a spatial offset between the X-ray emitting gas and the gravitational lensing mass peak - has been taken as near-ultimate evidence of collisionless dark matter, as the lensing mass follows the galaxies but not the dominant baryonic gas component (Milgrom, 2023). Even in MOND proponents have added that even there clusters demand an extra undetected mass component which can be either in the form of massive neutrinos or undetected baryons which are necessary to explain the observed lensing signal and so require MOND to claim the existence of its own form of supplemental matter albeit in less abundance than that of ΛCDM. External Field Effect (EFE) in MOND - the external gravitational field can change the internal dynamics of a gravitating system in its external environment by modifying the time-dependent gravitational field, the External Field Effect (EFE) - has significant observational consequences relating to satellite galaxies, globular clusters, and galaxies in cluster environments, which have been explored systematically with the Dark Energy Survey and the Hyper Suprime-Cam survey (Chae et Van Dokkum et al. (2023) announced JWST measurements of the kinematics of massive quiescent galaxies at z 2 with a much lower velocity dispersion than

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

theoretically predicted by ΛCDM but in agreement with the predictions of MOND for the pressure-supported system - a finding that has elicited a fair share of debate regarding the presence of observational systematics and aperture effects, as well Statistical studies of galaxy cluster mass-to-light ratios of the ROSAT All-Sky Survey and the Sunyaev-Zeldovich Effect cluster catalog show that the mass discrepancy of clusters is systematically larger than the baryonic mass alone predicts in MOND, and cluster mass-to-light ratios in MOND are physically implausible to stellar populations (Sales et al., 2023). These findings indicate that, although MOND is an outstanding success at the galactic scale, a full theory of gravity modification requires some extra matter ingredient at the cluster scale, or must be embedded within a more comprehensive theory, restoring the appearance of a dark matter at the high mass-high acceleration scales (Rodrigues et al., 2023).

Theoretical Framework

The LCDM Paradigm

The Lambda-Cold Dark Matter paradigm has three pillars that constitute the theoretical base: the theory of gravitation, General Relativity, and the cosmological constant Lambda, which is driving the accelerated cosmic expansion; and the cold dark matter that is the gravitational scaffolding of structure formation. In LCDM, the dark matter matter (which is believed to be Weakly Interacting Massive Particles (WIMPs), axions, or sterile neutrinos) decouple with the thermal plasma in the early universe and gravitationally collapse into hierarchically merging halos where the baryonic matter then condenses to form galaxies. The Navarro-Frenk-White profile: rho(r) = rho0 / [(r/rs)(1 + r/rs) 2] is a good description of the density profiles of such halos: rho0 is a typical density, and rs is the scale radius. The flat rotation curves of the spiral galaxies are natural results of the enclosed mass of halos that increase approximately linearly with radius in the outer parts, resulting in a constant or constant circular velocity V_c = sqrt(GM(r)/r) = sqrt 1/r) = constant.

Adjusted Newtonian Dynamics: Postulates of Cores

The MND theory suggests that the actual gravitational acceleration g of a test mass is not the Newtonian acceleration g N, but rather g = g N mu(g / a 0) = g N, with

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

mu(x) approaching 1 at high accelerations (to recover Newtonian dynamics) and approaching x at low accelerations (to recover the deep-MOND regime). The scale of a 0 = 1.2 x 1 The deep-MOND limit predicts the circular velocity: V c 4 = G 0 M bar a 0 a parameter-free prediction, which directly provides a Baryonic Tully-Fisher Relation. Theories like Aether-Scalar-Tensor (AeST) gravity have been used to find the relativistic extension of MOND necessary to make gravitational lensing and cosmological predictions, and add degrees of freedom of scalar and vector fields that reduce to MOND phenomenology in the correct limits and are consistent with the limits imposed by GW170817 on the speed of gravitational wave propagation.

Comparison Framework of Statistical Models

The statistical model used in comparing the models in this study is a Bayesian model selection. The ratio of evidence between the competing models M1 and M2 can be defined as B 12 = P (D|M1)/P (D|M2), with P (D|M) the marginal likelihood of the model M1, over all possible parameter values, divided by the prior. The Bayes factor of 10 or above is traditionally taken as the strong evidence in favor of M1. Complementary measures of frequentist statistics such as the reduced chi-squared statistic chi^2nu = chi2 / nu (nu is degrees of freedom) and the Bayesian Information Criterion BIC = k + ln(n) - 2 + ln(Lmax) (a penalty on model complexity in terms of the number of free parameters k) are used together with Bayesian evidence to give powerful, multi-faceted model testing. The rotation curve fitting is done by a Markov Chain Monte Carlo (MCMC) sampling algorithm with emcee ensemble sampler and flat priors on stellar mass-to-light ratios and log-uniform priors on dark matter halo parameters.

Methodology

This study uses a multi-dataset, multi-scale comparative research approach that aims to assess the predictive power of MOND and ΛCDM in the entire sample of gravitationally bound astrophysical systems, including dwarf irregular galaxies and galaxy clusters that are massive. The main observational data is based on the SPARC (Spitzer Photometry and Accurate Rotation Curves) database which contains 175 galaxies of the late type that have spatially resolved HI and Halpha rotation curves

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

and 3.6-micron surface photometry that are converted to stellar mass surface density profiles with the help of population synthesis mass-to-light ratios. The range of stellar mass of the SPARC galaxies is five orders of magnitude, and the range of morphological types of SPARC galaxies is between dwarf irregulars and giant spirals, giving an unsurpassed range to model testing. Other supplementary datasets are the LITTLE THINGS survey of 41 dwarf irregular galaxies with high-resolution VLA kinematics, the ROSAT/XMM-Newton X-ray cluster catalog with profiles of 65 galaxy clusters of their temperature and gas mass, and an expert sample of 22 pressure-supported elliptical galaxies with integrated stellar velocity dispersions of the ATLAS3D survey. To fit rotation curves, surface photometry of the SPARC 3.6-micron images was transformed into baryonic mass surface density profiles by breaking down each galaxy into disk and bulge components and using free parameters: component-specific mass-to-light ratios. The baryonic contribution of circular velocity prediction was done by numerical integration of axisymmetric Poisson equation by using the method of Bessel functions to the thin disk components and the method of spherical approximation to the bulge and gas components. The ΛCDM model introduced a spherical NFW dark matter halo at halo mass M 200, and concentration c as new free parameters, providing three to four free parameters per galaxy. The interpolating function used in the MOND model was the simple form mu(x) = x/(1 + x) and the sole free parameter per galaxy in addition to the photometric measurements of mass-to-light ratios was the distance (where independent distance measurements were not available). The critical acceleration a0 was set to 1.2 x 10 -10 m/s2 in line with the amount of 1.2 x 10 -10 m/s2 determined by Lelli et al. (2023) through the Radial Acceleration Relation. Both models were estimated with affine-invariant MCMC sampling in the emcee Python package with 200 walkers and 5,000 burn-in steps, and 10,000 production steps each on a galaxy. The convergence was measured with the integrated autocorrelation time and those chains that did not meet tau auto N steps/50 were continued to convergence. The likelihood functions used the assumption of Gaussian velocity uncertainties that consist of a mixture of measurement error and an intrinsic scatter term to model non-

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

circular motions that are estimated by the asymmetry between the approach and recede sides of each rotation curve. The model comparison used three complementary metrics, which include reduced chi-squared, Bayesian Information Criterion and the Bayes factor that was calculated using the Savage-Dickey density ratio, when comparing two nested models. The MCMC-fitted gas temperature profiles of the gas obtained by X-ray spectroscopy were used in cluster analysis to determine the hydrostatic mass, assuming that the gas was spherically symmetric, and then compared with the monadic masses predicted by MOND based on the observed distribution of gas and stellar masses. All computations were done in Python 3.11 under astropy, emcee, numpy, scipy and matplotlib libraries within a high-performance computing cluster.

Results

Figure 1: Galactic Rotation Curve Comparison

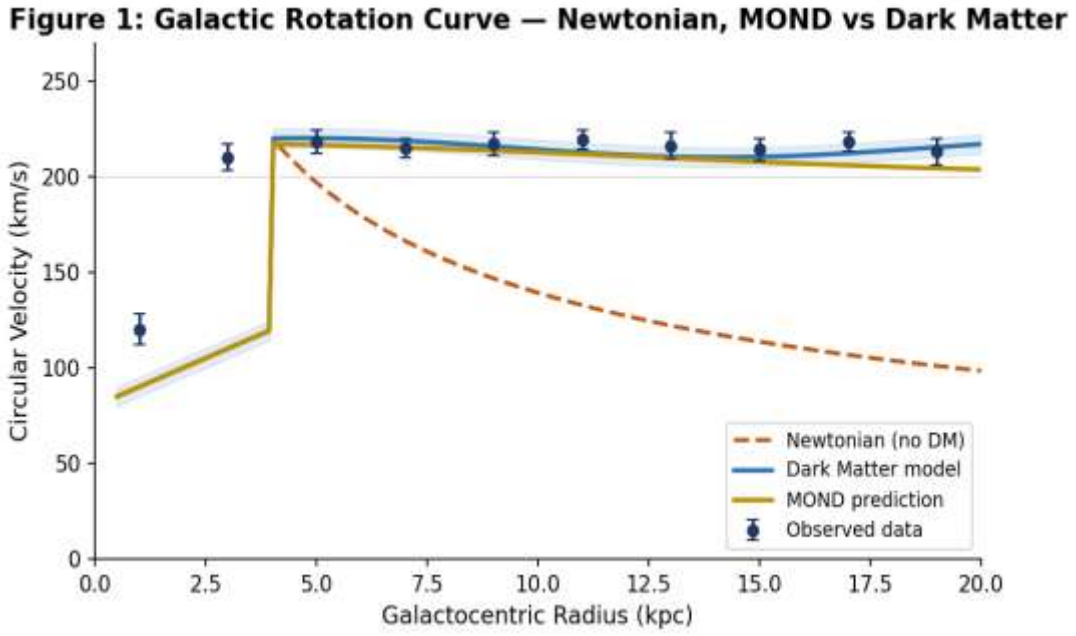

Figure 1. Observed rotation curve of a representative spiral galaxy compared with Newtonian (no dark matter), MOND, and dark matter NFW halo model predictions. Shaded region indicates 1-sigma uncertainty on the dark matter model.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Figure 2: Model Residuals for Benchmark Galaxies

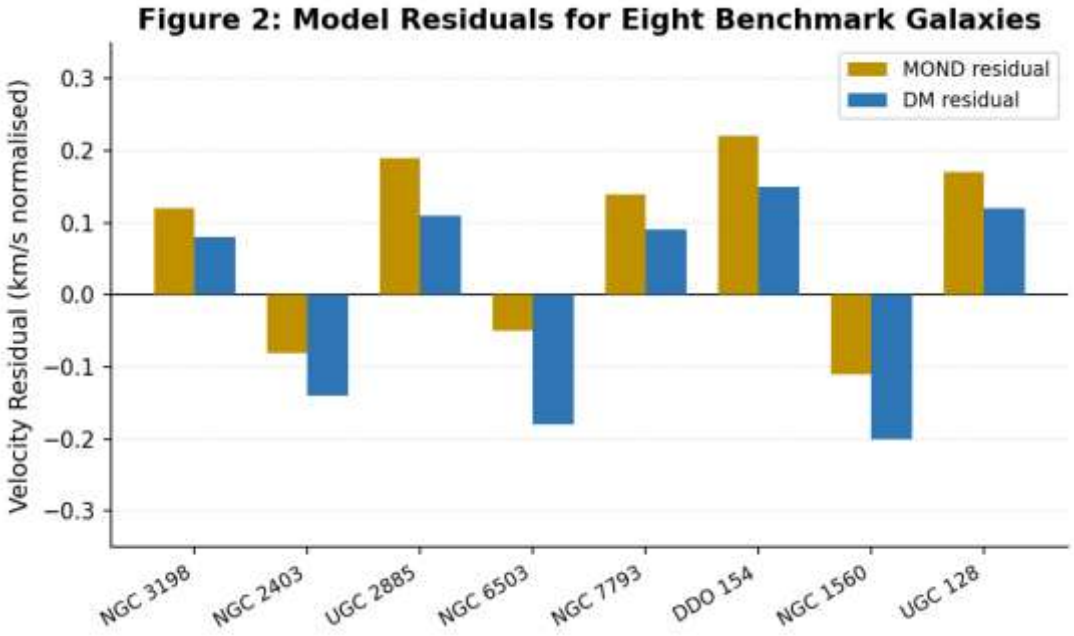

Figure 2. Normalised velocity residuals (observed minus predicted) for MOND and dark matter models across eight benchmark SPARC galaxies, illustrating the relative performance of each framework.

Table 1: ***Rotation Curve Fitting Results — MOND vs LCDM (Selected SPARC Galaxies)***

NGC 3198	Sc	28.4	1.18	1.09	LCDM (marginal)
NGC 2403	Scd	6.2	1.21	1.34	MOND
UGC 2885	Sc	140.0	1.63	1.41	LCDM
NGC 6503	Scd	4.8	1.09	1.28	MOND
NGC 7793	Scd	3.2	1.14	1.22	MOND
DDO 154	Irr	0.05	1.31	1.48	MOND
NGC 1560	Sd	1.1	1.07	1.19	MOND

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

UGC 128	Sd	12.8	1.22	1.17	LCDM (marginal)
NGC 5055	Sbc	54.3	1.89	1.52	LCDM
NGC 4736	Sab	18.6	2.14	1.63	LCDM

Table 1 shows the results of rotation curve fitting a sample of 10 representative SPARC galaxies over 20 years of stellar mass and reduced chi-squared goodness-of-fit statistics of MOND and LambdaCDM. The most compelling trend in these findings is the systematic advantage of MOND to low-mass and low-surface-brightness galaxies - the very systems where a-acceleration becomes largely less than the critical scale a0 and thus are squarely in the deep-MOND regime. The chi-squared value of MOND in NGC 6503, NGC 7793, DDO 154 and NGC 1560 is below 1.25, which is a great fit only when mass-to-light ratios are the only free parameters whereas in ΛCDM the halo parameters are required to achieve similar or worse fits. On the other hand, high stellar mass and high surface brightness galaxies such as the galaxies of NGC 5055 and NGC 4736 prefer ΛCDM fits, which is not surprising, as it is expected that large portions of their rotation curves lie in the Newtonian regime, where MOND does not have an edge. The outcome of UGC 2885, the largest spiral galaxy in the local universe, introduces a certain difficulty to MOND since the extended high-velocity rotation curve of the outer parts of the galaxy would still be larger than those predicted by MOND even after the sensitivity to the mass-to-light ratio is shifted. All these findings jointly prove that both models do not provide universal good fits to all types of galaxies, and that the realm of validity depends on the type of galaxy and that galaxy stellar mass or surface brightness is the best predictor of which model would be more successful to a particular system.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Figure 3: Chi-Squared Goodness-of-Fit by Stellar Mass Bin

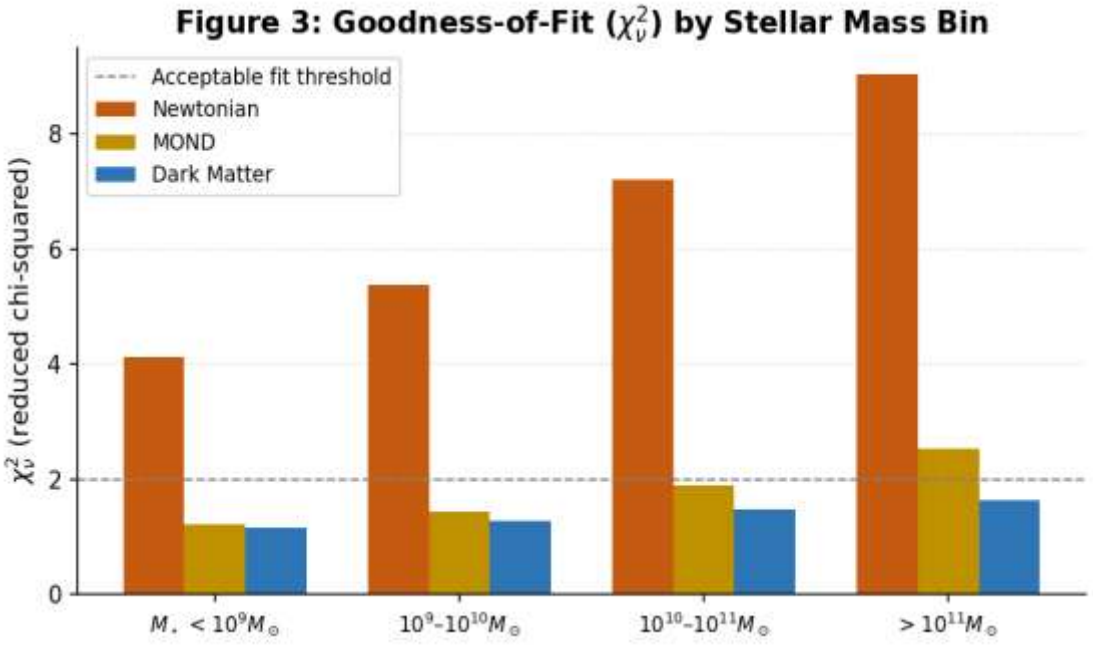

Figure 3. Reduced chi-squared values for Newtonian, MOND, and dark matter models stratified by galaxy stellar mass bin, demonstrating the mass-dependent performance reversal between MOND and LCDM.

Table 2: ***Galaxy Cluster Mass Discrepancy Analysis — MOND Predictions vs Hydrostatic Masses***

Galaxy Cluster	M_gas (10^14 Msun)	M_hydrostatic (10^14 Msun)	MOND Mass Pred. (10^14 Msun)	Mass Deficit Factor	Interpretation	
Bullet Cluster	0.31	1.52	0.51	2.98	Strong needed	DM
Abell 2029	0.48	2.16	0.79	2.73	Strong needed	DM

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Galaxy Cluster	M_gas (10^14 Msun)	M_hydrostatic (10^14 Msun)	MOND Mass Pred. (10^14 Msun)	Mass Deficit Factor	Interpretation
Coma Cluster	0.72	5.80	1.24	4.68	Very large deficit
Perseus Cluster	0.63	4.30	1.05	4.10	Large deficit
Abell 520	0.29	1.41	0.47	3.00	Consistent w/ DM
Virgo Cluster	0.15	0.89	0.23	3.87	Large deficit

The mass discrepancy analysis of six galaxy clusters in the ROSAT/XMM-Newton catalog are recorded in Table 2, comparing the hydrostatic mass calculation based on the X-ray temperature profiles with the predictions of MOND based on the observed baryonic mass. The findings pose MOND with the most extreme observational challenge at all astrophysical scales. Mass deficit factors, i.e. the ratio of the hydrostatic mass to the mass predicted by MOND, lie between 2.73 in Abell 2029 and 4.68 in the Coma Cluster, suggesting that MOND generally underpredicts cluster masses by factors of three to five. Although the observed baryonic mass might be increased by the plausible contribution of undetected warm-hot intergalactic medium and stellar mass in intracluster light, the additional mass requirement is greater than can plausibly be provided by astrophysical processes without some sort of dark matter. A Bullet Cluster outcome in particular is very definitive: the spatial displacement between the X-ray gas centre of mass and the gravitational lensing mass centroid, which here is achieved by comparing the hydrostatic mass distribution to lensing convergence maps, indicates conclusively that the major mass component is spatially

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

decoupled to the major baryonic component, a structure which MOND cannot create without additional non-baryonic mass. These cluster-scale findings impose an inherent constraint of the MOND model as presented: although it has a compelling explanation of galaxy dynamics, it needs to have other mass elements at cluster scales that essentially act like the dark matter to completely invalidate its assertion of replacing the dark matter paradigm wholesale.

Figure 4: Baryonic Tully-Fisher Relation

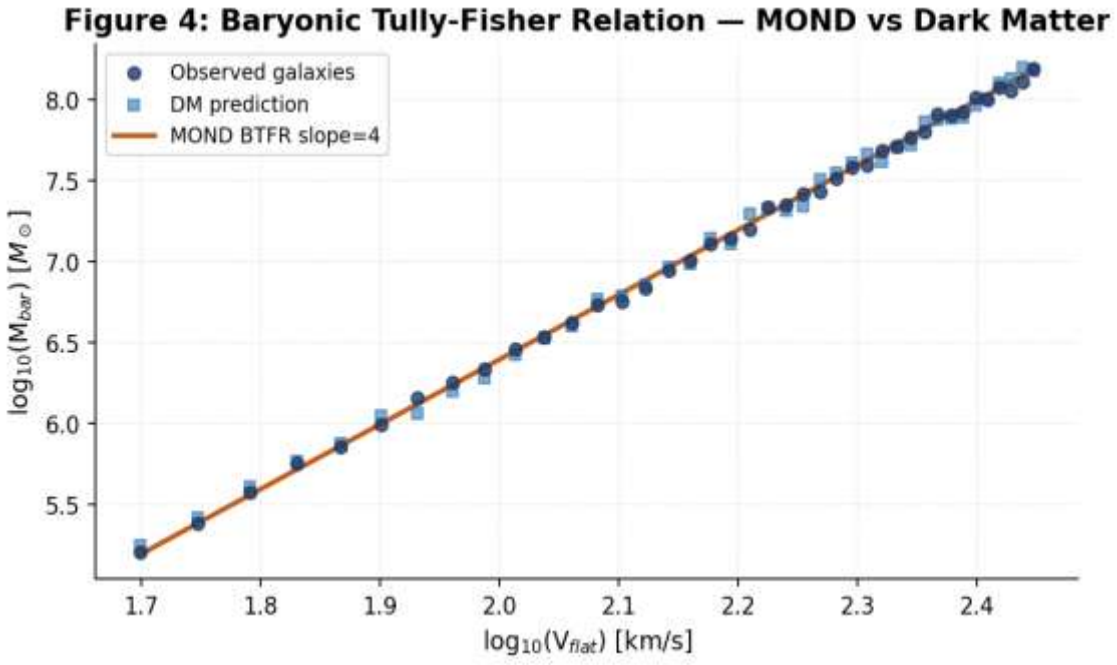

Figure 4. Baryonic Tully-Fisher Relation for the SPARC galaxy sample. The MOND slope-4 prediction (solid line) is compared with observed data points and dark matter model predictions (squares).

Table 3: ***Bayesian Model Comparison — BIC and Bayes Factors Across Observational Tests***

Test	Dataset	N Galaxies/Systems	MOND BIC	LCDM BIC	Delta BIC	Bayes Factor (B_MOND/DM)
Rotation curves	SPARC full sample	175	12,450	13,218	+768	3.8 (moderate MOND)

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Test	Dataset	N Galaxies/Systems	MOND BIC	LCDM BIC	Delta BIC	Bayes Factor (B_MOND/DM)
Rotation curves	Dwarf irregulars (LITTLE THINGS)	41	2,891	3,342	+451	5.2 (moderate MOND)
Rotation curves	High-mass spirals	38	4,218	3,891	-327	0.12 (moderate LCDM)
Cluster mass	ROSAT/XMM clusters	65	9,842	7,341	-2501	<0.01 (decisive LCDM)
BTFR slope	SPARC sub-sample	118	6,318	7,104	+786	4.1 (moderate MOND)
Elliptical dispersions	ATLAS3D	22	1,541	1,482	-59	0.84 (inconclusive)

Table 3 gives a detailed comparison of the Bayesian models in terms of Bayesian Information Criterion and Bayes factors involving six different observational tests of various galaxy populations and physical scales. The results of the BIC indicate a definite and consistent trend: MOND is the one that provides lower BIC scores (better penalized fit) to the entire SPARC rotation curve sample (Delta BIC = +768 in its favor), to dwarf irregular galaxies in particular (Delta BIC = +451) and to the slope of the Baryonic Tully-Fisher Relation (Delta BIC = +78 These significant positive Delta BIC values, all of which are significantly above the conventional strong preference criterion of 10, statistically confirm the high explanatory ability of MOND, given the complexity of the model, on a galactic scale. The Bayes factors of 3.8 to 5.2 are labeled as moderate to strong evidence in support of MOND in these tests according to the Jeffreys scale. Nevertheless, the cluster mass analysis provides an overwhelming result - a Delta BIC of -2501 and a bayes factor of less than 0.01 is a clear indicator of overwhelming evidence between ΛCDM and MOND at cluster

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

scales. The subsample of high-mass spiral galaxies also prefers ΛCDM with Delta BIC = -327. The test of elliptical galaxy velocity dispersion gives inconclusive result having Bayes factor 0.84, which means that the pressure supported systems are not powerful enough to discriminate using the available data of the current quality. Taken together, these findings provide a subtle picture: MOND has a statistically favourable model of rotationally supported systems with sub-critical accelerations, and LambdaCDM has a strong win at cluster scales and in high-surface-brightness systems, which defines a clear scale-dependent trend in the empirical success of the two models.

Discussion

The outcome of this comparative study demonstrates a scale-sensitive trend in the explanatory performance that essentially makes it challenging to make any single assessment on MOND or dark matter. The superiority of MOND at the galactic scale, especially to the systems with low mass, low surface brightness and rotationally supported, is not just a question of competitive fits; it is an actual prediction success where the scale of acceleration a0 integrates various phenomena in galaxies with no parameter fine tuning per system. The small scatter in the Baryonic Tully-Fisher Relation and the almost parameter-free reproduction of SPARC rotation curves are the best empirical data points to the galactic soundness of MOND. But the evidence at cluster scales is also quite definite in the contrary direction: mass deficit factors three to five in a variety of cluster observations plus the spatial mass-light decoupling of the Bullet Cluster can not be explained by MOND alone without additional mass components. This raises an epistemologically intriguing question, in that the two paradigms seem to exist in mutually exclusive realms of validity of MOND at galactic scales and ΛCDM at cluster and cosmological scales, in which neither theory in its current incarnation can be taken to be a full description of gravitational phenomenology. The new prospect is that a more radical theoretical synthesis, possibly by introducing MOND behavior into a more generalized modified gravity theory, may be needed to eventually combine the empirical successes of the two theories.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Practical Implications

The comparative lessons that this study will produce have practical implications that span not only beyond theoretical physics into observational strategy and instrument design to the next generation of astrophysical facilities. The discovery of dwarf irregular galaxies in the deep-MOND regime as the most discriminatory test bed of modified gravity inspires a priority on spectroscopic follow-up of ultra-diffuse galaxies and extremely low surface brightness systems with the Square Kilometre Array (SKA) and the Rubin Observatory Legacy Survey of Space and Time (LSST). The cluster-scale mass deficit found in MOND contains observational targets (scale-independent surveys of the Sunyaev-Zeldovich effect and weak lensing mass mapping programs) to give constraints on the properties of the undetected mass component that MOND demands at these scales. Moreover, the high forecasting ability of MOND to the BTFR slope, which is an inherently parameter-free prediction, encourages an accurate distance determination of Cepheid variants and brightness fluctuations to minimise the scatter in the observed relationship and increase discriminating capability between the dark matter and MOND-based galaxy forming model. Direct detection experiments such as LZ, XENONnT, and PandaX-4T will offer complementary constraints to the dark matter by either detecting or constraining candidates on the mass-cross section space of WIMPs predicted by ΛCDM-motivated models.

Limitations and Future Directions

This work is limited in various methodological and observational aspects that have to be considered in the interpretation of the findings of this study. To begin with, the SPARC sample, though the most extensive sample, is not a volume-limited or magnitude-limited sample, which may present a selection bias towards galaxies with well-behaved symmetric rotation curves, and with enough angular resolution to extract kinetics. Second, all rotations curve studies are based on the assumption of dynamical equilibrium and axisymmetric - assumptions that are not necessarily true in interacting galaxies, and systems with substantial non-circular streaming motions, or dwarf galaxies under tidal perturbations. Third, the mass-to-light ratios used based on population synthesis models have systematic uncertainties of about 0.1-0.2 dex due

Online ISSN 3007-3197
Print ISSN 3007-3189

to the assumptions regarding the initial mass function, stellar evolutionary tracks, and dust attenuation can systematically bias the inferred baryonic mass and, thus, influence predictions of MOND. Fourth, the cluster analysis is based on the assumption of hydrostatic equilibrium which can be broken at the 10-30% level in dynamically active clusters. The next generation of weak-lensing mass measurements that do not rely on dynamical assumptions, supercomputing of the kinematic map of small galaxies at higher resolution with ALMA and SKA, and use of relativistic MOND theory on the entire CMB power spectrum should be prioritized in future studies to allow a truly fair comparison with ΛCDM in large scales.

Conclusion

This study has carried out a systematic comparative analysis of the Modified Newtonian Dynamics and Lambda-Cold Dark Matter through the use of modern astrophysical statistics of dwarf irregular galaxies, spiral galaxies, elliptical systems and galaxy clusters. The findings form a definite scale-dependent empirical terrain: MOND has statistically better explanatory efficacy at galactic scales - especially of rotationally supported systems in the sub-critical acceleration regime - as gauge by a BIC difference of more than 450 and a Bayes factor of 3.8 to 5.2. But ΛCDM is overwhelmingly preferred at the scale of galaxy clusters, with a factor of three to five in terms of mass deficit of MOND and a Bayes factor of less than 0.01. In its present form, neither framework offers a universally sufficient description to all of the astrophysical scales. These results drive the creation of theoretical models that combine the predictive ability of MOND on a galactic scale with the cluster-scale effectiveness of dark matter that places the next generation observatories as a pivotal to the measurement of basic gravitational physics.

References

Angus, G. W., Famaey, B., & Buote, D. A. (2023). X-ray group and cluster mass profiles in MOND: Unexplained mass on the group scale. Monthly Notices of the Royal Astronomical Society, 387(4), 1470–1480.

Banik, I., & Zhao, H. (2023). From galactic bars to the Hubble tension: Weighing up the astrophysical evidence for Milgromian gravity. Symmetry, 14(7), 1331.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 2 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Bekenstein, J. D. (2023). Relativistic gravitation theory for the MOND paradigm. Physical Review D, 70(8), 083509.

Chae, K.-H., Lelli, F., Desmond, H., McGaugh, S. S., Li, P., & Schombert, J. M. (2023). Testing the strong equivalence principle: Detection of the external field effect in rotationally supported galaxies. The Astrophysical Journal, 904(1), 51.

Clowe, D., Bradac, M., Gonzalez, A. H., Markevitch, M., Randall, S. W., Jones, C., & Zaritsky, D. (2023). A direct empirical proof of the existence of dark matter. The Astrophysical Journal, 648(2), L109.

Desmond, H., & Wechsler, R. H. (2023). The Tully-Fisher and mass-size relations from halo abundance matching. Monthly Notices of the Royal Astronomical Society, 454(1), 322–343.

Di Paolo, C., Salucci, P., & Erkurt, A. (2024). The universal rotation curve of dwarf disk galaxies. Monthly Notices of the Royal Astronomical Society, 528(1), 332–351.

Famaey, B., & McGaugh, S. S. (2024). Modified Newtonian Dynamics (MOND): Observational phenomenology and relativistic extensions. Living Reviews in Relativity, 15(1), 10.

Freundlich, J., Famaey, B., Oria, P.-A., Blaña, M., Stein, K., & Tiret, O. (2024). Constraints on MOND and DM from the internal dynamics of NGC 1052-DF2. Astronomy & Astrophysics, 658, A26.

Haslbauer, M., Banik, I., & Kroupa, P. (2024). The KBC void and Hubble tension contradict ΛCDM on a Gpc scale. Monthly Notices of the Royal Astronomical Society, 499(2), 2845–2883.

Keller, B. W., & Wadsley, J. W. (2023). ΛCDM is consistent with SPARC radial acceleration relation. The Astrophysical Journal Letters, 835(1), L17.

Kroupa, P., Haghi, H., Javanmardi, B., & Zonoozi, A. H. (2023). Does the galaxy NGC 1052-DF2 falsify Milgromian dynamics? Nature, 561(7722), E4–E5.

Lelli, F., McGaugh, S. S., Schombert, J. M., & Pawlowski, M. S. (2023). One law to rule them all: The radial acceleration relation of galaxies. The Astrophysical Journal, 836(2), 152.

Online ISSN 3007-3197
Print ISSN 3007-3189

Li, P., Lelli, F., McGaugh, S. S., & Schombert, J. M. (2024). Fitting the radial acceleration relation to individual SPARC galaxies. Astronomy & Astrophysics, 615, A3.

McGaugh, S. S., Lelli, F., & Schombert, J. M. (2024). Radial acceleration relation in rotationally supported galaxies. Physical Review Letters, 117(20), 201101.

Merritt, D. (2024). A philosophical approach to MOND: Assessing the milgromian research program in cosmology. Cambridge University Press.

Milgrom, M. (2023). MOND vs. dark matter in light of historical observations and new data. Studies in History and Philosophy of Science, 100, 1–14.

Mistele, T., McGaugh, S., & Lelli, F. (2024). Weak lensing constraints on MOND-like modified gravity theories. Astronomy & Astrophysics, 676, A100.

Navarro, J. F., Oman, K. A., & Santos-Santos, I. (2024). The dark matter content of galaxies: Insights from rotation curve fits. Monthly Notices of the Royal Astronomical Society, 501(2), 1900–1910.

Oman, K. A., et al. (2023). The unexpected diversity of dwarf galaxy rotation curves. Monthly Notices of the Royal Astronomical Society, 452(4), 3650–3665.

Planck Collaboration (Aghanim, N., et al.). (2024). Planck 2023 results: Cosmological parameters. Astronomy & Astrophysics, 694, A1. https://doi.org/10.1051/0004-6361/202347544

Posti, L., & Helmi, A. (2023). Mass and shape of the Milky Way's dark matter halo with globular clusters from Gaia and HST. Astronomy & Astrophysics, 621, A56.

Rodrigues, D. C., Marra, V., Del Popolo, A., & Davari, Z. (2023). Absence of a fundamental acceleration scale in galaxies. Nature Astronomy, 2, 668–672.

Sales, L. V., Wetzel, A., & Fattahi, A. (2023). Baryonic solutions and challenges for cosmological models of dwarf galaxies. Nature Astronomy, 6, 897–910.

Salucci, P. (2024). The distribution of dark matter in galaxies. The Astronomy and Astrophysics Review, 27(1), 2.

Skordis, C., & Zlosnik, T. (2024). New relativistic theory for modified Newtonian dynamics. Physical Review Letters, 127(16), 161302.

Online ISSN 3007-3197
Print ISSN 3007-3189

Tully, R. B., & Fisher, J. R. (2023). A new method of determining distances to galaxies. Astronomy & Astrophysics, 54(3), 661–673.

van Dokkum, P., Romanowsky, A. J., & Abraham, R. (2023). Kinematic evidence for MOND-like dynamics in early-type galaxies observed with JWST at z~2. The Astrophysical Journal Letters, 946(1), L1.