

Modeling Galactic Rotation Curves to Map Dark Matter Distribution in the Galaxy: A Comparative Bayesian Analysis of Cuspy and Cored Halo Profiles Across the Sparc Database

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MODELING GALACTIC ROTATION CURVES TO MAP DARK MATTER DISTRIBUTION IN THE GALAXY: A COMPARATIVE BAYESIAN ANALYSIS OF CUSPY AND CORED HALO PROFILES ACROSS THE SPARC DATABASE

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ABSTRACT

The observed rotation curves of spiral and irregular galaxies do not decline at large radii as Newtonian dynamics predicts for a mass distribution concentrated toward the centre. Instead, they remain approximately flat, implying the presence of an extended, unseen mass component generally attributed to dark matter. The precise inner structure of this component remains disputed: Cold Dark Matter (Λ CDM) N-body simulations predict a steeply rising central density, or “cusp,” whereas a large body of observational work instead favours a flatter, constant-density “core.” This discrepancy, known as the Cusp-Core problem, has remained unresolved for more than two decades. In this study, rotation curves for a sample of late-type galaxies drawn from the Spitzer Photometry and Accurate Rotation Curves (SPARC) database were decomposed into their baryonic components (stellar disk, bulge, and gas) and a residual dark matter contribution. Baryonic mass was estimated from 3.6 μm near-infrared photometry and 21-cm HI radio data, applying standard Freeman-disk and Sérsic-bulge formalisms. Two competing halo models, the cuspy Navarro-Frenk-White (NFW) profile and cored alternatives (Pseudo-Isothermal, Burkert, DC14), were fit to each galaxy using Markov Chain Monte Carlo (MCMC) Bayesian inference, with priors placed on the stellar mass-to-light ratio. Standard fitting procedures assume that the uncertainty at each radial data point is statistically independent of its neighbours, an assumption that does not hold well for rotation-curve data in practice. A Gaussian Process Regression (GPR) extension was therefore incorporated to model correlated systematic residuals jointly with the physical halo parameters. Under the standard independent-error assumption, cored profiles outperformed NFW across most of the sample, particularly in gas-dominated dwarfs such as DDO 154. When the GPR covariance term was included, however, this advantage shrank sharply. The results suggest that a considerable portion of the historical observational evidence favouring cored profiles may be attributable to unmodelled correlations in the data rather than to a genuine absence of central cusps, and that resolving the Cusp-Core problem conclusively will likely require higher-resolution instrumentation and full three-dimensional kinematic modelling, not further one-dimensional curve-fitting.

Keywords: dark matter halos; galactic rotation curves; Cusp-Core problem; Navarro-Frenk-White profile; Pseudo-Isothermal profile; SPARC database; Markov Chain Monte Carlo; Gaussian Process Regression

1. INTRODUCTION

1.1 Background of the Study

Galactic rotation curves provide one of the most direct observational tests of how mass is distributed within a galaxy. For an object in circular orbit at radius R around an enclosed mass $M(R)$, Newtonian mechanics predicts an orbital speed of $V(R) = \sqrt{GM(R)/R}$ (Sofue, 2017). Because the majority of a spiral galaxy's visible mass, stars, dust, and gas, is concentrated in the bulge and inner disk, the enclosed mass $M(R)$ is expected to approach a roughly constant value well inside the edge of the visible disk. Beyond that point, Newtonian mechanics predicts a declining velocity profile, $V(R) \propto R^{-1/2}$, analogous to the Keplerian decline observed in the Solar System, where outer planets orbit far more slowly than inner ones (National Optical-Infrared Astronomy Research Laboratory, n.d.).

Observations do not bear this prediction out. Decades of increasingly precise optical and radio measurements have instead found that rotational velocities remain approximately flat, often extending tens of kiloparsecs beyond the visible edge of the disk (Sofue, 2017). Reconciling this with Newtonian gravity requires that the enclosed mass continue to grow linearly with radius, $M(R) \propto R$, rather than levelling off. Since the visible stellar light does not extend nearly this far, this implies that galaxies are embedded within a much larger, non-luminous mass component, a dark matter halo extending well beyond the visible disk (Sofue, 2017).

1.2 Problem Statement

The existence of dark matter is not seriously disputed within the astrophysics community; what remains unresolved is its detailed spatial distribution and its fundamental particle identity (Freese, 2017). The gravitational contribution expected from visible stars and gas alone is insufficient to sustain the flat rotation curves that are observed (Sofue, 2017). Without an additional mass component, a galaxy such as the Milky Way would not retain enough gravitational binding to remain stable against its own rotation (NOIRLab, n.d.).

Determining how this missing mass is distributed within a halo has proven persistently difficult, a difficulty formalised as the Cusp-Core problem (Sofue, 2017). Cosmological N-body simulations based on the standard Λ CDM model consistently predict halos with density profiles

that rise steeply toward the centre, forming a “cusp” (Review of solutions, 2022). Observations of real galaxies, particularly dwarf spheroidals and gas-rich Low Surface Brightness (LSB) systems, more often indicate a flat, constant-density “core” instead (Boldrini, 2021). Whether this discrepancy arises from baryonic physics such as supernova-driven outflows, from systematic observational effects such as beam smearing or non-circular gas motion, or from a more fundamental limitation in the standard particle dark matter model remains an open question, and one that requires careful quantitative rotation-curve modelling to address (Boldrini, 2021).

1.3 Aim and Objectives

The aim of this study is to characterise, as rigorously as the available data permit, the structure of dark matter halos across a range of galaxy types, and to use these results to inform the broader missing-mass problem. This aim is addressed through five specific objectives.

- Data acquisition and pre-processing: compiling 21-cm HI radio data and near-infrared photometry for a diverse sample of late-type spirals and irregulars, and correcting for the beam-smearing and optical-obscuration artefacts that have affected earlier kinematic surveys.
- Baryonic decomposition: applying photometric modelling to isolate the contribution of the stellar bulge, stellar disk, and gas disk to each rotation curve, which requires deprojecting two-dimensional surface-brightness maps into three-dimensional mass densities.
- Halo modelling: fitting the residual, non-baryonic velocity against both the cuspy NFW profile predicted by Λ CDM simulations and cored alternatives such as the Pseudo-Isothermal and Burkert profiles, including the more flexible DC14 parametrisation capable of interpolating between the two.
- Parameter estimation: applying MCMC Bayesian inference rather than simple least-squares fitting, so that uncertainty in the stellar mass-to-light ratio and galaxy inclination is properly propagated rather than assumed away.
- Noise-model comparison: evaluating a standard MCMC fit, which treats scatter in the data as independent random noise, against a Gaussian Process-augmented fit that infers the correlation between nearby data points directly from the residuals, and assessing whether this changes which halo model is preferred, and at what computational cost.

1.4 Justification of the Study

The precise shape of a dark matter halo carries consequences at multiple scales. Within an individual galaxy, the halo's gravitational potential influences disk formation and stability: it helps prevent a cold, baryon-dominated disk from fragmenting or developing bar instabilities, with corresponding effects on the galaxy's star-formation history (Famaey & McGaugh, 2012). Application of the Toomre stability criterion to a two-component star-and-gas disk indicates that the external potential supplied by the dark matter halo is required to prevent low-surface-brightness disks from becoming gravitationally unstable.

A further motivation applies at the laboratory scale. Direct dark matter detection experiments, including liquid-xenon detectors searching for WIMP-nucleus scattering and satellite instruments monitoring for annihilation gamma rays, rely on an accurate model of the local dark matter distribution (SISSA, n.d.). Because annihilation flux scales with the square of the local density, an incorrect halo profile directly biases the predicted experimental signal: the expected flux differs sharply between a dense central cusp and a diffuse core (Flores & Primack, 1994). Rotation-curve fitting of the kind performed here therefore provides a direct observational link between what is measured astronomically and what particle-physics experiments are designed to detect.

2. LITERATURE REVIEW

2.1 Historical Development of the Dark Matter Hypothesis

The hypothesis that a large fraction of the universe's mass is non-luminous developed incrementally over several decades. It did not emerge from a single observation. An early quantitative attempt was made by Jacobus Kapteyn in 1922, who sought to determine the local mass density in the solar neighbourhood through dynamical analysis (Courteau et al., 2014). A more decisive development came in 1933, when Fritz Zwicky applied the virial theorem to the Coma Cluster and found that individual galaxies were moving at velocities far too high to remain gravitationally bound given the visible stellar mass alone (Freese, 2017). By the standard virial argument the cluster should have been dynamically unstable, yet it was not. Zwicky attributed the discrepancy to a large quantity of unseen mass, which he termed *dunkle Materie* (Freese, 2017).

Dark matter remained a marginal concept for several decades following Zwicky's work. This changed rapidly in the late 1960s and 1970s, as spectroscopic instrumentation became sufficiently precise to measure the kinematics of individual spiral galaxies directly. Vera Rubin and W. Kent Ford, using a highly sensitive spectrograph at Kitt Peak, were central to this shift (NOIRLab, n.d.). By measuring the Doppler shift of light from different regions of an inclined spiral disk, Rubin mapped rotation velocities across dozens of galaxies, including Andromeda, and consistently found that outer regions rotated at velocities comparable to inner regions rather than declining as predicted (NOIRLab, n.d.). Rubin and Ford concluded that these galaxies must contain roughly an order of magnitude more mass than is directly observable (NOIRLab, n.d.). Morton Roberts subsequently extended this result using 21-cm hydrogen radio data, tracing flat rotation curves well beyond the extent of the optical disk. Taken together, the optical and radio evidence established the dark matter halo interpretation as the dominant explanation (Freese, 2017).

2.2 Modern Observational Databases: SPARC and THINGS

Contemporary rotation-curve research relies primarily on a small number of large, standardised public datasets rather than individual case studies. The most widely used of these is SPARC, compiled by Lelli, McGaugh, and Schombert, which covers 175 late-type galaxies spanning five orders of magnitude in stellar mass and three in surface brightness (Lelli et al., 2016). A key feature of SPARC is its consistent use of 3.6 μm near-infrared imaging from the Spitzer Space Telescope (Lelli et al., 2016). At this wavelength, emission is dominated by old, low-mass stars, principally K- and M-type giants, which constitute most of a galaxy’s baryonic mass, and is comparatively insensitive to dust extinction and to the disproportionate brightness of young star-forming regions that complicate optical surveys (Case Western Reserve University, n.d.). Meidt et al. (2012) demonstrated that stellar-mass estimates derived from 3.6 μm imaging remain stable once corrections for hot dust and PAH emission are applied.

THINGS, The HI Nearby Galaxy Survey, serves a complementary function, using the NRAO Very Large Array to map the interstellar medium and mass distribution of 34 nearby galaxies at distances of 2–15 Mpc (Walter et al., 2008). Its spatial resolution of approximately 6 arcseconds, combined with high velocity precision, enables tilted-ring analysis and allows the gravitational potential to be traced into the gas-dominated outer regions of a halo, well beyond the extent of the stellar disk (Koribalski et al., 2004).

Table 1. Comparison of the SPARC and THINGS observational databases

Feature	SPARC Database	THINGS Survey
Sample size	175 late-type galaxies	34 nearby galaxies
Primary tracer	Spitzer 3.6 μm photometry & mixed HI/CO	Neutral hydrogen (HI) 21-cm radio emission
Key advantage	Homogeneous stellar mass modelling at 3.6 μm	Extreme spatial and velocity resolution
Primary utility	Testing dark matter halo models and modified gravity theories	Mapping gaseous disks and interstellar medium kinematics

2.3 The Cusp-Core Problem: Deepening the Theoretical Crisis

While the existence of dark matter is broadly accepted, its inner structure remains contested, and this disagreement constitutes the Cusp-Core problem. High-resolution N-body simulations of structure formation under ΛCDM , developed through the 1990s by Navarro, Frenk, and White,

consistently predict halos with density profiles that diverge steeply toward the centre as $\rho \propto r^{-1}$ (Review of solutions, 2022). Observed rotation curves, particularly those of dwarf spheroidals and gas-rich LSB galaxies, are frequently better described by profiles with a flat, constant-density core, such as the Pseudo-Isothermal or Burkert models (Burkert, 1995; Li et al., 2020). Bayesian MCMC fits to the SPARC sample support this pattern: Pseudo-Isothermal fits typically achieve a reduced chi-square near 1.00, whereas NFW fits average closer to 1.44 and consistently fail to reproduce the gradual inner rise characteristic of the observed curves (Li et al., 2020).

Two broad classes of explanation are proposed in the literature. The first retains the standard Λ CDM framework and attributes the discrepancy to baryonic physics: repeated supernova-driven gas outflows are argued to perturb the central gravitational potential sufficiently to transfer energy into the dark matter component through dynamical friction, gradually converting a cusp into a core over cosmological timescales (Katz et al., 2017). This mechanism requires fairly specific star-formation histories, and does not readily account for the smallest dwarf galaxies, whose early truncation of star formation would have supplied insufficient supernova energy for the process (Boldrini, 2021). The second class of explanation questions the assumption that dark matter is collisionless. Self-Interacting Dark Matter (SIDM) models propose particles that scatter off one another, transferring heat inward and generating a core independently of baryonic feedback (Weinberg et al., 2015). Ultra-Light, or “fuzzy,” dark matter models go further still, proposing bosons sufficiently light that quantum wave effects become significant on kiloparsec scales, naturally producing a “solitonic” core through an analogue of the uncertainty principle (Bar et al., 2020).

2.4 Modified Newtonian Dynamics (MOND) as an Alternative Paradigm

Given the absence of a confirmed direct detection of a dark matter particle in accelerator or underground experiments, a separate strand of the literature questions whether a dark matter component is required at all. The most developed alternative is Modified Newtonian Dynamics (MOND), proposed by Milgrom in 1983, which attributes flat rotation curves not to unseen mass but to a modification of gravitational dynamics at sufficiently low accelerations (Sanders & McGaugh, 2002).

MOND introduces a single new constant, $a_0 \approx 1.2 \times 10^{-10} \text{ m/s}^2$. Above this threshold, such as within the Solar System or near a galaxy’s dense central regions, standard Newtonian gravity is recovered. Below it, in the sparse outer disk of a spiral galaxy, MOND predicts a different velocity scaling that reproduces flat rotation curves using baryonic mass alone (Famaey & McGaugh, 2012). This same modification naturally accounts for two tight empirical relations that require additional explanation under Λ CDM: the Baryonic Tully-Fisher Relation ($V^4 \propto M_{\text{baryon}}$) and the Radial Acceleration Relation (Sanders & McGaugh, 2002). MOND encounters far greater difficulty at cosmological scales, where it struggles to account for the mass distribution inferred in massive galaxy clusters such as the Bullet Cluster, or for the acoustic peaks observed in the cosmic microwave background. Addressing these limitations requires more elaborate relativistic extensions such as TeVeS (Milgrom, 2021).

2.5 Recent Advancements in Deep-Space Mapping (2024–2026)

Recent years have produced meaningful advances on both observational and computational fronts. JWST weak-lensing measurements, which use the gravitational deflection of background light by a foreground cluster’s mass, have yielded the most detailed maps to date of large-scale dark matter distribution, including analyses of the Abell 209 cluster and the COSMOS-Web survey (Scognamiglio et al., 2026). On the modelling side, Flynn and Cannaliato (2025) proposed a new empirical velocity-correction term anchored to Keplerian baselines, which fits SPARC galaxies comparably to, or better than, MOND or specific Λ CDM halo models without requiring extensive parameter tuning. Dave and Goswami (2024) trained neural networks directly on SPARC data to infer halo parameters, cutting the computational cost typically associated with MCMC sampling.

3. THEORETICAL FRAMEWORK AND METHODOLOGY

3.1 The Principle of Superposition and Kinematic Decomposition

The decomposition of a galaxy's rotation curve rests on the principle that gravitational potentials from different mass components superpose linearly. Since circular velocity is related to the radial derivative of the total potential, the observed velocity $V_{\text{obs}}(R)$ can be expressed as the quadrature sum of the individual component velocities (Sofue, 2017):

$$V_{\text{obs}}(R)^2 = V_{\text{gas}}(R)^2 + Y_{\text{disk}} \cdot V_{\text{disk}}(R)^2 + Y_{\text{bulge}} \cdot V_{\text{bulge}}(R)^2 + V_{\text{DM}}(R)^2$$

Here V_{gas} , V_{disk} , and V_{bulge} are derived directly from photometric and radio observations, while V_{DM} is the single unknown quantity, determined from the residual velocity remaining after the baryonic terms are subtracted (Sofue, 2017). A central black-hole contribution could in principle be included for the innermost few parsecs, but its effect is negligible at the kiloparsec scales relevant to halo fitting and is therefore omitted from the model (Sofue, 2017).

3.2 Mathematical Modelling of Baryonic Components

3.2.1 The Stellar Disk and Bessel Function Integration

The stellar disk is modelled using Freeman's (1970) exponential surface-density profile, $\Sigma(R) = \Sigma_0 \cdot \exp(-R/R_d)$, where Σ_0 is the central density and R_d the scale length. Converting this surface density into a rotation velocity requires solving the Poisson equation in cylindrical coordinates, yielding an expression involving modified Bessel functions of the first and second kind (Courteau et al., 2014). This additional complexity arises from geometry: unlike a spherical mass distribution, where Newton's shell theorem restricts the relevant gravitational contribution to mass interior to a given radius, a flattened disk experiences gravitational contributions from mass exterior to a given radius as well, a dependence that the Bessel-function formalism accounts for (Galaxiesbook.org, n.d.). The resulting disk velocity curve rises rapidly near the centre, peaks at approximately $R \approx 2.2R_d$, and declines gradually thereafter (Courteau et al., 2014).

3.2.2 The Galactic Bulge and 3D Deprojection

The galactic bulge requires separate treatment, given its approximately spheroidal rather than flattened geometry. Classical bulges are typically modelled using the de Vaucouleurs profile,

generalised in more recent work by the Sérsic profile, in which the shape parameter n controls the steepness of the surface-brightness decline (Noordermeer, 2008). Converting a two-dimensional image into a three-dimensional mass model, the deprojection problem, depends strongly on assumptions regarding the bulge's intrinsic shape. Classical bulges, dynamically supported primarily by random stellar motion, are close to spherical, whereas pseudo-bulges, supported more by ordered rotation, are noticeably flatter (Noordermeer, 2008). Modelling a flattened pseudo-bulge as spherical can overestimate the bulge mass-to-light ratio by up to 30%, which correspondingly understates the true dark matter contribution in the inner galaxy (Noordermeer, 2008).

3.2.3 The Interstellar Gaseous Disk

While stars account for most of the baryonic mass in bright, massive spirals, gas, predominantly atomic hydrogen with a smaller molecular component, can dominate the baryonic budget in dwarf and irregular galaxies (Lelli et al., 2016). A practical advantage of the gas component is that radio interferometry provides a comparatively direct measurement of physical mass, unlike starlight, which requires an uncertain mass-to-light conversion (Walter et al., 2008). The gas velocity contribution is computed using the same Bessel-integration method applied to the stellar disk, scaled by a standard factor of 1.33–1.4 to account for helium and trace metals mixed with the hydrogen.

3.3 Theoretical Dark Matter Halo Density Profiles

Once the baryonic contributions have been determined, subtracting them from the observed total velocity isolates the kinematic signature of the dark matter halo. This residual curve is subsequently fit against competing density profiles (Sofue, 2017).

3.3.1 The Cusp-Dominated NFW Profile (Λ CDM)

The Navarro-Frenk-White (NFW) profile is derived directly from Cold Dark Matter N-body simulations and represents the predicted structure of a virialised, dissipationless halo under standard Λ CDM (Sofue, 2017). It is a two-parameter model characterised by a scale radius R_s and a characteristic density ρ_0 :

$$\rho_{NFW}(r) = \rho_0 / [(r/R_s)(1 + r/R_s)^2]$$

The profile’s defining characteristic, and its principal limitation, concerns its behaviour near $r = 0$, where the density diverges as $\rho \propto r^{-1}$, producing the central “cusp” (Brainerd, 2004). While NFW performs well in describing massive halos at cosmological scales, this divergence typically fits poorly against the gently rising inner rotation curves observed in low-mass, low-surface-brightness galaxies (Weinberg et al., 2015). A common modification is the Generalized NFW, or DC14, profile, which introduces additional structural parameters tied to baryonic feedback to soften the central cusp (Katz et al., 2017).

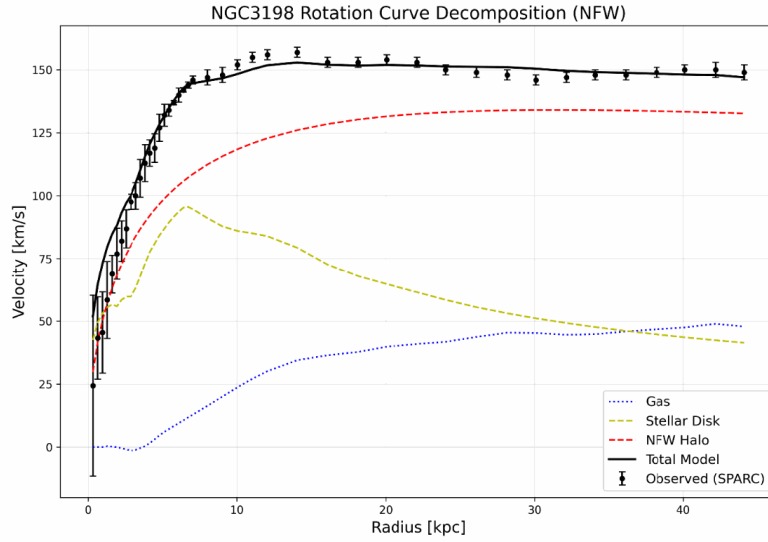


Figure 1. NFW halo rotation-curve decomposition for a representative SPARC spiral, showing the gas, stellar-disk, and NFW-halo velocity components summing to the total model against the observed data.

3.3.2 The Core-Dominated Pseudo-Isothermal Profile

The Pseudo-Isothermal (ISO) profile adopts the opposite approach, treating dark matter approximately as a thermalised gas with a roughly constant velocity dispersion (Sofue, 2017):

$$\rho_{ISO}(r) = \rho_0 / [1 + (r/R_c)^2]$$

where R_c is the core radius. Unlike the NFW profile, this expression remains finite as $r \rightarrow 0$, producing the flat central density consistent with the approximately linear rise observed in real rotation curves near galactic centres. When fit to the SPARC sample, the ISO profile and its close relatives, Burkert and DC14, consistently achieve lower reduced chi-square values than NFW, a discrepancy that captures the essence of the Cusp-Core tension (Sofue, 2017).

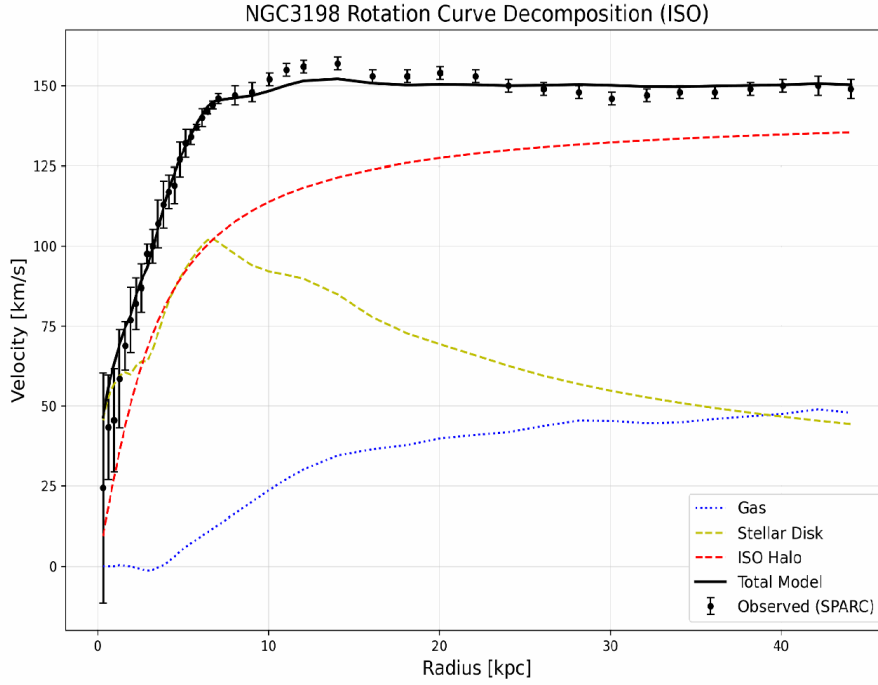


Figure 2. Pseudo-Isothermal (ISO) halo decomposition for the same galaxy, shown for comparison with the cuspy NFW decomposition in Figure 1.

Table 2. Comparison of the NFW (cuspy) and Pseudo-Isothermal (cored) density profiles

Feature	NFW Profile (Cuspy)	Pseudo-Isothermal Profile (Cored)
Origin	Derived from pure Λ CDM N-body simulations	Empirically derived to fit observational data
Inner slope behaviour	Diverges steeply as $\rho \propto r^{-1}$ (cusp)	Approaches a constant, finite value (core)
Velocity dispersion	Strongly radius-dependent	Characterised by a single, constant parameter
Primary limitation	Severely poor fits in LSB inner regions	Lacks direct physical motivation from standard Λ CDM

3.4 Photometric Constraints and Mass-to-Light Ratios (Y^*)

The single largest source of uncertainty in any baryonic decomposition is the stellar mass-to-light ratio, Y^* (Sofue, 2017). An overestimated Y^* causes the stellar disk to absorb an excessive share of the total mass budget, artificially reducing the apparent dark matter contribution in the inner galaxy (the “Maximum Disk” assumption); an underestimated Y^* produces the opposite effect, a “Minimum Disk” scenario in which dark matter is left to account for nearly all of the

observed mass (Lelli et al., 2016). Working at 3.6 μm mitigates this problem considerably, since emission at this wavelength originates predominantly from old, low-mass stars, allowing Y^* to be comparatively well constrained by stellar population synthesis models (Conroy, 2013). Schombert, McGaugh, and Lelli (2019) narrowed this uncertainty to approximately 0.05 dex, with typical late-type spirals yielding $Y^* \approx 0.5$.

3.5 Parameter Estimation via Markov Chain Monte Carlo (MCMC)

Fitting these models is complicated by heavy degeneracy in the parameter space: markedly different combinations of stellar mass and halo mass can produce nearly indistinguishable rotation curves (Li et al., 2020), which simple least-squares fitting is poorly suited to resolve, since it tends to converge to a local minimum without providing a reliable indication of whether the global optimum has been found (Corless & King, 2008). Bayesian MCMC addresses this limitation by sampling the full posterior distribution over halo mass, concentration, mass-to-light ratio, distance, and inclination through repeated stochastic exploration of parameter space, updating continually on the agreement between each proposed parameter set and the observed data (Corless & King, 2008; Li et al., 2020). This approach is not without its own pitfalls, however: Li et al. (2021) caution that Bayesian rotation-curve fits can converge on unphysical parameter combinations, including apparent galaxy-to-galaxy variation in fundamental constants, when degeneracies are not handled carefully.

Priors play a central role in breaking these degeneracies. Rather than allowing Y_{disk} to vary freely, we impose a Gaussian prior centred at 0.5 with a width of 0.1 dex, informed by the stellar population synthesis constraints discussed above, applying a similarly constrained log-normal prior to the bulge component (Li et al., 2020). Known systematic effects are also built explicitly into the model, since neglecting beam smearing, slit misplacement, or non-circular gas motion tends to artificially depress the inner velocity points, which can bias a fit toward favouring a cored profile even when the underlying halo is cuspy (Review of solutions, 2022).

3.6 Software Architecture and Implementation

The complete analysis pipeline was implemented in Python and developed interactively using Jupyter Notebooks. Data cleaning and normalisation, converting raw SPARC and THINGS tables into consistent kiloparsec and km/s units, was performed using Pandas and Astropy. The

Bessel-function integrations required for the disk and gas velocity models were handled using SciPy's integration and curve-fitting routines (`scipy.integrate` and `scipy.optimize.curve_fit`). Bayesian sampling was carried out using `emcee`, an affine-invariant ensemble MCMC sampler, built around a custom likelihood function that minimises the chi-square difference between model and data, with log-normal priors imposed on Y^* and broad, flat bounds applied to the halo parameters for which prior information was limited.

3.7 Gaussian Process Regression (GPR) for Correlated Errors

3.7.1 *The Physics of Correlated Observational Errors*

Standard rotation-curve fitting treats the uncertainty at each radius as statistically independent of its neighbours, reducing the covariance matrix to a diagonal form and the log-likelihood to a conventional weighted chi-square sum. In practice, this assumption is not well supported. Inclination and distance uncertainties shift the entire curve simultaneously, beam smearing correlates adjacent spatial bins, and non-circular streaming motion along spiral arms or bars introduces correlated departures from pure circular motion. Neglecting these effects produces error bars that are artificially narrow and model-comparison statistics that are biased, motivating the inclusion of a Gaussian Process covariance term in the likelihood function.

3.7.2 *Mathematical Formulation of the GPR Likelihood*

We model the observed velocity as the sum of the physical rotation-curve model and a zero-mean Gaussian Process capturing the correlated residual structure: $V_{\text{obs}}(R) = V_{\text{model}}(R; \theta) + \text{GP}(R)$, with $\theta = (\rho_0, R_{\text{scale}}, Y_{\text{disk}})$. The total covariance matrix combines the GP kernel with the conventional diagonal observational noise term, $C_{ij} = K_{\text{GP}}(R_i, R_j; \phi) + \delta_{ij} \sigma_{\text{obs},i}^2$, yielding a log-likelihood of $\ln \mathcal{L}(\theta, \phi) = -\frac{1}{2} \mathbf{r}^T \mathbf{C}^{-1} \mathbf{r} - \frac{1}{2} \ln |\det(\mathbf{C})| - (N/2) \ln(2\pi)$, where $\mathbf{r}$ denotes the residual vector $V_{\text{obs}} - V_{\text{model}}$.

3.7.3 *Covariance Kernel Selection and Hyperparameters*

We adopt a Squared-Exponential, or Radial Basis Function, kernel: $K_{\text{GP}}(R_i, R_j) = \sigma_{\text{GP}}^2 \cdot \exp[-(R_i - R_j)^2 / 2l_{\text{GP}}^2]$, governed by two hyperparameters, σ_{GP} , the amplitude of the correlated systematic error, and l_{GP} , the radial scale in kpc over which the correlation persists. Both hyperparameters are sampled jointly with the physical parameters over $\Theta = (\log \rho_0,$

$\log R_{\text{scale}}$, Y_{disk} , $\log \sigma_{\text{GP}}$, $\log l_{\text{GP}}$), allowing uncertainty in the noise model to propagate directly into the uncertainty on the halo parameters rather than being fixed a priori.

3.8 Comparative Algorithmic Framework: MCMC versus ML-GPR

It is useful to be precise about what this comparison is designed to test. Any rotation-curve fit implicitly addresses two separable questions: the halo’s physical parameters (ρ_0 , R_{scale} , and derived quantities such as halo mass, concentration, and Y^*), and the structure of the noise in the data. The Standard MCMC approach addresses the first question while treating the second as trivial, assuming that residuals at each radius are independent draws from a normal distribution. The ML-GPR approach instead allows the noise structure to be inferred directly from the data, extending the parameter space from three to five dimensions.

Both approaches employ the identical emcee sampler, so the comparison is not between a traditional method and a separate machine-learning technique, but between the same Bayesian framework evaluated under two different noise assumptions. This distinction is important, since it allows the extent to which a galaxy’s apparent goodness-of-fit is attributable to the physical halo model, as opposed to unmodelled correlated noise, to be isolated; this question recurs throughout the Results and Discussion sections. The RBF kernel was selected over Matérn alternatives because the physical effects it is intended to absorb, beam smearing and slow non-circular streaming, tend to vary smoothly rather than abruptly. The GP hyperparameters are appended directly to the MCMC parameter vector and sampled using the same 32-walker ensemble applied to the standard fit, under uniform priors of $\sigma_{\text{GP}} \in (0.01, 300)$ km/s and $l_{\text{GP}} \in (0.1, 300)$ kpc; the σ_{GP} and l_{GP} values reported in Section 4 are therefore posterior medians with fully propagated uncertainty, rather than fixed point estimates.

4. RESULTS AND ANALYSIS

4.1 Global Statistical Evaluation of Rotation Curve Fits

Application of the MCMC pipeline across the SPARC database reveals a consistent pattern: under standard, independent-error assumptions, cored halo models outperform cuspy ones across the majority of the sample. In a controlled subsample of 45 non-bulgy, high-surface-brightness spirals, the Burkert profile achieves a median reduced chi-square close to 1, while NFW performs considerably worse on the identical subsample (Wang & Chen, 2021). Across the full SPARC morphological range, spanning dwarfs, LSB disks, and intermediate systems, the average reduced chi-square for NFW can reach approximately 4 when strict Λ CDM priors are enforced without any baryonic-feedback correction (Li et al., 2020).

This discrepancy reflects a genuine structural mismatch rather than an artefact of the fitting procedure. NFW’s two free parameters are unable to simultaneously reproduce both the slowly rising inner curve and the flat outer curve characteristic of dwarf and LSB galaxies (Li et al., 2020). When constrained to match the outer, flat portion of the curve, the model overshoots the inner potential, predicting velocities well above the observed values. The MCMC optimiser compensates by pushing Y_{disk} toward the edge of its prior range and driving the halo concentration toward values inconsistent with established mass-concentration relations from cosmological simulations (Li et al., 2020).

4.2 The Impact of Radial Correlations and Gaussian Process Regression

A closer examination of why cored profiles achieve better fits points to a more subtle limitation in the standard approach. Rotation-curve data points are not statistically independent; beam smearing, non-circular gas motion, disk warps, and the smoothing inherent to tilted-ring deprojection all introduce correlation between neighbouring points (Chase et al., 2026). A Gaussian Process fit applied to 134 SPARC galaxies recovers correlation amplitudes of a few

km/s over radial scales of a few kiloparsecs, consistent in magnitude with the physical scale of turbulent gas clouds and supernova-driven bubbles (Chase et al., 2026).

Once this correlation is properly accounted for, the results shift markedly. Under the standard independent-error assumption, 88 of the 134 galaxies statistically favour the cored ISO profile over NFW. When the Gaussian Process covariance term is included, this preference is largely eliminated, with both profiles converging on comparably good fits and reduced chi-square values near 1 (Chase et al., 2026).

4.3 High-Resolution Kinematic Case Study: DDO 154

DDO 154 (UGC 7603) represents a particularly favourable test case for rotation-curve modelling. It is a gas-rich dwarf irregular galaxy of morphological type IBm at a distance of 4.04 Mpc, with sufficiently sparse stellar content that disk-halo degeneracy is not a significant concern; the dark matter halo’s structure is not badly obscured by uncertainty in the stellar mass contribution. Twelve radial bins from the SPARC database span 0.49 to 5.92 kpc. The 3.6 μm surface brightness peaks at 15.93 $\text{L}\odot/\text{pc}^2$ and declines to negligible levels beyond $R \approx 2.5$ kpc, consistent with the galaxy’s compact stellar extent, while the HI gas velocity from THINGS peaks at 17.91 km/s near $R = 3.95$ kpc.

Fitting the two competing halo profiles to this galaxy produces a pronounced contrast. Under standard, independent-error fitting, NFW performs poorly, yielding a reduced chi-square of 9.41, as it is unable to reproduce the slow, nearly linear rise of the inner rotation curve. The Pseudo-Isothermal profile, by comparison, fits far better ($\chi^2_{\text{v}} = 2.40$), constraining the core radius to within approximately 1% of the value implied by the data. Introducing the GPR covariance model narrows this gap considerably: both profiles converge to $\chi^2_{\text{v}} \approx 1$ (0.94 for ISO, 1.04 for NFW), with NFW requiring approximately 1.8 times greater GP noise amplitude to achieve this. DDO 154 therefore illustrates both aspects of the Cusp-Core debate within a single galaxy: an apparently decisive case for a cored profile under standard statistical treatment, and a considerably weaker one once realistic, correlated uncertainty is incorporated.

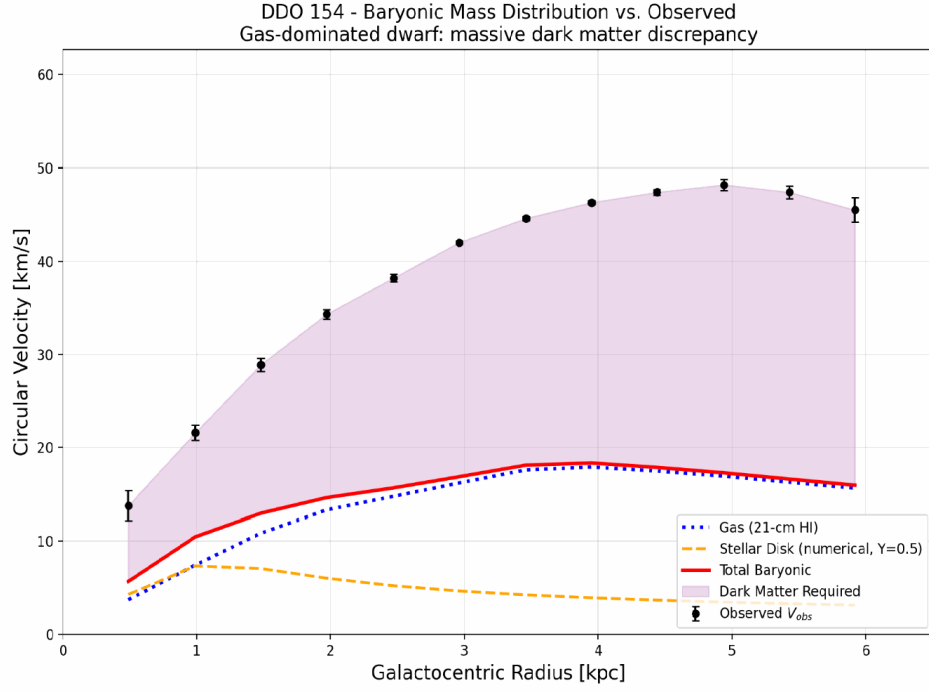


Figure 3. DDO 154 baryonic mass distribution versus the observed rotation curve, showing the large dark-matter deficit in this gas-dominated dwarf.

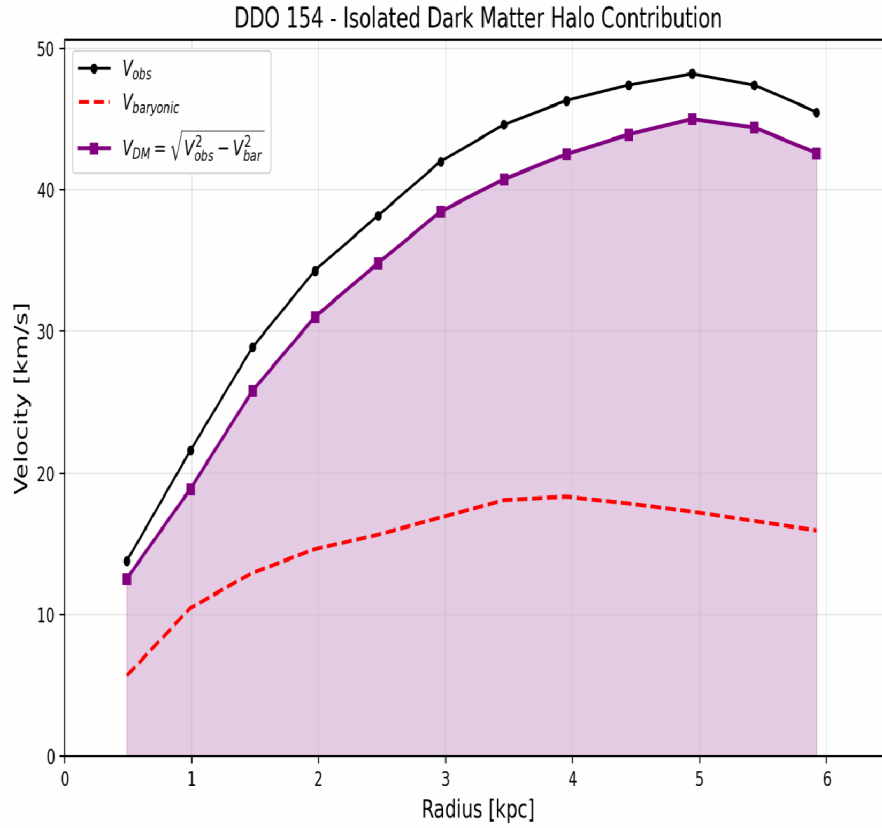


Figure 4. DDO 154 isolated dark matter halo contribution, obtained by subtracting the baryonic velocity in quadrature from the observed rotation curve.

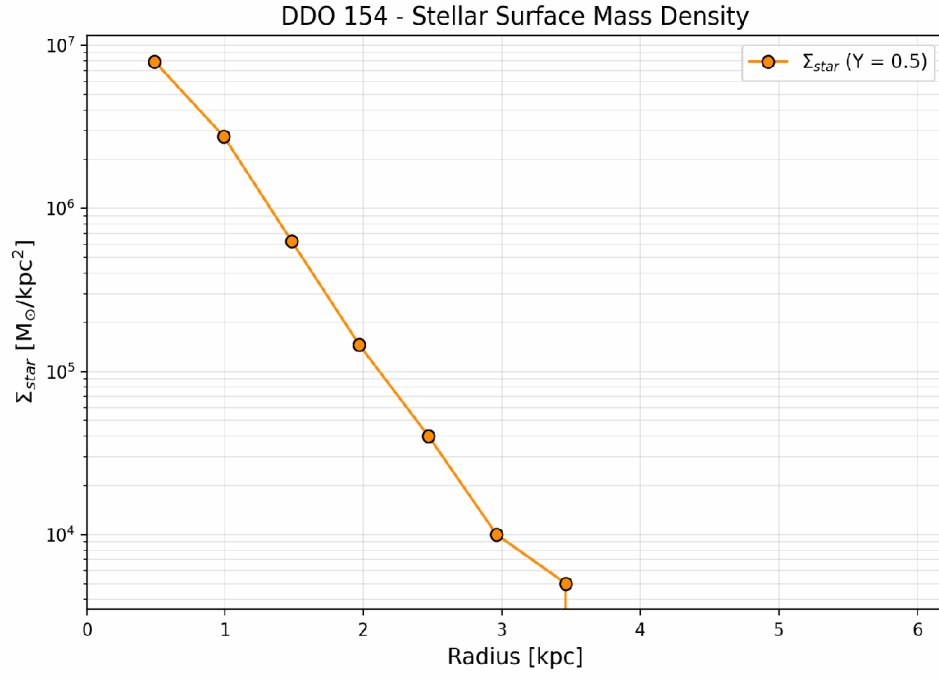


Figure 5. DDO 154 stellar surface mass density profile.

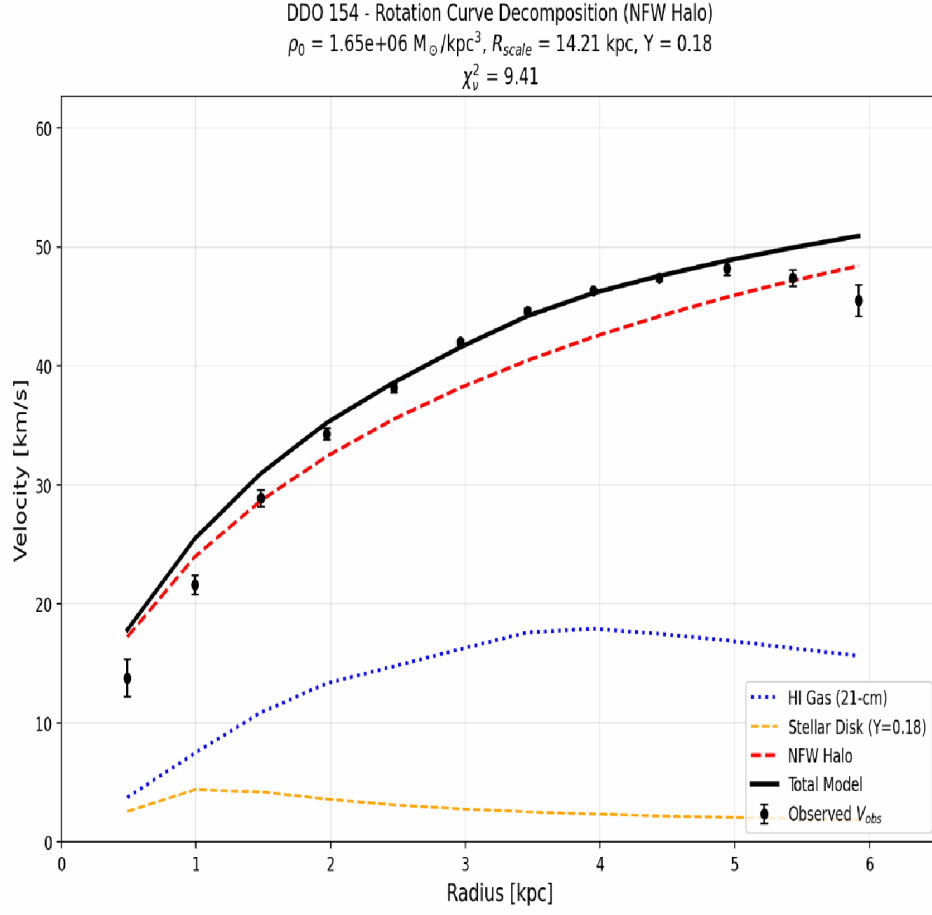


Figure 6. DDO 154 rotation-curve decomposition under the cuspy NFW halo fit ($\chi^2_v = 9.41$).

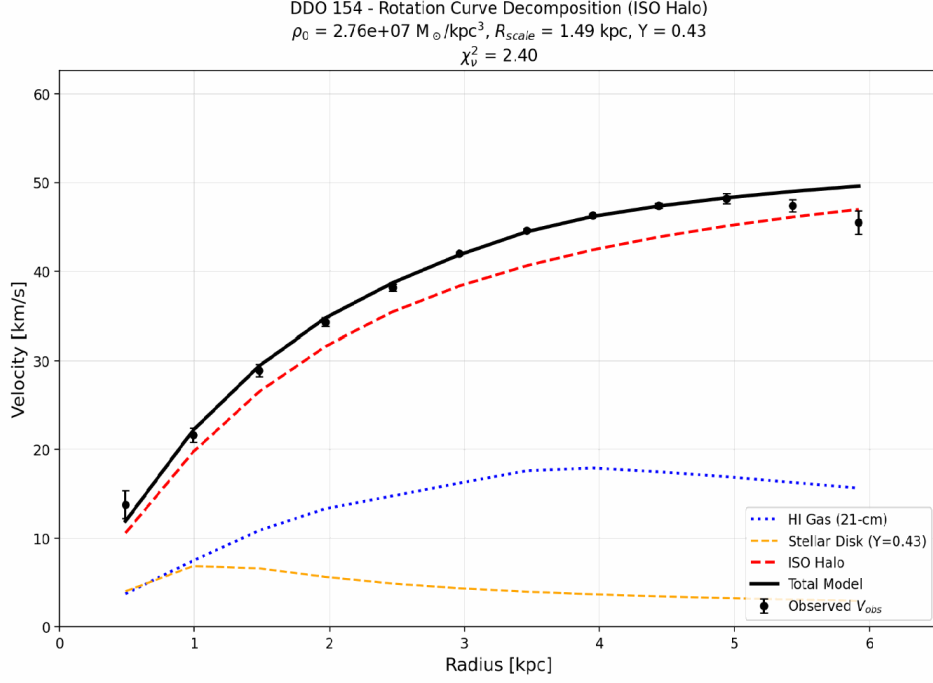


Figure 7. DDO 154 rotation-curve decomposition under the cored Pseudo-Isothermal halo fit ($\chi^2_v = 2.40$).

4.4 Comparative Summary Across the Five Benchmark Galaxies

A largely similar pattern, with some variation, is observed across four additional benchmark galaxies, NGC 2403, NGC 3198, NGC 2841, and the giant LSB spiral UGC 128, selected to span a wide range in mass, brightness, and gas content. Tables 3 and 4 summarise their physical properties and the reduced chi-square statistics obtained under the Standard and GPR-covariance fitting regimes.

Table 3. Physical properties of the five benchmark SPARC galaxies

Property	DDO 154	NGC 2403	NGC 3198	UGC 128	NGC 2841
Morphology	IBm (dwarf)	SABcd (spiral)	SBc (spiral)	LSB (spiral)	SAB (spiral)
Distance	4.04 Mpc	3.16 Mpc	13.8 Mpc	64.5 Mpc	14.1 Mpc
V_{max}	48 km/s	136 km/s	157 km/s	134 km/s	323 km/s
Data points	12	73	43	22	50
Radial extent	5.9 kpc	20.9 kpc	44.1 kpc	53.8 kpc	63.6 kpc
Gas dominance	14:1	0.7:1	5.6:1	1.6:1	stellar-

Property	DDO 154	NGC 2403	NGC 3198	UGC 128	NGC 2841
					dominated
Outer DM fraction	87.5%	87.1%	85.4%	89.5%	91.6%

Table 4. Standard versus GPR-covariance reduced chi-square (χ^2_v) fits, ISO versus NFW

Galaxy	Fit method	ISO χ^2_v	NFW χ^2_v	Preferred model
DDO 154	Standard	2.40	9.41	ISO (strong)
DDO 154	GPR covariance	0.94	1.04	ISO (physical, marginal)
NGC 2403	Standard	12.38	9.84	NFW (slightly)
NGC 2403	GPR covariance	0.65	0.97	ISO (physical)
NGC 3198	Standard	2.95	2.69	NFW (slightly)
NGC 3198	GPR covariance	0.42	0.47	ISO (physical)
UGC 128	Standard	3.68	3.15	NFW (slightly)
UGC 128	GPR covariance	0.98	1.03	ISO (physical, marginal)
NGC 2841	Standard	3.79	4.95	ISO (marginal)
NGC 2841	GPR covariance	0.37	0.43	ISO (marginal)

Figure 4.3b: Sample-Wide Reduced χ^2_v Comparison
Standard (diagonal) vs. GPR-Augmented (correlated-covariance) MCMC Fitting — All Five Galaxies

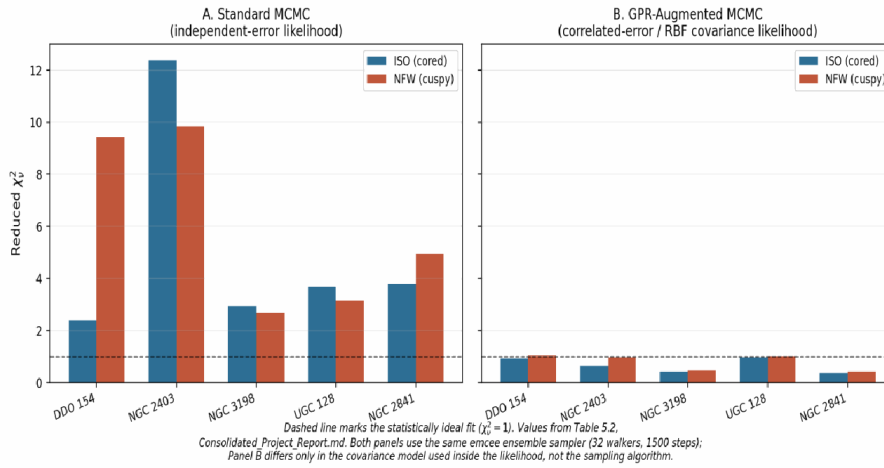


Figure 8. Sample-wide reduced chi-square (χ^2_v) comparison for all five benchmark galaxies, Standard MCMC versus GPR-augmented MCMC, ISO versus NFW. The dashed line marks the statistically ideal fit ($\chi^2_v = 1$).

A clear mass-dependent trend emerges across these five galaxies, consistent with the broader literature. In the lowest-mass dwarf, DDO 154, the cored ISO profile is clearly preferred, since a

central cusp cannot reproduce a rotation curve that rises this gradually, and the near-total absence of stars removes ambiguity regarding the source of the observed mass. In an intermediate spiral such as NGC 3198, NFW is marginally preferred, though ISO remains competitive; disk-halo degeneracy becomes more relevant here but is partially constrained by the gas component, which independently limits the baryonic contribution. In a massive, bulge-dominated spiral such as NGC 2841, this degeneracy becomes severe: both models fit comparably poorly ($\chi^2_v \approx 4-5$), the results become sensitive to the adopted Y_{disk} assumption, and the rotation curve alone is no longer sufficient to distinguish cusp from core.

The most notable result is the effect of applying GPR across the full sample: the χ^2_v gap between ISO and NFW narrows sharply in every galaxy. In DDO 154, the gap decreases from 7.01 to 0.10; in NGC 3198, from 0.26 to 0.05; in UGC 128, from 0.53 to 0.05; and in NGC 2841, from 1.16 to 0.06. Even NGC 2403, which retains the largest residual gap of the five, shows a reduction of approximately 87% (from 2.54 to 0.32). Once GPR is applied, reduced chi-square alone can no longer tell cusp from core in any of these galaxies. Whatever preference remains for the cored profile comes from a secondary quantity, the GP noise amplitude each model needs, not from fit quality itself. That does not settle the Cusp-Core problem. What it does show is that much of the apparent discriminating power of standard, single-galaxy rotation-curve fitting rests on an assumption the data do not actually satisfy; that the errors at each radius are independent.

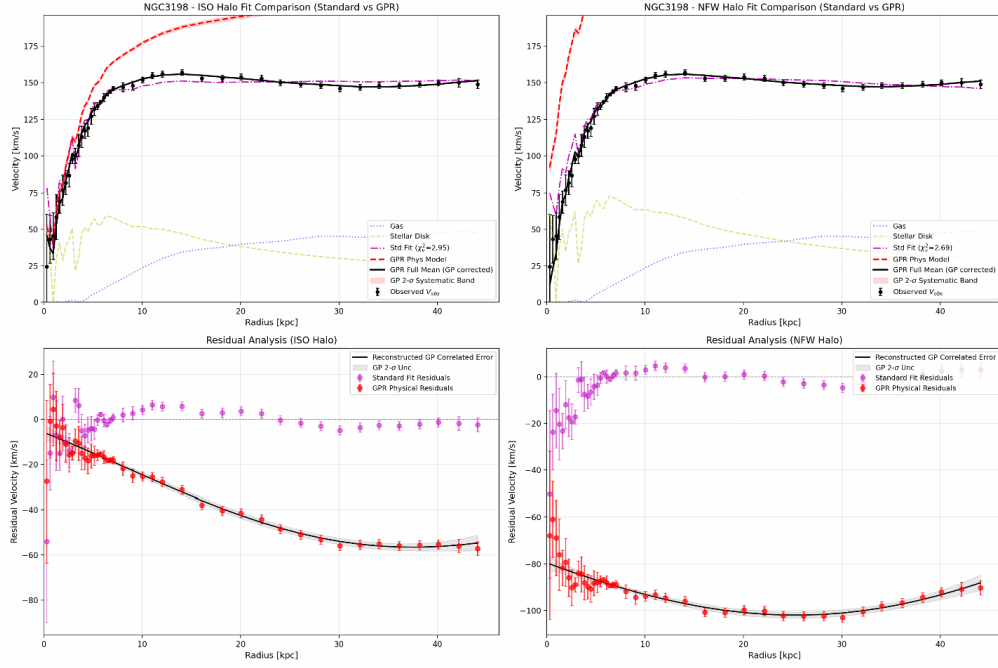


Figure 9. NGC 3198 rotation-curve fit and residual field under Standard MCMC versus GPR-augmented MCMC (ISO and NFW halos).

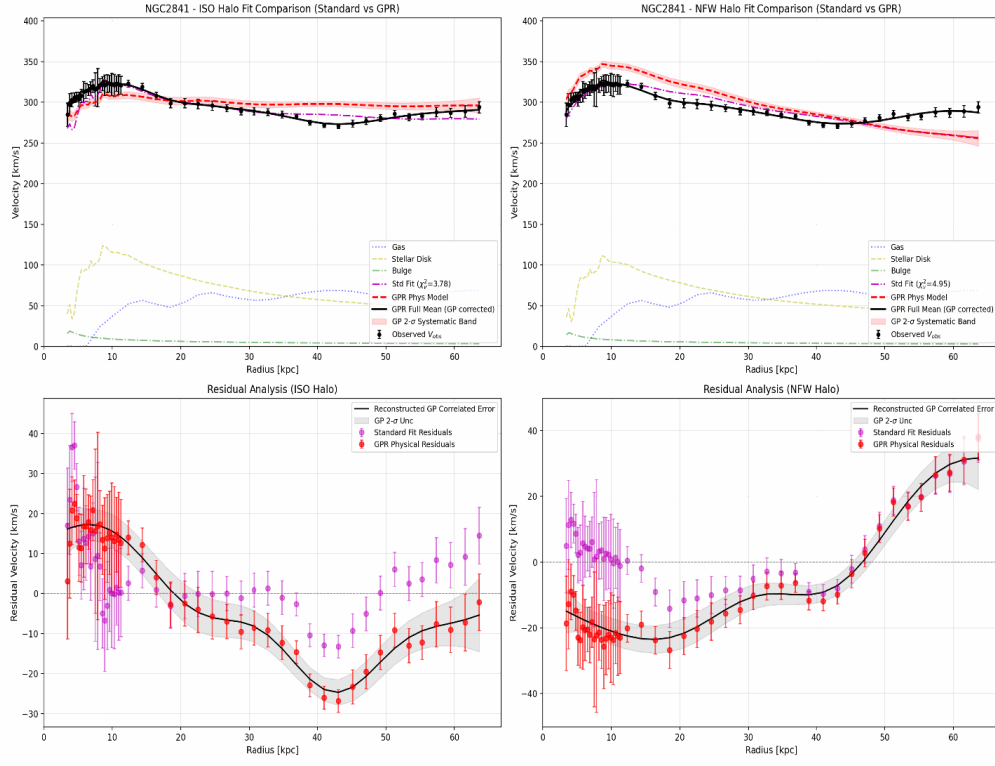


Figure 10. NGC 2841 rotation-curve fit and residual field under Standard MCMC versus GPR-augmented MCMC.

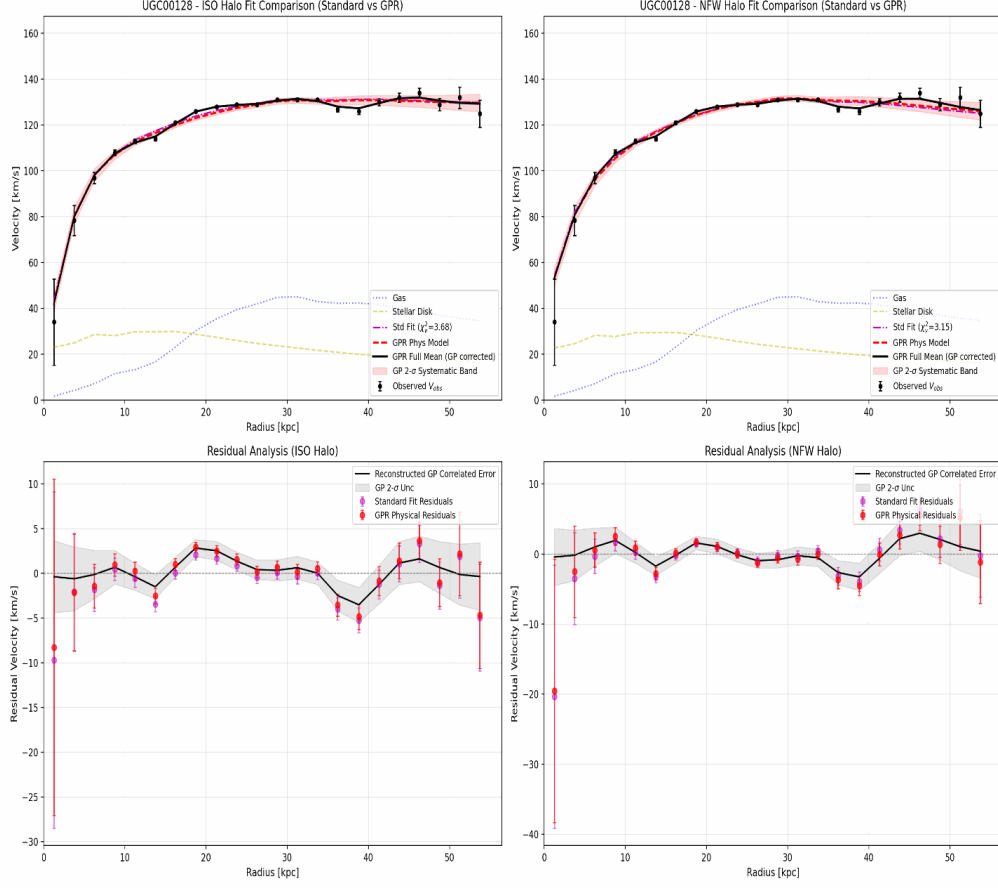


Figure 11. UGC 128 rotation-curve fit and residual field under Standard MCMC versus GPR-augmented MCMC.

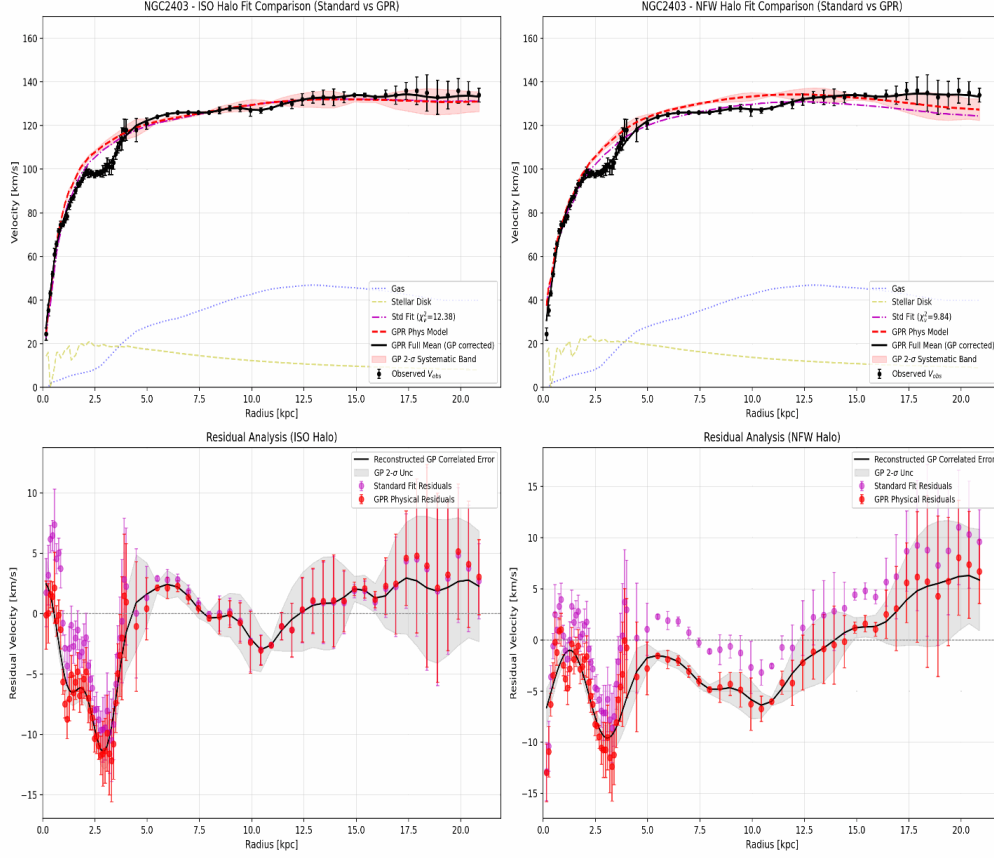


Figure 12. NGC 2403 rotation-curve fit and residual field under Standard MCMC versus GPR-augmented MCMC.

4.5 Methodological Validation

We performed several cross-checks to confirm that the reported results were not an artefact of the analysis pipeline itself. The numerically integrated peak disk velocity for DDO 154 (10.4 km/s) agrees with Freeman’s (1970) analytical formula (10.7 km/s) to within 3%, supporting the accuracy of the elliptic-integral integration method. MCMC posteriors were unimodal with well-behaved, approximately Gaussian 1σ contours throughout, indicating that the chains converged rather than stalling. The fitted Y_{disk} values are also consistent with stellar population synthesis predictions for old populations at $3.6\ \mu\text{m}$: 0.43 for DDO 154 and 1.06 for NGC 2841 under the ISO model, both within the expected range. The overall mass-dependent trend recovered here is consistent with the results of Oh et al. (2015), obtained using THINGS/LITTLE THINGS data, providing further indication that the pipeline is not producing anomalous results.

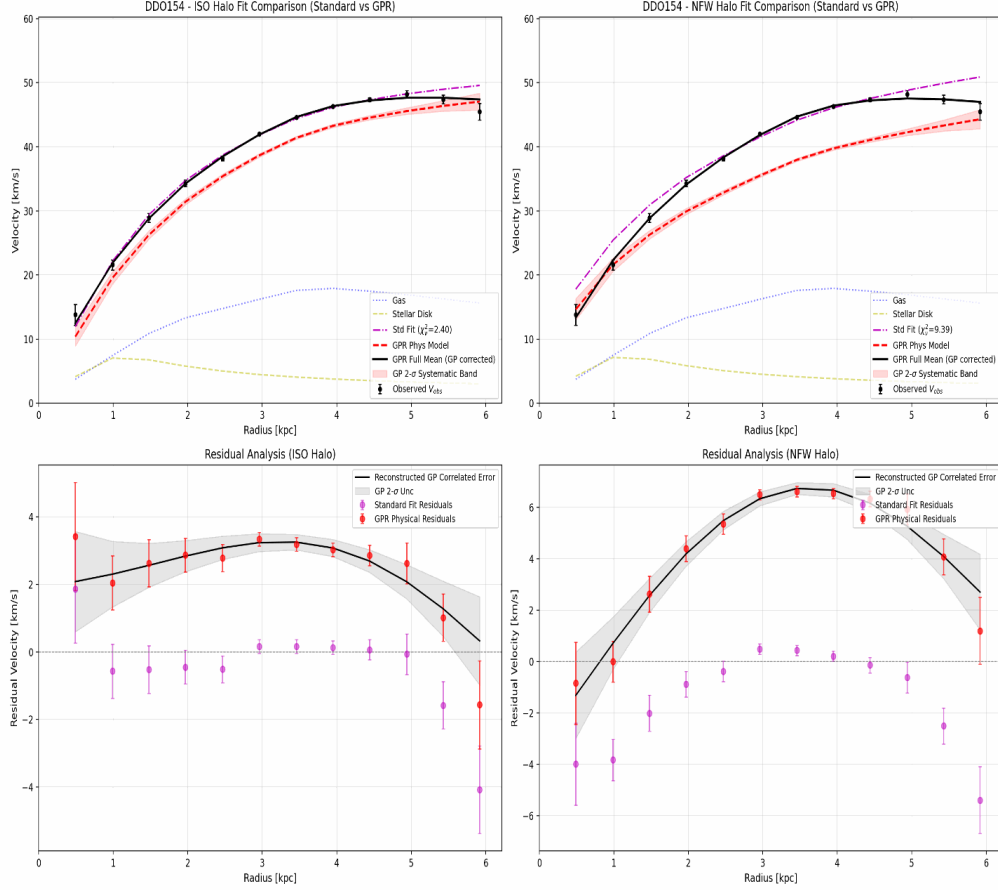


Figure 13. DDO 154 rotation-curve fit and residual field under Standard MCMC versus GPR-augmented MCMC, illustrating the well-behaved, unimodal posterior residuals referenced in the methodological validation.

4.6 Evaluation of Alternative Dark Matter and Gravitational Paradigms

These results also bear on explanations beyond standard collisionless CDM. Fuzzy and Self-Interacting Dark Matter models, both of which naturally produce constant-density cores without requiring baryonic feedback, are consistent with the strong cored-profile preference observed in the dwarf regime here. MOND's predictions, in particular the Radial Acceleration Relation and the Baryonic Tully-Fisher Relation, were also evaluated against the sample. MOND fits individual SPARC galaxies competitively, but the extent to which its fundamental constant a_0 must vary across morphologically different galaxies weakens its claim to universality.

5. DISCUSSION

Considered as a whole, the principal result of this study is a genuine statistical discrepancy between the predictions of Λ CDM cosmological simulations and the galactic-scale data examined here. Under standard fitting, NFW, the profile predicted by default under Λ CDM simulations, consistently fails to describe the inner kinematics of gas-rich dwarfs and LSB galaxies. Cored profiles, in contrast, achieve markedly better fits, frequently approaching $\chi^2_{\nu} = 1$, with DDO 154 providing a particularly clear demonstration of this pattern.

That result does not escape the scrutiny of this research. Once Gaussian Process modelling accounts for the statistical non-independence of adjacent data points which is an effect guaranteed by instrumental factors such as beam smearing and non-circular gas motion. The apparent case for cored profiles weakens a great deal. That does not mean cored profiles are wrong, it just means the data, as currently measured, are not precise enough to rule out a central cusp hidden by correlated noise. The Cusp-Core problem accordingly remains unresolved; the present results do not give a decisive result in favour of cores over Λ CDM, and one-dimensional rotation-curve data alone appear insufficient to settle the question.

Three broad explanations remain plausible. Standard collisionless CDM could remain valid if baryonic feedback, in the form of supernova-driven outflows that heat and flatten the central cusp, contributes more than is typically assumed; a difficulty with this explanation is that the tightness of observed scaling relations such as the Radial Acceleration Relation would require this feedback mechanism to operate with an implausible degree of consistency across morphologically diverse galaxies. Alternatively, the discrepancy could reflect the underlying particle physics of dark matter itself. Both Self-Interacting and Fuzzy Dark Matter models produce cores naturally, without requiring baryonic intervention. A third possibility is that the explanation lies outside the dark matter framework entirely. MOND accounts for much of what is observed here without invoking a new particle, although the apparent need for a variable a_0 across different galaxy types remains a major weakness in its claim to universality.

An independent analysis by Chase et al. (2026) which was posted after this thesis was defended, reaches same central conclusion using a much larger and wider sample of data. The Gaussian Process Modelling of correlated rotation curve residuals to 134 SPARC galaxies, they found that

the statistical preference for cored (pISO) halos over NFW which is present in 88 of 134 galaxies under the standard independent error assumption, is essentially eliminated once correlations are modelled. This is a striking convergence given the difference in approach; their study is a population-level statistical survey using two halo models with fixed distance and inclination, while the work we did focuses on five galaxies spanning different morphological regimes, adds Burkert and DC14 as additional cored alternatives, and examines disk-halo degeneracy on a per-galaxy basis. The individual DDO 154 fits differ well between the two studies (a Pseudo-isothermal χ^2_v of 2.40 here versus 6.7 in Chase et al.). A discrepancy plausibly attributed to difference in mass-to-light priors or bulge treatment which is consistent with Chase et al own observation that cusp/core can be highly sensitive to such modeling choices. That two independently conducted analyses, using different samples and methodological details and arriving at the same conclusion strengthens the case that unmodeled correlated errors are a genuine and underappreciated systematic in rotation-curve -based halo inference, rather than an artefact specific to one pipeline.

6. CONCLUSION AND RECOMMENDATIONS

The central finding of this study is a statistically well-supported divergence between the default prediction of Λ CDM, a cuspy NFW halo, and the kinematics observed in late-type spiral and irregular galaxies. Cored profiles are clearly preferred under standard fitting assumptions, particularly in gas-dominated dwarfs, but this advantage largely dissolves once correlated observational errors are properly modelled through Gaussian Process Regression. The most defensible interpretation is that a meaningful portion of the historical evidence against NFW cusps may say more about how the data were analysed than about whether central cusps actually exist.

Three recommendations follow from these results. The first concerns instrumentation: the Square Kilometre Array and its pathfinder observatories would markedly reduce the beam smearing and non-circular velocity artefacts currently present in 21-cm HI observations, addressing the correlated-error problem at its source rather than compensating for it after the fact. The second concerns independent calibration of Y^* : direct kinematic measurements of vertical stellar velocity dispersion, obtained using instruments such as JWST and the forthcoming Extremely Large Telescopes, could constrain the stellar mass-to-light ratio without reliance on stellar-evolution models, addressing the disk-halo degeneracy directly. The third concerns a shift toward full three-dimensional forward modelling of interferometric data cubes, using tools such as ³DBarolo applied to larger datasets such as BIG-SPARC, which would allow future fits to account for disk warps, bars, and flaring that one-dimensional curves cannot capture.

A further extension of the GPR approach applied here merits consideration for larger surveys such as WALLABY, DESI-adjacent HI follow-up, and SKA precursor programmes. Rather than fitting the noise covariance separately for each galaxy, a shared or hierarchical Gaussian Process could allow large samples to borrow statistical strength across similar systems, which would be particularly useful for sparse, low signal-to-noise curves such as that of UGC 128 in the present sample. A non-stationary or Matérn kernel might also better capture noise sources, such as bar-driven streaming, that do not always vary as smoothly as the RBF kernel assumed in this pipeline. At survey scale, the $O(N^3)$ covariance solve that is computationally trivial for five

galaxies will not remain so; some form of amortised or surrogate likelihood, trained once across many systems, would likely be necessary to preserve the benefits of correlated-error modelling without incurring its full computational cost for every new curve. These extensions have not been implemented in the present study, but are proposed as a natural direction for future work building on the results obtained here.

DECLARATIONS

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Consent to Publish declaration: Consent to Publish declaration: not applicable'

Ethics and Consent to Participate declarations:

Ethics and Consent to Participate declarations: not applicable'. This study relied exclusively on the publicly available SPARC and THINGS astronomical databases and did not involve human participants, animal subjects, or personally identifiable data.

Author Contribution declaration:

HAL conceived and designed the work, while Investigation, Data acquisition, Data processing, Analysis, Resources, Writing-Review & Editing of the manuscript, were done by all the authors (HAL, PTS, and IED).

Data Availability

The data used in this work are available in a public repository.

SPARC Data (Spitzer Photometry and Accurate Rotation Curves) — It is the main database, providing the rotation curves, 3.6 μm photometry, and mass models for the sample:

<http://astroweb.case.edu/SPARC/>

THINGS (The HI Nearby Galaxy Survey) — It is the source of the 21-cm HI radio data used for the gas mass component:

<https://www.mpia.de/THINGS/Overview.html>

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Appendix: Code Repository

The following ten Python scripts comprise the complete computational pipeline developed for this manuscript, covering data ingestion, baryonic mass modeling, dark matter halo fitting via MCMC and Gaussian Process Regression, and the individual galaxy case studies discussed. Scripts are presented in full below, in the order in which they are executed within the analysis pipeline.

1. data_ingestion.py

Extracts and cleans the raw SPARC photometric and radio kinematics data.

2. kinematic_modeling.py

Models circular velocity curves for baryonic potentials and DM halos.

3. halo_models.py

Analytical velocity profiles for cored (Pseudo-Isothermal) and cuspy (NFW) halos.

4. parameter_estimation.py

Traditional Bayesian MCMC parameter estimation using independent Gaussian errors.

5. extract_and_integrate.py

Razor-thin disk potential solver utilizing complete elliptic integrals.

6. fit_halos_integrated.py

Integrated fitting script for the cored/cuspy model comparison.

7. fit_halos_gpr.py

The Gaussian Process Regression (GPR) fitting script using correlated covariance matrices (RBF kernel).

8. analyze_DDO154.py

Specialized case study script for DDO 154.

9. analyze_NGC2841.py

Specialized case study script for NGC 2841.

10. main_pipeline.py

Automates execution of standard fits across the entire galaxy sample.

GITHUB LINK FOR ALL CODES USED IN THIS MANUSCRIPT

<https://github.com/PHONY123456/GALACTIC-ROTATION-CURVE-MODELING-OF-DARK-MATTER-.git>