Dean&Francis
ISSN 2959-6157

# The Role of Dark Matter in Galactic Dynamics: Insights from Rotation Curves

**Zifan Yang**[1]

[1]World Foreign Language Academy, Shanghai, China

*Corresponding author: zifan.yang008@gmail.com

**Abstract:**

The paper starts by introducing the basic information and findings about dark matter, followed by underscoring of dark matter's importance in galaxy formation, stability and evolution. The paper also reviews the relationship between galactic dynamics and dark matter and how this relationship, reflected on rotation curves, provide information about dark matter halos. Specifically, the author compares a galaxy's observed rotation curves and the calculated rotation curve with only visible matter. It demonstrates how the observation of the flatness of the rotation curves at large radii challenges conventional Newtonian mechanics and reveals dark matter halos' presence. At last, the paper evaluates the use of the findings for further understanding of the universe and the challenges that remained unsolved.

**Keywords:** dark matter; galactic dynamics; rotation curves

## 1. Introduction

Dark matter has been enigmatic since it was hypothesized, and, even till today, it is not fully understood. Dark matter's existance in the universe was first proposed in an observation conducted by Fritz Zwicky in the 1930s, when he observed that the mass of the Coma cluster, inferred from the motion of its galaxies, far exceeded the mass of visible matter[1]. However, it was Vera Rubin's work in the 1970s that brought dark matter into the mainstream of astronomy research. Rubin and her colleagues observed that the observed rotation curve for galaxies, especially the spiral ones, didn't match with the predicted rotation curve which based on Newtonian mechanics [1]. Specifically, according to Newtonian mechanics, the rotation velocity decreases as the radius increases, while the observed rotation curves remained flat even at distance far from the centre. This indicated that there is an unobservable type of matter that has masses in the galaxy, and that type of matter is what we called dark matter.

Since these early observations, dark matter has become crucial in explaining the formation of the universe's structures at large-scale, such as galaxy clusters, as well as phenomena such as gravitational lensing. Scientists currently believe that dark matter has taken up about approximately 85 percent of the total masses in the entire universe and is pivotal when studying the evolution of the universe [2]. However, because dark matter interacts with visible matter primarily through gravity, it cannot be directly observed through electromagnetic radiation. This has led scientists to develop various indirect means to study dark matter's property and distribution in the universe.

From all these methods, the rotation curve method is the most direct and convenient one. It allows astronomers to compare the observed motion of the stars and gases with the predicted motion of stellar without dark matter to corollary the density and distribution of dark matter [3]. The rotation curve in the outer radius of those galaxies becoming flattened has already been a significant sign for the dark matter halos' existence.

The purpose of this article is to investigate the role dark matter acts as in galactic dynamics, with a specified example demonstrating the way rotation curve works.

## 2. Theoretical Framework

### 2.1 Dark matter Theories

As the foundation of modern astrophysics, dark matter still has some unraveled properties. Even what it is made of is still a big problem we are talking about. Various theories are trying to explain dark matter's properties, ranging from weakly interacting massive particles (WIMPs) to changes in axions and gravity. WIMPs is one of the main candidates. It is an imaginary particle that interacts by gravitational forces and weak nuclear rather than electromagnetic forces, which makes them undetectable by conventional methods [5]. Axions is another potential candidate and a lighter one. If axions has the right properties, it can explain dark matter [6].

The dark matter's distribution in galaxies is often modeled as halo around the galaxy. Those dark matter halo, often considered enclosing most of the galaxies' mass, are far beyond the visible edge of the galaxies. The Navarro-Frenk-White curve is commonly used model to describe the dark matter halos' distribution of density in the universe. The curve shows that the density of dark matter halo decreases as their distance to the center of the galaxy increases, even not so fast as people expected. This helps explain why the rotation curve, in the outer radius of a galaxy, is flat [7].

### 2.2 Rotation Curves

Rotation curve is an important observation tool for studying the dynamics of galaxies. It is used to demonstrate the functional relationship between the rotational velocity of stars and gases and their distance to the center of the galaxy. According to Newtonian mechanics, the rotation velocity of matter in the galaxy will decrease as their distance to the center of the galaxy increases as most of the visible mass concentrate there. However, the observational data show that the rotation speed remains high at large radii, which indicates the existence of additional and invisible mass which is dark matter.

Through studying the rotation curves, astronomers can conclude the mass distribution of galaxies. By comparing the observed rotation velocities and the theoretical predictions, they can estimate the amount and distribution of dark matter in the galaxies. This insight is not only important for the understanding of any galaxy, but also essential to comprehend the formation and evolution of the structure of the universe as a whole.

## 3. Observational Evidence

### 3.1 Methods for measuring rotation curves

Measuring the rotation velocity curve relies on precise observation techniques. Spectroscopy is the main method. It works by analyzing the Doppler shift in the light from stars and gases to determine their velocity. This enables astronomers to further deduce the velocity of their rotation.

Another essential method to study the outer regions of galaxies is radio observation, especially the 21 cm neutral hydrogen (HI) line. The HI observations go beyond the visible disk, thus providing clearer graphs of the rotation curves [8]. Large surveys including the Sloan Digital Sky Survey (SDSS) and the Very Large Array (VLA) have enhanced our understanding of the rotation curves and the distribution of dark matter to a significant extent [8][9].

Gravitational lensing is another method to study dark matter indirectly. By observing the extent of the curvature of light in the galaxy or around the cluster, scientists can estimate the total mass of galaxies, including dark matter [11]. Even though gravitational lensing cannot directly measure the rotation curves, it can help to provide complementary data to refine the graph.

### 3.2 Evidence of Dark Matter from Rotation Curves

The observations reveal that the rotation curves of galaxies remain flat even at a large radius, which can be seen in our later demonstration of the method. This is peculiar since there are no visible masses in the outer parts of the galaxies. This flatness, therefore, suggests the existence of dark matter in the outer parts of the galaxies. The difference between observed rotation curves and predicted rotation curves cannot be explained by stellar alone, thus becomes strong evidence of the existence of dark matter

An important example is Low Surface Brightness, also known as LSB, galaxies. These galaxies have very little visible matter but their rotation curves are similar to those brighter galaxies, showing that dark matter is playing the

ISSN 2959-6157

major role among the components of the universe [12]. This finding supports the opinion that it is dark matter that makes the rotation curves flat at large radii.

In clusters, the influence of dark matter is more obvious. Through the observation of their rotation curve and the data of gravitational lensing, we provide more proofs of the existence of dark matter in another prospective.

# 4. Analytical Methods

## 4.1 Modeling Rotation Curves

To understand the importance of rotation curves, astronomers use different type of models to simulate the distribution of dark matter in the galaxies. These models typically assumes the existence of dark matter halo. By modifying the parameters, for example the concentration of dark matter halos and the scaling radius of the halo, the model can be similar to the rotation curves obtained from observation.

Besides dark matter, those models explains the baryonic matter, including stars, gas and dust. The interaction between dark matter and visible matter is especially important for acquiring the accurate results. Advanced simulations like Illustris and EAGLE is beneficial for us to enhance our understanding by returning detailed process of supernova explosions and feedback from active galactic nuclei [13][14].

## 4.2 Data Analysis

The analysis of rotation curve data needs complicated statistical methods to separate the contribution of dark matter and visible matter. A common approach is to put the predicted curves (with and without predicted dark matter) with the observed curve in the same graph.

The paper uses the data of galaxy 292365 provided by the Astronomy Department of the University of Michigan as an example to demonstrate the process. Because we need to demonstrate the rotation curve of a galaxy, it is better to use a spiral galaxy, and galaxy 292365 is exactly the type we need. Here is the picture of the star distribution in galaxy 292365.

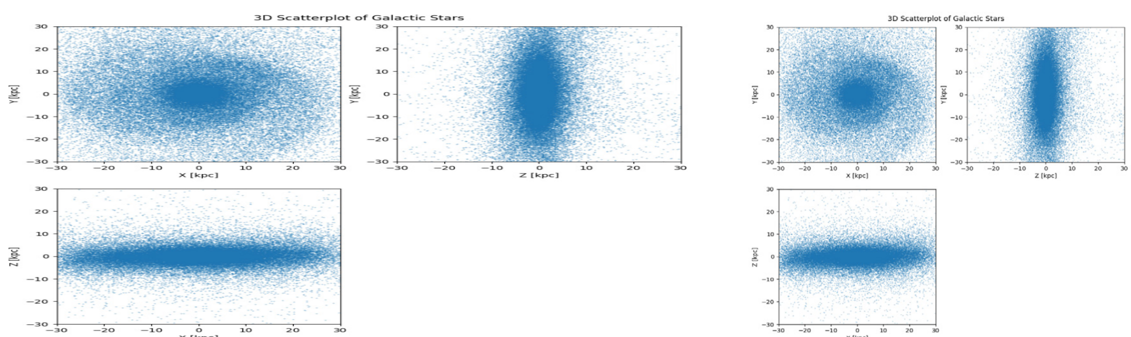


**Fig. 1 3D scatterplot of galactic stars**

Before measuring rotation curves, we first need to find out the effective radius of the galaxy. Computing a galaxy's effective radius is important since observationally, galaxy boundaries are difficult to define. The apparent size of a galaxy is dependent on two key factors: the sensitivity of the telescope used and the length of time that the galaxy is observed. To deal with this ambiguity, astronomers employ a more robust measure of effective radius to define a galaxy.

The effective radius of a galaxy refers to the radius that contains approximately half the galaxy's total light (luminosity). Unfortunately, we don't have luminosity data for our galaxy. Instead, we use mass as an approximation for luminosity. The effective radius we found for galaxy 292365 is around 11.95 kpc.

When astronomers want to measure a rotation curve of a galaxy they observe, they often use a technique called long-slit spectroscopy, wherein they block out light except for a narrow slit through the middle of the disk galaxy. The light which is allowed through is passed onto a spectrograph, which allows astronomers to see the red and blue Doppler shifting of light due to the rotation of the galaxy.

Using the Doppler shifting, astronomers will derive a line-of-sight (LOS) velocity (i.e., how fast the stars are moving toward or away from our telescope) in the disk. Since this velocity is tangent to the disk, we can say the galaxy is approximately rotating at this velocity at a given distance from the center.

Here, we'll do something similar, but instead of one long slit we'll place many narrow slits along the disk, moving outwards from the center. We use a small slit with a width (in the x direction) of 0.5 kpc and a height (in the z direction) of 3 kpc.

To display the LOS rotation velocity, we calculate the mean LOS velocity in every slit and display them on the graph (Figure 2)

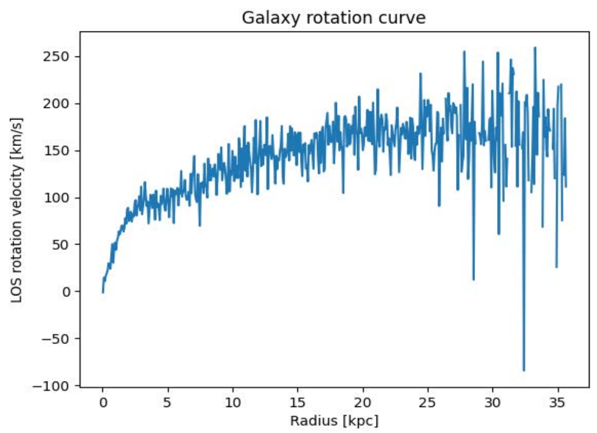


**Fig. 2 Galaxy rotation curve of Galaxy 292365**

From the graph, we can see that the line become unstable at larger radii. This is numerical instability caused by a lower number of particles in these bins and is why we will limit ourselves to two times the effective radius.

To determine the predicted rotation curve of the galaxy, we can use the law of gravitation and the function of circular motion. It is important to notice that Newton's Shell Theorem has to be considered while calculating the rotation curve of stars inside the Galaxy. Because the mass of the stars are too large to be neglected, we need to consider the mass inside the radius of corresponding stars or dark matter. Since this is a spiral galaxy, the mass distribution are relatively consistent. Therefore, we can neglect the difference caused by the distribution of stars. Thus, we need to calculate the cumulative mass of the galaxy. The result is shown in Figure 3.

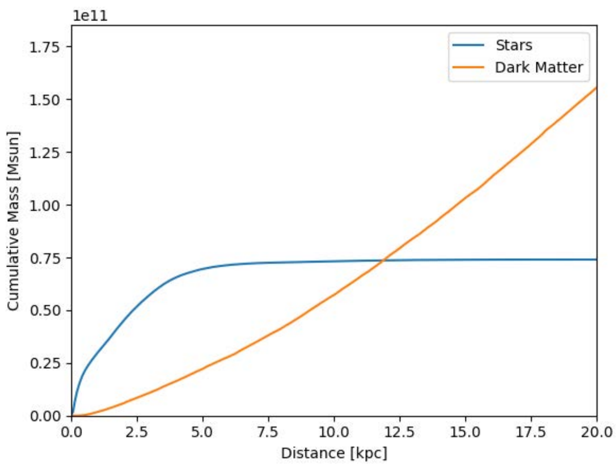


**Fig. 3 cumulative mass of Galaxy 292365**

We assume that the cumulative mass is concentrated in the center of the galaxy which can be proved by calculus but seems redundant in this paper. We then use Newton's law of gravity and the basic knowledge of circular motion to deduce:

$$v = \sqrt{\frac{GM}{R}} \quad (1)$$

Notice that the velocity $v$ is proportional to $\sqrt{M}$, so that increasing $M$ will also increase $v$. $G$ is Newton›s gravitational constant. We also specified $R$ ourselves, so we don't have to worry about those parameters. Also, we know the masses of each star particle directly, so we couldn't have mismeasured the mass.

Now we can figure out the contribution of the dark matter to the rotational velocity we can expect. Conveniently, the rotational velocities for the dark matter and stellar can be summed separately and added in quadrature:

$$v_{tot} = \sqrt{v_{star}^2 + v_{dm}^2} \quad (2)$$

This let us inspect the individual contributions of each component.

### 4.3 Results

We then combine all the graphs we have into a single diagram (Figure 4)

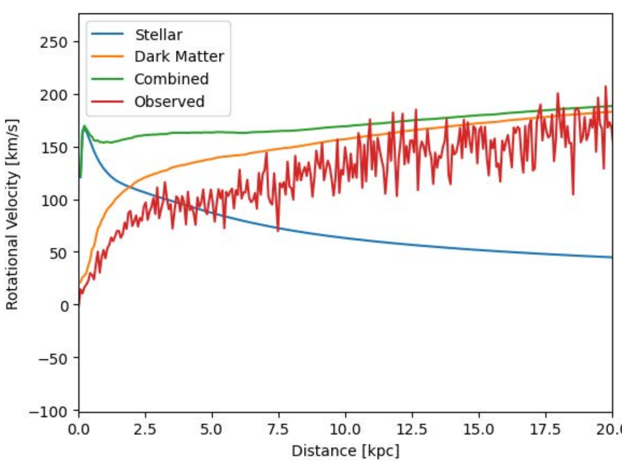


**Fig. 4 rotation curves of galaxy 292365**

From the diagram, it can be noticed that the rotation curve of stellar without dark matter has a significant difference with observed data while the rotation curve of combined matter, both stellar and dark matter has a smaller difference.

### 4.4 Discussion

The prediction still mismatches at the center of the galaxy though. That's because when we go towards the center of the galaxy, we approach the bulge component where the rotational support breaks down, and stars are instead thermally supported (i.e., they have many different kinds of orbits and somewhat resemble the motion of gas mole-

ISSN 2959-6157

cules, hence thermal).

Also, rotational velocity is affected by mass distribution. If the stellar mass and dark matter are distributed very unfavorably in a region, the rotational velocity could decrease significantly. This could account for the discrepancy between predicted and observed values.

From the diagram, we can see that there is a lot of Poisson noise in the observed curve which is deduced by using slits. To reduce it, we can apply statistical methods such as smoothing or deconvolution. Additionally, we could increase the slit size to decrease randomness, because Poisson noise declines proportionally to the square root of the number of data points.

## 5. Summary

The report investigates the fundamental role of dark matter in the behavior of galaxies, focusing in particular on galaxy rotation curves. The observations show that the rotation rate of stars remains constant even far from the galaxy Centre, contradicting predictions based only on visible matter. This flatness in the rotation curves strongly supports the idea of the existence of dark matter halos around galaxies. Comparing our observations with theoretical model, we can understand the distribution of mass in the galaxies and the importance of dark matter. This research also emphasizes that we need to make use of advanced observation techniques and computer models to enhance our understanding of the formation and growth of galaxies. Although we have made great progress, the challenges still remain, especially when comparing the predicted value with the observed value in the center of the galaxies. It is important to use better observation as well as modeling techniques to enhance our understanding of the basic role of dark matter in the universe and its impact on the revolution of the universe.

Acknowledgementsmy

The authors gratefully acknowledge the Department of Astrono of the University of Michigan for providing the data of Galaxy 292365.

## References

[1] Douglass K A, Smith J A, Demina R. The influence of the void environment on the ratio of dark matter halo mass to stellar mass in SDSS MaNGA galaxies. The Astrophysical Journal, 2019, 886(2): 153.

[2] Bertone G. The moment of truth for WIMP dark matter. Nature, 2010, 468(7322): 389-393.

[3] Sofue Y, Rubin V. Rotation curves of spiral galaxies. Annual Review of Astronomy and Astrophysics, 2001, 39(1): 137-174.

[4] Silk, Joseph. „Galaxy formation and dark matter.“ *The Invisible Universe: Dark Matter and Dark Energy*, 2007, 101-121.

[5] Roszkowski L, Sessolo E M, Trojanowski S. WIMP dark matter candidates and searches—current status and future prospects. Reports on Progress in Physics, 2018, 81(6): 066201.

[6] Duffy L D, Van Bibber K. Axions as dark matter particles. New Journal of Physics, 2009, 11(10): 105008.

[7] Evans N W, An J H. Distribution function of dark matter. Physical Review D—Particles, Fields, Gravitation, and Cosmology, 2006, 73(2): 023524.

[8] Crovisier J, Dickey J M. The spatial power spectrum of galactic neutral hydrogen from observations of the 21-cm emission line. Astronomy and Astrophysics (ISSN 0004-6361), vol. 122, no. 1-2, June 1983, p. 282-296., 1983, 122: 282-296.

[9] York D G, Adelman J, Anderson Jr J E, et al. The sloan digital sky survey: Technical summary. The Astronomical Journal, 2000, 120(3): 1579.

[10] Perley R A, Chandler C J, Butler B J, et al. The expanded very large array: a new telescope for new science. The Astrophysical Journal Letters, 2011, 739(1): L1.

[11] Kaiser N, Squires G. Mapping the dark matter with weak gravitational lensing. Astrophysical Journal, Part 1 (ISSN 0004-637X), vol. 404, no. 2, p. 441-450., 1993, 404: 441-450.

[12] van den Bosch F C, Robertson B E, Dalcanton J J, et al. Constraints on the structure of dark matter halos from the rotation curves of low surface brightness galaxies. The Astronomical Journal, 2000, 119(4): 1579.

[13] Vogelsberger M, Genel S, Springel V, et al. Introducing the Illustris Project: simulating the coevolution of dark and visible matter in the Universe. Monthly Notices of the Royal Astronomical Society, 2014, 444(2): 1518-1547.

[14] Schaye J, Crain R A, Bower R G, et al. The EAGLE project: simulating the evolution and assembly of galaxies and their environments. Monthly Notices of the Royal Astronomical Society, 2015, 446(1): 521-554.