

The NFW DM Profile Is Compatible with the Decay Law of Velocity with -0.25 as Power of Radius within the Halo

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Abstract

The purpose of this study is to demonstrate that the Navarro-Frenk-White (NFW) dark matter (DM) density profile is consistent with the velocity decay law characterized by a radial dependence of $r^{-0.25}$ within the halo regions of the MW, M31 and six other galaxies outside the Local Group, i.e. it is a universal law. The velocity law, expressed as $v = a \cdot r^{-0.25}$, was derived from a novel framework known as the **DM by Quantum Gravitation** theory (hereafter referred to as the **DMbQG theory**). This theory proposes that dark matter (DM) arises from the propagation of the gravitational field through an as-yet-unknown quantum gravitational phenomenon and as a consequence within the halo the rotation curve decays with the universal law mentioned. The DMbQG belongs to the category of Modified Gravity theories. Since the NFW profile has been extensively validated over the past three decades across thousands of galaxies, it is crucial to examine whether a novel framework such as DMbQG theory produces a total mass function that is effectively indistinguishable from NFW predictions. At the core of the DMbQG framework lies the direct mass formula, $M_{\text{TOTAL}}(<r) = a^2 \cdot \sqrt{r}/G$ which yields the total enclosed mass within a sphere of radius r . As discussed in Chapter 8 of Abarca's paper [1], the total mass depends on the parameter a^2 , where a is the proportionality constant in the velocity decay law $v = a \cdot r^{-0.25}$. These two expressions, which share the same constant a , provide dual approaches for its determination: (i) directly from the galactic rotation curve in the halo region, and (ii) indirectly from the virial mass and radius derived via the NFW model and using the direct mass to calculate the parameter a . In practice, the total galactic virial mass can be estimated by adding the baryonic mass—primarily confined to the bulge and disk—to the virial DM mass obtained through the NFW prescription. Consequently, if the parameter a derived from the rotation curve coincides with the value of a obtained using the direct mass formula with the total mass inferred

from the NFW formalism, the central thesis of this work is validated. The structure of this paper is as follows: In Chapter 2, the parameter a is calculated for the MW using rotation curve datasets from two independent authors. Chapter 3 introduces the NFW formalism and its principal expressions. Chapter 4 presents the derivation of a^2 from the direct mass formula using the virial mass obtained through the NFW method. In Chapter 5, the parameter a obtained through both approaches is compared for the MW using two independent datasets. Chapter 6 mirrors this analysis for the M31 galaxy, again employing two distinct datasets. Chapter 7 studies the compatibility of NFW method with the decay law velocity in two galaxies outside the Local Group. Chapter 8 studies the equivalence of virial data obtained by the NFW method and by the Direct mass in the framework of DMbQG theory using the data of four galaxies selected from the SPARC project. Chapter 9 study the NGC 3521 galaxy by a dual data set, the first from the SPARC project (2016) with a shorter radius dominion and the second from Vijayakumar *et al.* with a wider radius dominion. The conclusion about this dual approach is that the DMbQG theory is able to calculate a precise virial mass with a shorter dominion data than the NFW method. Across these eight galaxies, inside and outside the Local Group, the empirical results provide strong support for the central thesis of this paper.

Keywords

Dark Matter Problem, Milky Way, M31, NGC 3521, NGC 3621, SPARC Database, Modified Gravity

1. Introduction

Since 2014 up to 2025, I have published several papers studying DM in galactic halos, especially in M31 and Milky Way although I have also published some papers studying other galaxies and clusters. Through those works a new and original theory, called Dark matter by quantum gravitation theory, hereafter DMbQG, has been developed.

The reader must have at least a general knowledge about this original theory to understand this paper. The paper by Abarca (2024) [1] is the best work about the DMbQG theory, so the reader may consult such paper when it is cited in this work. In Abarca's paper [1], there are some tests of validation of the theory using results published for MW, for M31 and for the Local Group. On the other hand, in the paper by Abarca (2024) [2], the theory was extended to cluster of galaxies and its theoretical findings are tested using results published of the Virgo cluster. In a few words, the DMbQG theory is well developed and tested into the two previously cited papers.

In addition, in the paper by Abarca (2025) [3], it is also demonstrated that the equivalence of the direct mass function and the total mass using the NFW DM function mass plus the baryonic mass, but that study is more complex than the present work.

The novelty of this paper is that it is focused on the comparison of the parameter a , obtained by two different methods, and one of them involves the NFW DM mass formula.

The purpose of this paper is to demonstrate that the NFW dark matter density profile is consistent with the velocity decay law characterized by a radial dependence of $r^{-0.25}$ within the halo regions as a universal property for all the galaxies and consequently the NFW DM mass function plus the baryonic function is equivalent to the direct mass formula, which was derived within the framework of the DMbQG theory.

Given that the NFW profile has been extensively validated over the past three decades across thousands of galaxies, it is essential to verify whether a novel approach such as DMbQG yields a total mass function effectively indistinguishable from the NFW predictions.

The DMbQG theory, developed in Abarca's paper (2024) [1], postulates that dark matter arises from an as-yet unidentified quantum gravitational phenomenon induced by the gravitational field generated by the baryonic component of a galaxy. A distinctive feature of this hypothesis, in contrast to the NFW paradigm, is the assumption that the DM halo is unbounded rather than confined. The DMbQG belongs to the category of Modified Gravity because it is postulated that the DM arises from the gravitational field propagation so the DM is a quantum gravitation phenomenon more properly.

At the core of the DMbQG framework lies the *direct mass formula*

$$M_{\text{TOTAL}}(r) = \frac{a^2 \cdot \sqrt{r}}{G} \quad (1.1)$$

which yields the total enclosed mass within a sphere of radius r , and has been the radius unbounded. As discussed in Chapter 8 of Abarca's paper [1], the mass depends on the parameter a , where a is the proportionality constant in the velocity decay law $v = a \cdot r^{-0.25}$ into the halo region for any galaxy.

These two relations, sharing the same constant a , enable dual pathways to its determination: on the one hand, from the galactic rotation curve in the halo region; on the other, from the virial mass and radius conventionally derived through the NFW model and using the direct mass to calculate the parameter a . In practice, the total galactic mass may be estimated by adding the baryonic mass—primarily confined to the bulge and disk—to the virial DM mass obtained from the NFW prescription. This way demonstrates that the virial mass calculated using the NFW method is consistent with a power-law decay, with an exponent of -0.25 , for the rotation curve associated with the total mass in the halo region.

In the paper by Abarca (2025) [3], a comparison is made between the direct mass function and the NFW total mass function across a wide region of the galactic halo for both the MW and M31 galaxies but in this work, in addition to MW and M31, the thesis stated in the title of this paper is demonstrated in six galaxies out of the Local Group because the thesis of DMbQG theory aims to explain the DM in any galaxy.

2. Proportionality Constant Associated with the Velocity Decay Law in the DMbQG Theory

In the framework of DMbQG theory, into the halo region, the velocity decays according to $v = a \cdot r^{-0.25}$, being the parameter a constant, whose value may be calculated by a couple of data:

$$a = v \cdot r^{0.25} \quad \text{or} \quad a^2 = v^2 \cdot r^{0.5} \tag{2.1}$$

It is simple to check that the dynamical mass $M_{\text{DYN}} = V^2 \cdot \text{Radius} / G$ is mathematically equivalent to direct mass, $M_{\text{DIRECT}} = M_{\text{TOTAL}}(<r) = a^2 \sqrt{r} / G$ if it is assumed the velocity law $v = a \cdot r^{-0.25}$. The *direct mass formula* represents the total mass enclosed by the sphere with a specific radius, according the DMbQG theory.

The formula to calculate the parameter a comes from Abarca’s paper (2024) [1], see epigraph 8.7 where is explained that according the DMbQG theory, into the halo, the velocity decays according the formula $V = a \cdot r^{-0.25}$.

As the rotation curve data have non negligible errors and the total mass depend on the parameter a^2 , the parameter a is calculated for the whole dataset and afterward its average value. It is right to calculate the relative error of a^2 considering only the error associated to the velocity with the formula:

$$d(a^2) / a^2 = 2 \cdot dv / v \tag{2.2}$$

In the epigraph 10.1 of the paper [1] it is explained why the halo begins at 30 kpc for the MW Galaxy.

2.1. Calculation of Parameter a Using the Milky Way Data by Huang *et al.* [4]

Using the procedure explained before with the data of paper by Huang *et al.* [4] it is got in **Table 1** the parameter a , which is a 3% lower than the one got by Sofue. See **Table 2**.

Table 1. Parameter a using the data from Huang *et al.* (2016) [4] for the MW.

Velocity	Radius	Radius	Velocity	Parameter a
km/s	kpc	m	m/s	$\text{m}^{1.25}/\text{s}$
211.2	31.29	9.65516E+20	211200	3.7229E+10
217.93	33.73	1.04081E+21	217930	3.9143E+10
219.33	36.19	1.11671E+21	219330	4.0094E+10
213.31	38.73	1.19509E+21	213310	3.9661E+10
200.05	41.25	1.27285E+21	200050	3.7786E+10
190.15	43.93	1.35555E+21	190150	3.6486E+10
198.95	46.43	1.43269E+21	198950	3.8706E+10
192.91	48.71	1.50304E+21	192910	3.7984E+10
198.9	51.56	1.59099E+21	198900	3.9724E+10
185.88	57.03	1.75977E+21	185880	3.8071E+10
173.89	62.55	1.93011E+21	173890	3.6448E+10
196.36	69.47	2.14364E+21	196360	4.2251E+10

Continued

175.05	79.27	2.44603E+21	175050	3.8929E+10
			Average a	3.8655E+10
			Average a^2	1.4942E+21

In this table and hereafter, the letter E means the power of 10. e.g. $1.0E+10 = 1.0 \cdot 10^{10}$ and $1.5E-1 = 1.5 \cdot 10^{-1}$; Notice that the maximum of the relative difference regarding the average a^2 is about 5%.

The data of rotation curve, see [4], table 3 page 2633, have only velocity errors. In average the relative error of velocity is 10% so consequently by the formula (2.2) the relative error associated to a^2 is 20%.

2.2. Calculation of Parameter a Using the Milky Way Data by Sofue [5]

In **Table 2** the rotation curve data (radius and velocity) have been taken from table A2, page 15 of Sofue (2020) [5]. In the last column the parameter a is calculated for each point of the rotation curve and finally its average value a and a^2 is calculated.

Table 2. Parameter a using the Sofue (2020) data for the MW.

radius	velocity	radius	velocity	parameter a
kpc	km/s	m	m/s	$m^{1.25}/s$
30.448	229.60	9.40E+20	229600	4.01976E+10
33.493	222.50	1.03E+21	222500	3.98939E+10
36.842	215.00	1.14E+21	215000	3.94787E+10
40.527	207.10	1.25E+21	207100	3.89453E+10
44.579	200.30	1.38E+21	200300	3.85746E+10
49.037	194.70	1.51E+21	194700	3.84004E+10
53.941	189.80	1.66E+21	189800	3.83367E+10
59.335	186.20	1.83E+21	186200	3.85164E+10
65.268	184.70	2.01E+21	184700	3.91273E+10
71.795	183.90	2.22E+21	183900	3.98973E+10
78.975	181.40	2.44E+21	181400	4.03040E+10
86.872	175.50	2.68E+21	175500	3.99333E+10
95.560	167.70	2.95E+21	167700	3.90787E+10
			Average a	3.92834E+10
			Average a^2	1.543186E+21

Notice that the maximum of the relative difference regarding the average a^2 is about 5%.

The data of rotation curve, see [5], page 15, have an average error of velocities about 6% or bigger. The author does not give error of radius, so by the formula (2.2) the relative error of a^2 is bigger than 12%.

The average a^2 got using the Sofue data is a 3% bigger than the one got by Huang. See **Table 1**. Therefore if it is considered the experimental errors both values of parameter a^2 may be considered as equivalents.

3. The NFW profile for the Dark Matter

In this chapter, the most usual DM profile, which was developed by Navarro, Frenk and White, hereafter NFW DM profile, will be explained. This DM profile has been used widely by the scientific community to study the DM in thousands of galaxies during last 30 years. Previously to study this DM profile, will be explained two concepts usually connected with him: M_{200} and R_{200} , also known as virial mass and radius.

3.1. M_{200} and R_{200} or the Virial Data in the NFW Method

In the framework of NFW method, R_{200} is the radius of a sphere whose mean density of DM is 200 times bigger than the critic density of Universe

$$\rho_C = \frac{3H^2}{8\pi G} = 9.2055 \times 10^{-27} \text{ kg} \cdot \text{m}^{-3} \quad \text{and} \quad 200\rho_C = 1.8411 \times 10^{-24} \text{ kg} \cdot \text{m}^{-3} \quad (3.1)$$

(In this work it will be considered $H = 70 \text{ km/s/Mpc}$).

and M_{200} is the DM mass enclosed by the sphere with the radius R_{200} .

Considering the spherical volume formula, it is simple to get the following relations between both concepts.

$$R_{200}^3 = \frac{G \cdot M_{200}}{100 \cdot H^2} \quad (3.2)$$

$$\text{or} \quad M_{200} = \frac{100H^2 R_{200}^3}{G} \quad (3.3)$$

$$\text{or} \quad \frac{M_{200}}{R_{200}^3} = \frac{100H^2}{G} \quad (3.4)$$

3.2. The DM Mass Formula into the NFW Method

The NFW profile for the DM density is defined by two parameters: the scale radius and the characteristic density.

It is supposed a spherical symmetry and its formula it is

$$\rho(r) = \frac{\rho_0}{x \cdot (1+x)^2} \quad (3.5)$$

being ρ_0 a characteristic density, $x = r/R_0$ a dimensionless magnitude related with radius by R_0 , which is called the scale radius.

By integration it is obtained the formula for the Dark matter enclosed by a sphere with radius r .

$$M_{\text{DM}}(< r) = K_{\text{NFW}} \cdot f(x) \quad (3.6)$$

$$\text{being } K_{\text{NFW}} = 4\pi\rho_0 R_0^3, \text{ called the NFW characteristic mass} \quad (3.7)$$

$$\text{and } f(x) = \ln(1+x) - x/(1+x) \quad (3.8)$$

where $x = r/R_0$, being \ln the natural logarithm.

Two important concepts for NFW profiles are M_{200} and R_{200} both referred to DM only.

$$\text{So } M_{200} = M_{200\text{-DM}} = M_{\text{DM}}(< R_{200}) = K_{\text{NFW}} \cdot f(c) \quad (3.9)$$

$$\text{where } c = R_{200}/R_0 \quad (3.10)$$

is called the concentration parameter and $R_{200} = R_0 \cdot c$

3.3. Calculation of Concentration Parameter c

$$\text{As } \frac{M_{200}}{R_{200}^3} = \frac{100H^2}{G} \text{ see formula (3.4) then } \frac{M_{200}}{c^3 R_0^3} = \frac{100H^2}{G} \text{ and}$$

$$\frac{4 \cdot \pi \rho_0 \cdot R_0^3 \cdot f(c)}{c^3 R_0^3} = \frac{100H^2}{G} \text{ so}$$

$$\frac{c^3}{f(c)} = \frac{4\pi G \rho_0}{100 \cdot H^2} \quad (3.11)$$

That it is the equation for the concentration parameter. This equation is quite easy to solve numerically, and it is clear that c depend on the characteristic density only.

With this parameter c , it is easily calculated M_{200} and R_{200} .

For example, shown in **Table 3** are the NFW parameters published by Sofue [5].

Table 3. The NFW parameters for MW by Sofue (2020).

Characteristic density ρ_0	Scale radius R_0
$0.787 \pm 0.037 \text{ GeV} \cdot \text{cm}^{-3} = (1.403 \pm 0.066) \cdot 10^{-21} \text{ kg} \cdot \text{m}^{-3}$	$10.94 \pm 1.05 \text{ kpc}$

Using the characteristic density it is simple to get the equation:

$$c^3/f(c) = 2286.125 \text{ that gives the value } c = 16.348, \text{ and } f(c) = 1.91.$$

$$\text{So } R_{200} = R_0 \cdot c = 178.85 \text{ kpc.}$$

$$\text{Using (3.7) } K_{\text{NFW}} = 3.4 \cdot 10^{11} M_{\odot} \text{ then using (3.9) } M_{200} = 6.498 \cdot 10^{11} M_{\odot}.$$

It is easy to check that the density of the sphere with the previous data M_{200} and R_{200} is virtually equal to $200\rho_c$.

4. Calculation of Parameter a^2 Using the Direct Mass Formula for the MW Galaxy

In the chapter 8 of Abarca, M. (2024) [1], it was demonstrated that the direct mass formula

$$M_{\text{TOTAL}}(<r) = \frac{a^2 \cdot \sqrt{r}}{G} \quad (4.1)$$

is the most appropriate method to estimate the total mass (baryonic plus dark matter) enclosed within a sphere of a given radius extending into the galactic halo. The halo corresponds to the region where the density of baryonic matter becomes negligible compared to the dark matter density. E.g. the halo of the Milky Way extends beyond 30 kpc, while that of M31 extends beyond 40 kpc (see Abarca, M. [1], 2024, Chapters 5 and 10).

For example $M_{\text{TOTAL}}(<R_{200}) = a^2 \cdot \sqrt{R_{200}}/G$ gives the total mass enclosed by the sphere with radius R_{200} . Notice that $M_{\text{TOTAL}}(<R_{200})$ is bigger than M_{200} . Namely $M_{\text{TOTAL}}(<R_{200}) = M_{200} + M_{\text{BA}}$. Where M_{BA} represents the baryonic mass of the galaxy. As it is well known, virtually all of the baryonic mass is contained in the bulge and the galactic disc. Hereafter $M_{\text{TOTAL}}(<R_{200})$ will be renamed as $M_{200\text{-TOTAL}}$.

4.1. The Parameter a^2 Formula Depending on the Virial Radius and the Virial Mass

Since the direct mass formula has only one parameter, knowing the total mass associated with a specific radius is enough to calculate the parameter a^2 .

So from this formula $M_{\text{TOTAL}}(<R_{200}) = \frac{a^2 \cdot \sqrt{R_{200}}}{G}$ it is got

$$a^2 = \frac{G \cdot M_{200\text{-TOTAL}}}{\sqrt{R_{200}}} \quad (4.2)$$

In the following epigraphs the parameter a^2 will be calculated using the data provided by three authors.

4.1.1. Calculation of Parameter a^2 Using the Karukes Virial Data

For example, in **Table 4**, the virial data for MW published by Karukes *et al.* (2020) [6] are shown in **Table 3**, page 15 of his paper.

The first column shows the DM enclosed into the sphere with radius R_{200} and the second one shows the total mass (DM plus baryonic) and consequently its difference gives the total baryonic mass according this author.

Using the value $M_{200\text{-TOTAL}}$ and R_{200} into the formula (4.2) it is got $a^2 = 1.54 \cdot 10^{21} \text{ m}^{5/2}/\text{s}^2$ that it is virtually equal to the value got for this parameter in the chapter 2, using the rotation curve data method with the data provided by Huang or Sofue.

Using $M_{200\text{-DM}}$ and R_{200} it is right to check that the average density is virtually $200\rho_C$.

Table 4. The virial data for M.W. according Karukes *et al.* [6].

$M_{200\text{-DM}}$	$M_{200\text{-TOTAL}}$	R_{200}	Parameter a^2
M_{\odot}	M_{\odot}	kpc	$\text{m}^{5/2}/\text{s}^2$
$8.26_{-0.8}^{+1.2} \times 10^{11}$	$8.95_{-0.8}^{+1} \times 10^{11}$	193_{-6}^{+9}	$1.54 \cdot 10^{21}$
$M_{\text{BA}} = M_{200\text{-TOTAL}} - M_{200\text{-DM}} = 7 \cdot 10^{10} M_{\odot}$			

In **Table 5**, the parameter a^2 is calculated using a different set of data pairs, see [6] page 25. The only value to be excluded is that corresponding to 28 kpc, as it deviates significantly from the remaining data points. This discrepancy can be attributed to the fact that the galactic halo is considered to begin at approximately 30 kpc. At radii smaller than 30 kpc, the contribution of baryonic matter is non-negligible, and therefore the direct mass estimation formula is not applicable.

The direct mass formula is so simple because its domain is the halo region, where the baryonic matter density is negligible compared to the dark matter density.

As it is shown in **Table 5**, into the halo region the parameter a^2 is virtually constant.

Table 5. Total Mass and its radius according to [6].

Radius (kpc)	M_{TOTAL} ($\times 10^{11}$) M_{\odot}	Parameter a^2 $\times 10^{21}$ $\text{m}^{2.5}/\text{s}^2$
28.33	3.04 ± 0.10	1.3653
45.79	4.27 ± 0.20	1.5085
74.0	5.68 ± 0.40	1.5784
119.57	7.26 ± 0.60	1.5872
193.24	8.95 ± 0.90	1.54

4.1.2. Calculation of Parameter a^2 Using the Sofue Virial Data

In **Table 6** are collected the NFW parameters of MW from the paper [5] table 3, page 12. The baryonic mass may be calculated from the figure 3 (for the mass of bulge) and the table 3 for the mass of disc. Notice how different is the baryonic mass regarding the value calculated by Karukes. See **Table 4**.

Table 6. NFW parameters for M.W. according to [5].

Baryonic mass of MW $M_{\text{BA}} = 1.8 \cdot 10^{11} M_{\odot}$	
Characteristic density D_0	Scale radius R_0
$1.40 \cdot 10^{-21} \text{ kg} \cdot \text{m}^{-3}$	10.94 kpc

With the same data of **Table 6**, in the epigraph 3.3 was calculated the virial mass $M_{200\text{-DM}} = 6.5 \cdot 10^{11} M_{\odot}$ and $R_{200} = 178.85$ kpc.

So adding the baryonic mass it is got $M_{200\text{-TOTAL}} = M_{200\text{-DM}} + M_{\text{BA}} = 8.3 \cdot 10^{11} M_{\odot}$ and by the formula (4.2) it is calculated easily the parameter $a^2 = 1.484 \cdot 10^{21} \text{ m}^{2.5}/\text{s}^2$. In **Table 7** are summarized the results.

Table 7. Parameter a^2 using the Sofue virial data.

$M_{200\text{-TOTAL}}$	R_{200}	Parameter a^2
$8.3 \cdot 10^{11} M_{\odot}$	178.85 kpc	$1.484 \cdot 10^{21} \text{ m}^{2.5}/\text{s}^2$

4.1.3. Calculation of Parameter a^2 Using the Huang Virial Data

In **Table 8** are the NFW parameters provided by this author and the baryonic mass of the MW. These data have been got from table 4 at the page 2636 from Huang *et al.* [4].

Table 8. The NFW parameters for M.W. according Huang (2016).

Characteristic density D_0	Scale radius R_0
$8.196 \cdot 10^{-22} \text{ kg} \cdot \text{m}^{-3}$	14.39 kpc
Baryonic mass of MW $M_{BA} = 8.1 \cdot 10^{10} M_\odot$	

The equation for the concentration factor is $\frac{c^3}{f(c)} = \frac{4\pi G \rho_0}{100 \cdot H^2} = 1335.50$ whose solution is $c = 13.2046$ and $f(c) = 1.7240$.

Therefore $R_{200} = 13.2046 \cdot 14.39 = 190.014 \text{ kpc}$ and $M_{200} = K_{NFW} \cdot f(c) = 7.81 \cdot 10^{11} M_\odot$ where K_{NFW} is the characteristic mass of NFW profile, $K_{NFW} = 4.531 \cdot 10^{11} M_\odot$.

As M_{200} is the DM enclosed by the sphere with radius R_{200} , to calculate the total mass it is added the baryonic mass, so $M_{200-TOTAL} = (7.81 + 0.81) \cdot 10^{11} M_\odot = 8.62 \cdot 10^{11} M_\odot$.

Finally it is possible to calculate the parameter a^2 using $M_{200-TOTAL}$ and R_{200} obtaining by the formula (4.2) $a^2 = 1.4949 \cdot 10^{21} \text{ m}^{2.5}/\text{s}^2$ that it is very close to the one got in the table 1, $a^2 = 1.4942 \cdot 10^{21} \text{ m}^{2.5}/\text{s}^2$.

In **Table 9** are summarized the results.

Table 9. Parameter a^2 using the virial data by Huang *et al.* (Over density 200).

M_{200}	$M_{200-TOTAL}$	R_{200}	Parameter a^2
$7.81 \cdot 10^{11} M_\odot$	$8.62 \cdot 10^{11} M_\odot$	190.014 kpc	$1.4949 \cdot 10^{21} \text{ m}^{2.5}/\text{s}^2$

In the paper [4], the authors give a different virial data because they have considered an over density = 95 times the critic density of the Universe instead 200. In **Table 10** are shown the virial data provided by the authors. See the table 4 in the page 2636. The procedure to calculate the parameter a^2 is the same.

Table 10. Parameter a^2 using the virial data by Huang *et al.* (Over density 95).

R_{VIR}	M_{VIR}	$M_{VIR-TOTAL}$	Parameter a^2
255.69 kpc	$9 \cdot 10^{11} M_\odot$	$9.81 \cdot 10^{11} M_\odot$	$1.467 \cdot 10^{21} \text{ m}^{2.5}/\text{s}^2$

This value of the parameter a^2 is only 1.8% lower than the value one got by the Huang rotation curve data, see **Table 1**.

5. Comparison of Parameter a^2 from Rotation Curve and Virial Data in the MW Halo

In Chapters 2 and 4, the parameter a^2 has been calculated using two different

methods. Specifically, in Chapter 2, a^2 was obtained through the method directly related to the velocity decay law in the halo region, through the formula (2.1), whereas in Chapter 4, a^2 was derived through the formula (4.2) using the virial data calculated from the NFW profile and by adding the baryonic mass to the virial dark matter mass.

In this chapter, both values will be compared, taking into account their procedural errors. It will be shown that the NFW method is consistent with the velocity decay law stated in the title of this paper, since the relative difference in a^2 obtained by the two methods is clearly smaller than the specific error associated with each method.

A summary of the error analysis for each method is as follows:

First method: In Section 2.1, it was shown that the relative error of a^2 due to velocity uncertainties is about 20%. In Section 2.2, this error was reduced to about 12%, given that the velocity error is approximately 6%.

Second method: In Section 4.1.1, **Table 4** shows that the relative error of the virial total mass is about 11%, while that of the virial radius is about 4.7%. Using these values, and applying formula (4.2), the relative error of a^2 is about 13%.

The formula used for the relative error is: $d(a^2)/a^2 = dm/m + 1/2 \cdot dr/r$.

Table 11 summarizes the different values of a^2 obtained in Chapters 2 and 4. The third column shows the relative differences between the two methods: using Huang's data, the relative difference is 1.8%, while with Sofue's data, it is about 3.8%.

Table 11. Parameter a^2 by rotation curve (R.C.) versus a^2 by the virial data.

Parameter a^2 by rotation curve	Parameter a^2 by virial data	Relative difference
Huang's <i>et al.</i> Data—a^2 units $m^{2.5}/s^2$		
1.4942·10 ²¹ —see Table 1	1.4949·10 ²¹ —see Table 9	Virtually zero
1.4942·10 ²¹ —see Table 1	1.467·10 ²¹ —see Table 10	1.8%
Sofue's data—a^2 units $m^{2.5}/s^2$		
1.5432·10 ²¹ —see Table 2	1.484·10 ²¹ —see Table 7	3.8%
Karukes's <i>et al.</i> data—a^2 units $m^{2.5}/s^2$		
Rotation curve not published	1.54·10 ²¹ —see Table 4	

In conclusion, the relative difference in a^2 obtained by the two methods is much smaller than the characteristic errors associated with each method. Therefore, it can be stated that the NFW dark matter profile is compatible with the velocity decay law $v = a \cdot r^{-0.25}$ within the halo of the Milky Way.

6. Comparison of Parameter a^2 from Rotation Curve and Virial Data in the M31 Halo

In this chapter will be demonstrated that the NFW DM profile is equivalent with the velocity decay law $v = a \cdot r^{-0.25}$ into the halo region, for the M31 galaxy as well.

As sources of data will be used the papers [7] Sofue (2015) and [8] Zhang *et al.* (2024) where are published two rotation curves of M31.

6.1. The M31 Data from Sofue [7]

6.1.1. Calculation of Parameter a^2 Using the Rotation Curve Data of Sofue

In the chapter 2 of paper [1], it is introduced the rotation curve data published by [7] Sofue, Y. (2015) and in the chapter 8 of paper [1] it is calculated the parameter a using such rotation curve. Namely $a^2 = 2.235 \cdot 10^{21} \text{ m}^{5/2}/\text{s}^2$ is the value obtained by the rotation curve data of M31.

Unfortunately, the author does not provide the numerical data for the rotation curve, and the associated errors cannot be reliably inferred from the graph alone. As a result, it is not possible to conduct an error analysis for this method when calculating the parameter a^2 .

6.1.2. Virial Data and Calculation of Parameter a^2 by the Direct Mass Formula

In the table 2 of paper [7], it is introduced the NFW parameters shown in **Table 12**.

Table 12. The NFW parameters for M31 according to Sofue [7].

Characteristic density D_0	Scale radius R_0
$(1.51 \pm 0.15) \cdot 10^{-22} \text{ kg} \cdot \text{m}^{-3}$	$34.6 \pm 2.1 \text{ kpc}$
Baryonic mass of M31 $M_{\text{BA}} = 1.6 \cdot 10^{11} M_{\odot}$	

Now it will be calculated the virial data by the NFW method. The equation for the concentration factor is $\frac{c^3}{f(c)} = \frac{4\pi G \rho_0}{100 \cdot H^2} = 246.048$ whose solution is $c = 6.579$ and $f(c) = 1.1573$.

Therefore $R_{200} = 6.579 \cdot 34.6 = 227.63 \text{ kpc}$ and $M_{200} = K_{\text{NFW}} \cdot f(c) = 1.342 \cdot 10^{12} M_{\odot}$ where K_{NFW} is the characteristic mass of the NFW DM profile, $K_{\text{NFW}} = 1.16 \cdot 10^{12} M_{\odot}$.

As M_{200} is the DM enclosed by the sphere with radius R_{200} , to calculate the total mass, and the baryonic mass is added, so $M_{200\text{-TOTAL}} = (1.34 + 0.16) \cdot 10^{12} M_{\odot} = 1.50 \cdot 10^{12} M_{\odot}$.

Finally, it is possible to calculate the parameter a^2 using $M_{200\text{-TOTAL}}$ and R_{200} getting the value $a^2 = 2.377 \cdot 10^{21} \text{ m}^{2.5}/\text{s}^2$ that it is only 6% bigger than the value one got by the Sofue rotation curve data, whose value is $a^2 = 2.235 \cdot 10^{21} \text{ m}^{5/2}/\text{s}^2$.

In this case, the error analysis is more complex because the total mass depends on the parameter c , which is obtained by solving a transcendental equation involving c^3 . The characteristic density D_0 carries an uncertainty of approximately 10%. Consequently, the total mass must have an error significantly larger than 10%, which in turn propagates to the parameter a^2 . Despite this, the relative difference in a^2 between the two methods is only 6%. Therefore, it can be concluded that both methods are consistent, *i.e.*, the NFW profile is compatible with a veloc-

ity decay law in the halo region of the form $v = a \cdot r^{-0.25}$, mirroring what was found in the chapter 5 for the MW galaxy.

6.2. Data from Zhang *et al.* (2024) [8]

These authors provide both the rotation curve data and the virial data, each with known uncertainties. The error analysis in this case is somewhat lengthy and is presented in the following sections.

6.2.1. Calculation of Parameter a^2 Using the Rotation Curve Data of Zhang *et al.*

On page 9 of Zhang *et al.* [8], the rotation curve data are tabulated. In Chapter 5 of Abarca [1], it is shown that for galactocentric radii exceeding 40 kpc, the baryonic mass density becomes negligible in comparison to the dark matter (DM) density. Consequently, the parameter a^2 is evaluated starting at 40 kpc. Nevertheless, the velocity measurements at 46 kpc and 52 kpc reported by Zhang *et al.* [8] are anomalously low and have therefore been excluded from the analysis.

In **Table 13**, the remaining rotation curve data are presented. Their corresponding a^2 values are calculated, along with the average a^2 .

Table 13. Calculus of a^2 using the rotation curve of M31 data from Zhang *et al.* [8].

Radius	Velocity	Radius	Velocity	Param. a^2
kpc	km/s	m	m/s	$\text{m}^{2.5}/\text{s}^2$
54.85	196.28	1.6925E+21	196280.00	1.5850E+21
67.26	202.02	2.0754E+21	202020.00	1.8593E+21
98.74	192.59	3.0468E+21	192590.00	2.0473E+21
123.56	168.53	3.8127E+21	168530.00	1.7538E+21
			Average a^2	1.8113E+21

The average a^2 is a 19% lower than the one calculated by the Sofue rotation curve data (epigraph 6.1.1).

Error analysis of a^2 based on rotation curve data errors

From the formula of parameter $a^2 = v^2 \cdot r^{0.5}$, it is easy to calculate its relative error $d(a^2)/a^2 = 2dv/v + (1/2) \cdot dr/r$ where dv/v is the relative error of the velocity and dr/r is the relative error of radius.

In **Table 14** are shown the rotation curve data and its errors provided by Zhang *et al.*

Table 15 presents the rotation curve data along with their associated errors, expressed in SI units. **Table 15** also includes the relative error of parameter a^2 for each data point, with an average value of 43%.

Considering this relative error, the value of a^2 obtained by Zhang ($1.8 \cdot 10^{21}$) is reasonably consistent with that reported by Sofue ($2.2 \cdot 10^{21}$), since their relative difference is only 20%.

Table 14. Rotation curve data from Zhang *et al.* [8].

Radius	Radius error	Velocity	V. error
kpc	kpc	Km/s	Km/s
52.08	1.63	182.05	38.15
54.85	1.67	196.28	38.81
67.26	14.95	202.02	40.67
98.74	17.19	192.59	42.23
123.56	11.6	168.53	41.34

Table 15. R.C. with its data errors into SI units and relative error of a^2 .

Radius	Rad. Error	Velocity	Vel. Error	$d(a^2)/a^2$
m	m	m/s	m/s	%
1.693E+21	5.15312E+19	196280	38810	39.560771
2.075E+21	4.61312E+20	202020	40670	40.374476
3.047E+21	5.30432E+20	192590	42230	43.941868
3.813E+21	3.57941E+20	168530	41340	49.106455
			Average %	43.24589

6.2.2. Calculation of Parameter a^2 Using the Direct Mass Formula

In the graphic of page 8 of paper [8], it is plotted the rotation curves associated to the disc and the bulge mass, so by a simple calculus it is got the baryonic mass of M31, $M_{BA} = 10.5 \cdot 10^{10} M_{\odot}$. In addition, in the page 11 are given the virial data associated to DM purely, see **Table 16** below.

Table 16. Virial data and baryonic mass of M31 according to Zhang *et al.* [8].

M_{200}	R_{200}	Baryonic mass
$1.14 \pm_{0.35}^{0.51} \times 10^{12} M_{\odot}$	220 ± 25 kpc	$M_{BA} = 10.5 \cdot 10^{10} M_{\odot}$

As it is shown in the virial data, **Table 16**, the radius error is about 11%, the up error of mass is 45% and the low error one is 31%.

Using such data it is got $M_{200-TOTAL} = 1.245 \cdot 10^{12} M_{\odot}$ and as in the previous epigraphs, the parameter a^2 it is calculated by the equation (4.2), $a^2 = 2.006 \cdot 10^{21} \text{ m}^{2.5}/\text{s}^2$. This value is only a 10% bigger regarding the value got by the rotation curve method $a^2 = 1.8 \cdot 10^{21} \text{ m}^{2.5}/\text{s}^2$ (see epigraph 6.2.1).

Error analysis of a^2 based on the virial data errors

As it was shown in the chapter 5, the relative error of the parameter a^2 got by the formula (4.2) is $d(a^2)/a^2 = dm/m + (1/2) \cdot dr/r$ and considering the relative error of the virial data (see **Table 16**) is obtained a relative error of the parameter a^2 shown in **Table 17**.

Table 17. Relative error of parameter a^2 .

Relative error $M_{200-TOTAL}$	Relative Error R_{200}	Relative Error of a^2
Up error 45%	11%	Up error 50%
Low error 31%		Low error 36%

6.2.3. Equivalence of a^2 Obtained by the Two Different Methods Using the Zhang's Data

In **Table 18** are summarized the results obtained in the two previous epigraphs.

Table 18. The a^2 obtained by the two different methods and its errors.

a^2 by Rotation curve	$a^2 = 1.8 \cdot 10^{21}$	Relative error 43%
a^2 by Virial data	$a^2 = 2.006 \cdot 10^{21}$	Relative error 36%

If we consider the relative difference in the parameter a^2 between the two results—approximately 10%—alongside its own relative uncertainties (around 40%), it is reasonable to conclude that the two results are equivalent.

Once again, the values of a^2 obtained through the two different methods reinforce the central thesis of this work: the NFW dark matter profile is consistent with the velocity decay law $v = a \cdot r^{-0.25}$ in the halo region of M31, mirroring the conclusion obtained in Chapter 5 for the Milky Way galaxy.

7. Galaxies beyond the Local Group

7.1. Selection of the Galaxies

The principal difficulty in obtaining adequate rotation curves for these galaxies arises from their large distances. As a consequence, the velocity measurements are affected by larger uncertainties, and the radial extent over which the rotation curves are reliably measured is more limited.

The DMbQG framework requires only a single parameter, a , to define the direct mass formula. Therefore, knowledge of a single point on the rotation curve is, in principle, sufficient to determine the value of a . However, this point must be located at a sufficiently large radius, where most of the baryonic mass is enclosed within the corresponding sphere.

In the work of Vijayakumar *et al.* [9], three different rotation curves are presented, see **Figure 1**, in which it is possible to distinguish between the contribution of the stellar disc and that associated with the neutral hydrogen (H I) gas. When the gas rotation curve exhibits a declining behavior similar to that of the stellar disc, it can be inferred that the majority of the galactic baryonic mass is enclosed within the outer radius.

Figure 1 shows three different rotation curves, each graphic have three curves, the total velocity traced by white dots, the velocity associated to the stellar disc traced by the yellow line and the velocity associated to the gas HI, traced by the green line.

It is clear that NGC 3521 is the only galaxy whose gas rotation curve associ-

ated to the gas displays a “Keplerian-like” decline at the largest radii. Consequently, it is the only rotation curve from which data can be reliably extracted to determine the parameter a within the framework of the DMbQG theory because it is assumed that the majority of the baryonic mass is enclosed within the outer radius.

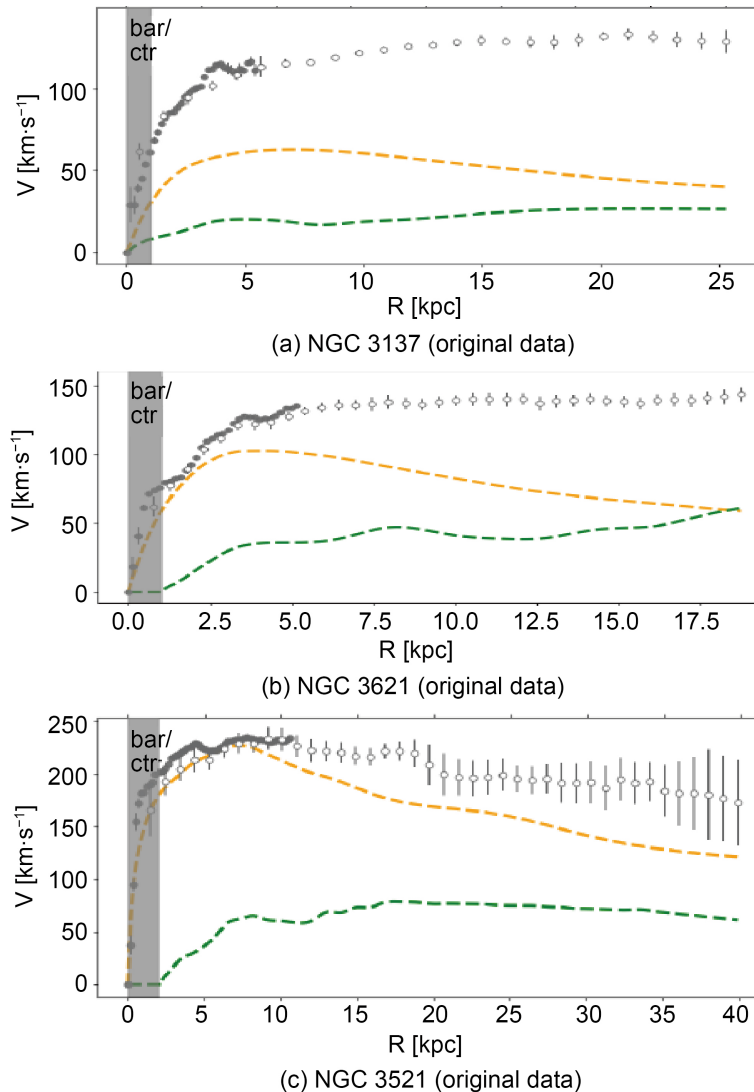


Figure 1. Three different rotation curves clipped from paper by Vijayakumar *et al.* [9].

7.2. The NGC 3521 Galaxy

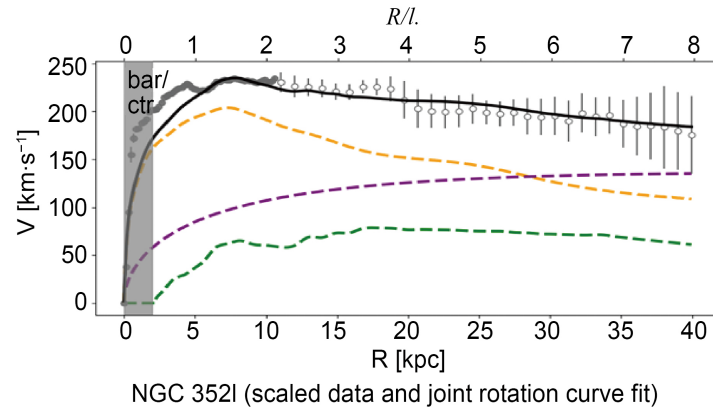
In this section, the NFW method is compared with the Direct Mass approach. It is ultimately concluded that both methods are equivalent when the range of measurement uncertainties associated with the rotation curve point at 40 kpc is taken into account.

The data, see **Table 19**, and **Figure 2** of NGC 3521 comes from Vijayakumar *et al.* [9].

Table 19. NFW parameters for the NGC 3521 galaxy.

Characteristic density	Scale of radius
$D_0 = 10^{-2.5} M_{\odot}/\text{pc}^3 = 2.14 \cdot 10^{-22} \text{ kg}/\text{m}^3$	$R_s = 23 \text{ kpc}$

Figure 2 shows the merged rotation curves and the joint stellar (in yellow)-gas (in green)-dark matter fitting results (in magenta), with the stellar component re-scaled according to the maximal disk assumption.

**Figure 2.** R.C. of NGC 3521 galaxy clipped from paper [9].

Baryonic mass calculus

In the table 1 of Vijayakumar *et al.* [9], the authors inform about the stellar mass of NGC 3521 $M_* = 10^{11} M_{\odot}$. In addition they inform that its distance is 13.2 Mpc.

As the green line in the graphic represents the rotation curve associated to the gas and at the 40 kpc its slope is similar to the keplerian rotation curve associated to the stars, the yellow line, then it is possible to estimate the total mass of the gas by the dynamical mass formula.

At 40 kpc the estimated velocity of the gas is 61.7 km/s so the $M_{\text{GAS}} = 3.5 \cdot 10^{10} M_{\odot}$ and consequently the estimated total baryonic mass for NGC 3521 is $M_{\text{BA}} = 1.35 \cdot 10^{11} M_{\odot}$.

Virial data calculus by the NFW method

By the equation $\frac{c^3}{f(c)} = \frac{4\pi G \rho_0}{100 \cdot H^2} = 349$ being $f(c) = \ln(1+c) - c/(1+c)$ it is possible to calculate the concentration parameter c .

So the equation $c^3/f(c) = 349$ that solved numerically gives the solution $c = 7.626$ and consequently $R_{200} = c \cdot R_s = 175.4 \text{ kpc}$; $V_{200} = 10 \cdot H \cdot R_{200} = 122.8 \text{ km/s}$ and $M_{200} = V_{200}^2 \cdot R_{200} / G = 6.1 \times 10^{11} M_{\odot}$. Adding the baryonic mass it is obtained the value $M_{200\text{-TOTAL}} = 7.45 \cdot 10^{11} M_{\odot}$ enclosed within the virial radius $R_{200} = 175.4 \text{ kpc}$.

Comparison Virial total mass by NFW versus Direct mass for NGC 3521

By **Figure 2**, it is estimated the velocity of rotation curve for the total mass at 40 kpc equal to 168.9 km/s and by the formula $a^2 = V^2 \cdot R^{0.5}$ it is obtained the value $a^2 = 1 \cdot 10^{21} \text{ m}^5/\text{s}^2$ in the framework of DMbQG theory.

Through the direct mass, formula (4.1) it is calculated the total mass associated to the radius $R_{200} = 175.4$ kpc obtaining the value $M_{\text{DIRECT}} (<R_{200}) = 5.54 \cdot 10^{11} M_{\odot}$

Table 20 compares the virial total mass by the NFW method and the Direct mass.

Table 20. Comparison Virial total mass by NFW versus Direct mass.

NFW $R_{200} = 175.4$ kpc	$M_{200\text{-TOTAL}} = 7.45E11 M_{\odot}$	Rel. diff. of the masses 25%
$a^2 = 1E21 \text{ m}^{5/2}/\text{s}^2$	$M_{\text{DIRECT}} (<R_{200}) = 5.54E11 M_{\odot}$	

This relative difference between the virial total masses is compatible with the thesis of this work because this galaxy is quite far away and the measures of rotation curve have high errors. The reader can check how big the error bars are in **Figure 2**, especially the ones associated to radius bigger than 35 kpc.

Therefore one more time this result backs the thesis of this work *i.e.* the NFW method is compatible with a decaying velocity into the halo region according the law $v = a \cdot v^{-0.25}$, which is the central hypothesis of DMbQG theory for the NGC 3521 galaxy.

Calculus of the $R_{200\text{-TOTAL}}$ and the $M_{200\text{-TOTAL}}$ in the framework of DMbQG

In the paper by Abarca, M. [3], the formulas are derived:

$$M_{200\text{-TOTAL}} = \frac{a^{12/5}}{G \cdot (10 \cdot H)^{2/5}} \quad \text{and} \quad R_{200\text{-TOTAL}} = \left[\frac{a^2}{100 \cdot H^2} \right]^{2/5} \quad (\text{see the formulas 3.3 and 3.4})$$

so knowing the parameter a^2 it is right to calculate such galactic parameters. See **Table 21**.

Table 21. Virial data for NGC 3521 galaxy by the parameter a^2 .

parameter	$a^2 = 1 \cdot 10^{21} \text{ m}^{5/2}/\text{s}^2$
$R_{200\text{-TOTAL}} = 168.29$ kpc	$M_{200\text{-TOTAL}} = 5.4267 \cdot 10^{11} M_{\odot}$

7.3. The NGC 3621 Galaxy

In the paper of Sorgho *et al.* [10] there are published two rotation curves where it is discriminated the rotation curves associated to the stellar disc and the gas. It has been selected NGC 3621 because its distance is only 6.6 Mpc whereas the other one is 13.6 Mpc far away. Obviously, the more near the more trustable the measures are.

The data of **Table 22** and **Figure 3** of NGC 3621 comes from Sorgho, A. *et al.* [10].

Table 22. NFW parameters for the galaxy NGC 3621 [10].

Mass-to-light ratio	Virial radius	Concentration factor	Chi-square
$\Upsilon_* = 0.5$	$R_{200} = 162.7 \pm 4.0$ kpc	$c = 5.3 \pm 0.5$	$\chi^2_{RED} = 2.4$

Baryonic mass calculus

As the green line in the graphic represents the rotation curve associated to the

gas and at the 47 kpc its slope is similar to the keplerian rotation curve associated to the stars disk, the blue line, then it is possible to estimate the total mass of the gas by the dynamical mass formula.

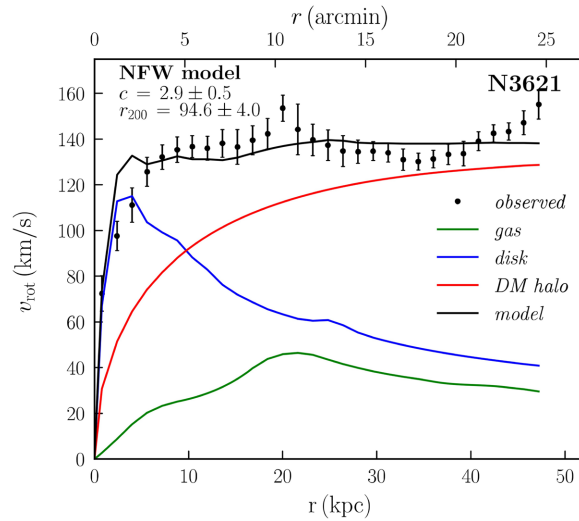


Figure 3. Rotation curve of NGC 3621 galaxy.

At 47 kpc the estimated velocity of the gas is 30.8 km/s so the $M_{\text{GAS}} = 1 \cdot 10^{10} M_{\odot}$.

At 47 kpc the estimated velocity of the stars curve is 40 km/s so $M^* = 1.75 \cdot 10^{10} M_{\odot}$ and consequently the total baryonic mass for NGC 3621 is $M_{\text{BA}} = 2.75 \cdot 10^{10} M_{\odot}$.

Virial data calculus by the NFW method

As $R_{200} = 162.7$ kpc and $V_{200} = 10 \cdot H \cdot R_{200} = 113.9$ km/s then $M_{200} = 4.9 \cdot 10^{11} M_{\odot}$. Adding the baryonic mass it is obtained the value $M_{200\text{-TOTAL}} = 5.17 \cdot 10^{11} M_{\odot}$ enclosed within the virial radius $R_{200} = 162.7$ kpc.

Comparison Virial total mass by NFW versus Direct mass for NGC 3621

As at the maximum radius, 47 kpc, the rotation curves of stars and the gas are keplerian, then may be considered that the majority of baryonic mass is enclosed within the radius 47 kpc and therefore it is possible to calculate the parameter a^2 using the point of the rotation curve at 47 kpc.

By **Figure 3** it is estimated the velocity of rotation curve at 47 kpc equal to 154 km/s and by the formula $a^2 = R^{0.5} \cdot V^2$ it is obtained the value $a^2 = 9 \cdot 10^{20} \text{ m}^{5/2}/\text{s}^2$.

Through the direct mass, formula (4.1) it is calculated the total mass associated to the radius $R_{200} = 162.7$ kpc obtaining the value $M_{\text{DIRECT}} (< R_{200}) = 4.8 \cdot 10^{11} M_{\odot}$.

Table 23 compares the virial total mass by the NFW method and the Direct mass.

Table 23. Comparison Virial total mass by NFW versus Direct mass.

NFW $R_{200} = 162.7$ kpc	$M_{200\text{-TOTAL}} = 5.17\text{E}11 M_{\odot}$	Relative diff. of the masses 7%
Parameter $a^2 = 9\text{E}20 \text{ m}^{5/2}/\text{s}^2$	$M_{\text{DIRECT}} (< R_{200}) = 4.8\text{E}11 M_{\odot}$	

Therefore one more time this result backs the thesis of this work *i.e.* the NFW method is compatible with a decaying velocity into the halo region according the law $v = a \cdot v^{-0.25}$, which is the central hypothesis of DMbQG theory for the NGC 3621 galaxy.

Relation formula between the NFW parameters and the parameter a in NGC 3621

In the epigraph (7.3) of the paper by Abarca, M. [3], it is shown that $a^2 \approx 2\pi G \rho_0 \cdot R_0^{5/2}$ is a very good relation between the parameters of NFW method and the parameter a^2 for the MW and M31 galaxies.

Here it will be shown that this relation is quite close for the galaxy NGC 3621 as well.

Through the data $R_{200} = 162.7$ kpc and $c = 5.3$ it was calculated $R_0 = 30.7$ kpc and $M_{200} = 4.9 \cdot 10^{11} M_\odot$ and using these data, through the formula of virial mass $M_{200-DM} = M_{DM}(< R_{200}) = K_{NFW} \cdot f(c)$ being $K_{NFW} = 4\pi \rho_0 R_0^3$ and $f(c) = 0.99928$ it is possible to calculate $\rho_0 = 9.13 \times 10^{-23} \text{ kg/m}^3$.

So the expression $2 \cdot \pi \cdot G \cdot \rho_0 \cdot R_0^{2.5} = 1.057 \times 10^{21} \text{ m}^{2.5} \cdot \text{s}^{-2}$ and this value is quite close to the parameter $a^2 = 9 \cdot 10^{20} \text{ m}^{5/2} / \text{s}^2$ obtained in the previous paragraph. Namely the relative difference is below 15%.

In conclusion, it can be stated that for these galaxies far from the Local Group, the virial mass calculated using the NFW method is consistent with a power-law decay, with an exponent of -0.25 , for the rotation curve associated with the total mass in the halo region of these galaxies.

8. Testing the Direct Mass by the SPARC Data File of Galaxies

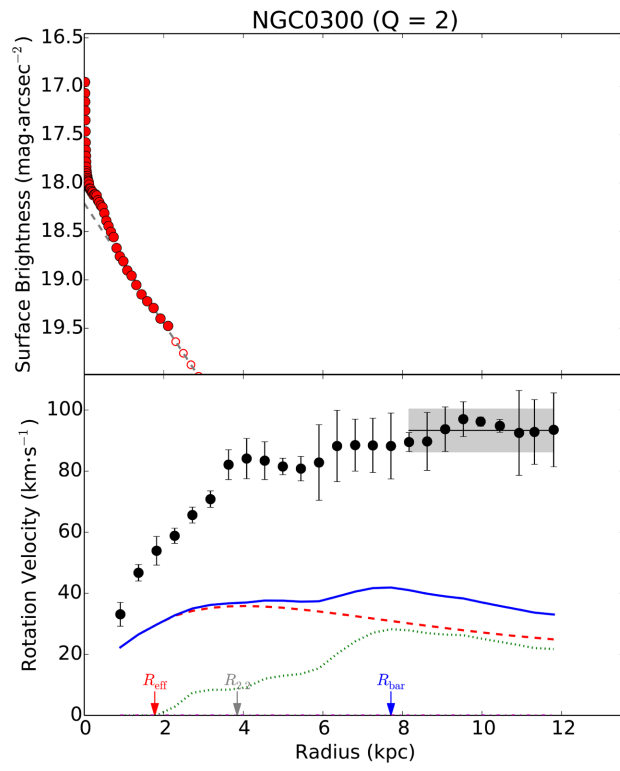
SPARC (Spitzer Photometry & Accurate Rotation Curves) is a database comprising 175 late-type galaxies, developed by the core team of Federico Lelli, Stacy McGaugh, and James Schombert [11]. The official SPARC repository can be accessed at <https://astroweb.cwru.edu/SPARC/>.

From this extensive dataset, four galaxies were selected: NGC 0300, NGC 2403, NGC 2903, and NGC 6503. These specific galaxies were chosen because they all exhibit a negligible amount of gas at the edge of their radial domain. Furthermore, these galaxies are located not far away to the Local Group, thereby minimizing observational uncertainties.

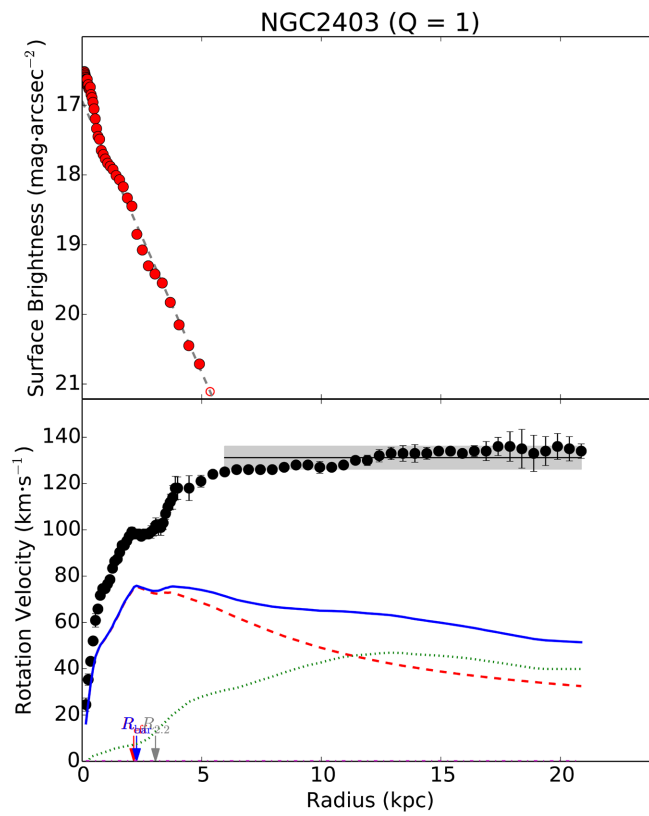
In **Figure 4** and **Figure 5**, obtained from the SPARC project, the convention for the rotation curves remains consistent: observed rotation curves are represented by black dots, while velocity contributions from gas, stars, and total baryons are indicated by green dotted, red dashed, and blue solid lines, respectively.

If the blue solid line (total baryons) exhibits a decaying profile similar to that of the stars (red dashed line), it can be concluded that the majority of the baryonic mass is contained within the considered domain. Consequently, this allows for the calculation of the parameter a using the final data point of the rotation curve.

In **Table 24** there are written down the final points of the blue lines to calculate the baryonic mass of the galaxies.



NGC 0300 Distance = 2 mpc



NGC 2403 Distance = 3.16 mpc

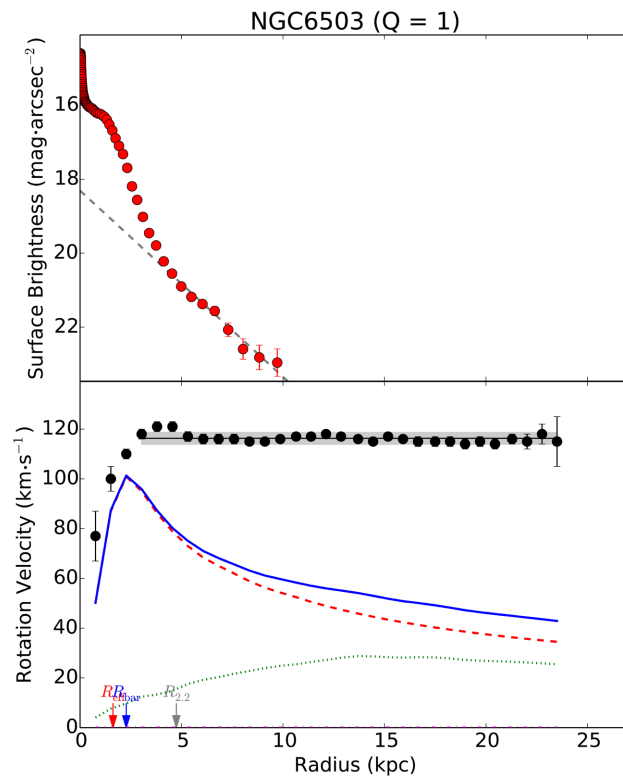
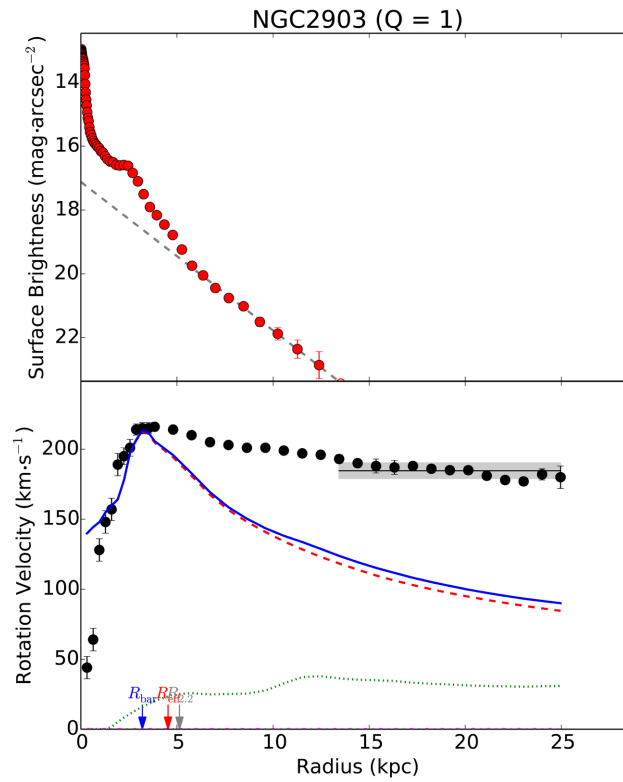


Figure 4. Rotation curves of the NGC 0300-NGC 2403-NGC 2903-NGC 6503.

Table 24. Baryonic masses of the galaxies.

Galaxies	Final Radius	Final Velocity	Baryonic mass
	kpc	Km/s	M_{\odot}
NGC 0300	11.7	33	3E9
NGC 2403	21	51	1.27E10
NGC 2903	25	89.4	4.64E10
NGC 6503	23.6	42.75	1E10

Taking the last black dot of the observational curves it is possible to calculate the parameter a^2 in the framework of DMbQG by the formula $a^2 = V^2 \cdot R^{0.5}$. See **Table 25**.

Table 26 presents the following parameters: the second column lists the halo mass obtained via the NFW method, as extracted from the “Dark Matter Halos” section of the SPARC database (see link: WP50_M200). The third column provides the R_{20} radius, calculated according to Equation (3.2). Finally, the fourth column shows the total mass enclosed within the R_{200} radius, which is determined by adding the baryonic mass (detailed in **Table 24**) to the aforementioned halo mass.

Table 25. Parameter a^2 of the galaxies.

Galaxy	Final radius	Final velocity	Parameter a^2
	kpc	Km/s	$m^{2.5}/s^2$
NGC 0300	11.7	92.8±12	1.64E20
NGC 2403	21	132.8±3	4.49E20
NGC 2903	25	178.9±8	8.89E20
NGC 6503	23.6	114.5±10	3.54E20

Table 26. Dark matter halo masses and total mass of the halos R_{200} .

	$M_{200} M_{\odot}$	R_{200} kpc	NFW $M_{200-TOTAL}$
NGC 0300	1.288E11	104.19	1.32E11 M_{\odot}
NGC2403	2.51E11	130.15	2.64E11 M_{\odot}
NGC2903	4.36E11	156.45	4.8E11 M_{\odot}
NGC6503	1.74E11	115.18	1.84E11 M_{\odot}

In **Table 27**, the third column shows the direct mass calculated at R_{200} and the last column shows the relative difference between the NFW $M_{200-TOTAL}$ and the Direct mass.

Table 27. Comparison NFW Total mass halo versus Direct mass.

	R_{200} kpc	Direct mass	NFW $M_{200-TOTAL}$	Relative difference
NGC 0300	104.19	7E10 M_{\odot}	1.32E11 M_{\odot}	47%
NGC2403	130.15	2.14E11 M_{\odot}	2.64E11 M_{\odot}	19%
NGC2903	156.45	4.65E11 M_{\odot}	4.8E11 M_{\odot}	3%
NGC6503	115.18	1.59E11 M_{\odot}	1.84E11 M_{\odot}	13.6%

Discussion

While three of the studied galaxies exhibit relative differences between the $M_{DIRECT} (<R_{200})$ and the NFW $M_{200-TOTAL}$ which are below 20%, the NGC 0300 galaxy shows an excessive discrepancy. A relative difference of 47% is too significant to consider the virial mass by the Direct Mass equivalent to the one by the NFW method ($M_{200-TOTAL}$). Consequently, an analysis of observational uncertainties was conducted, focusing specifically on NGC 0300.

Given the relation $a^2 = V^2 \cdot R^{0.5}$, and neglecting the error in radius, the relative error in a^2 can be expressed as: $d(a^2)/a^2 = 2 \cdot dv/v$.

For the galaxy NGC 0300, this yields $d(a^2)/a^2 = 0.26$ (refer to the velocity errors in **Table 25**). Similarly, the error propagation for the Direct Mass results to be $d(M_{DIRECT})/M_{DIRECT} = d(a^2)/a^2$, assuming the radial error is negligible.

Thus, for NGC 0300, $dM_{DIRECT} = 0.26 \cdot M_{DIRECT}$, resulting in an absolute error of $dM_{DIRECT} = 1.8 \cdot 10^{10} M_{\odot}$

Table 28 lists the Direct Mass values including these uncertainties, but even when considering the upper bound of the Direct Mass, the relative difference with $M_{200-TOTAL}$ (by NFW method) remains at 33%, which is still considerably high.

Table 28. Comparison Total mass halo masses versus Direct mass.

	R_{200} kpc	Direct mass	$M_{200-TOTAL}$	Rel. Difference
NGC 0300	104.19	$7 \pm 1.8E10 M_{\odot}$	1.32E11 M_{\odot}	47%
		Upper mass error $(7 + 1.8)E10 = 8.8E10$	1.32E11	33%

The ultimate solution to the apparent incompatibility of Direct mass and NFW total mass for the NGC 0300 galaxy may be understood with the case studied in the chapter 9.

9. Comparison NGC 3521 SPARC Data vs Data from Vijayakumar *et al.* [9]

In the epigraph 7.1 is studied this galaxy using the paper of Vijayakumar V. *et al.* [9]. Fortunately this galaxy was also studied in the SPARC project and both data set may be compared with useful conclusions.

Visiting the official site of SPARC, in the epigraph Figures and Videos, by the link of Mass Models for 175 SPARC LTGs, it is possible to download all the rotation curves studied by the SPARC project. Namely **Figure 5** shows the rotation curve (R.C.) of NGC 3521 whose dominion expands only up to 17.5 kpc whereas the R.C. studied by Vijayakumar expand up to 40 kpc. See in the chapter 7 **Figure 2** and how the R.C. decreases notably from 20 kpc up to 40 kpc.

In the epigraph 7.1 it is calculated the M_{200} by the NFW using the data provided by Vijayakumar *et al.* [9] and its result is $M_{200} = 6.1 \cdot 10^{11} M_{\odot}$ which may be compared with the halo mass extracted from the SPARC data base, namely in the section Dark matter halos, the link: WP50_M200 where for this galaxy the virial mass is $M_{200} = 2.6 \cdot 10^{12} M_{\odot}$ *i.e.* more than four times bigger. See in **Table 29** the both values for the virial mass.

Table 29. NGC 3521 virial masses SPARC data Vs Vijayakumar data using the framework NFW.

$M_{200} = 6.1 \cdot 10^{11} M_{\odot}$ from the Vijayakumar data. See epigraph 7.1

$M_{200} = 2.6 \cdot 10^{12} M_{\odot}$ from the SPARC data base. See the link: WP50_M200

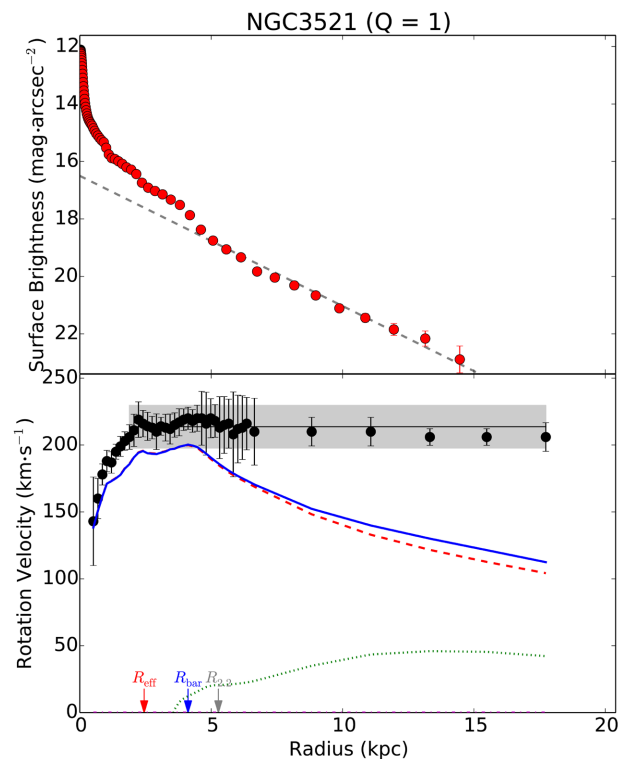


Figure 5. Rotation curve of NGC 3521 from the SPARC project.

In conclusion, using the data published by Vijayakumar, the halo mass calculated by the NFW method is four times lower (green value) than the same halo mass calculated in the SPARC project (red value) because in the former the dominion ex-

pand up to 40 kpc whereas in the later, the dominion expand only up to 17.5 kpc.

Calculus of the NGC 3521 Virial data in the framework of DMbQG theory

Surprisingly the virial data calculated by the parameter a^2 using the two rotation curves (Vijayakumar Vs SPARC) with a dominion so different are virtually equals as it will be shown in the following paragraphs.

In **Table 30**, there are written down the final point of R.C. of NGC 3521 (**Figure 5**) taken from the SPARC project and it is calculated the parameter a^2 .

Table 30. Parameter a^2 from SPARC data of NGC 3521.

Final radius 17.74 kpc	Final velocity 206 km/s
$a^2 = 9.93E20 \text{ m}^{2.5}/\text{s}^2$	

Table 31 shows the $R_{200\text{-TOTAL}}$ and $M_{200\text{-TOTAL}}$ calculated by its formulas in the framework of DMbQG theory, like it was made at the end of epigraph 7.1, see **Table 21**.

Table 31. NGC 3521 Virial radius and mass by parameter a^2 from SPARC data.

Virial radius	Virial velocity	Virial total mass
$R_{200\text{-TOTAL}} = 167.80 \text{ kpc}$	$V_{200\text{-TOTAL}} = 117.4 \text{ km/s}$	$M_{200\text{-TOTAL}} = 5.38E11 M_{\odot}$

By the other side, at the end of the epigraph 7.1 were calculated the virial data for the NGC 3521 in the framework of DMbQG theory but using the Vijayakumar data.

In **Table 32** are written down such parameters by the two different data set and the results are virtually equals.

Table 32. NGC 3521 Virial radius and mass SPARC data Vs Vijayakumar data. Using the framework of DMbQG theory.

From the SPARC data-See Table 31	From the Vijayakumar data-See Table 21
Parameter $a^2 = 9.93E20 \text{ m}^{2.5}/\text{s}^2$	Parameter $a^2 = 1.0E21 \text{ m}^{5/2}/\text{s}^2$
$R_{200\text{-TOTAL}} = 167.80 \text{ kpc}$	$R_{200\text{-TOTAL}} = 168.29 \text{ kpc}$
$M_{200\text{-TOTAL}} = 5.38E11 M_{\odot}$	$M_{200\text{-TOTAL}} = 5.4267E11 M_{\odot}$

It is important to compare the results obtained in **Table 29** with **Table 32** because the contrast is impressive. In the former table the relative difference is 400% whereas in **Table 32** the virial masses are virtually equals, see the data in green. In addition, notice how the result of M_{200} published by Vijayakumar using the NFW method is very similar, only 10% bigger, (see data from the Vijayakumar in **Table 29**) to the results of the virial total mass shown in **Table 32**.

The reason to explain all these facts is that the NFW method gives results similar to the framework of DMbQG theory when the rotation curve data is very wide.

For example for the NGC 3521 galaxy the NFW method works well when the

data radius expand up to 40 kpc but its calculus of M_{200} is four times bigger when it is calculated using a set of data radius up to 17 kpc, see in **Table 29** the data from the SPARC data base. However in the framework of DMbQG theory the parameter a^2 is virtually the same calculated at 17 kpc or calculated at 40 kpc and consequently the virial data are virtually the same as well.

These results obtained are very useful to explain the reason why for the galaxy NGC 0300, the relative difference of the virial mass obtained by the Direct mass and by the NFW method is 47%, because the radius dominion for NGC 0300 expands only up to 12 kpc whereas for the others three galaxies studied in the chapter 8 its dominion expand beyond the 20 kpc.

In other words, the wider is the radius dominion of data; the better is the matching of the virial radius and mass using the direct mass and the NFW method.

Another important conclusion is obtained from this analysis: A precise calculus of the virial radius and mass may be done using a shorter rotation curve through the parameter a and the DMbQG theory, the only condition needed is a dominion enough wide to enclose the majority of the baryonic mass.

In conclusion, also for the galaxies selected from the SPARC data set has been demonstrated that the virial mass calculated using the NFW method is consistent with a power-law decay, with an exponent of -0.25 , for the rotation curve associated with the total mass in the halo region of these galaxies.

Once again, these galaxies serve as a validation test for the DMbQG theory.

10. Concluding Remarks

In this study, the parameter a is determined through a double-calculation procedure, employing published datasets for the MW provided by two independent authors, and two distinct datasets for M31 contributed by two additional authors. Across these four independent comparisons, the empirical results strongly support the central thesis of this work.

For the Milky Way, the agreement is particularly remarkable. The relative discrepancy in parameter a amounts to only 1.8% when compared with the results of Huang *et al.* (2016) [4], and 3.8% relative to Sofue (2020) [5], despite the intrinsic uncertainty in the calculation of a^2 being on the order of 20% or greater.

Similarly, the M31 analysis exhibits very good consistency. The relative deviation in a^2 is 6% when benchmarked against the Sofue dataset and 10% with respect to the Zhang dataset. These discrepancies are at least three times smaller than the intrinsic uncertainty associated with the determination of a^2 . Further details on the error analysis are provided in Chapters 5 and 6.

As the NFW profile is a reliable method validated in thousands of galaxies, establishing the equivalence between the total mass obtained from the NFW dark matter mass formula plus the baryonic contribution and the direct mass, derived from the double-method test, is crucial for validating the DMbQG theory. This is particularly relevant because the Milky Way (MW) and Andromeda (M31) are the only galaxies for which the rotation curve can be measured across an extended

region of their halos.

Despite the difficulty of obtaining reliable and accurate rotation curves for galaxies located far beyond the Local Group, Chapter 7 presents two examples that constitute successful tests of the DMbQG theory. Specifically, these examples correspond to the galaxies NGC 3521 and NGC 3621, located at distances of 13.2 Mpc and 6.6 Mpc, respectively.

Chapter 8 compares the virial data obtained via the NFW method versus the DMbQG theory across four galaxies: NGC 0300, NGC 2403, NGC 2903, and NGC 6503. Utilizing data from the SPARC project, these comparisons represent a significant milestone for the present thesis. The results regarding the NGC 0300 galaxy are particularly noteworthy, as the relative difference in virial mass between the NFW method and the Direct Mass approach reached 47%. This substantial discrepancy is further analyzed and justified in the subsequent chapter.

Chapter 9 demonstrates that the NFW method and the DMbQG theory yield equivalent virial data only when the radial domain of the data is sufficiently broad. In this chapter, the NGC 3521 galaxy is analyzed using a dual data source: from SPARC project and from Vijayakumar *et al.*'s paper [9]. The latter work has a wider dominion than the former one (SPARC) and its virial mass is four times lower than published by the SPARC project.

When it is studied the virial mass in the framework of DMbQG theory, using the rotation curve supplied by the SPARC project, its value matches with the result published by the paper of Vijayakumar *et al.* [9].

In other words, the DMbQG theory is capable of calculating precise virial mass and radius using a shorter rotation curve, provided that the baryonic mass is negligible at the edge of the radial domain.

Once again, the DMbQG theory has successfully passed new tests, complementing the results previously reported in [1] Abarca, M. (2024), [2] Abarca, M. (2024) and [3] Abarca, M. (2025). The remaining challenge is to ensure broader dissemination of the theory within the scientific community, thereby enabling its evaluation in other galaxies and clusters.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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