Evidence for the Existence of Dark Matter from the Rotational Velocity Curve of the Spiral Galaxy NGC3198

How do the discrepancies between the theoretical and experimental rotation velocity curves for NGC3198 provide evidence for the existence of dark matter?

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INTRODUCTION

The purpose of this essay is to answer the research question:

How does the discrepancies between the theoretical and experimental rotation velocity curves for the spiral galaxy NGC3198 provide evidence for the existence of dark matter?

by analysing the discrepancies between the theoretical and experimental rotation velocity curves for the spiral galaxy NGC3198 and discussing dark matter (DM) and other possible explanations thereof. The galaxy NGC3198 was chosen, because data compiled from about 30 years of research, on the rotational velocities of orbiting bodies, with accompanying uncertainties in velocity, for a large range of radii, was available.[1;2] Hence, resulting in extensive and high-quality data, which enables the research question to be answered definitively. The concept and existence of DM was only generally considered after the conduction of numerous experiments on the rotational velocities of spiral galaxies by Rubin and Ford between 1970's and 1980's. Whose experiments provided compelling evidence for the existence of some unknown matter, as observed rotation velocity curves were in disagreement with the theoretical near-Keplerian rotation velocity curves. The curves were often flat or rising, where they should theoretically be declining.[3;4] Based on the observed centrally concentrated distribution of luminous baryonic matter, it was expected, according to Keplerian dynamics, that the radial velocities of spiral galaxies would be inversely proportional to the square root of the radius, thus decrease as radius increased.[5] Rubin and Ford's

[1] Lelli, et al., 2016 – p. 1
http://astroweb.cwru.edu/SPARC/RC_MRT.mrt
[2] Lelli, McGaugh, and Shombert 2016 – pp. 1-2
https://iopscience.iop.org/article/10.3847/0004-6256/152/6/157/pdf
[3] Rubin, Ford, and Thonnard, 1978 – p. L107
http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1978ApJ...225L.107R&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf
[4] Rubin, Ford, and Thonnard, 1980 – p. 479
http://articles.adsabs.harvard.edu/pdf/1980ApJ...238..471R
[5] Rubin, Ford, and Thonnard, 1980 – pp. 479, 485
http://articles.adsabs.harvard.edu/pdf/1980ApJ...238..471R

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most momentous paper, published 1980, concerned their data on the radial velocities of spiral galaxies spanning an extensive range of luminosities, radii and masses.[6] The paper contained irrefutable evidence for the existence of major discrepancies between the theoretically expected and experimentally obtained rotational velocity curves of spiral galaxies. None of the measured galaxies exhibited the theoretical near-Keplerian decline in rotational velocity at larger radii, as was expected after the initial increase in rotational velocity at smaller radii, caused by the large central mass-densities of the galaxies.[7] Finding instead, in direct contradiction to the theoretically expected trend, that the generally observed trend in spiral galaxies was an increase rotational velocity as the radii increased, or the continuation of high, near-constant rotational velocities of the largest spiral galaxies.[8] From their collected data, Rubin and Ford concluded that the total mass of spiral galaxies was not centralised, and that large amounts of unobserved matter must exist at larger radii in all spiral galaxies to account for their large, non-declining rotational velocities.[9] This led to the postulation that either the current theory of Newtonian gravity is inapplicable on a galactic scale,[10] or that some unobserved matter must exist to accommodate the larger observed rotational velocities of spiral galaxies. These speculations lead two separate paradigms regarding the observed mass discrepancy problem, these being MOND (Modified Newtonian Dynamics), and the more prominent DM theory.

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[6] Rubin, Ford, and Thonnard, 1980 – p. 471
http://articles.adsabs.harvard.edu/pdf/1980ApJ...238..471R
[7] Rubin, Ford, and Thonnard, 1980 – p. 482
http://articles.adsabs.harvard.edu/pdf/1980ApJ...238..471R
[8] Rubin, Ford, and Thonnard, 1980 – pp. 471, 479, 485
http://articles.adsabs.harvard.edu/pdf/1980ApJ...238..471R
[9] Rubin, Ford, and Thonnard, 1980 – p. 485
http://articles.adsabs.harvard.edu/pdf/1980ApJ...238..471R
[10] McGaugh, 2014 – pp. 1-2
https://arxiv.org/pdf/1404.7525.pdf

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DATA ANALYSIS

Indeed, the experimentally observed rotational velocity curve plotted for NGC3198 possesses the expected large near-constant rotational velocities of large spiral galaxies.[11] This can be seen in the near constant rotational velocities of orbiting bodies at large radii (from 7.06 to 44.08 kpc) of the total observed rotational velocity curve of NGC3198 experienced after the initial rapid increase in velocity at smaller radii (from 0 to 7.06 kpc), as seen in figure 1, which, as previously discussed, results from the large mass-density of the central region of NGC3198.

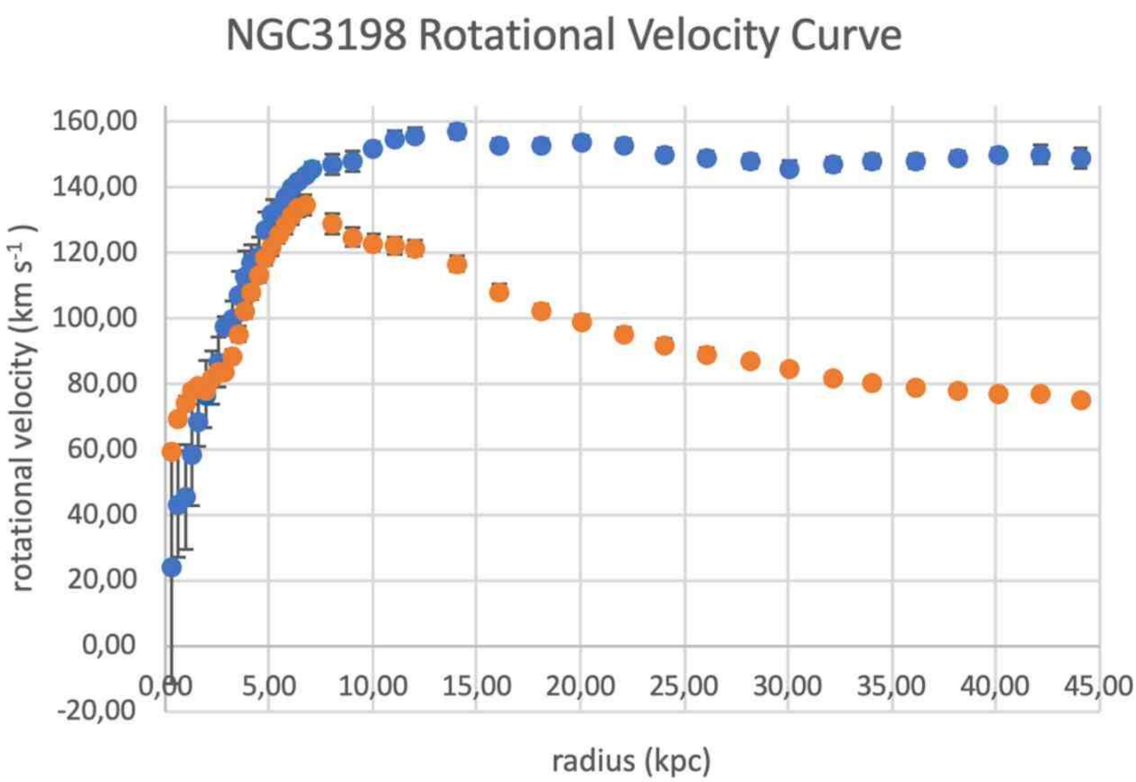

Figure 1. NGC3198 total observed rotational velocity curve (blue), and baryonic rotational velocity curve (orange), obtained from the SPARC (Spitzer Photometry & Accurate Rotation Curves) database.[12] Values are displayed in table 1.

[11] Rubin, Ford, and Thonnard, 1980 – pp. 479, 485
http://articles.adsabs.harvard.edu/pdf/1980ApJ...238..471R
[12] Lelli, et al., 2016 – p. 1
http://astroweb.cwru.edu/SPARC/RC_MRT.mrt

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r (kpc)	v_{obs} (km s^{-1})	δv_{obs} (km s^{-1})	$v_{baryoni}$ (km s^{-1})	$\delta v_{baryoni}$ (km s^{-1})
0.32	24.40	± 35.90	59.62	± 1.33
0.64	43.30	± 16.30	69.40	± 1.55
0.96	45.50	± 16.10	74.41	± 1.66
1.28	58.50	± 15.40	77.91	± 1.74
1.61	68.80	± 7.61	79.35	± 1.77
1.93	76.90	± 10.30	78.36	± 1.75
2.24	82.00	± 8.09	82.00	± 1.83
2.57	86.90	± 7.60	83.76	± 1.87
2.89	97.60	± 3.03	83.82	±1.87
3.21	100.00	± 5.31	88.37	± 1.98
3.54	107.00	± 7.51	95.36	± 2.13
3.85	113.00	± 7.32	102.25	± 2.29
4.17	117.00	± 5.21	108.25	± 2.43
4.50	119.00	± 5.67	113.58	± 2.54
4.82	127.00	± 5.39	118.83	± 2.64
5.15	132.00	± 4.34	122.06	± 2.72
5.46	134.00	± 2.36	125.65	± 2.80
5.78	137.00	± 0.89	128.82	± 2.87
6.10	140.00	± 2.84	131.68	± 2.93
6.43	142.00	± 0.88	134.06	± 2.98
6.74	144.00	± 1.23	134.60	± 2.99
7.06	146.00	± 1.57	133.40	± 2.96
8.04	147.00	± 3.00	128.87	± 2.84
9.04	148.00	± 3.00	124.84	± 2.72
10.04	152.00	± 2.00	122.99	± 2.65
11.04	155.00	± 2.00	122.37	± 2.60
12.05	156.00	± 2.00	121.53	± 2.55
14.05	157.00	± 2.00	116.50	± 2.38
16.07	153.00	± 2.00	108.27	± 2.15
18.13	153.00	± 2.00	102.46	± 1.98
20.05	154.00	± 2.00	99.17	± 1.86
22.12	153.00	± 2.00	95.47	± 1.74
24.03	150.00	± 2.00	92.02	± 1.63
26.10	149.00	± 2.00	89.31	± 1.52
28.16	148.00	± 2.00	87.23	± 1.42
30.08	146.00	± 2.00	84.78	± 1.35
32.14	147.00	± 2.00	82.16	± 1.30
34.06	148.00	± 2.00	80.44	± 1.24
36.12	148.00	± 2.00	79.29	± 1.18
38.19	149.00	± 2.00	78.24	± 1.13
40.10	150.00	± 2.00	77.37	± 1.08
42.17	150.00	± 3.00	76.99	± 1.03

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44.08	149.00	± 3.00	75.23	± 1.00

Table 1. Data used in plotting the total observed rotational velocity curve (v_{obs}), and the baryonic rotational velocity curve ($v_{baryonic}$) of NGC3198 in figure 1.

This contradicts the expected rotational velocity curve where the rotational velocities of orbiting bodies are attributed solely to the mass of luminous baryonic matter within NGC3198. As predicted, the baryonic rotational velocity curve of NGC3198 in figure 1. experiences the theoretically expected near-Keplerian decline at large radii. As seen in figure 1. the rotational velocities of the baryonic curve are greater than for the total rotational velocity curve between 0.00 and 2.24 kpc, where they should be in concordance.[13] This means that the discrepancies can be attributed to the assumptions made during the calculations of velocities from derived values for the velocities of the baryonic matter within NGC3198, acquired from data-assisted calculations, using the total rotational velocities of NGC3198.[14] This, paired with the fact that the velocities often fall within the uncertainties of the total rotational velocity curve of NGC3198, as seen in figure 1. indicates that the values are an accurate estimation of the baryonic rotational velocities of NGC3198, rather than factual values. It is noteworthy that the uncertainties of the total rotational velocities of NGC3198 at large radii (where the major discrepancies between the theoretical and experimental curve should lie) are significantly smaller than the uncertainties of rotational velocities at small radii. This can be seen in the uncertainties of the data on the observed rotational velocity curve of NGC3198 in table 1. and in the size of the error bars on the total rotational velocity curve in figure 1. Hence, the uncertainties of the total rotational velocities of NGC3198 in figure 1. displays that rotational velocities at large radii are more accurate than velocities at small

[13] Rubin, Ford, and Thonnard, 1980 – pp. 479, 482
http://articles.adsabs.harvard.edu/pdf/1980ApJ...238..471R
[14] Lelli, McGaugh, and Shombert 2016 – p. 6
https://iopscience.iop.org/article/10.3847/0004-6256/152/6/157/pdf

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radii. This indicates that the experimentally obtained velocities at large radii are accurate and not a product of imprecise equipment and measurements. Hence, one can conclude that the experimentally obtained rotational velocity curve accurately reflects the actual rotational velocities of NGC3198 at the measured radii. From this, combined with the fact that there is a large discrepancy between the theoretical and experimentally obtained rotational velocity curves for NGC3198, one can draw one of two conclusions. Either our understanding and models of the behaviour of matter at a cosmological scale possesses some elemental flaw and requires alteration to suit observations, or that the total mass of NGC3198 is not centrally concentrated, as the distribution of luminous baryonic matter would suggest, indicating that a large amount of unobserved matter must exist at large radii in order to for the elevated rotational velocities of NGC3198 at large radii.

DERIVATION OF THE DARK MATTER EQUATION

As discussed previously, the discrepancies between the theoretical and experimentally obtained rotational velocity curves for NGC3198 in figure 1. can theoretically be accounted for by the existence of a large amount of undetected DM at large radii. The unobservable nature of this matter indicates that it must emit little to no electromagnetic radiation, for it to remain undetected with current technology.[15;16] As this DM must be concentrated at large radii it indicates that it doesn't behave like baryonic matter, which tends to collapse and become centrally concentrated,[17] as seen in the baryonic rotational velocity curve of figure 2. This indicates that it is possible for the peripherally concentrated DM of NGC3198 to be comprised of some hitherto unknown form of

[15] CERN, 2019 – p. 1
https://home.cern/science/physics/dark-matter
[16] Frandsen, 2019 (Interview)
[17] Rubin, Ford, and Thonnard, 1980 – pp. 485
http://articles.adsabs.harvard.edu/pdf/1980ApJ...238..471R

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matter that doesn't emit electromagnetic radiation, and only interacts with baryonic matter gravitationally.[18] Hence it will be assumed that the hitherto unobserved matter concentrated at NGC3198's periphery is comprised of non-baryonic DM, and that it is distributed in a spherically symmetrical halo[19] that envelops the luminous baryonic matter of NGC3198.[20] Assuming that the centripetal acceleration is attributed solely to the force of gravity acting on the stellar bodies within a spiral galaxy ($F_c = F_g$), the rotational velocities of bodies orbiting within a spherically symmetrical halo of DM can be modelled with the equation:

$$v_{DM(r)} = \sqrt{\frac{GM_{DM(r)}}{r}} \qquad (1)$$

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If it is assumed that $v_{DM(r)}$ is the rotational velocity of the bodies as a function of radius, G is the universal gravitational constant measured in kpc $M_{\odot}^{-1}(\text{km s}^{-1})^2$ (value: 4.3×10^{-6} kpc $M_{\odot}^{-1}(\text{km s}^{-1})^2$),[20] $M_{DM(r)}$ is the mass of DM distributed within a given radius, and r is the orbital radius of stellar bodies. To derive the function for the rotational velocities of DM one would assume that the orbit of the stellar bodies is perfectly circular around a central point of mass. In reality, spiral galaxies do not contain point centres of mass, possessing instead dense, spherical bulges of compact matter, nor are the orbits perfectly circular in the flat galactic disk.[20] Therefore, the mass that stellar bodies orbit is not a central point, as in our solar system, but rather the total mass distribution within the radius of the given stellar body's orbital path. As DM has an assumed spherical mass distribution, its mass is therefore taken as the spherical integral of the mass-density distribution of DM as a function of radius:

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[18] CERN, 2019 – p. 1
https://home.cern/science/physics/dark-matter
[19] Kun, et al., 2017 – p. 2
https://arxiv.org/pdf/1604.02465.pdf
[20] Frandsen, 2019 (Interview)

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$$M_{DM(r)} = v_{(r)}\rho_{(r)} \quad (2)$$

$M_{DM(r)}$ is the mass of DM distributed within a given radius, $V_{(r)}$ is the volume of a sphere as a function of radius, and $\rho_{(r)}$ is the definite integral of density of the galaxy as a function from 0 to r. So, the equation becomes:

$$M_{(r)} = 4\pi \int_0^r \rho_{(r)} r^2 dr \quad (3)$$

Substitute $\rho_{(r)}$ for the pseudo-isothermal profile: $\rho_r = \frac{\rho_0}{(1+\left(\frac{r}{r_c}\right))}$, which is commonly used in modelling approximate DM halo distributions:[21]

$$M_{(r)} = 4\pi \int_0^r \frac{\rho_0}{(1+\left(\frac{r}{r_c}\right))} r^2 dr \quad (4)$$

Solve for the integral:[22]

$$M_{(r)} = 4\pi\rho_0 r_c^2 (r - r_c\, arctan(\frac{r}{r_c})) \quad (5)$$

Substitute equation (5) for $M_{(r)}$ in (1):

$$v_{DM(r)} = \sqrt{G4\pi\rho_0 r_c^2[1 - \frac{r_c}{r} arctan(\frac{r}{r_c})]} \quad (6)$$

This is the final equation modelling the rotational velocities of spherical halo distributed DM as a function of radius. G is the gravitational constant, r is the orbit radius, r_c (core scale length) and ρ_0 (central density) are variable parameters adjusted to suit observational data from the galaxy in question.[23;21] r_c is the core scale length (core radius), which is assumed to be the radius of the galactic bulge. It was assumed that r_c occurred at the point of inflection of the experimentally obtained rotational velocity curve of NGC3198 in figure 1. where the curve no longer increases convexly and the gradient of the tangent equals 0.[21] From this method, the value for r_c was found to

[21] Frandsen, 2019 (Interview)
[22] Solved with the programme Wolfram Alpha
https://www.wolframalpha.com/
[23] Kun, et al., 2017 – pp. 3, 6
https://arxiv.org/pdf/1604.02465.pdf

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be: 13.28 kpc. The lack of an uncertainty for r_c stems from an intrinsic limitation in the source of data on the total rotational velocities of NGC3198, as the radius values for which the rotational velocities were obtained lack uncertainties.[24] Hence, due to the method of its acquisition, r_c does not possess an uncertainty. The value of ρ_0 was obtained by manually adjusting it to suit the experimentally obtained rotational velocity curve of NGC3198 as well as possible, resulting in ρ_0 equalling 940000 $M_\odot$ kpc^3. It is therefore arbitrary, hence its limitation of an intrinsic lack in an uncertainty. This method of acquiring ρ_0 was deemed suitable as it was, along with r_c, a variable parameter designed to be adjusted to suit observational data.[25;26] Other methods of acquiring ρ_0 and r_c were used in scientific journal articles and papers. Most methods included the use of σ confidence ellipses along with the performance of a chi-squared test in finding the best fit values of both r_c and ρ_0.[27;28;29] Despite similarity in method, the values obtained for a given galaxy were rarely in concordance between articles, yet still managed to provide good fits to the observed rotational velocity curves.[28;29] This indicates that the values of both r_c and ρ_0 are arbitrary and can assume any value as long as they suit observational data. Hence, the values obtained in this essay for both ρ_0 and r_c can be deemed valid, although lacking uncertainties, as they suit observational data.

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[24] Lelli, et al., 2016
http://astroweb.cwru.edu/SPARC/RC_MRT.mrt
[25] Frandsen, 2019 (Interview)
[26] Kun, et al., 2017 – pp. 3, 6
https://arxiv.org/pdf/1604.02465.pdf
[27] Kun, et al., 2017 – pp. 5-6
https://arxiv.org/pdf/1604.02465.pdf
[28] Albada, et al., 1984 – p. 308
http://adsabs.harvard.edu/full/1985ApJ...295..305V
[29] Karukes, and Salucci, 2014 – p. 4
https://iopscience.iop.org/article/10.1088/1742-6596/566/1/012008/pdf

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THE DM CURVE AS A SOLUTION TO THE MASS DISCREPANCY PROBLEM

As the DM curve has been derived and the unknowns obtained in the previous paragraph, the rotational velocity curve of the spherically distributed DM will be plotted from equation (6), resulting in the red curve in figure 2. The grey curve in figure 2. was obtained by combining the rotational velocity curves of DM and baryonic matter, which was expected to result in the total rotational velocity curve of NGC3198, as it was assumed that: $v_{total} = v_{DM} + v_{baryonic}$.

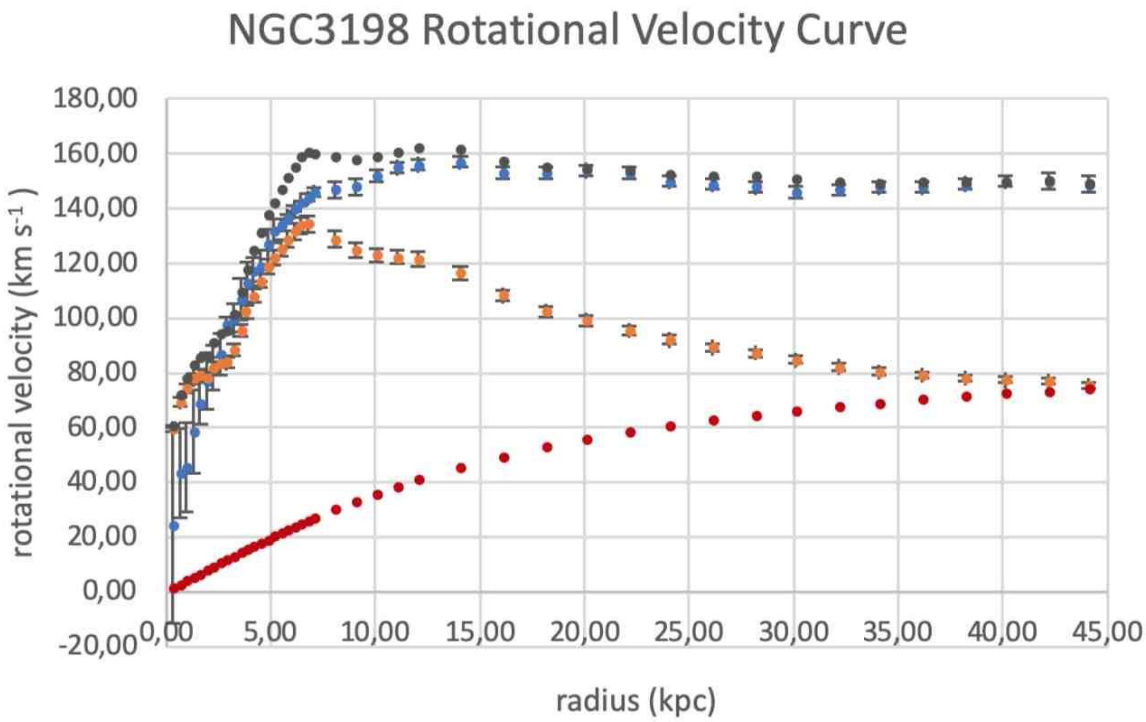

Figure 2. NGC3198 total observed rotational velocity curve (blue), baryonic rotational velocity curve (orange), derived DM rotational velocity curve (red), DM + Baryonic rotational velocity curve (grey).[30]

[30] Values in appendix A

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As expected, based on the assumption, the DM + Baryonic rotational velocity curve of NGC3198 closely resembles the experimentally obtained rotational velocity of NGC3198, as seen in figure 2. This is especially evident at radii greater than r_c (13.28 kpc), where the points of the DM + baryonic curve lie close to and within the error bars of the points of the experimentally determined rotational velocity curve of NGC3198. As can be seen in figure 2, both the derived DM and the DM + baryonic rotational velocity curves lack error bars as neither curve possesses uncertainties.[31] The decision to omit the uncertainties stems from the trend observed in academic papers and articles where the DM and the DM + baryonic curves are plotted without error bars, and don't possess uncertainties. The reason appears to be that these curves are models fitted to suit observational data,[32;33] and because they are theoretical rather than empirical in nature. The points of the DM + baryonic rotational velocity curve are significantly larger than, hence deviating from, the points of the experimentally obtained rotational velocity curve of NGC3198 between 4.82 and 12.05 kpc, in figure 2. . Regardless of the discrepancies between the two curves, the DM + Baryonic rotational velocity curve provides a good fit overall to the observed rotational velocity curve of NGC3198, indicating that the values of the DM + Baryonic curve are accurate. Hence, if one assumes that the baryonic rotational velocity curve is an accurate estimation, one must conclude that the derived model of the rotational velocities of DM can be considered a valid as a solution to the mass discrepancy problem of NGC3198, and thereby provides evidence for the existence of DM. Not only does the DM model provide evidence for the existence of DM through the good fit to the experimentally obtained data, it also indicates that the DM must be non-baryonic. This stems from the increase in velocities with radius for the rotational velocity curve of DM, as seen in figure 2.

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[31] Evidence in appendix A
[32] Kun, et al., 2017 – pp. 10-12
https://arxiv.org/pdf/1604.02465.pdf
[33] Albada, et al., 1984 – p. 310
http://adsabs.harvard.edu/full/1985ApJ...295..305V

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which can only occur if the DM follows the expected peripherally concentrated distribution, thereby evidencing that the DM is non-baryonic. Although the DM model provides evidence for the existence of non-baryonic DM, it required a multitude of assumptions in its derivation, that do not compute with reality. Hence, the model can be considered an accurate approximation of the theoretical distribution and velocities of DM, rather than a model on its actual distribution and velocity. This is especially evident from the use of the pseudo-isothermal density profile in the model's derivation, which is only valid as an approximate density distribution of DM of spiral galaxies.[34] Over time, better density profiles that more accurately model the density distribution of DM in galaxies have been obtained through research and N-body computer simulations.[35] In fact, it is common for the DM theory, regardless of profile used, to require adjustments to suit observed galactic rotational velocity curves.[36] If one goes beyond the scope of this essay, it emerges that the DM paradigm works better on an intergalactic than on a galactic scale, as it requires adjustments, and often artificial fine tuning, to suit observational data at the galactic scale.[36] Despite the apparent limitations of the DM paradigm on smaller scales, the DM paradigm as a theory has hitherto fared better than any proposed alternative in explaining the behaviour of the universe on a cosmological scale, and is, until further research provides evidence for its falsification, the predominant and preferred theory overall.[36] Remaining within the scope of this essay, the essay's data, combined with the general consensus, indicates that non-collapsing, non-baryonic DM is required in order to explain the vast discrepancies between the theoretical and experimentally obtained rotational velocity curve of NGC3198.

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[34] Frandsen, 2019 (Interview)
[35] Kun, et al., 2017 – p. 2
https://arxiv.org/pdf/1604.02465.pdf
[36] Farmaey, and McGaugh, 2012 -pp. 128
https://arxiv.org/pdf/1112.3960.pdf

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MACHO'S AS A SOLUTION TO THE MASS DISCREPANCY PROBLEM

Despite the strong indication that the elevated rotational velocities of stellar bodies orbiting at large radii of NGC3198 result from a large spherical halo of non-collapsing, non-baryonic DM (due to the amount of 'extra' mass required, along with its supposed distribution at the periphery of the galaxy, for the velocities of orbiting stellar bodies to be near-constant as their orbital radius increases), it is possible that this peripherally distributed, extra mass of NGC3198 can be constituted of regular baryonic matter rather than non-baryonic DM. More specifically, some scientists have suggested that the extra mass stems from stellar bodies comprised of regular baryonic matter, that emit little to no electromagnetic radiation, orbiting in the galactic halo, known as MACHO's (Massive Astrophysical Compact Halo Objects).[37] Due to their lack of radiation, MACHO's would be extremely difficult to detect, and their existence would only be observable through their gravitational interaction with other stellar objects, through gravitational microlensing.[38;39] MACHO's would be comprised of substellar objects and faint stars such as: brown-, and white dwarfs, along with neutron stars, all of which are low luminosity stellar bodies, whose existence is not easily detected.[40] MACHO's as a candidate for the solution to the mass discrepancy problem of spiral galaxies was popular for many years, but has, as of recent years, become highly implausible. Recent data studies have concluded that MACHO's do not comprise a large enough percentage of the total galactic mass in our galaxy, the Milky Way.[41] If MACHO's were the main constituent of the 'missing' mass in spiral galaxies, it would indicate that they should

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[37] Freese, Fields, and Graff, 1999 – pp. 1-2
https://arxiv.org/pdf/astro-ph/9904401.pdf
[38] Freese, Fields, and Graff, 1999 – p. 2
https://arxiv.org/pdf/astro-ph/9904401.pdf
[39] Gates et al. 1997 – pp. 1-2
http://cds.cern.ch/record/338204/files/9711110.pdf
[40] Freese, Fields, and Graff, 1999 – p. 1
https://arxiv.org/pdf/astro-ph/9904401.pdf
[41] Freese, Fields, and Graff, 1999 – p. 3
https://arxiv.org/pdf/astro-ph/9904401.pdf

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be present in similar ratios for all spiral galaxies. The data analysis performed by Gates, et al., indicates that MACHO's constitute only about 10% of the total mass of the Milky Way, [42] assuming that the Milky Way is a typical spiral galaxy, and that MACHO's have a similar percentage distribution amongst all spiral, their data indicates that MACHO's do not provide sufficient mass to account for the 'missing' mass in spiral galaxies. Therefore, one can conclude that MACHO's do not provide enough mass to be considered viable solutions to the mass discrepancy problem of NGC3198. Although they might constitute a percentage of the 'missing' mass, the presence of non-baryonic DM is still required in order to account for the elevated rotational velocities observed for NGC3198 relative to its theoretical rotational velocities.[43]

MOND AS A SOLUTION TO THE MASS DISCREPANCY PROBLEM

Thus far, it has been discussed whether the discrepancies between the theoretical and experimentally obtained rotational velocity curves for NGC3198, are attributed to the existence of either more baryonic matter than is currently detectable, or some hitherto unknown DM, that only interacts with baryonic matter gravitationally.[44] Hitherto, the only parameter that has been adjusted to suit observational data is $M_{(r)}$ (mass as a function of radius), as both the arguments for the existence of non-baryonic DM, and for undetected baryonic matter have attributed the discrepancies between the theoretical and experimentally obtained rotational velocities of NGC3198 to some unaccounted mass. $M_{(r)}$ is generally the only parameter considered adjustable, as it is assumed that gravity acts in correspondence to the present laws on a cosmological scale as the Newtonian law of

[42] Gates et al. 1997 – p. 1
http://cds.cern.ch/record/338204/files/9711110.pdf
[43] Freese, Fields, and Graff, 1999 – p. 1
https://arxiv.org/pdf/astro-ph/9904401.pdf
[44] CERN, 2019 – p.1
https://home.cern/science/physics/dark-matter

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gravity and Einstein's theory of general relativity have successful on countless occasions.[45] If one assumes that the current laws of gravitation are inapplicable on a cosmological scale, the mass discrepancy problem can be considered in terms of the force of gravity experienced by the orbiting stellar bodies. If one considers the problem purely empirically, the problem with the discrepancies between the theoretical and experimentally obtained rotational velocities of NGC3198 in figure 1. lies in the rotational velocities of the orbiting bodies. If one assumes that NGC3198 is governed by the current laws of gravitation, and that the only matter present in NGC3198 is baryonic, one finds that the rotational velocities are greater than can be accounted for by the baryonic matter present in NGC3198, and the orbiting bodies cannot remain gravitationally bound to NGC3198. Without alteration to the forces acting on the bodies or the mass of NGC3198, the orbiting bodies will be ejected into interstellar space, and NGC3198 will be flung apart by its own rotation.[46] Hence, one must conclude that the forces acting on the bodies must be greater than is possible for current theories of gravitation. This led to the theory that gravity acts differently on a cosmological scale and that the current theories of gravitation require modification in order to account for the discrepancies between the theoretical and experimentally determined rotational velocity curves of spiral galaxies.[47;48] The most prominent of these theories is MOND (Modified Newtonian Dynamics), which offers an alternative solution to the mass discrepancy problem that directly contradicts the solution from the currently favoured DM paradigm.[48] As its DM counterpart, the MOND paradigm provides good fits to the mass discrepancy problem that correspond closely to the observed rotational velocity curves of individual spiral galaxies. The MOND paradigm works

[45] McGaugh, 2014 – pp. 1, 2
https://arxiv.org/pdf/1404.7525.pdf
[46] McGaugh, 2014 – p. 5
https://arxiv.org/pdf/1404.7525.pdf
[47] Farmaey, and McGaugh, 2012 – p. 35
https://arxiv.org/pdf/1112.3960.pdf
[48] McGaugh, 2014 – pp. 1-2
https://arxiv.org/pdf/1404.7525.pdf

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incredibly well on the galactic scale but begins to break apart and require peculiar adjustments to match observed data once the scale is increased beyond the galactic.[49] Whereas, as previously discussed, the opposite is true for the DM paradigm, which requires adjustments to match observed data as the scale reduces to the galactic. Thus indicating that, although the DM paradigm fares better overall, until either is falsified, both paradigms should be considered possible candidates for the solution to the mass discrepancy problem, [49] that was first brought to light with the discovery of the discrepancies between the theoretical and experimentally obtained rotational velocity curves of spiral galaxies.

CONCLUSION

In conclusion, to answer the research question: **How do the discrepancies between the theoretical and experimental rotation velocity curves of the spiral galaxy NGC3198 provide evidence for the existence of dark matter?** This essays research provides strong evidence for the existence of non-collapsing, non-baryonic DM, as DM provides a valid explanation for the discrepancies between the theoretical and experimentally obtained rotational velocity curves of the spiral galaxy NGC3198. Firstly, the degree of the discrepancies between the rotational velocities of the theoretical and experimentally obtained rotational velocity curves of NGC3198, in figure 1, combined with the low uncertainties of the experimentally obtained velocities at large radii, indicates that some form of DM must exist to account for the elevated rotational velocities of NGC3198 at large radii. Secondly, the curve of the derived DM rotational velocity curve model, when combined with the baryonic rotational velocity curve provides a valid solution to NGC3198's mass discrepancy problem, as seen in figure 2., thereby providing further evidence for the existence

[49] Farmaey, and McGaugh, 2012 – p. 128
https://arxiv.org/pdf/1112.3960.pdf

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of DM. The DM model also evidences that the matter is non-baryonic, as the DM rotational velocity curve increases with radius, which is only possible if the DM, unlike luminous baryonic matter, is peripherally concentrated. In the past, MACHO's were suggested as a purely baryonic solution to the mass discrepancy problem of NGC3198, but it was found that they don't provide sufficient mass to solve the mass discrepancy problem. This indicates that non-baryonic DM is still required, thereby further evidencing the existence of non-baryonic DM. Although this essay's data indicates that the existence of DM is highly probable, there are other ways of explaining the discrepancies between the theoretical and experimentally obtained rotational velocity curves of NGC3198. MOND is an alternative theory that eliminates the necessity of DM to solve the mass discrepancy problem, solving it instead by modifying current Newtonian Dynamics. Despite their respective weaknesses, both MOND and DM remain viable candidates to the solution of the mass discrepancy problem of NGC3198, until either theory is falsified. Further research is required in both paradigms in order to find a theory capable of describing the behaviour of the universe at all scales. The dismissal of either paradigm could prove erroneous, as it could prevent the discovery of the final, all-encompassing theory.

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APPENDIX A : Data on the Rotational Velocity Curves Plotted in Figure 2.

r (kpc)	v_{obs} (km s^{-1})	δv_{obs} (km s^{-1})	$v_{baryonic}$ (km s^{-1})	$\delta v_{baryonic}$ (km s^{-1})	v_{DM} (km s^{-1})	$v_{DM+baryonic}$ (km s^{-1})
0.32	24.40	± 35.90	59.62	± 1.33	1.32	60.93
0.64	43.30	± 16.30	69.40	± 1.55	2.63	72.03
0.96	45.50	± 16.10	74.41	± 1.66	3.94	78.35
1.28	58.50	± 15.40	77.91	± 1.74	5.25	83.17
1.61	68.80	± 7.61	79.35	± 1.77	6.60	85.94
1.93	76.90	± 10.30	78.36	± 1.75	7.89	86.25
2.24	82.00	± 8.09	82.00	± 1.83	9.14	91.14
2.57	86.90	± 7.60	83.76	± 1.87	10.46	94.22
2.89	97.60	± 3.03	83.82	±1.87	11.73	95.54
3.21	100.00	± 5.31	88.37	± 1.98	12.98	101.36
3.54	107.00	± 7.51	95.36	± 2.13	14.27	109.63
3.85	113.00	± 7.32	102.25	± 2.29	15.46	117.71
4.17	117.00	± 5.21	108.25	± 2.43	16.68	124.93
4.50	119.00	± 5.67	113.58	± 2.54	17.92	132.49
4.82	127.00	± 5.39	118.83	± 2.64	19.10	137.94
5.15	132.00	± 4.34	122.06	± 2.72	20.31	142.37
5.46	134.00	± 2.36	125.65	± 2.80	21.42	147.07
5.78	137.00	± 0.89	128.82	± 2.87	22.56	151.38
6.10	140.00	± 2.84	131.68	± 2.93	23.68	155.36
6.43	142.00	± 0.88	134.06	± 2.98	24.81	158.87
6.74	144.00	± 1.23	134.60	± 2.99	25.85	160.45
7.06	146.00	± 1.57	133.40	± 2.96	26.92	160.32
8.04	147.00	± 3.00	128.87	± 2.84	30.05	158.92
9.04	148.00	± 3.00	124.84	± 2.72	33.06	157.89
10.04	152.00	± 2.00	122.99	± 2.65	35.88	158.87
11.04	155.00	± 2.00	122.37	± 2.60	38.53	160.90
12.05	156.00	± 2.00	121.53	± 2.55	41.02	162.56
14.05	157.00	± 2.00	116.50	± 2.38	45.49	161.99
16.07	153.00	± 2.00	108.27	± 2.15	49.41	157.68
18.13	153.00	± 2.00	102.46	± 1.98	52.90	155.36
20.05	154.00	± 2.00	99.17	± 1.86	55.75	154.92
22.12	153.00	± 2.00	95.47	± 1.74	58.45	153.92
24.03	150.00	± 2.00	92.02	± 1.63	60.66	152.68
26.10	149.00	± 2.00	89.31	± 1.52	62.78	152.10
28.16	148.00	± 2.00	87.23	± 1.42	64.67	151.90
30.08	146.00	± 2.00	84.78	± 1.35	66.24	151.02
32.14	147.00	± 2.00	82.16	± 1.30	67.76	149.92
34.06	148.00	± 2.00	80.44	± 1.24	69.05	149.49
36.12	148.00	± 2.00	79.29	± 1.18	70.30	149.59
38.19	149.00	± 2.00	78.24	± 1.13	71.45	149.69

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40.10	150.00	± 2.00	77.37	± 1.08	72.41	149.78
42.17	150.00	± 3.00	76.99	± 1.03	73.38	150.37
44.08	149.00	± 3.00	75.23	± 1.00	74.20	149.43

Table 2. Data used in plotting the the total observed rotational velocity curve (v_{obs}), the baryonic rotational velocity curve ($v_{baryonic}$), the derived DM rotational velocity curve (v_{DM}), and the DM + Baryonic rotational velocity curve ($v_{DM+baryonic}$) of NGC3198 in figure 2.

Sample calculation of a value for the rotational velocity curve of DM in figure 2.:

$$v_{DM(r)} = \sqrt{G4\pi\rho_0 r_c^2[1 - \frac{r_c}{r} arctan(\frac{r}{r_c})]}$$

$r = 0.32\ kpc$

$G = 4.3 \times 10^{-6}\ \mathrm{kpc\ M_\odot^{-1} (km\ s^{-1})^2}$

$\rho_0 = 940000\ \mathrm{M_\odot\ kpc^3}$.

$r_c = 13.28\ kpc$

$$v_{DM(r)} = \sqrt{4.3 \times 10^{-6} \times 4\pi \times 940000 \times 13.28^2[1 - \frac{13.28}{0.32} arctan(\frac{0.32}{13.28})]}$$

$\boldsymbol{v_{DM(r)} = 1.32\ km\ s^{-1}}$

Sample calculation of a value for the DM + Baryonic rotational velocity curve in figure 2.:

$V_{total} = V_{DM} + V_{baryonic}$.

$v_{DM(r)} = 1.32\ km\ s^{-1}$

$v_{baryonic(r)} = 59.62\ km\ s^{-1}$

$\boldsymbol{V_{total} = 1.32 + 59.62 = 60.93\ km\ s^{-1}}$