Visualizing Dark Matter Through Galaxy Rotation Curves: A Computational Exploration Using Python

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Galaxy rotation curves remain one of the clearest and most elegant demonstrations of the existence of dark matter. In this work, I construct an interactive Python simulation that models the rotation curve of a disk galaxy using three standard mass components: a Hernquist bulge, an exponential stellar disk, and a pseudo-isothermal dark matter halo. By adjusting structural parameters in real time, the tool makes it visually obvious how the luminous components fail to reproduce the observed flat rotation curve, and how the inclusion of a diffuse halo naturally resolves this discrepancy. This project serves both as an educational visualization and a compact numerical experiment linking astrophysical theory to observable galactic dynamics.

1 Introduction

One of the most surprising results in 20th-century astronomy came from a very simple measurement: how fast stars orbit the centers of spiral galaxies. According to Newtonian gravity, material farther from the galactic center should move more slowly, much like planets in the Solar System. Instead, observations show that rotation curves tend to remain *flat* well beyond the visible stellar disk (Rubin and Ford, 1970).

This mismatch—a dramatic excess of orbital velocity at large radii—is among the strongest pieces of evidence for dark matter. Despite being invisible, dark matter shapes nearly every galactic-scale gravitational phenomenon we can measure (Binney and Tremaine, 2008).

The goal of this project is straightforward: build a transparent computational model that lets one *see* how different galactic components contribute to the total circular velocity curve. Rather than presenting the result as a static figure, I built an interactive tool using Python, NumPy, Matplotlib, and `ipywidgets` that updates in real time as parameters are varied. This small interactivity shift makes the underlying physics feel much more tangible than a static diagram.

2 Methods

The numerical model follows a standard decomposition of galaxy mass into three components:

1. A spherical Hernquist bulge.
2. A thin exponential stellar disk (approximated as spherical for enclosed-mass calculations).
3. A pseudo-isothermal dark matter halo.

The total circular velocity at radius r is given by

$$v_c(r) = \sqrt{\frac{GM(<r)}{r}}, \tag{1}$$

where $M(<r)$ is the total mass enclosed within r and G is the gravitational constant.

The simulation samples radii from 0.1 to $30\,\mathrm{kpc}$ and evaluates the enclosed mass of each component using analytic cumulative mass expressions. A set of interactive sliders (implemented via `ipywidgets`) controls:

- Bulge mass M_b and scale radius a_b,
- Disk mass M_d and scale length R_d,
- Halo central density ρ_0 and core radius R_c.

All code was written in Python using:

- NumPy for vectorized computation,
- Matplotlib for plotting,
- `ipywidgets` for interactive sliders in a Jupyter environment.

The full implementation is listed in Appendix **??**.

3 Mass models

3.1 Bulge: Hernquist profile

The bulge is represented by a Hernquist profile:

$$M_{\rm bulge}(<r) = M_b \frac{r^2}{(r+a_b)^2}, \tag{2}$$

which reproduces a de Vaucouleurs-like central concentration while keeping the enclosed mass analytic and fast to evaluate.

3.2 Disk: exponential profile

The stellar disk follows the usual exponential form, with the cumulative mass (under a spherical approximation) given by

$$M_{\rm disk}(<r) = M_d \left[1 - e^{-r/R_d}\left(1+\frac{r}{R_d}\right)\right]. \tag{3}$$

This is not an exact treatment of a thin disk, but it captures the qualitative mass distribution very well and is widely used for rotation-curve demonstrations.

3.3 Dark matter halo: pseudo-isothermal

The dark matter halo is modeled as

$$\rho(r) = \frac{\rho_0}{1+(r/R_c)^2}, \tag{4}$$

which yields the enclosed mass

$$M_{\rm halo}(<r) = 4\pi\rho_0 R_c^3 \left(\frac{r}{R_c} - \arctan\left(\frac{r}{R_c}\right)\right). \tag{5}$$

This profile produces naturally flat rotation curves at large radii and is especially convenient for teaching and quick numerical experiments.

4 Results

Figure 1 shows a representative rotation curve generated by the simulation using typical Milky Way–like parameters. The bulge dominates the inner kiloparsec, the disk shapes the intermediate radii, and the dark matter halo controls the outer flat portion of the curve.

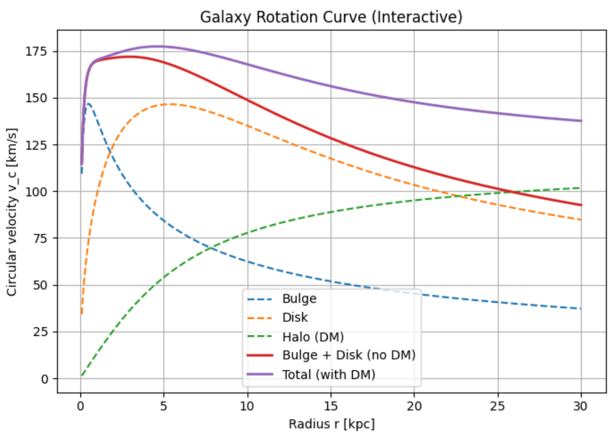

Figure 1: *Example rotation curve produced by the simulation. The bulge dominates the innermost region, the disk peaks at a few kiloparsecs, and the dark halo maintains a roughly flat total curve at large radii.*

The qualitative behavior is consistent with classical observations:

- The bulge contribution rises steeply in the central region and then fades.
- The disk peaks at a few kiloparsecs and then declines.
- The dark matter halo becomes increasingly dominant with radius, maintaining a roughly flat total curve.

The key point is immediately visible: the sum of bulge and disk alone cannot keep the rotation speed high at large radii. Once the halo is effectively "switched off" in the interactive tool, the outer rotation curve collapses; when the halo parameters are restored, the curve flattens again. It is a very direct way to internalize what is often presented as an abstract dark matter argument.

At around $r \approx 8\,\mathrm{kpc}$ (a rough Solar radius), the model typically shows a noticeable gap between the baryonic contribution and the total velocity. Dark matter fills this gap and brings the model closer to Milky Way rotation estimates of order $\sim 220\,\mathrm{km\,s^{-1}}$.

5 Discussion

The primary value of this project is pedagogical. The physics of rotation curves is well established, but for many students the idea that galaxies demand large amounts of unseen mass remains strangely detached from intuition. A small interactive simulation changes that: instead of treating dark matter as something they simply have to accept, users can see in real time how removing the halo breaks the fit.

The code is intentionally kept simple and modular, making it straightforward to extend. Possible next steps include:

- Replacing the pseudo-isothermal halo with an NFW profile to connect more directly to cosmological simulations.
- Adding a separate gas component with its own scale length.
- Dropping the spherical approximation for the disk and using more realistic disk potentials.
- Incorporating observational data points from specific galaxies for direct comparison.

Because everything is analytic and vectorized, the tool remains responsive even with fine radial sampling and frequent parameter updates. That responsiveness is exactly what makes experimentation feel natural.

6 Conclusion

Galaxy rotation curves are one of astronomy's cleanest arguments for the existence of dark matter. By building a compact interactive simulation in Python, we can make that argument concrete and visual: it becomes obvious how luminous matter alone fails, and how an extended dark halo neatly fixes the problem.

This project shows how a handful of equations and a few dozen lines of code can turn a textbook plot into something you can poke, stretch, and break until the underlying physics finally clicks. Dark matter may still be mysterious at the particle level, but its gravitational fingerprint on galactic rotation is hard to miss once you can literally watch it appear and disappear on your screen.

References

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