Understanding Dark Matter using Galactic Rotation Curves

Bachelor Thesis Project

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Historical Background: Dark Matter and Galaxies

- 1932, J. H. Oort.
  - Analysed the vertical motion of all known stars near the Galactic plane.
  - Potential by the known stars not sufficient to keep the stars bound to Galactic disk.
- 1933 : Fritz Zwicky
  - Coma cluster contained far more mass than the luminous matter visible to account for velocity dispersion.
- 1939 : H. W. Babcock
  - The total mass-to-light ratio increases in the outer regions of M31.
- Evidences include gravitational lensing of distant galaxies and Galactic Rotation curves to name a few.

Galactic Rotation Curves

- The rotation curve is a plot of the orbital rotation speed of visible stars or gas versus their radial distance.

- Condition for stability:

$$Centrifugal\ acceleration = gravitational\ pull.$$

$$v = \sqrt{\frac{GM(r)}{r}}$$

Galactic Rotation Curves

- At regions near the center of the Galaxy.
- $Velocity(v) \;\; \alpha \;\; \sqrt{r}$
- As we move outwards, velocity is expected to decrease such that:

$$Velocity(v) \;\; \alpha \;\; \frac{1}{\sqrt{r}}$$

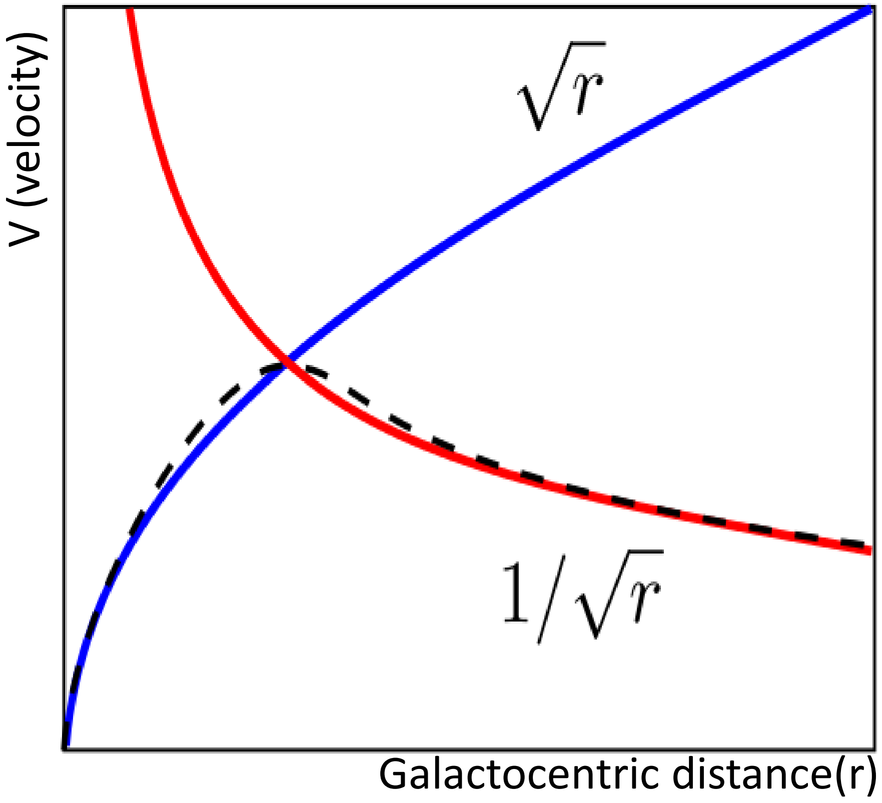

Figure 1: Expected galactic rotation curve

Galactic Rotation Curves

- Flat rotation curve observed, differing from expected rotation curves.
- This implies mass is increasing linearly with radius.
- Possible Solution: Large extending halos of dark matter.

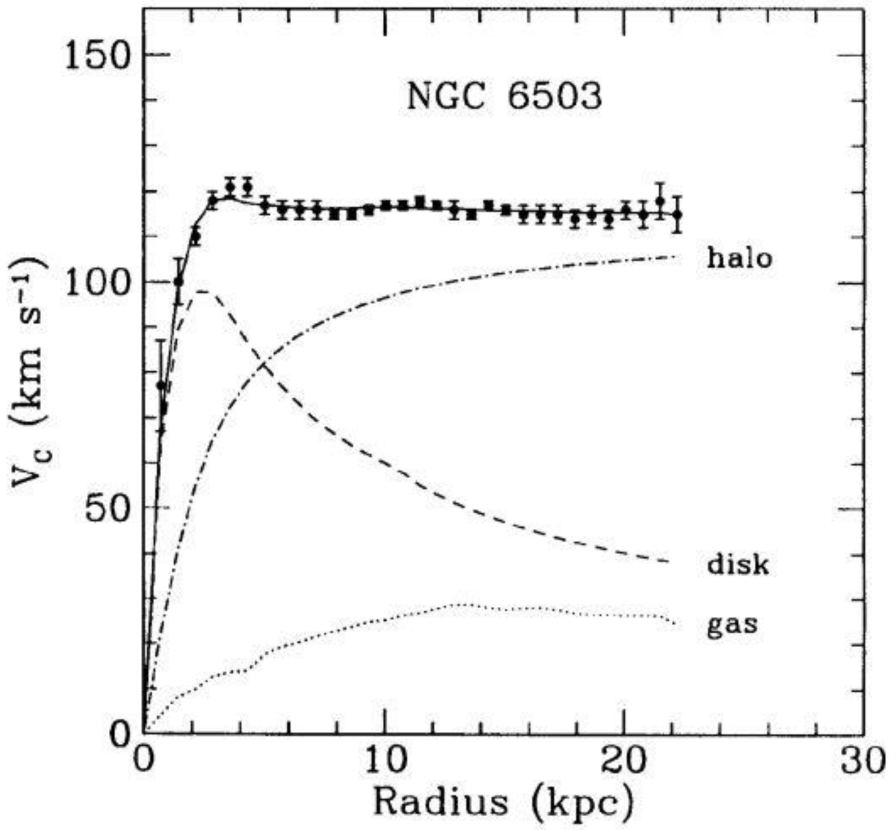

Figure 2: Measured rotation curve of NGC6503 with best fit and contributions from halo, disk and gas (Begeman et al, 1991)

Self-consistent Isothermal Model of Dark Matter Halo

- Weakly Interacting Massive Particles(WIMPs) used in our analysis.
  - Mass $\approx$ few GeV to a few TeV.
  - Weak interactions: Difficult to detect.

- DM halo: single component isothermal, Maxwellian velocity distribution

$$f(\boldsymbol{x}, \mathbf{v}) d^3\mathbf{v} = 4\pi\rho(\boldsymbol{x}) \left[\frac{3}{2\pi < v^2 >}\right]^{\frac{3}{2}} \exp\left[-\frac{3v^2}{2 < v^2 >}\right] dv$$

Here, $v = |\mathbf{v}|$,

$\rho(\boldsymbol{x})$ = density distribution of DM,

$< v^2 >^{\frac{1}{2}}$ = velocity dispersion.

Self-consistent Isothermal Model of Dark Matter Halo

- Standard halo Model
  - Isothermal non-truncating sphere model of the DM halo.
  - Value of the DM velocity dispersion:

$$< v^2 >^{\frac{1}{2}} = \sqrt{\left(\frac{3}{2}\right)}\, v_{c,\infty}.$$

  - Approximating $v_{c,\infty} \approx v_{c,\odot} = 220kms^{-1}$, we can calculate:

$$< v^2 >^{\frac{1}{2}} \approx 270 \text{ kms}^{-1}.$$

  - Local value of the DM density:

$$\rho_{DM,\odot} = 0.3 \frac{GeV}{cm}$$

Density Distributions.

- **Dark Matter Halo**

  - DM Density at any point x is given by: $\rho_{IS}(x) = \rho_0 \exp\left(-\frac{\phi(x)}{\sigma^2}\right)$
  - $\phi(x)$ = gravitational potential.
  - σ^2 is a measure of velocity dispersion given by $< v^2 > = 3\sigma^2$
  - ρ_0 **=** $\rho_{DM,\odot}$

- **Visible matter**

  - Density distribution (ρ_{vis}) = spheroidal bulge (ρ_s) + axisymmetric disk (ρ_d)

$$\rho_s(r) = \rho_s(0)\left(1 + \frac{\mathrm{r}^2}{\mathrm{a}^2}\right)^{-\frac{3}{2}} \qquad \rho_d(r) = \frac{\sum}{2h} e^{-\frac{R - R_0}{R_d}} e^{-\frac{|z|}{h}}$$

$$R^2 + z^2 = r^2$$

  - Total Density of visible matter at any point is given by: $\phi_{vis}(x) = \phi_d(x) + \phi_s(x)$

Numerical Solution to generate Rotation Curves

- *Poisson Equations* for both density distributions as follows:

$$\nabla^2 \phi_{DM}(x) = 4\pi G \rho_{DM}(x)$$
$$\nabla^2 \phi_{vis}(x) = 4\pi G \rho_{vis}(x)$$

$\phi_{DM}(x)$ = DM component gravitational potential,

$\phi_{vis}(x)$ = the gravitational potential of visible matter.

- **4th order Runge-kutta method** used to iteratively calculate the values of $\phi_{DM}(x)$.
- $\phi_{vis}(x)$analytically calculated using the Poisson equation.

$V_c(R)$can be calculated as:

$$\boldsymbol{V_c(R) = R\frac{\delta}{\delta r}[\phi_{vis}(R, z = 0) + \phi_{DM}(R, z = 0)]}$$

z = distance normal to equitorial plane, R = Galactocentric distance

Results

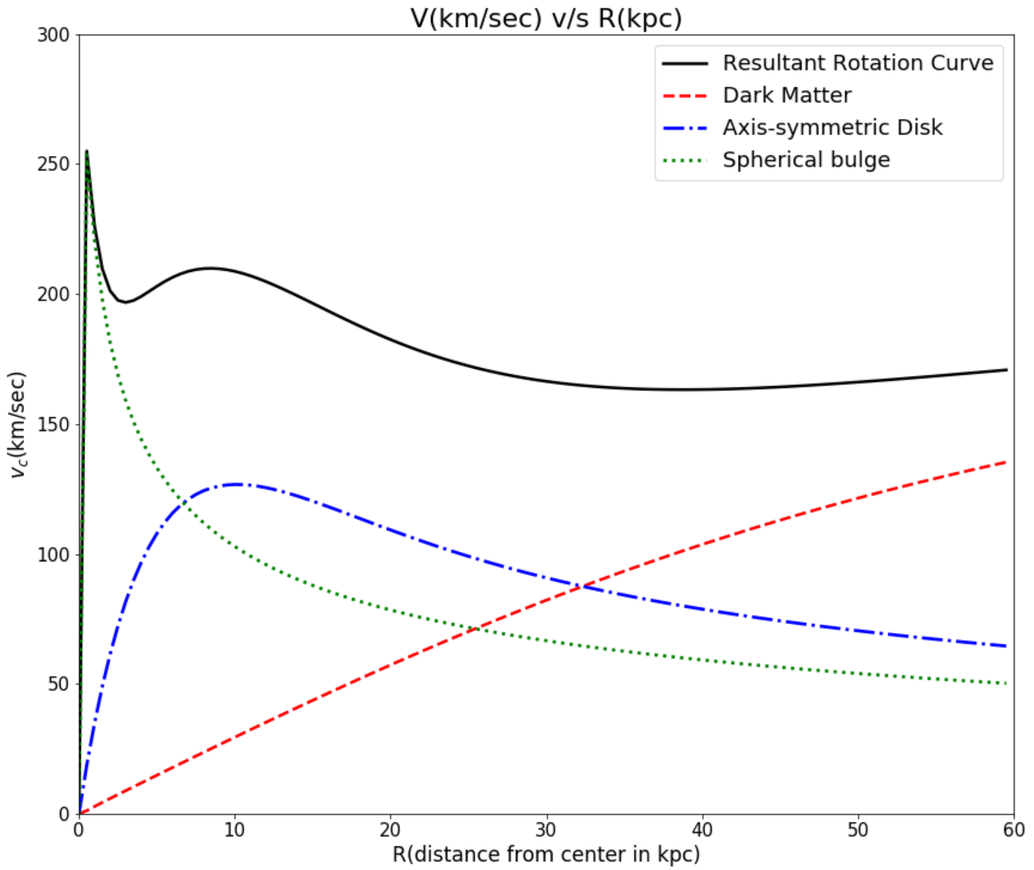

Figure 3: Numerically generated rotation curve of the Milky Way and its components.

Results

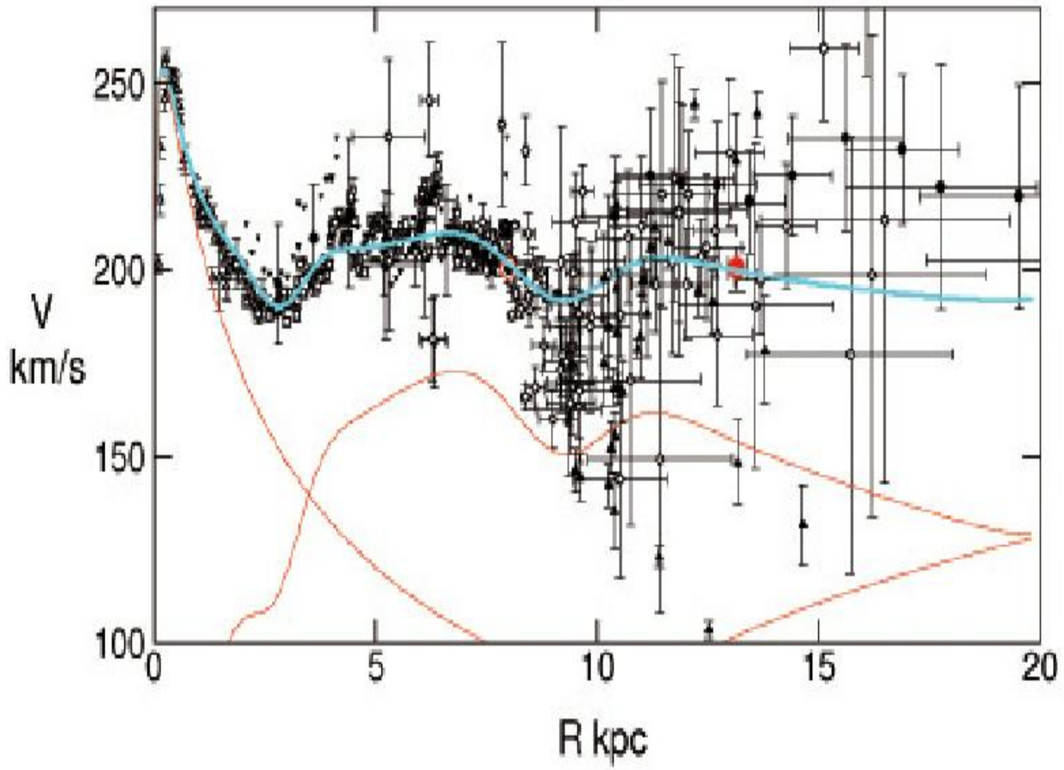

Figure 4(a): Rotation curve of the Milky Way with contributions from the central bulge, stellar disk + interstellar gas and dark matter halo.(Sofue et al, 2012)

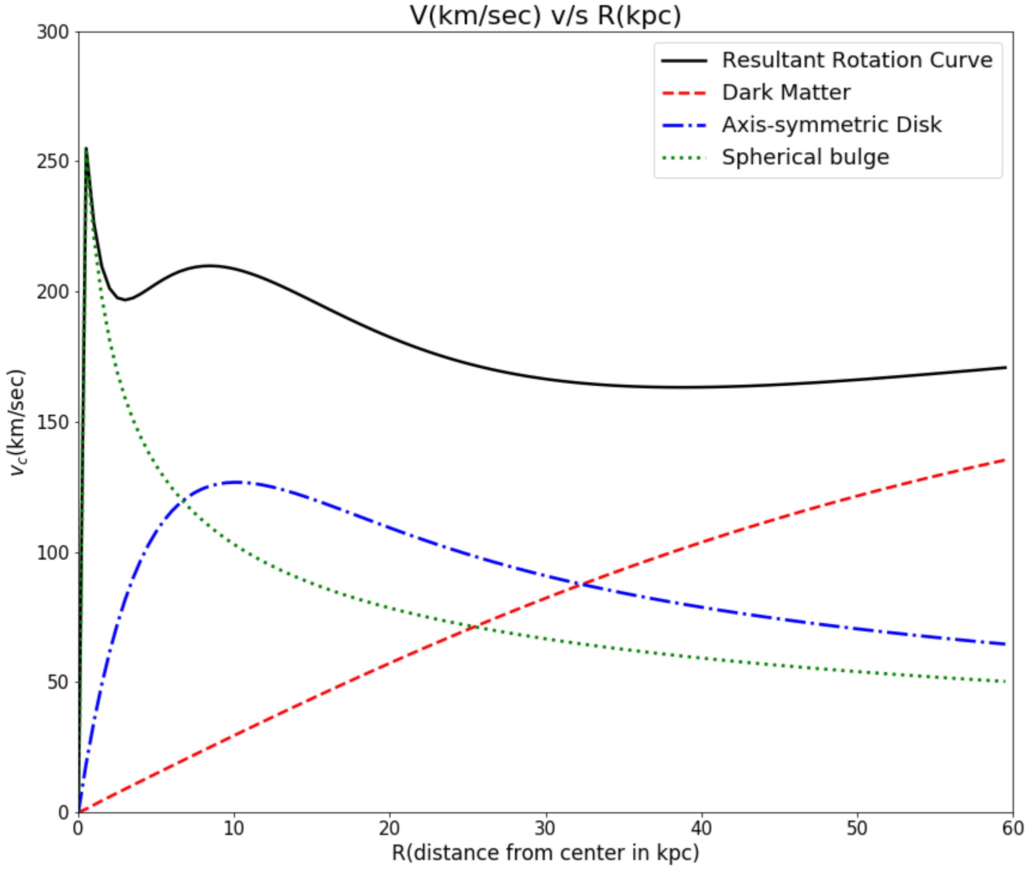

Figure 4(b): Numerically generated rotation curve of the Milky Way and its components.

Conclusion and Future Aspects

- Generated the galactic rotation curves given the density distribution of all the components of the galaxy using numerical methods.
- The isothermal sphere mass linearly increases with its radius r and tends to ∞ as $r \to \infty$. Not a realistic Dark Matter halo of finite physical size. Hence we plan to include a truncation to the model.
- All pieces of evidence in favour of dark matter infer dark matter's presence uniquely through its gravitational influence. No conclusive evidence for dark matter's non-gravitational interactions.
- An alternative explanation to the dark matter by **Extended Theories of Gravity.**

Thank You

Backup

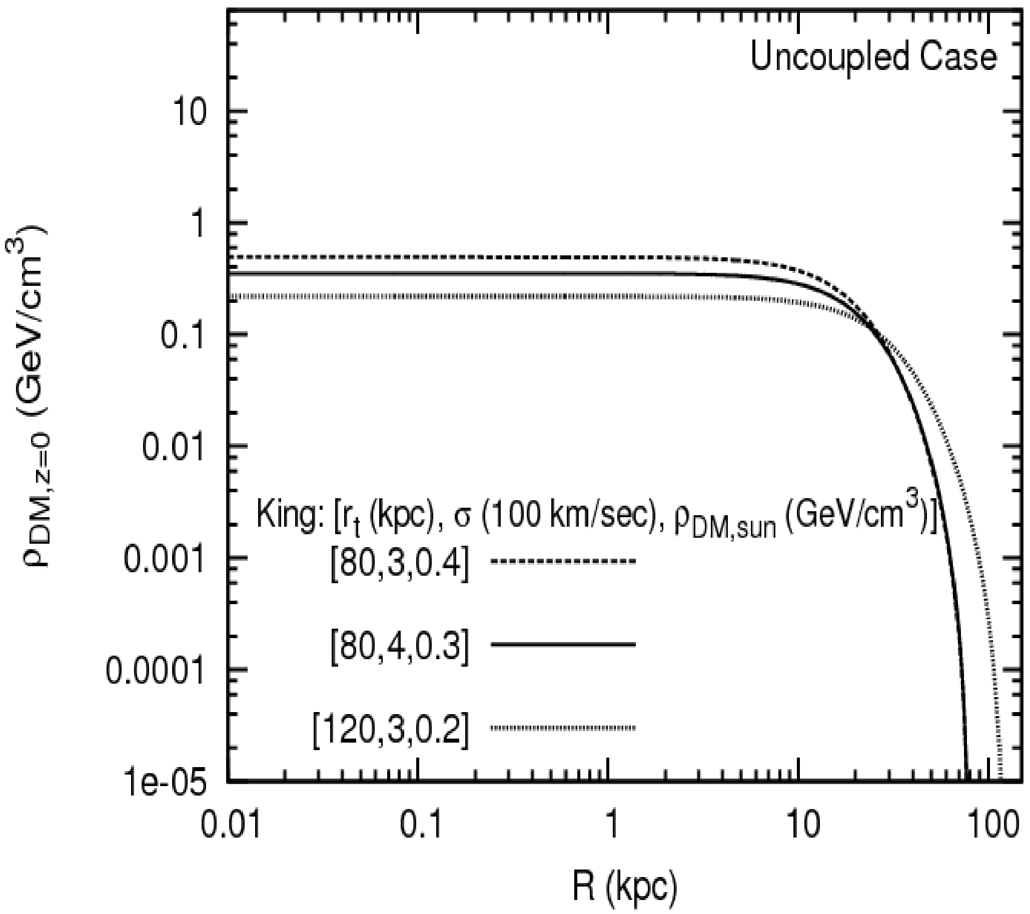

Figure 5: The density profiles of the lowered (truncated) isothermal dark matter halo described by the King model DF(Soumini et al)

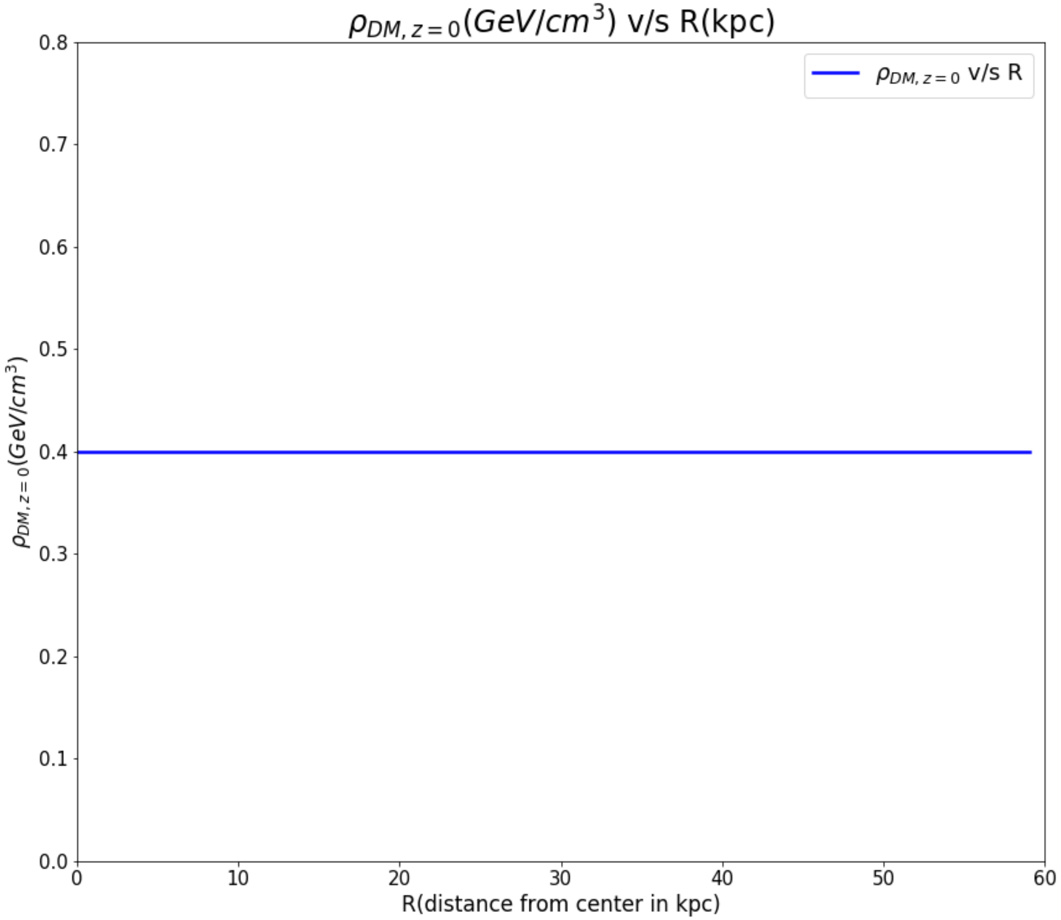

Figure 6: The density profiles of the non-truncated isothermal dark matter halo generated numerically