An Efficient and Versatile Method to study Self-Interacting Dark Matter Halos

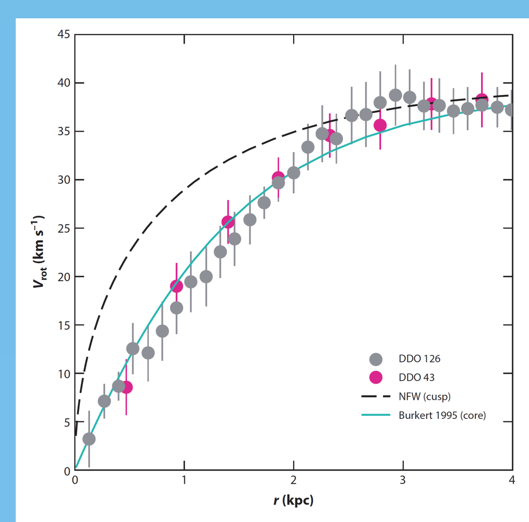
Wong Chak Tim & Ng Chi Kit

Self-Interacting Dark Matter

Self-Interacting dark matter (SIDM) is another class of dark matter particles (Kamada et al., 2017). Unlike cold dark matter (CDM) or decaying dark matter (DDM), SIDM particles have strong interactions among each other aside from gravitational interaction. The possible interactions range from nuclear weak interaction, degeneracy pressure, to even other unknown interactions. SIDM is proposed as a solution to correct the NFW profile and resolve the Core-Cusp problem. In this project, we chose to study SIDM with degeneracy pressure with the simple model mentioned in the following.

Motivation

As mentioned above, the rotational velocity calculated by the NFW profile fails to match the observational data near the center of the galaxy. We therefore try to construct a SIDM computational model to fit the observational rotation curves. Since degeneracy pressure is added on top of the original model when density is high, the central density can be reduced and the infinity can be avoided. Our goal is to get a reasonable fit for each observational rotation curve using a single particle mass of the dark matter, or to rule out this possibility if this fails.



(bullock and boylan-kolchin, 2017)

The Simplified Computational Model

The method we used is to connect the well-established NFW profile and a hydrostatic equilibrium degenerate core profile calculated with the Tolman-Oppenheimer-Volkoff (TOV) equation (see posters "Pushing the Limits of Degenerate Objects"):

$$P = \frac{m^4c^5}{8\pi^2\hbar^3}\left(x\sqrt{1+x^2}(\frac{2}{3}x^2-1)+\sinh^{-1}(x)\right)$$

$$x = \frac{\hbar}{mc}\left(\frac{3\pi^2\rho}{m}\right)^{\frac{1}{3}}$$

$$\frac{dP(r)}{dr} = -\frac{GM(r)\rho(r)}{r^2}\left(1+\frac{P(r)}{\rho(r)c^2}\right)\left(1+\frac{4\pi r^3P(r)}{M(r)c^2}\right)\left(1-\frac{2GM(r)}{rc^2}\right)^{-1}$$

$$\frac{dM(r)}{dr} = 4\pi r^2\rho(r)$$

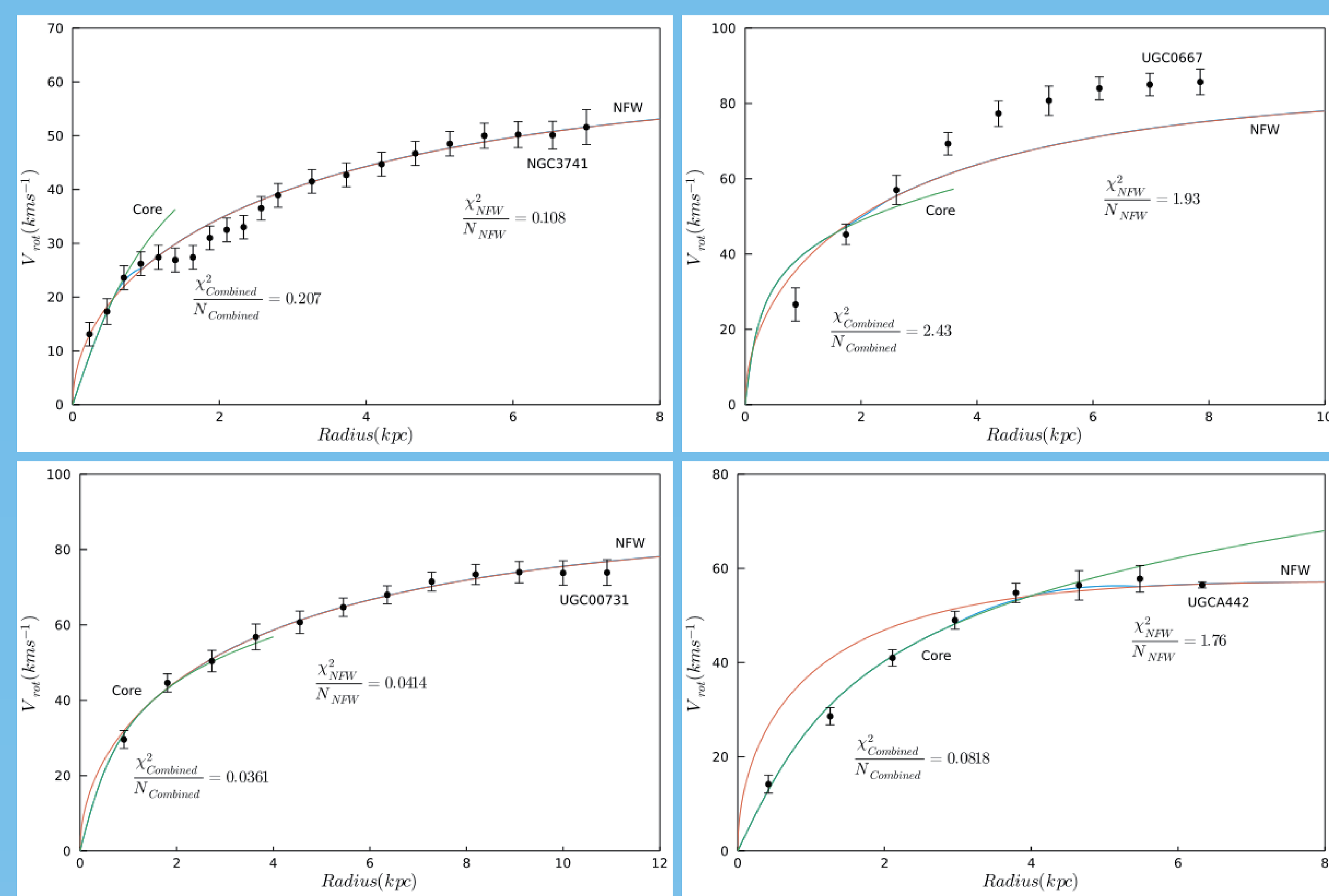
Our model assumes that the density of the halo is either high enough that the dark matter will have degeneracy pressure, or otherwise being collisionless. The program we constructed based on this idea requires 5 inputs: a dark matter particle mass $m_{particle}$, central density of the dark matter halo $\rho_{central}$, scale radius R_s and concentration parameter c of the NFW profile, and the connection position R_c of the two profiles. The two profiles are connected by adjusting the five parameters such that the values of the two mass profiles at R_c are close enough. On top of that, we applied linear interpolation at the neighboring region of R_c, $(R_c-\delta)<r<(R_c+\delta)$, in order to further smooth out the junction: The enclosed mass inside this region is given by $M(r)=\alpha(r)\cdot M_{core}(r)+\beta(r)\cdot M_{NFW}(r)$, $M_{core}(r)$ and $M_{NFW}(r)$ are the enclosed mass calculated by the core profile and NFW profile at r in the neighboring region of R_c, and α and β are some weighting factors depending on r where $\alpha(r)+\beta(r)=1$.

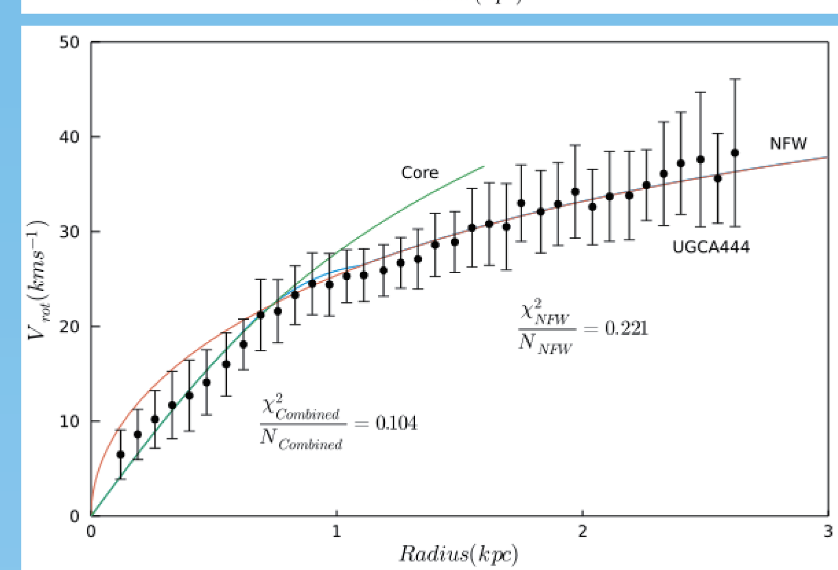
Efficiency and Versatility

The program we used is relatively efficient and requires a little computational power as it does not act as a simulation but as direct computation. This program can also be a useful mean when studying other kinds of possible interaction since we just need to easily alter the equation of state in the TOV equation. The fact that this program finishes within seconds further adds to the convenience of testing different models. Nevertheless, the transition state is neglected, this may fail to predict the intermediate situation of the dark matter halo and the accuracy might be compromised when trying to reconcile the two profiles directly.

Rotation Curves

We compared our calculated results with five observational rotation curves. The rotation curves are from five dwarf galaxies: NGC3741, UGC0667, UGC00731, UGCA442 and UGCA444. We used $m_{particle} = 67.5\ neV/c^2$ in the following fittings. $N_{Combined}$ and N_{NFW} refer to the degrees of freedom of the combined profile and NFW profile respectively in each fitting.





Parameter Table

Galaxy	NGC3741	UGC0667	UGC00731	UGCA442	UGCA444
$m_{particle}$ (neV/c^2)	67.5	67.5	67.5	67.5	67.5
$\rho_{central}$ $(10^6 M_\odot kpc^{-3})$	90.5	905	136	57.9	67.9
R_s (kpc)	10.9	9.51	13.4	3.92	7.09
c $(dimensionless)$	7.2	10.5	8.1	16	8.7
R_c (kpc)	0.7	1.8	2	4	0.8
$X^2_{Combined}/N_{Combined}$	0.207	2.43	0.0361	0.0818	0.104
X^2_{NFW}/N_{NFW}	0.108	1.93	0.0414	1.76	0.221

Discussion

The connections at R_c were oversimplified and were not treated ideally. The results are hence not very accurate. From the diagrams shown, we can observe that the core profiles do bring down the rotational velocities near the center. Three of our calculations give a smaller χ^2 per degree of freedom than the NFW profiles. However, the other two do not improve the fittings of the NFW profiles. The results are therefore not very convincing, but the possibility of SIDM can still not be ruled out. Further study on SIDM would be required.

Conclusion

The two models, DDM and SIDM, are both capable of correcting some existing problems in the well-accepted Lambda CDM model. DDM explains the unexpected loss in satellite halos, SIDM explains the inaccurate descriptions of the rotation curves of galaxies. They both introduce a suppressing mechanism to the central density of a dark matter system. Further studies would be useful to rule out the inaccurate descriptions and thereby push forward the identification of the proper class of dark matter.

Acknowledgement

We would like to express our gratitude to Prof. M.C. Chu for guiding us throughout our research project, and to the Department of Physics for providing us these valuable opportunities. We would also like to give credits to our colleagues, Epod Kwan, Kelvin Lam, and Nissen Lam for assisting us in our projects.