# The Motion of Satellite Galaxies in a Cold Dark Matter Universe

The Illustris Simulation

Ayush Dhananjai, Professor Tereasa G. Brainerd
Boston University Institute for Astrophysical Research

BOSTON UNIVERSITY

## Abstract

Cold Dark Matter (CDM) has been a very successful theory on length scales in the universe that are bigger than the sizes of typically large and bright galaxies such as our own Milky Way. The motivation behind this project was to use the motions of satellite galaxies, orbiting around large and bright host galaxies, as a test of CDM in situations where it hasn't been tested well to date, or has been problematic in reproducing the observed universe. This project measured the distribution of the velocities of the satellite galaxies relative to their hosts. This was done by creating seven histograms of the relative velocity differences (in the x, y and z directions) between the hosts and the satellites, and subdividing them by a 3D distance. The results show that the distributions are well-fitted by Gaussians, and that the velocity dispersion (as determined by Gaussian statistics) decreases monotonically with the host-satellite 3D distance. The next steps are to determine how the satellite velocity dispersion depends on the mass of the host galaxies, satellite galaxies and the projected host-satellite distance. We will then compare these results to the exact same results that have been calculated using the dark matter particles that surround the host galaxies, leading us to determine whether the motion of satellites galaxies, with respect to their hosts, trace the motions of dark matter particles. If they do, then observers should attempt to use the motions of satellite galaxies to inform us about the motion of dark matter.

## Introduction

Dark Matter is one of the most popularly researched topics in astrophysics today, as this theorized particle is responsible for roughly 85% of the mass of current observable universe. However the main challenge associated with studying this particle is that it is not directly observable, as it does not emit any light. As a result, we used simulated data, specifically from the Illustris-1 Simulation [http://www.illustris-project.org/]. The major motivating factor of this project was the fact that Cold Dark Matter (CDM) has provided a strong theoretical framework for the structure and formation of typical large bright galaxies such as the Milky Way galaxy.

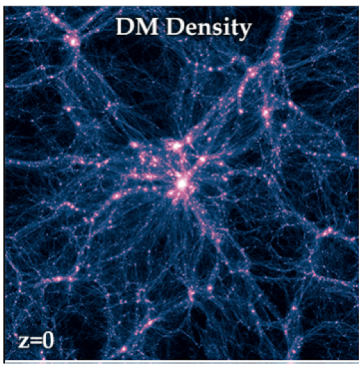



**FIGURE 1:** Image obtained from the Illustris website showing an animation of the density of dark matter in a certain cubic volume of the present day universe (i.e. redshift z = 0). The pink areas represent areas of high dark matter density and the blue areas depict areas of low dark matter density.

## Research Goals

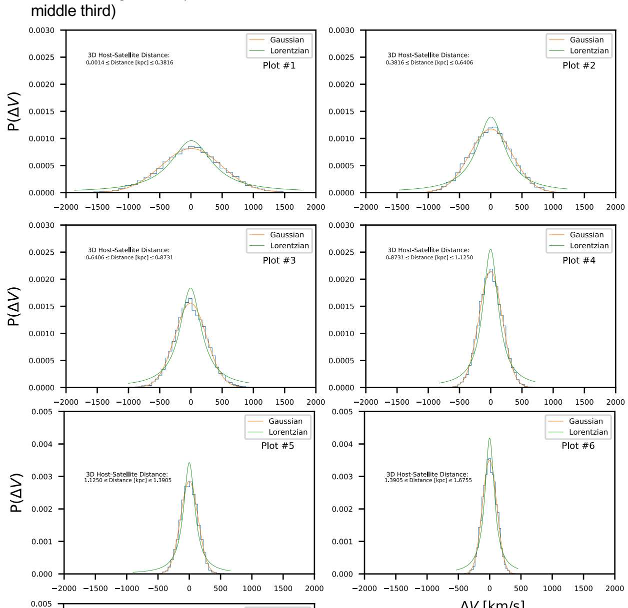
We aimed to determine whether the velocity dispersion profiles of light-emitting satellite galaxies (galaxies that are gravitationally bound to and orbiting, larger "host" galaxies) accurately trace the velocity dispersion profiles of the CDM halos that surround large and bright galaxies. If there is a similarity, then the conclusion will be that observers should seek to use the motions of satellite galaxies (with respect to their hosts) in order to infer the motion of dark matter in the universe.

## Method

- The data (such as velocities in the x, y and z directions, total stellar mass and virial radius for both the host and satellite galaxies) were obtained from the Illustris-1computer simulation and compiled into a text file.
- The text file contained data on 2174 host galaxies and 16849 satellite galaxies in total.
- The Python Programming Language was then utilized to calculate the relative velocity differences ($\Delta v_x$, $\Delta v_y$ and $\Delta v_z$) between the host velocities and the satellite velocities, which were then compiled and plotted into probability density histograms (figure 2)
- Using the Astropy Python library, a Gaussian and Lorentzian line of best fit was plotted to model the probability density histograms (figure 2)
- In order to properly understand the relationship between the histograms and the best fitting lines, the standard deviation of the Gaussians in each of the 7 histograms were plotted as a function of the hosts virial radius and were then compared to the standard deviations of the actual velocity data in each of the 7 histograms (figure 3)

## Results

- Figure 2 shows the relative velocity differences represented graphically in the form of probability density histograms [P(ΔV)]. Each plot is subdivided by the 3D host-satellite separation in units of the Host Virial Radius (the median value of the all the Host Virial Radii is roughly $200\ kpc$)
- Figure 3 represents the standard deviations of the actual data points represented in the histograms and the standard deviations of the best fitting Gaussians collectively on the same plot
- Figure 4 represents the same relative velocity differences between the host and satellite galaxies, however this time each plot is subdivided by the stellar mass of the satellite galaxies (i.e. the most massive third, the least massive third and the middle third)



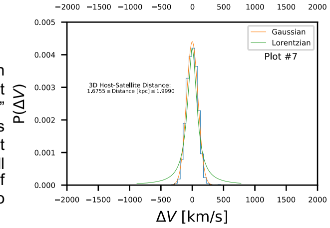




**FIGURE 2:** ΔV consists of all $\Delta v_x$ $\Delta v_y$ and $\Delta v_z$ pertaining to each host-satellite system. There are 7221 data points that make up each of the 7 histograms, leading to a total of 50,547 data points represented through all 7 plots of figure 2

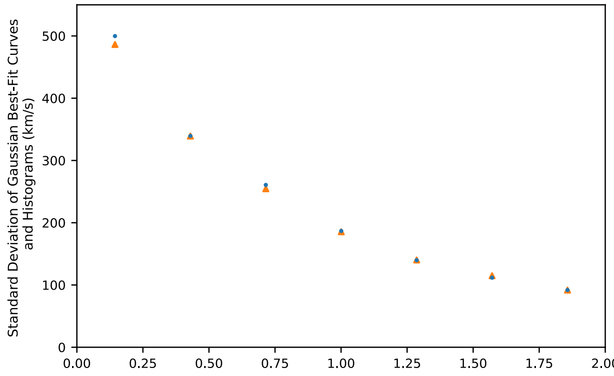
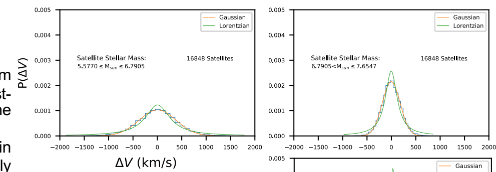



**FIGURE 3:** Figure 3 above represents the standard deviations of each of the 7 histograms. The blue data points represent the standard deviations of the histograms and the orange data points represent the standard deviations of the Gaussian lines of best-fit.



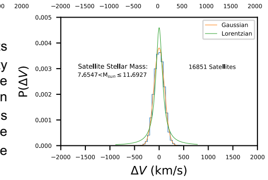




**FIGURE 4:** Figure 4 represents the probability density distribution of the relative velocity differences between the hosts and satellites subdivided by logarithm in base 10 of the stellar mass of the satellites.

## Conclusions

1. The results show that upon first glance, assuming Gaussian statistics, the distribution of the relative velocity differences between the host galaxies and the satellite galaxies are modelled best by Gaussians, regardless of the 3D distance of the satellite galaxies. The same can also be said about the relative host-satellite velocity differences that are subdivided by the stellar mass of the satellite galaxies.
2. The results from figures 3 also show that there is a smooth monotonic reduction in the velocity dispersion (determined through gaussian statistics) of both the histograms and Gaussian best-fit lines as a function of the Host-Satellite 3D distance. This can be interpreted physically from the plots in figure 1; As the 3D distance increases, the histograms (and therefore the Gaussians) become narrower in width, indicating that the probability of obtaining a relative velocity difference at $\Delta V \approx 0\ km/s$ increases.

## Future Directions

1. In order to prove that the relative velocities are best fitted by Gaussians, a proper statistical test, such as the chi-squared test must be run.
2. To fully understand the smooth fall-off in Figure 3, an ideal direction to take would be to put the results in the context of work that has been carried out by others. For example, figure 4 in Prada et al. 2003 analyses "line-of-sight" velocity dispersions using data from "about 3000 satellites" received from the Sloan Digital Sky Survey. Therefore, the next step would be to analyze the fall-off once each data value in figure 2 has been divided by $\sqrt{3}$. Once this comparison has been done, we can truly understand the rate at which the standard deviations decrease.
3. The next course of action would be to create these same velocity dispersion plots (as a function of 3D radius) but this time subdividing them by the masses and luminosities of the host galaxies and the luminosities of the satellite galaxies. When separating by host mass, the ideal situation would be to separate the hosts by the most massive third, least massive third and the middle third, in order to be consistent with figure 4.
4. The error on the standard deviations of the histograms must be calculated through the use of a statistical method commonly known as "bootstrap resampling".
5. Finally, the results obtained from these plots will then be compared to the same results conducted with the Cold Dark Matter Halos of the host galaxies. If there is an accurate and consistent "trace", then research can conclude that observers can use the motion of satellite galaxies to more accurately explain the motion of dark matter.

## Acknowledgements and References

- Acknowledgements: Undergraduate Research Opportunities Program (UROP), The Illustris Project, Professor Tereasa G. Brainerd, Boston University Institute for Astrophysical Research, MIT Kavli Institute for Astrophysics and Space Research, Professor Mark Vogelsberger
- References: F. Prada, M. Vitvitska, A. Klypin, J. A. Holtzman, D. J. Schlegel, E. K. Grebel, H. W. Rix, J. Brinkmann, T. A. Mckay, and I. Csabai, "Observing the Dark Matter Density Profile of Isolated Galaxies," *The Astrophysical Journal*, vol. 598, no. 1, pp. 260–271, 2003., M. Vogelsberger, S. Genel, V. Springel, P. Torrey, D. Sijacki, D. Xu, G. Snyder, D. Nelson, and L. Hernquist, "Introducing the Illustris Project: simulating the coevolution of dark and visible matter in the Universe," *Monthly Notices of the Royal Astronomical Society*, vol. 444, no. 2, pp. 1518–1547, 2014.