Using Stellar Kinematics to Map Dark Matter Distribution: A Gaia-Based Approach

Introduction

Dark matter remains one of the biggest mysteries in modern astrophysics. While its presence is inferred from gravitational effects, it has never been directly detected. One of the most effective ways to study dark matter is by analysing the motion of stars within galaxies. My research focuses on using data from the Gaia mission to measure dark matter distribution in our galaxy, an approach closely related to the **Velocity Dispersion Method.** However, by leveraging high-precision astrometric data from Gaia, I aim to refine and improve this method to produce more accurate and robust dark matter models.

The Velocity Dispersion Method

The Velocity Dispersion Method is widely used to study dark matter in galaxies that lack well-defined rotation curves, such as elliptical galaxies and dwarf spheroidals. Instead of relying on the rotational velocity of gas and stars (as done in rotation curve studies), this method uses the statistical distribution of stellar velocities to infer the gravitational potential of the galaxy. The fundamental principle is derived from the **Jeans Equations,** which relate the velocity dispersion of stars to the total mass distribution, including both visible and dark matter.

Limitations of the Traditional Velocity Dispersion Method

While effective, the traditional velocity dispersion method has several limitations:

1. **Reliance on Spectroscopic Data:** Traditional studies use radial velocities obtained from spectral Doppler shifts. These measurements only provide **line-of-sight velocities**, missing the full 3D motion of stars.
2. **Limited Sample Size:** Spectroscopic surveys are typically constrained to small sample sizes due to observational limitations, reducing statistical accuracy.
3. **Assumptions About Dynamical Equilibrium:** Many models assume that galaxies are in perfect equilibrium, which may not always be the case.
4. **Uncertainty in Stellar Motion:** The method struggles with uncertainties in orbital anisotropy, making it difficult to precisely model the mass distribution.

How My Research Improves on This Method

With the advent of the **Gaia mission**, we now have access to high-precision astrometric data that allows us to track the motion of millions of stars with unprecedented accuracy. My approach enhances the Velocity Dispersion Method in several key ways:

1. **Using Full 3D Stellar Motions**
   - Instead of relying only on radial velocities, Gaia provides **proper motions** (motion across the sky), allowing for a complete 3D velocity profile of stars.
   - This leads to **more accurate mass estimates** by reducing uncertainties in orbital anisotropy.
2. **Larger and More Precise Data Sample**
   - Traditional spectroscopic surveys are limited to thousands of stars, while Gaia's dataset includes **millions of stars** across different galactic regions.
   - A larger sample size leads to better statistical accuracy and more refined models of the dark matter distribution.
3. **Application of Advanced Statistical Methods**
   - By integrating **Bayesian inference** and **machine learning techniques**, I can model stellar velocity distributions more effectively.
   - These methods help separate dark matter effects from visible matter contributions more robustly.
4. **Exploring the Outer Galactic Halo**
   - Most velocity dispersion studies focus on **the inner regions of galaxies**, where baryonic matter dominates.
   - With Gaia's data, I can extend the analysis to the **galactic halo**, where dark matter is expected to be more dominant, providing a better test for dark matter models.

Expected Impact of My Research

By improving the Velocity Dispersion Method with Gaia data, my research aims to:

- Reduce the uncertainties in dark matter density profiles.
- Provide a more detailed and high-resolution **dark matter map** of the Milky Way.
- Offer a new benchmark for future studies using high-precision astrometry.

This work represents a step forward in the quest to understand dark matter by combining **cutting-edge observational data with modern computational techniques**, making it a powerful improvement over traditional approach.