Dynamical Mass Estimation of a Galaxy Cluster Using Spectroscopic Redshift Data

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Abstract

Galaxy clusters are the most massive gravitationally bound structures in the Universe and serve as powerful probes of large-scale structure formation and dark matter distribution. In this project, we identify a galaxy cluster using spectroscopic redshift data obtained from the Sloan Digital Sky Survey (SDSS) and estimate its dynamical mass through kinematic analysis. Cluster members are selected via redshift clustering, recession velocities are computed using relativistic Doppler relations, and the velocity dispersion is determined as a tracer of the gravitational potential. The physical size of the cluster is estimated within a ΛCDM cosmological framework, and the dynamical mass is derived using the virial theorem. The resulting mass is consistent with massive, dark-matter-dominated galaxy clusters.

1 Introduction

Galaxy clusters occupy the highest end of the mass hierarchy in the Universe and represent key laboratories for studying cosmology and galaxy evolution. Their mass content is dominated by dark matter, with baryonic matter contributing only a minor fraction. Reliable cluster mass estimation techniques are therefore essential for understanding large-scale structure formation and testing cosmological models.

One of the most direct observational approaches to estimate cluster mass is through the dynamics of its member galaxies. Under the assumption of virial equilibrium, the velocity dispersion of galaxies provides a measure of the depth of the cluster gravitational potential. In this project, spectroscopic redshift data are used to perform a dynamical analysis of a galaxy cluster.

2 Data and Methodology

2.1 Spectroscopic Data

The analysis is based on spectroscopic redshift measurements obtained from the Sloan Digital Sky Survey (SDSS). Only galaxies with reliable redshift determinations are considered to ensure accurate velocity measurements.

2.2 Cluster Identification

A redshift histogram is constructed to identify overdensities in redshift space corresponding to galaxy clusters. A statistically significant peak is selected, and galaxies lying within a 3σ range around the mean cluster redshift are classified as probable cluster members.

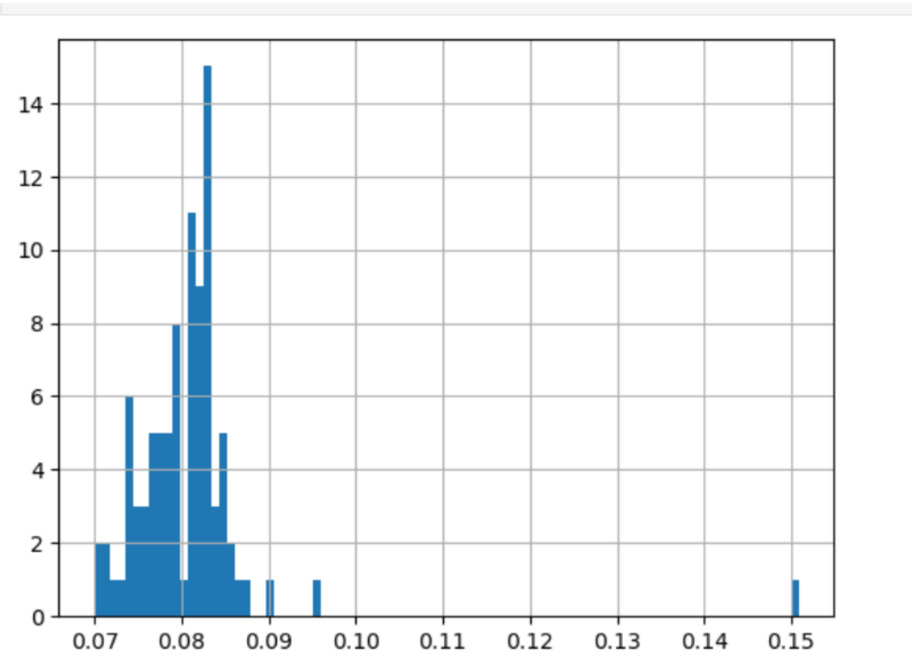

Figure 1: Redshift distribution of galaxies showing a prominent overdensity corresponding to the identified galaxy cluster.

3 Velocity Estimation

The mean redshift of the cluster, $z_{\rm cl}$, is computed from the selected cluster members. The relative line-of-sight velocity of each galaxy with respect to the cluster mean is calculated using the relativistic Doppler relation:

$$v = c\,\frac{(1+z)^2 - (1+z_{\rm cl})^2}{(1+z)^2 + (1+z_{\rm cl})^2}, \tag{1}$$

where c is the speed of light.

4 Velocity Dispersion

The velocity dispersion σ_v quantifies the spread of galaxy velocities and is computed as:

$$\sigma_v = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(v_i - \bar{v})^2}, \tag{2}$$

where N is the number of cluster galaxies and $\bar{v}$ is the mean velocity.

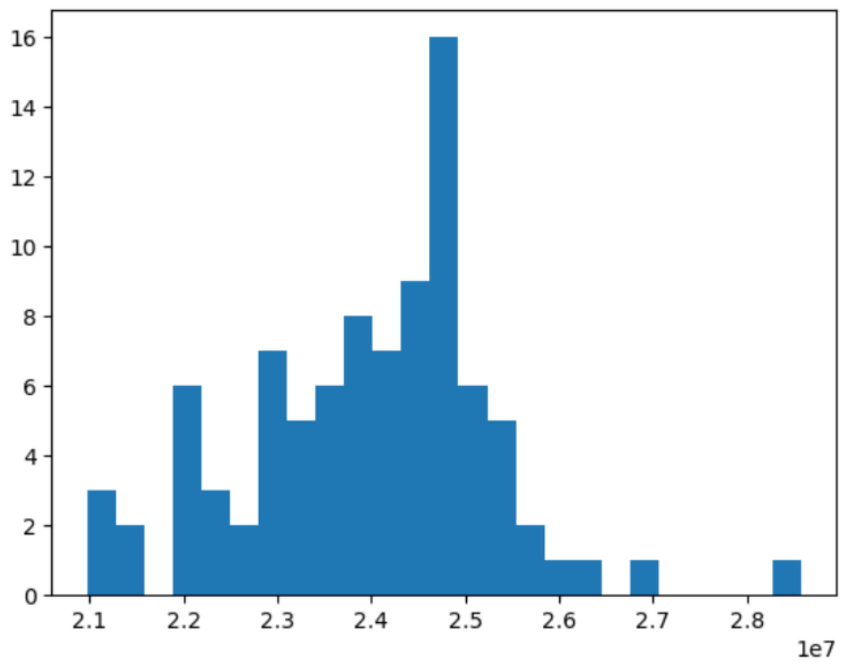

Figure 2: Velocity distribution of cluster member galaxies relative to the mean cluster velocity.

5 Physical Size Estimation

The physical size of the cluster is estimated using cosmological distance relations. For low-redshift systems, the comoving distance can be approximated as:

$$r = \frac{cz}{H_0}\left(1 - \frac{z}{2}(1+q_0)\right), \tag{3}$$

where H_0 is the Hubble constant and q_0 is the deceleration parameter. The angular diameter distance is then given by:

$$D_A = \frac{r}{1+z}. \tag{4}$$

Using the observed angular extent, the physical diameter of the cluster is found to be of order ~ 1 Mpc.

6 Dynamical Mass Estimation

Assuming virial equilibrium, the dynamical mass of the cluster is estimated using the virial theorem:

$$M_{\rm dyn} = \frac{3\sigma_v^2 R}{G}, \tag{5}$$

where R is the cluster radius and G is the gravitational constant. The resulting dynamical mass is of the order $10^{14}\,M_\odot$, consistent with massive galaxy clusters.

7 Discussion

The derived mass significantly exceeds the total stellar mass of the member galaxies, indicating that the system is strongly dominated by dark matter. The primary uncertainties arise from projection effects and the assumption of virial equilibrium. Despite these limitations, the results are consistent with expectations for relaxed galaxy clusters.

8 Conclusion

A complete dynamical analysis of a galaxy cluster has been performed using spectroscopic redshift data. By combining cluster identification in redshift space, velocity dispersion analysis, and virial mass estimation, a robust estimate of the cluster mass is obtained. This project demonstrates a standard observational astrophysics methodology applicable to galaxy cluster studies.