

Dark Matter Distribution and Its Impact on Galaxy Cluster Properties: A Weak Lensing Approach

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1. Introduction

Dark Matter

- 82% of all matter in the universe.[1]
- shaping the formation and evolution of the universe.
- **Does not interact with light**
- Can be detected through gravitational effects.

Weak Gravitational Lensing

- Produces **small distortions** in the observed shapes of background galaxies.
- Used to **map the total-projected mass distribution**

Why Galaxy Clusters?

- **Densest** known structure of dark matter (MPE, 2025)
- The **second largest gravitationally bound** structure in the universe.

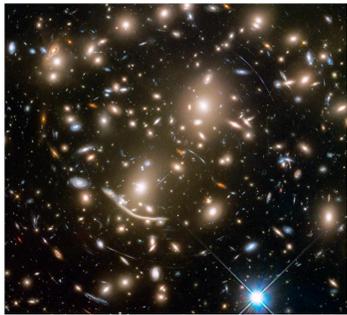


Fig 1: Image of galaxy cluster Abell 370
Image taken from NASA, ESA, and J. Lotz (STScI), 2017

Background Sources

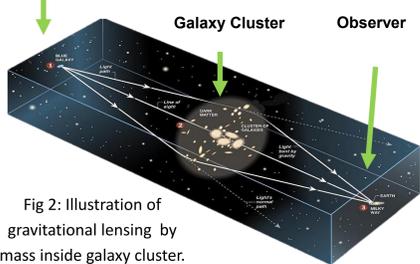


Fig 2: Illustration of gravitational lensing by mass inside galaxy cluster.
Image taken from Vera C. Rubin Observatory, 2025.



Fig 3: Illustration of observe galaxy from weak gravitational lensing.
Image taken from Gadgets 360 Staff, 2025.

Mass Density Profiles

mathematical models for explain dark matter distribution in galaxy clusters

NFW [7]

$$\rho = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^\beta \left(1 + \frac{r}{r_s}\right)^{3-\beta}}$$

gNFW [5]

$$\rho = \frac{\rho_0}{\left(\frac{r}{r_s}\right) \left(1 + \frac{r}{r_s}\right)^2}$$

2. Research Gaps and Research Questions

NFW Profile & Simulations [5]:

- using **N-body simulations** and the **NFW mass density profile** [3]
- **Findings: NFW parameters** correlate with the **physical properties of galaxy clusters**
- **Challenges: Correlation deviate from real observation**

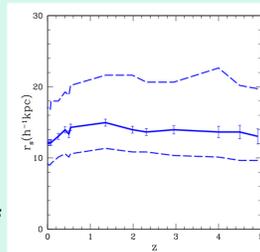


Fig 4: Relationship and between the characteristic radius r_g and redshift z , obtained from the **N-body simulation**.
Image taken from [7], 1996.

Application of gNFW Profile [2]

- Compare **observational data** via **gNFW profile**[4] with the **NFW predictions** [3]
- **Finding: Beta value** significant deviations from prediction
- **Challenge: not examine correlations with the physical properties of the clusters.**

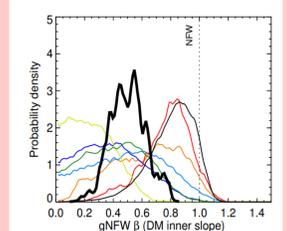


Fig 5: The probability density function of the gNFW β parameter from real observational samples. The thick black line represents the joint posterior distribution obtained by combining all clusters in the sample. The colored lines correspond to the individual clusters. The vertical dashed line marks the canonical NFW slope ($\beta = 1$) for comparison.
Image taken from [4], 2004.

Research Questions

- Which projected mass density profile $\Sigma(r)$ best describes the observed dark matter distribution in galaxy clusters?
- Are there correlations between the parameters of the best-fitting profile and the physical properties of galaxy clusters in **real observational data**?

3. Objectives

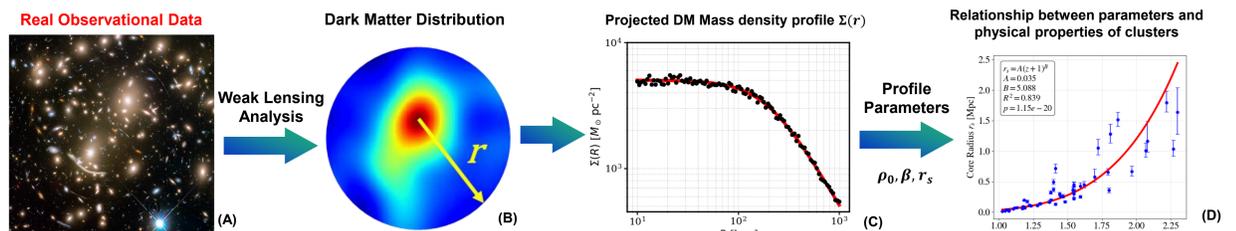


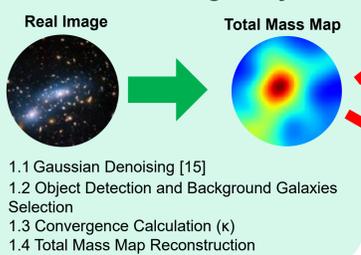
Fig 6: Pipeline of this project about the study of dark matter from weak lensing analysis.
Images taken from NASA, ESA, and J. Lotz (STScI), 2017 (A), and made by finalists using Python, 2025 (B, C and D)

1. To study dark matter distribution of galaxy clusters using **weak lensing**.
2. To **compare, select, modify, and establish** the mass distribution models based on real observational data.
3. To explore the **relationship** between the **parameters** of the best-fitting models and other physical properties of galaxy clusters: redshift and enclosed luminosity within core radius.

4. Methodology

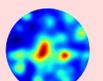
Equipment and Astronomical Databases :Visual Studio Code, SUBARU telescope [6] , XMM-Newton Space Telescope [7], Sources catalog NASA [8], SAS XMM-Newton [9], Heasoft from NASA [10] and XSPEC [11]

1. Weak Lensing analysis



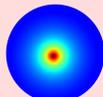
- 1.1 Gaussian Denoising [15]
- 1.2 Object Detection and Background Galaxies Selection
- 1.3 Convergence Calculation (κ)
- 1.4 Total Mass Map Reconstruction

2. Stellar Mass Map Reconstruction [13]

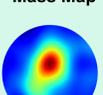


Subtraction with Visible Mass

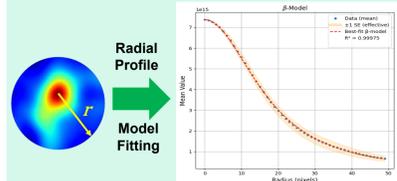
3. Gas Mass Map Reconstruction [12]



4. Dark Matter Mass Map

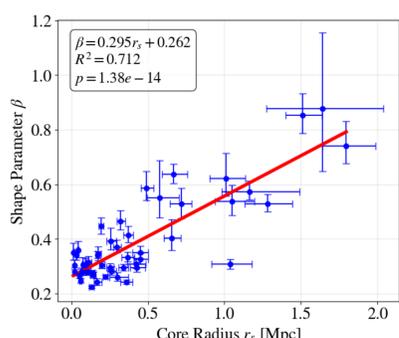


5. Model Fitting [22, 23]

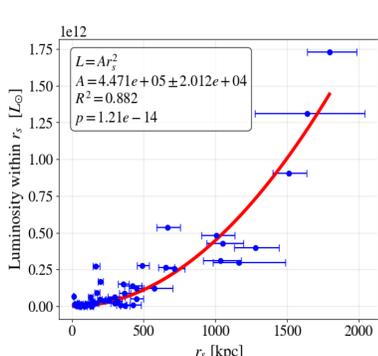
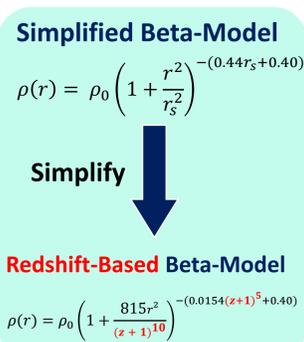
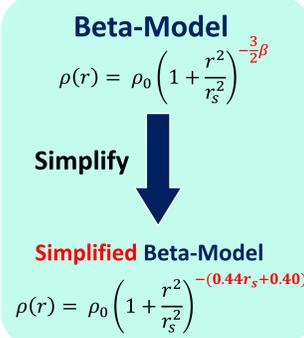


Final Step: Find Relationship between best fitting model parameters and Physical properties

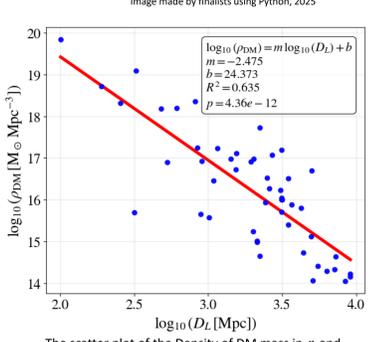
5. Results



The scatter plot of the shape parameter β versus the core radius r_s for 50 galaxy clusters along with the linear regression fit
Image made by finalists using Python, 2025



The scatter plot of the enclosed Stellar Luminosity in core radius and r_s for 50 galaxy clusters along with the quadratic fit
Image made by finalists using Python, 2025



The scatter plot of the Density of DM mass in r_s and Luminosity Distance D_L for 50 galaxy clusters along with the linear regression fit [log-log]
Image made by finalists using Python, 2025

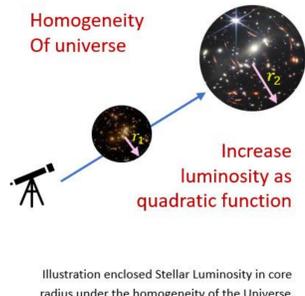


Illustration enclosed Stellar Luminosity in core radius under the homogeneity of the Universe.

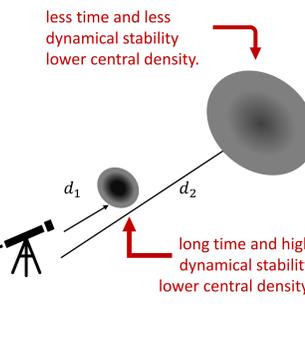
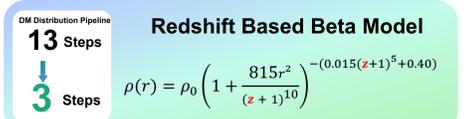


Illustration of how cluster's distance relates to dynamical evolution and central density of dark matter.

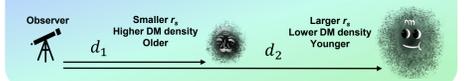
6. Conclusion

In this study, we used **weak lensing analysis** combine with the stellar and gas mass map reconstruction method to investigate the **real observational dark matter distribution** in 56 galaxy clusters vary from $0.02 < z < 1.3$

New Findings:



Evolution of Dark matter in Galaxy Clusters



Support Cosmological Principle: HOMOGENEOUS

Limitation
Our Model and relationships are only applied well with a single-cored galaxy clusters with low redshift

7. Acknowledgements

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8. References

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