Characterizing High Mass-to-Light Ratio Dark Matter Sub-Halos in MUSIC II Galaxy Cluster Simulations

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Abstract

A single dark matter halo can hold various clumps of dark matter virialized by gravity bound together. With the aid of ROCKSTAR halo finder algorithms, we identify the properties, distribution, and content within these multiple virialized clumps of dark matter based on Marenostrum-MultiDark Galaxy Cluster Simulation (MUSIC). We are focusing on the characteristics of the high mass-to-light ratio of dark matter subhalo with the help of ROCKSTAR halo finder in order to know the important concepts of DM subhalos and their contents. We determine the mass-to-light ratio of DM subhalos for cluster 281 within a radius of 15 kpc and 30 kpc and the minimum number of particles is 50 and 100, respectively. We also compared its value for cluster 282 within a radius of 10 kpc and 30 kpc and the minimum number of particles are 1000 and 100, respectively. On both clusters we found that the high mass-to-light ratio is found in the smaller mass of ($1\times10^{10}M_{\odot}/h$-$10\times10^{10}M_{\odot}/h$) of DM subhalos. We also analyzed the mass-to-light ratio of clusters at a radius of R to R_{200}. So, the high mass-to-light ratio is found to be at a distance around $0.5\times R_{200}$ and the concentration of dark matter subhalos is also high at this radius. We observed that the result from the graph can be interpreted simply as the high mass-to-light ratio of dark matter subhalos is very rare to be found in the inner volume of clusters. And we conclude that the distribution of the high mas-to-light ratio of dark matter subhalo peak at a distance of R$\sim$ R_{200}. These may suggest that the search for content of dark matter from subhalos in dark matter halo is most promising at a distance of R$\sim$ R_{200}.

1 Introduction

Humankind is quite obsessed with explaining our existence, understanding the world and our place in it, by justifying our nationality. So, while it's hard to try to map the universe because of its complexity, it's even difficult to try to describe the universe's matter that can't give light, but we know it exists. That kind of matter is dark matter (DM). In the universe, DM is a matter we do not directly see because it does not emit light. However, we know DM exists because of how its gravity affects the other universal bodies, like star and galaxies [1]. DM was postulated by Swiss astrophysicist Fritz Zwicky of the California Institute Technology in 1933. He applied the viral theorem to the Coma galactic clusters and acquired evidence of unseen mass. Zwicky calculated the cluster's total mass based on the motions of galaxies around its edge and compared the measurement to one based on the number of galaxies and the total brightness of the cluster. He discovered that the measured mass was about 400 times greater than what was visually measurable. For such fast orbits, the gravity of the observable galaxies in the cluster would be much too weak, so something extra was needed. On the basis of these assumptions, Zwicky concluded that some non-visible type of matter would exist that would provide ample mass and gravity to keep the cluster together [2].

According to the observations DM accounts for 25% of the mass-energy content of the visible universe [3]. In contrast, ordinary or baryonic matter accounts for just 5% of the observed universe's mass-energy content, with the remainder due to dark energy(DE) [4]. Current evidence shows that DM is five times more abundant and contributes to around a quarter of the universe than ordinary matter. Now we shall estimate the current understanding of the remaining 25% of the universe's mass-energy, which is known as DM. Evidence has been found on both tiny galactic and large cosmological scales for excess gravitational acceleration that can not be explained by detectable matter. If the standard model or general relativity of Newton is valid, then the universe must have a component of an unknown nature that only by gravitation betrays its existence. Particles may or may not be made of this DM. If so, the lack of a diffuse signal of excess baryonic matter dispersion requires that multiple candidate particles have recently been proposed by elastic dispersion in experimental tools or indirectly by an astronomical decay or annihilation signal [5].

In fact that clusters of galaxies are dominated by DM and it has responsibility for the creation of a skeleton on which stars, galaxies, and clusters of galaxies are born, evolve, and merge [6]. This gave us awareness and motivation for our studies. In this thesis, we are inspired by these observations and to study the characteristics of the high mass-to-light ratio of DM subhalos from the phase of simulated galaxy clusters at different distances. We extracted two simulated galaxy clusters (SGC281 and SGC282) from the MUSIC dataset for this purpose. Now it is clear that our ultimate aim in doing this work has two sides; on the one hand, in MUSIC dataset simulations, we concentrate on the statistical analysis of the high mass-to-light ratios within DM subhalos, and on the other hand, we are looking for DM distributions from two simulated galaxy clusters. And in doing this study, our specific objective is to produce the high mass-to-light ratio, DM fraction, baryon fraction, gas fraction, and star fraction within DM subhalos, also to demonstrate DM distribution within the galaxy cluster.

2 Materials and Methods

Generalized Viral theorem in hybrid metric gravity: Clusters of galaxies are gravitationally bound particles. In hybrid metric gravity, we prefer Virial theorem to explain the statistical distribution of DM. It is one of the strategies for researching DM. It is necessary to implement the hybrid metric model in order to extract the Virial theorem for galaxy clusters. The Boltzmann equation governing the evolution of the distribution function of cluster galaxies must also be understood. We use the relativistic Boltzmann equation along with the field equations to find the generalized Virial theorem by taking the galaxy cluster as a system of similar and collisionless point particles [7].

Hybrid metric palatini gravity: In addition to the existence of DM, this kind of adjusted gravity is capable of addressing the dynamics of many self-gravitating structures. In order to create the gravity Lagrangian, we considered a hybrid combination of metric and palatine elements and found that viable models sharing the properties of both formalisms are feasible. A fascinating feature of these theories is the possibility of creating long-range powers to interfere with local gravity tests and to invoke some type of mechanism for screening. The possibility of using a scalar-tensor representation to express these hybrid metric palatini theories simplifies the study of the field equations and the creation of solutions. A metric is given by an isolated spherically symmetric cluster [8]

$$ds^2 = -e^{v(r)}dt^2 + e^{\lambda(r)}dr^2 + r^2(d\theta + sin^2\theta d\varphi^2) \tag{1}$$

The galaxies in the cluster are known to be similar and collisionless point particles and a distribution function f_B defines their space-time distribution. In a curved arbitrary Riemannian space-time, the distribution function f_B obeys the general Boltzmann relativistic equation, which is the distribution function transport equation for a particle system [7]. The general relativistic equation of Boltzmann is given by

$$(p^\alpha \frac{\partial}{\partial x^\alpha} - p^\alpha p^\beta \Gamma^i_{\alpha\beta} \frac{\partial}{\partial p^i}) f_B = 0 \tag{2}$$

Where p^α is the four-particle momentum and $\Gamma^i \alpha\beta$ is the metric associated Christoffel sign. Thus, the Boltzmann collisionless equation states that the local phase space density seen by an observer co-moving with a star or galaxy is preserved. Consequently, the energy-momentum tensor of the matter is given by the tensor of matter.

$$T_{\mu\nu} = \int f_B m u_\mu u_\nu du \tag{3}$$

Where, m is the mass of the particle (galaxy), $u_\mu = (u_t, u_r, u_\theta, u_\varphi)$ is the four velocity of the galaxy, u_t, the temporal component, and $du = du_r du_\theta du_\varphi / u_t$ is the invariant volume element of the velocity space.

In terms of the effective density ρeff and two effective anisotropic pressures, the radial $P^{(r)}eff$ and the tangential $P^{\perp}eff$, respectively, the energy momentum tensor $T\mu\nu$ can be described.

$$\rho_{eff} = \rho < u_t^2 > \tag{4}$$

$$P_{eff}^{(r)} = \rho < u_r^2 > \tag{5}$$

$$P_{eff}^{\perp} = \rho < u_\varphi^2 >= \rho < u_\theta^2 > \tag{6}$$

Where, ρ is the density of the ordinary baryonic matter, $< u_i^2 >, i = t, r, \theta, \varphi$ is average value of $u_i^2, i = t, r, \theta, \varphi$, the gravitational field equation described a cluster of galaxy in hybrid metric palatini gravity, takes the form [8]

$$e^{-\lambda}(\frac{v^{''}}{2} + \frac{v^{'2}}{4}\frac{v^{'}}{r} - \frac{v^{'}\lambda^{'}}{4}) \simeq 4\pi G\rho < u^2 > +4\pi G\rho_\phi^{eff} \tag{7}$$

and the relativistic Boltzmann equation finally takes the form;

$$\int_0^R 4\pi\rho(< u_1^2 > + < u_2^2 > + < u_3^2 >)r^2 dr - \frac{1}{2}\int_0^R 4\pi r^3(< u_0^2 > + < u_1^2 >)\frac{\partial v}{\partial r}dr = 0 \tag{8}$$

Since, at the extragalactic level, we are interested in astrophysical applications. We can suggest that the deviations from standard general relativity are minimal, i.e. $\phi <<< 1$. We believe that galactic clusters often apply the approximations applicable to test particles in stable circular motion around galaxies.

First, assume v and λ are slowly varying functions of r (i.e. v' and λ' are small), so that all the quadratic terms are neglected. Secondly, assume that the motion of the galaxies is non-relativistic, so that they have velocities much smaller than the velocity of the light i.e., $< u_{1>}^2 \approx< u_2^2 >\approx< u_3^2 ><< u_0^2 \approx 1$. Thus, the gravitational field equations reduce to [8].

$$\frac{1}{2r^2}\frac{\partial}{\partial r}(r^2\frac{\partial v}{\partial r}) = 4\pi G\rho + 4\pi G\rho_\phi^{eff} \tag{9}$$

and the relativistic Boltzmann equation to

$$2k - \frac{1}{2}\int_0^R 4\pi r^3\rho\frac{\partial v}{\partial r}dr = 0 \tag{10}$$

where

$$k = \int_0^R 2\pi\rho[< u_1^2 > + < u_2^2 > + < u_3^2 >]r^2 dr \tag{11}$$

is the total kinetic energy of the galaxies, consider that the gravitational potential energies of the cluster are defined as

$$\Omega_B = -\int_0^R \frac{GM_B(r)}{r}dM_B(r) \tag{12}$$

$$\Omega_\phi^{eff} = \int_0^R \frac{GM_\phi^{(eff)}(r)}{r}dM_B(r) \tag{13}$$

Where R is the radius of the cluster. Since the quantity $M_\phi^{eff}(r)$ has essentially a geometric root in hybrid metric-Palatini gravity. The cluster's geometric mass, defined as

$$M_\phi^{eff}(r) = 4\pi\int_0^r \rho_\phi^{eff}(r')r'^2 dr' \tag{14}$$

We arrive at the generalization of the Virial theorem using the above equations, which takes the familiar form

$$2k + \Omega = 0 \tag{15}$$

Where Ω is the system's total gravitational potential energy, defined by
$\Omega = \Omega_B - \Omega_\phi^{eff}$, which contains the word Ω_ϕ^{eff}, consisting of a geometric origin

If we add the Rv and R_ϕ radii, described by a more transparent physical form, the generalized viral theorem can be expressed in a more transparent physical form.

$$R_v = \frac{M_B^2}{\int_0^R \frac{M_B(r)}{r} dM_B(r)} \tag{16}$$

$$R_\phi^{eff} = \frac{(M_\phi^{eff})^2}{\int_0^R \frac{M_\phi^{eff}(r)}{r} dM_B(r)} \tag{17}$$

Where, R_ϕ may be denoted as the geometric radius of the cluster of galaxies. Thus, the baryonic potential energy Ω_B and the effective scalar field potential energy Ω_ϕ^{eff} are finally given by

$$\Omega_B = \frac{-GM_B^2}{R_v} \tag{18}$$

$$\Omega_\phi^{eff} = \frac{G[M_\phi^{eff}]^2}{R_\phi^{eff}} \tag{19}$$

Now, we define the virial mass M_v of the cluster of galaxies as;

$$2K = \frac{GM_B M_v}{R_v} \tag{20}$$

We obtain the following relation between the Viral and the baryonic mass of the galaxy cluster after substitution into the Viral theorem.

$$\frac{M_V}{M_B} = 1 + \frac{[M_\phi^{eff}]^2}{M_B^2 R_\phi^{eff}} R_v \tag{21}$$

If $\frac{M_V}{M_B} > 3$, a condition which holds for most of the observed galactic clusters [9], then the above equation provides the Virial mass in hybrid metric-Palatini gravity, which can be approximated

$$M_v = \frac{[M_\phi^{eff}]^2}{M_B} \frac{R_v}{R_\phi^{eff}} \tag{22}$$

There is also a strict proportionality between the Viral mass of the cluster and its baryonic mass in the current model, a relationship that can also be observationally checked. Most of the mass in the cluster with mass M_{tot} is the shape of the geometry mass M_ϕ^{eff} according to the Virial theorem in the hybrid metric palatini gravity, so that most of the mass in the cluster with mass M_{tot} is the geometry mass M_ϕ^{eff} so that $M_\phi^{eff} \approx M_{tot}$. Accordingly, DM is dominated objects are galaxy clusters, the main contribution to their mass comes from the geometric mass M_ϕ, so we have $M_\phi \approx M_V \approx M_{tot}$ with a very good approximation [10]. Therefore, the Virial theorem immediately provides the following mass scaling relation:

$$M_V \approx M_B \frac{R_\phi}{R_v} \tag{23}$$

$$M_v = \frac{R_\phi}{R_v} M_b \tag{24}$$

This suggests that the Viral mass is equal to the baryonic mass and that the constant of proportionality has geometric roots.

Here we are trying to demonstrate that the mass of DM is dominant in the universe. The Viral mass is about the same as the total mass, which is the DM mass. We concluded that in galactic clusters, DM is the primary mass contribution. Thus, the presence of DM, related to its mass, was represented in the hybrid metric gravity model with Viral theorem. This model ensured that DM added a significant amount of mass to the galactic cluster.

Dark matter within galaxy cluster: Galaxy clusters are gravitationally bound particles, we have to use the annihilation flux of neutralino particle χ to explain the statistical distribution of DM, and easily understand the distributions of DM within the galaxy cluster by the product of two terms, the part of particle physics that depends on DM's particle physics model, and the cosmological part that includes a line-sight integral of the density squared of the dark matter.

$$\Phi = A_{DM} \int_{l.o.s} \rho_\chi^2 dV \tag{25}$$

Where the DM density is ρ_χ, using Smoothed Particle Hydrodynamics (SPH) kernel the density ρ_i of the i^{th} DM particle is calculated by taking the DM particle at the redshift of nil [11]. That evaluates the density to take into account the 44 neighboring particles in a normal grid. This helps us to quickly measure the square of the line-of-sight integrated DM densities.

Simulation: Cosmological N-body simulations are the key tools to investigate the nonlinear structure formations of the universe. For the purpose of our work we have used the MUSIC dataset to determine the annihilation flux from nuetralino particles by the line of site volume integral of density square map and also analyzed using SPH-kernel in order to know the DM distribution in the galaxy cluster. The MUSIC dataset used to determine DM subhalo and their contents in the DMhalo. There are different types of subhalo finders such as FOF, AMIGA, BDM, SURV, SUBFIND and ROCKSTAR. But we have to use the ROCKSTAR halo finder interested in. Becuase it is very efficient halo finders.

3 Result And Discussion

The distribution of dark matter in the galaxy clusters: The DM density maps shown in Fig.1 are in units of $M_\odot kpc^{-3}$, representing the DM distributed in a three dimensional cluster of galaxies projected onto a two-dimensional galaxy cluster. By integrating all the DM density along the line-of-sight. The dimensional map with other center substructures that are considerably thick, the cluster has one central dominant structure. The bright yellow regions on the maps are the densest DM regions in the galaxy clusters and demonstrate how the density of DM decreases as we go from the center to the edge of the clusters except for the off center substructures.

Mass-to-light ratio: When we divide total mass of the given cluster to the stellar mass in that cluster, we can determine mass-to-light ratio and we plot the graph of mass-to-light ratio versus mass DM subhalo in a given cluster at a radius of 30 kpc, 15 kpc and 10 kpc within the minimum number of particles are 100, 50 and 1000, respectively. On Fig.2 as shown below, for the mass of DM subhalos between $1{\times}10^{10} M_\odot h^{-1}$ and $10{\times}10^{10} M_\odot h^{-1}$, the mass-to-ight ratio is 100 and 10, respectively. So, 100 is the high mass-to-light ratio in the smaller mass of DM subhalo. And highly concentrated region of DM subhalos are located in this smaller mass region. But when the mass is above $10{\times}10^{10} M_\odot h^{-1}$ the mass-to-light ratio is exponentially decreasing.

Mass-to-light ratio versus distance: The viral radius R_{200} is a radius in which the density of the halo is 200 times the mean density of the universe. The overdense DM subhalos concentration at R to R_{200} is between 0.1 and 2.5 and the mass-to-light ratio is between 2 and 100, as shown in Fig.3. This area looks very dark and dense with subhalos of DM. The highest mass-to-light ratio is peak around $0.5{\times}R_{200}$ and the concentration of DM subhalos at this radius is also high. we conclude that the distribution of DM subhalos' high mass-to-light ratio is peaks of R$\sim R_{200}$.

The high mass-to-light ratio of DM subhalos: For the purpose of our work we were focused on the characteristics of the high mass-to-light ratio of DM subhalos, based on MUSIC data set for all 282 clusters we simulated using ROCK-

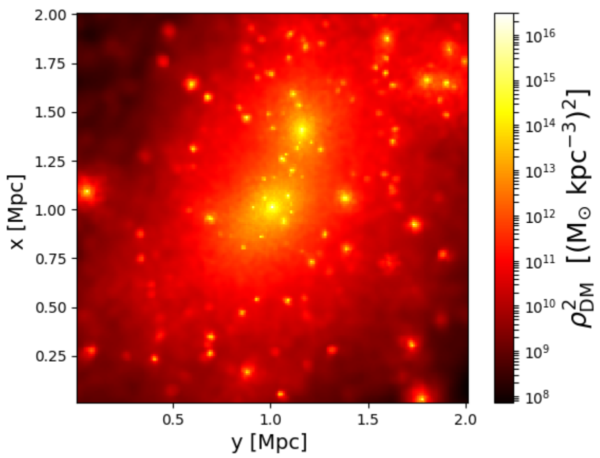

Figure 1: The DM density square map of the SGC 282 according to the dataset available on the MUSIC database

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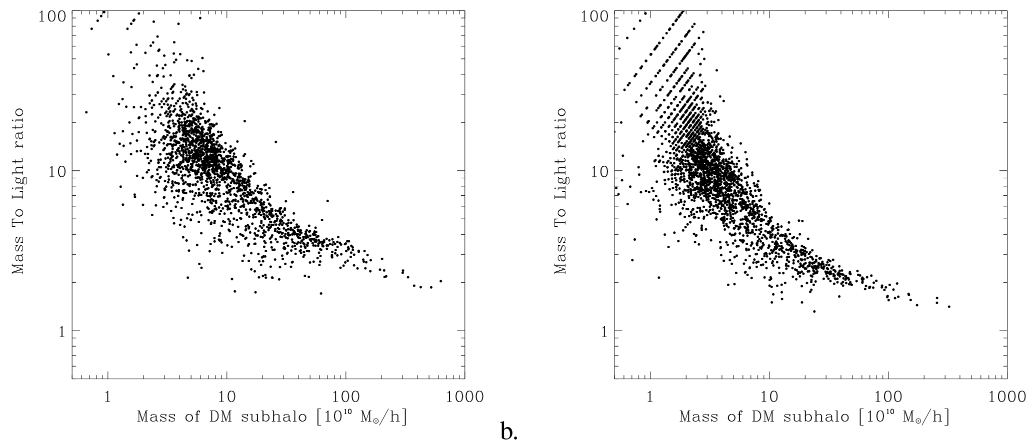


a. b.

Figure 2: Mass-to-light ratio of the SGC 281 at a radius of 30 kpc (left) and 15 kpc (right) within the minimum number of particles are 100 and 50, respectively.

STAR halo finder algorithm and we obtained 466, 621 subhalos. The result as we observed the high mass-to-light ratio is found in the smaller mass of DM subhalos. In other words, the smaller mass of DM subhalos are mainly concentrated by non-luminous matter and which have not much more stellar mass. We are plotting Fig. 4 to give more essential and clear idea about high mass-to-light ratio and stellar mass within the DM subhalos. In the left upper part our plot we get high mass-to-light ratio and lower amount of the star and gas. As we go to the right hand the stellar mass increase but the mass-to-light ratio is exponentially decreasing and we get zero.

As we observe the diagram given in Fig. 5 (a) displays the mass-to-light ratio of the subhalos plotted within the subhalos against the mass of the star in order to compare our results. We see that subhalos are seen to be found on the upper left portion of the plot that has single stars and less gas fraction. Nevertheless, to choose the best candidates for "naked" DM subhalos (DM subhalos with almost no baryonic content) which are needed for a robust analysis of the high mass-to-light ratio of DM subhalos [12].

A linear plot of the mass-to-light ratio of all these halos compared to their respective clusters against their relative distance. In other words, the ratio of the subhalo distance to the cluster radius belonging to the criterion R/R_{200} is shown in Fig. 5 (b) for the purpose of comparison. It is apparent to see some behavior of grouping of subhalos showing high mass-to-light ratio ($\sim 360 \pm 70$) as indicated in the shaded region around $\sim 0.5 \times R_{200crit}$ of there host clusters [12].

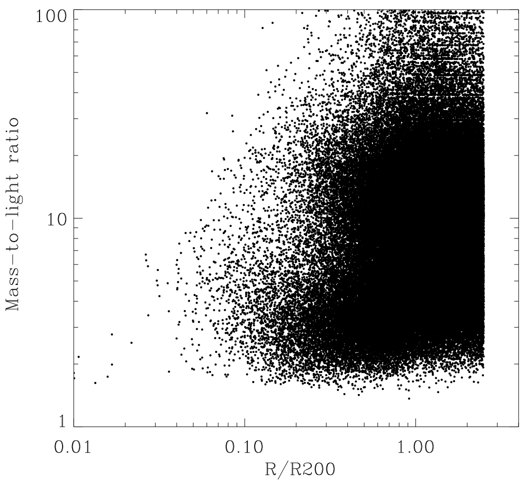


Figure 3: The mass-to-light ratio versus R to R_{200} within DM subhalos, the interpretaion of this plot is the same as with the prevous work [12]

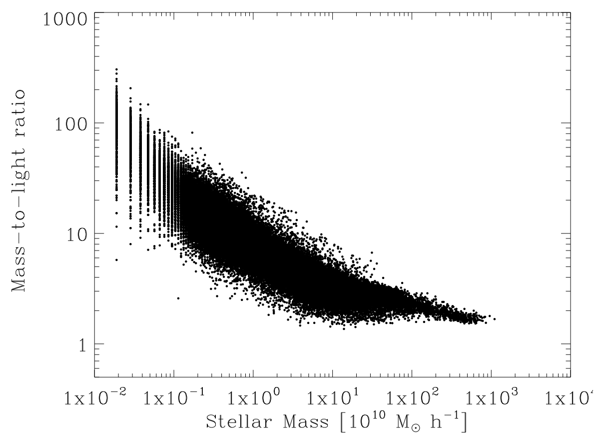
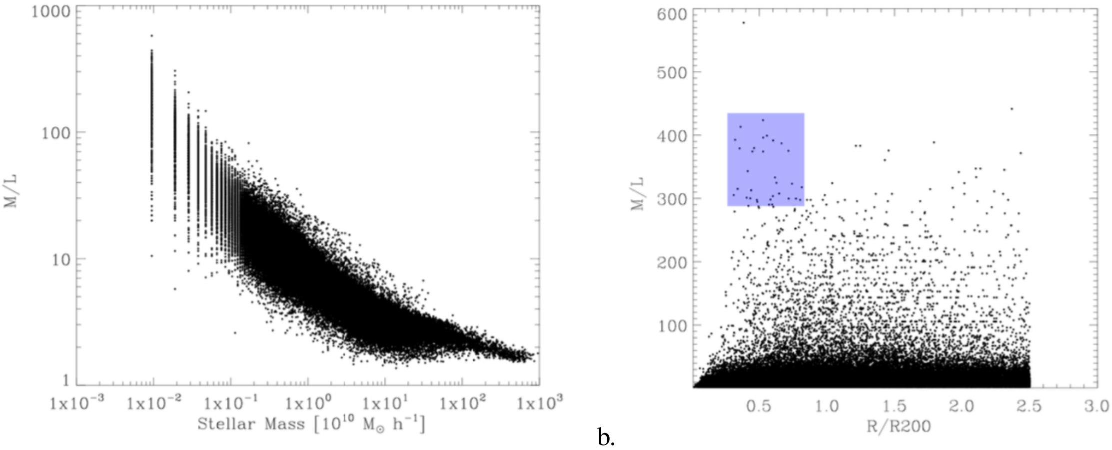


Figure 4: The mass-to-light ratio versus stellar mass within DM subhalos. Our result interpreted from this plot has looked a good agreement with the previous work [12], and we discussed vastly on this section Fig. 5 (a)

We looked our discussions in the above section to gave similar evidence with the relative distance of DM subhalos in the clusters that belong to the mass-to-light ratio found and the mass of the stellar within them.

4 Conclusions

We have obtained the distributions of DM particles within the galaxy clusters by applying the SPH kernel which allows us to determine the DM density, which decreases as we go from the center towards the edge of the galaxy clusters. For the purpose of our work we are focusing on the characteristics of the high mass-to-light ratio of DM subhalos, based on MUSIC data set for all 282 clusters we simulated using ROCKSTAR halo finder algorithm and we found 466, 621 subhalos. We understand that the mass of DM is directly related to the number of subhalos. If the number of subhalos increases, the amount of DM content will also increase. The high mass-to-light ratio is located around the smaller mass



a. b.

Figure 5: The graph of DM subhalos based on mass-to-light ratio and stellar mass in the (left) and the plot of DM subhalos based on M/L and the ratio of their radial distance (R) to radius of their clusters to the (right) [12].

of DM subhalos we also determine the mass-to-light ratio with respect to R to R_{200}. It is high within the radius around $0.5\times R_{200}$. In conclusion the major distributions of subhalos is found around 1 times R_{200}.

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