Analysis of the Dark Matter Halos and the Relation to Galactic Evolution Based on IllustrisTNG50

Jingyi Peng*

Beijing Etown Academy, Beijing, 100176, China

*Corresponding author: wyt123@mail.ustc.edu.cn

Abstract. In recent years, plenty of simulations have been carried out in order to investigate the relationship between galaxy evolution and dark matter halos. This study used the powerful IllustrisTNG50 simulation to investigate the nature of dark matter halos and explore their intricate relationship to galactic evolution. Based on careful analysis of the simulation data, this research investigates various features of dark matter halos, including their distribution, density profile, shape, and color. The analysis revealed distinct patterns in the distribution of dark matter halos in different mass ranges, illuminating the intricate interplay between dark matter and cosmic structure. In addition, this paper investigated the influence of dark matter halos on the collection and distribution of galaxies within them. These results revealed that galaxies tend to concentrate in the central regions of halos, due to the violent gravitational force that pulls surrounding galaxies toward the center. This phenomenon resulted in densely populated clusters of galaxies in the central regions of the halos, comprising numerous galaxies.

Keywords: Dark matter halos, galactic evolution, IllustrisTNG50.

1. Introduction

In recent decades, cosmological research has made tremendous progress, giving us a deeper understanding of the structure and evolution of the universe. Dark matter halos are fundamental building blocks of the cosmos, massive structures formed by the gravitational pull of dark matter that serve as the basis for the formation of visible matter, such as galaxies and clusters of galaxies. However, the true nature of dark matter remains a mystery, and its interactions with visible matter and its influence on the evolution of galaxies are still not fully understood. In cosmological simulations, IllustrisTNG50 is considered one of the most advanced models capable of reproducing the evolution of the universe with high resolution and precision. By using the IllustrisTNG50 data, one can study in depth the properties and evolution of dark matter halos and explore their links to the formation and evolution of galaxies.

A dark matter halo is the halo of invisible matter that permeates and surrounds a galaxy or a cluster of galaxies. Although dark matter has never been detected in laboratories, physicists are confident dark matter, which makes up 85% of the universe's matter, exists [1]. A dark matter halo is that part of the dark matter of a galaxy which extends over the entire visible galaxy and beyond, i.e. is a halo. A dark matter halo is a hypothetical region predicted by the ΛCDM model [2]. A single dark matter halo may contain multiple virialized clumps of dark matter bound together by gravity, known as subhalos [3]. Both halos and subhalos may contain galaxies [4]. Dark matter accounts for the apparent extra gravity of a galaxy, galaxy cluster, or other large structure that extends beyond the visible and derived stars, the interstellar medium, and other normal matter. The velocity distribution of orbiting stars depends on gravity (and hence mass) and can be determined from the Doppler shift of starlight, which can be used to determine the mass of the galaxy, including mass that is not apparent from the number and mass of stars.

Dark matter halos exhibit six properties commonly used to characterize dark matter halos: Mass, concentration, spin, shape, overdensity, and the angle between the major axis and the angular momentum vector. One can account for much of the variance of these properties with halo mass and concentration, on the one hand, and halo relaxedness on the other. Nonetheless, three principle components are usually required to account for most of the variance. It is argued that halo mass is not

as dominant as expected, which is a challenge for halo occupation models and semi-analytic models that assume that mass determines other halo (and galaxy) properties [5].

Data from the IllustrisTNG50 simulation show that the gravitational influence of dark matter halos causes the surrounding gas to contract, leading to the formation of galaxies. Through the simulation, one can trace the evolutionary history of galaxies and observe the distribution, velocities, and chemical composition of the stars within them. These data help reveal how dark matter halos drive the formation and evolution of galaxies. By studying dark matter, one can gain valuable insight into the evolution of the universe. The evolution of the cosmos plays a crucial role in determining its future state, especially in an environment where human existence is relatively unstable, which may affect human development. The study of dark matter allows us to better understand the evolution of the universe. This will allow us to anticipate changes at an early stage and give us enough time to react to possible unknowns. This study also uses the IllustrisTNG project's Jupyterlab to study the mass evolution of components in subhalos, such as stars, galaxies, dark matter, and black holes. IllustrisTNG is a large-scale galaxy formation simulation project that aims to predict the formation and evolution of galaxies and the large-scale structure of the universe.

2. Data and Method

2.1. Dark Matter Halo's Properties

The nature of the dark matter in the silver halo is still uncertain, but there are some candidates, such as superpartners, axions, etc. 95% of the mass of the Milky Way is dark matter, which appears to have no interaction with the matter and energy within the galaxy except through gravity. All of the dark matter in the Milky Way appears to exist in the dark matter halo, which is more than ten times the mass of the visible stars, gas, and dust. The total mass of the bright matter is about 90 billion solar masses, and that of the dark matter halo is about 600 billion to 3 trillion solar masses. The formation of dark matter halos (DM) is a complex process combining gravity and nonlinear phenomena in cosmology. One expression of this complexity is the shape of present-day DM halos: simulations and observations suggest that they are triaxial objects. Interestingly, these shapes carry cosmological information. One shows that cosmology, in particular dark energy models, has a lasting impact on the properties of present-day halos: When the DE models vary, the overall shape of the DM halos shows different behavior.

One of the most striking features of dark matter halos, even at z=0, is the deviation from sphericity they generally exhibit.This can be stated from N-body simulations [6], but is also observed in particular for the Milky Way halo [7]. A review of related observational methods and theoretical considerations can be found in [8]. It is natural for this to lead to studying the links between the shapes of halos and the underlying cosmological model. Dark matter halos typically have a spherical or ellipsoidal shape. This is determined by the gravitational interactions between dark matter particles. The dark matter density within dark matter halos is uneven, with higher density typically in the central region gradually decreasing outward. This density distribution influences the formation and evolution of galaxies within the halos. Dark matter halo are not evenly distributed in the universe, and they are usually concentrated in some regions, forming a "network" distribution in the Large-scale structure of the Universe of the universe. Through the simulation, one can observe the distribution of Dark matter halo on different scales, revealing the construction process of the cosmic vein.

A dark halo is the presumed halo of invisible material (dark matter) that permeates and surrounds individual galaxies and groups and clusters of galaxies. Evidence for the existence of dark matter was initially provided by studies of the motions of stars and gas in galaxies. For example, the quantity and distribution of luminous matter in disk galaxies, for example, cannot explain the observed rotation curves, suggesting a significant unseen component. Similarly, velocity dispersions measured in the outer regions of elliptical galaxies are higher than expected given the luminous matter in the galaxy. Estimates based on these considerations suggest that perhaps as much as 90% of the matter present in galaxies is in the form of dark matter. Evidence for dark matter is also found through observations

of the motions of galaxies in groups and clusters. Using a similar argument to that applied to stellar motions within galaxies, the velocities of galaxies in groups and clusters are so high that the group or cluster would fly apart if only the luminous matter were present [9]. A sketch is shown in Fig. 1. Dark matter halo gravity affects galaxy formation and evolution. Simulations can be used to understand the influence of the dark matter halo on the grouping and arrangement of galaxies, as well as the motion of galaxies within the halo. Dark matter halos are dynamic entities that change over time. The simulation can trace the historical evolution of dark matter halos and reveal their formation, merging, and division.

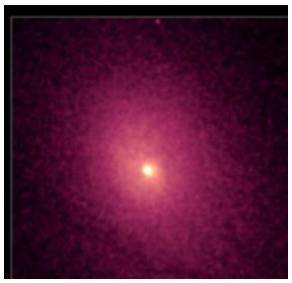


Fig. 1 X-ray image.The cluster is embedded in an enormous cloud of hot X-ray emitting gas. This hot gas would evaporate from the cluster if a dark halo was not present.

2.2. The Properties of Dark Matter Halos and Correlation with the Evolution of Galaxies

Dark matter in the universe plays an important role in the formation and evolution of galaxy clusters, mainly in two ways. First, star clusters tend to be located in regions with the highest density of dark matter and in intergalactic environments. The dark matter traps these clusters in this environment and accumulates mass, including black holes and stars, to form the cores of these stellar aggregates. Second, the influence of dark matter on the evolution of galaxy clusters is enormous. The evolution of these galaxy clusters is largely determined by the presence of dark matter. Certain fluid models suggest that the stability of a cluster increases when the dark matter in a cluster outweighs the other matter. Therefore, it becomes a key factor in maintaining the equilibrium of the galaxy cluster, protecting the stability of the cluster from the influence of large energy sources such as black holes and novae. It is a key factor in cluster formation by providing material and gravitational support and facilitating collision, aggregation, and dispersion of stellar bodies within clusters. In addition, it can modify the macroscopic properties of galaxy clusters, including the rotation rate, mass distribution, and structure of the visible cluster. Their interactions lead to relativistic effects that add a new complexity to the evolution of these clusters.

3. Results and Discussion

The IllustrisTNG50 simulation shows the shapes and distributions of dark matter halos of various sizes. Based on the simulation results, one can, for example, create distribution maps of dark matter halos in different mass ranges, which vividly illustrate their spatial arrangement in the cosmos. Within smaller mass regions, dark matter halos tend to be scattered and exhibit a relatively uniform distribution pattern. These lower mass dark matter halos likely represent early stage formations that have not yet undergone extensive merging processes. As the mass increases, the dark matter halos begin to exhibit a tendency toward greater concentration, clustering more tightly in certain regions. This could be due to the merging of lower mass halos, which gradually give rise to larger mass halos. In larger mass regions, the distribution of dark matter halos becomes denser, concentrating mainly in regions of high cosmic structure density, such as the centers of galaxy clusters. These more massive dark matter halos could be the result of multiple merging and accretion events.

Using the data from IllustrisTNG50 as illustrated in Fig. 2, one can construct distribution maps of galaxies, showcasing how they cluster together under the gravitational influence of dark matter halos. These images can illustrate the distribution patterns of galaxies in different regions of dark matter

halos. Most galaxies tend to cluster in the central regions of dark matter halos. This is because the gravitational pull of the dark matter halo is strongest in the central region, attracting the surrounding galaxies toward its core. As a result, denser galaxy clusters comprising numerous galaxies form in the central regions of the dark matter halo. This phenomenon is called central enrichment. Some galaxies may be located in the peripheral regions of the dark matter halo. These galaxies may not experience as strong an attraction from the dark matter halo, causing them to distribute in thinner regions. This distribution pattern could be related to the dynamical processes of the galaxies within the halo.

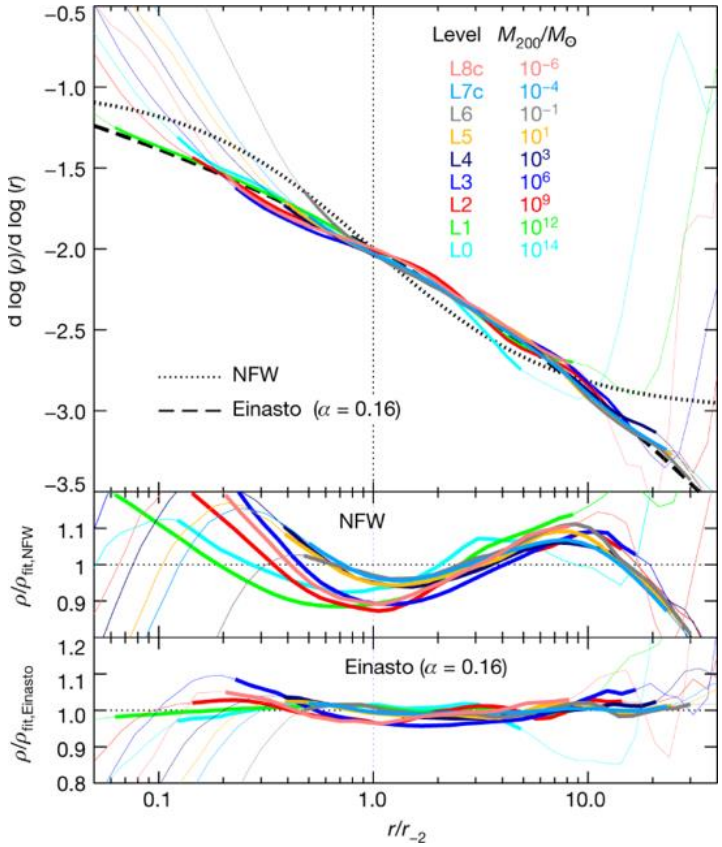


Fig. 2 Results of NFW.

In certain cases, galaxies can align along the filamentary structures of the dark matter halo, forming so-called "dark matter bridges" or "dark matter filaments" This phenomenon is more pronounced in larger dark matter halos, suggesting the influence of galactic interactions and motions within the halo. Within massive galaxy clusters, multiple levels of hierarchy can be observed, including different galaxy clusters and galaxies within these clusters. The galaxies within these clusters could cluster at different hierarchical levels, resulting in a broader cosmic structure.

The IllustrisTNG50 simulation has yielded several intriguing conclusions about the evolution of galaxies that include important aspects. During the course of cosmic evolution, galaxies are constantly undergoing mergers and interactions. These merging events can lead to changes in the morphology and characteristics of galaxies, potentially resulting in the formation of larger mass galaxies or clusters of galaxies. The simulation also vividly illustrates the evolution of galaxy morphology. From spiral to elliptical shapes, galaxy shapes can change significantly over time, often influenced by merger events and internal dynamics.In all cases the limitations of projection effects play a role, as data effectively provide two-dimensional structural characterizations. Recently, attempts to infer the three-dimensional geometry of galaxies - the least ambiguous description of a galaxy's mass distribution - have emerged, starting from the ansatz that the shapes of ellipticals and spirals can be well approximated by triaxial ellipsoids. For example, at high redshifts, analyses of a large sample of Lyman- break galaxies imply that a non-negligible fraction of star- forming galaxies at > 1.5 are intrinsically elongated, or strongly triaxial [10].

In addition, the simulation provides insight into the distribution of galaxy magnitudes as they relate to their brightness. These distributions provide insight into how the number of galaxies changes with respect to their brightness, which is useful in studying the properties of galaxy populations. The different color distributions of galaxies within the simulation are also important. These colors can be related to the age and metallicity of the stars in the galaxies, providing information about the formation and evolutionary history of the galaxies. In terms of the dynamics of galaxies within clusters, including relative velocities and orbits, the simulation provides valuable insight into the evolution and motion of galaxies. No studies have yet provided an extensive and conclusive kinematics analysis of populations of simulated star-forming galaxies that can be broadly contrasted to the results from slit-like and IFS-like current observations. So far, large uniform-volume simulations have been analysed in order to shed light on the dichotomy and formation of fast and slow rotators and to quantify the connection between galaxy morphology and spin on the one side and AGN feedback, environment or mergers on the other [10]. In essence, the IllustrisTNG50 simulation deepens our understanding of galaxy evolution and reveals the rich diversity and intricate processes that govern galaxies in the cosmos.

4. Limitations and Prospects

While the IllustrisTNG50 simulation has provided valuable insights into cosmic and galaxy evolution, it does come with certain limitations. Its spatial resolution is already quite high in current simulations, yet it may still fall short in capturing some small-scale physical processes and structures, especially within the intricacies of galaxies. The simulation's volume is finite, which implies that it might not fully represent all regions and structures present in the universe. Some rare yet significant astrophysical phenomena might not receive thorough consideration.

Moreover, to make the simulation feasible, certain simplifications may have been made in the physical models. These simplifications could lead to the omission of certain complex processes, potentially affecting the accuracy of certain conclusions. Additionally, the simulation might not encompass all possible physical processes, such as the particle nature of dark matter, potential unknown particles, and undiscovered forces. Furthermore, one is able to bound by limitations in computational resources. Despite continuous advancements in computing capabilities, simulating the evolution of the universe and galaxies still demands a substantial amount of computational power. Consequently, the scale and level of detail of the simulation could be constrained by available computational resources.

By simulating the evolution of the universe and galaxies, IllustrisTNG50 can provide profound insights that help us explore the origin, evolution, and structure of the cosmos. This is of great importance for answering key cosmological questions, including studying the nature of dark matter and dark energy, understanding the mechanisms underlying the formation of cosmic structures, and unraveling the processes involved in the formation and evolution of galaxies.

In addition, the simulations performed by IllustrisTNG50 provide a detailed understanding of the internal physical processes in galaxies. For example, one can study the formation of stars, the evolution of galaxies through mergers, and the growth and activity of black holes. This provides valuable information for studying the diversity and evolutionary pathways of galaxies and helps us interpret various observed galactic phenomena. In the realm of actual astronomical observations, IllustrisTNG50 simulation results play a critical role. They help scientists prioritize observational targets and develop appropriate observational strategies to better understand and interpret observational data. This synergy between simulation and observation will further advance our understanding of the universe and galaxies and help unravel more astronomical mysteries.

5. Conclusion

In summary, this study has addressed several crucial fundamental properties of dark matter halos and their interplay and implications for galactic evolution. The article analyzed the distribution, density profiles, shapes, and colors of dark matter halos, shedding light on their complex properties. At the same time, it is explored how galaxies react and manifest in different regions of dark matter halos. This article has provided fundamental insights and theories about the nature of dark matter halos and galactic evolution. Based on the analysis, it has laid the foundation for understanding the intricate relationship between these cosmic components. Looking ahead, it is anticipate that IllustrisTNG50 will continue to be an invaluable resource for astrophysics, providing robust data that will allow scientists to further explore the mysteries of the universe. Furthermore, it is believed that the insights derived from these simulations will enhance our understanding of the cosmos and make sound knowledge available to those interested in the wonders of the celestial world.

References

[1] Iqbal P. Why are dark matter halos of ultra-diffuse galaxies so odd. UCR News, 2018, 11.

[2] Einasto A J Kinematics and dynamics of stellar systems, Trudy Inst. Astrofiz. Alma-Ata 1965, 5: 87.

[3] Wechsler R, Tinker J. The Connection between Galaxies and their Dark Matter Halos. Annual Review of Astronomy and Astrophysics 2018, 56: 435–487.

[4] Mo H, Bosch F, White S. Galaxy Formation and Evolution. Cambridge University Press, 2010.

[5] Skibba R A, Macciò A V. Properties of dark matter haloes and their correlations: the lesson from principal component analysis. Monthly Notices of the Royal Astronomical Society, 2011, 416(3): 2388-2400.

[6] Allgood B, Flores R A, Primack J R et al. The Shape of Dark Matter Haloes: Dependence on Mass, Redshift, Radius and Formation. Mon. Not. R. Astron. Soc. 2006, 367: 1781–1796.

[7] Oguri M, Takada M, Okabe N, et al. Direct measurement of dark matter halo ellipticity from two-dimensional lensing shear maps of 25 massive clusters. Monthly Notices of the Royal Astronomical Society, 2010, 405(4): 2215-2230.

[8] Limousin M, Morandi A, Sereno M, et al. The Three-Dimensional Shapes of Galaxy Clusters. Space Sci. Rev., 2013, 177: 155–194.

[9] Dumar J. Kepler Made Me Do It. The Physics Teacher, 2021, 59(2): 130-133.

[10] Pillepich A, Nelson D, Springel V, et al. First results from the TNG50 simulation: the evolution of stellar and gaseous discs across cosmic time. Monthly Notices of the Royal Astronomical Society, 2019, 490(3): 3196-3233.