Dean&Francis
ISSN 2959-6157

The Role of Dark Matter Halos in Galaxy Formation and Evolution

Shijie Yang*

Department of Haidian Kaiwen Academy, Beijing, 100000, China
*Corresponding author: 20240927031@hd.kaiwenacademy.cn

Abstract:

Dark matter halos play a pivotal role in the formation and evolution of galaxies in the ΛCDM cosmological paradigm. This paper combines theoretical, observational, and simulation-driven approaches to expound their role. In theory, halos are formed through gravitational collapse, exhibiting characteristic properties (e.g., NFW density profiles, mass functions) that provide support for the cosmic web structure. The gravitational potential well generated by them can cause black hole matter accretion, thus regulating the cooling of gas, the formation of stars, and the process of supernova or Active galactic nucleus (AGN) feedback. The assembly history of dark halos (Halo mergers and their effects on galaxy morphology) and the environmental effect (The impact of cluster-scale halos on galaxy evolution) further shape the path of galaxy formation and evolution. Observational evidence – from Gravitation Lensing (Insights from lensing surveys) to Galaxy Kinematics (Rotation curves of galaxies). Regarding insights from simulations, another focus is on cosmological simulations and comparing the simulation data with observations. In summary, dark matter holes are a crucial center of cross-cosmic time, connecting cosmic structure and galaxy properties. The remaining open questions suggest a need for a deeper understanding of its interaction with galaxies through future observations and simulations.

Keywords: Dark matter halo; galaxy formation; galaxy evolution

1. Introduction

Within the modern framework of cosmological structure formation, dark matter holes are the fundamental building blocks of cosmic structure, and approximately five out of six of the universe‘s mass is composed of dark matter. The large-scale structure of the cosmos has been observed to exist and form through a combination of long-term gravitational collapse, gradual accretion, and other similar processes. Through this process, a fibrous and spongy structure gradually emerges. After 13.7 billion years, this

ISSN 2959-6157

slight density fluctuation was amplified by the gravitational influence of dark matter. Therefore, every galaxy was formed from a dark matter halo[1-3]. Each galaxy forms part of the entire cosmic structure; thus, dark matter halos are considered the fundamental units of cosmic structure. The galaxy-halo connection refers to the multivariate statistical distribution of the properties of galaxies and halos, which can be derived from both observations and simulations [1].

Empirical model construction related to galaxy-formation histories involves the influence of dark matter holes on galaxy properties. This model can track galaxies within dark halos over time, but it will directly impose restrictions on the galaxy-halo connection at different periods. The other model is the physics-based model of galaxy formation. This model aims to construct a framework of the fundamental physical steps in galaxy formation, or to simulate them directly [1]. Based on these, the primary purpose of this paper includes the following: Theoretical framework: dark matter holes in ΛCDM cosmology—what are the hole and halo properties? The formation and evolution of dark matter halos and galaxies: By the model, observation, and simulation of the relationship and interaction between galaxies and halos.

In the model part, the author focuses on the Empirical modeling of galaxy-formation histories and the physics model of galaxy formation. In observation, focusing on the methods of observation, like Gravitational lensing and Multi-wavelength Observations. Regarding the Simulations, the author focuses on cosmological simulations and Zoom-In Simulations. Then, comparing them with observations.

2. Theoretical Framework

2.1 Dark Matter Halos in ΛCDM Cosmology

2.1.1 The formation of halos through gravitational collapse

Within the modern framework of cosmological structure formation, the definition of a dark matter halo is the fundamental unit of matter that collapses into a gravitationally bound structure. Generally, the dark matter halo can be viewed as a region of substance constrained by gravitational force, which has already detached from Hubble expansion and collapsed under its own gravity [1]. The definition of numerical simulations is the following formula.

$$M_{vir} = \frac{4\pi}{3} R_{vir}^3 \Delta\rho_m \tag{1}$$

This means that in numerical simulations, it can be characterized by masses and radii specified by a given overdensity [1]. Back to the real definition, the dark matter halo formed by the gravitational collapse: the small-scale overdense region in the early cosmos, enhanced by the action of the gravitational force itself, attracts the surrounding substance until forming the "Virialized system" which was restricted by the gravitational force [4]. On a small scale, the dark matter halo, which was non-linear, collapsed and formed relatively dense, virialized clumps – dark matter halos [5].

2.1.2 The mass function of holes and its evolution over cosmic time

The halo mass function (also known as the abundance of dark matter halos) plays a central role in cosmology due to its ability to provide essential parameters, such as the cosmos' matter density and the Hubble parameter; however, it cannot provide accurate observational data. It is relevant to the cosmic time(redshift). For example, it plays a role in modeling the process of reionization, which occurs when the redshift is between 6 and 20 from the source of dark matter halos containing Population III Stars (Pop III Stars), primitive galaxies, and black holes undergoing accretion. This function is used in statistical analysis of galaxy cluster surveys, the purpose of which is to constrain cosmological parameters at low redshift. This is because these massive celestial bodies can detect the large mass end of this function [6].

2.2 Halo Properties

The numerical simulation shows that the properties of the dark matter halo depend not only on its mass, but also on its mass. On the contrary, the properties are also based on the environment in which the halo resides. The environmental definition categorizes halos into four classes with distinct dynamical properties: voids, sheets, filaments, and clusters. These environments are identified based on he tidal stability criterion of the test particles, which depends on the Zel'dovich approximation. At each redshift, the properties of dark matter halos which is researched have some relationship with the environment and mass. In addition, when these properties were examined, which were taken as the function of scale mass M/ M_*, the redshift dependence of dark matter halo properties with mass will be eliminated, where M_* is the typical mass scale collapsing at each epoch [7]. Thus, this conclusion indicates that mass is not the sole factor affecting the properties.

The dark matter halo has already been identified by three key features: the Navarro-Frenk-White (NFW) profile, virialization, and substructure. A general three-parameter family can describe this, also known as the Zhao models. They are defined by their density [8].

$$\rho(r)=\frac{2^{(\gamma_\infty-\gamma_0)/\eta}\rho_s}{(r/r_s)^{\gamma_0}\left(1+(r/r_s)^{\eta}\right)^{(\gamma_\infty-\gamma_0)/\eta}} \tag{2}$$

3. Dark Matter Halos and Galaxy Formation

3.1 Initial Conditions

How do dark matter halos generate the gravitational potential wells that allow baryonic matter to undergo gravitational collapse? The method characterizes these halos based on their mass accretion histories (MAHs) and their potential well growth histories (PWGHs), which were extracted from the Bolshoi simulation and the semi-analytic composite tree. A method is used to calculate the maximum peripheral velocity of the ancestral dark matter halos. Regarding the details, the formation of the dark matter halo is effectively described by the merger history tree, which illustrates how its progenitors merge and accrete material over universe time. As the merger tree traces the timeline, each dark halo is broken down into multiple progenitor halos, which are then further divided into earlier progenitors, and so forth. The main progenitor is the halo with the largest mass or the one contributing the most mass to the descendant halo. The primary branch of the merger tree is referred to as the branch that follows the primary ancestry of the main ancestry, tracing back in time. The evolution of mass changes is tracked along the main branch, denoted as M(z), which is known as the mass accretion history (MAH). It has a significant effect, which is the most commonly used physics quantity to illustrate the development of a dark halo assembly. With surprise, there is insufficient focus on the development of the dark matter potential wells. Moreover, another important property is the likely depth, which is strongly proportional to the maximum circular velocity of halos. Vmax is a commonly used parameter in halo abundance matching. Because the feedback is the key factor of galaxy formation, the Vmax could serve as a more effective ‚regulator' of galaxy formation compared to halo mass. The efficiency of the feedback process, which involves the discharge of matter and metal, depends on the escape speed; it is further based on the depth of the central potential well. Vmax also has another beneficial aspect, namely that it is measured more strictly than halo mass, not only in simulations but also in observational data. Furthermore, it does not have 'pseudo-evolution' and 'multiple definitions' problems [9].

3.2 The Halo-Galaxy Connection

Within the framework of ΛCDM cosmology, galaxies are assumed to form within dark matter halos, created through the gravitational instability of the cosmic density field. To understand the formation and evolution of the galaxy, it is necessary to establish the interconnection between galaxies and dark matter halos. To achieve this goal, people have developed various methods, including full numerical simulation, which models subgrid physics numerically, and clustering. These methods have already played a significant role. Depending on the simulation model, the understanding of subhalo properties was deeper. The subhalo catalogues of each simulation (eg, TNG and EAGLE) present a variety of quantities, such as the stellar mass, halo mass, and star formation rate. Regarding the Galaxy stellar-to-halo mass relation (SHMR), the sample will be split into disc galaxies and elliptical galaxies. The research indicates that the relationship between morphology and stellar mass varies depending on the conditions. Moreover, in the condition that the mass of dark matter halos is equal, using the methods that this work used to estimate the mass of stars, the median stellar mass of elliptical galaxies is always greater than that of their disk galaxy counterparts. Mandelbaum et al. also used stellar masses from Kauffmann et al., but they combined these with halo masses estimated from galaxy–galaxy lensing [10]. They separated the galaxies into blue and red(galaxies with g-$r \geq 0.8$ classified as red and galaxies with g-$r < 0.8$ as blue). They found that when the mass of the stellar system is constant, the mass of the red galaxies residing in halos is at least twice that of those halos hosting blue galaxies. In contrast, the color-SHMR is calculated in halo mass bins; the relation changes. Additionally, the mass of the stellar component is constant. Blue galaxies have slightly larger stellar masses, but when the mass of halos exceeds 10^13 solar masses, the relation changes, and the mass of red galaxies is greater than that of blue galaxies at a fixed halo mass [11].

4. Dark Matter Halos and Galaxy Evolution

4.1 Role of Halos in Assembly History

Within the conventional ΛCDM model at present, galaxies are considered to have formed due to baryon gas cooling and collapse within the dark matter halo. These dark matter halos existed within the cosmic web, which comprises filaments, sheets, knots, and voids. As a result, the properties of galaxies are likely to be strongly connected to their host halos and the surrounding large-scale environment

[12]. According to the N-body simulation, it has been proven that halo mass is not the sole factor influencing the properties of galaxies, but also relates to dark matter halos , other properties . For example, the halo formation time. This phenomenon is named “Halo assembly bias”. The N-body simulation reveals that the halo formation time is a crucial factor in the clustering of halos. When the mass of the halo is lower and constant, the older halo is intensely clustered than the younger one, but at the high-mass end, the situation will be opposite. Moreover, in observation, the concept of „galaxy formation bias“ lacks a precise and universally accepted definition to date [12].

4.2 Environmental Effect

To research the factors of properties of galaxies, which are the cluster-centered radius and the environment associated with the closest neighboring galaxy, by using the Sloan Digital Sky Survey galaxies related to the Abell galaxy cluster. The characteristic scale, which ranges from 1 to 3 times the cluster‘s virial radius, is based on galaxy luminosity. In this scale, the cluster-centric radius at a stationary neighbor environment suddenly becomes the key factor in determining the properties of galaxies. The existence of the characteristic scale indicates that the direct reason concerning the morphology–density relation in cluster systems is not the local galaxy number density [13]. This is because the local galaxy number density changes smoothly with the Center distance of galaxy clusters and typically does not exhibit discontinuities. In the clusters, the morphology–cluster–centric radius–neighbor environment relation plays a crucial role; the neighbor environment includes the morphology of the neighbor and the local mass density assigned to it. The morphology–density relation appears to be driven mainly by the distance to the nearest neighbor and the local galaxy number density. Late-type galaxies in galaxy clusters undergo morphological transformations (usually referred to as disc-shaped, star-forming, or active galaxies) that appear to occur through both hydrodynamic interactions between galaxies and gravitational interactions between galaxies and the galaxy cluster or between galaxies [14].

1. Conclusion

Under the ΛCDM cosmology framework, the dark matter halo is the gravitational core for the formation and evolution of a galaxy. They were born in original density fluctuations by gravitational collapse and compose the cosmic web, interwoven with fibers, sheets, and voids. They are also dominant in baryonic matter accretion, gas cooling, and star formation due to the gravitational potential well. In addition, the assembly history (Hierarchical integration and accretion mode of mass over time) and environmental effects (Tidal forces of galaxy clusters and interactions among neighboring galaxies) of the dark matter halo shape and stellar mass Core attributes, such as The combination of observation (Gravitational lensing and kinematic analysis of galaxies) and numerical simulation (Projects such as Bolshoi, Illustris TNG, and EAGLE) has already shown the universal properties of dark matter halos, such as NFW, SHMR, and the mass function that evolve with cosmic time. Moreover, in the cluster of galaxies, the evolution of galaxies is governed by the „morphological-central distance of galaxy clusters-neighboring environment relationship“. On a large scale, the gravitational potential well of the halo controls the motion of the galaxy; on a smaller scale, the morphology and local mass density of nearby galaxies also influence the galaxy‘s evolution. Although the areas mentioned above are addressed, there are also remaining challenges in understanding the interplay between halos and galaxies. The role of sub-halos in the evolution of satellite galaxies is contradictory - the number of predicted simulation sub-halos is far greater than the sub-halos that can be observed. With more, there is also a challenge regarding the unity between small-scale halo physics (such as subhalo dynamics) and large-scale cosmology. The model in the present cannot match the observed characteristic of „Ultra-faint dwarf galaxies“ or „dark matter deficiency systems such as NGC 1052-DF2.

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