The Impact of Dark Matter Halo on Galaxy Structure and Morphology in Early Universe

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Abstract. This essay will represent the importance of dark matter halo for galaxy formation and galaxy morphology in the early universe. The goal of this is to find the impact of dark matter halo on galaxy structure, and the relationship between different galaxies' dark matter halo. There are still some unknown parts of the dark matter halo, such as its radius and its peak distribution. In this essay, there are several citations from different research, from the dead massive galaxy MACS J2129.4-0741 to dwarf galaxy Tucana II, which aim to discuss the effect of dark matter halo widely. It includes the dark matter halo's properties and also includes the visual manifestation of dark matter halos. What's more, it includes the impact of dark matter halo in different kinds of galaxies. Overall, the essay presents some important conclusions about the importance of dark matter halo in structure and morphology summarizes some achievements of dark matter halo research, and some suggestions for future observation and simulation.

Keywords: Dark matter halo, Galaxy Morphology, Galaxy Formation.

1. Introduction

The dark matter halo is the invisible structure around the galaxies that control various properties of galaxies. Understanding these connections is useful for scientists to decrease the variance of observed data and control the number of variables in observations. There is much evidence both in simulations and observations showing the appearance of a dark matter halo, the dark matter that covers the galaxy. These invisible matters impact the formation, structure, and morphology of different types of galaxies. Nowadays, some ultra-faint dwarf galaxies (UFDs) around the Milky Way, such as Tucana II and Tucana III, are the main samples to observe and simulate the existence and effect of dark matter halo in the early universe. In 2021, scientists took deep observation and simulation on an ultra-faint dwarf galaxy: Tucana II, and found several far-flung stars were caught by the galaxy and moved far away from the center [1]. This represents that Tucana II has the bigger gravitational force on these stars to bind them within the tidal radius, this Is the effective result to predict there are huge dark matter halo covering the Tucana II galaxy [1, 2]. Dark matter halo could give useful information about the formation of the galaxy, as an example of Tucana II's halo, its extremely massive and extended halo structures directly imply that Tucana II was formed by the merger of two high redshift (z >~ 2) primitive galaxies [2]. Second, the dark matter halo could impact the mass-metallicity relation (MZR), the halo relates to some small-mass satellites, and these satellites' tidal stripping directly leads to the scatter of MZR's faint end [3]. This condition could strongly be shown in Tucana II, these extended stars around it are metal-poor [4].

Tucana II and Tucana II could also show the relationship between UFDs's dark matter halo and Milky Way's dark matter halo [4]. However, there are still some disagreements about the relationship. In 2008, Peñarrubia explained the extended stars in Tucana II by the Milky Way's tidal disruption, this represented Tucana II was impacted by the Milky Way's dark matter halo [4, 5]. However, this opinion was pointed out by some defects by Yuta Tarumi in 2021 [4]. He took two observable arguments to justify: Firstly, the distance between Tucana II and the Milky Way is too large to be impacted by the tidal disruption. Secondly, the relatively overall structure of Tucana II shows that it has not been destroyed and disintegrated by the tidal forces from the Milky Way [4]. Thus, although it has been confirmed that the dark matter halo of the Milky Way affects the UFD's dark matter halo, the extent of the impact is still being observed and simulated by scientists.

What's more, scientists could use the galaxy's dark matter halo to calculate the galaxy's rotation curve by observation and simulation. The rotation curve is the function between the radial velocity of the galaxy's stars, and dust and the distance from the center of the galaxy [6]. The dark matter surrounding the galaxy is inversely related to the brightness of the galaxy, which is, the more dark matter surrounds, the lower the luminosity of the galaxy, and this could be used by observation [7]. Moreover, the connection between galaxy dust and dark matter also represents the gravitational properties of the galaxy, which is necessary to obtain the rotation curve of this galaxy [7]. On the other hand, by simulating the dark matter halos in cosmological models, such as Λ cold dark matter (ΛCDM), a more macroscopic and massive galaxy model could be derived [8]. In ΛCDM, the dark matter halo expands along with the rotation curve, which will affect many nonlinear physical processes during the evolution of the galaxy, thereby affecting its properties. Finally, the simulation of this model, shows the massive spiral galaxy is the most efficient form of gas-to-star transformation because it only misses a few baryons [8].

2. First Galaxies' Dark Matter Halo

Dark matter halo, in the modern theory of cosmological structure formation, is the general unit of matter collapses and galaxy formation [9]. Since the dark matter halo covers galaxies, determining its radius could increase the understanding of the effects of galaxies' formation: Which is much wider and more complex than what the observation sees. In the simulation, the relationship between mass and radius generally used the equation as $M = \frac{4}{3}\pi R^3 \Delta\rho_m$.

What's more, in the radius of a dark matter halo, the peak is not unique [9]. There are many different peaks in one halo and they have relations by gravity, which means in one dark matter halo, there are several host halos and subhalos [9]. Subhalos always move around the host halo with the force of gravity. In simple words, it could be seen as an invisible star system: The host halo is the star, the subhalo is the planet, and the sub of subhalo is the satellite.

Similar to determining the radius of the star system, determining the radius of the dark matter halo is also complicated. This difficulty is not due to limited observations or missed data, it comes from the disagreements over the definition of "Dark matter halo's radius": Nowadays there are still many definitions of it and each of them has much effective evidence. For example, in 2017, scientists Kravtsov and Diemer suggested the dark matter halo's radius should be a "splashback radius" [9]. It focuses on the situation when the dark matter halo first collapses, defined as the radius of the subhalo structure, which stripped off the host halo, orbiting the host halo. However, different definitions could only lead to slight derivations in very detailed physics explanations, it will not cause a difference in overall conclusions.

2.1. Rotation Curves

The rotation curve is a realistic manifestation of the gravitational effect, and it is also an important argument for the existence of dark matter halos: Without dark matter halo, stars could move slower as the distance from the center of the galaxy increases. But rotation curves are not easy to measure in all types of galaxies, therefore, a low surface brightness (LSB) galaxy becomes a perfect choice for measuring the rotation curve [10]. In other types of galaxies, numerical simulations of cold dark matter (an important source of theory used to explain the fundamental properties of dark matter halo) have huge differences compared to the rotation curve observed. This makes it difficult to determine how rotation curves relate to dark matter. However, in LSB galaxies, the difference between these two is small. This means there are fewer negative impacts from other factors.

2.2. Galaxies in the Early Universe

Dark matter halo has occupied a large proportion of the universe since the birth of the universe. So, whether it played a huge role when the first galaxy and the first star were born is one of the focuses of scientists' research. In this research, three models are widely used: Cold dark matter (CDM), warm dark matter (WDM), and fuzzy dark matter (FDM). In these three simulations, the first galaxies appear similar filaments in WDM and FDM, which indicates that the dark matter halo affects the baryon distribution at small scales [11]. Especially in FDM simulations, the dark matter halo limits the number of stars formed in the early universe.

The density of the dark matter halo also determines the size of the potential galaxy evolution material [12]. The more potentially evolving matter, the greater the probability of galaxy formation. Although potentially evolving matter exists everywhere in the universe, the dark matter halo is an important medium that wraps and combines them. When there are enough evolved matter accumulates in a certain space, galaxies are born.

3. Dark Matter Halo in Different Morphology of Galaxies

The impact of dark matter halos on the morphology of early galaxies is also one of the current focuses of scientists. Nowadays, it has been confirmed by many simulations that dark matter halo with uniform internal mass distribution could foster galaxy formation, however, how the dark matter halo impacts old galaxies, even dead galaxies, still requires many observations and simulations to conclude [13]. Compared with today's universe, early galaxies, regardless of their mass, were very dense and compact. This also made the more intense explosions when galaxies formed at that time, a situation which is difficult to find in the universe today. Galaxies also take on different shapes during powerful nuclear star explosions. Some of these shapes are formed directly, while others are formed over a long period of evolution. Since these things have been happening for billions of years, some massive galaxies have already quenched and become dead galaxies such as MACS J2129.4-0741 [14]. Some galaxies are small and have extremely low metal content, which indicates that they do not form stars such as Tucana II and Tucana III [4, 15]. These galaxies are excellent samples for exploring the effects of dark matter halos on galaxy morphology because they are isolated (less affected by other galaxies) and stabilized (observed data are more constant).

3.1. Elliptical Galaxy

In 2017, scientists focused on two massive dead galaxies: disk galaxy MACS J2129.4-0741 ($z = 6.846 \pm 0.001$) and elliptical galaxy RG1M0150 (z = 2.636) [13, 15, 16].

MACS J2129.4-0741 is an elliptical galaxy that formed during the nuclear starbursts. This is a powerful example to show the effect of dark matter halo: It is a very fast-rotating galaxy, and its shape is maintained by it: This means stars in this galaxy are formed with the disk. Moreover, the shape of MACS J2129.4-0741 is acquired due to the significant changes in its kinematics [14]. The factor of change in the kinematics of a galaxy is the dark matter halo. Dark matter halo impact on cold gas streams which stabilize the galaxy morphology and star formation. Dark matter halo heats cold gas streams to cut off its supply to galaxies, this process leads to "halo quenching": Important materials for star formation are intercepted by the dark matter halo, causing the galaxy not to have enough material to form new stars in disk [14]. Overall, this directly leads to the death of MACS J2129.4-0741.

Another elliptical galaxy: RG1M0150, which is recently quenched, could show the process of rotation speed decreasing [17]. Since the dark matter halo has a strong correlation in the rotation curve (rotation speed), the slowdown in the rotation speed of the galaxy can be regarded as the influence of the dark matter halo. RGIM0150 still retains a large amount of net angular momentum after quenching to maintain the galaxy's rotation in the death state [17]. Dark matter halo could be a method to save these momentums.

3.2. Dwarf Spheroidal Galaxy

There are many ancient dwarf spheroidal galaxies in the universe, such as Cetus and Tucana. They are isolated and visible at huge distances from M33 and the Milky Way [5]. They have been affected by the Milky Way and M33 at the level of dark matter, an invisible level.

Among these dwarf galaxies, Tucana II is particularly special: it is a kind of Ultra Faint Dwarf Galaxies, which has a small population of ancient high-redshift star groups with extremely low metallicities [18]. Tucana II has no effective evidence that it ever experienced a period of explosive star formation, this suggests it is an inactive galaxy [19]. Therefore, the origin of several ancient stars in the periphery of Tucana II has become the focus of observations and simulations. Current opinion shows the situation is caused by the extended dark matter halo. It is the result of a merger of two young galaxies. The heating systems they generate induce the expansion of star halos and dark matter halos [4]. The expansion of star halos could also explain the star formation at a large distance from the galaxy center. Another possibility is the tidal stripping [3]. Either Tucana II is “stripping off” these stars from other galaxies, or Tucana II is being “stripped off” by other galaxies’ dark matter halo. After the mass loss, dark matter has more dominance over the galaxy [3].

Ultrafaint dwarf galaxies impact other galaxies and form tidal disruption. For example, the velocity gradient of Tucana III is $18.3 \pm 0.9\, km\, s^{-1}\, kpc^{-1}$, which shows it is undergoing tidal disruption [19]. However, in Tucana II, the velocity gradient is from $-8.7\, km\, s^{-1}\, kpc^{-1}$ to $3.6\, km\, s^{-1}\, kpc^{-1}$. This means Tucana II is not affected by tidal disruption. Therefore, the ancient stars in the outer reaches of Tucana II are not pulled out of the galaxy’s interior by trial disruption, but it’s not as intense as the Tucana III.

Table 1. Chemical abundances in stars of Tucana II [19]

Element	Stars	[X/H]	[X/Fe]
CH	TucII-301	-2.79	0.62
	TucII-303	< -2.14	< 0.60
	TucII-305	-2.78	0.81
	TucII-306	-2.74	0.52
	TucII-309	-1.46	0.48
Mn I	TucII-301	-4.05	-0.64
	TucII-303	-3.24	-0.50
	TucII-305	-4.04	-0.45
	TucII-306	-3.89	-0.63
	TucII-309	-3.32	-1.38
Fe I	TucII-301	-3.41	0.00
	TucII-303	-2.74	0.00
	TucII-305	-3.59	0.00
	TucII-306	-3.26	0.00
	TucII-309	-1.94	0.00

Table 1: Chemical abundances in stars of Tucana II (From Chiti A, Frebel A, Ji A P, et al. Detailed chemical abundances of stars in the outskirts of the Tucana II ultrafaint dwarf galaxy) [19]. This proves the stars in Tucana II are metal-poor [4].

4. Conclusion

This essay focuses on the dark matter halo, especially discussing the impact of the dark matter halo on the morphology and formation in the early universe. This essay also selected several representatives of early universe galaxies for basic analysis: Died Elliptical galaxies MACS J2129.4-0741 and RG1M0150, and dwarf spheroidal galaxy Tucana II.

From MACS J2129.4-0741 and RG1M0150, the existence time of the dark matter halo is greatly extended: it not only controls the morphology and star formation rate of the galaxy during its active period by heating the cold gas stream but also stores net angular momentum to maintain the motion of the galaxy after its death. Through Tucana II’s simulations, the radius of the dark matter halo was severely underestimated, although this might be the remnant of the merger of two galaxies. The dark matter halo is used for tidal stripping and preventing it from being stripped. This also means the influence between galaxies is often caused by the influence between dark matter haloes from different galaxies.

Understanding the influence of dark matter halo in early galaxies can infer the development trends of future galaxies. For example, as the distance between M33 and the Milky Way continues to shrink, the dark matter haloes of both galaxies will inevitably affect each other in the future (or have already begun to affect them), thus changing the structure and other properties of both galaxies. Scientists could determine the degree of influence of dark matter halo on numerical simulations through observations of ancient galaxies, then they can understand the data observation errors caused by mutual influence and eliminate these errors or variances in future simulations.

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