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Exploring Galaxy-Halo connection of MW-M31 merged remnant

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1. INTRODUCTION

Cold dark matter halo potential wells actively drive galaxy formation as they accrete and cool surrounding gas. A **dark matter halo** is the invisible structure of dark matter around a galaxy. This process allows us to predict a strong correlation between galactic properties, such as stellar mass and luminosity, with the halo mass (Girelli et al. 2020). For example, the **stellar-to-halo mass** (SHMR) relation measures the efficiency of a galaxy in converting the mass of its dark matter halo into stars. Since Dark matter halos grow their mass by merging with other such halos, it raises the question of how galaxies and the dark matter halo evolve together through mergers.

It is widely accepted that a significant and ubiquitous process that fuels galaxy evolution is through galaxy mergers. A **galaxy** is a system of stars held together by gravity, whose observed behavior cannot be fully accounted for by ordinary (baryonic) matter and Newtonian gravity alone (Willman & Strader 2012). Most massive galaxies are formed by smaller and other massive galaxies falling into their gravitational potential wells. **Galaxy evolution** is the process by which galaxies grow, morph, and change over time. It is, therefore, imperative to study the evolution of the dark matter halos through the mergers. The results of the study can help constrain various physical processes involved in galaxy mergers, such as feedback mechanisms and how efficiently baryonic matter converts into stars and galaxy assembly.

Though the Halo-Halo merger has been well constrained, the galaxy-galaxy mergers relative to halo-halo mergers remain largely unexplored (Hopkins et al. 2010). Various cosmological hydrodynamical galaxy simulations show that most of the stellar material in massive galaxies is a product of major mergers (merging with a similar massive galaxy) and orbiting satellites (Rodriguez-Gomez et al. 2016). Although there have been various studies in understanding the merger histories (Fu et al. 2022; Sotillo-Ramos et al. 2022), not much has been done to study the stellar remnant of Milky Way (MW), M31-type galaxies. Figure 1 shows that about 30 percent of simulated MW/M31 type galaxies go through at least one major merger since z = 1 (Sotillo-Ramos et al. 2022). For being so common, it motivates us to understand the Galaxy-Halo connection of stellar remnants of major mergers.

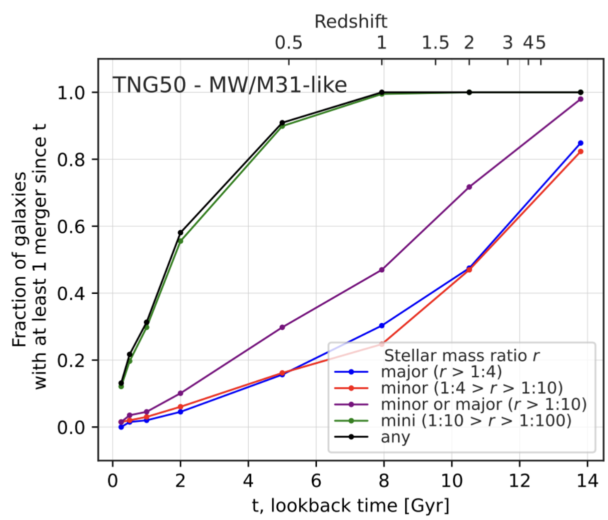

Figure 1. Fraction of galaxies with at least one merger versus the lookback time. A major merger, i.e., a merger with a similar massive galaxy, is shown in blue lines. Minor merger, i.e., a merger with a less massive galaxy, is shown in red line, and any merger is shown in black line (Sotillo-Ramos et al. 2022). 30 % of the MW-type galaxies go through a merger.

A leading open question in the Galaxy-Halo connection of stellar remnant is whether the stellar remnant of the merger follows the established SHMR (Moster et al. 2013). The observed burst in star formation in a merger event may cause a system to deviate from this relation(Hopkins et al. 2010). Or in the case of a **dry merger** (both the colliding systems don't have gas), does the stellar-to-halo mass relation (SHMR) change at different stages of the merger? Furthermore, how long would it take for the merged system to fall back on the relation if there is such a deviation? One kinematics question would be if the angular momentum of the remnant is conserved in a merger event, and what the velocity curve of the remnant halo would look like? Another intriguing question would be whether the phase space diagram of the halo of the remnant looks similar to the phase space diagram of either of the parent galaxies prior to the merger.

2. THE PROJECT

This paper will investigate the galaxy-halo connection of the MW-M31 merger's stellar remnant derived from collisionless N-body simulations of the MW and M31 (van der Marel et al. 2012) to see how galaxies and dark matter halos evolve through mergers. Here, N-body simulations simulate how particles like stars and dark matter particles interact with each other under the same physical forces such as gravity.

The main question that this study will answer is whether the stellar remnant follows the established SMHR relation (Moster et al. 2013).

Since MW-M31 is a dry merger, it will be intriguing to see if its remnant deviates from the SMHR. If it does deviate, it could highlight limitations in our current understanding of SMHR and motivate us to have a better relationship. If it lies on the current SMHR, it could motivate understanding how dry mergers without adding new gas or star formation can still follow the relation. This study will help calculate the merger's stellar mass and halo mass and determine its position on SMHR.

3. METHODOLOGY

This study uses the N-body simulations of MW and M31 (van der Marel et al. 2012). The model takes MW starting at rest at the origin in the galactocentric frame. Galactic disks, each with mass M_d, were modeled using exponential profiles characterized by a scale length R_d. The bulges, with mass M_b, followed the $R^{1/4}$ profiles. Additionally, a central supermassive black hole with mass $M_{\rm BH}$ was included in each galaxy. The surrounding dark matter halo was represented using a Hernquist (1990) density profile.

Since the focus is not on mapping the detailed galactic structure of the merger remnant, the analysis relies on low-resolution simulation data. The primary goal is to determine the stellar and halo mass of the merged remnant and compare it to the SHMR. The first part of the study would be to establish the SHMR from Moster et al. (2013), as shown in Figure 2, and follows the equation at z = 0:

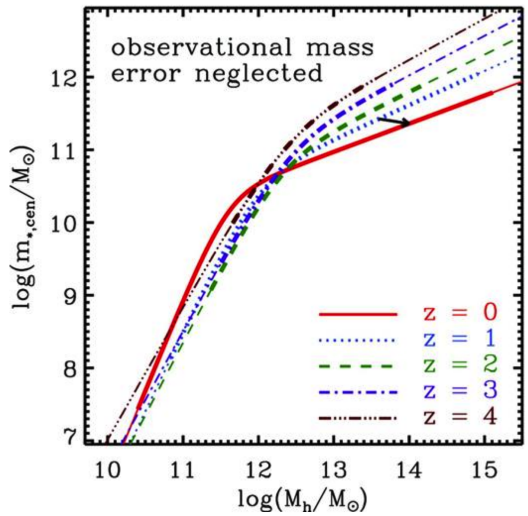

Figure 2. Moster relation, Stellar Halo mass relation as a function of halo mass for different redshifts (Moster et al. 2013).

$$\frac{m}{M} = 2N\left[\left(\frac{M}{M_1}\right)^{-\beta} + \left(\frac{M}{M_1}\right)^{\gamma}\right]$$

where, m = stellar mass, M = halo mass

$$\log M_1(z) = M_{10} + M_{11}\frac{z}{z+1}; N(z) = N_{10} + N_{11}\frac{z}{z+1}$$

$$\beta(z) = \beta_{10} + \beta_{11}\frac{z}{z+1}; \gamma(z) = \gamma_{10} + \gamma_{11}\frac{z}{z+1}$$

This study uses the same values of the constants as given in Moster et al. (2013).

The next part of the study is to find the halo and stellar mass of the merger remnant of MW and M31. By creating a function that loops over all the snapshots, we can compute the Center of Mass position and velocity as a function of time. This inherently is the orbit of both galaxies. Here, the Center of mass is computed using the following equation:

$$\mathbf{x}_{COM} = \frac{\Sigma x_i m_i}{\Sigma m_i}$$

where x is a vector, either position or velocity, and m is the mass of the particle in the simulation.

We find the epoch when the two systems merge by creating a function that finds the difference between the magnitude of the relative separation and velocity of the two systems. The first merger occurs when the distance

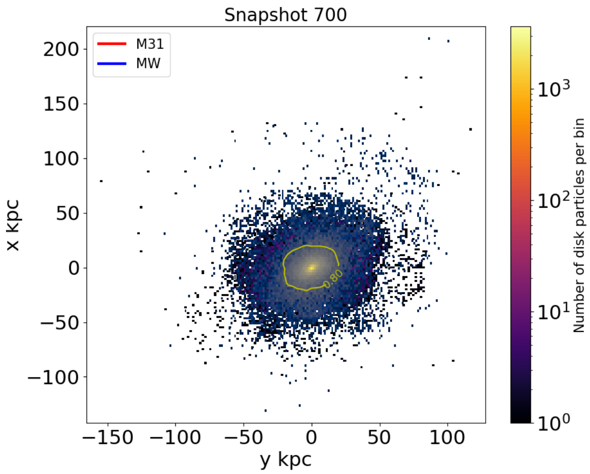

Figure 3. Snapshot of when the MW-M31 merger has settled down. MW particles are shown in blue. M31 particles are the ones in red. 80 % contour level is drawn in yellow.

between the two COMs is negligible. Any snapshot afterwards where the merger has settled down now will become our primary data for calculating the remnant's total stellar and halo mass. For this study, we picked a snapshot of 700. Figure 3 shows the merged remnant.

We will calculate the stellar mass using each galaxy's disk and bulge particles within the 80 % contour level and the halo mass by using the halo particles within r200 of the merged remnant. **R200** is the radius where the average halo density of the merger is equal to 200 × the critical density of the universe, taken as 125.6 $M_{\odot}/kpc^3$.

The last step would be to find the expected stellar mass for the simulated halo mass using the moster relation defined above. We then compare it to the simulated stellar mass and plot all these values on the SHMR at z = 0 and see how much it deviates. It will also be very intriguing to see how the merger remnant looks on the relationship as it evolves over time. Figure 4 illustrates this methodology.

This study believes that the remnant will not deviate from the SMHR, most likely because it is a dry merger. It does not have enough gas to form new stars, which raises the star formation rate due to the merger.

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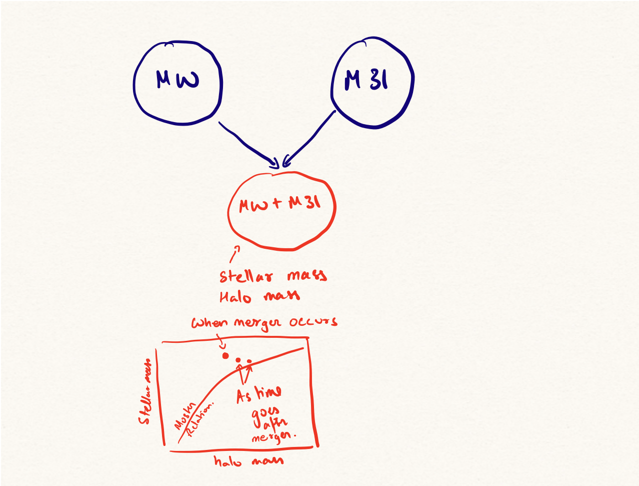

Figure 4. Visualization of the methods of this study.