Simulation of Two Massive Fuzzy Dark Matter Halos

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Abstract
This paper investigates a simulated collision between two equal mass Fuzzy Dark Matter (FDM) halos out to 400 Myr. The halo mass is on the order of magnitude of 10^{13} $M_{\odot}$. Further, I simulated a single FDM halo. The simulation of the single halo showed the radius oscillating and expanding. The simulation of the collision showed that the two halos merge into a dense clump of matter.

1. Introduction

Recent observations from the *James Webb Space Telescope (JWST)* provided significant information about the extremely red quasar, *SDSS J165202.64+172852.3*, at $z = 2.94$. In a paper by Wylezalek et al. (2022) [1], it was proposed that the system containing the quasar is "a good candidate for a merger of two or more dark matter halos, each with a mass of a few 10^{13} $M_{\odot}$" within a projected distance of 10-15 kpc. Wylezalek et al. claims that this could be one of the densest knots at $z \approx 3$. My goal was to simulate a merger between two dark matter halos at this mass and separation. In an attempt to make things more interesting, I decided to investigate this with *Fuzzy Dark Matter (FDM)* (Hu et al. 2000) [2].

FDM is an ultralight axion-like particles of masses $m_{\psi} \approx 10^{-23} - 10^{-21}$ eV. This creates a cutoff in the power spectrum that suppresses small-scale structure formation below the de Broglie wavelength. This aspect of FDM allows it to explain the central cusp in rotation curves, which cannot be explained with the λCDM model. There has been a lot of investigation into FDM, which has yielded mass functions and potential functions.

2. Methods

2.1. Theory

I used a FDM mass function derived in Bernal et al. (2017) [3]. The mass function transitions from a soliton mass function to NFW mass function at a transition radius, r_{ϵ}.

$$M_{FDM}(r) = \begin{cases} M_{sol}(r) & \text{if } r \leq r_{\epsilon} \\ M_{sol}(r_{\epsilon}) - M_{NFW}(r_{\epsilon}) + M_{NFW}(r) & \text{if } r > r_{\epsilon} \end{cases} \tag{1}$$

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where

$$M_{sol}(r) = \frac{4.210^6 M_\odot}{(m_\psi/10^{-23}eV)^2(r_c/kpc)} \frac{1}{(1+a^2)^7}$$
$$[3465a^{13} + 23100a^{11} + 65373a^9 + 101376a^7 + 92323a^5$$
$$+48580a^3 - 3465a + 3465(1+a^2)^7 arctana] \tag{2}$$

where $a := 0.301(r/r_c)$. The NFW mass function is

$$M_{NFW}(r) = 4\pi\rho_s r_s^3[ln(1+\frac{r}{r_s}) - \frac{r/r_s}{1+r/r_s}] \tag{3}$$

where ρ_s is

$$\rho_s = \rho_c \frac{(r_\epsilon/r_s)(1+r_\epsilon/r_s)^2}{[1+0.091(r_\epsilon/r_c)^2]^7} \tag{4}$$

and $\rho_c := 1.9(m_\psi/10^{-23}eV)^{-2}(r_c/kpc)^{-4}M_\odot pc^{-3}$. This leaves four free parameters: boson mass (m_ψ), half-light radius of soliton-like region (r_c), transition radius (r_ϵ), and scale radius (r_s). The boson mass is chosen to be $0.554x10^{-23}$eV, which is the value Bernal et al. chose for all low surface brightness (LSB) galaxies in their sample. LSB galaxies are primarily dark matter, which is why this boson mass was used. The remaining free parameters were chosen to fit the mass and radius conditions outlined in Wylezalek et al. With this in mind, the remaining parameters were assigned $r_c = 0.25$ kpc, $r_\epsilon = 0.1$ kpc, $r_s = 10$ kpc.

2.2. Simulation

The code for this project is published on GitHub (https://github.com/gabrielpfaffman/FDM-Halo-Collision). I primarily used the gravhopper python module (https://github.com/jbailinua/gravhopper). This python module allows you to insert particles, galpy potentials, and external forces to model a simulate a single potential or a collision. However, I did not import any external potential, and I built up the model using the Bernal et al. mass function (1). The gravhopper simulation runs a tree code simulator to calculate the sequential positions of masses.

The collision simulation calculates out to 100 Myr, with a time-step of 0.25 Myr. The FDM halo alone calculates out to 40 Myr with a 0.1 Myr step size. To create the distribution of points in the simulation, I wrote code to calculate the total mass at every 1000 pc. Then, the mass at one radius is subtracted from the mass in the step before it to get the amount that the mass has changed. From there, this mass is divided by $8x10^9$ $M_\odot$ to get an amount of particles, each with mass $8x10^9$ $M_\odot$. This amount of particles are added on a shell of radius that is 500 pc greater than the radius used for the calculation. Within 1000 pc of the center, the average density is calculated and uniformly dense sphere is produced.

For the collision, the two halos are placed 11.4 kpc apart in the xy plane. They are both moving at a speed of 150 km/s, directly towards each other. Each halo has a mass $2.85x10^{13}$ $M_\odot$. The simulation of the single halo is almost identical, except that it is situated at the center and has no relative velocity.

3. Discussion

The individual halo showed signs of expansion and contraction, as expected. The merger eventually settled into a dense clump of matter, not rotating much. To see for yourself, consult the videos posted on GitHub.

3.1. Limitations

A major limitation was having to clump the FDM into dense clumps of mass $5x10^8 M_\odot$. Making this simplification was necessary to get the code to run in a reasonable amount of time. It is possible that this simplification changes important aspects about the evolution of the halo.

I would have also liked to do more statistical analysis on the results and compare it to results from other papers and observable data. I did recreate some of the rotation curves from Bernal et al. (2017), however, none of the LSB galaxies that were used in Bernal et al were massive enough for this simulation. Due to this, I had to fit the parameters myself to get a result the necessary conditions.

3.2. Future Steps

In the future, it could be useful to obtain a rotation curve from the simulation and compare it to the data from Wylezalek et al. (2022). Doing this may allow us to obtain values for the free parameters from observation, and then further constrain the boson mass by fitting the model to the data. This would allow us to assess if the system in Wylezalek et al. (2022) may be explained by a merger of FDM halos.

Another future prospect is to use this framework for simulating a FDM halo to simulate spiral galaxies with FDM. This would require adding the additional, more common, potential/density functions. The validity of the model could be shown by comparing a rotation curve extracted from the model to the ones in Bernal et al. With this, one could model the evolution of a spiral galaxy with FDM. Beyond that, one may choose to also simulate a merger between two spiral galaxies with FDM, one spiral galaxy with FDM and one without, and a spiral galaxy consuming a galaxy primarily composed of FDM. It would be interesting to see how the inclusion of FDM would impact the dynamics of these events. However, it is possible that this method would not work, since the mass function from Bernal et al may not accurately describe the mass of an actively changing system.

Finally, a broader future step for FDM investigation is using Machine Learning (ML) algorithms. ML may be used to fit parameters to rotation curves, allowing us to constrain the boson mass using more data and much less time. I also suspect that ML may be useful in investigations about the possibility of several types of DM existing. Specifically, ML may be used to determine what relative abundances of different types of DM are most probable, based on observational data (namely rotation curves).

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