# The search for binary systems in ejected stars from galaxy mergers

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**Abstract**

We present the preliminary results of the search for binary systems of ejected stars from galaxy mergers. We discuss the impact of initial conditions on the amount of ejected stars during galaxy interaction. We predict that a higher initial relative velocity between the galaxies will result in a higher number of ejected stars. We have begun to setup a scheme to search for binary systems within our set of ejected stars, but have not been able to apply this to data.

## 1 Introduction

On of the features of the current cosmological model ($\Lambda$CDM) is its theory on formation of structures in the universe. We know from observations that structures like galaxies grow in size by merging with other galaxies. The merging of galaxies occurs everywhere, from large galaxies capturing small structures to major mergers of massive galaxies like our own Milky Way and Andromeda.
Galaxy interaction can be clean (like a low velocity merger), but they can also be destructive (like the bullet galaxy). A destructive interaction can partially destroy the structure of the passing galaxies, which results in the ejection of matter in the form of stars. Most of the stars have velocities that do not exceed the escape velocity of the merger, but if they do they are unbound from the merging galaxy and continue their path through the universe on their own.
During these mergers, many stars are ejected. This raises the question: Is it possible for ejected stars to form a binary system that is unbound to the galaxy merger?

The capture of stars to form a binary star system has been described by Tohline (2002)[2]. Here is described that binary stars can form from the relatively simple mechanism of capture. However, purely gravitational encounters are rare resulting in only few binaries. Described by Tohline (2002) is that for two unbound stars to form a binary a dissipation of the energy is needed. This dissipation of energy can occur by energy transfer of both unbound stars to a third unbound star. The third star then remains unbound and the other two stars form a binary star system. In this work we believe that this is not the case, but the moving away of the joint potentials of the two galaxies will do the trick.

In this project we analyse unbound binary formation by looking at simulations of a galaxy merger using the AMUSE code. This code is useful for initializing the galaxy merger and calculating the evolution, of the positions of the individual galaxies, in time. Furthermore, we will look at different initial conditions of the galaxy merger. This gives us insight in what conditions have to be met to, firstly, have unbound stars and, secondly, have binary formation between unbound stars.

We describe the methods in section 2. In section 3 we present the results which are discussed in section 4. Finally, the conclusion is provided in section 5.

# 2 Methods

This section will describe the search for binary star systems that are unbound to the merging galaxies. It will be divided in two parts. The first part will describe the setup of the galaxies and its evolution over time, and the second part describes the search for binary systems.

## 2.1 Model initialization

We setup two galaxies with equal mass of $M_{gal} = 10^{12} M_{\odot}$ with 20000, 10000 and 10000 particles for their Dark Matter halo, stellar disk and stellar bulge respectively. The models are created using GalactICs[1] in such a way that the Dark Matter Halo extents to a radius of 200 kpc. After creation the galaxies are moved to their initial position and velocity. We want to investigate the effect the initial conditions have on the merger, which includes the amount of ejected stars during the merging of the galaxies. We consider two different scenarios, and their initial conditions are listed in Table 1.

| scenario | $x_{rel}(kpc)$ | $y_{rel}(kpc)$ | $v_{x,rel}(km/s)$ | $v_{y,rel}(km/s)$ |
|---|---|---|---|---|
| 1 | 400 | 0 | -100 | 0 |
| 2 | 400 | 0 | -500 | 0 |

Table 1: The initial conditions for two scenario's of galaxy mergers.

The first scenario is a soft merger of galaxies that collide head on, this means that the galaxies are aligned and the only initial condition that is added is the velocity in the direction of the other galaxies. The second scenario is a head-on collision of the galaxies, but the difference with the soft merger is the initial velocity. The initial velocity is chosen in such a way that the galaxies are (partially) destroyed when they pass each other.

We are interested in the movement of individual stars within these galaxies. Therefore, we setup massless tracer particles that follow the same distribution as the galaxies they inhabit. We initiate the tracer particles in the same way as the galaxies, but only select the stars from the galactic bulge and disk, and set their mass to zero. Since the total number of initiated stars is low compared to the mass of the total galaxy we can assume that the initiated stars have negligible mass. However, since these massless stars can not interact with the 'real' galaxy we have to bridge both initiations. For this the AMUSE community code 'Bridge' is used, this makes it so that the massless stars still feel the gravity of the real galaxies.

Now that we have setup our galaxies we have to evolve them. We use a tree-code as gravity solver, and in particular BHTree. This choice is based on the fact that the gravity solver has to be compatible with Bridge as well as have a decently low calculation time. The system is then evolved with a timestep of 1 Myr and the system is evolved to 7 Gyr. If the timestep is chosen higher there occur more inaccuracies in the evolution which may result to the tracer particles 'exploding'. This means that stars are escaping the galaxy without interaction with another galaxy.

## 2.2 Binary classification

After the merging of the two galaxies we start by identifying unbound stars. In our eyes the merging of the two galaxies is done when the galaxies formed into a single object moving through space. The unbound stars are then identified by looking at if the star in question has a velocity higher than the necessary escape velocity. The condition of a star being unbound is thus:

$$v_{star} > v_{esc} = \sqrt{\frac{2 * G * M}{r}} \tag{1}$$

Here $G$ is the gravitational constant taken to be $6.67 \times 10^{-11}\ m^3 s^{-2} kg^{-1}$, $M$ is the mass of the merged galaxies and $r$ is the distance between the star in question and the center of mass of the merged galaxies.

These unbound stars can then form binaries if they are in close enough proximity. Therefore, we first start with checking whether or not stars are moving in a similar direction. This is done by comparing the velocities in the different spatial directions. If two out of the three velocity components are equal within a given range we say that the two stars move in a similar direction. By this we mean that stars following these conditions have the potential to move towards each other. This comes down to that two of the three conditions below have to be true:

$$v_{1,x} - \epsilon_v < v_{2,x} < v_{1,x} + \epsilon_v \tag{2}$$

$$v_{1,y} - \epsilon_v < v_{2,y} < v_{1,y} + \epsilon_v \tag{3}$$

$$v_{1,z} - \epsilon_v < v_{2,z} < v_{1,z} + \epsilon_v \tag{4}$$

In the three equations above $v$ is the velocity of the stars, the subscript 1 is for the first star and subscript 2 is for the second star and the subscript $x,\ y,\ z$ stand for the taken direction in 3D space.

If we find such a pair of stars we can move on to seeing whether or not these two stars form a binary. We do this by monitoring the distance between the two stars if the two stars move closer towards each other we say that the stars have potential. If the two stars move away from each other and they are out of a certain range we say that the two stars can not form a binary. If a pair of stars moves towards each other for a longer time and reach a relative distance smaller than a few tens of parsec we check if the system has formed a binary. WE check whether or not a system is a binary by looking at the energy. The limit energy is determined by the mass and kinetic energy, and thus the velocity, of the individual stars.

$$Limit\ Energy = \frac{E_{kin,1} + E_{kin,2}}{m_1 + m_2} * hardness \tag{5}$$

$$E_{kin} = \frac{1}{2} * m * v^2 \tag{6}$$

In Eq. 5 $E_{kin}$ is given by Eq. 6, $hardness$ is a certain constant taken to be 10, $m$ is the mass of the stars and the subscripts depict which star is in question. For a pair to be a binary the following condition has to be met:

$$Limit\ Energy < E_b = \frac{G * (m_1 + m_2)}{r_{rel}} - \frac{1}{2} * v_{rel}^2 \tag{7}$$

Here $r_{rel}$ is the relative distance between the two stars and $v_{rel}$ is the relative velocity between the stars. If two stars have a $LimitEnergy$ that is lower than their $E_b$ it means that the two stars have formed a binary.

# 3 Results

## 3.1 Initial conditions

Since unbound stars as a result of a galaxy merger is a rare phenomenon we first started by looking at optimal conditions. These are chosen such that more stars are getting unbound as a result of the merger. The initial conditions that were used to compare results are depicted in table 2. In words this table describes two head-on collisions (scenario 1 and 2) and two collisions where the galaxies more or less spiral around each other (scenario 3 and 4). The purpose of the relatively small velocity in the $y$-direction is to more or less have the two galaxies spiral around each other before merging.

| scenario | $x_{rel}(kpc)$ | $y_{rel}(kpc)$ | $v_{x,rel}(km/s)$ | $v_{y,rel}(km/s)$ |
|---|---|---|---|---|
| 1 | 400 | 0 | -100 | 0 |
| 2 | 400 | 0 | -100 | 10 |
| 3 | 400 | -100 | -100 | 0 |
| 4 | 400 | -100 | -100 | 10 |

Table 2: The initial conditions for four scenario's of galaxy mergers.

The scenario's in table 2 are run with a relatively small amount of particles to improve computation time; 2000, 1000 and 1000 for the halo, bulge and disk respectively. This resulted in the scenario's 3 and 4 both having no unbound stars. Scenario's 1 and 2, however, both show a single unbound star. Remarkable from scenario 2 is that the star is being shot out of the merger after the two galaxies forming a single object, whereas the unbound star from scenario 1 got unbound during the impact. However, this does seem like the best condition for stars being unbound is a head-on merger.

## 3.2 Mergers

In order to find binaries of ejected we need to determine which merger ejects the most stars. To determine this we compare 2 mergers with different initial conditions and look at the position of the particles of the merging galaxies. From their xy and xz positions we can determine if particles (or stars) are ejected from the merger. We plot positions of the mergers at different times:

1. Initial timestep
2. First approach before encounter
3. First encounter
4. After encounter
5. Second Encounter (if applicable)
6. Final timestep

The plots are shown on the last pages. Figure 1-3 display the first scenario, and Figure 4-6 display the second scenario [1]. We can see that no particles are ejected in either of the scenario's, but we have to take into account that the particles each have $\sim 10^6 M_\odot$ and thus have a mass that is much larger than actual stars. We can see some particles that move away from the center for a while, but are still bounded to the system. We expect our test particles to become unbound in such a situation.
As we predicted, the first scenario displays a soft merger that shows little structure change during the merger. We therefore do not expect many particles to

[1] movies of the merging galaxies can be fount at https://github.com/kappie07/Team_A, or send an email roewen@strw.leidenuniv.nl

be ejected during the merging of the galaxies.
The second scenario displayed the fast approaching galaxies, which do not merge, but only pass through each other. We can see slightly more structural change, especially in the top panel of figure 6 (after 1.1 Gyr). We expect that this is a point where stars get ejected, and thus expect some tracer particles to become unbound which we can trace to look for a binary system.

### Binary search

We have not yet been able to find a sufficient number of ejected stars to do any binary classification.

## 4 discussion

We started with looking at different initial conditions for the two merging galaxies. These gave us the result that head-on mergers have a single escaping star, whereas other tested initial conditions had no escaping star. After that, we created two stable galaxies that encounter each other head-on. Up to this point we have not been able to trace massless particles in this stable system, but that is something for the near future.
We have looked at two different scenario's: a soft merger, and a fast galaxy passing through the other. Looking at the structure over time of the galaxies, we can see that the second scenario is more promising than the first scenario. In the second scenario, around 1.1Gyr, we can see a wide spread in the particles of the galaxy. We expect the largest probability for star ejection at this moment. However, this means that the result from the lower amount of particles, used to investigate the initial conditions, could be wrong since the scenarios for different amount of particles differ.

## 5 conclusion

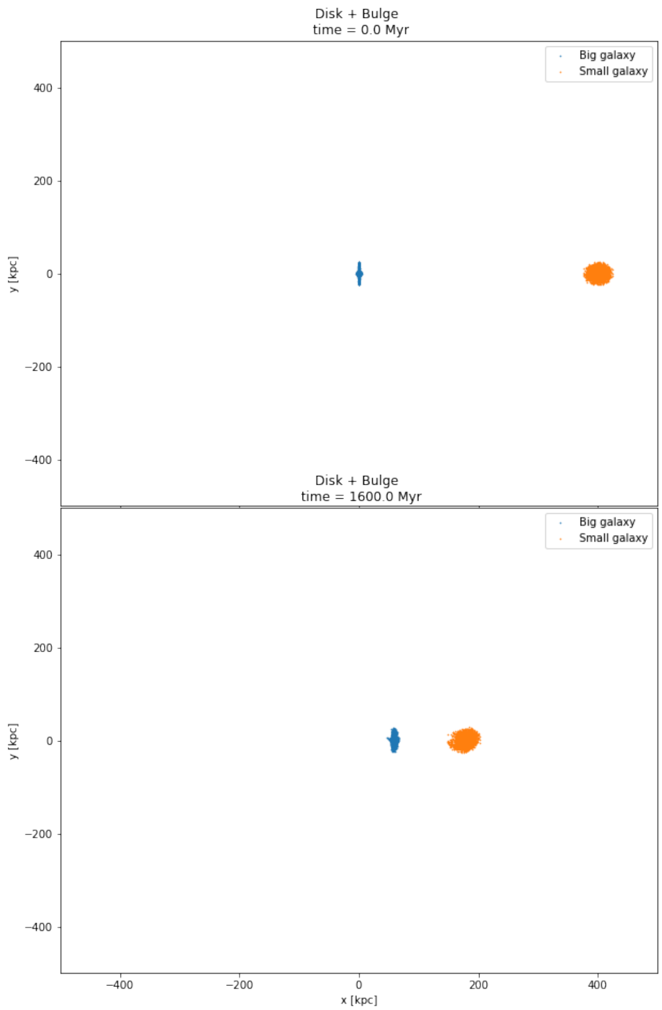
Soft merging galaxies, and fast encountering galaxies are not likely to eject enough stars to form a binary system with the current simulations. This unfortunately means that we can not say whether or not binaries can form from a galaxy merger. We can however say that the simulations we ran are not enough for finding a binary system.

## References

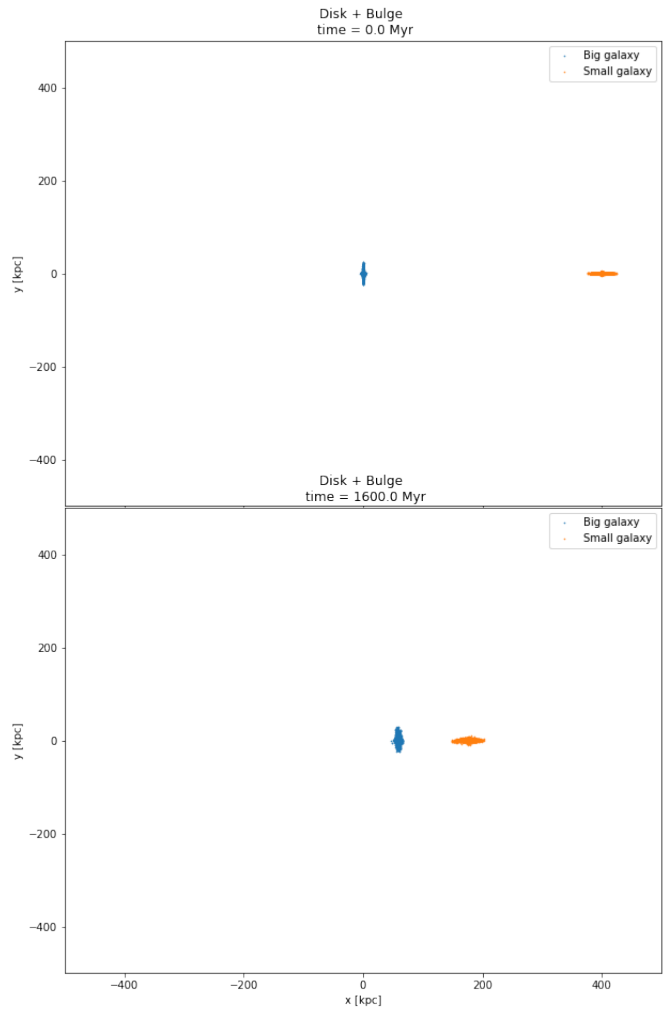
[1] K. Kuijken and J. Dubinski. Nearly self-consistent disc–bulge–halo models for galaxies. *Monthly Notices of the Royal Astronomical Society*, 277(4):1341–1353, 12 1995.

[2] J. E. Tohline. The origin of binary stars. *Annual Review of Astronomy and Astrophysics*, 40(1):349–385, 2002.

# 6 Appendix

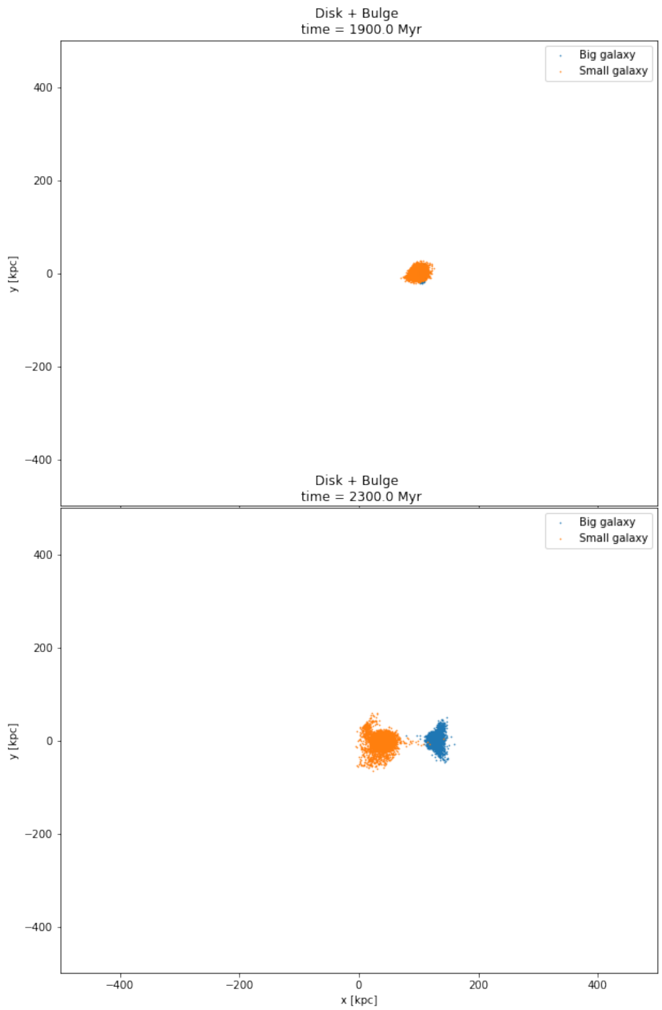



(a) X and Y position

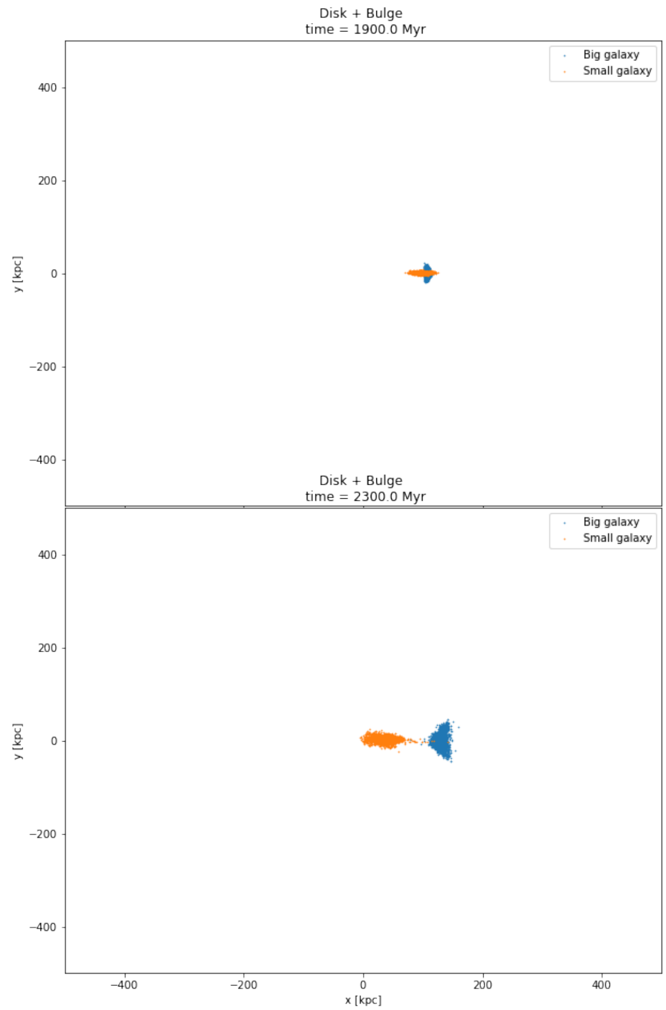



(b) X and Z position

Figure 1: Top: Initial, Bot: Before encounter

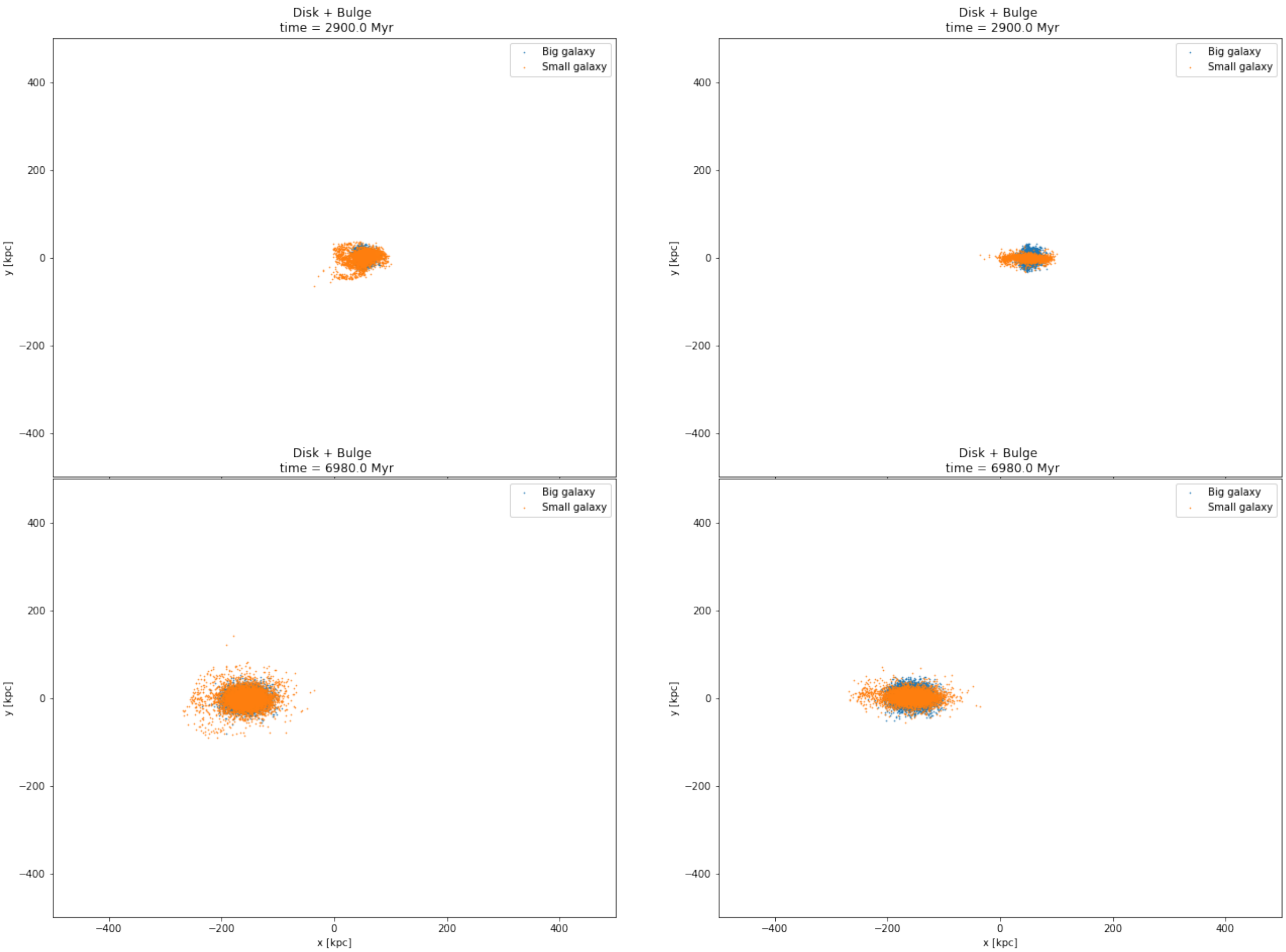



(a) X and Y position



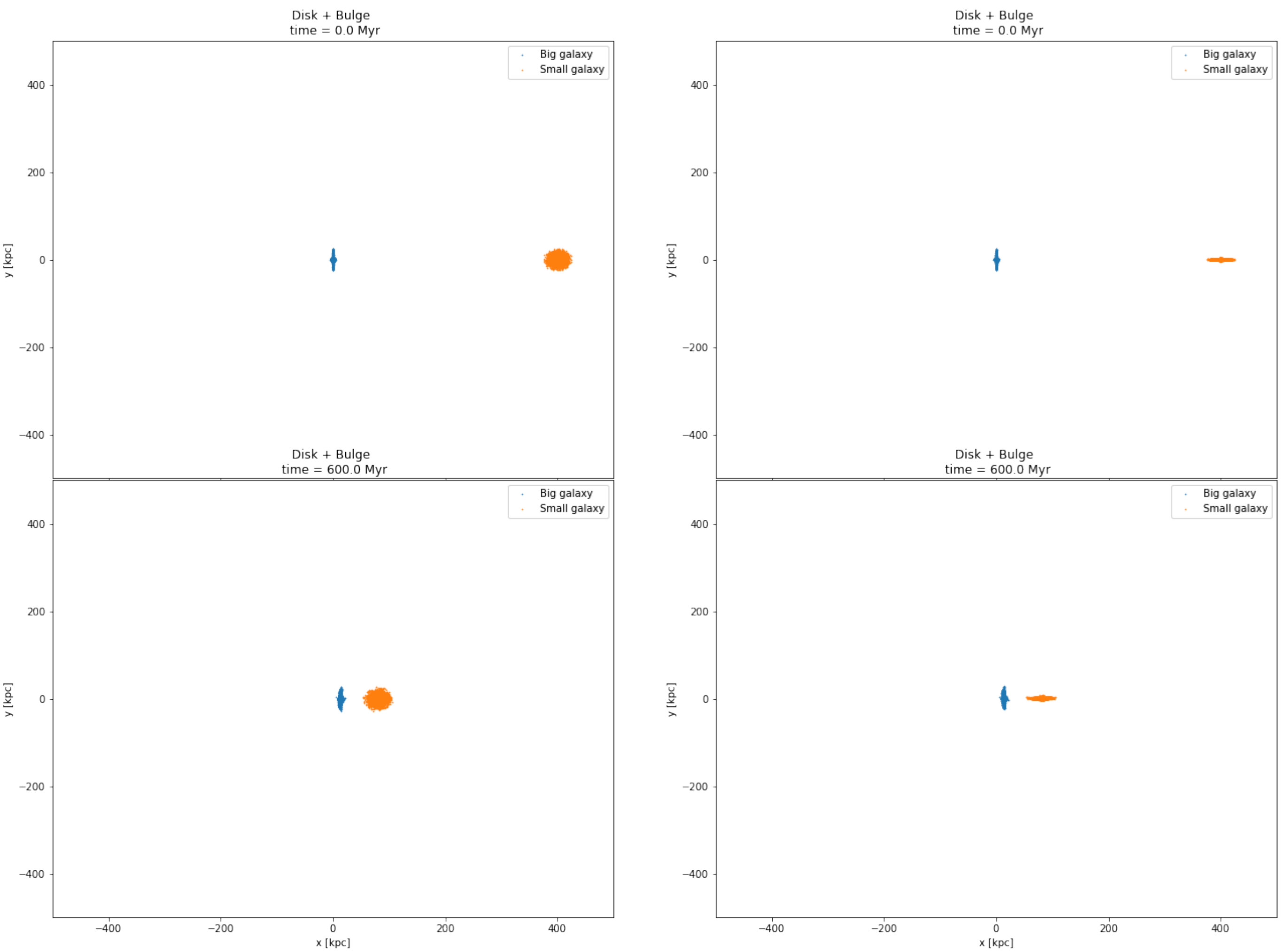

(b) X and Z position

Figure 2: Top: First encounter. Bottom: After first encounter




(a) X and Y position (b) X and Z position

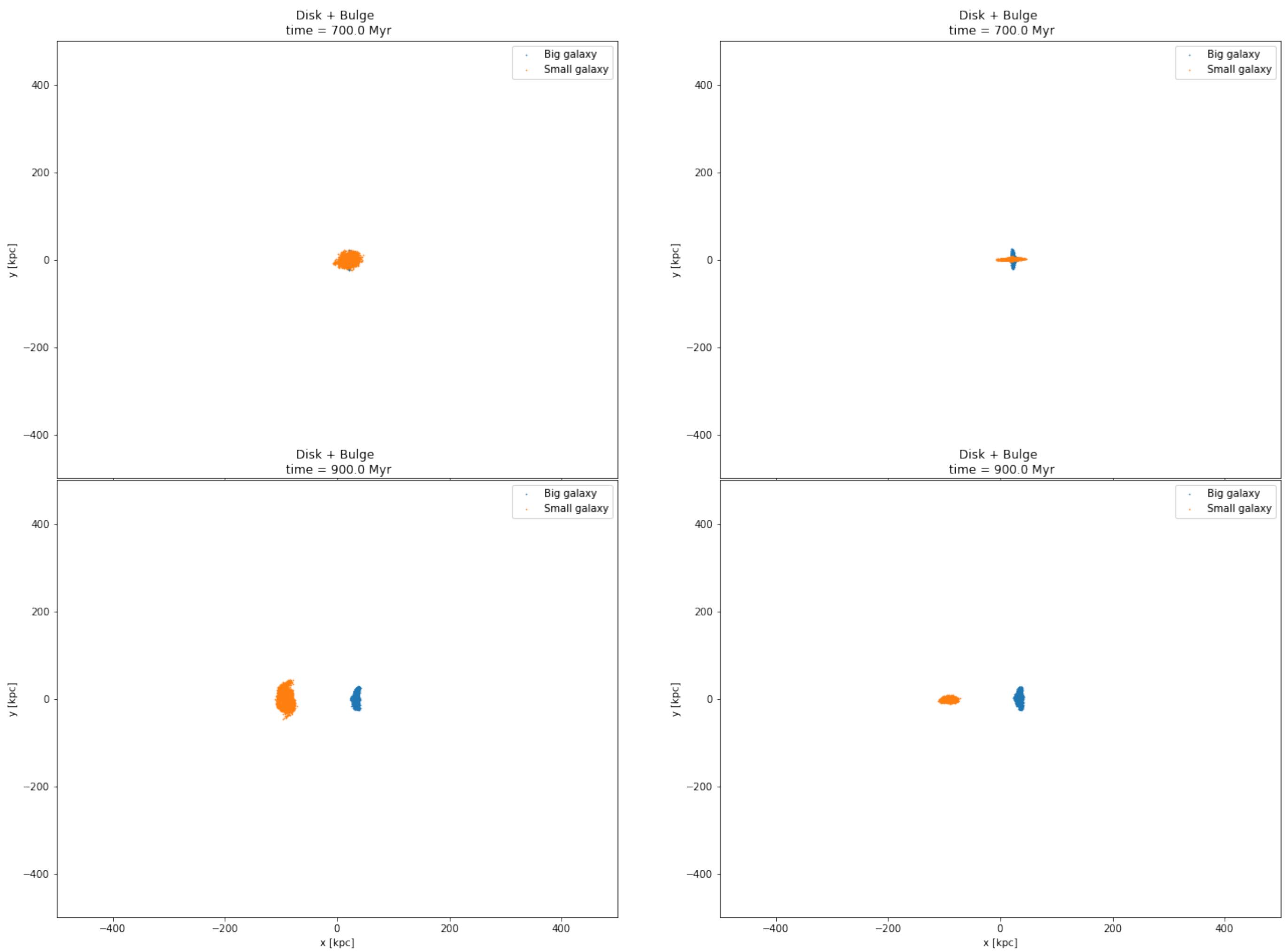
Figure 3: Top: Second encounter. Bottom: End situation




(a) X and Y position

(b) X and Z position

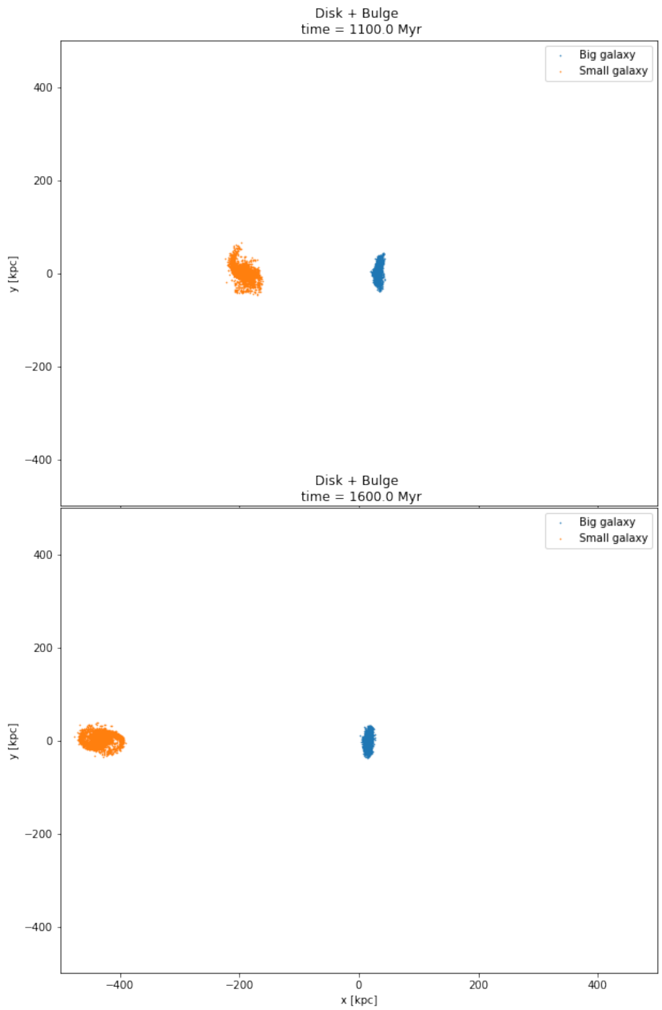
Figure 4: Top: Initial, Bottom: Moment before encounter



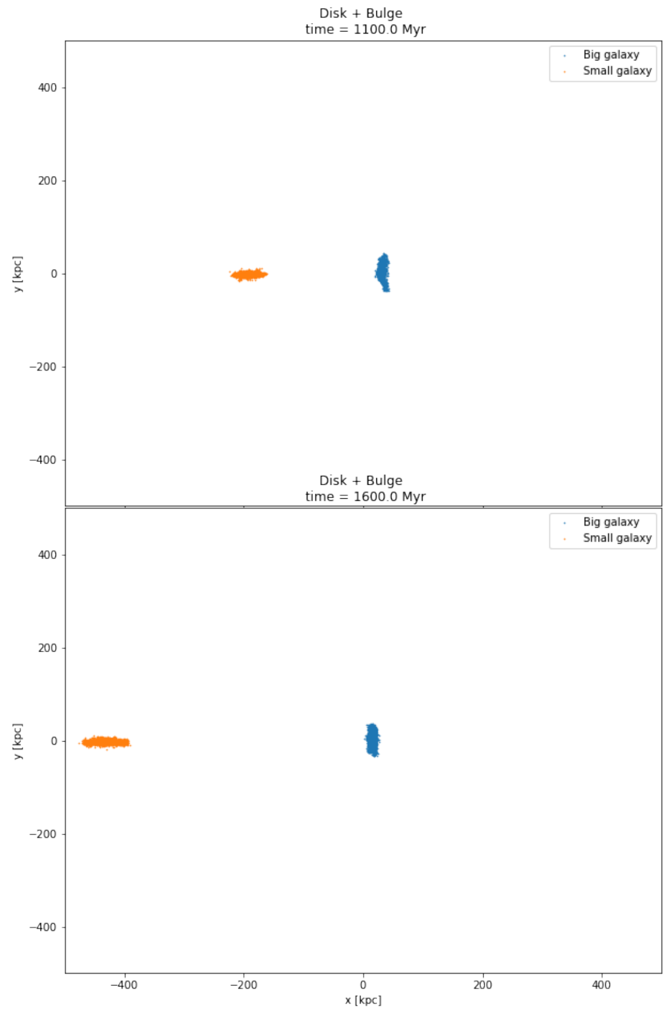

(a) X and Y position

(b) X and Z position

Figure 5: Top: First encounter. Bottom: After first encounter




(a) X and Y position




(b) X and Z position

Figure 6: Top: Disruption after encounter. Bottom: stabilized after encounter