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Simulation of The Mice with GalCollide

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ABSTRACT

N-Body simulation of galaxy mergers will allow us to understand how the composition of interacting galaxies affects the morphology of a merger. Specifically, gravitational features such as tidal tails could allow us to constrain the dark matter and gas components of a galactic halo. GalCollide is a tool for creating initial conditions of galaxy collisions to be integrated in N-Body simulations using ChaNGa. This software was developed with the goal of eventually reproducing observational images of galaxy mergers, and to search for the parameters that could lead to these conditions. Preliminary results suggest that we can match the merger morphology of previous simulations by utilizing the same gravitational interaction parameters in GalCollide. We now have the opportunity to keep orbital parameters consistent with previous work while manipulating the composition of our galaxy models; we can use previous simulations as a baseline, and experiment with galaxy model composition to determine what contributes to gravitational features in mergers. The first of such experiments is our exploration of The Mice, NGC 4676. A self-consistent simulation of The Mice was conducted by Privon et al. using Identikit. Unlike our simulations, Identikit uses a combination of N-Body and particle simulations to enable rapid exploration of the parameter space of galaxy mergers. The goal of this experiment is to recreate these results in a completely self-consistent N-Body simulation setup using GalCollide and ChaNGa, and following that to introduce a gas halo component. This will allow us to develop an understanding of the contribution that a gas halo makes to a galaxy merger.

Keywords: NBody, mergers, intergalactic astronomy, SPH

1. INTRODUCTION

The presence and dynamics of tidal features such as bridges and tails in galaxy merger systems could allow us to constrain the distribution of dark matter and gas in galaxy halos. N-Body simulation of these merger systems lets us work backwards by manipulating the galaxy models that we proceed to smash into one another. It provides us with an opportunity to develop an understanding of the composition of interacting galaxies affects the morphology of the eventual merger. This galaxy smashing, however, is a delicate process, and care must be taken when creating initial conditions for mergers if we seek to draw any comparison to reality.

GalCollide is a tool for creating initial conditions of galaxy collisions to be integrated in N-Body simulations using ChaNGa (Jetley et al. 2008). This software developed was with the goal of eventually reproducing observational images of galaxy mergers, and to search for the parameters that could lead to these conditions. GalCollide creates an initial condition by taking two user-defined galaxy models as inputs, and placing these galaxies on a Keplerian orbit defined by various orbital parameters. The system of interacting galaxies is then written to a file in the tipsysnap format. We refer to the initial condition file that GalCollide writes as a "snapshot". This snapshot can then be easily passed to ChaNGa. GalCollide currently supports galaxy models that include stars, dark matter, and gas.

As a test of the functionality of GalCollide, we seek to simulate a well-known merger system as a test case, and to successfully recreate tidal features found in that system. Although it is our eventual goal, rather than attempting to reproduce observational images of interacting galaxies, we start by recreating a previously conducted simulation.

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We do this because if we match exactly the initial parameters used in another simulation, we should arrive at similar results using ChaNGa.

The Mice, NGC 4676, is a visually striking interacting galaxy pair. The system received its name from the prominent tidal tails which resemble those of two mice. The Mice are a clear candidate for this experiment – they have distinct tidal features and have been studied and simulated extensively. If we can recreate a simulation of The Mice, we are likely to be sure that our code can reliably set up initial conditions for galaxy mergers.

Figure 1. Hubble image of The Mice, NGC 4676.

A self consistent simulation of The Mice, was conducted by Privon et al. (2013) in *Dynamical Modeling of Galaxy Mergers Using Identikit*. Identikit uses a combination of N-Body and particle simulations to enable rapid exploration of the parameter space of galaxy mergers (Barnes 2011). We attempt to recreate this simulation of The Mice using GalCollide to set up an initial conditions for integration in ChaNGa. This will allow us to confirm that this GalCollide is functional, and furthermore will allow us to observe differences in interaction behavior between our work and previous simulations. Once the tidal features of the galaxy pair are recreated, and the simulation is concluded to be successful, we can introduce changes in the initial galaxy models, such as adding a gas halo. We would like to observe how these changes affect the tidal features and overall merger behavior of the galaxies.

2. METHODS

2.1. *Recreating the Mice*

2.1.1. *Creating a Galaxy Model with GalactICs*

GalCollide is designed to place tipsy snapshots of galaxy models into an initial condition for a collision. One way to build these models is with GalactICS (Widrow & Dubinski 2005). GalactICS creates self-consistent galaxy models and allows the user to define their own based on a number of physical parameters.

For use in our simulation of The Mice, we seek to create a galaxy model that follow typically cosmologies, containing 84 percent dark matter. This differs from the Identikit simulation, but the effects should be subtle, and the tidal features will be present regardless. A galaxy model was created consisting of a Sersic bulge, an exponential stellar disk, a cuspy dark matter halo. This model will be used for both galaxies in our simulation. Figure 2 shows the initial density profile of this model. This profile was found to be stable over time when the model is integrated in isolation. Observation of the relative length of the tidal tails suggests the galaxies are of roughly equal mass (Privon et al. 2013), so identical models are used for both galaxies in the system.

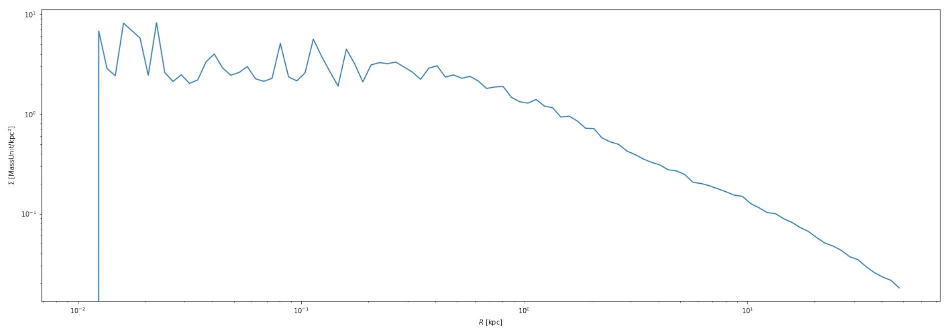

Figure 2. Density profile of our 84 percent dark matter galaxy model.

2.1.2. *Parameter Definitions*

GalCollide uses a number of parameters to define the orbits of the two galaxies in the merger system. The initial condition for this orbit is calculated by approximating each galaxy as a single point of mass $\frac{1}{2}M_{dyn}$, and solving the two body problem at a given eccentricity and pericentric separation. The galaxy is placed upon that orbit at a given initial separation. The two body problem is solved in a "top down" view of the system, with the disks of each being face on to the observer. GalCollide also includes an option to transform the initial condition snapshot into observation coordinates to allow for easy comparison to observational data.

Our goal is to define an orbit using the same values for each orbital parameters as in the Privon et al. simulation, as well as using the same viewing angles. These parameters and viewing angles are essentially a best fit to observational data, rather than user inputs, and detailed in table 1.

Table 1. Parameter values from Privon et al.

e	p	Δx_{init}	μ	(i_1, w_1)	(i_2, ω_2)	t	$(\theta_x, \theta_y, \theta_z)$	$\mathrm{M}_{dyn}(\times 10^{11} M_\odot)$	$\mathrm{t}_{now}(Myr)$
1	0.375	200	1	(15, 325)	(25, 200)	2.75	(78, −44, −130)	6.6	175

Note—e – orbital eccentricity, p – pericentric separation (simulation units), Δx_{init} – initial galactic separtion distance, μ – mass ratio, (i_1, w_1) (i_2, w_2) – disk orientations, t – time of best match, $(\theta_x, \theta_y, \theta_z)$ – viewing angle relative to orbital plane, t_{now} – time since first pericenter passage (Privon et al. 2013).

Table 1 does not include all parameters given in Privon et al., notably excluding velocity and length scaling factors. Velocity and length scaling factors are not not required by GalCollide. Instead, we are interested in the dynamical mass of the system. As stated, Identikit fits the orbital parameters of the system to observational data – the dynamical mass given by Privon et al. is an estimate calculated after scaling the velocity and length units of the simulation to match observational data. Contrarily, because we are attempting to reproduce results at a known dynamical mass, GalCollide simply takes this desired mass of the system as a parameter used in the generation of the initial condition and scales the mass of the galaxy models accordingly to meet this value. This ultimately has the same effect. Given the same orbital parameters and gravitational potential, we should find the same results without any need for scaling length or velocity - we are not at this point fitting an orbit to an image. Note however that scaling the dynamical mass of the system also involves scaling the velocity of each particle by the square root of the mass scaling factor. The same discussion is true for t_{now}, the time since pericenter passage. GalCollide uses this to determine the output time of the simulation, while Identikit produces it as an output.

There are minor differences between the GalCollide initial conditions and the parameters determined by Identikit. Rather than a 100 kpc initial separation distance, 200 kpc was used. If we use 100 kpc, the halos of the two galaxies overlap at the beginning of the simulation. This seems to have a inhibitory impact on the development of tidal features. While this has no effect on the shape of the orbit, only moving the starting points of the galaxies further along their paths, it is worth discussion in the future. Additionally, GalCollide is incapable of simulating orbits with e = 1, so e = .98 was used instead. The effect that this has on the the position of particles is around a factor of half of a percent.

It is important to mention that GalCollide uses the conventional Euler angles ($\Omega_{Euler}, i_{Euler}, \omega_{Euler}$) (Klioner 2016) to define the orientations of the galaxies, whereas Identikit uses angles i and ω defined by Toomre & Toomre (1972). In our case the conversion is simple. In the orbital plane, $\Omega_{Euler} = \pi - \omega$, $\omega_{Euler} = 0$ due to symmetry, and $i_{Euler} = i$.

Following is the parameter file used in GalCollide for this simulation:

```python
#!/usr/bin/env python

import pynbody

# Paths to tipsy files for galaxy models
Gal1 = pynbody.load('./InitialConditions/NoGas84')
Gal2 = pynbody.load('./InitialConditions/NoGas84')

# dDelta for changa param file
dDelta = .01

# Perigalactic distance in kpc
d_perigalactic = 14.8

# Initial separation distance in kpc
initial_separation = 200

# Eccentricity of system
eccentricity = 0.99

# Time in Myr since first perigalacticon passage of desired output snapshot
time = 175

# Dynamical mass of the system in kg
mDyn = 1.312687200755e+42

# Output file name
writename = "MiceNoGas200"

# Euler angles to transform each galaxy by
#W1, w1, i1 = 0, 4.10152, 0.261799
#W2, w2, i2 = 0, 3.49066, 0.436332
W1, w1, i1 = (3.1415) - 4.10152, 0, 0.261799
W2, w2, i2 = (3.1415) - 3.49066, 0, 0.436332

# Transform galaxies by Euler angles
transform = True

# Transform to observation frame
observation_frame = True
```

For more information on parameter definitions, see the GalCollide documentation.

2.2. *Introducing a Gas Halo*

A galaxy model was created consisting of a Sersic bulge, an exponential stellar disk, a cuspy dark matter halo, and a gas halo. This model was again composed of 84 percent dark matter with roughly 12 percent of the remaining mass being gas particles. The total dynamical mass of the galaxy models are again scaled to match that given by Privon et al. Note that when the dynamical mass of the system is scaled, the temperature of each gas particle must also be scaled by the mass scale factor. When introducing gas to a simulation, it is important to ensure that the gas halo is stable and gravitationally bound to the galaxy. The model was run in isolation to ensure that it behaved as expected. Figure 3 shows that this is in fact the case.

Following the generation of the galaxy model, all GalCollide parameters are defined as with the non-gas case. GalCollide automatically manages the inclusion of gas for the generation of ChaNGa input files.

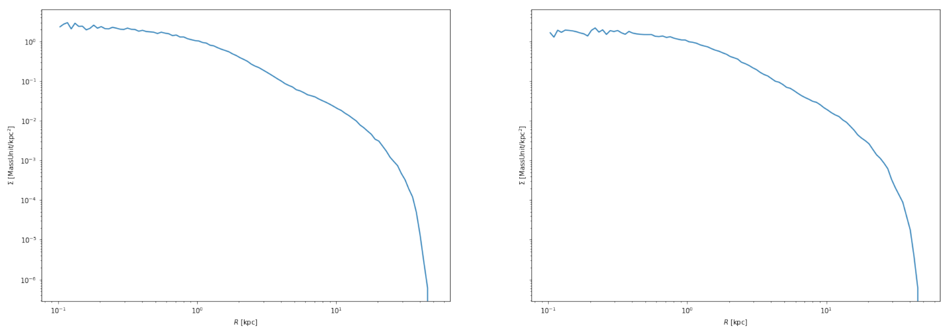

Figure 3. Left – Initial gas density profile. Right – Gas density profile at a much later time.

3. RESULTS AND DISCUSSION

3.1. *Comparison to Privon et al.*

An important result of our simulations is that adjustments to the observation angles of our final output are required to match the sky view of the system, as shown in 5, to that found by Privon et al., shown in figure 4. Once these adjustments are made, however, we do see a strong strong presence of the desired tidal features, and comparison to observational images such as figure 1 displays a great deal of similarity. Particularly, we see the characteristic straight northern tail (blue in figure 5) and curved southern tail (orange in figure 5).

Still, there does seem to be room for improvement in our simulation, especially in regard to the viewing angles used by GalCollide. Specifically the vertical separation between the galaxies is too great, the northern galaxy is not as edge-on as it should be, and while the general presence of tidal features is correct, their exact morphology leaves some to be desired. The northern tail is not as straight in our simulation as it is seen to be observationally, indicating that the spin vector of the northern galaxy should be closer to the plane of the sky. As corrections to the viewing angles were found qualitatively, changes can easily be made. Note also the discrepancy in velocity dispersion between our simulation and Privon et al. This difference is likely due to differences in the circular velocity of our galaxy models. Again, it is also possible that more fine-tuning is needed in our adjustments of the viewing angles.

3.2. *Effects of a Gas Halo*

Now that we have reproduced the tidal features of The Mice, we can investigate the effects of the introduction of a gas halo. Figure 6 is a reproduction of figure 5, but with the addition of a gas halo. We can see that the gas has little to no noticeable large-scale effect on the morphology of the interacting pair. The mass fraction of gas in the halo is low compared to that of dark matter, so this is not unexpected, but it is worth investigating the small-scale effect that gas could have on tidal features in the future. It would also be interesting to investigate the effect that the generation of these tidal features have on gas heating.

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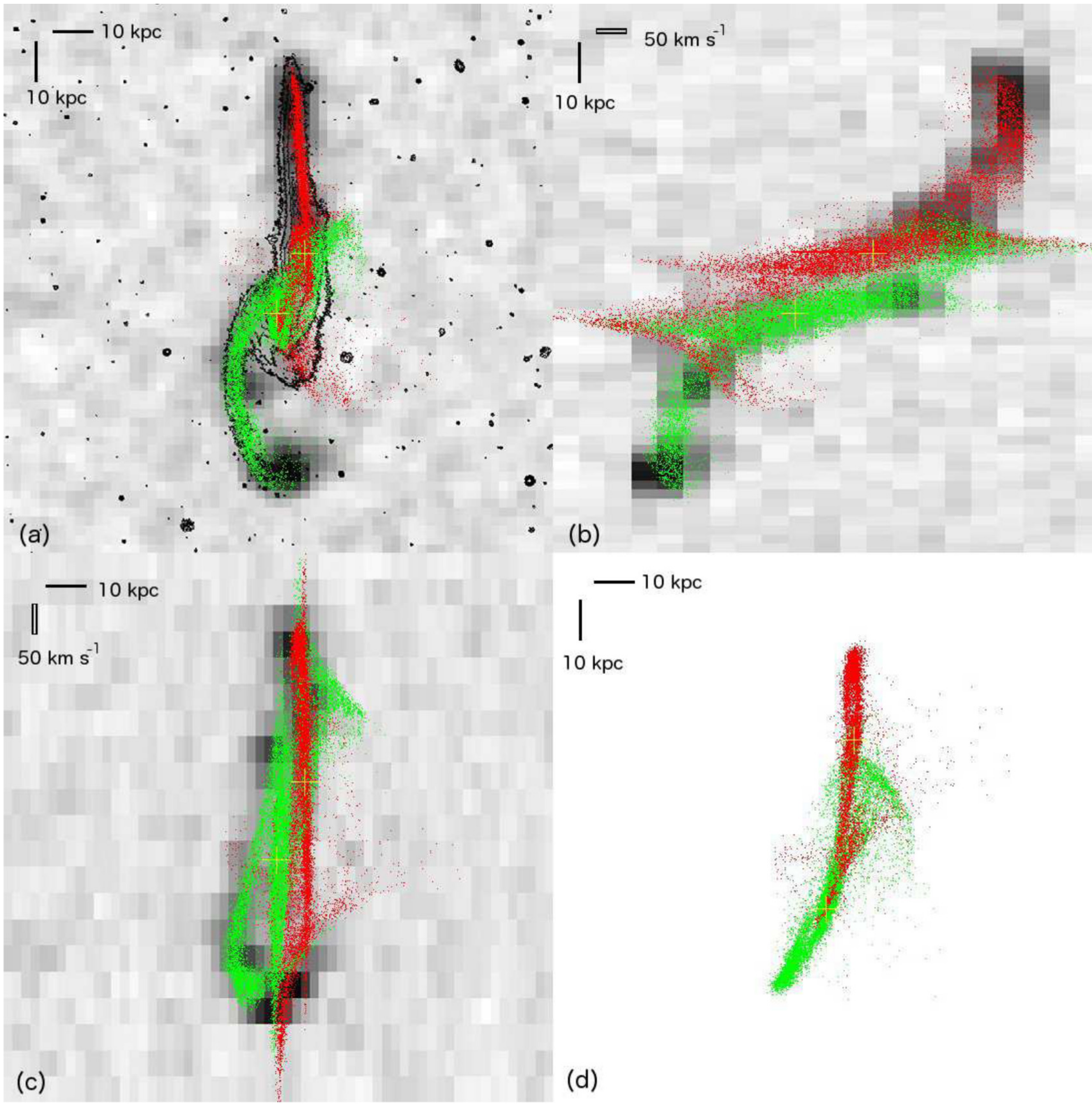

Figure 4. From Privon et al. – Identikit visualization of a self-consistent model for The Mice, matched to the system. (a): sky view of the system (-), (b)PV diagram (v-), (c): PV diagram (-v), and (d) "top-down" view (,z) (Privon et al. 2013).

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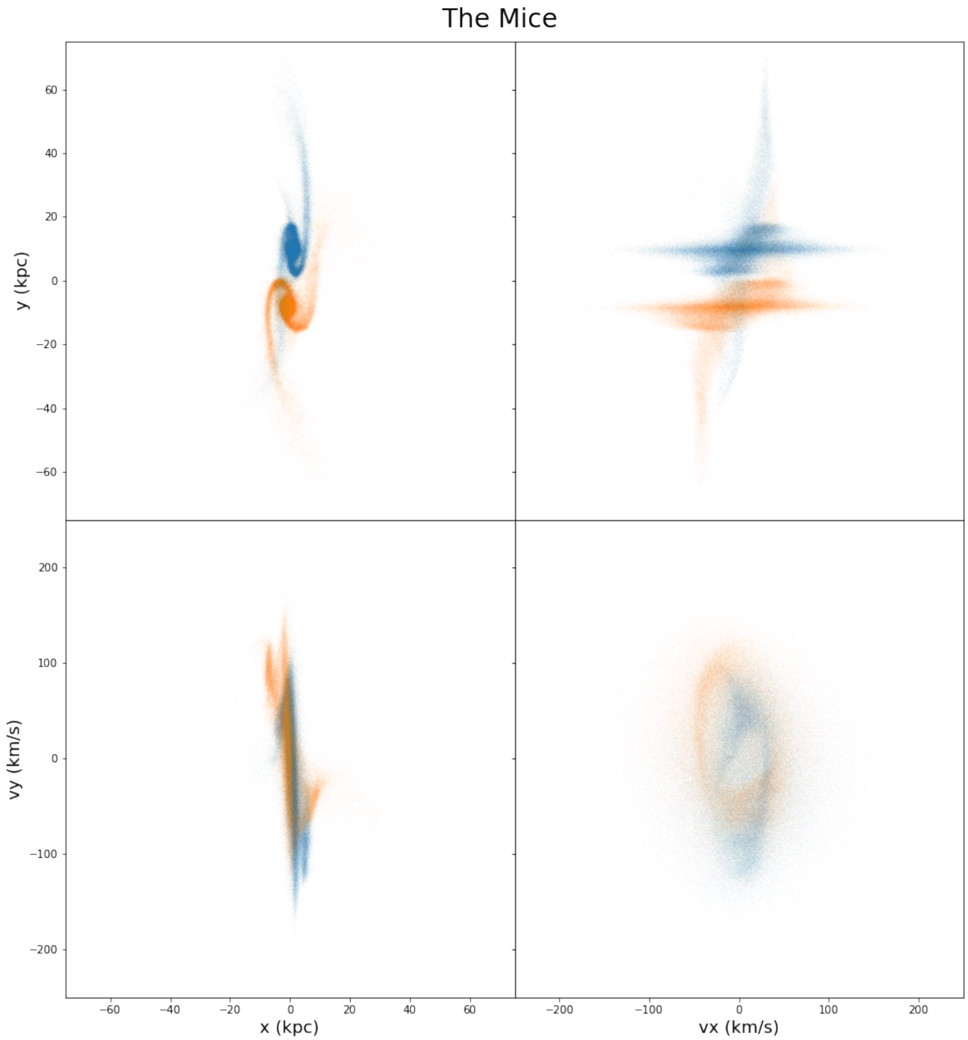

Figure 5. Visualization of simulation output. Top left – X vs. Y position of stars in the observation frame. Top right, bottom left – position vs. velocity plots of stars. Bottom right – x velocity vs. y velocity of stars.

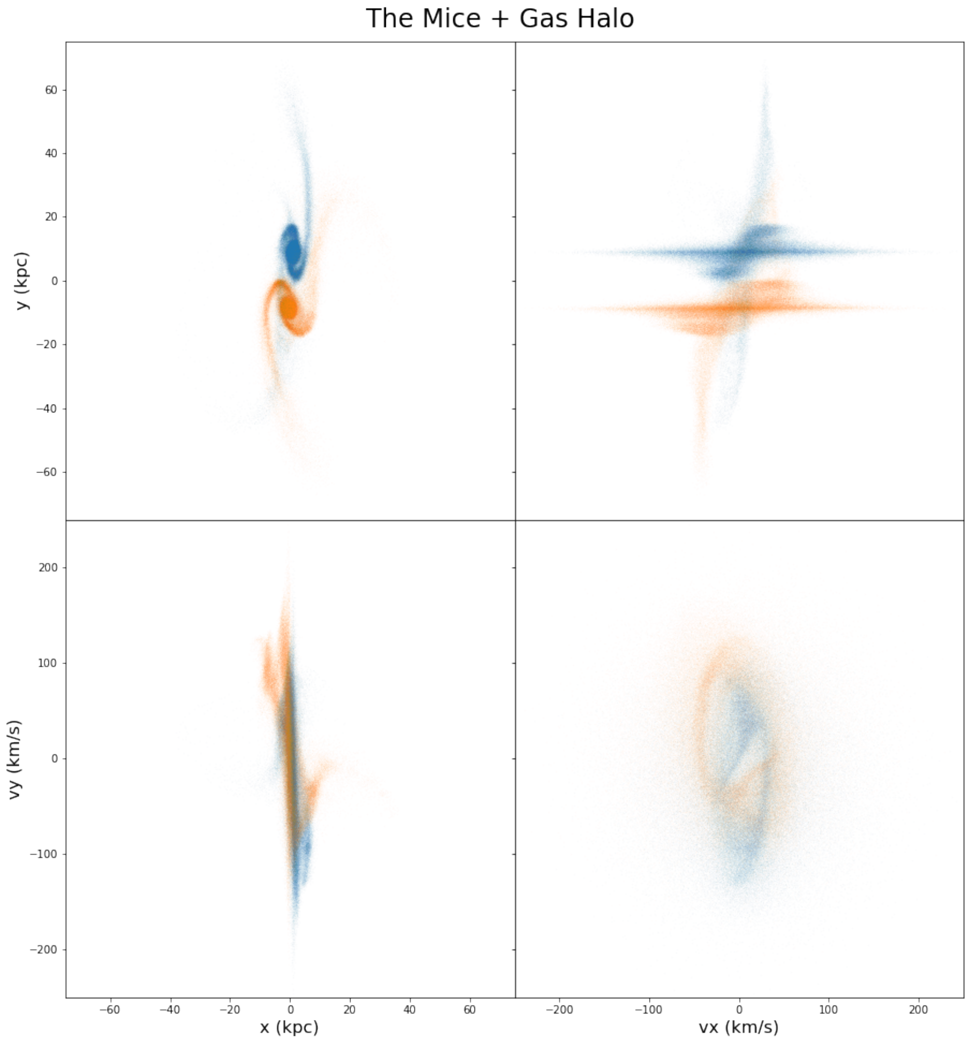

Figure 6. Reproduction of figure 5, this time including gas.