STUDYING THE EVOLUTION OF FORNAX AND ITS GLOBULAR CLUSTERS

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Studying the evolution of Fornax and its globular clusters

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We use N-body simulations to study the evolution of the Fornax dwarf spheroidal galaxy. Specifically, we study the effects of tides on the internal structure of Fornax, and its globular clusters. We adopt a cuspy NFW and a cored Burkert halo, as well as a contracted Sersic bulge, extending out to about 2.65 kpc, and an extended Plummer bulge, extending out to about 6 kpc - while retaining 95% of its mass within 3 kpc. We find that the internal structure of Fornax is largely unaffected by tidal effects, with a extended bulge causing a maximum of 7% of its original stellar mass to become unbound, while a contracted bulge results in a maximum of 2% of its original stellar mass to become unbound. Our final to initial stellar mass ratio within 1.6 kpc was between 0.92 and 0.98 and between 0.82 and 0.89 for DM. Outside of the internal areas, there is significant DM stripping. For globular clusters, we find that both a cuspy and cored halo is consistent with observations, but a cored halo allows for more formation scenarios. A possible, and perhaps likely, reason for why GC 1,2,5, and perhaps GC4 as well, have not yet sunk is that their current distance from the center of Fornax is large enough that they have decayed very little over the last several Gyr while also being small enough to not have been stripped from Fornax. This solution could also explain why GC3 has not yet sunk, but would require an even larger initial radius. Alternatively it is possible GC3 has been accreted into Fornax. Furthermore, we show that the eccentricity of the GC orbit as well as the presence of the MW can all affect the decay time of a GC. Lastly, we were unable to replicate a previously reported effect where globular clusters placed inside the core radius of an halo with a large core increased its distance from the center of Fornax.

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Contributors

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All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

GC(s)	Globular Cluster(s)
dSph	Dwarf Spheroidal
MW	Milky Way
Fnx	Fornax
NFW	Navarro–Frenk–White
DM	Dark Matter
M_*	Stellar Mass
$M_\odot$	Solar Mass

1. INTRODUCTION

There has been debate over whether the orbit of spherical dwarf galaxies around the Milky Way galaxy has caused the amount of dark matter in these spherical dwarf galaxies, as well as their stellar distribution, to change due to tidal effects. If there has indeed been significant tidal effects, then a stellar tidal stream may be observable through deep imaging surveys [1]. Spheroidal dwarf galaxies, that are satellites of the Milky Way (MW), are in general of great interest because of their proximity to us as well as the large amount of dark matter they contain, which can help shed light onto the nature of dark matter particles [2]. Other dwarf spheroidal galaxies around the Milky Way, such as the Carina dwarf galaxy have shown signs of tidal disturbances [3]. However, there has been conflicting results regarding the tidal stripping of Fornax. There has been evidence to suggest that Fornax has lost 10-20% of its infall stellar mass[1]. However, in another series of N-body simulations, that closely matched present day Fornax observables, no tidal stripping was seen[4]. This discrepancy may be due to the initial Fornax models used by both papers. For example, Wang et al. (2017) adopts an extended, and less massive, stellar bulge extending out to 7 kpc, while Battaglia et al. (2015) adopts a stellar bulge which only extends out to 2 kpc. Therefore, in this paper we explore several different Fornax models and investigate the tidal effects on each.

It is also unclear whether Fornax has a cored or a cuspy halo. One way this issue has been investigated is through studying the globular cluster system of Fornax. The five globular clusters we adopt in this paper are all spread out between projected distances of 0.24 kpc to 1.6 kpc. Several studies have suggested that Fornax's globular clusters should have all sunk to the center by now due to dynamical friction. It is unknown why the globular clusters have not sunk to date, with many possible explanations ranging from GCs starting from large radii as well as having larger initial masses [5], to clusters stalling out due to the presence of a cored halo [6], to a "dynamical buoyancy" effect keeping the GCs from sinking in halos with large cores [7]. In this paper we explore this issue through using both a cuspy and a cored halo, as well as exploring tidal effects on the orbits of globular clusters. For this paper, we use the widely adopted N-body code, Gadget-4, to model a two component Fornax orbiting inside a static Milky Way. While the globular clusters should not be significantly affected because they lie well inside the tidal radius, in the presence of large tidal effects, it is possible that the globular cluster orbits starting at larger radii are changed.

2. METHODS

We use the N body code Gadget-4 to simulate a two component Fornax orbiting through a static Milky Way potential. We model the globular clusters as single point particles softened at 10 pc. We soften the dark matter and stellar particles at 10 pc as well.

2.1 Fornax and Milky Way models

For the MW we adopt the potential from Allen $\&$ Santillan (1991) with revised parameters from table 1 of Irrang et al. (2013). The model consists of a
Miyamoto and Nagai[8] disc with M_d = 2856 M_{gal} , a_d = 4.22 kpc and b_d = 0.292 kpc

$$\phi_{disc} = -\frac{M_d}{\sqrt{R^2 + (a_d + \sqrt{z^2 + b_d^2})}} \quad \text{(Eq. 1)}$$

a Plummer[9] bulge with M_b = 409 M_{gal} and b_b = 0.23 kpc

$$\phi_{bulge} = -\frac{M_b}{\sqrt{r^2 + b_b^2}} \quad \text{(Eq. 2)}$$

and a spherical dark matter halo with M_h = 1018 M_{gal}, a_h = 2.562 kpc and Λ = 200 kpc

$$\phi_{halo} = \begin{cases} \frac{M_h}{a_h}(\frac{1}{(\gamma-1)}\ \ln(\frac{1+(\frac{r}{a_h})^{\gamma-1}}{(\frac{\Lambda}{a_h})^{\gamma-1}}) - \frac{(\frac{\Lambda}{a_h})^{\gamma-1}}{1+(\frac{\Lambda}{a_h})^{\gamma-1}}) & \text{if } r < \Lambda \\ -\frac{M_h}{r}\frac{(\frac{\Lambda}{a_h})^{\gamma}}{1+(\frac{\Lambda}{a_h})^{\gamma-1}} & \text{otherwise} \end{cases} \quad \text{(Eq. 3)}$$

Here r is the spherical radius, R the cylindrical radius and $M_{gal} \approx$ 2.325 x $10^7 M_\odot$. The total mass within 200 kpc is 1.9 x $10^{12} M_\odot$

For our Fornax model we vary our model between two dark matter halos, one cored and one cuspy, and two bulge models. The scale length is represented here with the variable a. The full parameters of each Fornax model can be found in table 1. We adopt two bulge models to test the effects of tidal effects on a tight and a extended stellar distribution. The second bulge model is modeled after the one introduced in [4] which is based off of the deprojection of the Sersic profile and matches closely with present day observations. However, in Wang et al. (2017) they assume a extended stellar distribution all the way out to 7 kpc, compared to approximately 2 kpc for the contracted bulge, which could result in larger tidal effects. For our dark matter halo we have a cored Burkert [10] potential

$$\rho(r) = \frac{\rho_0}{(1+(r/a))(1+(r/a)^2)} \quad \text{(Eq. 4)}$$

or a cuspy NFW[11] potential

$$\rho(r) = \frac{\rho_0}{(r/a)(1+r/a)^2} \quad \text{(Eq. 5)}$$

For our stellar bulge we have a Plummer[9] sphere

$$\rho(r) = (1+(\frac{r}{a})^2)^{-\frac{5}{2}} \quad \text{(Eq. 6)}$$

or a deprojected Sersic[12] profile as described in [3]

$$\rho(r) = \rho_0(\frac{r}{a})^{-p}e^{-(\frac{r}{a})^v} \quad \text{(Eq. 7)}$$

with m = 0.8, v = 1/m and p = 1 - 0.6097v + 0.05463v^2.

We used the initial conditions code DICE [13] to generate our Fornax model. To create a cored profile we used the rcore function in DICE with a value of 0.6 kpc. In order to create an extended bulge we use the cut command with a parameter of 6 kpc to extend the Plummer bulge to 6 kpc. Through this method we are able to retain the majority of the mass inside of 3 kpc (around 94.5$\%$), but still have stars that extend out to 6 kpc. Therefore our Burkert and Plummer models did not exactly follow the analytical form above. The exact initial density profiles can be seen in Figure 2.2

Table 2.1: Fornax Models

Halo Mass($M_\odot$)	Bulge Mass($M_\odot$)	Halo Model	Halo Scale (kpc)	Bulge Model	Bulge Scale (kpc)
3×10^9	5×10^7	NFW	2.7	Sersic	0.66
3×10^9	5×10^7	NFW	2.7	Plummer	0.7
3×10^9	5×10^7	Burkert	1.25	Sersic	0.66
3×10^9	5×10^7	Burkert	1.25	Plummer	0.7

Four fornax models adopted in this paper. The plummer bulges were extended to 6 kpc by using the cut function in DICE and the burkert profile was modified by using the rcore function in DICE.

We recalculate the tidal radius every few years using the equation:

$$r_t = r_p(\frac{M_s}{M_g(3+e)})^{\frac{1}{3}} \quad \text{(Eq. 8)}$$

Here r_t is the tidal radius, r_p is the pericenter radius, M_s is the satellite mass, M_g is the host galaxy mass and e is the eccentricity.

2.2 Orbit and Globular Clusters

We model the globular clusters as single point particles softened at 10 pc, the same softening length used for our Fornax DM and stellar particles. For the orbit of Fornax we rely on observations from the recent Gaia[14] data described in table 2. In order to test the effect of different GC orbits we ran simulations with circular GC orbits, e = 0, and eccentric orbits with e = 0.9. We also ran simulations with and without a MW to test the effects of the MW on globular cluster orbits. For the mass of the globular clusters we simply round up the present day masses described in [5]. We start our globular clusters at various radii from less than 1 kpc up to 3 kpc. The full globular cluster data is described in Tables 2.2 and 2.4.

To determine the 3D radial distance that each GC is from the center of Fornax, we take its inclination and declination, along with two different distance data sets and use Galpy [15] to determine possible 3D radial distances from the center of Fornax that would result in the GC matching distance measurements from both data sets.

Table 2.2: Fornax Orbital Parameters

Parameter	**Value**
Distance [kpc]	138
apocentre [kpc]	$156.4^{+26.9}_{-15.1}$
pericentre [kpc]	$85.9^{+47.7}_{-34.4}$
eccentricity	$0.29^{+0.18}_{-0.12}$
L_z [km/s kpc]	$7659.9^{+2586.9}_{-2516.9}$
T_a [Gyr]	$0.31^{+0.04}_{-0.60}$
T_p [Gyr]	$1.67^{+0.40}_{-0.96}$
M(<944±53 kpc) [$M_\odot$]	$7.39^{+0.41}_{-0.36}$ x 10^7

Table 2.3: Globular Clusters

GC	Observed Mass ($10^5 M_\odot$)	Adopted Mass($10^5 M_\odot$)	Projected Distance (kpc)
1	0.42 ± 0.10	1.0	1.6
2	1.54 ± 0.28	2.0	1.05
3	4.98 ± 0.84	5.0	0.43
4	0.76 ± 0.15	1.0	0.24
5	1.86 ± 0.24	2.0	1.43

The present day mass and projected distance from the center of Fornax. The adopted mass is the mass we chose for our simulations.

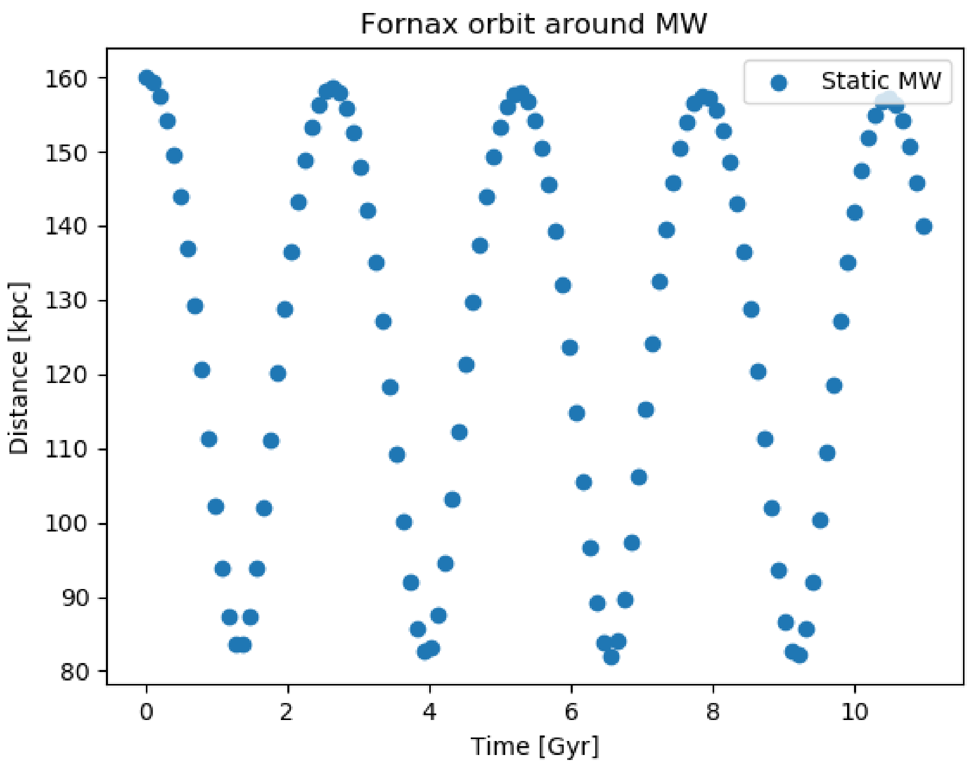

Figure 2.1: 11 Gyr orbit of Fornax around the MW

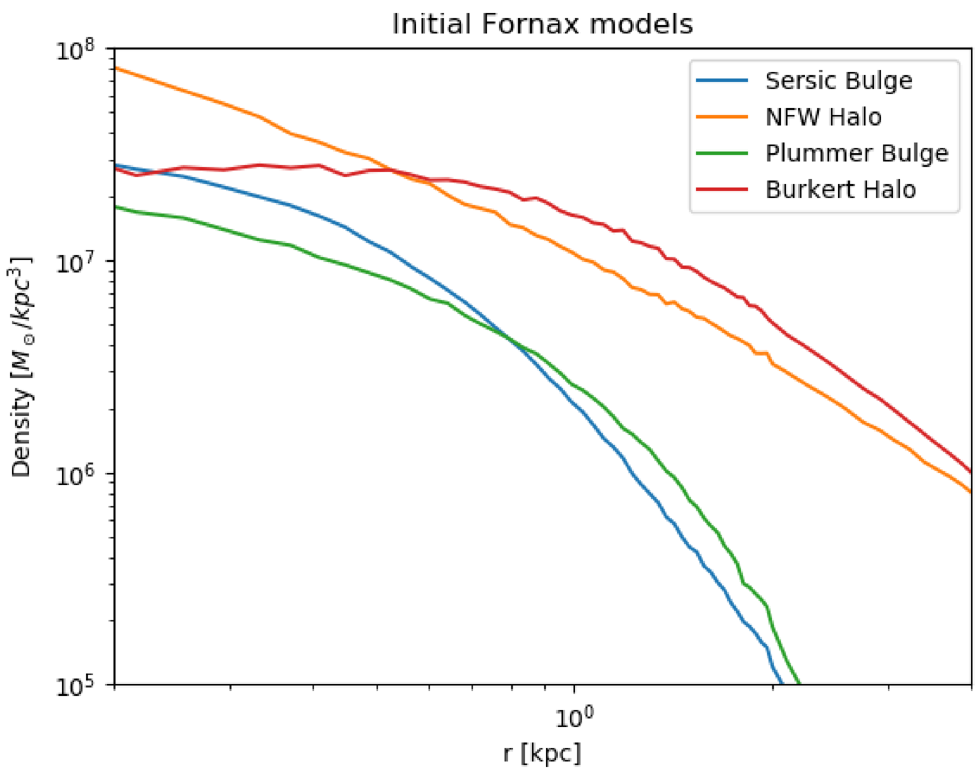

Figure 2.2: Initial densities of the various halo and bulge models

3. RESULTS

We separate our results into two main categories. In the first subsection we explore the impacts of tidal effects on Fornax while in the second subsection we explore the long term evolution of globular clusters. In both subsections we compare and contrast the effects of choosing each of our possible Fornax models. While in our simulations, 11 Gyr of evolution gave us a distance that is closest to the present day Fornax distance, our actual simulations ran up to 12 Gyr. Since we are also interested in the long term evolution of GCs we included all 12 Gyr of evolution for our GC results. For the purposes of tidal effects, we considered our simulation complete at 11 Gyr. Even though the MW has not remained the same over 11 Gyr, we chose to let Fornax orbit in a present day static MW in order to maximize tidal effects.

3.1 Tidal effects on Fornax

The internal structure of Fornax remains mostly unchanged over 11 Gyr. Outside of around 500 pc from the center of Fornax, the stellar density matches almost identically to the initial stellar density. Inside of 500 pc we see small changes in the initial and final density with the difference decreasing rapidly as we go out from the center of Fornax. We consider particles bound to Fornax if they lie within the tidal radius which we recalculate every few Gyr until the end of our simulation. Our final tidal radius is greater than observations, so our results for the amount of bound mass will also be higher. While all of our models were designed to have approximately 1 x $10^8 M_\odot$ within a spherical radius of 1 kpc, similar to Meadows et al. (2019), the Burkert profile had a higher DM density between 1 and 3 kpc, which may account for why we see fewer tidal effects in the Burkert models than the NFW ones. As expected, we see more stellar mass loss when adopting a extended Plummer bulge than the contracted Sersic bulge. However, even in the model that showed the most tidal effects, only 7$\%$ of the original stellar mass became unbound and less than 3$\%$ of the original stellar mass was found outside 10 kpc from the center of Fornax. Comparatively, in the model showing the least change, less than 2% of the original stellar mass becomes unbound and less than 0.5% is found outside 10 kpc. In our initial conditions, 7.5% ($\approx$ 3.75 x $10^6 M_\odot$) of the extended bulge is outside of 2.64 kpc, which is how far the contracted bulge extends. Notably, of the stellar mass more than 10 kpc from Fornax, around 80-90$\%$ of the that mass was more than 30 kpc from the center of Fornax in all of our models. The choice of bulge had little effect on DM stripping as the total bound mass as well as the unbound DM mass were very similar. The final to initial mass ratio within 1.6 kpc for both DM and stellar matter were very similar between models with the same halo but different bulge. While the DM to stellar ratio was again similar within a sphere of 1.6 kpc, the ratio was slightly higher for the extended Plummer bulge when we go out to a radius of 3 kpc. For both DM and stellar matter, more mass remains bound in the Burkert halos than the Fornax halos. This is likely due to this higher density between 1 and 3 kpc in the initial Fornax models. However, both halos have a final to initial stellar mass ratio inside of 1.6 kpc greater than 0.9 and a final to initial DM ratio within the same radius greater than 0.8. Both inside 1.6 kpc and 3 kpc, the DM to stellar ratio is greater in the Burkert halos than the NFW halos. Notably, while the internal structure of Fornax shows little sign of change, the outer regions of the halo showed significant DM stripping.

	Observation	NFW - C	NFW - E	BURK - C	BURK - E
Tidal Radius [kpc]	1.8 - 2.8	3.24	3.23	4.0	3.99
M(r $<$ 1 kpc) [$10^8 M_\odot$]	1.0	0.948	0.985	1.06	1.10
Bound mass [$10^8 M_\odot$]		3.73	3.68	7.102	7.045
M_*(R < 1.6 kpc) [$10^8 M_\odot$]	0.43	0.424	0.412	0.439	0.423
% * mass @ (R < 0.81 kpc)	$\approx$ 50.0$\%$	49.12$\%$	55.03$\%$	50.16$\%$	57.83$\%$

Table 3.1: Final results of our simulation compared to observations. -C refers to the contracted Sersic bulge and -E refers to the extended Plummer bulge

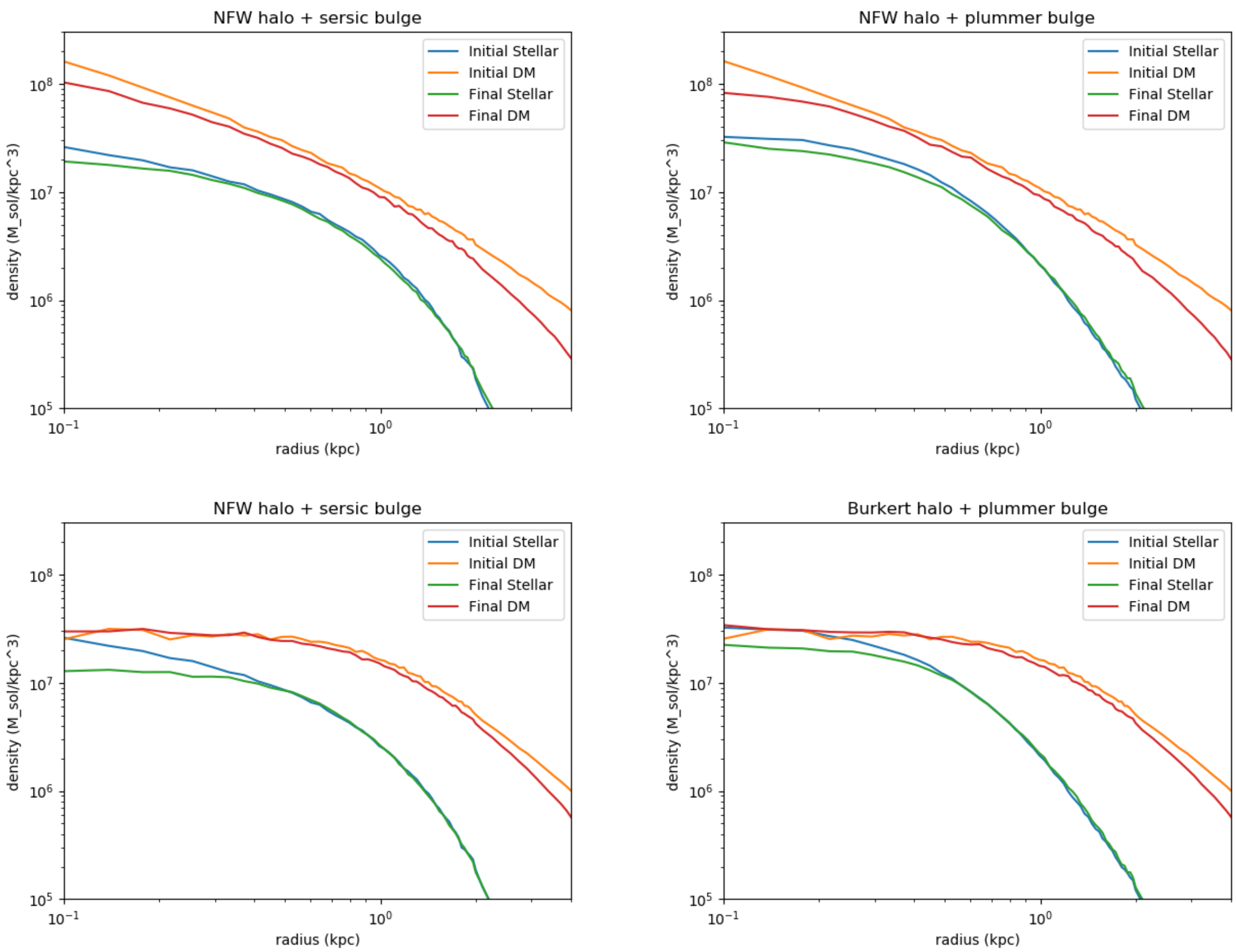

Figure 3.1: Initial and Final densities of Fornax models

	NFW - C	NFW - E	BURK - C	BURK - E
Unbound M_* [$M_\odot$]	9.37 x 10^5	3.55 x 10^6	1.65 x 10^5	1.69 x 10^6
M_* (r > 10 kpc) [$M_\odot$]	2.35 x 10^5	1.38 x 10^6	2.83 x 10^4	4.95 x 10^5
M_* (r > 30 kpc) [$M_\odot$]	2.12 x 10^5	1.23 x 10^6	2.6 x 10^4	4.61 x 10^5
Unbound M_{DM} [$M_\odot$]	2.68 x 10^9	2.68 x 10^9	2.34 x 10^9	2.34 x 10^9
M_{DM} (r > 30 kpc) [$M_\odot$]	2.44 x 10^9	2.45 x 10^9	2.05 x 10^9	2.05 x 10^9

Table 3.2: Results from the final snapshot of our simulation. -C refers to the contracted Sersic bulge and -E refers to the extended Plummer bulge

	NFW - C	NFW - E	BURK - C	BURK - E
M_{DM} (r < 1.6 kpc) [$M_\odot$]	1.47 x 10^8	1.46 x 10^8	2.14 x 10^8	2.12 x 10^8
M_* (r < 1.6 kpc) [$M_\odot$]	3.72 x 10^7	3.73 x 10^7	3.9 x 10^7	3.87 x 10^7
F/I DM (r < 1.6 kpc)	0.823	0.82	0.892	0.886
F/I * (r < 1.6 kpc)	0.925	0.945	0.97	0.98
DM/* (r < 1.6 kpc)	3.95	3.91	5.47	5.49
DM/* (r < 3.0 kpc)	6.21	6.54	10.3	10.82

Table 3.3: Results from the final snapshot of our simulation. F/I is the final to initial mass ratio. DM/* refers to the DM to stellar mass ratio.-C refers to the contracted Sersic bulge and -E refers to the extended Plummer bulge

3.2 Globular clusters

3.2.1 Cuspy vs Cored

Comparing the end results of our simulations to present day observations, we find that both a cuspy NFW halo and a cored Burkert halo can reproduce present day GC observations. However, a cored halo allows for more flexible formation scenarios than a cuspy halo. We also found that in both cored and cuspy halos, the decay time was similar, and the orbits only differed in their end results. GCs in cuspy halos sank to the center of Fornax while GCs in cored halos stalled, thus preventing them from sinking to the center of Fornax.

Table 3.4: GC distances

Name	D_{MW} [16] [kpc]	D_{LOS} [kpc]	Minimum [kpc]	Maximum [kpc]
Fornax	141.4 [17]	139.3 [17]		
GC1	147.2 ± 4.1	130.6 ± 3.0 [18]	1.6	2.5+
GC2	143.2 ± 3.3	136.1 ± 3.1 [18]	0.95	1.6
GC3	141.9 ± 3.9	135.5 ± 3.1 [18]	0.9	2.5+
GC4	140.6 ± 3.2	134.0 ± 6.0 [19]	0.17	2.5+
GC5	144.5 ± 3.3	140.6 ± 3.2 [18]	1.6	2.5+

The last two columns refer to the minimum and maximum possible 3D radial distance from the center of Fornax for each GC that does not violate the measurements in column 2 and 3 (except for GC1). These values were calculated through Galpy [15]. 2.5+ means that the maximum possible distance is greater than 2.5 kpc. This data can be found in table 3.4.

Through combining existing position and distance data we can obtain approximate lower limits on the minimum 3D radial distance from the center of Fornax for GC two through five. GC1 is a special case in which the two observational data sets cannot be reconciled to give a reasonable 3D radial distance. Based off of our simulations, and the minimum 3D radial distances calculated, we can estimate minimum starting radii for the globular clusters. GC1 could have started at a radii similar to, or larger than, its present day radii and thus can be easily reconciled in both cuspy and cored halos. Similarly, in both cuspy and cored halos, GC2 likely started its orbit at a minimum 3D radius of 1.5 kpc. In both cored and cuspy halos, GC3, whose minimum 3D radial distance is well outside the stalling radius, is likely to have started at a very large initial radii of greater than 2.5 kpc if it was formed inside of Fornax . Since our results indicate that even in circular orbits, which take longer to decay than elliptical orbits, a cluster as massive as GC3 would have sunk or stalled to the center within the last 11 Gyr if it started inside 2 kpc, GC3 may have been accreted into Fornax, as suggested by Cole et al. (2012). In a cored halo we expect GCs to stall at radius around one-third the core radius. However, in a cuspy halo we expect GCs to not stall, but rather sink to the center of the galaxy. Therefore, assuming GC4 is close to its minimum possible 3D radial distance, in a cuspy halo we would have to argue that GC4 is decaying but not yet sunk, severely limiting its possible initial conditions, while in a cored halo we could argue that GC4 has simply been stalled for several Gyr. Therefore a cored halo allows for more flexible formation scenarios. Because the possible 3D radial values of GC4 has a high upper bound, it is possible GC4 has not yet started the process of sinking but is rather in a stable orbit between 1.5 and 2 kpc, in which case both a cuspy and cored halo would have a similar number of possible initial conditions. GC5 likely started at a distance greater than 1.5 kpc.

The above estimates are all based off of a circular orbit. It is of course possible that the starting radius could be even further if we assume an elliptical orbit. But given their relatively large distance from the center of Fornax, an elliptical orbit would severely limit the possible initial conditions for the GCs since GCs in elliptical orbits can decay much faster than those in circular orbits. Based off of these results we find that a cuspy and cored halo can both be reconciled with observations, but a cored halo allows more flexibility since allowing GCs to stall allows for a greater number of initial conditions. To exactly reconcile observations, a more refined simulation is needed that would model globular clusters as multi particle systems. But given the number of variables that can effect globular cluster orbits, and the uncertainty of current kinematic data, it would be a significant task.

Since GCs in circular orbits can typically stay at a constant radii over 11 Gyr, given a sufficiently large initial distance from the center of Fornax, it appears that the solution for why GC 1,2 and 5 have as of yet not sunk to the center of Fornax is that there current distance from the center of Fornax is large enough to have been able to stay in a stable orbit without decaying, but also small enough that they are not stripped from Fornax. A distance of 1.5 - 2.5 kpc, depending on the GC, would be compatible with this scenario. The same argument could be applied to GC4 if in fact it has a relatively large 3D radial distance. If in reality it's distance from the center of Fornax is close to its minimum possible distance of 0.17 kpc, GC4 could have stalled inside a cored halo. In a cuspy halo, GC4 could be sinking but not yet sunk, but this solution would severely limit the possible initial conditions. Overall, given the uncertainties in the exact 3D radial distances from the center of Fornax for each GC, GCs may not yet be suitable on their own to distinguish between cuspy and cored halos.

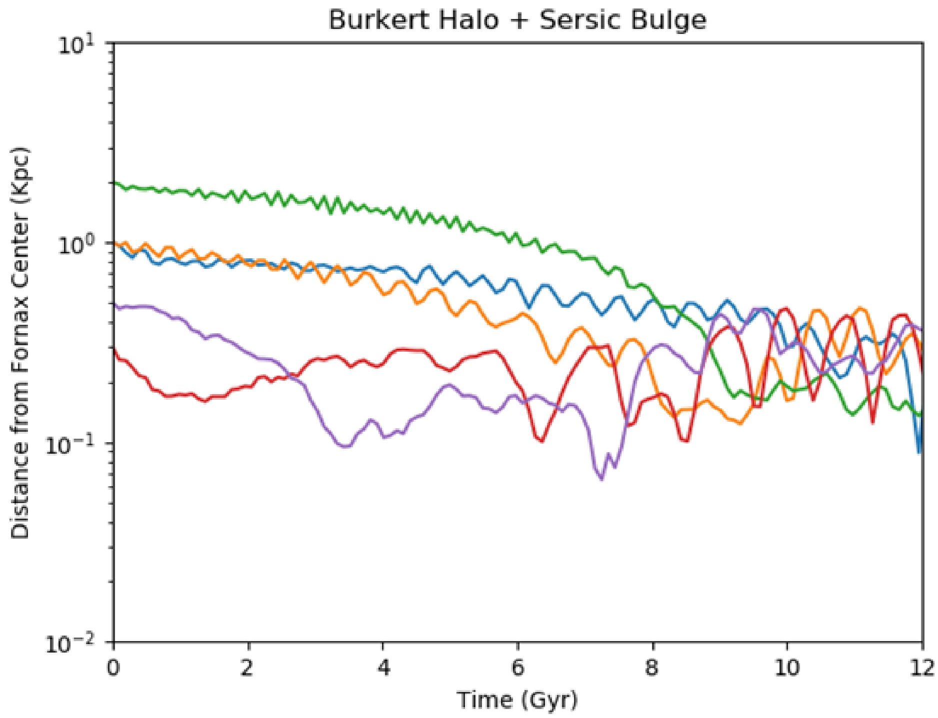

Figure 3.2: Five GCs in a cored halo stalling at a common radius

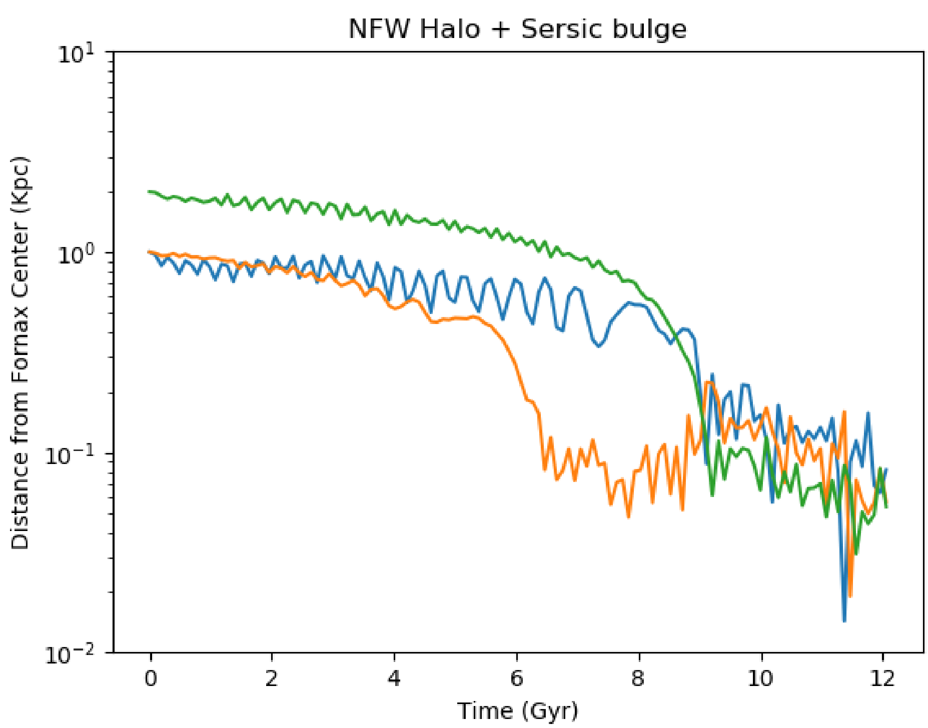

Figure 3.3: Three GCs in a cuspy halo showing sinking behavior

3.2.2 Dynamical Buoyancy

Previous work by Cole et al. (2012) reported that a GC placed inside the core radius of a large core halo would experience a "dynamical buoyancy" effect. That is, the GC would gain energy and its distance from the center of Fornax would increase. We tested this effect by simulating three different GCs of mass 1, 2 and 5 x $10^5 M_\odot$ starting at radii of either 300 or 500 pc. Figure 3.2 shows the resulting orbits. As can be seen in the figure, the GCs do not increase their distance from Fornax but rather stall out similar to how GCs starting outside the core radius do. It is unclear why we are unable to replicate the dynamical buoyancy effect. Similar to Cole et al. (2012) we use a 2M particle Fornax softened at 10 pc. Previous work by Meadows et al. (2019) was also unable to replicate this effect. They utilized a 1.6M Fornax halo with a higher softening length, so it is unlikely this effect is due to any obvious factors such as our Fornax model, our softening length or the presence of the MW.

3.2.3 Secondary Effects

We also investigated the effects the MW can have on both circular and elliptical orbits, as well as whether an extended or contracted bulge can have a significant effect. As expected, elliptical orbits decay significantly faster than circular orbits. As such, GCs on elliptical orbits can have significantly higher initial radii while still sinking or stalling within 11 Gyr when compared to similar GCs started at lower radii on circular orbits. While in most of our simulations, the MW, as well as the choice of the bulge did not have a significant effect on the GC orbit, in certain scenarios we did see an effect. The top right plot in Figure 3.7 shows the largest effect seen due to the presence of the MW. In certain figures shown in this picture, it may appear that a GC in a cuspy NFW halo may appear to increase its radius significantly after having sunk. However, we ignore this effect as it is a byproduct of having our GCs modeled as single particles as in reality the cluster will be destroyed once it gets close enough to the center of the galaxy.

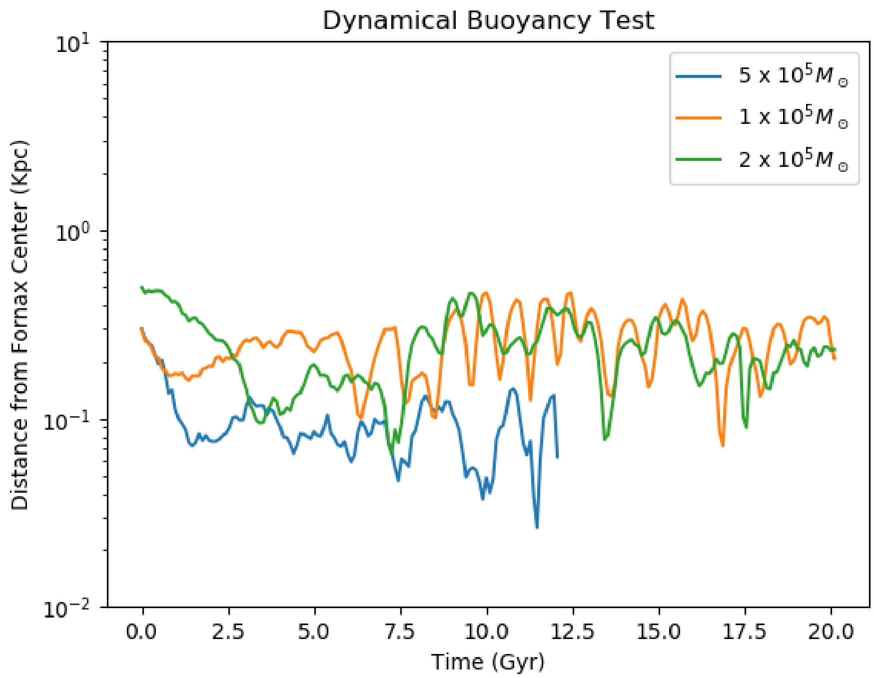

Figure 3.4: Three globular clusters placed inside a large core

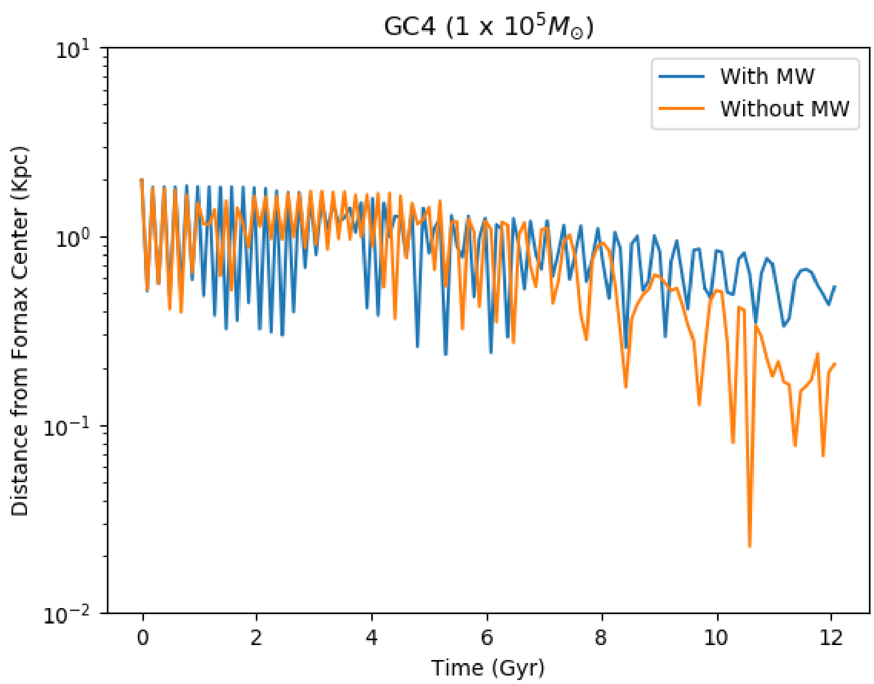

Figure 3.5: Largest effect seen on a GC orbit due to the MW

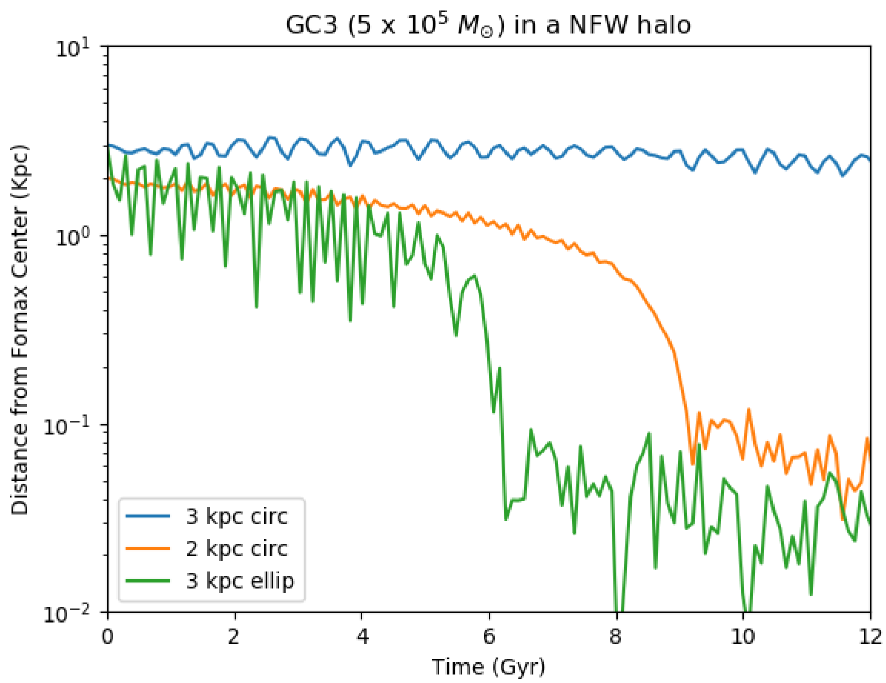

Figure 3.6: Comparison of circular and elliptical GC orbits

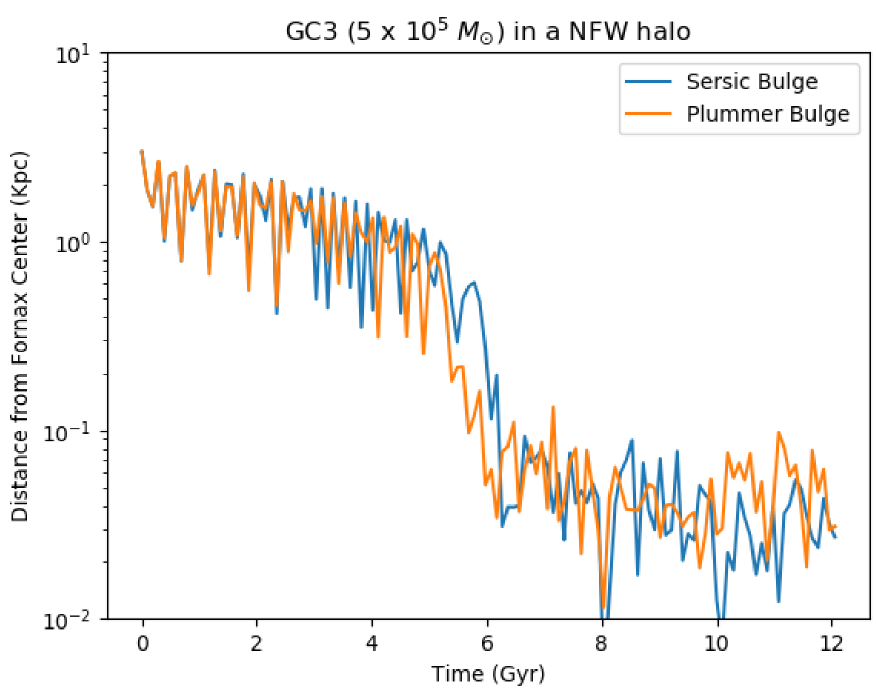

Figure 3.7: Difference between a Sersic and Plummer bulge on an elliptical orbit

3.3 Comparison with other work

3.3.1 Tidal Effects

In Battaglia et al. (2015) they adopt a contracted stellar bulge in which 99% of the stellar particles are located within 2 kpc from the center. In Wang et al. (2017) they adopt a significantly lighter stellar bulge that extends out all the way to 7 kpc. Our contracted stellar bulge matches closely to the one adopted by Battaglia et al. (2015) while our extended bulge is both heavier and slightly less extended than the one adopted by Wang et al. (2016). Our orbit with an eccentricity of 0.31 falls between the P07 best and the P07 eccentric model adopted in Battaglia et al. (2015). We limit our comparison with their work to our contracted bulge models. While they made comparisons between their initial and final conditions within a projected radius of 1.6 kpc, we measured within a spherical radius of 1.6 kpc. Similar to their work, the inner structure of Fornax remains mostly unchanged as well as having a relatively low DM to stellar mass ratio

In Wang et al. (2016) they estimate Fornax to have lost 10-20$\%$ of its infall stellar mass. However, even in our extended bulge model, and even though we increased the chance of tidal effects by orbiting inside of the MW for 11 Gyr, Fornax loses a maximum of 7$\%$ of its original stellar mass. In our Burkert model with an extended bulge, we lose less than 4$\%$ of our original stellar mass. The difference between this and previous work may be due to our relatively high tidal radius. Because of their low initial stellar mass, their unbound stellar mass is equivalent to around 7 x $10^5 M_{\odot}$. All of our models, except the third model with a Burkert halo and a contracted bulge, result in a higher unbound mass total. Therefore, while the internal structure of Fornax loses very little of its original mass, the mass it does lose is comparable, if not greater than the mass loss in Wang et al. (2016). However, the vast majority of this unbound mass does not escape far from the center of Fornax. In our simulations less than 3$\%$ of the initial stellar mass ($\approx$ 1.5 x $10^6 M_{\odot}$) ended up outside 3 kpc from the center of Fornax and the vast majority of that mass was at distances greater than 30 kpc. Furthermore, the majority of the unbound mass is spread roughly spherically around the center of Fornax. Therefore it is unlikely there is a detectable tidal stream emanating from Fornax.

3.3.2 Globular Clusters

Similar to previous work, we find both cuspy and cored halos are consistent with Fornax's globular cluster distribution. However, cored halos allow for a greater number of initial globular cluster conditions. Similar to Meadows el al. (2019) we are unable to reproduce the "dynamical buoyancy" effect reported by Cole et al. (2012). It is unclear what the source of this discrepancy is, and further work may be needed to investigate this effect in more detail.

4. CONCLUSION

4.1 Conclusion

We investigated tidal effects due to the Milky Way on Fornax when adopting various halo and bulge models. As expected an extended bulge results in more mass loss than a contracted bulge, but the internal structure of Fornax remains mostly unchanged over 11 Gyr with a lowest final to initial stellar mass ratio within 1.6 kpc of 0.93 and a lowest final to initial DM mass ratio within a sphere of radius of 1.6 kpc of 0.82.

Concerning the evolution of GCs inside of Fornax, we have shown both a cuspy and a cored halo are consistent with observations. However, a cored halo allows for a greater number of formation scenarios since GC4 can be argued to have been stalled at its current radius for several Gyr. Furthermore, the reason GC 1,2,5, and possibly GC4 have not yet sunk could simply be that their current distance from the center of Fornax is large enough that they have stayed in a roughly stable orbit over the last 11 Gyr. Of course the distance for each GC would, at the same time, have to be small enough to avoid being stripped from Fornax. A 3D radial distance of 1.5 - 2.5 kpc, depending on the GC, would allow for such a solution to be possible and would be in agreement with observational data.

However, given the uncertainty in the current 3D radial distance each GC is from the center of Fornax, it is difficult to use GCs to distinguish between a cuspy and cored halo. More accurate distance measurements in the future may make this task more reliable. Furthermore, we showed that while for the most part the MW, as well as the choice of a bulge, has negligible effects on GC orbits starting under 2 kpc, in certain scenarios the MW can have a small, but not insignificant, effect. Lastly, we were unable to replicate the dynamical buoyancy effect previously reported by Cole et al. (2012). As expected, GCs placed inside a large core did not gain energy and rise, but rather stalled at the expected radius.

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APPENDIX: Fornax plots

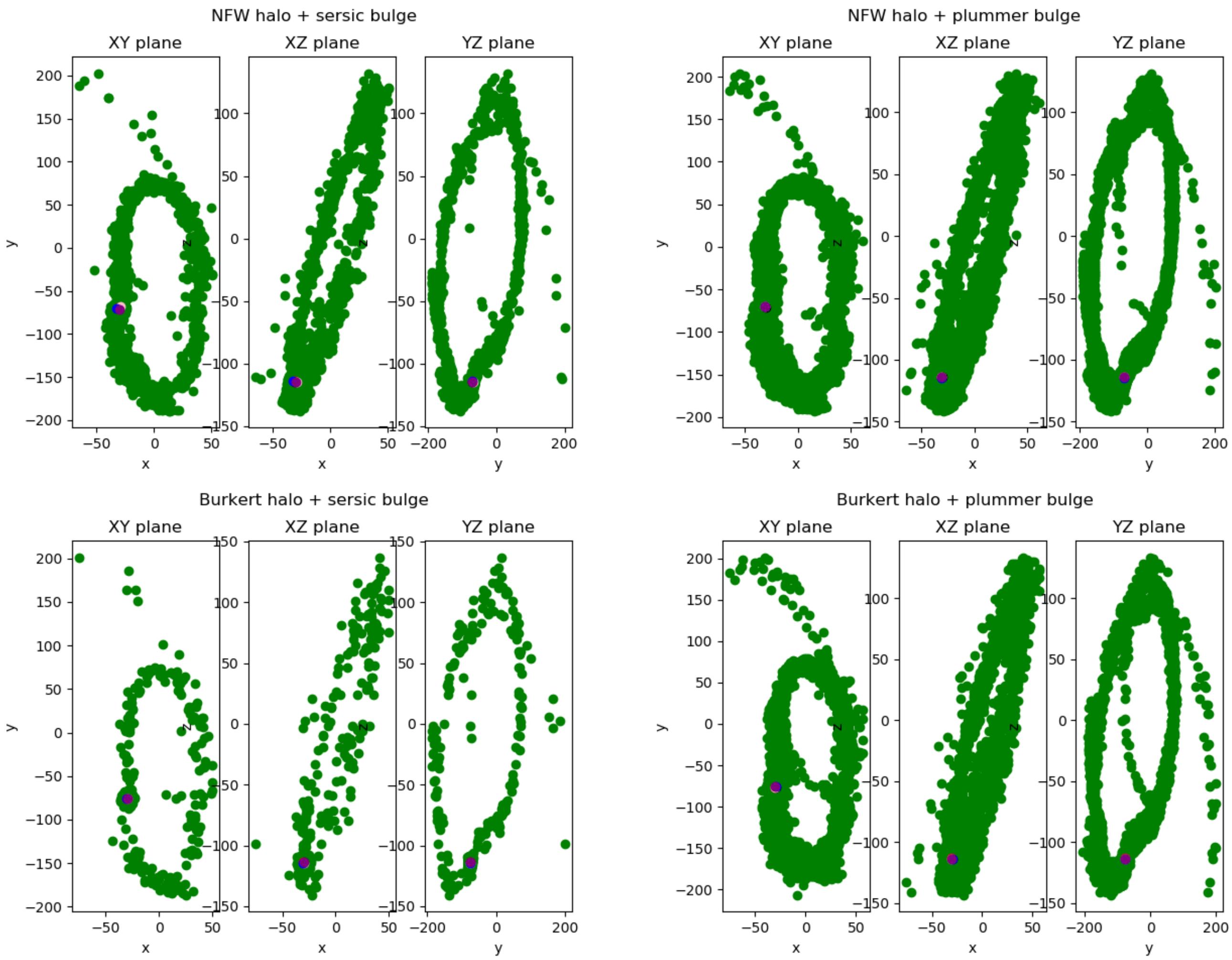

Figure 4.1: Only stellar and gc particles plotted

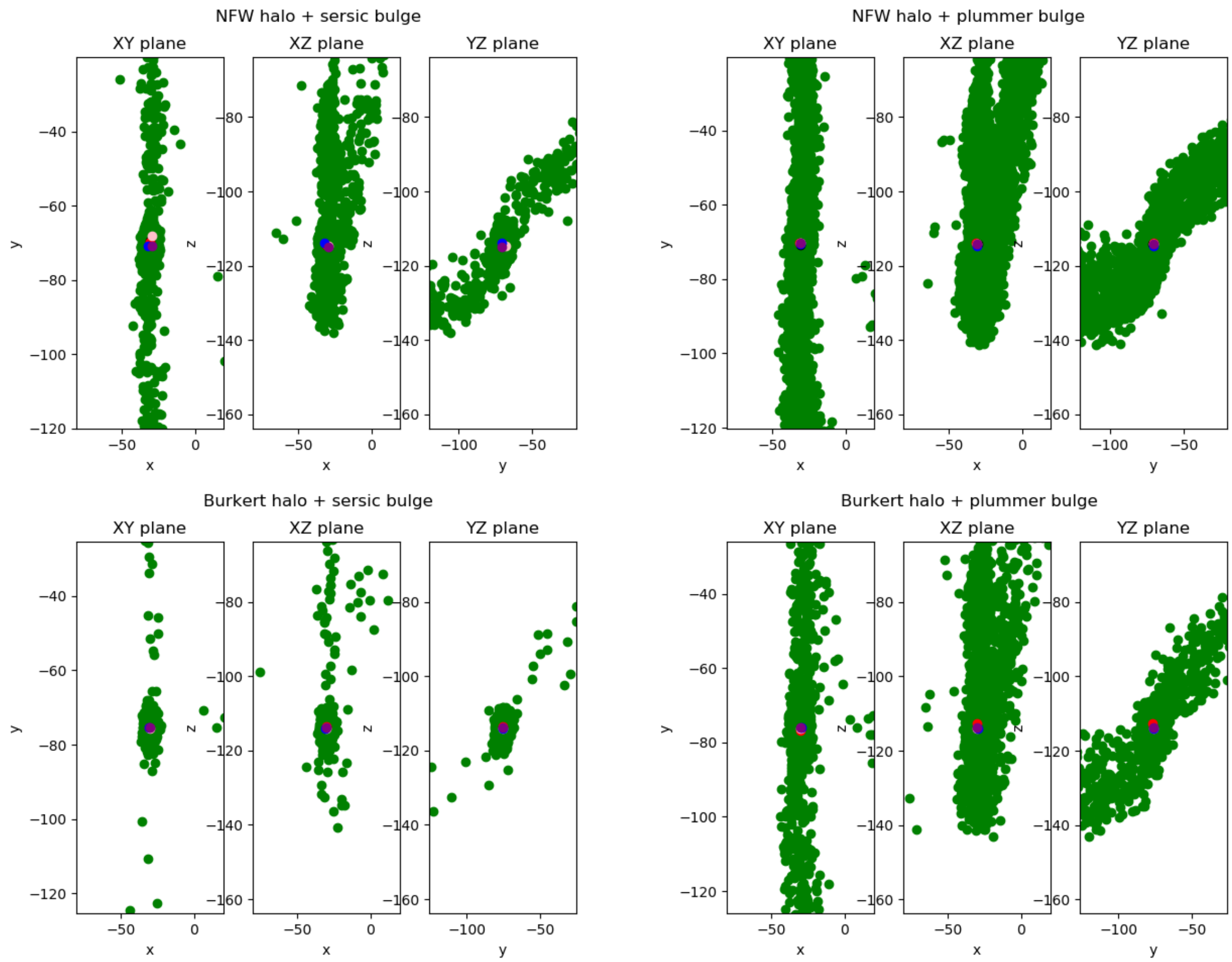

Figure 4.2: 50 kpc box around center of fornax

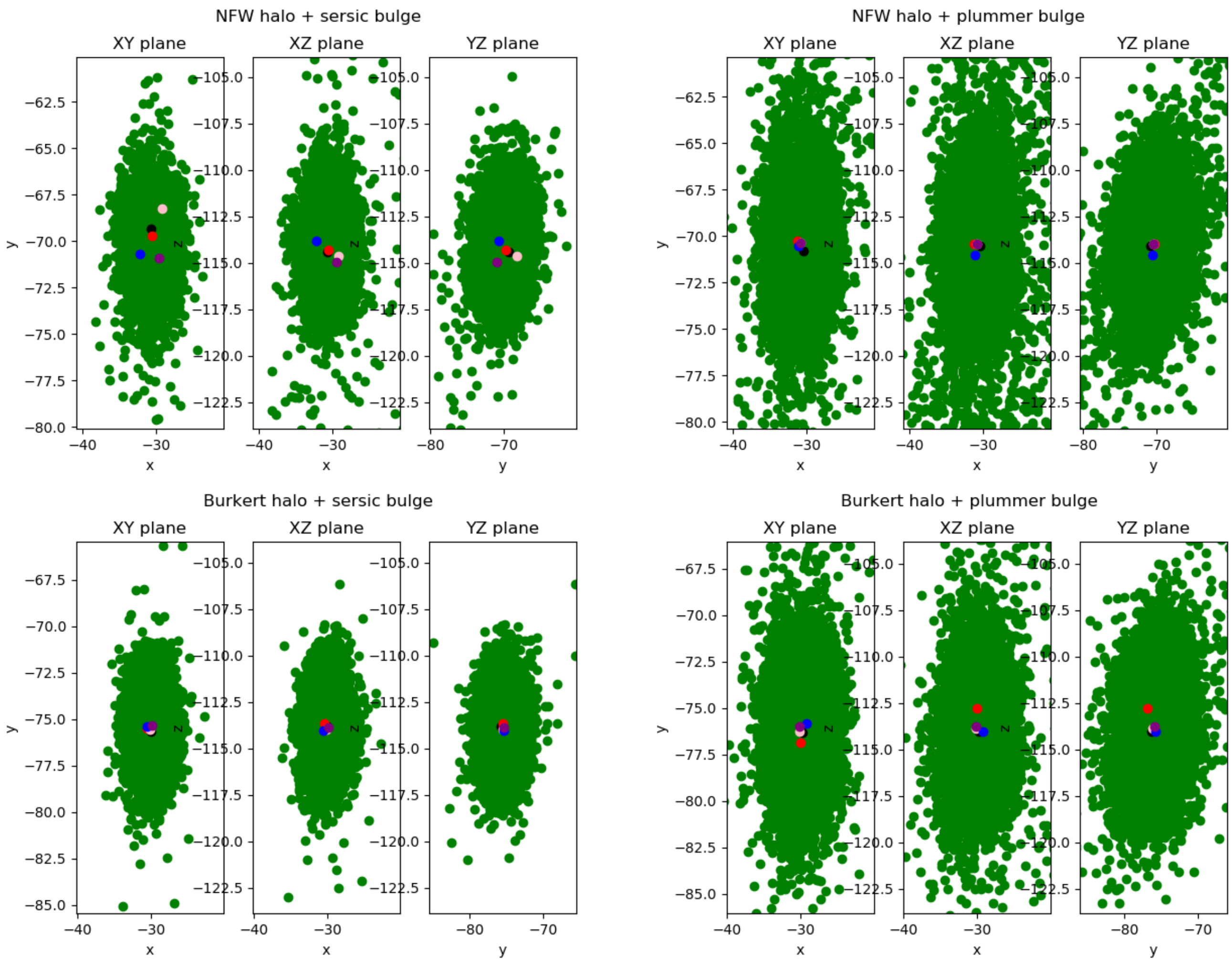

Figure 4.3: 10 kpc box around center of fornax