Density profile fitting on Gadget4 N-body simulation data

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ABSTRACT

Context. Dark matter only simulations are a great way of exploring galaxy formation in a more precise way. This could help us define the shape and formation process of DM Halos in galaxies all around us.
Aims. In this work we will analyze the shape of the radial density profiles resultant of DM formation for different initial conditions.
Methods. Gadget will be used for this purpose, which is an N-body simulation program developed primarily in the Max Plank institute of technology, currently on its version 4.
Results. Simulations fit better to theoretical profiles as new initial velocity elements are included in the initial conditions. Larger particle simulations tend to have a steeper outer region profile.

Key words. N-body simulation - Gadget4 - NFW - Density profile - Hubble flow

1. Introduction

We won't be focusing on the theoretical point of view in this Gadget4 simulations because it is not the purpose of this project. This section will serve as an introduction to the theoretical density profiles used in this work to fit the simulated Dark Matter halos, which are described with detail by Dan, 2010.

As generic as it gets, DM halos density profiles are normally described with a double-power law model, also known as General Density Profile (GDP), that has the following generic expression:

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

This profile can be plotted as shown in Figure 1. In which α is the sharpness of the transition between the two slopes, with γ and β parameters, r_s and ρ_s are the scaling parameters of density and radius.

1.1. The Navarro Frenk and White profile (NFW)

Using N-body simulations and fitting the DM halo profiles to this double-power law the Navarro Frenk White profile was born, using values of $(\alpha, \beta, \gamma) = (1, 3, 1)$. This is the most used profile to fit DM halos nowadays. The analytical expression comes substituting the values:

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1+\left(\frac{r}{r_s}\right)\right)^2}$$

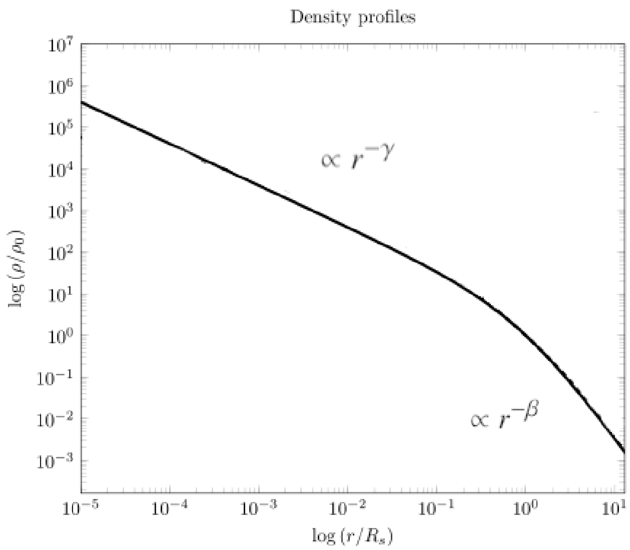

Fig. 1. Generic DM halo density profile. (Hernquist 1990; Jaffe 1983)

2. Methodology

We will start by making some chosen initial conditions for the particle distribution that later on will be used to perform simulations on `Gadget4` software. This simulations will result in an output of a series of snapshots which describe the evolution of the system.

2.1. Initial Conditions

We will now focus on different possible initial conditions for our simulations. These initial conditions where developed by creating `.hdf5` binary files containing the data of initial positions and velocities. For this we developed a script where you can create the initial conditions you like. It is fully automatized so you can just tell the algorithm if you want to apply Hubble Flow or rotation to your particles, as well as if you want a spherical or cubical distribution. This script can be found as an external `.pdf` file called `ICs_generator.pdf`.[1]

First, we will create initial conditions with zero particle velocity (v_0=0). This, as well as for any other velocities, will be performed for a 1000 and 10000 particles. The difference in scale is meant to serve as a test for the simulation working properly, once 1000 particles work well we can jump straight to n=10000.

In second place we will apply Hubble flow to the particles, following the equation:

$$v_{Hubble} = H \cdot d$$
$$H = H_{init} \cdot (1 - \Delta_{init}/3)$$

Lastly, we will add to this velocity rotation in the plane z=0. Which will be simply following angular momentum:

$$v = r * \omega$$

2.2. Snapshot animations

Once `Gadtget4` software was executed we will use final snapshots to see the evolution of the particle system. In fact, for every case of initial velocities and particle set an animation was made. This animations can be found in the `gif/` external folder. We will plot different starting and ending snapshots during this document anyway. The script used to make this plots and animations is `3D-plots.pdf`

2.3. Density profile fitting

Once all the snapshots are loaded into our python script we can calculate a density profile based on the number of particles at each radius. For doing this we started by making an histogram on the data for same radius bins but this gave a wrong result, as spherical shells of bigger radius and equal bin have a higher volume, which would led in a higher number of particles inside the shell than it should.

To solve this problem we basically divided each number of particles for that radius bin by its shell volume, giving us the actual particle density of the shell. Finally, to calculate particle mass we assumed a Milky Way mass of 10^{11} Solar masses.

At this point we have the radial density profile of each final snapshot of the whole set. We can perform some fitting to study the behavior of the simulations comparing with the models explained in section 1.

All the process of radial density calculation and profile fitting is performed in the script `dens_prof_fit.py` and it is again full automatized so giving it the location of the snapshot folder the program gives the two fits as an output.

[1] All these scripts are uploaded and version controlled in my github at: https://github.com/andygarciaserra/tsn-hyd_sims/tree/master/content/project1

3. Results

Now we present the results for the different initial particle velocities we explained above (v_0=0, Hubble flow and Hubble flow with rotation). For each of this we made a n=1000 and n=10000 particle simulation.

3.1. Zero Initial velocity, n=1000 particles

As the collapse of the particles happens so quickly we had to select a higher number of snapshots, which let us to really see whats happening in the evolution. The particles (as can be seen in animation `v0_n1000_start.gif`) start collapsing forming little clumps to finally form a very dense central region. Then, a big number of particles disperse, while in a big central nucleus stays still. In figure 2 we can see the starting point of the simulation, where the initial velocity of the particles is zero (as shown in the color bar). Figure 3 shows the ending snapshot, in which the external particles are already dispersed and a very dense central clump has collapsed.

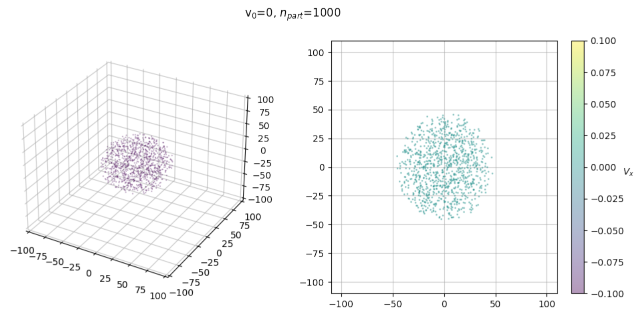

Fig. 2. First snapshot with initial zero velocity and n=1000 particles. (t = 0 Gyr)

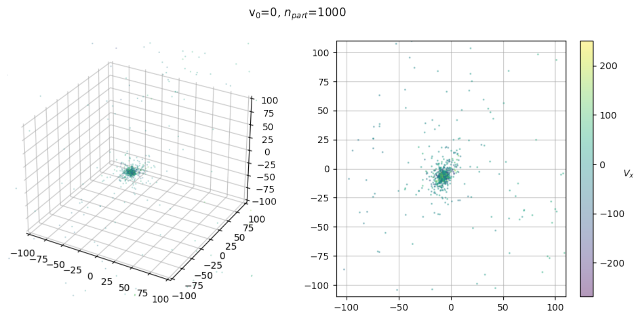

Fig. 3. Last snapshot with initial zero velocity and n=1000 particles. (t = 13.5 Gyr)

Now we can study the radial density profile of the last snapshot, which is shown in figure 4. In it we can see how this final radial profile has an exponential behavior, as we are plotting in logarithmic scale we can see how it fits very good a line with slope around $\alpha = -3$. As the particles have no starting velocity the profile isn't that close to the real case, having a more uniform distribution, as can be seen.

Both theoretical profiles fit with ease, but they show a very low r_s parameter, again because of the exponential behavior of the profile. These values are r_s=1.17 for the NFW and r_s=1.18

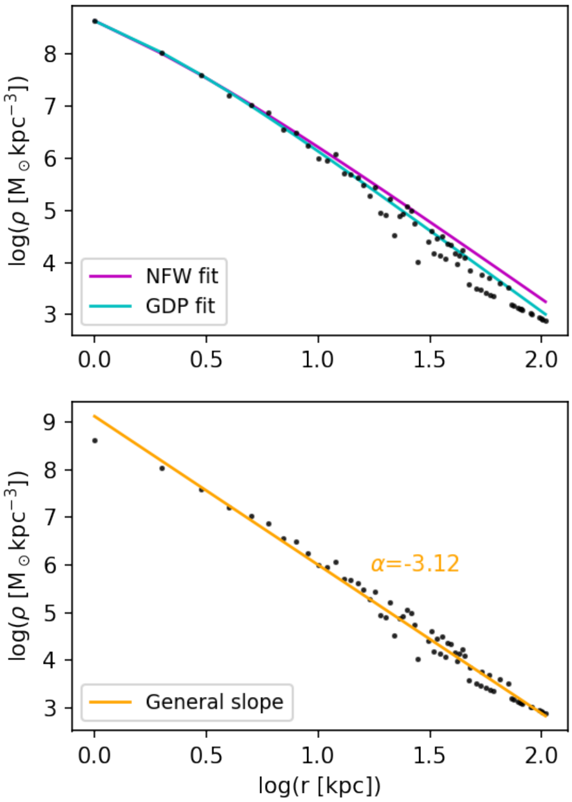

Fig. 4. Radial density profile of last snapshot in v_0=0 and n=1000 particles simulation. Parameters of the NFW fit are r_s=1.17, $\log(\rho_0)$=9.10. For GDP, r_s=1.18, $\log(\rho_0)$=9.08 and (α, β, γ) = (1.30, 3.12, 0.63).

for the GDP.

3.2. Zero Initial velocity, n=10000 particles

This case is very similar to the one with n=1000 particles. We are showing the starting snapshot positions on figure 5 and the ending in figure 6. The density profile is shown in figure 7.

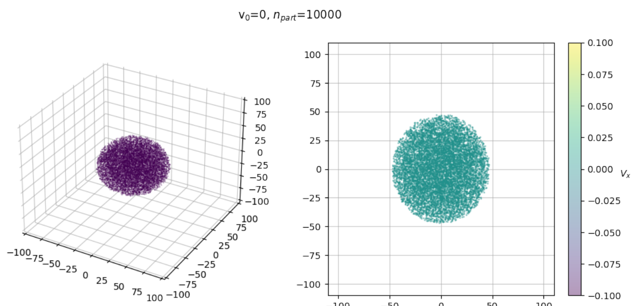

Fig. 5. First snapshot with initial zero velocity and n=10000 particles. (t = 0 Gyr)

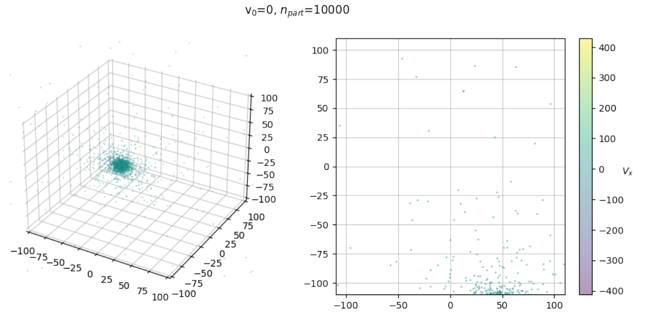

Fig. 6. Last snapshot with initial zero velocity and n=10000 particles. (t = 13.5 Gyr)

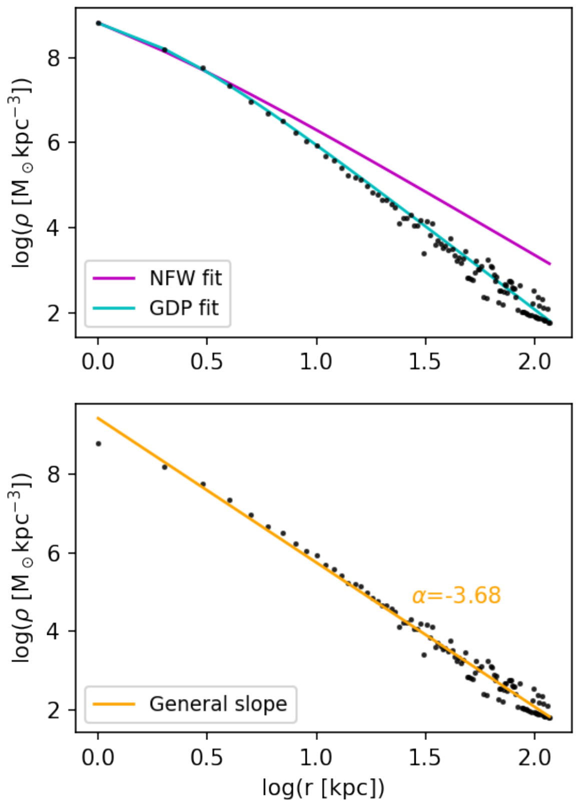

Fig. 7. Radial density profile of last snapshot in v_0=0 and n=10000 particles simulation. Parameters of the NFW fit are r_s=0.91, $\log(\rho_0)$=9.49. For GDP, r_s=1.39, $\log(\rho_0)$=9.37 and (α, β, γ) = (1.39, 1.44, 0.05).

In this case the profile fits again with a nearly exponential shape of slope $\alpha = -3.68$. The behavior is the same as before, with very low fitted r_s parameter. It is important to mention that in this case as the number of particles is one order of magnitude greater each particle is 10 times less massive, what makes them more sensible to interaction, having a higher acceleration with the same gravitational interaction. This change in particle number means also more particle-to-particle interactions, ending in a more dispersed final particle distribution.

3.3. Hubble flow and n=1000

Now, applying starting velocity as the Hubble flow and 1000 particles we get to the initial and ending snapshots shown in figures 8 and 10.

We can see this Hubble flow on the first snapshot looking at the x-axis velocity distribution. Particles on the left hand side of the distribution are speeding to the left and the ones on the right are speeding to the right. This confirms the expansion of the universe is correctly applied to the initial conditions.

For this number of particles we can try to isolate the snapshot where the particles form small clumps before the collapse of the system, but it won't be as discernible as for a larger particle number. This snapshot is the one we are showing on figure 9.

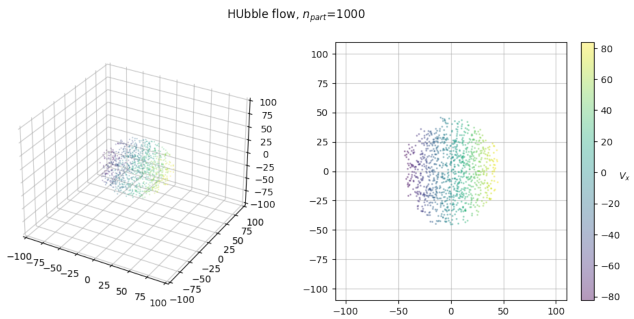

Fig. 8. First snapshot with Hubble flow initial velocity and n=1000 particles. (t = 0 Gyr)

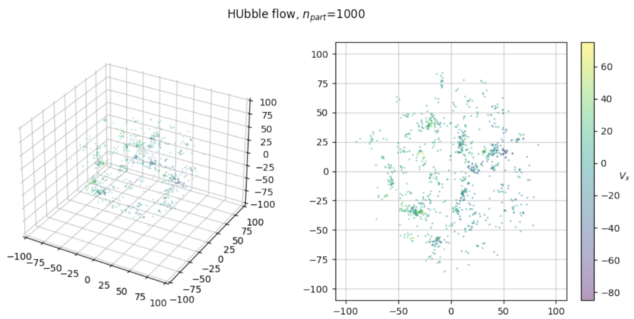

Fig. 9. Clump-forming snapshot with Hubble flow initial velocity and n=1000 particles. (t = 2 Gyr)

The radial density profile is presented in figure 11. We can clearly see that for this setup the profile is very close to the real general behavior of a general Dark Matter density profile, as the inner slope is α = -1.35 and the outer is β = -3.36 . For this case we have a fitted r_s=11.61, which is in the normal range of values.

The GDP profile fits with ease again, following the behavior of the slope, the NFW is fitting very correctly in this case too, even though at the outer region of the profile it differs. This is on top of giving a higher weight to the points on the central region, applying a sigma of 1/r in the fit. Its also important to mention that the actual parameters of the

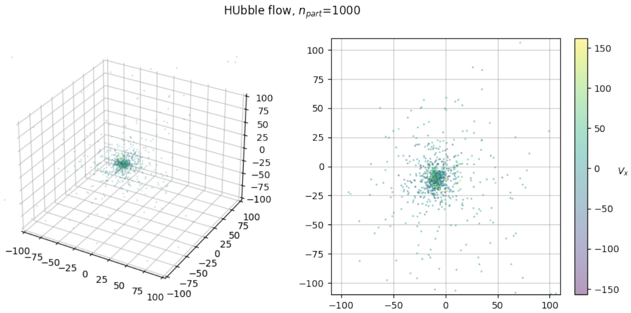

Fig. 10. Last snapshot with Hubble flow initial velocity and n=1000 particles. (t = 13.5 Gyr)

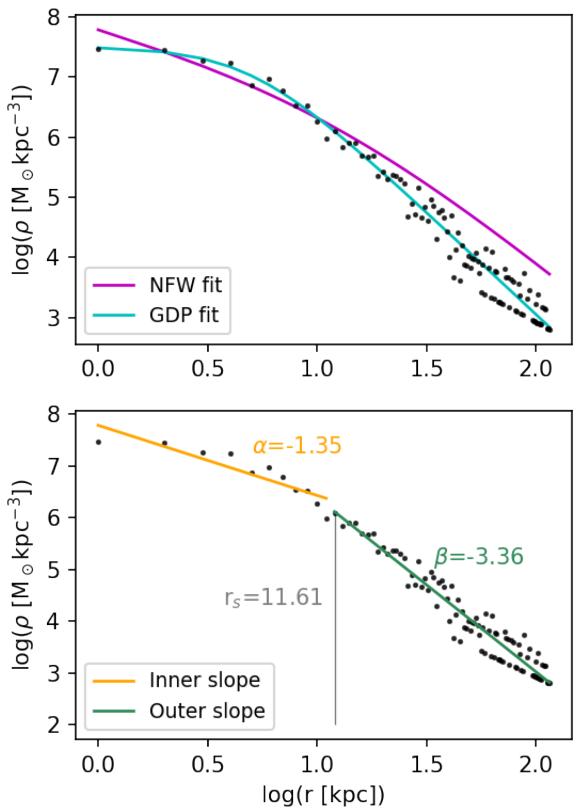

Fig. 11. Radial density profile of last snapshot with Hubble flow and n=1000 particles simulation. Parameters of the NFW fit are r_s=11.61, $\log(\rho_0)$=6.79. For GDP, r_s=4.93, $\log(\rho_0)$=7.51 and (α, β, γ) = (1.28, 3.41, 0.85).

GDP fit are close to what an NFW profile is fitting normally $(\alpha, \beta, \gamma)_{NFW}$ = (1, 3, 1), as can be checked in the caption at figure 11.

3.4. Hubble flow and n_{part}=10000

Repeating this conditions with a larger particle number of n=10000, we can see the initial and ending snapshots, as well as the clump forming snapshot in figures 12, 14 and 13 respectively.

In figure 13 we can now differentiate clearly the clumps forming before de collapse of the system. This happens at around t = 2 Gyr. Right after this clumps form the collapse happens, as can be seen in the animation `hf_n10000.gif`

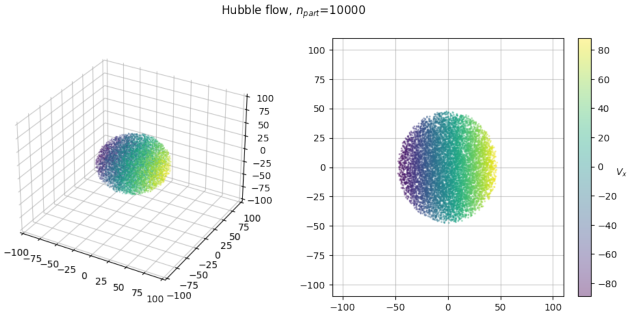

Fig. 12. First snapshot with Hubble flow initial velocity and n=10000 particles. (t = 0 Gyr)

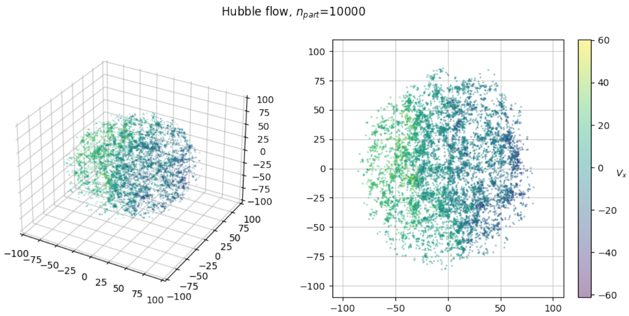

Fig. 13. Clump-forming snapshot with Hubble flow initial velocity and n=10000 particles. (t = 2 Gyr)

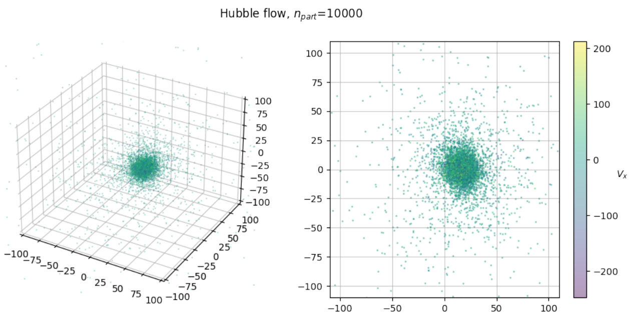

Fig. 14. Last snapshot with Hubble flow initial velocity and n=10000 particles. (t = 13.5 Gyr)

The profile density for this setup is similar to the one for n=1000 particles and it is presented in figure 15. Again, when going for higher resolution at n=10000 particles the outer slope of the profile gets steeper, to a value of around -4. This happens, as before, because of the final distribution of particles. As the number of particles grows they are more likely to disperse into larger distances.

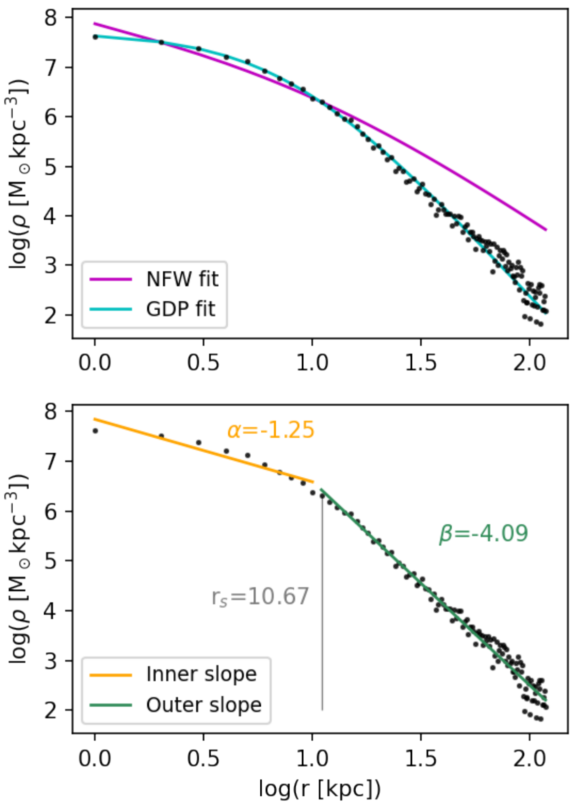

Fig. 15. Radial density profile of last snapshot with Hubble flow and n=10000 particles simulation. Parameters of the NFW fit are r_s=10.67, $\log(\rho_0)$=6.93. For GDP, r_s=7.68, $\log(\rho_0)$=7.71 and (α, β, γ) = (1.43, 4.75, 0.00).

3.5. Hubble flow, angular momentum and n=1000

Now that we analyzed the Hubble flow setup we can apply initial rotation to our particles and see the behavior of the collapsing system. In first place we will make sure our system is initially rotating. In figure 16 we are showing the rotation velocity distribution of the initial snapshot for v_x and v_y, as this is just to check the angular rotation we will be using n=10000 particles for it to be easier to analyze. As it shows, the system is rotating clockwise in an overhead view.

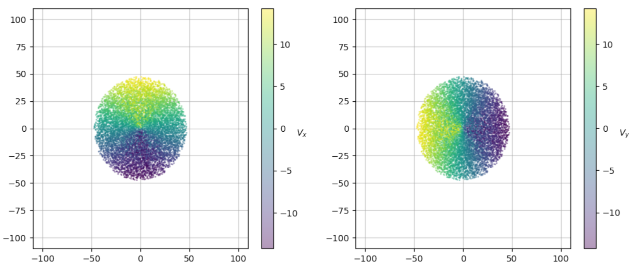

Fig. 16. Initial angular rotation of the particle distribution for n=10000 particles. (t = 0 Gyr)

Now that we confirmed the rotation is well set, the initial, clump-forming and ending snapshots are shown in figures 17, 18 and 19 respectively.

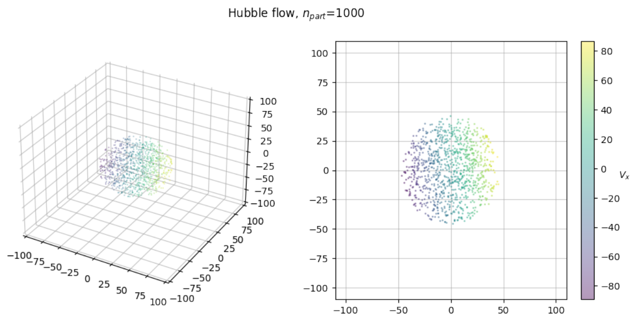

Fig. 17. First snapshot with Hubble flow initial velocity, angular momentum and n=1000 particles. (t = 0 Gyr)

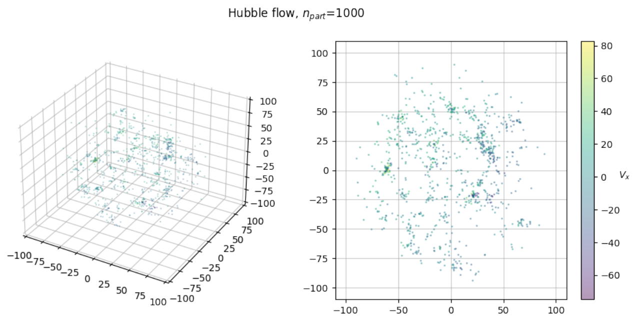

Fig. 18. Clump-forming snapshot with Hubble flow initial velocity, angular momentum and n=1000 particles. (t = 2 Gyr)

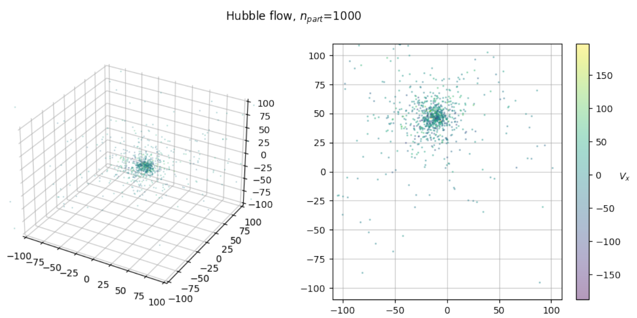

Fig. 19. Last snapshot with Hubble flow initial velocity, angular momentum and n=1000 particles. (t = 13.5 Gyr)

Rotation can be noticed in figure 18, where the clumps are collapsing forming a spiral-like structure. THis rotation is more noticeable in the animation `hf_rot_n1000.gif` where the system can be seeing spinning before collapsing.

The radial profile of this setup is presented in figure 20. This profile is the closest to an NFW yet, as the simulation is getting more realistic to a real Dark Matter halo behavior. We can see now again that the parameters of the inner and outer slopes are close to -1 and -3.

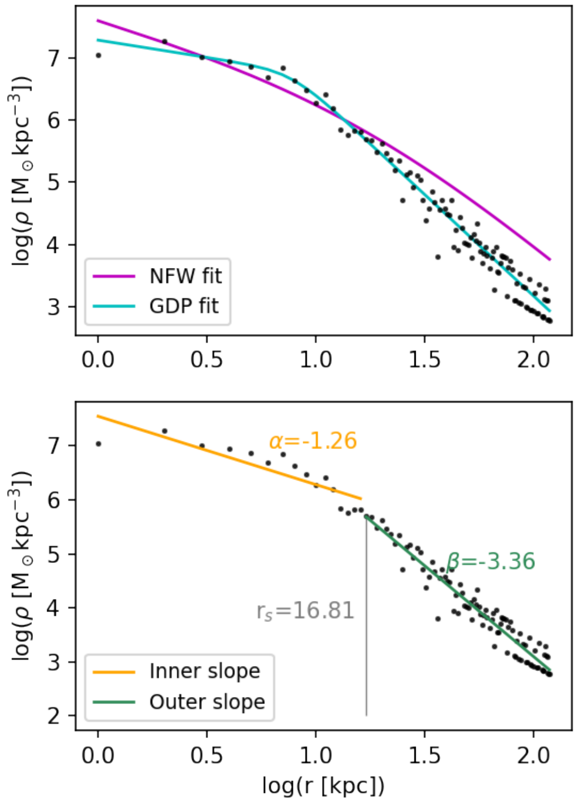

Fig. 20. Radial density profile of last snapshot with Hubble flow, rotation and n=1000 particles simulation. Parameters of the NFW fit are r_s=16.81, log(ρ_0)=6.42. For GDP, r_s=7.76, log(ρ_0)=6.79 and (α, β, γ) = (6.00, 3.26, 0.56).

3.6. Hubble flow initial velocities, rotation and n=10000

Finally, we can make the same simulation for n=10000, without having to double check the initial rotation. We present then in figures 21, 22 and 23 the starting, clump-forming and ending snapshots.

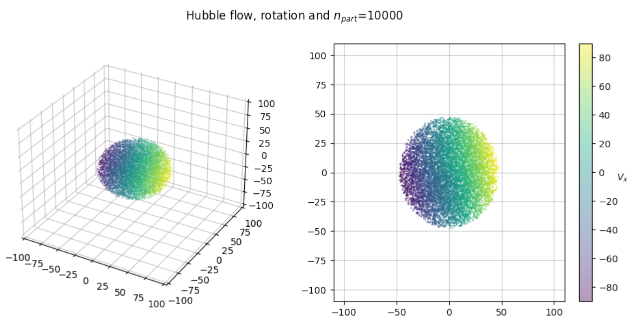

Fig. 21. First snapshot with Hubble flow initial velocity, angular momentum and n=10000 particles. (t = 0 Gyr)

And the density profile fitted is the one shown in figure 24. We can see again the effect of having 10000 particles. The

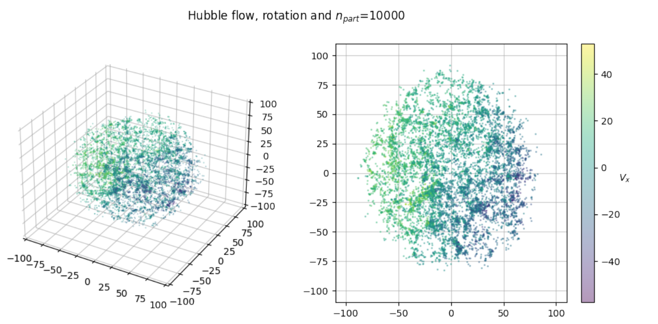

Fig. 22. Clump-forming snapshot with Hubble flow initial velocity, angular momentum and n=10000 particles. (t = 2 Gyr)

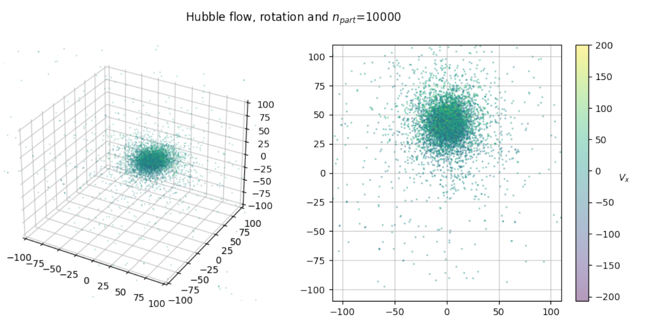

Fig. 23. Last snapshot with Hubble flow initial velocity, angular momentum and n=10000 particles. (t = 13.5 Gyr)

density profile is much steeper in its outer region, with a slope of -4.36.

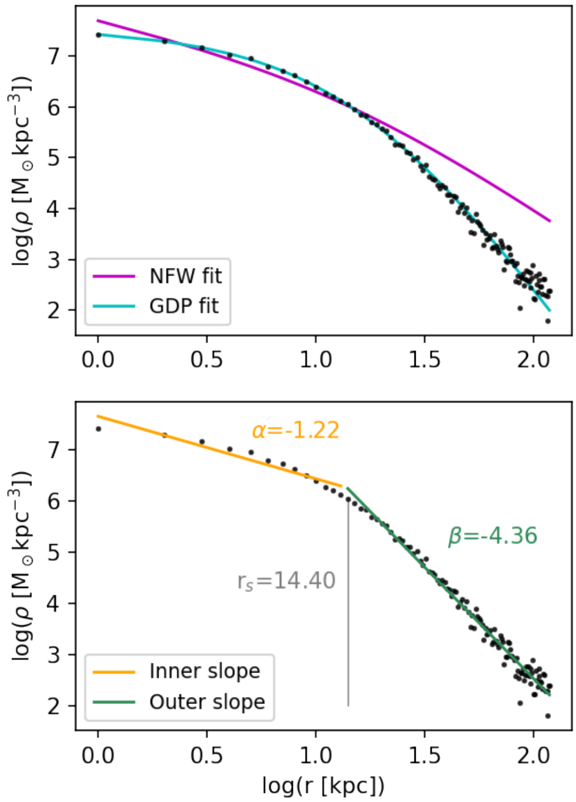

Fig. 24. Radial density profile of last snapshot with Hubble flow, rotation and n=1000 particles simulation. Parameters of the NFW fit are r_s=14.40, $\log(\rho_0)$=6.60. For GDP, r_s=16.13, $\log(\rho_0)$=7.39 and $(\alpha, \beta, \gamma) = (1.16, 4.23, 0.16)$.

4. Discussion

To finish the document, we will discuss some important concepts as well as answering the questions asked.

In the first simulation for zero initial velocities de density profile isn't really following a normal cosmological simulation, which is obvious because we are not giving the simulation a real initial condition setup. This changes as we add more realistic components to the velocity.

In the second simulations with Hubble flow as initial velocities we can clearly see how between the snapshot 3 and 4 the system starts collapsing after an initial expansion.

Another important point is that we applied a weighting sigma in the fitting process of the theoretical profiles. Giving more weight to the inner radial distance than to the outer radii.

Finally, it is important make a point on initial conditions of Hubble and angular momentum. When we are plotting the initial velocity of the system with Hubble flow and rotation we can see how it behaves as a system with only Hubble flow (See velocity distribution in the x axis on figure 21). This is happening because Hubble velocities are almost one order of magnitude greater than rotation velocities as we are applying them.

5. References

[1] Coe, Dan. *Dark Matter Halo Mass Profiles*, 2010