3D Visualization of Early Cosmic Structure Formation

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Contents

1 Introduction

The aim of this project is to create 3D visualizations of data from a particle based simulation. This project is completed at the Institute for Astronomy at the University of Edinburgh under the supervision of Ben Morton. Section 3 of this report is dedicated to the 2D Analysis of multiple snapshots, section 4 concentrates on the main aims of this project which is 3D visualization. All the results and findings are summarized in 5.

All the data used in this project for all simulations and plots included are from a particle based simulation ran at the Institute of Astronomy at the University of Edinburgh by the members of the Theoretical Modeling of Cosmic Structures (TMoX) group lead by Prof. Sadegh Khochfar. The project was completed using Python and its `yt` library used for plotting data from particle and grid based simulations.

2 Data

Figure 1 below summarizes the data used throughout this project. In the rest of this report the different datasets are referred to by their name stated in the figure. All the snapshots shown in the figure are from the Legacy project simulation, which includes dark matter particles only. Since the data used is from particle based simulation and the features of `yt` are optimized for grid based simulations, a covering grid was created. This means that the plots in the rest of this report show binned dark matter particles as opposed to real particle positions.

Name	L_{box} (Mpc/h)	L_{box}^{hr} (Mpc/h)	N^{hr}	$N_{eff.}$	m_p (M_o)	Comment
1600n64	1600.0	1600.0	64^3	64^3	1.2E+15	Large box super low res
1600n256	1600.0	1600.0	256^3	256^3	2.78E+13	Large box low res
100n256	100.0	100.0	256^3	256^3	6.78E+9	100 Mpc low res

Figure 1: List of data used throughout this project taken from the Legacy simulation including dark matter particles only. Figure taken from `https://sites.google.com/site/tmoxwiki/legacysuite/infolegacy`

3 2D Analysis

At the beginning of the project the functionality of `yt` was explored by creating several projection plots. The dataset 1600n64 was used for all the plots in this section.

3.1 Density Analysis

The density distribution of dark matter particles was be analyzed across 16 available snapshots. There were 262144 gas particles in each of the supplied snapshots.

Figure 2 shows how the density profile develops across snapshots 8 to 15 in 3 different planes (y-z, x-z and x-y respectively). Snapshots before number 8 were not included since they are all identical to snapshot 8 and absolutely uniform. Density variation can only be seen from snapshot 12 onwards. Afterwards areas of high and low density develop and form small clusters.

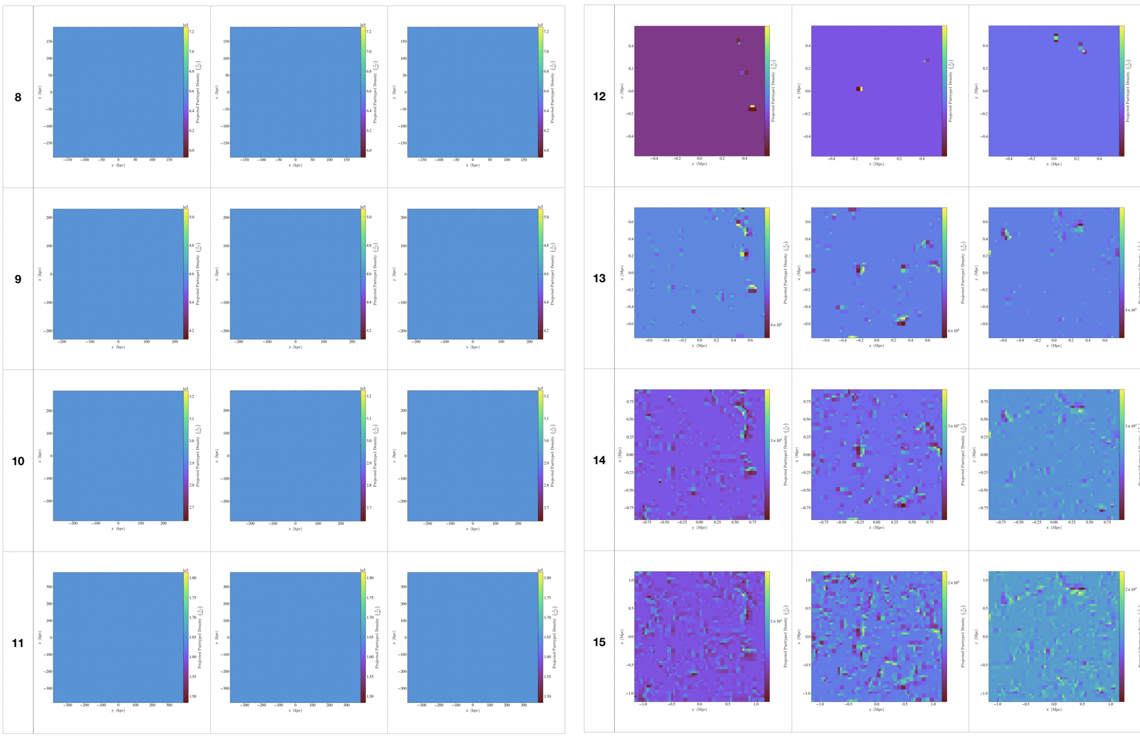


Figure 2: Density profiles of given snapshots in 3 perpendicular planes (y-z, x-z and x-y corresponding to left, middle and right column respectively) starting at snapshot 8 since all previous snapshots are identical.

Afterwards the maximum density value was analyzed, namely how it varies with redshift. The plot of maximum density against redshift is shown in Figure 3. Datapoints from only the first 11 snapshots were included to better depict the general trend of how maximum density varies with redshift.

3.2 Nearest Neighbor Velocity Analysis

This section looks at the nearest neighbor velocity of dark matter particles and its relationship to the density distributions from subsection 3.1. For this reason the density contours were included in the nearest neighbor velocity plots in Figure 4.

The plots for the 16 given snapshots with the density contours are shown in Figure 4. The density contours are only visible in the last 4 snapshots, since the density distribution is uniform for the first 12. Due to that it is desirable to look more closely at the last 4 snapshots and examine any relationship between the density and nearest neighbor x-velocity distribution.

Figure 5 shows a close up of the nearest neighbor x-velocity distributions with density contours.

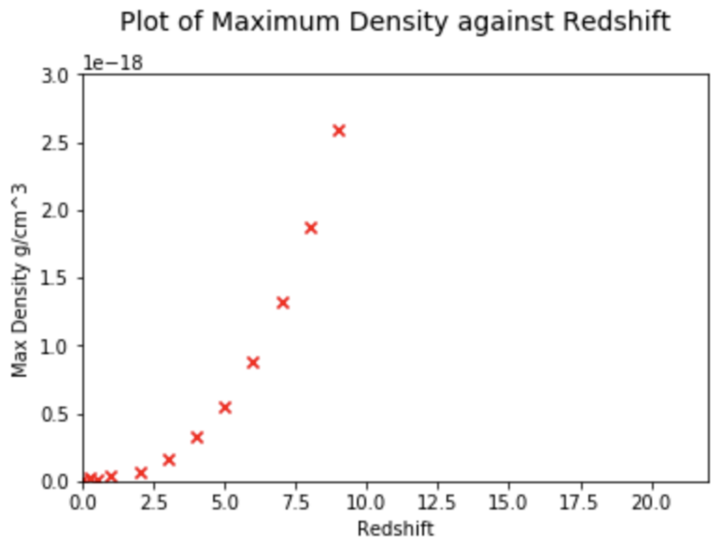


Figure 3: A plot of maximum density against redshift. Only the first 11 datapoints are shown to better depict the general trend. The omitted data points are at much larger densities and therefore in the scale of the plot disguise the overall trend.

In snapshots 12 and 13 specifically, the density contours are found around the non-uniform velocity regions. For the last two snapshots the correlation between the velocity distribution and the density distribution is harder to spot, since the variation in both distributions is much larger. We can find a lot of contours around non-uniform velocities however there are also denesity contours around regions where the x-velocity is perfectly uniform (light blue regions in Figure 5).

4 3D Analysis

The next step in this project was to create 3D plots of the dark matter density distribution in the supplied snapshots and also to create 3D animations of the dark matter density distribution. Before the animations, different variables influencing the appearance of the 3D plots were explored. For more detail on the parameters needed to create a 3D plot and their meaning, the reader is advised to go over the Code Report issued along with the animation code.

4.1 Sigma Clipping

At first the sigma clipping in 3D plotting was explored. This parameter determines how enhanced are regions of higher density. A plot of how the same 3D plot changes with the value of `sigma_clip` is shown in Figure 6. The 100N256 dataset was used for all the plots in Figure 6 with 128 pixels along each axis (see section 4.2 for details on number of pixels). From the various plots in Figure 6 it is clear that higher `sigma_clip` leads to brighter high density regions. Quite often no sigma clip (`sigma_clip` = None) leads to dark images therefore `sigma_clip` of at least 6.0 was used in all future plots.

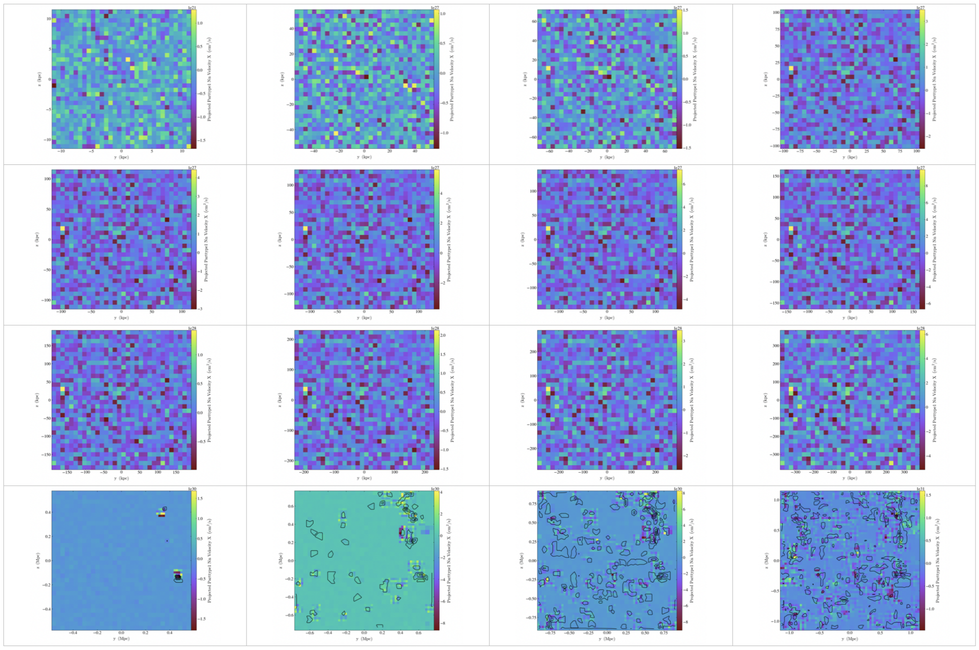


Figure 4: Nearest neighbor x-velocity distribution across all 16 given snapshots (starting at the top left and in rows) with density contours. The density contours are only visible in the last 4 snapshots due to the uniform density distribution of the first 12 (see Figure 2).

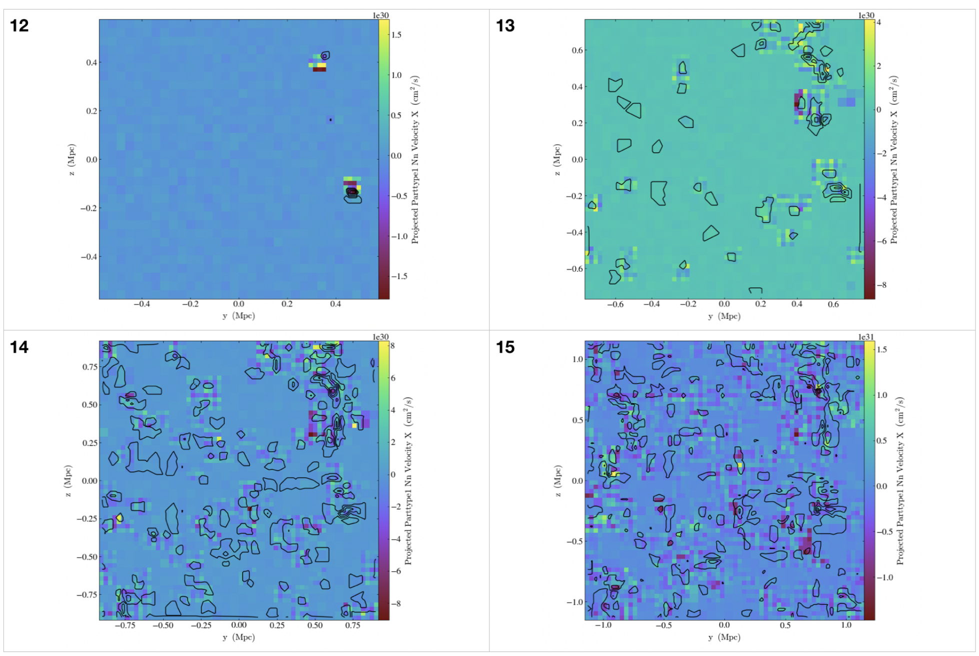


Figure 5: Close up of nearest neighbor x-velocity distribution in the last 4 snapshots with density contours. The number of the snapshot is displayed in the top left corner.

4.2 Number of Pixels

The number of pixels along each axis was explored next. Figure 7 shows how the 3D plots' resolution varies with the number of pixels used to plot them. The data used for these plots was the 100N256 dataset with `sigma_clip` = 5.0.

It is clear that a higher number of pixels leads to better resolution, however higher computational power is needed for higher resolution images. All plots are displayed from the same angle apart from the 1024 pixel plot, which was generated as part of an animation and its angle is therefore different. A simulation of this resolution can only be ran on a computational cluster such as Cuillin. From the plots it can also be seen that higher resolution can lead to darker images. This is because smaller structures are resolved and therefore more empty space is depicted compared to the low resolution images. The improve the visual appearance of those plots, a smaller value of `sigma_clip` is recommended (further described in section 4.1).

4.3 3D Animations

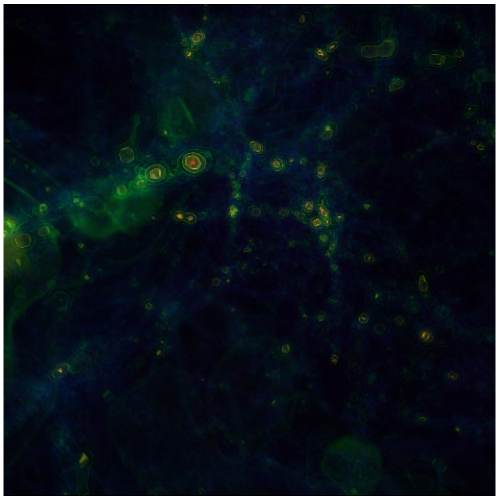
The next task in this project was to create animations from the 3D plots shown in sections 4.2 and 4.1. All three supplied datasets were used (see Figure 1), however 100N256 produced the most interesting results due to its high resolution. This was done by utilizing functions of the `Scene` object in `yt`, which enables to move, rotate and zoom the camera therefore showing the same plot from different angles and positions. 100 frames were generated for each animation, to ensure smooth transitions. The `.png` files created were then put together into a single movie by `ArtistAnimation`, which is a function of the `matplotlib` Python package. This method enabled to create `.mov` files showing the same plot being rotated around any point in the box (e.g. maximum density value or box center) or zooming in on any particular point (e.g. density maximum).

Although the animations themselves are not included in the report, the source code is available along with detailed documentation enabling anyone to create their own 3D animation from any supplied dataset.

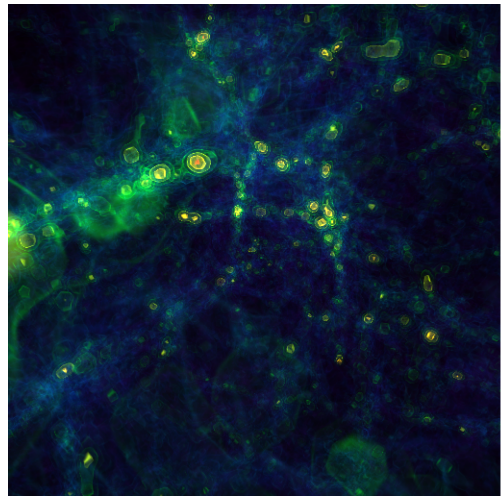
4.4 Rockstar Halo Catalog

Upon requests from the TMoX group members, the Rockstar halo catalog was incorporated into the program. This enables the user to center an animation or a single frame on any halo in the catalog just by supplying the `halo_id`. The pathway to the Rockstar catalog is also required. This functionality proves to be useful namely when looking for specific structures withing the animation and when trying to visualize a particular halo without the need for many 2D plots.

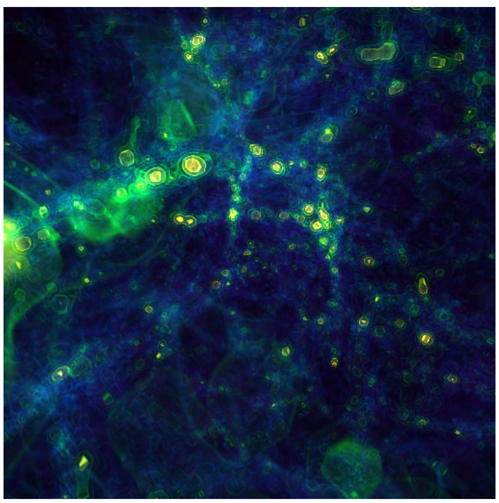
5 Conclusion



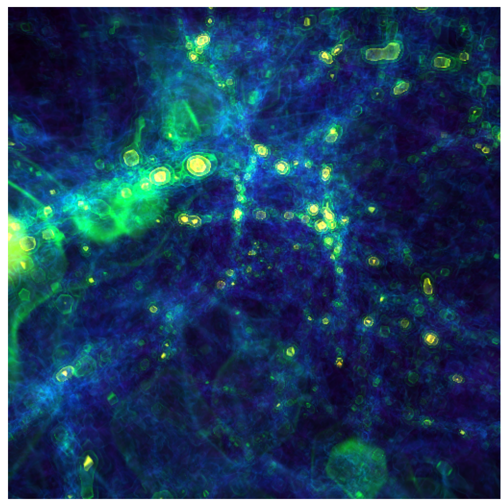
(a) sigma clip = None



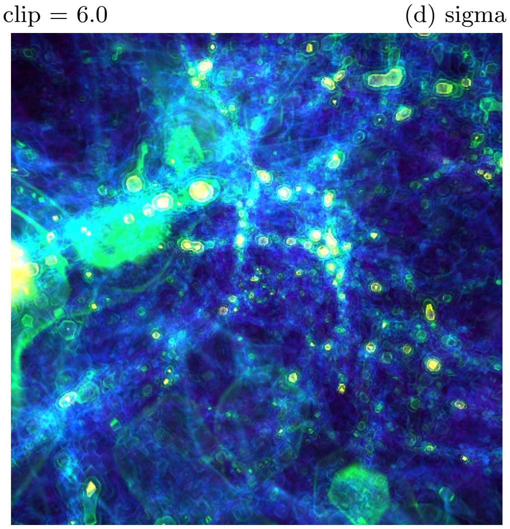
(b) sigma clip = 8.0



(c) sigma clip = 6.0

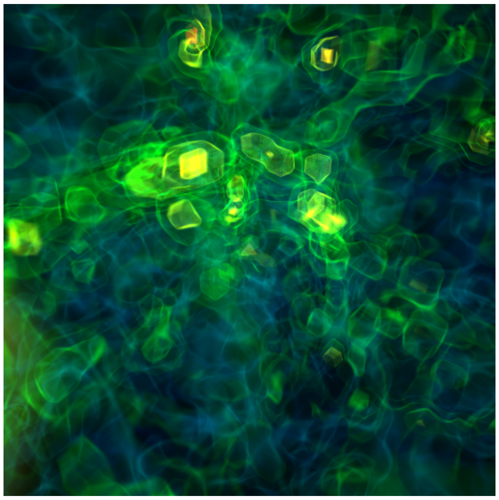


(d) sigma clip = 4.0

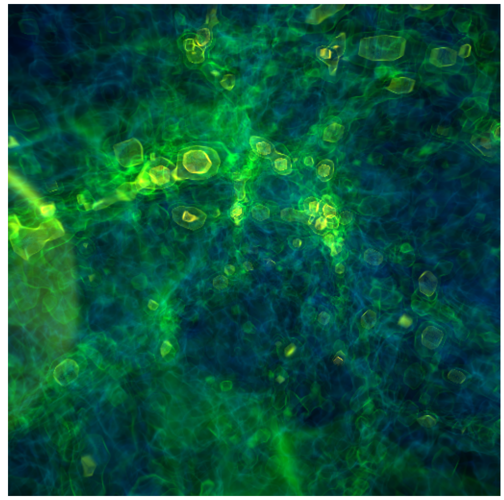


(e) sigma clip = 2.0

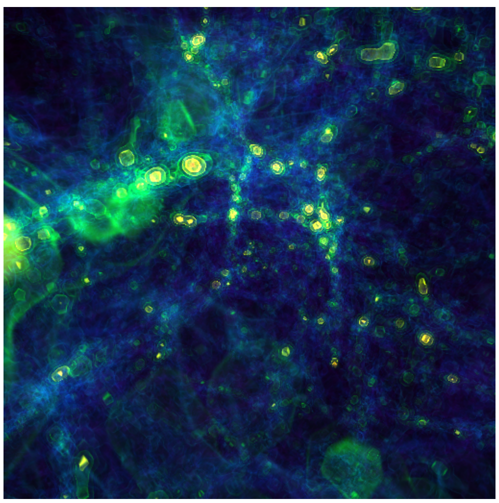
Figure 6: Set of 3D plots corresponding to `sigma_clip` = None, 8.0, 6.0, 4.0 and 2.0 respectively. The value of `sigma_clip` changes how enhanced high density regions are. Higher `sigma_clip` means less enhancement. All plots contain 128 pixels along each axis.



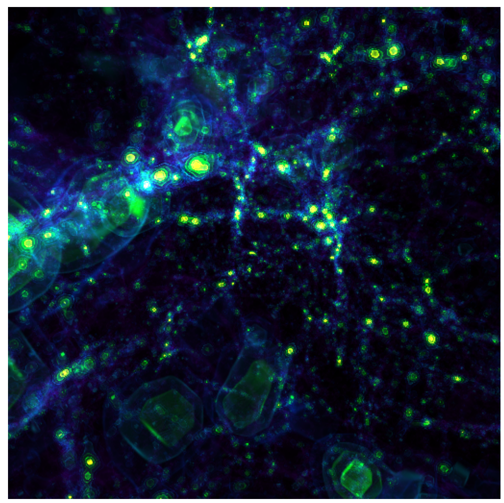
(a) 32 pixels



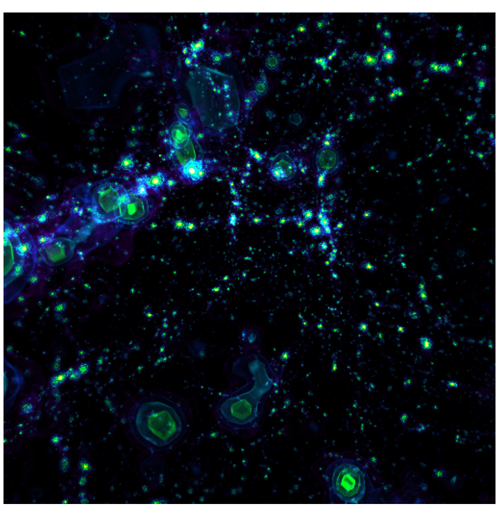
(b) 64 pixels



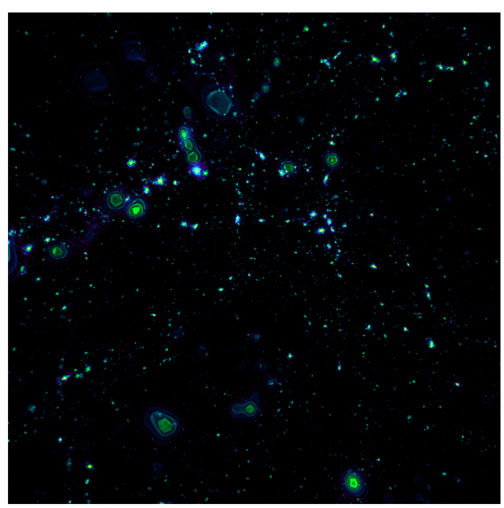
(c) 128 pixels



(d) 256 pixels



(e) 512 pixels



(f) 1024 pixels

Figure 7: Set of 3D plots corresponding to number of pixels = 32, 64, 128, 256, 512 and 1024 respectively.