Visualizing the Evolution of Dark Matter Merger Trees

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Abstract— **Cosmological simulations allow us to recreate the evolution of the cosmic web and better understand the dark matter halos that compose it. The direct output of simulations is the positions of particles at various points in time. With the particles we can determine the locations of halos and the history of those halos through merger trees. Most visualizations of simulations focus on 3D rendering the particle data, with recent work producing highly interactive tools to simultaneously explore different aspects of the particles, halos, and merger trees. My project attempts to visualize dark matter halo trees in novel ways. Three aproaches were taken: (1) visualizing the evolution of the density profiles of halos over time, with the goal of better understanding how they relate to the certain properties of the halo (e.g. mass, radius, accretion rate), (2) using tree maps to visualize the hierarchical structure of present day halos and all of their progenitors, and (3) using chord diagrams to display the mergers of individual halos in a tree. Ultimately, we wish to gain more intuition and provide a clearer picture of the physical processes that dictate how halos evolve.**

I. INTRODUCTION

A. *Motivation*

Dark matter makes up around 25% of the energy density of the present day universe, greater than five times that of "regular" baryonic matter. For this reason, it is fundamental to understand the distribution of dark matter in the universe. At the present time, at the largest scales, dark matter is distributed in a web-like structure, with filaments connecting regions of high concentrations of dark matter (clusters), and the space in between being largely devoid of matter (voids).

According to our current understanding of the formation of structure in the universe, dark matter collapses into halos, which are bound spherical units of dark matter that vary in mass and size. Halos are structured hierarchically such that smaller halos can exist within larger ones, although if the tidal gravitational forces are strong enough, the halos will merge and result in a larger halo. Because halos grow through mergers, the most massive halos will be located in clusters, the regions of highest global matter density in the universe. Dark matter also traces the location of baryonic matter in the universe, so these dark matter halos are the locations of galaxies like the Milky Way [1]. There is a strong connection between galaxies and their dark matter halos, in terms of their masses and evolutionary histories. This is demonstrated by various successful models of galaxy-halo connection. Understanding the structure and evolution of dark matter halos is crucial to understanding the Universe at the largest scales, and the details of this cosmology tell us about the evolution of galaxies, which tells us about ourselves.

Because we cannot yet observe dark matter directly and because the universe has 13.8 billion year history we are unable to understand the full story of dark matter with observations alone. For this we rely on cosmological simulations which are able reproduce the universe in more reasonable timescales. They simulate dark matter as a particle that interacts gravitationally. Depending on their size, they require $\gtrsim 10^9$ particles of $\gtrsim 10^8 M_\odot$ mass and volumes of $\sim$ 100Mpc ($\sim$ 2000 times the size of our galaxy). The base level data from the simulations, will be the particle data with their positions at different time steps. From these particle data, we can determine the locations of halos and measure various properties (e.g. size, mass), using halo finding algorithms [2, 3]. From these halo catalogs at different time steps, we can determine the merger history of the halos and create merger trees that show all of the halos at past times that merged over time to create a halo at a future time. This requires the use of tree builders [4]. Combining a halo finder and tree builder, we can build halo merger trees, which trace the evolution of halos across simulation snapshots.

- particle data
- halo data
- merger tree data

These three levels of data hold different information about the large scale structure of the universe, and together they help paint the complex picture of cosmology. Developing visualizations for each of these has often been a challenge, but finding novel ways to visualize this information can provide a new understanding for the bigger picture of what is going on.

B. *Related Work*

Typically, the visualization of cosmological simulations is focused on 3D rendering of the simulation particles within the simulation volume. We often see the beautiful cosmic web from massive cosmological simulations like Illustris [5], which show us the distribution of matter in space. These are generally created for aesthetic display purposes (awe people during presentations) but also for the creation of mocks when studying images from the simulation (as one would do to compare to real observations). Usually in astronomy, this kind of visualization is not used for exploration of the data, as it is sometimes used in other fields. This is due to a variety of reasons: (1) it is usually the astronomers themselves who create the visualizations, so they often have their own personal pipelines for data exploration, (2) with the size of simulation data sets, rendering a complete version for

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user exploration would be very computationally expensive and probably not very useful, given that spatial location is not very important.

In 2015, the IEEE Scientific Visualization Contest[1] challenged the community to develop 'grand unified visualization tool' that would allow for the exploration of the Dark Sky simulation data that was provided. This required the visualizing both particle data and halo data, as well as analyzing the resulting hierarchical substructure of the halos, and the semi-analytic models that dictate the evolution of physical properties of the halos.

Several outstanding entries showed different approaches to the problem. [6] created a three-view integrated explorer which allowed for simultaneous views of 3D rendered particle data (or halo data), the merger trees, and statistical plots of particle (or halo) properties. It is highly customizable, with options to select specific simulation timesteps, selecting a semi-analytic model of halo properties, or the transfer function for coloring the particles. Key to their interface is the fact that all views are linked so that any selections made in one view will also be reflected in the others in order to simultaneously study the data from different perspectives.

[7] focused more on an interactive, single-view visualization of particle, halo, and merger tree data simultaneously. Their elegant work allows users to understand the temporal evolution of halos and their underlying structure by interacting with individual halos to allow for various forms of visual analysis. It is easy to identify substructure of the halo and how they evolve over time, with a slider that allows you to select a time step or animate it to step forward in time on its own. It also allows for the simultaneous comparison of multiple trees at once. Finally, a key component of their tool is the ability to jump from one halo to another. It is freely available as a web applet[2].

[8], the contest winners, created an incredibly complete, multi-view tool which allows for interactive exploration of each of the layers of data (particles, halos, and merger trees) including integration with the semi-analytic models of the simulation to study additional properties for each halo. Two different visualization approaches for the particles allow users to see their spatial distribution and properties. From thees views particles of interest can be identified and selected and their halo properties can be seen in the third view, which allows for interactive exploration of the merger tree and hierarchical substructure over time. The final view provides details about the local particles within that selected halo, which allows for easy understanding of the motion of those particles, to give information about the movement of subhalos within a parent halo and the evolution of substructure during a merger.

Traditionally merger trees are represented in a tree-like structure as in Figure 1. In 2018, [9] developed a novel visualization approach for merger trees, which they call MergerTree-Dendrograms [3], which allows for tracking of subhalo orbit, mergers, and the evolution of halo properties. This allows for a comprehensive characterization of the assembly history of a halo. They even use their visualizations with different halo finding algorithms and tree builder and are able propose improvements.

II. METHODS

A. Data Description

The data used here is from a suite of simulations from [11] from various runs of different sizes and resolutions. The data includes a halo catalog (with several properties for each halo) at various timesteps, and merger tree data. The goal is to visualize how the density profile of a halo evolves over time, and understand how that differs for halos of different properties. Some of these properties include mass, radius, and accretion rate. We will also attempt to see how the combination of these properties affects the evolution of the profile and perhaps use principal component analysis to determine the most significant properties in producing a difference.

B. Data Preparation

The initial data preparation involved measuring density profiles for each halo at each timestep, for each simulation run, with the particle data. Luckily this was previously done and I was able to work with the density profiles directly. I also had access to the halo catalog data (which included halo ids, id of their host halo, masses, sizes, time since last major merger, and several other variables which were not used), and also the merger tree data (which has the ids and masses of all of the halos at each timestep, and the ids of all of the halos which merged with that halo in the past or will merge with it in the future).

An important measurement that needed to be made for comparison of different halos was the mass accretion rate, often presented as the variable Γ. This is a unitless quantity first introduced by [12], which measures the amount of mass growth over a finite range of time:

$$\Gamma(a_1) \equiv \frac{\Delta \log(M)}{\Delta \log(a)} = \frac{\log(M_1) - \log(M_0)}{\log(a_1) - \log(a_0)}$$

where M is the mass of bound particles defined in the 200b overdensity, a is the scale factor (a quantity used to parameterize the age of the universe),and the $a_1 - a_0$ corresponds roughly to 1 dynamical time (defined as the crossing time of the halo within its host halo).

We measure Γ at different simulation snapshots to obtain information on its evolution. Finally, we match halos across snapshots with their progenitors and descendants at past and future timesteps to understand how individual halos evolve over time and how their density profiles change over time due to mergers and disruptions.

C. Visualization

The proposed project with have a different goal and approach compared to previous work. This work will not render particles or actually use the particle data directly

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[1] http://darksky.slac.stanford.edu/scivis2015/

[2] https://www.evl.uic.edu/krbalmryde/projects/DarkSky/app/scivis.html

[3] https://github.com/rhyspoulton/MergerTree-Dendrograms

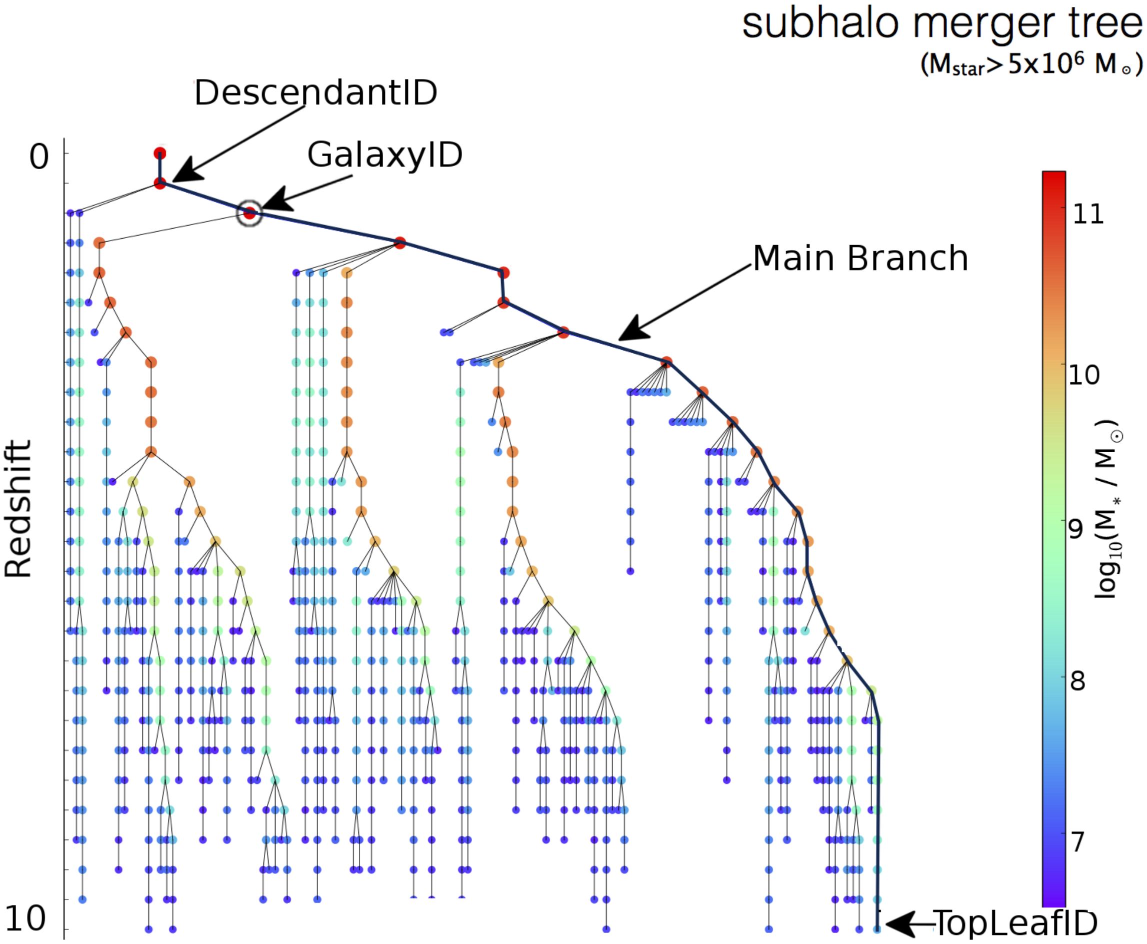

Fig. 1. Traditional representation of a halo merger tree from the EAGLE simulation [10].

at all. Instead we will focus on the halo data and merger trees. Additionally, this will likely not not result an interactive exploration tool, but rather an informative animated visualization for the purpose of better understanding a halo property.

The main challenge will be working with the data, since it has a relatively complex structure and matching halos at different timesteps in the halo catalog to their progenitors and descendants in the merger trees can be non-trivial. We are particularly interested in observing how different parts of the profile evolve. The inner region will likely only change due to a major merger between halos of similar mass. This will provide a new way to visualize major mergers. The outer part will grow with minor mergers. Of special interest is studying the role of accretion rate in the evolution of the density profile, since accretion rate is related to total mass accretion but not necessarily to number of major mergers. Ultimately, we wish to provide a clearer picture of the physical processes that dictate how the density profile will evolve.

III. RESULTS

A. *Density Profiles*

This was initially the main task of the project with the goal being to visualize the evolution of the density profiles of halos and understand how different properties of the halo affected how the density profile would evolve. Unfortunately, this visualization approach did not work as originally planned. The data was incomplete and there were matching issues between the halos in the merger trees and halo catalogs (which contained the profiles). But we were able to at least plot density profiles for halos of different accretion rates (Figure 2).

B. *Tree Maps*

Tree maps show hierarchical structure by displaying all constituents as boxes within a fixed larger box of fixed size. The area of each constituent is mapped to the quantity to be compared. In this case I was interested in making a treemap of a specific merger tree. In the initial view, this would show all of the halos at the present time (or some other snapshot). The total area would represent the total mass of the halos at the present time and each interior box would represent an

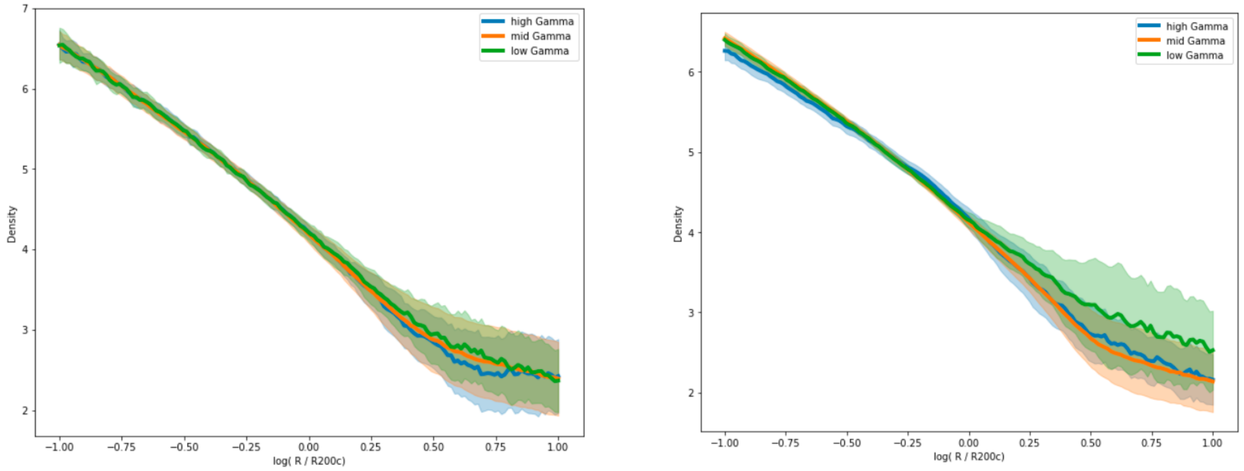

Fig. 2. Density profiles for halos of different accretion rates (Gamma). The left shows an earlier time (z=0.2) and the right is at the present day (z=0).

individual halo, with the area of the box mapped to the mass of that halo (top left of Figure 3). A user could then click on any of the halos and the view would transition from that of all halos at the current time to the merger history of that particular halo. So the total area would then represent the total mass of that halo and each of the interior boxes would be a halo that has merged to assemble into the larger halo (bottom left of Figure 3). The sizes could also be mapped to the logarithm of the mass of the halo in order to get a better representation for the sheer number of halos that make up that halo, or that exist in the present day universe (as with the first view) (right side of Figure 3). The user could then continue to click on halos to continue to see the constituents of that halo (as long as the data and simulation resolution allow it). The idea here is that we can see both the extremely large number of halos that make up each present-day halo, and also how the majority of the mass is made up from a few larger halos. It provides an intuition that traditional representations do not with regards to the mass content.

These visualizations were created using the `squarify` Python [13] package [4], which is based on the "Squarified Treemaps" algorithm [14].

C. Chord Diagrams

Chord diagrams show relationships between objects that are typically placed around a circle. The relationships are drawn as lines between the object to create chords of the circle. In this case I wanted to display the merger history of a halo. Each progenitor is represented as a node, placed in a circle. The size and color of the node are given by the halo's mass. The order of the nodes around the circle can be either by mass or redshift, with each option giving slightly different information about the history of the halo. Edges between nodes represent a direct ancestry between the two halos (i.e. within a single timestep, one halo is a progenitor and the other is a descendant) and they are drawn as cubic Bzier curves. They are colored by the mass of the descendant halo (i.e. the more massive one). Figure 4 shows some examples of this visualization technique. The top row shows a relatively massive halo (M= $10^{13}M_{\odot}$) and all of its ancestors from redshift 0.5 onward. The reason for the redshift cut is a practical one, otherwise there would be too many halos shown and the visualization would get quite messy and take much longer to render, but in theory it can be done just the same. The left side shows all of the progenitor halos ordered by mass and the right shows them ordered by redshift. With the mass ordered view we can see the range of masses that merge to create the most massive (red) halos. With the redshift-ordered view we can follow the most massive progenitor of the halo and see different epoch of merging. The same views are seen on the bottom row of Figure 4 but for a less massive halo (M= $10^{11}M_{\odot}$). Here we can see a very different assembly history with very few mergers. These views can be used to directly compare between halo assembly histories.

These visualizations were created using the Plotly [15] graphing library.

IV. SUMMARY

This project aimed to visualize halo evolution in novel ways. The main attempt was to visualize the evolution of density profiles as a function of different halo properties (halo mass, radius, accretion rate). Unfortunately, this approach was not successful. The two other approaches were more successful. One used Treemaps to examine the hierarchical structure of halos, allowing an intuitive view of mass and number distribution of all halos today and their progenitors. The other approach used a chord diagram to represent the merger history of a single halo, with different views allowing for a focus on mass-order or redshift order.

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[4] https://github.com/laserson/squarify

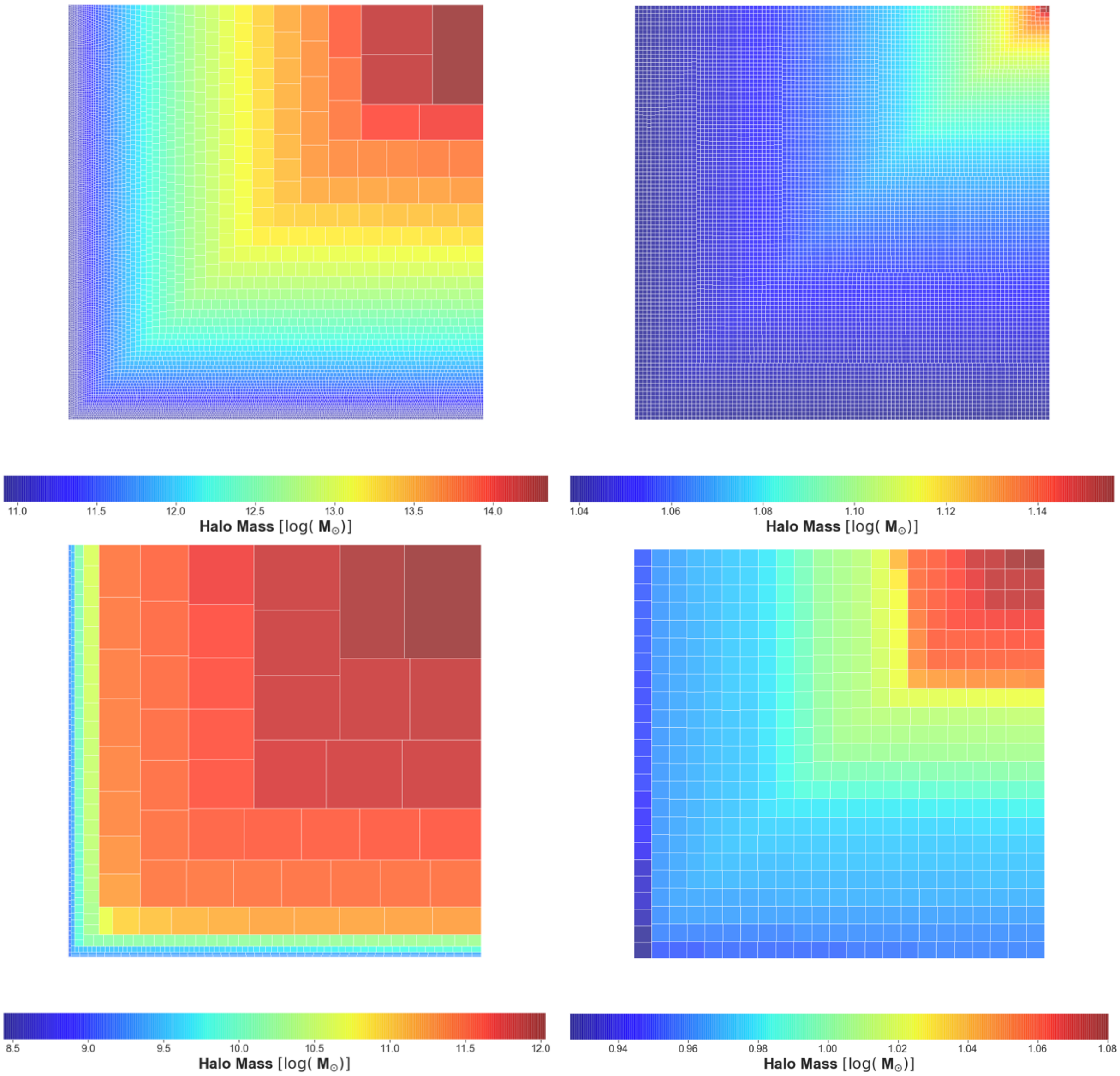


Fig. 3. In the top row we show all of the halos at the present day, with color scaled to halo mass. On the left size is scaled to halo mass as well, on the right it is scaled to the logarithm of halo mass. Scaling to log allows us to more clearly see the number of halos, while not doing so allows us to more clearly see the distribution of masses. The bottom row shows a similar situation but for all of the progenitors of a present day halo of mass 10^{12} M$_\odot$.

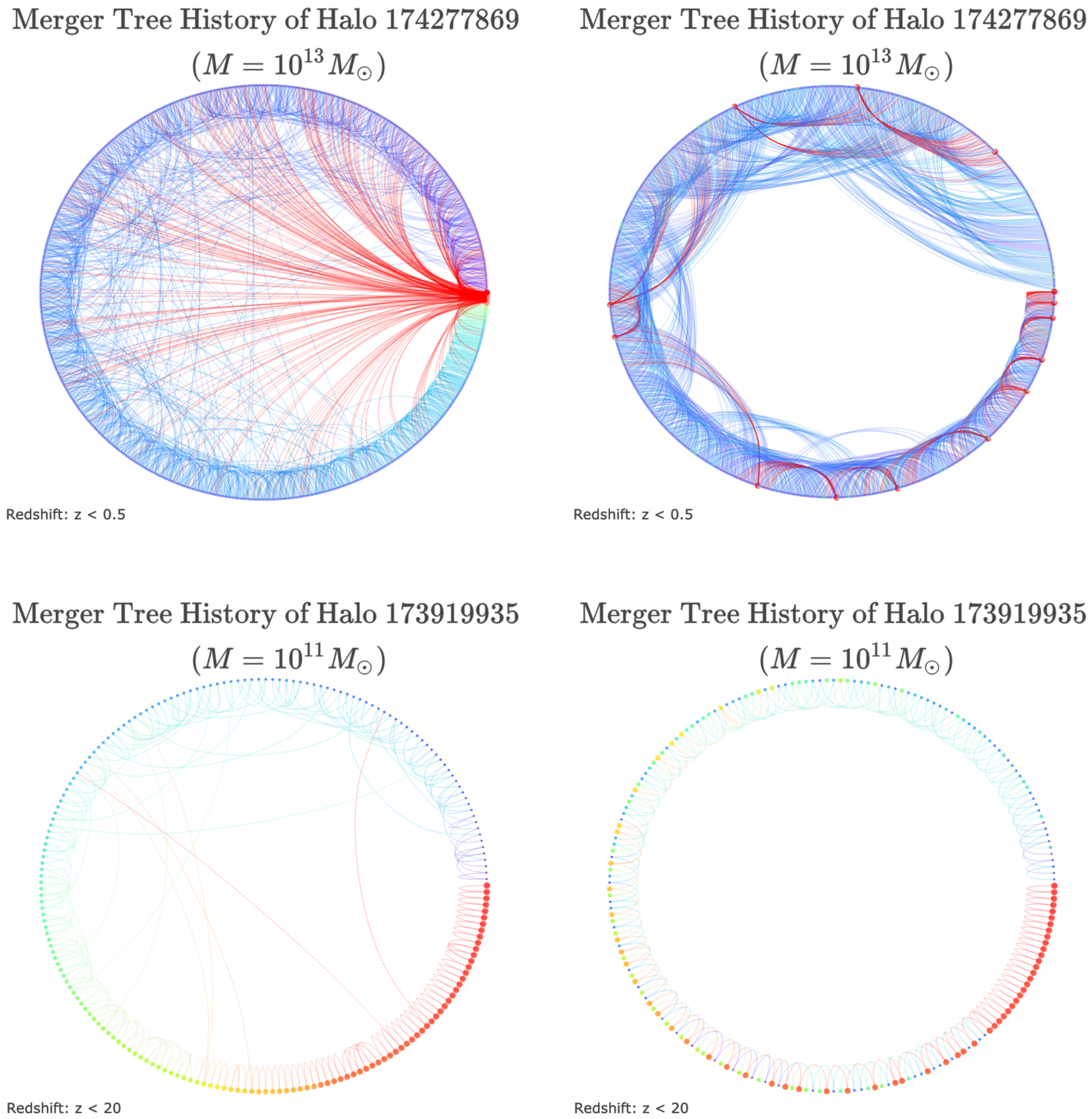
These last two approaches provide novel ways of examining the assembly history of halos.

A. *Future Direction*

There are many ways to extend this project.

From a scientific point of view, one of the more simple and straightforward ways would be too look at the other simulation volumes. The simulation suite we are using has several larger and smaller volumes. It could be quite interesting to compare them. Additionally, adding baryonic matter would be an obvious though probably more difficult extension too. We would like to see how this evolution plays out in galaxies. In this way we are able o gain some more information about the galaxy halo connection. Though this would require either a hydrodynamic simulation (e.g. Illustris) or some model which assumes a way of populating the dark matter halos with galaxies, depending on what exaactly we wanted to look at.

From a visualization perspective, a lot could be done to extend this. The current state of the project is very much an early one. There is a lot that still needs to be done to allow the visualizations to work seemlessly and even more to allow for other users. There are plenty of details that can be altered (size, color, transparency, annotations) that would allow for a more user friendly understanding of the visualization. A more interactive and modular structure would allow this to become more of a tool for exploration rather than a simple visual. One could envision a design where one simply selects the simulation and range of parameters of interest (e.g. redshift, mass accretion rates) and the same sort of animated


Merger Tree History of Halo 174277869 $(M = 10^{13} M_\odot)$

Merger Tree History of Halo 174277869 $(M = 10^{13} M_\odot)$

Merger Tree History of Halo 173919935 $(M = 10^{11} M_\odot)$

Merger Tree History of Halo 173919935 $(M = 10^{11} M_\odot)$

Fig. 4. Top row shows the chord diagram view for a the merger tree of a halo of mass 10^{13} $M_\odot$. Each node around the circle represents a halo which is a progenitor of the present day halo. The node are sized and colored according to mass. On the left the halos are ordered by mass as well. On the right they are ordered by redshift. The bottom row shows the same views but for a less massive halo with a sparser merger history.

evolution could be shown but with those selected parameters. This project served as a proof of concept for some of these ideas and simply the first step.

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