

# Halos in a Dark Sky: Interactively Exploring the Structure of Dark Matter Halo Merger Trees

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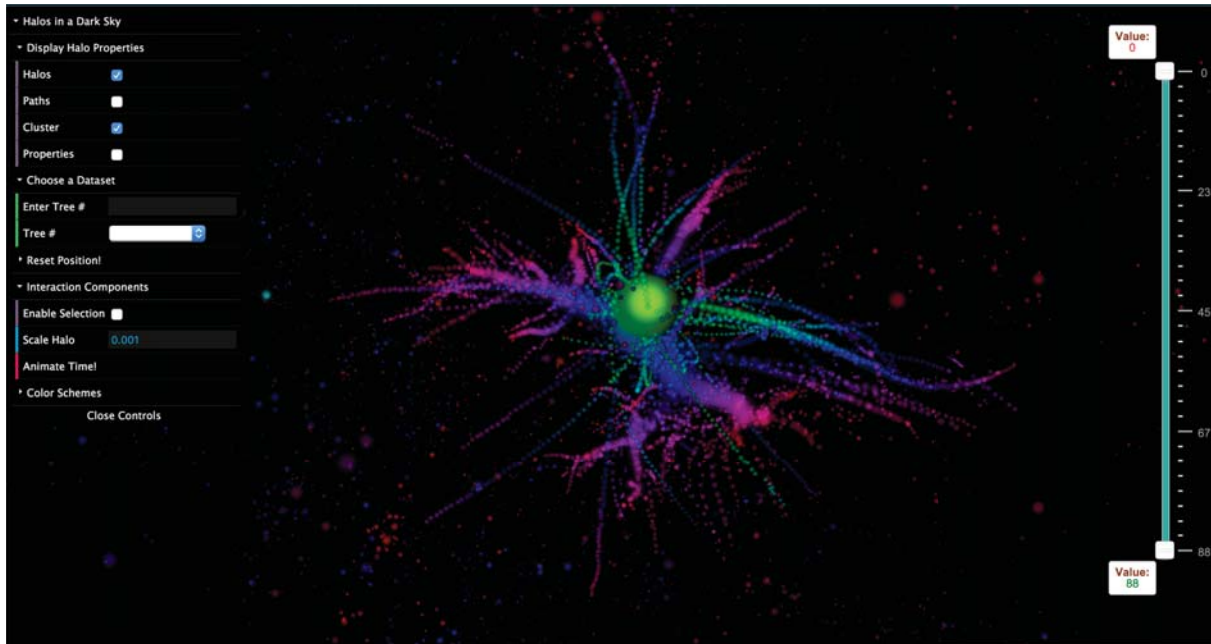


Figure 1: A screen capture of our web application showing a complete dark matter halo merger tree.

## ABSTRACT

This paper introduces a novel web application that visualizes dark matter halo merger trees and their evolution through space and time. Our application enables users to interact with individual halos within these trees in order to perform a range of visual analysis tasks, including: identifying the substructure and superstructure of the halos; observing the movement of halos across a specified range of time steps; and comparing the branching characteristics of multiple trees. Central to our application is the ability to navigate the halos by interactively “jumping” from tree to tree. By clearly marking halos that have “tributaries”—that is, halos that split off into multiple halos or that merge with one or more halos—we make it easy for the user to traverse the complex structure of the universe. Our application is publicly available online and runs at interactive rates on the browser.

## 1 INTRODUCTION

Large-scale cosmological simulations provide a representation of our best understanding of how the structure of the Universe has

changed from the Big Bang to today, some 14 billion years later. Recent efforts in modeling the formation of the Universe show results consistent with those actually observed by astronomers in the night sky [1, 2, 11]. The Dark Sky dataset simulates the formation of the structure of the Universe through time by tracking a large number of dark matter particles [10]. Through gravitational interactions these particles form *halos*, complex structures that represent galaxies or clusters of galaxies. Visualizing how these halos expand, split, merge, grow, and collapse over time can offer researchers a more informed understanding of cosmological events [9].

This paper describes the main features of our novel visualization tool (which is freely available on the web<sup>1</sup>), especially as they relate to data integration, halo identification, and exploring halo substructures (Tasks 1, 2, and 4 of the IEEE SciVis 2015 Contest, respectively). Specifically, our visualization tool:

- Makes it easy to identify nested halo structures, both at individual time steps and across a range of time steps;
- Uses animation to make it easier to understand the temporal evolution of halo structures;
- Makes it possible to examine and compare multiple merger trees simultaneously;

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<sup>1</sup><https://www.evl.uic.edu/krbalmryde/projects/DarkSky>

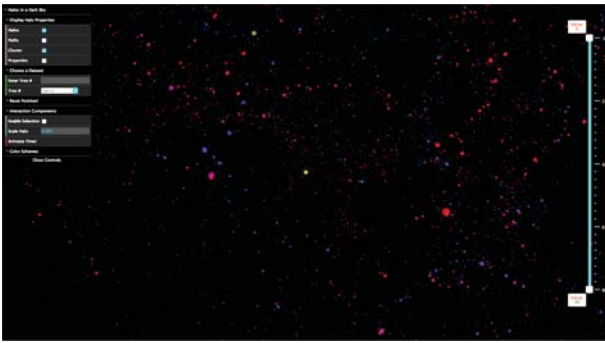


Figure 2: A screen capture showing the entry point of our application. Displayed are the main interface controls on the left hand side, with the temporal slider bar on the right. The center view of the application initially shows a point cloud consisting of every root node of the halo merger tree database (containing 7000 merger trees). A user can interactively select each halo to explore it in greater detail.

- Introduces an interactive mode that facilitates the spatiotemporal navigation of complex merger trees.

Our visualization tool consists of a series of integrated views, each of which enables different features relevant to the SciVis Contest tasks. This work builds off of previous explorations into visualizing complex temporal data using animation and motion [4, 5, 6, 7].

## 2 IDENTIFYING SPATIAL AND TEMPORAL HALO STRUCTURES

The Dark Sky merger tree database consists of information regarding each halo's position, mass, and radial velocity, as well as its parent and descendant halo or halos (if they are present) across a total of 89 time steps. The final time step contains halos that represent the current structure of the Universe; each of these halos is the culmination of hundreds or thousands of these halos merging, or splitting over billions of years.

Upon startup, our application initially displays an interactive point cloud of the merger tree forest, i.e., the root node of every tree found within the merger tree database. The root nodes coincide with the final time step of the data series (again, which represents the current state of our cosmos). From this view, the user can use the mouse to select halos of interest found anywhere within the scene to generate the associated tree. Alternatively, the user can select from a list of preselected "sample" merger trees, each of which demonstrate interesting merging or splitting properties. Finally, a user more familiar with the dataset can input the numerical id of a halo into a text field in order to generate a specific tree of interest. Fig. 2 shows a screen capture of our visualization when it is first run, before any halos have been selected.

Halo data is represented as 2D billboarded sprites positioned within the 3D scene corresponding to the halo's  $xyz$  coordinates. The sprites are rendered using transparency to provide visual clues as to the internal structure of the halos, which could otherwise obscure the subhalos' structure. The sprites are scaled by the halo's radius attribute, or  $r_{vir}$ , as defined within the halo data entry found in the merger tree database and halo catalog. The halos are color-mapped to their radial velocity via the red and blue color channels (red denotes the direction moving away from center and blue denotes movement towards the center). Additionally, the halo's mass, or  $m_{vir}$ , is mapped to the green color channel. This produces a coloring that makes it easy to quickly identify potentially interesting merger trees within the point cloud representation.

Fig. 4 depicts an example tree using our visualization tool. Users have the option to map the green channel to the halo's normalized

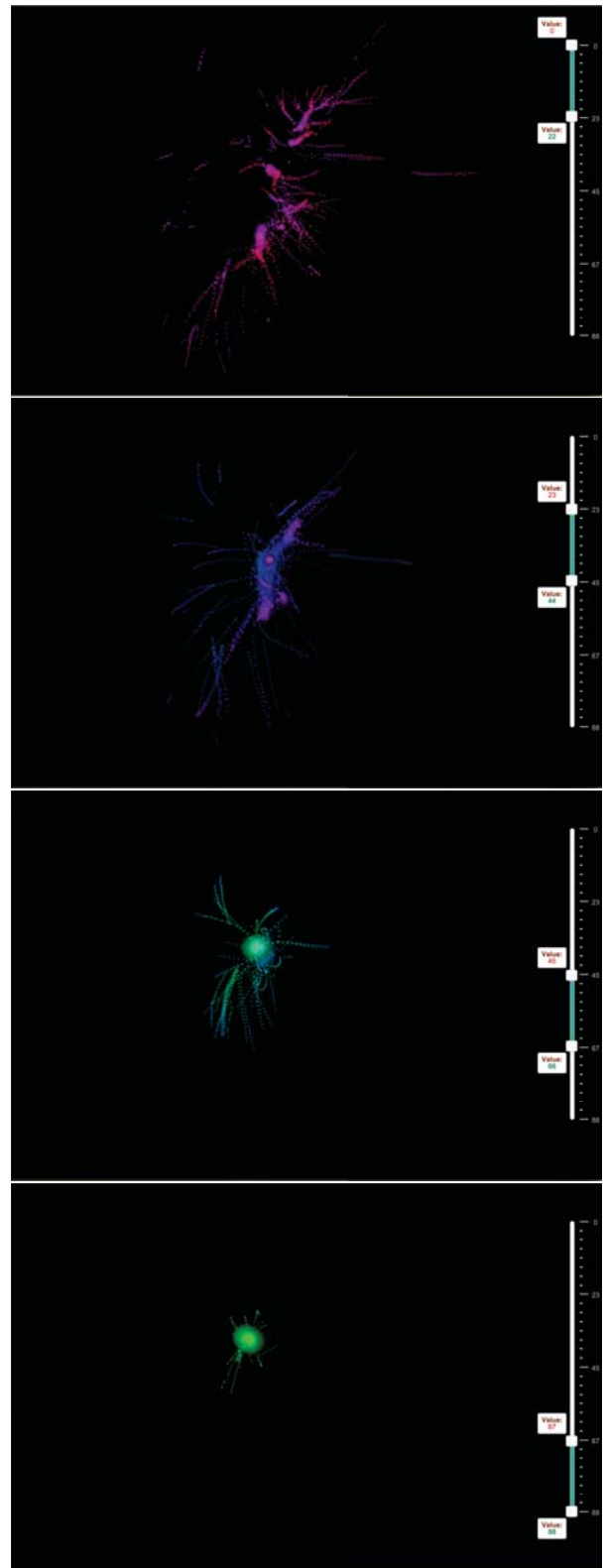


Figure 3: Four screen captures from an animation moving through all 89 time points of a selected merger tree. In this animation, the user has chosen a window of 21 time points to more clearly gain insight into how the halos evolve over time.

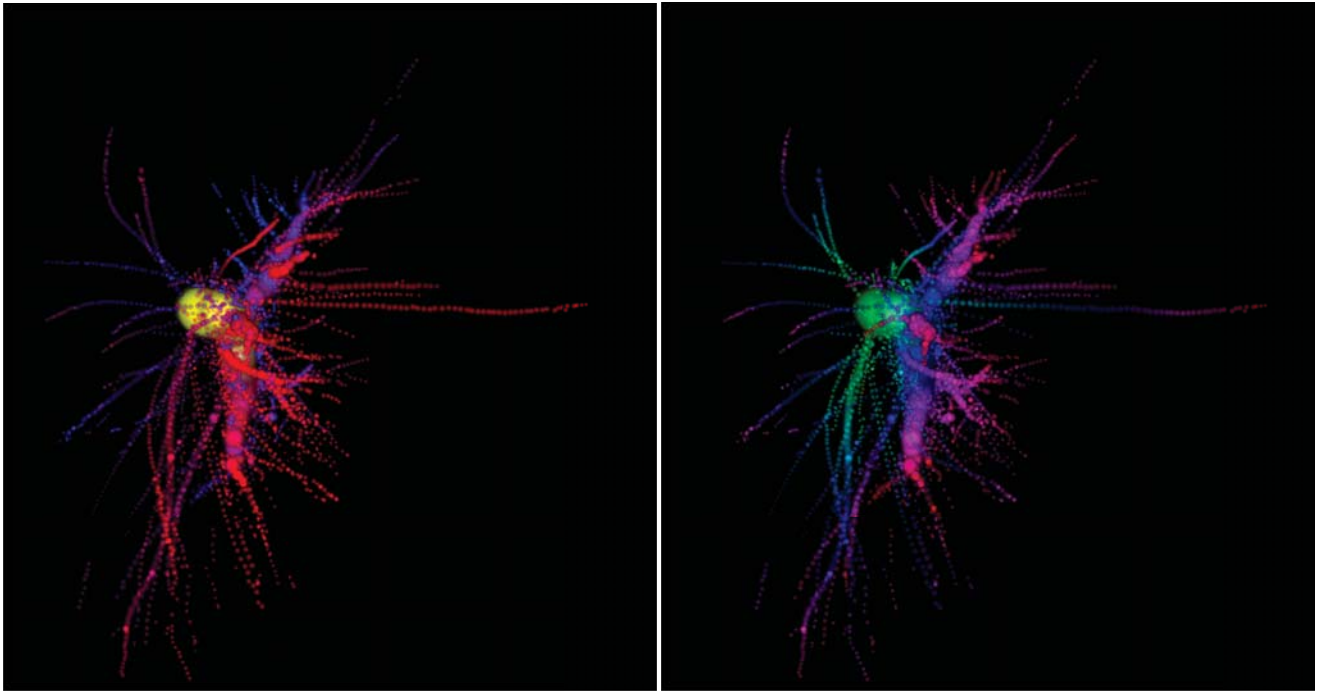


Figure 4: Screen captures showing two different color coding schemes on an example merger tree. The left image uses a color coding that emphasizes mass and the right image highlights changes in time.

mass and other scalar attributes contained within the halo catalog and merger trees. Additional color schemes are available, including a basic one in which red indicates early time points, blue indicates halos in the middle range of time points, and green indicates the later time points. Moreover, a user can customize the color mapping as desired.

### 3 USING ANIMATION TO EXAMINE THE TEMPORAL EVOLUTION OF HALOS

Once a halo of interest has been selected, the point cloud (which provides an overview of all available root halos) disappears, with only the halo of interest remaining. A bidirectional range slider lets the user apply a temporal range filter and interactively choose either a single time point or a set of time points to explore particular halos. Further, the user can manually “scrub” the temporal range slider in order to view the progressive evolution of the halo merger trees. Our tool also incorporates an animated version of this temporal scrubbing, allowing the user to create a looping animated movie. To facilitate tracking the trajectories of halos across time, the user can enable a “path tracing” feature, which emphasizes the lineage between parent and descendant halos. Fig. 3 shows a series of screen captures of the application as the visualization animates between two selected time steps.

### 4 INTERACTIVE EXPLORATION OF MERGER TREE BRANCHES

An important task in analyzing the evolving structure of the Universe requires an understanding of the temporal trajectories of individual halos. An additional view integrated within our visualization tool highlights the internal structure of the halos within the tree. This makes it easy to traverse the complex structure of the trees as a user can select halos that have descendants and then choose to follow any of these descendants as they branch into their different lineages, either forwards or backwards in time. We use a custom path generation algorithm which recursively tracks each halo’s descen-

dants over time. Our visualization clearly highlights the projected trajectories of any branch of the tree and the influences of gravitational forces that affect the halos in that branch. In an associated view, the user can enable an inspection mode that identifies halos that act as “convergence points” at particular time steps, such as when a halo merges with or splits from another halo. Fig. 5 shows two example screen captures from when the halo traversal mode is enabled, facilitating the exploration of the lineage of a selected halo. Fig. 6 shows an additional example of how this functionality can be used for comparative tasks, enabling the user to identify distinguishing features between merger trees that are (relatively) near to each other.

### 5 USAGE SCENARIOS

Our visualization tool provides a range of interactive exploration modes that can enable a range of visual analyses of the merger tree database.

For example, we can imagine a scenario in which a user has determined that a particular tree from the database is potentially interesting and requires further examination. She uses our tool to load up the tree via the drop-down list and sees immediately that there is an interesting pattern related to how it evolves over time. Using the temporal slider bar, she notices specifically that there is a large spatial jump between time steps 44 and 45. Curious as to whether or not this jump is seen in nearby halos, she turns on the point cloud at time step 45 and selects halos that are nearby. She then turns the point cloud view off again, and uses the temporal slider bar to visually compare the differences in the halo trees. In this case, her initial hypothesis is not confirmed, as the halo trees do not have a discernibly similar pattern. However, once the user clicks on the “halo substructure” view, she can see at a glance that the halo at this time step splits into three subtrees. By selecting those subtrees, the user gains more insight into the structure at the exact coordinates where there are interesting cosmological features.

In another scenario, a user is interested in understanding the re-

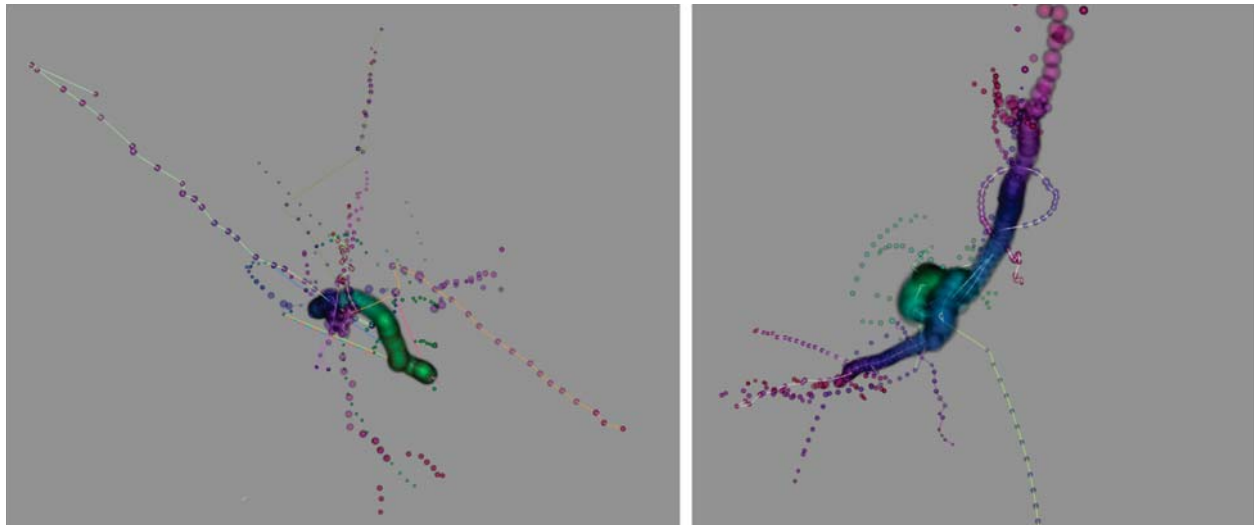


Figure 5: Details from two different examples of the interaction mode facilitating the exploration of halo “tributaries” by tracing halo lineages. The background color changes to indicate that this halo traversal mode is enabled.

relationship between halo merging and the *rvir* property. By using the default view, he can at a glance see points of interest colored so as to indicate merging halos. By using our navigation tools, he can zoom into that region of the Universe and then use our temporal slider bar to gain more information about a particular halo or set of halos. Additionally, a pop-up informational screen provides detailed information about each attribute of the halo.

## 6 SYSTEM DETAILS AND DATA INTEGRATION

Our visualization tool makes use of the halo catalogs and merger tree database derived from the 11GB, 2,000,000+ particle dataset provided by the IEEE SciVis 2015 Contest website. Pre-processing steps involved using a custom Python script built with ThingKing<sup>2</sup> to extract the individual trees from the merger tree database. This extraction was guided by the halo catalog data file which corresponded to the merger tree root halos. To facilitate the integration into our web application, these data were first converted to JSON format. We chose to preserve all of the halo attributes for ease of access within the visualization. In total, over 7,000 JSON files, each containing a single merger tree, were generated and stored on our server. We validated our halo tree entries with the halo catalog corresponding to the last time point, since this dataset contains the root of every tree in the merger tree database. This file was used to generate the halo point cloud seen at the beginning of the visualization.

To reduce the load on available memory, data is input into the web application using Oboe.js<sup>3</sup>, a JavaScript library that efficiently streams data only as it is needed. Since in some cases the file containing the merger tree is larger than available memory, we use an incremental “read and drop” method of data transfer. This enables us to capably render large and complex merger trees and maintain interactive frame rates.

## 7 CONCLUSION AND FUTURE DIRECTIONS

Our visualization tool makes it easy for expert users to find interesting patterns in the Dark Sky dataset. Future work will make it possible for our tool to automatically identify these patterns given selected criteria, such as halos that have particular branching patterns. Additionally, we plan to utilize the depth information inherent

in this data in order to incorporate stereoscopic displays. We plan to augment our visualization with a linked view that shows flattened representations of the tree data to facilitate better navigation. Furthermore, we also plan to improve the animation component to provide more control over playback.

In conclusion, we have introduced a novel web-based approach to the visualization of cosmological dark matter data. Our tool facilitates the interactive exploration of the temporal evolution of halo merger trees and their underlying structural interactions.

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<sup>2</sup><https://pypi.python.org/pypi/thingking/1.0.2>

<sup>3</sup><http://oboejs.com/>

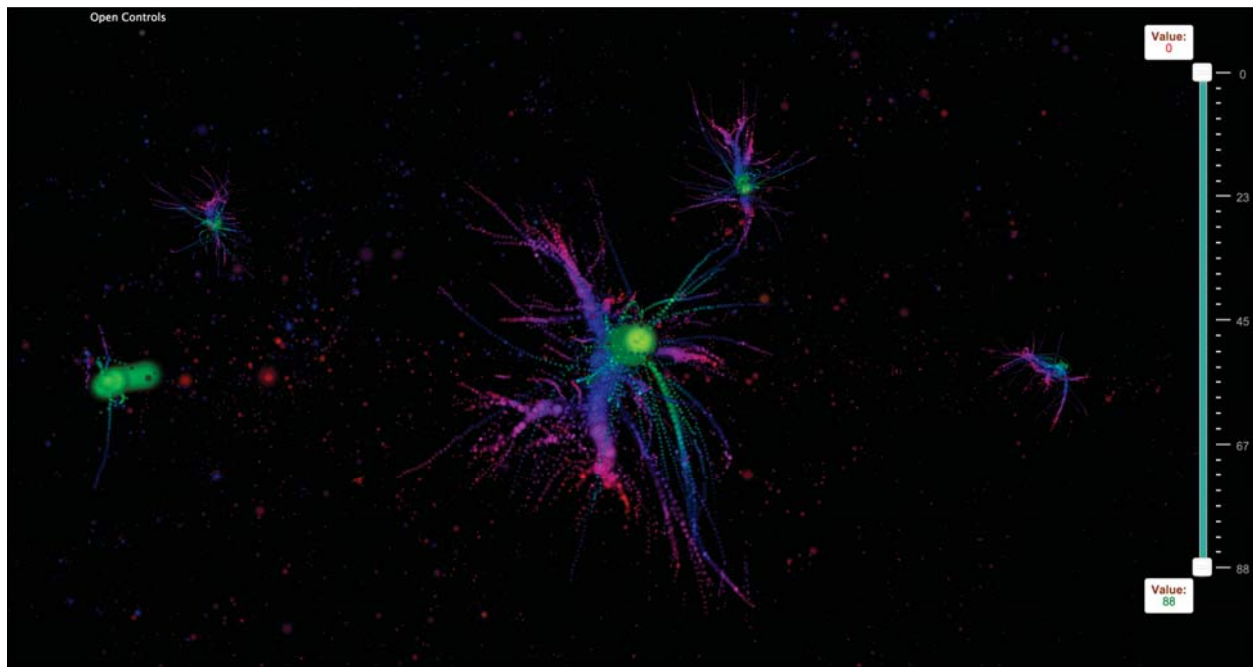


Figure 6: A screen capture showing multiple merger trees in the same view to facilitate visual comparison.

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