A Case Study: Tracking and Visualizing the Evolution of Dark Matter Halos and Groups of Satellite Halos in Cosmology Simulations

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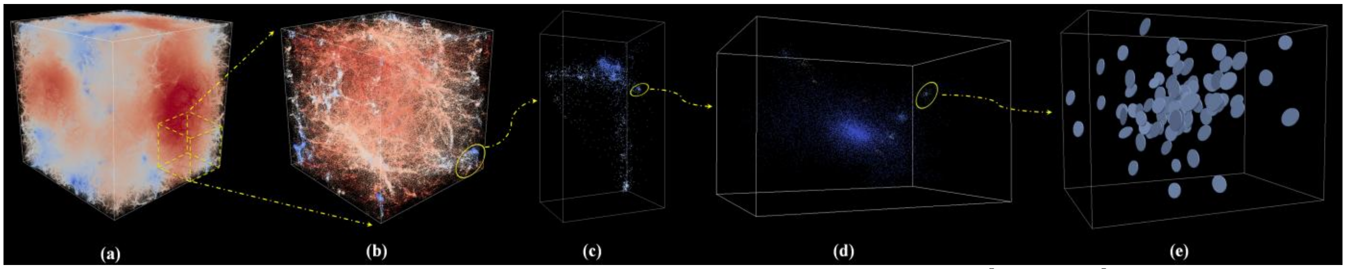

Figure1: Visualization of hierarchy of the universe. (a)The Simulated Universe: Covering a volume of (8.35x10^8 light-years)^3 each particle in this figure represents a dark matter tracer particle equivalent to 10^{11} solar masses. Approximately 100 dark matter tracer particles represent a galaxy. Particles are colored according to their potential value (time step 499). (b)Subset of the Simulated Universe: Focusing on a smaller portion of the simulation data shows filaments, clusters and voids that make the universe. (c)Supercluster: A supercluster as the name suggests is a cluster of smaller dark matter tracer particle groups called Dark Matter Halos. (d)Dark Matter Halo: Dark Matter Halos or Host Halos envelope numerous smaller groups of dark matter tracer particles called satellite halos. Each of these satellite halos would host galaxies that are held together by dark matter gravitational fields. (e)Satellite Halo: Each satellite halo is represented by numerous dark matter tracer particles. One tracer particle is equivalent to 10^{11} solar masses while each galaxy is equivalent to 10^{13} solar masses. Thus a satellite halo holds a galaxy for approximately every 100 dark matter tracer particles inside itself.

ABSTRACT
In this poster, we track the evolution of cosmic structures and higher level host structures in cosmological simulation as they interact with each other. The structures found in these simulations are made up of groups of dark matter tracer particles called satellite halos and groups of satellite halos called host halos. We implement a multi-level tracking model to track dark matter tracer particles, satellite halos and host halos to understand their behaviour and show how the different structures are formed over time. We also represent the evolution of halos in the form of merger trees for detailed analysis by cosmologists.

Keywords: Group tracking, multi-level tracking, merger tree.

1 INTRODUCTION
In cosmology, dark matter is a currently unknown type of matter theorized to account for a large part of the total mass in the universe. Estimated to constitute 83% of the matter in the universe, dark matter neither emits nor absorbs light or other electromagnetic radiation, and thus cannot be directly seen with telescopes. The only way of detecting dark matter is by observing the effect of its gravitational forces on stars and galaxies. Scattered in the form of clumps or in cosmological terms dark matter halos, the gravitational forces exerted by halos aid in the formation of clusters of galaxies. To understand the physics behind the formation of these structures and the galaxies within, cosmologists have to accurately study the evolution of dark matter halos over time and space. Understanding the behaviour of dark matter holds the key to unravelling numerous questions pertaining to galaxies and the whole universe [1].

The goal in computational cosmology is to simulate the universe down to each of the individual galaxies. Since the physics of galaxy formation is not known in detail, cosmologists perform a gravity-only simulation using super computers. The simulation formulated to compute the dark matter distribution covers a massive volume of (256 h^{-1}Mpc)^3 or (8.35x10^8 light-years)^3 of the observable universe and evolves 256^3 dark matter tracer particles [1]. These simulations determine the distribution of dark matter throughout the observable universe. The dark matter halos are then extracted from the simulations and galaxies are populated within these halos using various methods. Approximately 100 dark matter tracer particles can host a galaxy [5]. Instead of the simpler Halo Occupation Distribution method [5], cosmologists can also use a more sophisticated method that takes into account the evolution history of these halos [5]. The formation time of the halo (old or young) including events such as merging of halos, influences the galaxy population within. These models are checked by comparing their results with observations from survey telescopes which map the visible universe.

Dark matter halos have a complicated substructure and they are dominated by primary halos known as satellite halos as shown in figure 1(d). Gravitational forces exerted by halos and satellite halos can give rise to various dynamic multi-level interactions. These satellite halos can merge with other satellite halos within the same host halo. They may also change their host halos by transferring from one host halo to a different host halo. In this poster we apply a tracking algorithm to follow the evolution of each satellite halo and host halo from their birth until they either merge, split or die.

We track halos, satellite halos and individual dark matter tracer particles as the halos and satellite halos emerge, die, merge and continue to exist over time. This group tracking model is an extension to the feature tracking framework [2] and also represents the evolution of halos and satellite halos in the form of a merger tree. We visualize the merger trees in 3D along with statistical halo information to provide a detailed overview of structural evolution.

2 HALO AND SATELLITE HALO TRACKING
2.1 Halo Extraction and Grouping: In order to track the evolution of satellite halos and host halos, we have to first extract satellite halos from the simulation data. Each particle in the simulation represents a dark matter tracer particle. As shown in Figure 1(e) each satellite halo is made up of a group of these particles. The particles are first grouped in halos using the friend-of-friend algorithm (FOF) [7]. The simulation assigns a halo ID to every particle. The satellite halos within are then determined by an extended form of the friend-of friend algorithm [7]. Each host halo envelopes a group of satellite halos as shown in Figure 1(d).

2.2 Satellite Halo Tracking: At each time step we have a list of satellite halos, host halos and particles. To understand the evolution of these structures we have to correlate satellite halos from one time step to the other. Since each satellite halo consists of a group of particles, we consequently track each dark matter tracer particle at every time step. We track satellite halos using the feature tracking framework in [2]. In this framework, features are tracked over time by overlapping the area of one feature in the current time step to the area of the feature in the next time step. Correlations are made based upon maximum overlap. Instead of using spatial overlap here, we use particle overlap as the particles are all referenced by unique halo ID's. Thus by correlating the particles in two consecutive time steps, we find out whether a satellite halo in time step t_i dies, splits into two or more satellite halos, merges with a different satellite halo or just continues as the same satellite halo in time step t_{i+1}.

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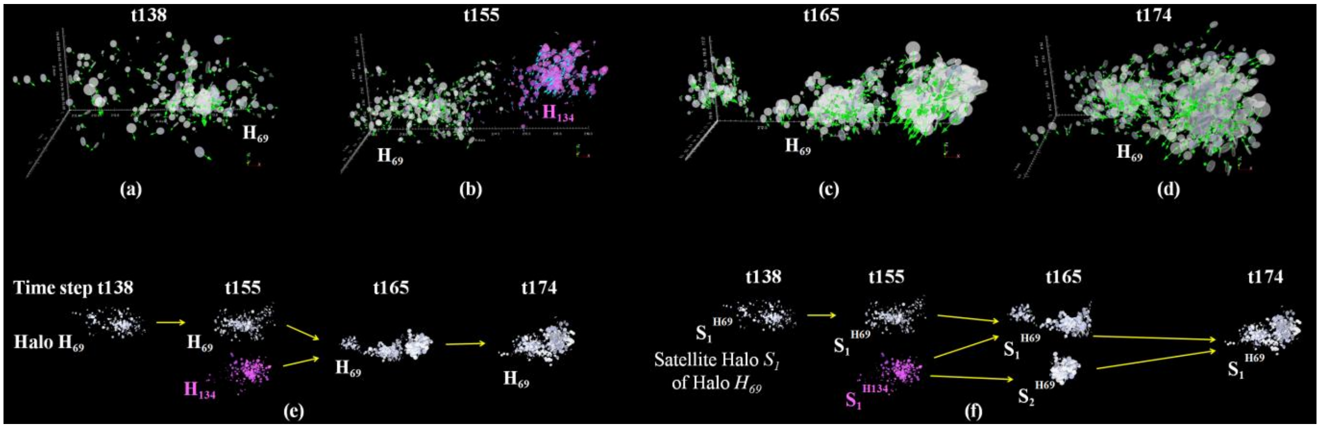

Figure 2: Merger of host halos and satellite halos from time step t138 to t174. (a)Birth of a new halo H_{69} enveloping a single satellite halo (particles in white). Glyphs show direction of movement of each particle. (b)Birth of a new halo H_{134} consisting of a single satellite halo (particles in pink) along with continuation of the existing white halo H_{69}. Blue glyphs on the pink particles show halo H_{134} moving towards the existing white halo H_{69}. (c)The halo H_{69} and the halo H_{134} merge into one halo represented by H_{69} with two satellite halos (both represented by white particles). (d)Both the satellite halos inside halo H_{69} eventually merge into one satellite halo represented by white particles. (e)The Halo merger tree shows birth, continuation and merger of halo H_{69} and halo H_{134} from time step t138 to t174. (f)The satellite halo merger tree shows birth, continuation and merger of satellite halos that are part of halos H_{69} and H_{134} from time step t138 to t174.

2.3 Host Halo Tracking: As mentioned in the halo grouping process in section 2.1 we assign halo ID's to each particle before the satellite halo tracking. Since we group the satellite halos into their respective host halos before the tracking phase, both the satellite halos and their host halos are tracked simultaneously.

2.4 Merger Tree: To understand the physics behind galaxy evolution, cosmologists have to accurately know the evolution of the dark matter halos in terms of hierarchical merging at each time step [4]. The hierarchy of merger of halos can be represented by merger trees [4, 6]. A Merger trees thus describes the sequence in which halos merge and grow. Every node represents a halo and an edge connected to the node tells about the halo's descendents and ancestors. Traditional visualization of halo merger trees is achieved by representing halos in the form of circles [6]. In this poster we extend the traditional representation by visualizing halos in 3D, thus providing useful particle distribution and velocity information. Using the output from the tracking modules in section 2.2 and 2.3, we classify whether a satellite halo or host halo is born, dies, splits, merges or continues. Depending on the classification, we update the merger tree for that specific satellite halo or host halo. The final result is thousand of merger trees for halos that exist at the last time step. Cosmologists can query for interesting statistical quantities and study the evolution of different halos by analyzing the merger tree.

Figure 2(d) shows a merger tree for the merging process of halo H_{69} and halo H_{134}. The merger tree in figure 2(e) show the births of H_{69} and halo H_{134} along with continuation of halo H_{69}. After a merger process between two structures is complete, the resultant merged structure retains the halo ID or satellite halo ID of the structure with the smaller ID between the two participating structures. In figure 2(e), since halo H_{69} has the smaller ID, the merger leads to a resultant halo with halo ID and color of H_{69}. In figure 2(f), we also represent interactions of the inner satellite halos in the form of merger trees.

3 VISUALIZATION: MERGER OF HALOS

3.1 Tracking: Figure 2 shows an example of the merger of halos and satellite halos. Figure 2(a) shows the birth of a new halo H_{69} at time step t138 consisting of a single satellite halo with white coloured particles. The arrows on each particle represent the direction of movement of each particle. In time step t155 (figure 2(b)), a new halo H_{134} is born, enveloping only one satellite halo (particles shown in pink). Figure 2(c) shows the merger of H_{69} and H_{134} into a single halo. After merging, the resultant halo retains the halo ID and color of the smaller of the two halos ID's, H_{69}. The halo merger tree in figure 2(e) gives a detailed overview of the halo merger process.

3.2 Cross-Level Interactions: Satellite halos are the dominating substructures within halos. They may interact with other satellite halos inside the same host halo, as shown in the transition from figure 2(c) to figure 2(d). In addition, the halos themselves may interact with other neighbouring halos to merge into a bigger halo over time, as shown in the transition from figure 2(b) to figure 2(c). Tracking becomes challenging when the satellite halos participate in cross-level interactions. Cross-level events can occur when satellite halos change their host halos to interact with other satellite halos as shown in figure 2(f), in the transition from time step t155 to t165.

4 DISCUSSION & CONCLUSION

In this poster we implemented the tracking framework to track satellite halos and their host halos over time. We use the feature tracking model in [2] and extend it to track clusters of dark matter tracer particles (satellite halo) along with groups of satellite halos (host halo). Both the satellite and their host halos are tracked simultaneously. We also visualize the evolution of halos in the form of merger trees. The merger trees will be useful for detailed analysis of halo evolution. The merger tree data will also be used as an input to the software for galaxy distribution analysis, GALACTICUS. This implementation helps cosmologists understand the evolution of dark matter halos, their complex substructure and galaxy formation.

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