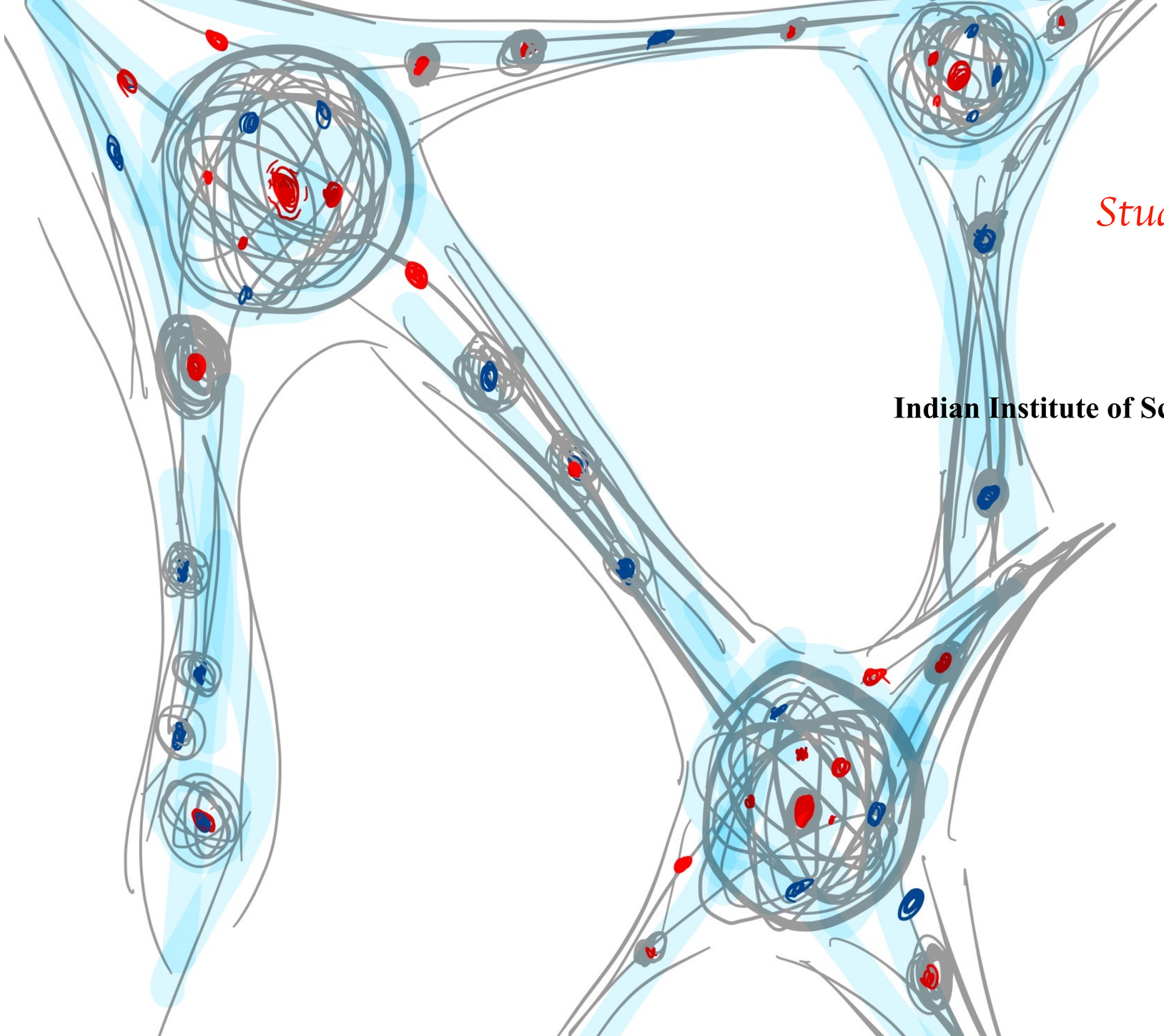


Studying dynamical structures within Dark Matter Halos

Susmita Adhikari

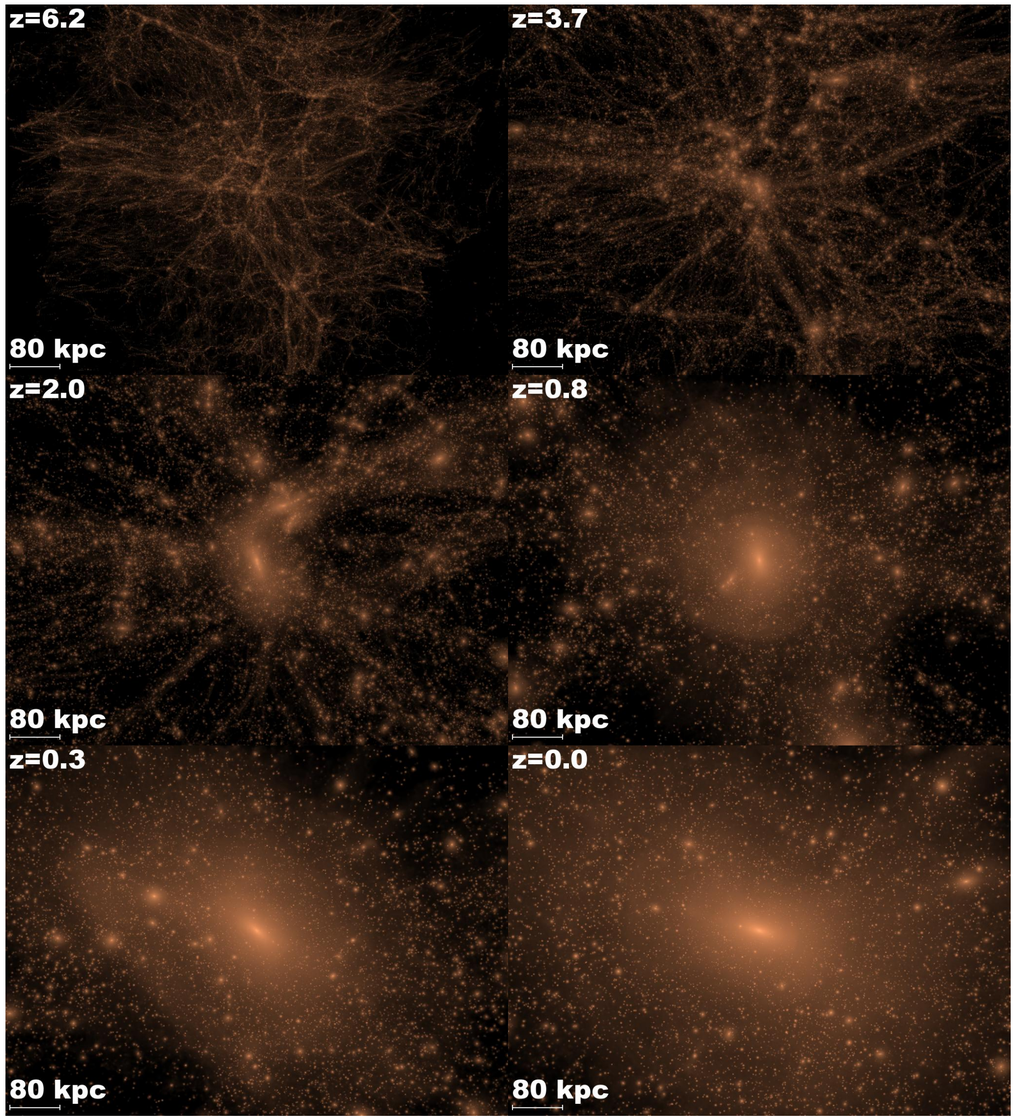
Indian Institute of Science Education and Research (IISER), Pune

COSMO21, Chania, Crete, 2024

with Soorya Narayan R

IISER PUNE

Dark Matter Halos

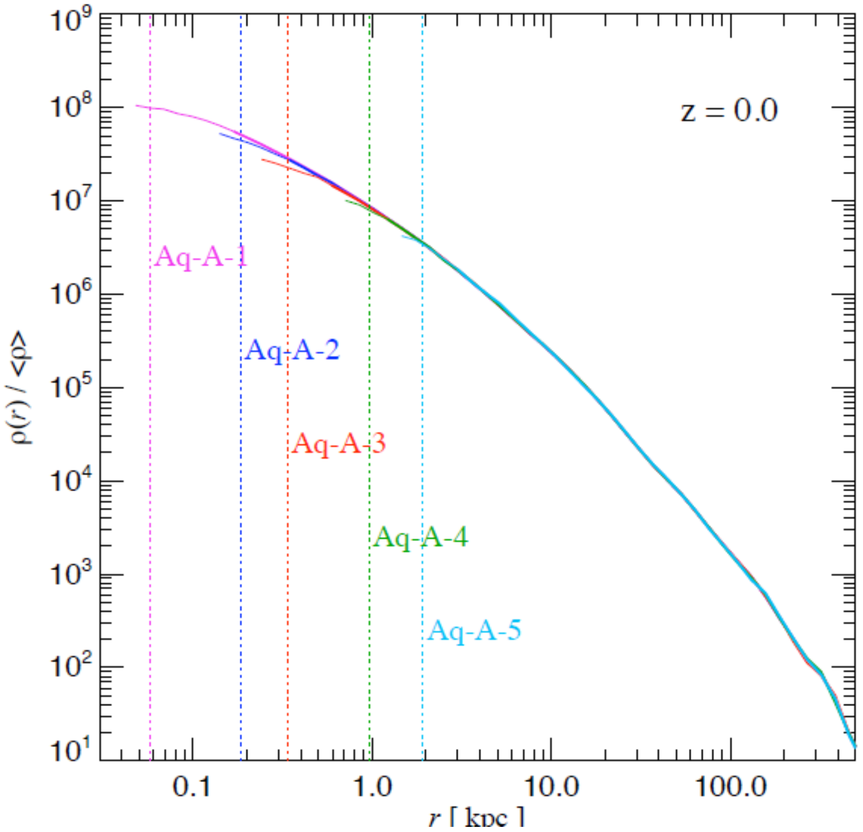


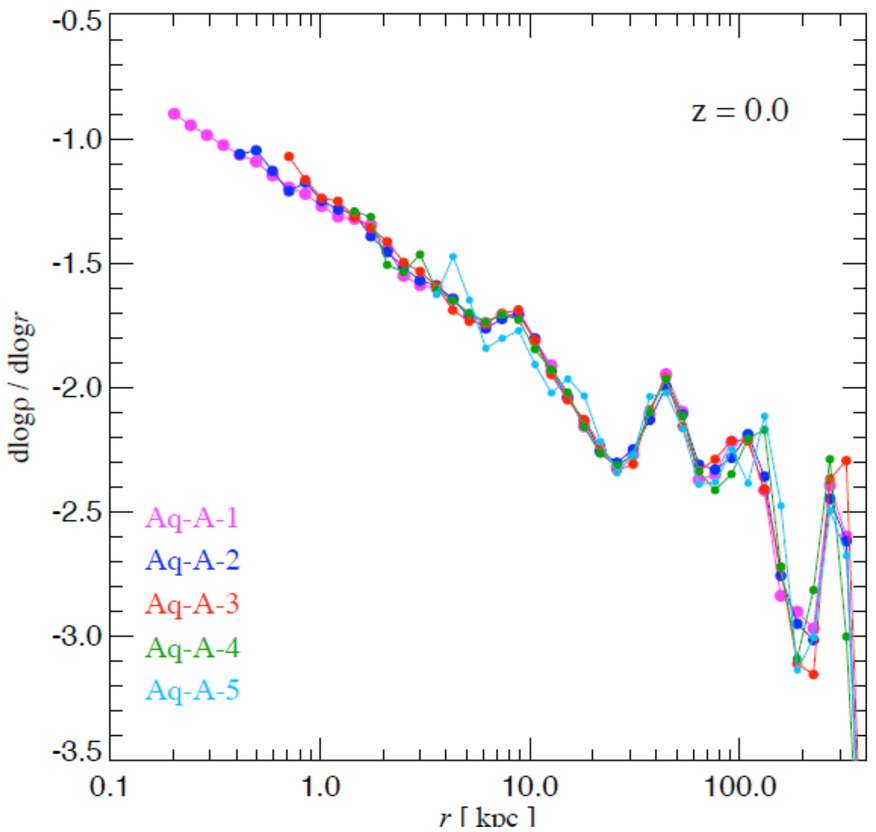
Via Lactea simulation

- Dark matter halos are endpoints of all cosmological structure formation
- Self-bound structures, virialized
- Highest dark matter densities
- Harbor all stars, galaxies, quasars

Formation of structure tells us about the history of the universe

Density Profiles of dark matter halos





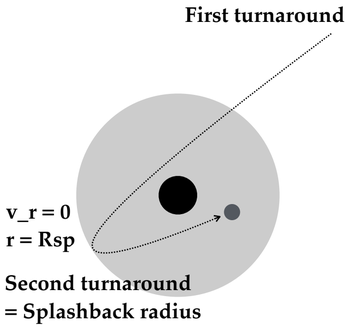
"Aquarius" Springel et. al 2008

- The density of halos is well described by the NFW profiles

$$\frac{\rho_0}{\frac{R}{R_S}\left(1+\frac{R}{R_s}\right)^2}$$

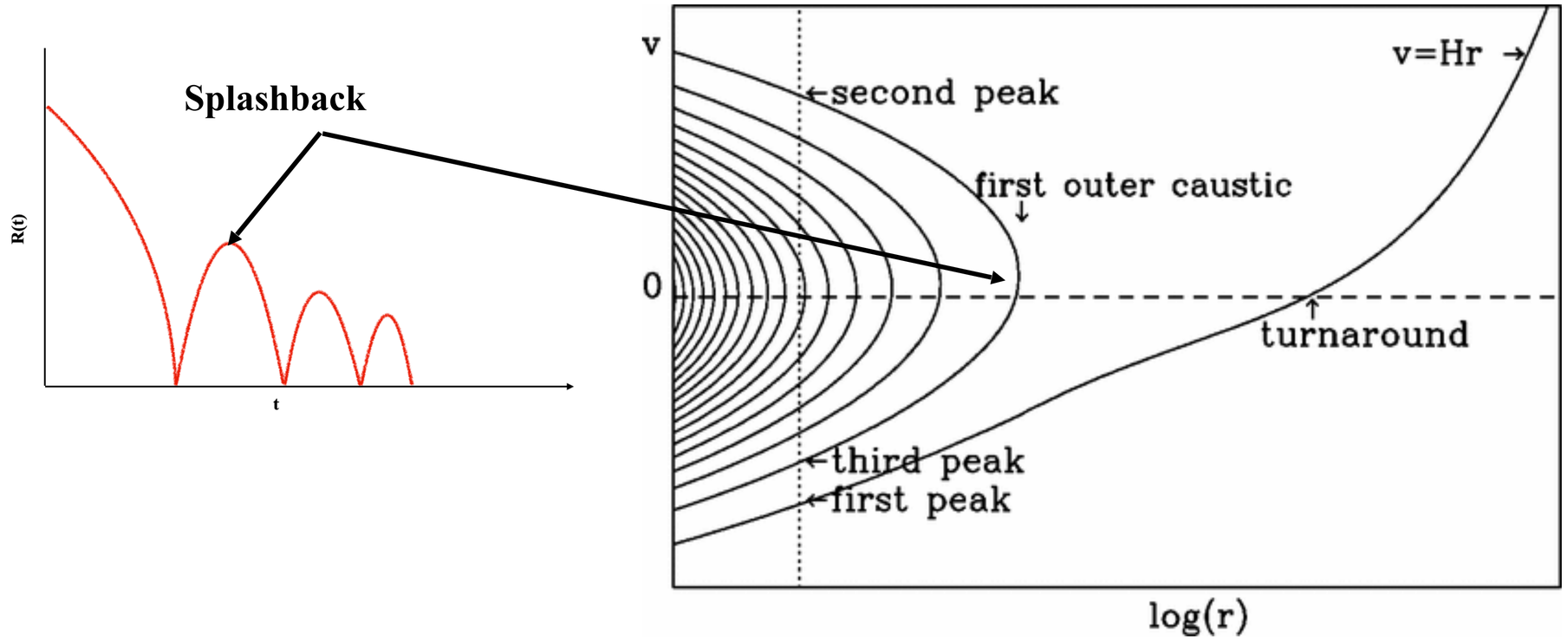
- Slope is -1 in the inner regions and rolls over to -3 in the outskirts of the halo.

Phase space Diagram of Halo evolution



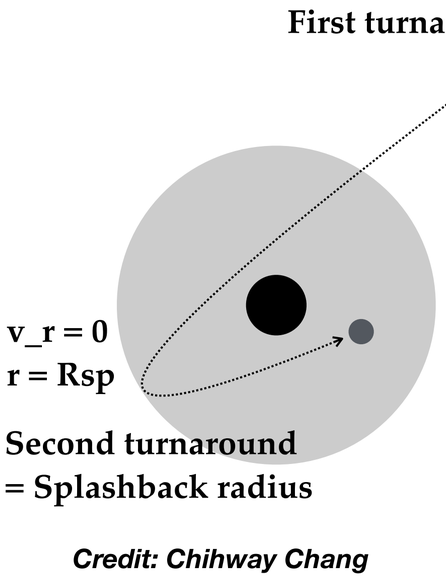
Collapse of a single isolated peak

(For spherical potential and smooth accretion)

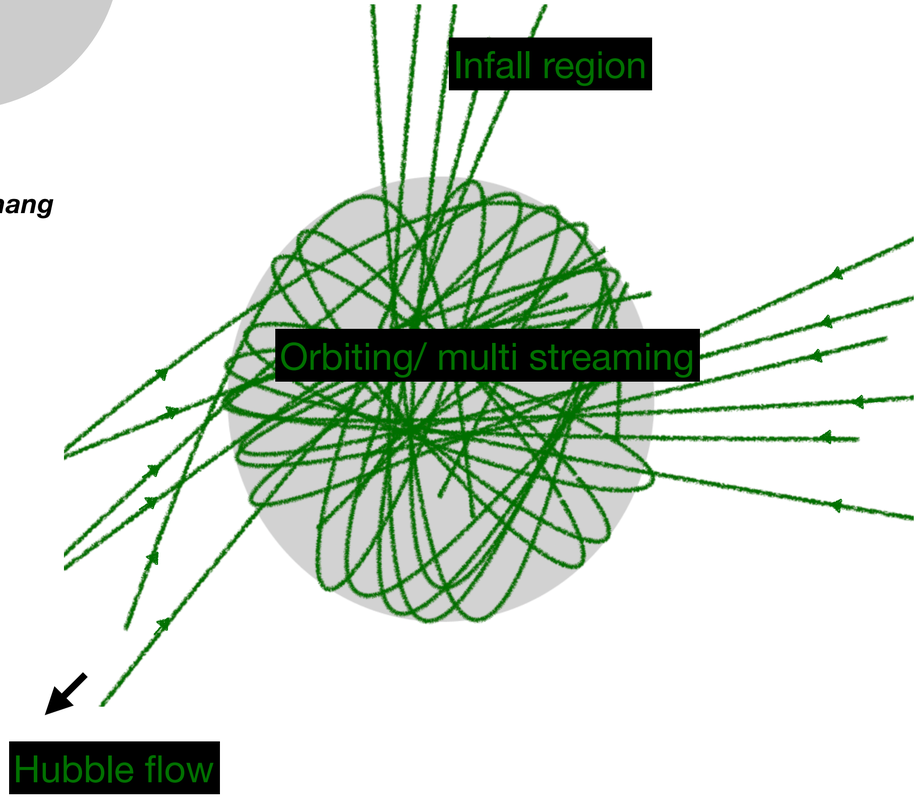


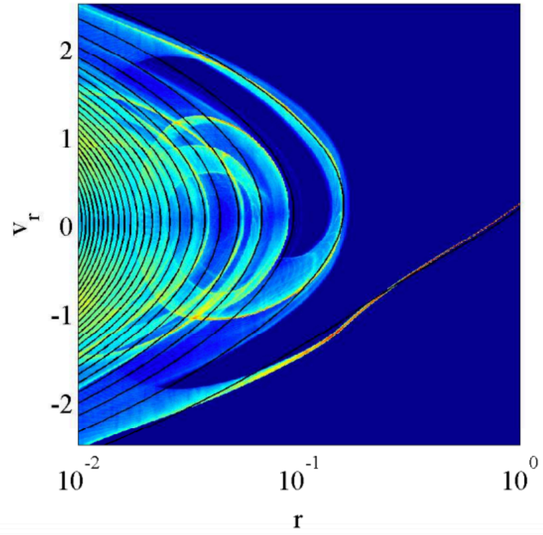
Splashback - corresponds to first apoapses passage after collapse

The structure of a dark matter halo

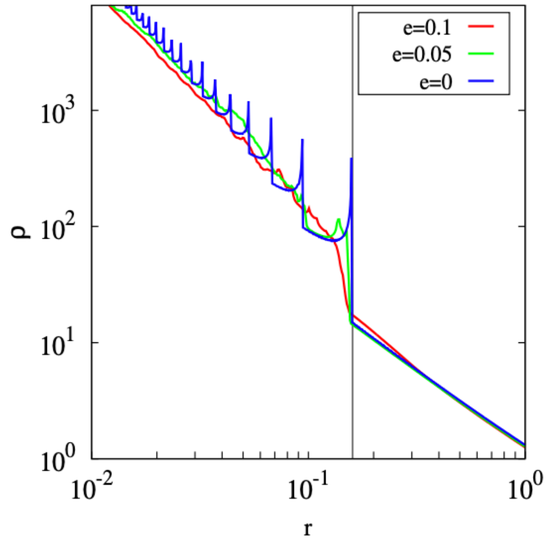


Credit: Chihway Chang





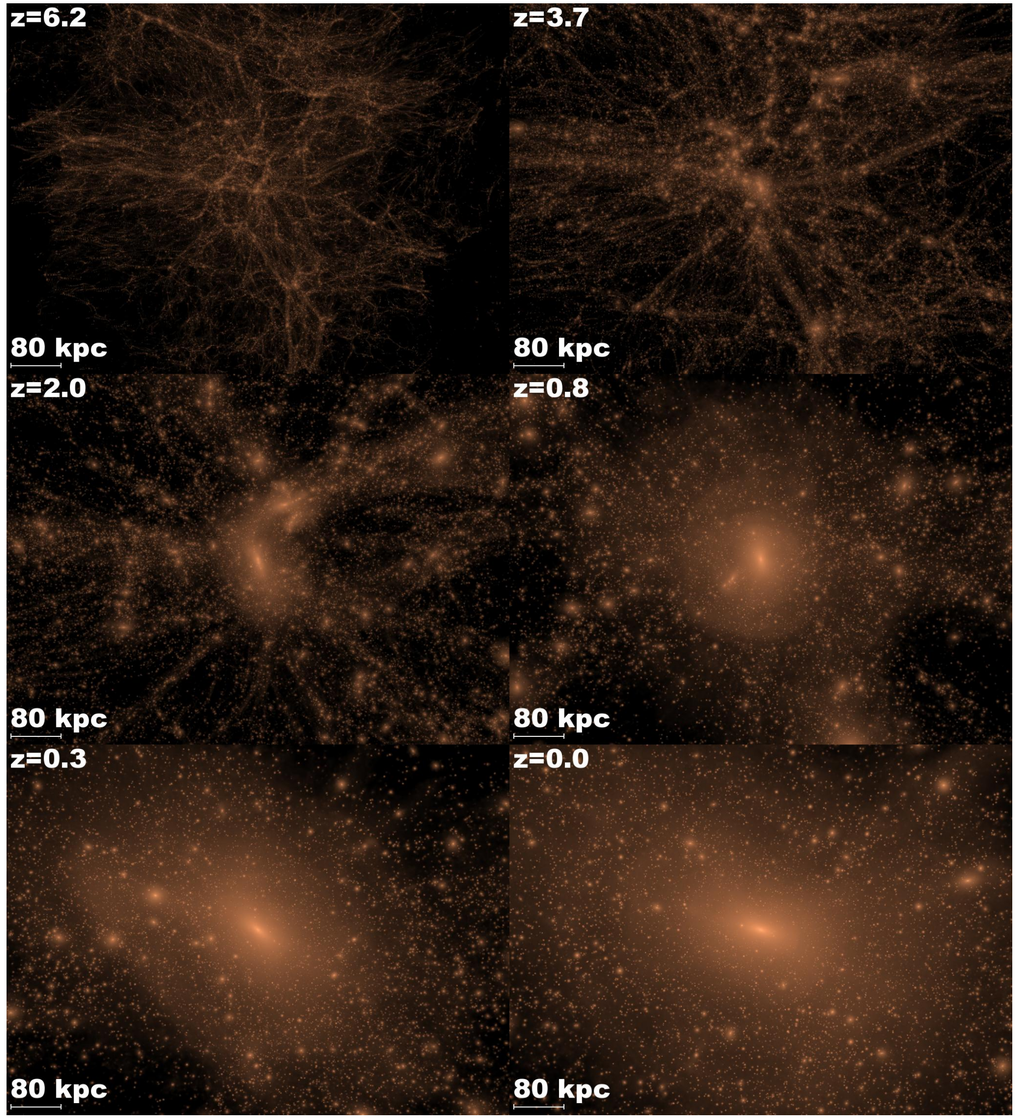
Phase space of a halo



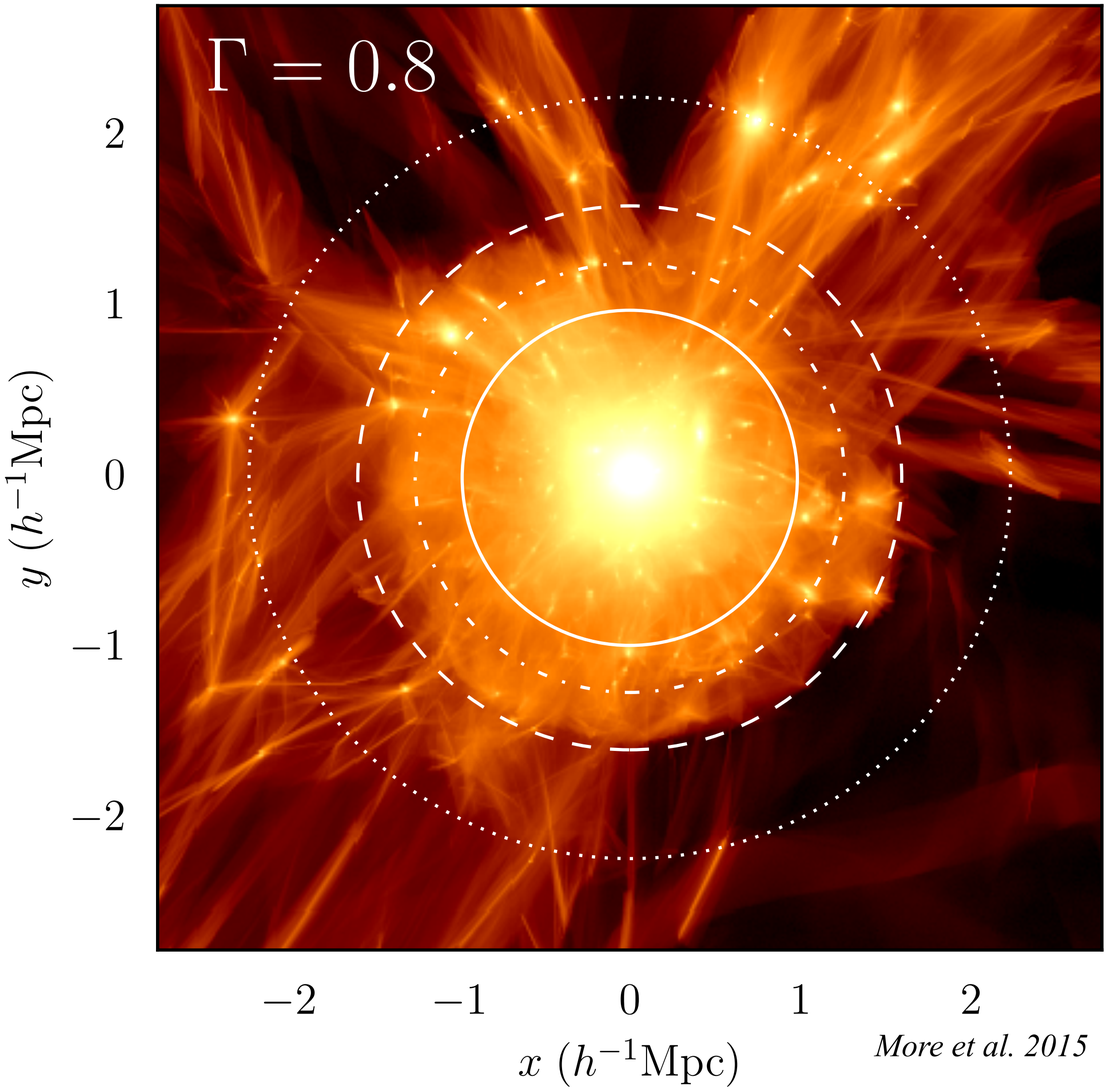
Density around a halo

Adhikari, Dalal, Chamberlain 2014

Dark Matter halos in simulations

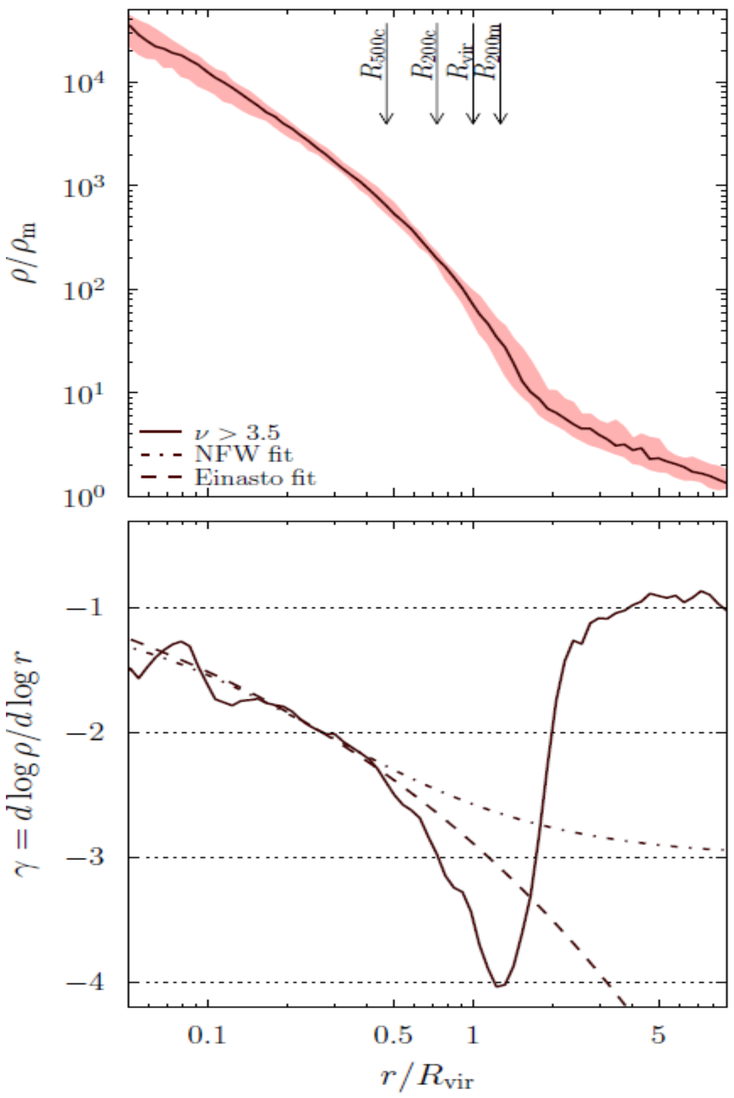


Via Lactea simulation

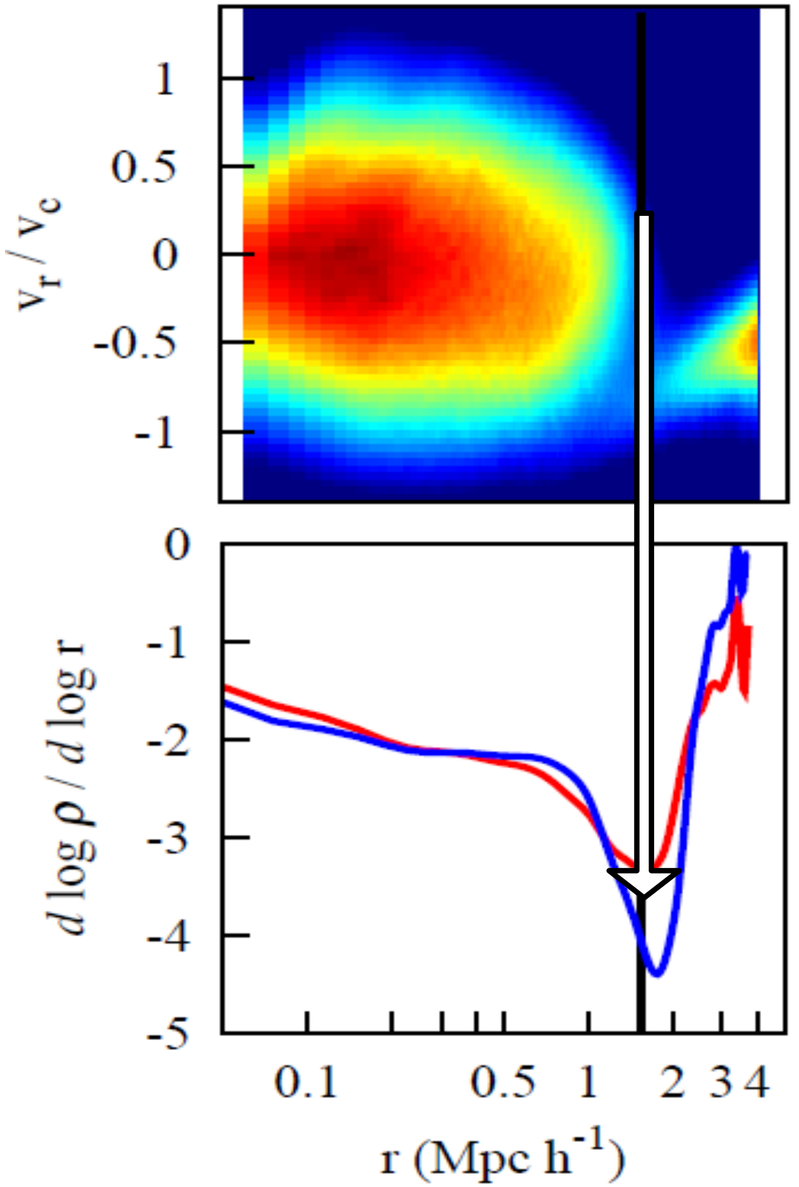


More et al. 2015

Outer density profiles of Dark Matter Halos

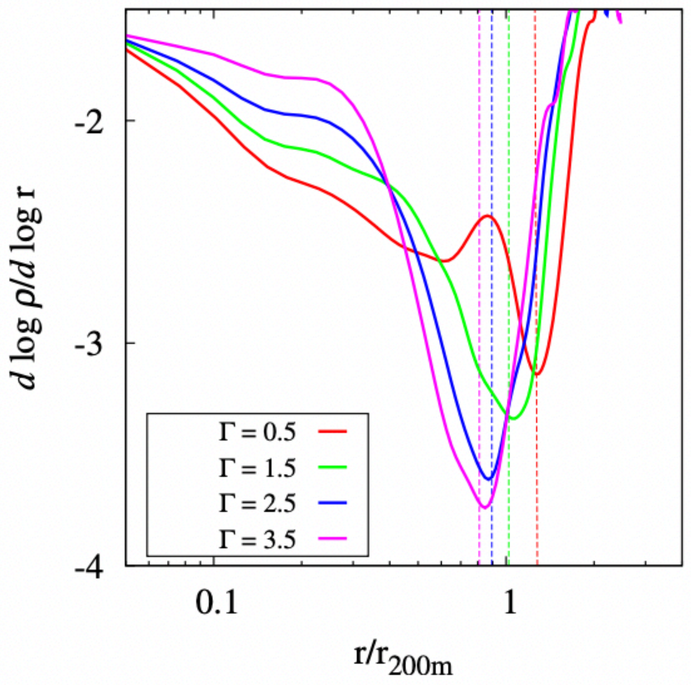


Diemer & Kravtsov 2014



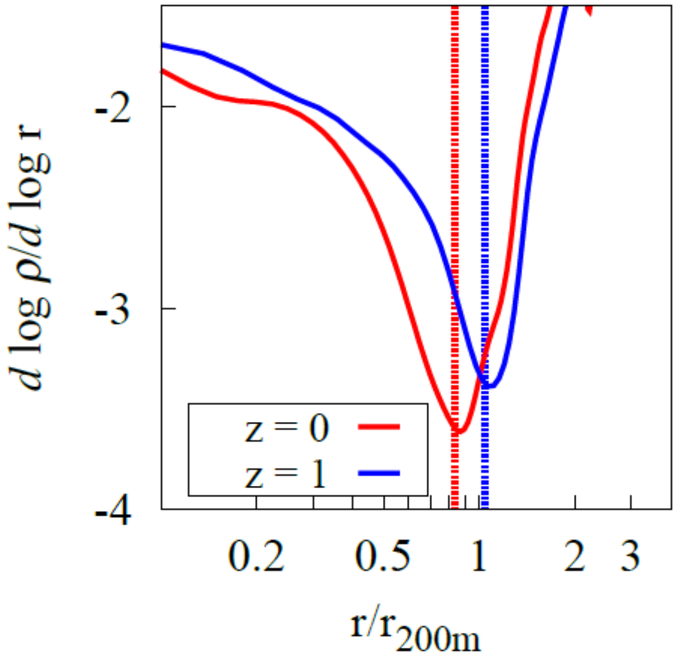
Adhikari, Dalal, Chamberlain 2014

Logarithmic Slope of the density profile Accretion Rate and halo redshift

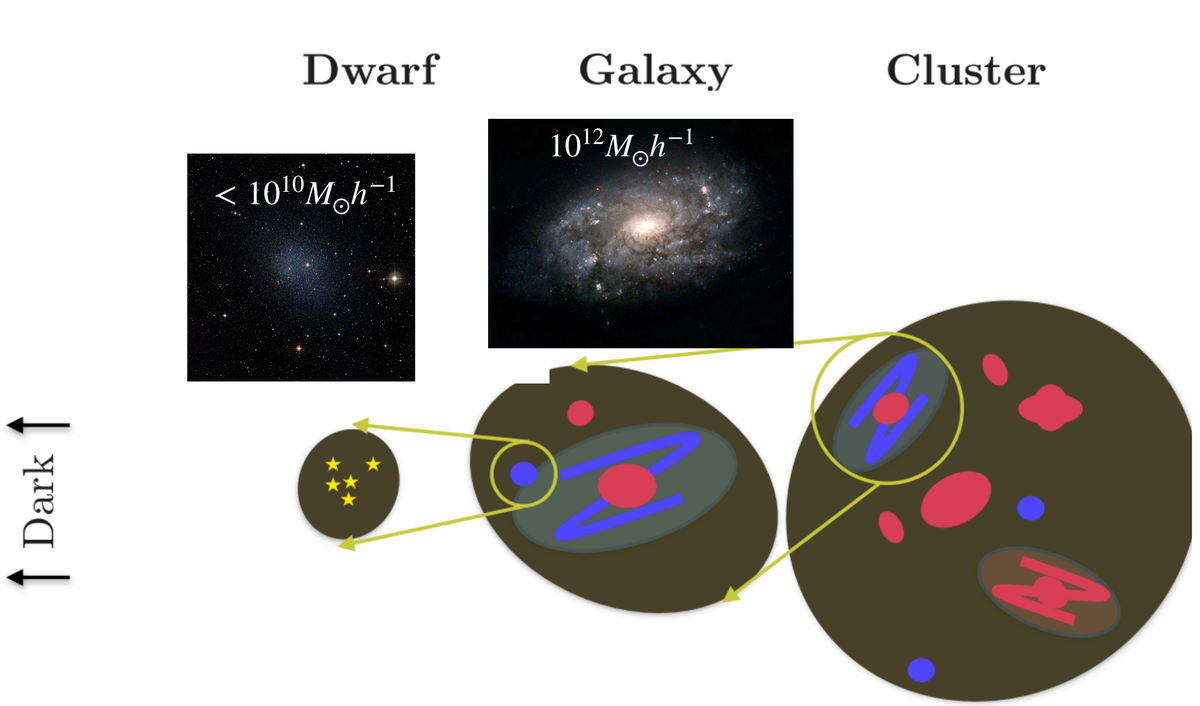


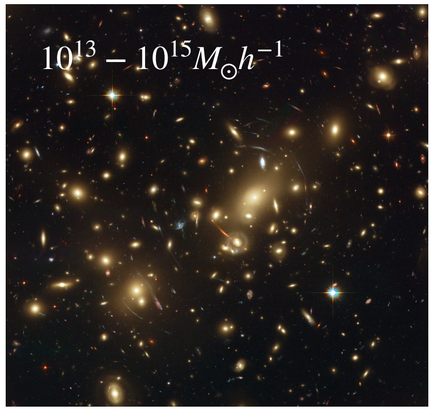
At a given accretion rate it is a function of redshift

Faster a halo grows, the smaller is its splashback radius in units of R200.



Hierarchical structure formation





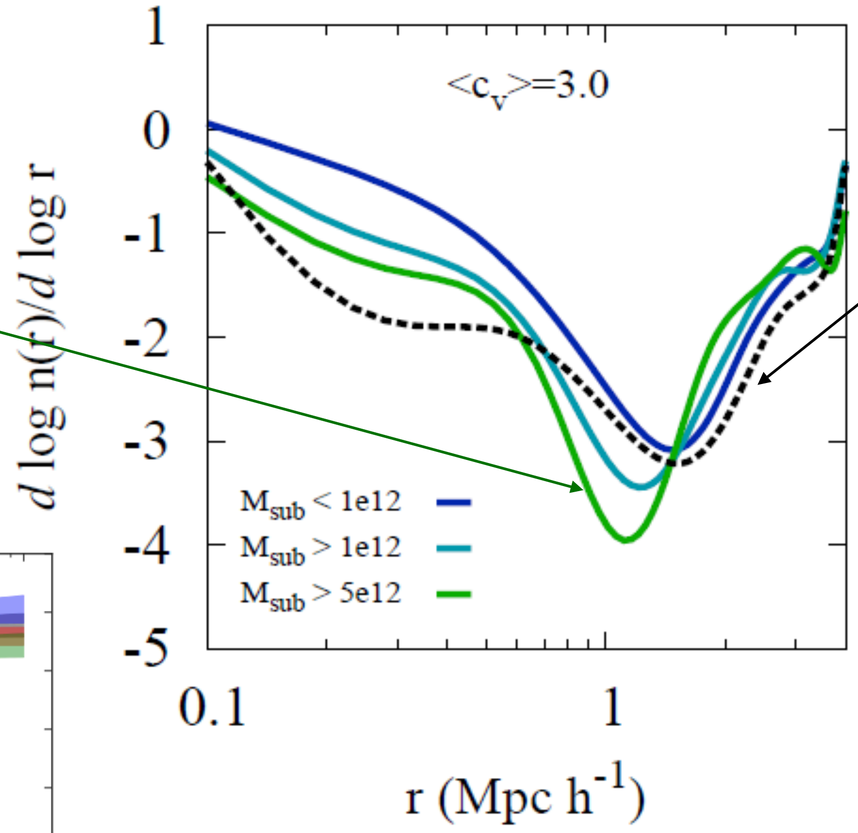
	Dwarf	Galaxy	Cluster
$v_{\rm vir} \sim M_{\rm vir}^{1/3}$:	$10 - 1000$ km/s	$100 - 1000$ km/s	$1000 - 2000$ km/s
$R_{\rm vir} \sim M_{\rm vir}^{1/3}$:	$10 - 100$ kpc	$100 - 1000$ kpc	$1 - 2$ Mpc
$R_* \sim 0.02 R_{\rm vir}$:	$\sim 0.1 - 1$ kpc	$\sim 1 - 10$ kpc	~ 20 kpc
$k_{\rm hm} \sim M_{\rm vir}^{-1/3}$:	$\sim 4 - 40$ Mpc^{-1}	$\sim 0.4 - 4$ Mpc^{-1}	$\sim 0.2 - 0.4$ Mpc^{-1}

credit: Buckley and Peter 2017

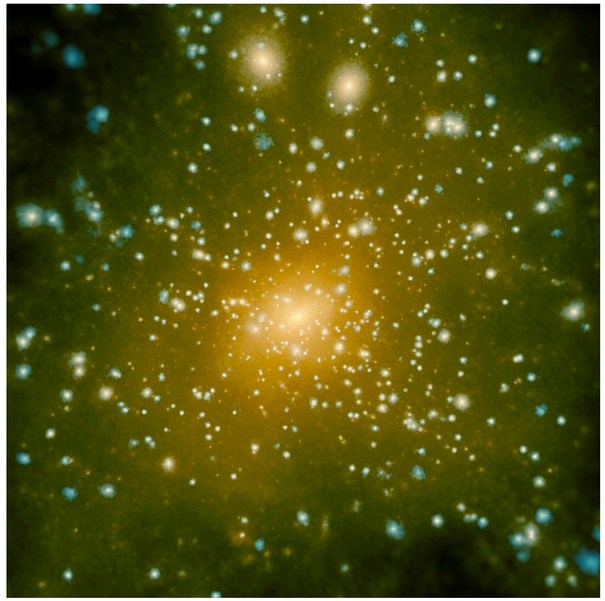
Small halos form first and merge to form more massive halos

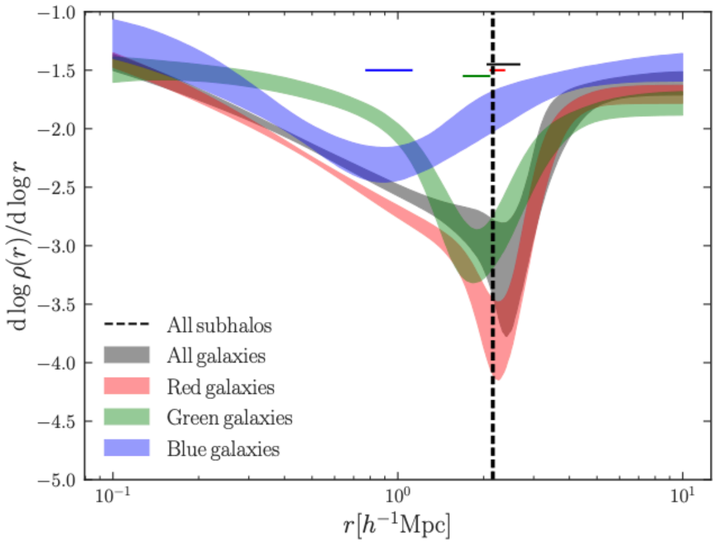
Substructure also show a significant spread in their distribution within the halo

Subhalos



Dark matter

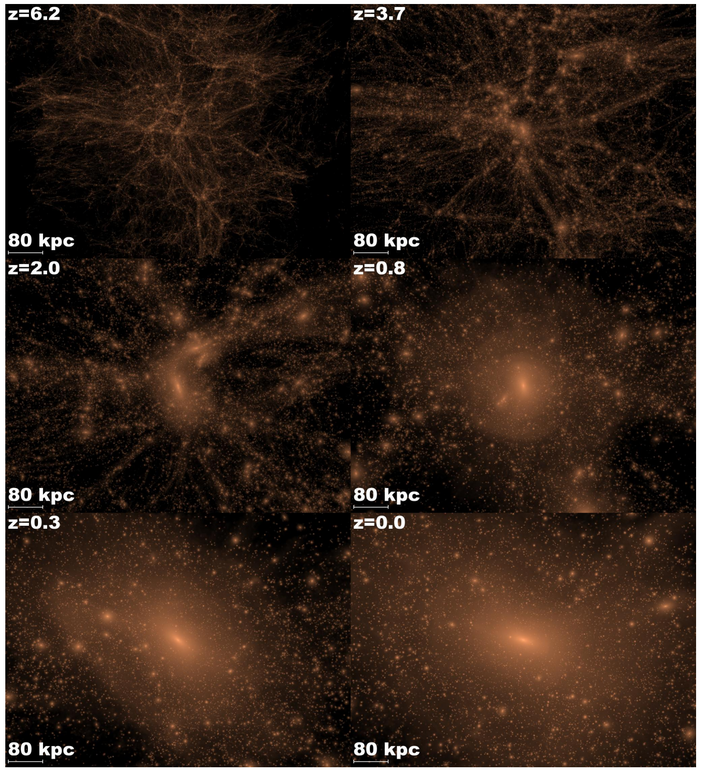


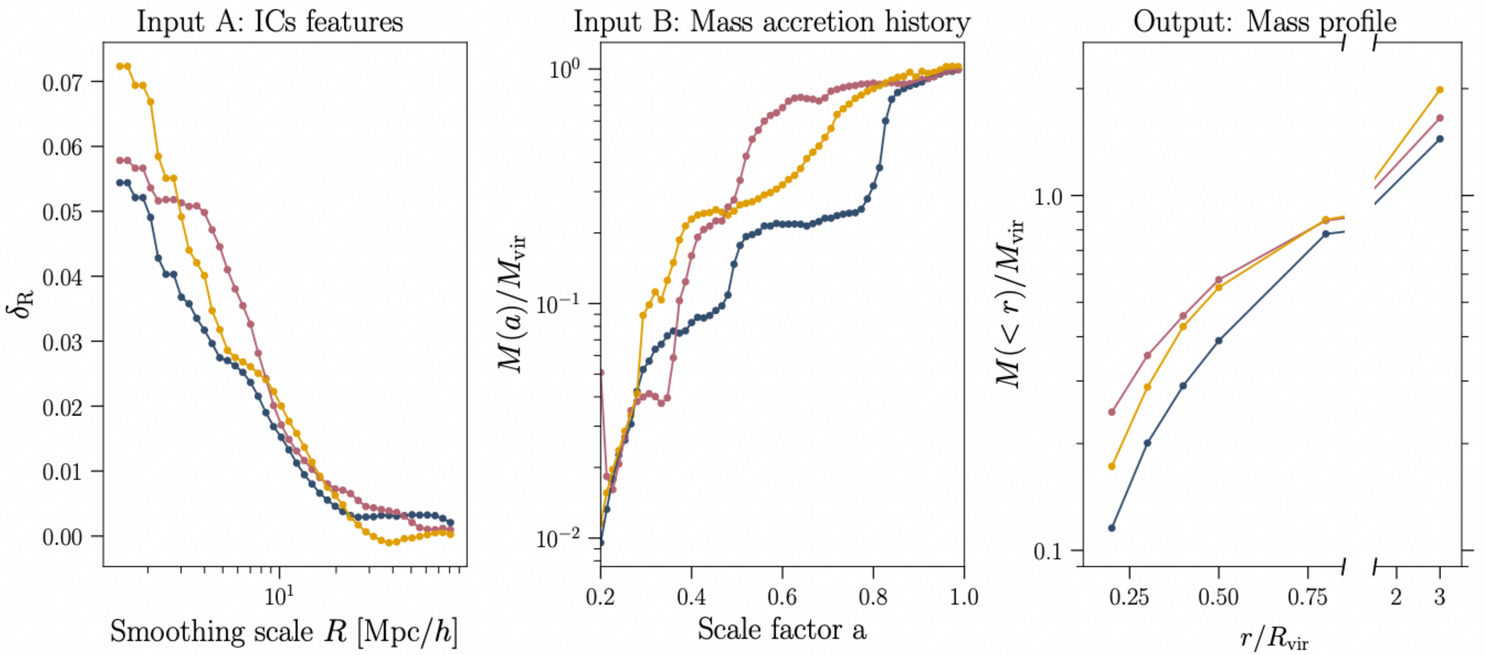


Observed galaxies

Dynamical Halo

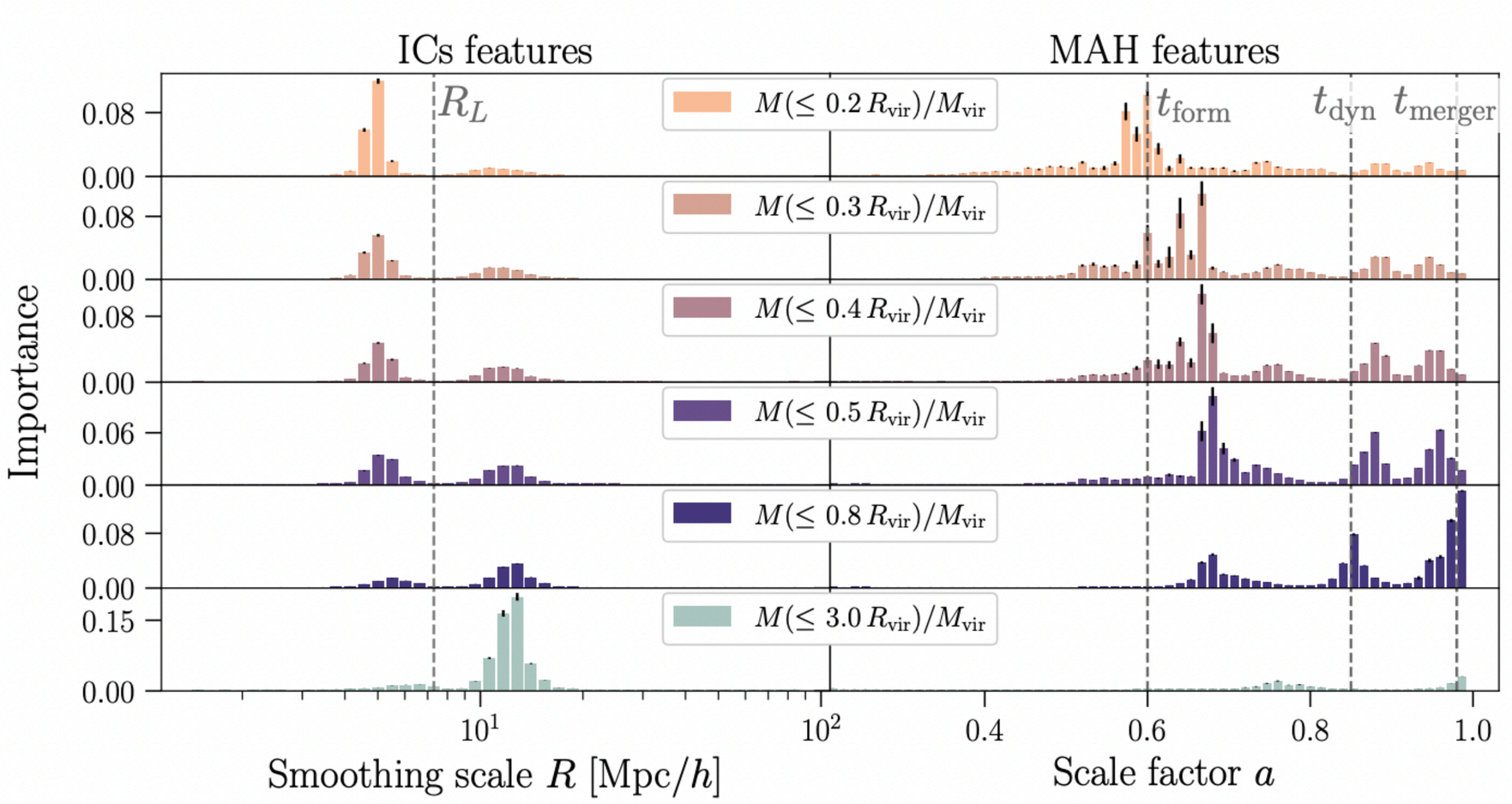
ICs ⟶ Mass Accretion Histories ⟶ Profiles





Lucie-Smith, Adhikari, Wechsler 2022

Feature Importances from Machine Learning

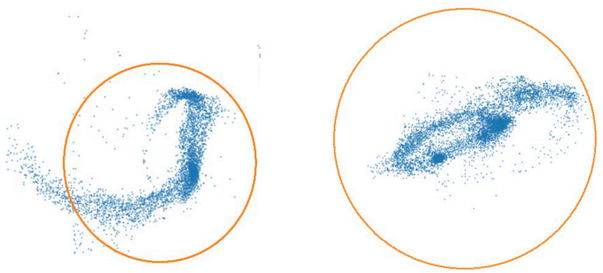


Lucie-Smith, Adhikari, Wechsler 2022

Understand if ML/Clustering methods can isolate structures within the halo

Soorya Narayan R
Masters student at IISER Pune

- **Is the halo a uniform virialized structure?**
- **Are there physical dynamical boundaries?**
- **How do we efficiently extract structures within dark matter halos?**
- **Streams, subhalos, sub-subhalos**



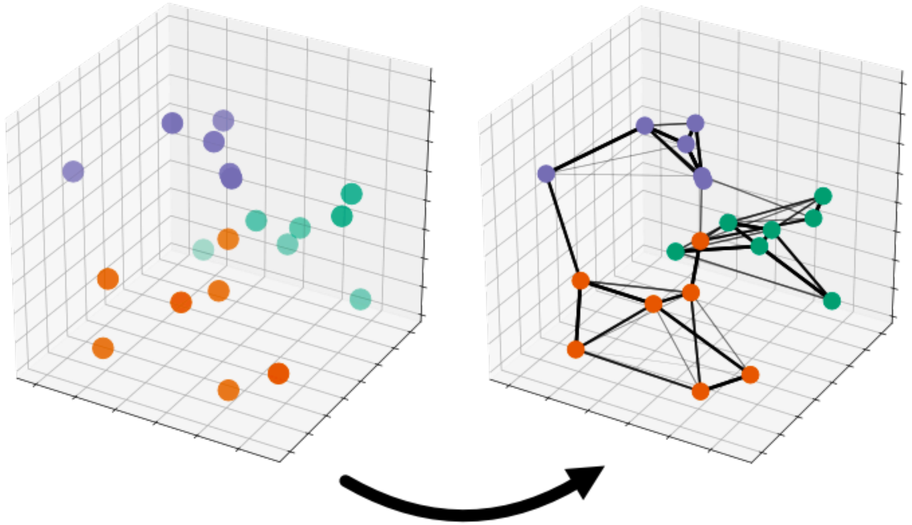
- **Does the current halo structure contain information about its history?**
- **How are these structured assembled?**

Unified Manifold Approximation and Projection **(UMAP)** *for Dimension Reduction*

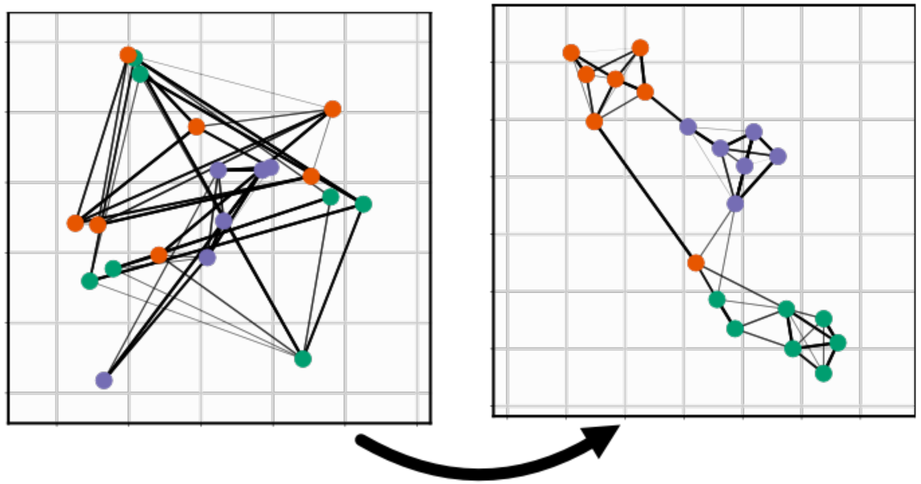
UMAP

Unified Manifold Approximation and Projection for Dimension Reduction

- **Graph in higher dimension space, weighted by distances**
- **The metric is allowed to be non-Euclidian that preserves the topological structures**
- **Projects to lower dimension space such to optimally conserve this topology of the original higher dimensional space.**

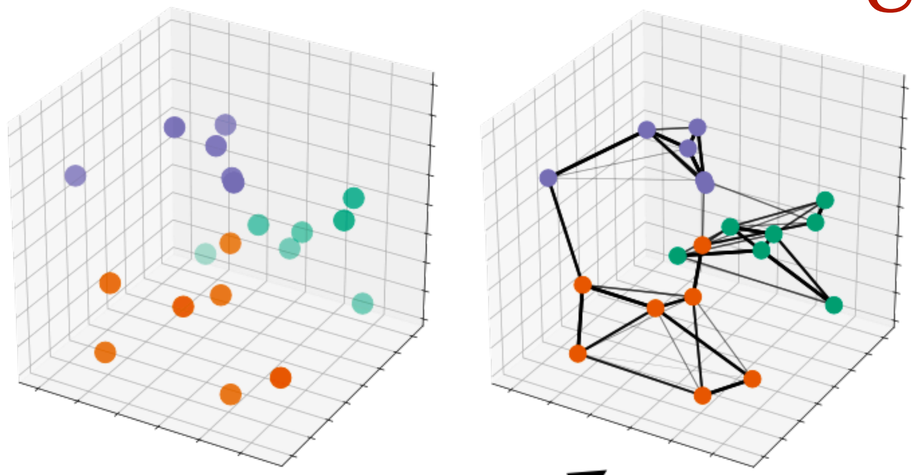


Compute a graphical representation of the dataset

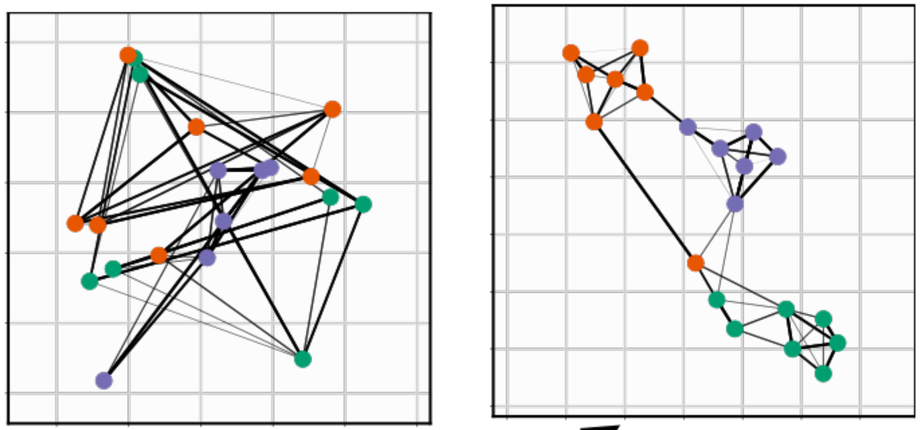


Learn an embedding that preserves the structure of the graph

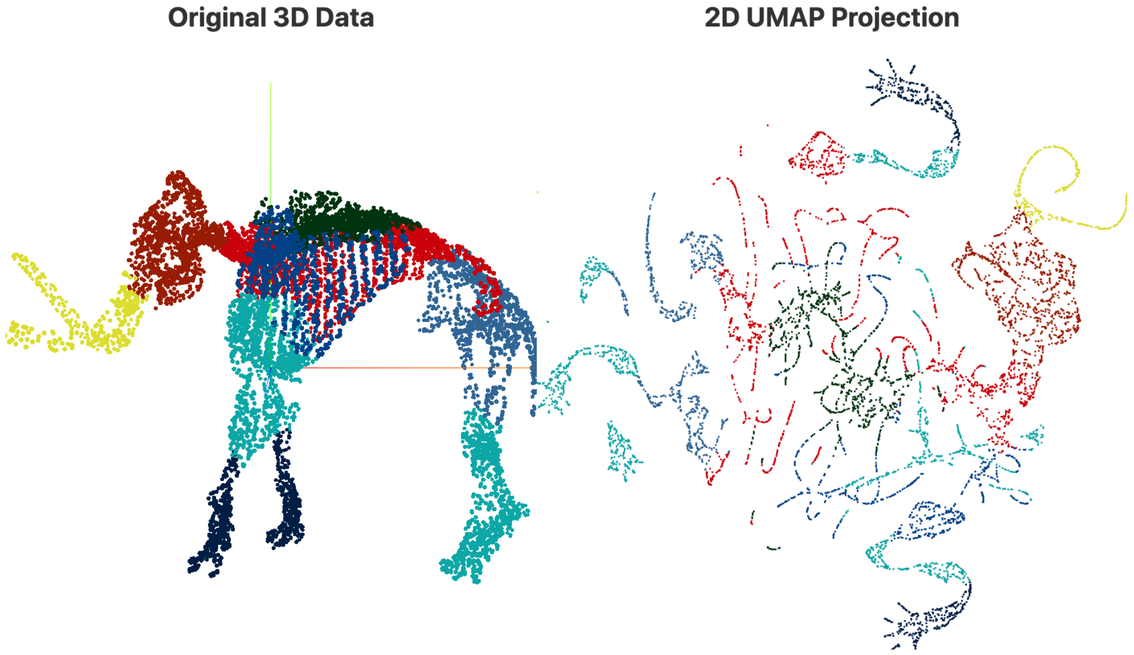
UMAP



Compute a graphical representation of the dataset



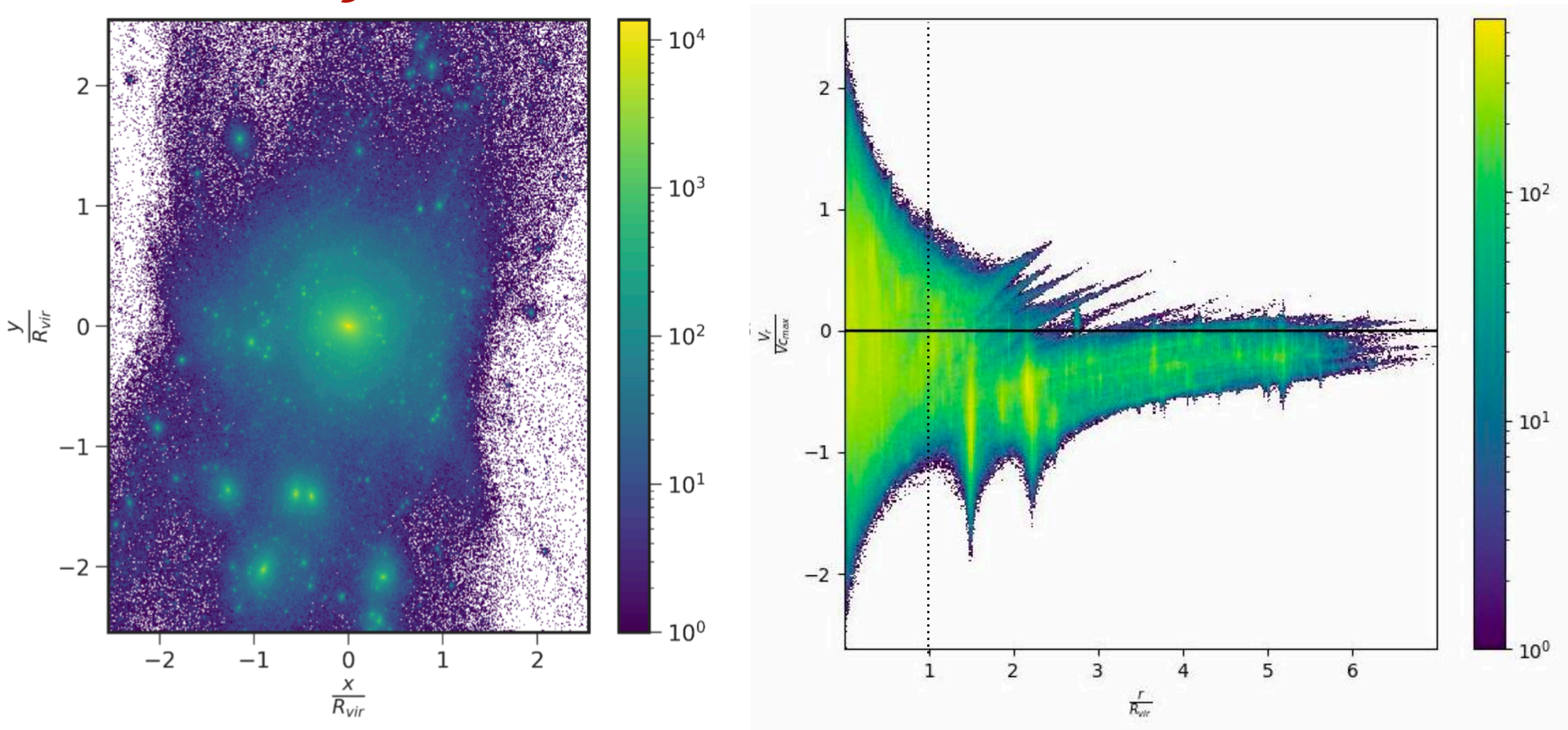
Learn an embedding that preserves the structure of the graph



UMAP Projection of a woolly mammoth

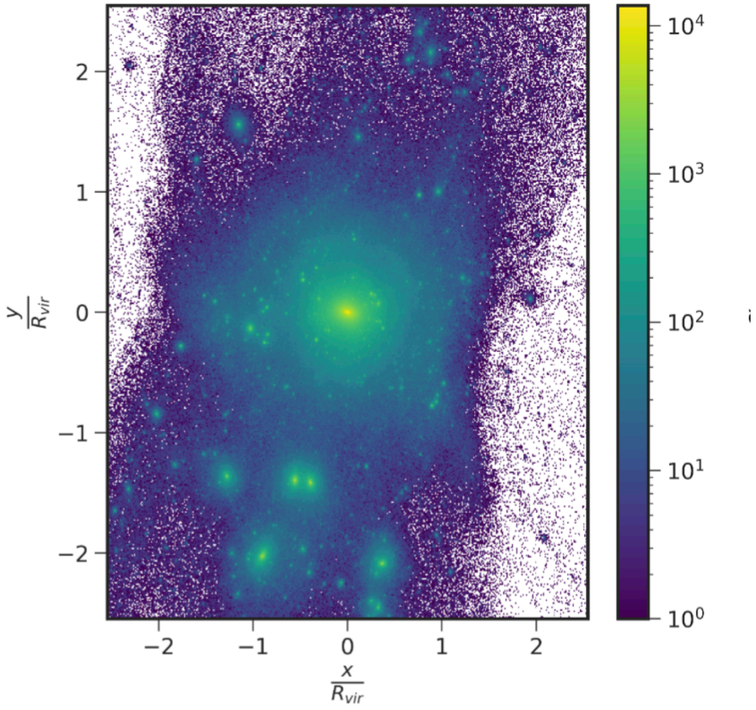
https://pair-code.github.io/understanding-umap/

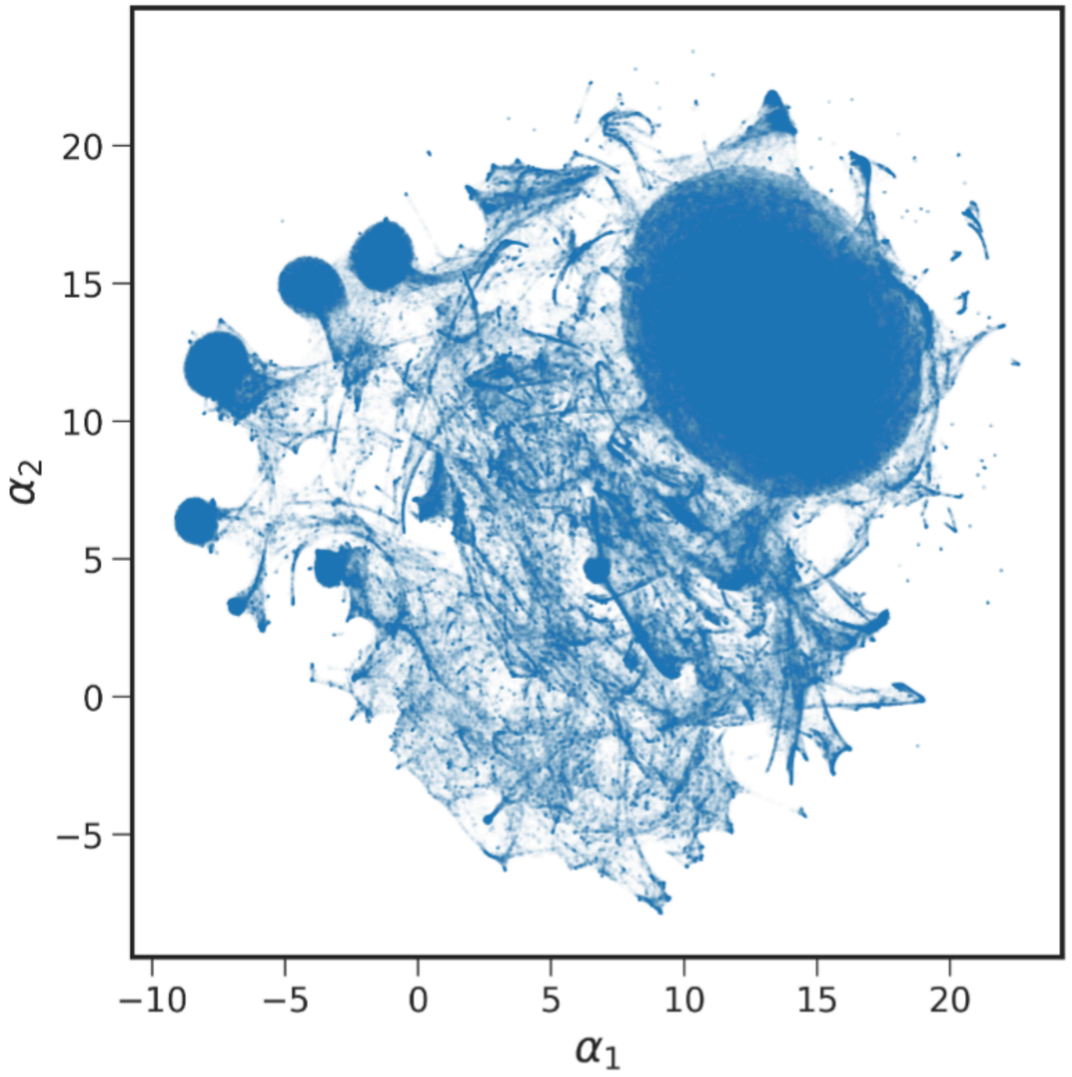
Dynamical structures within the dark matter halo



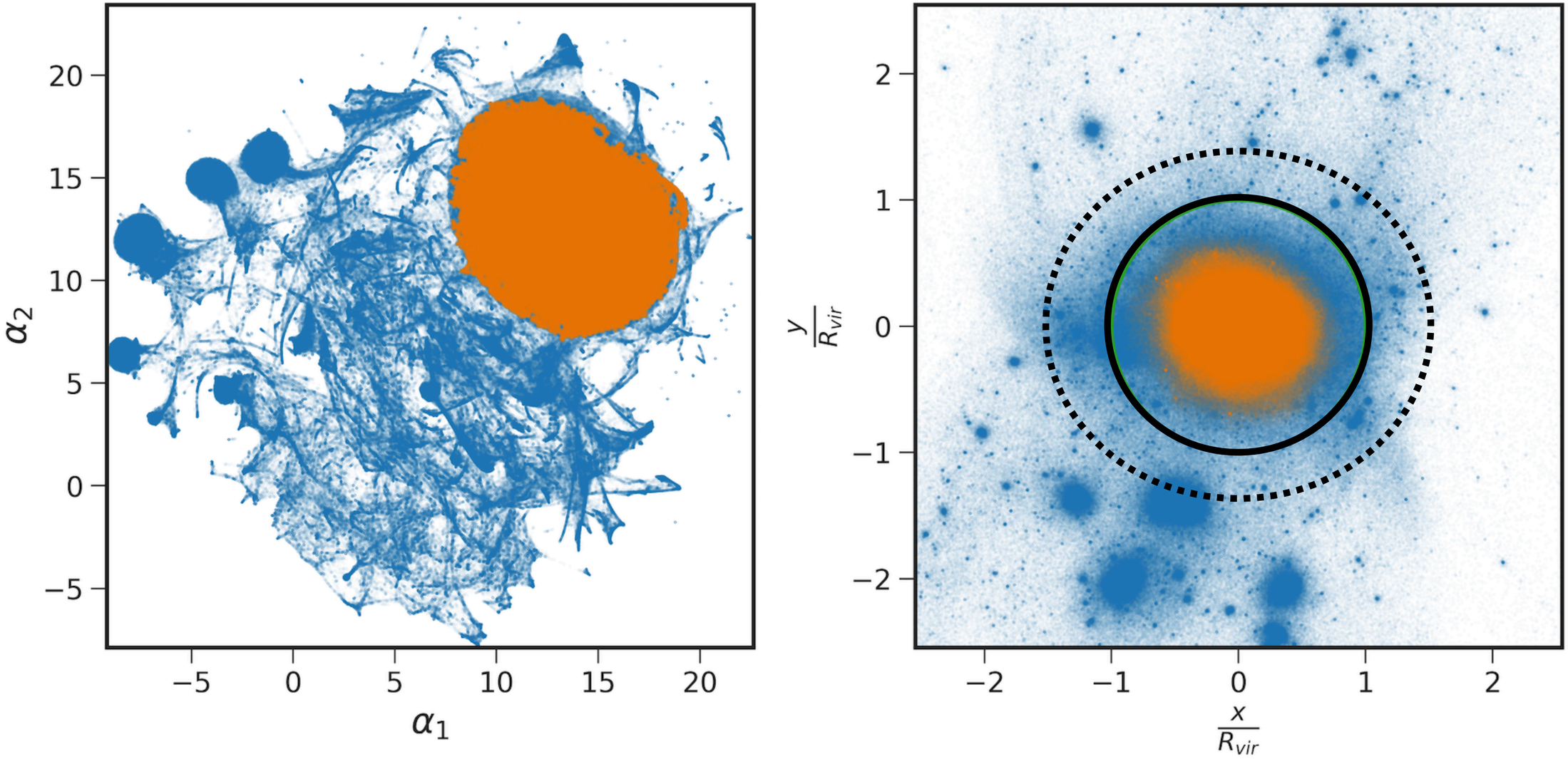
- **Zoom-in simulation of a Milky Way mass,** $8.8 \times 10^{12} M_{\odot}/h$**, dark matter halo, Particle mass resolution =** $3 \times 10^{5} M_{\odot}/h$
- **Use the 6D phase space information** $\left[\frac{x}{R_{\rm vir}}, \frac{y}{R_{\rm vir}}, \frac{z}{R_{\rm vir}}, \frac{v_x}{V_{\rm cmax}}, \frac{v_y}{V_{\rm cmax}}, \frac{v_z}{V_{\rm cmax}}\right]$ **for every particle in a ~**1Mpc/h **region around the Milky Way centre.**
- **Use UMAP to visualise distinct groups.**

UMAP Projection of the Milky Way Halo



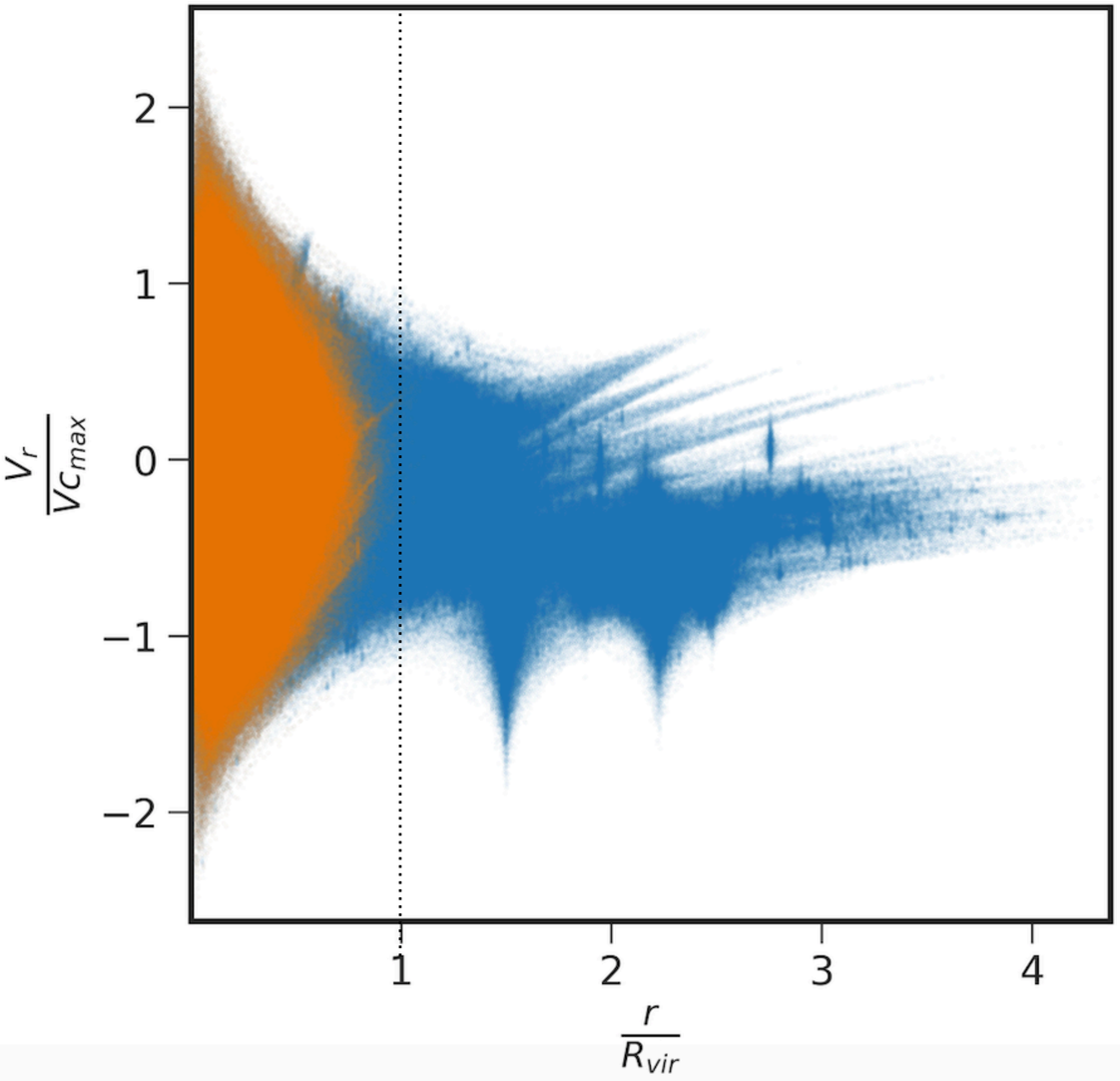


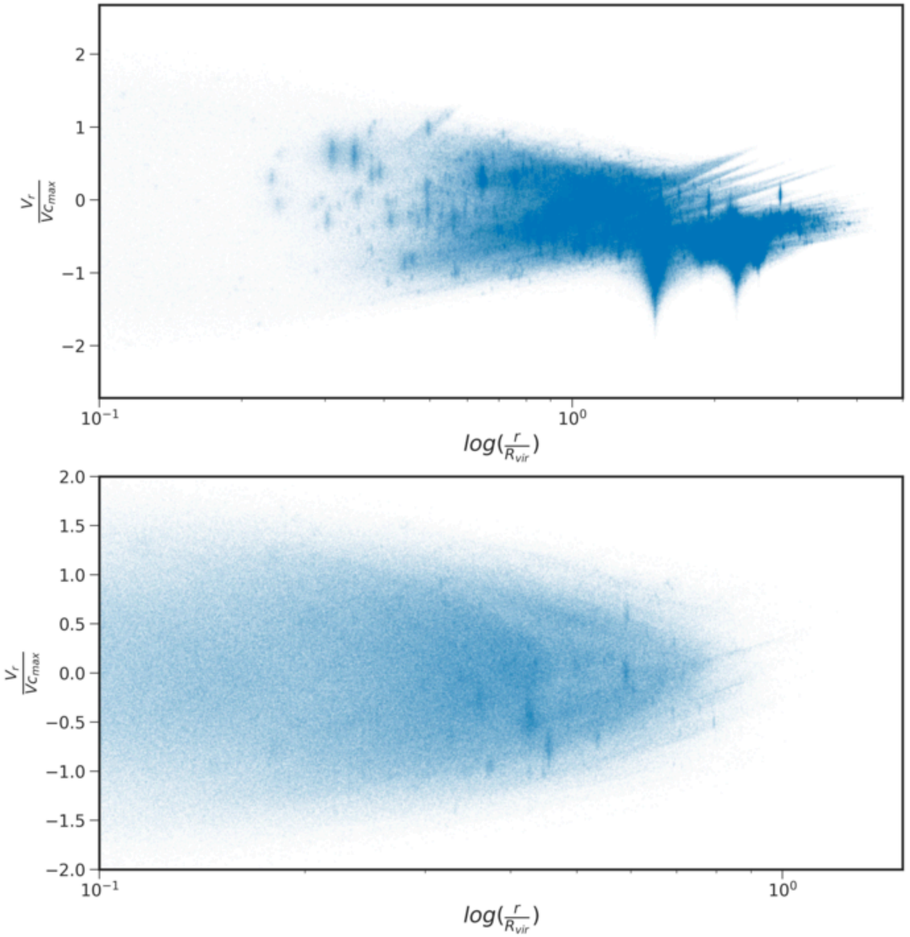
Largest UMAP cluster position space



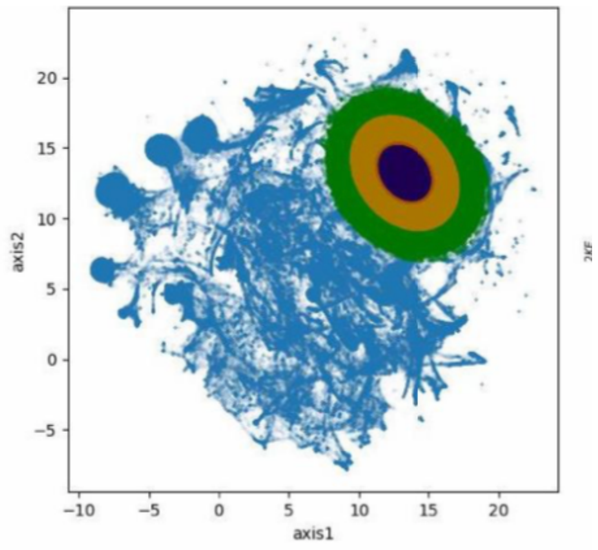
Largest cluster using DBSCAN in the UMAP space

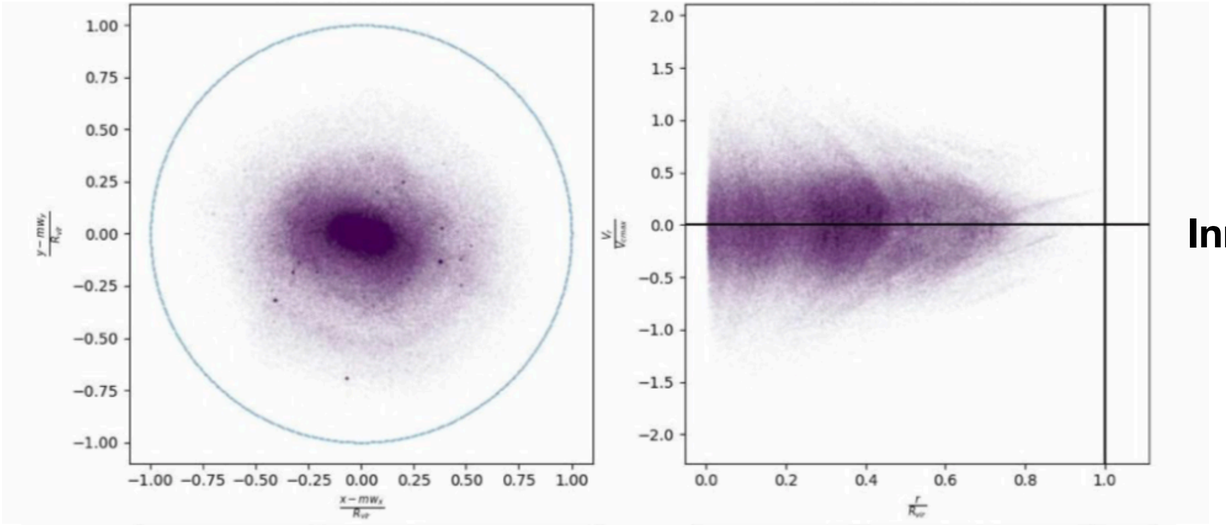
Largest UMAP cluster phase space



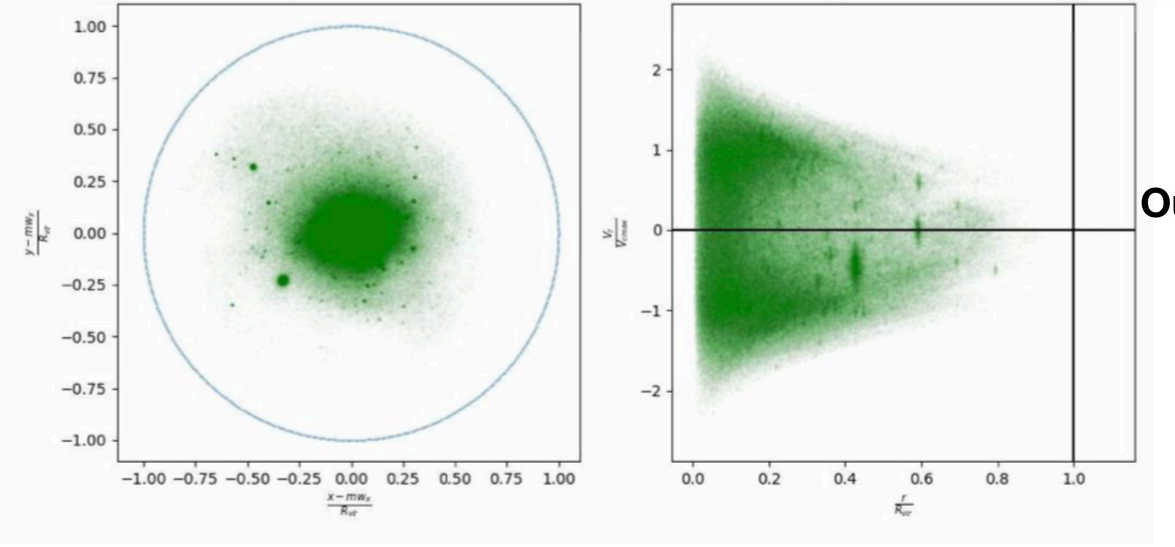


Separates out the inner halo, while the outer halo is put out of the ellipse





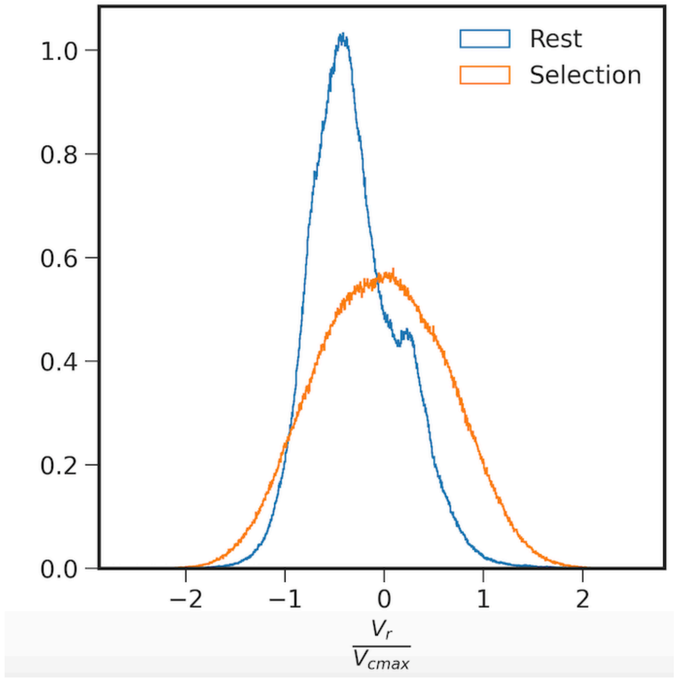
Inner region of the ellipse

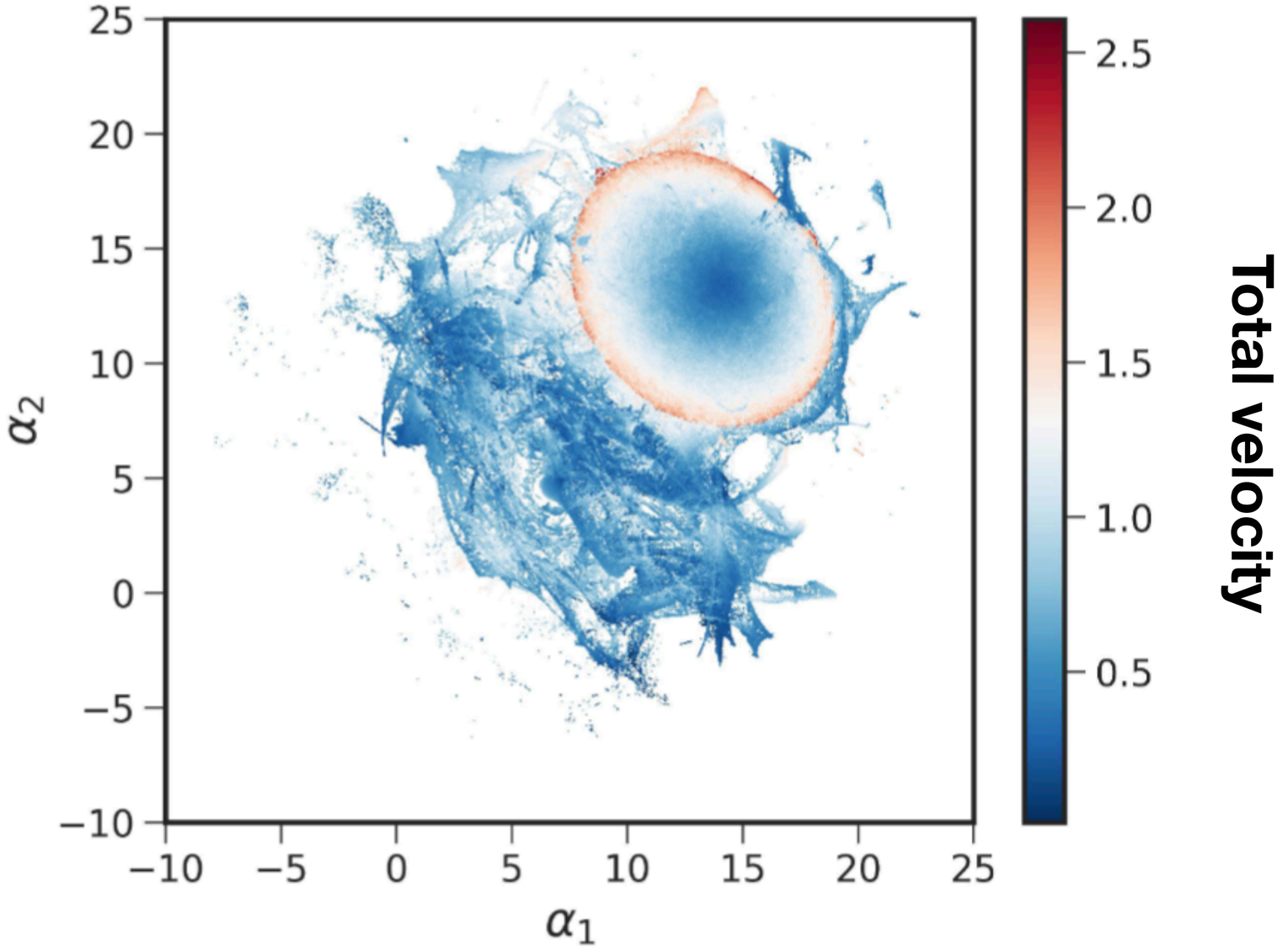


Outermost region of the ellipse

Zooming into the largest structure in the field

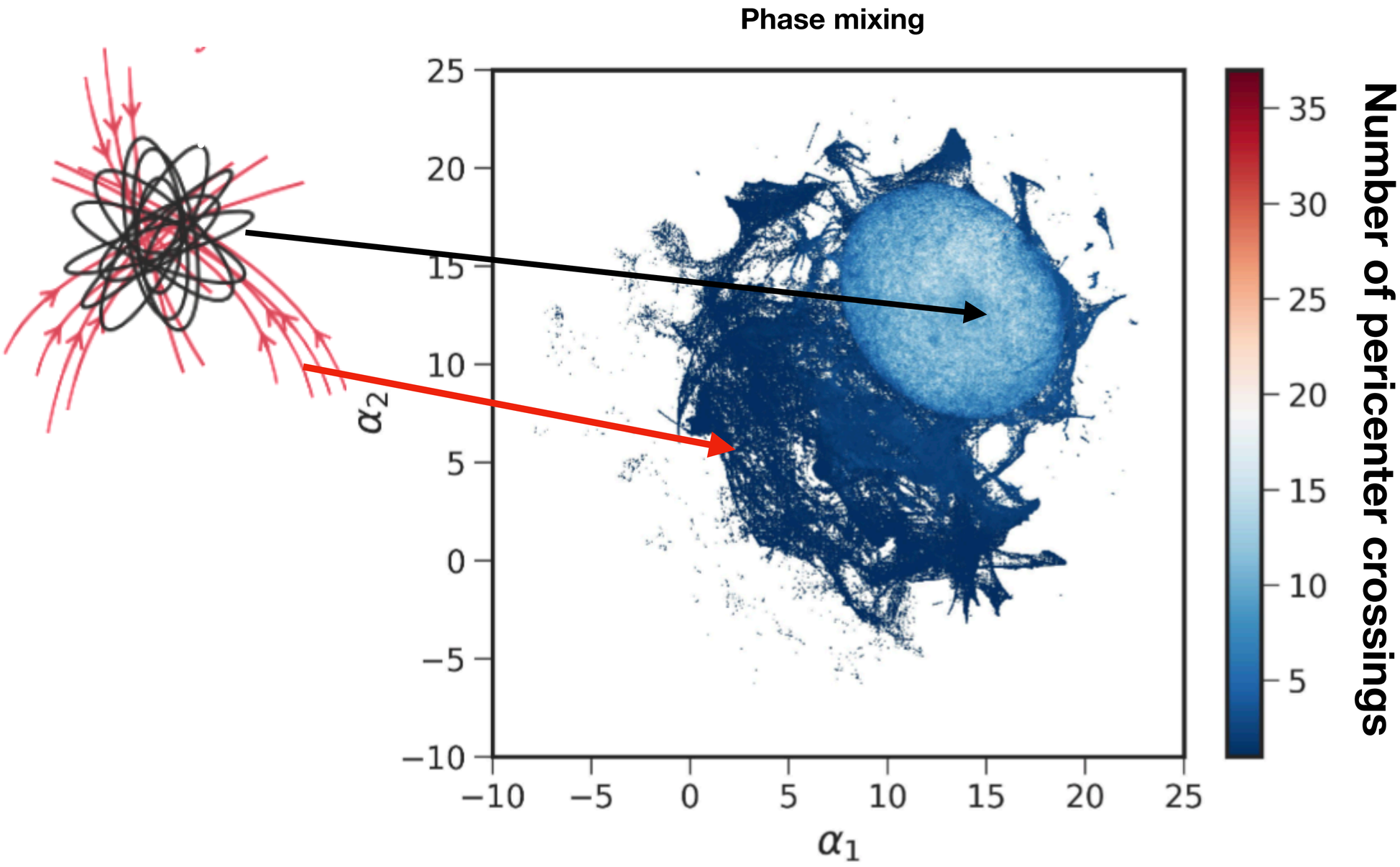
What is **UMAP** *doing?*



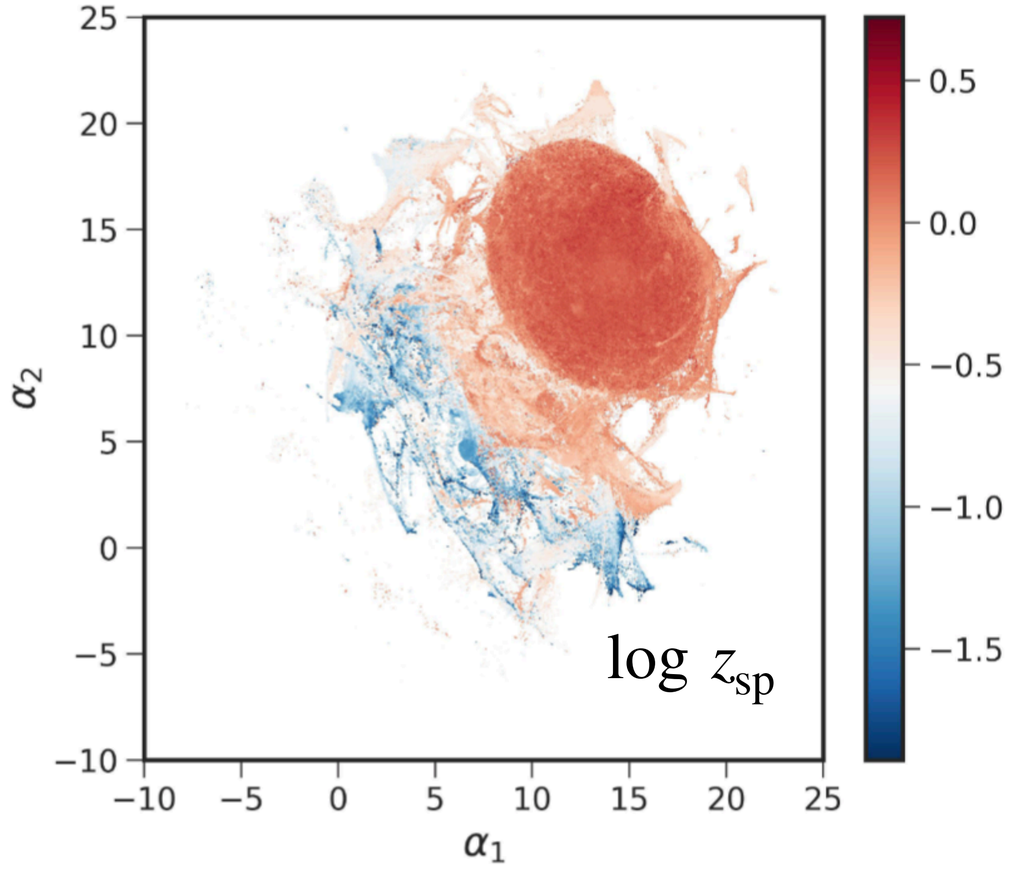


Everything that has had at least one pericenter crossing - so ‘orbiting particle’

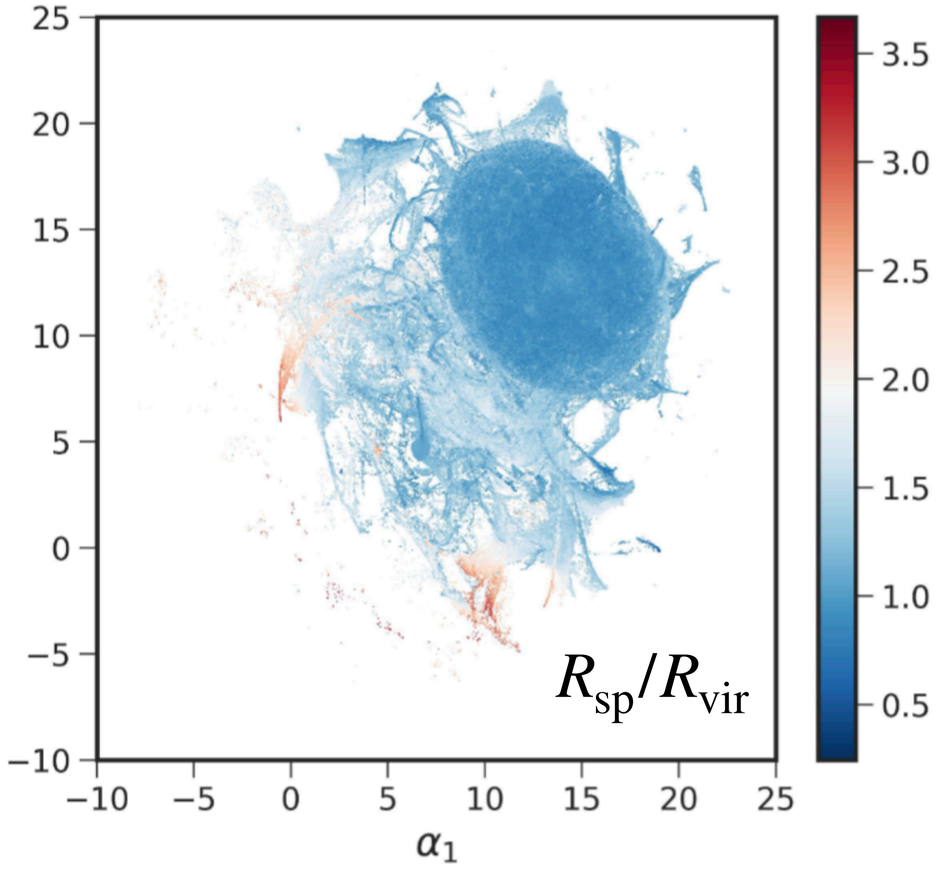
Particle history or assembly information



Splashback

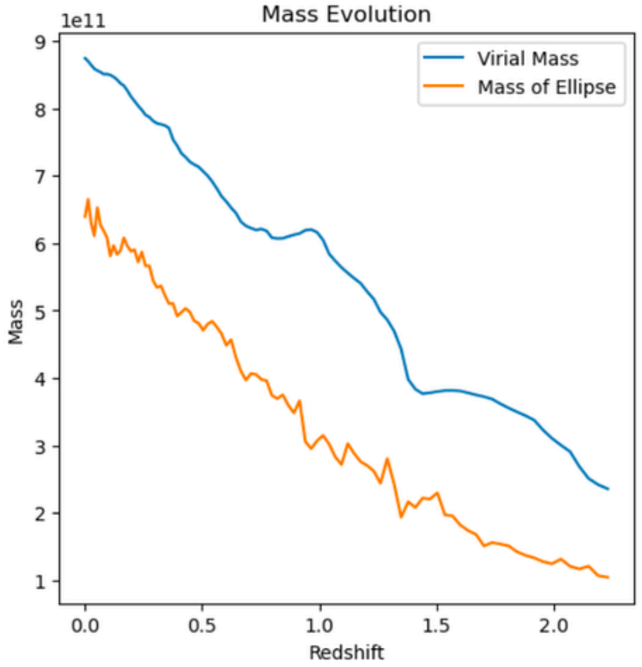


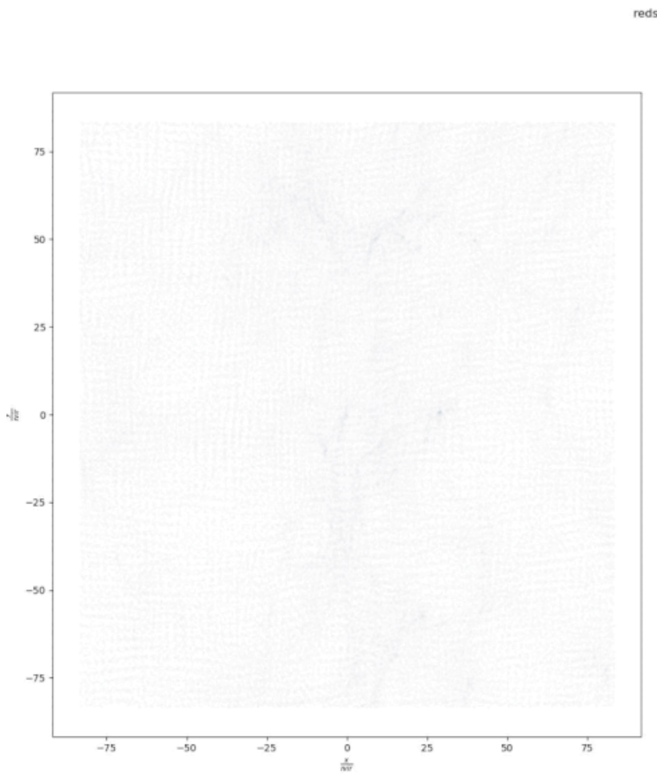
When did each particle reach splashback?

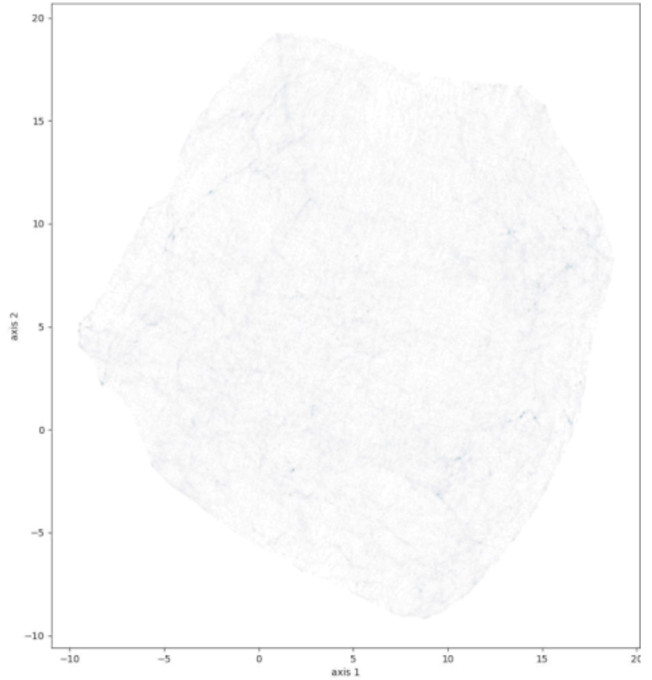


Where did each particle reach splashback

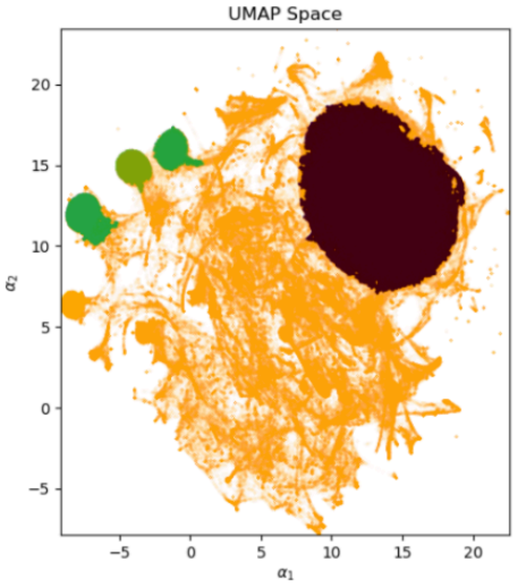
Evolution history of the halo

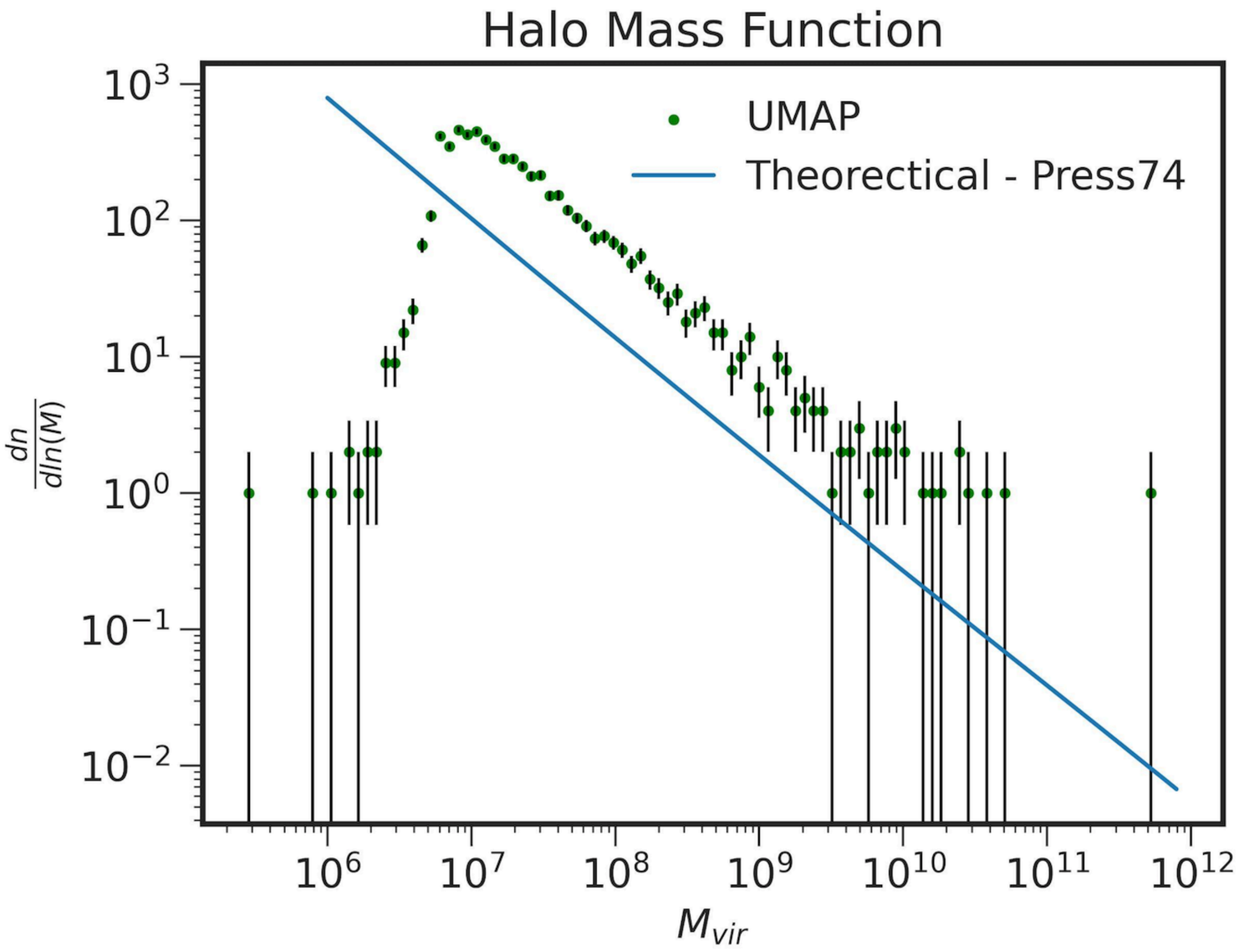




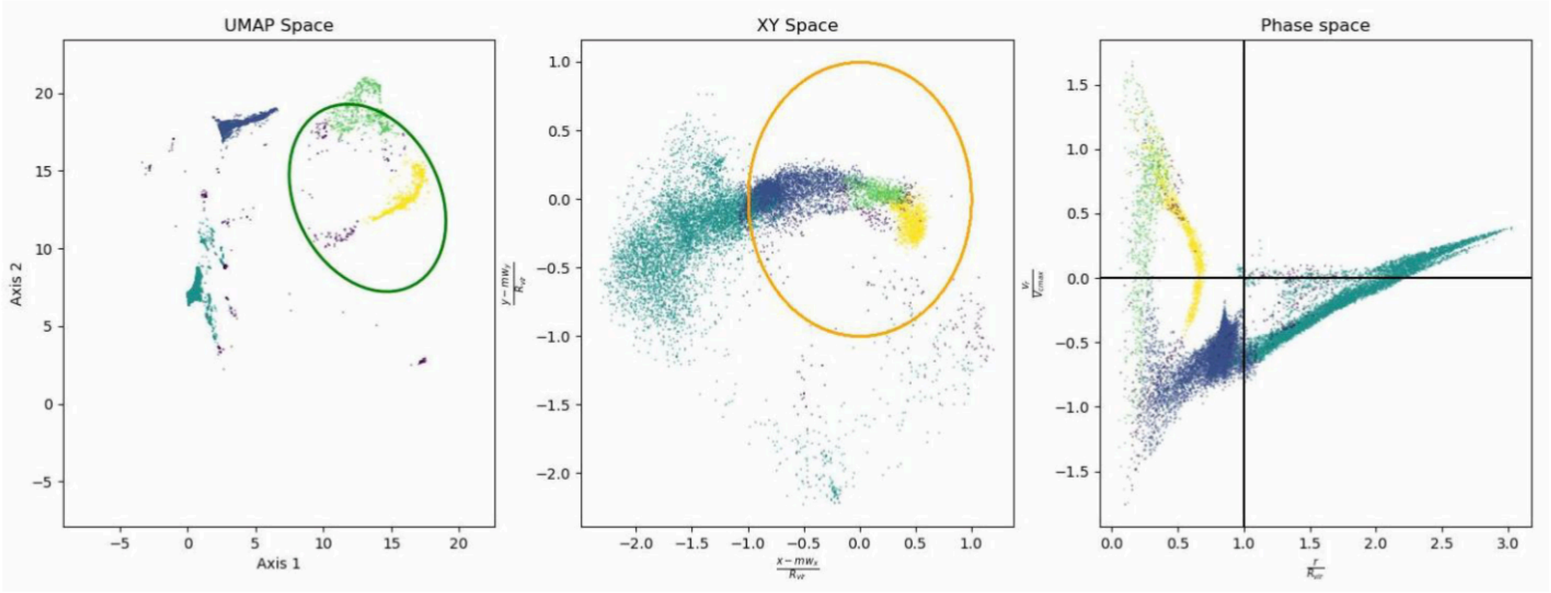


Cluster finding

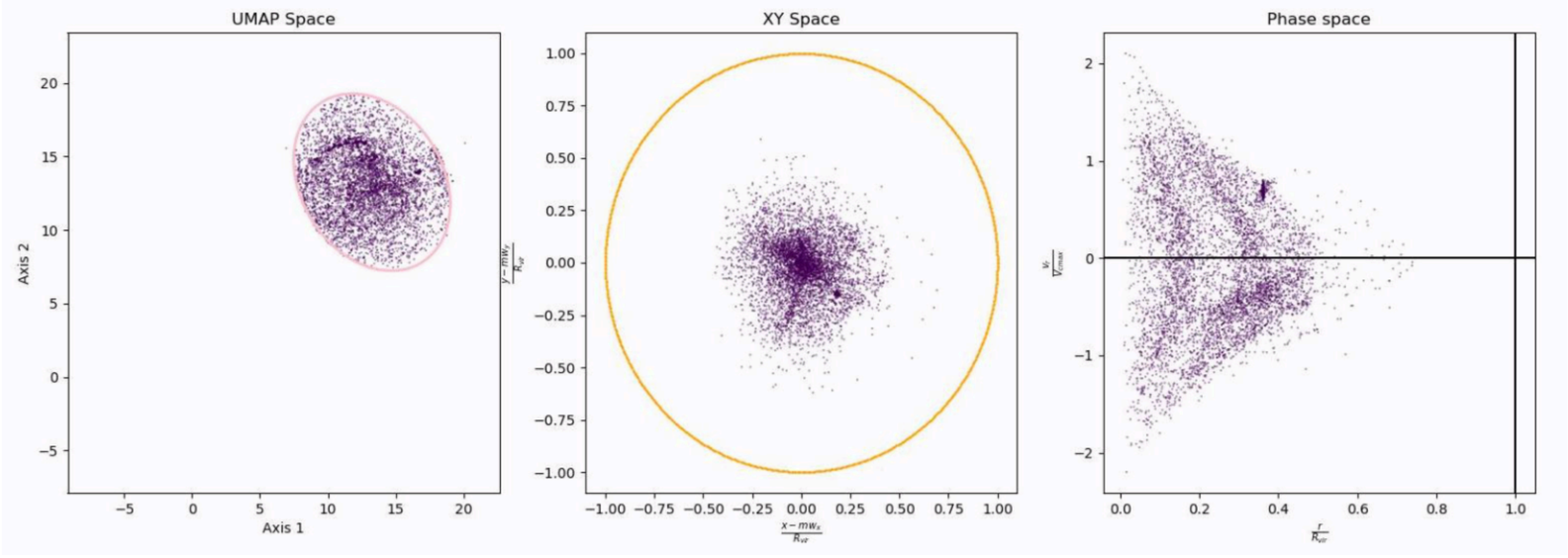




Studying tidal streams

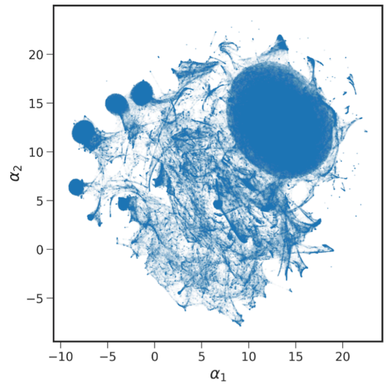


Recently accreted subhalo



Phase wrapped subhalo

Summarizing



- **The dark matter halo is dynamically evolving.**
- **The relaxed part of the halo can be cleanly separated out in UMAP space**
- **Outskirts of the halo are dynamically distinct from the inner regions. Including the splashback region**
- **Outer regions contain particle recently accreted that are not phase mixed.**

UMAP like visualisation techniques can be a tool to disentangle structures in cosmic fields like dark matter halos. Giving us new perspectives and tools when combined with physical intuitions.

- **Use this as an intermediate layer for halo finding, stream finding, looking at evolution in the context of the relaxed and unrelaxed halo.**

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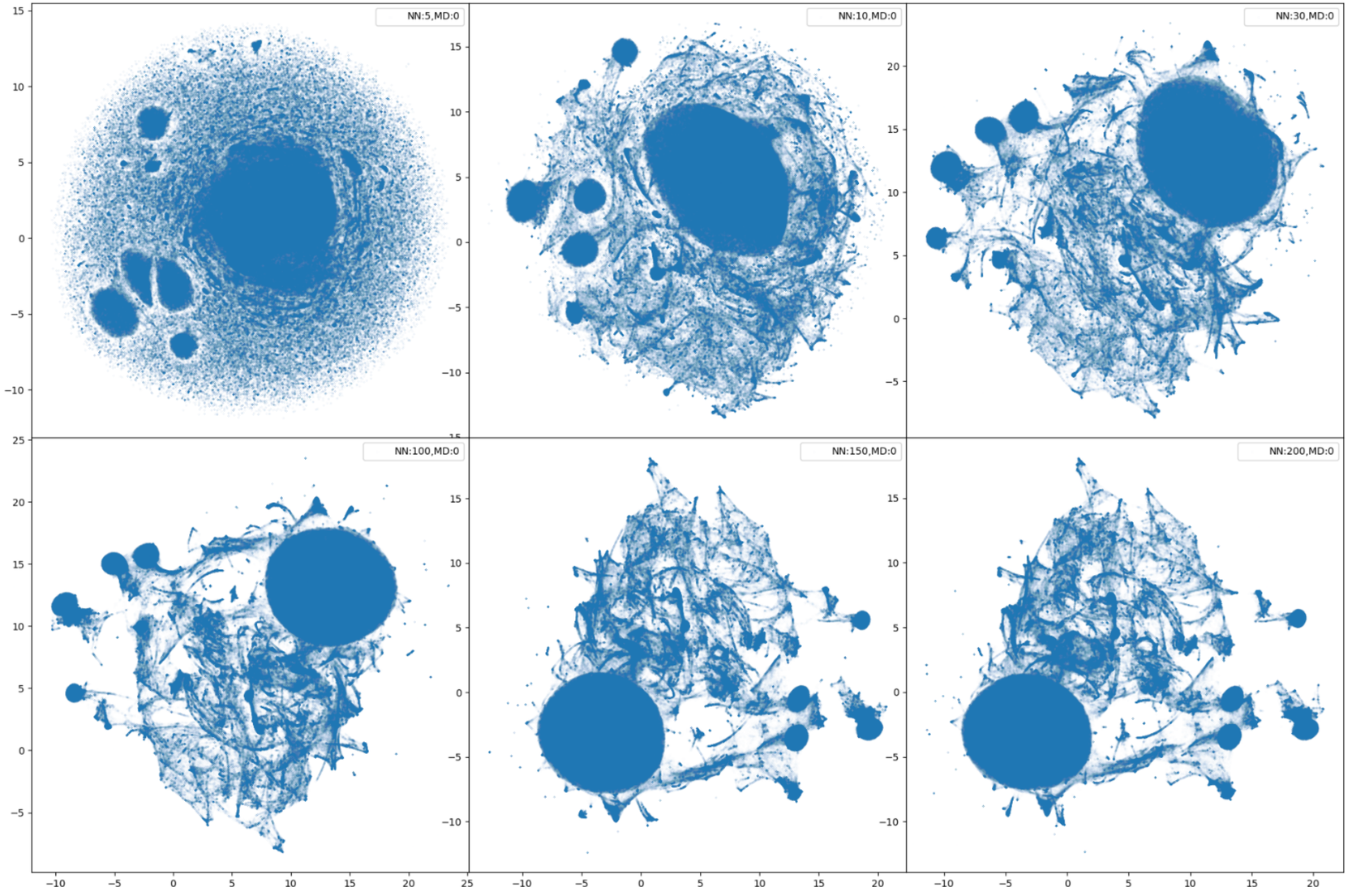
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