Disentangling the Cosmic Web

Characterizing Relationships among Cosmic Structures

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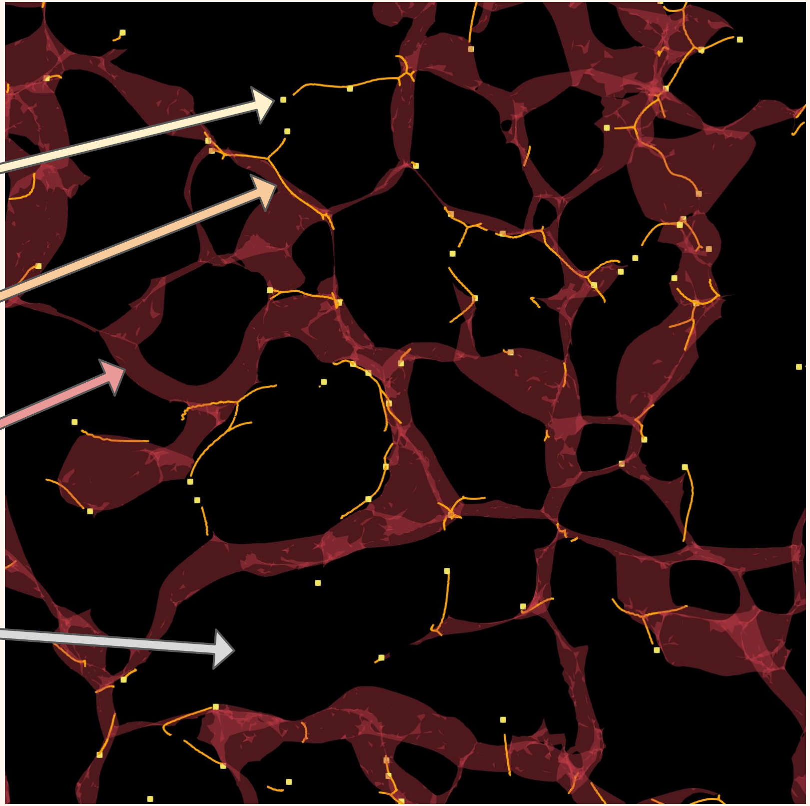
INTRODUCTION:

Cosmic web is composed of:

- Clusters: high density regions
- Filaments: 1D thread-like structures
- Walls: 2D sheets made of galaxies and gas
- Voids: empty/low density areas



Research Question: How do walls fit into the cosmic web? How does their density and spatial distribution compare to other structures?

METHODOLOGY:

1. Obtain N-body simulation from Quijote
2. Crop to manageable size
3. DisPerSE
   a. Delaunay Tessellation Field Estimator
   b. Morse-Smale Complex extraction
   c. Persistence based simplification
4. Statistics
5. Visualization

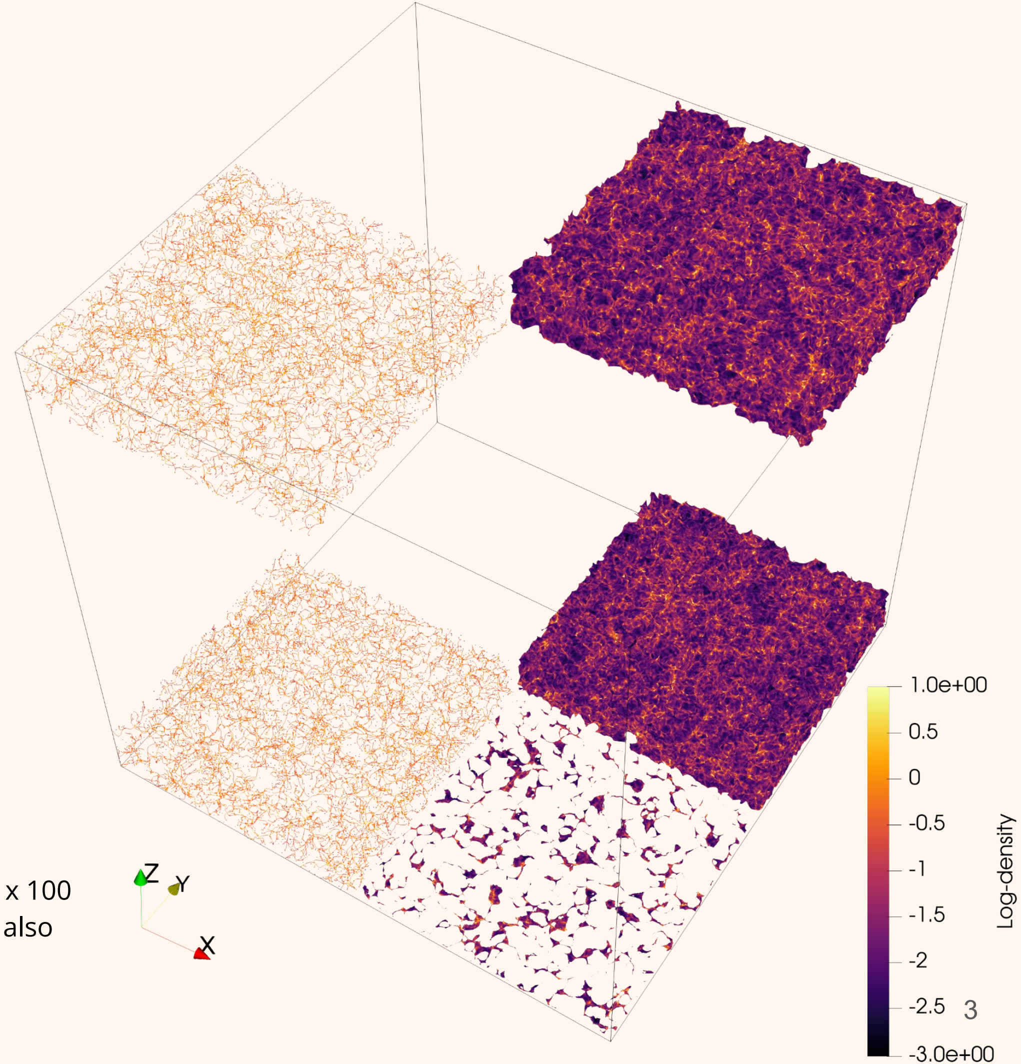


Figure. Outline of the entire 1 Gpc3 cube and crops sized 500 x 500 x 100 Mpc3, with filaments on the left and walls on the right. Foreground also shows a 500 x 500 x 5 Mpc3 slice of walls.
Image created by Emma Fuleky using Paraview 2026 (pvpython)

Particle simulation → density estimation → cosmological structures

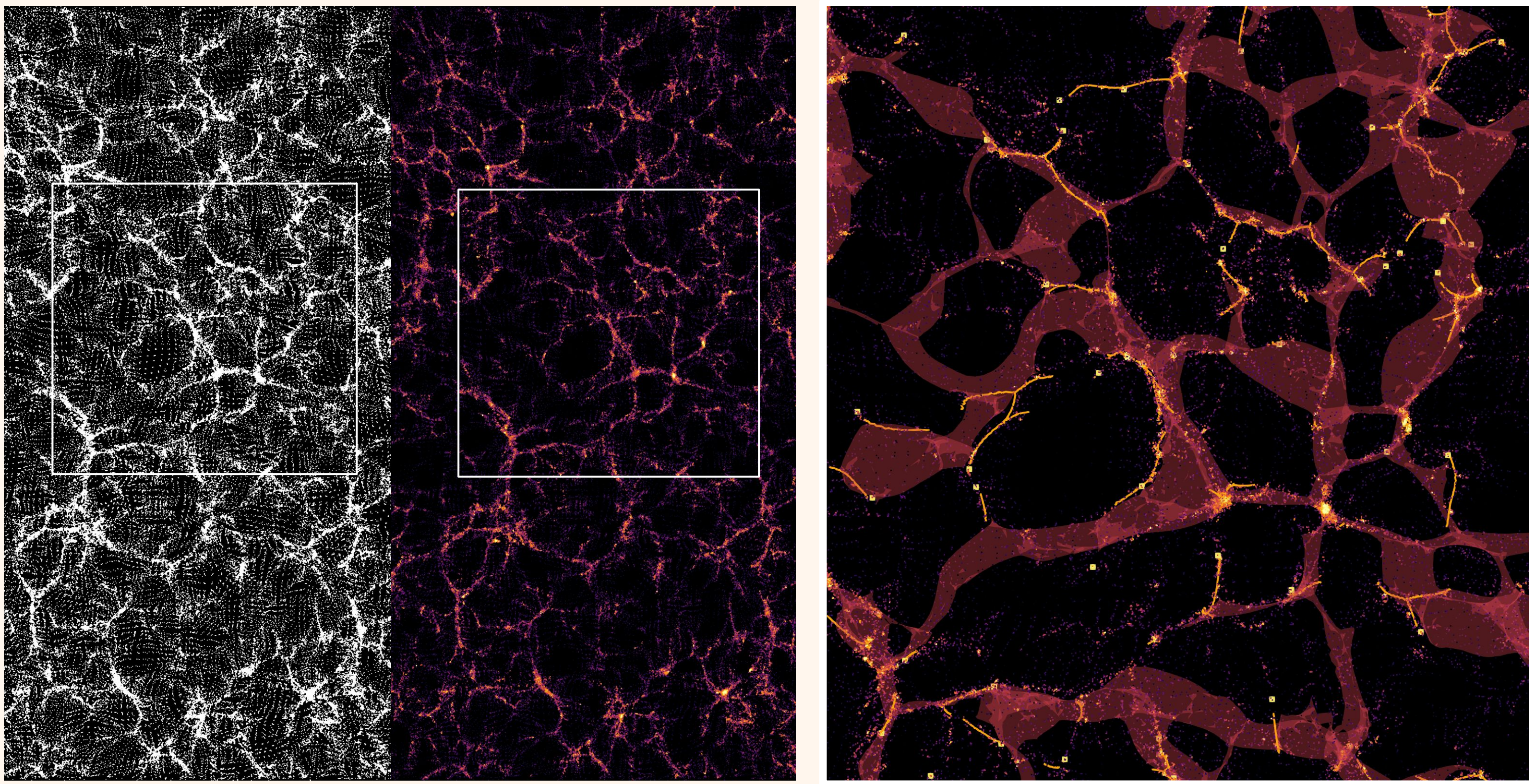


Figure. Left: Original particle simulation in a 500 x 500 x 10 Mpc3 slab (left half) and the same slab colored by log-density (right half).
Right: enlarged area of the white box with overlay for walls (red), filaments (orange), and clusters (yellow).
Image created by Emma Fuleky using Paraview 2026 (pvpython)

Discrete Persistent Structures Extraction:

<u>Delaunay Tessellation Field Estimator</u>: creates a density field from discrete particles.

<u>Morse-Smale Complex Extraction</u>: identifies critical points, regions where the gradient of the field is zero:

- 0D maxima (cluster peaks)
- 1D saddle path (filaments)
- 2D saddle sheet (walls)
- 3D around minima (voids)

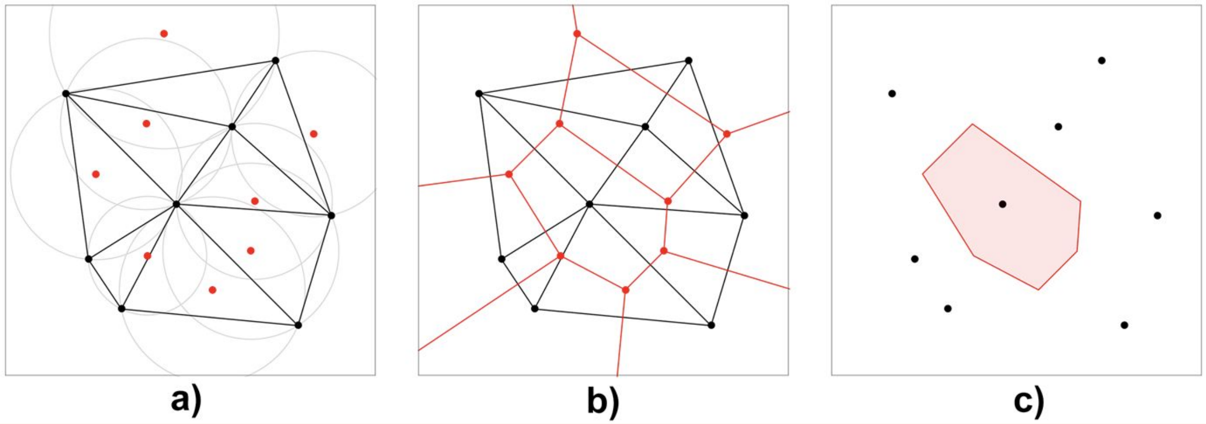


Figure: From Hafver, Andreas & Agrell, Christian & Vanem, Erik. (2022). Environmental contours as Voronoi cells. Extremes. 25. 1-36. 10.1007/s10687-022-00437-7.

The figure illustrates the process of converting a discrete data set into a density field. a) Delaunay Triangulation: no points lie in the circumference of any triangle. The red points are the circles' centers. b) Voronoi vertex: the centers from the triangles become connected by each side's bisector. c) Voronoi cell: set of points that are closer to that vertex than to any of the other vertices. This generalizes to n dimensions. Before tessellation: each point has unit weight of 1. After tessellation: the inverse volume of each cell in which the point is located becomes the density.

Gravity and dark energy move matter from voids to other cosmic structures

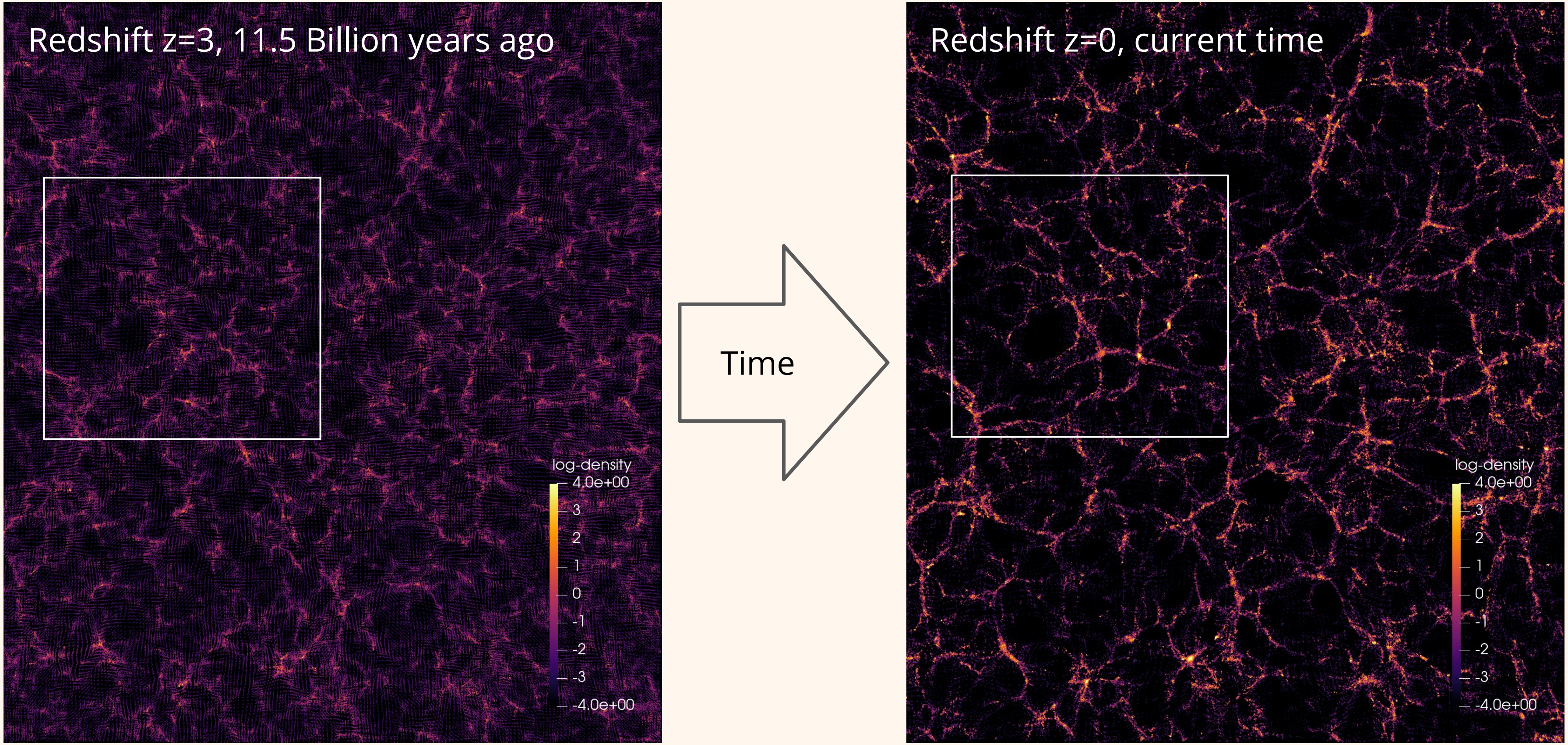


Figure. Density distribution in a 500 x 500 x 10 Mpc3 slab. Left: ~11.5 Billion yeas ago. Right: present. Compare box with other figures.
Image created by Emma Fuleky using Paraview 2026

RESULTS:

Density is the inverse of the volume of the Voronoi cell. I calculate mean particle proximity as the cube root of the volume of a Voronoi cell.

During the evolution of the universe, gravitational collapse reduced particle proximity and increased density (compare z=3 and z=0).

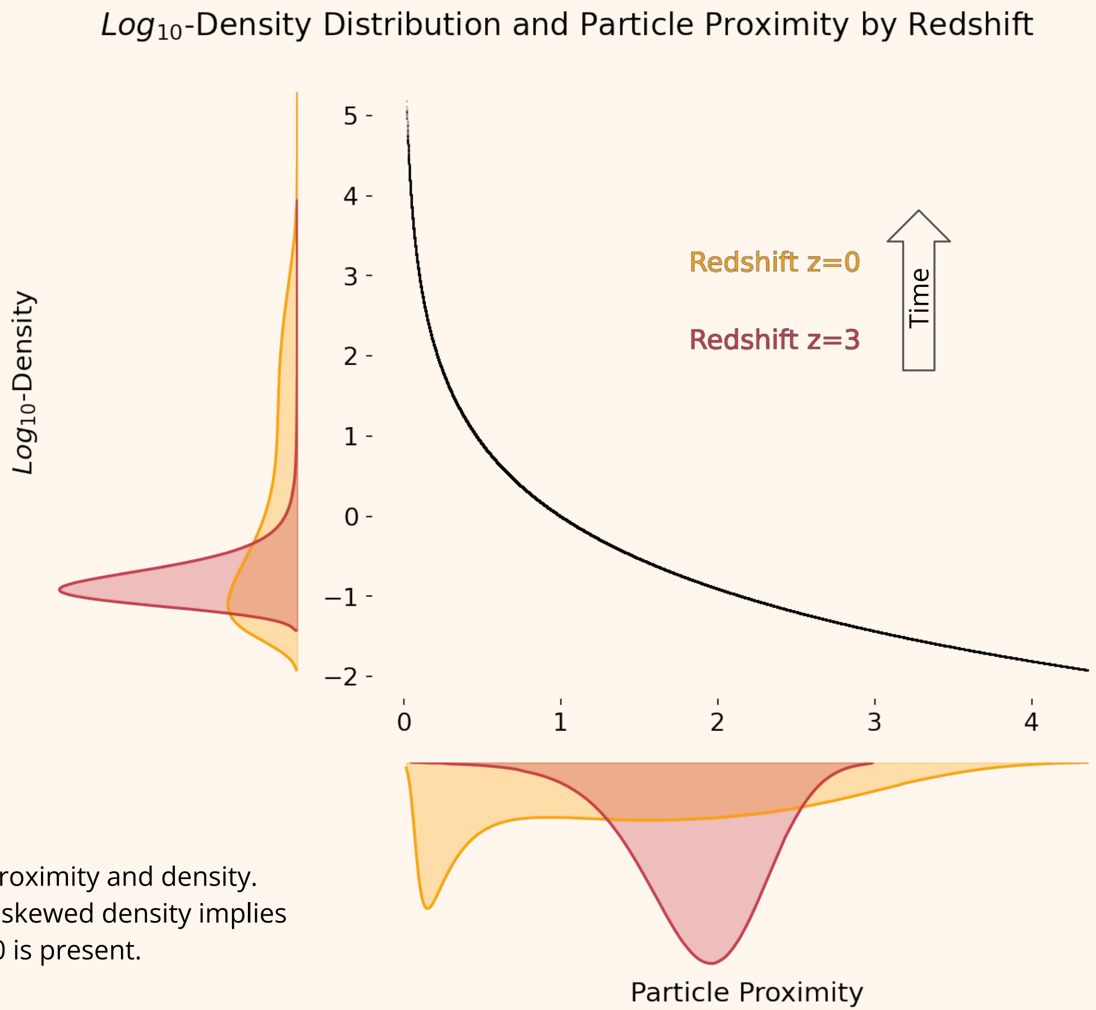


Figure. Nonlinear inverse relationship between particle proximity and density. Greater heterogeneity of distance between particles and skewed density implies clustering of matter. Redshift z=3 is ~11.5B years ago, z=0 is present.
Image created by Emma Fuleky using python

Where is the matter?

Clusters are peak densities, and therefore relatively rare. Walls spread over two dimensions and therefore contain many simulated particles.

Due to gravity, over time more particles merged into clusters, filaments and walls, while the number of “unassigned” particles has declined.

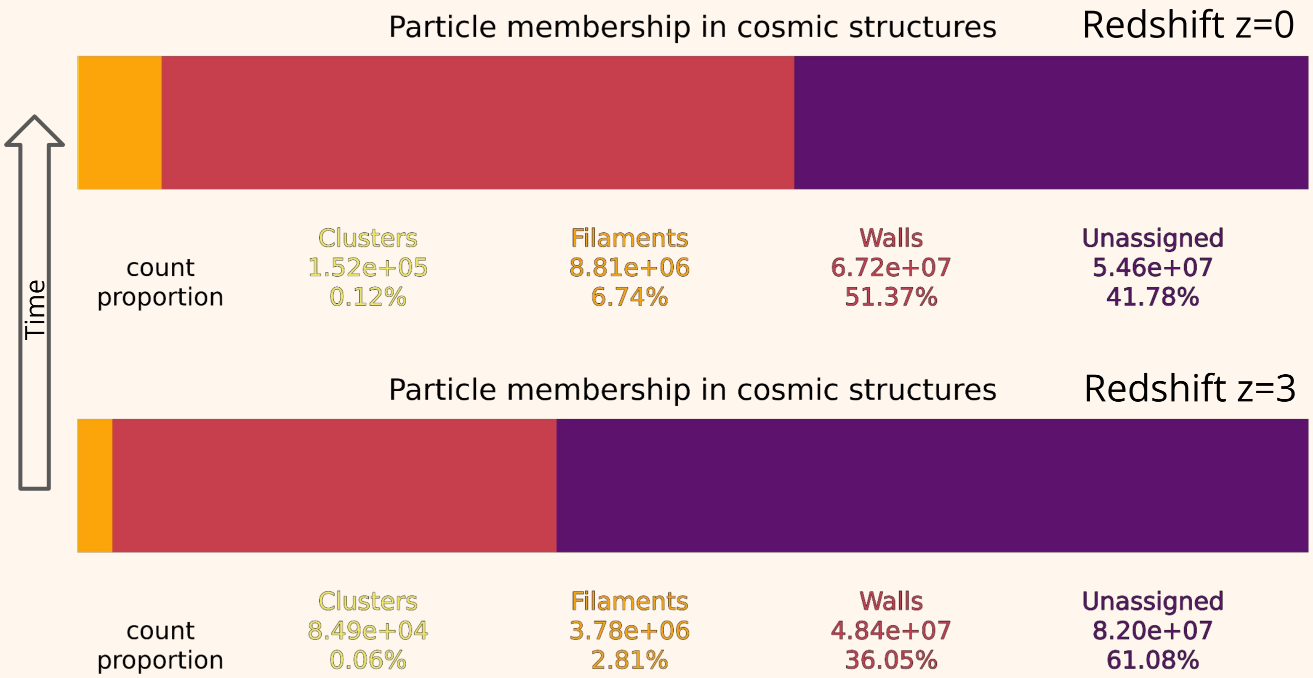
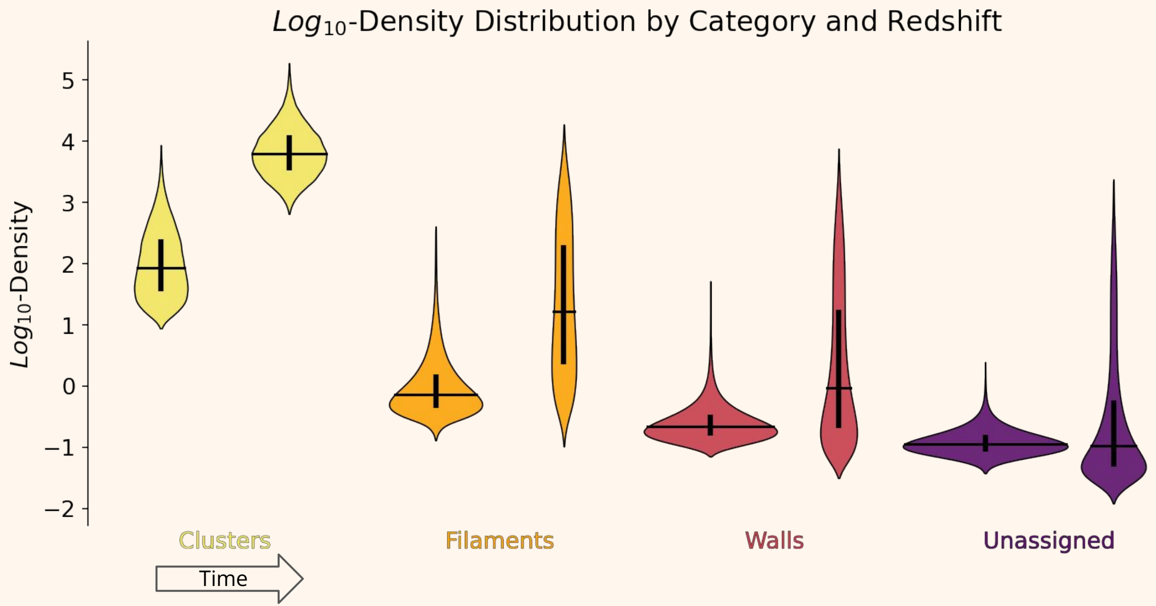


Figure. Proportion of simulated particles by category. The color coded legend lists the count and proportion of simulated particles associated with each structure in the universe. Bottom: proportions at redshift *z*=3. Top: proportions at redshift *z*=0. The proportion of simulated particles in clusters is 0.06% at z=3 and 0.12% at z=0; therefore they are not visible in the charts at the current scale.
Graph and table created by Emma Fuleky using python



	Clusters		Filaments		Walls		Unassigned	
	z=3	z=0	z=3	z=0	z=3	z=0	z=3	z=0
max	3.937	5.276	2.609	4.275	1.714	3.878	0.393	3.378
q75	2.398	4.093	0.195	2.301	−0.472	1.246	−0.799	−0.233
mean	2.004	3.822	−0.012	1.347	−0.608	0.333	−0.918	−0.584
median	1.935	3.800	−0.132	1.222	−0.665	−0.026	−0.943	−0.975
q25	1.551	3.524	−0.352	0.359	−0.816	−0.686	−1.067	−1.322
min	0.944	2.814	−0.887	−0.985	−1.150	−1.503	−1.425	−1.917
sd	0.562	0.408	0.496	1.183	0.310	1.241	0.215	1.067
skew	0.122	0.055	0.242	0.105	0.184	0.289	0.117	0.366
count	8.47e+04	1.52e+05	3.77e+06	8.80e+06	4.83e+07	6.70e+07	8.18e+07	5.45e+07

Density of cosmic structures is inversely related to their dimensionality, with clusters (0D) being more dense than filaments (1D), which are more dense than walls (2D).

Over time each structure got denser and more heterogeneous due to clustering.

Figure. Each voilin-plot shows the distribution of log10-density for a cosmic structure at z=3 (left) and z=0 (right). Below each plot are the corresponding summary statistics.
Image created by Emma Fuleky using python

DISCUSSION:

I confirmed that clusters appear at the ends and intersections of filaments, which is consistent with previous findings, validating my approach.

This is the first study to show that:

- ~99% of filaments form within walls
- Filaments (and clusters) found inside walls have a higher density than those found outside walls
- Walls, in the current universe, account for the largest share of particles compared to other structures, proving their importance in defining the overall geometry of the cosmic web

These results challenge the literature's neglect of walls and prove that walls are structurally fundamental in the cosmic web.

CONCLUSIONS:

- I developed a workflow to characterize specific features of large scale structures emerging in the universe.
- I produced qualitative and quantitative analysis of the density and spatial distribution of structures, tracking how those features evolve over time.
- Walls provide a feeding structure for filaments, which act as “highways” for matter to fuel clusters, allowing them to create more stars.

Next Steps:

I will use this workflow to analyze the cosmic web simulated from different cosmological models. Comparing the results will illustrate the impact of various parameter values and validate the models against the real universe.

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