

Are Galaxy Tendrils Consistent with the Standard Model of Cosmology?

Jocelyn P. Elphick

Saratoga Springs High School 1 Blue Streak Boulevard, Saratoga Springs, NY 12866

## **Acknowledgements**

I would like to thank Professor Odekon for being my mentor throughout this project and helping me understand the material needed to do this research project. I would like to thank my science research teachers, Mrs. Lohnes, Mr. Robinson, and Mrs. Goldfischer for being teachers of the science research course. Also, I would like to thank my peers and my family for being supportive.

**Abstract:**

Testing the standard model of cosmology plays a critical role in astrophysics. In previous research, the Millennium Simulation, a cosmic mathematical model, has been compared to real-life observations to determine if it is an accurate representation of the universe. Here, galaxies and groups of galaxies from the Millennium Simulation were used to examine if tendrils, which are large-scale structures that are made up of galaxies, can be found within the simulation, as they have been previously found in observed data sets. Additionally, filaments, also large-scale structures, were searched for as they have also been found in previous studies. The sample of galaxies and groups from the Millennium Simulation included 10,107 galaxies and 1,311 groups. To determine if tendrils could be calculated, the nearest neighbor density (the number of galaxies near another galaxy) was found within the data set for every galaxy and group, as calculated based on the third-nearest neighbor to a galaxy. Then, using the same minimum spanning tree algorithm; that has been applied in real-life observational studies, tendrils along with filaments were searched for in the Millennium Simulation. The algorithm found seven filaments and 65 tendrils, which is similar to reported real-life data. By searching for filaments and tendrils not only did this study validate the accuracy of the Millennium Simulation, but it also provides insight into the dynamics of gravity and dark matter on a large scale.

**Table of Contents:**

Introduction	6
Hypothesis	8
Methodology	8
Millennium Simulation	8
Galaxies in the Millennium Simulation	9
Groups in the Millennium Simulation	12
The Nearest Neighbor Density	14
The Minimum Spanning Tree Algorithm	15
Results	15
Filaments	15
Distance from Filaments	17
Tendrils	18
Discussion	19
Conclusion	20
Bibliography	21

**List of Figures**

Figure 1, Galaxies from simulation:	10
Figure 2, Stellar mass:	12
Figure 3, Dark matter halo:	12
Figure 4, Groups from simulation:	13
Figure 5, Nearest Neighbor Density:	14
Figure 6, Filaments:	17
Figure 7, Distance from Filaments:	18
Figure 8, Tendrils:	19

**List of Tables:**

Table 1, Galaxies from simulation:	10
Table 2, Groups from simulation:	13
Table 3, Filament information:	17
Table 4, Distance from filament, and NND:	18
Table 5, Tendril Information:	19

**Introduction:**

Galaxies are commonly thought of as the most massive structures in the universe, however, they are a part of much larger structures. Large-scale structures are made up of galaxies, and include clusters and groups, filaments, voids, and tendrils. To understand how galaxies evolve and form, it is vital to understand the larger cosmic structures to which galaxies belong (Inoue et al. 2022).

Clusters and groups are dense areas of galaxies contained in a singular massive dark matter (i.e., matter that is not visible) halo. A cluster is a very large group containing hundreds of galaxies, while a group could have as few as three member galaxies (Yang et al. 2021). A galaxy's composition is dependent on its location within a group or cluster. For example, the removal of H i in galaxies in clusters is faster than in other environments (Odekon et al. 2016). Previous research (Park et al. 2009) has found a morphology-density relation within groups which means that the composition of a galaxy is dependent on the density of the environment it is in.

Filaments are structures made up of at least two groups (Alpaslan et al. 2014), many more galaxies, various gases, and dark matter. Filaments channel galaxies towards groups and clusters (Odekon et al. 2016). They are very large structures and can span up to  $200 h^{-1}$ . Like groups, the environment in a filament affects the composition of the galaxies that make up them. For example, as the distance between galaxies and a filament decreases it has been found that the H i deficiency increases (Odekon et al. 2018).

Voids are the absence of dense concentrations of galaxies; they still contain galaxies; however, it is a comparatively sparse number. Voids take up the majority of the total area of the universe.

The galaxies within voids tend to have similar compositions to their counterparts in filaments or tendrils (Porter et al. 2023).

Tendrils, a relatively recent discovery (2014), are smaller than filaments and are made up of around six galaxies and generally are  $10 h^{-1}$  Mpc in length (Alpaslan et al. 2014). Although they are smaller versions of filaments, the composition of their galaxies is very different than what would be expected. For example, tendrils lack the H i deficiency that would be expected in them when comparing them to filaments or groups (Odekon et al. 2018).

The environments of these large-scale structures cause the galaxies within them to have unique compositions. It is therefore important to study these structures to better understand the effect each unique environment will have on galaxy formation and evolution. These large-scale structures are primarily developed due to a gravitational pull, however the way in which gravity works within them is not completely clear. The current accepted theory regarding how gravity works in space is Einstein's general theory of relativity. However, several problems arise when using just this theory. Due to this, several ideas have been proposed regarding the ability of large-scale structure formation. The most widely accepted is the theory of the influence of dark matter, however several others have been presented including the use of Modified Newtonian Dynamics which would remove the need for dark matter (Milgrom 1996). The theory of dark matter stems from the analysis that baryonic (visible) matter in galaxies and clusters move faster around their center than the predicted laws of gravity would show. It is thought that this dark matter drives the formation of large-scale structures, but the formation of the galaxies themselves is not fully understood (P. Nurmi et al. 2013).

It is important to examine how real-life observations and theoretical models compare when identifying large-scale cosmic structures. If the theoretical models use the predicted way that gravity works (i.e., Einstein's theory of relativity) and the results are comparable, the role of dark matter is supported. Using N-body simulations, which are models using particles under the

influence of physical forces, these theories can be checked. N-body simulations allow for work done in real life observations to be checked by equally accurate theoretical predictions (Springel et al. 2005). The N-body simulation used in this paper is the Millennium Simulation which is an example model of a potential universe.

### **Hypothesis:**

If accurate mathematical analyses used to identify tendrils, filaments, and other large-scale structures in real-life observations are applied to the Millennium Simulation, which is based on the predicted properties of gravity, large scale structures, specifically tendrils will be outputted.

### **Methodology:**

To gather the data used in this project and analyze it, applicable Python codes were written to take data from the Millennium Simulation and to analyze those data. The code then outputted files that were transferred into TOPCAT (a program that allows analysis of tables with many rows and columns) to render graphs for analysis.

### **Millennium Simulation:**

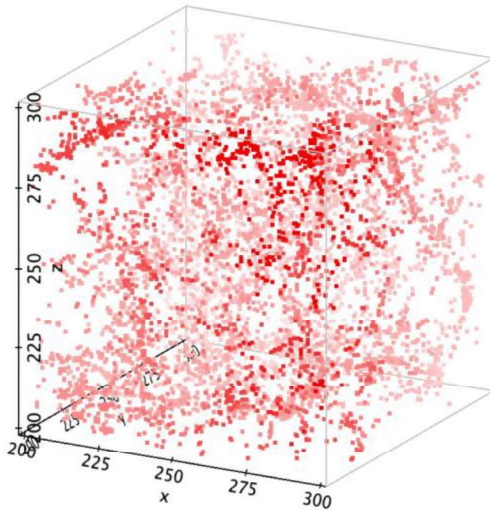
The Millennium Simulation (Springel et al. 2005) is an N-body simulation of dark matter. It shows the evolution of more than  $10^{10}$  particles across a cubic region reaching  $500h^{-1}$  Mpc across (over 2 billion light-years across on each side).  $h$  is Hubble's constant in units of  $100\text{kms}^{-1}\text{Mpc}^{-1}$ . The Millennium Simulation considers the cold dark matter (CDM) model, which uses the dark energy field (cosmological constant ' $\Lambda$ ') to theoretically predict galaxy

formation (Springel et al. 2005). Cold dark matter is non-baryonic matter and makes up roughly 27% of the universe, while baryonic matter only makes up around 5% (dark energy makes up the other 68%). Using the  $\Lambda$ CDM, a “cosmic web” is created filled with dark matter halos (Springel et al. 2005). Dark matter halos show that the vast amount of galaxy clusters and the two-point correlation function agree with observations. Several studies have used the Millennium Simulation to compare results found in galaxy catalogues such as the SDSS DR7 to theoretical expectations (Nurmi et al. 2013) or the GAMA survey to the Millennium Simulation (Alpaslan et al. 2014). These studies identified filaments within the Millennium Simulation.

The Python code written to gather Millennium Simulation data used Lagos2012a.MR to define values within the simulation. This allowed for data to be extracted which included specific galaxies and groups. These data extracted were taken from the center of the  $500h^{-1}$  Mpc so  $250h^{-1}$  Mpc was considered the center. From there out  $50h^{-1}$  Mpc in all directions was taken for a total of 10107 galaxies with a stellar mass greater than  $0.5e10M_{\text{solar}}/h$ . A specific section was chosen and the stellar mass above  $0.5e10M_{\text{solar}}/h$  in order to have a more manageable amount of data.

Galaxies within the Millennium Simulation:

The galaxies that were gathered from the Millennium Simulation can be seen in Figure 1.



**Figure 1.** 3D graph depicting galaxies taken from the Millennium Simulation. Each dot is an individual galaxy.

The specific galaxy information gathered can be seen in Table 1 and included the x coordinates, y coordinates, z coordinates within the Millennium Simulation as well as stellar mass (Figure 2), MD halo mass (Figure 3), and cold gas content (atomic).

#	GalaxyID	coldgas_atomic	mdhalo	stellarmass	x	y	z
1	1.700222E15	0.00468	58.09433	1.60726	284.34671	291.61459	288.89136
2	2.100508E15	0.0001	7442.79932	0.53985	299.7131	188.59903	189.9644
3	2.700149E15	0.00886	3615.60791	7.58324	224.80244	236.78783	304.36218
4	6.300530E15	0.0005	3781.58032	0.60688	234.04782	304.48364	212.73544
5	7.600230E15	0.01891	59.73614	0.93706	310.18021	289.63196	175.14206
6	8.200389E15	0.17462	31.32791	0.51489	311.04535	309.91727	197.47252
7	1.010029E16	0.00468	237.11798	6.30409	200.69969	309.19696	276.3103
8	1.120009E16	0.03338	33.65607	0.60262	203.08543	228.27235	316.39481
9	1.120013E16	4.837103E-5	71.77877	0.77162	237.63986	225.9498	206.60741
10	1.120016E16	0.67002	22.29279	0.57448	265.90042	252.5332	316.81583
11	1.220029E16	1.55439	102.18372	3.33953	283.17349	274.89801	233.98419
12	1.630034E16	0.07295	46.90709	0.71441	288.85251	282.53583	275.16904
13	1.630035E16	0.00814	1257.41943	0.59656	191.4437	186.99733	243.48514
14	1.630039E16	0.00051	6421.12402	1.45625	249.47343	184.8335	323.50375
15	1.680029E16	0.0002	34.42627	0.65281	264.89877	225.46707	306.52264
16	1.900005E16	0.	190.8994	0.67211	307.25879	246.60486	283.48734
17	1.900007E16	0.00834	136.95604	4.28176	182.88417	190.1032	242.64262
18	2.580015E16	0.00959	1356.9115	6.46424	265.48462	306.68903	280.93341
19	2.580016E16	0.00537	404.77493	1.92481	256.44089	261.24692	274.50378
20	2.580018E16	0.25859	60.41811	1.09662	286.37567	298.32483	214.75284

**Table 1.** Example of the first 20 galaxies taken from the Millennium Simulation including their ID, cold gas content, halo mass, stellar mass, and coordinates

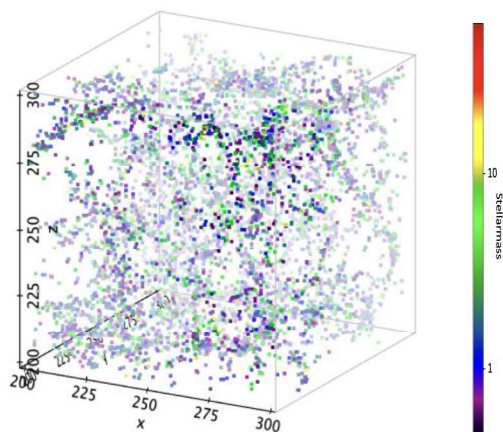
The coordinates in the Millennium Simulation (x, y, z) use Mpc/h and use comoving to factor out the expansion of the universe in the simulation.

The stellar mass (Figure 2) is the mass of the stars within a specific galaxy and is in  $10^{10} M_{\text{solar}}/h$ . Understanding stellar mass allows insight into how large a galaxy is relative to its environment and the galaxies surrounding it.

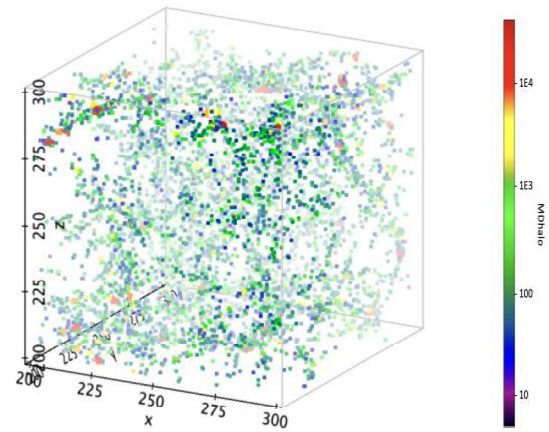
The MD Halo mass (Figure 3) is the mass of the dark matter halo which a specific galaxy belongs to, this includes the mass of the satellite subhalos and is also measured in solar masses to the 10<sup>th</sup> power. Understanding the size of the MD Halo allows for understanding of how the mass of the MD halo can affect star formation in a specific galaxy; without dark matter, a galaxy cannot form as it as the gravitational pull will be too low to contain the number of particles required to have large-scale star formation.

The H I content amount within a galaxy is affected by the structure a galaxy is in. For example, it has been reported that the H I content is dependent on if the galaxy is within a tendril, filament, void, or group/cluster (Odekon et al. 2018).

# Galaxy ID is the identification of a galaxy and is unique to the galaxy and the Millennium Simulation. In total the number of galaxies extracted from the Millennium Simulation and gathered for this data set was 10,107.



**Figure 2.** 3D model of the stellar mass of the galaxies within the data set from the Millennium Simulation the closer to red the galaxy is the larger its stellar mass. The axis are labeled in Mpc/h and the stellar mass is in units of  $1e10M_{\text{solar}}/h$ .

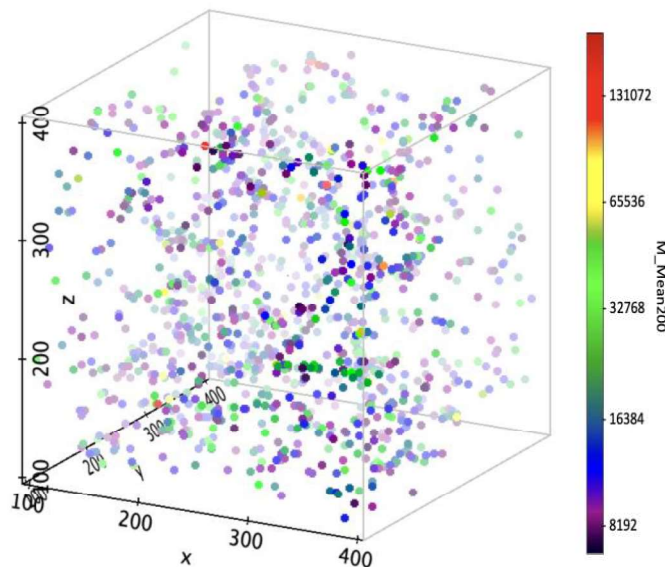


**Figure 3.** 3D model of the dark matter halo of each galaxy within the data set from the Millennium Simulation, the closer to red the galaxy the larger the halo mass. The axis are labeled in Mpc/h. The dark matter halo is in units of  $1e10M_{\text{solar}}/h$ .

Groups within the Millennium Simulation:

In order to gather data for groups another set of data was created using Lagos2012a.MR the same as when locating the galaxies. For the groups the length of the cube was extended to 300 Mpc in length. To locate groups, large dark matter halos were extracted as a group is defined as being under one massive dark matter halo. Individual galaxies also have dark matter halos however they are considered their own and would be much smaller than a groups would be. The x coordinates, y coordinates, and z coordinates were gathered along with the mean halo mass as seen in Table 2 and Figure 4.

	haloID	x	y	z	M_Mean200
1	148000043000000	332.52228	384.04465	221.88194	19980.059
2	99011963001016	181.49316	319.20535	160.78093	9238.461
3	101000107007124	224.39757	309.84818	138.37848	9907.536
4	226000080000000	347.34982	210.90724	168.13423	29263.447
5	226022132000000	373.90167	211.02823	130.52875	13328.99
6	228004998000000	327.62653	157.33554	189.0287	11703.8125
7	283000682000356	352.1017	170.96591	283.25952	35306.117
8	250008107000000	388.53537	166.31514	183.51561	12390.1
9	466000110000000	132.77498	145.44537	282.85962	11482.71
10	352012927000000	361.5864	336.11792	255.036	8489.174
11	381000156000000	348.20215	296.3368	386.59164	8039.739
12	154000069000000	303.19296	277.88025	178.46503	9399.404
13	465001633000000	178.5523	236.64818	271.5824	20148.748
14	471000192000000	227.46191	241.42732	323.78244	12157.034
15	471000183001815	230.62257	191.31367	375.85492	1.098687E5
16	420000390000000	244.56592	168.14201	244.8692	7224.4385
17	228005003006512	323.18753	136.42259	237.47859	9417.563
18	39009265018588	228.3235	236.35701	102.89625	10576.61
19	235000167005638	259.68124	117.23933	174.12033	11689.095
20	232000072000074	292.53534	120.99449	186.51872	17956.053



**Table 2.** Example of the first 20 groups found. The data included the group ID (labeled haloID) the coordinates, and the mean halo mass ( $M_{\text{Mean200}}$ ). Notice that the halo masses are much larger than that for the galaxies in Table 1.

**Figure 4.** A 3D model of the groups found from the Millennium Simulation. The groups are colored by the halo mass. The halo mass is in  $1e10M_{\text{solar}}/h$

Once the data from the Millennium Simulation was gathered another code using python was written and used several mathematical analyses in order to find nearest neighbor density, filaments, and finally tendrils.

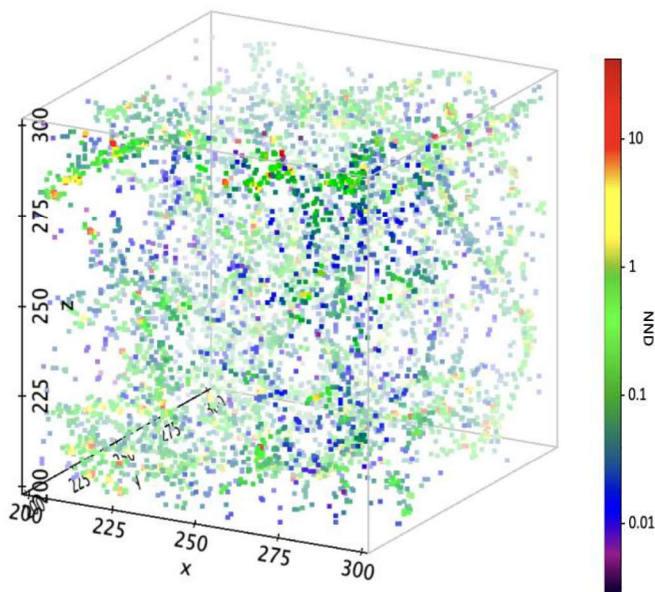
The Nearest Neighbor Density:

Nearest neighbor density is used to compare the effects of large-scale structures on local density.

For each galaxy in the sample the distance from it to every other galaxy was found. Nearest neighbor density (NND) is the density of galaxies in a certain area. It is calculated first by using a modified distance formula to take into account the three-dimensions of the cube and can be seen below:

$$\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} = \text{distance}$$

Distance was then assigned as  $r$  and the neighbor galaxy assigned  $n$ .  $n$  was assigned to the third nearest neighbor to determine local density. Next, using  $n/(\pi r^2) = \text{density}$ , the nearest neighbor density for all galaxies within the sample was calculated; this can be seen in *figure 5*.



**Figure 5.** This graph shows a 3D representation of the log of the nearest neighbor density. The closer to red the galaxy is the denser the local environment is.

The Minimum Spanning Tree Algorithm:

The minimum spanning tree algorithm or MST is an algorithm also used in (Odekon et al 2018) and is how tendrils and filaments were found. The minimum spanning tree uses the distance each galaxy is from one another.

Once the distance is calculated between two galaxies or groups the minimum spanning tree algorithm checks to see if the distance between the two objects is below the maximum linking length, if it is the galaxies or groups are considered a part of the same large-scale structure. If the connection between the two galaxies is too great, the connection is cut they are not considered a part of the same or any filament, or tendril.

The minimum number of groups a filament can have is two (Alpaslan, et al. 2014) and for the purposes of this study the minimum number of groups was set to 5. If a filament did not meet the 5-group requirement, it was removed. The maximum linking length for the filaments groups was set to 17 Mpc/h.

For the tendrils the maximum linking length was set to 5 Mpc/h as it was found to create the largest number of tendrils. The minimum number of galaxies for the tendrils was set to 5.5.

This methodology of using the Minimum Spanning Tree is an accepted way for locating large-scale structures (e.g., Alpaslan et al. 2014; Nurmi et al 2013; Odekon et al. 2016; Odekon et al. 2018). Because of this there was no need for statistical analysis.

**Results:**

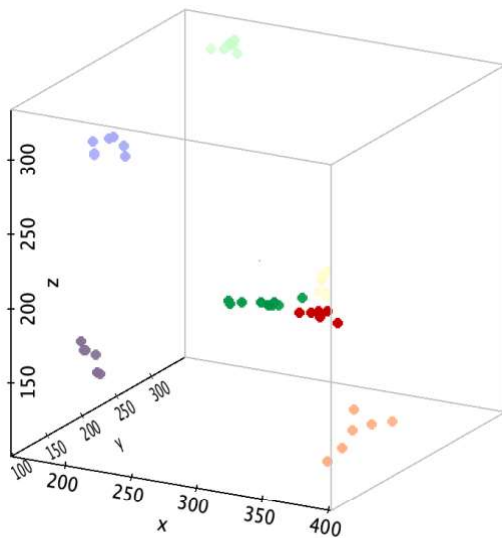
The goal of this study was to determine if the same mathematical principles that were used in real life observations (Odekon et al, 2018) were applied to the Millennium Simulation if similar results would be found. This analysis used the minimum spanning tree algorithm to find filaments and tendrils. This is important as it furthers the understanding of how gravity operates within tendrils. Using the Minimum Spanning tree, filaments, the distance from the filaments, and tendrils were seen within the Millennium Simulation As seen in Figure 6, Figure 7, and Figure 8. These results are similar to previous research (Odekon et al. 2018) which also found these structures in real-life observations.

**Filaments:**

In Figure 6 and Table 3 it can be seen that filaments were found within the Millennium Simulation. The dots within the graph are individual groups within the filament and the color of the dot represents the filament identification. These results are similar to the real-life observations found in (Odekon et al. 2018)

Group ID	x	y	z	Filament ID	Number of groups	length (Mpc/h)
167292	208.66211	108.32397	176.86163	1	6	24.42467
22011	213.82425	115.33916	172.6686	1	6	24.42467
36082	219.89534	109.99833	162.30258	1	6	24.42467
30125	206.25575	108.36737	182.49828	1	6	24.42467
33025	207.78766	108.87682	176.73073	1	6	24.42467
15128	220.07767	104.83961	164.82535	1	6	24.42467
15456	163.842	207.51714	276.89233	2	7	24.45243
15871	172.98712	209.6936	287.8801	2	7	24.45243
17109	164.38203	202.69861	286.52594	2	7	24.45243
19791	182.24792	214.07936	282.93756	2	7	24.45243
20398	177.9322	208.4725	290.66446	2	7	24.45243
23878	185.46298	211.34547	277.652	2	7	24.45243
55339	163.48369	206.60135	276.19104	2	7	24.45243
21041	350.61832	103.89416	230.52124	3	9	50.54806
22123	320.59097	104.40285	226.56003	3	9	50.54806
18076	346.13794	127.50839	223.01431	3	9	50.54806
27743	343.8752	122.82938	223.88168	3	9	50.54806
24218	359.5159	136.54778	227.74516	3	9	50.54806
54088	318.30377	107.28552	227.12341	3	9	50.54806
26399	326.64987	109.8643	227.03175	3	9	50.54806

**Table 3.** Shows the first 20 groups, their coordinates within the Millennium Simulation, the Filament they are a member of (Filament ID), the number of groups in each filament, and the length in Mpc/h.



**Figure 6.** 3D model of the filaments found within the Millennium Simulation. The groups are colored by the Filament ID

Distance from Filaments:

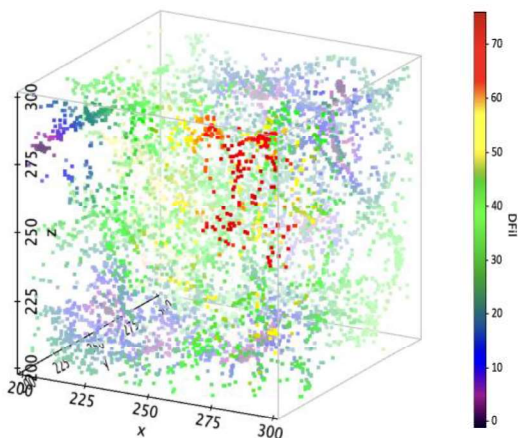
The Distance from the Filaments (DFil) was calculated. DFil is the distance a galaxy is from the nearest filament spine or axis. In Table 4 the distance to the nearest filament can be seen.

Galaxies 18, 19, and 20 are seen to have a distance of 0 Mpc. This is because the galaxy would be considered within the filament so there is no distance between them and the nearest filament.

A graph of the distance from the filament can be seen in Figure 7. The distance from the nearest filament can potentially be used to see how environment affects galaxies in a theoretical simulation versus in real space.

	# Galaxy ID	x	y	z	NND	DFil
1	3.200000E16	215.66591	208.06844	248.85974	0.02816	33.58556
2	3.210000E16	269.32773	213.88084	294.10995	25.02035	59.49524
3	3.210000E16	269.49081	213.88701	294.20776	932.34022	59.45281
4	3.210000E16	269.48987	213.88576	294.23401	412.95382	59.45426
5	3.220000E16	270.62427	280.19696	258.50534	0.04076	19.16722
6	3.990050E16	244.9697	280.59616	247.9211	2.36261	24.87967
7	4.000010E16	250.46101	289.23074	264.10818	0.13547	20.96135
8	4.000040E16	228.15109	254.17714	271.59219	0.06757	35.65604
9	2.700060E15	247.26674	284.4346	283.32855	0.49216	1.19476
10	4.900450E15	228.84747	260.6257	200.83199	6.52457	28.02823
11	1.000000E16	230.43457	230.96687	295.63675	0.13527	39.80969
12	1.330040E16	251.25771	274.42621	262.86295	0.0189	22.38284
13	1.340010E16	226.04765	218.57907	265.91867	0.00766	29.60554
14	2.250010E16	214.16684	200.83475	297.39853	0.17276	16.38031
15	3.940020E16	211.60483	208.07097	212.11955	0.67506	17.6635
16	4.430010E16	225.27214	201.29561	210.23106	26.60713	23.19537
17	4.000230E15	286.93909	273.13016	205.65369	0.21428	32.48482
18	7.800450E15	205.47836	201.75545	281.74963	2.39499	0.
19	7.800450E15	205.72095	202.63173	281.47241	0.5095	0.
20	7.800450E15	206.73242	200.70723	281.78854	5.1818	0.

**Table 4.** Shows the distance from filaments (DFil) for each galaxy in Mpc along with the Nearest Neighbor Density (NND) for each galaxy.

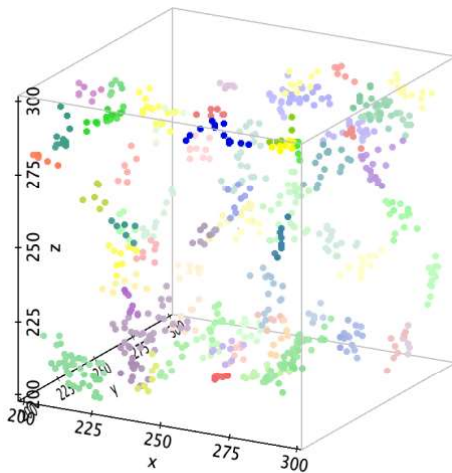


**Figure 7.** 3D model of the distance from filament for each galaxy. The redder the galaxy the further it is from a filament.

Tendrils:

As seen in 8 and Table 5, tendrils were found using the MST algorithm in the Millennium Simulation. These same methods were used in (Odekon et al. 2018) which applied them to real-life observations. Figure 8 shows an example of a tendril found that consisted of nine individual galaxies. A total of 65 tendrils were outputted.

	# Galaxy ID	x	y	z	Tendril ID	Number of galaxies	length (Mpc/h)
1	50700505660000000	235.66177	245.50822	244.44852	1	9	10.55585
2	4000385700000000	237.16531	248.05957	244.38687	1	9	10.55585
3	25800243710000000	240.47383	249.65735	247.14433	1	9	10.55585
4	33600287130000000	243.02484	244.06566	248.48094	1	9	10.55585
5	69002261500000000	239.63373	246.10611	250.53874	1	9	10.55585
6	26300026600000000	241.20503	251.26703	247.97574	1	9	10.55585
7	31500321310000000	239.98271	252.88661	247.65033	1	9	10.55585
8	30300271170000000	237.44533	250.58197	242.65504	1	9	10.55585
9	43002087800000000	239.68124	243.45943	250.11803	1	9	10.55585



**Table 5.** Shows an example of one of the tendrils identified in the Millennium Simulation. It shows the galaxies in the tendrils (the ID) the coordinates of each galaxy, the tendrils ID, the number of galaxies in the tendrils, and the length of the tendrils in Mpc/h

**Figure 8.** 3D model of the tendrils found within the Millennium Simulation. Each dot represents a galaxy, and the color represents a tendril ID.

## Discussion:

Data were gathered from the Millennium Simulation and analyzed using Python code. The same algorithms to identify large-scale structures used in (Odekon et al. 2018) were used and modified for the Millennium Simulation. Using the principles of nearest neighbor density and the

Minimum spanning tree algorithm, the goal of this study was to see if tendrils would be found within the Millennium Simulation.

Both tendrils and filaments were identified in the Millennium Simulation. Filaments have been found in the simulation in previous studies (Odekon et al. 2018) and identifying them in this model supports that the model is aligning with other research. Importantly, this model also identified tendrils using the method of the Minimum Spanning Tree algorithm which was developed through real-life observations. These results support that using the current cosmological model, including dark matter along with baryonic matter, to estimate the role of gravity in large-scale structures is closely aligned with what would be expected in a real-life observation.

Limitations of this study include the available computing power available. The data set had to be limited to within a reasonable amount to run the code. Additionally, due to the recent discovery of tendrils, the amount of research available was limited.

Tendrils are a relatively new cosmic large-scale structure discovery and appear to have different characteristics than other cosmic environments (Odekon et al. 2018). Being able to verify their existence not only in space but also in the Millennium Simulation helps further support the accuracy of current theories regarding gravity. Deepening the understanding of how gravity behaves by comparing real-life observations to a mathematical model will allow for exploration of galaxy formation in both direct observation and virtually.

**Conclusion:**

The evolution and formation of galaxies is not completely understood. It is therefore important to study the types of large-scale structures galaxies are part of such as groups and clusters, filaments, tendrils, and voids. Tendrils are a recent discovery and have not been studied as extensively compared to other large-scale structures. The formation and properties of galaxies seem to depend on their large-scale structure environments; therefore analysis of these large-scale structures will help predict and define the nature of individual galaxies.

**Bibliography:**

- Alpaslan, M., Robotham, A. S. G., Driver, S., Norberg, P., Baldry, I., Bauer, A. E., Bland-Hawthorn, J., Brown, M., Cluver, M., Colless, M., Foster, C., Hopkins, A., Van Kampen, E., Kelvin, L., Lara-Lopez, M. A., Liske, J., Lopez-Sanchez, A. R., Loveday, J., McNaught-Roberts, T., . . . Pimblet, K. (2013). Galaxy and mass assembly (GAMA): The large-scale structure of galaxies and comparison to mock universes. *Monthly Notices of the Royal Astronomical Society*, 438(1), 177-194. <https://doi.org/10.1093/mnras/stt2136>
- Alpaslan, M., Robotham, A. S. G., Obreschkow, D., Penny, S., Driver, S., Norberg, P., Brough, S., Brown, M., Cluver, M., Holwerda, B., Hopkins, A. M., van Kampen, E., Kelvin, L. S., Lara-Lopez, M. A., Liske, J., Loveday, J., Mahajan, S., & Pimblet, K. (2014). Galaxy and mass assembly (GAMA): Fine filaments of galaxies detected within voids. *Monthly Notices of the Royal Astronomical Society: Letters*, 440(1), L106-L110. <https://doi.org/10.1093/mnrasl/slu019>
- Inoue, S., Si, X., Okamoto, T., & Nishigaki, M. (2022). Classification of cosmic structures for galaxies with deep learning: Connecting cosmological simulations with observations. *Monthly Notices of the Royal Astronomical Society*, 515(3), 4065-4081. <https://doi.org/10.1093/mnras/stac2055>
- Milgrom, M. (1997). Large-Scale filaments: Newtonian versus modified dynamics. *The Astrophysical Journal*, 478(1), 7-12. <https://doi.org/10.1086/303779>

- Nurmi, P., Heinämäki, P., Sepp, T., Tago, E., Saar, E., Gramann, M., Einasto, M., Tempel, E., & Einasto, J. (2013). Groups in the millennium simulation and in SDSS dr7. *Monthly Notices of the Royal Astronomical Society*, 436(1), 380-394. <https://doi.org/10.1093/mnras/stt1571>
- Odekon, M. C., Hallenbeck, G., Haynes, M. P., Koopmann, R. A., Phi, A., & Wolfe, P.-F. (2018). The effect of filaments and tendrils on the H i content of galaxies. *The Astrophysical Journal*, 852(2), 142. <https://doi.org/10.3847/1538-4357/aaae8>
- Odekon, M. C., Koopmann, R. A., Haynes, M. P., Finn, R. A., McGowan, C., Micula, A., Reed, L., Giovanelli, R., & Hallenbeck, G. (2016). THE H i CONTENT OF GALAXIES IN GROUPS AND CLUSTERS AS MEASURED BY ALFALFA. *The Astrophysical Journal*, 824(2), 110. <https://doi.org/10.3847/0004-637x/824/2/110>
- Park, C., & Hwang, H. S. (2009). INTERACTIONS OF GALAXIES IN THE GALAXY CLUSTER ENVIRONMENT. *The Astrophysical Journal*, 699(2), 1595-1609. <https://doi.org/10.1088/0004-637x/699/2/1595>
- Porter, L. E., Holwerda, B. W., Kruk, S., Lara-López, M., Pimblet, K. A., Henry, C. P. A., Casura, S., & Kelvin, L. S. (2023). The loneliest galaxies in the universe: A GAMA and galaxy zoo study on void galaxy morphology. *Monthly Notices of the Royal Astronomical Society*, 524(4), 5768-5780. <https://doi.org/10.1093/mnras/stad1125>
- Springel, V., White, S. D. M., Jenkins, A., Frenk, C. S., Yoshida, N., Gao, L., Navarro, J., Thacker, R., Croton, D., Helly, J., Peacock, J. A., Cole, S.,

Thomas, P., Couchman, H., Evrard, A., Colberg, J., & Pearce, F. (2005).

Simulations of the formation, evolution and clustering of galaxies and

quasars. *Nature*, 435(7042), 629-636. <https://doi.org/10.1038/nature03597>

Yang, X., Xu, H., He, M., Gu, Y., Katsianis, A., Meng, J., Shi, F., Zou, H.,

Zhang, Y., Liu, C., Wang, Z., Dong, F., Lu, Y., Li, Q., Chen, Y., Wang, H.,

Mo, H., Fu, J., Guo, H., . . . Zu, Y. (2021). An extended halo-based group/

cluster finder: Application to the DESI legacy imaging surveys dr8. *The*

*Astrophysical Journal*, 909(2), 143. [https://doi.org/10.3847/1538-4357/](https://doi.org/10.3847/1538-4357/abddb2)

abddb2