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Multiscale Detection and Analysis of Cosmic Web Environments

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Introduction

Galaxy redshift surveys and, later on, cosmological numerical simulations have shown that the galaxies are not distributed randomly in the Universe, but that they form a complex web like pattern that is called the Cosmic Web. The Cosmic Web is described in terms of 4 components: clusters of galaxies (the most massive virialized objects that form the web centers), filaments (linear structures connecting the clusters), walls (sheet-like tenuous structures) and voids (almost empty regions with few galaxies).

The Cosmic Web environments are important since they affect the properties and evolution of the halos and galaxies that lie within. The environments, due to different density distributions and their anisotropic nature, determine the size and direction of matter accretion onto halos and galaxies.

Identifying the Cosmic Web components is a challenging task because of both the multiscale character and to the huge variation in density from galaxy clusters to voids (over 6 orders of magnitude). This is especially a difficulty when designing an automatic algorithm with no user-input and free parameters.

In the following we present two methods for environment identification, methods that are user-input free, parameter free and scale independent.

Cosmic Web Feature Identification

The **M**ultiscale **M**orphology **F**ilter (MMF) uses image processing techniques to identify point-, line- and sheet-like regions which correspond to the clusters, filaments and walls of the Cosmic Web (Aragon-Calvo *et. al.* 2007). The algorithm can be summarized into 5 steps:

1. Apply a filter to your input data.
2. Compute the Hessian of the filtered field.
3. Use the Hessian's eigenvalues λ_i (with $\lambda_1 \leq \lambda_2 \leq \lambda_3$) to assign cluster-, filament- or wall-like response values to each spatial point:

cluster	$\lambda_1 \simeq \lambda_2 \simeq \lambda_3$	$\lambda_1 < 0, \lambda_2 < 0, \lambda_3 < 0$
filament	$\lambda_1 \simeq \lambda_2 \gg \lambda_3$	$\lambda_1 < 0, \lambda_2 < 0$
wall	$\lambda_1 \gg \lambda_2, \lambda_1 \gg \lambda_3$	$\lambda_1 < 0$

4. Repeat steps **1 – 3** for a set of different filter scales (this makes the procedure scale independent)
5. For each spatial point, using the results from all filter scales, select only the maximum environment response value.

Below we apply the MMF algorithm to two input fields: density and density logarithm. This results in two very successful methods of identifying Cosmic Web environments.

Method 2: Density MMF

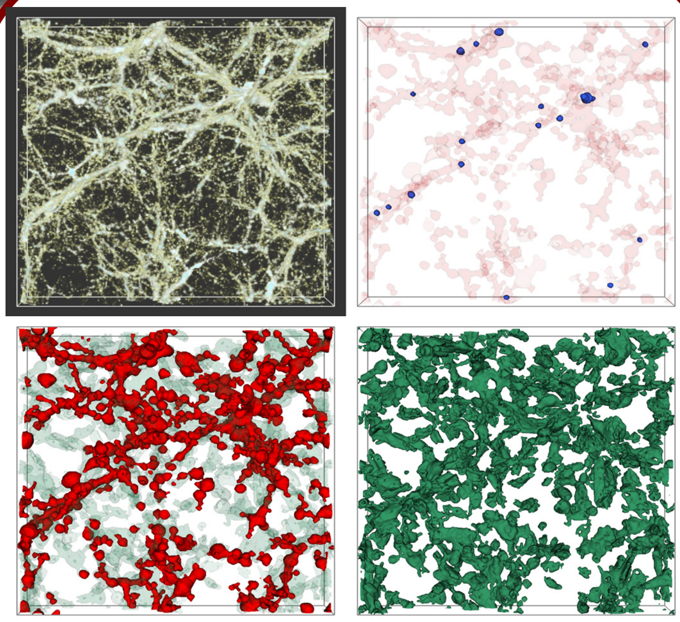

Figure 1: The Cosmic Web environments obtained using the **density MMF** method (100 x 100 x 20 (Mpc/h)^3 slice from an N-body dark matter only simulation):
Upper-left: Logarithmic rendering of the density field in the slice.
Upper-right: MMF clusters (blue) and filaments (red transparent).
Lower-left: MMF filaments (red) and walls (green transparent).
Lower-right: MMF walls (green).

Method 2: Density Logarithm MMF

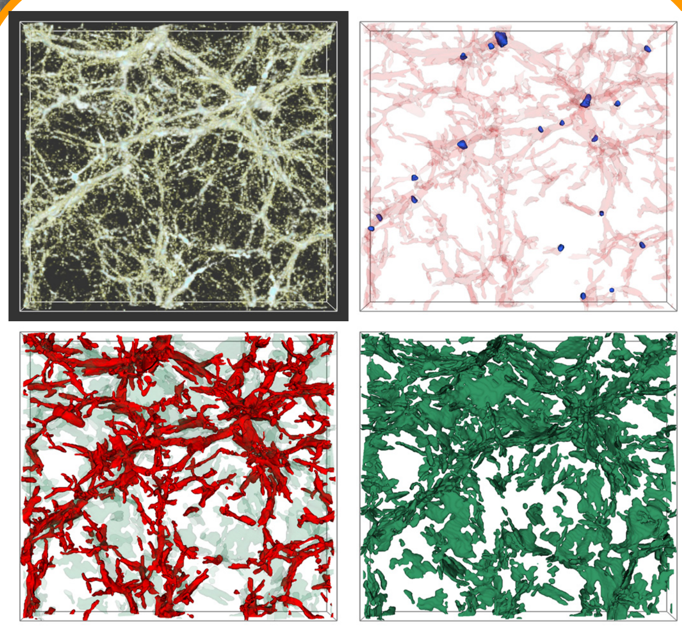

Figure 2: The Cosmic Web environments obtained using the **density logarithm MMF** method (100 x 100 x 20 (Mpc/h)^3 slice from an N-body dark matter only simulation):
Upper-left: Logarithmic rendering of the density field in the slice.
Upper-right: MMF clusters (blue) and filaments (red transparent).
Lower-left: MMF filaments (red) and walls (green transparent).
Lower-right: MMF walls (green).

Results

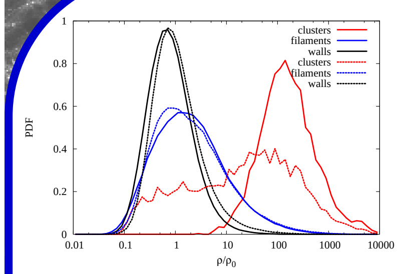

Figure 3: The probability distribution function (PDF) for the density in the environments detected using the two methods. Continuous lines give the density MMF results while the dashed lines give the second method results. Environments correspond to a wide range of densities, so a simple density threshold does not suffice in identifying the Cosmic Web environments.

	Volume fraction (%)		Mass fraction (%)	
	Method 1	Method 2	Method 1	Method 2
clusters	0.02	0.03	7	5
filaments	4	3	42	35
walls	6	4	9	12
field	90	93	42	48

Table 1: The volume and mass fraction in the environments detected using the two methods.

❖ Both methods identify similar regions as the Cosmic Web environments. The density logarithm MMF better reproduces the environments as seen by the human-eye in the density maps (the density MMF is plagued by "blobby" around the very high density regions) – compare Figures 1 & 2.

❖ Method 2 better captures the filaments in lower density regions. This method also better reproduces the walls which indeed look like continuous sheets – see Figure 2.

❖The density logarithm MMF also identifies lower density regions as potential clusters – see Figure 3. The solution is to use method 1 for cluster identification.

❖ Method 2 also better captures the expected halo population in walls (the density MMF wall population has an unexpected deficiency of high mass halos compared to the field).

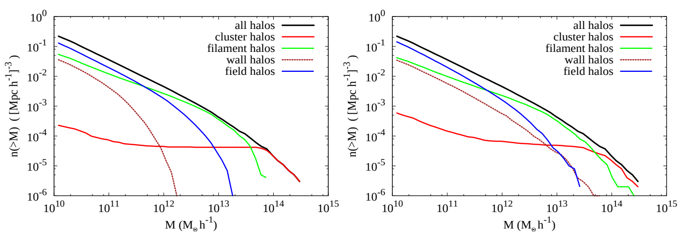

Figure 4: The halo mass function (for AHF halos – Knollmann & Knebe 2009) for the halos that reside in the different Cosmic Web environments. density in the environments detected using the two methods. *Left-panel:* First method results. *Right-panel:* Second method results.

1. Aragon-Calvo, M.A., Jones, B.J.T., van de Weygaert, R., van der Hulst, J.M., "TheMultiscale Morphology Filter", 2007, Apj, 474, p. 315
2. Knollmann, S.R., Knebe, A., "AHF: Amiga's Halo Finder", 2009, AJS, 182, pp. 608
3. Cautun, M., van de Weygaert, R., Jones, B.J.T., "Cosmic Web environment detection", in prep.