The Multi-stream Signature of Cosmic Web structures

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Introduction

New insights into the complex velocity flow composition of cosmic web elements - nodes, filaments, walls and voids - is obtained and presented. We explore the **multi-stream** nature of cosmic web environments. Unlike the usual assumption, we find the multi-stream structure of filaments, walls and even voids to be more **complex and varied**. This gives us new insights into the dynamical evolution of the cosmic web and will be important in the analysis and interpretation of upcoming peculiar velocity surveys.

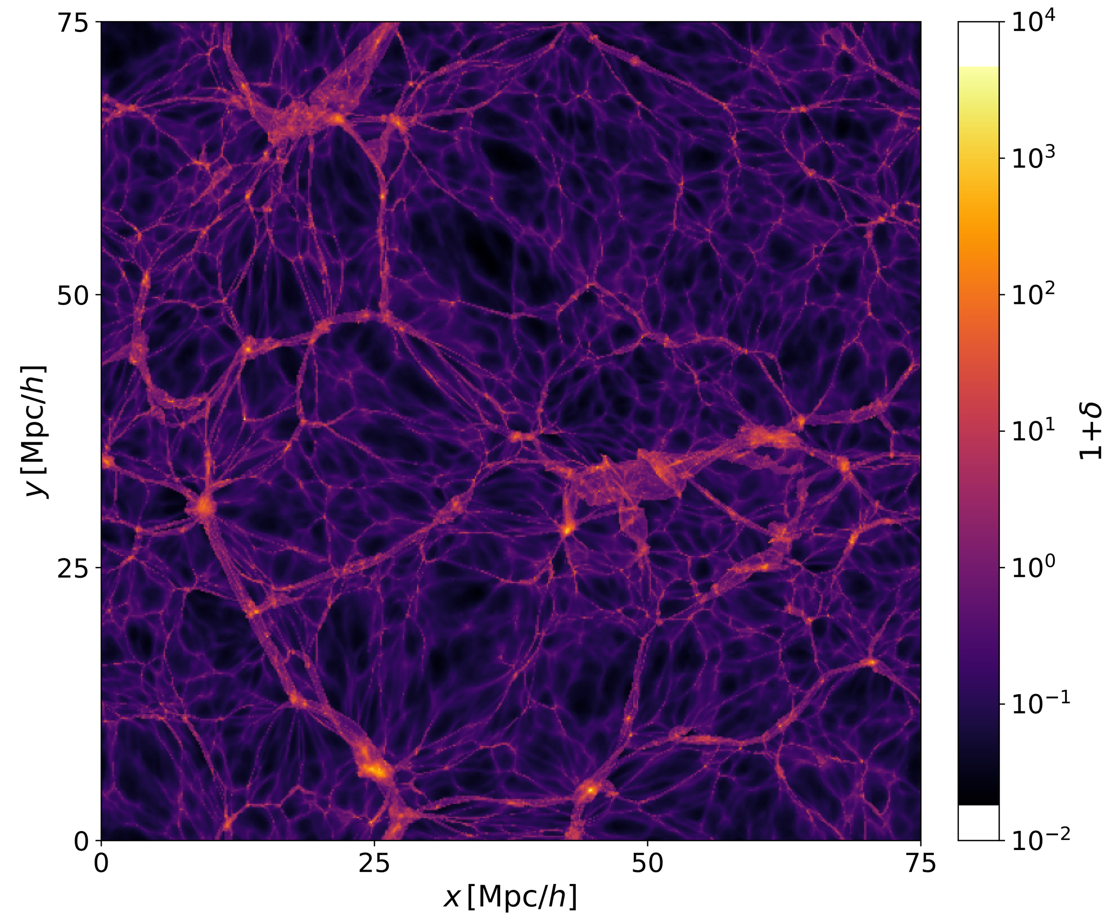
The course of action:

- Start from N-Body simulation (Illustris-3)
- Reconstruct density field with Phase-Space method
- Identify cosmic web environments with NEXUS+
- Multi-stream dissection of the density distribution

Density field Reconstruction

For the Phase-space density field reconstruction we use the state of the art Phase-Space Delaunay Tessellation Field Estimator (PS-DTFE) [6, 7], which is a Phase-Space extension of the Delaunay Tessellation Field Estimator (DTFE) [8, 10]. The PS-DTFE density estimator is optimal but requires "initial" conditions.

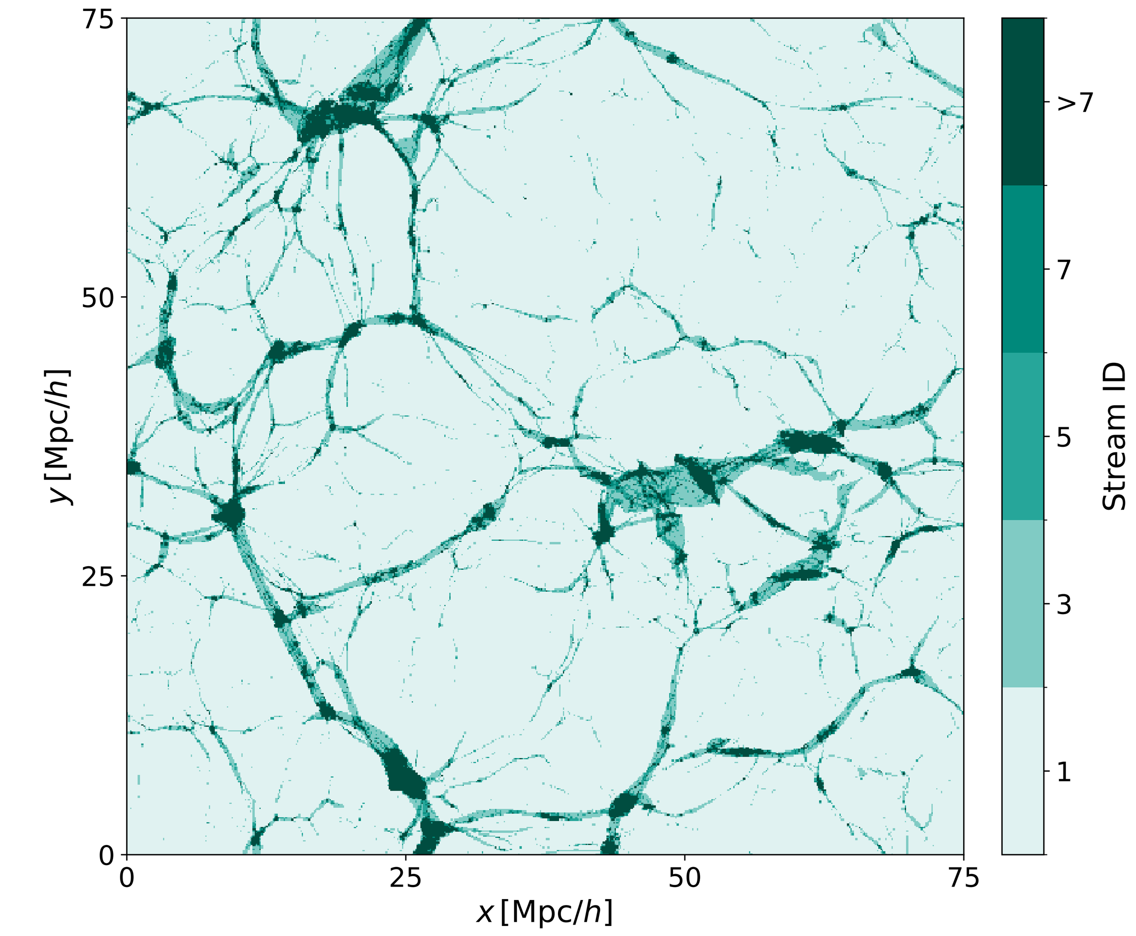
- Delaunay tessellation (see background image) of particles in snapshot before shell crossings
- Deform tessellation with Lagrangian map ⟼ phase-space information [9, 1, 5]
- Calculate density from Voronoi cell volumes
- Linearly interpolate Delaunay tessellation tetrahedra to get density field



Result ⟼ incredibly detailed continuous density field which respects geometry of matter field.

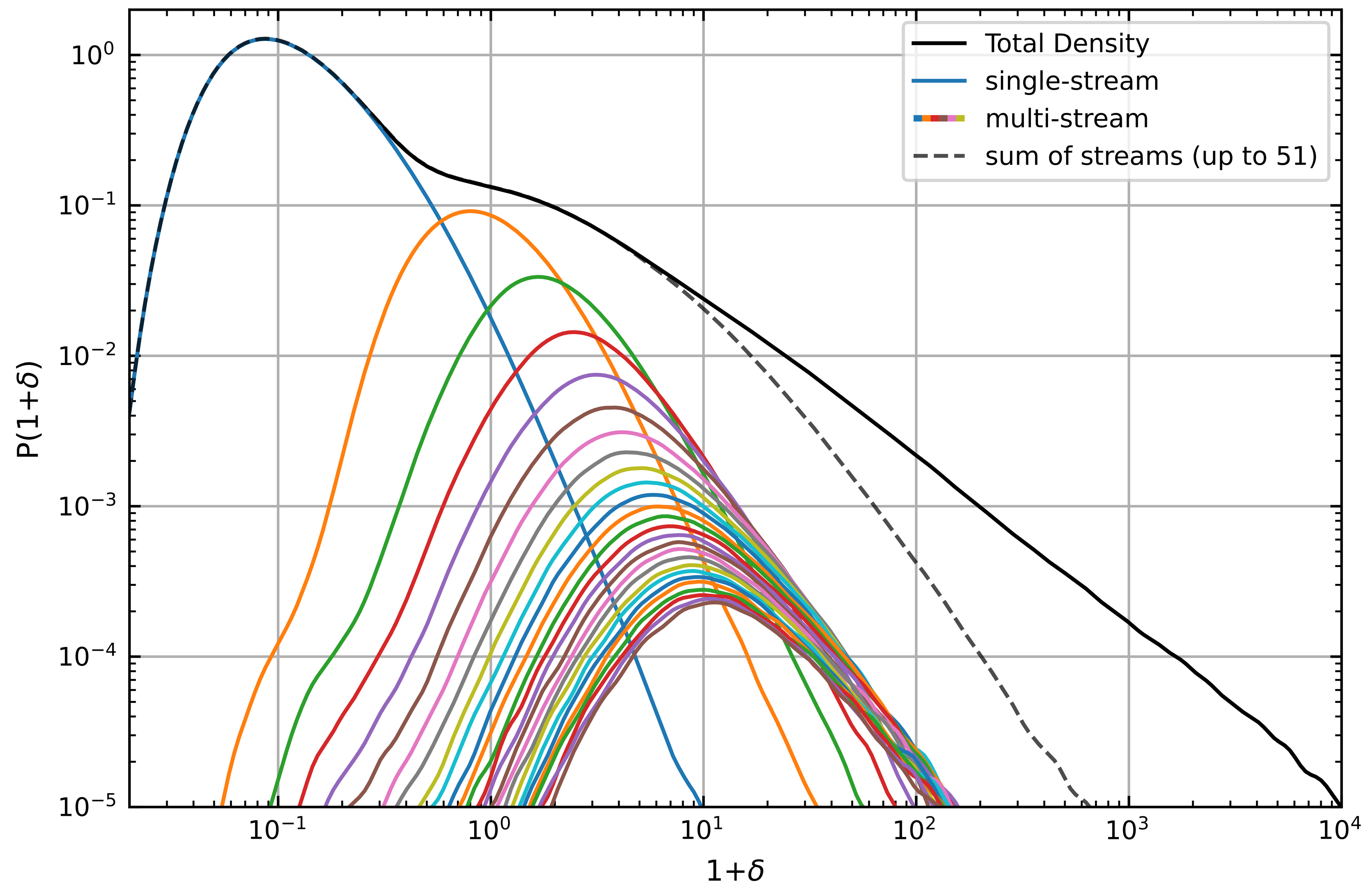
The Multi-Stream cosmic web

Phase-space information ⟼ shell crossing information ⟼ stream count. Shell crossings add two streams ⟼ odd number. "Tracks" folds of the dark matter sheet. Resulting field follows major features of the cosmic web.



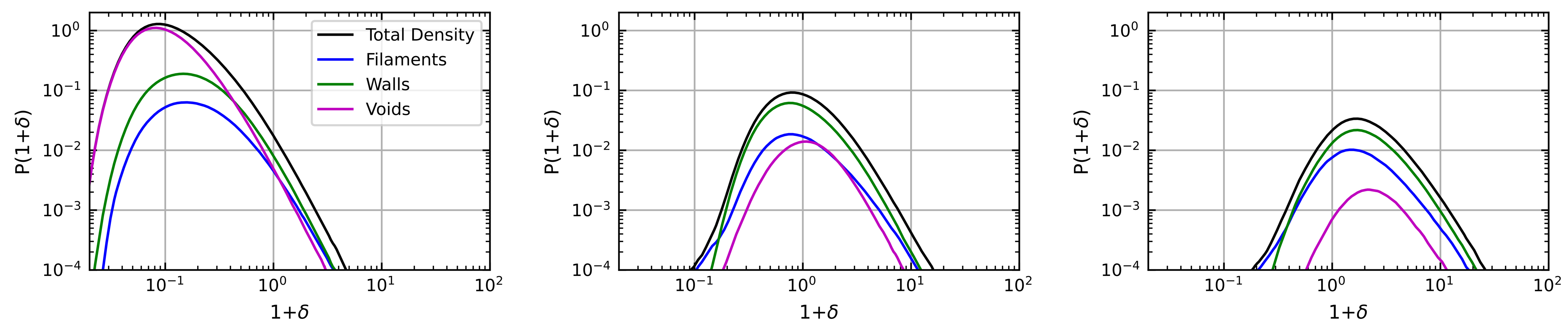
New insights into the multi-stream signatures of cosmic web environments. Density distribution approximately lognormal per multi-stream component.

Multi-stream dissection



The probability density of the density field, dissected by stream count. From left to right, each colour represents a number of streams (i.e. folds) of the dark matter field. The main peak arises from the single-stream (no shell crossings) components of the universe, while the tail and shoulder of the distribution emerge from the multi-stream regions. Each component resembles a lognormal-like distribution.

Multi-stream signatures of cosmic web environments

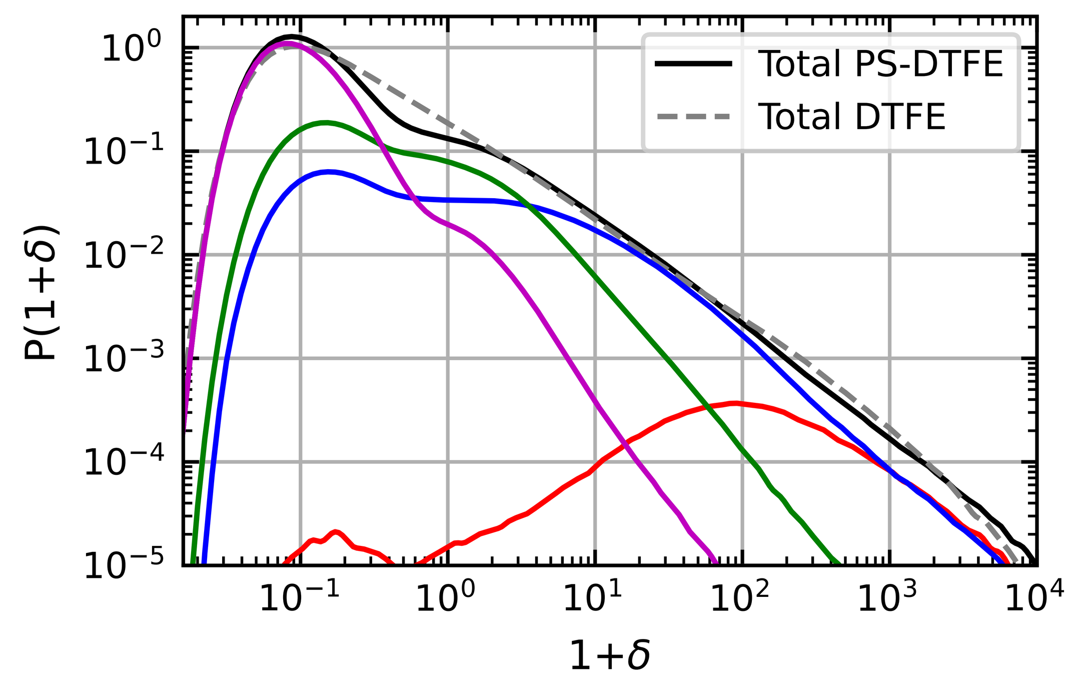


From left to right we show one, three, and five stream PDFs dissected by cosmic web environment. Voids dominate single-stream regions at low densities. At high densities, the walls contribute significantly. At three streams, the walls dominate everywhere but filaments and voids are not negligible. Walls still dominate at five streams, but filaments contribute more and voids become insignificant. Only beyond 11 streams filaments dominate over walls.

NEXUS: Cosmic web classification

We use NEXUS+ for cosmic web classification. This is part of the MMF/NEXUS pipeline for cosmic web identification and classification formalisms [2, 3, 4]. NEXUS+ is the highest spatial resolution method of the multiscale morphology filter formalism, which incorporates two fundamental aspects of the cosmic web, the **morphological** and **geometric** nature of the local mass distribution as well as its **multiscale** nature. The local geometry is assessed through the evaluation of the **Hessian**, while the multiscale nature follows from the **scale-space** implementation. It assigns to every location within a simulation or survey volume whether it has a filament, wall, node or void signature, and at what scale.

- Gaussian smoothing of (log) density field at multiple scales
- Calculate environment signature from eigenvalues of Hessian
- Combine multi-scale signatures to scale independent signature map
- Hierarchically classify environments using physically motivated detection thresholds



PDF dissected by cosmic web environment. Shows multi-scale nature of each cosmic web environment. Density is not a good tracer of cosmic web environments.

Discussion & Conclusions

The usual assumption that specific cosmic web features are to be identified with a specific singular multi-stream signature appears to be incorrect, a more elaborate characterization is required. In each component of the cosmic web we find a more varied multi-stream composition of the velocity field. To a major extent, this is a reflection of the multiscale structure of the cosmic web as a result of its hierarchical buildup, which leads to complex substructures in each environment. The theoretical underpinnings and possible implications for upcoming peculiar velocity surveys of this study need to be explored further.

The multi-stream dissection reveals the lognormal-like nature of each n-stream component of the density distribution. The physical origins of this lognormal behaviour warrant further investigation.

Key Takeaways

Multi-stream signature of cosmic web structural components is multivaried and complex.
Density distribution approximately lognormal per multi-stream component.

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Our Julia implementation of the NEXUS+ method is available as a package at `github.com/BDAlferink/MMFNEXUS.jl`. Poster presented by Bram Alferink (picture on the right).