# Radio Emission in the Cosmic Web

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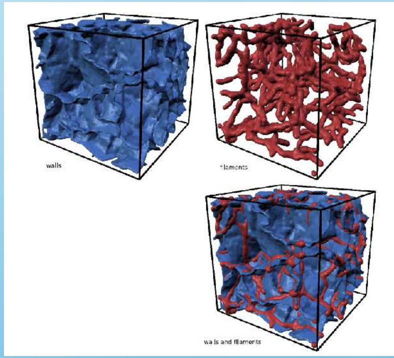
## Introduction

Cosmological shocks play a major role in heating the baryonic gas in the large-scale structure of the Universe. They drive the evolution of the warm-hot intergalactic medium (WHIM), the intra-cluster medium (ICM) are responsible for diffuse radio emission in Galaxy Clusters. They form abundantly in the course of structure formation, both due to infalling cosmic plasma which accretes onto filaments, sheets and halos, as well as due to supersonic flows associated with merging structures. Since they are an ubiquitous consequence of structure formation, a proper identification of the different structures in the Cosmic Web is of primordial importance to understand their properties.

## 1. The Spine of the Cosmic Web Method

The SpineWeb method is based on the segmentation of the cosmic density field. It allows the identification of voids, walls, filaments and nodes in the matter distribution. It traces the critical points in the density field and the separatrices defined by them. This separatrices are classified into walls, filaments and clusters.



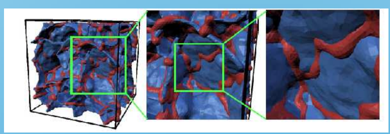



Fig. 1. Top: Surfaces showing the regions in a simulation box identified as walls (blue), filaments (red), and both components combined. Bottom: zoom-in onto one region, highlighting the intricate connections between walls, filaments and clusters.

## 2. Shock Identification

Our aim is to identify shock fronts in a cosmological simulation and to derive the Mach number of the shocks. With this in hand, combined with the identification of the different structures of the Cosmic Web, we can single out many properties in any region of the large-scale structure, such as the Mach number and the radio emission.

By using a novel shock finding algorithm, we can determine the Mach number and estimate the radio emission in and around galaxy clusters.

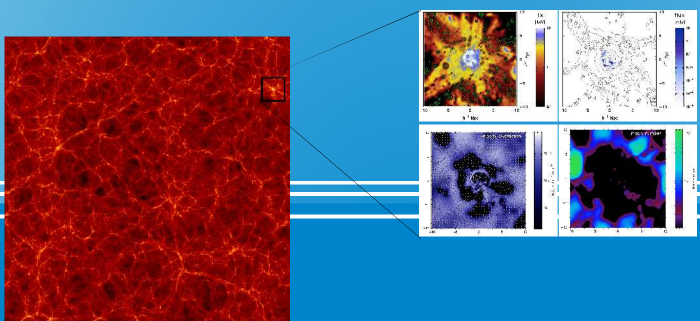


Fig. 2 Right: Density field of a cosmological simulation. The box within shows the most massive cluster. Left: the panels shows the zoom-in region in the box in the left, of 20x20 h$^{-1}$Mpc side. Temperature, synthetic observations of the X-ray and radio emission, the velocity divergence and the Mach number in and around the cluster are shown.

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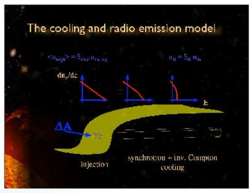
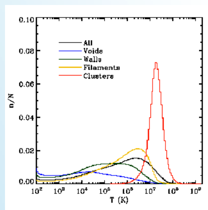
Radio emission model: radio emission is produced by ICM electrons accelerated by shock waves to ultra-relativistic speeds required for synchrotron and inverse Compton radiation. The injected electrons follows a power-law distribution that is related to the Mach number of the shocks. The radio emission is then calculated in a post-process, taking into account synchrotron cooling, the Mach number and the surface area of the shock.



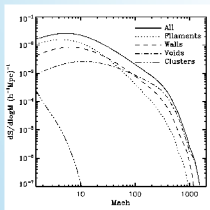

## 3. Results

With the identification of the different environments, temperatures, Mach numbers and radio emission within the simulation, we are able to study different properties of the gaseous Cosmic Web.

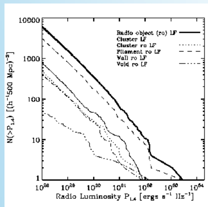
- Temperature distribution: the figure on the right shows the distribution of the temperature in the different environments of the Cosmic Web. As expected, clusters are the most hotter structures, then filaments, walls and voids being the coolest.




- Shock surface area: the shock surface area provides an effective inverse comoving mean distance between shock surfaces. The figure on the right shows the distribution of the differential shock surface area for the different environments of the Cosmic Web.




- Radio luminosity function: the figure on the right shows the cumulative number density of radio objects. The plot shows the radio luminosity function of all the objects in the simulation box (thick solid line) and also the luminosity of the same objects but now according to the environment they belong to (different linestyles). We also show the cluster LF, that is, the clusters identified in the simulation box.



## 4. Conclusions and future work.

With the use of the SpineWeb method and using a novel shock finding algorithm, we are able to study the different properties of cosmic shock waves, and, therefore, of the "gaseous" Cosmic Web. We are able to elucidate where and when the gas is heated to its present temperatures, and which shocks are responsible for it. We can also study radio luminosity, allowing us to give an estimate to what is predicted to be observed with the new generation of radio telescopes. We wish to apply the same procedures to cosmological simulations at higher redshift, enabling us to understand the the history of the "gaseous" Cosmic Web.

## References

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