

The Cosmic Web: Unveiling the Hidden Structure of the Universe through Observational Cosmology

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Abstract. Comprising dense nodes, filamentary structures, and cosmic voids, the cosmic web reflects fundamental large-scale matter distribution. A comprehensive exploration into the cosmic web will shed light on the processes governing the universe's large-scale structural formation and evolution, validate cosmological models, enhance comprehension of galaxy formation and evolution, and provide deeper insights into dark matter and dark energy. This paper aims to investigate the cosmic web through observational cosmology, concentrating on methodological techniques, the defining traits of cosmic-web structures, their statistical attributes, evolutionary dynamics, and insights gained from observational analyses. However, relatively low observational precision and resolution and the gap between simulations and observational data are still severe problems for scientists. There will be more observational projects in the future, with the aim to integrate multi-wavelength and multi-method approaches and build a unified model describing cosmic-web structures and their evolutionary processes.

Keywords: Cosmic web, Large-scale structure, Observational cosmology.

1. Introduction

Understanding the nature of the universe's large-scale structure constitutes a major objective of modern cosmology. At the largest cosmic scales, matter arranges itself into dense knots, elongated filaments, extended sheets, and vast voids, which together constitute the intricate cosmic web revealed by both simulations of structure formation and observations of galaxy distributions [1]. These four types of structures arise from the process of matter collapsing under gravity. Developing a deeper understanding of this large-scale structure is essential for mapping dark matter and galaxy distributions and simulating their evolution over cosmic history, from the universe's early stages to today. Therefore, accurate modeling and a deeper understanding of galaxy formation demand a comprehensive grasp of the large-scale structure.

Observational cosmology provides methods to detect, map, and analyze the hidden structure of the cosmic web [2]. Early efforts to map the nearby universe through galaxy redshift surveys firstly suggested its presence. Later, various large-scale surveys of galaxy redshifts—covering major surveys including 2MASS redshift survey, 2dFGRS, and the Sloan Digital Sky Survey—confirmed galaxies' filamentary configuration. Recently, maps from deeper surveys such as VIPERS have further supported this distribution.

Investigating the cosmic web follows several key scientific questions: What are the fundamental characteristics within the cosmic web structure? How does cosmic web architecture advance knowledge in dark matter and dark energy? What role do cosmic webs play in shaping the history and development of galaxies, clusters, and voids? These questions are of central scientific significance for understanding the characteristics of the cosmos, where its structure came from, and the rules guiding its development.

This paper aims to explore the cosmic web using observational cosmology with existing knowledge and methods and to analyze its connection to galaxy formation, dark matter distribution, and large-scale structure.

2. Theoretical Background of the Cosmic Web

2.1. Formation of the Cosmic Web

One of the most obvious examples of anisotropic gravitational collapse, which is what propels the creation of cosmic structures, is the cosmic web [3]. In essence, gravitational instability, which arises from minute disturbances in the universe's primordial density field, is what propels gravitational collapse [4]. This picture of gravitational instability has been substantially supported by perturbative analyses in the weakly nonlinear regime and further validated through numerical N-body simulations. Any initial anisotropy is amplified by gravitational instability, which causes matter to collapse in phases: regions first contract into walls, then into filaments, and finally collapse completely along all directions. In the end, cosmic web fundamental structure is directly shaped by this process. Smaller subunits first cluster and then merge into larger dark-component halos within the cold dark matter (CDM) paradigm, which constructs large-scale structures hierarchically in a bottom-up manner. The most massive galaxy clusters are expected within the largest dark matter (DM) halos, which tend to locate at junctions of one-dimensional filamentary structures. According to dark matter dynamics, this filamentary network shows the preferred paths of matter flow, which are dictated by the dark matter gravitational potential gradients. Massive and dense structures are created as matter builds up at the nodes along these directions.

The Cosmic Microwave Background (CMB) serves as the primary observational probe for early-universe perturbations. Being the radiation left over from the epoch roughly 380,000 years after the Big Bang, CMB has anisotropies that record the primordial density fluctuations, which act as the seeds for later large-scale structures, including the cosmic web. These primordial perturbations then experienced nonlinear evolution driven by gravitational instability under the dominance of dark matter gravity: underdense regions expanded into voids, while overdense regions contracted to form the filaments and intersections in the cosmic web (e.g., galaxy clusters) [5]. The extensive arrangement of the cosmic web ("filament–node–void") structure was eventually shaped by this process. The properties of the perturbations observed in the CMB therefore provide crucial evidence for tracing the origin and evolution of these cosmic web“seeds”.

2.2. Components of the Cosmic Web

Several key structural elements make up the cosmic web. Filaments are skeletons composed of dark matter, galaxies, and diffuse gas, spanning tens to hundreds of megaparsecs. They are the main channels for the transport of matter, responsible for gathering matter into the densest regions and connecting galaxy clusters into a coherent network. Filaments have an extremely low volume-filling rate [6]. Galaxy clusters are situated where several filaments converge and represent densest components within the cosmic web, serving as the physical carriers of massive galaxy clusters. They include numerous galaxies, large reservoirs of hot intracluster gas, and deep gravitational potential wells dominated by dark matter. In contrast, voids are the largest volumetric component of the cosmic web. These huge low-density regions extend to hundreds of megaparsecs, contain only a few galaxies, and expand faster than the mean cosmic expansion rate, forming a low-density supplement to the filament-cluster network. The morphology of voids is non-spherical - it is highly anisotropic due to the influence of external tidal fields (gravity of nearby large-scale structures). Crucially, these components are arranged in a hierarchy: small halos and clusters merge into larger systems, filaments transport mass into galaxy clusters, and galaxy clusters themselves are embedded in superclusters, all of which are interwoven with surrounding voids. This hierarchy together creates the characteristic "filament-node-void" structure of the cosmic web.

2.3. Significance of the Cosmic Web

Formation and structural scale about cosmic web are sensitive to key cosmological quantities, including matter density (Ω_m) and the cosmological constant density (Ω_Λ). The cosmic web can undergo substantial changes as a result of even minor deviations. As a result, observations of the

cosmic web is able to detect changes in parameters and reflect the general state of the universe. Research has shown that the galaxies within large-scale structures interact with them, affecting their orientation and spin, the fraction of red galaxies, and galaxy formation [1]. The cosmic web also influences the mass, shapes and formation times, spin and orientation directions, peculiar velocity profiles, and bias in dark matter halos where these galaxies reside. The large-scale structure also provides fundamental information on anomalous features observed in halo substructures, including the alignments, spins, merger histories, and planar arrangement of the satellite galaxies.

3. Observational Cosmology Methods

3.1. Observational Data Sources

Mapping the cosmic web requires a multitude of observational datasets, each of which looks at a different aspect. The Dark Energy Survey, Euclid, and the Sloan Digital Sky Survey are large redshift surveys that create three-dimensional maps of millions of galaxies over cosmic time [7]. The CMB consists of relic photons originating in a 3000 K plasma that permeated cosmic space about 380,000 years after the Big Bang. The radiation and matter were successfully separated as the universe expanded and the plasma cooled until neutral atoms were formed. Measurements of CMB anisotropies have revealed key information on the universe's composition and evolutionary history, enhancing comprehension of the standard cosmological model [8]. Additionally, the CMB, which is measured with unprecedented precision by missions like WMAP and the Planck Satellite, reveals the initial conditions for the development of large-scale structures. Galaxy distribution on large scales, the dark energy's nature, and the relationship between galaxy properties and their environments are all revealed by spectroscopic and photometric redshift measurements [9]. Photometric redshifts offer a cost-effective substitute for spectroscopy in estimating distances to millions of galaxies. Recently, it has been demonstrated that photometric redshifts gain higher precision when integrated with cosmic web structures inferred from spectroscopic surveys.

3.2. Data Analysis Techniques

Advanced data analysis techniques are required to extract valuable insights regarding the cosmic web from observational data. A high-precision real-space density field is derived by reconstructing galaxy redshift distributions, mitigating shot noise, and rectifying redshift-space distortions. As the fundamental building block of the entire pipeline from raw observational data to examine cosmic web structure, it enables accurate identification of nodes, filaments, and voids, alongside determining their physical properties, such as redshift ranges and spatial scales [10]. Weak gravitational lensing is among the most effective techniques for probing dark filaments. Since gravitational lensing does not depend on the luminosity or kinematics of matter, it enables the mapping of mass distributions via induced gravitational distortions, making it an ideal method for detecting the cosmic web and dark matter's mass distribution [11]. Machine learning techniques and dimensionality reduction methods (such as PCA) are increasingly being explored in the analysis of large-scale sky survey data. These methods can extract subtle and complex patterns from massive amounts of observational data, not only improving the efficiency of cosmic environment classification but also showing great potential in revealing the underlying connections within the structure of the cosmic web.

3.3. Numerical Simulations and Models

The essence of N-body simulations is to directly calculate the mutual gravitational forces between N particles in a gravitational system (such as stars and dark matter particles) and combine them with high-precision numerical integration to simulate the dynamical evolution of the system. Millennium Simulation and Illustris Simulation are typical N-body simulations [12]. Finally, calibrating simulations against observations is a crucial step in connecting theoretical models with the real Universe. By comparing these models to observational benchmarks, researchers can adjust free parameters so that the simulations reproduce the statistical properties of galaxies and large-scale

structure. Calibration not only improves the realism of the simulations but also enhances their predictive power, enabling them to predict as-yet-unobserved phenomena and providing theoretical guidance for future large-scale sky surveys. Furthermore, achieving consistent calibration across multiple observational quantities facilitates the verification of cosmological models and theories.

4. Observational Studies of the Cosmic Web

4.1. Mapping Cosmic Webs

Mapping cosmic webs requires complicated techniques to identify filaments, galaxy clusters, and voids. Numerous techniques have been put forth to describe the cosmic web, ranging from two- and higher-order correlation functions, minimal spanning trees, shape statistics, Minkowski functionals, to genus and other topological measures [3]. Most of these approaches provide global statistical descriptions of the large-scale pattern but do not enable the local identification of individual components of the web. Filament detection employs techniques grounded in Morse theory and the DisPerSE algorithm determine the morphological traits associated with the density field's saddle points and maxima, establishing a mathematically rigorous framework. Voids can be discerned utilizing the Watershed Void Finder (WVF), the SpineWeb procedure, or morphological techniques, whereas clusters are typically identified through halo finders such as the Friends-of-Friends (FoF) algorithm, the Spherical Overdensity method, and SUBFIND.

Galaxy surveys and weak lensing analyses furnish essential observational proof of the cosmic web. Initial redshift surveys (e.g., Gregory & Thompson 1978; de Lapparent et al. 1986) first uncovered extensive structures, indicating a filamentous or sheet-like arrangement of matter [3]. Contemporary surveys, such as 2dFGRS, SDSS, and the 2MASS redshift survey, have substantiated the prevalence of the cosmic web. In particular, SDSS observations show that galaxies's distribution is a network of filaments, cluster, and void, consistent with N-body simulations. Bond et al. identified significant filamentary connectivity between clusters, supporting the node–filament skeleton model. Observationally, luminous galaxies preferentially reside in clusters and filaments, while low-mass galaxies are more sparsely distributed in walls and voids, in agreement with simulated halo environment segregation.

Weak lensing studies probe the mass distribution in high-density cosmic web areas. Kartaltepe et al. used weak lensing to detect filamentary structures connecting galaxy clusters, confirming the simulation-predicted mass accretion along filaments [3]. Observed filament densities are broadly consistent with N-body predictions, and lensing results further constrain filament baryonic content, supporting the scenario in which filamentary structures contain an important share of the warm–hot intergalactic medium.

4.2. Statistical Properties of the Cosmic Web

Most common statistical methods to explain the universe structure are correlation functions (2D or 3D) and power spectra [13]. These describe real parts of the density distribution [13]. The power spectrum contains the Fourier mode amplitude, while correlation functions contain some spatial correlation details of the density field mode.

$P(V)$, the void probability function, expresses the probability of finding zero galaxies within a randomly selected spatial region of size V in the dataset. The VPF was employed to characterize the cosmic-distribution of galaxies. The radial density distribution of filaments reveals how matter is organized within these structures and serves as an important test for models of dark matter. While still exceeding the cosmic mean density, filament mass density typically declines as radial distance from the filament axis increases [14]. The radial density characteristics of long and short filaments differ. Throughout the whole radial distance range, the density profiles of long filaments are lower than those of short filaments.

4.3. Tracing the Cosmic web growth over time

A particularly powerful aspect in observational cosmology is its capacity to monitor the cosmic web's evolution over cosmic time. Observations indicate that filaments become increasingly compact and interconnected as the universe evolves, while voids expand due to dark energy. This dynamic evolution reflects the transition from a matter-dominated universe to one dominated by dark energy. Galaxies in voids evolve in relative isolation; however, evidence indicates that galaxies situated within filaments acquire more gas, thereby enhancing star formation. The cosmic web directly influences galaxy history while also mirroring cosmological parameters.

5. Implications for Cosmology

5.1. Probing Dark Matter and Dark Energy

Characteristics of dark matter are limited by cosmic webs. For example, diminutive halos can be generated and augmented by cold dark matter (CDM) [15]. In scenarios concerning self-interacting dark matter or warm dark matter, this is not applicable. This indicates that dark matter models may be evaluated through the distribution of halos. A crucial element of modern cosmology is the use of the cosmic web to study dark energy's impact. Dark energy parameters are influenced by data (e.g. the positions, number density, and peculiar velocities of galaxies at their centers, along with the dynamical structure of voids) [16].

5.2. Understanding Galaxy Formation and Evolution

Intricate velocity fields, shaped by the infall of diffuse matter along filaments, the accretion of gas and galaxies onto clusters, and shock waves induced by substructures, delineate the periphery of galaxy clusters [17]. Filaments serve as highways, continuously directing galaxies and gas into the dense interiors of clusters. Their fundamental role in transporting matter into galaxy clusters and driving their growth is demonstrated by their properties, which range from massive bridges between cluster pairs enriched with substructures and collapsed halos to thin tendrils permeating cosmic voids. Voids and filaments are two types of cosmic web features that strongly influence galaxy formation and evolution. The primary distinctions between void galaxies and filament galaxies are that the former are often more gas-rich, bluer, and less massive [18]. Furthermore, because of the highly inhomogeneous large-scale matter distribution, tidal torques are anticipated to give galaxies and galaxy systems inside filaments more angular momentum. Large-scale galaxy filaments have a unique effect on the constituent galaxies, decreasing the rate of star formation and increasing the likelihood of elliptical morphology at a certain environment density level. They are not just a density increase. Progressing from voids toward filament spines shows a clear trend: the proportion of elliptical to spiral galaxies increases as the $g - i$ color index rises and the star formation rate decreases. Interestingly, these changes are particularly noticeable in galaxies that are relatively bright ($M_r < -20$ mag).

5.3. Testing Theoretical Predictions

At cosmological scales, filament connectivity in the group-cluster regime may be used as a probe of gravity models (e.g. Λ CDM and alternative cosmological models) [19]. In particular, the Λ CDM model provides clear expectations about the geometry, connectivity, and evolution of filaments, voids, and galaxy clusters. In addition to Λ CDM, alternative cosmological frameworks forecast unique imprints on density profiles, filamentary connectivity, and void statistics. However, discrepancies frequently emerge when confronting these predictions with observational data, underscoring the necessity for higher-resolution simulations and more precise observations.

6. Future Directions

The next generation of astronomical surveys and space missions will significantly advance our understanding of the cosmic web. Dark Energy Spectroscopic Instrument, Euclid, Wide-Field Infrared Survey Telescope, 4-meter Multi-Object Spectroscopic Telescope, Large Synoptic Survey Telescope, and the Extended Baryon Oscillation Spectroscopic Survey represent several recently developed wide-field galaxy surveys aimed at addressing these fundamental questions. Furthermore, dense and deep photometric surveys—including the Javalambre-Physics of the Accelerated Universe Astrophysical Survey and the Dark Energy Survey—alongside pencil-beam surveys with smaller areas but richer sampling, such as Prime Focus Spectrograph and the VIMOS Public Extragalactic Redshift Survey, provide insights into large-scale structures [7]. These surveys are producing observational data that may be able to meet the precise standards needed to address not just the aforementioned questions, but deeper ones, including whether general relativity holds true on the biggest cosmological scales. Moreover, advances in CMB and gravitational lensing studies will further benefit the understanding of the cosmic web.

6.1. Challenges and Opportunities

Improving observational accuracy and resolution and bridging the gap between simulation and observation data directly determine the depth of human understanding of cosmic web, dark matter, dark energy and the mechanism of galaxy formation. Enhancing observational precision—via advanced imaging, elevated spectral resolution, and refined photometric redshift calibration—will be essential for quantifying connectivity, density profiles, and the dynamical state of cosmic filaments. Bridging this gap necessitates more accurate simulations and enhanced observational methodologies that reduce biases.

6.2. Toward a Comprehensive Understanding in the Cosmos

Intricate characteristics of cosmic webs indicate that no singular observational band or research methodology can entirely encapsulate its essence. The integration of multi-wavelength and multi-method approaches will facilitate a more comprehensive understanding of filaments, voids, and galaxy clusters, thereby mitigating the systematic biases associated with any singular detector. Ultimately, these endeavors seek to establish a coherent representation of the evolution of the cosmic web.

7. Conclusion

Through observational cosmology, the investigation of the cosmic web has made significant progress and provided new physics insights. Weak lensing, CMB anisotropies, and redshift surveys have solidified the filament–cluster–void framework, validating predictions from Λ CDM and alternative cosmological models. Quantitative benchmarks that link observational results with theoretical models have been made possible by statistical analyses such as filament density profiles, correlation functions, distribution spectrum of cosmic structures, and void probability functions. Cosmic web structures exert a strong influence over dark matter, dark energy, angular momentum, star formation activity, and galaxy morphology, as revealed by observational studies. The primary conduits for the movement of matter, filaments direct gas and galaxies into enormous clusters.

Future surveys like Euclid and the Roman Space Telescope will produce previously unheard-of datasets that will allow us to track the cosmic web. These will enable more accurate detection of the cosmic web, in conjunction with developments in weak lensing, CMB polarization, and multi-wavelength observations. In the meantime, machine learning, cross-survey data integration, and increasingly complex simulations will aid in bridging the gap between theory and observation. Cosmologists' ultimate goal is to create a cohesive model of the cosmic web and its evolution by combining various theoretical and observational techniques. This will help people to better understand gravity, dark matter, dark energy, and the universe overall.

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