Structure of the cosmic web

Web Spun out of Darkness

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Contemporary cosmology poses fundamental questions on the nature and structure of the Universe, its evolution and future

Our current understanding of the Universe is described by the standard Lambda-CDM (Lambda Cold Dark Matter, where lambda is Einstein's cosmological constant) cosmological model. It posits that the main two components of the universe are dark matter (DM) and dark energy (DE), while its evolution is driven by gravity alone.

Dark components

The key attribute of DM and DE is that neither emits or absorbs light. We know of their existence through indirect astronomical observations. Although invisible, dark matter is similar to the ordinary matter that forms planets, stars, and all living beings. They both gravitate, hence DM is able to cluster into structures, which in turn form a "scaffolding" for galaxies - homes to billions of glistening stars.

Without dark matter, galaxies would have never been able to form, since there would have been insufficient gravity for gas to accumulate into large enough aggregations. Like an invisible puppet master, DM guides the fates of galaxies in a cosmic theater.

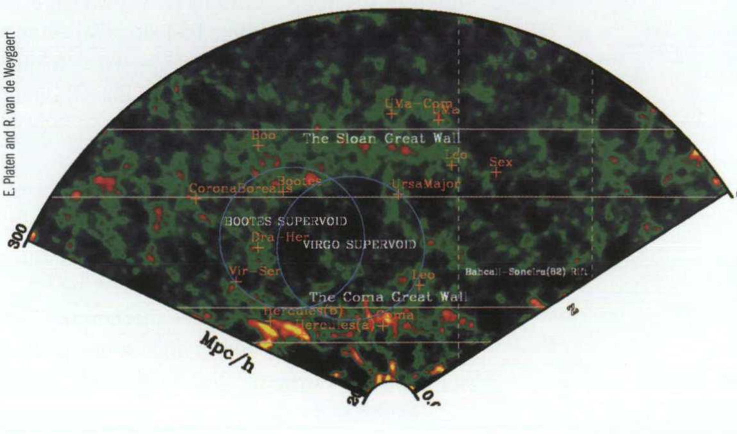
Continuing with the analogy of a theater (or cosmic stage, as coined by Newton), we can conclude that if DM is in charge of the motion of galaxies, then DE can be described as the director orchestrating the events on the whole cosmic stage. It does not cluster into structures, but is instead distributed uniformly across the Universe, from the densest accumulations of matter to the vastest cosmic voids, utterly deprived of light and matter. It interacts gravitationally with the entire Universe, acting in a very specific manner: it creates a repulsive force which - at its greatest scale - counters the gravitational attraction of DM, causing the Universe as a whole to expand faster and faster.

Era of precision cosmology

Following a series of deep sky surveys conducted over the last ten years and studies performed at ultra-sensitive orbiting observatories, it has now become possible to define the values of parameters describing the standard cosmological models and the Universe itself with incredible precision. Unfortunately, as has often been the case in scientific history, the increasingly precise measurements have brought more questions that remain unanswered, mainly about the physical nature of dark matter and energy.

This is why key cosmological research focuses on explaining the mysteries of dark matter and dark energy. Such research activity can be roughly divided into two

Patterns of the cosmic tapestry visible in the averaged density field of galaxies observed in the SDSS galaxy survey



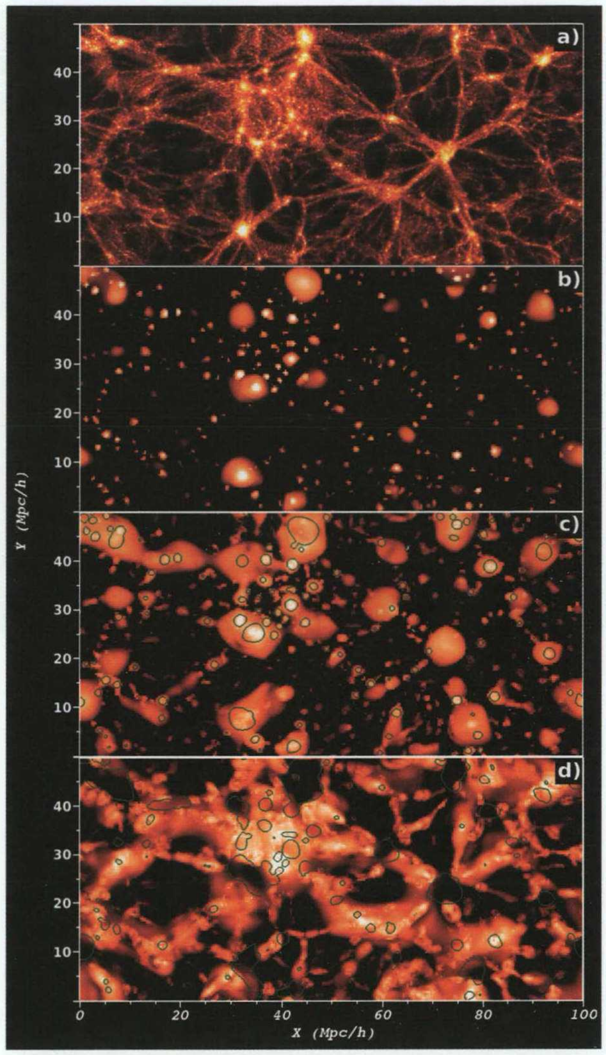
categories; one is dominated by the development of theoretical physics concerning DM and DE, supported by experiments and research conducted at Earth-based laboratories such as the Large Hadron Collider at CERN, situated underground beneath Geneva. The other concerns the analysis of complex computer simulations studying the effects of different models of dark matter and energy on the formation of structures in the Universe by comparing the results of simulations with actual astronomical observations. Research based on computer simulations has been developing rapidly thanks to new algorithms and methods for analyzing cosmological simulations.

A new branch of cosmology has developed in recent years, studying what is known as the "cosmic web" and the information on DM and DE that is encoded within it. Such studies use methods and techniques originating from other fields, often unrelated to cosmology and astronomy, such as topology, computational geometry, and medical imaging.

Cosmic net

The existence of the cosmic web is a consequence of the anisotropic (non-spherical) nature of gravitational collapse - the main mechanism responsible for the formation of structures in the Universe. Major structures, comprising millions of observable galaxies, originate from primal, microscopic perturbations in density and velocity as a result of a process known as gravitational instability. This instability is a consequence of the nature of gravitational forces, which are exclusively attractive. With time, the primary disturbance to the density - a location where slightly more matter is present - will start attracting matter from less dense regions. The greater the attraction, the greater its effect on its surroundings, resulting in an increasing density. After a sufficiently long time - gravity is an exceptionally patient force - the process stops being linear, and it can lead to the formation of massive agglomerations of matter.

Over almost 14 billion years of cosmic evolution, gravitational instability has led to the formation of objects such as galactic clusters, where thousands of galaxies spin at enormous speeds and collide with each other in a powerful gravitational field.



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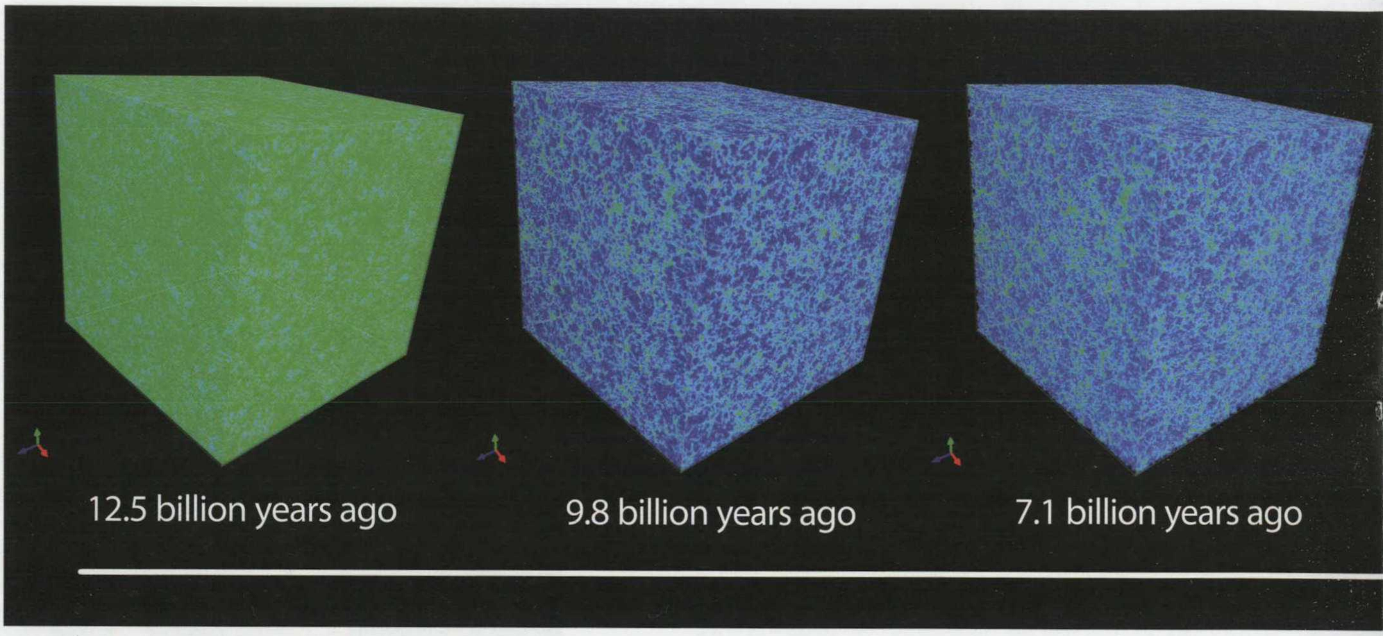
Elements of the web identified by the NEXUS+ algorithm in a small selected fragment of the (simulated) Universe. The panels show: a) the matter density field obtained from computer simulations, b) nodes in the web, c) filaments, and d) walls

Computer simulations illustrate how the field of matter in the Universe has evolved into a complex cosmic tapestry comprising filaments intertwining to form dense, compact nodes of the web. The filaments stretching between the nodes act as transport routes, channeling rivers of matter towards massive galaxy clusters.

The cosmic web is, therefore, a structure woven from galaxies and dark matter by the ever-patient force of gravity. It includes four very different components; when put together and repeated, they form a pattern which appears uniform, although no two areas are identical. The four components are galaxy clusters, filaments, walls or sheets, and voids.

Galaxy clusters are the densest and most massive objects, acting as nodes of the cosmic web. The nodes are like huge gravita-

Structure of the cosmic web



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tional spiders, devouring matter from their surroundings. Cosmic matter flows to galaxy clusters mainly along huge, dense filaments reminiscent of giant threads stretching between nodes. The majority of galaxies in the Universe are located along these filaments.

The thin, less dense sheets or walls stretch between filaments and clusters. Matter within them moves more slowly, flowing gently towards the nearest filament or cluster. Walls also contain galaxies, albeit far fewer than filaments. Our own galaxy - the Milky Way - is likely to be located in such a peripheral region of the cosmos.

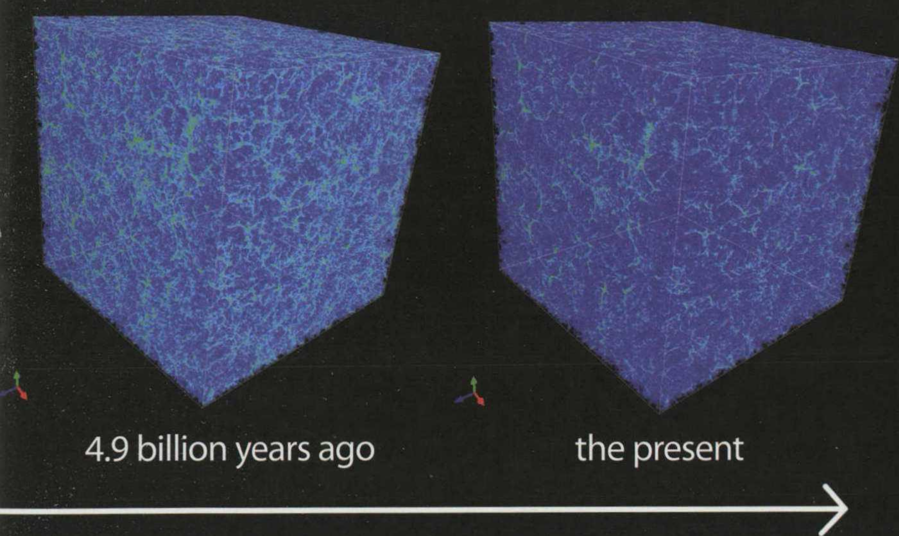
The final component of the cosmic web is immense voids. These are vast, dark domains almost entirely devoid of light and matter, filling the space between the walls and the filaments. Galaxies within them are few and far between, and generally poorly developed.

The properties, features, and structure of the cosmic web result from complex relationships between the original conditions (primary minor fluctuations in density) and the physical nature of dark matter and dark energy. In theory it should be possible to learn more about the nature of DE and DM by studying the properties and structures of the cosmic web, comparing the results of computer simulations with observational data.

However, researching the cosmic web is an extremely difficult challenge. The main problem stems from its complex nature, since its patterns and elements are found at almost all distance scales, as well as being subject to non-linear evolution. This means that aside from galaxy clusters, none of the remaining elements of the web have clearly defined boundaries. Filaments gradually become walls, which in turn dissolve around the boundaries of voids. Immense voids may also contain smaller voids, separated by thin filaments and walls.

Supercomputer web

Research into the cosmic web is being conducted within the new field of computational cosmology. The application of methods widely used in medical research has made it possible to identify the individual components of the cosmic web with a high degree of precision, using physical criteria. In recent years, Prof. Rien van de Weygaert's research team from the Kapteyn Astronomical Institute in Groningen (the Netherlands) has proposed a state-of-the-art method of analyzing the cosmic web, known as NEXUS+, based on algorithms used for X-ray and tomography images. It has been refined and developed for the purposes of studying astronomical data and computer simulations. Preliminary re-



Universe inside a computer

State-of-the-art astronomy tools, such as large telescopes and observatories on the ground as well in orbit, provide extraordinary images of galaxies and distant regions of the Universe. The main aim of modern cosmology is to study the processes by which the galaxy structure, as well as the galaxies themselves, were formed. Progress in theoretical understanding of the structure of the Universe and the galaxies within it has been made possible by large-scale sophisticated computer simulations. Such simulations are used to study the non-linear formation and evolution of matter density fields in a certain part of the Universe. They usually require powerful supercomputers, making it possible to "observe" billions of years of cosmic evolution during a few weeks' worth of calculations.

sults show that the properties and structure of the cosmic web are sensitive to specific properties of DM and DE.

Although we are still a long way from obtaining spectacular results, it appears that by combining computer simulations, advanced methods of their analysis, and data from new deep galactic surveys we will soon be able to unlock the secrets that lie hidden within the cosmic tapestry and shed some light on the mysteries of dark matter and dark energy. ■

Further reading:

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Cautun M., van de Weygaert R., Jones B.J.T. (2012). *NEXUS: Tracing the Cosmic Web Connection.* MNRAS (submitted). http://arxiv.org/abs/1209.2043.

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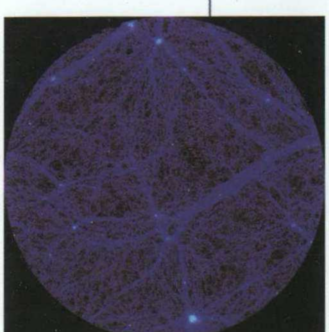
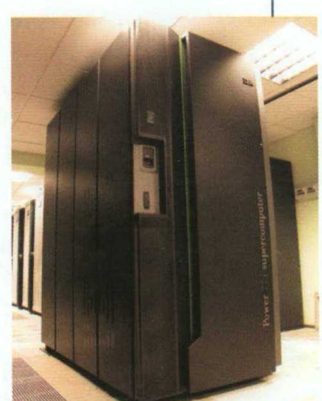
Cosmological supersimulations in Poland



In recent years, one of the largest and most precise cosmological simulations ever was conducted in Poland. Known as "Copernicus Complexio" (CoCo), it comprises over 13 billion particles simulating the density field of dark matter. The project was completed by the Interdisciplinary Center for Mathematical and Computer Modeling (ICM) at the University of Warsaw and the Institute for Computational Cosmology at the University of Durham. As part of the POWIEW program (Infrastructure for Grand Challenges of Science and Engineering – www.wielkie-wyzwania.pl), co-financed by the EU, last year the ICM obtained a new IBM Power 775 supercomputer named "Boreas," which was used to perform the CoCo simulation. "Boreas" runs at 74 TFLOPS (74 trillion operations per second) and has an internal memory of 9.8 terabytes. In spite of its great power, the supercomputer required 6 weeks to complete the simulation. Analysis of CoCo results should reveal answers to many questions on the nature of dark matter, such as whether the Milky Way with its system of satellite galaxies is a rare object, or whether such systems are widespread across the Universe. The Copernican principle, widely accepted in contemporary cosmology, states that the Earth is not in a central, specially favored position. This is what inspired the name of the simulation, which translates as Copernicus' Conundrum.



IBM Power 775 supercomputer "Boreas" in the server room at the ICM, Warsaw