DR FLORENT LECLERCQ OF THE UNIVERSITY OF PORTSMOUTH, UK, DISCUSSES THE CREATION OF NEW MAPS OF DARK MATTER DYNAMICS IN THE UNIVERSE

A light in the dark

Using advanced computer modelling techniques, a research team at the University of Portsmouth, UK, led by Dr Florent Leclercq, has translated the distribution of galaxies into detailed maps of matter streams and velocities for the first time using legacy survey data obtained between 2000 and 2008 from the Sloan Digital Sky Survey (SDSS), a major three-dimensional survey of the Universe. The survey has deep multi-colour images of one-fifth of the sky and spectra for more than 900,000 galaxies.

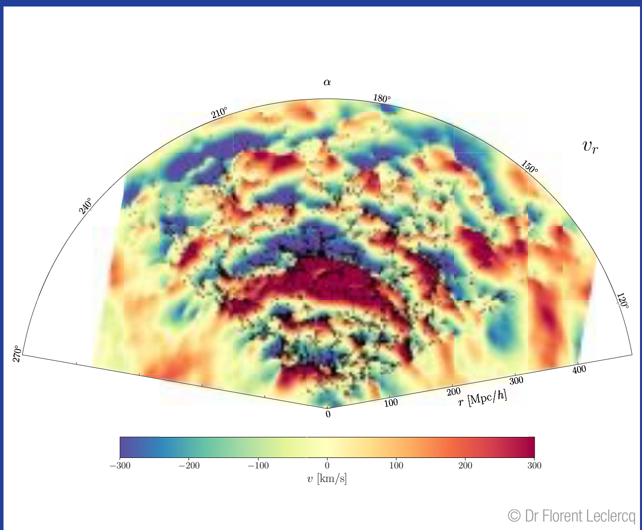
The new dark matter maps cover the northern sky up to a distance of 600 megaparsecs, which is the equivalent of looking back about two billion years.

Pan European Networks asked Leclercq about this new research, the benefits of a phase-space approach, and what applying new techniques to next-generation deep surveys of galaxies could yield.

What challenges are involved in inferring the distribution and evolution of dark matter, and why is it important that it is nevertheless attempted?

Standard techniques to deal with galaxy surveys generally involve a massive compression of the raw data – known as 'measuring summary statistics'. Typically, one measures the so-called 'correlation functions' of the galaxy distribution and then fits the results to a cosmological model using a handful of parameters. In contrast, the approach that my collaborators and I are exploring is orders of magnitude more ambitious, as the parameters being considered are now the actual distribution of dark matter in the Universe, measured at some resolution. That is arguably what one really wants to do in a statistical analysis of data (i.e. merge all available galaxy observations with our understanding of physics) and forms the aim of the code that we wrote (BORG: Bayesian Origin Reconstruction from Galaxies).

In contrast to standard techniques, this endeavour leads to a detailed understanding of the network



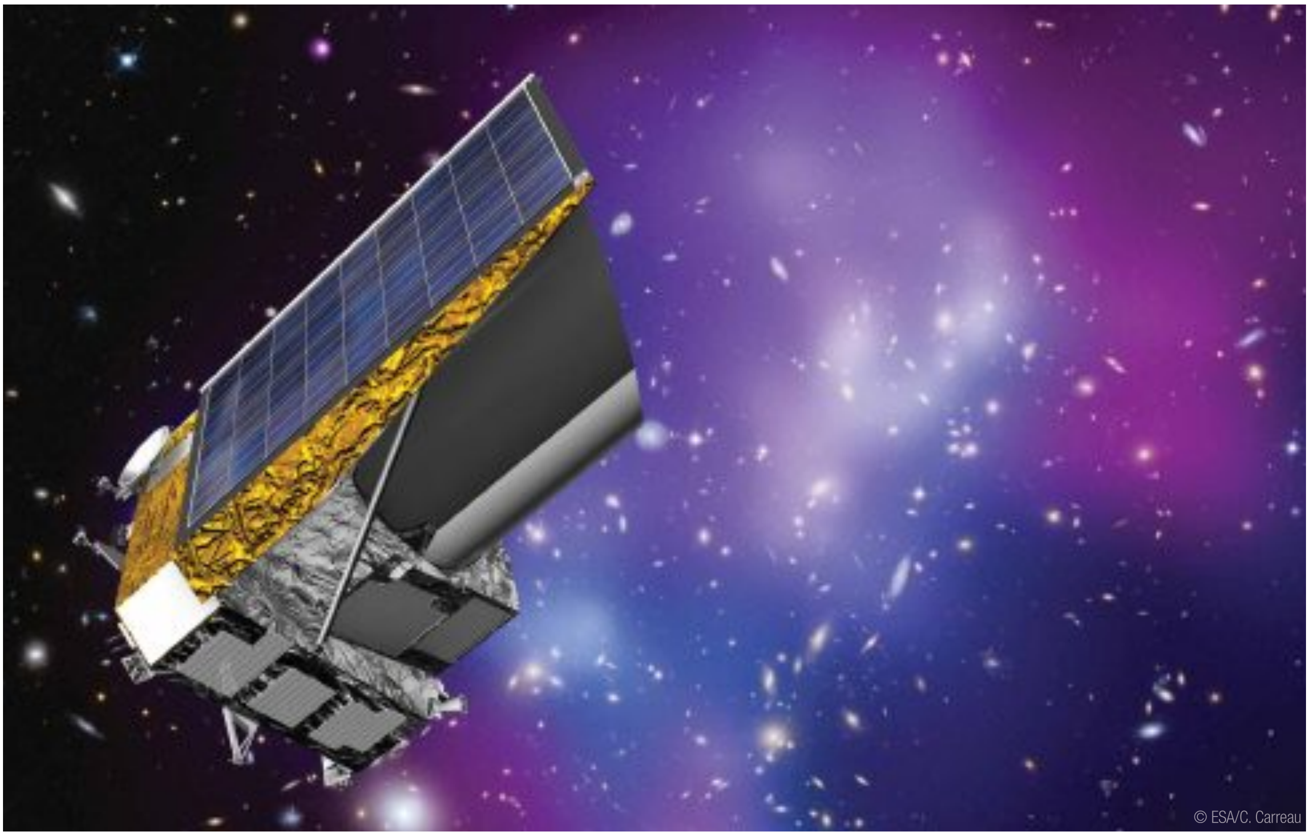
Slice through the celestial equator showing the radial component of the velocity field (in kilometres per second). Blue regions are falling towards us and red regions are flying away from us. Galaxies of the Sloan Digital Sky Survey main galaxy sample are over-plotted. In the centre of the slice, the in-falling dynamics of the Sloan Great Wall, one of the largest structures of the known Universe, can be observed

SDSS

As one of the most successful surveys in the history of astronomy, the Sloan Digital Sky Survey (SDSS) has created the most detailed three-dimensional maps of the Universe ever made, with deep multi-colour images of one-third of the sky, and spectra for more than three million astronomical objects.

The SDSS began regular survey operations in 2000, after a decade of design and construction. It has progressed through several phases – SDSS-I (2000-2005), SDSS-II (2005-2008), SDSS-III (2008-2014), and SDSS-IV (2014-) – each of which has involved multiple surveys with interlocking science goals. The three surveys that comprise SDSS-IV are eBOSS, APOGEE-2, and MaNGA.

Planning is underway for the future of SDSS in its next phase, to begin in 2020 after the end of SDSS-IV. This programme ('After SDSS-IV' or AS4) plans to operate SDSS facilities at Apache Point Observatory, New Mexico, US, and Las Campanas Observatory in Chile, to survey the entire sky, mapping the Milky Way using rapid, wide-field, repeated observations, mapping local volume galaxies using wide integral field spectroscopy, and mapping black holes using time domain spectroscopy of quasars.



of voids, sheets, filaments and clusters that forms the large-scale structure of the Universe, which was so far inaccessible in observations.

Euclid is an ESA mission to map the geometry of the Dark Universe

What would you say were the most significant achievements/results in your recent work to produce new maps of dark matter in the Universe?

The formidable challenge arises since the full statistical description of the data (required for a principled analysis) requires of the order of ten million parameters to be sampled – an extremely high dimensional space. The mathematical tools that allow this to be done have only been known for a few years. These 'data assimilation' techniques belong to the absolute state-of-the-art in cosmology, but also several other sciences (e.g. meteorology, geophysics, oceanography, climate sciences and medical imaging). Therefore, beyond the maps of dark matter dynamics that we have been able to produce (which are interesting in themselves), I would say that the most significant achievement is methodological: we are demonstrating that new astrophysical insights can be wrested from extremely vast

Euclid

An ESA medium class astronomy and astrophysics space mission, Euclid was selected by the European Space Agency (ESA) in October 2011, with its launch planned for 2020. In June 2012, ESA officially selected the 'Euclid Consortium' as the single team having the scientific responsibility of the mission, the data production and of the scientific instruments.

The Euclid mission aims at understanding why the expansion of the Universe is accelerating and what is the nature of the source responsible for this acceleration, which physicists refer to as 'dark energy'.

Euclid will explore how the Universe evolved over the past ten billion years to address questions related to fundamental physics and cosmology on the nature and properties of dark energy, dark matter and gravity. It will also provide insightful information on the physics of the early Universe and on the initial conditions which seed the formation of cosmic structure.

Euclid will observe 15,000 square degrees (deg^2) of the darkest sky that is free of contamination by light from the Milky Way Galaxy and our Solar System. Three 'Euclid Deep Fields' covering around 40 deg^2 in total will also be observed, extending the scientific scope of the mission.

The complete survey represents hundreds of thousands images and several tens of petabytes of data. About ten billion sources will be observed by Euclid, of which more than one billion will be used for weak lensing and several tens of millions of galaxy redshifts will be measured and used for galaxy clustering. The scientific analysis and interpretation of these data is led by the scientists of the Euclid Consortium.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data sets without much reduction. The transition from hypothesis-driven to data-driven research is sometimes referred to as the emerging 'fourth paradigm' of science, and our work falls within this context.

What benefits did adopting a phase-space approach have here?

Using phase-space tools allowed us to assess the morphology of the cosmic web in the nearby Universe as probed by the Sloan Digital Sky Survey (SDSS), by means of a dynamical characterisation of the corresponding mass distribution. Translating the observed distribution of a discrete number of galaxies into a full 6D (three positions + three velocities) phase-space rendering of the spatial dark matter distribution and velocity field structure is something that was hardly imaginable ten years ago. It leads to a valuable study of the void population and of the filamentary network on the basis of their dynamical characteristics. Remarkably, it also allows a new delineation and identification of the cluster population as the sites where ample vorticity has been generated.

Do you have any plans to continue using SDSS data? What are your hopes for future initiatives set to explore dark matter – such as Euclid?

My collaborators and I are indeed currently working with new SDSS data, which have been/are acquired after the main galaxy sample (SDSS-II). These include the CMASS and LOWZ samples, the two of which form BOSS (the Baryon Oscillation Spectroscopic Survey), a part of the SDSS-III programme. In the future, we also plan to use eBOSS (the extended Baryon Oscillation Spectroscopic Survey) data, which are currently being taken as part of the fourth phase of operations (SDSS-IV).

Generally, accessing the phase-space structure of dark matter in galaxy surveys opens up new ways of assessing the validity of theoretical models in light of observations. Applying these techniques to the next-generation deep surveys of galaxies, such as the one performed by the Euclid satellite (http://www.euclid-ec.org), the Dark Energy Spectroscopic Instrument (http://desi.lbl.gov) or the Large Synoptic

Accessing the phase-space structure of dark matter in galaxy surveys opens up new ways of assessing the validity of theoretical models in light of observations

DESI

The Dark Energy Spectroscopic Instrument (DESI) will measure the effect of dark energy on the expansion of the Universe. It will obtain optical spectra for tens of millions of galaxies and quasars, constructing a three-dimensional map spanning the nearby universe to ten billion light years.

DESI will be conducted on the Mayall four-metre telescope at Kitt Peak National Observatory in Arizona, US, starting in 2018. It is supported by the Department of Energy Office of Science to perform this Stage IV dark energy measurement, using baryon acoustic oscillations (BAO) and other techniques that rely on spectroscopic measurements.

DESI will measure the expansion history of the Universe using BAO imprinted in the clustering of galaxies, quasars and the intergalactic medium. The BAO technique is a robust way to extract cosmological distance information from the clustering of matter and galaxies. It relies only on very large-scale structures and does so in a manner that enables scientists to separate the acoustic peak of the BAO signature from uncertainties in most systematic errors in the data. BAO was identified in the 2006 Dark Energy Task Force report as one of the key methods for studying dark energy. In May 2014, the High-Energy Physics Advisory Panel, a federal advisory committee, commissioned by the US Department of Energy (DOE) and the National Science Foundation (NSF), endorsed DESI.

Survey Telescope (https://www.lsst.org), will allow unprecedented tests of the standard paradigm of cosmic web formation and evolution. My collaborators and I are extremely enthusiastic about these opportunities and we are looking forward to working on these analyses.

The construction phase of the LSST will deliver the facilities needed to conduct the survey: a large-aperture, wide-field, optical imaging telescope, a giga-pixel camera, and a data management system

Finally, and in light of the above, where will your future research interests lie? What are your hopes for the future?

My future research plan – which I will be carrying out as part of my Research Fellowship at the Imperial Centre for Inference and Cosmology (ICIC) at Imperial College London – addresses a central problem in doing cosmology with galaxy surveys: accessing the untapped information in the large number of small-scale fluctuation modes. Extending cosmological data analysis to smaller, progressively more non-linear scales is an unsolved problem at the forefront of physical cosmology.

The prize for solving this problem is a detailed understanding of the cosmic web (our new maps of dark matter dynamics being a part of this aspect), but also, potentially, a vast gain of information for the determination of fundamental physics parameters, such as the equation of state of dark energy or neutrino masses.

We live in unique and very exciting times in cosmology research, when we expect to see a qualitative leap in our knowledge of the Universe within a lifetime. I consider myself incredibly fortunate to be part of this adventure.

LSST

The goal of the Large Synoptic Survey Telescope (LSST) project is to conduct a ten-year survey of the sky that will deliver a 200 petabyte set of images and data products that will address some of the most pressing questions about the structure and evolution of the Universe and the objects in it. The LSST survey is designed to address four science areas: understanding dark matter and dark energy; hazardous asteroids and the remote Solar System; the transient optical sky; and the formation and structure of the Milky Way.

The scientific questions that LSST will address are profound, and yet the concept behind the design of the LSST project is remarkably simple: conduct a deep survey over an enormous area of sky; do it with a frequency that enables images of every part of the visible sky to be obtained every few nights; and continue in this mode for ten years to achieve astronomical catalogues thousands of times larger than have ever previously been compiled.

The construction phase of the project will deliver the facilities needed to conduct the survey: a large-aperture, wide-field, optical imaging telescope, a giga-pixel camera, and a data management system.

LSST will probe the nature of dark matter and dark energy using several billion galaxies, employing a variety of methods to enable cross-checking of results. By mapping galaxies through time and space, cataloguing their masses, and studying their influence on the distortion of space-time, LSST will gain new insight into the nature of dark matter and dark energy. Of particular interest are the dynamical behaviours of dark energy, i.e. how it behaves with cosmic time or with redshift, and the influence of dark matter on the development of structure on a cosmic scale.

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