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Calculating what's in the universe from the biggest color 3-D map

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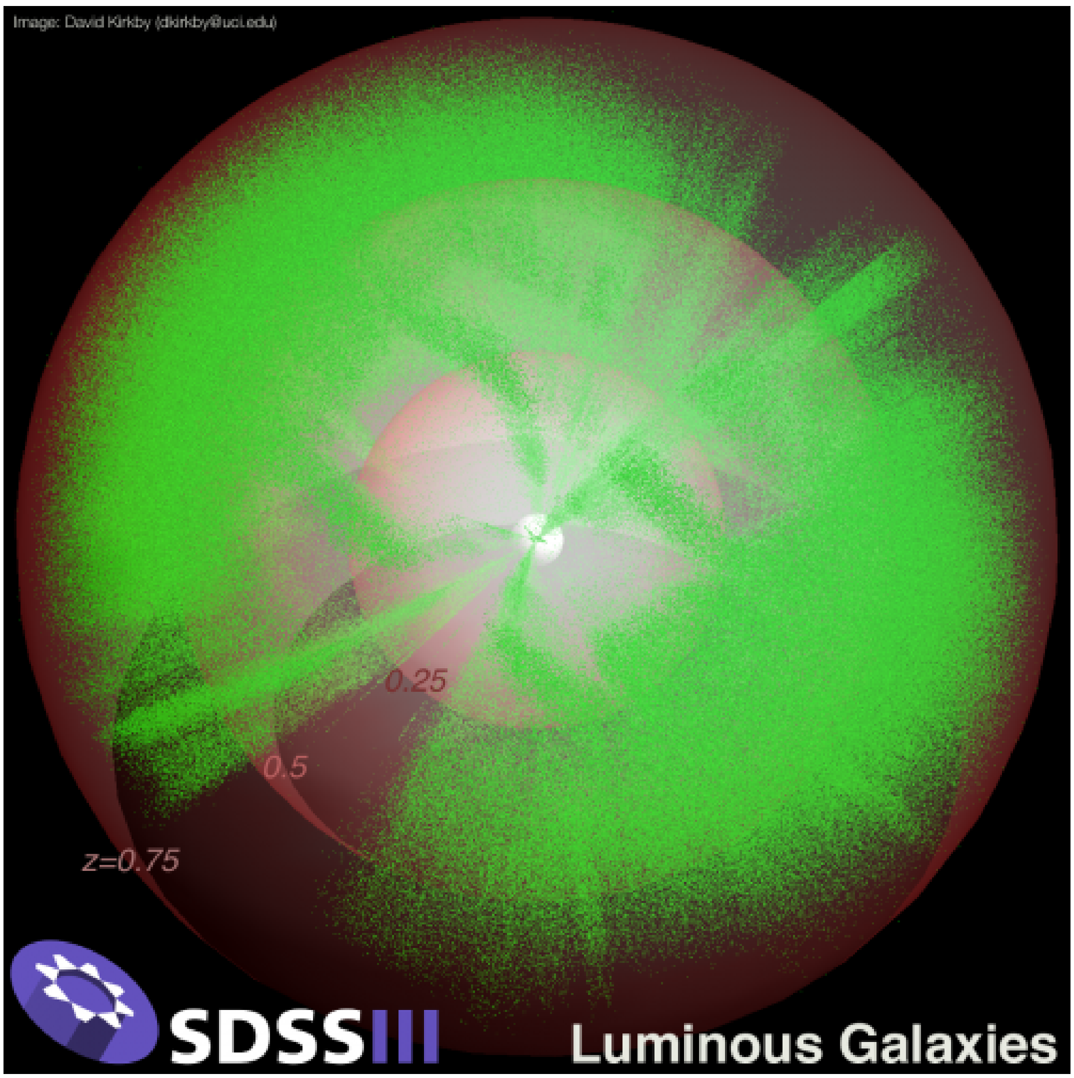

The Sloan Digital Sky Survey III surveyed 14,000 square degrees of the sky, more than a third of its total area, and delivered over a trillion pixels of imaging data. This image shows over a million luminous galaxies at redshifts indicating times when the universe was between seven and eleven billion years old, from which the sample in the current studies was selected. Credit: David Kirkby of the University of California at Irvine and the SDSS collaboration

Since 2000, the three Sloan Digital Sky Surveys (SDSS I, II, III) have surveyed well over a quarter of the night sky and produced the biggest color map of the universe in three dimensions ever. Now scientists at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) and their SDSS colleagues, working with DOE's National Energy Research Scientific Computing Center (NERSC) based at Berkeley Lab, have used this visual information for the most accurate calculation yet of how matter clumps together – from a time when the universe was only half its present age until now.

"The way galaxies cluster together over vast expanses of the sky tells us how both ordinary visible matter and underlying invisible dark matter are distributed, across space and back in time," says Shirley Ho, an astrophysicist at Berkeley Lab and Carnegie Mellon University, who led the work. "The distribution gives us cosmic rulers to measure how the universe has expanded, and a basis for calculating what's in it: how much dark matter, how much dark energy, even the mass of the hard-to-see neutrinos it contains. What's left over is the ordinary matter and energy we're familiar with."

For the present study Ho and her colleagues first selected 900,000 luminous galaxies from among over 1.5 million such galaxies gathered by the Baryon Oscillation Spectrographic Survey, or BOSS, the largest component of the still-ongoing SDSS III. Most of these are ancient red galaxies, which contain only red stars because all their faster-burning stars are long gone, and which are exceptionally bright and visible at great distances. The galaxies chosen for this study populate the largest volume of space ever used for galaxy clustering measurements. Their brightness was measured in five different colors, allowing the redshift of each to be estimated.

"By covering such a large area of sky and working at such large distances, these measurements are able to probe the clustering of galaxies on incredibly vast scales, giving us unprecedented constraints on the expansion history, contents, and evolution of the universe," says Martin White of Berkeley Lab's Physics Division, a professor of physics and astronomy at the University of California at Berkeley and chair of the BOSS science survey teams. "The clustering we're now measuring on the largest scales also contains vital information about the origin of the structure we see in our maps, all the way back to the epoch of inflation, and it helps us to constrain – or rule out – models of the very early universe."

After augmenting their study with information from other data sets, the team derived a number of such cosmological constraints, measurements of the universe's contents based on different cosmological models. Among the results: in the most widely accepted model, the researchers found – to less than two percent uncertainty – that dark energy accounts for 73 percent of the density of the universe.

The team's results are presented January 11 at the annual meeting of the American Astronomical Society in Austin, Texas, and have been submitted to the *Astrophysical Journal*. They are currently available online at http://arxiv.org/abs/1201.2137.

The power of the universe

"The way mass clusters on the largest scales is graphed in an angular power spectrum, which shows how matter statistically varies in density across the sky," says Ho. "The power spectrum gives a wealth of information, much of which is yet to be exploited." For example, information about inflation – how the universe rapidly expanded shortly after the big bang – can be derived from the power spectrum.

Closely related to the power spectrum are two "standard rulers," which can be used to measure the history of the expansion of the universe. One ruler has only a single mark – the time when matter and radiation were exactly equal in density.

"In the very early universe, shortly after the big bang, the universe was hot and dominated by photons, the fundamental particles of radiation," Ho explains. "But as it expanded, it began the transition to a universe dominated by matter. By about 50,000 years after the big bang, the density of matter and radiation were equal. Only when matter dominated could structure form."

The other cosmic ruler is also big, but it has many more than one mark in the power spectrum; this ruler is called BAO, for baryon acoustic oscillations. (Here, baryon is shorthand for ordinary matter.) Baryon acoustic oscillations are relics of the sound waves that traveled through the early universe when it was a hot, liquid-like soup of matter and photons. After about 50,000 years the matter began to dominate, and by about 300,000 years after the big bang the soup was finally cool enough for matter and light to go their separate ways.

Differences in density that the sound waves had created in the hot soup, however, left their signatures as statistical variations in the distribution of light, detectable as temperature variations in the cosmic microwave background (CMB), and in the distribution of baryons. The CMB is a kind of snapshot that can still be read today, almost 14 billion years later. Baryon oscillations – variations in galactic density peaking every 450 million light-years or so – descend directly from these fluctuations in the density of the early universe.

BAO is the target of the Baryon Oscillation Spectroscopic Survey. By the time it's completed, BOSS will have measured the individual spectra of 1.5 million galaxies, a highly precise way of measuring their redshifts. The first BOSS spectroscopic results are expected to be announced early in 2012.

Meanwhile the photometric study by Ho and her colleagues deliberately uses many of the same luminous galaxies but derives redshifts from their brightnesses in different colors, extending the BAO ruler back over a previously inaccessible redshift range, from $z = 0.45$ to $z = 0.65$ (z stands for redshift).

"As an oscillatory feature in the power spectrum, not many things can corrupt or confuse BAO, which is why it is considered one of the most trustworthy ways to measure dark energy," says Hee-Jong Seo of the Berkeley Center for Cosmological Physics at Berkeley Lab and the UC Berkeley Department of Physics, who led BAO measurement for the project. "We call BAO a standard ruler for a good reason. As dark energy stretches the universe against the gravity of dark matter, more dark energy places galaxies at a larger distance from us, and the BAO imprinted in their distribution looks smaller. As a standard ruler the true size of BAO is fixed, however. Thus the apparent size of BAO gives us an estimate of the cosmological distance to our target galaxies – which in turn depends on the properties of dark energy."

Says Ho, "Our study has produced the most precise photometric measurement of BAO. Using data from the newly accessible redshift range, we have traced these wiggles back to when the universe was about half its present age, all the way back to $z = 0.54$."

Seo adds, "And that's to an accuracy within 4.5 percent."

Reining in the systematics

"With such a large volume of the universe forming the basis of our study, precision cosmology was only possible if we could control for large-scale systematics," says Ho. Systematic errors are those with a physical basis, including differences in the brightness of the sky, or stars that mimic the colors of distant galaxies, or variations in weather affecting "seeing" at the SDSS's Sloan Telescope – a dedicated 2.5 meter telescope at the Apache Point Observatory in southern New Mexico.

After applying individual corrections to these and other systematics, the team cross-correlated the effects on the data and developed a novel procedure for deriving the best angular power-spectrum of the universe with the lowest statistical and systematic errors.

With the help of 40,000 central-processing-unit (CPU) hours at NERSC and another 20,000 CPU hours on the Riemann computer cluster at Berkeley Lab, NERSC's powerful computers and algorithms enabled the team to use all the information from galactic clustering in a huge volume of sky, including the full shape of the power spectrum and, independently, BAO, to get excellent cosmological constraints. The data as well as the analysis output are stored at NERSC.

"Our dataset is purely imaging data, but our results are competitive with the latest large-scale spectroscopic surveys," Ho says. "What we lack in redshift precision, we make up in sheer volume. This is good news for future imaging surveys like the Dark Energy Survey and the Large Synoptic Survey Telescope, suggesting they can achieve significant cosmological constraints even compared to future spectroscopy surveys."

More information: Animated visualizations of the luminous galaxies in the SDSS-III dataset can be accessed at darkmatter.ps.uci.edu/lrg-sdss

"Clustering of Sloan Digital Sky Survey III photometric luminous galaxies: The measurement, systematics, and cosmological implications," by Shirley Ho, Antonio Cuesta, Hee-Jong Seo, Roland de Putter, Ashley J. Ross, Martin White, Nikhil Padmanabhan, Shun Saito, David J. Schlegel, Eddie Schlafly, Uroŝ Seljak, Carlos Hernández-Monteagudo, Ariel G. Sánchez, Will J. Percival, Michael Blanton, Ramin Skibba, Don Schneider, Beth Reid, Olga Mena, Matteo Viel, Daniel J. Eisenstein, Francisco Prada, Benjamin Weaver, Neta Bahcall, Dimitry Bizyaev, Howard Brewinton, Jon Brinkman, Luiz Nicolaci da Costa, John R. Gott, Elena Malanushenko, Viktor Malanushenko, Bob Nichol, Daniel Oravetz, Kaike Pan, Nathalie Palanque-Delabrouille, Nicholas P. Ross, Audrey Simmons, Fernando de Simoni, Stephanie Snedden,and Christophe Yeche, has been submitted to *Astrophysical Journal* and is now available online at arxiv.org/abs/1201.2137 .

"Acoustic scale from the angular power spectra of SDSS-III DR8 photometric luminous galaxies," by Hee-Jong Seo, Shirley Ho, Martin White, Antonio Cuesta, Ashley Ross, Shun Saito, Beth Reid, Nikhil Padmanabhan, Will J. Percival, Roland de Putter, David Schlegel, Daniel Eisenstein, Xiaoying Xu, Donald Schneider, Ramin Skibba, Licia Verde, Robert Nichol, Dmitry Bizyaev, Howard Brewington, J. Brinkmann, Luiz Costa, J. Gott III, Elena Malanushenko, Viktor Malanushenko, Dan Oravetz, Nathalie Palanque-Delabrouille, Kaike Pan, Francisco Prada, Nicholas Ross, Audrey Simmons, Fernando Simoni, Alaina Shelden, Stephanie Snedden, and Idit Zehavi, has been submitted to *Astrophysical Journal* and will be available online shortly.

Provided by Lawrence Berkeley National Laboratory

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