A Dark Matter map of our Local Cosmic Neighborhood

Since it was first theorized in the 1970s, astrophysicists and cosmologists have done their best to resolve the mystery that is Dark Matter. This invisible mass is believed to make up 85% of the matter in the Universe and accounts for 27% of its mass-energy density. But more than that, it also provides the large-scale skeletal structure of the Universe (the cosmic web), which dictates the motions of galaxies and material because of its gravitational influence.

Unfortunately, the mysterious nature of Dark Matter means that astronomers cannot study it directly, thus prevented them from measuring its distribution. However, it is possible to infer its distribution based on the observable influence its gravity has on local galaxies and other celestial objects. Using cutting-edge machine-learning techniques, a team of Korean-American astrophysicists was able to produce the most detailed map yet of the local Universe that shows what the “cosmic web” looks like.

The team responsible for this breakthrough was led by senior researcher Sungwook E. Hong from the University of Seoul and the Korea Astronomy and Space Science Institute (KASI). He was joined by associate professor Donghui Jeong of the Institute for
Gravitation and the Cosmos (IGS) at Penn State, and researchers Ho Seong Hwang and Juhan Kim of Seoul National University and the Korea Institute for Advanced Study (KIAS), respectively.

How Do We Know Dark Matter Exists?

In the past, previous attempts to map the cosmic web started with a model of the early Universe and then simulated its evolution over the course of billions of years. However, this method has met with limited success because of the tremendous amount of computing power required. Taking a different approach, the team built a model that
used machine learning to predict the distribution of dark matter based on the known
distribution and motion of galaxies.

The team built and trained this model with the help of Illustris-TNG, a cosmology
project that has conducted multiple simulations complete with galaxies, gasses, other
forms of baryonic (aka. visible) matter, as well as dark matter. The team selected
simulated galaxies from Illustris-TNG that were comparable to the Milky Way and
identified the properties that are needed to predict dark matter distribution. Said Jeong:

“Ironically, it’s easier to study the distribution of dark matter much further
away because it reflects the very distant past, which is much less complex.
Over time, as the large-scale structure of the universe has grown, the
complexity of the universe has increased, so it is inherently harder to make
measurements about dark matter locally.”

“When given certain information, the model can essentially fill in the gaps
based on what it has looked at before. The map from our models doesn’t
perfectly fit the simulation data, but we can still reconstruct very detailed
structures. We found that including the motion of galaxies—their radial
peculiar velocities—in addition to their distribution drastically enhanced the
quality of the map and allowed us to see these details.”
Map of the distribution of dark matter within the local universe, using a model to infer its location due to its gravitational influence on galaxies. Credit: Hong et. al., Astrophysical Journal

The next step involved applying this model to real data from the local Universe, which the team obtained from the Cosmicflow-3 database. This astronomical catalog contains comprehensive data on the distribution and movement of over 17,000 galaxies in a 650 million light-year (200 megaparsecs) region around the Milky Way. The resulting map successfully reproduced known prominent structures in the local Universe.

These included the “Local Sheet,” region of space that contains the Milky Way, Andromeda (and other members of the “local group”), and the galaxies of the Virgo Cluster. Another prominent structure was the “Local Void,” a relatively empty region of space next to the local group. In addition, the map identified several new structures, such as smaller filamentary structures that act as hidden connections between galaxies.

As you can see from the cross-sections of the map (shown above), large concentrations of luminous matter are indicated in red while largely empty stretches are indicated in blue. Galaxies are denoted as small black dots, the Milky Way is denoted by the black X in the center, and the arrows represent the motion of these large-scale structures. These connecting filaments, which appear as wispy yellow strings, require follow-up
observation in order to learn more about these previously unknown features. Said Jeong:

“Having a local map of the cosmic web opens up a new chapter of cosmological study. We can study how the distribution of dark matter relates to other emission data, which will help us understand the nature of dark matter. And we can study these filamentary structures directly, these hidden bridges between galaxies.”

“Because dark matter dominates the dynamics of the universe, it basically determines our fate. So we can ask a computer to evolve the map for billions of years to see what will happen in the local universe. And we can evolve the model back in time to understand the history of our cosmic neighborhood.”

Illustris simulation, showing the distribution of dark matter in 350 million by 300,000 light-years. Galaxies are shown as high-density white dots (left) and as normal, baryonic matter (right). Credit: Markus Haider/Illustris
For example, scientists have known for some time that the Milky Way and Andromeda galaxies are slowly getting closer to each other. However, whether or not they will eventually collide to form a supergalaxy (uncreatively nicknamed Milkomeda) in an estimated 4.5 billion years remains unclear. By studying the dark matter filaments that connect our two galaxies, astrophysicists could gain valuable insights into their futures.

Hong and his colleagues also plan to improve upon the accuracy of their map by adding more galaxies. This will be possible thanks to next-generation missions like the James Webb Space Telescope (JWST), which will finally launch to space on October 31st, 2021. Using its advanced suite of instruments, the JWST will study the Universe in the long-wavelength visible and near-infrared to mid-infrared wavelengths.

This will allow astronomers to identify galaxies that are smaller, fainter, and located farther away from our Solar System. Improvements in computing and machine learning will also lead to bigger and better simulations that can account for more galaxies over longer stretches of time. Similarly, missions like the ESA's Gaia Observatory are providing more accurate data concerning the proper motions and velocities of galaxies (astrometry).

It’s planned successor, the ESA’s Euclid Observatory, is scheduled for launch in 2022 and will gather data on two billion galaxies across 10 billion light-years of space. This will be used to create the most detailed 3D map of the local area of the Universe to date,
which is expected to reveal vital clues about the role of Dark Matter (and Dark Energy) in cosmic evolution. These maps will give astronomers a means of comparison that will let them know that their physics models are right on the money.

Further Reading: PSU, The Astrophysical Journal

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