Success Stories in Universe Sciences

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Space:

An endless expanse we can barely pierce, even with the most advanced telescopes. Universe simulations like those performed on PRACE supercomputers, however, can show us more. Scientists have studied the evolution of stars and galaxies from the Big Bang until today. With supercomputers, they can explore the role of black holes and supernovae, test theories, or improve the interpretation of observations from telescopes. Here, we showcase three of the most relevant simulation projects in universe science: from a closer look into the history of the Milky Way, to simulations of thousands of galaxies, to the exploration of dark matter and dark energy — the biggest unsolved mysteries in the makeup of our universe.

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On the birth and evolution of galaxies

Even today, insight into the evolution of the universe is limited by the complexity of "ordinary" baryonic matter, as opposed to dark matter. Ordinary matter particles interact electromagnetically, which means that they emit radiation when they collide. They lose energy, cool down, and can be compressed to the high densities necessary to form stars and galaxies. These processes are challenging to model — even more so since the range of timescales involved is huge, from mere hundreds of years to the age of the universe.

"EAGLE was the first set of simulations that produced an overall realistic population of galaxies when compared to observations," says Joop Schaye, a professor at Leiden University and the project's PI. In fact, the breakthrough simulations have been used by many scientists for a variety of investigations. Schaye's team especially gained insights into the connection of stellar masses and the masses of dark matter haloes, which are the phenomena that trigger galaxy formation, and investigated why galaxies stop forming stars. "We knew that galaxies form stars with a frequency in proportion to the amount of dark matter present — at least up to a point," says Schaye. With EAGLE, the team was able to follow how gas spiralling into black holes at the centre of galaxies causes an energy rise and chain reaction that ultimately leads to the collapse of star formation. Another important application of the EAGLE simulations is to improve the interpretation of observations from telescopes. "Observations drive progress in astronomy, but they are often difficult to interpret," says Schaye. Simulations can help because they can be used to generate virtual observations that can then be compared back to what is really going on in the simulation revealing biases in analyses.

In Summer 2022, Schaye's team is already planning to run their next set of simulations named COLIBRE. A faster code will allow for a 100-fold higher resolution than EAGLE — and simulate the evolution of hundreds of thousands of galaxies.

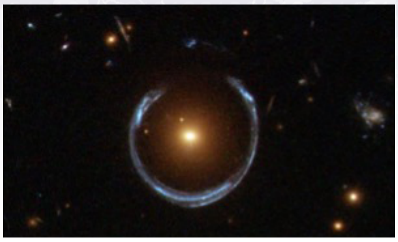
Supercomputing Resources: Hawk at GCS/HLRS (Germany)

A Dark Matter Mystery

While "ordinary" matter accounts for only 4 percent of today's universe, 28 percent is made up of dark matter. And dark energy, which is thought to drive the acceleration of the universe's expansion, represents almost 70 percent of the total matter and energy content. To better understand the latter phenomenon, the ESA Euclid mission aims to map the entire universe by recording the positions and masses of its galaxies and capturing the distribution of dark matter by measuring gravitational lensing — a dark matter induced light distortion. Dark matter distribution, in turn, relates to the physical properties of dark energy.

Even before the satellite's launch, its future measurements need to be predicted to ensure that the aim is, in fact, realistic. That's why a team led by Joachim Stadel, a professor at the University of Zurich, performed a giant simulation of the universe that included over 4 trillion particles, achieving the largest mock galaxy catalogue ever assembled. "From this mock universe, colleagues will simulate what Euclid would measure — and compare the outcome back to the mock universe, to determine error margins and improve data analysis," says Stadel. Such a simulation requires a certain volume and resolution to allow scientist to draw connections between galaxies and dark matter. "With our Euclid simulation, we are just reaching this threshold."

Supercomputing Resources: Piz Daint at ETH Zurich/CSCS (Switzerland)



Gravitational lensing: The circular mirage arises from the light of a galaxy that is aligned precisely behind the central galaxy.

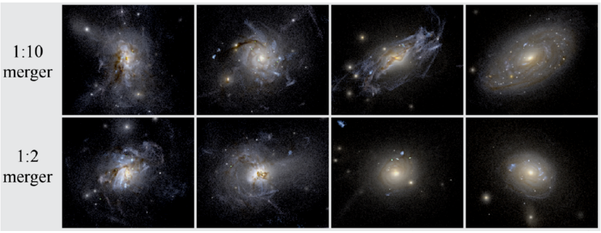
Image credit: ESA/Hubble

From humble beginnings to the Milky Way of today

Unlike celestial objects far away, we can study the Milky Way in luxurious detail: We can map the positions and velocities of billions of stars and measure their chemical makeup, which points to the composition of the cosmic gas at their birth. But to better understand the evolution of the Milky Way and of disk galaxies in general, such observations need to be supported by simulations covering the entire history of the universe.

Now, Oscar Agertz, an associate professor at Lund University, and his co-workers have carried out a set of such simulations using what they call "genetic modification". "With this technique developed by the group of Andrew Pontzen at University College London, we can change fundamental aspects early in a galaxy's history and then follow the effect," Agertz explains. His team is currently studying galaxy mergers. "We know from observations that, in the evolution of the Milky Way, a merger with another galaxy likely happened around ten billion years ago," recounts Agertz. Within the simulations, the team experimented with partner galaxies, varying their masses. Preliminary analyses indicate that many galaxy mergers do not lead to a Milky Way-like structure. It is only after a relatively light collision with a 10-fold smaller galaxy that a large disk galaxy like the Milky Way evolves. The team will now further analyse the simulation data to investigate how well a galaxy can recover after a major collision and on what circumstances this depends.

Supercomputing Resources: Joliot-Curie Rome at GEINCI (France)



The formation of a galaxy from the early universe to today (from left to right): Two mergers are simulated, the first with a galaxy ten times smaller (ratio 1:10), the second with a larger one (ratio 1:2). It is only after the light collision that a disk galaxy similar to our Milky Way evolves. *Image credit:* O. Agertz

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