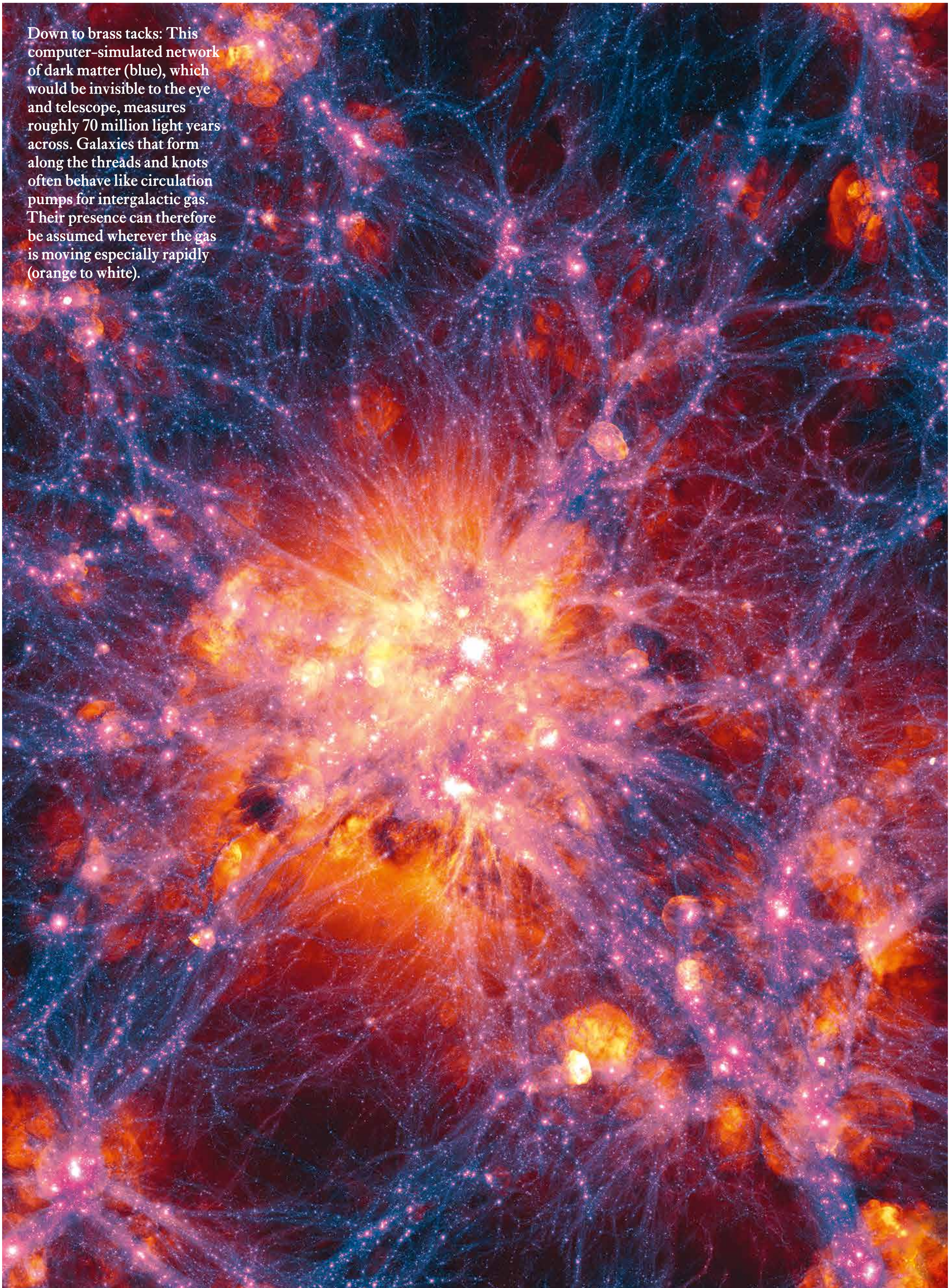


Down to brass tacks: This computer-simulated network of dark matter (blue), which would be invisible to the eye and telescope, measures roughly 70 million light years across. Galaxies that form along the threads and knots often behave like circulation pumps for intergalactic gas. Their presence can therefore be assumed wherever the gas is moving especially rapidly (orange to white).

PHOTO: ILLUSTRIS COLLABORATION

THE DIGITAL UNIVERSE

TEXT: THOMAS BÜHRKE

Dark matter and dark energy determine how the universe looks. But that is pretty much all cosmologists know about these phenomena. Their nature is still completely unclear. While they cannot be directly observed, a team led by Volker Springel at the Max Planck Institute for Astrophysics in Garching is simulating how this mysterious matter and enigmatic energy have influenced the development of space, which has brought further insights about their properties as well as other aspects.

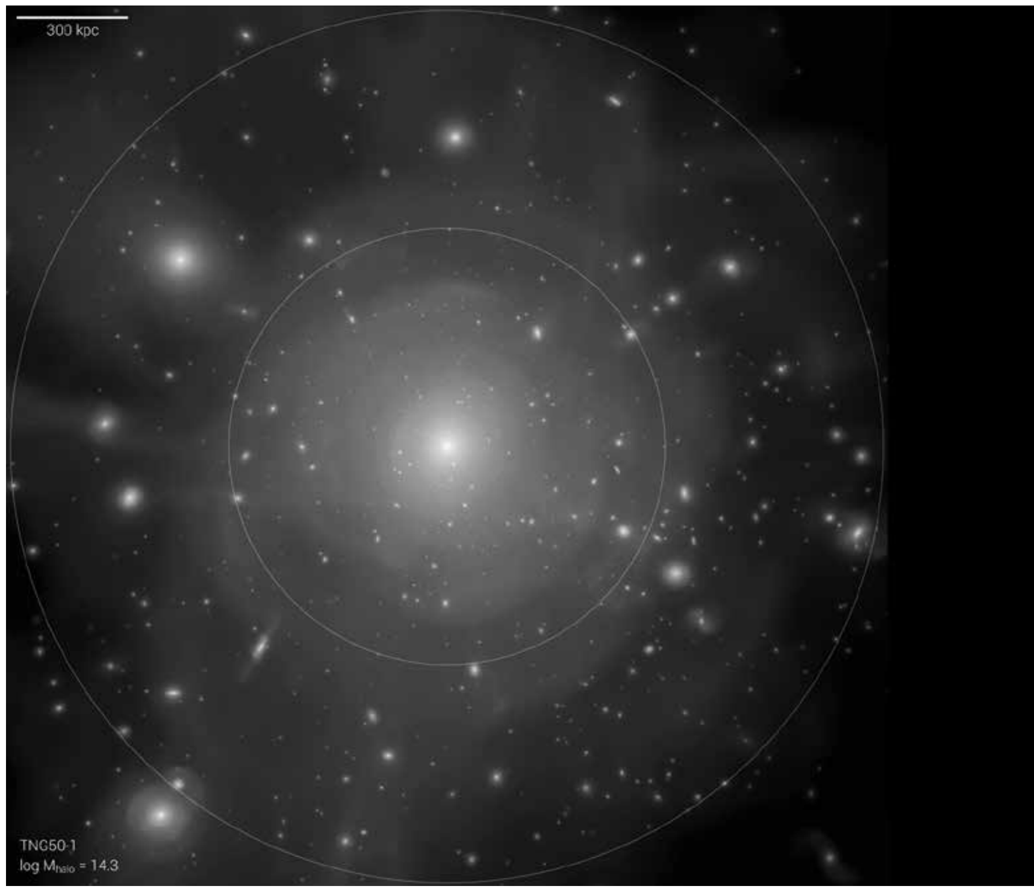
Dozens of black boxes stand like mystical monoliths at the Leibniz Supercomputing Centre in Garching. Combined, they form the SuperMUC-NG, the highest-performance supercomputer in Germany. This machine performs an unfathomable 27 billion calculations per second – ideal for Springel's massive simulations. Springel joined the Max Planck Institute for Astrophysics in the mid-1990s, just as British astrophysicist Simon White was beginning to build a research group. The much-lauded White is considered a pioneer in numerical simulations of the large-scale structure of the cosmos. In other words: he used computer models to examine how the diversity of galaxies and galaxy clusters we see today formed from hot gas in the billions of years following the Big Bang. The goal goes beyond just simulating the development of the universe so that it takes the same shape on the computer that we can observe today with telescopes: more importantly, when the calculations result in the correct outcome, this is a good indication that the cosmologists have a proper understanding of the underlying processes.

Unlike most astronomers, Springel never felt the urge to observe the sky through a telescope. A desire to study physics was present from an early age, however, and as a high school student he had already begun exploring the numerical side of astrophysics. "I did, in fact, participate in 'Jugend forscht' [a science competition for young Germans] with a computer simulation," he recalls. When White's work caught his attention later on, he knew he wanted White to be his PhD supervisor. It turned out to be the right choice.

Twenty years and several major breakthroughs later, Springel is now a much-lauded scientist in his own right.

The cosmic simulations follow a relatively simple principle. Particles of virtual matter are placed in a digital volume. Their motion, determined solely by gravitational effects between the particles, is then tracked at specific increments in time. Fortunately, the initial configuration is known. It can be perceived in cosmic microwave background radiation. This arose around 380,000 years after the Big Bang and is detectable as an almost homogeneous distribution across the entire sky. "With Europe's Planck space telescope, we have managed to determine a spot pattern with tiny fluctuations, which can be attributed to density variations in the primordial gas," explains Springel. Consequently, the gas, too, must have had a relatively homogeneous distribution shortly after the Big Bang. And this observation provides the initial conditions for the simulations.

The density variations in the primordial gas were so low that individual regions with more accumulated mass would have been unable to condense under their own gravity into today's galaxies and galaxy clusters, even over billions of years. This is partly because when a gas contracts, it heats up, creating thermal pressure, which counteracts further contraction into, say, a star. The phenomenon is familiar to anyone who has pumped a tire. If you hold the valve closed and compress the air, it warms up and can't be compressed anymore. And yet galaxies exist – and this is why researchers 40 years ago were already postulating the existence of dark matter particles as galactic midwives. When these particles compress under their own gravity, no pressure builds to counteract further compression. And that enabled the dark matter to form gigantic structures, which worked as gravity traps. Ordinary matter poured in, cooled slowly, and formed stars and galaxies. Simulations help us understand how dark matter is distributed in the universe and what properties it might have. Dark matter neither emits light nor absorbs it. Although a billion or so particles of dark matter presumably pass through our bodies every second, it remains unclear what they are made of. We know, however, that they account for around five times more of the total mass of the universe than ordinary matter, which quite clearly interacts with light and is therefore visible to telescopes. For that reason, numerical simulations of cosmic evolution always have to factor in both dark matter and the ordinary matter we can see. All stars. planets, and we ourselves are made of the latter.



Around 20 years ago, a team led by White and Springel attracted widespread attention with the Millennium simulation. The researchers succeeded in calculating how the distribution of dark matter in an expanding universe must have changed over billions of years. The simulation involved more than 10 billion dark matter particles in a cubical volume with

SUMMARY

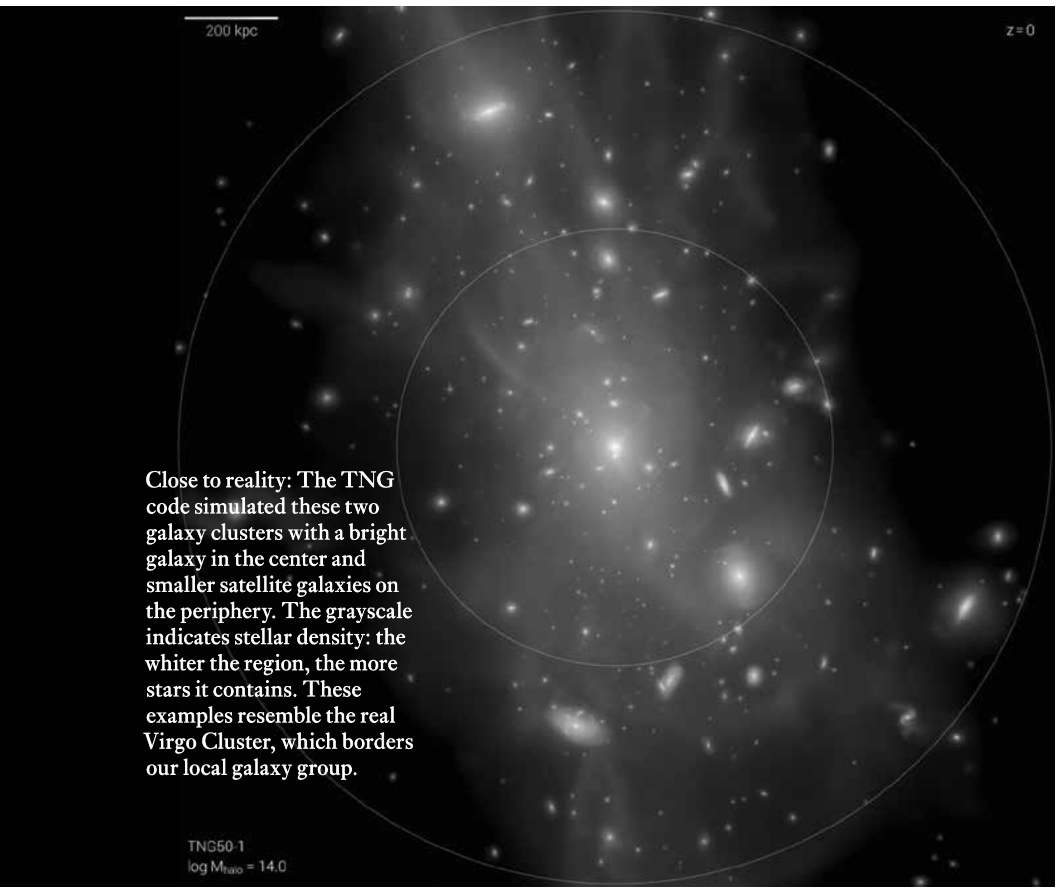
Numerical simulations on supercomputers allow researchers to reconstruct the development of the cosmos from hot primordial gas to today's galaxies.

The calculations account for both the visible matter that every star and planet is made of and dark matter and dark energy, and they provide information on their distribution and properties.

PHOTO: TNG COLLABORATION

sides measuring 1.6 billion light years. Impressively, the outcome coincided with the distribution of galaxies in the universe as observed from Earth with telescopes. Galaxies gather in groups and clusters of various sizes. These in turn are tied to galaxy superclusters, which form a bubble-like structure of threads and walls encompassing vast empty spaces, much like foam. The galaxies seem to have formed precisely where dark matter clumped together in the cosmological simulation.

Many months of computing time were required to simulate the development of dark matter particles from the Big Bang 13.4 billion years ago to today in 11,000 time increments – a resounding success, but with two caveats. First, each particle in the computer simulation represented a mass of 860 million solar masses, equivalent to the mass of a small galaxy. The simulation therefore represented the distribution of dark matter at a very low resolution. Second, the Millennium simulation was only able to calculate the distribution of dark matter. Ordinary matter was added at the end in the form of radiant galaxies using a simple and highly uncertain procedure.



Close to reality: The TNG code simulated these two galaxy clusters with a bright galaxy in the center and smaller satellite galaxies on the periphery. The grayscale indicates stellar density: the whiter the region, the more stars it contains. These examples resemble the real Virgo Cluster, which borders our local galaxy group.

It would soon become clear that galaxy formation depends not only on the size of the dark matter structures, known as halos, but also on their time of formation and their rotation, shape, density distribution, and possible substructure. In other words, the formation of halos is a highly dynamic process. Dark matter halos can merge, resulting in larger structures with small subhalos. To approximate the actual, observable distribution of galaxies, a top-tier algorithm runs a parallel simulation of ordinary matter, which forms automatically into galaxies along the dark matter's gravity trap. This requires a lot more processing power, because it has to factor in physical processes that do not occur with dark matter. When ordinary matter compresses, for example, it heats up until nuclear fusion is triggered in very dense parts of gas clouds, resulting in stars. Massive stars in particular change their environment in turn with intense radiation and strong particle winds until they explode as supernovae. The formation of cosmic structures therefore becomes a self-regulating process in which stars act on their environment, influencing the development of the next generation of stars and by extension the shape of the galaxy itself.

The Illustris simulation was the first to account for this complex interaction. A team led by Springel and Mark Vogelsberger of Massachusetts Institute of Technology ran the simulation to calculate the numerous physical interactions between dark and ordinary matter throughout the entire history of the cosmos. And although it simulated a universe only one 70th the size of the Millennium simulation, it was a real processor hog. Even so, the results were astonishing: the sophisticated models actually yielded a realistic population of galaxies like the ones we observe today.

An eye for detail

One trick played a decisive role in their success: the moving-mesh code known as Arepo. Rather than simulating the universe in the standard way as a rigid mesh, Arepo uses a moving mesh whose cells adjust their size dynamically depending on the circumstances. The mesh shrinks in areas where a lot is happening, so that small details can be calculated. Uneventful areas, by contrast, expand. This zoom technique significantly reduces computational effort.

In this way, the team observed how approximately 50,000 galaxies of vari-

⟶

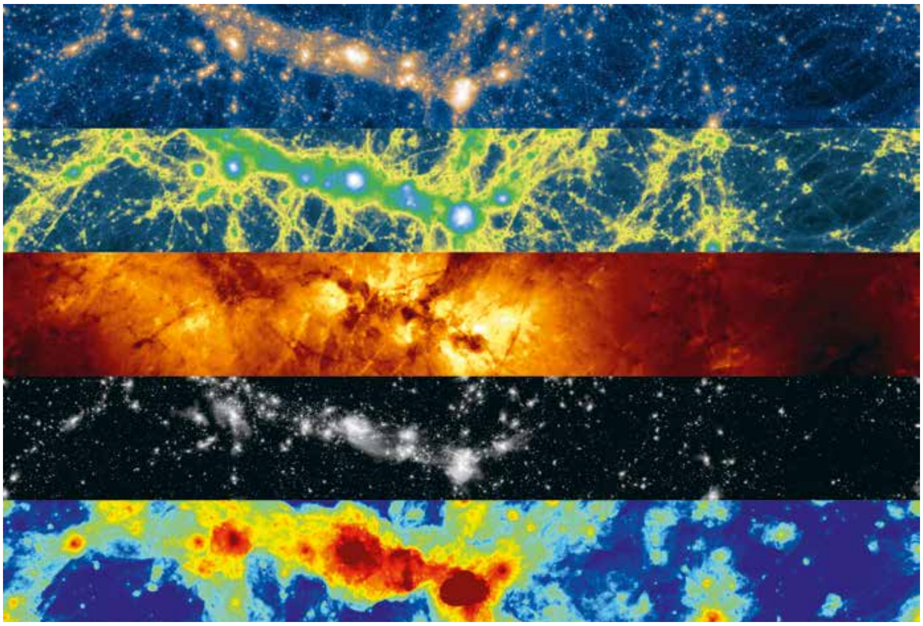


PHOTO: TNG COLLABORATION

Multilayered: The same section measuring 350 million light years in diameter from the Illustris TNG simulation in different display formats. From top to bottom: Dark matter density, gas density, velocity distribution of the gas, star density, and gas temperature.

ous sizes emerged and developed, and then compared the results directly with the observations. The researchers discovered that the simulated evolution of the universe produced all the types of galaxies classified by Edwin Hubble back in the early 20th century. The successor to Illustris, dubbed Illustris Next Generation or Illustris TNG, yielded simulations with different spatial zoom levels, allowing researchers to study galaxy clusters and the behavior of the galaxies they contain over billions of years. A few billion years ago, for example, the universe was particularly active. Galaxies merged, flushing large quantities of matter into the vicinity of supermassive black holes at the centers of galaxies. Clustered particle streams, known as jets, hurled some of that matter in turn into the intergalactic gas. These cosmic circulation pumps, also known as active galactic nuclei, can actually be observed. And they influence how many stars, if any, form in the galaxy, both in the simulation and in reality: another self-regulating mechanism.

Using Illustris TNG the researchers explored still other questions, for example, how the galactic matter became enriched with heavy elements. Hydrogen and helium, the lightest elements, were almost the only ones to form shortly after the Big Bang. All the other, heavier elements on the Periodic Table, such as carbon, nitrogen, oxygen, and iron, were not formed until later through nuclear fusion in stars. From there, particle winds or stellar explosions carried them into the interstellar medium, where they became available as raw material for new stars and planets. Later generations of stars would therefore have to contain higher percentages of heavy elements than earlier ones. Scientists have actually observed this chemical evolution within our own Milky Way and in galaxies far, far away. The Illustris TNG simulation scores points in this area, too. Its predictions of the average age of stars and the percentage of heavy elements they contain correspond closely with observations.

And so the world simulated by the computer is already looking very similar to the real world. Massive processing power is partly to thank for this, as is clever computer code, which translates astrophysical relationships from observations into simulation parameters. This is necessary because Illustris TNG cannot simulate the birth of individual stars directly. Even in variants with the highest resolution, every mass element of ordinary matter represents 85,000 solar masses, while every element of dark matter represents a whopping 450,000 solar masses. Because we now know most of the conditions (size, density, temperature) under which an interstellar cloud collapses and how many stars are born within it and with what masses, these processes can now be calculated as well. The result is an astrophysical evolution occurring virtually over billions of years.

Small meets big

From a cosmological standpoint, the volumes in which Illustris TNG simulates dark and ordinary matter simultaneously are still relatively small. With a new simulation called Millennium TNG, released last year, researchers have now built upon the Millennium simulation, which had simulated the largest section of the universe to date. Millennium TNG exceeds even this magnitude, simulating a space 1,000 times larger than Illustris TNG could manage.

Millennium TNG needed four months of computing time to determine how around 100 million galaxies developed in a region 2.4 billion light years in diameter. That made it the most complex of all the simulations run in Munich that year. "We had to increase the efficiency of the code dramatically just to get the program up and running," explains Springel's colleague Rüdiger Pakmor, a major contributor to Millennium TNG. One significant challenge was optimizing the parallelization of over 120,000 computing cores. "We couldn't use all 300,000 cores, because that would have completely paralyzed other user's activities at the time.

The work paid off: Millennium TNG has supplied more than three petabytes of simulation data – about enough to fill several hundred standard hard drives. So far, only part of the data has been evaluated. Many questions remain, such as how galaxies formed in the early universe. The James Webb Space Telescope recently detected galaxies whose extreme luminosity suggests they grew to enormous size just a few hundred million years after the Big Bang. "Our simulations have a really hard time with this rapid growth," says Springel. "Maybe star formation was much more efficient shortly after the Big Bang than later on, or maybe massive, luminous stars formed in larger numbers back then, making those galaxies incredibly bright," adds Pakmor. Simulations may yield clues to what really happened back then as well.

The simulations provide an impressive confirmation of today's standard model of cosmology. It attains a precision no one would have dared dream of two decades ago. What's more, it is free of internal contradictions, which was not always the case. However, it only works when the simulations include the ominous dark matter and the even more enigmatic dark energy. The latter allows the universe to expand at an accelerating rate. Today's cosmologists are therefore faced with the astounding knowledge that although they can reconstruct the roughly 14-billion-year evolution of the cosmos quite accurately, they know next to nothing about the nature of the two main actors: dark matter and dark energy.

←

The creators of Millennium TNG at work: Volker Springel (left) and Rüdiger Pakmor work together to interpret the dark matter structures of the universe, which they've simulated with the help of a supercomputer.

PHOTO: AXEL GRIESCH FOR MPG