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High-Speed and Detailed Reproduction of the Milky Way Galaxy Using a Fusion of Simulation and AI

To faithfully reproduce the details of the universe's evolutionary process through simulation, it is necessary to incorporate a wide variety of phenomena that occur over time into the calculations. As a result, the amount of computation becomes so enormous that it cannot be completed within a realistic time frame, making further acceleration of numerical computation essential. However, there is a trade-off between high-resolution detail and computational speed, and conventional numerical methods have their limitations.

Believing that simply increasing the number of CPUs or nodes would not be sufficient to realistically reproduce the detailed processes of cosmic evolution within a feasible computation time, Dr. Fujii's research group is working on a project to dramatically reduce the computational load by replacing parts of the simulation with AI.

Michiko Fujii
Associate Professor,
Department of Astronomy, Graduate School of Science,
The University of Tokyo

The Challenges of Large-Scale Computation

Simulations using facilities like the supercomputer Fugaku have achieved large-scale computations by increasing the number of CPUs and nodes. This is because using many CPUs in parallel distributed processing reduces the computational load per CPU and improves processing speed.

However, as the number of CPUs increases, so does the volume of data transmitted between CPUs and nodes. This communication becomes a bottleneck, and at a certain point, adding more CPUs no longer results in faster computation. This is a well-known challenge in large-scale computing.

To address this issue, Dr. Fujii's research group, which studies the evolution of the universe with a focus on galaxies, is working on replacing part of the simulation with AI. This innovative approach aims to dramatically reduce the computational load and overcome the limitations of traditional simulation methods.

Using AI to Predict Phenomena Occurring in Small Regions Over Short Time Periods

The galaxies that Dr. Fujii studies have rotating, disk-shaped structures (Fig. 1). Galaxies are composed of numerous stars and interstellar gas primarily made up of hydrogen and helium, as well as dust and dark matter. They are constantly evolving due to the gravitational forces of stars, the flow of interstellar gas leading to the birth of new stars, and supernova explosions that occur when massive stars reach the end of their lifespans.

"Currently, my research group is working on uncovering, through simulations, how our home galaxy—the Milky Way—came to look the way it does today. We're exploring how the galaxy evolves, almost like a living organism, and how the energy released by events like supernova explosions influences the birth of new stars within the galaxy. If we can find the conditions under which the Earth formed, I believe we may make new discoveries," Dr. Fujii says.

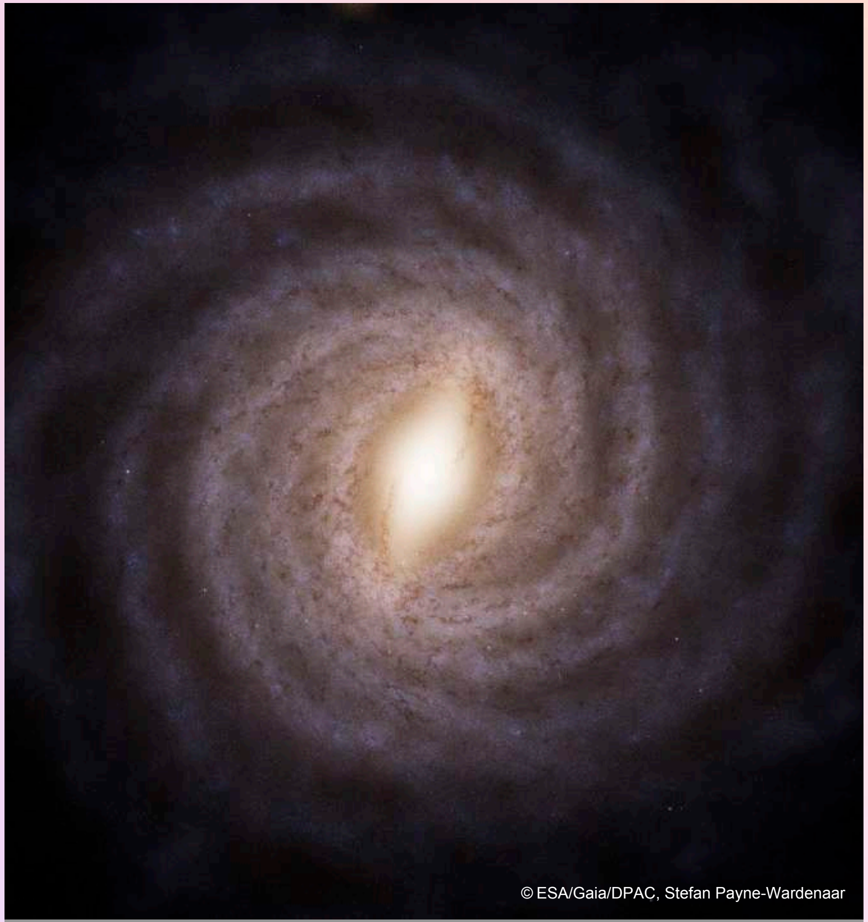

Fig. 1 : Artist's impression of the Milky way galaxy based on data from the Gaia space telescope

However, the Milky Way contains approximately 100 billion (10^{11}) stars. In addition to stars, it also includes dark matter and interstellar gas with mass comparable to that of stars. To accurately simulate the evolutionary process of the Milky Way in detail, all of these components must be incorporated into the simulation.

Moreover, simulating the evolution of the Milky Way requires modeling over vast spatial scales and long time periods. Yet, there are also events that occur in small regions over short timeframes that significantly impact the galaxy's evolution. In the Milky Way, phenomena occur across vastly different spatial and temporal scales. If we aim for greater detail in our simulations—adjusting time steps and spatial resolution more finely to capture phenomena in narrow regions and short durations—the total computation time for simulating the entire Milky Way becomes enormous.

"Normally, to handle phenomena that occur in small regions over short time spans, we need to assign shorter time steps only to the relevant particles, as a way to reduce the computational load. However, even with this approach, it's difficult to significantly reduce the total computation time," Dr. Fujii explains.

To address this challenge, Dr. Fujii's research group came up with an alternative: rather than simulating phenomena in small, time-intensive regions, they would predict them using AI models. They chose supernova explosions as the target phenomena for this AI-based approach.

Supernova Explosions Have a Major Impact on the Entire Galaxy

A supernova explosion is an explosive phenomenon that occurs at the end of the life of a massive star with a mass eight times or more that of the Sun. From the perspective of the entire Milky Way galaxy, it is an event that occurs in an extremely small region and finishes within a very short time, but it has a significant impact on the galaxy's evolution.

Supernova explosions cause the surrounding interstellar gas to be ejected vertically from the disk of the Milky Way galaxy. At the same time, the energy from the supernova explosion compresses the interstellar gas, which is believed to lead to the formation of new stars. The materials that form stars include heavy elements such as carbon, oxygen, and iron. These elements are produced inside stars through nuclear fusion reactions starting with hydrogen and helium, and are then scattered by the supernova explosion.

"It's easier to imagine a supernova explosion as an engine driving the evolution of the galaxy," explains Keiya Hirashima, Special Postdoctoral Researcher, Division of Fundamental Mathematical Science, RIKEN Center for Interdisciplinary Theoretical and Mathematical Sciences (iTHEMS). Dr. Hirashima belonged to Dr. Fujii's laboratory until March 2025, where he worked alongside her on developing simulation programs for the Milky Way galaxy.

However, accurately reproducing the details of a supernova explosion requires dividing time and space into extremely fine segments for calculation, which results in enormous computational time and cost. Among these, the most time-consuming part is simulating how the ambient gas expands around after the supernova explosion.

Dr. Keiya Hirashima
Special Postdoctoral Researcher, Division of Fundamental Mathematical Science, RIKEN Center for Interdisciplinary Theoretical and Mathematical Sciences (iTHEMS)
Recipient of the Next Generation Researcher Award (FY2024)

To address this, Dr. Fujii and Dr. Hirashima attempted to utilize AI. First, they performed simulations that focused solely on the supernova explosion and used the results to train their deep learning model. This enabled the model to predict the complex structures of interstellar gas resulting from a supernova explosion. By coupling these predictions back into the galaxy simulation, they greatly reduced the total computation time, even while incorporating the supernova explosion in detail (Fig. 2).

First, Creating the AI Model

In simulations of a galaxy, we model dark matter, stars, and gas using particles. The gas is represented by overlapping particles. By solving fluid equations for density, temperature, velocities, and other variables on this basis, the simulation results reveal the formation of structures such as star-forming regions, bubbles from the rapidly expanding interstellar gas, and so on.

Supernova explosions frequently occur throughout the Milky Way galaxy, but the patterns of these phenomena vary enormously depending on the density and temperature distributions of the interstellar gas. Therefore, in the simulations for our training dataset, the physical quantities—density, temperature, and velocity distributions of the interstellar gas in 3D—are varied to produce multiple patterns in interstellar gas.

Our AI model was trained with simulation data of the spread of interstellar gas caused by a supernova explosion. We generated 3D data of the ambient interstellar gas during a supernova explosion by hydrodynamical simulations to train our model. Initially, we created a set of initial conditions of gas with a density contrast, mimicking molecular clouds where stars are born. Thermal energy is then injected into the clouds to simulate a supernova explosion, causing the heated gas to expand rapidly. Through training the model using

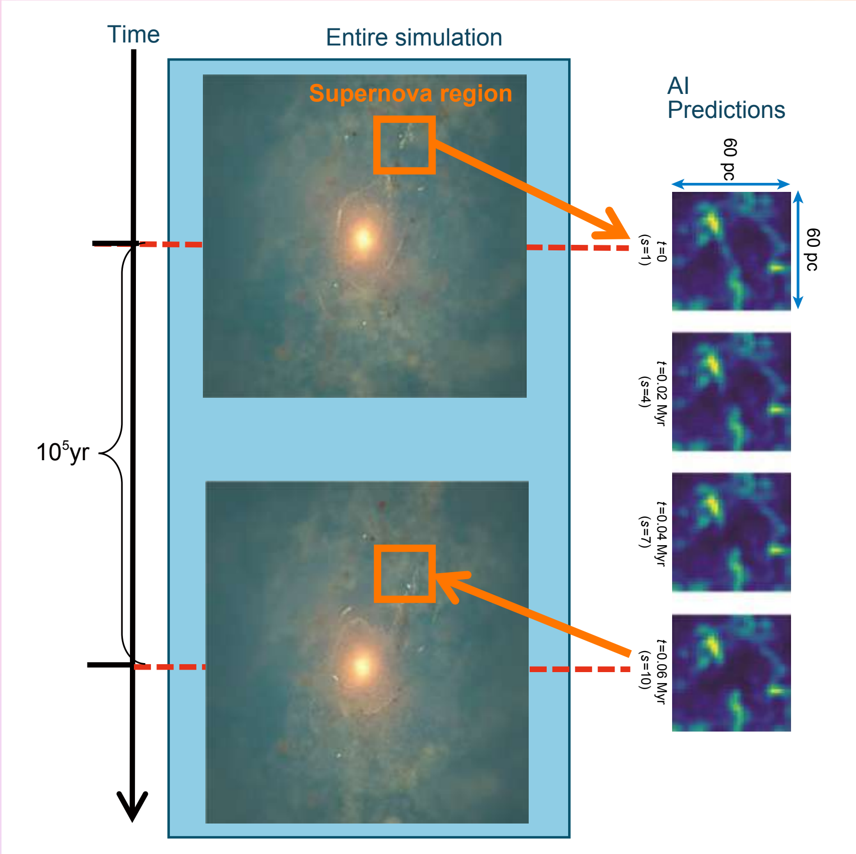

Fig. 2 : Conceptual diagram of a Milky way simulation incorporating AI predictions for supernova explosion regions

A schematic diagram illustrating Dr. Fujii and her team's concept. Time progresses from top to bottom. On the left is the simulation of the entire galaxy. Instead of extracting the supernova explosion region—outlined by a red square—and simulating its 10^5 years with increased resolution, it is replaced by AI predictions, shown on the right.
Simulation: Takayuki Saitoh, Visualization: Takaaki Takeda
Modified with permission from the original video:
https://www.youtube.com/watch?v=Rdd9KAUcvgQ

those simulation data, our AI model acquired the ability to make predictions of bubbles from the rapidly expanding interstellar gas.

Integrating the Simulation and AI Model

Next is the method of integrating the constructed AI model into the simulation. In our framework, while the simulation of the Milky Way galaxy is running, whenever supernovae explode during the simulation, the AI model is called each time. The AI model receives the information of the ambient gas of supernovae, including three-dimensional distributions of the interstellar gas's density, temperature, and three-dimensional velocity. Based on these input quantities, the AI model predicts the spread of interstellar gas caused by a supernova explosion and returns the prediction results as updated distributions of the quantities back to the Milky Way simulation. The simulation continues with those updated quantities (Fig. 3).

A First Attempt in the Field of Astronomy

To build the AI model, Dr. Hirashima created about 300 different sets of 3D simulation data with varying interstellar gas density, temperature, and velocity distributions using the supercomputers "ATERUI II" and Fugaku as training data.

"By utilizing the AI model, we found that the process becomes about 100 times faster compared to the conventional method," Dr. Hirashima proudly states (Fig. 4).

Dr. Fujii explains: "There is an increasing number of cases where simulation data is used as training data for deep learning, and surrogate models that replace complex simulations with machine learning or deep learning have also emerged. However, there are very few examples of

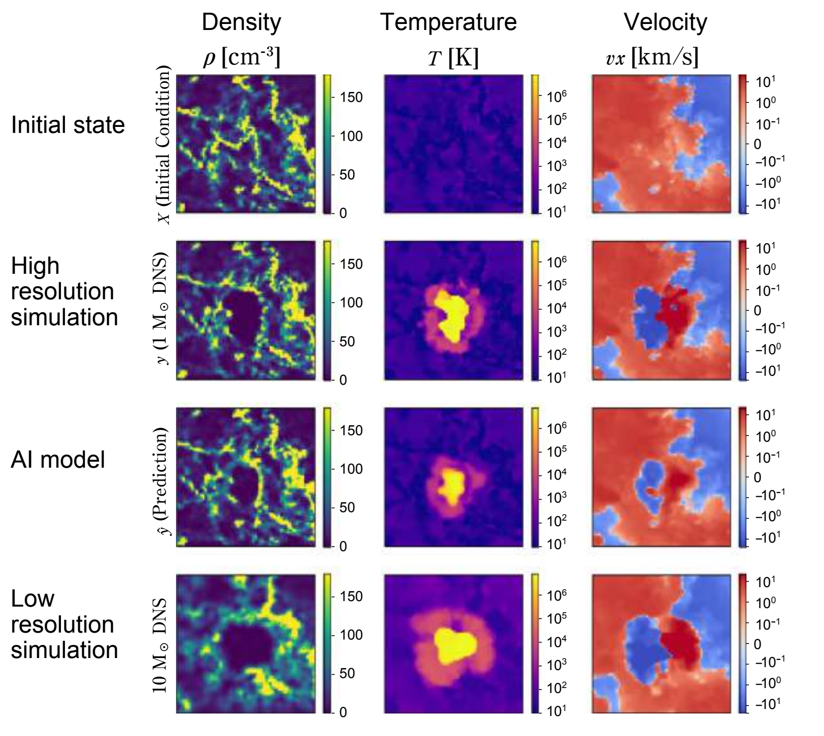

Fig. 3 : Potential of AI models in supernova explosion simulations

Comparison of density distribution, temperature distribution, and velocity distribution between high-resolution and low-resolution traditional simulations, and the AI model's prediction trained via deep learning. In the bottom three rows, the AI model more closely resembles the high-resolution simulation than the low-resolution one.

Computing resources used to generate this data:

- **Simulations for producing training data (for AI model learning):** National Astronomical Observatory of Japan's astronomy-specific supercomputer "ATERUI II" or Fugaku
- **Deep learning (training):** University of Tokyo's GPU supercomputer "Wisteria/BDEC-01 Aquarius"
- **AI model inference optimization:** Fugaku

simulations being coupled with AI models in real-time like we have done. Especially in the field of astronomy, this was the world's first successful implementation." She emphasizes the novelty of their approach.

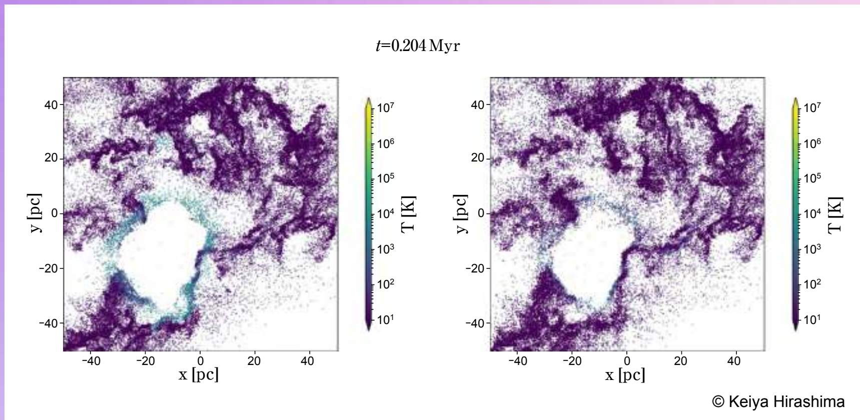

Fig. 4 : Simulation of a supernova explosion using AI (at 1/100 scale of the Milky way galaxy)

A scene from the simulation video. (Left) The supernova explosion is reproduced using only simulation. (Right) The supernova explosion region is predicted by the AI model. Here, "Myr" stands for million years; "pc" (parsec) is a unit of length approximately equal to 3.26 light-years. The color of the dots represents temperature in Kelvin (0 K = -273.15 °C). In the AI model, the region where interstellar gas spreads suddenly appears at a slightly delayed time due to the supernova explosion. However, the overall impact on the entire galaxy is almost the same in both cases. Specifically, the spread of interstellar gas, the rotation of the galaxy, the number of stars formed per year, and the amount of interstellar gas in the vertical outflow (the phenomenon where gas is blown upward, shown vertically in the video) all match. The computation time for (right) was about 100 times faster than (left). Although the simulation was conducted in 3D, the results shown here are 2D.

Computers used to obtain this data:

- **Simulations to create training data for the AI model:** National Astronomical Observatory's astronomy-dedicated supercomputer "ATERUI II" or Fugaku
- **Deep learning:** The University of Tokyo's GPU supercomputer "Wisteria/BDEC-01 Aquarius"
- **Galaxy simulation:** the Popeye cluster of the Flatiron Institute, Simons Foundation in the U.S., or Fugaku

Simulation of One-Tenth Scale of the Milky Way Galaxy Using Fugaku

Dr. Fujii and Dr. Hirashima conducted a simulation of one-tenth the scale of the entire Milky Way galaxy using Fugaku, employing 10^{10} particles (Fig. 5).

These two figures are snapshots of the density distribution (left) and the temperature distribution (right). Looking at the overlay panel in the left figure,

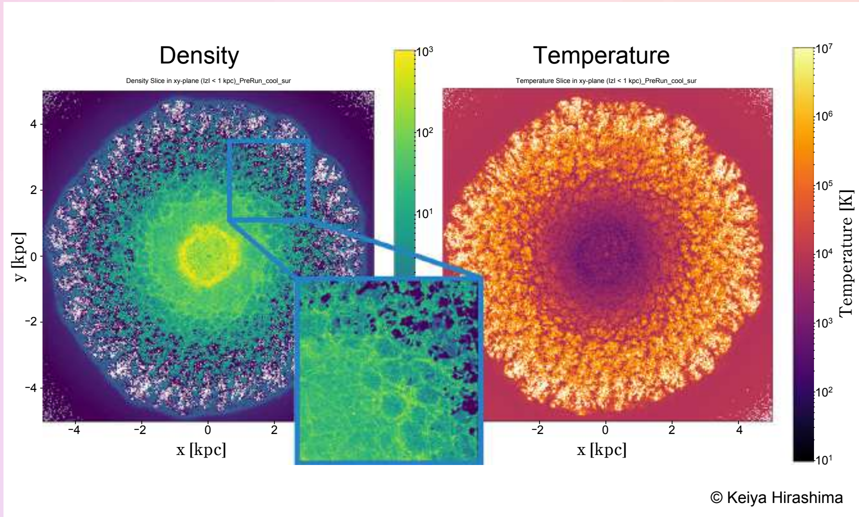

Fig.5 : A galaxy simulation at one-tenth scale of the entire Milky way galaxy *1

(Left) Density distribution at a certain point in time. (Right) Temperature distribution at the same time as the left image.

Computers used to obtain this data:

- **Simulations to create training data for the AI model:** National Astronomical Observatory's astronomy-dedicated supercomputer "Atelier II" or Fugaku
- **Deep learning:** The University of Tokyo's GPU supercomputer "Wisteria/BDEC-01 Aquarius"
- **Galaxy simulation:** Fugaku

you can see the effect of increasing the resolution by a factor of 10. The navy regions indicate sparse regions of interstellar gas, while the green and yellow regions indicate dense regions. Many shells have formed, and at their centers, supernova explosions can be seen occurring. At the locations where supernova explosions happen, interstellar gas is blown upward, and the shells are expanding.

Thanks to highly resolved simulations with such fine structures, we can track individual massive stars, which eventually explode as supernovae, from formation to death, and may be able to quantitatively analyze the balance between the frequency of supernovae and the number of stars formed. Additionally, as many regions with high density appear in high-resolution simulations, the number of stars that could form in one year may be revised. On the other hand, if the number of stars formed is higher than previously expected, the frequency of supernova explosions would also increase, which could in turn reduce the number of stars formed annually. Regarding this matter, there are plans to continue researching in the future, Dr. Fujii says.

Only Fugaku can Reproduce the Entire Milky Way Galaxy at the Resolution of a Single Star

Regarding the success of this world-first challenge of accelerating simulations utilizing AI techniques, Dr. Fujii says, “The key was choosing methods according to the physical scales—appropriately deciding which parts actually to calculate and which parts to replace with AI models. In particular, focusing on supernova explosions—phenomena that are crucial in the formation process of the Milky Way, despite intensive computation—was a good choice. Eventually, we also want to replace the star-forming regions with AI models. Because the timescale for this process is longer compared to supernova explosions, the AI model must predict further into the future, making it even more challenging,” she explains.

Dr. Fujii also highlights the advantage of using Fugaku for large-scale computations: the sheer number of nodes and CPUs. “Fugaku is one of a few supercomputers capable of simulating the entire Milky Way at the resolution of a single star. Although other supercomputers have sufficient memory for the calculations, they lack enough nodes and CPUs, which might cause the computation time to be at least 10 times longer than on Fugaku. For example, a simulation that takes one year on Fugaku would take 10 years on other supercomputers. That’s simply not practical.”

Dr. Fujii’s research group is also advancing simulations of the entire Milky Way galaxy by using Fugaku at full system scale.“Through this, we hope to reproduce in even finer detail how supernova explosions impact the star formation history and the evolution of the Milky Way,” she says.

The lab members

From left: Dr. Hirashima, Chi Hong Lin (3rd-year doctoral student), Dr. Fujii, Itsuki Maruzuka (1st-year master’s student), and Dr. Naoto Harada (Research Fellow). (Photo taken on June 12, 2025)

*1 Developing AI-enhanced high-resolution galaxy simulations (hp250186)
Principal Investigator : Keiya Hirashima, Division of Fundamental Mathematical Science, RIKEN Center for Interdisciplinary Theoretical and Mathematical Sciences (iTHEMS)

About the Researcher

Michiko Fujii
Associate Professor, Department of Astronomy, Graduate School of Science, The University of Tokyo

“I like creating things I imagine in my mind,” Dr. Fujii says. She lights up when talking about simulations: “There’s a joy in making things move.” Originally, she wasn’t particularly interested in programming, but during her student years, she took an astronomy lecture that included practical training on galaxy simulations, which fascinated her. She enjoyed looking at beautiful astronomical photos of spiral galaxies and the Milky Way, and was deeply impressed that simulations allowed her to see their motions. This inspired her to join a research lab focused on cosmic simulations in her senior year. “Since then, research has felt like a hobby to me.”

At home, she is a parent to two elementary school children and enjoys creative activities. She has been sewing as a hobby for a long time and is currently passionate about making clothes for her children late at night after they go to bed. “I have a boy and a girl, and it’s rare to find matching clothes for both, so I enjoy designing and sewing them myself,” she says.

Interview date: June 12, 2025

Associated Research Projects:

Structure and Evolution of the Universe Unraveled by Fusion of Simulation and AI (hp230204/hp240219)
Principal Investigator: Ken Ohsuga, Center for Computational Sciences, University of Tsukuba

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