

The world's fastest Intel and AMD supercomputers are helping to unravel the true phenomenon occurring at the edge of black holes.

Thanks to exascale supercomputers like Frontier and Aurora, scientists have for the first time accurately simulated the process of matter falling into black holes, helping to better understand their structure and behavior.

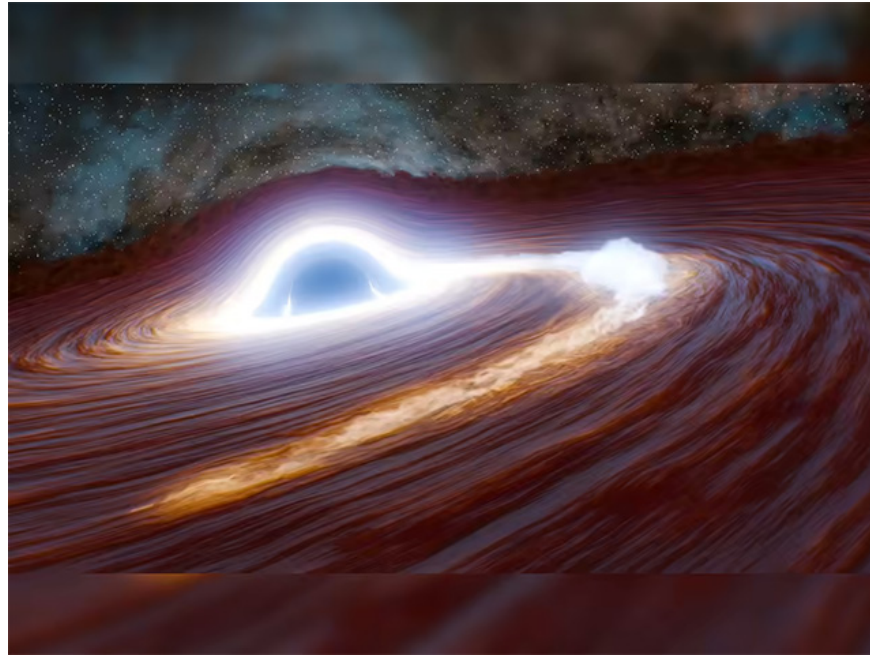
A team of astrophysicists from the Institute for Advanced Study and the Flatiron Institute has just built the most detailed computer model ever created describing how matter falls into a black hole.

The study, published in *The Astrophysical Journal* , marks the first time scientists have been able to simulate this process using full general relativity and under radiation-dominated conditions, without having to use the simplification assumptions previously employed.

The study's lead author, Lizhong Zhang, said this is the first time scientists have been able to accurately observe what happens when the most important physical processes in the accretion of matter into black holes are incorporated into a computational model.

He explained that these systems are extremely complex nonlinearities, so even a small simplification assumption can completely change the results. Notably, the new simulations have very well reproduced the observed behavior in cosmic black hole systems, from superluminal X-ray sources to X-ray-emitting binary star systems.

According to Zhang, in a sense, scientists have been 'observing' these systems not with telescopes, but with computers.



Simulating how matter falls into a black hole.

In the study, the scientific team investigated the accretion flows of matter in a radiation-dominated environment under various conditions. They varied the rate at which matter fell into the black hole, experimented with two levels of black hole rotation, and tested various magnetic field configurations.

Models using a new algorithm can directly solve the radiation transport equation in general relativity, something previously almost impossible due to the enormous computational demands. This was only possible with modern exascale supercomputers.

The results show that when a black hole absorbs matter at a rate exceeding the so-called Eddington limit, the flow of matter forms thick disks maintained by radiative pressure and pushes out strong gusts of wind along the equatorial plane.

In this state, a narrow, funnel-like structure forms near the center, where light escapes very poorly. This results in extremely low radiation efficiency, meaning that most of the energy is trapped inside instead of being emitted as light.

The Eddington limit is the maximum brightness a black hole or star can reach before the radiation pressure pushes matter out, preventing further accretion. For black holes, this is considered the theoretical limit to their growth rate.

The role of magnetic fields and the formation of matter rays.

When the deposition rate is near or below the Eddington limit, the structure of the system becomes dependent on the magnetic flux of the magnetic field.

If a vertical magnetic flux exists, the material disk will form a dense layer in the central plane, surrounded by a corona region dominated by the magnetic field. Conversely, if this magnetic flux is absent, the entire accretion disk will remain dominated by the magnetic field.

The models in the study did not reach a state called a magnetically arrested disk (MAD) — a type of accretion disk where the magnetic field is so strong that it slows the flow of matter. However, in cases with magnetic flux and a rapidly rotating black hole, the system still produced extremely strong relativistic jets of matter.

This research focuses primarily on stellar-mass black holes, which have masses approximately 10 times that of the Sun.

These types of black holes are more difficult to observe directly than the supermassive black holes at the center of galaxies, which can be photographed. Therefore, scientists often have to rely on radiation spectra to understand their structure and behavior.

One advantage of stellar-mass black holes is that they change very rapidly, with cycles lasting only a few minutes to a few hours. This allows scientists to study how the system changes almost in real time.

The simulations in the study yielded results that closely matched actual observational data, including the radiation spectra from X-ray-emitting binary star systems and superluminal X-ray sources such as Cyg X-3 and SS433.

The research team also suggests that their super-Eddington models may help explain the 'little red dots' recently discovered by the James Webb telescope.

The power of exascale supercomputers

This project was made possible using two of the world's fastest supercomputers currently available: Frontier, which uses AMD processors at Oak Ridge National Laboratory, and Aurora, an Intel-based system at Argonne National Laboratory.

These exascale machines are capable of performing a quadrillion calculations per second, allowing scientists to solve physics equations that were previously too complex to handle.

Christopher White designed the radiation transport algorithm, while Patrick Mullen implemented it into AthenaK software, a simulation system optimized for exascale supercomputers.

In the future, the research team plans to expand this method to simulate supermassive black holes, objects that play a crucial role in the evolution of galaxies.

They also want to continue improving the model to more accurately describe how radiation interacts with matter under a variety of conditions.

Co-author James Stone stated that the project's uniqueness lies in two factors. First, the time and effort required to develop the mathematical methods and software capable of simulating such complex systems. Second, the access to the enormous computing resources on the world's largest supercomputers.

According to him, the next challenge is not just running the simulations, but also fully understanding the new scientific knowledge they provide.

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