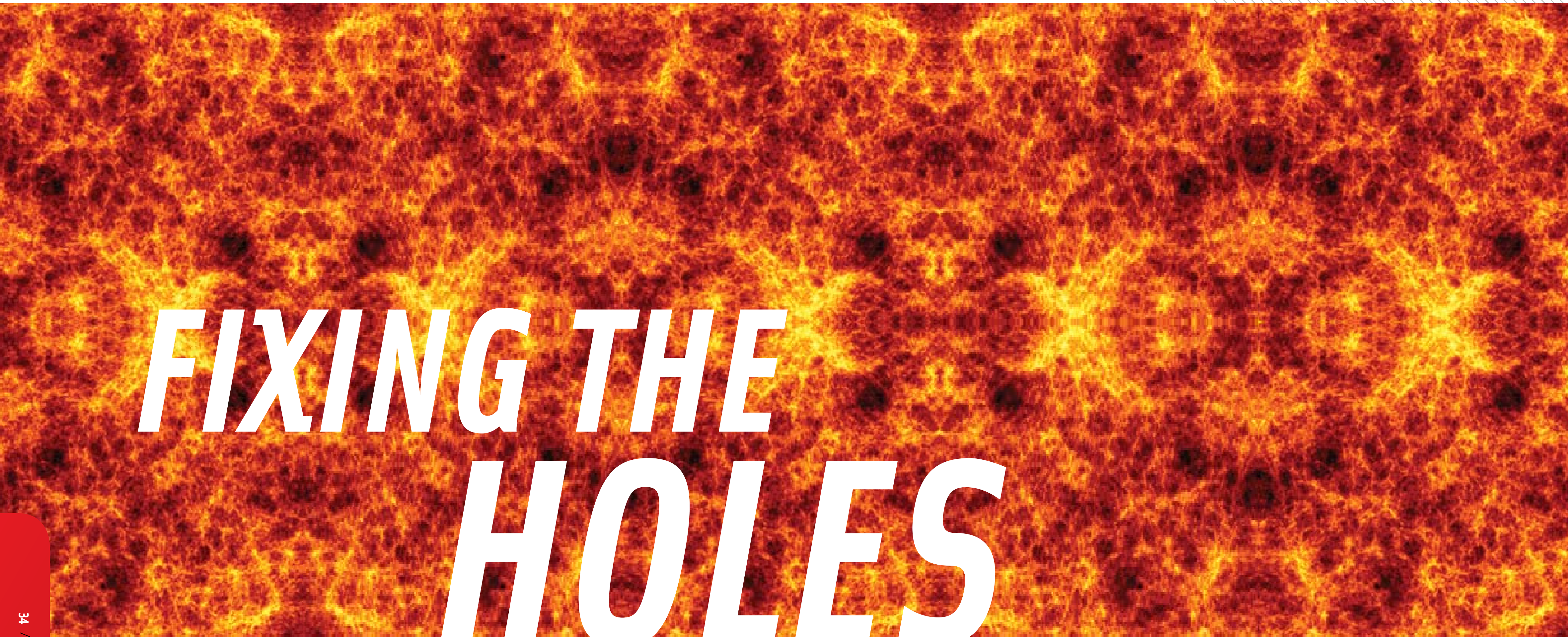

FIXING THE HOLES

Tiziana Di Matteo,
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Once thought to be rare, exotic bodies, black holes have turned out to be fundamental focal points in the architecture of the cosmos. Among the sprawling, intricate arrangement of matter in every galaxy, they are the invisible centerpiece. Their tremendous mass, which can be many billion times the mass of the Sun, gives them gravitational pull to swallow huge quantities of interstellar gas. As this gas swirls outside the lip of the drain, just before falling in, it heats to extreme temperatures and radiates energy as light waves, producing one of the brightest bulbs in the universe — a quasar. Once over the edge of this lip, however, nothing escapes, not even light.

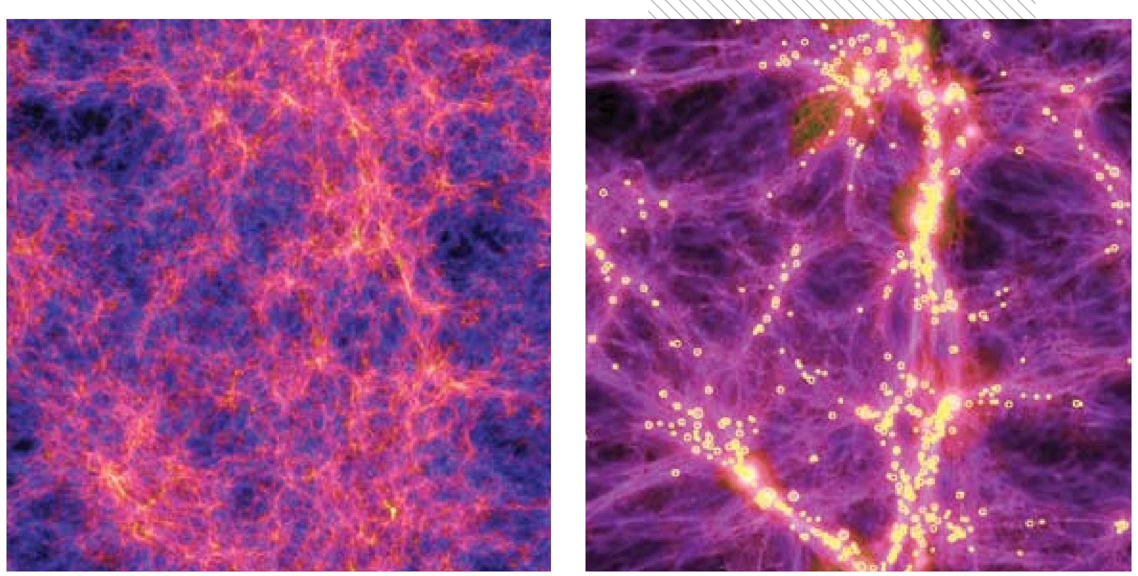
Despite their ubiquitous presence, black holes and the quasars they spawn have been until now absent from large-scale simulations of the universe — too small to be resolved within the big picture of cosmic structure. With PSC's Cray XT3, however, Carnegie Mellon University astrophysicist Tiziana Di Matteo and her colleagues included black holes in what is perhaps the most computationally demanding cosmological simulation ever, encompassing a sizeable fraction of the universe. Their intentions were bold. "We wanted to simulate the universe," says Di Matteo, "and go from the Big Bang until today."

The result can be viewed as a movie that shows evolution of structure over the 14 billion years of the universe's existence, with black holes in a lead role. Far from being only destroyers, gobbling up any matter within reach, black holes in this new picture are also regulators: Their mass is related to the size of the galaxy they reside in as well as to its total star mass.

The goal is a more fundamental understanding of the evolution of the universe. "What kind of quasars formed in what kind of galaxies at what time?" asks Di Matteo. "What is the progenitor of the most massive black hole today?" There is also a more immediate benefit — directing astronomers where to aim the Next Generation Space Telescope — the successor to the Hubble Space Telescope — to observe the formation of the first galaxies and black holes.

BY INCLUDING BLACK HOLES FOR THE FIRST TIME IN A LARGE-SCALE COSMOLOGICAL SIMULATION, PHYSICISTS UNCOVER THEIR FUNCTION IN REGULATING THE GROWTH OF GALAXIES

Evolution of Structure in the Cosmos
Snapshots from the simulation show evolution of structure in a large volume of the universe. Gas density is shown (increasing with brightness) with temperature (increasing from blue to red color). Yellow circles indicate black holes (diameter increasing with mass). At about 450 million years after the big bang (left), as the early universe still shows a relatively uniform structure, the first black hole appears. At about 6 billion years (right), the universe has many black holes and a pronounced filamentary structure.



"THE XT3 IS IDEAL FOR THIS SIMULATION BECAUSE IT HAS INCREDIBLY FAST BUILT-IN COMMUNICATION."

A NEW COSMIC RECIPE

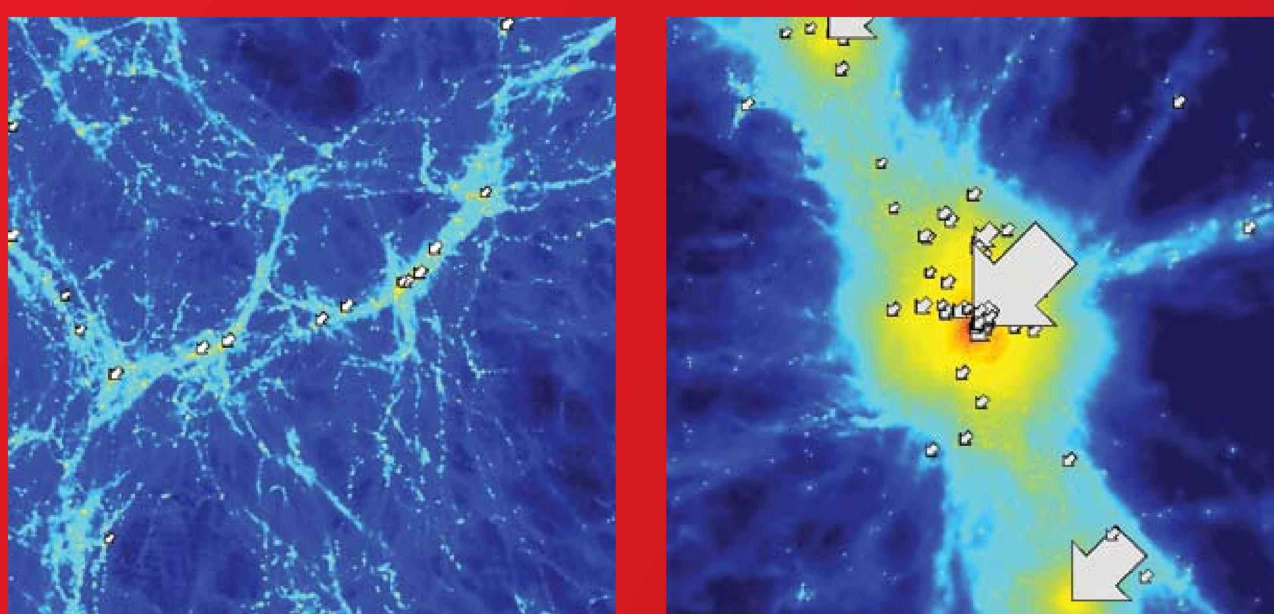
For this huge simulation, Di Matteo started with the software called GADGET-2 developed by Volker Springel of the Max Planck Institute for Astrophysics. To account for black holes, Di Matteo added code to "seed" black holes at the centers of forming galaxies. Next, she added an equation to describe how black holes "accrete" or swallow gas, adding to their mass and gravitational pull. Finally, she included calculations for "feedback" — heating of surrounding gas in the galaxy by quasar radiation produced at the lip of the black hole.

The researchers first applied this approach on a small system of two colliding galaxies with black holes at their centers. The success of this simulation, which revealed new behavior when black holes were included, led to a 2005 paper in *Nature*. It also prompted Di Matteo to move to a much bigger scale. The idea, says Di Matteo, was to simulate a large portion of the universe "at the same resolution and with the same spatial scale as those idealized calculations."

To obtain this high resolution, the researchers scattered 230 million hydrodynamic particles over a 33 megaparsec cube, a huge volume encompassing a million galaxies, a representative chunk of the universe. To track these particles, the simulation used 2,000 XT3 processors — the whole system — over four weeks of run time. They followed the evolution of superclusters of galaxies — the largest structures in the universe — while simultaneously resolving the growth of black holes at the centers of galaxies. The XT3 was key.

"The XT3 is ideal for this simulation because it has incredibly fast built-in communication," says Di Matteo. "If we didn't have the bandwidth to communicate large chunks of data among 2,000 processors, it would have been really tough. I don't think we could run this simulation anywhere else right now."

Galaxy Closeup
These simulation snapshots zoom-in on the galaxy that hosts the most massive black hole in the universe today. This galaxy resides in one of the most massive elliptical galaxies, at the center of a large galaxy cluster. At about 600 million years after the big bang (left), matter is more diffuse than it is about 4.5 billion years later. Gas density increases from blue to red, and arrows indicate black holes (arrow-size relative to mass).



REPENTANT OVEREATERS

While the researchers are still analyzing the huge quantity of data from this simulation, about ten trillion bytes, initial results are exciting. The major finding is the regulatory role black holes play in galaxies. It turns out that after gobbling gas for millennia, a black hole eventually begins pushing gas away, like a repentant overeater. "The black hole tries to swallow a lot of gas," says Di Matteo, "but this growth is kind of suicidal. As it tries to swallow more and more it will radiate so much energy that it will affect its surroundings and stop more gas from flowing in."

This first effect of this purging "feedback" process is that it shuts off the quasar associated with the black hole. Because gas is no longer falling in, gas at the lip of the black hole is no longer heated and eventually radiation stops. In effect, feedback blows out the candle of the quasar, which explains why — though virtually every galaxy had a quasar when the universe was young — now there are quasars in only about one in 10,000 galaxies.

While blowing out the quasar, the black hole also expels most of the galaxy's interstellar gas into inter-galactic space. As a result, since interstellar gas is the stuff that stars are made of, stars stop forming. This helps to explain the "red and dead" phenomenon with which astronomers have long struggled: the preponderance of old galaxies in which no new stars are forming. Old galaxies tend to appear red due to the overwhelming dominance of old stars. Stars should form readily if there is interstellar gas to feed the process, yielding young blue stars. Di Matteo's simulation shows that there is very little interstellar gas left, leaving old galaxies "red and dead."

Another conundrum was the common ratio found between the mass of the central black hole and the mass of its host galaxy. Precise measurement using the Hubble Space Telescope and other instruments has shown that the black hole has a mass approximately 1/1000th the mass of the stars in its galaxy. This same ratio emerged from Di Matteo's simulation, which helps to validate the model, but the reason for the ratio is not yet evident. Some mechanism related to a galaxy's critical mass might cause the black hole to stop swallowing when it does, but that mechanism remains a mystery. "Black holes clearly regulate how the galaxy forms in some way that is still debated," says Di Matteo, "and that is what we are still trying to understand."

Perhaps one of the most exciting end products of this huge calculation is a movie showing how the universe evolved over 14 billion years. The simulation begins before galaxies have formed, and the first frames (each frame is about half a million years) show a virtually uniform universe, with matter dispersed rather evenly, and just small perturbations in this background — corresponding well with the picture provided by cosmic microwave background studies. The first black holes appear when the universe is 300 million years old — just a child.

As the movie proceeds, matter in the universe clumps together in a filamentary fashion. "Empty regions become emptier and emptier," says Di Matteo. Dense regions become denser, and the universe starts to look like a spider web. By the end, supermassive black holes are lurking in the center of most galaxies, quasars shine bright and then blow out, and galaxies change colors from blue to red as they age.

Because of the extremely high resolution, Di Matteo can zoom in at any time and watch the growth of a particular black hole. "This is the most massive black hole that forms at an early time," she says, pointing to a specific black hole on a movie frame, "but it does not end up being the largest black hole today. It grows really fast then it stops. Other black holes start to grow later on and they grow at a faster rate at a much later stage, and so that's very exciting too."

Di Matteo and her colleagues don't know what other fascinating results await them in the huge mass of data they have begun to analyze. Perhaps they will learn where to point telescopes to see the remnants of the first quasars, or maybe they will see astronomical phenomena never dreamed of before. "The hugest challenge was to do this very large simulation," says Di Matteo. Analyzing the data will be a pleasure. "Both in terms of the resolution and the physics," she says, smiling, "nobody else has a simulation like this right now." (TP)

MORE INFORMATION:
http://www.psc.edu/science/2006/blackhole.html