Machine learning reveals how black holes grow

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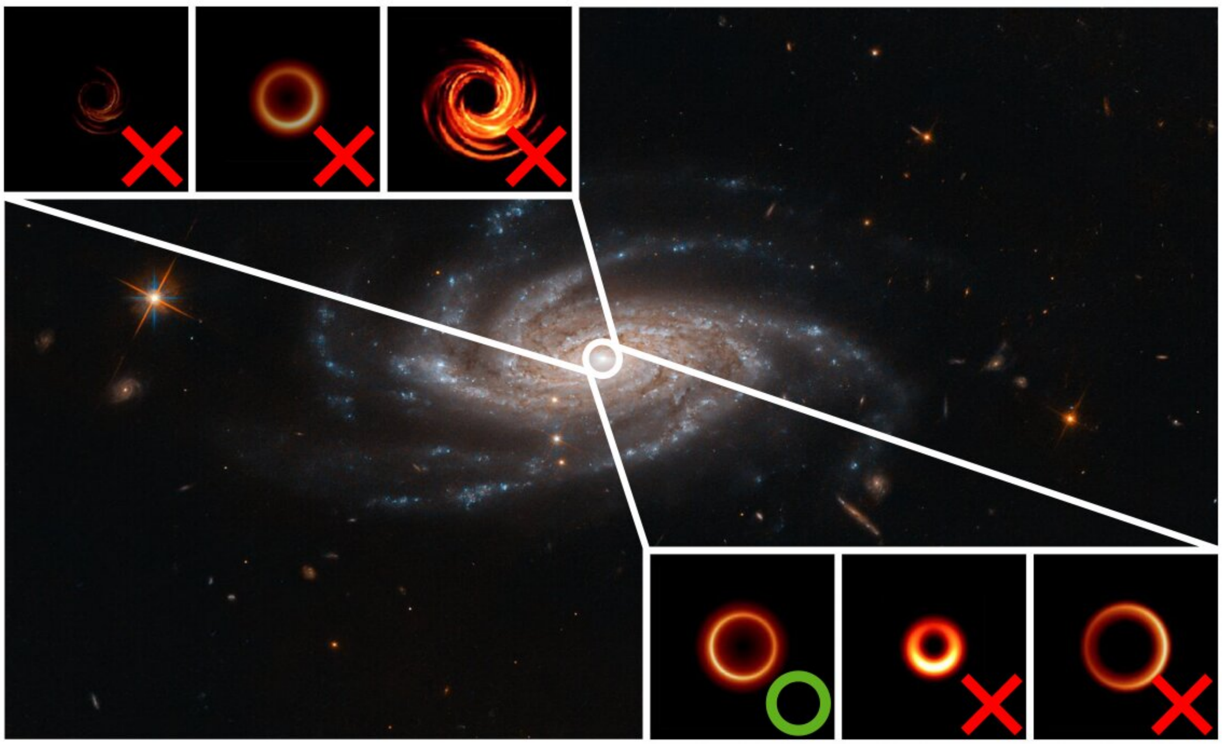

How it works: Using trial and error, machine learning tests many different pairings of simulated galaxies and black holes created using different rules, and then chooses the pairing that best matches actual astronomical observations. Credit: H. Zhang, Wielgus et al. (2020), ESA/Hubble & NASA, A. Bellini

As different as they may seem, black holes and Las Vegas have one thing in common: What happens there stays there—much to the frustration of astrophysicists trying to understand how, when and why black holes form and grow.

Black holes are surrounded by a mysterious, invisible layer—the event horizon—from which nothing can escape, be it matter, light or information. The event horizon swallows every bit of evidence about the black hole's past.

"Because of these physical facts, it had been thought impossible to measure how black holes formed," said Peter Behroozi, an associate professor at the University of Arizona Steward Observatory and a project researcher at the National Astronomical Observatory of Japan.

Together with Haowen Zhang, a doctoral student at Steward, Behroozi led an international team to use machine learning and supercomputers to reconstruct the growth histories of black holes, effectively peeling back their event horizons to reveal what lies beyond.

Simulations of millions of computer-generated "universes" revealed that supermassive black holes grow in lockstep with their host galaxies. This had been suspected for 20 years, but scientists had not been able to confirm this relationship until now. A paper with the team's findings has been published in *Monthly Notices of the Royal Astronomical Society*.

"If you go back to earlier and earlier times in the universe, you find that exactly the same relationship was present," said Behroozi, a co-author on the paper. "So, as the galaxy grows from small to large, its black hole, too, is growing from small to large, in exactly the same way as we see in galaxies today all across the universe."

Most, if not all, galaxies scattered throughout the cosmos are thought to harbor a supermassive black hole at their center. These black holes pack masses greater than 100,000 times that of the sun, with some boasting millions, even billions of solar masses. One of astrophysics' most vexing questions has been how these behemoths grow as fast they do, and how they form in the first place.

To find answers, Zhang, Behroozi and their colleagues created Trinity, a platform that uses a novel form of machine learning capable of generating millions of different universes on a supercomputer, each of which obeys different physical theories for how galaxies should form. The researchers built a framework in which computers propose new rules for how supermassive black holes grow over time.

They then used those rules to simulate the growth of billions of black holes in a virtual universe and "observed" the virtual universe to test whether it agreed with decades of actual observations of black holes across the real universe. After millions of proposed and rejected rule sets, the computers settled on rules that best described existing observations.

"We're trying to understand the rules of how galaxies form," Behroozi said. "In a nutshell, we make Trinity guess what the physical laws may be and let them go in a simulated universe and see how that universe turns out. Does it look anything like the real one or not?"

According to the researchers, this approach works equally well for anything else inside of the universe, not just galaxies.

The project's name, Trinity, is in reference to its three main areas of study: galaxies, their supermassive black holes and their dark matter halos—vast cocoons of dark matter that are invisible to direct measurements but whose existence is necessary to explain the physical characteristics of galaxies everywhere. In previous studies, the researchers used an earlier version of their framework, called the UniverseMachine, to simulate millions of galaxies and their dark matter halos. The team discovered that galaxies growing in their dark matter halos follow a very specific relationship between the mass of the halo and the mass of the galaxy.

"In our new work, we added black holes to this relationship," Behroozi said, "and then asked how black holes could grow in those galaxies to reproduce all the observations people have made about them."

"We have very good observations of black hole masses," said Zhang, the paper's lead author. "However, those are largely restricted to the local universe. As you look farther away, it becomes increasingly difficult, and eventually impossible, to accurately measure the relationships between the masses of black holes and their host galaxies. Because of that uncertainty, observations can't directly tell us whether that relationship holds up throughout the universe."

Trinity allows astrophysicists to sidestep not only that limitation, but also the event horizon information barrier for individual black holes by stitching together information from millions of observed black holes at different stages of their growth. Even though no individual black hole's history could be reconstructed, the researchers could measure the average growth history of all black holes taken together.

"If you put black holes into the simulated galaxies and enter rules about how they grow, you can compare the resulting universe to all the observations of actual black holes that we have," Zhang said. "We can then reconstruct how any black hole and galaxy in the universe looked from today back to the very beginning of the cosmos."

The simulations shed light on another puzzling phenomenon: Supermassive black holes—like the one found in the center of the Milky Way—grew most vigorously during their infancy, when the universe was only a few billion years old, only to slow down dramatically during the ensuing time, over the last 10 billion years or so.

"We've known for a while that galaxies have this strange behavior, where they reach a peak in their rate of forming new stars, then it dwindles over time, and then, later on, they stop forming stars altogether," Behroozi said. "Now, we've been able to show that black holes do the same: growing and shutting off at the same times as their host galaxies. This confirms a decades-old hypothesis about black hole growth in galaxies."

However, the result poses more questions, he added. Black holes are much smaller than the galaxies in which they live. If the Milky Way were scaled down to the size of Earth, its supermassive black hole would be the size of the period at the end of this sentence.

For the black hole to double in mass within the same timeframe as the larger galaxy requires synchronization between gas flows at vastly different scales. How black holes conspire with galaxies to achieve this balance is yet to be understood.

"I think the really original thing about Trinity is that it provides us with a way to find out what kind of connections between black holes and galaxies are consistent with a wide variety of different datasets and observational methods," Zhang said.

"The algorithm allows us to pick out precisely those relationships between dark matter halos, galaxies and black holes that are able to reproduce all the observations that have been made. It basically tells us, 'OK, given all these data, we know the connection between galaxies and black holes must look like this, rather than like that.' And that approach is extremely powerful."

More information: Haowen Zhang (???) et al, Trinity I: self-

consistently modelling the dark matter halo–galaxy–supermassive black hole connection from z = 0–10, *Monthly Notices of the Royal Astronomical Society* (2022). DOI: 10.1093/mnras/stac2633

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