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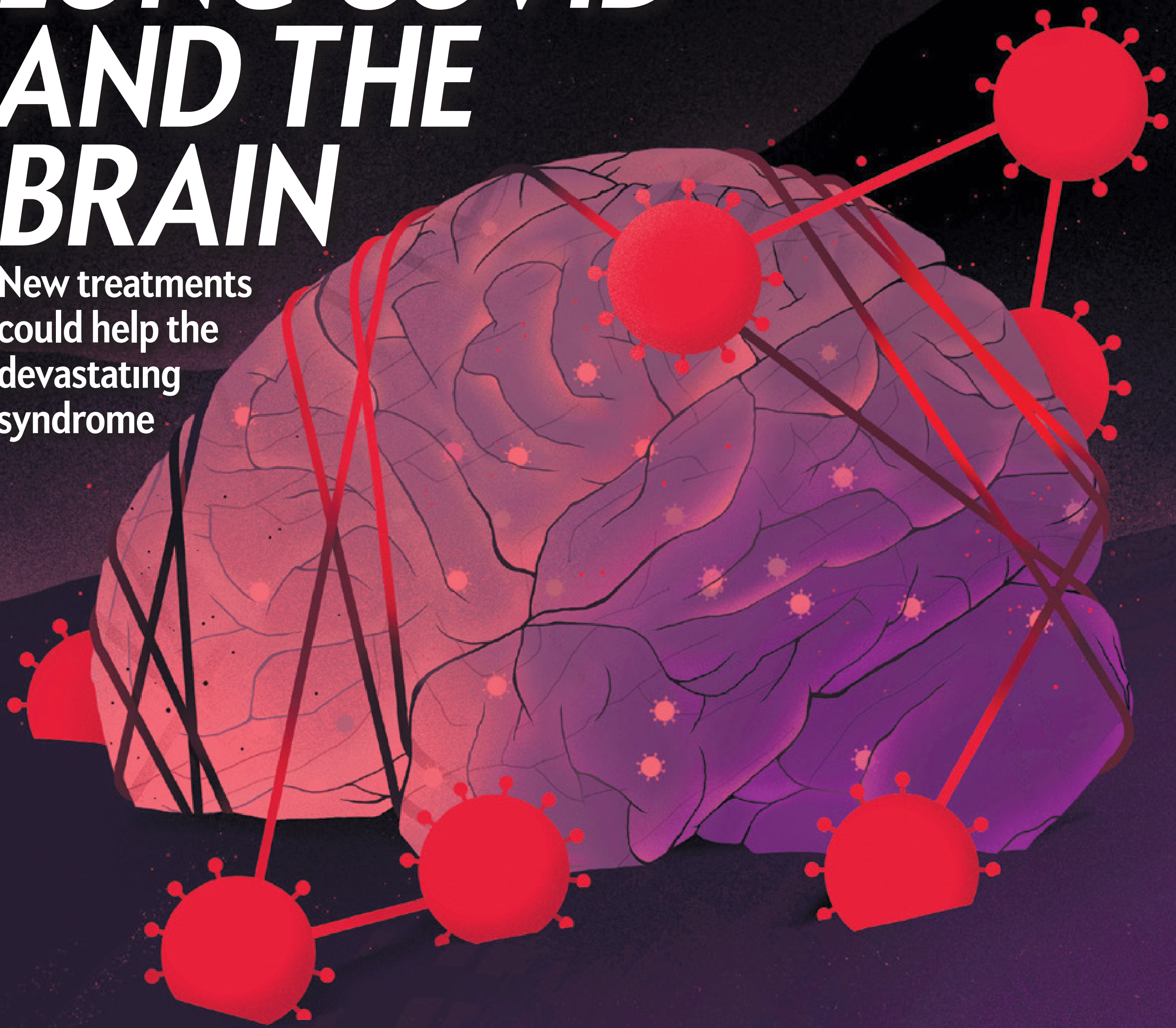

Neutrinos Reveal Black Hole Secrets

Particles from an active galaxy show how supermassive black holes gobble matter

By Phil Plait

In the zoo of subatomic particles, neutrinos are strange beasts. Unlike more familiar particles such as electrons and protons, ghostly neutrinos barely interact with other matter at all: they can fly right through a planet as if it weren't even there. This makes it irritatingly difficult to detect them and, for neutrinos streaming in from cosmic objects in the sky, even harder to know exactly where they come from. In a recent study published in *Science,* however, researchers identified an extragalactic source for these subatomic particles.

For the first time, astronomers have confidently detected neutrinos from NGC 1068, a galaxy with a huge and actively feeding black hole in its center. The neutrinos are being created outside the black hole's "point of no return"—its event horizon—although it's not clear just how; several mechanisms are plausible. Scientists are hoping this discovery will change how they understand not just NGC 1068 but *all* such galaxies. As a bonus, they think the finding may have revealed the source of a faint glow of neutrinos we see everywhere we look in the sky.

Material that falls toward a black hole first forms a flattened accretion disk orbiting around it. Friction heats this disk of matter to incredible temperatures, causing it to glow so brightly it outshines the entire host galaxy. We call such galaxies "active," and they are among the most luminous objects in the universe.

In the case of NGC 1068, detecting that brilliant light is difficult because thick clouds of opaque cosmic dust absorb essentially all of it, letting virtually no signal out. This is where neutrinos' most annoying property is an advantage to us: they can pass right through those dust clouds and fly out into space, eventually reaching Earth. Still, we're left with the problem of detecting them. How do you measure neutrinos when they pass unscathed through your detector? The good news is that to neutrinos, matter is only *mostly* permeable. Although it's extraordinarily rare, some do manage to interact with matter—but it takes a very special kind of observatory to see it.

Located almost exactly at Earth's South Pole, the IceCube Neutrino Observatory is just such a place, and it's not your standard astronomical facility. For one thing, it doesn't use a mirror to collect and focus light from cosmic objects as telescopes do; instead it has a series of relatively simple optical sensors hung along dozens of vertical strings, creating a 3-D array of more than 5,000 sensors that can detect the locations and times of flashes of light.

For another, it's buried under more than a kilometer of Antarctic ice. When a neutrino travels through the ice, it has some small chance of slamming into the nucleus of one of the oxygen or hydrogen atoms in that ice. But actual impacts are exceedingly uncommon: trillions of neutrinos pass through every cubic centimeter of matter on Earth every second, but measurable physical interactions with that matter may only happen days apart.

When they do occur, they create high-speed subatomic shrapnel—particles moving away from the nuclear collision site at just under the speed of light. These then plow through the ice as well. Here's the fun part: they actually travel faster than light can move through the ice. No laws of physics are being broken, though. The speed of light in a vacuum is the ultimate cosmic speed limit, but light moves more slowly when it travels through matter. Particles cannot move faster than light in a vacuum, but they can travel faster than light through matter. When they do, they create a kind of photonic boom, like the shock wave created when something travels through air faster than the speed of sound. These faster-than-light events manifest as bright flashes of blue light called Cherenkov radiation. They can be seen for some distance through the clear Antarctic ice and can be picked up by IceCube's detectors.

This phenomenon allows scientists to detect neutrino events from space, but there's a problem with unwanted events that mimic the desired signals. Subatomic particles from other sources in the universe called cosmic rays can hit our atmosphere and create similar flashes of light, confusing the measurements. Scientists can differentiate between the two kinds of signals in a clever way, though: by using Earth itself as an immense filter. Neutrinos coming from space will come from every direction, including up through Earth. Cosmic rays, however, will come only from the sky above the Antarctic observatory because they can't beam straight through Earth as neutrinos do. The detectors in IceCube can measure direction and filter out the events coming from above, thus ensuring scientists keep only the hits from cosmic neutrinos.

IceCube has detected millions of neutrinos overall, but only a few hundred at most appear to have come from bona fide cosmological objects. Some things out there in the universe are the sources of these neutrinos. The question is, What are they?

Looking over data taken from 2011 to 2020, the IceCube Collaboration—a huge collection of scientists, engineers, data analysts, and more—very carefully processed every event detected. Using the directional information from the flashes to trace the trajectories of the incoming cosmic neutrinos, they found several spots on the sky that appeared to be statistically significant sources of neutrinos.

The detection with the largest number of neutrinos? A total of 79 (plus or minus 20 or so) neutrinos over that period coming from the direction of NGC 1068.

This lovely spiral galaxy is relatively close—a mere 47 million light-years from us—and bright enough to be spotted with binoculars. Earlier work analyzing IceCube neutrinos pointed to NGC 1068 as a possible source, but the data weren't strong enough at the time to claim a discovery. These results change that.

The detection of neutrinos ostensibly coming from this active galaxy is a big deal. The neutrinos that the astronomers saw have phenomenally high energy: more than a tera-electron volt each. That is trillions of times the energy of the visible-light photons we see coming from the galaxy. The particles' huge energy must be cre-

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Scientists detected neutrinos from spiral galaxy Messier 77, also known as NGC 1068, seen here in a Hubble Space Telescope image.

NASA/ESA/A. van der Hoeven

ated in an extremely powerful cosmic particle accelerator, and with an actively feeding big black hole, several options are possible.

For example, the turbulent ionized miasma of matter above and below the disk of material around the black hole is infernally hot and contains powerful magnetic fields that can pump vast energies into particles, accelerating them almost to light speed. Another way involves the magnetic field in that accretion disk getting twisted up near the black hole, creating twin vortices such as tornadoes, called jets, that can fling particles away at high speeds. Shock waves generated in the jets as charged particles slam into one another can also produce the energies needed for high-energy neutrinos. Such jets are known to exist in NGC 1068.

Detecting these neutrinos from NGC 1068 will give astronomers insight into the forces involved there, as well as into which specific engines are responsible for them—quite a boon given the hidden nature of black holes.

Fewer than 100 NGC 1068 neutrinos were detected at Earth, but they would have been diluted as they traveled across the vast volume of space. Accounting for this reduction, the astronomers say the total number of neutrinos generated by the black hole must be so huge that they carry away *a billion times* as much energy as the sun emits.

These observations also provide a major clue for another mystery. Neutrinos come to Earth from all over the sky, creating a background glow across the heavens. The source of this glow has been difficult to pin down. Neutrinos from several other active galaxies were also seen in the IceCube data (though with less statistical certainty than for NGC 1068), and there are many millions of these galaxies throughout the universe. The new data indicate that if they emit neutrinos much as NGC 1068 does, these more distant galaxies could be the source of the cosmic neutrino background, similar to how individual stars in the sky blur together to form the continuous glow of the Milky Way you can see from a dark site at night.

Not too long ago we knew of only two astronomical neutrino sources: the sun, where neutrinos are created in the nuclear fires of its core, and Supernova 1987A, a relatively nearby exploding star that emitted a transient flash of neutrinos once and then was gone.

Every big galaxy in the universe has a supermassive black hole in its core, and any of them can potentially be active. Yet, though ubiquitous, they can be difficult to observe. With a positive detection of neutrinos coming from at least one and probably several of them, astronomers have opened up a new window on these prodigious monsters. SA

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