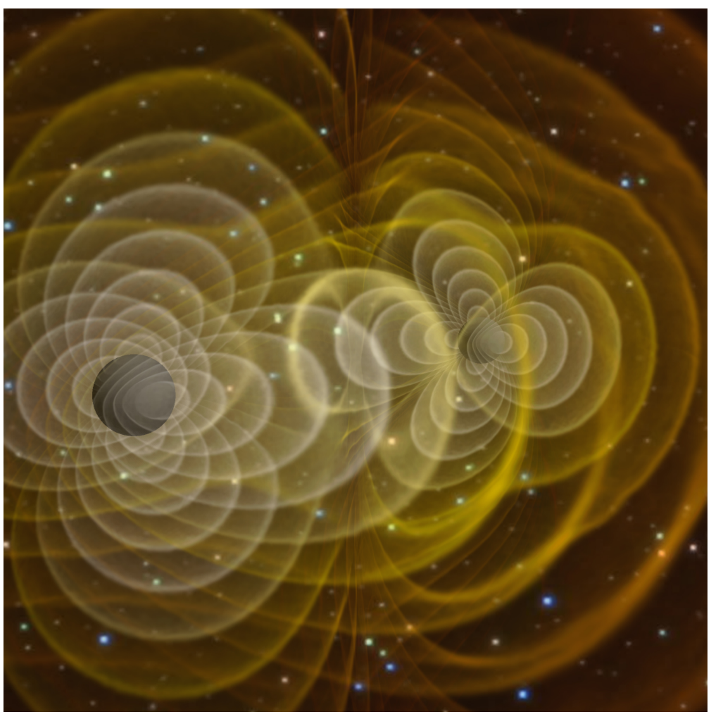
Heaviest Black Hole Merger Flouts a Forbidden Gap

Scientists observe the most massive merger event yet, with the colliding black holes lying in a mass range that is incompatible with the standard stellar-formation scenario.

By **Michael Schirber**

The largest-to-date black hole merger is making headlines and defying astronomers' expectations. The record-breaking event involved black holes with masses around 100 times that of the Sun, a range where the conventional formation process of stellar collapse is deemed impossible. The new observations—reported earlier this week—suggest that some black holes form through a multimerger scenario [**1**].



A visualization from a black hole merger simulation.
Credit: C. Henze/NASA

Since the first merger detection in 2015, around 300 black hole mergers have been observed by the LIGO-Virgo-KAGRA (LVK) Collaboration, a network of scientists operating gravitational-wave detectors in the US, Europe, and Japan. When two black holes spiral into each together, they create ripples in spacetime that can be recorded on Earth with highly sensitive interferometers. Most of these black holes tip the scales at around 10 solar masses, a size that can be explained within a scenario where a massive star runs out of fuel and collapses into a black hole.

But not all stars have this fate. Very massive stars of around 200 solar masses are unstable, according to theoretical models [**2**]. The energy within the core of such a star would be so high that it would produce electron–positron pairs, a matter–antimatter combination that reduces the star's self-sustaining pressure. The drop in pressure leads to a destructive implosion—and no chance for the star to reach a black hole finale. The implication is that stellar collapse cannot produce black holes in the mass range between about 60 and 130 solar masses.

However, in 2019, the LVK Collaboration detected a merger of black holes whose measured masses—65 and 85 solar masses—were at the lower end of the gap (see **Viewpoint: A Heavyweight Merger**). This surprising observation led to speculations about alternative black hole formation scenarios, but since the predicted mass range for the gap was uncertain, it remained possible that these black holes formed through some modified stellar-collapse scenario.

Now the LVK Collaboration has raised the stakes by detecting two heavier black holes, with one squarely in the gap. “This event provides good evidence that black holes in the mass gap can exist,” says LIGO Scientific Collaboration spokesperson Stephen Fairhurst from Cardiff University in the UK.

The new event, which goes by the name GW231123, was observed in November 2023 by the two LIGO observatories in the US. The gravitational-wave signal was in the low-frequency range of the detectors, which implies that the black holes were on the heavy side. The signal was also short—just one-fifth of a second—which complicated the interpretation, says LVK member Sophie Bini from Caltech. The collaboration uses so-called waveform models to determine parameters such as mass, orbital orientation, and distance. “The analysis is more uncertain because you have less information to start with,” Bini says.

The best fit turned out to be a merger of two black holes with masses of 103 and 137 solar masses, with the resulting black hole weighing in at 225 solar masses. Because of the signal’s brevity, the researchers could not pinpoint the location in the sky where the event happened. Bini presented these results on Monday at the GR–Amaldi meeting in Glasgow, Scotland.

“This is indeed exciting news!” says astrophysicist Davide Gerosa from the University of Milano-Bicocca in Italy, who was not involved in the study. “With the first gravitational-wave event, now 10 years ago, we were surprised that black holes of 30 solar masses exist. Now we have black holes of more than 100 solar masses, which is just spectacular.”

The question becomes: How can these Goliaths form? “A possible scenario is that these black holes originate from hierarchical mergers,” Bini says. This model assumes that earlier generations of mergers create highly massive black holes that go onto merge with other heavyweights. “It’s like a family tree of black holes,” Bini says. One challenge for this model is having merged black holes meet up. Normally, a merger event gives a recoil kick to the final black hole, which can cause it to fly out of star-rich regions where further mergers would be expected, explains Bini.

A possible clue related to hierarchical merging is the rotation, or “spin,” of the black holes around their axes. In the standard stellar-collapse scenario, the two merging black holes formed in a binary system, so their spins are predicted to be aligned and relatively small. Indeed, most mergers recorded by the LVK Collaboration have small spin values for the two incoming black holes. However, the final black hole—the one that results from the merger—should have a relatively large spin value [**3**]. That’s because it essentially assimilates all the orbital angular momentum from the rapid orbital motion of the merging black holes, Gerosa explains.

The researchers determined the spins of the two merging black holes for GW231123. And although the values have large uncertainties (about 20% to 50%), both objects appear to be spinning near the maximum allowed values: one at 80% of maximum and the other at 90%. Such high spins suggest that these black holes were created in previous mergers. However, Gerosa points out that the observed spin values are actually a bit too high. “The typical prediction for spins in the hierarchical merger scenario is around 70%,” he says. But he speculates that the estimates for the observed spins may come down slightly as modelers further analyze the data.

Another possibility that the LVK Collaboration considers is that a massive star merges with another star—bypassing the pair-creation instability. But these models have difficulty explaining the large spin values that the team observes.

Even if scientists remain uncertain about how these black holes formed, they may be able to discern where they formed, says theorist Rosalba Perna from Stony Brook University in New York, who was also not involved in the study. She says the GW231123 merger probably occurred in an environment where the density of stars is high enough that black hole interactions are frequent or where the surrounding medium is dense enough that black holes can accrete a lot of additional material. “The disks of active galactic nuclei come to mind,” she says.

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