Meet GW190521—a black-hole merger for the record books

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Numerical simulation of two black holes that inspiral and merge, emitting gravitational waves. The black holes have large and nearly equal masses, with one only 3% more massive than the other.
The LIGO/VIRGO collaboration has picked up a gravitational wave signal from another black-hole merger—and it's one for the record books.

The merger is the most massive and most distant yet detected by the collaboration, its signal traveling across the Universe for a billion years before reaching Earth. The merger also produced the most energetic signal detected thus far, showing up in the data as more of a "bang" than the usual "chirp." And the new black hole resulting from the merger is the rarest of all in terms of its intermediate mass (about 150 times as heavy as our Sun), making this the first direct observation of an intermediate-mass black hole.

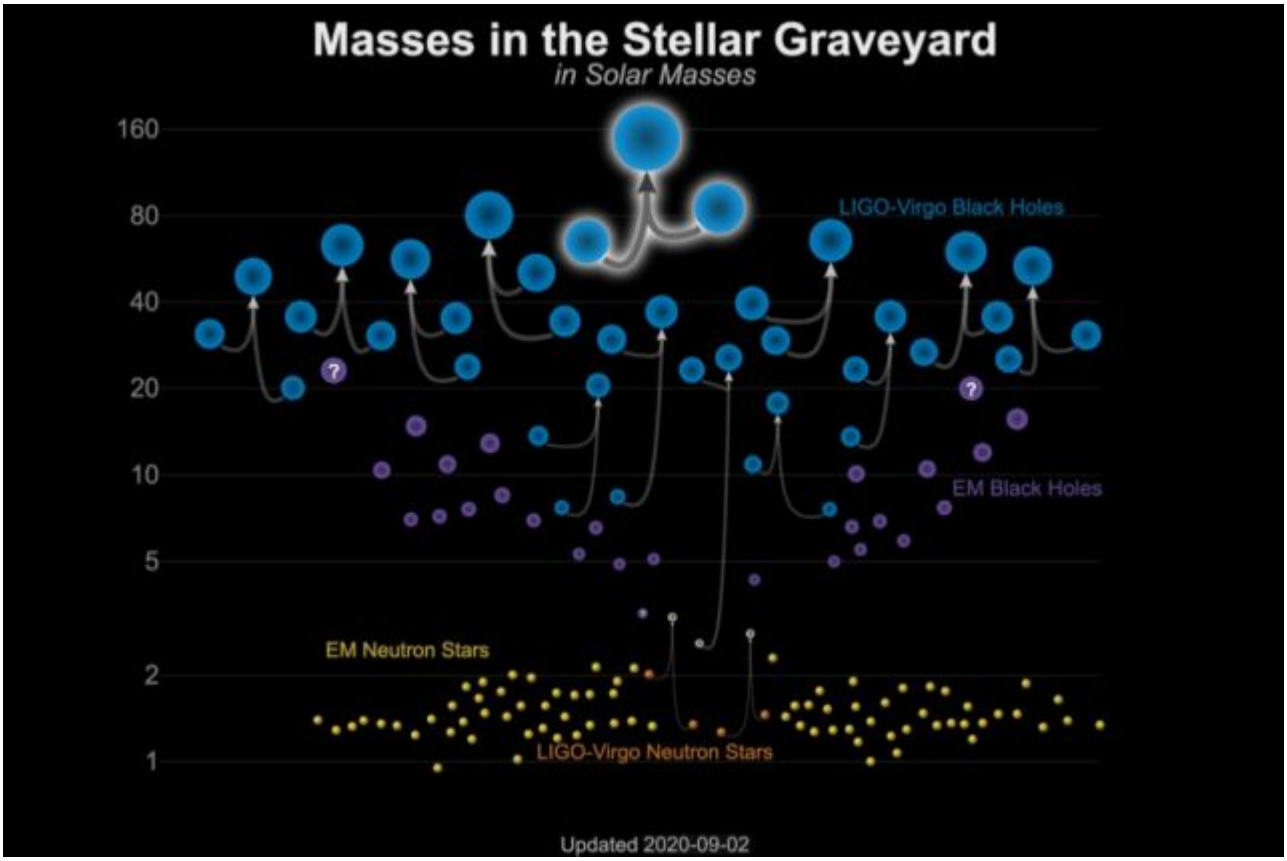
"One of the great mysteries in astrophysics is how do supermassive black holes form?" said Christopher Berry of Northwestern University. "They are the million solar-mass elephants in the room. Do they grow from stellar-mass black holes, which are born when a star collapses, or are they born via an undiscovered means? Long have we searched for an intermediate-mass black hole to bridge the gap between stellar-mass and supermassive black holes. Now, we have proof

that intermediate-mass black holes do exist.”

Details of this latest discovery, dubbed GW190521, appeared today in two concurrent papers published in Physical Review Letters and Astrophysical Journal Letters. The former details the discovery of the gravitational wave signal, while the latter discusses the signal’s physical properties and its astrophysical implications.

Hunting mergers

LIGO detects gravitational waves via laser interferometry, using high-powered lasers to measure tiny changes in the distance between two objects positioned kilometers apart. (LIGO has detectors in Hanford, Washington, and in Livingston, Louisiana. A third detector in Italy, Advanced VIRGO, came online in 2016.) On September 14, 2015, at 5:51am EST, both detectors picked up signals within milliseconds of each other for the very first time—direct evidence for two black holes spiraling inward toward each other and merging in a massive collision event that sent powerful shockwaves across spacetime.



Enlarge / Updated plot of the masses of black holes. The most recent black-hole merger tops the chart at 142 solar masses.
LIGO-Virgo/Northwestern U/Frank Elavsky/Aaron Geller

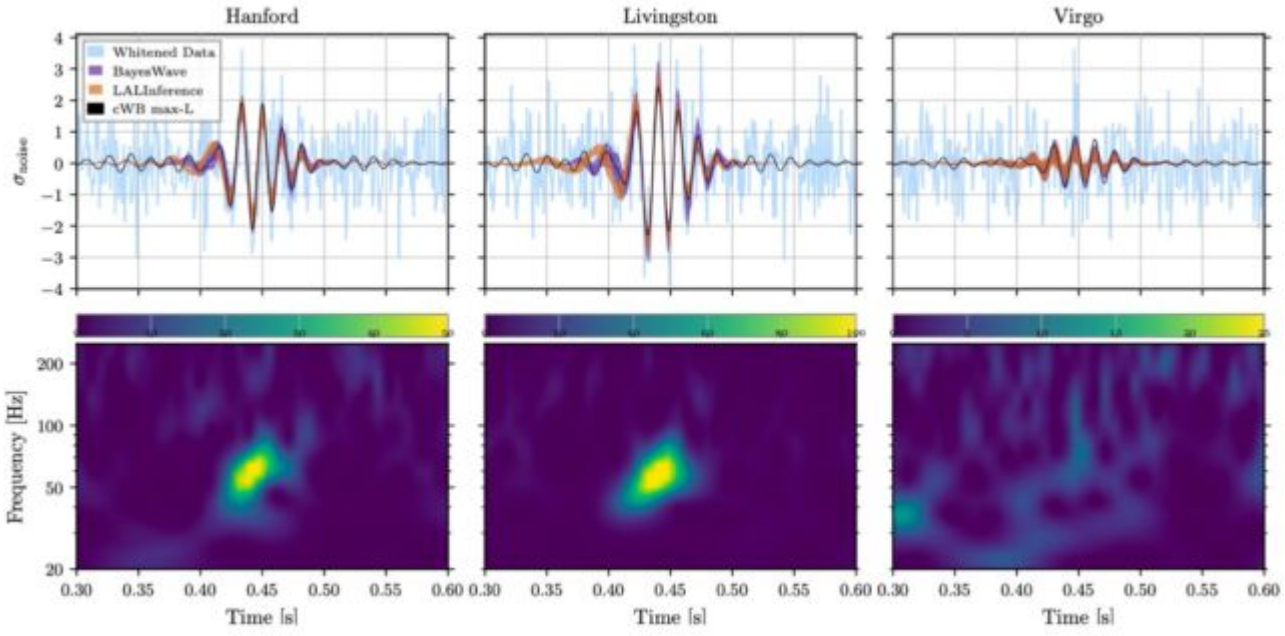
LIGO has been upgraded and has conducted two more runs since then, kicking off its third run April 1, 2019. Within a month, the collaboration detected five more gravitational wave events: three from merging black holes, one from a neutron star merger, and another that may have been the first instance of a neutron star/black-hole merger. (For hardcore LIGO buffs, there's now an iPhone app that lets you follow the event announcements, with an Android version in the works.)

More recently, in June 2020 the collaboration announced the detection of a binary black-hole merger on May 21, 2019 (designated S190521g). That binary system may have formed in the accretion disk surrounding a supermassive black hole at the center of a galaxy. It could also be the first evidence that there might be unusual conditions in which such a merger could produce an accompanying explosion of light.

Rumors began flying last year about a new candidate event with

a signal suggesting a much more massive black-hole merger than prior detections. Those rumors are now confirmed. On May 21, 2019, the collaboration's detectors picked up the telltale signal of a binary black-hole merger: four short wiggles lasting less than one-tenth of a second. The shorter the signal, the more massive the black holes that are merging—in this case, 85 and 66 solar masses, respectively. The black holes merged to form a new, even larger black hole of about 142 solar masses, emitting the energetic equivalent of eight solar masses in the process—hence the powerful signal picked up by the detectors.

What makes this event so unusual is that 142 solar masses falls smack in the middle of what's known as a "mass gap" for black holes. Most such objects fall into two groups: stellar-mass black holes (ranging from a few solar masses to tens of solar masses) and supermassive blackholes like the one in the middle of our Milky Way galaxy (ranging from hundreds of thousands to billions of solar masses). The former are the result of massive stars dying in a core-collapse supernova, while the latter's formation process remains something of a mystery.



Enlarge / The GW event GW190521 observed by the LIGO Hanford (left), LIGO Livingston (middle), and Virgo (right) detectors.

LIGO-Virgo/PRL

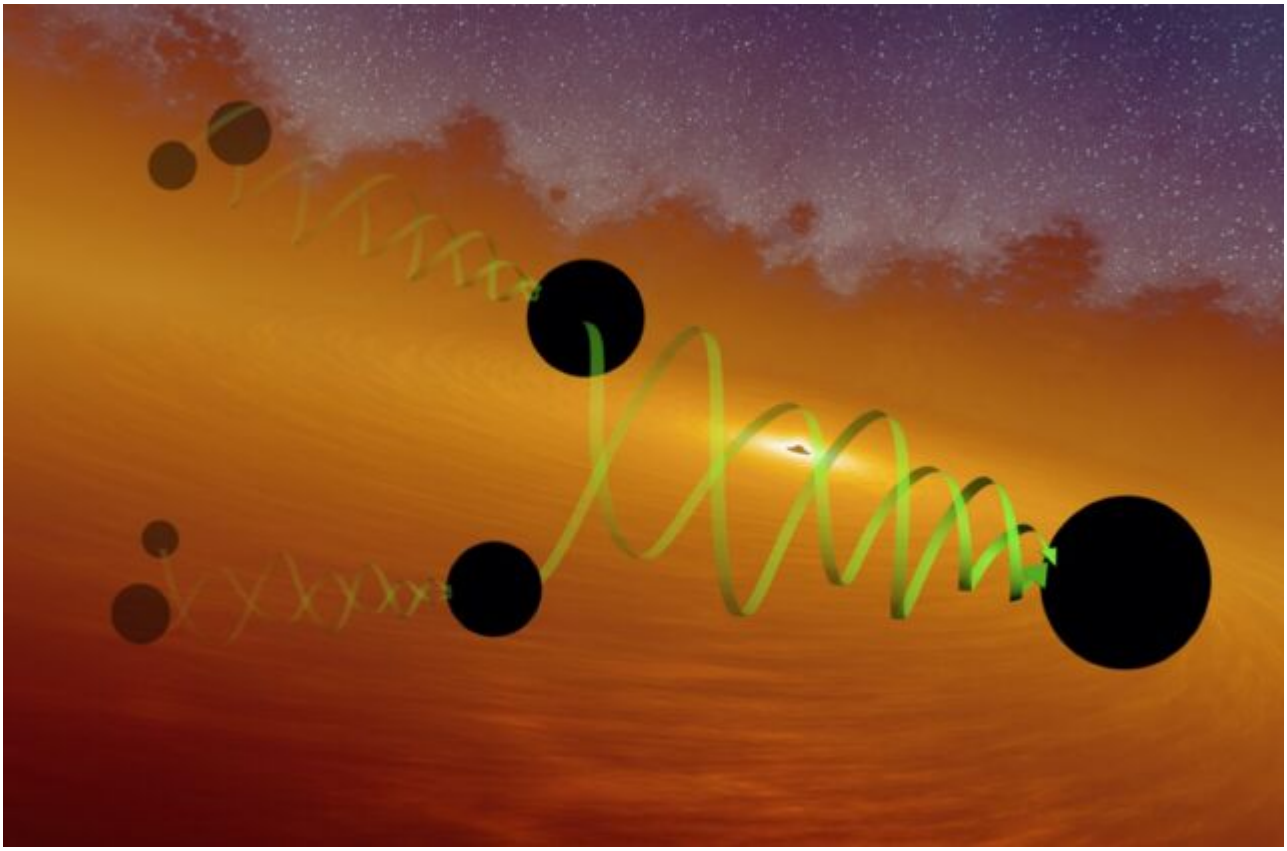
The fact that one of the progenitor black holes here weighs in at 85 solar masses is also highly unusual, since this is at odds with current models of stellar evolution. The kinds of stars that would give rise to black holes between 65 and 135 solar masses would not go supernova and thus would not end up as black holes. Rather, such stars would become unstable and slough off a significant chunk of their mass. Only then would they go supernova—but the result would be a black hole of less than 65 solar masses.

"From our understanding of how stars age and evolve we expect to find black holes with either less than 65 solar masses or more than 120 solar masses, but none in between," said Frank Ohme, who leads an Independent Max Planck Research Group at AEI Hannover. "The 85 solar-mass black hole in the GW190521 origin system falls right in that gap where it shouldn't be. This can mean two things: our understanding of stars' evolution is incomplete or something different has happened here."

The explanation currently favored is that this is an example of a so-called "hierarchical merger," meaning the two progenitor black holes were themselves each the result of a previous merger before they found each other and merged. That scenario implies sufficient other black holes nearby to enable multiple mergers. However, "there are many ideas about how to get around this—merging two stars together, embedding the black hole in a thick disc of material it can swallow, or primordial black holes created in the aftermath of the Big Bang," said Berry, who personally favors the hierarchical merger scenario. But thus far the evidence is not conclusive.

Physicists might get additional clues from possible corresponding electromagnetic data. The Zwicky Transient Facility (ZTF) detected a flare emerging 35 days after the gravitational-wave signal from the same region of the sky. "This flare could have been produced by the gas in the black

holes' environment, which gets heated by shock waves induced by the merger," Rosalba Perna of Stony Brook University, New York, wrote in an accompanying viewpoint. "If the connection between flare and merger is true, then the merger occurred in the disk of an active galactic nucleus. In this environment, which is conducive to multiple-generation black holes weighing more than 50 solar masses, the presence of a black hole within the mass gap wouldn't be surprising."



Enlarge / Artist's concept of a hierarchical scheme for merging black holes. Scientists hypothesize that the two black holes were themselves each the result of an earlier merger of two smaller black holes.
LIGO/Caltech/MIT/R. Hurt (IPAC)

More detectors

So what's next for the collaboration? LIGO-Virgo scientists have identified 56 possible gravitational wave detections (candidate events) from the now-completed third run, only four of which have been confirmed and publicly announced (including

today’s announcement). Analysis of the remaining 52 candidates is ongoing, so it’s possible the collaboration will announce more discoveries in the future. Any additional discoveries should help shed more light on the many questions raised by GW190521.

“We don’t know yet whether GW190521 is an entirely new class of binary black holes or just the high-mass end of the source spectrum we’ve seen so far,” said Karsten Danzmann, director at the AEI Hannover and director of the Institute for Gravitational Physics at Leibniz University Hannover. “Soon, when we have analyzed all binary black-hole mergers seen by LIGO and Virgo in their third observing run, we might know more.”

In addition to planned upgrades for both LIGO (LIGO-Voyager) and Virgo—which physicists expect will increase the detection rate by a factor of eight—the collaboration continues to expand its reach around the globe. In Japan, KAGRA is now online, and it’s the first gravitational wave detector in Asia and the first to be built underground. Construction began on LIGO-India earlier this year, and physicists expect it will turn on sometime after 2025.

“More facilities would also help in pinpointing the exact spot from which the gravitational waves emanated,” B.S. Sathyaprakash (Penn State University) and Matthew Evans (MIT) noted in an accompanying commentary. “With KAGRA and LIGO-India up and running, researchers could record a ‘quintuple hit’—the same waves deforming all five detectors. That would enable astronomers to more easily watch the mergers with conventional telescopes, reducing the sky area that they would need to survey by a factor of four.”

DOI: Physical Review Letters, 2020. 10.1103/PhysRevLett.125.101102 (About DOIs).

DOI: Astrophysical Journal Letters, 2020.

10.3847/2041-8213/aba493 (About DOIs).

[embedded content]
Artistic rendering (not a numerical simulation) of “the impossible black hole.” Two monster black holes merge to form an intermediate-mass black hole, about 150 times as heavy as the Sun (GW190521).
Listing image by N. Fischer, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes (SXS) Collaboration

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