Pair of Distinct Black Hole Mergers Sheds New Light on Nature of Their Formation and Evolution

The mergers, measured one month apart in 2024 by LIGO-Virgo-KAGRA collaboration, advance scientific understanding of the nature of black hole formation and fundamental physics.

October 28, 2025 – A pair of distant cosmic black hole mergers, measured just one month apart in late 2024, is improving how scientists understand the nature and evolution of the most violent deep-space collisions in our universe. Data collected from the mergers also validates, with unprecedented accuracy, fundamental laws of physics that were predicted more than 100 years ago by Albert Einstein and furthers the search for new and still unknown elementary particles with the potential to extract energy from black holes.

In a new paper published Oct. 28 in *The Astrophysical Journal Letters,* the international LIGO-Virgo-KAGRA Collaboration reports on the detection of two gravitational wave events in October and November of last year with unusual black hole spins.

Gravitational waves are “ripples” in space-time that result from cataclysmic events in deep space, with the strongest waves produced by the collision of black holes. The first merger described in this paper, GW241011 (Oct. 11, 2024), occurred roughly 700 million light years away and resulted from the collision of two black holes weighing in at around 20 and 6 times the mass of our sun. The larger of the black holes in GW241011 was measured to be one of the fastest rotating black holes observed to date.

Almost one month later, GW241110 (Nov. 10, 2024) was detected around 2.4 billion light years away and involved the merger of black holes roughly 17 and 8 times the mass of our sun. While most observed black holes spin in the same direction as their orbit, the primary black hole of GW241110 was noted to be spinning in a direction opposite its orbit – a first of its kind.

“Each new detection provides important insights about the universe, reminding us that each observed merger is both an astrophysical discovery but also an invaluable laboratory for probing the fundamental laws of physics,” says paper co-author Carl-Johan Haster, assistant professor of astrophysics at the University of Nevada, Las Vegas (UNLV). “Binaries like these had been predicted given earlier observations, but this is the first direct evidence for their existence.”

Uncovering Hidden Properties of Black Hole Mergers

Gravitational waves were first predicted by Albert Einstein as part of his general theory of relativity in 1916, but their presence – though proven in the 1970s – wasn’t directly observed by scientists until just 10 years ago when the LIGO observatory confirmed detection of the waves as the result of a black hole merger.

Today, LIGO-Virgo-KAGRA is a worldwide network of advanced gravitational-wave detectors and is in the midst of its fourth observing run, O4. The current run started in late May 2023 and is expected to continue through mid-November of this year. To date, approximately 300 black hole mergers have been observed through gravitational waves, including candidates identified in the ongoing O4 run.

Together, the detection of GW241011 and GW241110 highlight the remarkable progress of gravitational-wave astronomy in uncovering the properties of merging black holes. Interestingly, both detected mergers point toward the possibility of “second-generation” black holes.

"GW241011 and GW241110 are among the most novel events among the several hundred that the LIGO-Virgo-KAGRA network has observed,” says Stephen Fairhurst, professor at Cardiff University and spokesperson of the LIGO Scientific Collaboration. “With both events having one black hole which is both significantly more massive than the other and rapidly spinning, they provide tantalizing evidence that these black holes were formed from previous black hole mergers."

Scientists point to certain clues, including the size differential between the black holes in each merger – the larger was nearly double the size of the smaller – and the spin orientations of the larger of the black holes in each event. A natural explanation for these peculiarities is that the black holes are the result of earlier coalescences. This process, called a hierarchical merger, suggests that these systems formed in dense environments, in regions like star clusters, where black holes are more likely to run into each other and merge again and again.

"These two binary black hole mergers offer us some of the most exciting insights yet about the earlier lives of black holes,” said Thomas Callister, co-author and assistant professor at Williams College. ”They teach us that some black holes exist not just as isolated partners but likely as members of a dense and dynamic crowd. Moving forward, the hope is that these events and other observations will teach us more and more about the astrophysical environments that host these crowds."

Implications for Fundamental Physics

The precision with which GW241011 was measured also allowed key predictions of Einstein’s theory of general relativity to be tested under extreme conditions.

Because GW241011 was detected so clearly, it can be compared to predictions from Einstein’s theory and mathematician Roy Kerr’s solution for rotating black holes. The black hole’s rapid rotation slightly deforms it, leaving a characteristic fingerprint in the gravitational waves it emits. By analyzing GW241011, the research team found excellent agreement with Kerr’s solution and verified Einstein’s prediction with unprecedented accuracy.

Additionally, because the masses of the individual black holes differ significantly, the gravitational-wave signal contains the “hum” of a higher harmonic – similar to the overtones of musical instruments, seen only for the third time ever in GW241011. One of these harmonics was observed with superb clarity and confirms another prediction from Einstein's theory.

"The strength of GW241011, combined with the extreme properties of its black hole components provide unprecedented means for testing our understanding of black holes themselves," says Haster. "We now know that black holes are shaped like Einstein and Kerr predicted, and general relativity can add two more checkmarks in its list of many successes. This discovery also means that we're more sensitive than ever to any new physics that might lie beyond Einstein's theory."

Advanced Search for Elementary Particles

Rapidly rotating black holes like those observed in this study now have yet another application – in particle physics. Scientists can use them to test whether certain hypothesized light-weight elementary particles exist and how massive they are.

These particles, called ultralight bosons, are predicted by some theories that go beyond the Standard Model of particle physics, which describes and classifies all known elementary particles. If ultralight bosons exist, they can extract rotational energy from black holes. How much energy is extracted and how much the rotation of the black holes slows down over time depends on the mass of these particles, which is still unknown.

The observation that the massive black hole in the binary system that emitted GW241011 continues to rotate rapidly even millions or billions of years after it formed rules out a wide range of ultralight boson masses.

"Planned upgrades to the LIGO, Virgo, and KAGRA detectors will enable further observations of similar systems, enabling us to better understand both the fundamental physics governing these black hole binaries and the astrophysical mechanisms that lead to their formation," said Fairhurst.

Joe Giaime, site head for the LIGO Livingston Observatory, noted that LIGO scientists and engineers have made improvements to the detectors in recent years, which has resulted in precision measurements of merger waveforms that allow for the kind of subtle observations that were needed for GW241011 and GW241110.

"Better sensitivity not only allows LIGO to detect many more signals, but also permits deeper understanding of the ones we detect," he said.

Publication Details

"GW241011 and GW241110: Exploring Binary Formation and Fundamental Physics with Asymmetric, High-Spin Black Hole Coalescences" was published Oct. 28 in *The Astrophysical Journal Letters.*

The LIGO-Virgo-KAGRA Collaboration

LIGO is funded by the NSF, and operated by Caltech and MIT, which conceived and built the project. Financial support for the Advanced LIGO project was led by NSF with Germany (Max Planck Society), the U.K. (Science and Technology Facilities Council) and Australia (Australian Research Council) making significant commitments and contributions to the project. More than 1,600 scientists from around the world participate in the effort through the LIGO Scientific Collaboration, which includes the GEO Collaboration. Additional member institutions are listed at https://my.ligo.org/census.php.

The Virgo Collaboration is currently composed of approximately 880 members from 152 institutions in 17 different (mainly European) countries. The European Gravitational Observatory (EGO) hosts the Virgo detector near Pisa in Italy, and is funded by Centre National de la Recherche Scientifique (CNRS) in France, the Istituto Nazionale di Fisica Nucleare (INFN) in Italy, and the National Institute for Subatomic Physics (Nikhef) in the Netherlands. More information is available on the Virgo website at https://www.virgo-gw.eu.

KAGRA is the laser interferometer with a 3 km arm-length in Kamioka, Gifu, Japan. The host institute is Institute for Cosmic Ray Research (ICRR), the University of Tokyo, and the project is co-hosted by National Astronomical Observatory of Japan (NAOJ) and High Energy Accelerator Research Organization (KEK). KAGRA collaboration is composed of over 400 members from 128 institutes in 17 countries/regions. KAGRA's information for general audiences is available at https://gwcenter.icrr.u-tokyo.ac.jp/en/. Resources for researchers are accessible from http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/KAGRA.

Media Contacts:

LIGO-Virgo-Kagra Collaboration
LVK Communications Group
Lead Susanne Milde +49 172 3931349
susanne.milde@ligo.org

Caltech
Whitney Clavin
wclavin@caltech.edu
626-395-1944

MIT
Abigail Abazorius
abbya@mit.edu
617-253-2709

Virgo
Simone Mastrogiovanni
simone.mastrogiovanni@roma1.infn.it

EGO
Vincenzo Napolano
napolano@ego-gw.it
+393472994985

NSF
Jason Stoughton
Staff Associate for Science Communications
703-292-7063
jstought@nsf.gov

KAGRA
Shinji Miyoki
kagra-pub@icrr.u-tokyo.ac.jp
+81-578-85-2623