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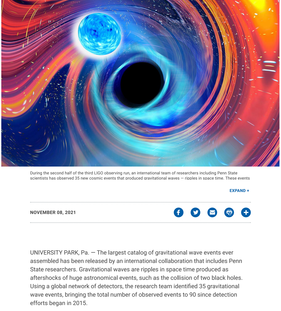
Black holes of all shapes and sizes in new gravitational wave catalog



During the second half of the third LIGO observing run, an international team of researchers including Penn State scientists has observed 35 new cosmic events that produced gravitational waves — ripples in space time. These events

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UNIVERSITY PARK, Pa. — The largest catalog of gravitational wave events ever assembled has been released by an international collaboration that includes Penn State researchers. Gravitational waves are ripples in space time produced as aftershocks of huge astronomical events, such as the collision of two black holes. Using a global network of detectors, the research team identified 35 gravitational wave events, bringing the total number of observed events to 90 since detection efforts began in 2015.

The new gravitational wave events were observed between November 2019 and March 2020, using three international detectors: The two Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors in Louisiana and Washington state in the U.S. and the Advanced Virgo detector in Italy. Data from these three detectors were carefully analyzed by a team of scientists from the LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration. The catalog of new events from the second half of LIGO's third observing run is described in a paper appearing Nov. 7 in the preprint server arXiv.

"In the third observation run of LIGO and Virgo, we have begun to detect the more elusive types of gravitational wave events," said Debnandini Mukherjee, a postdoctoral researcher at Penn State and a member of the LIGO collaboration. "This has included heavy mass black holes, more extreme mass ratio binaries and neutron star–black hole coalescences detected with higher confidence. We are in the exciting era where such observations have begun to complement existing well-known astrophysics and have begun to contribute towards a clearer understanding of formations of such objects."

New detections

Of the 35 events detected, 32 were most likely to be black hole mergers — two black holes spiraling around each other and finally joining together, an event that emits a burst of gravitational waves.

The black holes involved in these mergers have a range of sizes, the most massive of which is around 90 times the mass of our sun. Several of the resulting black holes that formed from these mergers exceed 100 times the mass of our sun and are classed as intermediate-mass black holes. This marks the first observation of this type of black hole, which had long been theorized by astrophysicists.

Two of the 35 events were likely to be mergers of neutron stars with black holes — a much rarer type of event and one that was first discovered during the most recent observing run of LIGO and Virgo. One of these newly detected mergers seems to show a massive black hole about 33 times the mass of our sun colliding with a very low-mass neutron star about 1.17 times the mass of our sun. This is one of the lowest-mass neutron stars ever detected, using gravitational-waves or electromagnetic observations.

The masses of black holes and neutron stars are key clues to how massive stars live and ultimately die in supernova explosions.

"In this latest update to the catalog, we were finally able to observe mergers of black holes with neutron stars, which we didn't find in any the previous observing runs," said Becca Ewing, graduate at Penn State and a member of Penn State's LIGO group. "With every new observing run, we find signals with new and different properties, expanding our understanding of what these systems can look and behave like. In this way, we can begin to improve our understanding of the universe more and more with each new observation."

The final gravitational wave event came from a merger of a black hole with a mass around 24 times the mass of our sun with either a very light black hole or a very heavy neutron star of around 2.8 times the mass of our sun. The research team has deduced it is most likely to be a black hole, but cannot be entirely sure. A similar ambiguous event was discovered by LIGO and Virgo in August 2019. The mass of the lighter object is puzzling, as scientists expect that the most massive a neutron star can be before collapsing to form a black hole is around 2.5 times the mass of our sun. However, no black holes had been discovered with electromagnetic observations with masses below about 5 solar masses. This led scientists to theorize that stars do not collapse to make black holes in this range. The new gravitational wave observations indicate that these theories may need to be revised.

The LIGO-Virgo collaboration has detected a wide range of cosmic collisions, including between two black holes and between black holes and neutron stars, from the gravitational waves emitted by these events. Each line in this graphic

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Monumental progress

Since the first gravitational wave detection in 2015, the number of detections has risen at a thundering rate. In a matter of years, gravitational wave scientists have gone from observing these vibrations in the fabric of the universe for the first time, to now observing many events every month, and even multiple events on the same day. During this third observing run, the gravitational wave detectors reached their best-ever performance thanks to a program of constant upgrades and maintenance to improve the performance of the pioneering instruments.

As the rate of gravitational wave detections increases, scientists have also improved their analytical techniques to ensure the high accuracy of results. The growing catalog of observations will enable astrophysicists to study the properties of black holes and neutron stars with unprecedented precision.

In another significant advancement in this recent run, within minutes of the initial gravitational wave detections, astronomers issued a call to other observatories and detectors around the world. This network of neutrino detectors and electromagnetic observatories focused on the area of sky where the waves were coming from, to try to identify the source event. Cosmic events that produce gravitational waves can also produce neutrinos and electromagnetic emissions that, if detected, can provide additional information about the cosmic event. However, none of the newly announced gravitational waves have a reported counterpart.

"Rapidly communicating with other observatories is essential to detect counterparts and contribute to multi-messenger astronomy," said Bryce Cousins, assistant researcher at Penn State and a member of the LIGO collaboration. "By studying a cosmic event via multiple signals, we can not only learn about the specific properties of black holes and neutron stars, but also investigate broader areas of astrophysics, such as stellar evolution and the expansion of the universe. The alert systems and observatory networks established during this observing run will be vital for detecting the counterparts we need to better understand these topics in future observing runs."

For the next full observing run, expected to begin next summer, the KAGRA observatory in Japan will also join the search. Located deep under a mountain, KAGRA completed a successful first observing run in 2020, but has yet to join LIGO and Virgo in making joint observations. With more detectors, potential events can be located more accurately.

"KAGRA joining the detector network can contribute to improving the sky localization area of gravitational wave candidate sources by about a factor of two, which can then benefit detections of counterparts since knowing the precise locations of the sources in the sky is crucial for telescopes to make observations," said Shio Sakon, graduate student at Penn State and a member of the LIGO collaboration. "With the developments of the detection pipeline, upgrades of LIGO and VIRGO, and KAGRA's partaking in the detector network, we expect to detect and analyse gravitational waves candidate events more frequently than ever, and sending out high-quality low-latency public alerts will be vital to the advancement of multi-messenger astronomy."

About the gravitational-wave observatories:

This material is based upon work supported by National Science Foundation's LIGO Laboratory, which is a major facility funded by the NSF. LIGO is operated by Caltech and MIT, which conceived of LIGO and led the Advanced LIGO detector project. Financial support for the Advanced LIGO project was principally from the NSF with the Max Planck Society in Germany, the Science and Technology Facilities Council in the U.K., and the Australian Research Council-OzGrav in Australia making significant commitments and contributions to the project. Approximately 1,400 scientists from around the world participate in the effort to analyze the data and develop detector designs through the LIGO Scientific Collaboration, which includes the GEO Collaboration. A **list of additional LIGO partners** is available at the **LIGO website**.

The Virgo Collaboration is currently composed of approximately 650 members from 119 institutions in 14 different countries including Belgium, France, Germany, Hungary, Italy, the Netherlands, Poland, and Spain. The European Gravitational Observatory hosts the Virgo detector near Pisa in Italy and is funded by the Centre National de la Recherche Scientifique in France, the Istituto Nazionale di Fisica Nucleare in Italy, and Nikhef in the Netherlands. A **list of the Virgo Collaboration groups** and additional information can be found at the **Virgo website**.

The KAGRA detector is located in Kamioka, Gifu, Japan. The host institute is the Institute of Cosmic Ray Researches at the University of Tokyo, and the project is co-hosted by National Astronomical Observatory in Japan and High Energy Accelerator Research Organization. KAGRA completed its construction in 2019, and later joined the international gravitational-wave network of LIGO and Virgo. The actual data-taking was started in February 2020 during the final stage of the run called "O3b." The KAGRA collaboration is composed of over 470 members from 11 countries/regions. The **list of KAGRA researchers** and additional information is available at the **KAGRA website**.

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