LIGO–India Scientific Collaboration

THE CURIOUS CASE OF GW190814:

THE COALESCENCE OF A BLACK HOLE AND A MYSTERY COMPACT OBJECT

The network of two advanced-LIGO detectors (at Hanford, Washington and Livingston, Louisiana, USA) and the advanced-Virgo detector (in Cascina, Italy), have detected gravitational waves from the inspiral and merger of a stellar-mass black hole and another compact object of undetermined nature. This new event has been named GW190814.

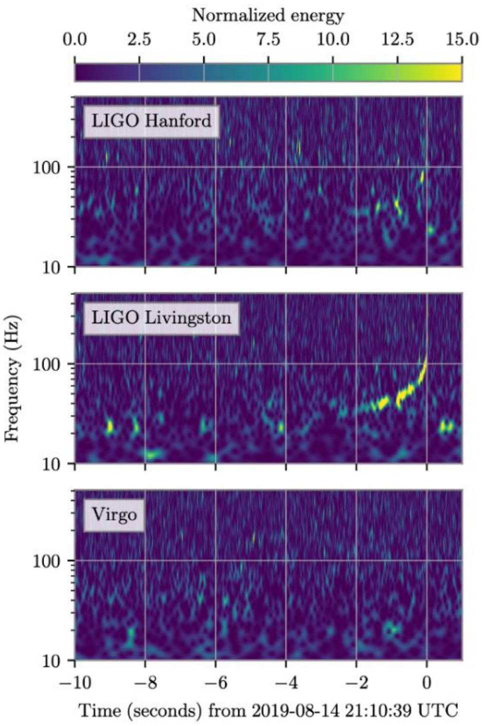
The gravitational signal from this merger event travelled for nearly 800 million years through the expanding universe and arrived at the LIGO detectors in the wee hours of 15th August 2019, just past 02:40 am Indian Standard Time.

The LIGO-Virgo detectors were in the middle of their third observing run when they observed this extremely loud event. In fact, GW190814 is the third loudest event that has been seen to date (after the binary neutron star system GW170817 and the first binary black hole system GW150914 observed by the LIGO detectors). A paper about the detection has been published in *The Astrophysical Journal Letters*.`

GW190814 has two outstanding features that make it unique:

- Before the two objects merged, their masses differed by a factor of 9, making this the most extreme mass ratio known for a gravitational-wave event. In comparison, the recent LIGO-Virgo event GW190412 had a mass ratio of about 4:1.
- From the measured mass of the lighter compact object, we can infer it to be either the lightest black hole or 'the most massive neutron star' ever discovered in a compact binary system. But at this point, we can't be sure which one it is.

Together, these features challenge our understanding of the masses of compact astrophysical objects and the way they end up in merging systems.

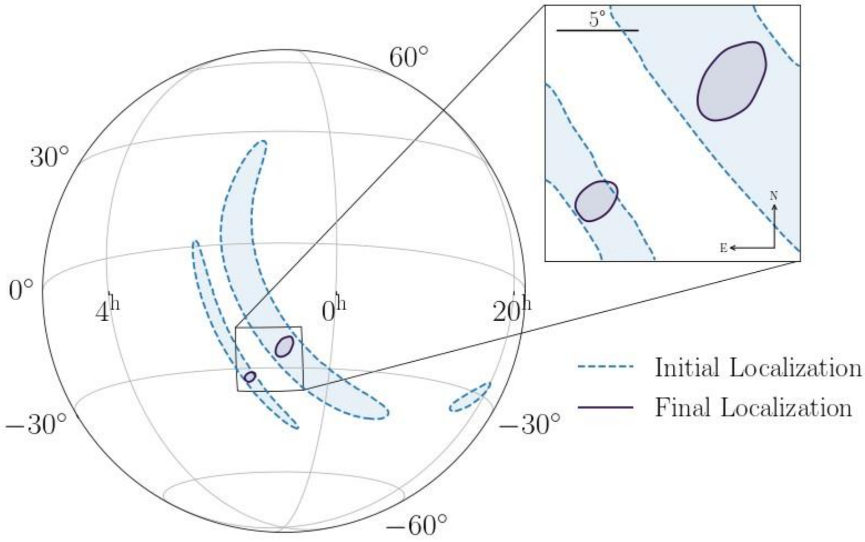


Time-frequency spectrograms of data containing GW190814, observed by LIGO Hanford (top), LIGO Livingston (middle), and Virgo (bottom). Times are shown from around 10 seconds before the event. The energy in a certain time-frequency bin is represented by the colour palette. A "chirping" signal can be clearly seen in the middle panel (LIGO Livingston data), where the signal was the loudest.

NO ELECTROMAGNETIC COUNTERPARTS SEEN

The GW190814 source was localized to a small area in the sky of about 20 square degrees following which alerts were sent out to the astronomical community. Follow-up searches carried out by dozens of ground- and space-based telescopes across the electromagnetic spectrum and with neutrinos did not turn up any optical counterparts to the gravitational wave signal.

So far, such electromagnetic counterparts to gravitational-wave signals have been seen only once, in an event called GW170817. That event, discovered by the LIGO-Virgo network in August of 2017, involved a fiery collision between two neutron stars that was subsequently witnessed by dozens of telescopes on Earth and in space. Neutron star collisions are messy affairs with matter flung outward in all directions and are thus expected to shine with light. Conversely, black hole mergers, in most circumstances, are thought not to produce light.



The area in the sky where the GW190814 signal likely came from. The blue patches are from an initial online analysis of the data, while the purple patches are the final sky localisation.

According to the LIGO and Virgo scientists, electromagnetic counterparts of the GW190814 event were not seen for a few possible reasons. First, this event was six times farther away than the merger observed in 2017, making it harder to pick up any light signals. Secondly, if the collision involved two black holes, it likely would not have shone with any light. Thirdly, if the object was, in fact, a neutron star, its 9-fold more massive black-hole partner might have swallowed it whole; a neutron star consumed whole by a black hole would not give off any light.

DETERMINING SOURCE PROPERTIES

The asymmetry between the larger and smaller masses helped scientists to measure the source properties more precisely: the mass of the more massive compact object in the system was deduced to be approximately 23 M⊙, consistent with the population of black holes previously observed by LIGO and Virgo detectors. On the other hand, the mass of the lighter compact object was determined to lie between 2.5 and 3 M⊙. placing it above the most massive known neutron star, MSP J0740+6620, and below the typical masses of black holes detected indirectly through electromagnetic observations.

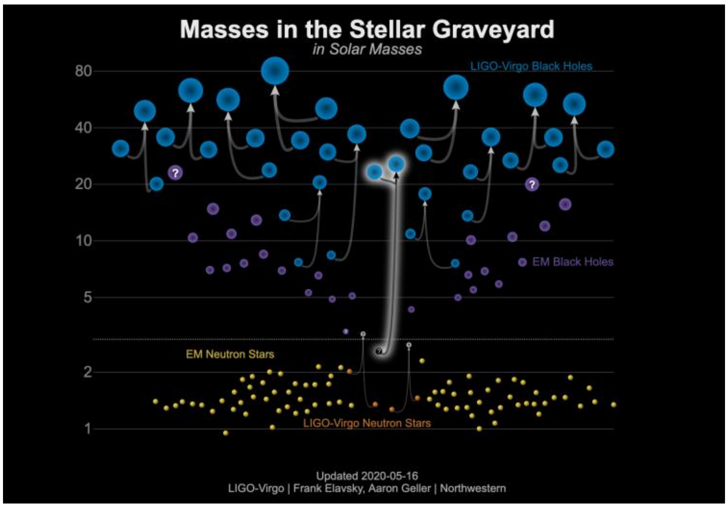
As in the case of the recently announced unequal-mass black hole merger GW190412, the ambiguity between the distance and the inclination of the system was partially broken by the extra information contained in the higher-multipoles of the GW signal. This led to a more definitive estimate of the distance to the GW190814 system: estimated to be about 800 million light-years away.
The asymmetry in masses has also resulted in more substantial evidence for the presence of higher-multipoles of the gravitational-wave signal from this system over the GW190412 event. This is a striking validation of General Relativity which predicts the multipolar structure of gravitational radiation.

The GW190814 observations also permitted a new, gravitational-wave based, measurement of the Hubble constant H0 that quantifies the present expansion rate of the Universe.. The Hubble constant H0 was determined to be about 75 km per second per Megaparsec.

IS THE LIGHTER COMPACT OBJECT A NEUTRON STAR OR A BLACK HOLE?

The lighter compact object's mass makes it hard to determine if it is either an exceptionally heavy neutron star or an unusually light black hole.

In a merging binary system involving a neutron star, the gravitational force exerted by its companion raises a tide on the neutron star, similar to the ocean tides raised on Earth by the gravity of the Moon. These tides leave an imprint on the gravitational wave signal which are measurable. For a system as massive and asymmetric as GW190814, however, the tidal imprint was too small to measure. Thus, we still do not know for sure if the signal originated from the merger of a black hole and a neutron star, or from two black holes.



The masses of neutron stars and black holes measured through gravitational waves and electromagnetic observations. The yellow and purple markers represent the electromagnetic measurements of neutron stars and black holes, respectively, while the orange and blue markers are the corresponding measurements using gravitational waves. GW190814 is highlighted in the middle of the graphic as the merger of a black hole and a mystery object of mass around 2.6 times the mass of the sun, an event that produced another black hole.

On the other hand, theoretical models for neutron-star matter, as well as observations of neutron stars with electromagnetic astronomy, make it possible to estimate the maximum mass that a neutron star can possibly attain. These estimates are at odds with the mass of the lighter component of GW190814: it is probably too heavy to be a neutron star.
However, we also can't rule out the possibility that GW190814 contains an especially heavy neutron star, a scenario that would cause us to dramatically revise the estimates of the maximum possible neutron star mass.

GW190814 has raised fascinating questions about the masses of compact objects and the processes which lead to their mergers. Future gravitational-wave observations will be crucial to shed light (or gravitational waves!) on the larger population of asymmetric mergers, of which GW190814 is just the first example.

IMPORTANT TARGETS FOR LIGO-INDIA

LIGO-India will be able to play a major role in solving these mysteries. Owing to its geographical location relative to the other detectors on the globe, LIGO-India will enable much more precise localisation of the compact binary merger events. The electromagnetic (EM) telescopes will then be able to scan a much smaller area on the sky to look for possible optical, X-ray, gamma ray, radio emission from the events. For GW190814 no EM radiation has been detected so far, but this could also be because the telescopes had to scan through such a large area on the sky that by the time they reached the correct spot, the intensity of any radiation that might have been emitted had already become too faint. Detection of EM radiation could provide strong evidence that one of the companion stars is not a black hole. This would also allow pin-pointing the galaxy where the merger event happened, enabling more precise measurement of the Hubble constant, which is the rate at which the universe is expanding.

INDIAN CONTRIBUTIONS

Scientists from several Indian research institutes participated in the analysis and made critical contributions to this discovery.

Gravitational radiation from compact binaries is predominantly emitted at twice the orbital frequency. This is analogous to the main sound that you hear when plucking a guitar string. However, just like musical instruments, gravitational radiation from such systems is also predicted to ring at higher harmonics of this fundamental frequency. The asymmetric masses of the GW190814 system allowed for these subtle (faint) components of the signal to be better “heard”. The evidence for higher-multipoles in this event was much stronger than in the recently discovered binary black hole merger event GW190412.

Scientists from IIT Gandhinagar and Chennai Mathematical Institute collaborated with LIGO-Virgo researchers to analyze data which resulted in the convincing discovery of the faint, sub-dominant components of the signal, as predicted in Einstein's theory of gravitation.

Scientists from Chennai Mathematical Institute also contributed an analysis which confirmed that the binary is consistent with a binary black hole, though the measurements do give room for one or more of the binary constituents not being a black hole.

A rich legacy

Indian scientists have made pioneering contributions to the gravitational-wave (GW) science over the last three decades. In particular, they have contributed to the fundamental algorithms crucial to search for inspiraling binaries in noisy data from multiple detectors, in computing the theoretical waveforms of GW signals by solving Einstein's equations, in separating astrophysical signals from numerous instrumental and environmental artefacts, in the interpretation of joint gravitational-wave and gamma-ray observations, tests of Einstein's theory and many other aspects of the data analysis.

The Indian team in LIGO includes scientists from CMI Chennai, DCSEM Mumbai, ICTS-TIFR Bangalore, IISER Kolkata, IISER Pune, IIT Bombay, IIT Gandhinagar, IIT Hyderabad, IIT Madras, IPR Gandhinagar, IUCAA Pune, RRCAT Indore and TIFR Mumbai.

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