GW190412: THE FIRST OBSERVATION OF AN UNEQUAL-MASS BLACK HOLE MERGER

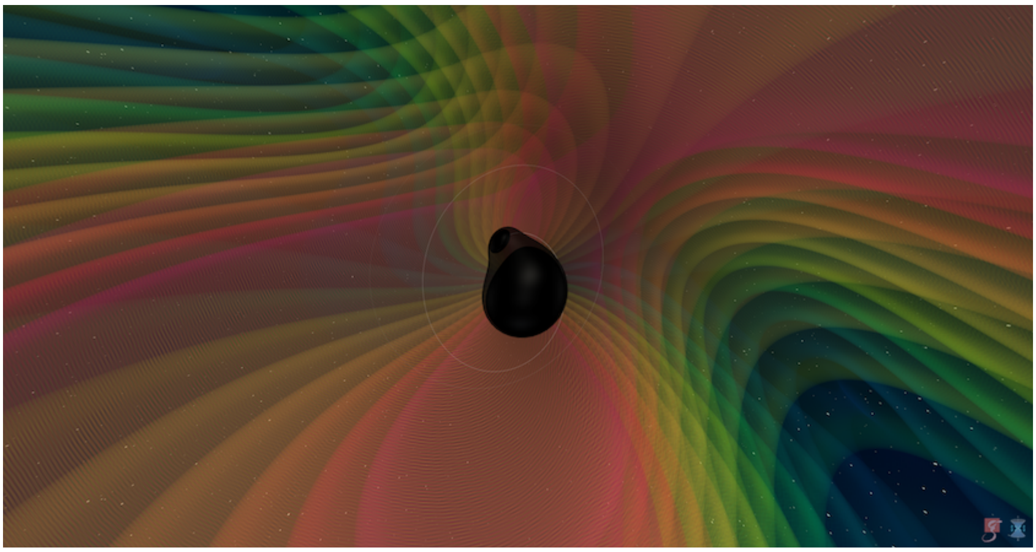
On April 12, 2019, just after 11:00 AM (IST), the LIGO Scientific Collaboration and Virgo Collaboration observed gravitational waves produced by the inspiral and merger of two black holes.

This event, dubbed GW190412, was observed with both LIGO detectors (at Hanford, Washington and in Livingston, Louisiana USA) as well as the Virgo detector (located in Cascina, Italy).

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

Highlights of the discovery

- First binary black hole merger where the masses of the two black holes are definitively unequal — one black hole in the system is more than 3 times heavier than the other.
- This asymmetry in masses has important ramifications: we can better measure the distance to the source, and inclination of the system and the speed of rotation (spin) of the heavier black hole, etc.
- The larger black hole was found to be spinning at about 40% of the maximal spin allowed by general relativity. Also, GW190412 occurred almost 2.5 billion lightyears away from Earth!
- In addition, the unequal masses of GW190412 enabled researchers to verify a fundamental prediction of Albert Einstein's General relativity: that gravitational waves include more than one harmonic of the orbital frequency.
- Important to our understanding of binary black hole population: observation of this single event tells us that black hole systems with unequal masses are relatively common, and that we should expect to observe many more such systems in future.



Face-on Merger: Numerical simulation of GW190412 showing the inspiral and merger of two black holes as observed by the LIGO and Virgo gravitational wave detectors on April 12th, 2019. One black hole is 3.5x more massive than the other and spins, which makes the orbit precess. **Credit**: *N. Fischer, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes (SXS) Collaboration.*

Getting to know GW190412

GW190412 was detected near the beginning of Advanced LIGO and Virgo's third observing run, known as O3, which started on April 1st 2019 and was suspended on March 27th 2020.

The individual masses of the two black holes in GW190412 were found to be consistent with detections made in prior observing runs. The heavier black hole was about 30 times the mass of the Sun, and its companion about 8 times the mass of the Sun. However, the ratio of their masses is unlike any of the other black hole mergers we have detected before.

The asymmetry in their masses modifies the gravitational-wave signal in such a way that we can better measure other parameters, such as the distance and inclination of the system, the spin of the heavier black hole, and the amount that the system is precessing.

GW190412 occurred almost 2.5 billion lightyears away from Earth! The effective spin is found to be positive, which implies that at least one of the black holes is spinning in an orientation close to the orbit of the two black holes around each other. We found the larger black hole to be spinning at about 40% of the maximal spin allowed by general relativity.

In addition, the unequal masses of GW190412 enable us to verify a fundamental prediction of Albert Einstein's General relativity: that gravitational waves "ring" at more than one fundamental frequency, so-called higher multipoles.

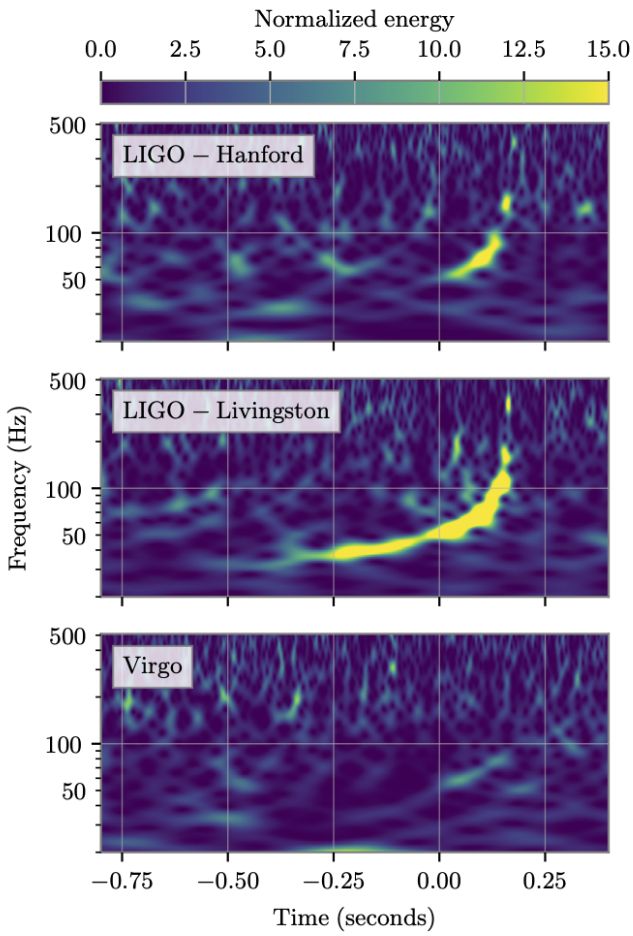


Image 1 description: *A time-frequency representation of GW190412 in the three gravitational-wave detectors. The horizontal axis represents time, and the vertical axis shows the frequency of the signal. Colour represents the amount of energy in a certain frequency at a certain time. The familiar "chirp" can be seen from this signal as an increase in frequency and energy over time, resulting from the increased power of gravitational-wave emission as the two black holes orbit closer and closer (the "inspiral") and subsequently merge.*

HEARING THE HUM OF HIGHER HARMONICS

The unique properties of GW190412 also allow for the observation of a fundamental property of gravitational waves.

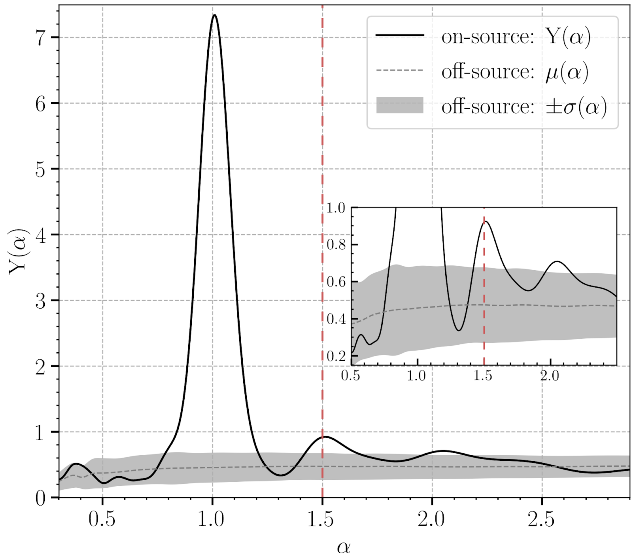


Image 2 description: *The energy of different components of the signal (multipoles) is shown in the figure. The variable* α *along the horizontal axis denotes different multipoles:* $\alpha = 1$ *denotes the dominant multipoles and* $\alpha = 1.5$ *denotes the second strongest multipole. The vertical axis represents the cumulative energy for each multipole. The large peak shows the energy from the dominant quadrupolar mode, and the smaller peak shows the detectable energy from the next strongest multipole component. The inset zooms in on these peaks.*

Starting with the pioneering work of *Einstein*, and later refined by *Newman*, *Penrose*, *Thorne* and many others, the gravitational radiation from compact binaries was shown to be predominantly quadrupolar. This quadrupolar radiation can be thought of like the main sound that is heard when plucking a string on a guitar. However, just like musical instruments, gravitational radiation is predicted to also ring at higher harmonics.

These higher harmonics or higher multipoles components are exceptionally difficult to parse out of a signal when the black holes are near equal in mass. The asymmetric masses of GW190412 allow for these subtle signals to be better “heard” in the gravitational-wave emission. We find that the data support the hypothesis that there are higher harmonics in the signal, by a factor of greater than 1000:1!

In future, the relative intensity of higher multipoles of the signal may help to better disentangle the properties of coalescing black holes.

A suite of tests was also performed to determine if GW190412 is consistent with general relativity. We found no inconsistencies with general relativity, adding another point of support for Einstein’s theory of gravity

INDIAN CONTRIBUTIONS

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

Notably,

- 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.

  Gravitational radiation from compact binaries is predominantly composed of a quadrupolar component, analogous to the main sound that you hear when plucking a guitar string. However, just like musical instruments, gravitational radiation is also predicted to ring at higher harmonics. The asymmetric masses of the GW190412 system allows for these subtle (faint) components of the signal to be better "heard".

  A new technique was developed by this Indian team to separate out the signal components (see Image 2) using time-frequency spectrograms. This was followed by a sophisticated statistical analysis for detecting the fainter higher multipole component. The chances of a false-positive is determined to be less than 0.06 %, which underlines the high significance of the detection.

  In future, the relative intensity of the subtle signal components (multipoles) may help to better disentangle the properties of coalescing black holes.

- Researchers from the International Centre for Theoretical Sciences (TIFR), Bangalore were part of another analysis in collaboration with researchers in the LIGO and Virgo Collaboration that verified the consistency of the signal with the prediction of General Relativity. This analysis checks the compatibility between the low- and high-frequency parts of the observed signal.

- The waveform models, accounting for the effect of higher multipoles of the signal, were developed by various Indian groups at ICTS-TIFR, Bangalore, CMI-Chennai, IIT Madras and Raman Research Institute Bangalore, over the past three decades. Such theoretical models have played a central role in this discovery. Several physical effects observed in this new LIGO discovery were studied in various contexts in the past by the Principal Investigators of the research groups at IIT Gandhinagar, CMI Chennai, ICTS-TIFR Bangalore, IUCAA Pune, IIT Bombay and IIT Madras.

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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