EMBARGOED UNTIL
08:00 hrs US EDT/ 17:30 hrs IST ON
WEDNESDAY, 2nd SEPTEMBER 2020

GW190521: The most massive black hole collision with an intermediate mass black hole as a remnant

GW190521 is a record-breaking gravitational wave observation that revolutionized our knowledge about how black holes are formed, and provided a new way to study the theory of gravity.

On May 21, 2019, at 8:32am IST, the Advanced LIGO detectors (at Hanford, Washington and Livingston, Louisiana) and advanced Virgo (in Cascina, Italy) detector during the third observing run observed a gravitational-wave signal from the merger of an extraordinarily massive pair of black-holes orbiting in a binary system. The event has been named GW190521.

The research papers detailing the detection and the astrophysical implication have been published in the *Physical Review Letters and Astrophysical Journal Letters respectively.*

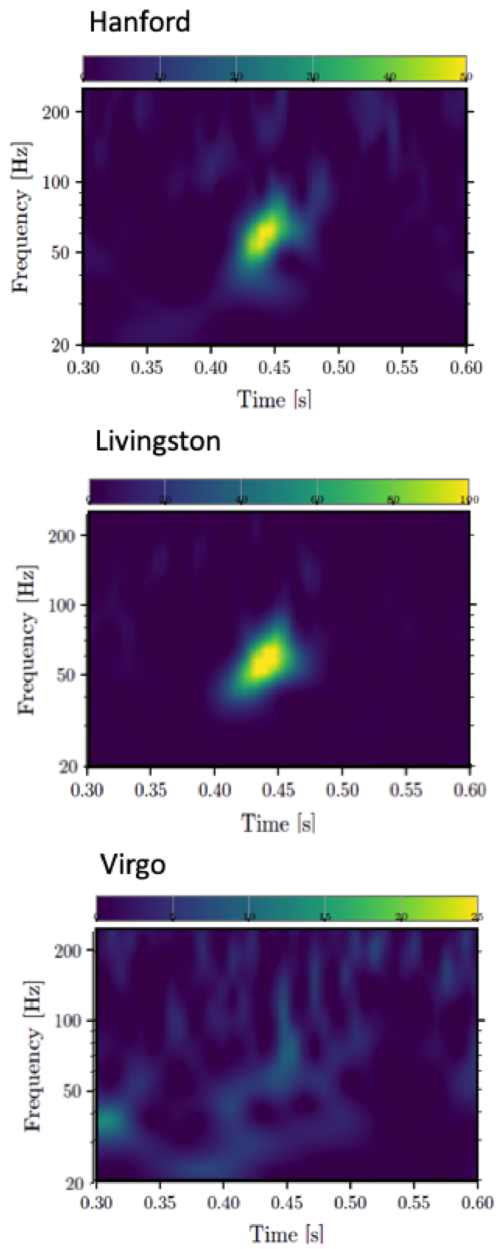


Figure 1. Time–frequency representations of data containing the GW190521 signal, observed by LIGO Hanford (top), LIGO Livingston (middle), and Virgo (bottom). Times are shown relative to 8:32am IST on May 21, 2019. The energy in a certain time-frequency bin is represented by the color palette. The signal is first seen in this visualization at around 50 Hz and sweeps quickly up over a twentieth of a second to around 60 Hz, when the two black holes become one. (Adapted from Fig. 1 of GW190521 discovery paper)

What is the GW190521 event?

The GW190521 event is the gravitational wave signal emitted during the collision of two black holes of mass 85 and 66 times the mass of our Sun in the binary system, forming a remnant black hole of mass 142 times the mass of the Sun. This signal travelled for the distance of 17.2 billion light years through the expanding Universe. This is the most distant gravitational wave signal observed so far by the gravitational wave detectors.

In a compact binary system (See. Fig 2), the two black holes inspiral, coming ever closer to each other, culminating in a massive collision and emitting a burst of gravitational waves. At the end, the system settles into a single final black hole. This signal has three phases — inspiral phase, merger phase and ringdown phase. Heavier binary systems pass quickly from our detector's lowest detectable frequencies to coalescence, giving rise to shorter signals. The observed duration of the signal from GW190521 was 0.1 sec.

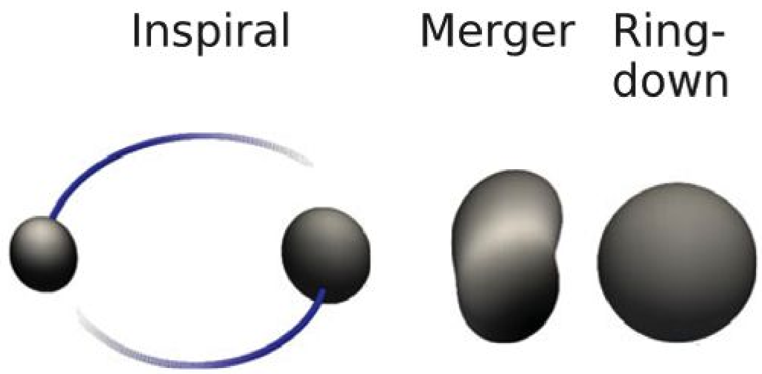


Figure 2: Cartoon representing the three different regimes of the gravitational-wave signal from the collision of two black holes in a binary orbit.

What makes GW190521 an interesting event?

- The final black hole is not only the most massive black hole amongst all the LIGO-Virgo black holes detected so far [See. Fig 3] but also the first intermediate mass (100–100,000 times that of the Sun) black hole observed by the LIGO-Virgo detectors.
- Originating from a collision of two particularly massive black holes, the event gave a unique opportunity to test Einstein's General Theory of Relativity.
- This extraordinarily heavy pair of stellar mass black holes in the binary system challenges our understanding of the formation of the black holes.

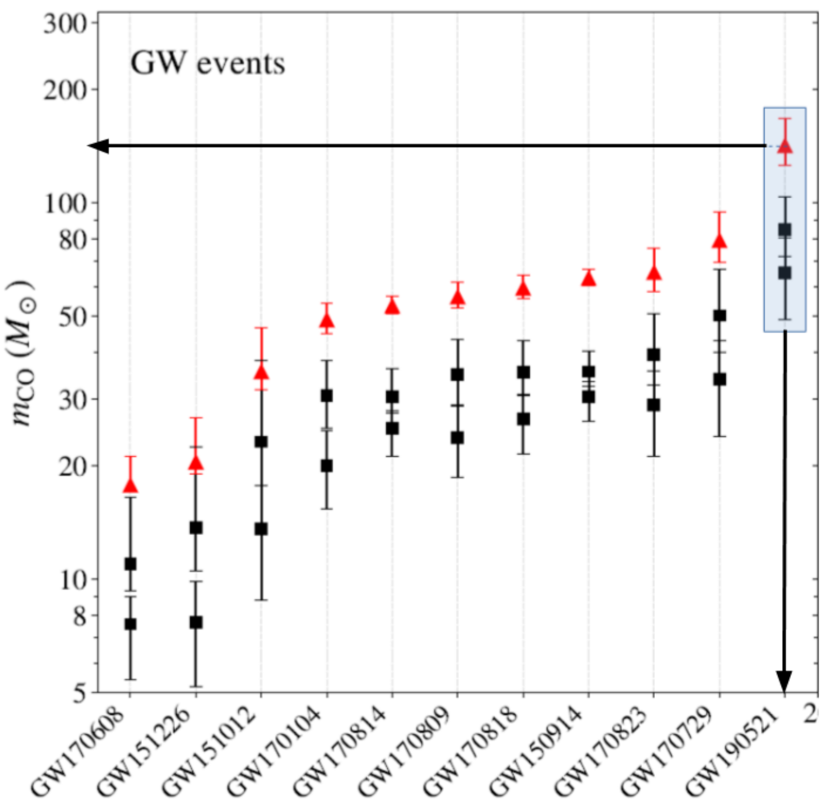


Figure 3. Plot showing the component masses (shown as black boxes) of the GW190521 black holes in comparison with the masses of other black hole mergers detected during LIGO and Virgo's first and second observing runs, O1 and O2. For each event the mass of the merged remnant is shown as a red triangle. In all cases the length of the vertical bar indicates the range of uncertainty in the estimated mass. The record-breaking masses of GW190521 are clear from this plot. (Adapted from Figure 10 of the paper on the astrophysical implications of GW190521)

Making big black holes

Astronomers classify black holes according to their masses. At one end of the mass range are the "stellar mass black holes" with masses below 100 times the mass of the Sun. Pairs of such black holes make up the observed LIGO-Virgo black hole mergers till date.

They are thought to be the end stages of massive stars and formed by the gravitational collapse after undergoing the volatile supernova explosion phase. Astrophysical models suggest that black holes with masses between about 65 and 120 times the mass of the Sun cannot be formed by a collapsing star. This mass range is termed as the ''mass gap".

The other end of the black hole mass range are "supermassive black holes" with masses above hundreds of thousands to billions of times that of the Sun. Our own Milky Way galaxy has a black hole of 4 million times the mass of the Sun at its centre. Exactly how these monstrous black holes are formed remains a bit of mystery.

Between stellar mass and supermassive black holes is the mysterious realm of "intermediate mass black holes" (IMBH) with masses in the range of 100–100,000 times that of the Sun. There was no conclusive direct observation of an IMBH in astronomy till the observation of GW190521.

Lessons learnt from GW190521

- The remnant black hole mass of above 100 times the mass of the Sun makes it the first direct observation of the IMBH in the gravitational wave astronomy.
- The primary black hole with mass 85 times the mass of the Sun falls in the forbidden mass gap. This indicates an alternative way of formation of massive black holes in the Universe – possibly by successive collisions between pairs of smaller black holes in a special environment such as a globular cluster with closely spaced many black holes.

Testing the gravity with GW190521

The GW190521 signal provided a unique opportunity to test the General theory of relativity especially to test the merger and ring down part of the signal. Tests were performed to search for extra features of the signal predicted from alternative theories of gravity. The observation of GW190521 was consistent with the physics given by Einstein's general theory of relativity.

Important source for LIGO-India

LIGO-India will play an important role in learning more about the source properties of such massive binaries. 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 black hole merger events. Further, adding one more detector in the detector network will enable the network to test Einstein's theory of gravity even greater precision and in more detail.

Indian contribution to the discovery

The gravitational wave research group from IIT Bombay is playing a key role in the intermediate mass black hole search in the LIGO-Virgo data along with the colleagues from LIGO Scientific and Virgo collaboration since the first observing run. The group was involved in the detection studies of GW190521 event. To confirm the astrophysical nature of the weak gravitational wave signal, scientists study and assess the chance that the noise could have mimicked the signal. The group was involved in such a study to assess the detection significance of GW190521 in the phase matching signal detection search along with the colleagues of LIGO-Virgo scientists. In addition the group contributed in assessing the distance reach of various searches in the intermediate mass black hole parameter space. The research group at IIT Gandhinagar was involved in developing the filter bank used for the detection of the black holes in the third observing run along with LIGO-Virgo scientists.

A rich legacy

Indian scientists have made pioneering contributions to the gravitational-wave 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, SINP Kolkata and TIFR Mumbai.

ADDITIONAL GRAPHICS

1. Masses in the stellar graveyard (in solar masses)
   [Click here for full resolution image]

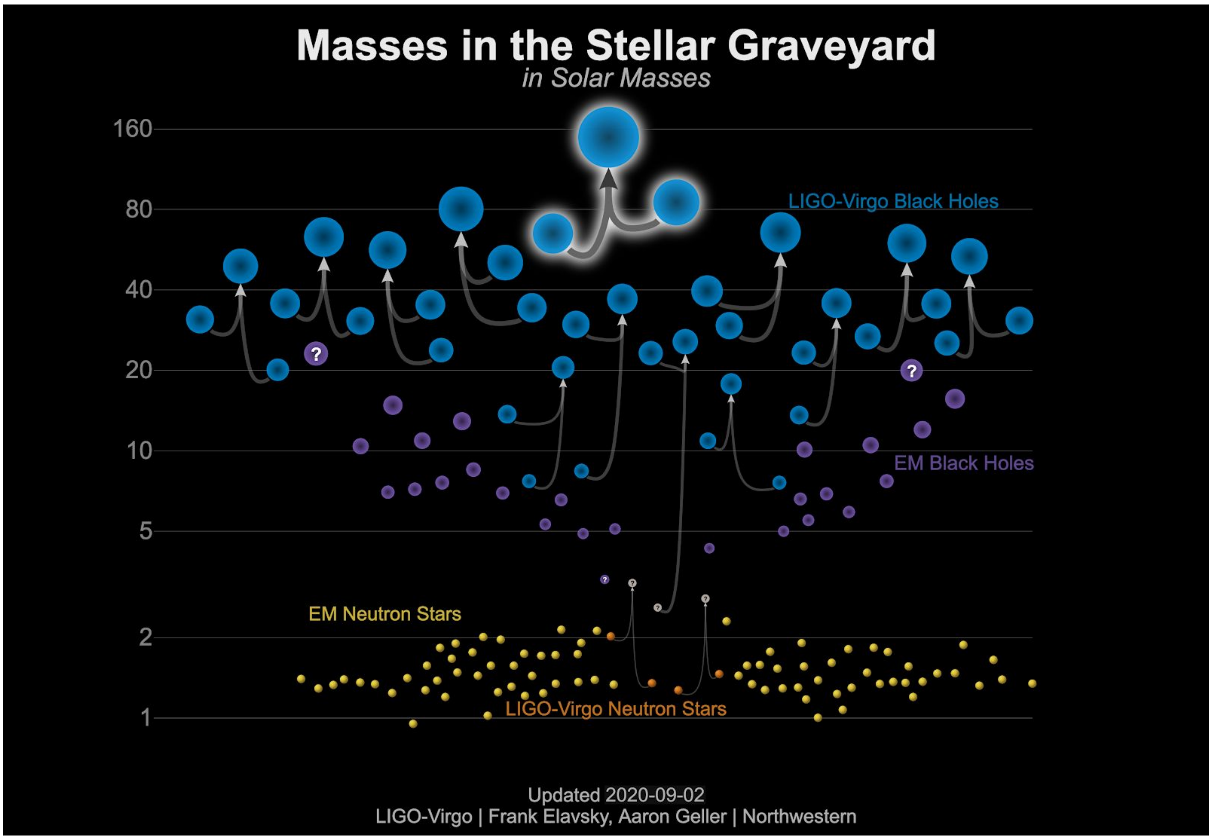
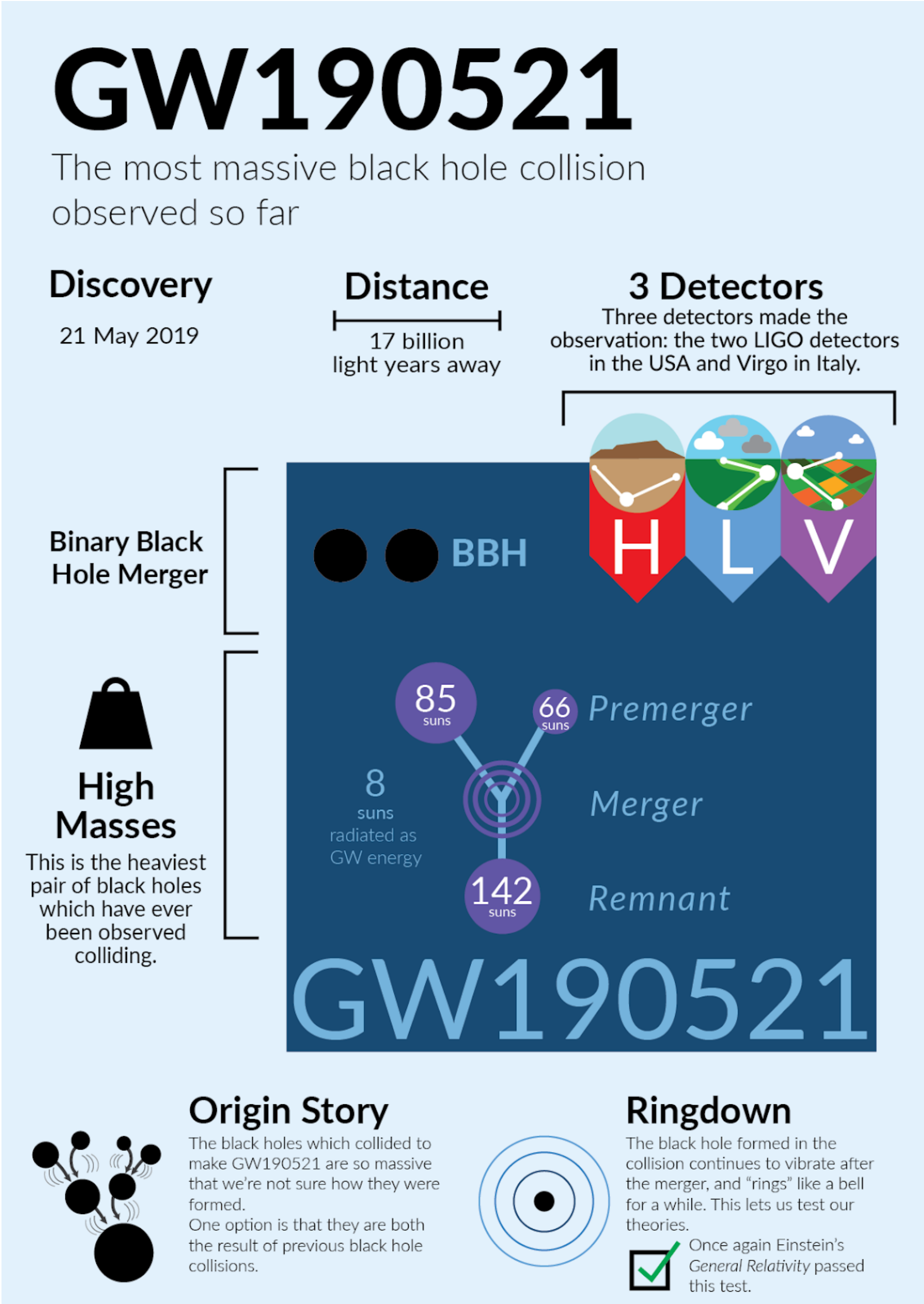


Image caption: This graphic shows the masses of black holes detected through electromagnetic observations (purple), black holes measured by gravitational-wave observations (blue), neutron stars measured with electromagnetic observations (yellow), and neutron stars detected through gravitational waves (orange). GW190521 is highlighted in the middle of the graphic as the merger of two black holes that produced a remnant that is the most massive black hole observed yet in gravitational waves.
[Image credit: LIGO-Virgo/Northwestern U./Frank Elavsky & Aaron Geller]

2. GW190521 Infographic

[Click here for full resolution image]



[Credit LVC/Daniel Williams]

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