THE CURIOUS CASE OF GW190814: THE COALESCENCE OF A STELLAR MASS BLACK HOLE AND A MYSTERY COMPACT OBJECT

On August 14, 2019, exactly two years to the day since the first ever three-detector observation of a gravitational wave signal (GW170814), the two Advanced LIGO detectors in the US, at Hanford, Washington and Livingston, Louisiana, and the Advanced Virgo detector in Cascina, Italy, observed another gravitational wave signal from what is perhaps an even more intriguing source. The LIGO-Virgo detectors were in the middle of their third observing run, O3, when they observed this extremely loud event, produced by the inspiral and merger of two compact objects -- one, a black hole, and the other of undetermined nature.

Two outstanding features make the source of GW190814 unique. First, the heavier compact object is about nine times more massive than its companion, making this the most asymmetric system observed with gravitational waves to date. Second, the mass measured for the lighter compact object makes it either the lightest black hole or the heaviest neutron star ever discovered in a system of two compact objects -- but we can't be sure which it is. Together, these features challenge our understanding of the masses that compact objects can have and the way they end up in merging systems.

GRAVITATIONAL WAVE SIGNAL

The search for gravitational wave signals in the data recorded by the detectors uses matched filtering techniques, which compare the observed data with predictions for signals based on Einstein's General Relativity. Such an analysis yields a chance of less than 1 in 10,000 years that GW190814 could be due to random detector noise. GW190814 is the third loudest event we have observed to date (after GW170817 and GW150914). This is loud enough to be visible to the naked eye in the spectrogram in **Figure 1**, which shows how the frequency of the signal changes over time.

Throughout O3, the LIGO-Virgo collaboration has been releasing in real time public alerts about potential gravitational wave detections. These open public alerts contain preliminary information about the likely source of the signal, in the form of a source classification.

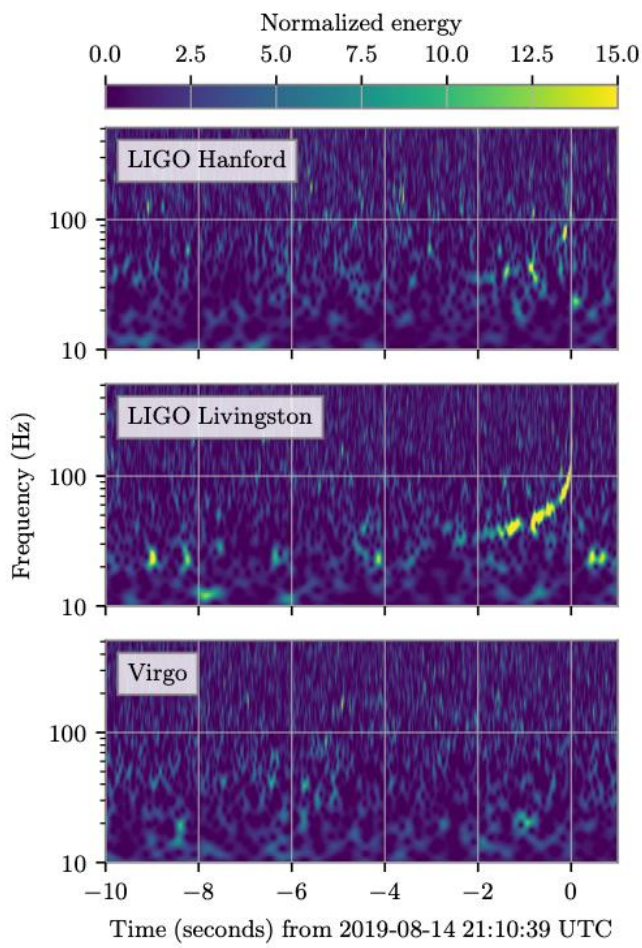

Figure 1: *Time–frequency representations of data containing GW190814, observed by LIGO Hanford (top), LIGO Livingston (middle), and Virgo (bottom). Times are shown from around 10 seconds before the event. The energy in a certain time-frequency bin is represented by the color palette. A "chirping" signal can be clearly seen in the middle panel (LIGO Livingston data), where the signal was the loudest.*

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GW190814 was announced to the public within 20 minutes of detection with a classification of "Mass Gap" meaning that at least one of its compact objects was estimated to have a mass between 3 and 5 times the **mass of the Sun, $M_\odot$**. This definition of "Mass Gap" is inspired by the scarcity of observations of black holes with masses below about 5 $M_\odot$. This part of the black hole mass distribution is known as the "lower" mass gap.

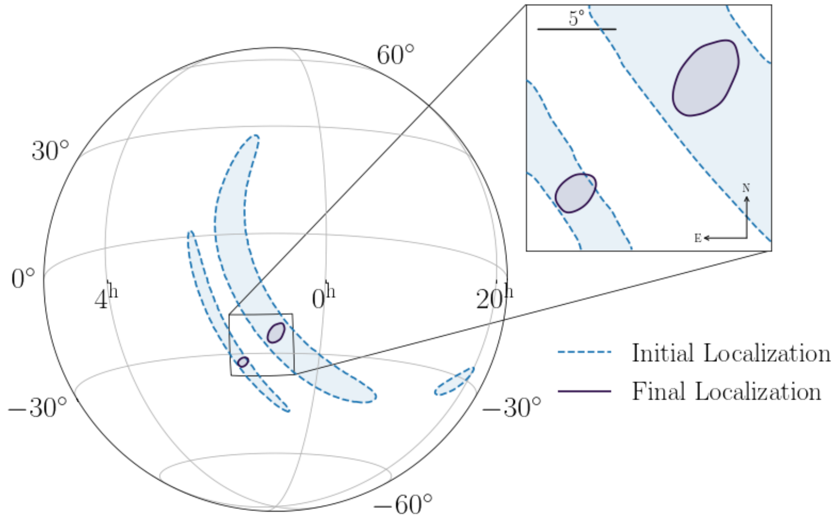

***Figure 2**: The area in the sky where the GW190814 signal likely came from. The blue patches are from initial online analysis of the data, while the purple patches are the final sky localisation.*

Further analysis of the signal enabled a more precise estimate of the masses, and an update circulated 11 hours later changed the source classification to "NSBH" meaning that one of the compact objects was found to have a mass below 3 $M_\odot$, which is a rough estimate of the maximum mass for a neutron star. The source was also localized to a small sky area of about 20 square degrees (see **Figure 2**). Using this information, follow-up searches, like in the case of GW170817, were carried out across the electromagnetic spectrum and with neutrinos, but these did not turn up any counterparts to the gravitational waves. This is not particularly unexpected, however, since GW190814 is much more distant than GW170817 and given that the measured source properties (see

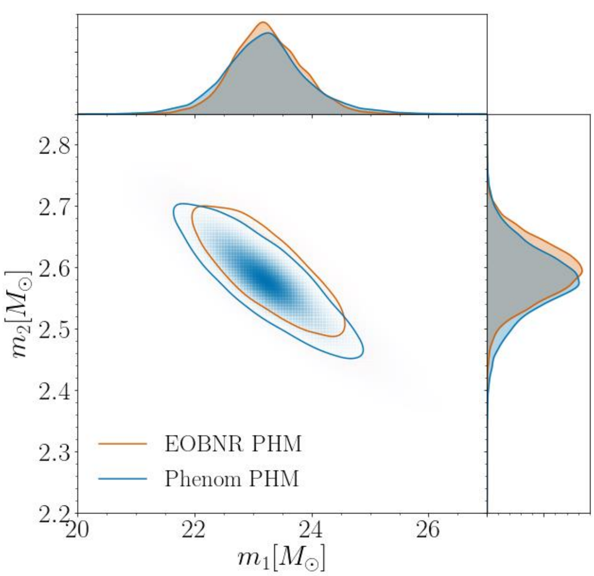

***Figure 3**: The inferred masses of the two compact objects which produced GW190814. The horizontal axis represents the mass of the heavier object, while the vertical axis represents the mass of the lighter object (which could be a neutron star or a black hole). The contours and shaded region show the possible combinations of masses consistent with the data. The curves in the additional panels on the top and right give the corresponding distributions of possible values for the individual masses. The two colours are for two slightly different model predictions of the signal in General Relativity.*

PROPERTIES OF THE SOURCE

The heavier compact object in the system has a mass of approximately 23 $M_\odot$, consistent with the population of black holes observed by LIGO and Virgo so far (see **Figure 3**). The mass of the lighter compact object lies between 2.5 and 3 $M_\odot$, placing it above what is arguably the heaviest known neutron star, MSP J0740+6620, and below the typical masses of black holes detected indirectly through electromagnetic observations. However, it is comparable in mass to the compact object (likely a black hole) produced by the merger of the two neutron stars observed in GW170817.

The asymmetry of the larger and smaller masses helps us to measure the source properties more precisely. The greater the asymmetry, the stronger the signature of higher "harmonics" of the fundamental frequency in the gravitational wave signal, which are analogous to the overtones of a guitar string when plucked. As in the case of the unequal-mass black hole merger GW190412, the ambiguity between the distance and the inclination of the system is partially broken by the extra information contained in the higher harmonics. We are consequently able to determine that the gravitational waves from GW190814 originated around 800 million **light-years** away.

Compact objects like neutron stars and black holes are expected to be spinning. Although their spins do not affect the gravitational wave signal as strongly as their masses, and hence are more difficult to measure, GW190814 was a long signal that lasted in our detectors for over 10 seconds. Coupled with the signal's loudness, this allows us to make the most precise gravitational-wave measurement of a black hole spin to date: it is less than 7% of the maximum spin allowed in general relativity. We are also able to determine that the system was likely not precessing.

PUTTING EINSTEIN AND HUBBLE TO THE TEST

GW190814 provides us with a very rich environment to do science. Since GW190814 is significantly more asymmetric than GW190412, we find much stronger evidence for the presence of *higher harmonics, or higher multipoles* of gravitational radiation in the underlying signal. This is a wonderful validation of General Relativity which predicts the multipolar structure of gravitational radiation.

We perform several additional tests of General Relativity on GW190814 and find that the signal (see **Figure 4**) could be well-described by the merger of two black holes. Significantly, there is no evidence to suggest that the lighter object was anything *other* than a black hole, such as a neutron star or something even more exotic.

With GW190814, we are also able to make a new, gravitational-wave-based measurement of the Hubble Constant, H_0, the present expansion rate of the Universe. GW190814 is, to date, the best-localised gravitational-wave source on the sky for which we have not observed a counterpart in the electromagnetic spectrum or neutrinos. In principle, to measure H_0, we need the redshift of the source's host galaxy. But without a counterpart that identifies the host galaxy uniquely, we can instead consider as possible hosts *all* known galaxies in GW190814's well-localized region of origin. To determine the Hubble constant we then combine all of their redshifts, weighted by the probability that each galaxy *is* the host, with the gravitational-wave distance measurement. Performing this calculation, we measure H_0, with some uncertainty, to be about 75 km per second per Megaparsec, which is as precise as was possible with any previously observed gravitational-wave source without a counterpart.

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

The lighter compact object's mass makes it either an exceptionally heavy neutron star or an unusually light black hole. Normally, we would be able to infer the presence of a neutron star from the imprint of tides on the gravitational wave signal: in a merging system involving a neutron star, the gravitational force exerted by its companion raises at a tide on the neutron star, akin to the ocean tides raised on Earth by the Moon. However, for a system as massive and asymmetric as GW190814, the tidal imprint is too small to measure. In this case, our attempt to measure tides does not tell us whether GW190814 was caused by the merger of a black hole and a neutron star, as opposed to two black holes. On the other hand, theoretical models for neutron-star matter, as well as observations of the population of neutron stars with electromagnetic astronomy, allow us to estimate the maximum mass that a neutron star can attain. These predictions suggest that the lighter compact object is probably too heavy to be a neutron star, and is therefore more likely to be a black hole.

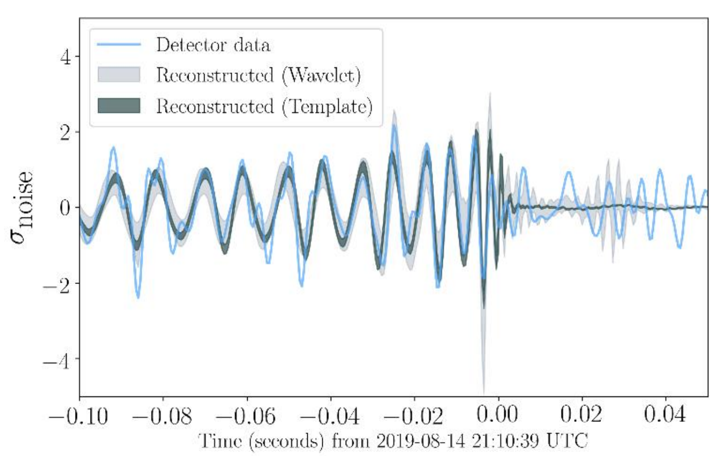

Figure 4: Representations of the actual detector data (blue curve) around the time (horizontal-axis) of the event, along with predictions of what the underlying signal looks like. The dark grey band represents a model prediction of the signal in General Relativity, while the light grey band represents a reconstruction of the signal using minimal assumptions about any specific underlying theory of gravity. The vertical axis is scaled so that a value of 1 corresponds to the typical level of noise fluctuations seen in the data.

However, we can't rule out the possibility that GW190814 contains an especially heavy neutron star, a scenario that would cause us to dramatically revise our estimates of the maximum possible neutron star mass.

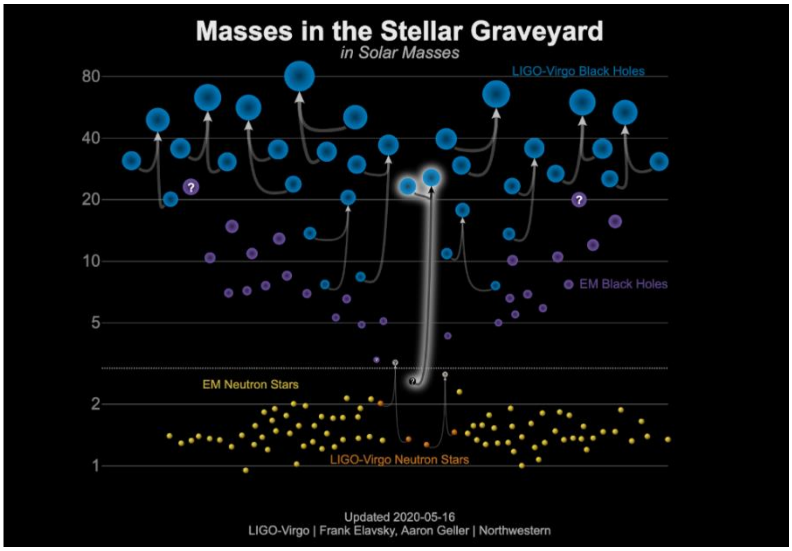

Figure 5*: The masses of neutron stars and black holes measured through gravitational waves and electromagnetic observations. The yellow and purple markers represent the electromagnetic measurements of neutron stars and black holes, respectively, while the orange and blue markers are the corresponding measurements using gravitational waves. Our signal, GW190814, is highlighted in the middle of the map 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.*

ORIGIN STORY: HOW DID THE SYSTEM FORM?

Because the lighter compact object's mass lies in between typical neutron star and black hole values, and is about nine times smaller than its companion's mass, GW190814 does not resemble any of the mergers observed by LIGO and Virgo so far (see **Figure 5**). It is also unlike most of the systems produced in simulations of the population of merging compact objects in the Universe. We expect mergers of this kind to occur much less frequently than the more typical mergers of two black holes or two neutron stars. For these reasons, explaining this system's formation is very challenging for all current models.

Comparing the properties and inferred merger rate of GW190814 to predictions based on theoretical models of stellar evolution developed by astronomers, we find that young dense star clusters and disks around active galactic nuclei seem to be more promising hosts for these events than globular clusters, but *all* compact-object formation models need to be revised. This event may have formed from the evolution of an isolated binary system, though the predictions from this scenario depend crucially on the adopted assumptions and compact-object formation models. It is also possible that the lighter object in the system could itself have been formed through a previous merger event, as a second-generation merger remnant. Such a remnant could then acquire a black hole companion via gravitational interactions in dense stellar environments like globular clusters. However, it is unlikely that this is the main mechanism by which such binaries are formed.

GW190814 raises 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.

GLOSSARY

Compact Object: Highly dense objects, like white dwarfs, neutron stars or black holes, which usually mark the end-points of the life-cycle of a star

Black Hole: A compact object so dense that light cannot escape its gravitational attraction

Neutron star: An extremely dense compact object which remains after the collapse of a massive star.

$M_\odot$: Mass of the Sun and a standard unit of mass in astronomy, equal to approximately $2{\times}10^{30}$ kg

Mass-gap: A gap in the black hole population suggested by the dearth of observations of compact objects with masses between 2.5 and 5 $M_\odot$

Higher Harmonics/Multipoles: Emission from gravitational waves can be described as an expansion of "spherical harmonics". Higher harmonics are terms in this expansion beyond the dominant leading term.

Precession: Due to conservation of angular momentum, when black holes are spinning in a direction different than the orbit of the binary, the plane of the orbit will rotate ("precess") around the direction of the total angular momentum.

Light-year (ly): Unit of distance defined as the distance travelled by light in a year, equal to about 10 million million kilometers.

Megaparsec (Mpc): Unit of distance equivalent to around 3.26 million light years

Redshift: Increase in wavelength (of sound, light, or gravitational waves) due to motion of the source with respect to the observer. Due to cosmological expansion of the universe, objects such as galaxies are receding from us, and light and other electromagnetic radiation coming from them have a longer wavelength.

Globular Cluster: A spherical collection of densely packed stars in orbit around a galaxy. A globular cluster can contain up to a million stars.

Active Galactic Nuclei: Very compact and very luminous regions found at the centers of a number of galaxies. They are among the most powerful, steady energy sources in the Universe.