

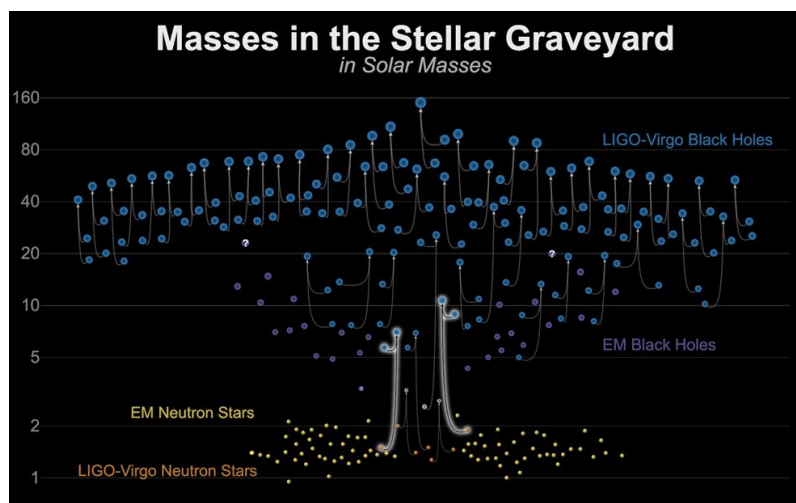
# A NEW SOURCE OF GRAVITATIONAL WAVES: NEUTRON STAR – BLACK HOLE BINARIES

## WHAT DID WE DISCOVER?

On January 5<sup>th</sup> 2020 the [Advanced LIGO detector](#) in [Livingston](#), Louisiana in the US and the [Advanced Virgo detector](#) in Italy observed gravitational waves consistent with an entirely new type of astronomical system. The gravitational waves were produced by the death spiral of two of the most extreme objects in the Universe: one, a [neutron star](#), and the other a [black hole](#). LIGO and Virgo observed the last few decaying orbits ([inspiral](#)), followed by the merger of the neutron star with the black hole. Remarkably, just ten days later a second gravitational-wave signal from the inspiral and merger of a neutron star with a black hole, was observed, this time by both Advanced LIGO detectors (in Livingston and also in [Hanford](#), Washington) and the Virgo detector. This is the first time gravitational waves have been observed from a mix of neutron stars and black holes (see [Figure 1](#)).

Before this new discovery, gravitational waves had been observed from the merger of pairs of black holes and pairs of neutron stars. Our new discoveries are nicknamed [GW200105](#) and [GW200115](#).

These two discoveries represent the first detections of neutron star-black hole (NSBH) systems. For several decades, NSBH systems had been predicted to exist, but without convincing observational evidence until now. With the observation of NSBHs, we now have seen all three types of binaries that can be formed from black holes and neutron stars. Systems made of black holes and neutron stars are known as "[compact binaries](#)". These new discoveries, together with future observations of compact binaries, will shed light on the birth, life, and death of stars, as well the surroundings in which they form.



**Figure 1:** 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 signals, [GW200105](#) and [GW200115](#), are highlighted as the merger of neutron stars with black holes. (Image credit: LIGO-Virgo & Frank Elavsky, Aaron Geller, Northwestern University)

## DETECTING THE GRAVITATIONAL-WAVE SIGNALS

The search for gravitational-wave signals in the data recorded by the detectors uses "[matched filtering](#)". This compares the observed, noisy, data to predictions of signals from Einstein's [General Relativity](#). Matched filtering can pick out gravitational-wave signals from noisy data in a way similar to how we can distinguish individual instruments in a piece of music. We consider [GW200115](#) to be an astrophysical gravitational wave signal with very high confidence, with a chance of occurring due to random noise of less than **once in 100,000 years**. The astrophysical nature of [GW200105](#) is more challenging to establish statistically, but it also clearly stands apart from all noise effects we've ever seen, and we consider such a signal likely to occur due to noise less than **once in 2.8 years**.

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NSBH mergers can, in principle, produce light across the [electromagnetic spectrum](#). Unfortunately, the sky direction of the sources could be measured only very imprecisely, to an area of sky between 2,400 and 29,000 times the size of the full moon. Together with the large distance to the source (discussed in more detail below), this made observation of electromagnetic light unlikely, and none was observed. Future observations of NSBH mergers may produce observable light which could possibly reveal the black hole “tidally disrupting” (tearing apart) the neutron star. This could provide information about the extreme form of matter that makes up neutron stars.

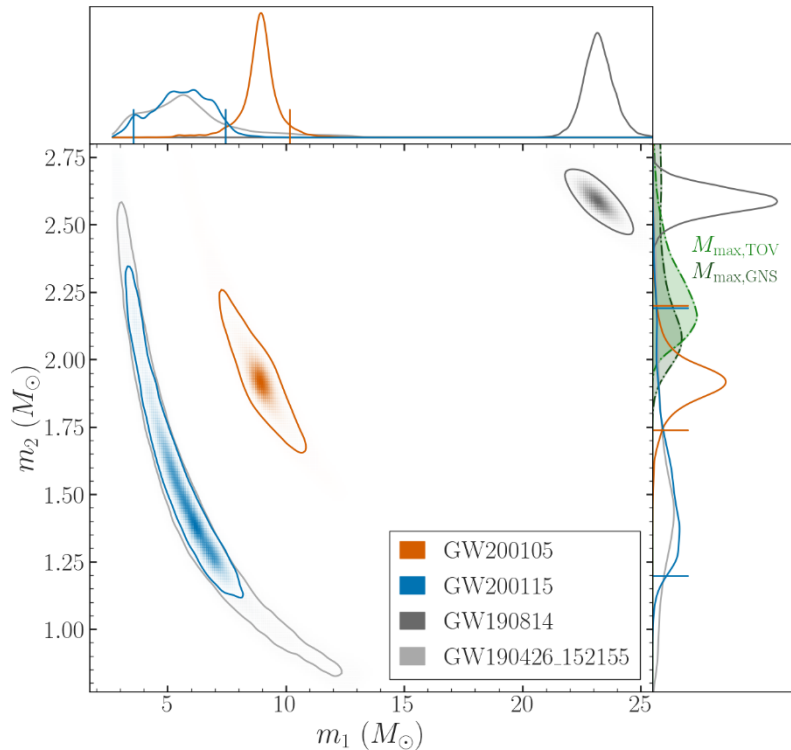
## PROPERTIES OF THE SOURCES

Gravitational waves encode rich information about their origin, for example, the masses of the compact binary stars. The black hole and neutron star that created GW200105 are about 8.9 times and 1.9 times more massive than our Sun (with mass  $M_{\odot}$ ), respectively. The GW200105 event happened around 800 million years ago, hundreds of millions of years before the first dinosaurs appeared on Earth. For the GW200115 event, we estimate the black hole and neutron star had masses around 5.7  $M_{\odot}$  and 1.5  $M_{\odot}$  respectively, and their merger happened nearly one billion years ago. The masses are summarized in **Figure 2**.

We found the black hole spin for GW200105 could lie between 0 and as high as 30% of the maximum rotation rate of black holes, while for GW200115, the spin lies between 0 and 80% of the maximum rate. We do not have strong evidence of neutron star spin because our measurements are not sensitive to it (see **Figure 3**).

Why do we think we observed NSBHs? To produce the observed gravitational waves, the objects have to be very compact and dense compared to typical stars, since otherwise they would break apart before they merged. The masses of the heavier objects in each binary are 8.9  $M_{\odot}$  and 5.7  $M_{\odot}$  so the only

known objects they could be are black holes. The masses of the lighter objects are around 1.9  $M_{\odot}$  and 1.5  $M_{\odot}$ , much lighter than any known black hole. These masses are consistent with known neutron stars, like the ones observed in the Milky Way, or with gravitational waves (e.g., [GW170817](#)). The masses of the black holes are consistent with predictions from models of star formation and evolution.



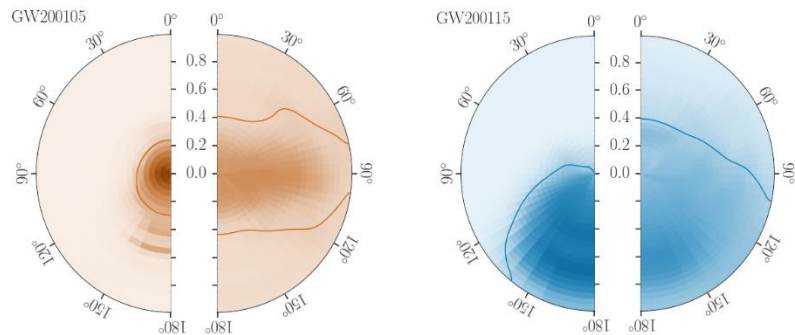
**Figure 2** (figure 4 from the publication) Summary of our knowledge of the component masses of the objects that produced GW200105 and GW200115. The horizontal axis represents the mass of the heavier object (the black hole), whereas the vertical axis represents the mass of the lighter object (the neutron star). The color-shading indicates mass-combinations consistent with the data, orange for the first event, and blue for the second event. Darker shading indicates better agreement, i.e. a higher probability for such mass-combinations. The top panel summarizes the information about the black hole mass, with—for instance—the blue curve showing that the black hole in GW200115 had a mass somewhere between  $\sim 3.5M_{\odot}$  and  $\sim 7.5M_{\odot}$ . The right panel summarizes the information about the neutron star mass—for instance, the orange curve in this panel indicates that GW200105’s neutron star had a mass between 1.75  $M_{\odot}$  and 2.2  $M_{\odot}$ . The green shadings in this right panel summarize the present astronomical knowledge about how massive neutron stars can be, showing that our observed objects have masses small enough to be neutron stars. The figure also shows information about two earlier gravitational wave discoveries: GW190814, which is probably the merger of a 23  $M_{\odot}$  black hole with a 2.5  $M_{\odot}$  black hole (the lightest ever observed); and GW190426\_152155, a signal that looks like a neutron star-black hole system, but is so weak that it is unclear whether it is of astrophysical origin.

## HOW DID THEY FORM, AND HOW OFTEN DOES THIS HAPPEN?

So, how did these NSBH systems form? There are two main possibilities. One of these starts with two stars already orbiting each other. The stars have masses such that when they age, they eventually explode in supernova explosions, one star leaving behind a black hole and the other leaving a neutron star. This is called “isolated binary evolution”. The other possibility is that the neutron stars and black holes form separately in unrelated supernova explosions, and only afterwards find each other. This is called “dynamical interaction” and can occur in dense stellar environments such as [globular clusters](#). To distinguish between these two possibilities, the spin orientations of the black holes give a strong hint. In isolated binary evolution, the spin directions of black holes tend to align with their binary orbit, i.e., we expect the neutron star to orbit in the equatorial plane of the black hole. In contrast, the dynamical interaction scenario doesn't prefer a particular direction of the spin, and so the neutron-star orbit could have any orientation relative to the black hole's equatorial plane.

The inferred black hole spin of GW200105 does not allow us to distinguish either of these formation scenarios. However, for GW200115, we find that the black hole spin direction is likely to be opposite to the direction of the binary orbit. For example, if the neutron star orbits the black hole clockwise, then the black hole would rotate on its axis counterclockwise. This hints that the source of GW200115 could have formed in a dense environment, such as a globular cluster.

How many NSBHs in the Universe merge within a given time period? The observation of the two NSBH systems tells us that between 5 and 15 such systems merge per year within a distance of one billion light years. Also, this estimated merger rate could be explained by isolated binary evolution or dynamical interaction in young star clusters alone, but we cannot single out a specific scenario.



**Figure 3** (figure 6 from the publication) The inferred spin magnitude and direction of the black holes (left half-disks) and neutron stars (right half-disks) of GW200105 and GW200115. The radius of the disk indicates the spin magnitude, and range between 0 (no spin) to 1 (maximum rotation rate of black holes). The spin direction is shown as an angle, which ranges from 0° (objects spin in the same direction as the orbit of the binary) to 180° (objects spin in the opposite direction of the orbit of the binary). Shading indicates probable values of spin magnitude and direction. The left-most hemisphere has shading that peaks near the centre, indicating that GW200105's black hole has a spin that is likely small. The second to right hemisphere's shading extends downward, indicating that GW200115's black hole may be spinning in a direction opposite to the orbital motion.

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### GLOSSARY

**Inspiral:** The orbital motion of objects in a binary system such as a neutron star-black hole binary. As the binary loses energy by emitting gravitational waves, the neutron star and black hole orbit faster and faster, and approach ever closer until finally merging.

**Neutron star:** The relic of a massive star that has reached the end of its life. When a massive star has exhausted its nuclear fuel, it dies in a catastrophic way—a supernova—that often results in the formation of a neutron star: an object so massive and dense that atoms cannot sustain their structure as we normally perceive them on Earth. These stars are about as massive as our sun, but are only a few tens of kilometers in diameter.

**Black hole:** A region of space-time with gravity so intense that it prevents anything, including light, from escaping. [Black holes](#) come in different sizes: [stellar-mass black holes](#) originate from stellar collapses and their masses range from a few solar masses to about 65 solar masses. [Intermediate-mass black holes](#) range in mass from around 100 solar masses to 10<sup>5</sup> solar masses. Finally, [supermassive black holes](#) range from more than 10<sup>5</sup> solar masses to more than 10<sup>9</sup> solar masses.

**Compact binary:** A system made of two compact stellar remnants, e.g. neutron stars or black holes, orbiting around each other very closely.

**Matched filtering:** A technique to detect signals buried within noisy data. Templates of gravitational waveforms calculated from general relativity are scanned across the data, and ring off when matching patterns are found in the data.

**General Relativity:** The theory of gravity proposed by Albert Einstein in 1915. In this theory, space and time are like a malleable fabric that warps in the presence of matter and energy, and objects follow trajectories through this curved space.

**Globular cluster:** A very dense group of stars bound together by gravity.

**Electromagnetic spectrum:** Visible light stretches from red to violet, but outside the range our eyes can see, this spectrum continues. Beyond red light there is infra-red, microwaves and radio waves, and beyond violet there is ultraviolet, X rays and gamma rays. This is the spectrum of electromagnetic radiation, and astronomers use each part of the spectrum to learn more about the Universe. All electromagnetic radiation takes the form of ripples in electric and magnetic fields, and differ in their frequency or wavelength (the length of a ripple).

**Light year:** A unit of distance equivalent to the distance that light travels in one year. A light year is approximately equal to 9.46 trillion kilometers (or roughly 5.88 trillion miles).

**M<sub>⊙</sub> (solar mass):** The mass of the Sun (around 2x10<sup>30</sup> kilograms). Solar mass is a common unit for representing masses in astronomy