GWTC-3, A THIRD CATALOG OF GRAVITATIONAL-WAVE DETECTIONS

Introduction

GWTC-3 is the third Gravitational-Wave Transient Catalog from LIGO, Virgo, and KAGRA. GWTC-3 updates our previous catalogs with gravitational-wave observations from the second part of Observing Run 3 (imaginatively called O3b), which lasted from November 2019 to March 2020. Collectively, GWTC-3 represents the largest number of gravitational-wave observations assembled to date.

So, what gravitational-wave catalogs have there been so far?

- GWTC-1, which contains a total of 11 events from the first and second **observing runs** (O1 and O2).
- GWTC-2, which added 39 events to GWTC-1, bringing the total number of events to 50 (from O1, O2, and O3a, the first part of O3).
- GWTC-2.1 revisited the O3a analysis, finding an additional 8 candidates, but also reclassifying 3 of the original GWTC-2 candidates because their **probability of being real astrophysical signals** dropped to less than 50% (see the "Detecting gravitational waves" section below). This brought the total to 55 events.
- GWTC-3 (this publication) adds a further 35 gravitational-wave events from O3b, bringing the total number of events observed to date to a whopping 90. (**Figure 3** below illustrates the sheer number and our growing population of detected events).

In O3b, KAGRA joined LIGO and Virgo for the final part of the run and in April 2020 completed a two-week observation run with the GEO 600 detector located in Germany. The results of this observing run will be presented separately.

All of our gravitational-wave observations so far come from merging binaries consisting of **black holes** and **neutron stars**. We refer to these as **compact objects**, and we believe them to be the remains of massive stars. Events include **binary black hole** coalescences, **binary neutron star** coalescences and **neutron star-black hole** coalescences. As our detectors have become more sensitive, our rate of discovery has accelerated. We have come a long way from making our first detection in 2015.

In this summary you can read about how we collect our data, how we make detections, how we estimate the properties of the merger events, the highlights from GWTC-3, and future planned observing runs.

Gravitational-wave detectors

Over the years, the sensitivity of LIGO and Virgo has improved due to a combination of detector upgrades, and improved data quality and analysis techniques. There are several ways to measure the sensitivity of a gravitational-wave detector. One is by estimating the approximate range to which an observatory can detect a typical binary neutron star merger: *the bigger the range, the further away signals can be detected, and so the more detections we can expect*. O3 was divided in two halves (named O3a and O3b) which were separated by a month-long break in October 2019. Many upgrades and repairs were completed during this month, including mirror cleaning at LIGO Livingston, replacing vacuum equipment at LIGO Hanford, and increasing the laser power at Virgo. This work, as well as continuous maintenance throughout observing runs, allows the detectors to maintain or increase their sensitivity. Figure 1 shows the **median** binary neutron star range has changed for each detector. Between O3a and O3b, the median binary neutron star range increased by 13.3% for Virgo, 6.5% for LIGO Hanford, and stayed around the same for LIGO Livingston (our most sensitive detector) with a slight decrease in sensitivity of 1.5%.

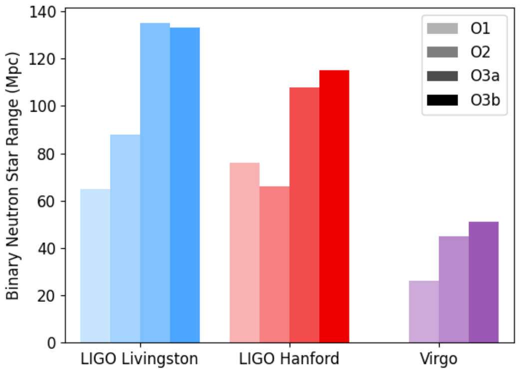

***Figure 1**: The **median** binary neutron star ranges for each detector during the first (O1) and second (O2) observing runs, the first part of observing run 3 (O3a), and the second part of observing run 3 (O3b). The ranges are shown in units of **megaparsecs**. Credits: LIGO-Virgo-KAGRA Collaborations/Hannah Middleton/OzGrav.*

The raw data from a gravitational-wave detector comes from the time-varying intensity of the laser light measured at the interferometer output. This raw data needs to be calibrated to obtain the corresponding gravitational-wave strain amplitude. Calibration needs to be done carefully. We use laser light to push precisely on the mirrors to measure how the output of the interferometer changes. Initial calibration is done in near real-time. If needed, later re-calibration and subtraction of long-duration noise are used to produce the best available strain data which is used in this analysis.

After calibration and noise subtraction, the data needs to be quality checked. The most common issue we have when assessing data quality for binary merger signals is glitches, which are short-duration (seconds to minutes long) noise transients in the data. Some glitches have a known origin such as **light scattering**, but sometimes their origin is a mystery. Glitches occasionally overlap with a gravitational-wave signal and in these cases, we can perform *glitch subtraction* to remove them from the data as shown in **Figure 2**. Glitch subtraction was an important part of our analysis of the first binary neutron star signal, GW170817 and in GWTC-3, 7 events out of 35 required glitch subtraction. To discover more about glitches and to help us in our quest to understand more about them, head over to the community-science project, Gravity Spy.

Detecting gravitational waves

Throughout O3a and O3b we issued public alerts of initial gravitational-wave candidate detections. Rapid public alerts enable the astronomy community to search for multimessenger signals from the events using electromagnetic telescopes and neutrino detectors. Public alerts were typically released within a few minutes of detections in O3b. Later re-analysis of the gravitational-wave data can lead to some events being retracted and further events being discovered. The final analysis presented in GWTC-3 benefits from improvements in calibration, data quality, and data analysis from the entirety of the observing run to assess if candidates are interesting or not. In O3b there were 39 public alerts reported, of which 18 survive the re-analysis and are included in GWTC-3 as candidates with greater than a 50% probability of being real. A further 17 events are reported for the first time in the GWTC-3 analysis.

We use two types of analysis to look for gravitational-wave candidates: template searches and minimally modeled searches. Template searches use a selection of simulated compact binary signals (or templates), which we use to filter the data for things that match the shape of the template and how it changes over time. Minimally modeled searches do not look for an exact type of signal, but do require that the same signal appears in multiple detectors. The template approach is usually better at picking out binary signals (as we know what they should look like), but the minimally modeled approach ensures that we do not miss anything because of not having the right template. When assessing whether or not a candidate could be a real signal, we calculate how likely it is that random noise could look like the candidate's signal by chance. Normally, the more consistent the signal is between detectors, the more confident we can be that it is is real.

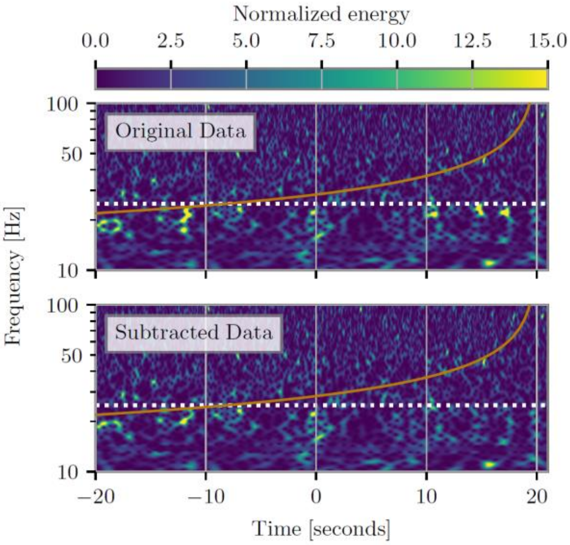

***Figure 2**: (Fig. 14 from our publication) An example of glitch subtraction. The plots show the time-frequency data for event GW200115_042309 and the color indicates the energy in each time-frequency bin. The top plot shows untreated data and the bottom plot shows the results of noise subtraction. The estimated signal track is shown by the orange line and is unaffected by the glitch subtraction process.*

In GWTC-3, we list all of our candidates that we estimate have at least a 50% chance of being real, as opposed to noise. This estimate relies not only on understanding the noise in our detectors, but also how often gravitational-wave signals should be observed by our detectors. As we are just starting to learn about the population of merging compact objects, these numbers can be uncertain. As we learn more about the population by making more observations in the future, we will be able to come back to check the candidates about which we are currently less certain.

Additionally, GWTC-3 includes a list of weaker signals which do not pass the threshold of a 50% chance of being real. Just like in GWTC-2.1, the subthreshold list for GWTC-3 includes any candidate event with a **false alarm rate** lower than 2 per day. There are 1,048 subthreshold candidates, most of which we expect to be noise; however this list may be useful to help astronomers in identifying potential multimessenger events.

Naming a gravitational wave

Gravitational-wave names represent the date and time when the signals are detected in Coordinated Universal Time (UTC). Several previous event names only include the date, but as the detectors improve their sensitivity, we may detect more than one event per day. So, like we did with GWTC-2 and GWTC-2.1, we now add the time to the names so we can distinguish them more easily. As an example GW200208_222617 was observed on the 8th February 2020 at 22:26:17 UTC time.

Properties of our gravitational-wave sources

Our gravitational-wave observations contain information about the properties of the binaries that produced them. Properties can be *intrinsic* or *extrinsic*. Intrinsic properties describe the source itself, such as the masses and **spins** of the compact objects. Extrinsic properties describe how we observed the event from Earth and include the location of the source on the sky, its distance from the Earth, and the orientation of the plane in which the two compact objects orbit around one another.

We learn the properties of the binaries through **parameter estimation**. This is a statistical technique where we compare many possible **gravitational waveforms** (with different properties) to the observation data. The comparison tells us what values of the source properties are consistent with the data (assuming that we have a real gravitational-wave signal). In our results we select the 90% credible intervals from these ranges, which means that we are 90% certain that the properties of the binary lie inside that range.

The contours in **Figure 4** show the 90% regions for two properties: the **total mass** and the **mass ratio**. The total mass tells us how heavy the binary system was overall. Masses are measured in units of **solar masses** $M_\odot$. The mass ratio tells us how asymmetric the masses of the two compact objects that merged were. A mass ratio close to 1 means that the two compact objects were close to the same mass.

Studying the properties of the population as a whole helps us to learn about how these systems formed. We can also use these observations to put Albert Einstein's theory of general relativity to the test and even measure the rate at which the universe is expanding.

A selection of highlight events from O3b are summarized below.

Highlights of GWTC-3

Based on the properties of the new 35 events listed in GWTC-3, 32 of them are likely binary black hole coalescences, and three are possible neutron star-black hole coalescences. We consider compact objects that are likely to have masses less than 3 $M_\odot$ to be possible neutron star candidates. There were no binary neutron star candidates detected in O3b. **Figure 5** also summarizes the most probable values of three key parameters for eight selected events.

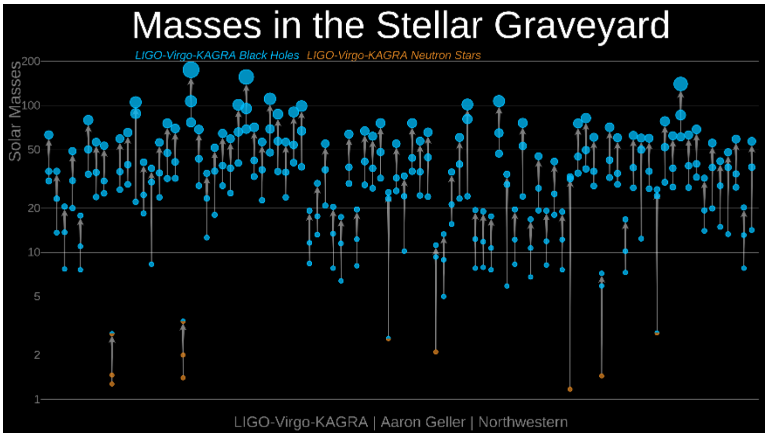

***Figure 3**: Compact object masses. Each circle represents a different compact object and the vertical scale indicates the mass as a multiple of the mass of our Sun. Blue circles represent black holes and orange circles represent neutron stars. Half-blue / half-orange mixed circles are compact objects whose classification is uncertain. Each merger involves three compact objects: two merging objects and the final resulting object. The arrows indicate which compact object merged and the remnant they produced. Credits: LIGO Virgo Collaboration/Frank Elavsky, Aaron Geller/Northwestern.*

Neutron star-black hole coalescence highlights

The three possible neutron star-black hole coalescences are:

- **GW191219_163120** is a neutron star-black hole coalescence with extremely unequal mass components. The black hole has a mass of about 31 $M_\odot$ and the neutron star a mass of about 1.2 $M_\odot$. The neutron star is one of the least massive ever observed.
- **GW200115_042309** is a clear neutron star-black hole coalescence previously reported in its own paper. We estimate the black hole mass to be about 6 $M_\odot$ and the neutron star mass to be about 1.4 $M_\odot$.
- **GW200210_092254** is a possible neutron star-black hole binary. We consider the heavier object to be a confident black hole due to its mass of about 24 $M_\odot$. However the lighter object is about 2.8 $M_\odot$, which could indicate either a heavy neutron star or a light black hole. This event is quite similar to O3a's GW190814. Given what we know about neutron stars, GW200210_092254's source is probably a binary black hole, but we can't be certain.

Keen gravitational-wave watchers might notice the absence of GW200105_162426, which was reported along with GW200115_042309 in a previous publication. When we consider all the events in O3b together, we find that the probability of GW200105_162426 being a real astrophysical signal is 36%, which is below the 50% threshold for inclusion in the catalog. For more information about this, see the **GW200105_162426** glossary entry below. Despite not passing the GWTC-3 threshold, the event does stand out against the background noise, so we definitely consider it an event of interest! If GW200105_162426 is real, then its source comprises a 9 $M_\odot$ black hole and a 1.9 $M_\odot$ neutron star.

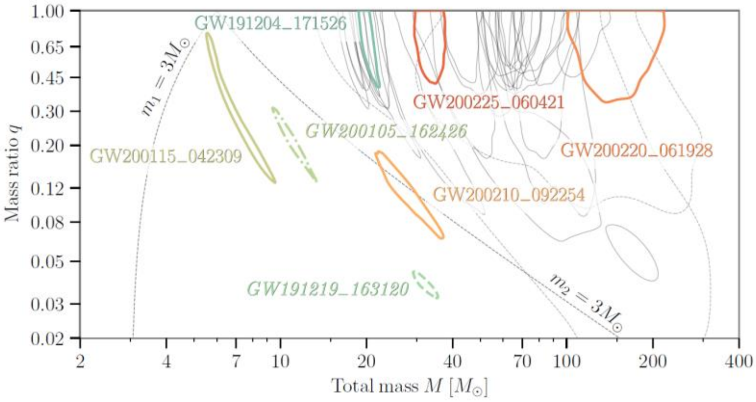

***Figure 4**: (Fig. 8 from our publication) Estimates of the total mass (M) and mass ratio (q) between the least massive and most massive component, for all O3b events. Each contour represents a different event and encloses the most probable values of the parameters at 90% probability (the 90% credible region). Several events are highlighted in color due to their interesting properties (see main text and our paper).*

Binary black hole coalescence highlights

A selection of highlights from our binary black hole coalescences are:

- **GW200220_061928** is probably the binary black hole which has the highest total mass in O3b (but less than GW190521 and GW190426_190642 in O3a). The combined mass of the two black holes was 148 $M_\odot$ (87 $M_\odot$ and 61 $M_\odot$ for each black hole). The final black hole formed from the merger has a mass of 141 $M_\odot$, surpassing the 100 $M_\odot$ threshold to be classified as an intermediate-mass black hole.
- **GW191204_171526** is a binary black hole merger where we can be confident that its **effective inspiral spin** is positive. The effective inspiral spin is a parameter that is convenient to measure from a gravitational-wave signal. A positive value indicates that at least one of the black holes is spinning, and that overall the spins are aligned with the direction of the orbital rotation. This spin information is a key clue to how the binary formed. The first observation we have of a system with positive effective inspiral spin was GW151226. For GW191204_171526, the masses of the two merging black holes were about 12 $M_\odot$ and 8 $M_\odot$ and the resulting final black hole mass was about 19 $M_\odot$.
- **GW191129_134029** has the lowest total mass of the O3b events that we are confident are binary black holes. Their total mass is about 17.5 $M_\odot$ (about 10.7 $M_\odot$ and 6.7 $M_\odot$ for each black hole). The black hole resulting from the merger has a mass of about 16.8 $M_\odot$.
- **GW191109_010717** is a binary black hole with significant support for negative effective inspiral spin. This would indicate that overall the spins of the black holes are aligned in the opposite direction to the orbital angular momentum (this means that the two compact objects may have been rotating in the opposite direction to their orbital motion in the binary system). The probability of its spin being negative is

90%. Negative effective inspiral spin seems to be rarer among our detections than positive effective inspiral spin. GW191109_010717 also has one of the more massive sources; about 65 $M_\odot$ and 47 $M_\odot$ for each black hole and about 107 $M_\odot$ for the final black hole. Since its mass is close to that of GW200220_061928's, in the plots we highlight GW200225_060421, which is our other candidate with a good probability (about 85%) of having negative effective inspiral spin.

Looking to the future

The LIGO and Virgo Collaborations have revealed a universe abundant in gravitational-wave sources. To date, we have observed 90 events. GWTC-3 adds 35 events, including our best candidates for neutron star-black hole coalescences. As we continue to observe more events, we will learn more and more about the objects producing them and their properties as a population, and use them to continue putting General Relativity to the test. Detecting more events also means we increase our chances of seeing the more unusual members of these populations.

The LIGO and Virgo dectectors are now offline for improvements before the upcoming fourth observing run, currently set to get underway in 2022. The KAGRA detector in Japan will also join O4 for the full run. Adding more detectors to the network will help to improve how well we can localize potential sources.

In the meantime, we continue to analyze our data, learn from compact-object observations, as well as searching for as yet undiscovered types of gravitational waves including continuous gravitational waves, stochastic gravitational waves, and of course surprises!

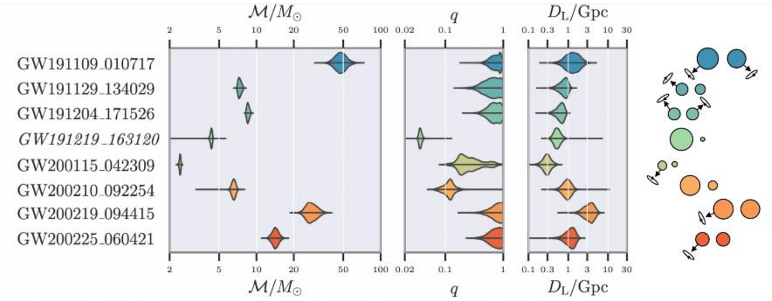

Figure 5: *Plots showing the most probable values of three key parameters of eight binary compact objects from GWTC-3: the binary chirp mass, M; the mass ratio, q, between the least massive and most massive component; and the luminosity distance, D_L. Each binary is illustrated to the right-hand side of the plot, with circle size representing mass and the component spins indicated (not to scale). Credits: LIGO-Virgo-KAGRA Collaborations/Isobel Romero-Shaw/OzGrav.*

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https://www.ligo.org/news.php

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Glossary

Binary Black Hole: A system consisting of two black holes in close orbit around each other. (See here.)

Binary Neutron Star: A system consisting of two neutron stars in close orbit around each other. (See here)

Black hole: A region of extremely warped space-time caused by an extremely compact mass where the gravity is so intense it prevents anything, including light, from leaving.

Chirp mass: A mathematical combination of masses for each compact object in a binary (see here for the formula). The chirp mass dictates the increase in frequency characteristic of a gravitational chirp for lower-mass binaries.

Compact object: An extremely dense astrophysical object such as a black hole, neutron star, or white dwarf.

Effective Inspiral Spin: The best-measured parameter encoding spin information in a gravitational-wave signal. It describes how much of each individual black hole's spin is rotating in the same way as the orbital rotation (e.g. if the spin and the orbit are both clockwise or anticlockwise).

False Alarm Rate: This rate measures how often a detector noise fluctuation could produce a signal similar to the candidate event being considered. The smaller this false-alarm rate is, the more likely the candidate event is to be astrophysical.

Gravitational waveform: A representation of a gravitational-wave signal's evolution with time.

GW200105_162426: A possible neutron star-black hole coalescence reported previously. This candidate has a 36% probability of being a real astrophysical signal. It is a particularly challenging source to analyse for two reasons. The first is that it is a single detector observation by LIGO Livingston. At the time of the event, LIGO Hanford was not taking data. Virgo was taking data, but no such signal could be identified. An event being visible in one detector but invisible in another is not unexpected: it depends on the relative sensitivity of the instruments and on the position of the source of the gravitational-wave signal in the sky (there was a similar situation for GW170817). It is always challenging to estimate the significance of a signal if there is data from only one detector. The second reason is that at this stage little is known about the neutron star-black hole binary systems as we do not have many observations of them. This makes reliably classifying neutron star-black hole coalescences difficult. As we observe more neutron star-black hole systems, we will learn more about these binaries and can come back to check candidates like GW200105_162426.

Light scattering: When laser light hits an optical component, a small proportion of it can be scattered (reflected at a random angle). The scattered light can be reflected off of other surfaces and make its way back into the detector laser beam and cause scattered light glitches. For more information about these glitches and other, have a look at Gravity Spy.

$M_\odot$ (solar mass): The mass of the Sun (around 2×10^{30} kilograms). Solar mass is a common unit for representing masses in astronomy.

Mass Ratio: The ratio of the lighter compact object's mass to the heavier compact object's mass.

Median: The value exactly in the middle of a distribution, so that half of the other values lie above and half of them below the median.

Megaparsec: A unit of distance. One megaparsec (1 Mpc) is about 3.26 million light-years.

Neutron star: A relic of a massive star. When a massive star has exhausted its nuclear fuel, it dies in a catastrophic way — a supernova — that may result in the formation of a neutron star: an object so massive and dense (though not as much as a black hole) that atoms cannot sustain their structure as we normally perceive them on Earth. These stars are about as massive as our sun, but with a radius of about ten kilometers.

Neutron Star-Black Hole binary: A system consisting of one black hole and one neutron star in close orbit around each other. (See here.)

Observing run: A period of time in which gravitational wave detectors are taking data for astrophysical observations.

Parameter estimation: A statistical technique used to infer the astrophysical parameters corresponding to a gravitational-wave signal.

Probability of being astrophysical: This quantifies the probability that a signal is a real gravitational wave. It depends both on how loud the signal is compared to background noise and on our understanding of the population that the source belongs to. Having many observations of binary black holes aids our understanding of the binary black hole population and helps us to compute the probability of candidates signals of that type to be astrophysical. As we have fewer observations of neutron star-black hole mergers, this quantity is harder to compute and we may need to revisit the current estimates once we have more observations and know more about the population.

Spin: The speed and direction of rotation (i.e., angular momentum) of a black hole around its center of mass.

Total Mass: The sum of the masses of the two compact objects in the binary.