GWTC-1: A NEW CATALOG OF GRAVITATIONAL-WAVE DETECTIONS

We present a new catalog (known as GWTC-1 or "Gravitational-Wave Transient Catalog 1") of gravitational-wave sources discovered during the first and second observing runs of the global network of Advanced gravitational-wave detectors.

Our catalog features four new binary black hole mergers not previously reported — including a new "triple detection", observed by both LIGO detectors and the Virgo detector on August 18th 2017. For this event, the position on the sky of the binary black holes, which were located 2.5 billion light-years from Earth, was pin-pointed with a precision of 39 square degrees — better than any other binary black hole merger observed to date.

We have refined our estimates of the source properties of all eleven confirmed gravitational-wave events in our catalog, with a total of ten binary black hole events and one binary neutron star event detected so far. Finally, we provide a list of 'marginal' candidate events, where a gravitational-wave detection could not be confirmed — as well as updating our estimates of the rate at which binary black hole and binary neutron star mergers occur in the universe and providing an upper limit on the rate of neutron star-black hole mergers.

The emerging field of gravitational-wave astronomy is entering an exciting new era!

THE FIRST TWO OBSERVING RUNS OF ADVANCED LIGO AND ADVANCED VIRGO

The past three years have witnessed the first two observing runs of the Advanced LIGO and Advanced Virgo gravitational-wave (GW) detector networks. Advanced LIGO made its first observing run (O1) from 12th September 2015 to 19th January 2016 and its second run (O2) from 30th November 2016 and 25th August 2017.

During O2, on the 1st August 2017, Advanced Virgo joined the two Advanced LIGO detectors for the first time. Some major highlights from O1 and O2 were:

- GW150914: the first ever detection of gravitational waves from the merger of two black holes more than a billion light years away;
- GW170814: the first GW signal measured by the three-detector network, also from a binary black hole (BBH) merger;
- GW170817: the first GW signal measured from a binary neutron star (BNS) merger – and also the first event observed in light, by dozens of telescopes across the entire electromagnetic spectrum.

In the interval between O1 and O2 the sensitivity of both LIGO instruments was improved and at LIGO Livingston (LLO) further improvements were made during O2. As a result, the LLO "BNS range" (a number used to quantify the performance of a detector, corresponding roughly to the average distance at which we can detect a binary neutron star merger) increased from about 60 Mpc (1 Mpc = 1 million parsecs) during O1, to 80 Mpc at the beginning of O2 and then to more than 100 Mpc by the run's end.

The BNS range of LIGO Hanford (LHO) was about 80 Mpc as O1 ended and was increased by an average of about 20% over all of O2. The Advanced Virgo detector builds on the first-generation Virgo detector that completed operations in 2011. The main improvements made to Virgo include a new optical design with a larger beam size and higher "finesse" of the arm cavities, better quality mirrors, and optical benches that are suspended and in vacuum. The BNS range of Advanced Virgo during O2 was about 25 Mpc.

Figure 1 shows the BNS range of the three detectors, and the best sensitivity that they achieved during O2.

FIGURES FROM THE PUBLICATION

For more information on these figures and how they were produced, read the freely available preprint.

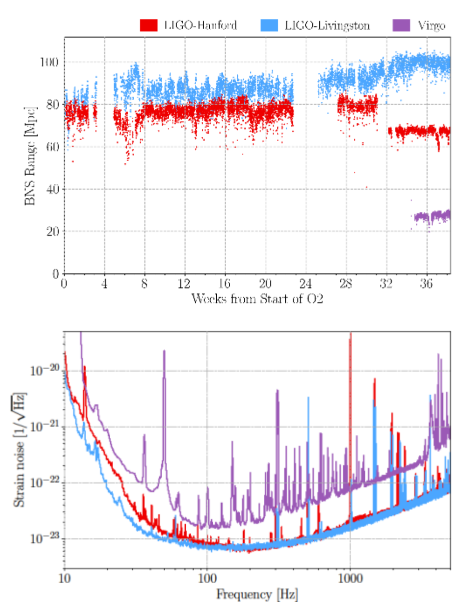

***Figure 1:** The upper panel shows the "BNS range" of the LIGO and Virgo detectors during O2. The break at week 3 was for the end-of-year 2016 holidays. There was an additional break in the run at week 23 to make improvements to instrument sensitivity. The impact on the LIGO Hanford instrument sensitivity, due to an earthquake in Montana, can be seen at week 31. Virgo joined O2 in week 34. The lower panel shows the sensitivity of each detector, indicated by the amplitude of the total strain noise as a function of frequency. The curves represent the best performance of each detector during O2. (Adapted from Figure 1 of our paper.)*

The individual LIGO detectors were taking data about 60% of the time, with data taken simultaneously by both detectors (referred to as 'coincidence data') 45% of the time. After removing the intervals affected by instrumental disturbances, the period of 'coincidence data' amounts to 118 days. 15 of these days were also in coincidence with Virgo, which took sensitive data about 80% of the time.

Searches for gravitational-wave signals from the merger of compact binary systems were carried out by two independent search algorithms, named "PyCBC" and "GstLAL", that compare the observed data with the theoretical signal predicted by General Relativity using a technique called "matched filtering". In addition, another generic search algorithm, named "cWB", that does not assume a specific, theoretical model for the gravitational-wave signal, was also used. Improvements in these search algorithms and an extension of the search, in terms of the properties of the astrophysical objects being searched for, motivated the reanalysis of data from O1. Similarly, the application of a "data cleaning" procedure, to remove some of the detector noise and improve the sensitivity, has also motivated re-analysis of the O2 data.

Each search method produces a list of candidate events which are ranked in terms of their signal strength with respect to the detector's noise — a quantity called the "signal-to-noise-ratio" (SNR) — and their statistical significance, quantified by the false alarm rate (FAR), i.e. the rate at which one might expect such a candidate event to have occurred by chance, due simply to the noise characteristics of the detector data mimicking an actual gravitational-wave detection. By setting a FAR threshold of less than 1 per 30 days (about 12.2 per year) in at least one of the two matched-filter analysis algorithms, we restricted the list of candidate events and eliminated many candidate signals that are very likely to have been simply artefacts of the detector noise: within these candidates we found 11 events with a probability larger than 50% of having an astrophysical origin, rather than being instrumental noise. These candidates are labeled with the prefix 'GW' followed by the date of the detection (i.e. GW150914). The other candidates are considered as 'marginal' events, unlikely to be of astrophysical origin.

SOME OLD FRIENDS – AND SOME NEW DISCOVERIES

Our three search algorithms have identified a total of eleven confident detections in the O1+O2 data. Seven of these have been previously reported: three BBH mergers from O1, and three further BBH mergers and one BNS merger from O2. One of the BBH mergers from O1 was previously referred to as LVT151012 (detected October 12th 2015), as its initial discovery reported in 2016 was at too low a statistical significance to merit being claimed as a GW detection at that time. However, a detailed re-analysis of this event has now demonstrated that it does indeed meet the criteria of a confident detection, and it is now re-labeled as GW151012.

In addition we have discovered four new gravitational-wave events during O2: GW170729 (detected July 29th), GW170809 (August 9th), GW170818 (August 18th) and GW170823 (August 23rd), all from coalescing black hole binaries. GW170818 stands out among the new discoveries, as the second BBH triple-coincident detection (after GW170814) observed by both LIGO detectors and by Virgo.

MEASURING THE PROPERTIES OF OUR GRAVITATIONAL-WAVE SOURCES

A pair of black holes undergoing nearly-circular orbits around each other before merging together is described by a combination of 15 physical quantities, or parameters. 8 of these parameters are properties of the black hole system itself: these are the black hole masses and its "spin" , which is related to the angular momentumof each body. 7 further parameters are related to how the gravitational-wave source is observed here on Earth: these are the position of the source on the sky, its distance from us, how much the BBH's orbital plane is inclined with respect to the line-of-sight to the source, the angle of polarization of the gravitational waves that the source emits, the time at which the pair of black holes merge together and the phase of the gravitational-wave emission at that time. Since neutron stars are made of matter, the gravitational waves produced by BNS systems depend also on another parameter known as their "tidal deformability"; this measures how much each star is deformed by the tidal distortion caused by its companion during the final orbits before the merger. Measurements of the tidal deformability can tell us about the internal structure of the neutron stars.

Figure 2 shows our estimates of the component masses of all the GW events discovered, inferred from the data; for each event the area shown is a way of representing the range of values within which we are 90% sure that the component masses lie — referred to as a "90% credible region". (Note that in each case we have labeled the binary component with the larger mass as '1'). We can see that the masses of the components of the of BBH systems cover a wide range, from about 5 times the mass of the Sun to about 70 times the mass of the Sun — which is consistent with the range expected for stellar-mass BHs. The heaviest BBH system is GW170729 and the two lightest systems are GW151226 and GW170608.

The gravitational-wave signal generated well before the merger, known as the "inspiral") mainly depends on a special combination of the individual masses of the components, called the "chirp mass", a parameter which can be measured with higher precision for lower mass binary systems. Other important parameters, such as the ratio between the component masses and the "effective aligned spin" (which is related to a particular combination of the spins of the individual components before they merge) are more difficult to measure precisely, since different values of these parameters lead to rather similar effects on the predicted gravitational-wave signal.

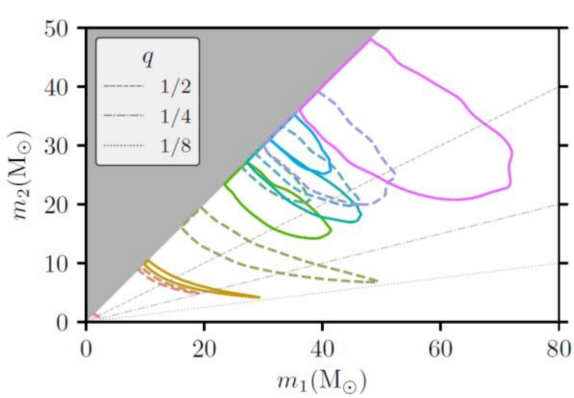

Figure 2: 90% credible regions for the estimated component masses of our gravitational-wave detections, in units of the mass of the Sun. The estimated masses of the neutron stars in GW170817 are shown in the bottom left hand corner of the plot. All other events are binary black hole mergers. It can be seen that the estimated masses cover a wide range, from about 5 times to about 70 times the mass of the Sun. For each event we have labeled the more massive component of the binary pair as '1'. (Adapted from Figure 4 of our paper.)

We can see this in Figure 3, for example: for all events, the distribution of the effective spin is centered around zero, except for GW170729 and GW151226, where we can rule out a zero value for the effective spin with more than 90% confidence. More precise measurements of the spins and masses in the future will give us greater insight into different scenarios for how stellar binary systems form and evolve. For the moment, however, with our current detector sensitivity it is difficult to measure the spins of individual black holes.

Some other important quantities inferred from our gravitational-wave signals are the final mass and spin of the merged object, the amount of GW energy radiated and the corresponding peak [luminosity] emitted in GWs. We found that a few percent of the binary's total mass is radiated away in GWs: the larger the total mass, the larger is the the amount of radiated energy. For example, for GW170729, the heaviest BBH system detected so far, the radiated energy corresponds to nearly five solar masses and the peak luminosity to more than 4 x 10^{56} erg/s — or roughly 50 times more luminous than the light power of every star in the entire universe!

The amplitude of the GW signal that we measure is inversely proportional to the distance of the GW source (more specifically, a particular measure known as its ["luminosity distance"]) allowing us to estimate their distance. Our estimates do carry a substantial uncertainty, particularly for the more remote systems, but it is clear that we are detecting GW events that occurred "a long time ago in a galaxy far, far away"

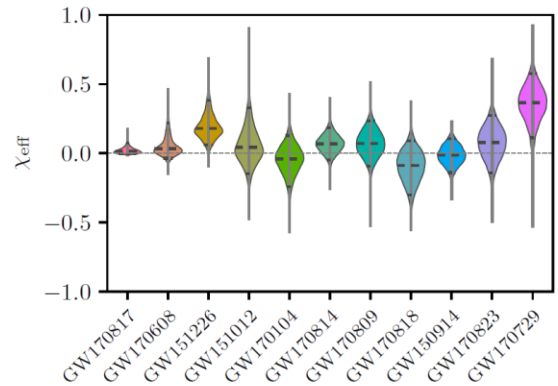

Figure 3: Estimated values of the effective aligned spin for each of our gravitational-wave detections. We can see that in all cases our estimate of this quantity is centered around zero, except for GW170729 and GW151226 where we can rule out a zero value for the effective spin with more than 90% confidence. (Adapted from Figure 5 of our paper.)

Of the ten BBH systems in our catalog, six have estimated distances of about a Gigaparsec (1 Gpc = 1 billion parsecs) or more: the most distant source (which was also the heaviest) is GW170729, at a distance of 2.76 Gpc, or about 9 billion [light-years], while the closest source is GW170608 which is 0.32 Gpc (or about 1 billion light years distant). On the other hand the BNS system GW170817 is, relatively speaking, on our cosmic doorstep at a distance of only 0.04 Gpc, or 130 million light-years.

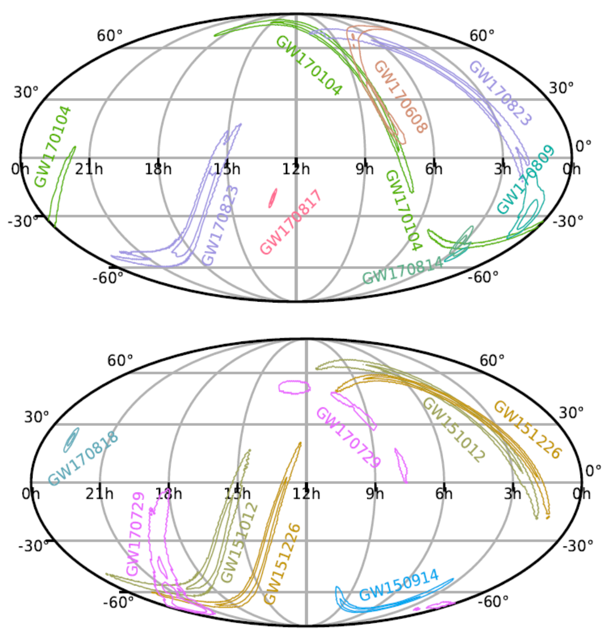

***Figure 4**: Sky maps showing 50% and 90% credible regions for the measured location on the sky of our gravitational-wave detections. The significantly better sky localization provided by the network of three detectors (LLO, LHO and Virgo) is apparent for e.g. GW170818. (Adapted from Figure 8 of our [paper].)*

THE IMPORTANCE OF THE NETWORK

When a GW signal reaches the Earth it will arrive at the different detector sites at slightly different times. These observed arrival times and also the amplitude of the GW signal measured at each detector allows us to localize the direction on the sky from which signal came. Two detectors can constrain the direction to lie somewhere on a broken ring on the sky, but with a third detector in the network we can pinpoint the sky location much better — providing critical information to alert astronomers who can search that area of sky with telescopes spanning the entire [electromagnetic spectrum] (optical or in other wavelengths).

The improvement in sky localization provided by the network is very clear in our results, and can be seen in Figure 4, which shows how well the sky positions of our gravitational-wave events were localized. For example, the most poorly localized event in our catalog is the BBH merger GW170823 — which was observed by only the two LIGO detectors and was located within a sky area of more than 1600 square degrees (or about 5000 times the area of the full moon). On the other hand the BBH merger GW170818, which had a quite similar signal strength to GW170823, was observed by all three detectors and was pinpointed to about 39 square degrees on the sky. Only the BNS triple detection, GW170817, was pinpointed more precisely than this — at only 16 square degrees.

Finally, Figure 5 shows the GW data for all of the BBH mergers displayed (in the left panel for each merger) as a ["time-frequency"] map: a representation of the data that uses time as the horizontal axis and the GW frequency as the vertical axis, with a measure of the strength of the signal represented by the color bar.

In many cases the characteristic upwardly-sweeping "chirp" pattern expected for an inspiraling BBH system is clearly visible. The right hand panels for each merger show the reconstructed signal waveforms using two different reconstruction methods; these are found to be consistent with each other when we take into account the uncertainties in the process.

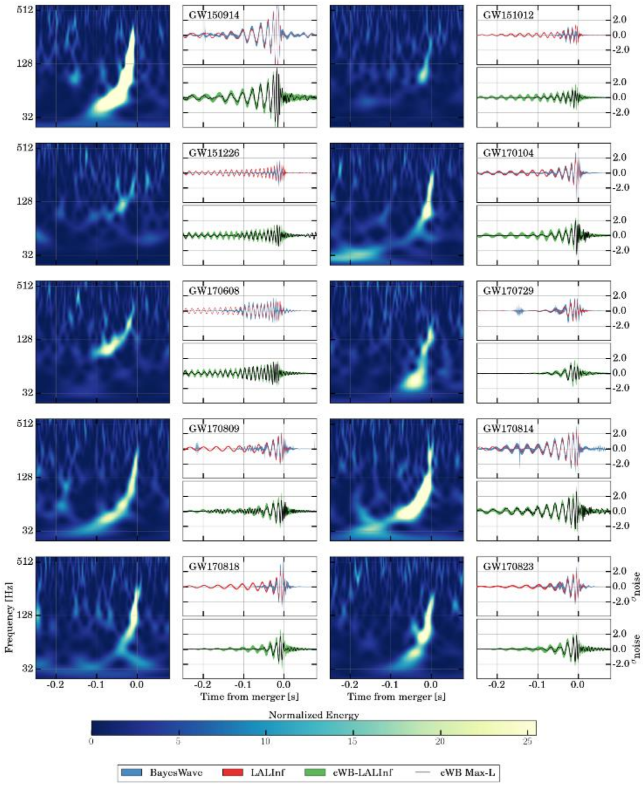

Figure 5: Time frequency maps and reconstructed signal waveforms for the ten binary black hole events reported in our catalog. In the right hand panel for each detection, the different colors represent different methods for reconstructing the waveforms; these are found to be consistent with each other when we take into account the uncertainties in the process. (Adapted from Figure 10 of our paper.)

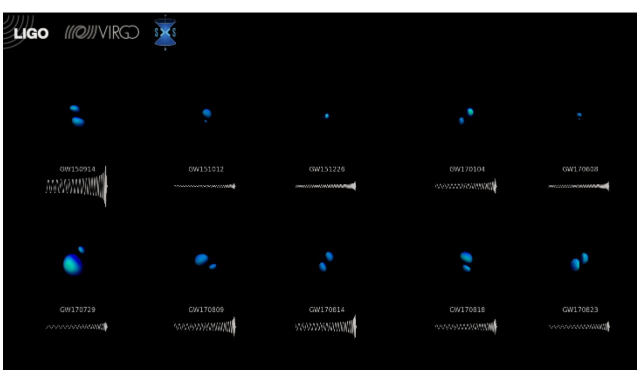

Figure 6: Still image from LIGO's and Virgo's "Binary Black Hole Orrery": a visualization of the merging black holes that LIGO and Virgo have observed so far. The full video (available here) shows numerical-relativity calculations of the black holes' horizons and the emitted gravitational waves, during the final few orbits of the black holes as they spiral inwards, merge and ring down. Each numerical-relativity calculation is consistent with one of the observations in the LIGO-Virgo catalog. As the horizons of the black holes spiral together and merge, the emitted gravitational waves become louder (larger amplitude) and higher pitched (higher in frequency). This movie is inspired by the Kepler Orrery. (Credit: Teresita Ramirez / Geoffrey Lovelace / SXS Collaboration / LIGO Virgo Collaboration).

LOOKING TO THE FUTURE

The GW detections presented in our catalog have allowed us to improve our estimate of the rate at which the 'global' population BBH and BNS mergers takes place in the Universe, and to place an upper limit on the rate of mergers of neutron star-black hole binary systems, in view of the fact that we did not detect such a merger in O1 or O2. More details of these population rate estimates, and how they were measured, can be found in a companion article to our catalog paper. Although our rate estimates are still quite uncertain, they will continue to improve as we make many more GW detections in the future.

Advanced Virgo and Advanced LIGO are currently undergoing further upgrades to their sensitivity and a third Observing Run, known as O3, is expected to start in spring 2019 and last for an entire year — leading to the discovery of tens of binary merger events during that run. Moreover, the Japanese detector KAGRA is also expected to join the network around the end of 03 — which will further extend the global network and so should further improve our ability to pinpoint GW sources on the sky.

The publication of GWTC-1 is a landmark moment for gravitational-wave astronomy, and an important stepping stone to a very bright future.

GLOSSARY

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

Neutron star: An extremely dense remnant from the collapse of more massive stars.

Noise: Fluctuation in the gravitational-wave measurement signal due to various instrumental and environmental effects. The sensitivity of a gravitational-wave detector is limited by noise.

Observing run: A period of observation in which gravitational wave detectors are taking data.

Sensitivity: A description of a detector's ability to detect a signal. Detectors with lower noise are able to detect weaker signals and therefore are said to have higher (or greater) sensitivity.

Strain: The fractional change in the distance between two measurement points due to the deformation of space-time by a passing gravitational wave.

Waveform: Representation of how a gravitational-wave signal varies with time.

Spin: Quantity that measures how fast an object rotates around itself.

Gravitational-wave polarization: The geometric shape of the stretching and squeezing of space-time caused by a gravitational wave as it moves.

Tidal deformation: Deformation of an object induced by the gravitational field of another object. As an example, on the Earth tides are caused by the Sun and the Moon and produce a deformation of the surface of the oceans with consequent daily fluctuation in ocean level.

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