GW170814: A THREE-DETECTOR OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY BLACK HOLE COALESCENCE

The GW170814 event is the fourth confirmed detection of gravitational waves reported by the LIGO Scientific Collaboration and Virgo Collaboration from a coalescing pair of stellar-mass black holes, and the first such signal to be observed by the Advanced Virgo detector. This detection illustrates the enhanced capability of a three-detector global network (the twin Advanced LIGO detectors plus Advanced Virgo) in particular to localize the gravitational-wave source on the sky and to test the general theory of relativity. GW170814 therefore marks an exciting new breakthrough for the emerging field of gravitational-wave astronomy.

Aerial view of the Virgo gravitational-wave detector, situated at Cascina, near Pisa (Italy). Virgo is a giant Michelson laser interferometer with arms that are 3km long. (Image credit: Nicola Baldocchi / The Virgo collaboration)

INTRODUCTION

On August 1, 2017, the Advanced Virgo detector joined the Advanced LIGO second observation run ('O2') which ran from November 30, 2016 until August 25. On August 14, 2017, at 10:30:43 UTC, a transient gravitational-wave signal, now labelled as **GW170814**, was detected by automated software analyzing the data recorded by the two Advanced LIGO detectors. The signal was found to be consistent with the final moments of the coalescence of two stellar-mass black holes, and subsequent analysis using all the information available from the three detectors showed clear evidence of the signal in the Advanced Virgo detector as well. This makes GW170814 the first confirmed gravitational-wave event to be observed by three detectors.

DETECTORS AND DATA QUALITY

The LIGO and Virgo detectors are giant Michelson laser interferometers with arms 4km and 3km long respectively. The LIGO detectors are located in the USA while Virgo is located in Italy: at Cascina, near Pisa. These three detectors were designed in the 1990's, built around the year 2000 and operated the following decade in their initial configuration – alongside the GEO600 instrument, located in Germany. They have all undergone a significant multi-year upgrade program aimed at improving their sensitivity by about a factor 10 (and hence increasing the volume of the Universe probed for a given source by a factor 10^3 = 1, 000).

The LIGO upgrade program started in 2010 and was completed in 2015, allowing the first LIGO observation run ('O1') to start in September that year – with the first gravitational-wave event detected a few days' later and two more confirmed detections in December 2015 and January 2017.

The Virgo upgrade program started a year later in 2011. The whole apparatus – from the mirrors and vacuum systems to the photodiodes sensing the laser beams – was upgraded and, after about a year of commissioning, the as-new instrument joined O2 on August 1, 2017. While the LIGO and Virgo detectors use the same method (interferometry) to detect gravitational waves, and share many common design features, they have been built and operate completely independently.

Figure 1 compares the typical sensitivity curves achieved by the three detectors around the time of the GW170814 event. The data were then cleaned, using well-identified noise sources which contaminate the strain sensitivity in a known way[1]. Extensive checks of the environmental and instrumental status at all three sites showed no indication of any problems.

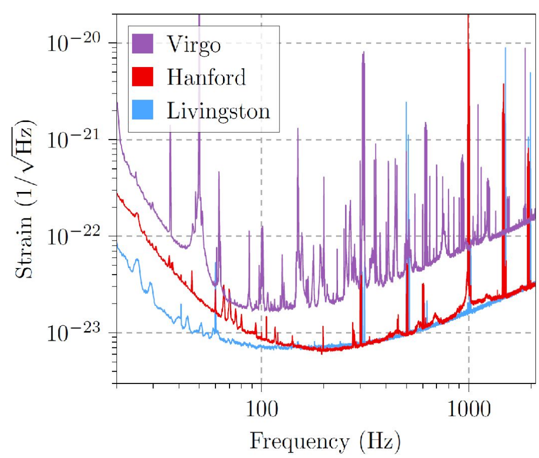

Figure 1: *This figure (which is Figure 2 in our publication) compares the sensitivity (labelled 'Strain' on the vertical axis) of the three detectors as a function of frequency (in Hertz, on the horizontal axis). Note that both axes have a logarithmic scale. At a given frequency, the lower the sensitivity shown on the graph, the weaker the gravitational-wave signal that can be detected. The blue curve shows the sensitivity of LIGO Livingston, the red one is for LIGO Hanford and the purple one is for Virgo.*

1. The same principle is used by noise-cancellation headsets which sense the ambient noise using probes located on the device and remove that noise by sending the 'opposite' signal to the ears

THE OBSERVED GW170814 SIGNAL

The identification of a new transient gravitational-wave event follows several steps. The first one takes place right after the data taking and relies on so-called low-latency pipelines which use matched-filtering techniques to look for coincident 'triggers' (i.e. candidate signals) in the two LIGO interferometers. Virgo data were not used at that stage as the Virgo sensitivity of this detector is currently not as good as the LIGO detectors and most of O2 took place with only the LIGO detectors in operation.

The GW170814 signal was thus observed with high significance within 30 seconds of its arrival; an alert was then generated and sent out to the various telescope partners of the LIGO-Virgo collaboration. Then, the significance of the candidate detection was computed more accurately, using about six days of LIGO coincident data and a procedure similar to those used for the previous confirmed detections – allowing computation of the false alarm rate associated with the event, i.e. how long one might expect to wait before seeing pure noise fluctuations in the two detectors conspiring to produce an apparent signal at least as strong as the one observed. With GW170814, the corresponding false alarm rate was found to be lower than **1 in 27,000 years**, making the detection case rock-solid.

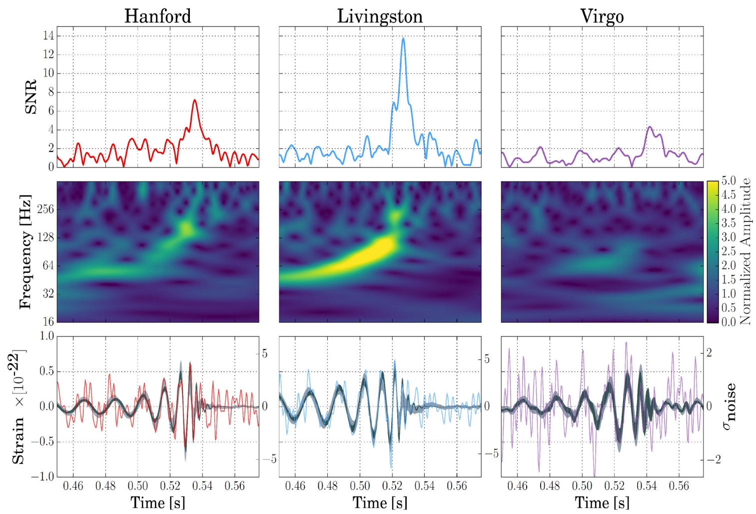

***Figure 2:** (which is Figure 1 in our publication)*

***Top row**: signal-to-noise ratio as a function of time; the peaks are slightly shifted in time as gravitational waves propagate at the speed of light, which is large but not infinite. So the signal does not reach the different detectors at the same time. GW170814 arrived first in LIGO-Livingston, then 8ms later in LIGO-Hanford and 6ms after that in Virgo.*
***Middle row**: time-frequency representation of the strain data: the brighter a given pixel in any of the three 2D-maps, the larger the signal at this particular time and frequency with respect to the expected noise level.*
***Bottom row**: strain time series with the best waveforms selected by the matched filtering (black solid curves) and un-modelled search methods (grey bands) superimposed.*

Virgo also saw this gravitational wave event, as demonstrated by two independent analyses. The first one, based on matched-filtering, compares two models: one model assuming a GW170814 observation in all three detectors (i.e. with Virgo included) and the other model assuming a signal only in the two LIGO detectors plus pure noise in Virgo. Our computations found that the former model was more than 1600 times more likely than the latter. The second method searches for un-modelled gravitational-wave transients with a frequency that increases with time – i.e. like the chirp signal produced by the merging of two compact objects – but without assuming that particular waveform shape. This analysis is not optimal for binary black hole mergers but it can catch other types of signal, and its coherent use of all interferometer data allows one to reconstruct the gravitational-wave signal. Moreover, for all the confirmed detections to date, the reconstructed waveforms match very well the binary black hole model.

Two such coherent analyses were compared for GW170814: one using only the two LIGO detectors, the other based on the three-detector network. Again, the strength of the reconstructed signal can be converted into a false-alarm rate stating the likelihood of independent noise fluctuations producing a signal that large. Using only two detectors, the computed false alarm rate was approximately 1 in 300 years; with the full network, the rate was reduced to lower than 1 in 5,700 years. Hence, the three-detection case is clearly favored over the two-detection hypothesis. Figure 2 shows three different ways of looking at the data recorded by the three interferometers at the time when GW170814 was detected.

SOURCE LOCALIZATION OF GW170814

The localization of a source in the sky can be estimated using the differences between the arrival times of the gravitational-wave signal in the various detectors of the network. These differences are due to the finite value of the speed of light – for instance up to 10ms for the two LIGO detectors which are about 3,000 km apart. Assuming the arrival times are known perfectly, each time difference will be associated with a circle in the sky, indicating the sky positions with which it is consistent. With a three-detector network, one obtains three time differences and hence three circles, which intersect in two points[2].

In reality, the arrival times have uncertainties, which mean that the circles are thick bands which form a sky region more or less wide when they intersect. To improve further the source localization, the amplitude and shape differences between the signals detected in the network can be used. To understand this, first recall that a gravitational-wave interferometric detector is more like a microphone than a telescope, in the sense that it can be sensitive to signals coming from most directions, although with some limitations: e.g. a gravitational wave coming from directly above (or below) the plane containing the instrument arms would be seen best – whereas the same wave coming exactly along the bisector of the arms would be completely invisible. Generally speaking, the higher the source over the local horizon, the better the detector response, and each instrument has four blind spots, all located in the plane of the arms. If a gravitational wave is not detected by an instrument which is in principle sensitive enough to see it, that means that the signal is coming from the direction of one of these blind spots.

2. With four or more detectors, all circles intersect in a single point. This is one of the reasons why adding a fourth interferometer (KAGRA in Japan) by the end of this decade and a planned fifth detector (LIGO India) a few years later will enhance even further the localization power of the global network.

Figure 3 summarizes the localization of the GW170814 source in the sky provided by the successive data analysis methods: initial rapid localization with only the two LIGO detectors shown in blue; addition of Virgo shown in orange; results of the full parameter estimation (see below) shown in green. The network can also constrain the distance to the source, as shown in the right-hand plot of Figure 3. Therefore, the localization of the source is carried out in three dimensions.

In favorable cases, the most credible volume might only contain a limited number of galaxies which would simplify the search for a visible counterpart by partner telescopes. 25 observatories made follow-up observations of GW170814 but no counterpart could be identified. In fact no other emission than gravitational waves is expected for binary black hole mergers.

MEASUREMENT OF THE GW170814 PARAMETERS

Accurate estimation of the GW170814 parameters was performed using the same techniques as for the previous confirmed detections – that is by comparing the detected signals with two independently-developed families of model waveforms the characteristics of which depend on the parameters one is seeking to measure. The better that the waveforms generated for a given set of parameters match the signals, the closer these parameters should be to their true values.

Details of the measured GW170814 source parameters can be found in our publication or in the GW170814 factsheet. For example, Figure 4 shows the parameter constraints inferred on the masses of the primary black holes.

TESTING GENERAL RELATIVITY WITH GW170814

Tests of general relativity similar to those carried out for the previous confirmed detections have been performed for GW170814. The new results are consistent with the theoretical predictions of Einstein's theory, and are similar to those obtained before. More in-depth analyses will be carried out in upcoming publications.

Operating a network comprising detectors which have different orientations (the two LIGO instruments are almost co-aligned but Virgo is not) allows, in addition, one to study the **polarization** of the gravitational waves – i.e. the way in which they distort spacetime while they propagate through it.

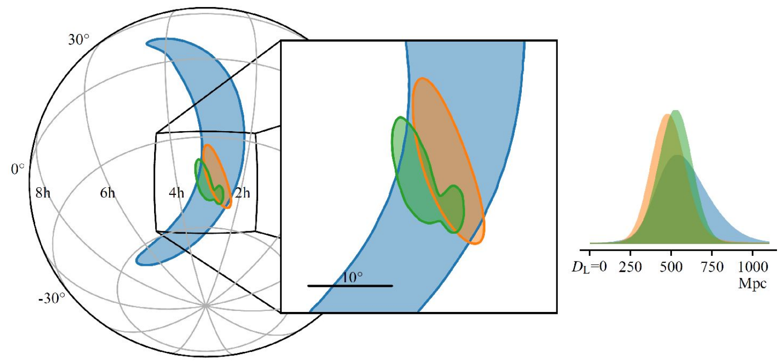

Figure 3*: Localization of GW170814 source on the sky. The left part of the figure compares the sky regions selected by the different analyses as the most likely to contain the source of the GW170814 signal – these are called 90% credible regions as they are defined such that the probability that they include the source is equal to 90%. The blue area corresponds to the rapid localization based on data from the two LIGO detectors only. Adding Virgo leads to the orange area, which is more than one order of magnitude smaller: 100 square degrees compared to 1160 square degrees. Finally, the green region is the result of the full parameter estimation analysis: an area of 80 square degrees using the three detectors – to be compared with the 700 square degrees area computed for the full parameter estimation with the two LIGO detectors only.*

The right part of the figure compares the probability distributions for the luminosity distance of the source. Adding Virgo narrows this distribution by cutting away the tail corresponding to large distances.

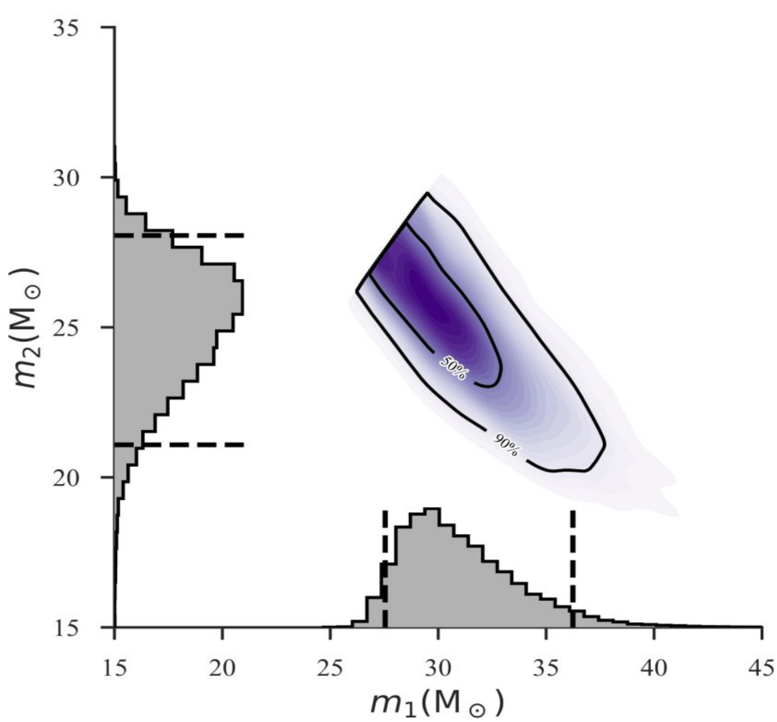

Figure 4: *(which is the upper panel of Figure 4 from our publication): measuring the masses (expressed in units of the Solar mass) of the two initial black holes for the GW170814 event. These masses are estimated simultaneously from our data, so the resulting joint constraints are shown in the m_2 vs. m_1 plane (where we adopt the convention that $m_2 \leq m_1$): the darker the color, the higher the probability that the black hole masses are equal to that pair of (m_1 , m_2) values. The black contours show the 50% and 90% credible regions respectively. In addition, one-dimensional probability distributions for the mass of each individual black hole are shown in grey on both axes.*

Within the framework of general relativity, gravitational waves are **transverse**, which means that they stretch and squeeze spacetime in the plane perpendicular to their direction of travel. Moreover, the allowed distortions are of only two types (or 'polarizations'), called '+' ('plus') and '×' ('cross'). Their effect on a ring of particles is shown in panels (a) and (b) of Figure 5.

Mathematically speaking, a generic so-called "metric" theory of gravitation can accommodate up to six different polarizations – including the two allowed by general relativity. Any additional polarization state would distort space-time in a different way, which would change how an interferometric detector responds to such a signal. This behavior would reveal itself when comparing the signals detected in two non-parallel instruments, as their differences could not then be accounted for by general relativity. Panels (c) to (f) of Figure 5 show the effect of these other polarizations. While panel (c) again denotes a transverse wave, propagating out of the plane of distortion, panels (d) to (f) denote gravitational waves propagating in the *same* plane as the spacetime distortion – as indicated by the arrow in these cases.

A first test of gravitational-wave polarization has been carried out with the GW170814 data. In particular, the full parameter estimation analysis described above has been performed again – this time allowing for different gravitational-wave polarizations that are forbidden by general relativity. All the alternative polarizations tested in this way are disfavored by this analysis – again indicating that our GW170814 data are consistent with Einstein's theory.

CONCLUSIONS

GW170814 is the fourth binary black hole merger to be confirmed by the LIGO-Virgo collaboration. The black holes identified are similar to those from the first (GW150914) and third (GW170104) detections, and are consistent with the astrophysical populations and merger rate inferred from the past detections.

What makes this event quite unique is that this is the first detection made by the two Advanced LIGO interferometers *and* Advanced Virgo. A three-detector network has enormous scientific potential, and this is well-illustrated by GW170814 with its much better localization (in terms of both sky-position and distance) and suitability for carrying out additional tests of general relativity. With the third LIGO-Virgo observing run, "O3", scheduled to start in about a year, the prospects for gravitational-wave astronomy now look exceedingly bright.

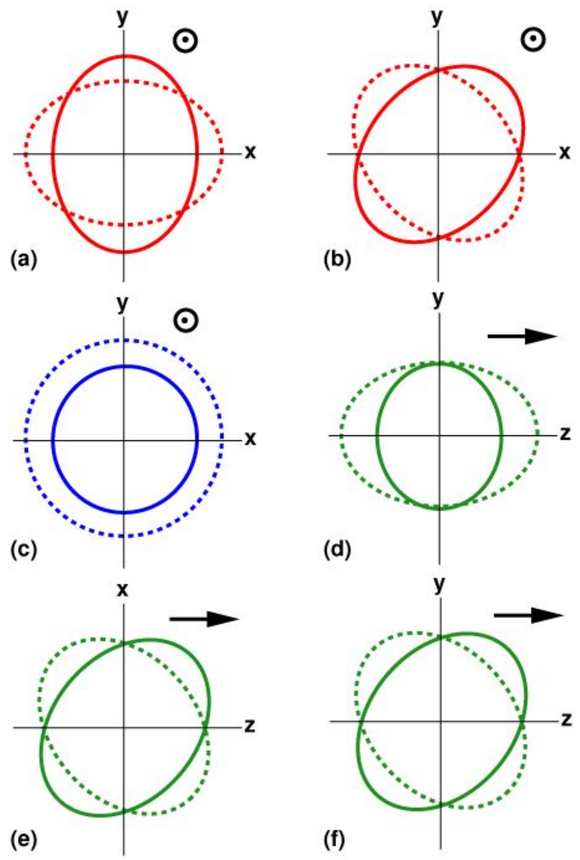

Figure 5: *Representation of the six polarizations permitted in general "metric" theories of gravity. Panels (a) and (b) denote respectively the '+' and 'x' polarizations permitted by General Relativity. In these two cases the spacetime distortion is in the plane perpendicular to the direction in which the gravitational wave travels: an initially circular ring of particles is stretched in one direction in this plane while being squeezed in the perpendicular direction in the plane, before the pattern reverses. Panels (c) to (f) denote polarizations that are not permitted in General Relativity. Panel (c) again shows a transverse polarization, while panels (d) to (f) illustrate distortions that propagate in a direction (shown by the arrow) that lies in the same plane as the spacetime distortion. (Credit: Clifford Will – Living Reviews in Relativity)*

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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.
- **Gravitational waveform**: A curve describing how the disturbance caused by a gravitational wave varies with time.
- **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 spacetime by a passing gravitational wave.