GW230529: OBSERVATION OF THE MERGER OF A NEUTRON STAR AND AN UNKNOWN COMPACT OBJECT

The first direct detection of gravitational waves (GWs) in 2015, with GW150914, marked the dawn of a new era for astronomy. Since then, many more GW detections have been made, originating from different types of source. All of them have been **compact binary coalescences**, consisting of neutron stars (NSs) and/or black holes (BHs). Here, we report the detection of GW230529, a compact binary coalescence observed on 29 May 2023, during the first part of the fourth observing run (O4a) of the **LIGO-Virgo-KAGRA** detectors, with one of the components of uncertain nature that has a mass larger than the expected range for NSs and smaller than the expected range for BHs.

HOW DID WE DETECT THIS EVENT?

We analyze the data of each operating detector using the **matched-filtering** technique. This involves comparing detector data to predicted signals in order to find the prediction that matches best, in the case that a real signal is hidden in the data. This yields an estimate of the signal strength as a function of time, or, a signal-to-noise ratio time series. If there is indeed an astrophysical signal in the detector data the signal-to-noise ratio will be high, otherwise it will be low. This technique has proven to be efficient at identifying faint GW signals within the detector data, but it is not fool-proof. Various sources of noise can interfere with our measurements or even mimic GW signals.

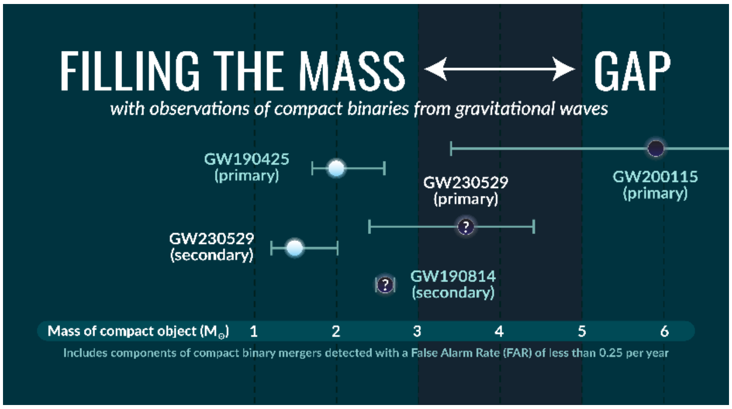

***Figure 1**: An illustration showing some of the component masses of gravitational wave events that lie within or around the 3-5 solar mass region, also referred to as the "lower mass gap". The light blue circles represent sources that are neutron stars, the black circles represent sources that are black holes, and the black circles with question marks indicate that the source is likely a black hole, but there is also a possibility it could be a neutron star. The primary mass of GW230529 is located in this mass gap. (Credit: S. Galaudage, Observatoire de la Côte d'Azur.)*

HOW DO WE KNOW THAT GW230529 IS A REAL EVENT?

Most of the time we search for signals that coincide both in time and source parameters in our different detectors. But we are not limited to searching for coincident events. We have refined our analysis techniques such that only a single detector is enough to confidently claim a detection, and fortunately so, because it allowed the detection of the exceptional GW230529 event, when the only usable data was from LIGO-Livingston. Three independent **search pipelines** (or search algorithms) reported the detection of GW230529. All of them use the matched-filtering technique but implement it differently and have developed powerful tools to discriminate astrophysical events from noise. The maturity of these search pipelines allows us to confidently cross-check their results.

It is thus extremely unlikely that detector noise could have produced a signal such as GW230529. The event was detected during a real-time analysis of the detector data and the detection was verified at the end of the observing period. The event was reported with a **false alarm rate** of less than one per thousand years. This means that, in the absence of any compact binary coalescence signal in the detector data, we expect such a signal to occur in the noise by chance less than once every thousand years. We show in **Figure 2** how this event stands out from the rest of the candidates.

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WHY IS THIS EVENT INTERESTING?

Scientists have proposed for several years the existence of a **lower mass gap** in the mass distribution of compact objects, between 3 $\mathrm{M}_\odot$ and 5 $\mathrm{M}_\odot$ (here $\mathrm{M}_\odot$ stands for **solar mass**), where we expect few compact objects. However, recent observations of binaries through **electromagnetic waves** or GWs have proposed candidates for binaries with a component in the mass gap. For instance, the mass of the secondary object in **GW190814** was estimated to lie, with very high probability, between 2.50 $\mathrm{M}_\odot$ and 2.67 $\mathrm{M}_\odot$ – higher than the heaviest NS known at the time of the detection but lower than projected BH masses.

With an estimated primary mass of about 3.6 $\mathrm{M}_\odot$, GW230529 is the first binary candidate with the *primary* component in the mass gap, as shown by **Figure 3**. Given our current understanding of NS and BH populations, the primary mass is consistent (with a probability of 99%) with a BH of mass smaller than 5 $\mathrm{M}_\odot$. However, the probability that the primary component is a NS was also estimated, taking into account our current knowledge from nuclear physics theory and experiment, as well as from astrophysical source populations. This probability of being a NS is small but non-zero, and under certain assumptions it can even reach a few percent; thus, we cannot exclude this scenario with certainty. On the other hand, the secondary component of GW230529, the mass of which has a 90% chance of lying between 1.2 $\mathrm{M}_\odot$ and 2.0 $\mathrm{M}_\odot$, is almost certainly a NS.

FIGURES FROM THE PUBLICATION

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

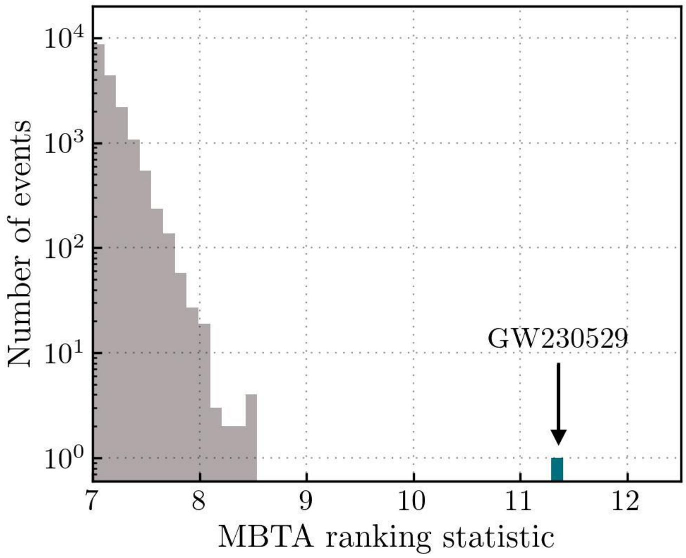

Figure 2: *Ranking statistic distribution of one of the search pipelines (called MBTA) for all candidate events in LIGO Livingston during the first two weeks of the fourth observing run (O4a). The horizontal axis gives the value of the ranking statistic, which is used to rank search pipeline triggers and also incorporates various tests to discriminate against noise. The ranking statistic is derived from the signal-to-noise ratio; the larger the ranking statistic, the louder the event and the more consistent it is with an astrophysical signal. The grey distribution is for events that were not significant enough to be classified as being of astrophysical origin. The blue bin is for GW230529. We see that the ranking statistic for GW230529 is much larger than that of the rest of the events, with no events detected at a ranking statistic larger than about 8.5, other than GW230529 with a ranking statistic of 11.4.*

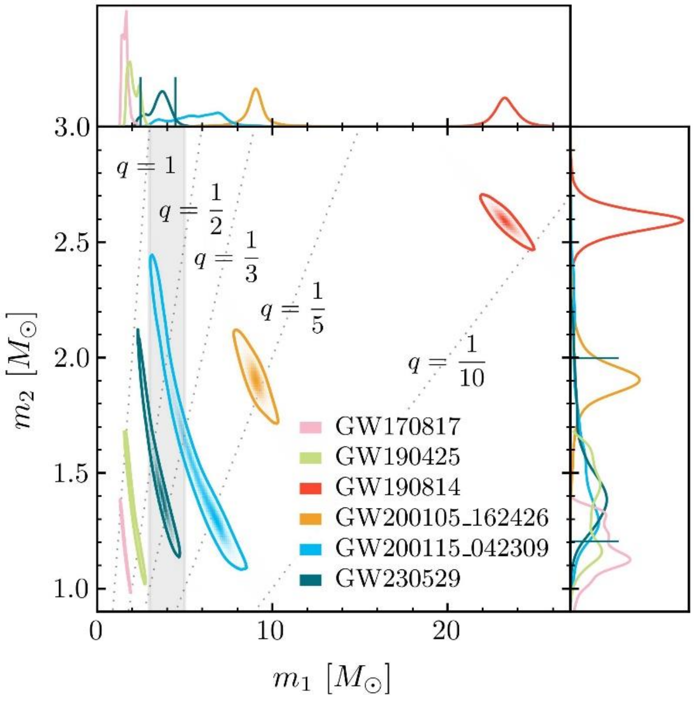

Figure 3*: Probability distribution for the component masses of several binary systems. The most-likely values for the mass are indicated by the peaks in the probability distribution functions. The top plot is the projected distribution for the mass of the primary component and the right plot is the projected distribution for the mass of the secondary component. Dashed lines of equal mass ratio* $q = m_2 / m_1$ *are also drawn. GW170817 (pink) and GW190425 (green) were consistent with BNS systems. GW200105_162426 and GW200115_042309 (orange and blue respectively) were consistent with NSBH systems. The GW190814 (red) secondary mass may be either a BH or a NS. The mass gap between 3 and 5* $\mathrm{M}_\odot$ *is shown as a shaded grey area. We see that GW230529 (teal) is right in between the two BNS and the two NSBH systems, with its primary mass in the mass-gap region.*

WHAT DOES IT TEACH US?

NS-BH mergers are rare events. Therefore, every additional detection is extremely valuable for the study of merger rates – as well as to characterize the populations of BHs and NSs, which is one of the goals of GW astronomy. This means inferring the shape of their mass distributions, deriving the minimum and maximum mass for BHs and NSs and studying the abundance of rotating compact objects of different masses. Using only GW230529, the inferred merger rate for similar events is about 39 events per year in a volume of about 3.5 x 10^{28} cubic **light years**. An analysis including other NSBH candidate events detected during the third observing run (O3) yields about 61 events per year in a volume of about 3.5 x 10^{28} cubic light years. Yet another analysis including additional, less significant, candidates gives a merger rate of about 95 events per year in a volume of about 3.5 x 10^{28} cubic light years. We find from these analyses that the inferred merger rate for binaries similar to GW230529 is comparable to the merger rate that was inferred during O3 for other events whose primary component was without doubt a BH. This reinforces the hypothesis that the primary component of the GW230529 binary system was a BH. The probability distribution for NSBH merger rates is shown in **Figure 4**.

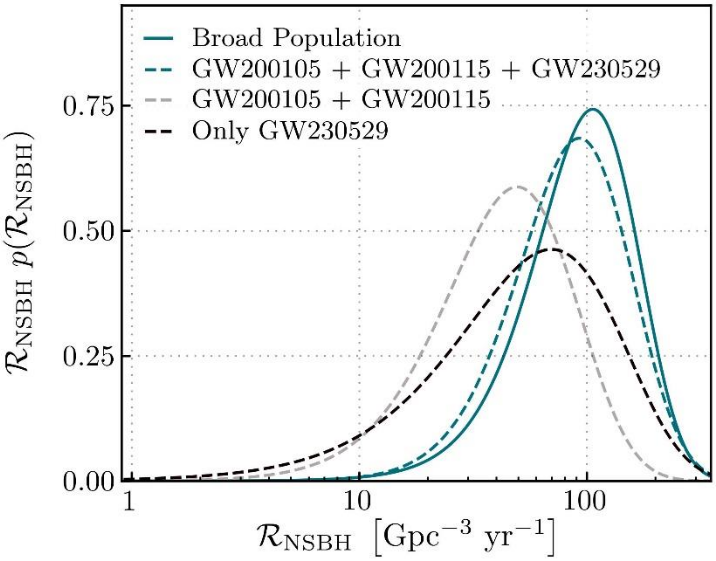

Figure 4: *Probability distributions for the merger rate of NSBH systems. The probability distribution functions are peaked at the most likely value of the merger rate, shown on the horizontal axis. The dashed lines are derived using NSBH-only population models indicated in the caption. The solid line, denoted by "broad population" is derived using a population model that includes additional less significant events, as explained in the text. We see that the peak values for the various distributions are relatively close to each other in the sense that all populations overlap to some degree. In particular, the peak value found using GW230529 only is comparable to the peak value found when including other NSBH events.*

Due to its primary mass being most likely in the mass gap, GW230529 is a prime candidate to refine **population models**. Three population models are considered, in order to study how they are affected by the observation of GW230529. The first two models encompass all types of compact-object binaries (BNS+BBH+NSBH) while the third one considers the NSBH population only. Including GW230529 in the first two models does not change significantly the outcome, meaning that GW230529 is not an outlier for these models. The third model, however, is significantly altered, as shown in **Figure 5**. We see that in this case the abundance of low mass BHs is increased and the minimum mass of a BH is pushed towards lower values. When we include GW230529, we find a minimum mass of about 3.36 $M_\odot$ compared to the previous value of about 6.04 $M_\odot$ for this model.

The formation process that led to GW230529 is uncertain. Current knowledge of **core-collapse supernovae** in massive stars disfavors such a scenario as the origin of the primary component in the binary due to its low mass. A more plausible scenario is formation by **fallback**, where a BH forms after the supernova due to accretion of residual matter by the core. Recent results from numerical models showed evidence that formation of 3 – 6 $M_\odot$ BHs was possible through this formation mechanism. Simulations of core-collapse for helium stars have predicted BH masses as low as the maximum NS mass, although the mass range below 5 $M_\odot$ is less populated. To this day core-collapse models still carry large uncertainties regarding the outcome of the process, making it hard to determine with precision limits for the masses of compact objects. GW230529 is, therefore, a valuable asset for constraining these models.

Another possible scenario for the formation of the primary component is through a binary NS merger. In this case we can imagine that the secondary component is a member of a former triple or quadruple system, or that it was captured by the primary component while it was evolving in a young star cluster or an active galactic nucleus. We also cannot exclude a non-stellar origin such as a **primordial BH**.

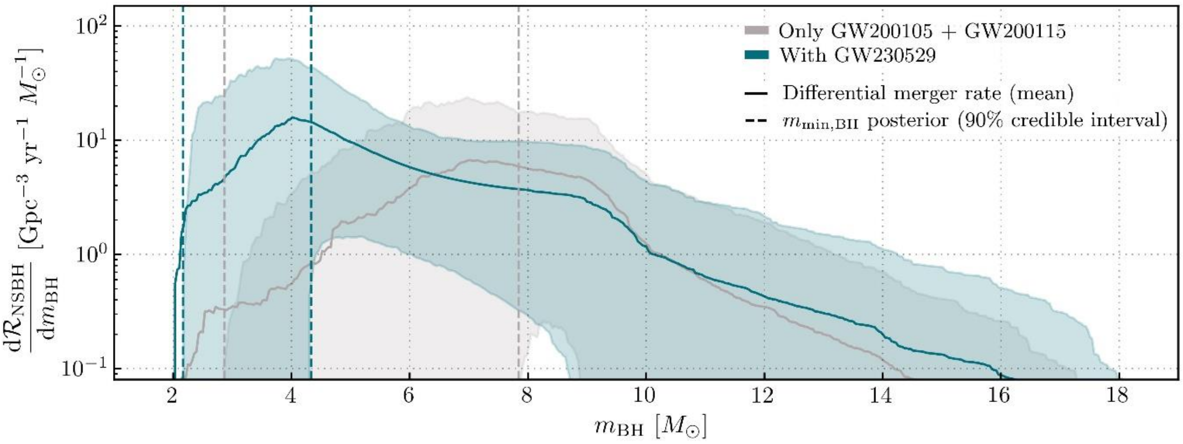

Figure 5: *Merger rate of NSBH binaries (vertical axis) as a function of the mass of the BH (horizontal axis) in the system. The solid curves show the merger rates for two different models and the shaded areas show the uncertainties corresponding to these models. The dashed vertical lines show the expected range for the minimal mass of a BH, with 90% probability. The grey color considers an NSBH-only population model excluding GW230529. The blue color also includes GW230529 in the NSBH population model. We see that the inclusion of GW230529 increases the abundance of binaries with low mass BHs, as well as pushing the minimal mass for BHs towards lower values.*

Further investigation of mass-gap systems like GW230529 will allow us to refine our understanding of BH and NS populations. This will in turn allow us to better understand their formation mechanisms and, for NSs, their internal structure.

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GLOSSARY

Compact binary coalescence: commonly abbreviated as CBC, it consists of two BHs, two NSs, or one BH and one NS that inspiral and eventually merge. The whole process produces GWs that increase in frequency and amplitude as the two objects get closer to each other and accelerate. The resulting merger object can be either a NS or a BH, depending on the initial system. The objects forming the binary are called its components, the primary component being defined as the one having the largest mass.

Black hole: compact object that is so dense that the velocity needed to escape its grasp is higher than the speed of light. This makes it appear as a black region of space since no light from this region can reach us.

Neutron star: extremely dense compact object constituted almost entirely of neutrons with a small admixture of protons and electrons as atoms cannot handle the pressure. They result from the collapse of massive stars following a process called a core-collapse supernova. The maximum mass expected for NSs is roughly 3 $M_\odot$.

Primordial black hole: a hypothetical BH that may have formed in the early universe, soon after the Big Bang. Predicted masses range from roughly $10^{-18}\ M_\odot$ to $10^{36}\ M_\odot$.

LIGO, Virgo and KAGRA: respectively located in the USA, Italy and Japan, these are the instruments that allow us to detect GWs. The basic concept of the LIGO, Virgo and KAGRA detectors consists of two arms, of kilometer-scale length, forming an “L” shape, with mirrors at their end and in which a laser beam circulates. We use the laser to measure relative variations in the length of the arms caused when GWs cross the Earth. The distance between the arms of each detector is constantly monitored and constitutes the data in which we search for GW signatures.

Matched-filtering: a method we use to analyze the detector data and detect compact binary coalescence events. It involves comparing at all times the data from our detectors with theoretically predicted GW signals which depend on the properties of the binary system, looking for correlations. When a real GW crosses the Earth, we should find a good match between the detector data and the predicted signal.

Lower mass gap: a mass range where we expect no or few compact objects to exist. This range extends from roughly 3 $M_\odot$ for the maximum mass of a NS, to 5 $M_\odot$ for the minimum mass of a BH.

Solar mass or $M_\odot$: mass of the Sun, used as a standard mass unit in astronomy. It equals roughly 2×10^{30} kg.

Light year: unit of distance. 1 light-year is the distance travelled by light in one year, computed based on the velocity of light in vacuum, equal to roughly 9.5×10^{12} km.

Population model: a theoretical model which gives the abundance of compact objects of a given type as a function of any combination of binary parameters.

Core-collapse supernova: In a star, the pressure of its gas is constantly compensating the gravitational pull from its core. When nearing the end of its life, the pressure drops and the star cannot any longer withstand the gravitational pull. It suffers an extremely rapid gravitational collapse towards its core which has several possible outcomes. The sudden collapse can create an extremely high pressure in the star causing it to explode in a supernova – hence the name “core-collapse supernova”. The supernova can then leave behind a NS or a BH in the case of fallback. If the star was too massive to begin with, it will collapse directly into a BH, skipping the supernova step.

Fallback: in the scenario of a core-collapse supernova that forms a NS, residual matter can “fall back” towards the NS. This accretion of matter can drive the mass of the NS above its maximum mass and lead to the formation of a BH.

Search pipeline: computing programs that consist of a chain of several processes. They condition the data for analysis, filter them and then compute various quantities in order to reject as many noise events as possible and estimate the significance of candidate astrophysical events. Some pipelines run in real-time, some run offline and some do both. More information can be found on the IGWN public alerts user guide.

Offline search: analyses that are performed on data from a previous observation period, typically during breaks when the detectors are not operating, for maintenance and upgrades. They complement real-time analyses (also called online analyses) which are carried out during the observation periods.

False alarm rate: this is used to quantify how likely an event is to have been caused by noise. It is computed by simulating events coming from noise and looking at their signal strength, to derive a distribution of the expected rate of such events as a function of the signal strength. In more concrete terms, if an event has a false alarm rate of 1 per day, this means that we expect the noise of our detector to produce such an event about once every day. We would therefore have little confidence in this event being astrophysical in origin.