

THE POPULATION PROPERTIES OF COMPACT OBJECTS FOLLOWING LIGO / VIRGO RUN O3A

What are typical black holes like? How many are there? Has the population of black holes changed as the Universe evolved? What can we learn about the formation of binary black holes using gravitational waves?

The third observing run (O3) of the LIGO and Virgo observatories has ended and, with it, so too has the assembly of our [second catalog of gravitational wave observations](#) (GWTC-2) which includes many new gravitational-wave events detected during the first half of O3 (denoted O3a). With this new catalog, we have more than quadrupled the number of gravitational-wave events compared with the number confidently identified in our previous catalog, (GWTC-1). And just as our first catalog unveiled new distinct populations and created new questions about their origin, with respect to the black holes we knew about from electromagnetic observations, this catalog raises new questions about the underlying astrophysical population and challenges our current best theories of binary black hole formation.

Astrophysical black holes are described by two properties: their mass and their spin. Astrophysical black hole **binaries** are further characterized by the orientation of the black holes' spin with respect to the [orbital plane](#) of the binary, and the distance to the binary. With distance, we gain a proxy to the [cosmic time](#) when the binary merged, since we know that gravitational waves [travel at the speed of light](#).

Scientists have proposed three possible binary black hole formation scenarios: “in-the-field”, dynamical, and primordial. [Primordial black hole](#) binaries are made of black holes that were never stars. These black holes formed by [density fluctuations](#) in the first few minutes of the universe, right after the [big bang](#). In-the-field binaries are made from black holes that are the last stage in the life of some stars: stars that collapsed under their own gravity. Dynamical binaries are made by black holes formed far apart, and only later running into each other by virtue of inhabiting a dense environment. Each scenario is associated with different distributions of the binary parameters – parameters that we can measure and which can help us distinguish between these different kinds of binaries. For instance, dynamical binaries are expected to have misaligned spins, whereas in general, in-the-field binaries should be aligned.

The binaries found in this catalog widen the mass range for binary black hole systems reported in the previous catalog. On the lower end, they bridge the mysterious “[mass gap](#)” between the heaviest neutron stars and the black hole population. On the higher end, they go beyond the mass cut-off predicted by so-called [pair-instability supernova](#) explosions. Their spins are also measurably non-zero and at least partially counter-aligned with their overall [angular momentum](#), hinting towards the existence of a dynamically formed portion of the population. These and other key findings in this catalog are big steps towards answering, and even asking, the right questions about the population of binary black holes that occupy our Universe.

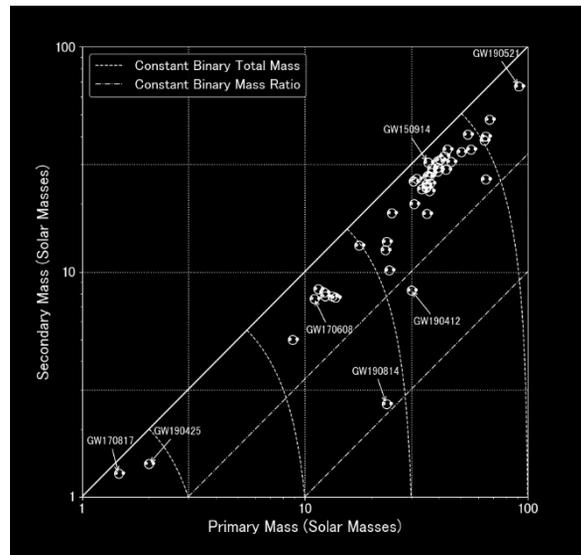


Figure 1: Masses of the binary component objects for the merger events observed in O1, O2 and O3a that were used to infer population properties in this paper. Selected individual events have been highlighted. (Credit: LIGO-Virgo Collaboration / IGF AE / Thomas Dent.)

GRAVITATIONAL-WAVE TRANSIENT CATALOG 2

Data for O3a, measured using the Advanced LIGO and Virgo detectors, were collected from April to October of 2019. During this time, 39 new mergers were observed: one binary neutron star, 36 confident binary black holes, and two possible neutron star black hole candidates. Including the 11 mergers from [GWTC-1](#), that makes 50 detected events in GWTC-2, all with a [false-alarm-rate](#) of less than two per year. For purity's sake, in this population analysis, we chose a false-alarm-rate of 1 per year. This restricted the sample to 47 candidates.

MASS DISTRIBUTION

Most black holes are believed to be the remnants of a star's gravitational collapse and subsequent supernova explosion. Since stars have a power-law mass distribution, we might also expect a power-law mass distribution for black holes.

In GWTC-1, the underlying mass distribution was well fitted with a truncated power-law with an index between -0.1 and 3.1 , starting at $\sim 7.9M_{\odot}$ and ending at $\sim 42.0M_{\odot}$. The value of the low-mass cut-off was mysterious and not well constrained. The high-mass cut-off was explained by the onset of a pair-instability supernova: a supernova thought to happen when a very massive star reaches a high enough density to produce [electron-positron pairs](#), creating a sudden drop in the internal pressure of the star. This leads to a collapse and explosion that obliterates the star, leaving behind no black hole remnant. Pair-instability supernovae are thought to prevent black holes with masses between ~ 50 - $150 M_{\odot}$ forming from supernovae.

With GWTC-2, all of the above has changed. The lightest black hole is smaller than what was believed possible ($2.3M_{\odot}$ or $6M_{\odot}$ depending on whether or not the lower mass object in [GW190814](#) is a black hole or a neutron star) and the most massive black hole is larger ($\sim 85M_{\odot}$ or $55M_{\odot}$ depending on whether or not we include [GW190521](#), an extreme event in which one of the black holes has a mass of $\sim 85M_{\odot}$). The preferred distribution is now a power law with an index between 2.00 and 2.73 . Instead of a sharp cut-off at high masses, the distribution is better characterized with an added “[bell curve](#)” peak set somewhere between 28.0 and $38.0M_{\odot}$. What could be the explanation for such a peak? Highly dense stellar environments, like those within the cores of [globular clusters](#), could make it possible for passing black holes to disturb the [gravitational potential](#) of binary black holes, tightening the binaries and enhancing their merger rate. Such binaries are said to merge through dynamical interactions.

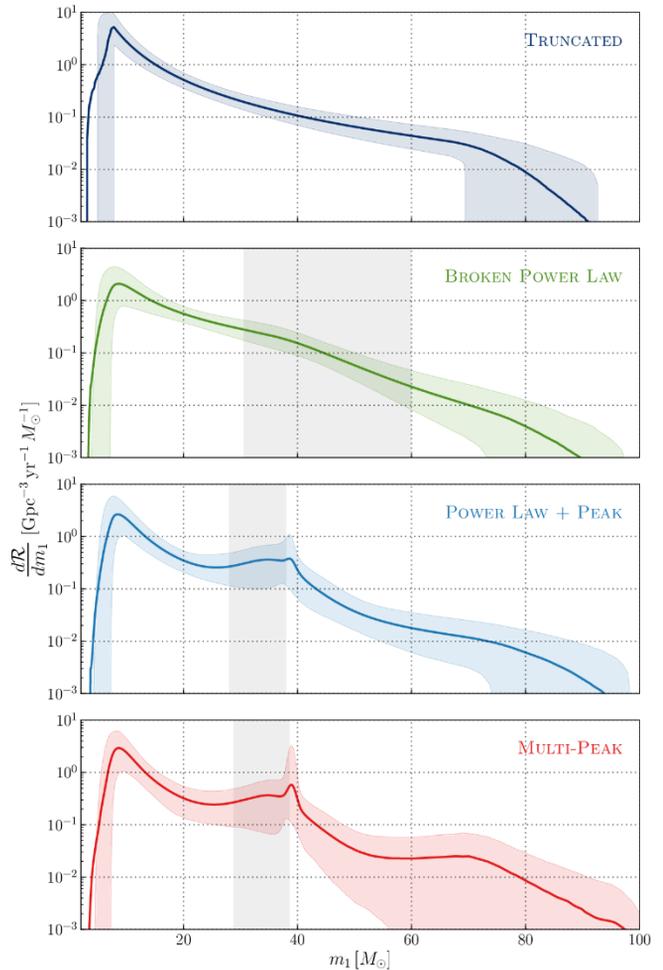


Figure 2: This plot shows the chance of measuring a given black hole mass for four different assumptions about the shape of the underlying mass distribution. The solid curve is the average prediction while the shaded region shows the 90% credible interval. Models with a peak in the distribution are preferred by the data. (Figure 3 of our [paper](#))

Dynamical interactions create a particular mass and spin distribution of merging black holes. Conservation of momentum favors larger masses ending up with smaller velocities, and smaller masses with larger velocities, bounding higher mass objects to orbits closer to the center of the cluster. Higher mass binaries will thus be in a denser environment, having a higher chance of dynamical interaction, and hence higher counts in the mass distribution of merging black holes. If the black holes produced by dynamical mergers merge with another black hole later on (a so-called second-generation binary), it may be possible to see black holes merging in the pair instability gap. Other formation mechanisms, like primordial black holes, could also produce one or more bell-curve features in the mass spectrum.

Alternatively, if the sharp cut-off predicted to be the signature of pair instability supernovae could be smoothed out, this pile-up of high-mass binaries could be explained without the need for dynamical interactions. The different formation scenarios were accounted for by adding a bell curve on top of our power-law baseline distribution. If more than one generation were to be present, we modeled this by adding extra bell curves at higher masses. **Figure 2** shows the different astrophysical population models we tested.

Finally, while each GWTC-1 binary had very similar component masses (i.e. mass ratios close to 1), GWTC-2 has two events, [GW190814](#) and [GW190412](#), with mass ratios unambiguously different than 1. Being both an outlier in minimum component mass and mass ratio, GW190814 seems to be indicative of a new population.

SPIN DISTRIBUTION

It is convenient to parametrize gravitational waveforms with two phenomenological parameters: the effective precessing spin and the effective spin. The effective precessing spin describes spin-induced [precession](#) of the orbital plane, while the effective spin describes how the merger is sped up or slowed down due to the black hole spin being aligned to the [angular momentum](#).

Binary black holes formed in the field are believed to contain components with nearly aligned spins, whereas dynamically merged binaries are expected to be misaligned. As a result, dynamical mergers are expected to undergo [precession](#), and about half of them should have anti-aligned spins.

While the binary black hole candidates in GWTC-1 yielded no evidence for this relativistic spin precession, we see signs of precession in GWTC-2. Furthermore, overall preferring small spins aligned with the orbital angular momentum, the catalog shows that between 2% and 50% of binary black holes have anti-aligned spins (this even when removing GW190814, our biggest outlier in all categories).

Binary black holes formed from merger products are expected to inherit most of their spin from the orbital angular momentum of their progenitor binaries. Hence, a smoking gun detection for dynamical formation would be the identification of different spin distributions in different mass components. However, we find no evidence of such a population.

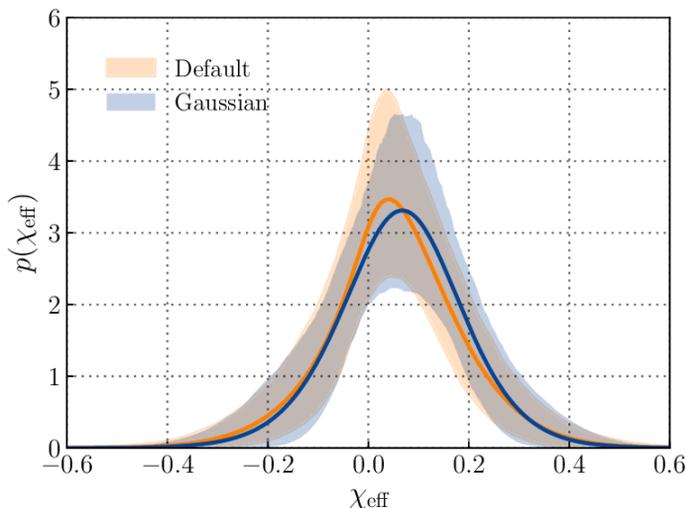


Figure 3: This plot shows the distribution of the effective spin parameter χ_{eff} for two different models. One can see that while most spins will be aligned with the orbital angular momentum, there is a significant fraction that will have a part of its spin rotating in the opposite direction. (Adapted from Figure 11 of our [paper](#))

RATE EVOLUTION WITH REDSHIFT

The universe is believed to be [expanding homogeneously](#) and it's been doing so ever since the big bang. This expansion stretches everything within it, including electromagnetic and gravitational waves. As a wave stretches, its frequency changes. For visible light, this implies going from blue to red, that is, "[redshifting](#)". The further away the object is, the greater the expansion, and the greater the redshift. Hence, redshift is another measure of distance, and, since the velocity of light and gravitational waves is fixed, also a measure of time. The higher the redshift of our merging binary, the older the binary.

Measuring the redshift evolution of the binary black hole merger rate, and comparing it to the stellar formation rate, enables us to better understand how compact binaries form. If we were to

make a cube with sides 1000 times the distance to the [Andromeda Galaxy](#), we would expect that, every year, there should be about 11 binary mergers in such a cube. As **Figure 4** shows, this rate is consistent with both a distribution of binaries that doesn't evolve over cosmic time and a distribution that locally tracks the star formation rate. We also find, given the longer observing time and only one new detection, that the number of binary neutron star mergers in the same size cube would be 151, a number smaller than for GWTC-1.

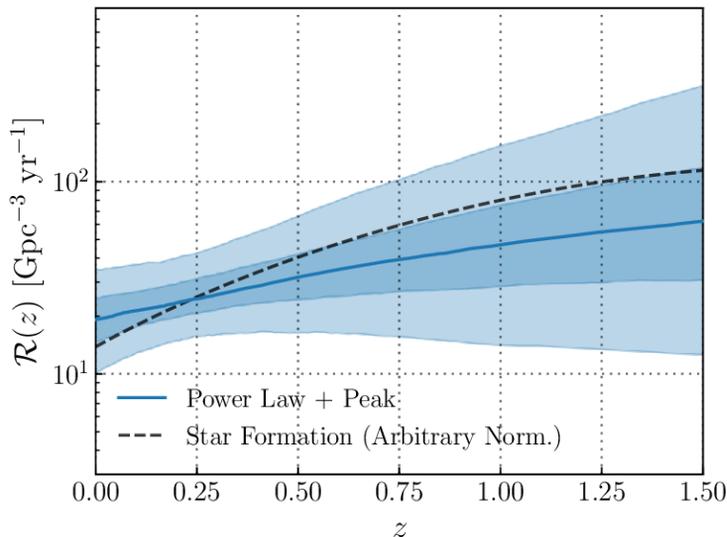


Figure 4: The merger rate density as a function of redshift, fit to the Power-Law Evolution model. The solid line shows the median rate density, while the dark (light) shaded region shows "1-sigma" ("2-sigma") credible intervals. The data exhibit a mild preference for redshift evolution of the merger rate, but is consistent with a flat distribution. (Figure 14 of our [paper](#))

FUTURE QUESTIONS

While a clearer picture is emerging of the population properties of compact binaries, key questions remain: How do we best characterize the deviations from power-law in the primary black hole mass spectrum, and what is the physical origin of these new features? What is the origin of binary black hole mergers in the high-mass gap: hierarchical mergers, stars producing remnants heavier than expected from pair instability supernovae theory, or something else? Is the observation of anti-aligned spins indicative of dynamical mergers? This hypothesis might be confirmed by observations of eccentric binaries, which are also expected from dynamical mergers. The unambiguous detection of hierarchical mergers (characterized by high mass and high spin) could also provide strong circumstantial evidence for the role of hierarchical mergers in the LIGO-Virgo bandwidth.

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Explore the GWTC-2 catalog data [here](#) at the [Gravitational Wave Open Science Center](#).

GLOSSARY

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

Supernova Explosion: A luminous and brief stellar explosion that occurs in the last evolutionary stages of a massive star.

Power Law Mass Distribution: Model for the probability of a black hole existing at a given mass is equivalent to the mass to some power: $p(m) \propto m^\alpha$ where α is the slope of the power law (i.e., how steeply the probability changes with increasing mass).

Solar mass M_\odot : the mass of the Sun. Solar mass is a common unit for representing masses in astronomy. 1 Solar mass = 1.989×10^{30} kg.



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