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# Ancestral Black Holes of Binary Merger GW190521

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## Abstract

GW190521 was the most massive black hole merger discovered by LIGO/Virgo so far, with masses in tension with stellar evolution models. A possible explanation of such heavy black holes is that they themselves are the remnants of previous mergers of lighter black holes. Here we estimate the masses of the ancestral black holes of GW190521, assuming it is the end product of previous mergers. We find that the heaviest parental black holes has a mass of $56^{+20}_{-18} M_\odot$ (90% credible level). We find 70% probability that it is in the $50\,M_\odot$–$120\ M_\odot$ mass gap, indicating that it may also be the end product of a previous merger. We therefore also compute the expected mass distributions of the "grandparent" black holes of GW190521, assuming they existed. Ancestral black hole masses could represent an additional puzzle piece in identifying the origin of LIGO/Virgo/KAGRA's heaviest black holes.

*Unified Astronomy Thesaurus concepts:* Gravitational waves (678)

## 1. Introduction

Some massive stars end their lives giving birth to black holes through stellar core collapse. Stars can produce black holes within a broad mass range, with a lower limit of about $5\,M_\odot$. However, nuclear processes in some of the most massive stars are expected to lead to early stellar explosion, leaving no stellar remnants behind. This process can lead to a mass range of $\sim 50\,M_\odot$–$120\ M_\odot$ with no remnant left behind (Woosley 2017). Nonetheless, the boundaries of this so-called pair-instability *mass gap* are currently uncertain (Limongi & Chieffi 2018; Belczynski 2020; Farmer et al. 2020; Belczynski et al. 2021; Costa et al. 2021).

The more massive component of the binary merger GW190521 has the highest estimated mass ($95.3^{+28.7}_{-18.9}\ M_\odot$ assuming uninformative priors; Abbott et al. 2020) among the black holes detected by the LIGO (Aasi et al. 2015) and Virgo (Acernese et al. 2015) gravitational-wave detectors. A similarly high mass is expected even if the binary's possible eccentricity is taken into account (Gayathri et al. 2020b; Romero-Shaw et al. 2020; Gamba et al. 2021). This black hole's mass is likely within the fiducial mass gap of $\sim 50\,M_\odot$–$120\ M_\odot$, indicating that it might not have been formed directly through stellar evolution. Interestingly, the secondary black hole of GW190521, with a mass of $69.0^{+22.7}_{-23.1}\ M_\odot$, might also be in the mass gap.

An attractive explanation for the high black hole mass is that it is itself the remnant of a previous merger of two, less massive black holes (Fishbach et al. 2017; Gerosa & Berti 2017). Such hierarchical mergers can occur in environments with large black hole number density such as galactic nuclei (Doctor et al. 2020; Kimball et al. 2020; Liu & Lai 2021) or globular clusters (Rodriguez et al. 2019), and may be particularly common in active galactic nuclei (AGNs) that facilitate the further increase of the black hole density in the AGN accretion disk (McKernan et al. 2012; Bartos et al. 2017; Stone et al. 2017; Yang et al. 2019; Gayathri et al. 2020a). The consecutive mergers of multiple black holes could explain the observed high masses even if these masses are inconsistent with stellar evolution.

In this Letter we derive the mass probability densities of the black holes that may have previously merged to produce the components of GW190521, assuming that GW190521 is indeed the latest stage of a chain of hierarchical mergers. We investigate the properties of the "parent" black holes and consider the possibility that GW190521 is a third-generation merger, computing the expected properties of the "grandparent" black holes. While we focus on mass here, parental properties based on the black holes' spin was separately investigated by Baibhav et al. (2021).

## 2. Computing the Parental Mass Distribution

We start with the posterior probability density $p(M)$ of a black hole mass $M$. Mass $M$ can be, for example, one of the component masses of GW190521. This posterior density depends on the reconstructed likelihood distribution $\mathcal{L}(M)$ based on the observed data and a prior distribution $\pi(M)$, such that $p(M) = \mathcal{L}(M)\pi(M)$.

We neglected black hole spin here whose role we discuss separately below. Given $p(M)$ and assuming that $M$ is the merger remnant of two black holes with masses $m_1$ and $m_2 \leqslant m_1$, we want to know the probability density $p(m_1, m_2|p(M))$.

In the following we consider probability densities as a series of discrete values, reflecting the fact that they are obtained numerically. The probability that the parental masses fall into bin $i, j$ centered around $m_{1i}, m_{2j}$ can be written as

$$p(m_{1i}, m_{2j}|p(M)) = \sum_k p(m_{1i}, m_{2j}|M_k)p(M_k), \tag{1}$$

where $p(M_k)$ is the probability of $M$ being in bin $k$ centered around mass $M_k$. We use Bayes' theorem to express the first term in the above sum as (see also Doctor et al. 2021)

$$p(m_{1i}, m_{2j}|M_k) = p(M_k|m_{1i}, m_{2j})\frac{\pi(m_{1i}, m_{2j})}{\pi(M_k)}, \tag{2}$$

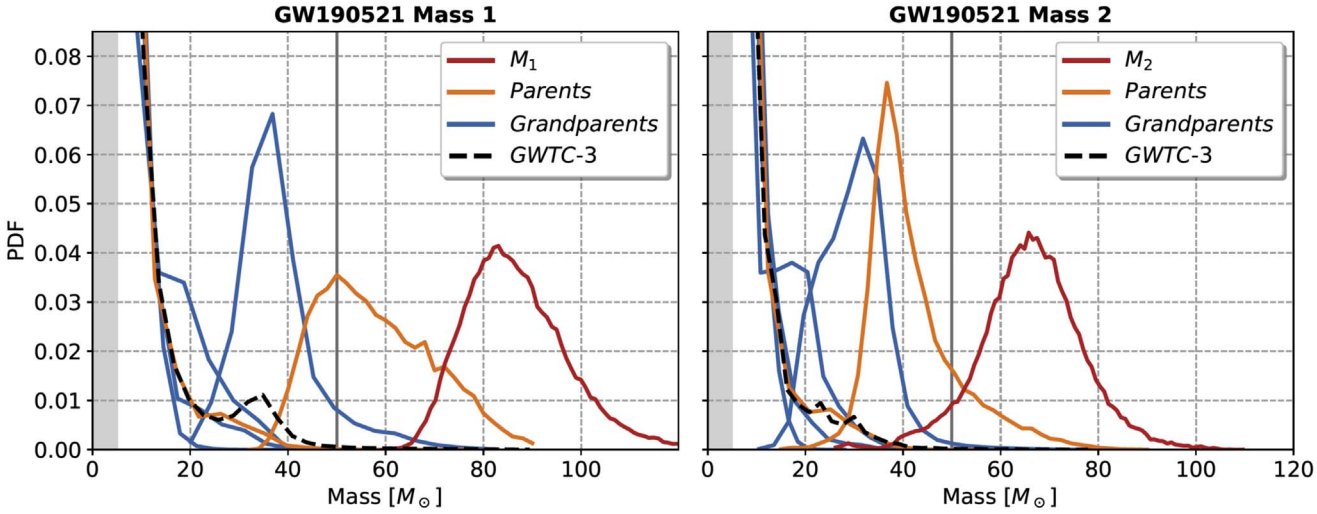


**Figure 1.** Probability density of ancestral black hole masses of GW190521, separately for the more massive (left) and less massive (right) black hole in the binary. We show masses for two previous generations of mergers, and for comparison the mass distribution inferred from the GWTC-3 gravitational-wave catalog (see legend).

where $\pi(m_1, m_2)$ is the prior probability density of $\{m_1, m_2\}$ and

$$\pi(M_k) = \sum_q \sum_r p(M_k|m_{1q}, m_{2r})\pi(m_{1q}, m_{2r}) \quad (3)$$

is the prior probability density of $M_k$.

The probability $p(M_k|m_{1i}, m_{2j})$ is 1 if the remnant of a binary $m_{1i}$, $m_{2j}$ has a mass in the $k$ bin of $M$, and 0 otherwise. Substituting Equation (2) into (1) and marginalizing over $m_{2j}$ we obtain the posterior probability of $m_{1i}$:

$$p(m_{1i}|p(M)) = \sum_j \sum_k p(M_k|m_{1i}, m_{2j})\pi(m_{1i}, m_{2j})\frac{p(M_k)}{\pi(M_k)}. \quad (4)$$

A similar expression applies to $p(m_{2j}|p(M))$.

## 3. Remnant Mass Computation

If we know the masses $(m_1, m_2)$ and spins $(\boldsymbol{S}_1, \boldsymbol{S}_2)$ of two black holes in a binary, the mass and spin of their remnant black hole can be determined. For this computation we use the phenomenological formulas of Healy et al. (2014), who developed an analytical prescription for computing the remnant mass and spin based on a suite of numerical relativity simulations.

Generally, both mass and spin are relevant in determining the properties of the remnant black hole. However, in the case of GW190521, the black hole spins are poorly determined, presenting only marginal constraints on the parental properties. Further, spin magnitudes and directions have limited effect on mass loss by the binary due to gravitational-wave emission. Using extreme spin values and the phenomenological formulas of Healy et al. (2014), we find that mass loss is altered by $\lesssim 5\%$ for any spin value, i.e., much less than typical mass uncertainties. For grandparents and further generations, spin will be even more uncertain, therefore we neglect it here. Baibhav et al. (2021) considered the spin of GW190521 to constrain its parental black holes, and found that it is more consistent with at least one of the parents being itself the remnant of a merger.

For a binary with well constrained black hole spins it is beneficial to extend our treatment to include spins as well (Baibhav et al. 2021). In particular, the ancestral mass ratio can have significant effect on the remnant black hole's spin Baibhav et al. (2021).

Considering only the masses in reconstructing the properties of ancestral black holes for GW190521 gives us the function $p(M_k|m_{1i}, m_{2j})$ used above.

The phenomenological formulas of Healy et al. (2014) are accurate only if the mass ratio $m_2/m_1$ is not too small. We considered these formulas only for cases in which $m_2/m_1 > 0.33$. For more extreme mass ratios, we consider the mass loss by the binary through gravitational waves to be negligible, and adopt a remnant mass $M = m_1 + m_2$. The mass loss in these cases is expected to be less than in the more equal-mass cases, and is much smaller than reconstruction uncertainties of the masses (Abbott et al. 2020; The LIGO Scientific Collaboration et al. 2021).

## 4. Results

We computed the posterior probability distributions of the parental masses for both black holes in the binary GW190521 following Equation (4). For the prior probability $\pi(M_k)$ we adopted an uninformative, uniform prior, the same that was used by LIGO/Virgo (Abbott et al. 2020). Integrals involving $M_k$ were approximated as Monte Carlo integrals. For the prior probability $\pi(m_1, m_2)$ we adopted the average over the posterior population distribution of the model fit on the GWTC-3 gravitational-wave catalog (power law + peak model; Abbott et al. 2021). This model takes into account the mass distributions for both black holes, including the correlation between them (Talbot & Thrane 2018). The prior $\pi(m_1, m_2)$ may somewhat underestimate the masses of the parental black holes from dynamical and AGN-assisted formation channels, which are the most likely sites of hierarchical merger and have top-heavy mass distributions (Yang et al. 2019; Fragione et al. 2021). Other priors are also possible that can give very different mass estimates for GW190521's black holes (Fishbach & Holz 2020; Nitz & Capano 2021).

Results are shown in Figure 1. We see that for both black hole masses $M_1$ and $M_2$ within GW190521, one of the parents has a relatively high mass while the lighter parent essentially follows the GWTC-3 distribution. In particular, we find that the heaviest parental black hole has a reconstructed mass

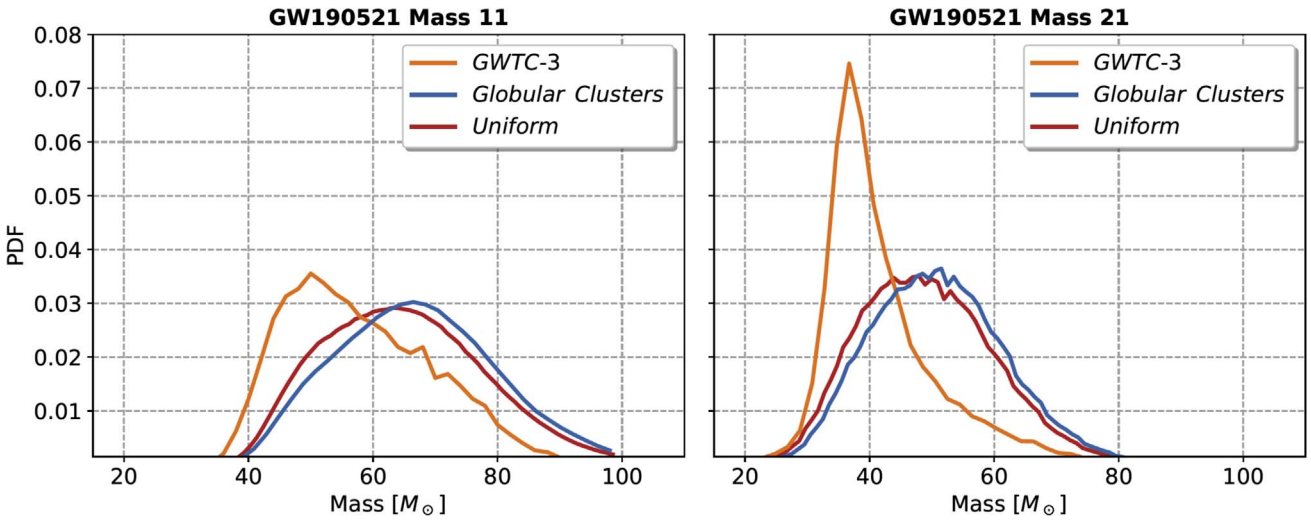


**Figure 2.** Mass probability density of the heaviest ancestors of GW190521 for different prior distributions. We considered the prior distribution from the GWTC-3 gravitational-wave catalog (power law + peak model; The LIGO Scientific Collaboration et al. 2021), an expected distribution for globular clusters based on O'Leary et al. (2016), and a uniform independent prior in $m_1$ and $m_2$.

$m_{11} = 56^{+20}_{-18} M_\odot$ (90% credible level). Here, $m_{xy}$ denotes mass $y$ in the binary whose remnant is $x$, with $x, y \in \{1, 2\}$. This heaviest parent has 70% probability to be in the $50\,M_\odot$–$120\,M_\odot$ mass gap, or 27% if we adopt a more conservative lower limit of $65\,M_\odot$.

To understand the role of the prior distribution in ancestral masses, we considered three different prior distributions for the heaviest parents of both black holes in GW190521. Priors included the GWTC-3 based prior, a uniform prior, and the mass distribution expected in globular clusters (O'Leary et al. 2016). For globular clusters we adopted a probability density $\propto (m_1 + m_2)^4 (m_1 m_2)^{-2.3}$. Results are shown in Figure 2. We find that for the heaviest ancestor $m_{11}$, the choice of prior results in limited difference, with its mass being somewhat higher for both uniform and globular-cluster models than for GWTC-3. For the uniform prior, we find 86% probability to be in the $50\,M_\odot$–$120\,M_\odot$ mass gap, or 46% for a $65\,M_\odot$ lower limit. A larger difference is found for the heavier parent, $m_{21}$, of $m_2$. Note, however, that for our alternative distributions we considered no upper bound for the mass. In a more realistic model, the mass distribution would change within the mass gap even if hierarchical mergers populate this mass range.

The assumption of the above prior distributions also does not take into account that the distribution of hierarchical mergers is different than first-generation mergers. There can also be distributions for intergenerational mergers in which one of the black holes in a binary is the remnant of a previous merger, while the other is first generation. For example, for our uniform and globular-cluster models above, one could introduce a mass cutoff at $50\,M_\odot$ representing the limited fraction of events that are of hierarchical origin. This would appear as a cutoff at this mass in Figure 2, and lead to a lower estimated mass for the black holes. For simplicity, the effect of these possibilities is not accounted for in the present analysis.

The distribution GWTC-3 we adopt here was obtained by taking into account GW190521 itself. To understand whether this can bias our results, we carried out our mass estimation with a similar distribution fit on LIGO/Virgo's previous, GWTC-2 catalog (Abbott et al. 2020) with the exclusion of GW190521 (no similar fit without GW190521 was readily available for GWTC-3). We find similar results, with $m_{11} = 53^{+17}_{-15} M_\odot$ and a probability of 64% that this black hole is in the $50\,M_\odot$–$120\,M_\odot$ mass gap.

Given the nonnegligible probability that at least one of the parents falls in the mass gap, which might indicate that this parent is also the product of a previous merger, we computed the expected masses of GW190521's grandparents as well. The obtained distributions are shown in Figure 1. We see that, similarly to parents, the heaviest grandparent has a mass significantly above that of the GWTC-3 distribution, while the lighter grandparent masses follow the GWTC-3 distribution. We further find that, assuming GWTC-3 prior distribution, going back an additional generation, the heaviest great-grandparent has a mass of roughly $30\,M_\odot$ and has about the same mass uncertainty as the heaviest grandparent.

## 5. Conclusion

We introduced and carried out a Bayesian reconstruction of the ancestral black hole masses of the black holes in the merger GW190521, assuming that GW190521 is the end product of consecutive mergers. We found that, given our prior assumptions, one of the parental black holes has a 70% (27%) probability of falling in the upper mass gap assuming a lower mass limit of $50\,M_\odot$ ($65\,M_\odot$), making this parent a plausible candidate for a merger remnant.

With this possibility in mind we reconstructed the expected mass distribution of grandparent black holes, i.e., the ones two generations before those in GW190521. Remarkably, we found that even after two generations the mass of the heaviest grandparents have limited mass uncertainty, indicating that the reverse engineering of ancestral masses can provide nontrivial information on the ancestors' properties. This information, along with the possible indication that GW190521 might be a 3 + generation merger, might carry indications of the origin of the merger. In particular, galactic nuclei and AGNs appear to be the most likely sites where multiple generations of hierarchical mergers might take place.

Our results represent further support to previous findings that some of LIGO/Virgo's black hole mergers are of hierarchical mergers origin. Baibhav et al. (2021) showed that the

reconstructed spins of the black holes within GW190521 support a hierarchical origin. Examining the broader population of the properties of all detected mergers, Doctor et al. (2020) and Kimball et al. (2021) found evidence that a subpopulation of the detections likely has a hierarchical origin.

Future detections of even heavier black holes by LIGO/Virgo/KAGRA, and a better theoretical understanding of the pair-instability mass gap, could shed further light onto the formation of binary black holes, where the reconstruction of ancestral black hole masses could play an important role.

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