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What GW170729's exceptional mass and spin tells us about its family tree

Chase Kimball,[1] Christopher P L Berry,[1] and Vicky Kalogera[1]

[1]*Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Department of Physics and Astronomy, Northwestern University, 1800 Sherman Ave, Evanston, IL 60201, USA*

ABSTRACT

Gravitational-wave observations give a unique insight into the formation and evolution of binary black holes. We use gravitational-wave measurements to address the question of whether GW170729's source, which is (probably) the most massive binary and the system with the highest effective inspiral spin, could contain a black hole which is a previous merger remnant. Using the inferred mass and spin of the system, and the empirically determined population of binary black holes, we compute the evidence for the binary being second-generation compared with first-generation. We find moderate evidence (a Bayes factor of ~ 6–7) that the mass and spin better match a second-generation merger, but folding in the expectation that only a small fraction of mergers are second-generation, we conclude that there is no strong evidence that GW170729 was the result of a second-generation merger. The results are sensitive to the assumed mass distribution, and future detections will provide more robust reconstructions of the binary black hole population.

Keywords: Gravitational wave sources — Gravitational wave astronomy — Astrophysical black holes

1. INTRODUCTION

LIGO–Virgo (Aasi et al. 2015; Acernese et al. 2015) have observed gravitational waves from 10 binary black holes (Abbott et al. 2019a). Of these, GW170729's source stands out as (probably) the system with the highest mass and the highest effective inspiral spin χ_{eff}. With a total mass of $M = 84.4^{+15.8}_{-11.1}M_\odot$ and a chirp-mass of $\mathcal{M} = 35.4^{+6.5}_{-4.8}M_\odot$, the primary-component mass $m_1 = 50.2^{+16.2}_{-10.2}M_\odot$ encroaches on the hypothesised (pulsational) pair-instability supernovae mass-gap (Woosley 2017). Its $\chi_{\text{eff}} = 0.37^{+0.21}_{-0.25}$ makes it one of two observations for which a non-spinning component is excluded at 90% probability. Given GW170729's exceptional properties, it is natural to ask if it formed through a different channel.

Hierarchical mergers—wherein at least one of the components is the product of a binary black hole merger—may occur in dense environments (O'Leary et al. 2016; Mapelli 2016; Antonini & Rasio 2016). These systems may be identified by their masses and spins (Fishbach et al. 2017; Gerosa & Berti 2017). Being made from smaller black holes, merger remnants are more massive, and their spins are ~ 0.7 as they are dominated by orbital angular momentum of the merged binary (Buonanno et al. 2008). We consider if GW170729's high mass and non-zero spin are evidence for it being a second-generation (Gen 2) merger. Using population distributions from Abbott et al. (2019b) and parameter posterior distributions from Abbott et al. (2019a), we show that—even under the generous assumption that *all* binary black hole mergers occur in dense clusters—there is not strong evidence that GW170729 is the result of a hierarchical merger.[1]

2. METHODOLOGY

Corresponding author: Chase Kimball
CharlesKimball2022@u.northwestern.edu

[1] The population distributions are available from dcc.ligo.org/LIGO-P1800370/public and GW170729's parameter posterior distribution is available from dcc.ligo.org/LIGO-P1800324/public.
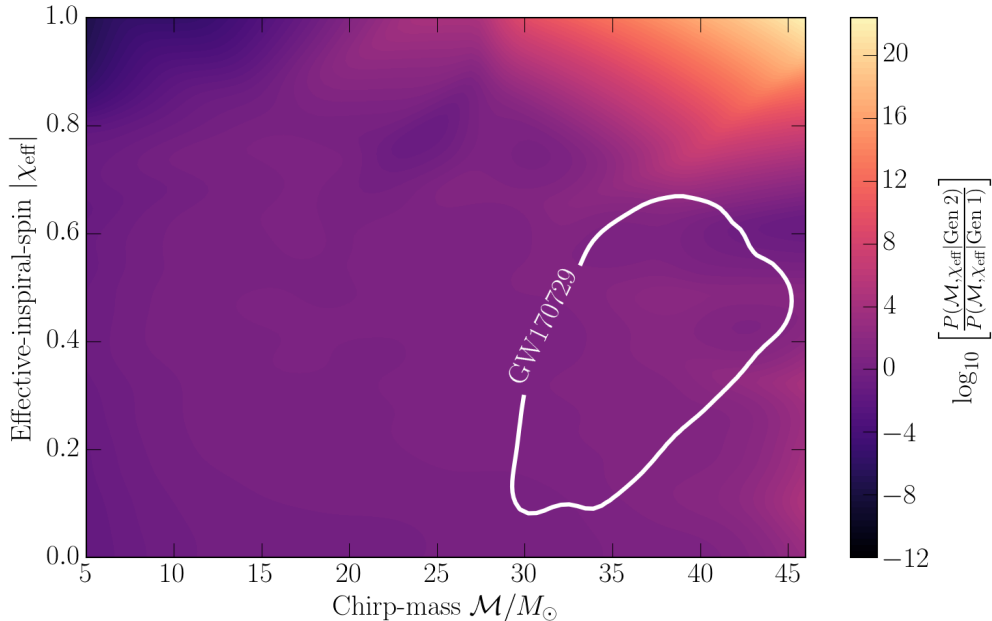
Figure 1. Relative likelihood of a binary black hole being second-generation versus first-generation as a function of chirp-mass $\mathcal{M}$ and the magnitude of the effective inspiral spin $|\chi_{\rm eff}|$. For comparison, the white contour gives the 90% credible area for GW170729 (Abbott et al. 2019b).

We form an initial (Gen 1) binary black hole population, drawing masses and spins from the posterior population distributions inferred from gravitational-wave observations (Abbott et al. 2019b). We use mass Model A—a power-law with a variable exponent, a $5M_\odot$ lower cut-off, and a variable upper cut-off—and the non-parametric binned spin model with isotropic alignments. Model A has been calculated both including and excluding GW170729, allowing exploration of the result's sensitivity to the mass distribution. For our default model, we include GW170729 when calculating the probability that it is a first-generation merger (all 10 binary black holes are first-generation), and exclude it when calculating the probability that it is a second-generation merger (the other 9 binary black holes are first-generation). We use an isotropic distribution of spins under the optimistic assumption that all binary black holes form dynamically in clusters and so may go on to form a new binary.

Remnant spins and masses are calculated following Healy et al. (2014). Second-generation binary black holes are formed from one merger remnant and one initial-population black hole.[2] For second-generation mergers we assume that the primary black hole is a merger product, and draw the secondary from the m_1 distribution of initial black holes.

For each generation, we fit a distribution $P(\mathcal{M}, \chi_{\rm eff}|{\rm Gen}\,N)$ over $\mathcal{M}$ and $\chi_{\rm eff}$. Since we assume isotropic spins for both generations, the probabilities are symmetric about $\chi_{\rm eff} = 0$, and we work in terms of $|\chi_{\rm eff}|$. In Figure 1, we plot the relative probability in favor of Gen 2 for different points in $\mathcal{M}$–$|\chi_{\rm eff}|$ space; higher-mass systems are more likely to be second-generation. To assess whether GW170729 is a second-generation merger, we calculate the odds ratio $P({\rm Gen}\,2|{\rm GW170729})/P({\rm Gen}\,1|{\rm GW170729})$. The second-generation versus first-generation odds ratio is

$$\frac{P({\rm Gen}\,2|{\rm GW170729})}{P({\rm Gen}\,1|{\rm GW170729})} = \frac{P({\rm Gen}\,2)}{P({\rm Gen}\,1)} \left[\frac{\int P({\rm GW170729}|\mathcal{M}, \chi_{\rm eff})P(\mathcal{M}, \chi_{\rm eff}|{\rm Gen}\,2)\,{\rm d}\mathcal{M}\,{\rm d}\chi_{\rm eff}}{\int P({\rm GW170729}|\mathcal{M}, \chi_{\rm eff})P(\mathcal{M}, \chi_{\rm eff}|{\rm Gen}\,1)\,{\rm d}\mathcal{M}\,{\rm d}\chi_{\rm eff}} \right]. \tag{1}$$

Here, $P({\rm Gen\,N})$ are prior probabilities for each generation, and $P({\rm GW170729}|\mathcal{M}, \chi_{\rm eff})$ is the likelihood of the observed gravitational-wave signal given the parameters, obtained by dividing the posterior from Abbott et al. (2019a) by the priors used in that analysis. If first- and second-generation mergers occur at equal rates, then the odds ratio is given by the term in square brackets—the Bayes factor.

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[2] We neglect the probability of forming binary black holes from two merger products.

3. RESULTS & DISCUSSION

Using the parameters inferred for GW170729 with the `SEOBNRv3` (`IMRPhenomPv2`) waveform and our default population model, the estimated Bayes factor is ~ 7 (~ 6). Both the `SEOBNRv3` (Pan et al. 2014; Taracchini et al. 2014) and `IMRPhenomPv2` (Hannam et al. 2014; Khan et al. 2016) waveforms include spin-precession effects, but do not include non-quadrupolar modes; the effect of these (including an independent calculation of the second-generation merger probability) are investigated in Chatziioannou et al. (2019). Calculating both first- and second-generation probabilities using Model A-excluding-GW170729 gives ~ 16 (~ 11), and using Model A-including-GW170729 gives ~ 7 (~ 6).[3] Excluding GW170729 gives the highest Bayes factor—the result is sensitive to the upper mass cut-off, and we have selected to exclude the most massive of the observed 10 binary black holes from the population. Therefore, it was expected to favor second-generation mergers in this case. Overall, our results moderately favor GW170729 as a second-generation merger. However, adopting a relative prior $P(\mathrm{Gen}\,2)/P(\mathrm{Gen}\,1) \lesssim 0.2$ (Rodriguez et al. 2019) results in marginally favoring second-generation or favoring a first-generation merger. Including the presence of binary black holes merging in the field, which will not undergo multiple mergers, further decreases the probability of a second-generation origin.

In conclusion, we find little evidence that GW170729, despite its mass and spin, is the result of a second-generation merger. Results are sensitive to the mass distribution, and in particular the upper mass cut-off; a better understanding of the first-generation population will make it easier to identify second-generation mergers.

Software: `matplotlib` (Hunter 2007)

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[3] Using other mass models from Abbott et al. (2019b), `SEOBNRv3` (`IMRPhenomPv2`) Bayes factors for Models B and C—which both include GW170729—are ~ 4 (~ 3) and ~ 0.2 (~ 0.2), respectively.