Draft version March 14, 2019
Typeset using LaTeX **RNAAS** style in AASTeX62

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] *CIERA, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA*

Keywords: black hole physics — gravitational waves — stars: black hole

LIGO–Virgo (Aasi et al. 2015; Acernese et al. 2015) have observed gravitational waves from 10 binary black holes (BBHs) (Abbott et al. 2018b). Of these, GW170729's source stands out as (probably) the most massive system with the highest effective-inspiral-spin $\chi_{\rm eff}$. With a total mass of $M = 85.1^{+15.6}_{-10.9} M_\odot$ and a chirp-mass of $\mathcal{M} = 35.7^{+6.5}_{-4.7} M_\odot$, the primary-component mass $m_1 = 50.6^{+16.6}_{-10.2} M_\odot$ encroaches on the hypothesised (pulsational) pair-instability supernovae mass-gap (Woosley 2017). Its $\chi_{\rm eff} = 0.36^{+0.21}_{-0.25}$ makes it one of two observations for which a non-spinning component is excluded at 90% probability. Given GW170729's exceptional properties, it's natural to ask if it formed through a different channel.

Hierarchical mergers—wherein at least one of the components is the product of a BBH 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 (BHs), 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. (2018a) and parameter posterior distributions from Abbott et al. (2018b), we show that—even under the generous assumption that *all* BBH mergers occur in dense clusters—there is not strong evidence that GW170729 is the result of a hierarchical merger.

We form an initial (Gen 1) BBH population, drawing masses and spins from the posterior population distributions inferred from gravitational-wave observations (Abbott et al. 2018a). 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's a first-generation merger (all 10 BBH are first-generation), and exclude it when calculating the probability that it's a second-generation merger (the other 9 BBHs are first-generation). We use an isotropic distribution of spins under the optimistic assumption that all BBHs 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 BBHs are formed from one merger remnant and one initial-population BH.[1] For second-generation mergers we assume that the primary BH is a merger product, and draw the secondary from the m_1 distribution of initial BHs.

For each generation, we fit a distribution $P(\mathcal{M}, \chi_{\rm eff}|\text{Gen } N)$ 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 (OR) $P(\text{Gen 2}|\text{GW170729})/P(\text{Gen 1}|\text{GW170729})$. The second-generation versus first-generation OR is

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

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

[1] We neglect the probability of forming BBHs from two merger products.

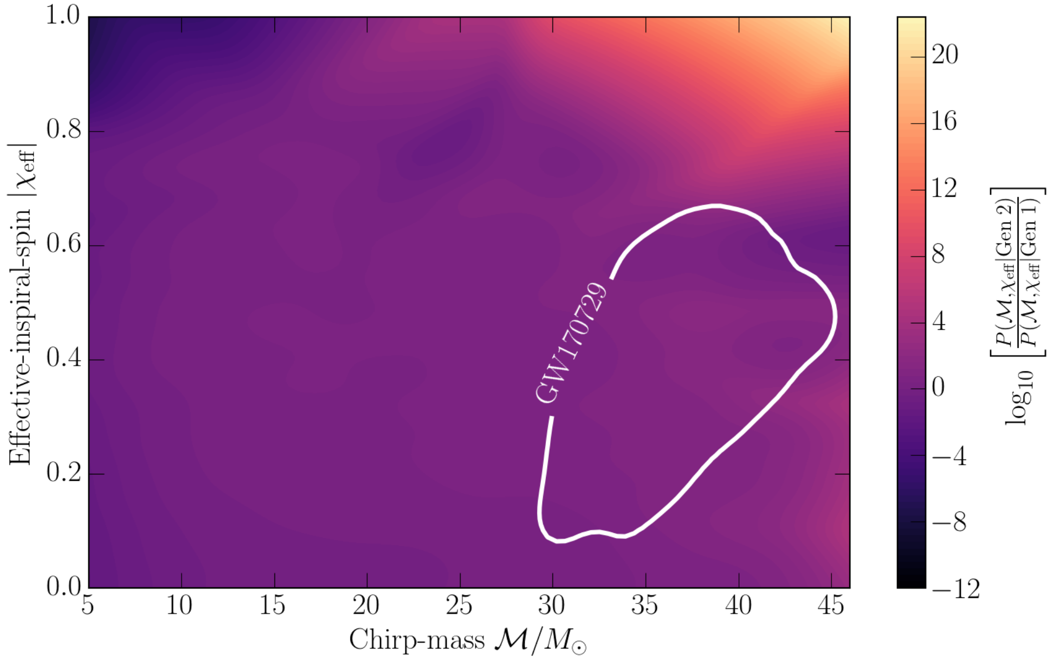

Figure 1. Relative probability of a BBH being second-generation versus first-generation as a function of chirp-mass $\mathcal{M}$ and the magnitude of the effective-inspiral-spin $|\chi_{\mathrm{eff}}|$. For comparison, the white contour gives the 90% credible area for GW170729 (Abbott et al. 2018a).

Here, $P(\mathrm{Gen\,N})$ are prior probabilities for each generation, and $P(\mathrm{GW170729}|\mathcal{M},\chi_{\mathrm{eff}})$ is the likelihood of the observed gravitational-wave signal given the parameters, obtained by dividing the posterior from Abbott et al. (2018b) by the priors used in that analysis. If first- and second-generation mergers occur at equal rates, then the OR is given by the term in square brackets—the Bayes factor (BF).

Using the parameters inferred for GW170729 with the `SEOBNRv3` (`IMRPhenomPv2`) waveform and our default population model, the estimated BF is ~ 8 (~ 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 on the probability of a second-generation merger) are investigated in Chatziioannou et al. (2019). Calculating both first- and second-generation probabilities using Model A-excluding-GW170729 gives ~ 17 (~ 13), and using Model A-including-GW170729 gives ~ 8 (~ 6).[2] Excluding GW170729 gives the highest BF—the result is sensitive to the upper mass cut-off, and we have selected to exclude the most massive of the observed 10 BBHs from the population. Therefore, it was expected to favor second-generation mergers in this case. Overall, our results are moderate favoring 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. 2018b,a) results in marginally favoring second-generation or favoring a first-generation merger. Including the presence of BBHs 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.

[2] Using other mass models from Abbott et al. (2018a), `SEOBNRv3` (`IMRPhenomPv2`) BFs for Models B and C—which both include GW170729—are ~ 3 (~ 2) and ~ 0.3 (~ 0.2), respectively.

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