Evidence for hierarchical black hole mergers in the second LIGO–Virgo gravitational-wave catalog

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ABSTRACT

We study the population properties of merging binary black holes in the second LIGO–Virgo Gravitational-Wave Transient Catalog, assuming they are all forming dynamically in gravitationally bound clusters. Using a phenomenological population model, we infer the mass and spin distribution of first-generation black holes, while searching for hierarchical mergers. Considering a range of cluster masses, we see compelling evidence for hierarchical mergers for clusters with escape velocities \( \gtrsim 100 \text{ km s}^{-1} \). For our highest-likelihood cluster mass, we find that at least one catalog binary contains a second-generation black hole with \( > 0.999 \) probability, the hierarchical model is preferred over an alternative model with no hierarchical mergers (Bayes factor \( B = 25000 \)), GW190521 is favored to contain two second-generation black holes with odds \( O > 700 \), and GW190517, GW190519, GW190602, GW190620, and GW190706 are mixed-generation binaries with \( O > 10 \). However, results depend strongly on the cluster escape velocity, with more modest evidence for hierarchical mergers when the escape velocity is \( \lesssim 100 \text{ km s}^{-1} \). Assuming all binary black holes are formed dynamically in globular clusters with escape velocities on the order of tens of \( \text{km s}^{-1} \), GW190519 is favored to include a second-generation black hole with odds \( O > 1 \). In this case, we find that 99% of black holes from the inferred total population are less than \( 48 \text{M}_{\odot} \), and that this constraint is robust under our choice of prior on the maximum black hole mass.

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

1. INTRODUCTION

The second LIGO–Virgo Gravitational Wave Transient Catalog (GWTC-2) has significantly expanded our set of gravitational wave (GW) observations (Abbott et al. 2020a). It contains a total of 46 binary black holes (BBHs) candidates, excluding GW190814 (Abbott et al. 2020b) whose source could also be a neutron star–black hole binary, whereas the previous catalog only contained 10 BBHs (Abbott et al. 2019). Multiple astrophysical formation channels have been suggested to explain the population of BBHs, and each of these have uncertainties in their underlying physics (e.g., Abbott et al. 2016a; Rodriguez et al. 2016; Kruckow et al. 2016; Klencki et al. 2018; Sasaki et al. 2018; Tang et al. 2020; Tagawa et al. 2020).
GW observations can constrain the relative contribution of formation channels and their uncertain physics, and as the catalog grows these constraints become more precise (Vitale et al. 2017; Stevenson et al. 2017; Talbot & Thrane 2017; Zevin et al. 2017; Barrett et al. 2018; Fishbach et al. 2018).

Amongst the GWTC-2 systems there are high-mass BBHs which have components with masses of $\gtrsim 45M_\odot$ (Abbott et al. 2020a), the most massive being the source of GW190521 (Abbott et al. 2020c). Black holes of $\sim 45-135M_\odot$ are not typically expected to form via standard stellar evolution as the pair-instability process either limits the maximum mass of the progenitor star’s core or completely disrupts the star entirely (Fryer et al. 2001; Heger & Woosley 2002; Belczynski et al. 2016; Spera & Mapelli 2017; Stevenson et al. 2019; Farmer et al. 2019, 2020). Potential (non-mutually exclusive) formation mechanisms for black holes in this mass gap include hierarchical mergers, where the remnant of a previous merger becomes part of a new binary (Miller & Hamilton 2002; Antonini & Rasio 2016; Rodriguez et al. 2019; Yang et al. 2019; Banerjee 2020; Fragione & Silk 2020; Mapelli et al. 2020a; Anagnos tou et al. 2020); stellar mergers, which may result in a larger hydrogen envelope around a core below the pair-instability threshold (Spera et al. 2018; Di Carlo et al. 2019; Kremer et al. 2020); formation of black holes from Population III stars which are able to retain their hydrogen envelopes (Farrell et al. 2020; Kinugawa et al. 2020; Vink et al. 2020), formation via stellar triples in the field (Vigna-Gómez et al. 2020), or growth via accretion in an active galactic nucleus (AGN) disk (McKernan et al. 2012; Secunda et al. 2020; Tagawa et al. 2020; Tiwari & Fairhurst 2020).

Hierarchical mergers in globular clusters were considered as an origin for GW190521 (Abbott et al. 2020d) with inconclusive results. However, hints of eccentricity in follow-up analyses of GW190521 add weight to this explanation (Romero-Shaw et al. 2020a; Gayathri et al. 2020). In order to confidently identify hierarchical mergers, it is important to study events in the context of a population model, which fits the mass distribution (and any mass cut-offs) for the first-generation (1G) black holes not formed through mergers (Kimball et al. 2020a; Doctor et al. 2019; Arca Sedda et al. 2020).

We apply the population inference framework from Kimball et al. (2020b) to analyze the BBHs from GWTC-2. This framework assumes a phenomenological population model based on simulations of metal-poor globular clusters (Rodriguez et al. 2019). Considering a fiducial set of globular cluster masses, we simultaneously infer the properties of the 1G+1G BBH population (whose remnants are 2G black holes) and the relative merger rates of hierarchical mergers. The expanded catalog enables the population parameters, including the mass distribution, to be more precisely determined (Abbott et al. 2020e). With our models, we find that several of the BBHs could be the results of hierarchical mergers: the leading candidates are GW190519 and GW190521.

In Sec. 2 we review the key components of our population inference framework; the results of this are given in Sec. 3, with additional description of the population hyperparameters in Appendix A, and we discuss our findings in Sec. 4. As the GW catalog continues to grow, we will continue to improve constraints on the astrophysical population, making now the perfect time to develop more accurate predictions for the formation of hierarchical mergers.

2. METHODS

We perform Bayesian hierarchical inference to infer the the population properties of BBHs following Kimball et al. (2020b). We employ phenomenological models for the mass and spin distributions of 1G+1G, 1G+2G, and 2G+2G BBHs merging in a dense stellar environment; see Fig. 1 and Fig. 2. The 1G+1G model is nearly identical to population models used in Abbott et al. (2020e): it is equivalent to the POWER LAW + PEAK mass model (but omits the low-mass smoothing) and is similar to the DEFAULT spin model. The DEFAULT spin model does not allow the spins of the first generation black hole to be exactly zero, we therefore add an additional zero-spin subpopulation.

The 2G black holes are assumed to be roughly twice the mass of 1G black holes; the mass ratio distribution for 1G+2G binaries is peaked around $q \approx 1/2$ while the 2G+2G distribution is similar to the 1G+1G model but with an increased preference for near equal mass binaries (Heggie et al. 1996; Sigurdsson & Phinney 1993; Downing et al. 2011). The 1G+2G and 2G+2G spin models presume that 2G black holes have dimensionless spin $\chi \approx 0.67$ inherited from the orbital angular momentum of the progenitor binary (Pretorius 2005; Buonanno et al. 2008; Gonzalez et al. 2007). The population models are described as conditional priors $\pi(\theta|\Lambda)$ where $\theta$ are the parameters of a single binary (e.g., mass and spin) while $\Lambda$ refers to the population hyperparameters describing the shape of the mass and spin distributions (e.g., the power-law index of the primary black hole mass spectrum). Our goal is to two-fold: estimate the population hyperparameters $\Lambda$ and carry out model selection to evaluate the Bayesian odds that events in GWTC-2 are formed hierarchically.
The relative rates of $1G+1G$, $1G+2G$, and $2G+2G$ mergers depend upon the masses and spins of the BBH population. GW recoil kicks may lead to remnants being ejected from a cluster; kick magnitudes are strongly dependent on progenitor spins with larger spins leading to larger kicks (Gonzalez et al. 2007; Campanelli et al. 2007; Bruegmann et al. 2008; Lousto & Zlochower 2011; Varma et al. 2019), as well as the mass ratio of the merging binary. We calculate the fraction of retained merger remnants $F_{\text{ret}}$ given the population properties of the 1G black holes and assuming a cluster described by a Plummer potential (Plummer 1911) mass of $M_c$ with Plummer radius $r_c$. For our default cluster, we assume that $M_c = 5 \times 10^5 M_\odot$ and $r_c = 1$ pc. We assume that the relative merger rates scale as $R_{1G+2G}/R_{1G+1G} \propto F_{\text{ret}}, R_{2G+2G}/R_{1G+1G} \propto F_{\text{ret}}^{3/2}$, with the constant of proportionality calibrated against globular cluster simulations (Rodriguez et al. 2019).

For our analysis, we consider the 44 BBH used in the GWTC-2 population analysis of Abbott et al. (2020e). For GWTC-1 events, we use the same single event posterior samples as Kimball et al. (2020b), for GW190412 we use samples from Zevin et al. (2020a), for the preferred samples from Abbott et al. (2020d), and for the other GWTC-2 events we use the public samples from Abbott et al. (2020a). For the new GWTC-2 events we use results calculated with the IMRPHENOMD and IMRPHENOMPy2 waveforms (Khan et al. 2016; Hannam et al. 2014). We generate posterior samples for population hyperparameters $\Lambda$ using the nested sampler dynesty (Speagle 2020) using the GWpopulation framework (Talbot et al. 2019), which takes advantage of Bilby (Ashton et al. 2019; Romero-Shaw et al. 2020b).

3. APPLICATION TO GWTC-2

3.1. Inferred populations

Applying our analysis to the 44 BBH candidates in GWTC-2 analyzed in Abbott et al. (2020e), we infer population hyperparameters for our mass and spin models (plotted in Fig. 8 and Fig. 9 in Appendix A). We find that including the $1G+2G$ and $2G+2G$ population components is favored by a Bayes factor of 7 relative to excluding the hierarchical components.

In our inferred $1G$ mass distribution, the Gaussian mass component is constrained to $\mu_m = 31.5^{+23.0}_{-9.0} M_\odot$. We recover our prior on the maximum mass cutoff $m_{\text{max}}$. In Fig. 1 and Fig. 2, we plot the posterior predictive distributions for the $1G+1G$, $1G+2G$, and $2G+2G$ populations. We find that 99% of $1G+1G$ black holes are less than $47 M_\odot$, and 99% of black holes in the total population are less than $48 M_\odot$, consistent with the results of Kimball et al. (2020b). These upper limits are lower than those found for the Power Law + Peak model in Abbott et al. (2020e), but that model does not include a high-mass hierarchical component, and requires a flatter power law to fit the heavier black holes in GWTC-2.

Relaxing the prior on the maximum mass cutoff to a uniform prior out to $100 M_\odot$ (Fig. 10 and Fig. 12), we no longer constrain $m_{\text{max}}$, but find that it peaks around $\sim 80 M_\odot$. In this case, we find that 99% of $1G+1G$ black holes are less than $49 M_\odot$, and 99% of black holes in the total population are less than $50 M_\odot$.

We find that 90% of $1G+1G$ black holes have spins less than 0.5, while the fraction $\lambda_0$ of black holes originating from the zero-spin subpopulation is constrained to be less than 0.12 at the 99% credible level, and is consistent with $\lambda_0 = 0$.

3.2. Relative merger rates

We plot the posteriors for the relative $1G+2G$ and $2G+2G$ versus $1G+1G$ merger rates, as well as for the fraction $\lambda_0$ of $1G+1G$ black holes with zero spin in Fig. 3. We infer median relative rates of $R_{1G+2G}/R_{1G+1G} = 5.3 \times 10^{-3}$ and $R_{2G+2G}/R_{1G+1G} = 1.4 \times 10^{-5}$ with 99%, upper limits of 0.04 and $9.8 \times 10^{-4}$, respectively. The median inferred relative rates are roughly twice those found using the same model in Kimball et al. (2020b), though consistent with the upper limits reported there. The results are consistent with those from Monte Carlo models of black hole populations in globular clusters. Rodriguez et al. (2019) find that the \( \approx 14\% \) of merging binary black holes in their models contain 2G black holes in the extreme case where all 1G black holes have zero spin (this fraction drops to \( \lesssim 1\% \) when they increase 1G black hole spins to $\chi = 0.5$).

3.3. Odds ratios for hierarchical origin

For each event in GWTC-2, we calculate the odds ratio $O$ in favor of hierarchical versus $1G+1G$ origin. We plot the odds ratios in favor of $2G+2G$ versus $1G+1G$ origin in Fig. 4.

We find that the probability that at least one binary in GWTC-2 contains a 2G black hole is 96%. GW190519 is marginally favored to have a $1G+2G$ origin with 1:1 odds over a $1G+1G$ origin. Meanwhile, GW190521 has roughly even odds of being $1G+2G$ versus $1G+1G$ at

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1. Posterior samples for GW190412, GW190521 and the other GWTC-2 systems are available from doi.org/10.5281/zenodo.3900546, doi.org/10.7935/1502-wj52 and doi.org/10.7935/99gf-ax93, respectively.
3.4. Varying cluster parameters
Our default Plummer model is chosen as representative of a typical globular cluster environment such as those in the Milky Way today, where central escape velocities are on the order of tens of kilometers per second (Baumgardt & Hilker 2018). However, globular clusters in the Milky Way may have been up to a few times more massive at formation than present-day (Webb & Leigh 2015). Furthermore, hierarchical mergers may occur in a wide range of dynamical environments with significantly different escape velocities, including AGN disks and nuclear star clusters. Although our phenomenological models are tuned to the results of simulations of typical present-day globular clusters (Rodriguez et al. 2019), we can get an illustrative idea of how results scale with the mass and compactness of the assumed dynamical environment by varying the parameters of our simple Plummer model. We do not expect all BBHs to come from a single type of cluster, but our results let us explore a range of different average cluster sizes.

In Fig. 5, we show results when considering models with Plummer masses $10^4–10^9M_\odot$ and radii 0.01–1 pc; both these parameters vary cluster escape velocities and thus the retention rate of hierarchical mergers. At low escape velocities ($\sim 10–50$ km s$^{-1}$), almost no 1G+1G merger products are retained and the relative 1G+2G and 2G+2G rates are negligible. In this case, the inferred posterior on the maximum black hole mass $m_{\text{max}}$ shifts upwards away from the astrophysical prior in order to accommodate massive GWTC-2 events as 1G+1G BBHs. As we move toward models with higher central escape velocities, the fraction of retained 1G+1G merger products and the relative 1G+2G and 2G+2G rates rapidly increase, and the odds ratios in favor of GWTC-2 events being of hierarchical origin grow. We find that for even a modest increase in the central escape velocity to $\sim 90$ km s$^{-1}$ leads to the conclusion that GW190521 is favored to be a 2G+2G versus 1G+1G merger at $>10:1$ odds, and that the probability that at least one of the BBHs in GWTC-2 contains a 2G black hole is $>99.99\%$.

We find that for all of our assumed cluster models, the events in GWTC-2 are better fit including the hierarchical channels than when excluding those channels (equivalent to setting $V_{\text{esc}} = 0$ km s$^{-1}$), with the highest Bayes factors corresponding to models where the central escape velocities are $\sim 300$ km s$^{-1}$. In Fig. 5, we show Bayes factors in favor of our hierarchical model versus a model with only 1G+1G BBHs; taking the ratio of these Bayes factors gives the Bayes factors comparing how well the data are supported by different cluster models. For clusters with escape velocities of $\sim 300$ km s$^{-1}$, which have the highest Bayes factors, we find that 99% of 1G+1G black holes are below 40 $M_\odot$ and that 99% of all black holes are below 66$M_\odot$. We infer median relative rates of 1G+2G and 2G+2G versus 1G+1G mergers of 0.14 and $9.2 \times 10^{-3}$, respectively, with 99% upper limits of 0.25 and 0.03. In Fig. 6 and Fig. 7 we plot the odds ratios in favor of the events in GWTC-2 being 1G+2G or 2G+2G versus 1G+1G. When $V_{\text{esc}} \sim 300$ km s$^{-1}$, we find that GW190521 is most likely of 2G+2G origin, with 700:1 odds in favor of being 2G+2G versus 1G+1G, and favoring 2G+2G over 1G+2G origin at $\sim 3.5:1$. We find that GW190517, GW190519, GW190602, GW190620, and GW190706 are most likely of 1G+2G origin, favored over 1G+1G origin at $>10:1$ odds.

4. CONCLUSIONS

GW observations have demonstrated that black holes merge to form more massive black holes (Abbott et al. 2016b). If these merger products form new binaries, they may again merge as a detectable GW source. It is necessary to consider this hierarchical merger channel when using catalogs of GW sources to make inferences about the physics of black hole formation. For example, inference of the location of the lower edge of the pair-instability mass gap, which could potentially constrain nuclear reaction rates (Farmer et al. 2020) or beyond Standard Model physics (Croon et al. 2020; Straight et al. 2020), using detections of black holes in the Hubble regime when using catalogs of GW sources to make inferences about the physics of black hole formation. For example, inference of the location of the lower edge of the pair-instability mass gap, which could potentially constrain nuclear reaction rates (Farmer et al. 2020) or beyond Standard Model physics (Croon et al. 2020; Straight et al. 2020), using detections of black holes in the $\gtrsim 50M_\odot$ regime would be contaminated by the presence of 2G black holes. In order to distinguish between 1G and 2G black holes, we must account simultaneously for the shapes of 1G and 2G populations and the relative frequencies of hierarchical mergers. Here, we apply the analysis of Kimball et al. (2020b) to 44 binary black holes in GWTC-2, and self-consistently infer a black hole population that accounts for 1G+1G, 1G+2G, and 2G+2G binary mergers, as well as the relative branching ratios between them, in order to identify candidate hierarchical mergers in the current catalog of GW sources.

We find that, assuming our nominal globular cluster model with $M_c = 5 \times 10^5M_\odot$ and $r_c = 1$ pc:

1. The 44 events in GWTC-2 are best modelled when allowing for hierarchical formation channels. We find a Bayes factor of 7 in favor of including hierarchical components.

2. At least one BBH in GWTC-2 contains a 2G black hole with 96% probability.

3. The two binaries which are most likely to contain a 2G black hole are GW190519 and GW190521. We find that both events have approximately equal odds of being 1G+2G and 1G+1G.
4. The median relative merger rates of 1G+2G and 2G+2G to 1G+1G mergers are inferred to be $5.3 \times 10^{-3}$ and $1.4 \times 10^{-5}$, with 99% upper limits of 0.04 and $9.8 \times 10^{-4}$, respectively.

5. 99% of 1G+1G black holes are below $40M_\odot$ and 99% of all black holes are below $66M_\odot$.

While we do not believe that all BBHs to come from a single type of cluster, we did consider a range of other typical cluster sizes, demonstrating that results depend upon assumed the escape velocity. For a cluster model with $M_c = 10^6 M_\odot$ and $r_c = 0.1$ pc, which has the highest Bayes factor:
1. We overwhelmingly favor models including hierarchical formation channels. We find a Bayes factor of 25000:1 in favor of including hierarchical components.

2. At least one BBH in GWTC-2 contains a 2G black hole with probability $> 99.99\%$.

3. GW190521 is most likely of 2G+2G origin, with 700:1 odds in favor of being 2G+2G versus 1G+1G, favoring 2G+2G over 1G+2G origin at $\sim 3.5:1$.

4. We find that GW190517, GW190519, GW190602, GW190620, and GW190706 are most likely of 1G+2G origin, favored over 1G+1G origin at $> 10:1$ odds.

5. The median relative merger rates of 1G+2G and 2G+2G to 1G+1G mergers are inferred to be 0.14 and $9.2 \times 10^{-3}$, with 99% upper limits of 0.25 and 0.03, respectively.

Our analysis indicates that there are plausible hierarchical merger candidates in GWTC-2, meriting further study.

There are a number of possible extensions to this analysis. Most importantly, we have assumed that all merging binaries are formed dynamically in globular clusters with a specific mass and density. While illustrative, this is unrealistic as (i) the observed BBH population may come from a mixture of formation channels including isolated field evolution, and (ii) dynamically formed binaries may occur in a wide range cluster types ranging from young open clusters to nuclear star clusters. An excess for events with aligned spin in GWTC-2 suggests that at least some binaries are assembled in the field (Abbott et al. 2020c). The potential for multiple formation channels could be accounted for by including an additional mixture model for dynamically formed binaries versus those formed in isolation (Kimball et al. 2020b). Previous analyses have suggested using the distribution of spin orientations and eccentricities to measure the fraction of binaries formed dynamically (Vitale et al. 2017; Nishizawa et al. 2016; Breivik et al. 2016; Stevenson et al. 2017; Talbot & Thrane 2017; Gondán & Kocsis 2019; Romero-Shaw et al. 2019; Abbott et al. 2020c). Relaxing the assumption that all dynamically formed binaries form in identical environments requires a model for the distribution of globular cluster properties and other dense environments, e.g., AGNs. It is possible that future GW observations will allow us to directly probe the distribution of cluster masses if we obtain sufficient observations to reconstruct the population of host environments. We leave incorporating these extensions to future work.

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APPENDIX

A. INFERRED POPULATION HYPERPARAMETERS

Here, we include the full sets of inferred population hyperparameter posteriors for our hierarchical model. The 1G+1G primary mass distribution consists of two components. The first is a truncated power law with minimum mass $m_{\text{min}}$, maximum mass $m_{\text{max}}$, and power-law index $\alpha$. The second is a Gaussian component with mean $\mu_m$ and standard deviation $\sigma_m$. The mass ratio distribution is governed by a power-law with index $\beta_q$. We draw the 1G+1G component spins from Beta distribution with shape parameters $\{\alpha_{\chi}, \beta_{\chi}\} > 1$, and allow a fraction $\lambda_0$ of the population to have spins drawn from a delta function at zero. This zero-spin subpopulation is inspired by simulations of massive stars with efficient angular momentum transfer, where black holes would be born with spins of $\sim 0.01$ (Qin et al. 2018; Fuller & Ma 2019), and may also describe primordial black holes (De Luca et al. 2020). The 1G+2G and 2G+2G mass and spin distributions are obtained using the transfer functions defined in Kimball et al. (2020b).

In Fig. 8, we plot the parameters governing the mass and mass ratio distributions. When using the astrophysically-motivated prior on $m_{\text{max}}$, a Gaussian centered at $50 M_\odot$ and standard deviation $10 M_\odot$ (Farmer et al. 2019; Mapelli et al. 2020b; van Son et al. 2020), we mostly recover this prior: we do not yet have an informative catalog to measure this within our phenomenological model. As in Kimball et al. (2020b), we find that $m_{\text{max}}$ is restricted at small values of the power-law index $\alpha$ where the mass distribution is flatter and more sensitive to the upper mass cut-off. We are able to place stronger constraints on the minimum black hole mass, finding $m_{\text{min}} < 7.0 M_\odot$ at the 99% credible level. Overall, the inferred mass distributions are largely consistent between our two spin models.

In Fig. 9, we plot the parameters governing the component spin distributions. We prefer low values of $\alpha_{\chi}$, which increases support at low component spin, but find that $\beta_{\chi}$ is unconstrained. We find that the fraction $\lambda_0$ of black holes originating from the zero-spin subpopulation (plotted in Fig. 3) is constrained to be less than 0.06 (0.12) at the 90% (99%) credible level, and is consistent with $\lambda_0 = 0$.

We plot the posteriors for the population hyperparameters governing the mass distributions inferred when we assume a flat prior on $m_{\text{max}}$ in Fig. 10. Using the flat prior on $m_{\text{max}}$, we no longer constrain the maximum mass cutoff, and the posterior peaks at around $\sim 80 M_\odot$. We constrain the mean of the Gaussian component to be $\mu_m = 31.6^{+4.5}_{-7.3} M_\odot$. The preference for high $m_{\text{max}}$ means that the high-mass tail on $\mu_m$ is no longer required to fit the more massive events in GWTC-2, even though the relative 1G+2G and 2G+2G versus 1G+1G merger rates (as well as the events-wise odds of hierarchical merger) drop by an order of magnitude under the flat prior on $m_{\text{max}}$. We plot the posteriors over the relative merger rates and fraction of black holes formed in the zero-spin subpopulation in Fig. 11.

In Fig. 12, we plot the posteriors of the population hyperparameters governing the component spin distributions inferred when we assume a flat prior on $m_{\text{max}}$. We find that the inferred spin distributions are consistent across choices of prior on $m_{\text{max}}$. We find that the fraction $\lambda_0$ of black holes originating from the zero-spin subpopulation is constrained to be less than 0.04 (0.09) at the 90% (99%) credible level, and is still consistent with $\lambda_0 = 0$. $\alpha_{\chi}$ and $\beta_{\chi}$ are less constrained, as when we allow high values for $m_{\text{max}}$ it easier to explain higher mass systems as 1G+1G, and hence we do not require a low-spin population to enable high relative hierarchical merger rates.
Figure 8. Posterior distributions of the population hyperparameters governing the mass and mass ratio distributions. The dashed lines give the 90% credible intervals, and the green lines indicate the priors.
Figure 9. Posterior distributions of the population hyperparameters governing the component spin distributions. The dashed lines give the 90% credible intervals.
Figure 10. Posterior distributions of the population hyperparameters governing the mass and mass ratio distributions when we assume a flat prior on \( m_{\text{max}} \). The dashed lines give the 90% credible intervals, and the green lines indicate the priors.
Figure 11. Posteriors of the inferred branching ratios, and the fraction \( \lambda_0 \) of 1G+1G BBHs with zero spin, when we assume a flat prior on \( m_{\text{max}} \). The branching ratios give the relative 1G+2G versus 1G+1G and 2G+2G versus 1G+1G merger rates.

Figure 12. Posterior distributions of the population hyperparameters governing the component spin distributions when we assume a flat prior on \( m_{\text{max}} \). The dashed lines give the 90% credible intervals.