

Population properties of compact objects from the second LIGO–Virgo Gravitational-Wave Transient Catalog

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ABSTRACT

We report on the population properties of the 47 compact binary mergers detected with a false-alarm rate (FAR) $< 1 \text{ yr}^{-1}$ in GWTC-2, including all Advanced LIGO–Virgo observing runs through the most recent observing run O3a. We investigate the mass distribution, spin distribution, and merger rate as a function of redshift. We observe several binary black hole (BBH) population characteristics not discernible until now. First, we find that the primary mass spectrum contains structure beyond a power-law distribution with a sharp high-mass cut-off; it is more consistent with a *broken* power law with a break at $39.7_{-9.1}^{+20.3} M_{\odot}$, or a power law with a Gaussian feature peaking at $33.5_{-5.5}^{+4.5} M_{\odot}$ (90% credible interval). While the primary mass distribution must extend to $\sim 65 M_{\odot}$ or beyond, only $2.9_{-1.7}^{+3.4}\%$ of systems have primary masses greater than $45 M_{\odot}$. At low masses, we find that the primary mass spectrum has a global maximum at $7.8_{-2.1}^{+2.2} M_{\odot}$, consistent with a gap between $\sim 2.6 M_{\odot}$ and $\sim 6 M_{\odot}$. Second, we find evidence that a nonzero fraction of BBH systems have component spins misaligned with the orbital angular momentum, giving rise to precession of the orbital plane. Moreover, we infer that 12% to 44% of BBH systems have spins tilted by more than 90° with respect to their orbital angular momentum, giving rise to a negative effective inspiral spin parameter. Third, we provide improved estimates for merger rates using astrophysically motivated mass distributions: for BBH, $\mathcal{R}_{\text{BBH}} = 23.9_{-8.6}^{+14.9} \text{ Gpc}^{-3} \text{ yr}^{-1}$ and for binary neutron stars (BNS), $\mathcal{R}_{\text{BNS}} = 320_{-240}^{+490} \text{ Gpc}^{-3} \text{ yr}^{-1}$. We constrain the BBH merger rate as a function of redshift and find that the rate likely increases with redshift (85% credibility), but not faster than the star-formation rate (87% credibility). Additionally, we examine recent exceptional events in the context of our population models, finding that the asymmetric masses of GW190412 and the high component masses of GW190521 are consistent with our population models, but the low secondary mass of GW190814 makes it an outlier. We discuss the implications of these results for compact binary formation and for the evolution of massive stars.

Keywords: gravitational waves

1. INTRODUCTION

We analyze the population properties of black holes and neutron stars in compact binary systems using data from the LIGO–Virgo Gravitational-wave Transient Catalog 2 (GWTC-2) (Abbott et al. 2020d). The GWTC-2 catalog combines observations from the first two observing runs (O1 and O2) (Abbott et al. 2019b) and the first half of the third observing run (O3a) (Abbott et al. 2020d) of the Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2015) gravitational-wave observatories. With the 39 additional candidates from O3a, we have more than quadrupled the number of events

from O1 and O2, published in the first LIGO–Virgo Transient Catalog, GWTC-1 (Abbott et al. 2019b). Counting only events with false alarm rate (FAR) $< 1 \text{ yr}^{-1}$ (as opposed to the less conservative FAR threshold of $< 2 \text{ yr}^{-1}$ in GWTC-2), the new combined catalog includes: two binary neutron star (BNS) events, 44 confident binary black hole (BBH) events, and one neutron-star black hole (NSBH) candidate, which may be a BBH—a topic we discuss below. These events are listed in Table 1. Our chosen FAR threshold ensures a relatively pure sample with only ~ 1 noise event (see Section 2) and excludes three marginal triggers presented in GWTC-

2. Two of these excluded events are BBH candidates (GW190719_215514 and GW190909_114149) and one is an NSBH candidate (GW190426_152155).

The latest observations include a number of individually remarkable events, which invite theoretical speculation while providing challenges to existing models. The observation of high-mass binaries such as GW190521 (Abbott et al. 2020e), which has a primary mass $m_1 \sim 85 M_\odot$, is in tension with the sharp mass cutoff $m_{\max} = 40.8_{-4.4}^{+11.8} M_\odot$ inferred from the GWTC-1 detections, forcing us to reconsider models for the distribution of black hole (BH) masses in binary systems (Abbott et al. 2020e,f). Here and in the following, the primary mass m_1 refers to the bigger of the two component masses in the binary, while the secondary mass m_2 refers to the smaller of the two. Along with GW190521, GW190602_175927 and GW190519_153544 also have primary masses above $45 M_\odot$ at $> 99\%$ credibility. These high-mass binaries are interesting from a theoretical perspective since they occur in the predicted pair-instability gap (Barkat et al. 1967; Fowler & Hoyle 1964; Heger & Woosley 2002; Heger et al. 2003; Woosley & Heger 2015; Belczynski et al. 2016). Furthermore, GWTC-2 includes the first systems with confidently asymmetric component masses, including GW190412 with mass ratio $m_2/m_1 \equiv q = 0.28_{-0.06}^{+0.12}$ (Abbott et al. 2020b) and GW190814 (Abbott et al. 2020c), with $q = 0.112_{-0.009}^{+0.008}$. Furthermore, the secondary mass of GW190814, $m_2 = 2.59_{-0.09}^{+0.08} M_\odot$, is near the purported neutron-star – black-hole gap (Bailyn et al. 1998; Özel et al. 2011; Farr et al. 2011), posing a challenge to our understanding of binary formation (Abbott et al. 2020c; Zevin et al. 2020; Mandel et al. 2020). We can gain insight into these exceptional events by studying them in the context of the larger population of compact binaries (Fishbach et al. 2020b).

In particular, studying the enlarged population of BBH events enables us to investigate how compact binaries form. Several evolutionary channels have been proposed to explain the origin of the compact binary mergers observed with Advanced LIGO and Advanced Virgo. The isolated binary channel may occur via common envelope evolution (e.g. Bethe & Brown 1998; Portegies Zwart & Yungelson 1998; Belczynski et al. 2002; Dominik et al. 2015), the remnants of Population III stars (e.g., Madau & Rees 2001; Inayoshi et al. 2017), or chemically homogeneous stellar evolution (e.g., Marchant et al. 2016; de Mink & Mandel 2016; Mandel & de Mink 2016). Evolution via common envelope predicts BBH systems with component masses up to $\sim 50 M_\odot$, mass ratios in the range $0.3 \lesssim q < 1$, and nearly aligned spins (Kalogera 2000; Mandel & O’Shaughnessy 2010; Dominik et al.

2013; Giacobbo et al. 2017; Eldridge et al. 2017; Olejak et al. 2020).

In the chemically homogeneous scenario, BBH systems are expected to form with nearly equal mass components, in addition to aligned spins and component masses in the range $\sim 20\text{--}50 M_\odot$. In isolated formation scenarios, component black holes form via stellar collapse, and are thus not expected to occur within the pair-instability mass gap, $\sim 50\text{--}120 M_\odot$, but may populate either side of the gap.

Alternatively, BBH mergers could form via dynamical interactions in young stellar clusters, globular clusters, or nuclear star clusters (e.g., Portegies Zwart & McMillan 2000; Kulkarni et al. 1993; Sigurdsson & Hernquist 1993), triple systems (e.g. Antonini et al. 2014; Kimpson et al. 2016; Antonini et al. 2017) or the disks of active galactic nuclei (e.g. McKernan et al. 2012; Bartos et al. 2017; Stone et al. 2017). Dynamical formation in dense stellar clusters typically produces an isotropic distribution of spin directions (e.g. Vitale et al. 2017b; Rodriguez et al. 2016), and may enable hierarchical mergers characterized by relatively high-mass binaries (e.g. Antonini & Rasio 2016; Mapelli 2016; McKernan et al. 2018; Rodriguez et al. 2018) and large black hole spins (Fishbach et al. 2017; Gerosa & Berti 2017). Finally, BBH systems might originate as part of a primordial black hole population in the early Universe (Carr & Hawking 1974; Carr et al. 2016). Most primordial black hole models predict low spins and isotropic spin orientation.

Before we continue, we summarize key questions addressed in the previous analysis of GWTC-1 data (Abbott et al. 2019a) and how the inclusion of O3a events affects our findings:

1. *Are there BBH systems with component masses $\gtrsim 45 M_\odot$?* Following O1 and O2, we inferred that 99% of BBH systems have primary mass below $m_{99\%} \approx 45 M_\odot$. Moreover, this limit was consistent with a sharp cutoff at $m_{\max} = 40.8_{-4.4}^{+11.8} M_\odot$, hypothesized to correspond to the lower edge of the pair-instability mass gap expected from supernova theory (Woosley & Heger 2015; Heger & Woosley 2002; Heger et al. 2003; Fishbach & Holz 2017; Talbot & Thrane 2018). While the GWTC-2 events remain consistent with $97.1_{-3.4}^{+1.7} \%$ of BBH systems having primary masses below $45 M_\odot$ (inferred using the the POWER LAW + PEAK mass model described in Section 3, or “Model C” from Abbott et al. 2019a), high-mass detections such as GW190521, GW190602_175927 and GW190519_153544 imply a non-zero rate of BBH mergers beyond the $\sim 45 M_\odot$ mass limit. We infer that the merger rate for systems with primary masses in the range

$45 M_{\odot} < m_1 < 100 M_{\odot}$ is $0.71_{-0.37}^{+0.65} \text{ Gpc}^{-3} \text{ yr}^{-1}$, consistent with estimates inferred from GWTC-1 (Fishbach et al. 2020b).

2. *Is there a preference for nearly equal component masses?* All of the GWTC-1 observations are consistent with equal-mass binaries, with mass ratios $q \equiv m_2/m_1 = 1$. In O3a, however, we detected two events with mass ratios bounded confidently away from unity: GW190814 and GW190412, though, most binaries are consistent with equal-mass. (The NSBH candidate GW190426_152155, if real, also has unequal component masses $q = 0.26_{-0.15}^{+0.41}$, but is above the FAR threshold for this work.)
3. *Does the merger rate evolve with redshift?* From GWTC-1 we inferred that the BBH merger rate is $53.2_{-28.2}^{+55.8} \text{ Gpc}^{-3} \text{ yr}^{-1}$, assuming a rate density that is uniform in comoving volume. Allowing for a rate that evolves with redshift (Fishbach et al. 2018), we found that the local merger rate is $\mathcal{R}_{\text{BBH}}(z = 0) = 19.7_{-15.9}^{+57.3} \text{ Gpc}^{-3} \text{ yr}^{-1}$, and that, while still consistent with a uniform-in-comoving volume model, the rate density is likely increasing with redshift with 93% credibility (Abbott et al. 2019a). With GWTC-2, we are able to more tightly bound the BBH merger rate at $\mathcal{R}_{\text{BBH}} = 23.9_{-8.6}^{+14.9} \text{ Gpc}^{-3} \text{ yr}^{-1}$ (assuming the POWER LAW + PEAK mass model), as well as its evolution with redshift. The data remain consistent with a merger rate that does not evolve with redshift, but prefer a rate that increases with redshift (85% credibility). Using the POWER LAW redshift evolution model of Section 3, we find that the merger rate evolves slower than the naive expectation of $(1+z)^{2.7}$ from the star formation rate (SFR, Madau & Dickinson 2014) at 87% credibility.
4. *How fast do black holes spin?* From GWTC-1, we inferred that the black hole spin component aligned with the orbital angular momentum is typically small (Abbott et al. 2016a; Farr et al. 2017; Farr et al. 2018; Tiwari et al. 2018; Abbott et al. 2019a; Wysocki et al. 2019a; Miller et al. 2020; Roulet & Zaldarriaga 2019; Roulet et al. 2020); GW151226 is the only event to exhibit unambiguous signs of spin (Abbott et al. 2016b; Vitale et al. 2017a). We were unable to determine if this typical smallness was because the spin vectors are misaligned, because the spin magnitudes are small, or both, although the GWTC-1 data weakly disfavors the scenario in which all spins are perfectly aligned (Farr et al. 2017; Tiwari et al. 2018; Abbott et al. 2019a; Biscoveanu et al. 2020). With

additional data, we can now say confidently that some BBH systems have spins misaligned with the orbital angular momentum. A nonzero fraction of systems have measurable in-plane spin components, leading them to undergo precession of the orbital plane. Additionally, 12% to 44% of BBH systems merge with a negative effective inspiral spin χ_{eff} (see Eq. (5) below), implying that some component spins are tilted by more than 90° relative to the orbital angular momentum axis. We refer to spins tilted more than 90° as “anti-aligned spins.”¹ While some events identified in O3a have individually measurable nonzero spin, they occur infrequently, consistent with our previous estimates. We identify nine out of 44 BBH events in GWTC-2 with a positive effective aligned spin that excludes zero at greater than 95% credibility.² These nine events include both massive BBH systems like GW190519_153544, with a source-frame primary mass $m_1 = 64.5_{-13.2}^{+11.3} M_{\odot}$ (90% credibility, uniform in detector-frame mass prior) and comparatively lighter BBH systems like GW190728_064510, with $m_1 = 12.2_{-2.2}^{+7.1} M_{\odot}$. No individual BBH events are observed with confidently negative effective aligned spin.

5. *What is the minimum black hole mass?* Using GWTC-1, we previously inferred that, if there is a low-mass cut-off in the BBH mass spectrum, it is somewhere below $9M_{\odot}$ (Abbott et al. 2019a). With GWTC-2, we tighten the constraints on the minimum black hole mass in a BBH system, finding $m_{\text{min}} < 6.6 M_{\odot}$ (90% credibility). Furthermore, we find that if the black hole mass spectrum extends down to $3 M_{\odot}$, it likely turns over at $\sim 7.8_{-2.1}^{+2.2} M_{\odot}$. This suggests that there may be a dearth of systems between NS and black hole masses (Fishbach et al. 2020a). However, the O3a observation of GW190814 (Abbott et al. 2020c), with a secondary mass $m_2 = 2.59_{-0.09}^{+0.08} M_{\odot}$, complicates this picture. If the secondary mass is a BH, it would indicate that the black hole mass spectrum extends below $3 M_{\odot}$, to much lower masses than exhibited by the Galactic black hole population (Bailyn et al. 1998; Özel et al. 2011; Farr et al. 2011, but see also Kreidberg et al. 2012). Alternatively, the secondary

¹ We stress that our definition of “anti-aligned” does not imply *perfect* anti-alignment (tilt angles of exactly 180°) as the phrase is sometimes used to mean in the context of numerical relativity.

² This result is obtained using a prior informed by the full population of GWTC-2 events. In particular, we employ the GAUSSIAN model described in Section 3.

object in GW190814 could be an NS. Although, unless it were significantly spinning, this may be in tension with constraints in the NS maximum mass (Abbott et al. 2020c; Most et al. 2020; Tan et al. 2020; Essick & Landry 2020; Tews et al. 2020; Zhang & Li 2020). Either way, we find that GW190814 is an outlier with respect to the BBH population and the models we consider in this work. Unless stated otherwise, when presenting results on the BBH population, we exclude GW190814.

The remainder of this paper is organized as follows. In Section 2 we describe the data used in this study and detail how we select events for analysis. In Section 3, we provide a high-level overview of our models for the distributions of binary mass, spins, and redshift. In Section 4, we describe the hierarchical method used to fit population models to data. In Section 5, we present key results and discuss the astrophysical implications. Concluding remarks are provided in Section 6. The Appendix provides detailed descriptions of models (Appendix B, D, E), outlier analyses and model checking (Appendix C), and other supplementary material, including a discussion of gravitational lensing (Appendix F).

2. DATA AND EVENT SELECTION

Searches for gravitational wave transients in the O3a data identified 39 candidate events with false alarm rate (FAR) below 2 yr^{-1} (Abbott et al. 2020d). The event list was collated by combining results from several pipelines searching for compact binary mergers using archival data. The search pipelines include `GstLAL` (Sachdev et al. 2019; Hanna et al. 2020; Messick et al. 2017) and `PyCBC` (Nitz et al. 2019a; Allen et al. 2012; Allen 2005; Canton et al. 2014; Usman et al. 2016; Nitz et al. 2017), which use template-based matched filtering techniques, and `cWB` (Klimenko & Mitselmakher 2004; Klimenko et al. 2016), which uses a wavelet-based search that does not assume a physically parameterized signal model. These pipelines, along with two additional pipelines, `MBTA` (Adams et al. 2016), and `SPIIR` (Chu 2017), recovered most of the event candidates in low-latency.

For the population studies presented here, the event list is further restricted to the 36 events with $\text{FAR} < 1 \text{ yr}^{-1}$ as a means to increase the purity of the sample. This FAR threshold excludes the lower-significance triggers GW190426 (a potential NSBH or BBH candidate), GW190719, and GW190909 that appear in Abbott et al. (2020d). At this FAR threshold, we expect ~ 1 noise

event, and therefore a contamination fraction of $\lesssim 3\%$.³ In this work we assume that all of the event candidates that meet this FAR threshold are of astrophysical origin. For the population analysis of the GWTC-1 BBH events, the selection criteria used for inclusion in the study is the FAR and the probability p_{astro} that the source is of astrophysical origin. This value was only computed for BBHs with $\text{FAR} < 2 \text{ yr}^{-1}$ in Abbott et al. (2020d), so we simplify our criterion to only select on FAR. We note that the set of GWTC-1 events that pass this FAR threshold is identical to the previous set chosen by FAR and p_{astro} . Therefore, while the selection criteria here are different from our GWTC-1 analysis, the analyzed events are consistent.

In addition to the 36 events from O3a which passed the FAR threshold, the 11 detections presented in GWTC-1 (Abbott et al. 2019b) are also included in the event list used here to infer properties of the underlying population. All 47 events used in this analysis are tabulated in Table 1. Of these systems, 44 have both masses confidently in the black hole mass range, with $m_1 \geq m_2 > 3 M_{\odot}$. Unless stated otherwise, we restrict BBH population results to these 44 (see also Appendix C.3). Since our statistical framework relies on accurately quantifying the selection effects of our search, we only include events identified in GWTC-2, for which we have measured the search sensitivity; see Appendix A. In particular, the event list does not include candidates identified by independent analyses (Zackay et al. 2020; Venumadhav et al. 2020, 2019; Zackay et al. 2019; Nitz et al. 2019b, 2020; Magee et al. 2019) of the publicly released LIGO and Virgo data (Abbott et al. 2019c; Trovato 2020). Galaudage et al. (2019) and Roulet et al. (2020) suggest that our results are unlikely to change significantly with the inclusion of these events, and in the future it may be possible to include events from independent groups using a unified framework for the calculation of significance (Ashton & Thrane 2020; Pratten & Vecchio 2020; Roulet et al. 2020).

Parameter estimation results for each candidate event (Abbott et al. 2020d) were obtained using the `LALInference` (Veitch et al. 2015; LIGO Scientific Collaboration 2018), `RIFT` (Lange et al. 2018; Wysocki et al. 2019b), and `Bilby` (Ashton et al. 2019; Romero-Shaw et al. 2020) pipelines, the latter employing the `dynesty` nested sampling tool (Speagle 2020). The parameter estimation pipelines use Bayesian sampling methods to produce fair draws from the posterior distribution function of the source parameters, conditioned on the

³ In this estimate, we do not include a trial factor penalty for the fact that we look for candidates with multiple pipelines.

data and given a models for the signal and noise (Abbott et al. 2016c).

For the BBH events previously published in GWTC-1, we use the published posterior samples inferred using the IMRPHENOMPv2 (Hannam et al. 2014; Khan et al. 2016; Husa et al. 2016; Bohé et al. 2016) and SEOBNRv3 (Pan et al. 2014; Taracchini et al. 2014; Babak et al. 2017) waveform models. For the new BBH events of GWTC-2, we use waveform approximants that include higher-order multipole content, including the IMRPHENOMPv3HM (Khan et al. 2020), NRSUR7DQ4 (Varma et al. 2019) and SEOBNRv4PHM (Bohé et al. 2017; Ossokine et al. 2020). Note that for all events, we average over these waveform families, in contrast to our previously published parameter estimation results for GW190521, which highlighted results from one waveform, NRSUR7DQ4 (Abbott et al. 2020e). A more complete description of the parameter estimation methods and waveform models used can be found in Section V of Abbott et al. (2020d).

3. POPULATION MODELS

In this section, we provide a high-level overview of the different population models used in this paper. Each model is given a nickname indicated in boldface. There are three categories of models: models for the shape of the mass distribution (Section 3.1), models for the spin distribution (Section 3.2), and models for the redshift distribution (Section 3.3). Readers interested in the astrophysical results may wish to skip ahead to Section 5. In Fig. 1, we provide graphical representations of each mass model described below. Additional details about each model are provided in Appendix B, including their mathematical definitions, lists of hyper-parameters, and their associated prior distributions.

3.1. Black hole mass distribution

- **TRUNCATED** (4 parameters; Appendix B.1). Our simplest mass model, the distribution of primary masses is a power-law with hard cut-offs at both low (m_{\min}) and high (m_{\max}) masses. The high-mass cut-off corresponds to the lower edge of the theorized pair-instability gap in the black hole mass spectrum (Woosley & Heger 2015; Heger & Woosley 2002; Heger et al. 2003). The mass ratio distribution is also assumed to be a power law (Kovetz et al. 2017; Fishbach & Holz 2017). In Abbott et al. (2019a), it is referred to as “Model B.” This model struggles to accommodate high-mass events like GW190521, necessitating more complicated models.

- **POWER LAW + PEAK** (8 parameters; Appendix B.2). Similar to the TRUNCATED model, but with two modifications. At low masses we implement a smoothing function to avoid a hard cut-off. At high masses, we include a Gaussian peak, initially introduced to model a pile-up from pulsational pair instability supernovae (PPSN) (Talbot & Thrane 2018). This model is better able to accommodate the high-mass events that pose a challenge for the TRUNCATED model. In Abbott et al. (2019a), it is referred to as “Model C.”
- **BROKEN POWER LAW** (7 parameters; Appendix B.3). The same as TRUNCATED except, instead of a single power-law between m_{\min} and m_{\max} , the model allows for a break in the power-law at some mass m_{break} . This model includes the low-mass smoothing function used in the POWER LAW + PEAK model. The high mass feature m_{break} may correspond to the onset of pair-instability, and the second power-law can be thought of as either a gradual tapering off, or a subpopulation of black holes within the pair-instability mass gap. This model accommodates the high-mass events that pose a challenge for the TRUNCATED while providing an alternative to the POWER LAW + PEAK model.
- **MULTI PEAK** (11 parameters; Appendix B.4). This phenomenological model is similar to POWER LAW + PEAK except we allow for two peaks. The resulting mass distribution can accommodate hierarchical BBH mergers (Miller & Hamilton 2002b; Gültekin et al. 2004; Antonini & Rasio 2016; Rodriguez et al. 2019), in which second-generation mergers create a second high-mass peak in the black hole mass spectrum. We use this model to test if GWTC-2 exhibits evidence for hierarchical mergers.

3.2. Spin Distribution

- **DEFAULT** (4 parameters; Appendix D.1). This parameterization for the component black hole spin magnitudes and tilts was previously used to explore the spin distribution of compact binaries in GWTC-1 (Abbott et al. 2019a). The spin of each component black hole in a binary is assumed to be independently drawn from the same underlying distribution. The dimensionless spin magnitude is described using a beta distribution as in Wysocki et al. (2019a). The spin tilt distribution from Talbot & Thrane (2017) is a mixture model comprising

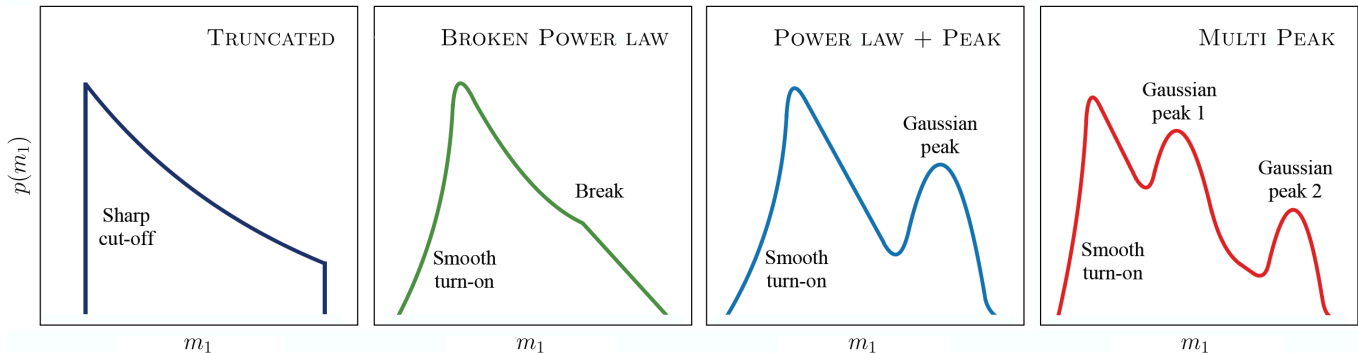


Figure 1. Graphical representations of the various mass distributions described in Section 3.1. MULTI SPIN, a model of both mass and spin, is similar to the mass distribution of POWER LAW + PEAK, with a sharp lower mass cutoff rather than the smooth low mass turn-on.

two components: an isotropic component designed to model dynamically assembled binaries, and a second component in which the spins are preferentially aligned with the orbital angular momentum, as expected for isolated field binaries.⁴ For this latter component, the spin tilt angles are distributed as a truncated Gaussian peaking when the black hole spin is aligned to the orbital angular momentum. We use this model in concert with the mass models described above.

- **GAUSSIAN** (5 parameters; Appendix D.2). While the DEFAULT spin model is physically inspired, this model, based on that of Miller et al. (2020), allows us to fit the distribution of phenomenological spin parameters χ_{eff} (“the effective inspiral spin parameter,” Eq. 5) and χ_p (“the precession spin parameter,” Eq. 6), assuming that their distribution is jointly described as a bivariate Gaussian. The ensemble properties of χ_{eff} and χ_p allow us to conclude that the BBHs in GWTC-2 exhibit general relativistic spin-induced precession of the orbital plane ($\chi_p > 0$), and that some systems have component spins misaligned by more than 90° ($\chi_{\text{eff}} < 0$) relative to their orbital angular momentum.
- **MULTI SPIN** (12 spin parameters, 10 mass parameters; Appendix D.3). This model allows for multiple subpopulations of BBH systems with distinct mass and spin distributions. Specifically, this model assumes a TRUNCATED power-law mass distribution with the additional presence of a 2-D

Gaussian subpopulation in m_1 and m_2 , truncated such that $m_1 \geq m_2$. While similar to the POWER LAW + PEAK mass model, there is no smooth turn on and the mass ratio distribution is allowed to differ between each subpopulation. Most importantly, the two subpopulations have independently parameterized DEFAULT spin distributions. We use this model to test whether the BBH spin distribution varies as a function of mass as expected if higher-mass systems are the products of hierarchical mergers.

3.3. Redshift evolution

- **NON-EVOLVING** (0 parameters). Our default model posits that the merger rate is uniform in comoving volume.
- **POWER-LAW EVOLUTION** (1 parameter; Appendix E). Following Fishbach et al. (2018), the merger rate density is described by a power-law in $(1+z)$ where z is redshift. Given the finite range of Advanced LIGO and Virgo to BBH mergers, we only expect to constrain the redshift evolution at redshifts $z \lesssim 1$ (Abbott et al. 2013). The farthest event in our analysis is likely GW190706_222641, at redshift $z = 0.79^{+0.31}_{-0.28}$.

4. METHOD

We adopt a hierarchical Bayesian approach, marginalizing over the properties of individual events to measure parameters of the population models described above; see, e.g., (Thrane & Talbot 2019; Mandel et al. 2019; Vitale 2020). Given data $\{d_i\}$ from N_{det} gravitational-wave detections, the likelihood of the data given population parameters Λ is (Loredo 2004; Mandel et al. 2019; Thrane

⁴ Throughout the paper, spin tilt is measured at a reference frequency of 20 Hz for all events except GW190521, for which the spin tilt is measured at 11 Hz (see discussion in Abbott et al. 2020d). We verified that for GW190521, the difference between the spin measurements at 20 Hz and 11 Hz are smaller than the systematic uncertainty between the waveform models.

Event	$m_1 [M_\odot]$	$m_2 [M_\odot]$	FAR [yr ⁻¹]
GW150914	35.7 ^{+4.8} _{-3.1}	30.6 ^{+3.1} _{-4.4}	$< 1.0 \times 10^{-7}$
GW151012	23.3 ^{+14.7} _{-5.5}	13.6 ^{+4.1} _{-4.8}	7.9×10^{-3}
GW151226	13.7 ^{+8.7} _{-3.2}	7.7 ^{+2.2} _{-2.5}	$< 1.0 \times 10^{-7}$
GW170104	31.0 ^{+7.3} _{-5.7}	20.0 ^{+4.9} _{-4.6}	$< 1.0 \times 10^{-7}$
GW170608	11.0 ^{+5.6} _{-1.7}	7.6 ^{+1.4} _{-2.2}	$< 1.0 \times 10^{-7}$
GW170729	50.7 ^{+16.5} _{-10.5}	34.0 ^{+9.3} _{-10.2}	2.0×10^{-2}
GW170809	35.1 ^{+8.4} _{-5.9}	23.8 ^{+5.2} _{-5.2}	$< 1.0 \times 10^{-7}$
GW170814	30.6 ^{+5.6} _{-3.0}	25.3 ^{+2.8} _{-4.1}	$< 1.0 \times 10^{-7}$
* GW170817	1.46 ^{+0.12} _{-0.10}	1.27 ^{+0.09} _{-0.09}	$< 1.0 \times 10^{-7}$
GW170818	35.4 ^{+7.5} _{-4.7}	26.7 ^{+4.3} _{-5.2}	4.2×10^{-5}
GW170823	39.7 ^{+11.2} _{-6.7}	29.0 ^{+6.8} _{-7.7}	$< 1.0 \times 10^{-7}$
GW190408_181802	24.5 ^{+5.1} _{-3.4}	18.3 ^{+3.2} _{-3.5}	1.0×10^{-5}
GW190412	30.0 ^{+4.7} _{-5.1}	8.3 ^{+1.6} _{-0.9}	1.0×10^{-5}
GW190413_052954	33.4 ^{+12.4} _{-7.4}	23.4 ^{+6.7} _{-6.3}	7.2×10^{-2}
GW190413_134308	45.4 ^{+13.6} _{-9.6}	30.9 ^{+10.2} _{-9.6}	4.4×10^{-2}
GW190421_213856	40.6 ^{+10.4} _{-6.6}	31.4 ^{+7.5} _{-8.2}	7.7×10^{-4}
GW190424_180648	39.5 ^{+10.9} _{-6.9}	31.0 ^{+7.4} _{-7.3}	7.8×10^{-1}
* GW190425	2.0 ^{+0.6} _{-0.3}	1.4 ^{+0.3} _{-0.3}	7.5×10^{-4}
GW190503_185404	42.9 ^{+9.2} _{-7.8}	28.5 ^{+7.5} _{-7.9}	1.0×10^{-5}
GW190512_180714	23.0 ^{+5.4} _{-5.7}	12.5 ^{+3.5} _{-2.5}	1.0×10^{-5}
GW190513_205428	35.3 ^{+9.6} _{-9.0}	18.1 ^{+7.3} _{-4.2}	1.0×10^{-5}
GW190514_065416	36.9 ^{+13.4} _{-7.3}	27.5 ^{+8.2} _{-7.7}	5.3×10^{-1}
GW190517_055101	36.4 ^{+11.8} _{-7.8}	24.8 ^{+6.9} _{-7.1}	5.7×10^{-5}
GW190519_153544	64.5 ^{+11.3} _{-13.2}	39.9 ^{+11.0} _{-10.6}	1.0×10^{-5}
GW190521	91.4 ^{+29.3} _{-17.5}	66.8 ^{+20.7} _{-20.7}	2.0×10^{-4}
GW190521_074359	42.1 ^{+5.9} _{-4.9}	32.7 ^{+5.4} _{-6.2}	1.0×10^{-5}
GW190527_092055	36.2 ^{+19.1} _{-9.5}	22.8 ^{+12.7} _{-8.1}	6.2×10^{-2}
GW190602_175927	67.2 ^{+16.0} _{-12.6}	47.4 ^{+13.4} _{-16.6}	1.1×10^{-5}
GW190620_030421	55.4 ^{+15.8} _{-12.0}	35.0 ^{+11.6} _{-11.4}	2.9×10^{-3}
GW190630_185205	35.0 ^{+6.9} _{-5.7}	23.6 ^{+5.2} _{-5.1}	1.0×10^{-5}
GW190701_203306	53.6 ^{+11.7} _{-7.8}	40.8 ^{+8.3} _{-11.5}	1.1×10^{-2}
GW190706_222641	64.0 ^{+15.2} _{-15.2}	38.5 ^{+12.5} _{-12.4}	1.0×10^{-5}
GW190707_093326	11.5 ^{+3.3} _{-1.7}	8.4 ^{+1.4} _{-1.6}	1.0×10^{-5}
GW190708_232457	17.5 ^{+4.7} _{-2.3}	13.1 ^{+2.0} _{-2.7}	2.8×10^{-5}
GW190720_000836	13.3 ^{+6.6} _{-3.0}	7.8 ^{+2.2} _{-2.2}	1.0×10^{-5}
GW190727_060333	37.2 ^{+9.4} _{-5.9}	28.8 ^{+6.6} _{-7.9}	1.0×10^{-5}
GW190728_064510	12.2 ^{+7.1} _{-2.2}	8.1 ^{+1.7} _{-2.6}	1.0×10^{-5}
GW190731_140936	39.3 ^{+11.8} _{-8.2}	28.0 ^{+8.9} _{-8.4}	2.1×10^{-1}
GW190803_022701	36.1 ^{+10.2} _{-6.7}	26.7 ^{+7.1} _{-7.6}	2.7×10^{-2}
† GW190814	23.2 ^{+1.1} _{-1.0}	2.59 ^{+0.08} _{-0.09}	1.0×10^{-5}
GW190828_063405	31.8 ^{+5.8} _{-3.9}	25.9 ^{+4.4} _{-4.6}	1.0×10^{-5}
GW190828_065509	23.8 ^{+7.2} _{-7.0}	10.2 ^{+3.5} _{-2.1}	1.0×10^{-5}
GW190910_112807	43.5 ^{+7.6} _{-6.2}	35.1 ^{+6.3} _{-7.0}	1.9×10^{-5}
GW190915_235702	34.9 ^{+9.5} _{-6.2}	24.4 ^{+5.5} _{-6.0}	1.0×10^{-5}
GW190924_021846	8.8 ^{+7.0} _{-2.0}	5.0 ^{+1.3} _{-1.9}	1.0×10^{-5}
GW190929_012149	64.7 ^{+22.4} _{-18.9}	25.7 ^{+14.4} _{-9.7}	2.0×10^{-2}
GW190930_133541	12.3 ^{+12.5} _{-2.3}	7.8 ^{+1.7} _{-3.3}	3.3×10^{-2}

Table 1. A summary of the events included in this analysis. Asterisks (*) denote binaries in which both components lie in the NS mass range while a dagger (†) indicates a system in which the nature of the secondary component is unknown. Both of these classes are excluded from our analyses unless explicitly stated. From left to right, the columns show the event ID, the 90% credible interval for primary source-frame mass (units of M_\odot), the 90% credible interval for secondary mass (units of M_\odot), and the minimum available FAR. For events detected in more than one CBC detection pipeline, we report the lowest of the available FAR estimate. These credible intervals are obtained using a prior that is uniform in detector-frame component mass and comoving volume.

& Talbot 2019)

$$\mathcal{L}(\{d\}|\Lambda, N) \propto N^{N_{\text{det}}} e^{-N\xi(\Lambda)} \prod_{i=1}^{N_{\text{det}}} \int \mathcal{L}(d_i|\theta) \pi(\theta|\Lambda) d\theta. \quad (1)$$

Here, N is the total number of events expected during the observation period (including both resolvable and unresolvable signals). Each event is described by a set of parameters θ , the likelihood of which is $\mathcal{L}(d|\theta)$. The conditional prior $\pi(\theta|\Lambda)$, meanwhile, is defined by the mass, spin, and redshift models described above in Sec. 3. It serves to quantify the predicted distribution of event parameters θ given the hyper-parameters Λ of the population model. An example of a hyper-parameter is the power-law index α governing primary mass distribution $\pi(m_1|\alpha) \propto m_1^{-\alpha}$ for the TRUNCATED mass model. Finally, $\xi(\Lambda)$ is the fraction of binaries that we expect to successfully detect for a population described by hyper-parameters Λ . The procedure for calculating $\xi(\Lambda)$ is described in Appendix A. One of our primary goals in this paper is to constrain the population hyper-parameters describing the distribution of gravitational-wave signals. Given a log-uniform prior on N , one can marginalize Eq. (1) over N to obtain (Fishbach et al. 2018; Mandel et al. 2019; Vitale 2020)

$$\mathcal{L}(\{d\}|\Lambda) \propto \prod_{i=1}^{N_{\text{det}}} \frac{\int \mathcal{L}(d_i|\theta) \pi(\theta|\Lambda) d\theta}{\xi(\Lambda)}. \quad (2)$$

To evaluate the single-event likelihood $\mathcal{L}(d_i|\theta)$, we use posterior samples that are obtained using some default prior $\pi_{\varnothing}(\theta)$. In this case, integrals over the likelihood can be replaced with weighted averages “ $\langle \dots \rangle$ ” over discrete samples. Equation (2), for example, becomes

$$\mathcal{L}(\{d\}|\Lambda) \propto \prod_{i=1}^{N_{\text{det}}} \frac{1}{\xi(\Lambda)} \left\langle \frac{\pi(\theta|\Lambda)}{\pi_{\varnothing}(\theta)} \right\rangle_{\text{samples}}, \quad (3)$$

where the factor of $\pi_{\varnothing}(\theta)$ serves to divide out the prior used for initial parameter estimation. We evaluate the likelihoods for population models using the `emcee`, `dynesty`, and `stan` packages (Foreman-Mackey et al. 2013; Speagle 2020; Carpenter et al. 2017; Riddell et al. 2018). The likelihoods are implemented in a variety of software including `GWPopulation` (Talbot et al. 2019) and `PopModels` (Wysocki & O’Shaughnessy 2017). The priors adopted for each of our hyper-parameters are described in Appendix B.

Throughout this paper, we find it useful to distinguish between the *astrophysical* distribution of a parameter—the distribution as it is in nature—and the *observed* distribution of a parameter—the distribution as it appears among detected events due to selection effects. The

posterior population distribution for a given model represents our best guess for the *astrophysical* distribution of some source parameter θ , averaged over the posterior for population parameters Λ :

$$p_{\Lambda}(\theta) = \int d\Lambda \pi(\theta|\Lambda) p(\Lambda|\{d\}). \quad (4)$$

Meanwhile, the *posterior predictive distribution* refers to the population-averaged distribution of source parameters θ conditioned on detection.

5. RESULTS AND DISCUSSION

5.1. Mass Distribution

In this subsection we report results obtained using the mass models described in Section 3.1 (see Fig. 1). We employ the DEFAULT spin model and the NON-EVOLVING redshift model. The results shown here marginalize over the hyperparameters of the spin distribution.

A truncated power law fails to fit the high-mass BBH events. The TRUNCATED model applied in Abbott et al. (2019a) measured the sharp high-mass cutoff to be $m_{\text{max}} = 40.8_{-4.4}^{+11.8} M_{\odot}$. When we fit this model to GWTC-2 data, we obtain $m_{\text{max}} = 78.5_{-9.4}^{+14.1} M_{\odot}$, in significant tension ($> 99\%$ credibility) with the GWTC-1 result; see Fig. 2. The TRUNCATED model struggles to accommodate the high-mass systems of GWTC-2. At 99% credibility, three events of GWTC-2 have $m_1 > 45 M_{\odot}$ (regardless of whether we use a population-informed prior; Fishbach et al. 2020b). This tension remains (at the $> 93\%$ credibility level) even when we exclude the highest-mass event GW190521 (Abbott et al. 2020e,f). The poor fit of the TRUNCATED model is further seen in the posterior predictive check of Fig. 18 in Appendix C, which shows that the TRUNCATED model fails to capture the relative excess of observations with $m_1 \sim 30$ compared to the number of events with $m_1 \gtrsim 40 M_{\odot}$.

The POWER LAW + PEAK, BROKEN POWER LAW, and MULTI PEAK models provide better fits to the shape of the mass distribution, particularly at high masses. Although our updated fit to the mass distribution extends to higher masses than the GWTC-1 fit, we find that $97.1_{-3.4}^{+1.7}\%$ of BBH systems have primary masses below $45 M_{\odot}$ (POWER LAW + PEAK model), consistent with the GWTC-1 estimate that 99% of primary masses lie below $\sim 45 M_{\odot}$ (Abbott et al. 2019a; Kimball et al. 2020). In Table 2, we provide log Bayes factors ($\log_{10} \mathcal{B}$) comparing the mass models; each Bayes factor is measured relative to the model with the highest Bayesian evidence: POWER LAW + PEAK. In each case we use the DEFAULT spin model. For context, $\log_{10} \mathcal{B} > 1.5$ is often interpreted as a strong preference for one model over another, and $\log_{10} \mathcal{B} > 2$ as decisive evidence (Jeffreys 1961).

Mass model	\mathcal{B}	$\log_{10} \mathcal{B}$
POWER LAW + PEAK	1.0	0.0
MULTI PEAK	0.25	-0.61
BROKEN POWER LAW	0.12	-0.91
TRUNCATED	0.01	-1.9
BROKEN POWER LAW + PEAK	0.76	-0.12
POWER LAW + PEAK ($\delta_m = 0$)	0.57	-0.24
BROKEN POWER LAW ($\delta_m = 0$)	0.36	-0.45
POWER LAW + PEAK ($\lambda_{\text{peak}} = 0$)	0.04	-1.35

Table 2. Bayes factors for each mass model relative to the favored POWER LAW + PEAK model, which gives the highest Bayesian evidence for GWTC-2. For models that have a smooth turn on at low masses parameterized by δ_m , we also compare the corresponding sub-model with a sharp minimum mass cutoff ($\delta_m = 0$). For the POWER LAW + PEAK model which includes a fraction λ_{peak} of systems in the Gaussian component, we compare the sub-model with $\lambda_{\text{peak}} = 0$.

While Bayes factors depend on the choice of hyper-parameter priors, it is nonetheless possible to see that the TRUNCATED model is disfavored compared to the more complicated models. Meanwhile, there is not a strong preference for POWER LAW + PEAK over BROKEN POWER LAW or MULTI PEAK. We currently lack the resolving power to determine whether the deviations from TRUNCATED are best modeled as a break, a Gaussian peak, or two Gaussian peaks. As a further check, we carried out a follow-up analysis using a bespoke BROKEN POWER LAW + PEAK model, which indicated only modest support for a peak on top of the BROKEN POWER LAW distribution ($\log_{10} \mathcal{B} = 0.79$).

There are features in the black-hole mass spectrum beyond a power-law. Figure 3 shows the astrophysical merger rate density as a function of primary black hole mass for the TRUNCATED, POWER LAW + PEAK, MULTI PEAK and BROKEN POWER LAW models. Figure 4, meanwhile, shows the posterior predictive distribution for primary masses, including selection effects. Corner plots showing the constraints for the parameters in each model are available in the Appendix; see Figs. 16 and 17. Also in the Appendix, we show posterior predictive checks for each model (Fig. 18), comparing mock observations predicted by the model to the empirical distribution inferred from GWTC-2.

We turn first to the BROKEN POWER LAW model (second panel in Fig. 3), which is characterized by two spectral indices, α_1 and α_2 , with $p(m_1) \propto m_1^{-\alpha_1}$ for $m_1 < m_{\text{break}}$, and $p(m_1) \propto m_1^{-\alpha_2}$ above the break. We find the data prefer a break at $m_{\text{break}} = 39.7_{-9.1}^{+20.3} M_{\odot}$; 90% credible bounds on the location of this break are denoted by the gray vertical band in the second panel of Fig. 3. For masses above the break, the BROKEN

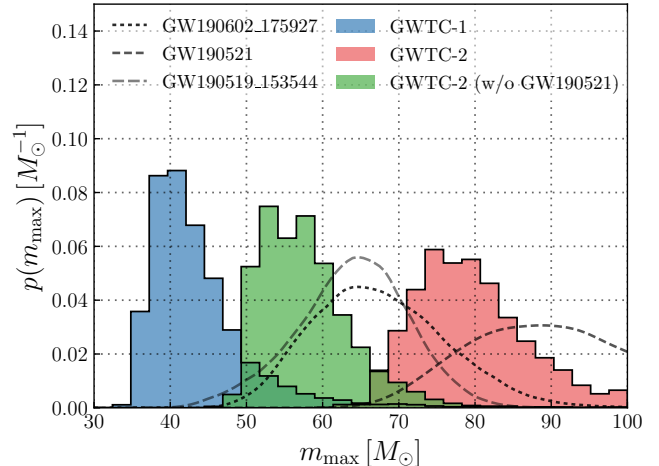


Figure 2. Posterior for the maximum mass using GWTC-1 and fit to the TRUNCATED model (blue), compared to the posterior obtained by adding events from O3a data (red). The two distributions are inconsistent, suggesting the TRUNCATED model is inadequate. The tension between GWTC-1 and GWTC-2 is somewhat alleviated by the exclusion of the high-mass event GW190521 (green). However, there remain several other high-mass events in O3a. The black dashed lines show primary mass posteriors for the three events in which $m_1 > 45 M_{\odot}$ at 99% credibility (we employ a prior that is uniform in detector-frame masses). These events cause a significant shift in the m_{max} posterior if we assume a simple power-law fits the data.

POWER LAW model prefers a significantly steeper power-law slope, from $\alpha_1 = 1.58_{-0.86}^{+0.82}$ before to $\alpha_2 = 5.6_{-2.5}^{+4.1}$ after. Figure 5 shows the joint posterior on α_1 and α_2 . We infer that $\alpha_2 > \alpha_1$ at credibility 98%. The break aligns with the cutoff m_{max} inferred with GWTC-1 data (Abbott et al. 2019a), and we speculate that the steep drop-off in the merger rate that occurs after m_{break} may be an imprint of PPSN, which are expected to become important for black hole masses around $35 M_{\odot}$ (Woosley & Heger 2015; Heger & Woosley 2002; Heger et al. 2003).

The POWER LAW + PEAK model (third panel of Fig. 3) produces a qualitatively similar fit to the one obtained from the BROKEN POWER LAW model. However, a key feature of the POWER LAW + PEAK model is the Gaussian peak at $33.5_{-5.5}^{+4.5} M_{\odot}$, denoted by the gray vertical band in the third panel of Fig. 3. Throughout the text, we use the mean of the Gaussian component when referring to the location of the peak in the POWER LAW + PEAK model. Evidence for a peak can be seen in Fig. 6, which shows the posterior for λ_{peak} , the fraction of systems that belong to the Gaussian component. We see that $\lambda_{\text{peak}} = 0$ (pure power law) is disfavored. It was envisioned (Talbot & Thrane 2018) that the power-law component of the POWER LAW + PEAK model would

Events	Mass model	$m_{1\%} (M_{\odot})$	$m_{99\%} (M_{\odot})$
All confident BBH events - (excludes GW190814)	TRUNCATED	$6.0^{+0.8}_{-2.1}$	$65.5^{+10.4}_{-9.6}$
	BROKEN POWER LAW	$5.6^{+1.3}_{-1.6}$	$57.8^{+12.5}_{-8.7}$
	POWER LAW + PEAK	$6.0^{+1.0}_{-1.7}$	$60.2^{+14.5}_{-13.2}$
	MULTI PEAK	$6.1^{+0.9}_{-1.6}$	$66.5^{+13.4}_{-15.9}$
All confident BBH events - <i>including</i> GW190814	TRUNCATED	$2.4^{+0.2}_{-0.3}$	$60.3^{+10.1}_{-13.2}$
	BROKEN POWER LAW	$2.6^{+0.5}_{-0.3}$	$56.1^{+12.5}_{-9.0}$
	POWER LAW + PEAK	$2.5^{+0.3}_{-0.3}$	$59.6^{+14.5}_{-16.1}$
	MULTI PEAK	$2.6^{+0.4}_{-0.3}$	$65.8^{+10.0}_{-20.7}$
All confident BBH events - <i>excluding</i> GW190521	TRUNCATED	$5.8^{+0.9}_{-2.8}$	$52.3^{+8.9}_{-5.2}$
	BROKEN POWER LAW	$5.6^{+1.3}_{-1.8}$	$52.3^{+9.5}_{-5.9}$
	POWER LAW + PEAK	$6.0^{+1.0}_{-1.6}$	$52.1^{+13.8}_{-7.3}$
	MULTI PEAK	$6.1^{+1.0}_{-1.6}$	$61.2^{+10.4}_{-12.8}$

Table 3. The $m_{1\%}$ and $m_{99\%}$ credible intervals (90%) for various mass models and combinations of events. These variables are defined such that, among the *astrophysical* BBH population, 1% of systems have primary masses $m_1 \leq m_{1\%}$, while 99% have primary masses $m_1 \leq m_{99\%}$. The POWER LAW + PEAK, MULTI PEAK, and BROKEN POWER LAW models are preferred over the TRUNCATED model.

terminate in the vicinity of this peak to create a high-mass gap. However, in order to accommodate the most massive binaries in GWTC-2, the power-law extends to values of $m_{\max} = 87^{+12}_{-12} M_{\odot}$.

While the mass spectrum must extend to these high masses, we find that 99% of primary black hole masses lie below $m_{99\%} \sim 60 M_{\odot}$; see Table 3. The *astrophysical* rate density at $\sim 80 M_{\odot}$ (the primary mass of GW190521) is two orders of magnitude lower than the rate density at $\sim 40 M_{\odot}$. However, because of selection effects, the posterior predictive distribution skews to much higher masses, as seen in Fig. 4, so that the probability of detecting at least one event with $m_1 \geq 80 M_{\odot}$ after observing 44 BBH events drawn from the POWER LAW + PEAK posterior predictive distribution of Fig. 4 is high: 36%.

We cannot determine whether the high-mass events of GWTC-2 belong to a distinct subpopulation rather than a high-mass tail of the normal BBH population. An additional subpopulation may be expected if high-mass black holes have a different origin from low mass ones; for example, if they are the products of hierarchical mergers (Fishbach et al. 2017; Gerosa & Berti 2017; Chatziioannou et al. 2019; Doctor et al. 2019; Kimball et al. 2020). Using the MULTI PEAK model (bottom panel in Fig. 3), which allows for a second high-mass Gaussian component at $m_1 > 50 M_{\odot}$ in addition to the Gaussian component at $m_1 \lesssim 40 M_{\odot}$, we find that the addition of a second Gaussian peak is not preferred by the data.

The MULTI PEAK model is mildly disfavored compared to POWER LAW + PEAK, with a $\log_{10} \mathcal{B} = -0.61$ (or Bayes factor $\mathcal{B} = 0.25$) for MULTI PEAK relative to POWER LAW + PEAK. A similar conclusion is found

using the MULTI SPIN model; as discussed in Section 5.2, we find no significant evidence for subpopulations with distinct spin distributions. Furthermore, the most massive event, GW190521, appears to be a normal member of the BBH population—at least within the framework of the BROKEN POWER LAW, POWER LAW + PEAK and MULTI PEAK models and the BBH events of GWTC-2 (see Appendix C.2). The event GW190521 *is* an outlier if we consider it in the context of GWTC-1 with the TRUNCATED model, but we interpret this as a limitation of the TRUNCATED model (see Fig. 2; Abbott et al. 2020f).

The GWTC-1 detections showed that black holes more massive than $\sim 45 M_{\odot}$ merge relatively rarely, based on simple extrapolations from below $45 M_{\odot}$. With GWTC-2, we are beginning to resolve the shape of the primary black hole mass spectrum above $45 M_{\odot}$. The implications are not yet clear, but there are intriguing possibilities. One hypothesis is that the events with $m_1 > 45 M_{\odot}$ are simply the high-mass tail of the ordinary BBH population, and do not form through a distinct channel. For example, if the lower edge of the PPSN gap may be modeled as a smooth tapering rather than a sharp cut-off, the feature at $m_{\text{break}} = 39.7^{+20.3}_{-9.1}$ may represent the onset of pair-instability. This explanation may pose challenges to our understanding of stellar evolution since the pair-instability cutoff of black-hole masses at $\sim 40 M_{\odot}$ is thought to be relatively abrupt (Woosley et al. 2002; Woosley 2017; Farmer et al. 2019), even though its precise location is uncertain (Mapelli et al. 2020; Spera & Mapelli 2017; Giacobbo et al. 2017; van Son et al. 2020; Farmer et al. 2020; Croon et al. 2020; Marchant & Moriya 2020). If the PPSN cutoff is indeed sharp and all observed BBH systems lie below the PPSN gap, the cutoff

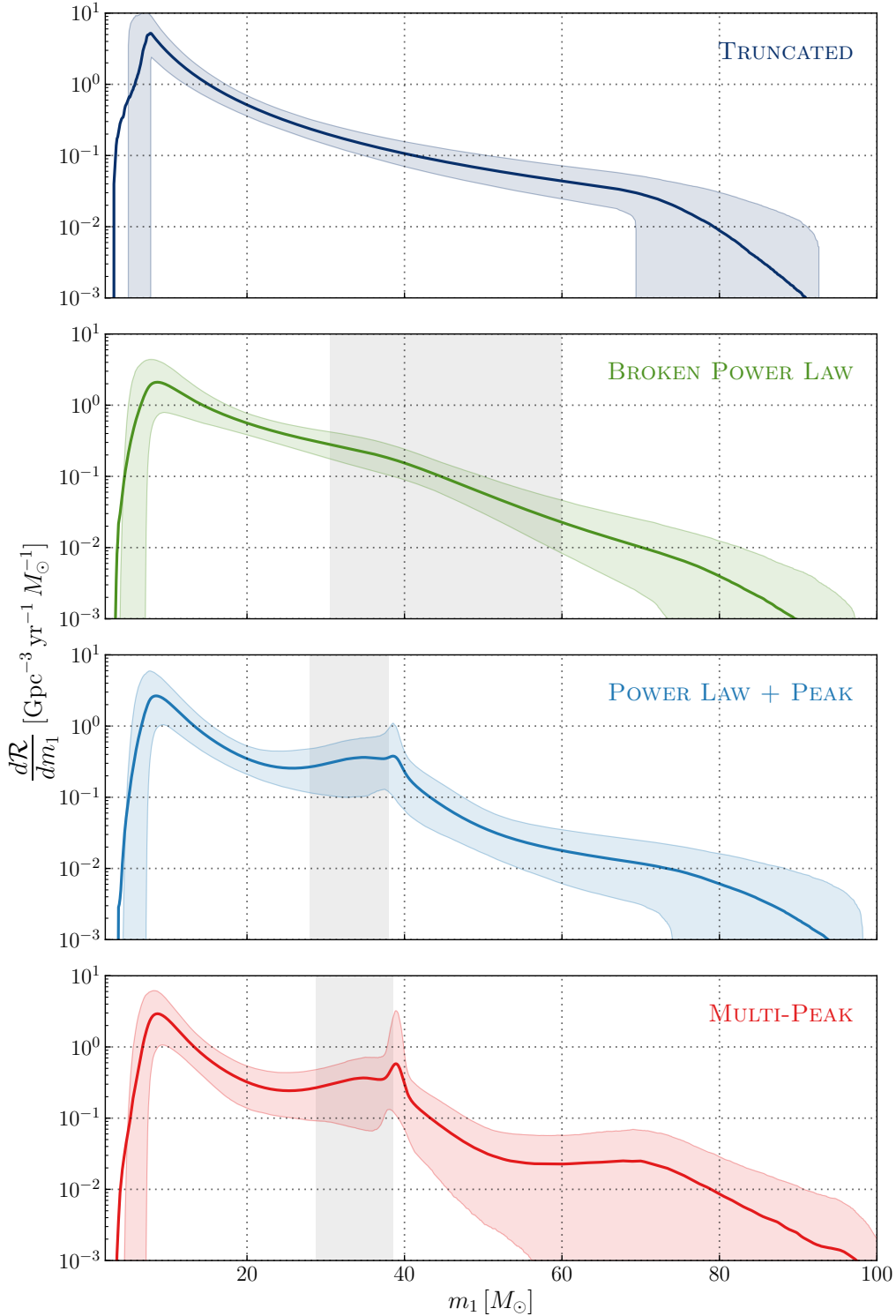


Figure 3. *Astrophysical* primary black hole mass distribution for the TRUNCATED, BROKEN POWER LAW, POWER LAW + PEAK and MULTI PEAK models. The solid curve is the posterior population distribution (averaging over model uncertainty) while the shaded region shows the 90% credible interval. Note that while the median rate is always inside the credible region, the solid curve represents the *mean*, which can be outside the credible region. Top (navy) is the TRUNCATED model, second from the top (green) is the BROKEN POWER LAW model, third from the top (blue) is for the POWER LAW + PEAK model, and bottom (red) is for the MULTI PEAK model. The TRUNCATED model is disfavored compared to the three latter models that predict a feature at $\sim 40 M_{\odot}$: a break in the mass spectrum in the BROKEN POWER LAW model or additional Gaussian peaks in the POWER LAW + PEAK and MULTI PEAK models. The vertical grey bands show 90% credible bounds on the locations of these additional features.

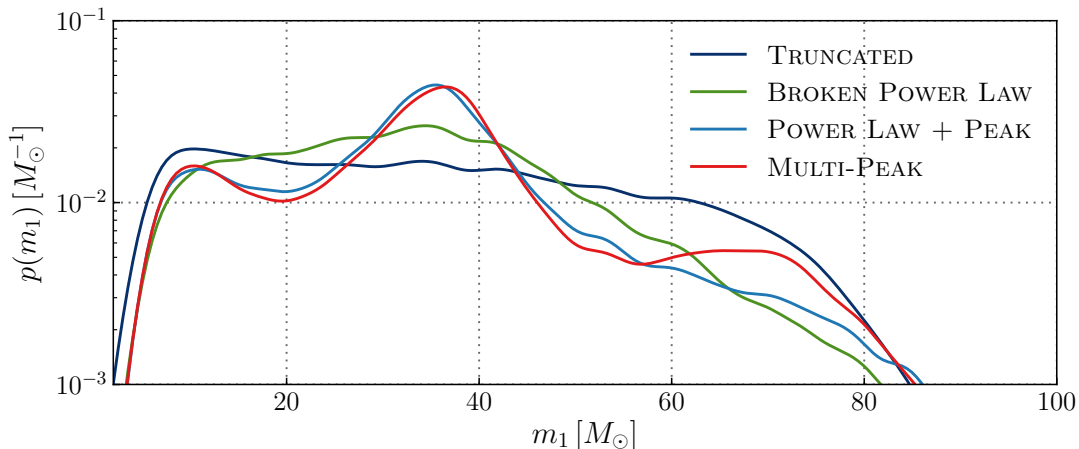


Figure 4. Observed primary black hole mass distributions predicted by each mass model. For each model, we average over the uncertainty in the hyper-parameter posterior. The *observed* distribution describes the events successfully detected by LIGO–Virgo, preferentially favoring more massive systems relative to the astrophysical distribution due to selection effects.

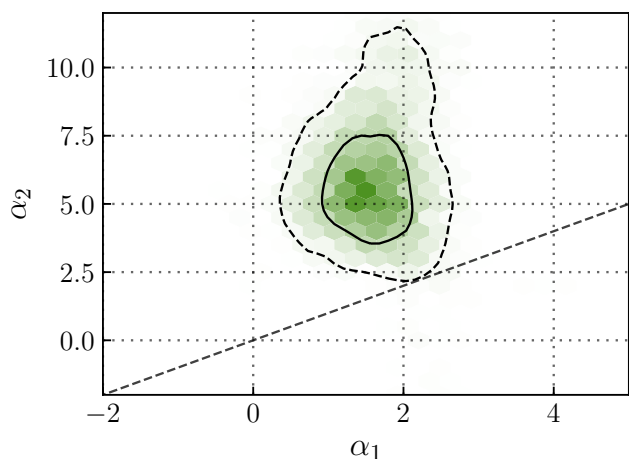


Figure 5. Constraints on the power-law indices governing the primary mass distribution within the BROKEN POWER LAW model. The parameter α_1 is the power-law index below the break, which is found to be $m_{\text{break}} = 39.7^{+20.3}_{-9.1}$ while α_2 is the index above the break. The dashed and solid contours mark the central 50% and 90% posterior credible regions, respectively, under a flat prior on α_1, α_2 in the range $(-4, 12)$. We rule out with high confidence the hypothesis that $\alpha_1 = \alpha_2$, indicated by the dashed diagonal line, finding $\alpha_2 > \alpha_1$ with 98% credibility.

must occur at relatively high masses; in the TRUNCATED model, $m_{\text{max}} = 78.5^{+14.1}_{-9.4} M_{\odot}$ (or, excluding the most massive event, GW190521, $m_{\text{max}} = 57.0^{+11.9}_{-6.6} M_{\odot}$). This may have significant implications for nuclear (Farmer et al. 2020) and particle (Croon et al. 2020; Ziegler & Freese 2020) physics.

Another hypothesis is that the events with $m_1 > 45 M_{\odot}$ constitute a distinct population, created, for example, from hierarchical mergers of lower mass bi-

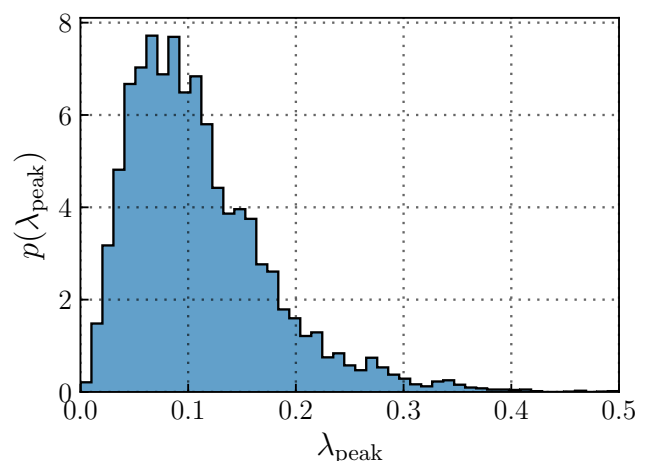


Figure 6. Posterior distribution on the fraction of binaries (λ_{peak}) in the Gaussian component of POWER LAW + PEAK model, under a flat prior on λ_{peak} ; see Appendix B.2. We find that $\lambda_{\text{peak}} = 0$ (which corresponds to no Gaussian peak) is disfavored, supporting the hypothesis that there is a feature in the black hole primary mass spectrum.

naries in globular clusters or galactic nuclei (Miller & Hamilton 2002a; Antonini & Rasio 2016; Kimpson et al. 2016; Rodriguez et al. 2018; Yang et al. 2019). Alternatively, the high-mass gap might be populated from low-metallicity stellar mergers in young star clusters, the remnants of which can merge dynamically (Carlo et al. 2019a,b), black hole growth through accretion (Rice & Zhang 2020; Natarajan 2020; Safarzadeh & Haiman 2020), or Population III stellar remnants with large hydrogen envelopes (Tanikawa et al. 2020; Farrell et al. 2020; Liu & Bromm 2020).

There is a dearth of BBH systems with masses between ~ 2.6 and $\sim 6 M_{\odot}$. Figure 7 shows the joint

posterior for the m_{\min} and δ_m parameters inferred using the POWER LAW + PEAK and BROKEN POWER LAW mass models, including only BBH events with $m_2 \geq 3 M_\odot$. Recall that, while the TRUNCATED model has a sharp cutoff at m_{\min} , the remaining models implement a smooth turn-on of width δ_m above m_{\min} , causing the mass spectrum to peak and turn over between m_{\min} , and $\delta_m + m_{\min}$ (Talbot & Thrane 2018). Using both the BROKEN POWER LAW model and the POWER LAW + PEAK model, we find that the primary mass spectrum does not decrease monotonically from $3 M_\odot$. Rather, it turns over at $7.8^{+2.2}_{-2.1} M_\odot$ (POWER LAW + PEAK model) or $6.02^{+0.78}_{-1.96} M_\odot$ (BROKEN POWER LAW model). In other words, the mass distribution must turn over at $m_1 > 3 M_\odot$, with 99.99% credibility (assuming the POWER LAW + PEAK model) or 98.5% credibility (BROKEN POWER LAW model). As seen in Fig. 7, if the black hole low-mass cutoff is sharp ($\delta_m = 0$), then $m_{\min} \gtrsim 4 M_\odot$. Conversely, if the black hole mass spectrum extends below $m_{\min} \lesssim 4 M_\odot$, an extended turn-on $\delta_m \gtrsim 3 M_\odot$ is required. These results support the existence of a low-mass gap between $\sim 2.6 M_\odot$ (the secondary mass of GW190814; the most massive component mass observed below $3 M_\odot$) and $\sim 6 M_\odot$, strengthening results from Fishbach et al. (2020a), although we cannot determine whether the low-mass gap is empty.

Since our BBH mass distribution models are not designed to simultaneously fit systems above and below the low-mass gap, they struggle to accommodate GW190814 (with secondary mass at $m_2 = 2.59^{+0.08}_{-0.09}$). This system occurs below the turnover mass, as inferred above from systems with both component masses above $3 M_\odot$. If GW190814 is a BBH system, the minimum black hole mass must extend to $m_{\min} = 2.18^{+0.27}_{-0.17} M_\odot$ (see the dashed histograms in Fig. 8a). In Fig. 8b we show how the inclusion/exclusion of GW190814 affects the shape of the primary mass distribution below $\lesssim 5 M_\odot$. This effect can also be seen in the $m_{1\%}$ values inferred with/without GW190814, shown in Table 3. Assuming the TRUNCATED and POWER LAW + PEAK models, the m_{\min} posteriors inferred with GW190814 lie at the $0.25^{+0.44}_{-0.20}$ and $0.88^{+2.12}_{-0.79}$ percentiles, respectively, of the m_{\min} posteriors obtained without GW190814. Even using the BROKEN POWER LAW model, which admits greater overlap in the 1-dimensional m_{\min} posteriors inferred with/without GW190814, the addition of GW190814 significantly shifts the two-dimensional (δ_m, m_{\min}) posterior and the inferred mass spectrum. Assuming the BROKEN POWER LAW model with GW190814, the mass at which the mass spectrum turns over is shifted down to $2.59^{+1.28}_{-0.39} M_\odot$, which is inconsistent with the turnover mass inferred without GW190814, $6.02^{+0.78}_{-1.96} M_\odot$. This in-

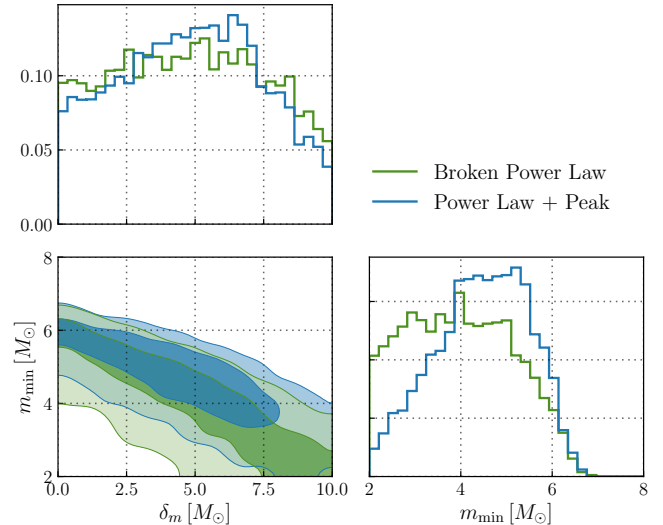
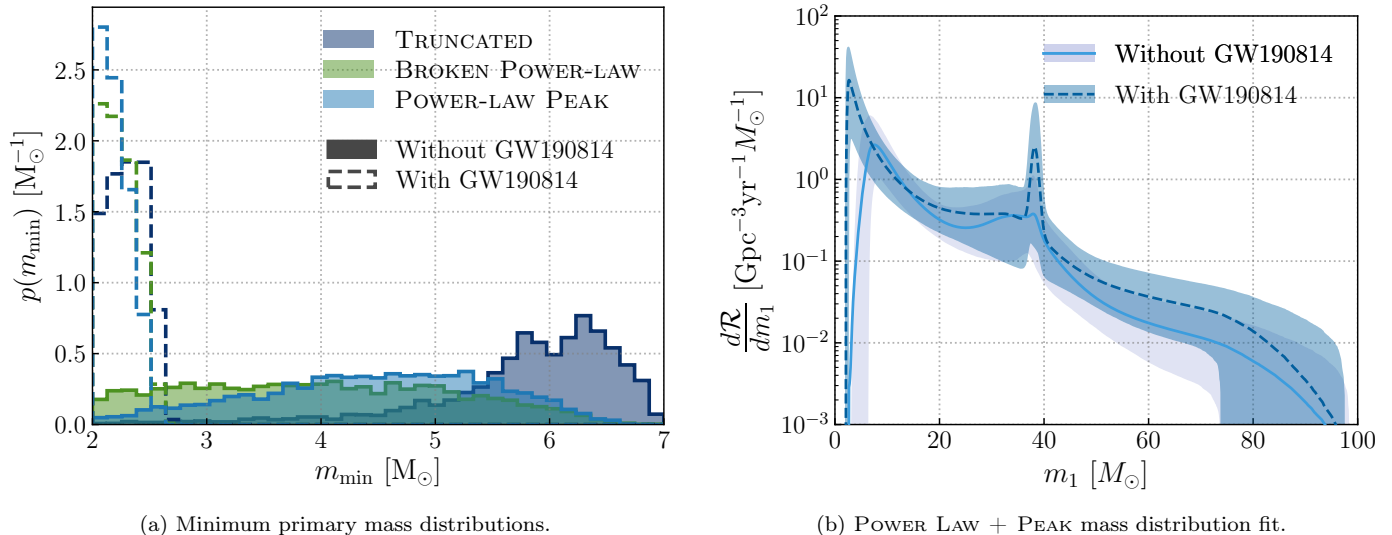


Figure 7. Posterior distribution for population parameters m_{\min} , the minimum black hole mass, and δ_m , which controls the sharpness of the low-mass cut-off. A sharp cut-off corresponds to $\delta_m = 0$. Analyzing the 44 BBH events (with the exclusion of GW190814), both models exclude ($m_{\min} = 3 M_\odot, \delta_m = 0$) with $> 99\%$ credibility, indicating that the rate drops off at low masses. To varying degrees, both models allow for $m_{\min} \leq 3 M_\odot, \delta_m > 0$, suggesting that the low-mass gap may not be empty. See Appendices B.3 and B.2 for additional details about the δ_m, m_{\min} parameters.

icates a failure of our models to fit GW190814 together with the BBH systems of GWTC-2. This finding is supported by additional studies described in Appendix C.3. Because GW190814 is a population outlier with respect to the BBH events of GWTC-2, we exclude it from the analyses here unless otherwise indicated.

The distribution of mass ratios is broad. The GWTC-1 events are all individually consistent with $q = 1$. Describing the conditional mass-ratio distribution as a power law $p(q|m_1) \propto q^{\beta_q}$, a population analysis of GWTC-1 allowed $\beta_q = 12$ (our maximum prior bound), consistent with a mass-ratio distribution sharply peaked at equal-mass pairings (Abbott et al. 2019a; Roulet & Zaldarriaga 2019; Fishbach & Holz 2020). GWTC-2 saw the first detections of confidently asymmetric systems: GW190412 (Abbott et al. 2020b) and GW190814 (Abbott et al. 2020c). Excluding GW190814, our reconstruction of the mass ratio distribution is consistent with the results published in Abbott et al. (2020b): $\beta_q = 1.3^{+2.4}_{-1.6}$ for the POWER LAW + PEAK model and $\beta_q = 1.4^{+2.5}_{-1.5}$ for the BROKEN POWER LAW model. We rule out distributions that are sharply peaked around $q = 1$, with $\beta_q < 3.0$ (POWER LAW + PEAK) and $\beta_q < 3.1$ (BROKEN POWER LAW) at 90% credibility. However, we also disfavor distributions that prefer unequal-mass pairings,



(a) Minimum primary mass distributions.

(b) POWER LAW + PEAK mass distribution fit.

Figure 8. (a) Posterior distribution for the minimum mass parameter in the TRUNCATED (navy), BROKEN POWER LAW (green) and POWER LAW + PEAK (blue) models. The solid bars show the posterior for m_{\min} when fitting the models to the confident BBH events excluding the extreme-mass-ratio event, GW190814, while the dashed lines show the fits to the BBH events including GW190814. The TRUNCATED model is disfavored. (b) Distribution of primary masses inferred using the POWER LAW + PEAK model when including (navy, dashed line) and excluding (light blue, solid line) GW190814. The effect of GW190814 on the mass spectrum at low masses inferred using the BROKEN POWER LAW model is similar.

with $\beta_q > 0$ at 89% (POWER LAW + PEAK) and 94% (BROKEN POWER LAW) credibility. We find that 90% of systems in the underlying population have mass ratios $q > 0.26_{-0.08}^{+0.14}$.

5.2. Spin Distribution

In this subsection, we highlight the results from the GAUSSIAN, DEFAULT, and MULTI SPIN models. We fix the redshift distribution to a NON-EVOLVING merger rate. The GAUSSIAN and MULTI SPIN models assume the mass distributions described in Appendix D.2 and D.3, respectively. For the DEFAULT spin model, we employ the POWER LAW + PEAK mass model, simultaneously fitting the mass and spin distribution as in the previous subsection.

We observe spin-induced general relativistic precession of the orbital plane. As two black holes merge, the morphology of the resulting gravitational waveform depends on their spins. The spin-dependence of a gravitational waveform is determined in part by two phenomenological parameters. First, the effective inspiral spin parameter χ_{eff} quantifies the spin components aligned with the orbital angular momentum (Damour 2001):

$$\chi_{\text{eff}} = \frac{\chi_1 \cos \theta_1 + q \chi_2 \cos \theta_2}{1 + q}. \quad (5)$$

Here, χ_1 and χ_2 are the dimensionless component spins, defined by $\chi_i = \left| \frac{cS_i}{Gm_i^2} \right|$ where S_i is the spin angular

momentum of component i , and θ_1 and θ_2 are the misalignment angles between the component spins and the orbital angular momentum. Second, spins with components perpendicular to the orbital angular momentum drive relativistic precession of the orbital plane (Apostolatos et al. 1994). The effect is quantified by the effective precession spin parameter (Schmidt et al. 2012; Hannam et al. 2014; Schmidt et al. 2015)

$$\chi_p = \max \left[\chi_1 \sin \theta_1, \left(\frac{4q + 3}{4 + 3q} \right) q \chi_2 \sin \theta_2 \right]. \quad (6)$$

A non-zero value of χ_p indicates the presence of relativistic spin-induced precession of the orbital plane. Although the component spin tilts θ_1 and θ_2 appearing in Eqs. (5) and (6) generically evolve over the course of a binary inspiral, χ_{eff} and χ_p are themselves approximately conserved quantities (Kidder 1995; Schmidt et al. 2015).

The first unambiguous measurements of black hole spin in gravitational-wave astronomy came from analyses of the BBH event GW151226. This system had $\chi_{\text{eff}} > 0$ at 99% credibility, with at least one of its components having spin magnitude $\chi > 0.2$, and spin misalignment angles consistent with $\theta_1 = \theta_2 = 0$ (Abbott et al. 2016b). While analyses of GWTC-1 found no clear evidence for spin in the other events in GWTC-1 (Miller et al. 2020, but also see Zackay et al. 2019 and Huang et al. 2020), GWTC-1 is collectively inconsistent with a population of non-spinning black holes, if one allows for both spinning and non-spinning subpopulations (Kimball et al. 2020).

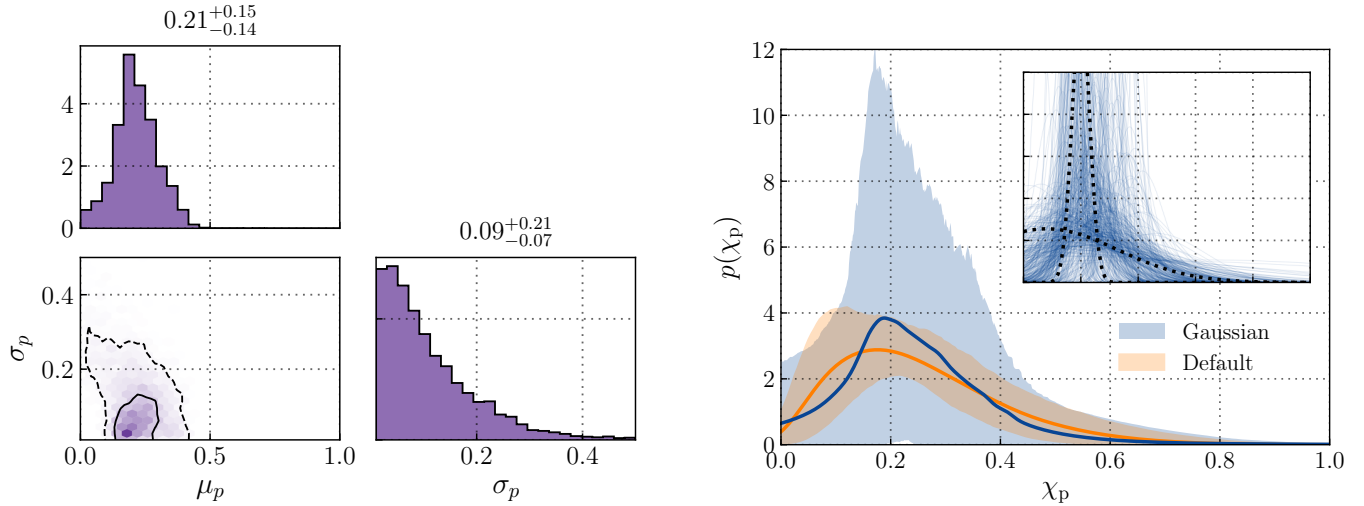


Figure 9. *Left:* Marginal posterior for the mean μ_p and standard deviation σ_p of the χ_p distribution for BBH mergers obtained using the GAUSSIAN spin model (see Appendix D.2 for additional details). A population with perfectly aligned spins corresponds to $\mu_p = \sigma_p = 0$, which is excluded at $> 99\%$ credibility, indicating the presence of in-plane spin components among the GWTC-2 BBH population. *Right:* Population predictive distributions for the effective aligned precessing spin χ_p of BBH systems obtained using the GAUSSIAN (blue) and DEFAULT (orange) spin models. Shaded regions show the central 90% credible bounds on $p(\chi_p)$ at a given spin value, while the solid lines show the median posterior prediction. The inset shows draws of the GAUSSIAN χ_p distributions implied by the posterior on μ_p and σ_p . Broadly, we see support for two possible morphologies, indicated schematically by the dashed black curves. GWTC-2 is compatible with a χ_p distribution that is either broad, or one that is narrow and centered at $\mu_p \sim 0.2$.

Moreover, population analyses of GWTC-1 mildly disfavor the scenario in which all spins are perfectly aligned ($\theta_1 = \theta_2 = 0$), although the degree of misalignment is degenerate with the spin magnitude distribution (Farr et al. 2017; Farr et al. 2018; Tiwari et al. 2018; Abbott et al. 2019a; Wysocki et al. 2019b).

In GWTC-2, additional BBH events have confidently measured positive effective aligned spins. No individual event is observed with confidently negative χ_{eff} (Abbott et al. 2020d). Several events, including GW190521 (Abbott et al. 2020e,f) and GW190412 (Abbott et al. 2020b), show moderate evidence for non-zero χ_p , but no single event unambiguously exhibits spin-induced precession (Abbott et al. 2020d).

Using the GAUSSIAN model described in Sec. 3 (see also, Appendix D.2), we measure clear evidence for relativistic spin-induced precession among the population of BBH events in GWTC-2. In the left side of Fig. 9, we provide a joint posterior for the mean μ_p and standard deviation σ_p of the χ_p distribution. We have marginalized over the parameters of the χ_{eff} distribution as well as the covariance between χ_{eff} and χ_p . Although neither μ_p nor σ_p are individually well-constrained, $\mu_p = \sigma_p = 0$ is ruled out at $> 99\%$ credibility; fewer than 0.02% of posterior samples occur at $\mu_p \leq 0.05$ and $\sigma_p \leq 0.05$. Since any non-zero μ_p or σ_p implies the existence of spin-induced precession, this result constitutes a clear observation of spin-induced precession of the orbital plane.

The right side of Fig. 9 shows the example χ_p distributions drawn from the posterior on μ_p and σ_p . The dark blue curve and shaded blue region mark the median and 90% credible bound, respectively, on $p(\chi_p)$ inferred from the GAUSSIAN model, while the orange curve and shaded region show the inference from the DEFAULT model. While the blue region in this figure suggests a χ_p distribution that peaks at ~ 0.2 , there are in fact two morphologies preferred by the data according to the GAUSSIAN model: the χ_p distribution is *either* broad—or narrowly peaked at $\chi_p \approx 0.2$. This is illustrated by the inset, in which we plot an ensemble of distributions corresponding to individual draws from the (μ_p, σ_p) posterior; the dashed black curves highlight traces representative of the two permitted morphologies. We disfavor populations in which the χ_p distribution is confined to very small (corresponding to nearly aligned spins) or very large (corresponding to preferentially in-plane spins) values.

As mentioned above, GW190521 and GW190412 individually show mild evidence of precession, with χ_p posteriors shifted away from their respective priors (Abbott et al. 2020b,e,f). To verify that our population-level conclusions are not driven primarily by these two events, we have repeated the GAUSSIAN analysis excluding GW190521 and GW190412. Our results again exclude $\mu_p = \sigma_p = 0$ at a similar level of confidence ($> 99\%$ credibility). This implies that the signature of precession

observed here is due to the combined influence of many systems with only weakly measured χ_p , consistent with expectations from simulation studies (Fairhurst et al. 2019; Wysocki et al. 2019b).

The injection sets used to quantify search selection effects (see Appendix A) contain only events whose component spins are perfectly aligned with their orbital angular momenta. The results in Fig. 9 therefore *do not* account for systematics possibly affecting our ability to detect events with non-zero χ_p . The matched filter template banks adopted by the GstLAL and PyCBC search pipelines, for instance, are composed of purely aligned-spin waveforms, and so may underestimate the significance of precessing events (Abbott et al. 2020b). Selection effects can, however, only *decrease* the efficiency with which events with large χ_p are detected; incorporating such effects would shift the posterior in Fig. 9 towards larger values of μ_p and/or σ_p and further rule out $\mu_p = \sigma_p = 0$. Thus, the presence of in-plane spin components is robust to selection effects. The specific preference for $\mu_p \approx 0.2$, though, may not be. In the future, accurately characterizing the effects of in-plane spins on detection efficiency will be crucial in order to robustly determine the shape of the χ_p distribution.

A similar conclusion regarding the presence of in-plane spin components may be drawn using DEFAULT spin model, which imposes an entirely different parameterization for the black hole spin distribution and makes different assumptions regarding their masses. In Fig. 10 we show the posteriors for the component spin magnitude and tilt angle distributions obtained using the DEFAULT model. Together, these distributions themselves imply a posterior for the χ_p distribution of BBH systems; this implied χ_p distribution is shown in orange on the right side of Fig. 9. As discussed further below, the DEFAULT model excludes perfect spin alignment (i.e. spin tilts identically zero) at >99% credibility. As a result, the corresponding χ_p distribution excludes the case of vanishing χ_p . The identification of spin-induced precession within the binary black hole population is therefore robust to the systematic differences exhibited by our DEFAULT and GAUSSIAN models.

There are, though, several potentially meaningful differences between the results from the GAUSSIAN and DEFAULT models. In particular, the DEFAULT model predicts χ_p distributions that are generally broader and peaked at lower values. This is due to additional physical constraints imposed by the DEFAULT spin model; component spins are presumed to preferentially cluster about $\theta = 0$, an assumption that preferentially favors

smaller χ_p values. Nevertheless, the two models agree within statistical uncertainties.⁵

We observe anti-aligned spin, which may suggest the presence of more than one binary formation channel. Using the GAUSSIAN model described in Sec. 3, we infer the presence of systems with negative effective aligned spin: $\chi_{\text{eff}} < 0$. Thus, there exist BBH systems with at least one component spin tilted by $\theta > 90^\circ$ relative to their orbital angular momenta. Figure 11 shows posteriors for the mean μ_{eff} and standard deviation σ_{eff} of the χ_{eff} distribution, marginalized over μ_p , σ_p , and the covariance between effective and precessing spins. With a peak at $\mu_{\text{eff}} = 0.06_{-0.05}^{+0.05}$, we find that most systems have small but positive χ_{eff} , in agreement with the inference from GWTC-1 (Miller et al. 2020; Roulet & Zaldarriaga 2019). With GWTC-2, we can now also constrain the width of the χ_{eff} distribution. The result, $\sigma_{\text{eff}} = 0.12_{-0.04}^{+0.06}$, requires that a nonzero fraction of BBH systems have $\chi_{\text{eff}} < 0$. Unlike the constraints on the χ_p distribution presented above, the results for the presence of negative effective inspiral spin *do* incorporate selection effects via the prescription described in Sect. 4.

Analysis with the DEFAULT spin model is also suggestive of an anisotropic distribution of spin orientations. In Fig. 10, we plot the population distribution of $\cos\theta_{1,2}$ reconstructed using the DEFAULT model. While the $\cos\theta_{1,2}$ distribution shows a preference for primarily aligned spins, with $\cos\theta_{1,2} > 0$, it also exhibits non-vanishing posterior support for $\cos\theta_{1,2} < 0$, indicating the presence of component spins misaligned by more than 90° . The χ_{eff} distribution inferred with the DEFAULT model closely matches the distribution inferred using the GAUSSIAN model; compare the orange and blue bands in the right panel of Fig. 11. The two models therefore agree on the fraction of systems with anti-aligned component spins.

To further verify that the apparent presence of events with negative χ_{eff} is physical and not an artifact of our choice of models, we repeat our inference of the GAUSSIAN χ_{eff} distribution, this time permitting the minimum allowed effective inspiral spin $\chi_{\text{eff}}^{\text{min}}$ (until now fixed to $\chi_{\text{eff}}^{\text{min}} = -1$) to vary as an additional hyperparameter to be inferred from the data. When fitting for $\chi_{\text{eff}}^{\text{min}}$ alongside μ_{eff} and σ_{eff} , we find that $\chi_{\text{eff}}^{\text{min}}$ is less than zero at 99% credibility (see Fig. 25 in the Appendix), confirming that the evidence for anti-aligned spin is not an artifact of our parameterization. Allowing $\chi_{\text{eff}}^{\text{min}}$ to vary yields similar results for the implied χ_{eff} distribution, and in particular, the fraction of systems with negative χ_{eff} .

⁵ We do not have a Bayes factor to compare the DEFAULT and GAUSSIAN spin models.

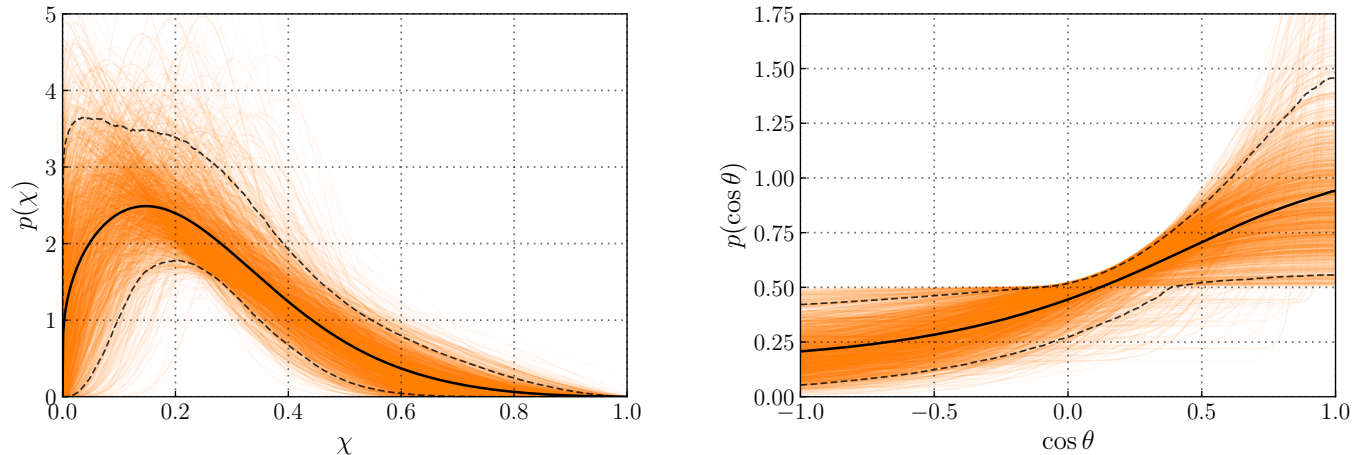


Figure 10. Reconstructions of the black hole spin magnitude and tilt distributions. *Left:* The distribution of dimensionless spin magnitude χ as inferred using the DEFAULT spin model (see Appendix D.1). Light traces show individual draws from the DEFAULT posterior, while the solid black curve shows the posterior population distribution for χ . Dashed lines mark the central 90% quantiles. *Right:* the reconstructed distribution of tilt angle $\cos \theta_{1,2}$ of black hole component spins relative to their orbital angular momenta. An isotropic spin orientation, which corresponds to a uniform distribution in $\cos \theta_{1,2}$, is disfavored but not ruled out. The data do, however, rule out a highly peaked distribution at $\cos \theta_{1,2} = 1$. Rather, the data are consistent with a gently peaked distribution, with a modest preference for aligned spin ($\cos \theta_{1,2} > 0$).

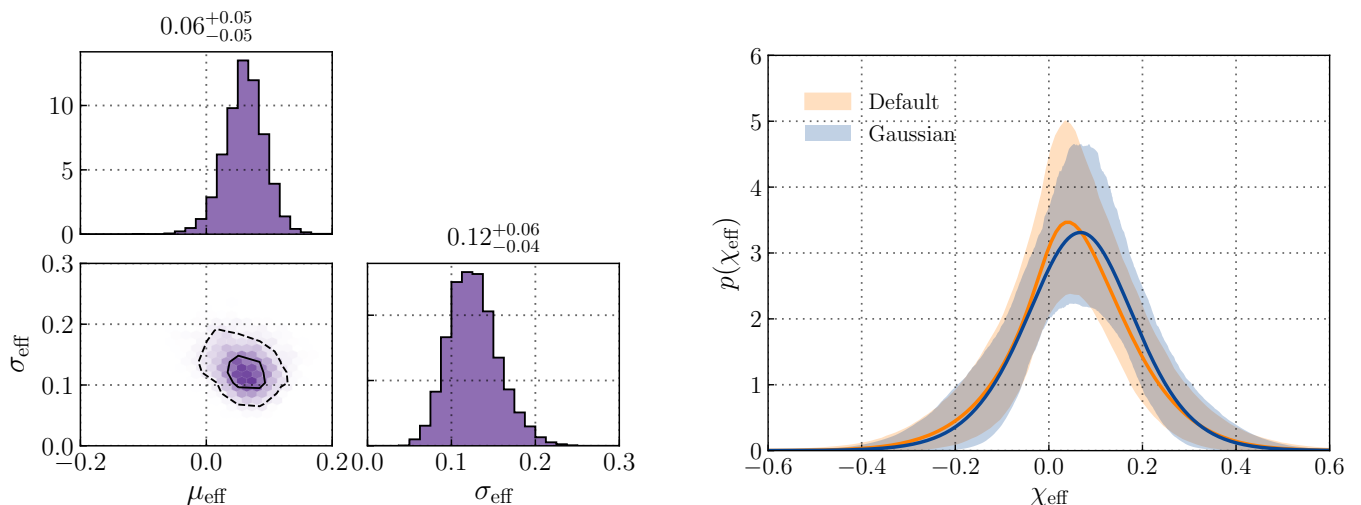


Figure 11. *Left:* Posterior for the mean μ_{eff} and standard deviation σ_{eff} of the BBH χ_{eff} distribution, obtained using the GAUSSIAN model described in Appendix D.2. We marginalize over the parameters governing the distribution of effective precessing spins. While we infer a χ_{eff} distribution that is peaked at positive values, its measured width implies that a non-zero fraction of BBH systems have negative χ_{eff} , implying component spins misaligned by $t > 90^\circ$ relative to the orbital angular momentum. *Right:* Population predictive distributions for the effective inspiral spin χ_{eff} obtained with both the GAUSSIAN and DEFAULT spin models. Shaded regions show the central 90% credible bounds on $p(\chi_{\text{eff}})$ and the solid lines show the median posterior prediction for the χ_{eff} distribution.

The presence of BBH systems with negative effective inspiral spins carries implications for the formation channels that give rise to stellar-mass BBH mergers. Binary black holes born in the field from isolated stellar progenitors are predicted to contain components whose spins are nearly aligned with their orbital angular momenta, although sufficiently strong supernova kicks might pro-

duce modest misalignment (O’Shaughnessy et al. 2017; Stevenson et al. 2017; Gerosa et al. 2018; Rodriguez et al. 2016; Bavera et al. 2019). In contrast, binaries assembled dynamically in dense stellar environments are expected to have randomly oriented component spins, yielding positive or negative χ_{eff} with equal probabilities (Rodriguez et al. 2016; Zevin et al. 2017; Rodriguez

et al. 2018; Doctor et al. 2019; Kalogera 2000; Mandel & O’Shaughnessy 2010). Measurements of BBH spin (Mandel & O’Shaughnessy 2010; Stevenson et al. 2017; Fishbach et al. 2017; Talbot & Thrane 2017; Wysocki et al. 2019a) provide one means to differentiate between these formation channels. Other gravitational-wave observables may also offer clues about binary formation. The observation of orbital eccentricity (Samsing et al. 2014; Samsing & Ramirez-Ruiz 2017; Samsing 2018; Romero-Shaw et al. 2019; Lower et al. 2018) or hierarchical merger candidates Fishbach et al. (2017); Chatziioannou et al. (2019); Doctor et al. (2019); Kimball et al. (2020) could also provide strong circumstantial evidence for the role of dynamical mergers in the LIGO–Virgo catalogs.

Using the posteriors for μ_{eff} and σ_{eff} from Fig. 11, in Fig. 12 we show posteriors for the implied fractions of BBH systems with negative ($\chi_{\text{eff}} < -0.01$) and positive ($\chi_{\text{eff}} > 0.01$) effective inspiral spins. Motivated by recent work suggesting that black holes are born with natal spins as small as $\chi \approx 10^{-2}$ (Qin et al. 2018; Fuller et al. 2019; Fuller & Ma 2019; Bavera et al. 2019), as well as the tendency of vanishingly small spins to confound efforts to distinguish between positive and negative χ_{eff} (Farr et al. 2018; Abbott et al. 2019a), we include a third bin containing vanishingly small spins between $-0.01 \leq \chi_{\text{eff}} \leq 0.01$. At 90% credibility, we find that fractions $f_p = 0.67_{-0.16}^{+0.16}$, $f_n = 0.27_{-0.15}^{+0.17}$, and $f_v = 0.05_{-0.01}^{+0.02}$ of BBH systems have positive, negative, and vanishing χ_{eff} , respectively. All three posterior distributions are peaked away from zero. In particular, $f_n > 7\%$ at 99% credibility. This result is in contrast to results obtained using GWTC-1 alone, which did not exhibit a confidently non-zero fraction of events with negative χ_{eff} (Abbott et al. 2019a; Miller et al. 2020). Additionally, the relatively small fraction f_v of binaries with vanishing spins may provide clues about how black holes gain angular momentum, given recent studies suggesting that most black hole are born slowly rotating (Fuller & Ma 2019). While we define the vanishing bin to be $-0.01 \leq \chi_{\text{eff}} \leq 0.01$, the exact choice of width for the vanishing bin does not strongly affect the values of f_p and f_n , relative to one another.

As mentioned above, dynamical formation in dense clusters is not the only astrophysical explanation of negative effective inspiral spin. If stellar progenitors experience both strong natal kicks in supernovae *and* inefficient spin realignment, $\lesssim 10\%$ of BBH systems formed through isolated binary evolution may have $\chi_{\text{eff}} < 0$ (Rodriguez et al. 2016; O’Shaughnessy et al. 2017; Stevenson et al. 2017; Wysocki et al. 2018), although these results depend on the poorly understood physics of natal kicks and binary interaction via torques and mass transfer. Moreover, we have so far neglected the possibility of other formation

channels that may operate in both the field and dynamical regimes. Isolated hierarchical triples, for example, may produce binary mergers with preferentially in-plane component spins (Rodriguez & Antonini 2018; Antonini et al. 2018; Liu et al. 2019). Hierarchical mergers in the disks of active galactic nuclei, meanwhile, yield component spins that are preferentially parallel or anti-parallel to a binary’s orbital angular momentum (McKernan et al. 2018; Yang et al. 2019; McKernan et al. 2020).

With these qualifications in mind, if we interpret negative χ_{eff} as indicative of dynamical formation in stellar clusters, then our constraints on f_n can be used to infer the fraction of dynamically assembled binaries. We assume that dynamical assembly in dense stellar environments yields a χ_{eff} distribution that is symmetric about zero, while isolated binary evolution produces only *positive* χ_{eff} . Among the binaries with non-negligible spin (excluding those in the "vanishing" category above), the fractions f_d and f_i of binaries arising from dynamical and isolated channels are

$$f_d = \frac{2f_n}{f_p + f_n}, \quad (7)$$

$$f_i = \frac{f_p - f_n}{f_p + f_n}. \quad (8)$$

We find $0.25 \leq f_d \leq 0.93$ at 90% credibility, suggesting that both the field and the dynamical cluster scenarios contribute to the BBH mergers observed in GWTC-2. Because the relative values of f_n and f_p are not sensitive to the width of the vanishing χ_{eff} bin, this conclusion does not depend strongly on the definition of vanishing spin.

At present, we are unable to include a systematic investigation of waveform error in our analysis of anti-aligned spin and orbital precession. However, preliminary studies suggest that waveform error is unlikely to significantly affect this and other results in this paper. For future work, it would be worthwhile to estimate the systematic error using different waveform approximants.

No strong evidence for variation of the spin distribution with mass. Black holes born in hierarchical mergers inherit the orbital angular momenta of their progenitor systems, leading to significant spin magnitudes $\chi \approx 0.7$ for nearly equal-mass systems (Pretorius 2005; Fishbach et al. 2017; Gerosa et al. 2018; Doctor et al. 2019; Rodriguez et al. 2018, 2019; Kimball et al. 2020). If hierarchical mergers are present in GWTC-2, then one may expect correlations between the spins and masses of BBH systems, with more massive hierarchical mergers also possessing larger spins. We use the MULTI SPIN model to explore possible trends in the BBH spin distribution with mass, allowing for a distinct low-mass

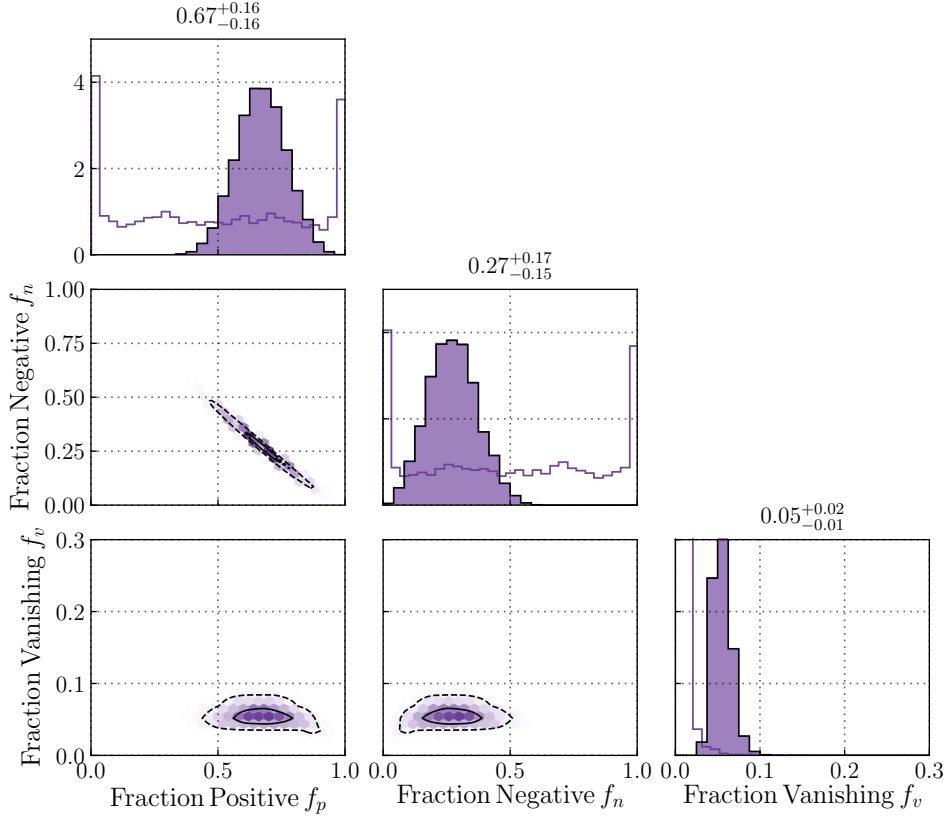


Figure 12. Posterior distribution for the fraction of BBH events with positive or negative χ_{eff} (corresponding to alignment or anti-alignment of the black hole spin with the orbital angular momentum; see Eq. 5). We also include the fraction of events that is consistent with vanishingly small spins $|\chi_{\text{eff}}| < 0.01$. We confidently infer that a nonzero fraction of events are spinning with tilts less than 90° (positive χ_{eff}), and a nonzero fraction of events have vanishingly small spins. A smaller fraction of events has spin tilts $> 90^\circ$ (negative χ_{eff}). The *prior* distributions on the parameters are marked with the non-filled histograms.

and high-mass subpopulation (with primary mass distributions parameterized by a power-law and Gaussian, respectively; see Sec. D.3), each with a distinct spin distribution. The low-mass power-law has a weak preference for smaller spins, as compared to the high-mass Gaussian. Both subpopulations disfavor perfectly aligned systems, though the low-mass subpopulation has more support for small misalignments. In spite of these differences, the uncertainties on both of these subpopulations are broad enough that the two are fully consistent with each other, and we cannot confidently claim to detect a mass-dependence to the spin distribution at this stage. This is demonstrated in Fig. 13, which shows the posteriors for the spin distribution hyper-parameters associated with each mass subpopulation. These findings support the results of previous studies on GWTC-1, which could neither exclude nor confidently detect variation of the spin distribution with mass (Safarzadeh et al. 2020; Tiwari 2020).

5.3. Merger rate and redshift evolution

In this subsection we use the POWER LAW + PEAK and BROKEN POWER LAW mass models with the DEFAULT spin model, and infer the merger rate using the NON-EVOLVING redshift model and the POWER-LAW evolution redshift model.

We better constrain the binary black hole merger rate. Assuming a log-uniform prior, we find a BBH merger rate of $R_{\text{BBH}} = 23.9^{+14.9}_{-8.6} \text{ Gpc}^{-3} \text{ yr}^{-1}$ using the POWER LAW + PEAK mass distribution and the assumption of a NON-EVOLVING merger rate density. We find that estimates of the BBH merger rate are robust to our choice of mass model, with excellent agreement between the POWER LAW + PEAK, BROKEN POWER LAW, and MULTI PEAK models. The TRUNCATED model yields a higher merger rate than the other models, but the results agree within statistical uncertainties: $R_{\text{BBH}} = 33^{+22}_{-12} \text{ Gpc}^{-3} \text{ yr}^{-1}$.

This merger rate includes only systems with $m_1 \geq m_2 \geq 3 M_\odot$, which notably excludes GW190814. If we calculate the merger rate for all systems down to $m_2 \geq 2 M_\odot$ using our models, thereby including GW190814, we infer a higher merger rate: $R_{\text{BBH}} = 58^{+54}_{-29} \text{ Gpc}^{-3} \text{ yr}^{-1}$

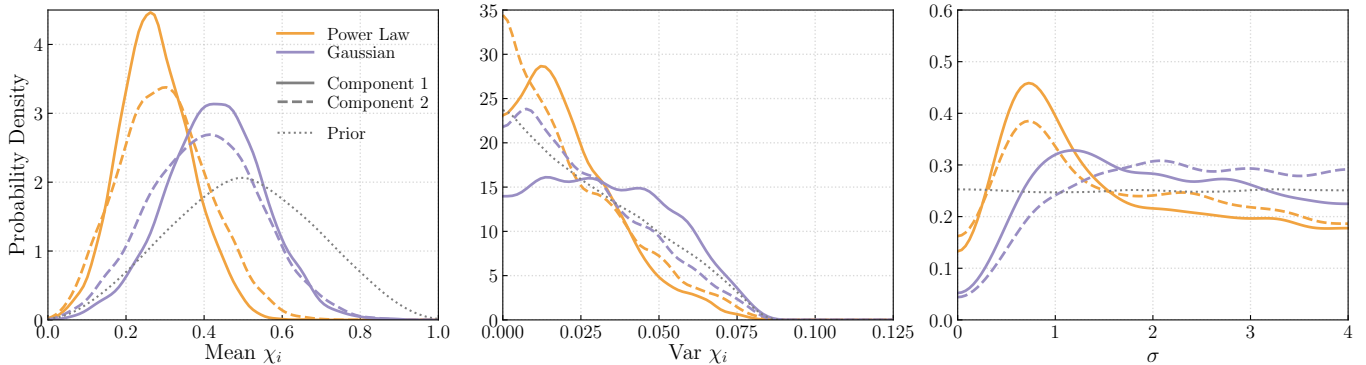


Figure 13. Posterior distribution for MULTI SPIN spin hyper-parameters. Each subplot corresponds to a different parameter controlling the shape of the spin distribution (see Appendix D.3 for details). Each color corresponds to a different subpopulation (power-law or Gaussian) or component (primary mass or secondary mass) of the binary. The power-law subpopulation is slightly better measured than the Gaussian component, as a large number of detections are assigned to it. The results hint at a potential correlation between mass and spin, but the large measurement errors mean the spin distributions are consistent between the two subpopulations.

for the POWER LAW + PEAK model. The reason for this change is that including GW190814 increases the low-mass rate (see Fig. 8b). However, because our mass distribution models do not extrapolate well to $m_2 < 3 M_\odot$ (see Section 5.1), the fit with GW190814 likely overestimates the rate of systems with masses between ~ 2.6 and $\sim 6 M_\odot$.

Because of the uncertainty regarding the nature of GW190814 and the low significance of GW190426_152155 (the other NSBH candidate in GWTC-2), we do not attempt to model the NSBH mass distribution, and do not calculate an NSBH merger rate. An estimate of the merger rate for GW190814-like systems can be found in Abbott et al. (2020c).

We update the binary neutron star merger rate. We give an update to the BNS rate based on the two confident BNS detections in GWTC-2, GW170817 and GW190425. As in Abbott et al. (2020a), we assume a fixed BNS mass distribution: uniform in component masses between $1 M_\odot$ and $2.5 M_\odot$, with each mass independently drawn from this distribution, and zero spins, though, see Farrow et al. (2019) for a fit to the mass distribution of Galactic double neutron stars. Because of the longer observing time and the lack of additional detections, we find a slightly smaller value for the BNS rate than previously reported: $R_{\text{BNS}} = 320^{+490}_{-240} \text{ Gpc}^{-3} \text{ yr}^{-1}$. Assuming that there are 0.01 Milky Way equivalent galaxies (MWEG) in 1 Mpc^3 (Kopparapu et al. 2008), this implies a rate of $R_{\text{BNS}} = 32^{+49}_{-24} \text{ MWEG}^{-1} \text{ Myr}^{-1}$.

The BBH merger rate probably increases with redshift, but slower than the star-formation rate. Figure 14 shows the merger rate as a function of redshift using the POWER LAW evolution model (see Appendix E for additional details, and Fig. 26 for a posterior predic-

tive check). When we allow the merger rate to evolve with redshift according to $(1+z)^\kappa$, we find that the $z=0$ merger rate is $\mathcal{R}(z=0) = 19.1^{+16.2}_{-9.0} \text{ Gpc}^{-3} \text{ yr}^{-1}$. The posterior for the rate evolution parameter κ is shown in Fig. 15. Since GWTC-2 includes events with greater redshifts than the events in GWTC-1, we obtain a much tighter constraint on the evolution of the merger rate; compare our updated constraints of $\kappa = 1.3^{+2.1}_{-2.1}$ (POWER LAW + PEAK model) and $\kappa = 1.8^{+2.1}_{-2.2}$ (BROKEN POWER LAW model) to the GWTC-1 result of $\kappa = 8.4^{+9.6}_{-9.5}$. We find that the merger rate is consistent with a non-evolving distribution ($\kappa = 0$), but is more likely to increase with increasing redshift, with $\kappa > 0$ at 85% credibility (POWER LAW + PEAK model) or 91% (BROKEN POWER LAW model).

Locally ($z \approx 0$), the Madau–Dickinson star-formation rate (Madau & Dickinson 2014) corresponds to $\kappa = 2.7$ in our POWER-LAW REDSHIFT parameterization. We infer $\kappa < 2.7$ at 87% credibility with the POWER LAW + PEAK mass model (77% with BROKEN POWER LAW). Another way of comparing our inferred merger rate to the star-formation rate is by looking at the ratio between the rate at $z=1$ and $z=0$, $\mathcal{R}_{\text{BBH}}(z=1)/\mathcal{R}_{\text{BBH}}(z=0)$. For the star-formation rate $\mathcal{R}_{\text{SFR}}(z=1)/\mathcal{R}_{\text{SFR}}(z=0) \approx 6$, while for BBH systems, we infer $\mathcal{R}_{\text{BBH}}(z=1)/\mathcal{R}_{\text{BBH}}(z=0) = 2.5^{+7.8}_{-1.9}$ (POWER LAW + PEAK model). These results are consistent with most astrophysical formation channels, which predict a factor of ~ 2 increase between the merger rate at $z=0$ and $z=1$ (Santoliquido et al. 2020; Dominik et al. 2013; Neijssel et al. 2019; Eldridge et al. 2019; Mapelli et al. 2017; Baibhav et al. 2019; Rodriguez & Loeb 2018).

6. CONCLUSIONS

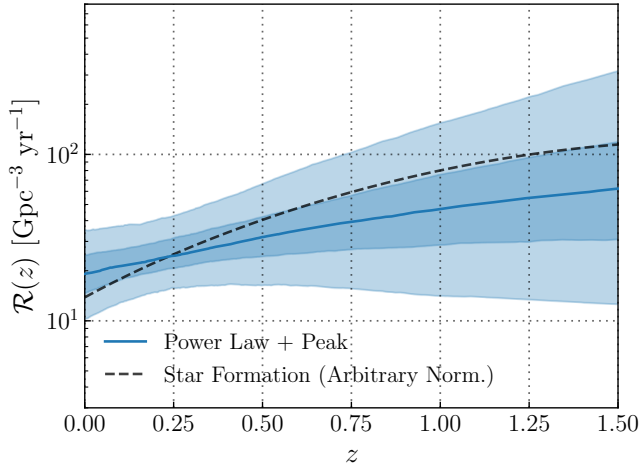


Figure 14. Merger rate density as a function of redshift, fit to the POWER-LAW EVOLUTION model. The solid curve shows the median rate density, while the dark (light) shaded region shows 50% (90%) credible intervals. The dashed curve shows the shape of the SFR. The data exhibit a mild preference for the merger rate to increase with redshift, but are consistent with a flat distribution as well as one that tracks the SFR.

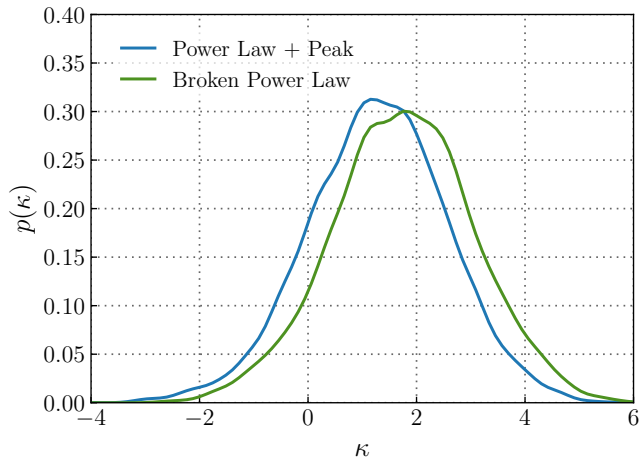


Figure 15. Posterior for the redshift evolution parameter κ from the POWER-LAW EVOLUTION model, which assumes that rate density scales like $(1+z)^\kappa$. We assume the POWER LAW + PEAK and BROKEN POWER LAW mass models, and take a flat prior on κ .

The publication of the second LIGO–Virgo gravitational-wave transient catalog has increased the population of BBH events by a factor of more than four. The new catalog has highlighted the limitations of some early population models while yielding remarkable new signatures:

1. We find that the BBH primary mass spectrum is not well-described as a simple power-law with an abrupt cut-off; there is a strong statistical pref-

erence for other models with non-trivial features such as a peak or a tapering. These features occur at $\approx 37 M_\odot$, where one might expect pair instability supernovae (and pulsational pair instability supernovae) to shape the mass distribution of black holes.

2. At the opposite end of the spectrum, we observe a dearth of systems between NS and black hole masses, suggesting that the black hole mass spectrum likely turns over at $\sim 7.8_{-2.1}^{+2.2} M_\odot$. We constrain the minimum mass of black holes in BBH systems to be $m_{\min} < 6.6 M_\odot$ at 90% credibility. This is greater than the mass of black hole candidates in Galactic binaries, e.g., [Thompson et al. \(2019\)](#). Meanwhile, we find GW190814 is an outlier in both secondary mass and mass ratio, indicating that it may belong to a distinct population compared to the other BBH systems. This is perhaps unsurprising as the combination of mass ratio, merger rate, and secondary mass inferred from this system pose a challenge to our current understanding of compact binary formation [Abbott et al. \(2020c\)](#); [Zevin et al. \(2020\)](#); [Safarzadeh \(2020\)](#).
3. We detect clear evidence of spin-induced, general relativistic precession of the orbital plane. We determine that this signature is not due to a single precessing merger, but from the overall preference of the data for precessing waveforms.
4. We observe that some fraction of the black holes in GWTC-2 are spinning with an orientation that is anti-aligned with respect to the orbital angular momentum of the binary. If we plausibly assume that all binaries with anti-aligned spins are assembled dynamically, this may imply that LIGO–Virgo events merge both dynamically and in the field. Based on the inferred mass and spin distributions, we find no clear evidence for or against hierarchical mergers in GWTC-2.
5. We compute the rate of compact binary mergers, finding $\mathcal{R}_{\text{BNS}} = 320_{-240}^{+490} \text{ Gpc}^{-3} \text{ yr}^{-1}$ and $\mathcal{R}_{\text{BBH}} = 23.9_{-8.6}^{+14.9} \text{ Gpc}^{-3} \text{ yr}^{-1}$. The data are consistent with both a merger rate that is constant in time and one that tracks the SFR in the local universe, though the data prefer a merger rate that is somewhere in between. We find that the merger rate at $z = 1$ differs from the merger rate at $z = 0$ by a factor of $\mathcal{R}_{\text{BBH}}(z = 1)/\mathcal{R}_{\text{BBH}}(z = 0) = 2.5_{-1.9}^{+7.8}$, to be compared with the SFR, $\mathcal{R}_{\text{SFR}}(z = 1)/\mathcal{R}_{\text{SFR}}(z = 0) \sim 6$.

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 BBH mergers in the high-mass gap: hierarchical mergers, stars producing remnants heavier than expected from pair instability supernovae theory, or something else? What is the shape of the mass spectrum between NS and black hole masses, and does the current dearth of systems between $\sim 3 M_{\odot}$ and $\sim 6 M_{\odot}$ represent an empty low-mass gap? If so, do systems like the secondary mass of GW190814 belong to the neutron-star or black-hole side of the gap? Is the observation of anti-aligned spins indicative of dynamically assembled binaries? As the sensitivity of LIGO, Virgo, and Kagra improves, and as more gravitational-wave transients are detected, we expect to begin to answer these questions.

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APPENDIX

A. ESTIMATING THE DETECTION FRACTION

A key ingredient in Eqs. (1) and (2) is the “detection fraction” $\xi(\Lambda)$, the fraction of systems within some prior volume (redshift $z < 2.3$) that we expect to successfully detect. The detection fraction quantifies selection biases, and so it is critical to accurately characterize. For a population described by hyper-parameters Λ , the detection fraction is

$$\xi(\Lambda) = \int P_{\text{det}}(\theta)\pi(\theta|\Lambda)d\theta. \quad (\text{A1})$$

Here, $P_{\text{det}}(\theta)$ is the “detection probability”: the probability that an event with parameters θ is detectable. The detection probability depends primarily on the masses and redshift of a system, and, to a lesser degree, on the spins.

We calculate $\xi(\Lambda)$ using injections. We simulate compact binary signals from a reference population and record which ones are successfully detected by the PyCBC and GstLAL search pipelines; see Abbott et al. (2020d). Following Tiwari (2018); Farr (2019); Vitale (2020); Loredano (2004), the point estimate for Eq. A1 is calculated using a Monte Carlo integral over found injections:

$$\hat{\xi}(\Lambda) = \frac{1}{N_{\text{inj}}} \sum_{j=1}^{N_{\text{found}}} \frac{\pi(\theta_j | \Lambda)}{p_{\text{draw}}(\theta_j)}, \quad (\text{A2})$$

where N_{inj} is the total number of injections, N_{found} are the injections that are successfully detected, and p_{draw} is the probability distribution from which the injections are drawn; see LIGO-Virgo (2020) for additional details. When sampling the population likelihood, we marginalize over the uncertainty in $\hat{\xi}(\Lambda)$ following Farr (2019), and ensure that the effective number of found injections remaining after population re-weighting is sufficiently high ($N_{\text{eff}} > 4N_{\text{det}}$).

For the O3a observing period, we use the injection campaign described in Abbott et al. (2020d) and characterize the found injections as those recovered with a FAR below our threshold of 1/yr in either PyCBC or GstLAL. For the O1 and O2 observing period, we supplement the O3a pipeline injections with mock injections drawn from the same distribution p_{draw} above. For the mock injections, we calculate $P_{\text{det}}(m_1, m_2, z, \chi_{1,z}, \chi_{2,z})$ according to the semi-analytic approximation described in Abbott et al. (2019a), based on a single-detector SNR threshold $\rho = 8$ and the ADVANCED LIGO EARLY-HIGH NOISE PSD (Abbott et al. 2013). We combine O1, O2 and O3 injection sets ensuring a constant rate of injections across the total observing time, yielding $N_{\text{inj}} \approx 7.7 \times 10^7$ injections for O3a and $N_{\text{inj}} \approx 7.1 \times 10^7$ for O1 and O2. To control computational costs, not all of the injections are performed in real data. Before injecting, the expected network SNR of the injections is computed, and the “hopeless” injections with $\text{SNR} < 6$ are removed.

Due to the finite number of injections, we approximate Eq. A1 with a fixed spin distribution instead of the distribution implied by Λ . When combining the TRUNCATED, POWER LAW + PEAK, BROKEN POWER LAW and MULTI PEAK mass models together with the DEFAULT spin distribution, we assume that the aligned spin components $\chi_{1,z}, \chi_{2,z}$ are independently drawn from a uniform distribution $U(-0.5, 0.5)$. By making this approximation, we are in effect ignoring selection effects due to spin. Nevertheless, we expect this approximation to have a negligible impact on the inferred spin distribution compared to the statistical uncertainties. For aligned spin components in the range $(-0.5, 0.5)$, the detection probability varies by no more than a factor of 2 (Ng et al. 2018a). Furthermore, our main conclusions regarding the spin distribution inferred from the DEFAULT model are supported by the GAUSSIAN model, which requires no approximations for spin selection effects. The MULTI SPIN model calculates Eq. A1 by calibrating a semi-analytic approximation to the list of found injections (Wysocki 2020).

B. DETAILS OF MASS POPULATION MODELS

In this section we provide details about the population models described above in Section 3; see also Fig. 1. Each subsection includes a table with a summary of the parameters for that model and the prior distribution used for each parameter. The prior distributions are indicated using abbreviations: for example, $U(0, 1)$ translates to uniform on the interval $(0, 1)$ and $\text{LU}(10^{-6}, 10^5)$ translates to log-uniform on the interval $10^{-6}, 10^5$.

B.1. TRUNCATED *mass model*

This model is equivalent to “Model B” in Abbott et al. (2019a). The primary mass distribution for this model follows a power-law with spectral index α , and with a sharp cut-off at the lower end m_{min} and the upper end of the distribution

Parameter	Description	Prior
α	Spectral index for the power-law of the primary mass distribution.	U(-4, 12)
β_q	Spectral index for the power-law of the mass ratio distribution.	U(-4, 12)
m_{\min}	Minimum mass of the power-law component of the primary mass distribution.	U($2 M_{\odot}$, $10 M_{\odot}$)
m_{\max}	Maximum mass of the power-law component of the primary mass distribution.	U($30 M_{\odot}$, $100 M_{\odot}$)

Table 4. Summary of TRUNCATED parameters.

m_{\max} :

$$\pi(m_1 | \alpha, m_{\min}, m_{\max}) \propto \begin{cases} m_1^{-\alpha} & m_{\min} < m_1 < m_{\max} \\ 0 & \text{otherwise,} \end{cases} \quad (\text{B3})$$

Meanwhile, the mass ratio $q \equiv m_2/m_1$ follows a power-law distribution with spectral index β_q

$$\pi(q | \beta_q, m_{\min}, m_1) \propto \begin{cases} q^{\beta_q} & m_{\min} < m_2 < m_1 \\ 0 & \text{otherwise.} \end{cases} \quad (\text{B4})$$

The hyper-parameters for this model are summarized in Table 4.

B.2. POWER LAW + PEAK mass model

This is equivalent to ‘‘Model C’’ from [Abbott et al. \(2019a\)](#). It is motivated by the idea that the mass loss undergone by pulsational pair-instability supernovae could lead to a pile-up of BBH events before the pair-instability gap ([Talbot & Thrane 2018](#)). The primary mass distribution is an extension of TRUNCATED with the addition of tapering at the lower mass end of the distribution and a Gaussian component:

$$\pi(m_1 | \lambda_{\text{peak}}, \alpha, m_{\min}, \delta_m, m_{\max}, \mu_m, \sigma_m) = \left[(1 - \lambda_{\text{peak}}) \mathfrak{P}(m_1 | -\alpha, m_{\max}) + \lambda_{\text{peak}} G(m_1 | \mu_m, \sigma_m) \right] S(m_1 | m_{\min}, \delta_m). \quad (\text{B5})$$

Here, $\mathfrak{P}(m_1 | -\alpha, m_{\max})$ is a normalized power-law distribution with spectral index $-\alpha$ and high-mass cut-off m_{\max} . Meanwhile, $G(m_1 | \mu_m, \sigma_m)$ is a normalized Gaussian distribution with mean μ_m and width σ_m . The parameter λ_{peak} is a mixing fraction determining the relative prevalence of mergers in \mathfrak{P} and G . Finally, $S(m_1, m_{\min}, \delta_m)$ is a smoothing function, which rises from 0 to 1 over the interval $(m_{\min}, m_{\min} + \delta_m)$:

$$S(m | m_{\min}, \delta_m) = \begin{cases} 0 & (m < m_{\min}) \\ [f(m - m_{\min}, \delta_m) + 1]^{-1} & (m_{\min} \leq m < m_{\min} + \delta_m) \\ 1 & (m \geq m_{\min} + \delta_m) \end{cases} \quad (\text{B6})$$

with

$$f(m', \delta_m) = \exp\left(\frac{\delta_m}{m'} + \frac{\delta_m}{m' - \delta_m}\right). \quad (\text{B7})$$

Note that the conditional mass ratio distribution in this model also includes the smoothing term:

$$\pi(q | \beta, m_1, m_{\min}, \delta_m) \propto q^{\beta_q} S(qm_1 | m_{\min}, \delta_m). \quad (\text{B8})$$

The hyper-parameters for this model are summarized in Table 5.

In Fig. 16, we provide a corner plot representation of the posterior distribution for the POWER LAW + PEAK hyper-parameters. The $(\mu_m, \lambda_{\text{peak}})$ panel describes the Gaussian component: μ_m is the center of the Gaussian while λ_{peak} is the fraction of mergers taking place in the Gaussian (as opposed to the power-law distribution). Judging from this panel, it appears at first that λ_{peak} peaks close to 0 (corresponding to no Gaussian peak). However, if we zoom in as in Fig. 6, we see that the posterior for λ_{peak} is peaked clearly away from zero at ~ 0.02 . This is consistent with the large Bayes factor indicating preference for POWER LAW + PEAK over TRUNCATED.

Parameter	Description	Prior
α	Spectral index for the power-law of the primary mass distribution.	U(-4, 12)
β_q	Spectral index for the power-law of the mass ratio distribution.	U(-4, 12)
m_{\min}	Minimum mass of the power-law component of the primary mass distribution.	U($2 M_{\odot}$, $10 M_{\odot}$)
m_{\max}	Maximum mass of the power-law component of the primary mass distribution.	U($30 M_{\odot}$, $100 M_{\odot}$)
λ_{peak}	Fraction of BBH systems in the Gaussian component.	U(0, 1)
μ_m	Mean of the Gaussian component in the primary mass distribution.	U($20 M_{\odot}$, $50 M_{\odot}$)
σ_m	Width of the Gaussian component in the primary mass distribution.	U($0.4 M_{\odot}$, $10 M_{\odot}$)
δ_m	Range of mass tapering at the lower end of the mass distribution.	U($0 M_{\odot}$, $10 M_{\odot}$)

Table 5. The parameters that describe the BBH mass distribution for Model POWER LAW + PEAK.

Parameter	Description	Prior
α_1	Power-law slope of the primary mass distribution for masses below m_{break} .	U(-4, 12)
α_2	Power-law slope for the primary mass distribution for masses above m_{break} .	U(-4, 12)
β_q	Spectral index for the power-law of the mass ratio distribution.	U(-4, 12)
m_{\min}	Minimum mass of the power-law component of the primary mass distribution.	U($2 M_{\odot}$, $10 M_{\odot}$)
m_{\max}	Maximum mass of the primary mass distribution.	U($30 M_{\odot}$, $100 M_{\odot}$)
b	The fraction of the way between m_{\min} and m_{\max} at which the primary mass distribution breaks, e.g. a break fraction of 0.4 between $m_{\min} = 5$ and $m_{\max} = 85$ means the break occurs at $m_1 = 32$.	U(0, 1)
δ_m	Range of mass tapering on the lower end of the mass distribution.	U($0 M_{\odot}$, $10 M_{\odot}$)

Table 6. Summary of BROKEN POWER LAW parameters.

B.3. BROKEN POWER LAW *mass model*

This model is an extension of TRUNCATED. The primary mass distribution consists of a broken power-law. This is motivated by the potential tapering of the primary mass distribution at high masses. Also, the model employs a smoothing function to prevent a sharp cut-off at low masses.

$$\pi(m_1 | \alpha_1, \alpha_2, m_{\min}, m_{\max}) \propto \begin{cases} m_1^{-\alpha_1} S(m_1 | m_{\min}, \delta_m) & m_{\min} < m_1 < m_{\text{break}} \\ m_1^{-\alpha_2} S(m_1 | m_{\min}, \delta_m) & m_{\text{break}} < m_1 < m_{\max} \\ 0 & \text{otherwise.} \end{cases} \quad (\text{B9})$$

Here,

$$m_{\text{break}} = m_{\min} + b(m_{\max} - m_{\min}), \quad (\text{B10})$$

is the mass where there is a break in the spectral index and b is the fraction of the way between m_{\min} and m_{\max} at which the primary mass distribution undergoes a break. Meanwhile, $S(m_1, m_{\min}, \delta_m)$ is a smoothing function as in Eq. B6. The conditional mass ratio distribution is the same as in the POWER LAW + PEAK model; see Eq. B8. The hyper-parameters for this model are summarized in Table 6. In Fig. 17 we provide a corner plot for BROKEN POWER LAW. In the limit of no low-mass smoothing ($\delta_m = 0$), and in the limit of a second power-law with a steep slope that mimics a sharp cutoff ($m_{\text{break}} = m_{\max}$), this model reduces to TRUNCATED. Above, we noted that the BROKEN POWER LAW model prefers a break in the primary mass spectrum near $40 M_{\odot}$. On the other hand, if we believe that the feature represented by m_{break} should be closer to a sharp cutoff, then the cut-off must occur at higher masses approaching the maximum mass of TRUNCATED at $m_{\max} = 74.6^{+15.4}_{-8.6} M_{\odot}$. This can be seen by the correlation between b and α_2 in Fig. 17.

B.4. MULTI PEAK *mass model*

This model is an extension of POWER LAW + PEAK, where there is an additional Gaussian component at the upper end of the mass distribution motivated by a possible subpopulation of objects in the upper mass gap:

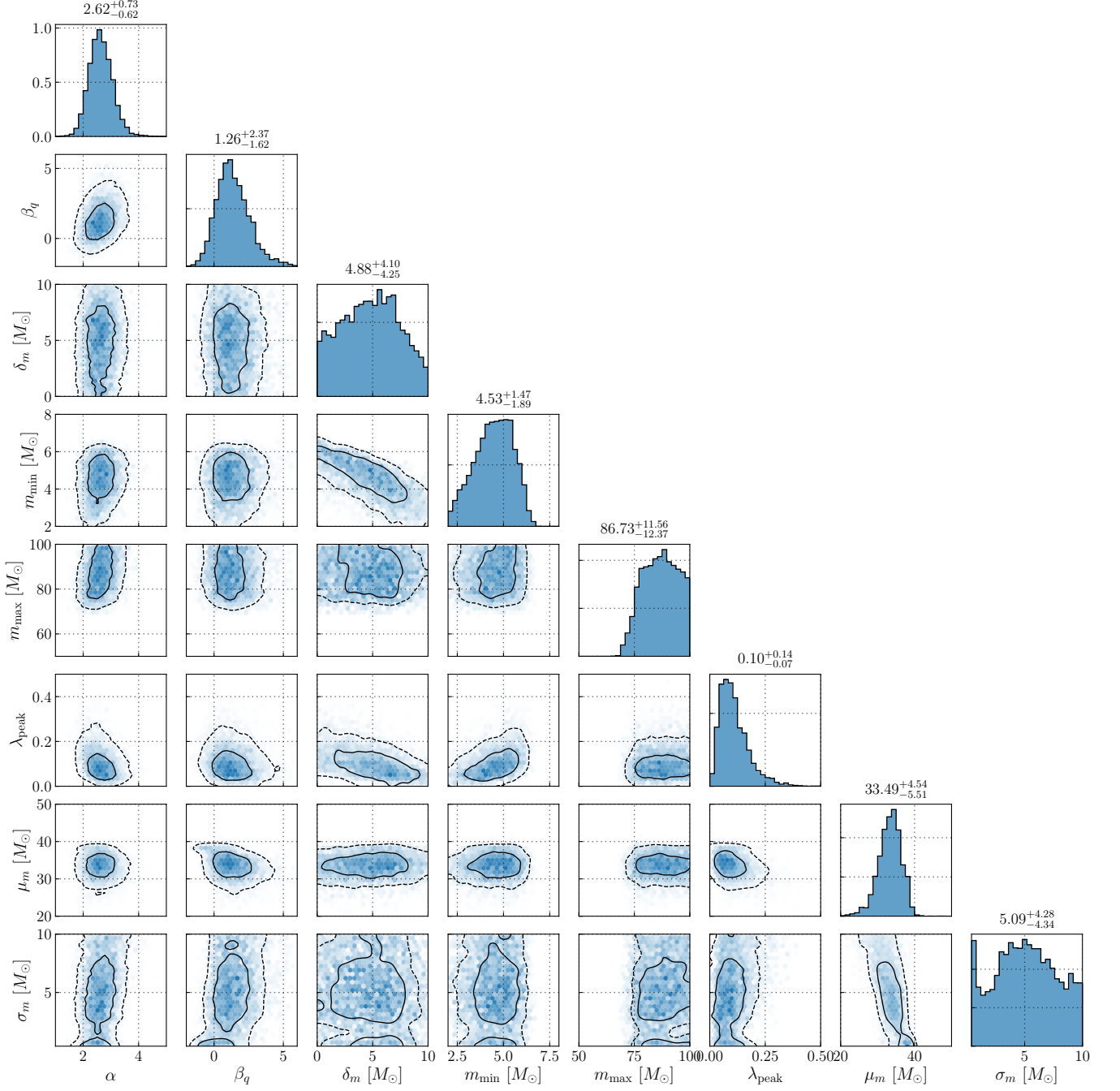


Figure 16. Posterior distribution for mass hyper-parameters for POWER LAW + PEAK. The fit excludes the extreme-mass-ratio event, GW190814. The contours represent 50% and 90% credible bounds.

$$\pi(m_1 | \lambda, \alpha, m_{\min}, \delta_m, m_{\max}, \mu_m, \sigma_m) = \left[(1 - \lambda) \mathfrak{P}(m_1 | -\alpha, m_{\max}) + \lambda \lambda_1 G(m_1 | \mu_{m,1}, \sigma_{m,1}) + \lambda (1 - \lambda_1) G(m_1 | \mu_{m,2}, \sigma_{m,2}) \right] S(m_1 | m_{\min}, \delta_m). \quad (\text{B11})$$

Here, the parameters λ and λ_1 correspond to the fraction of binaries in any Gaussian component and the fraction of binaries in the lower-mass Gaussian of the Gaussian components, respectively. The distribution $G(m_1 | \mu_{m,1}, \sigma_{m,1})$ is a normalized Gaussian distribution for the lower-mass peak with mean $\mu_{m,1}$ and width $\sigma_{m,2}$ and $G(m_1 | \mu_{m,2}, \sigma_{m,1})$ is a

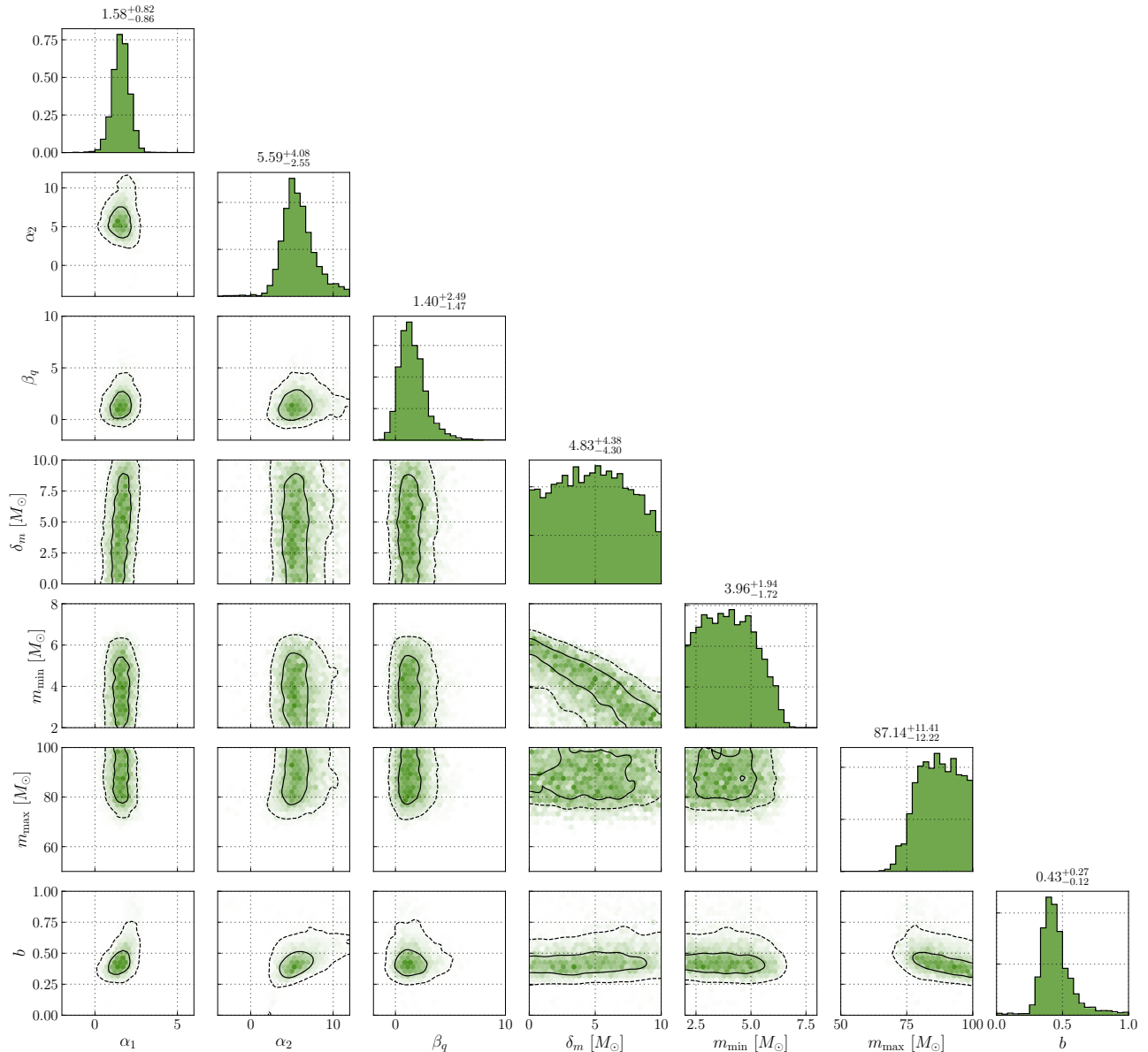


Figure 17. Posterior distribution for mass hyper-parameters for BROKEN POWER LAW. The fit excludes the extreme-mass-ratio event, GW190814. The contours represent 50%, 90% credible bounds.

normalized Gaussian distribution for the upper-mass peak with mean $\mu_{m,2}$ and width $\sigma_{m,2}$. The hyper-parameters for this model are summarized in Table 7. In Fig. 18, we provide a posterior predictive check for all of the mass models used in this analysis.

C. MASS MODEL CHECKING

Section 5.1 describes the inferred mass distribution obtained with the TRUNCATED, BROKEN POWER LAW, POWER LAW + PEAK, and MULTI PEAK models, and compares the different models by calculating their Bayes factors. Here we assess the goodness-of-fit of the models using posterior predictive checks, comparing predicted and empirical catalogs of observed m_1 distributions in Fig. 18. The light colored bands show the cumulative distribution of m_1 as predicted by the model, while the darker bands show the empirical distribution based on the actual events observed in GWTC-2. The bands represent a family of curves, where each curve corresponds to a different draw from the population hyper-posterior. Each draw from the hyper-posterior updates both the predicted distribution (in the lighter color) and the empirical distribution (in the darker color), as the individual event posteriors are updated according to the inferred population

Parameter	Description	Prior
α	Spectral index for the power-law of the primary mass distribution.	U(-4, 12)
β_q	Spectral index for the power-law of the mass ratio distribution.	U(-4, 12)
m_{\min}	Minimum mass of the power-law component of the primary mass distribution.	U($2 M_{\odot}$, $10 M_{\odot}$)
m_{\max}	Maximum mass of the power-law component of the primary mass distribution.	U($30 M_{\odot}$, $100 M_{\odot}$)
λ	Fraction of BBH systems in the Gaussian components.	U(0, 1)
λ_1	Fraction of BBH systems in the lower-mass Gaussian peak of the Gaussian components.	U(0, 1)
$\mu_{m,1}$	Mean of the lower-mass Gaussian component in the primary mass distribution.	U($20 M_{\odot}$, $50 M_{\odot}$)
$\sigma_{m,1}$	Width of the lower-mass Gaussian component in the primary mass distribution.	U($0.4 M_{\odot}$, $10 M_{\odot}$)
$\mu_{m,2}$	Mean of the upper-mass Gaussian component in the primary mass distribution.	U($50 M_{\odot}$, $100 M_{\odot}$)
$\sigma_{m,2}$	Width of the upper-mass Gaussian component in the primary mass distribution.	U($0.4 M_{\odot}$, $10 M_{\odot}$)
δ_m	Range of mass tapering on the lower end of the mass distribution.	U($0 M_{\odot}$, $10 M_{\odot}$)

Table 7. Parameters for the BBH mass distribution for Model MULTI PEAK.

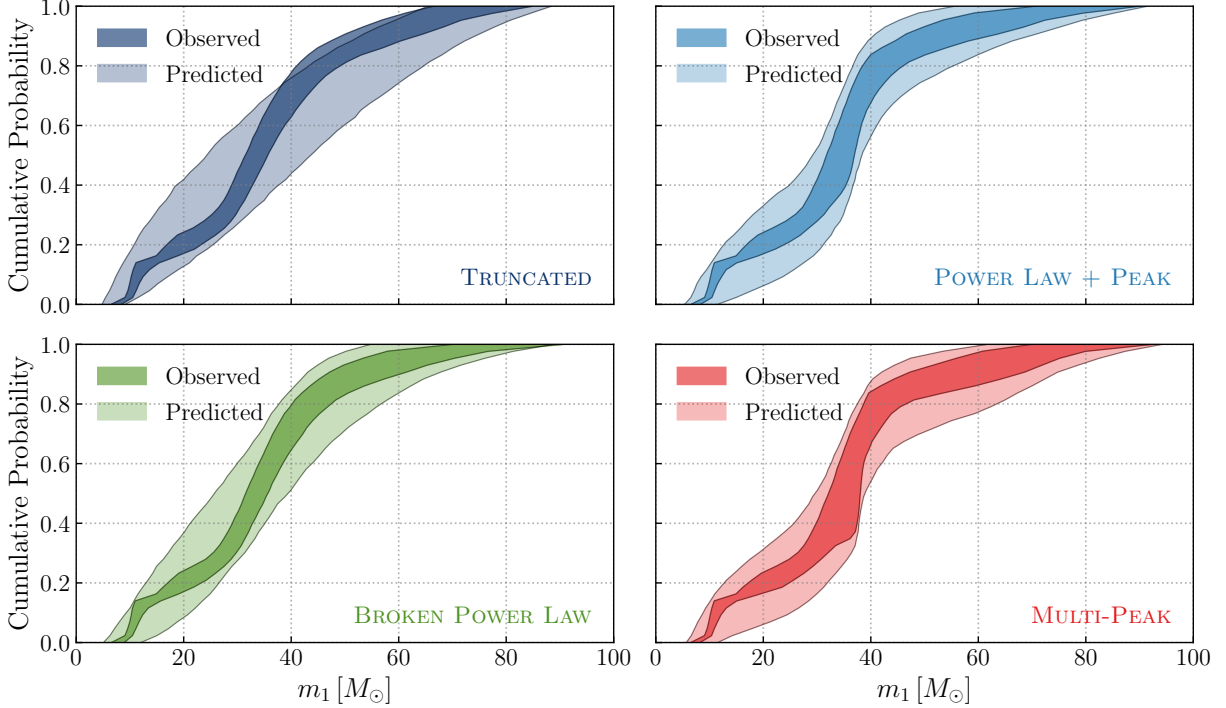


Figure 18. A posterior predictive check: the cumulative density function (CDF) of the observed primary mass distribution for the TRUNCATED, POWER LAW + PEAK, BROKEN POWER LAW and MULTI PEAK models. The observed event distribution is shown in the darker colors. The thickness of the bands indicates the 90% credibility range. The POWER LAW + PEAK, BROKEN POWER LAW and MULTI PEAK models are a better fit than the TRUNCATED model; the dark band overlaps entirely with the light colored band. This is due to the POWER LAW + PEAK, BROKEN POWER LAW and MULTI PEAK models having more flexibility to fit the relative excess of binaries in the $30 M_{\odot}$ – $40 M_{\odot}$ region compared to the $\gtrsim 40 M_{\odot}$ region. The extreme-mass-ratio event, GW190814, is excluded from this analysis.

distribution (Fishbach et al. 2020b; Galadage et al. 2019; Miller et al. 2020). If the model is a good fit to the data, the dark colored bands should overlap with the light colored bands. Figure 18 shows the relatively poor fit for the TRUNCATED model, which cannot capture the excess of events at ~ 30 – $40 M_{\odot}$ compared to $\gtrsim 40 M_{\odot}$. The remaining panels show the improved fits with the POWER LAW + PEAK, BROKEN POWER LAW and MULTI PEAK models. These results are consistent with the Bayes factors in Table 2, which conclude that the TRUNCATED model is disfavored by a Bayes factor of 10–80 relative to the other models.

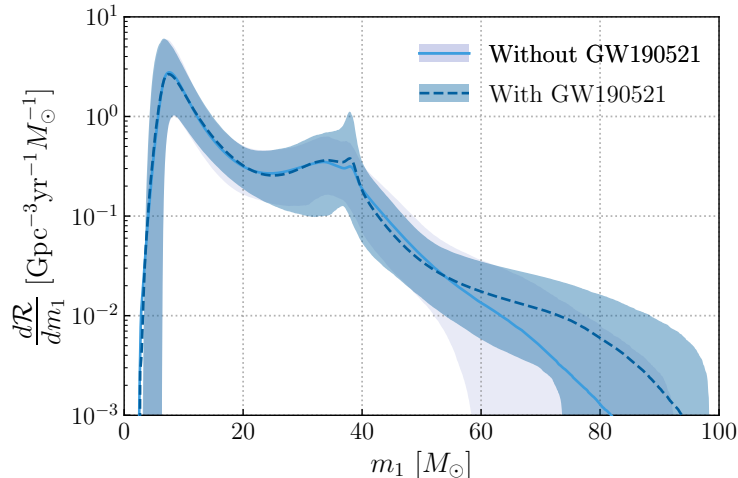


Figure 19. A comparison of the primary black hole mass distribution for the population with and without GW190521. The data are fit using the POWER LAW + PEAK model; the BROKEN POWER LAW model produces similar results. The solid curves are the posterior predictive distributions while the shaded regions show the 90% credible interval. The inclusion/exclusion of GW190521 does not have a significant effect on the fit. GW190814 is excluded from this analysis.

C.1. On GW190412

Other than GW190814, we find that GW190412 (Abbott et al. 2020b), when analyzed with a population informed prior, remains the only system for which we can confidently bound the mass ratio away from unity, yielding $q < 0.55$ at 99% credibility (using the POWER LAW + PEAK mass model). All other events, when analyzed with a population-informed prior, are consistent with $q = 1$ at 99% credibility. Repeating the analysis in Abbott et al. (2020b), we perform a leave-one-out analysis without GW190412 and find $\beta_q = 3.2^{+6.1}_{-2.7}$ ($\beta_q = 4.5^{+5.9}_{-3.5}$) for the POWER LAW + PEAK (BROKEN POWER LAW) model. The β_q posterior inferred with the inclusion of GW190412 ($\beta_q = 1.3^{+2.4}_{-1.6}$ for the POWER LAW + PEAK model; $\beta_q = 1.4^{+2.5}_{-1.5}$ for the BROKEN POWER LAW model) has moderate ($\sim 50\%$) overlap with the leave-one-out β_q posterior, indicating that, consistent with the conclusion in Abbott et al. (2020b), GW190412 likely belongs to the low mass ratio tail of the distribution rather than a distinct subpopulation of asymmetric systems.

C.2. On GW190521

As discussed in Section 5.1, the most massive event, GW190521 (Abbott et al. 2020e), is an outlier with respect to the TRUNCATED model (see Fig. 2), but fits well within the mass distributions inferred from the other models. In Fig. 19, we show the effect of GW190521 on the primary mass distribution. This event shifts the best-fit mass distribution, but this shift is within the statistical uncertainties. Thus, we find no evidence that GW190521 is an outlier within the framework of the POWER LAW + PEAK and BROKEN POWER LAW mass models. This finding is supported by the posterior predictive check in subsection C.4. In Fig. 20, we show how the primary mass posterior distribution for GW190521 changes when we use the POWER LAW + PEAK model to inform our prior. While the population-informed posterior on the primary mass prefers smaller masses (Fishbach et al. 2020b), the conclusion that the primary mass of GW190521 is above $69 M_\odot$ (99% credibility) is robust to the choice of prior, consistent with the claims in Abbott et al. (2020e).

C.3. On GW190814

On the other hand, we see clear indication that GW190814 is an outlier with respect to the BBH population within the framework of the POWER LAW + PEAK and BROKEN POWER LAW mass models, as discussed in Section 5.1. As an additional posterior predictive check, following the analysis described in Fishbach et al. (2020b) and Abbott et al. (2020b), we use the posterior predictive distribution, inferred without GW190814, to construct a distribution for the minimum m_2 detected in a sample of 45 events. When using both the POWER LAW + PEAK and BROKEN POWER LAW models, we find that the observation of a system with a secondary mass equal to or smaller than the that of GW190814 ($2.59^{+0.08}_{-0.09} M_\odot$) is highly improbable, with probability $< 0.02\%$ for both POWER LAW + PEAK and BROKEN POWER LAW; see Fig. 21b for the distribution of the minimum observed secondary mass in a sample of 45 events predicted by

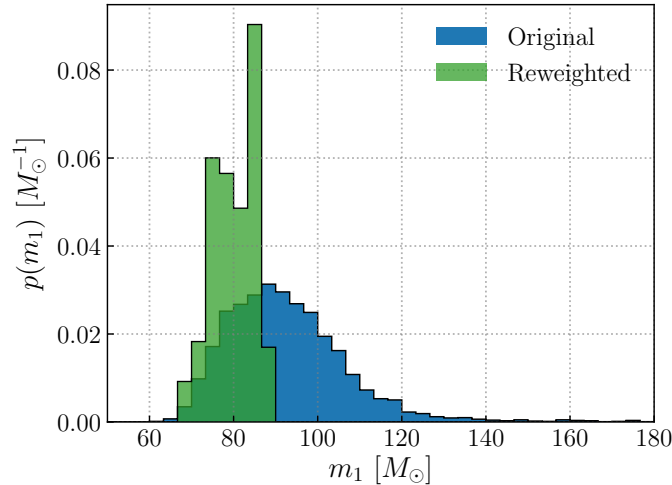


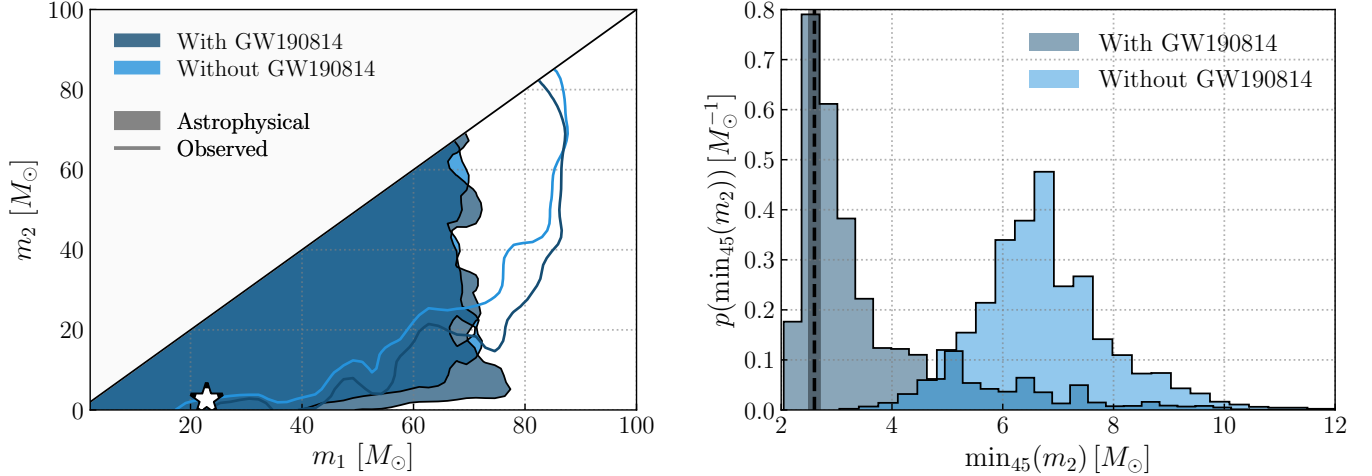
Figure 20. The posterior probability density for the primary mass of GW190521 using the original default prior (blue; flat in detector-frame masses) and a reweighted version (green) obtained by using the POWER LAW + PEAK mass model. Results using the BROKEN POWER LAW mass model are similar. The reweighted version shifts the posterior support to lower masses, with $m_1 < 86 M_\odot$ (99% credibility).

the POWER LAW + PEAK model. The distribution for BROKEN POWER LAW is qualitatively similar. The mass ratio of GW190814 is also somewhat unusual according to this posterior predictive check; see Fig. 21a. Observing an event with the mass ratio of GW190814 or smaller, based on the fit to the other 44 BBH events, has probability $< 0.02\%$ in both the POWER LAW + PEAK and BROKEN POWER LAW models. These posterior predictive checks suggest that GW190814 is not a typical BBH, and support the conclusion that there may be a dearth of systems between ~ 2.6 and $\sim 6 M_\odot$. Future observations will reveal the precise shape of the mass distribution at low masses and extreme mass ratios, and better determine the nature of GW190814.

C.4. Mass and distance checks with a burst analysis

The COHERENT WAVEBURST (cWB) pipeline (Klimenko & Mitselmakher 2004; Klimenko et al. 2016) is designed to detect unmodeled gravitational-wave transients also known as bursts. The cWB analysis resulted in the detection of 22 BBH events during O1, O2 and O3a. Among these detections is GW190521, which is remarkable for its large mass (Abbott et al. 2020e,f). As a posterior predictive check, we investigate whether the set of cWB observations is consistent with the model predictions. In particular, we examine whether GW190521 is an outlier in the context of our mass and redshift models. Following Klimenko et al. (2016), we calculate the expected distribution of the central frequency f and coherent signal-to-noise ratio ρ for two different population models: POWER LAW + PEAK and BROKEN POWER LAW, using the NON-EVOLVING redshift model. We then compare the empirical distribution of (f, ρ) , as recovered by the cWB pipeline to the distribution predicted by the population model. We quantify the comparison by calculating a p -value for each event i , which measures how unusual its observed (f_i, ρ_i) is, given the distribution of predicted (f, ρ) . The central frequency is a proxy for the detector-frame mass while the signal-to-noise ratio is a proxy for the distance.

To compute the predicted distribution of (f, ρ) , we inject simulated waveforms drawn from the POWER LAW + PEAK and BROKEN POWER LAW distributions into the O1, O2 and O3a data and compile injections recovered by cWB with a FAR $< 1 \text{ yr}^{-1}$. The central frequencies and coherent signal-to-noise ratios of the recovered injections generated according to POWER LAW + PEAK are plotted in Fig. 22. The results for BROKEN POWER LAW are similar. The locations of the 22 detections on this plane are visually consistent with the model predictions, indicating that the model is a reasonably good fit to the data. The event with the lowest p -value (least consistent with predictions) is GW190521, with p -values of 0.053 and 0.077 for the BROKEN POWER LAW model and the POWER LAW + PEAK model respectively. These p -values indicate that GW190521 is a moderately unusual detection, but it is consistent with the population models.

(a) The model-averaged astrophysical mass distribution $p(m_1, m_2)$.

(b) Observed minimum secondary mass distribution.

Figure 21. Left: the posterior population distribution for primary and secondary mass with and without the extreme-mass-ratio event GW190814. Shown here are the 99% credible intervals. Dark blue is with GW190814 and light blue is without. The shaded regions show the *astrophysical*, while the colored contours show the *observed* distribution (as it appears in the catalog due to selection effects). The median values of the posterior of GW190814 is marked with a star. Right: Distribution of the minimum secondary mass detected out of 45 detections, predicted from the fit to the POWER LAW + PEAK model to the BBH population excluding GW190814 (light blue) and the BBH population including GW190814 (dark blue). The dashed line and shaded region (gray) denote the median and 90% symmetric credible interval on the secondary mass of GW190814. This distribution is qualitatively similar to the distribution predicted from the fit to the BROKEN POWER LAW model.

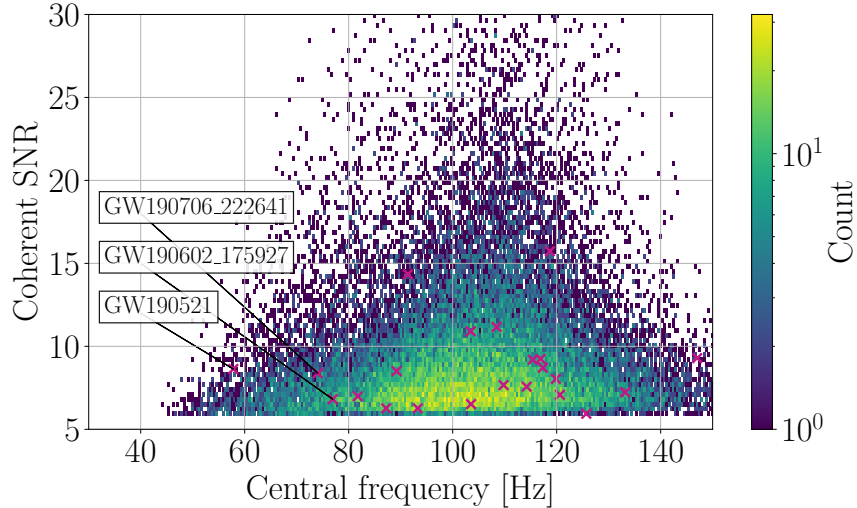


Figure 22. The coherent signal-to-noise ratio and central frequency for 22 BBH events detected by cWB in O1, O2 and O3a (violet dots) compared to simulated BBH events from the POWER LAW + PEAK model detected by cWB.

D. DETAILS OF SPIN POPULATION MODELS

D.1. DEFAULT *spin* model

This model was introduced in Abbott et al. (2019a). Following Wysocki et al. (2019a), the dimensionless spin magnitude distribution is taken to be a Beta distribution,

$$\pi(\chi_{1,2}|\alpha_\chi, \beta_\chi) = \text{Beta}(\alpha_\chi, \beta_\chi), \quad (\text{D12})$$

Parameter	Description	Prior
μ_χ	Mean of the Beta distribution of spin magnitudes.	U(0,1)
σ_χ^2	Variance of the Beta distribution of spin magnitudes.	U(0,0.25)
ζ	Mixing fraction of mergers from truncated Gaussian distribution.	U(0,1)
σ_t	Width of truncated Gaussian, determining typical spin misalignment.	U(0.01,4)

Table 8. Summary of DEFAULT spin parameters.

where α_χ and β_χ are the standard shape parameters that determine the distribution’s mean and variance. The Beta distribution is convenient because it is bounded on (0,1). The distributions for χ_1 and χ_2 are assumed to be the same. Following [Talbot & Thrane \(2017\)](#), we define $z = \cos \theta_{1,2}$ as the cosine of the tilt angle between component spin and a binary’s orbital angular momentum, and assume that z is distributed as a mixture of two populations:

$$\pi(z|\zeta, \sigma_t) = \zeta G_t(z|\sigma_t) + (1 - \zeta)\mathcal{I}(z). \quad (\text{D13})$$

Here, $\mathcal{I}(z)$ is an isotropic distribution, while $G_t(z|\sigma_t)$ is a truncated Gaussian, peaking at $z = 0$ (perfect alignment) with width σ_t . The mixing parameter ζ controls the relative fraction of mergers drawn from the isotropic distribution and Gaussian subpopulations. The isotropic subpopulation is intended to accommodate dynamically assembled binaries, while G_t is a model for field mergers. The hyper-parameters for this model and their priors are summarized in Table 8. Additional constraints to the priors on μ_χ and σ_χ^2 are applied by setting $\alpha_\chi, \beta_\chi > 1$.

In Fig. 23 we provide a corner plot for the DEFAULT spin model. This model prefers modest spin magnitudes. It favors the hypothesis that binaries are preferentially aligned ($\zeta \rightarrow 1$ and $\sigma_t \lesssim 2$), albeit with potentially large misalignment angles ($\sigma_t > 0$). The case of *perfect* alignment, which would correspond to $\zeta = 1$ and $\sigma = 0$, is disfavored, lying outside the 99% credible bound on ζ and σ_t . Within the main text, Fig. 10 shows the implied distributions of component spin magnitudes and tilt angles. The implied distributions of effective precessing (χ_p) and inspiral spins (χ_{eff}) are shown in Figs. 9 and 11, respectively; these distributions are in good agreement with the results obtained using the GAUSSIAN model described below. In particular, both models predict the existence of systems with anti-aligned spins (negative χ_{eff}), and in-plane spin components (non-zero χ_p).

D.2. GAUSSIAN spin model

The GAUSSIAN spin model offers an alternative description of BBH spins. It is convenient to measure the distribution of effective inspiral (χ_{eff}) and precessing (χ_p) spin parameters, which are better constrained than individual component spin magnitudes or tilts. We parameterize the distributions of χ_{eff} and χ_p , using a bivariate Gaussian:

$$\pi(\chi_{\text{eff}}, \chi_p | \mu_{\text{eff}}, \sigma_{\text{eff}}, \mu_p, \sigma_p, \rho) \propto G(\chi_{\text{eff}}, \chi_p | \boldsymbol{\mu}, \boldsymbol{\Sigma}). \quad (\text{D14})$$

The distribution has a mean $\boldsymbol{\mu} = (\mu_{\text{eff}}, \mu_p)$ and a covariance matrix

$$\boldsymbol{\Sigma} = \begin{pmatrix} \sigma_{\text{eff}}^2 & \rho \sigma_{\text{eff}} \sigma_p \\ \rho \sigma_{\text{eff}} \sigma_p & \sigma_p^2 \end{pmatrix}. \quad (\text{D15})$$

The population parameters appearing in Eqs. (D14) and (D15) and their associated priors are summarized in Table 9. We truncate and normalize Eq. (D14) based on the allowed regions of the effective inspiral spin parameters: $\chi_{\text{eff}} \in (-1, 1)$ and $\chi_p \in (0, 1)$. The results from the GAUSSIAN model are obtained assuming a TRUNCATED mass model with $\alpha = -2.2$, $\beta_q = 1.3$, $m_{\text{min}} = 5 M_\odot$, and $m_{\text{max}} = 75 M_\odot$, consistent with the median values obtained when fitting the TRUNCATED model to GWTC-2. We additionally assume a comoving merger rate density that grows as $(1 + z)^{2.7}$. Although the TRUNCATED model is disfavored relative to the more complex mass models discussed above, it is sufficient for purposes of constructing an informed mass ratio distribution, the primary confounding factor in efforts to measure χ_{eff} and χ_p ([Ng et al. 2018a](#)).

The marginal posterior distributions on μ_p and σ_p is shown in Fig. 9, while the marginal posterior on μ_{eff} and σ_{eff} is shown in Fig. 11. We find no correlation between the parameters of the χ_{eff} and χ_p distributions, nor do we obtain any information regarding the degree of correlation ρ between effective inspiral spin variables. As discussed in Sec. 5.2, analysis with the GAUSSIAN spin model suggests the BBH population exhibits non-vanishing χ_p , such

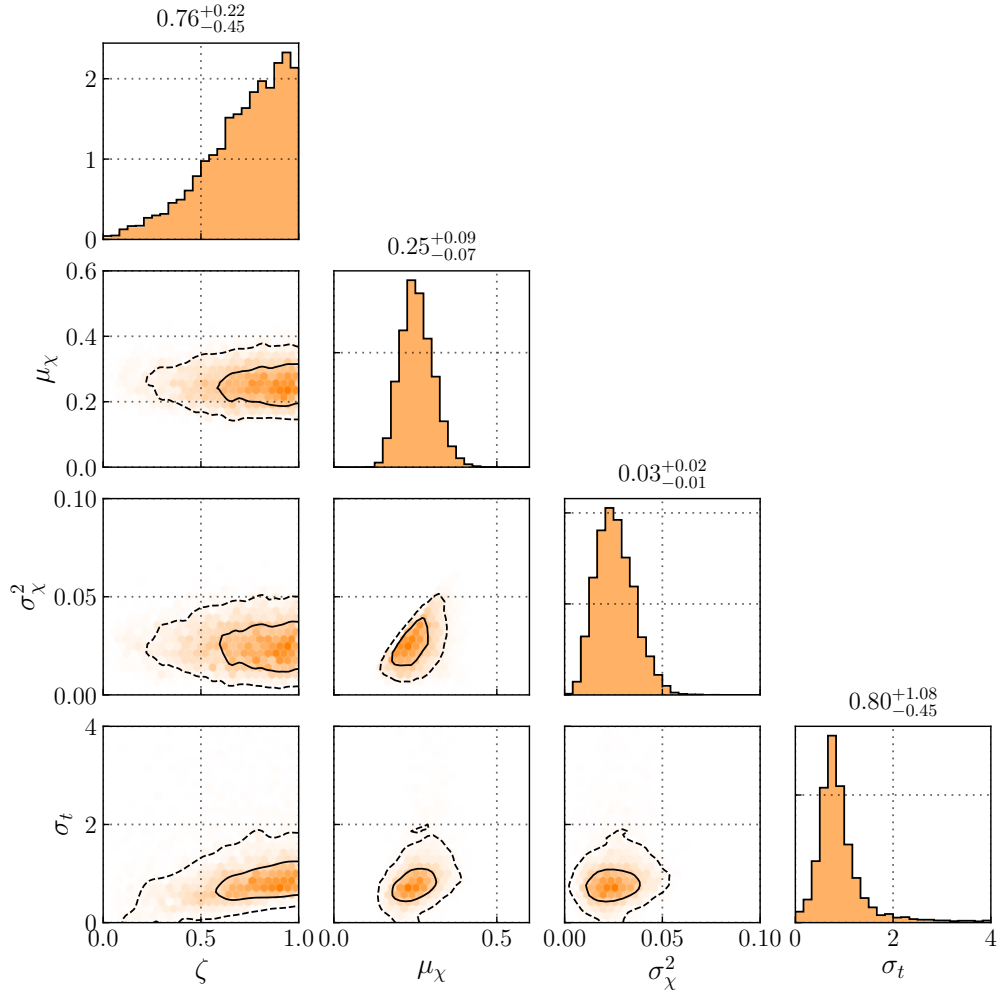


Figure 23. Posterior distribution for spin hyper-parameters for DEFAULT, assuming the POWER LAW + PEAK mass model and NON-EVOLVING redshift distribution. The fit excludes the extreme-mass-ratio event, GW190814. The contours represent 50%, 90% credible bounds. A *perfectly* aligned spin distribution ($\sigma_t = 0$, $\zeta = 1$) is ruled out at $> 99\%$ credibility, consistent with the results of the GAUSSIAN model, but the data disfavor a purely isotropic distribution ($\zeta = 0$ or $\sigma_t \gtrsim 2$).

Parameter	Description	Prior
μ_{eff}	Mean of the χ_{eff} distribution.	U(-1,1)
σ_{eff}	Standard deviation of the χ_{eff} distribution.	U(0.01,1)
μ_p	Mean of the χ_p distribution.	U(0.01,1)
σ_p	Standard deviation of the χ_p distribution.	U(0.01,1)
ρ	Degree of correlation between χ_{eff} and χ_p .	U(-0.75,0.75)

Table 9. Summary of GAUSSIAN spin parameters.

that $\mu_p = \sigma_p = 0$ is ruled out. Furthermore, we find strong evidence that at least some black holes have anti-aligned spins, with $\theta > 90^\circ$, such that $\chi_{\text{eff}} < 0$. To further evaluate the robustness of our GAUSSIAN model fits, in Fig. 24 we show posterior predictive comparisons between predicted and empirical catalogs of χ_{eff} and χ_p measurements. The light blue bands mark 90% credible bounds on the predicted cumulative distribution of observed effective inspiral spin parameters values, given our posterior on the GAUSSIAN model parameters. The dark shaded regions, meanwhile, show 90% credible bounds on the true distribution observed within GWTC-2, achieved by reweighting single event χ_{eff} and χ_p by repeated random draws from the GAUSSIAN hyper-posterior.

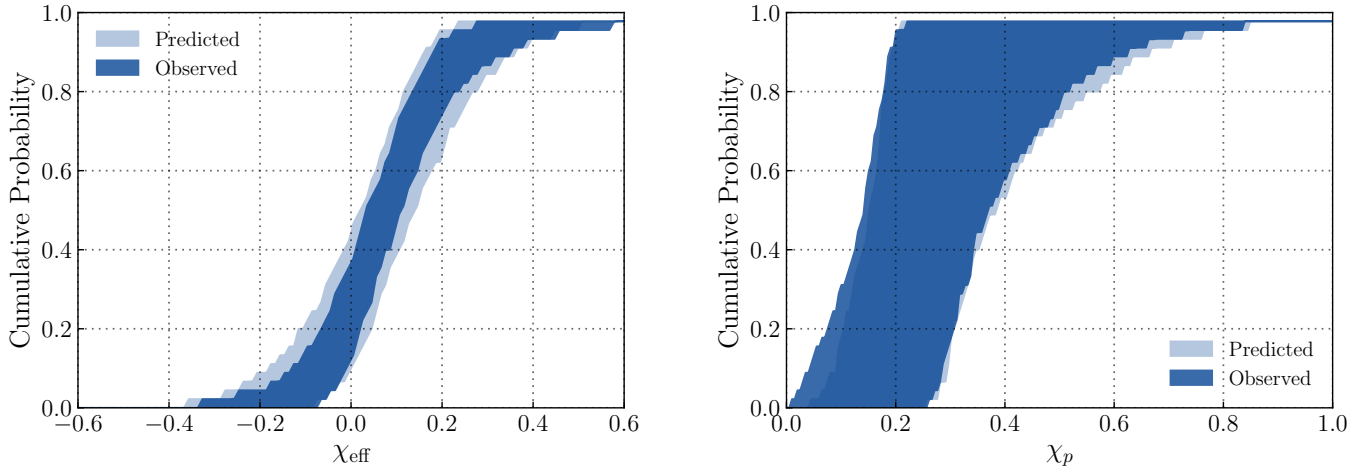


Figure 24. Population predictive checks for the effective aligned spin χ_{eff} (*left*) and effective precessing spin χ_p (*right*) of BBH mergers using the GAUSSIAN spin model. The light shaded regions show the central 90% credible bounds on the posterior predictive distributions. According to the model, we expect the observed distributions on χ_{eff} and χ_p to lie within the light shaded region 90% of the time. The dark shaded regions show the 90% credible bounds on the observed distributions in GWTC-2, found using the population-informed posteriors of the confident BBH events in GWTC-2. The overlap between the dark and light regions shows that the model passes the posterior predictive check. The results for the DEFAULT model are similar, indicating that both models are a good fit to the data.

There are several sources of possible bias that might influence our GAUSSIAN model conclusions. One possible source is the Gaussian functional form we impose on the χ_{eff} and χ_p distributions, enforcing a unimodal distribution with smooth tails. As discussed in Sect. 5.2, though, the DEFAULT spin model yields near-identical χ_{eff} and χ_p distributions, despite its different parametrization and different physical assumptions. Here, as an additional check, we repeat the GAUSSIAN spin analysis, truncating the χ_{eff} distribution not on $(-1, 1)$, but on $(\chi_{\text{eff}}^{\text{min}}, 1)$, where $\chi_{\text{eff}}^{\text{min}}$ is inferred from the data. Figure 25 shows the marginal posterior for $\chi_{\text{eff}}^{\text{min}}$. We find that $\chi_{\text{eff}}^{\text{min}}$ is constrained to be negative at 99% credibility, confirming that negative effective inspiral spins are a feature of the data and not simply an artifact of the GAUSSIAN model.

An alternative source of bias is the mass model presumed for the GAUSSIAN spin analysis. As noted above, measurements of a binary’s χ_{eff} and mass ratio q are generally anti-correlated (Ng et al. 2018a). Therefore, our particular choice of $\beta_q = 1.3$ could conceivably affect conclusions regarding the χ_{eff} distribution. We have directly verified that the results in Fig. 25 remain robust under different fiducial choices of β_q between -1.5 and 2 .

Finally, we have verified that prior effects do not spuriously lead to false-positive signatures of spin-induced precession. In particular, we verify that, upon replacing each event’s χ_p posterior samples with random draws from the spin prior (conditioned on the event’s χ_{eff} and q posteriors), we recover featureless posteriors in μ_p and σ_p . We further test our calculation via the injection and analysis of several mock BBH populations, both with and without negative χ_{eff} , and with vanishing and non-vanishing χ_p distributions. In all cases we draw the correct conclusions regarding the mock populations.

D.3. MULTI SPIN *model*

This model is an extension of the TRUNCATED mass model with an additional Gaussian component. It is similar to the POWER LAW + PEAK model, but there are several differences. First, the high-mass subpopulation in MULTI SPIN is described by a Gaussian in both m_1 and m_2 (up to the $m_1 \geq m_2$ truncation) while POWER LAW + PEAK only models m_1 as a Gaussian, and assumes that all BBH systems are described by a power-law distribution in mass ratio q . Most importantly, as its name suggests, MULTI SPIN allows each subpopulation to have its own independent spin distribution, each of which follows the DEFAULT model, with $\zeta = 1$. This allows us to probe whether the spin distribution varies with mass. The parameters for MULTI SPIN are summarized in Table 10.

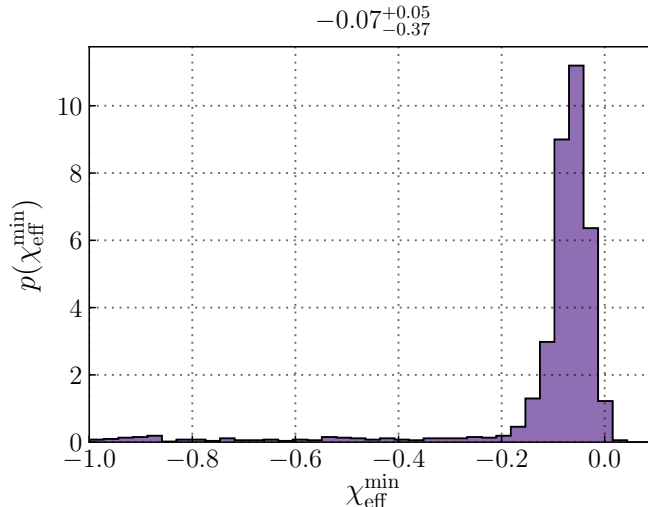


Figure 25. Posterior distribution for $\chi_{\text{eff}}^{\text{min}}$, below which we truncate the GAUSSIAN χ_{eff} distribution. While the results shown in the main text presume $\chi_{\text{eff}}^{\text{min}} = -1$, in Sec. D.2 we elevate $\chi_{\text{eff}}^{\text{min}}$ to a free hyper-parameter to be determined by the data; the resulting marginalized posterior distribution is shown here. In this case, we exclude $\chi_{\text{eff}}^{\text{min}} \geq 0$ at 99% credibility. This finding affirms that the signatures of anti-aligned BH spins are present in our BBH catalog, and not a bias due to our choice of parameterized spin model.

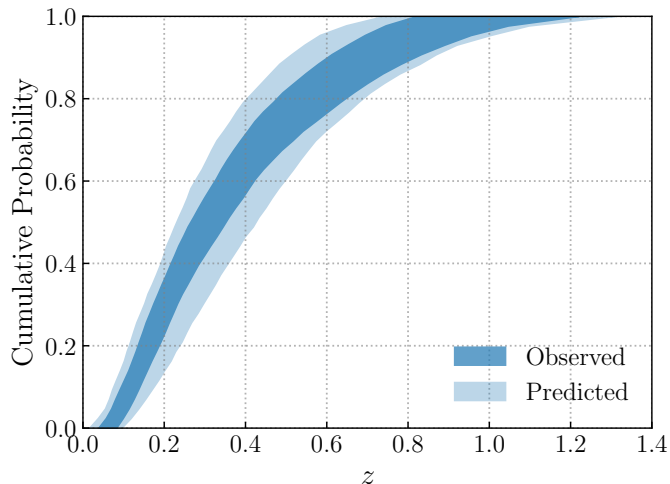


Figure 26. A posterior predictive check: the cumulative density function (CDF) for the POWER LAW EVOLUTION model. The model is a good fit to the data. The extreme-mass-ratio event, GW190814 is excluded from this analysis. ,

E. REDSHIFT EVOLUTION MODELS

The POWER-LAW redshift evolution model parameterizes the merger rate density as

$$\mathcal{R}(z) = \mathcal{R}_0(1+z)^\kappa, \quad (\text{E16})$$

where \mathcal{R}_0 denotes the merger rate density at $z = 0$. This implies that the redshift distribution is

$$\frac{dN}{dz} = \mathcal{C} \frac{dV_c}{dz} (1+z)^{\kappa-1}, \quad (\text{E17})$$

where dV_c/dz is the differential comoving volume, and \mathcal{C} is related to \mathcal{R}_0 by

$$\mathcal{R}_0 = \mathcal{C} \frac{dV_c}{dz} \left[\int_0^{z_{\text{max}}} \frac{dV_c}{dz} (1+z)^{\kappa-1} \right]^{-1}. \quad (\text{E18})$$

Parameter	Description	Prior
\mathcal{R}_{pl}	Local merger rate for the low-mass power-law subpopulation.	$U(0, 5000)$
\mathcal{R}_{g}	Local merger rate for the high-mass Gaussian subpopulation.	$U(0, 5000)$
α_m	Power-law slope of the primary mass distribution for the low-mass subpopulation.	$U(-4, 12)$
β_q	Power-law slope of the mass ratio distribution for the low-mass subpopulation	$U(-4, 10)$
m_{min}	Minimum mass of the primary mass distribution for the low-mass subpopulation.	$U(2, 10)$
m_{max}	Maximum mass of the primary mass distribution for the low-mass subpopulation.	$U(30, 100)$
μ_{m_1}	Centroid of the primary mass distribution for the high-mass subpopulation	$U(20, 50)$
σ_{m_1}	Width of the primary mass distribution for the high-mass subpopulation	$U(0.4, 10)$
μ_{m_2}	Centroid of the secondary mass distribution for the high-mass subpopulation	$U(20, 50)$
σ_{m_2}	Width of the secondary mass distribution for the high-mass subpopulation	$U(0.4, 10)$
$\text{Mean}\chi_{1,\text{pl}}$	Mean of the beta distribution of primary spin magnitudes for the low-mass subpopulation.	$U(0, 1)$
$\text{Var}\chi_{1,\text{pl}}$	Variance of the beta distribution of primary spin magnitudes for the low-mass subpopulation.	$U(0, 0.25)$
$\sigma_{1,\text{pl}}$	Width of the truncated Gaussian distribution of $\cos(\text{primary spin tilt angle})$ for the low-mass subpopulation.	$U(0, 4)$
$\text{Mean}\chi_{2,\text{pl}}$	Mean of the beta distribution of secondary spin magnitudes for the low-mass subpopulation.	$U(0, 1)$
$\text{Var}\chi_{2,\text{pl}}$	Variance of the beta distribution of secondary spin magnitudes for the low-mass subpopulation.	$U(0, 0.25)$
$\sigma_{2,\text{pl}}$	Width of the truncated Gaussian distribution of $\cos(\text{secondary spin tilt angle})$ for the low-mass subpopulation.	$U(0, 4)$
$\text{Mean}\chi_{1,\text{g}}$	Mean of the beta distribution of primary spin magnitudes for the high-mass subpopulation.	$U(0, 1)$
$\text{Var}\chi_{1,\text{g}}$	Variance of the beta distribution of primary spin magnitudes for the high-mass subpopulation.	$U(0, 0.25)$
$\sigma_{1,\text{g}}$	Width of the truncated Gaussian distribution of $\cos(\text{primary spin tilt angle})$ for the high-mass subpopulation.	$U(0, 4)$
$\text{Mean}\chi_{2,\text{g}}$	Mean of the beta distribution of secondary spin magnitudes for the high-mass subpopulation.	$U(0, 1)$
$\text{Var}\chi_{2,\text{g}}$	Variance of the beta distribution of secondary spin magnitudes for the high-mass subpopulation.	$U(0, 0.25)$
$\sigma_{2,\text{g}}$	Width of the truncated Gaussian distribution of $\cos(\text{secondary spin tilt angle})$ for the high-mass subpopulation.	$U(0, 4)$

Table 10. Summary of MULTI SPIN parameters.

We take $z_{\text{max}} = 2.3$ in the analysis, as this is a conservative upper bound on the redshift at which we could detect BBH systems during O3a within the mass range considered here. When fitting this model, we employ a uniform prior on κ centered at $\kappa = 0$. The value $\kappa = 0$ corresponds to no evolution; i.e., a merger rate that is uniform-in-comoving volume and source-frame time. We take a sufficiently wide prior so that the likelihood is entirely within the prior range, $\kappa \in (-6, 6)$.

F. GRAVITATIONAL-WAVE LENSING

It has been suggested that gravitational-wave lensing could bias the estimate of binary masses (Dai et al. 2017; Ng et al. 2018b; Li et al. 2018; Oguri 2018; Hannuksela et al. 2019), which could lead to a biased population inference. However, based on the predictions on the number of expected gravitational-wave sources and the distribution of galaxy lenses in the Universe, Li et al. (2018); Oguri (2018) predict that only around one in a thousand observed events are lensed, although this estimate can vary depending on the redshift evolution of the merger-rate density. The lensing rate

is expected to be similarly rare for galaxy clusters ([Smith et al. 2018](#)). As the expected lensing rate is low compared to the number of events in GWTC-2, we assume that all events in our sample are unlensed.