A search for intermediate-mass black holes mergers in the second LIGO–Virgo observing run with the Bayes Coherence Ratio

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The detection of an intermediate-mass black hole population ($10^2 - 10^6$ M$_\odot$) will provide clues to their formation environments (e.g., disks of active galactic nuclei, globular clusters) and illuminate a potential pathway to produce supermassive black holes. Ground-based gravitational-wave detectors are in principle sensitive to such mergers and have been used to detect one 142^{+28}_{-16} M$_\odot$ intermediate-mass black hole formation event. Ground-based detector data contain numerous short-duration noise transients that can mimic the gravitational-wave signals from merging intermediate-mass black holes, limiting the sensitivity of searches. Here we demonstrate a Bayesian-inspired ranking statistic to detect binary black hole mergers with a total mass $\gtrsim 55$ M$_\odot$. We use this statistic to identify candidate events with total masses > 55 M$_\odot$ using data from LIGO's second observing run. Our analysis does not yield evidence for new intermediate-mass black holes. However, we find support for some stellar-mass binary black holes not reported in the first LIGO–Virgo gravitational-wave transient catalog, GWTC-1.

I. INTRODUCTION

A variety of techniques have been employed to search for $10^4 - 10^6$ M$_\odot$ intermediate-mass candidates including reverberation mapping [1], direct kinematic measurements [2, 3], applying macroscopic galaxy to black hole mass scaling relations (M_{BH}-σ and M_{BH}-L relations) [4, 5], studying X-ray luminosity and spectra [6, 7], gravitational lensing of gamma-ray burst light curves [8], and others [9–11]). However, because intermediate-mass black holes have smaller gravitational spheres of influence than those of supermassive black holes, it is much more challenging to observe them with these observational techniques [11]. Additionally, the numerous intermediate-mass black hole candidates discovered using these techniques are ambiguous as other sources can describe observations from the candidates (e.g., light sources orbiting clusters of stellar-mass black holes [12, 13], anisotropic emission from neutron stars [14, 15]).

Stellar mass ($M_{\rm BH} < 10^2$ M$_\odot$) and supermassive black holes ($M_{\rm BH} > 10^6$ M$_\odot$) have been observed and well studied since the 1970s [16–22]. However, there is a deficiency of observational evidence for black holes in the intermediate-mass range $10^2 - 10^6$ M$_\odot$. The discovery of an intermediate-mass black hole population will bridge this observational gap, probe intermediate-mass formation environments (e.g. accretion disks of active galactic nuclei [23–35], the centers of dense stellar clusters [36–46], Population-III stars [47–51]), and illuminate our understanding of supermassive black hole formation [52–55].

Compact binary coalescences (CBCs) can provide unambiguous gravitational-wave signals for intermediate-mass candidates e.g., the 142^{+28}_{-16} M$_\odot$ remnant observed from the gravitational-wave event GW190521 [56] and other candidates [57–59]. As a binary's total mass M$_T$ is associated with its gravitational-wave merger frequency, $f \sim$ M$_T^{-1}$, ground-based gravitational-wave detectors ($f \sim 10^1 - 10^3$ Hz) are sensitive to the last milliseconds of merging systems with 100M$_\odot <$ M$_T < 400$M$_\odot$ [60–62], while space-based detectors ($f \sim 10^{-2} - 10^1$ Hz) can study the full signals of merging systems with 10^4M$_\odot <$ M$_T < 10^7$M$_\odot$ [62, 63]. Because of the short-duration of intermediate-mass gravitational-wave signals in ground-based detectors, data quality is critical for their detection. Gravitational-wave data is characterized by numerous non-stationary terrestrial artifacts called *glitches* [64–66]. Like signals from intermediate mass mergers, most glitches last for a fraction of a second, making them difficult to distinguish from astrophysical signals. These glitches can decrease the sensitivity of searches for binary black hole mergers with total masses > 55 M$_\odot$ [64].

Although a significant fraction of the glitches can be identified by testing them for coherence amongst two or more detectors and performing matched-filtering, these methods are insufficient to identify all glitches [64–66]. One method to discriminate more glitches while searching for CBC is the Bayesian odds [67–72]. The Bayesian Coherence Ratio $\rho_{\rm BCR}$ [69, 70] is a Bayesian odds comparing the probability that the data contains coherent signals vs. incoherent glitches. In this paper, we the $\rho_{\rm BCR}$ to rank O2's candidate gravitational-wave signals from $55 - 500$ M$_\odot$ (detector-frame) total mass systems. For each candidate, we calculate the probability of astrophysical origin, $p_{\rm S}$ and compare to candidate events reported by other authors including the LIGO-Virgo-KAGRA (LVK) collaboration in GWTC-1 [73], the Py-

CBC-team [74–83], by the Institute of Advanced study's team (IAS) [84–86], or by Pratten and Vecchio [72].

We find that (a) high-mass events reported in the GWTC-1, including GW170729 (the heaviest event in GWTC-1) are very statistically significant $p_{\rm S} > 0.9$; (b) three out of the eight IAS events and candidates have $p_{\rm S} > 0.5$, corroborating IAS's detection claims for GW170304, GW170727, and GW170817A; and that (c) our ranking statistic does not identify any new intermediate-mass black holes, but does identify an unreported marginal stellar-mass binary black hole candidate, 170222 with $p_{\rm S} \sim 0.5$.

The remainder of this paper is structured as follows. We outline our methods, including details of our ranking statistic and the retrieval of our candidates in Section II. We present details on the implementation of our analysis in Section III. Finally, we present our results in Section IV and discuss these results in the context of the significance of gravitational-wave candidates in Section V.

II. METHOD

A. A Bayesian Ranking Statistic

The standard framework to identify CBC gravitational-wave signals in data is to quantify the significance of candidates with null-hypothesis significance testing [73, 87]. In this framework, the candidates' ranking statistic is compared against a background distribution. The independent matched-filter searches, e.g., PyCBC [79], SPIIR [88] and GstLAL [89], and Coherent WaveBurst [90] used by LVK to search for signals in gravitational-wave data all use ranking statistics in such a manner [73]. Both PyCBC and GstLAL's ranking statistic incorporate information about the relative likelihood that the data contains a coherent signal versus noise. In contrast, cWB's ranking statistic uses the information of coherent energy present in the network of detectors [73].

Bayesian inference offers an alternative means to rank the significance of candidate events by computing the odds that the data contain a transient gravitational-wave signal versus instrumental glitches [69]. This method relies on accurate models for the signal and glitch morphologies [69]. In principle, Bayesian odds is the optimal method for hypothesis testing [70]. Much of its power comes from the Bayesian evidence, the likelihood of the data given a hypothesis. However, the evidence is not used in current matched filter searches. Here, we explore a hybrid frequentist/Bayesian ranking statistic that makes use of the Bayesian evidence. We compute the Bayesian evidence under the assumption that they either contain a coherent gravitational-wave signal, noise, or a glitch (Z^S, Z^N, Z^G, defined in Appendix A). However, instead of computing true Bayesian odds, we use the evidences as a ranking statistic. We form a bootstrapped distribution of the evidence for simulated foreground and background events in order to form a frequentist ranking statistic.

B. Formalism

Introduced by Isi *et al.* [69], the Bayesian Coherence Ratio for a candidate signal in a network of D detectors is given by

$$\rho_{\rm BCR} = \frac{\hat{\pi}^S Z^S}{\prod_{i=1}^{D} \left[\hat{\pi}^G Z_i^G + \hat{\pi}^N Z_i^N\right]} , \tag{1}$$

where $\{\hat{\pi}^S, \hat{\pi}^N, \hat{\pi}^G\}$ are estimates of the astrophysical prior-odds of obtaining a signal, noise or a glitch from a stretch of data. In the limit where the estimated prior-odds equal the astrophysical prior-odds, the $\rho_{\rm BCR}$ becomes the optimal Bayesian odds described by Ashton *et al.* [70]. However, as the astrophysical prior-odds are unknown, it is invalid to use the $\rho_{\rm BCR}$ as an odds-ratio to discriminate signals from glitches. Instead, we use the $\rho_{\rm BCR}$ as a ranking statistic to obtain a frequentist significance of a candidate $\rho_{\rm BCR}$-value, $\rho^c_{\rm BCR}$, measured against a background $\rho_{\rm BCR}$ distribution, $\rho^b_{\rm BCR}$.

Since it is impossible to shield ground-based gravitational-wave detectors from gravitational-wave signals, the LVK empirically estimates the background by repeatedly time-shifting strain data by amounts larger than the light-travel time between the two LIGO detectors [73]. We use time-shifted data to generate $\rho^b_{\rm BCR}$. Following this, each candidate's single-event false alarm probability p_1 of being miss-classified as a glitch is given by

$$p_1 = \frac{\text{Count of } \rho^b_{\rm BCR} \leq \rho^c_{\rm BCR}}{\text{Count of } \rho^b_{\rm BCR}} . \tag{2}$$

Moreover, as we have several candidates (N candidates), each with their $\rho^c_{\rm BCR}$, we account for them by calculating a false-alarm probability with trial factors p_N given by

$$p_N = 1 - (1 - p_1)^N . \tag{3}$$

Finally, we can calculate the probability of the candidate signal event occurring from a gravitational-wave, $p_{\rm S}$ with

$$p_{\rm S} = 1 - p_N . \tag{4}$$

III. ANALYSIS

We acquire O2 candidate signal triggers (times when the detector's data has a signal-to-noise ratio above a predetermined threshold) for $\rho_{\rm BCR}$ analysis from PyCBC [74–81]. Some of the triggers are associated with gravitational-wave events and candidates, while others

TABLE I. Trigger-selection parameter space (parameters correspond to signals with durations < 454 ms).

	Minimum	Maximum
Component Mass 1 [$M_\odot$]	31.54	491.68
Component Mass 2 [$M_\odot$]	1.32	121.01
Total Mass [$M_\odot$]	56.93	496.72
Chirp Mass [$M_\odot$]	8.00	174.56
Mass Ratio	0.01	0.98

are glitches. We also acquire background and simulated triggers from PyCBC to calculate $\rho^b_{\rm BCR}$ and estimate values for $\{\hat{\pi}^S, \hat{\pi}^G\}$ (see Appendix B for details on the estimation process). Note that the triggers are divided into two week time-frames because the detector's sensitivity does not stay constant throughout the eight-month-long observing period [79].

For our study, we filter triggers to include those in the parameter ranges presented in Table I. This region focuses our analysis on binary black hole mergers with total masses above $> 55\mathrm{M}_\odot$, corresponding to binary systems with signal durations < 454 ms. The filtering process leaves us with 60,996 background, 5,146 simulated, and 25 candidate signal triggers. We also include events and candidate events reported by GWTC-1 and the IAS group in our list of candidate signal triggers. A plot of the PyCBC triggers from April 23 - May 8, 2017, is presented in Fig. 1. This figure also depicts the gravitational-wave templates used by PyCBC's search.

To evaluate $\{Z^S, Z^G_i, Z^N_i\}$ and calculate the $\rho_{\rm BCR}$ Eq. 1 for triggers, we carry out Bayesian inference with Bilby [91, 92], employing dynesty [93] as our nested sampler. Nested sampling, an algorithm introduced by Skilling [94, 95], provides an estimate of the Bayesian evidence and is often utilized for parameter estimation within the LIGO collaboration [91, 96, 97].

We use a likelihood that marginalizes over coalescence time, the phase at coalescence, and luminosity distance (Eq. 80 from Thrane and Talbot [98]). We use identical parameter estimation priors for the glitch and signal models, reflecting our ignorance of the distribution of the population properties of signals and signal-like glitches. The complete list of the priors is in Table II.

The waveform template we utilize is IMRPhenomPv2, a phenomenological waveform template constructed in the frequency domain that models the in-spiral, merger, and ring-down (IMR) of a compact binary coalescence [100]. Although there exist gravitational-wave templates such as IMRPhenomXPHM [101], NRSur7dq4 [102] and SEOBNRv4PHM [103] which incorporate more physics, such as information on higher-order modes, we use IMRPhenomPv2 as it is computationally inexpensive compared to others.

To generate the PSD, we take 31 neighboring off-source non-overlapping 4-second segments of time-series data before the analysis data segment d_i. A Tukey window with a 0.2-second roll-off is applied to each data segment to suppress spectral leakage. After this, we fast-Fourier transform and median-average the segments to create a PSD [104]. Like other PSD estimation methods, this method adds statistical uncertainties to the PSD [105–107]. To marginalize over the statistical uncertainty, we use the median-likelihood presented by Talbot and Thrane [105] as a post-processing step. We find that this post-processing step improves the search efficiency by 49.26% the details of this calculation are in the Appendix C.

TABLE II. Prior settings for the parameters used during our parameter estimation. The definitions of the parameters are documented in Romero-Shaw *et al.* [99] Table E1. The trigger time t_c is obtained from the data products of PyCBC's O2 search.

Parameter	Shape	Limits
$\mathcal{M}/\mathrm{M}_\odot$	Uniform	7–180
q	Uniform	0.1–1
$M/\mathrm{M}_\odot$	Constraint	50–500
$d_{\rm L}/\mathrm{Mpc}$	Comoving	100–5000
a_1, a_2	Uniform	0–1
θ_{JN}	Sinusoidal	0–π
ψ	Uniform	0–π
ϕ	Uniform	0–2π
ra	Uniform	0–2π
dec	Cosine	0–2π
t_c/s	Uniform	$t_c \pm 0.1$

The data we use are the publicly accessible O2 strain data from the Hanford and Livingston detectors, recorded while the detectors are in "Science Mode". We obtain the data from the gravitational-wave Open Science Center [108] using GWpy [109].

Finally, with the $\rho^c_{\rm BCR}$ and $\rho^b_{\rm BCR}$, we calculate the candidate signal's $p_{\rm S}$. We present the $p_{\rm S}$ with $p_{\rm astro}$ of other pipelines for comparison in Table III.

IV. RESULTS

Various pipeline $p_{\rm astro}$ are not mathematically equivalent [110]. However, by comparing pipeline $p_{\rm astro}$ values for a given candidate along with $p_{\rm S}$ in Table III, we can compare how significant each pipeline deems various candidates. Note that the $\hat{\pi}^S$ and $\hat{\pi}^G$ values utilized for each time-frame are reported in Appendix D.

A. GWTC-1 Events

All the confirmed gravitational-wave events from binary black hole mergers reported in GWTC-1 and within our prior space (specifically GW170104, GW170608, GW170729, GW170809, and GW170814) have $p_{\rm S} > 0.9$, indicating a high probability of an astrophysical signal.

In addition to the above confirmed gravitational-wave events from GWTC-1, we have also analyzed several candidate events from GWTC-1, most of which have low

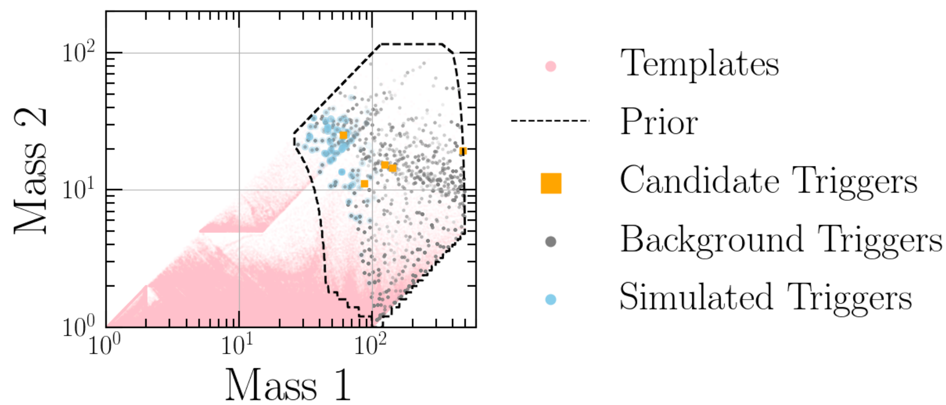

FIG. 1. The templates (pink) used by PyCBC to search a section of O2 data from April 23 - May 8, 2017. Our search is constrained to the parameter space enclosed by the dashed line. The candidate, background, and simulated triggers detected in this region of the parameter space during this period are plotted in orange, gray, and blue, respectively.

TABLE III. The $p_{\rm astro}$ of gravitational wave events from various detection pipelines, along with the event candidates with $p_{\rm S} > 0.3$. Only the candidates and events within our prior space are displayed. The various pipeline $p_{\rm astro}$ represented in this table, $p^{\rm ext}_{\rm astro}$, are from the following pipelines: GstLAL ♥ [73], PyCBC ♠ [73], PyCBC OGC-2 ♣ [83], PyCBC 'single-search' ♦ [82], IAS ★ [85, 86], and Pratten and Vecchio [72]'s significances ▲. The catalogs labelled IAS-1 and IAS-2 correspond to the candidates published in Venumadhav *et al.* [85] and Zackay *et al.* [86].

Event	Catalog	$p_{\rm S}$	$p^{\rm ext}_{\rm astro}$	t_c
GW170104	GWTC-1	0.94	1.00♥; 1.00♠; 1.0▲	1167559934.60
GW170121	IAS-1	0.76	1.00♣; 1.00★; 0.53▲	1169069152.57
170222	-	0.49	-	1171814476.97
170302	IAS-1	0.64	0.45★; 0.0▲	1172487815.48
GW170304	IAS-1	0.83	0.70♣; 0.99★; 0.03▲	1172680689.36
GWC170402	IAS-2	0.38	0.68★; 0.03♦; 0.0▲	1175205126.57
GW170403	IAS-1	0.33	0.03♣; 0.56★; 0.27▲	1175295987.22
GW170425	IAS-1	0.10	0.21♣; 0.77★; 0.74▲	1177134830.18
GW170608	GWTC-1	0.95	0.92♥; 1.00♠; 1.0▲	1180922492.50
GW170727	IAS-1	0.92	0.99♣; 0.98★; 0.66▲	1185152686.02
GW170729	GWTC-1	0.96	0.98♥; 0.52♠; 1.0▲	1185389805.30
GW170809	GWTC-1	0.98	0.99♥; 1.00♠; 1.0▲	1186302517.75
GW170814	GWTC-1	1.00	1.00♥; 1.00♠; 1.0▲	1186741859.53
GW170817A	IAS-2	0.83	0.86★; 0.36♦; 0.02▲	1186974182.72

$p_{\rm S}$. For example, consider the candidate event 170412, assigned a $p_{\rm astro}$ of 0.06 by GstLAL and has a $p_{\rm S}$ of 0.01. This candidate was reported to be excess power caused due to noise appearing non-stationary between 60-200 Hz [73]. This candidate acts as an example of how $p_{\rm S}$ may be utilized to eliminate candidates originating from terrestrial noise sources.

B. IAS Events

Our analysis of the IAS events and candidates with $M_T > 55$ M$_\odot$ in O2 has resulted in three events with disfavored $p_{\rm S} < 0.5$ (GWC170402, GW170403, GW170425), and four events and one candidate with $p_{\rm S} \geq 0.5$ (GW170121, 170302, GW170304, GW170727, GW170817A). While GW170727 and GW170817A's $p_{\rm S}$ are similar to the $p_{\rm astro}$ reported from IAS (the differences between $p_{\rm S}$ and the IAS $p_{\rm astro}$ is $|\Delta p| < 0.1$), the remaining candidates have contradicting $p_{\rm S}$ and $p_{\rm astro}$ values (with $|\Delta p| > 0.15$).

GWC170402, detected by Zackay *et al.* [86], is reported to originate from a binary with non-zero eccentricity [86]. Hence, we might have computed a low $p_{\rm S}$ due to our usage of `IMRPhenomPv2`, a waveform that does not account for eccentricity. Additionally, the search conducted by Zackay *et al.* [86] was a single-detector search. Our ranking statistic relies on the signal to appear coherent, even if just faintly coherent, amongst the various detectors to have a high $p_{\rm S}$. The lack of coherence and the non-eccentric waveform may be the leading factors for a low $p_{\rm S}$. GW170403 and GW170425 which have $p_{\rm S} < 0.35$ also have low $p_{\rm astro}$ reported by Nitz *et al.* [83], suggesting that these events may have been false alarms.

From the candidates with $p_{\rm S} > 0.5$, GW170727 and 170302 are of particular interest, with $p_{\rm S}$ of 0.92 and 0.63. GW170727 was emitted from a black hole binary system with a source frame total mass $\approx 70\ {\rm M}_\odot$. In addition to the high $p_{\rm S}$ reported by our study, Venumadhav *et al.* [85] and Nitz *et al.* [83] have also reported high $p_{\rm astro}$ values of 0.98 and 0.99, making it a viable gravitational-wave event candidate. Similarly, the sub-marginal-candidate 170302 reported by [85] with a $p_{\rm astro}$ of 0.45 appears to have a higher significance from our analysis, resulting in a $p_{\rm S}$ of 0.63.

C. New Candidate Events

Although no clear detections are made with the $\rho_{\rm BCR}$, a marginal-candidate 170222 has been discovered with a $p_{\rm S} \sim 0.5$. This candidate has a SNR$\sim$ 7.7, low spin magnitudes, and source-frame component masses of $(47.16^{+8.00}_{-5.77}, 35.50^{+5.79}_{-6.35}){\rm M}_\odot$, making it one of the heavier black-hole mergers from O2 and GWTC-1. This candidate may be of interest as one component black hole may lie in the pair-instability mass gap $(55^{+10}_{-10} - 148^{+13}_{-12}{\rm M}_\odot)$ [111, 112]. More details on the candidate are presented in Appendix E. The remaining coherent trigger candidates all have $p_{\rm S} \ll 0.5$, making them unlikely to originate from astrophysical sources.

V. CONCLUSION

In this paper, we demonstrate that the Bayesian Coherence Odds-Ratio $\rho_{\rm BCR}$ [69] can be used as a ranking statistic to provide a measure of significance for gravitational-wave signals originating from CBCs with total masses between $55{\rm M}_\odot$ and $400{\rm M}_\odot$, a range that includes intermediate-mass black holes. To compute the $\rho_{\rm BCR}$ for candidates, we utilize Bayesian inference to explicitly calculate the probability of data under various hypotheses (the hypotheses that the data contains a coherent signal, just noise, or an incoherent glitch). This Bayesian ranking method takes a step towards building a unified Bayesian framework that provides a search-pipeline agnostic measure of significance for candidates and estimates their parameters, utilizing the same level of physical information incorporated during detected parameter estimation studies.

In our study, we analyze O2 binary-black hole events and candidates with $M_T > 55{\rm M}_\odot$ reported by the PyCBC search [83], the IAS-team [85, 86] and those reported in GWTC-1 [73]. Using $p_{\rm S}$, we find that the GWTC-1 events have high probabilities of originating from an astrophysical source. We also find that some of the GWTC-1 marginal triggers that have corroborated terrestrial sources (for example, candidate 170412) have low $p_{\rm S}$, indicating this method's ability to discriminate between terrestrial artifacts and astrophysical signals. Our analysis of the IAS events demonstrates that GW170121, GW170727, and GW170817A are likely to originate from astrophysical sources, while GWC170402, GW170402, and GW170425 are not. Finally, we do not identify any new gravitational-wave events, but we find a new marginal binary-black hole merger candidate, 170222.

Although our analysis targets triggers with $M_T > 55{\rm M}_\odot$, this method can be extended to include the entire range of LIGO-detectable gravitational-wave sources. Additionally, to further improve the method's infrastructure, we can use more robust gravitational-wave templates (such as templates that incorporate higher-order modes and orbital precession) and sophisticated glitch models. Future analysis can also incorporate data from all available detectors in a network to increase the sensitivity of $p_{\rm S}$.

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Appendix A: Bayesian Evidence Evaluation

1. Noise Model

We assume that each detector's noise is Gaussian and stationary over the period being analyzed [104]. In practice, we assume that the noise has a mean of zero that the noise variance σ^2 is proportional to the noise power spectral density (PSD) $P(f)$ of the data. Using the $P(f)$, for each frequency-domain data segment d_i in each of the i detectors in a network of D detectors, we can write

$$Z_i^N = \mathcal{N}(d_i|\mu = 0, \sigma^2 = P(f)), \tag{A1}$$

where $\mathcal{N}$ is a normal distribution.

2. Coherent Signal Model

We model coherent signals using a binary black hole waveform template $\mu(\vec{\theta})$, where the vector $\vec{\theta}$ contains a point in the 12-dimensional space describing aligned-spin binary-black hole mergers. For the signal to be coherent, $\vec{\theta}$ must be consistent in each 4-second data segment d_i for a network of D detectors. Hence, the coherent signal evidence is calculated as

$$Z^S = \int\limits_{\vec{\theta}} \prod_{i=1}^{D} \left[\mathcal{L}(d_i|\mu(\vec{\theta}))\right] \pi(\vec{\theta}|\mathcal{H}_S)\ \mathrm{d}\vec{\theta}\ , \tag{A2}$$

where $\pi(\vec{\theta}|\mathcal{H}_S)$ is the prior for the parameters in the coherent signal hypothesis $\mathcal{H}_S$, and $\mathcal{L}(d_i|\mu(\vec{\theta}))$ is the likelihood for the coherent signal hypothesis that depends on the gravitational-wave template $\mu(\vec{\theta})$ and its parameters $\vec{\theta}$.

3. Incoherent Glitch Model

Finally, as glitches are challenging to model and poorly understood, we follow Veitch and Vecchio [67] and utilize a surrogate model for glitches. The glitches are modeled using gravitational-wave templates $\mu(\vec{\theta})$ with uncorrelated parameters amongst the different detectors such that $\vec{\theta}_i \neq \vec{\theta}_j$ for two detectors i and j [67]. Modeling glitches with $\mu(\vec{\theta})$ captures the worst-case scenario: when glitches are identical to gravitational-wave signals (excluding coherent signals). Thus, we can write Z_i^G as

$$Z_i^G = \int\limits_{\vec{\theta}} \mathcal{L}(d_i|\mu(\vec{\theta}))\ \pi(\vec{\theta}|\mathcal{H}_G)\ \mathrm{d}\vec{\theta}\ , \tag{A3}$$

where $\pi(\theta|\mathcal{H}_G)$ is the prior for the parameters in the incoherent glitch hypothesis $\mathcal{H}_G$.

Appendix B: Tuning the prior-odds

After calculating the ρ_{BCR} for a set of background triggers and simulated triggers from as stretch of detector-data (a data chunk), we can compute probability distributions for the background and simulated triggers, $p_b(\rho_{\mathrm{BCR}})$ and $p_s(\rho_{\mathrm{BCR}})$. We expect the background trigger and simulated signal ρ_{BCR} values to favor the incoherent glitch and the coherent signal hypothesis, respectively. Ideally, these distributions representing two unique populations should be distinctly separate and have no overlap in their ρ_{BCR} values. The prior odds parameters $\hat{\pi}^S$ and $\hat{\pi}^G$ from Eq. 1 help separate the two distributions. Altering $\hat{\pi}^S$ translates the ρ_{BCR} probability distributions while adjusting $\hat{\pi}^G$ spreads the distributions (refer to Appendix A of Isi *et al.* [69]). Although Bayesian hyper-parameter estimation can determine the optimal values for $\hat{\pi}^S$ and $\hat{\pi}^G$, an easier approach is to adjust the parameters for each data chunk's ρ_{BCR} distribution. In this study, we tune $\hat{\pi}^S$ and $\hat{\pi}^G$ to maximally separate the ρ_{BCR} distributions for the background and simulated triggers.

To calculate the separation between $p_b(\rho_{\mathrm{BCR}})$ and $p_s(\rho_{\mathrm{BCR}})$, we use the Kullback–Leibler divergence (KL divergence) D_{KL}, given by

$$D_{KL}(p_b|p_s) = \sum_{x\in\rho_{\mathrm{BCR}}} p_b(x) \log\left(\frac{p_b(x)}{p_a(x)}\right)\ . \tag{B1}$$

The $D_{K.L.} = 0$ when the distributions are identical and increases as the asymmetry between the distributions increases.

We limit our search for the maximum KL-divergence in the $\hat{\pi}^S$ and $\hat{\pi}^G$ ranges of $[10^{-10}, 10^0]$. We set our values for $\hat{\pi}^S$ and $\hat{\pi}^G$ to those which provide the highest KL-divergence and calculate the ρ_{BCR} for candidate events present in this data chunk. Note that we conduct the analysis in data chunks of a few days rather than an entire data set of a few months as the background may be different at different points of the entire data set.

Appendix C: Marginalizing over PSD statistical uncertainties

To generate the results presented in Table III, we applied a post-processing step to marginalize the uncertainty in the PSD. In Fig. 2, we demonstrate the impact of the post-processing step. Marginalizing over uncertainty in the PSD yields an improvement in the separation of the noise and signal distributions (left plot). Quantitatively, at a threshold ${\rho_{\mathrm{BCR}}}^T = 0$ the post-processing step results in a reduction in the number of background $\rho_{\mathrm{BCR}} > {\rho_{\mathrm{BCR}}}^T$ from 60.7% to 25.28% in the

TABLE IV. The prior odds used for each time-frame of data from O2. Each time frame commences at the start date and concludes at the following time-frame's start date.

Start Date	$\hat{\pi}^S$	$\hat{\pi}^G$
2016-11-15	-	-
2016-11-30	-	-
2016-12-23	1.00E+00	6.25E-01
2017-01-22	1.00E+00	2.33E-02
2017-02-03	1.00E-10	2.44E-01
2017-02-12	1.76E-08	5.96E-02
2017-02-20	6.55E-10	2.22E-03
2017-02-28	1.00E-10	5.96E-02
2017-03-10	2.56E-10	3.91E-01
2017-03-18	1.60E-10	1.00E+00
2017-03-27	1.10E-08	5.96E-02
2017-04-04	3.73E-02	2.33E-02
2017-04-14	1.05E-09	2.44E-01
2017-04-23	2.68E-09	1.46E-02
2017-05-08	1.00E+00	2.44E-01
2017-06-18	6.55E-10	3.39E-04
2017-06-30	2.02E-05	5.69E-03
2017-07-15	1.05E-09	9.54E-02
2017-07-27	1.00E+00	2.12E-04
2017-08-05	2.12E-04	3.73E-02
2017-08-13	2.68E-09	8.69E-04
2017-08-21	-	-

August 13 - 21, 2017 time-frame of data. For the entirety of O2, PSD marginalization resulted in a 49.26% improvement in search efficiency.

Appendix D: Tuned prior odds

O2 lasted several months, over which the detector's sensitivity varied. Hence, a part of our analysis entailed tuning the prior odds for obtaining a signal and a glitch, $\hat{\pi}^S$ and $\hat{\pi}^G$, as described in Section II. Table IV presents the signal and glitch prior odds utilized for each time-frame of O2 data.

Tuning the prior odds can dramatically affect the p_S. For example, consider Table V, which reports tuned p_S and un-tuned p'_S (where $\hat{\pi}^S = 1$ and $\hat{\pi}^G = 1$) for various events and candidates. By tuning the prior odds, the p_S for some IAS events (for example, GW170403 and GW170817A) can change by more than 0.5, resulting in the promotion/demotion of a candidate's significance.

TABLE V. The BCR p-astro after tuning the prior odds, p_S, and without tuning the prior odds, p'_S (where $\hat{\pi}^S = 1$ and $\hat{\pi}^G = 1$).

Event	Catalog	p_S	p'_S
161202	-	0.09	0.41
GW170104	GWTC-1	0.94	0.93
GW170121	IAS-1	0.76	0.72
170206	-	0.11	0.52
170222	-	0.49	0.49
170302	IAS-1	0.64	0.54
GW170304	IAS-1	0.83	0.81
GWC170402	IAS-2	0.38	0.01
GW170403	IAS-1	0.33	0.89
GW170425	IAS-1	0.10	0.22
GW170608	GWTC-1	0.95	0.95
GW170727	IAS-1	0.92	0.96
GW170729	GWTC-1	0.96	0.94
GW170809	GWTC-1	0.98	0.99
GW170814	GWTC-1	1.00	1.00
GW170817A	IAS-2	0.83	0.36

Appendix E: A closer look at 170222

PyCBC found the candidate 170222 with $\mathcal{M}_c = 49.46$ and $q = 0.68$, values that fall within our uncertainty limits. Some of the posteriors that were produced as a by-product of our ρ_BCR calculation can be viewed in Fig. 3.

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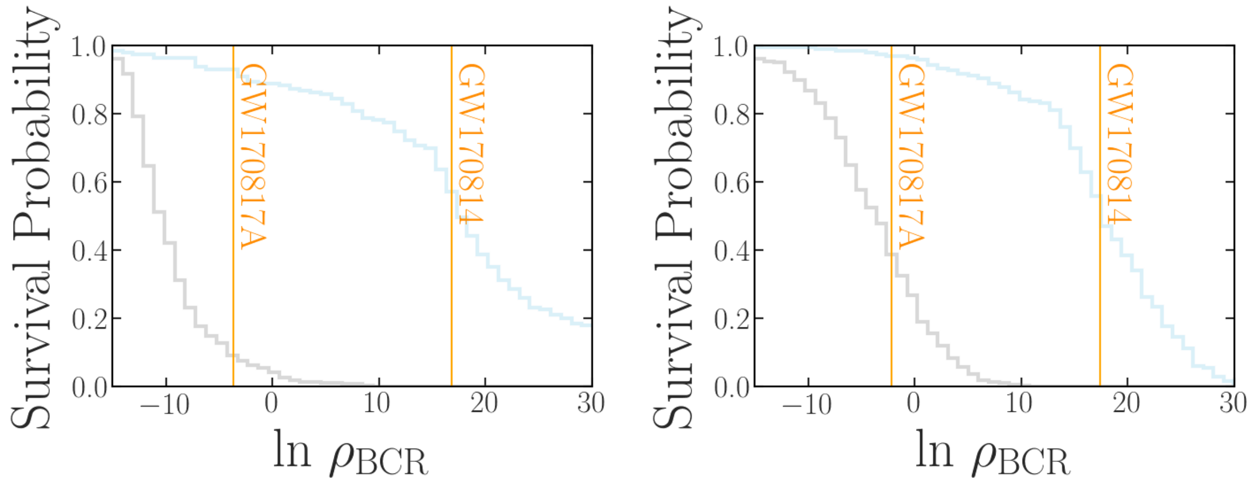

FIG. 2. Histograms represent the survival function (1-CDF) from our selection of background triggers (gray) and simulated signals (blue) triggers obtained from PyCBC's search of data from August 13 - 21, 2017. Vertical lines mark the $\ln\,\rho_{\rm BCR}$ of IAS's GW170817A and GWTC-1's GW170814. Left: Survival functions with using the post-processing step to marginalize over PSD statistical uncertainties. Right: Survival functions without the post-processing step. Without the post-processing step, there is a greater overlap between the background (gray) and foreground (blue) survival functions

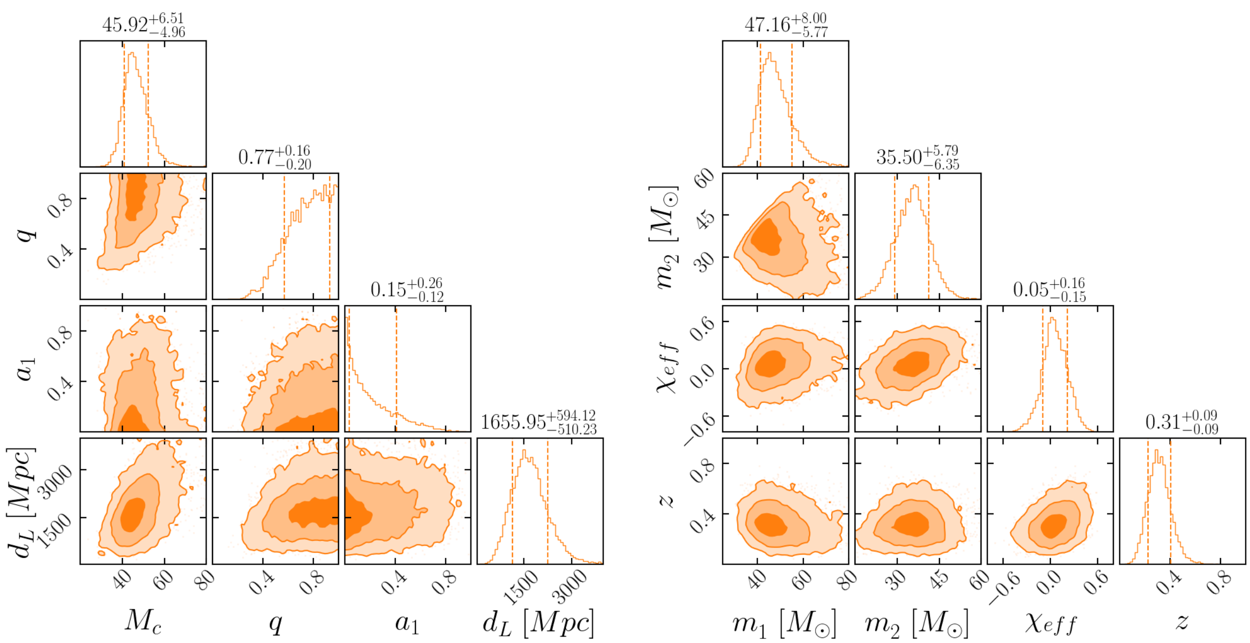

FIG. 3. Posterior distributions for 8 parameters of 170222. Left: Posterior probability distributions for 4 of the 12 search parameters. Right: Posterior probability distributions for 4 derived parameters.

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