A search for high-mass black holes in data from the second LIGO observing run using a Bayesian ranking-statistic

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The detection of an intermediate-mass black hole population ($10^2 - 10^6$ M$_\odot$) will provide probes to their formation environments (e.g., disks of active galactic nuclei, globular clusters) and illuminate a potential pathway to produce supermassive black holes. Numerous methods to search for 10^4 – 10^6 M$_\odot$ intermediate-mass black holes exist, while the primary method to find $10^2 - 10^3$ M$_\odot$ is by identifying gravitational-waves emitted from the merger of stellar binaries. Theoretically, ground-based gravitational-wave detectors are sensitive to such mergers and have found one 142^{+28}_{-16} M$_\odot$ intermediate-mass black hole. In reality, ground-based detectors are plagued with short-duration instrumental transients that mimic the gravitational-wave signals from mergers capable of producing intermediate-mass black holes. Here we demonstrate a ranking statistic utilizing Bayesian inference to detect high-mass binary black hole mergers (with a total mass > 55 M$_\odot$). We apply this technique to the high-mass triggers during LIGO's second observing run to search for previously unresolved gravitational-wave signals from high-mass binary black holes. Our analysis does not discover new intermediate-mass black holes. However, we find support for some previously identified borderline stellar-mass binary black hole detections and gravitational-wave detections made externally from the LIGO-Virgo-KAGRA collaboration.

I. INTRODUCTION

Since the 1970s, there has been a steady accumulation of evidence for stellar mass ($\mathrm{M_{BH}} < 10^2$ M$_\odot$) and supermassive black holes ($\mathrm{M_{BH}} > 10^6$ M$_\odot$) [1–7]. 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 [8–20], the centers of dense stellar clusters [21–31], Population-III stars [32–36]), and illuminate our understanding of supermassive black hole formation [37–40]. A variety of techniques have been employed to search for $10^4 - 10^6$ M$_\odot$ intermediate mass candidates (reverberation mapping [41], direct kinematic measurements [42, 43], applying macroscopic galaxy to black hole mass scaling relations (M_{BH}-σ and M_{BH}-L relations) [44, 45], studying X-ray luminosity and spectra [46, 47], gravitational lensing of light curves [48], and others [49–51])). However, these observational techniques are challenging to use for intermediate mass black holes, due to their small sphere of influence. Additionally, some candidates discovered with these techniques can be attributed to sources without intermediate-mass black holes (e.g. clusters of stellar-mass black holes [52, 53], anisotropic emission from neutron stars [54, 55]), while others have high uncertainties due to the observational techniques utilized [49]. Compact binaries coalesces (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 ground-based detectors can probe the lower-end $10^2 - 10^3$ M$_\odot$ of the intermediate mass range. Mergers involving either a binary system with at least one intermediate-mass component, or a system whose merger results in an intermediate-mass remnant will have large total masses M_T. As a binary's M_T is associated with its gravitational-wave merger frequency, $f \sim \mathrm{M}_T^{-1}$, systems with large M_T have very low merger frequencies $f < 100$ Hz. Hence, ground based gravitational wave detectors ($\sim 10^1 - 10^3$ Hz) are sensitive to the last milliseconds of merging systems with $100\mathrm{M}_\odot < \mathrm{M}_T < 400\mathrm{M}_\odot$ [57–59], while space-based detectors ($\sim 10^{-2} - 10^1$ Hz) can study the full signals of merging systems with $10^4\mathrm{M}_\odot < \mathrm{M}_T < 10^7\mathrm{M}_\odot$ [59, 60].

Because of high-total mass systems' short-durations in ground-based gravitational wave data steams, handling data quality is critical to their detection. The low-frequency ranges of ground-based observatories are plagued with incoherent non-stationary terrestrial artifacts, called *glitches* [61–63]. Some glitches, similar to signals from high total mass mergers, last for a fraction of a second, making them difficult to distinguish from the signals. These glitches that mimic astrophysical signals can severely decrease the confidence in detection of true gravitational-waves from high total mass mergers.

Although a significant fraction of the glitches can be removed by testing them for coherence amongst various ground based detectors and performing matchedfiltering, these methods are insufficient to remove all the glitches [61–63]. One method to account for more glitches while searching for high total mass CBC gravitational-waves is by utilizing a Bayesian odds [64–69]. In this paper, we utilize a Bayesian method, called the Bayesian Coherence Odds-Ratio $\rho_{\rm BCR}$ [66], to rank the candidate gravitational-wave signals from high-mass compact binary coalescences (systems with total masses in the range of $55-500\ \mathrm{M}_{\odot}$) in the detector data recorded during O2. The $\rho_{\rm BCR}$ used in this study is a bootstrap-Bayesian odds computed using Bayesian evidences that describe the explicit probability of data under the hypothesis that the data contains coherent signals vs incoherent glitches, and empirically calculated prior-odds that describe how likely each hypotheses is. The high-mass candidate $\rho_{\rm BCR}$ values are then used to calculate the probability that the candidate is of astrophysical origins, $p_{\rm astro}^{\rm BCR}$. Finally, if the candidate has a $p_{\rm astro}$ reported by the the LIGO-Virgo-KAGRA (LVK) collaboration in `GWTC-1` [70], the PyCBC-team [71–80], by the Institute of Advanced study's team (IAS) [81–83], or by Pratten and Vecchio [69], we compare their $p_{\rm astro}$ with the $p_{\rm astro}^{\rm BCR}$.

We find that (a) high-mass events reported in the `GWTC-1`, including GW170729 (the heaviest event in `GWTC-1`) are very statistically significant $p_{\rm astro}^{\rm BCR} > 0.9$; (b) three out of the eight `IAS` events and candidates have $p_{\rm astro}^{\rm BCR} > 0.5$, corroborating `IAS`'s detection claims for those events (GW170304, GW170727, 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 $p_{\rm astro}^{\rm BCR} \sim 0.5$.

The remainder of this paper is structured as follows. We outline our methods, including details of our ranking statistic and the retrieval of our candidate 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

The standard framework to identify CBC gravitational-wave signals hidden in data is by quantifying the significance of candidates with null-hypothesis significance testing [70, 84]. In this framework, the candidates' ranking statistic is compared against a background distribution in a frequentist approach. The independent matched-filter searches, e.g. `PyCBC` [76] and GstLAL [85], and the coherent burst search cWB [86] used by LVK to search for signals in gravitational-wave data all use ranking statistics in such a manner [70]. Both `PyCBC` and GstLAL's ranking statistic incorporate information of the relative likelihood that the data contains a coherent-signal versus just noise, while cWB's ranking statistic uses the information of coherent energy present in the network of detectors [70].

In a similar vein, this work utilizes Bayesian inference to calculate the Bayesian Coherence Odds-Ratio [66], $\rho_{\rm BCR}$, of high-mass candidates in LIGO's second observing run. We use the $\rho_{\rm BCR}$ not as an odds-ratio but instead as a ranking statistic.

A. The Bayesian Coherence Odds-Ratio

Bayes theorem states that the posterior probability distribution $p(\vec{\theta}|d,\mathcal{H})$ for data d and a vector of parameters $\vec{\theta}$ that describe a model which quantifies a hypothesis $\mathcal{H}$, is given by

$$p(\vec{\theta}|d,\mathcal{H}) = \frac{\mathcal{L}(d|\vec{\theta},\mathcal{H})\ \pi(\vec{\theta}|\mathcal{H})}{\mathcal{Z}(d|\mathcal{H})}\ , \tag{1}$$

where $\mathcal{L}(d|\vec{\theta},\mathcal{H})$ is the likelihood of the data given the parameters $\vec{\theta}$ and the hypothesis, $\pi(\vec{\theta}|\mathcal{H})$ is the prior probability of the parameters, and finally,

$$\mathcal{Z}(d|\mathcal{H}) = \int_{\vec{\theta}} \mathcal{L}(d|\vec{\theta},\mathcal{H})\ \pi(\vec{\theta}|\mathcal{H})\ d\vec{\theta} \tag{2}$$

is the likelihood after marginalizing over the parameters $\vec{\theta}$. To compare two hypotheses $\mathcal{H}_A$ and $\mathcal{H}_B$ with the Bayes theorem one can calculate an odds-ratio

$$\mathcal{O}_B^A = \frac{\mathcal{Z}^A\ \pi(\vec{\theta}|\mathcal{H}_{\mathcal{A}})}{\mathcal{Z}^B\ \pi(\vec{\theta}|\mathcal{H}_{\mathcal{B}})}\ , \tag{3}$$

where $\{\mathcal{Z}^A,\mathcal{Z}^B\}$ are shorthand for the evidences $\{\mathcal{Z}(d|\mathcal{H}_A),\mathcal{Z}(d|\mathcal{H}_B)\}$ and $\{\pi(\vec{\theta}|\mathcal{H}_{\mathcal{A}}),\pi(\vec{\theta}|\mathcal{H}_{\mathcal{B}})\}$ are the prior-odds for each hypotheses. The odds-ratio can tell us which of the two hypotheses is more likely. For example, if $\mathcal{O}_B^A >> 1$, then this odds ratio indicates that the $\mathcal{H}_A$ describes the data much better than $\mathcal{H}_B$.

The $\rho_{\rm BCR}$ is a Bayesian odds-ratio like the above, of a coherent signal hypotheses $\mathcal{H}_S$ and an incoherent instrumental feature hypothesis $\mathcal{H}_I$ (the null-hypotheses) for a network of D detectors. $\mathcal{H}_{\mathcal{I}}$ states that each detector i has either pure stationary Gaussian noise $\mathcal{H}_N$ or Gaussian noise and an incoherent noise transient (glitch) $\mathcal{H}_G$. Taking Z^S, Z_i^G and Z_i^N as the Bayesian evidences (defined in Appendix A) for $\mathcal{H}_S$, $\mathcal{H}_N$, and $\mathcal{H}_G$, the $\rho_{\rm BCR}$ is given by

$$\rho_{\rm BCR} = \frac{P^S Z^S}{\prod_{i=1}^{D} \left[P^G Z_i^G + (1-P^G) Z_i^N\right]}\ , \tag{4}$$

where P^S and P^G are the prior-odds of obtaining a signal or a glitch from a stretch of data. The prior-odds can be defined more explicitly as

- $P^S = P(\mathcal{H}_S)/P(\mathcal{H}_I)$, the prior-odds for obtaining a coherent signal versus an incoherent instrumental feature.

- $P^G = P(\mathcal{H}_G|\mathcal{H}_I)$, the prior-odds for obtaining a glitch assuming there is an incoherent instrumental feature.

When $\mathcal{H}_S$ and $\mathcal{H}_I$ are precisely described and the correct prior-odds are known, the ρ_{BCR} is a Bayesian odds-ratio. As an odds-ratio, the ρ_{BCR} is the optimal discriminator between coherent signals and incoherent instrumental features. However, as the priors-odds are unknown, it is invalid to use the ρ_{BCR} as an odds-ratio to make an informed decision about whether a candidate is from an astrophysical or terrestrial source. Instead of interpreting the ρ_{BCR} as a Bayesian odds-ratio, it can be used as a ranking statistic. Using the ρ_{BCR} as a ranking statistic we can obtain a frequentist significance of a candidate ρ_{BCR}-value measured against a background ρ_{BCR} distribution.

When using the ρ_{BCR} as a detection statistic, the physical interpretation of the prior-odds is lost. Hence, the prior-odds are empirically tuned to maximize the separation between the ρ_{BCR} distribution of the background (expected to favor the $\mathcal{H}_I$ hypothesis) and the ρ_{BCR} distribution of artificially manufactured simulated signals (expected to favor the $\mathcal{H}_S$ hypothesis). Increasing the separation between the two distributions can improve ability of the ρ_{BCR} to discriminate candidate events as coherent signals or incoherent instrumental features. The tuning process is described in detail in Appendix B.

B. Estimation of astrophysical signal probability

Candidate ρ_{BCR}-values are either statistically insignificant compared to the background ρ_{BCR} distribution, implying the candidate is more probable to be an incoherent instrumental feature (the $\mathcal{H}_I$ null-hypothesis), or statistically significant to the background distribution, indicating the possible presence of an astrophysical signal (the $\mathcal{H}_S$ hypothesis). A false alarm probability with trial factors, FAP, for the candidate ρ_{BCR}-value can quantify the significance. The FAP is the probability that a candidate originating from a non-astrophysical source can be falsely identified as a signal.

To calculate the FAP, each candidate ρ_{BCR} is considered a single statistical trial that can occur at a fixed false alarm probability f, where f is the probability of observing a background ${\rho_{\mathrm{BCR}}}'$ greater than or equal to the candidate ρ_{BCR},

$$f = \frac{\text{Count of } {\rho_{\mathrm{BCR}}}' \leq \rho_{\mathrm{BCR}}}{\text{Count of } {\rho_{\mathrm{BCR}}}'} \; . \tag{5}$$

The false alarm probability with trials FAP that the ρ_{BCR} measurement occurs at least once for N trials ($N > 0$), where N is the number of candidate triggers is

$$\mathrm{FAP} = 1 - (1-f)^N \; . \tag{6}$$

Finally, the FAP can be used to construct a p_{astro}, the probability that a signal is of astrophysical origin [87–89]

$$p_{\mathrm{astro}} = 1 - \mathrm{FAP} \; . \tag{7}$$

[AV: Talk about the differences in pastro calculation [90–92]]

[Greg: This needs more explanation and discussion. I know that in the Gaebel paper [91], they make the connection (they don't in FGMC [90]). But, effectively the FAP is the p-value, the probability that the event arose from the background noise alone. Taking 1-FAP as identifying a real signal can be hugely problematic (Wikipedia has its own page on it `https://en.wikipedia.org/wiki/Misuse_of_p-values`). In this case, it is a reasonable thing to do, because you are saying "anything which rings up our detection statistic is astrophysical by virtue that it is coherent". But, that needs to be spelled out. Also, it may be useful to say that the p-astro calculated from, say, PyCBC/GSTLAL are not 1-FAP, but instead apply the FGMC population approach.]

C. Data for Analysis

The LIGO Scientific collaboration operates several search pipelines that scan for gravitational-waves from compact binary mergers such as GstLAL [85], `MBTAOnline` [93], `SPIIR` [94] and `PyCBC` [76]. The output of `PyCBC`'s search is a list of times and their corresponding `PyCBC` ranking statistic ρ_{PC} values. The ρ_{PC} ranking-statistic is akin to the matched-filter signal-to-noise ratio ρ. However, unlike ρ, ρ_{PC} includes candidate signal's intrinsic and extrinsic properties and other information that feeds into determining if the signal can have astrophysical origins [78]. Whenever a local maximum of $\rho_{\mathrm{PC}} > \rho_{\mathrm{T}}$, where ρ_{T} is some predetermined threshold value, the `PyCBC` search pipeline produces a single-detector *trigger* associated with the detector and time t_c where the apparent signal in the data has its merger [78].

When `PyCBC` observes a trigger between detectors with coincident parameters and a time of arrival difference less than the gravitational-wave travel time between detectors, the trigger is labeled a *candidate event trigger*, a trigger that may be from astrophysical origins [73]. To test the pipeline's sensitivity `PyCBC` also conducts searches for *simulated triggers*, artificial triggers manufactured by injecting signals into the detector data. Finally, to quantify the statistical significance of candidate triggers, `PyCBC` artificially constructs *background triggers* to compare against the candidate events. These background triggers are coherent signal-free events, constructed by applying relative offsets, or time-slides, between the data of different detectors [78]. The background trigger's ρ_{PC} distribution is used to calculate the candidate trigger's significance, using null-hypothesis sig-

TABLE I. High-mass 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

nificance testing, under the assumption that all candidate event triggers are due to noise.

Our work demonstrates that the ρ_{BCR} can be used in the same way as ρ_{PC} to measure candidate triggers' statistical significance. The ρ_{BCR} can be a powerful ranking statistic as it incorporates information of not only all possible binary black hole systems that might have merged to produce the trigger but also the various incoherent glitches that might cause a false-detection.

III. ANALYSIS

A. Acquisition of triggers

Advanced LIGO's second observing run O2 lasted 38 weeks [95]. The software package, PyCBC [71], was used by LVK to process the O2 data in 22 time-frames (approximately 2 weeks per frame) and found several gravitational-wave events and numerous gravitational-wave candidates [72–78]. Some candidate events were vetoed to be glitches, while others were rejected due to their low significance. The data are divided into these time-frames because the detector's sensitivity does not stay constant throughout the eight-month-long observing period.

In addition to finding candidate events, PyCBC also identified several million background triggers for each time-frame, by searching background data manufactured by time-sliding data within that time-frame. The background triggers help quantify the candidate events' significance for the respective time-frames. Finally, to test the search's sensitivity, PyCBC produced and searched for thousands of simulated signals.

For our study, we filter the PyCBC background, simulated and candidate triggers to include only high-mass triggers with masses in the ranges of the parameters presented in Table I. A plot of the PyCBC triggers from one time-frame, during April 23 - May 8, 2017, is presented in Fig. 1. This figure also depicts the gravitational-wave templates used during the search through this time-frame of data.

B. Calculating the BCR for triggers

To evaluate Z^S, Z_i^G and Z_i^N and calculate the ρ_{BCR} Eq. 4 for triggers, we carry out Bayesian inference with

TABLE II. Prior settings for the parameters used during our parameter estimation. The definitions of the parameters are documented in Romero-Shaw *et al.* [104] 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
$d_{\mathrm{L}}/\mathrm{Mpc}$	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	$t_c \pm 0.1$

Bilby [96, 97], employing dynesty [98] as our nested sampler. Nested sampling, an algorithm introduced by Skilling [99, 100], provides an estimate of the true Bayesian evidence and is often utilized for parameter estimation within the LIGO collaboration [96, 101, 102].

The most computationally intensive step during Bayesian inference is evaluating the likelihood $\mathcal{L}(d_i|\mu(\vec{\theta}))$. To accelerate our analysis, we use a likelihood that explicitly marginalizes over coalescence time, phase at coalescence, and luminosity distance (Eq. 80 from Thrane and Talbot [103]). While this marginalized likelihood reduces the run time without introducing errors to our evidence evaluation, it does not generates samples for the marginalized parameters. However, these parameter samples can be calculated as a post-processing step [103].

We set the priors $\pi(\vec{\theta}|\mathcal{H}_S)$ and $\pi(\vec{\theta}|\mathcal{H}_G)$ to be identical. These priors restrict signals with mass parameters in the ranges presented in Table I. The spins are aligned over a uniform range for the dimensionless spin magnitude from $[0, 1]$. The luminosity distance prior assigns probability uniformly in comoving volume, with an upper cutoff of 5 Gpc. The full list of the priors, along with their shapes, limits and boundary conditions are documented in Table II.

The waveform template we utilize is IMRPhenomPv2, a phenomenological waveform template constructed in the frequency domain that models the inspiral, merger, and ring-down (IMR) of a compact binary coalescence [105]. Although there exist gravitational-wave templates such as SEOBNRv4PHM [106] which incorporate more physics, such as information on higher-order modes, we use IMRPhenomPv2 as it is computationally inexpensive compared to others.

We take 31 neighboring, off-source, non-overlapping, 4-second segments of time-series data before the analysis data segment d_i to generate the PSD. We use off-source to avoid the inclusion of a signal in the PSD calculation. A Tukey window with 0.2-second roll-offs is applied to each data segment to suppress spectral leakage after which the segments are fast-Fourier transformed and median-

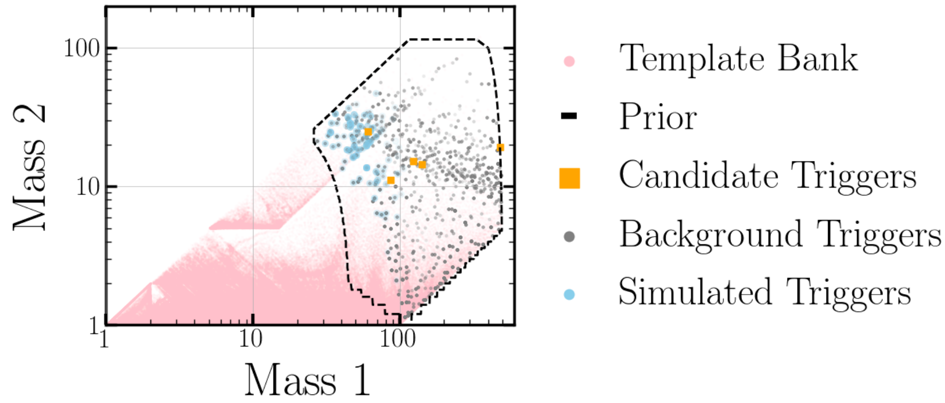

FIG. 1. The template bank (pink) used by `PyCBC` to search a section of O2 data from April 23 - May 8, 2017. Our search is constrained to the high-mass parameter space enclosed by the dashed line. The candidate, background and simulated triggers detected in this region of the parameter space during this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

averaged to create a PSD [107]. Like other PSD estimation methods, this method adds statistical uncertainties to the PSD [108, 109]. To marginalize over the statistical uncertainty, we use the median-likelihood presented by Talbot and Thrane [108] as a post-processing step.

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Finally, we neglect detector calibration uncertainty and acquire data from from the gravitational-wave Open Science Center [95]. 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 using `GWpy` [111].

C. Assigning p_{astro} to candidate events

After the calculating the ρ_{BCR} for the entire set of high-mass background and simulated triggers, we calculate probability distributions $p_b(\rho_{\mathrm{BCR}})$ and $p_s(\rho_{\mathrm{BCR}})$ for each 2-week time-frame of O2 data. These distributions are used to 'tune' prior-odd P^S and P^G values.

Using the tuned prior odds the ρ_{BCR} for the candidate events can be calculated. Fig. 2 shows the ρ_{BCR} distributions for the background triggers, simulated triggers and candidate events. The bulk of the background and simulated trigger distributions are separate but slightly overlap due to some of the simulated signal's being very faint. The separation suggests that the ρ_{BCR} can successfully distinguish signals from noise or glitches. The vertical lines in Fig. 2 displays the ρ_{BCR} for gravitational-wave candidate events. On comparing the candidate event ρ_{BCR} values with the background distribution, we can estimate p_{astro} values for the candidate events.

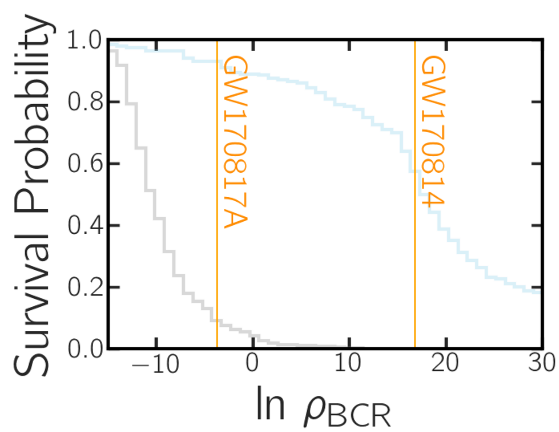

FIG. 2. Histograms represent the survival function (1-CDF) from our high-mass selection of background triggers (gray) and simulated signals (blue) triggers obtained from `PyCBC`'s search of data from August 13 - 21, 2017. Vertical lines mark the ln ρ_{BCR} of `IAS`'s GW170817A and `GWTC-1`'s GW170814.

IV. RESULTS

We analyze the 60,996 background, 5,146 simulated, and 25 candidate triggers reported by `PyCBC`'s search on

TABLE III. The $p_{\rm astro}$ of gravitational wave events from various detection pipelines, along with the event candidates with $p_{\rm astro}^{\rm BCR} > 0.3$. Only the candidates and events within our prior space are displayed. The various pipeline $p_{\rm astro}$ represented in this table, $p_{\rm astro}^{\rm ext}$, are from the following pipelines: GstLAL $^{\heartsuit}$ [70], PyCBC $^{\spadesuit}$ [70], PyCBC OGC-2 $^{\clubsuit}$ [80], PyCBC 'single-search' $^{\diamondsuit}$ [79], IAS * [82, 83], and Pratten and Vecchio [69]'s significances $^{\blacktriangle}$. The catalogs labelled IAS-1 and IAS-2 correspond to the candidates published in Venumadhav *et al.* [82] and Zackay *et al.* [83].

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

the data from LIGO's second observing run, restricting our analysis to the triggers that fall within our mass-space as described in Section II.We also analyze events and candidate events reported by `GWTC-1` and the IAS group (note: some of these were identified as candidates by the PyCBC search). In Table III, we summaries the $p_{\rm astro}^{\rm BCR}$, along with the $p_{\rm astro}$ of other pipelines for comparison. Although the various pipeline $p_{\rm astro}$ are not mathematically equivalent, by comparing pipeline $p_{\rm astro}$ values for a given candidate, we can compare how significant each pipeline deems various candidates. The P^S and P^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 $p_{\rm astro}^{\rm BCR} > 0.9$, indicating a high probability of the presence 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 $p_{\rm astro}^{\rm BCR}$. For example, consider the candidate event 170412, assigned a $p_{\rm astro}$ of 0.06 by GstLAL and has a $p_{\rm astro}^{\rm BCR}$ of 0.01. This candidate was reported to be excess power caused due noise appearing non-stationary between 60-200 Hz [70]. This candidate acts as an example of how $p_{\rm astro}^{\rm BCR}$ may be utilized to eliminate candidates originating from terrestrial noise sources.

B. IAS Events

Our analysis of the high-mass IAS events and candidates in O2 has resulted in three events with disfavored $p_{\rm astro}^{\rm BCR} < 0.5$ (GWC170402, GW170403, GW170425), and four events and one candidate with $p_{\rm astro}^{\rm BCR} \geq 0.5$ (GW170121, 170302, GW170304, GW170727, GW170817A). While GW170727 and GW170817A's $p_{\rm astro}^{\rm BCR}$ are similar to the $p_{\rm astro}$ reported from IAS (the differences between the $p_{\rm astro}$ from $\rho_{\rm BCR}$ and IAS is $|\Delta p_{\rm astro}| < 0.1$), the remaining candidates have opposing $p_{\rm astro}$ values (with $|\Delta p_{\rm astro}| > 0.15$).

GWC170402, detected by Zackay *et al.* [83], is reported to originate from a binary with non-zero eccentricity [83]. Hence, we might have received a low $p_{\rm astro}^{\rm BCR}$ due to our usage of IMRPhenomPv2, a waveform that does not account for eccentricity. Additionally, the search conducted by Zackay *et al.* [83] 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 $p_{\rm astro}^{\rm BCR}$. The lack of coherence and the non-eccentric waveform may be the leading factors for a low $p_{\rm astro}$. GW170403 and GW170425 which have $p_{\rm astro}^{\rm BCR} < 0.35$ also have low $p_{\rm astro}$ reported by Nitz *et al.* [80], suggesting that these events may have been false alarms.

From the candidates with $p_{\rm astro}^{\rm BCR} > 0.5$, GW170727 and 170302 are of particular interest, with $p_{\rm astro}^{\rm BCR}$ 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 $p_{\rm astro}^{\rm BCR}$ reported by our study, Venumadhav *et al.* [82] and Nitz *et al.* [80] 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 [82] with a $p_{\rm astro}$ of 0.45 appears to have a higher significance from our analysis, resulting in a $p_{\rm astro}^{\rm BCR}$ 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 $p_{\rm astro}^{\rm BCR} \sim 0.5$. This candidate has an SNR~ 7.7, low spin magnitudes and source-frame component masses of $47.16^{+8.00}_{-5.77}, 35.50^{+5.79}_{-6.35}$, 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 $(55^{+10}_{-10} - 148^{+13}_{-12}{\rm M}_{\odot})$ [112, 113]. More details on the candidate are presented in Appendix E. The remaining coherent trigger candidates all have $p_{\rm astro}^{\rm BCR} \ll 0.5$ making them unlikely to originate from astrophysical sources.

V. CONCLUSION

Until 2016, a majority of intermediate-mass black hole candidates were from electromagnetic observations. The dawn of gravitational waves astronomy has provided a new lens to identify and study these massive objects – from the mergers of heavy black holes' gravitational wave emission. In the future, space-based gravitational wave detectors will uncover black holes in the upper end of the intermediate-mass range. In the present ground-based gravitational-wave observatories can probe the lower-end of the intermediate-mass range. However, many short-duration terrestrial artifacts that mimic intermediate-mass gravitational-wave signals plague ground-based detectors, making intermediate-mass detection challenging.

In this paper, we demonstrate that the Bayesian Coherence Odds-Ratio $\rho_{\rm BCR}$ [66] 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 high-mass candidates detected by `PyCBC`, the high-mass binary black hole events in O2 reported in `GWTC-1` [70] and by the `IAS`-team [82, 83]. Using $p_{\rm astro}^{\rm BCR}$, we find that the high-mass `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 $p_{\rm astro}^{\rm BCR}$, indicating this method's ability to discriminate between terrestrial artifacts and astrophysical signals. Our analysis on the high-mass `IAS` events demonstrates that GW17072 is likely to originate from an astrophysical source, while GW17040 is 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 high-mass triggers, 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 $p_{\rm astro}^{\rm BCR}$.

[Greg: If the search is better at identifying high-mass black holes and has not found any.. doesn't this mean we can better constraint their population properties? Do we know how much (if at all) this method outperforms current searches? This question may be stretching the scope of the paper, but I wondered if you had some thoughts.]

[AV:

- Unlike for stellar-mass BBH, there are still alot of uncertainties for IMBH formation scenarios. Hence, upper limits would be challenging to calculate
- We would require to do more robust simulation studies to see what would fall in/outside our detection threshold, to put constraints on population properties and study the search's sensitivity

]

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We thank Stuart Anderson for assistance with accommodating this analysis which was performed on the California Institute of Technology computing cluster. All

analyses (inclusive of test and failed analyses) performed for this study used 1.3M core-hours, amounting to a carbon footprint of 167 t of CO^2 (using the US average electricity source emissions of 0.429 kg/kWh [114] and 0.3 kWh for each CPU).

This research has made use of data, software and/or web tools obtained from the Gravitational Wave Open Science Center (https://www.gw-openscience.org), a service of LIGO Laboratory, the LIGO Scientific Collaboration and the Virgo Collaboration. LIGO is funded by the U.S. National Science Foundation. Virgo is funded by the French Centre National de Recherche Scientifique (CNRS), the Italian Istituto Nazionale della Fisica Nucleare (INFN) and the Dutch Nikhef, with contributions by Polish and Hungarian institutes.

Appendix A: Bayesian Evidence Evaluation

1. Noise Model

We assume that each detector's noise is Gaussian and stationary over the period being analyzed [107]. 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

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

where $\pi(\vec{\theta}|\mathcal{H}_S)$ is the prior for the parameters in the coherent signal hypothesis, 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 [64] and utilise 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 [64]. Modelling 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.

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 P^S and P^G from Eq. 4 help separate the two distributions. Altering P^S translates the ρ_{BCR} probability distributions while adjusting P^G spreads the distributions. Although Bayesian hyper-parameter estimation can determine the optimal values for P^S and P^G, an easier approach is to adjust the parameters for each data chunk's ρ_{BCR} distribution. In this study, we tune P^S and P^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 $D_{KL} = 0$ 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 P^S and P^G ranges of $[10^{-10}, 10^0]$. We set our values for P^S and P^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 in Fig. 2, we applied a post-processing step to marginalize the uncertainty in the PSD. In Fig. 3, we show the results if this post-processing step is not applied. Clearly, marginalizing over uncertainty in the PSD yields an improvement in the separation of the noise and signal distributions. Quantitatively, at a threshold ${\rho_{\rm BCR}}^T = 0$ the post-processing step results in a reduction in the number of background $\rho_{\rm BCR} > {\rho_{\rm BCR}}^T$ from 60.7% to 25.28% in the August 13 - 21, 2017 time-frame of data. For the entirety of O2 PSD marginalization resulted in a 49.26% improvement in search efficiency.

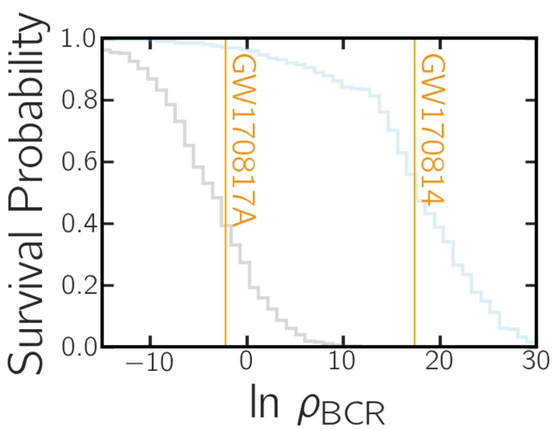

FIG. 3. This plot is analogous to Fig. 2, but without using the post-processing step to marginalize over PSD statistical uncertainties. Without the post-processing step, there is a greater overlap between the background (gray) and foreground (blue) survival functions. For more details about this plot, refer to the caption of Fig. 2.

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, P^S and P^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 $p_{\rm astro}^{\rm BCR}$. For example, consider Table V, which reports tuned $p_{\rm astro}^{\rm BCR}$ and un-tuned $p_{\rm astro}^{\rm BCR\prime}$ (where $P^S = 1$ and $P^G = 1$) for various high-mass events and candidates. By tuning the prior odds, the $p_{\rm astro}^{\rm BCR}$ 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 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	P^S	P^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	-	-

Appendix E: A closer look at 170222

PyCBC found in chunk7, with template, corresponds to parameters Xyz. Our parameters state that it is xyz. Put in corner, write notes from

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TABLE V. The BCR p-astro after tuning the prior odds, $p_{\rm astro}^{\rm BCR}$, and without tuning the prior odds, $p_{\rm astro}^{\rm BCR\prime}$ (where $P^S = 1$ and $P^G = 1$).

Event	Catalog	$p_{\rm astro}^{\rm BCR}$	$p_{\rm astro}^{\rm BCR\prime}$
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

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