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The second gravitational-wave transient catalog, GWTC-2, reported on 39 compact binary coalescences observed by the Advanced LIGO and Advanced Virgo detectors between 1 April 2019 15:00 UTC and 1 October 2019 15:00 UTC. Here, we present GWTC-2.1, which reports on a deeper list of candidate events observed over the same period. We analyze the final version of the strain data over this period with improved calibration and better subtraction of excess noise, which is now publicly released. We employ three matched-filter search pipelines for candidate identification, and estimate the probability of astrophysical origin for each candidate event. While GWTC-2 used a false alarm rate threshold of 2 per year, we include in GWTC-2.1, 1201 candidates that pass a false alarm rate threshold of 2 per day. We calculate the source properties of a subset of 44 high-significance candidates that have a probability of astrophysical origin greater than 0.5, using the default priors. Of these candidates, 36 have been reported in GWTC-2. If the 8 additional high-significance candidates presented here are astrophysical, the mass range of candidate events that are unambiguously identified as binary black holes (both objects $\geq 3\mathrm{M}_\odot$) is increased compared to GWTC-2, with total masses from $\sim 14\mathrm{M}_\odot$ for GW190924_021846 to $\sim 184\mathrm{M}_\odot$ for GW190426_190642. The primary components of two new candidate events (GW190403_051519 and GW190426_190642) fall in the mass gap predicted by pair-instability supernova theory. We also expand the population of binaries with significantly asymmetric mass ratios reported in GWTC-2 by an additional two events ($q < 0.61$ and $q < 0.62$ at 90% credibility for GW190403_051519 and GW190917_114630 respectively), and find that 2 of the 8 new events have effective inspiral spins $\chi_{\mathrm{eff}} > 0$ (at 90% credibility), while no binary is consistent with $\chi_{\mathrm{eff}} < 0$ at the same significance.

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I. INTRODUCTION

We are in the era of gravitational wave (GW) astronomy, started by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) [1] and the Advanced Virgo [2] detectors. The first observing run (O1) of the advanced detectors yielded the first detection of GWs from a binary black hole (BBH), GW150914 [3]. By the end of O1, the LIGO Scientific Collaboration and Virgo Collaboration (LVC) had reported on three BBH events [4]. The second observing run (O2) of the advanced detectors saw the first direct detection of GWs from a binary neutron star (BNS), GW170817 [5]. This event was also detected in electromagnetic waves [6], expanding the field of multimessenger astronomy to include GWs. By the end of O2, the LVC had reported on a total of ten BBHs and one BNS event, described in the first Gravitational-Wave Transient Catalog, GWTC-1 [7]. The second Gravitational-Wave Transient Catalog, GWTC-2 [8], added GW events from the first half of the third observing run (O3a), containing a total of 50 events. The GW data until the end of O3a have been made available to the public by the LVC. Since the public release of the LIGO and Virgo data, groups other than the LVC have also performed analyses searching for GW signals [9–18] and reported additional candidate events in some cases.

GW events between 1 April 2019 15:00 UTC and 1 October 2019 15:00 UTC (O3a) that passed a false alarm rate (FAR) threshold of 2 per year were presented in GWTC-2. Here, we present GWTC-2.1, a deep catalog that includes 1201 candidates passing a low-significance FAR threshold of 2 per day. Although most of the candidates in this catalog are noise events, they can be used for multimessenger searches by comparing against other astronomical surveys. Temporal and spatial coincidences between candidates in distinct astrophysical channels could lead to multimessenger discoveries [19, 20]. Multimessenger observations could enhance our understanding of the physical processes associated with such systems. Previous GW searches, both from the LVC [21] and independent groups [10, 13, 14, 21, 22], including most recently, the 3-OGC analysis of public data from O1 to O3a [17], have released subthreshold candidates. It is computationally unfeasible to determine detailed source properties of the large set of subthreshold GW candidates, therefore, we identify a subset of compact binary coalescence (CBC) candidates that have a probability of astrophysical origin p_{astro} [23–25] greater than 0.5, and calculate the source properties of these events. This probability p_{astro} uses both the signal rate in addition to the noise rate in order to determine the significance of events. There are 44 such candidate events, 36 of which have already been reported in GWTC-2 and their source properties have been described in detail [8]. Here we present the source properties of the 8 new events that have a p_{astro} greater than 0.5. A subset of these 8 additional events have been found in the LVC search on O3a data [26] for faint gravitationally lensed counterpart images [27, 28], and in the independent 3-OGC [17] analysis. While the 8 new events presented here have a non-negligible probability of being from noise, some of these have astrophysically interesting source properties under the default prior. Two of the new candidates presented here have a primary component mass in the pair instability gap [29–37], and one of those shows support for high spin and unequal mass ratio. We also find a new candidate whose masses are consistent with a neutron star–black hole binary (NSBH), although as in the case of GW190814 [38], we cannot rule out the possibility that the secondary component of the candidate could be a low-mass black hole.

In this work, all the analyses make use of the final version of the strain data with improved calibration and noise subtraction, which includes non-linear subtraction around 60 Hz US power grid [39, 40]. The data used in this work have been released to the public [41]. We use three matched-filter pipelines for candidate identification: GstLAL [42–44], PyCBC [45–49], and MBTA [50]. MBTA is reporting results from an archival search for the first time. Previously, in GWTC-2, only the GstLAL matched-filter pipeline included Virgo data; now all three pipelines analyze the data from all three detectors. For inferring the source properties, we use waveform models that include effects of spin-induced precession of the binary orbit, contributions from both the dominant and sub-dominant spherical harmonic modes, and tidal effects as appropriate [51–60].

The paper is structured as follows: Section II describes the instruments and the data that are analyzed by the searches, including methods on calibration, data quality, and glitch mitigation. Section III describes the methods used by the search pipelines. Section IV describes

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[a] Deceased, August 2020.

the events in GWTC-2.1, comparison to GWTC-2, sensitivity of the search pipelines used, and inferred rates of BNSs and BBHs. Section V describes the methods used for estimating the source parameters of the GW candidates and results, and in Section VI, we discuss the astrophysically interesting events and their implications. Finally, in Section VII we describe the data products being released alongside this catalog and our conclusions.

II. INSTRUMENTS AND DATA

The Advanced LIGO [1] and Advanced Virgo [2] instruments are kilometer-scale laser interferometers. The two LIGO detectors are located in Hanford, Washington and Livingston, Louisiana in the United States, and the Virgo detector near Pisa in Italy. The advanced generation of interferometers began operations in 2015, and observing periods have alternated with commissioning periods since then [61]. In the time between O2 and the third observing run (O3), all three detectors underwent significant upgrades that substantially increased their sensitivity [8, 62].

Major instrumentation upgrades on the LIGO detectors included: replacement of main lasers to increase beam stability, replacement of test masses to lower scattering and absorption losses, installation of acoustic mode dampers to mitigate parametric instabilities [63], installation of a squeezed vacuum source to reduce quantum noise [64], addressing issues with scattered light [65], and implementation of improved feedback control systems for the instruments. Compared to the O2 run, the Hanford BNS range (as defined in [45, 66]) increased by 64% (from 66 Mpc to 108 Mpc), and for Livingston by 53% (from 88 Mpc to 135 Mpc).

For Virgo, major upgrades included: replacement of the steel wire suspensions of the four test masses with fused-silica fibers [67], modification of the vacuum system to avoid dust contamination of the lowest suspension stage, replacement of the main laser to increase power, installation of a squeezed vacuum source to reduce quantum noise [68], improvements in beam stability [69], and addressing issues with scattered light. Compared to the O2 run, the Virgo BNS range increased by 73% (from 26 Mpc to 45 Mpc).

The processing of the data recorded by the LIGO and Virgo detectors includes several steps that occur both in near-real time to allow for the broadcasting of public alerts, and in higher latency to shape the final data set and update the catalogs of GW events. Raw data calibration and the subtraction of noise from known instrumental sources – documented in Section II A – occur first and the GW strain data, reconstructed independently in each detector, are then jointly processed. Significant GW candidates are vetted with several data quality tests as a part of the standard analysis procedure. This procedure is described in Section II B.

A. Calibration and noise subtraction

The strain data used for astrophysical analyses is derived from the optical power variations at the output ports of the interferometers. Calibration of the raw photodetector signal to GW strain requires a detailed understanding and modeling of the control system and optomechanical response of the interferometers throughout an observing run. This allows for accurate and reliable calibration of the strain and also for quantifying its systematic and statistical uncertainty. The detailed procedure for the calibration and the determination of the systematic and statistical uncertainty of the LIGO and Virgo detectors for O3 can be found in [70–72].

There are usually two calibrations applied to the data; a low-latency calibration and, if needed, an offline calibration. The low-latency (online) estimate of the strain uses the best models of the detector at the time of recording. However, over the course of any observing run, data drop-outs due to computer failures, incomplete modeling of the detector, and unknown residual systematic errors are often identified. The offline calibration incorporates the necessary corrections and improvements, producing a better calibrated strain with better known systematic uncertainty.

In addition, numerous noise sources and calibration lines that limit detectors' sensitivity are measured and linearly subtracted from the data [39, 73–75]. This subtraction is performed online to generate the LIGO and Virgo low-latency strain data, and it is also performed when regenerating the LIGO offline strain data. Additionally, noise due to non-stationary coupling of the power mains with the LIGO detectors was subtracted from the offline data [39]. As an example of noise subtraction, Fig. 1 shows the improvement in the noise levels around the 60 Hz mains line in the Hanford detector, after non-linear noise subtraction was applied to the strain time series. Taking as a figure of merit the BNS range of the detectors [45, 66], the subtraction results in a median range increase of 0.9 Mpc for Hanford and 0.2 Mpc for Livingston.

In GWTC-2, search pipelines and parameter estimation analyses used a mix of low-latency and offline calibrated frames. In contrast to this, all searches and analyses presented in this paper use strain data with the best available calibration and noise subtraction for each detector. For LIGO, this corresponds to the offline recalibrated data with 60 Hz non-linear subtraction. For Virgo, the online strain data stream was good enough to be used offline, except for the last two weeks of O3a which were reprocessed to improve subtraction of control and laser frequency noise [76].

In addition, the LIGO offline data are accompanied with a much improved systematic and statistical error estimate compared to the online data. The probability distribution of the calibration uncertainty estimate for LIGO in O3a is characterized in [70], with the systematic error over the detectors' bandwidth being under 3%

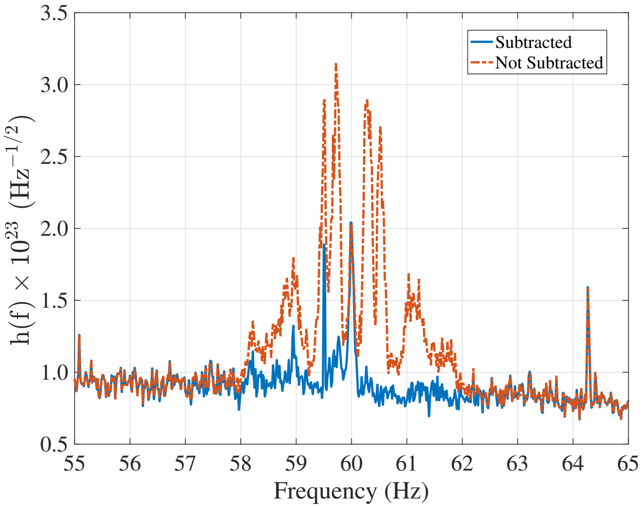

FIG. 1. Comparison of the amplitude spectral density at Hanford around the 60 Hz mains line, between data with subtracted non-stationary noise and data with no subtraction. The data correspond to a typical one-hour observation-ready data stretch during O3a.

in magnitude and under 2° in phase. The uncertainty in the Virgo strain data in O3a had a maximum systematic error over the detector's bandwidth under 5% in magnitude and under 2° in phase [71]. Parameter estimation takes into account calibration uncertainties, as described in Section V. Given the size of calibration uncertainties in O3, there is no evidence that they have a significant impact on the inference of source parameters [77, 78].

B. Data quality, event validation & glitch mitigation

LIGO and Virgo data quality is continuously monitored during an observing run both on site and remotely, as reported in [79, 80]. This can include, for example, internal detector summary pages which detail the status of the detectors and interferometer subsystems [81, 82]. Feedback from GW searches also gives an indication of the impact of data quality on the sensitivity of a search. To exclude identified instances of poor data quality from the searches and produce the results in Section III, we used the same methods and data products as reported for GWTC-2 [8].

Once a GW event has been identified by the search pipelines, we check the quality of data around the time of the event. We followed the same procedures outlined in [8] to validate the data quality around each new GW candidate reported in this paper. The aim of these validation procedures is to identify any instrumental or environmental noise that may impact the estimation of GW signal parameters. As summarized for GWTC-2 [8], in some cases short-duration noise transients, or *glitches* [83–86], can be subtracted from the data [87–90]. When this is not possible, analyses use tailored configurations, for example, a modified low-frequency cutoff, to exclude data that could be corrupted by the presence of a nearby glitch. The 8 candidates whose source properties are discussed in Section V D did not require data mitigation.

III. CANDIDATE IDENTIFICATION

GW data is analyzed to search for candidates in two stages: first in low-latency in order to generate public alerts that subsequently trigger follow-up astronomical observations, and then in higher latency in the form of an offline analysis of the archival strain data, which is used to create GW catalogs. Five pipelines were used in real time to analyze O3 data: an unmodeled burst search (coherent WaveBurst [91–95]), and four matched-filter [45, 46] pipelines (GstLAL [42–44], MBTA [50], PyCBC [47–49, 96], and SPIIR [97]). Collectively, they identified 56 unretracted candidates during O3, 33 of which were found in O3a. GWTC-2 [8] presented 39 events identified by coherent WaveBurst, GstLAL, and PyCBC in the first offline search over O3a.

We present here results from a refined offline search of O3a. The search employs three matched-filter pipelines: GstLAL, PyCBC, and MBTA [50], marking the first time that MBTA results from archival data are presented and included in a GW catalog. All three pipelines analyze the data from all three detectors. While GWTC-2 imposed a FAR ceiling of 2 per year on candidates, here we release a deep list of GW candidates with a FAR smaller than 2 per day [98]. In addition, we identify the 44 CBC candidates with an estimated $p_{\rm astro}$ greater than 0.5 (Table I). There are also 2 candidates with $p_{\rm astro}$ below 0.5 that do meet the FAR criterion used in GWTC-2; these are presented as marginal triggers. This GW catalog contains the largest number of candidates with $p_{\rm astro}$ greater than 0.5 to date.

In Section III A, we first lay out a general description of matched filter searches and in Section III B, we describe the methods employed by the three CBC searches used in this work. We describe the search results in the following Section IV.

A. Matched-filter searches

The matched-filter method relies on having a model of the signal, as a function of the physical parameters. The parameters include those that are intrinsic to the source: two individual component masses m_1, m_2 and two dimensionless spin vectors $\vec{\chi}_1$, $\vec{\chi}_2$,[1] and seven extrinsic parameters that provide the orientation and position of the

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[1] The dimensionless spin is related to each component's spin angular momentum $\vec{S}$ by $\vec{\chi}_i = c\vec{S}_i/(Gm_i^2)$.

source in relation to the Earth: the luminosity distance D_{L}, two-dimensional sky position (right ascension α and declination δ), inclination between total angular momentum and line-of-sight θ_{JN}, time of merger t_{c}, a reference phase ϕ, and polarization angle ψ. The search pipelines create a template bank [99–101] of GW waveforms covering the desired intrinsic parameter space,[2] and use these to filter against the data and produce signal-to-noise ratio (SNR) time series.

For each set of intrinsic parameters, extrinsic parameters affecting the signal's amplitude and phase may be maximized over analytically [45], if the signal can be approximated as a pure quadrupole mode, i.e. $(\ell, |m|) = (2, 2)$. In particular, for this search, the templates use only the dominant quadrupole mode and assume quasi-circular orbits with component spins aligned with the total orbital angular momentum. Peaks in the resulting SNR time series are stored as triggers. GW candidates are formed by imposing consistency in time and in template intrinsic parameters between triggers in different detectors; in addition, GstLAL also considers non-coincident triggers as candidates [42].

When considering a single template in a single detector with stationary, Gaussian noise, the matched filter SNR is an optimal statistic for ranking candidates. However, additional terms are needed to optimize sensitivity in searches of real data covering a wide signal parameter space. To account for the multi-detector network, the distribution of signals over relative times, phases and amplitudes between detectors is considered [43, 49]. Since detector noise is not stationary or Gaussian, signal-consistency tests such as chi-squared [46] are calculated and used to rank candidates.

The distribution of noise triggers may vary strongly over the template masses and spins; we then model its variation empirically, as a function of combinations of parameters that are typically well-constrained by GW measurements. The binary's chirp mass [102],

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}, \tag{1}$$

determines to lowest order the phase evolution during the inspiral, and is typically better constrained than the component masses. At higher orders, the binary phase evolution is affected by the mass ratio $q = m_2/m_1$ (where $m_2 \leq m_1$) and by the effective inspiral spin χ_{eff}, defined as [103]

$$\chi_{\mathrm{eff}} = \frac{(m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2) \cdot \hat{L}_{\mathrm{N}}}{M}, \tag{2}$$

where $M = m_1 + m_2$ is the total mass and $\hat{L}_{\mathrm{N}}$ is the unit vector along the Newtonian orbital angular momentum. Finally, the ranking of events by the search pipelines may account for an assumed prior distribution of signals over masses and spins [104, 105].

The significance of each candidate event is quantified by its FAR, the estimated rate of events due to noise with equal or higher ranking statistic value. The FAR is calculated by each search pipeline by constructing a set of background samples designed to have the same distribution over ranking statistic as search events in the absence of binary merger GW signals.

By considering also the expected distribution of GW signal events recovered by a given search, we may derive an estimate of the relative probabilities of noise (terrestrial) origin p_{terr}, and signal (astrophysical) origin p_{astro} [23–25]. For the bulk of released events, detailed estimates of source parameters are not calculated. Therefore, based only on the matched-filter search results we also estimate the probability for each event to belong to three possible astrophysical binary source classes, labeled BNS, NSBH and BBH. The classes are defined by binary component masses: BNS corresponds to $\{m_1, m_2\} < 3\,\mathrm{M}_{\odot}$, NSBH to $m_1 > 3\,\mathrm{M}_{\odot}$, $m_2 < 3\,\mathrm{M}_{\odot}$, and BBH to $\{m_1, m_2\} > 3\,\mathrm{M}_{\odot}$. For MBTA, a $2.5\,\mathrm{M}_{\odot}$ cut is used instead of $3\,\mathrm{M}_{\odot}$, with a gap to $5\,\mathrm{M}_{\odot}$ for BBH. These definitions are chosen for simplicity: they *do not* imply that every binary component within a given mass range is necessarily a neutron star (NS) or a black hole (BH). Such inference would ultimately require measurement of the effects of NS matter on observed signals, which is beyond the capabilities of the search pipelines. The probabilities for an event to belong to each class (p_{BNS}, p_{NSBH}, p_{BBH}, and p_{terr}) are calculated from the template masses and spins recovered by the searches, under the assumption that events from each class occur as independent Poisson processes. Implementation details differ between pipelines, as summarized below; the resulting probability estimates are listed in Tables I and II.

While the p_{astro} values given here represent our best estimates of the origin of candidates using the information available from search pipelines, they are subject to statistical (random) and systematic errors, as well as in some cases clearly differing for a given candidate between different pipelines. One such uncertainty arises from methods used to rank events between pipelines, including tests for noise artifacts: such tests, such as chi-squared statistics, will in general add (different) random variations to the ranking of a given event, in addition to their differing power in distinguishing signals from artifacts. For single-detector candidates, there is an additional inherent uncertainty in estimating the rate of comparable noise events, which may only be bounded to (less than) 1 per observing time. An inherent source of potential systematic error also lies in the search ranking statistic used in the calculation of p_{astro}: such statistics are optimized to detect a specific (usually broad) distribution of signals over binary intrinsic parameters. The resulting p_{astro} estimates may be biased if this distribution deviates significantly from the (unknown) true signal distribution.

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[2] The component masses describing template waveforms are affected by source redshift z as $m_i^{\mathrm{det}} = (1+z) m_i$.

The risk of such bias is largest for regions of parameter space containing few, or zero, confirmed detections. For all these reasons, our current $p_{\rm astro}$ values may be revised in the future, particularly as and when current uncertainties in the true signal rate and distributions are eventually reduced.

We next review specific methods used by individual matched-filter pipelines.

B. Search pipelines

In this section we describe the pipelines that were used to identify the candidates presented in GWTC-2.1.

1. *GstLAL*

The GstLAL analysis used in this search is largely similar to the one used in the previous analysis [8] and uses the same log-likelihood ratio $\mathcal{L}$ as the ranking statistic. Improvements have been made to the input data products generated by iDQ, the statistical inference framework to autonomously detect non-Gaussian noise artifacts in strain data based on auxiliary witness sensors [106, 107]. This iDQ timeseries is used to compute one of the terms in the log-likelihood ratio within the GstLAL analysis, that informs the search of the presence of non-Gaussian noise in close proximity to a GW candidate. Compared to GWTC-2, the timeseries generated by iDQ was reprocessed offline, having access to an expanded set of auxiliary witness sensors and trained with an acausal binning scheme [106]. As a result, the generated iDQ timeseries performs better in identifying noise artifacts in strain data. In addition, for GWTC-2 the iDQ term was only used when ranking single-detector triggers, whereas now it is used for both coincident and single-detector triggers. Because of changes in the iDQ term, the empirically determined penalty for single-detector candidates had to be retuned compared to GWTC-2, and was increased to a penalty of $\Delta\mathcal{L} = -12$ from $\Delta\mathcal{L} = -10$.[3]

For the GstLAL analysis, $p_{\rm terr}$ and $p_{\rm astro}$ shown in Tables I and II are estimated following the multicomponent population analysis [23, 108]. The response of each GstLAL template to each astrophysical source class, computed semi-analytically [105] is used in estimating these probabilities. The volume–time sensitivity of the pipeline used in this calculation is estimated based on simulated sources injected into the pipeline and is rescaled to the astrophysical distribution [109]. The volume-time ratios are used to combine triggers from various observation runs and perform a multicomponent analysis yielding $p_{\rm astro}$ and merger rates [23, 108] inferred from O1 to O3a. The astrophysical distribution assumed in this analysis uses a log-uniform distribution for the source component masses, the component spins aligned with the orbital angular momentum, and a uniform distribution for the component spin magnitudes. The BH masses in BBHs and NSBHs are distributed between $3\,{\rm M}_\odot$ and $300\,{\rm M}_\odot$ with aligned component spins distributed in the range $[-0.99, 0.99]$. The NS masses in NSBHs and BNSs are distributed between $1\,{\rm M}_\odot$ and $3\,{\rm M}_\odot$. In NSBHs, the NS spins are assumed to be aligned and distributed in the range $[-0.4, 0.4]$, whereas, in BNSs the NSs are assumed to have small spins in the range $[-0.05, 0.05]$. These choices match previous analyses [8].

2. *MBTA*

The Multi-Band Template Analysis (MBTA) pipeline [50] is based on matched filtering, relying on coincidences between triggers observed in different detectors. The version used for the offline search is close to the online version which contributed to the LVC public alerts [110]. The archival-search version benefits from offline-specific improvements, with a background estimate made over a longer duration, and with a reranking of the candidates using information collected not just before but also after the candidate.

The parameter space covered by this analysis ranges from $1\,{\rm M}_\odot$ to $195\,{\rm M}_\odot$ for the primary (more massive) component, with total masses up to $200\,{\rm M}_\odot$; or from $1\,{\rm M}_\odot$ to $100\,{\rm M}_\odot$ for the primary when the mass of the secondary is between $1\,{\rm M}_\odot$ and $2\,{\rm M}_\odot$. Component spins are aligned with the total angular momentum and are limited to 0.05 for objects below $2\ {\rm M}_\odot$, and going up to 0.997 for objects above $2\,{\rm M}_\odot$. The waveform used for the search is SpinTaylorT4 [111–113] if both binary masses are lighter than $2\,{\rm M}_\odot$, and SEOBNRv4 [114] if the mass of one of the components is above $2\,{\rm M}_\odot$. The total number of templates in the bank used is 727,992. The SNR threshold for recording triggers in each detector is 4.5, or 4.8 if one of the components is above $2\,{\rm M}_\odot$.

The FAR is calculated for each coincident event by forming random coincidences among single detector background triggers. This computation is performed independently for three large regions of the parameter space bounded by a $2\,{\rm M}_\odot$ limit for the mass of each component. These three regions are allowed to contribute equally to the background, while within each of them we sum the background contributions from all the templates.

The $p_{\rm BNS}$, $p_{\rm NSBH}$, $p_{\rm BBH}$, and derived $p_{\rm astro}$ quantities are computed as the fraction of recovered simulated events, representative of an astrophysical population, to this foreground plus background estimate provided by the pipeline. The parameterizations of the populations are described in Section IV D, with the POWER LAW + PEAK model used for BBH [115]. The rate of each type

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[3] The single-detector event penalty is determined by comparing the recovery of simulated signals in single detector versus combinations of detectors and the sensitive volume–time for each configuration.

of source is adjusted using a multicomponent population analysis [23]. To follow the population and background evolution across the parameter space, 165 subregions are used. This finer resolution has the benefit of revealing events in population-rich areas, even if the overall background rate for their ranking statistic value is larger than few per year, as in the case of the high mass BBH event GW190916_200658 presented in Table I.

3. *PyCBC*

In previous LVC searches [4, 7, 8, 116], the offline PyCBC [48, 117] pipeline has analyzed data only from the two LIGO detectors. In this analysis, PyCBC was extended to search data from the three-detector LIGO–Virgo network, along with updates to the event ranking statistic [96] and the $p_{\rm astro}$ calculation and a new method to estimate source class probability [118].

The PyCBC search uses the same template bank as in GWTC-2 [8], constructed using a hybrid geometric-random algorithm outlined in [119, 120]. Peaks in SNR time series exceeding a threshold of 4 constitute single-detector triggers. Two-detector coincident events are formed from triggers with the same component masses and spins with a physically allowed time difference between detectors, allowing for timing errors. Three-detector triple coincidences require triggers in all pairs of detectors to pass this consistency test.

The detection statistic is given by the logarithm of the ratio of estimated signal event rate density to noise event rate density. We model the noise distribution in each detector as a decreasing exponential of the matched-filter SNR, reweighted based on a chi-squared signal–glitch discriminator [46, 121], with parameters that depend on the template intrinsic parameters. The signal distribution includes terms accounting for dependence on relative times of arrival, phases and amplitudes between detectors, as well as relative sensitivities of the participating detectors [49]. We estimate the FAR separately for each combination of detectors via time-shifted analyses [48, 122]. The significance for each candidate event is then found through addition of the FARs at the candidate's ranking statistic value over all active detector combinations [96].

In addition to the generic PyCBC search, which covers the full parameter space [8] including a range of possible signal types, we also conduct a focused PyCBC BBH search [8, 14], capable of uncovering fainter BBH mergers by imposing a prior form for the signal distribution over the template bank [104]. This search is targeted at systems with mass ratios from 1 to 1/3, primary component masses from $5\,{\rm M}_\odot$ to $350\,{\rm M}_\odot$, and effective inspiral spins from $\chi_{\rm eff} = -0.998$ to 0.998.

The inference of $p_{\rm astro}$ and $p_{\rm terr}$ for each candidate event employs a Poisson mixture model of signal and noise events [23–25]. Here, the distribution of signal events is estimated via a set of simulated signals analyzed by the pipeline, and the rate and distribution of noise events are estimated from time-shifted analyses [48]. In GWTC-2 the calculation was only performed on potential BBH events with template chirp mass above $4.35\,{\rm M}_\odot$.[4] Here, we include potential BNS and NSBH events by performing independent calculations over ranges of template chirp mass below $2.18\,{\rm M}_\odot$ (corresponding to equal $2.5\,{\rm M}_\odot$ components), and between $2.18\,{\rm M}_\odot$–$4.35\,{\rm M}_\odot$, respectively. Although the implied signal distribution over template chirp mass does not correspond to any specific astrophysical model, it is adequate for assignment of $p_{\rm astro}$ given the current knowledge of BNS and NSBH merger populations. Systematic biases in $p_{\rm astro}$ calculation may arise if the (unknown) true mass distribution is different from that assumed. The calculation is also extended relative to previous analyses to account for different possible coincident combinations of detectors [123]. The results given here are obtained from events occurring during O3a only, except for the BNS region where prior information of 1 highly significant detection was applied to represent GW170817 [5].

The estimation method for binary source class probabilities [118] uses the binary chirp mass as input, and assumes a uniform density of candidate signals over the plane of component masses $\{m_1, m_2\}$. Here we take the classes to be defined by boundaries between different types of binary component at $3\,{\rm M}_\odot$. To estimate source chirp mass, we correct the search template masses for cosmological redshift, using an estimate of the luminosity distance derived from the search SNRs and the corresponding templates' sensitivity. We then derive the relative probabilities of each source class and enforce that the sum of astrophysical source probabilities is equal to $p_{\rm astro}$.

IV. SEARCH RESULTS

We recover 1201 candidates that have FAR less than 2 per day in any of the search pipelines. These events and their estimated source probabilities are shown in Fig. 2. The candidates are shown in decreasing order of $p_{\rm astro}$. The total sum of $p_{\rm astro}$ represents the Poisson rate of sources that pass the FAR threshold of 2 per day in each source class per O3a experiment, as estimated by the search pipelines. We find that this corresponds to between 24.95–44.50 signals in the BBH class, 0.66–3.80 signals in the NSBH class, 0.22–0.81 signals in the BNS class in O3a. The range represents the difference in the search pipelines. Names are marked for the candidate events with $p_{\rm BNS}$ or $p_{\rm NSBH}$ greater than 20%. The dashed vertical line shows the least significant event with $p_{\rm astro}$ greater than 0.5. An estimate of the rate of sources in the subthreshold candidate list per O3a experiment is obtained by the contribution to the sum from events with

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[4] This value corresponds to equal $5\,{\rm M}_\odot$ component masses.

$p_{\rm astro}$ less than 0.5. This corresponds to between 2.55–12.40 signals in the BBH class, 0.36–2.39 signals in the NSBH class, and 0.02–0.49 signals in the BNS class in the subthreshold candidates in O3a.

We find 44 high probability CBC candidates that have $p_{\rm astro}$ greater than 0.5. These events are listed in Table I. This list includes 8 new candidates that were not present in GWTC-2 [8]. These are marked in bold in Table I. Out of the 44 candidates, 4 were found with significant SNR only in one of the detectors by the GstLAL search, which is the only pipeline that looked for GW signals in single-detector data. These are listed with a dagger (†) next to the FAR in the Table I. For the majority of events listed in Table I, $p_{\rm astro} \approx p_{\rm BBH}$; the exceptions are listed in Table II, which provides the list of candidates that have $p_{\rm BNS}$ or $p_{\rm NSBH}$ greater than 0.01.

A. New high probability candidates

We recover all the events found in GWTC-2 as having $p_{\rm astro}$ above 0.5, with the exception of three: GW190424_180648, GW190426_152155, and GW190909_114149. Since the rate of BBH events detectable by the LIGO–Virgo detectors is greater than the rate of detectable BNS or NSBH events, the $p_{\rm astro}$ for events in the BBH class is higher than that of the events in the BNS or NSBH class at a fixed FAR. Therefore, in switching to a $p_{\rm astro}$ threshold from a FAR threshold, one can expect to add BBH events while dropping some low-mass events.

All the 8 new candidates with $p_{\rm astro}$ greater than 0.5 are classified as BBHs, that is, $p_{\rm BBH}$ is greater than $p_{\rm NSBH}$ and $p_{\rm BNS}$. Only one new candidate, GW190725_174728, has a non-negligible probability in a source class other than BBH, with non-zero $p_{\rm NSBH}$ (Table II). Out of the 8 candidates, only two (GW190725_174728 and GW190916_200658) are assigned $p_{\rm astro} > 0.5$ by more than one pipeline. Differences between pipelines are expected, due to the effects of random noise fluctuations on the different ranking statistics used, and due to different assumed signal distributions and other choices. In principle, a more accurate assessment of the candidates' origins could be obtained by considering information from all pipelines; however, this is not currently implemented as a quantitative measure. One of the events, GW190917_114630, is identified as a BBH by the GstLAL pipeline, with $p_{\rm BBH} = 0.77$ (Table I). However, when its source properties are inferred by follow-up pipelines, the mass parameters are found to be consistent with NSBH systems. Had it been classified as an NSBH to begin with by the search pipeline, the resulting $p_{\rm astro}$ would not have made the threshold of 0.5. There is also non-stationary noise in the LIGO Livingston detector at the time of this event, but we have no evidence that the FAR of the event is misestimated. Out of the 8 new candidates, 5 candidates (GW190426_190642, GW190725_174728, GW190805_211137, GW190916_200658, and GW190925_232845) were identified in the LVC search for gravitationally lensed candidates in O3a data [26], while 4 candidates (GW190725_174728, GW190916_200658, GW190925_232845, and GW190926_050336) were also independently identified and presented in 3-OGC [17]. The source properties of all 8 candidates are discussed in Section V D.

B. GWTC-2 candidates with $p_{\rm astro} < 0.5$

The three events in GWTC-2 that have a $p_{\rm astro}$ smaller than 0.5 in GWTC-2.1 analyses are:

GW190424_180648: This event was found by GstLAL as a single detector BBH event in Livingston. However, the data surrounding this event recorded periodic glitching from a camera shutter and iDQ (Section III B 1) heavily downranked the timespan surrounding this event [107]. Figure 4 in [107] shows both the inspiral track and the surrounding glitches in the time–frequency spectrogram surrounding this event and the response of iDQ. While the down-ranking due to iDQ for this particular event remains largely the same between GWTC-2 and GWTC-2.1, the retuning of the singles penalty (Section III B 1) in GstLAL for GWTC-2.1 caused the significance of the event to go down. Consequently, in GWTC-2.1, this event does not meet either the FAR threshold of 2 per year or the $p_{\rm astro}$ threshold of 0.5.

GW190426_152155: This event is in the marginal-significance event list for GWTC-2.1 (Table III); the FAR is similar to the one in GWTC-2 and still passed the threshold of 2 per year considered in the previous catalog. However, based on the masses recovered by the pipeline, it is assigned to the NSBH class with $p_{\rm NSBH} = 0.14$. The low $p_{\rm astro}$ in the NSBH class is due to the fact that the inferred rate of detectable NSBHs is lower than that of detectable BBHs.

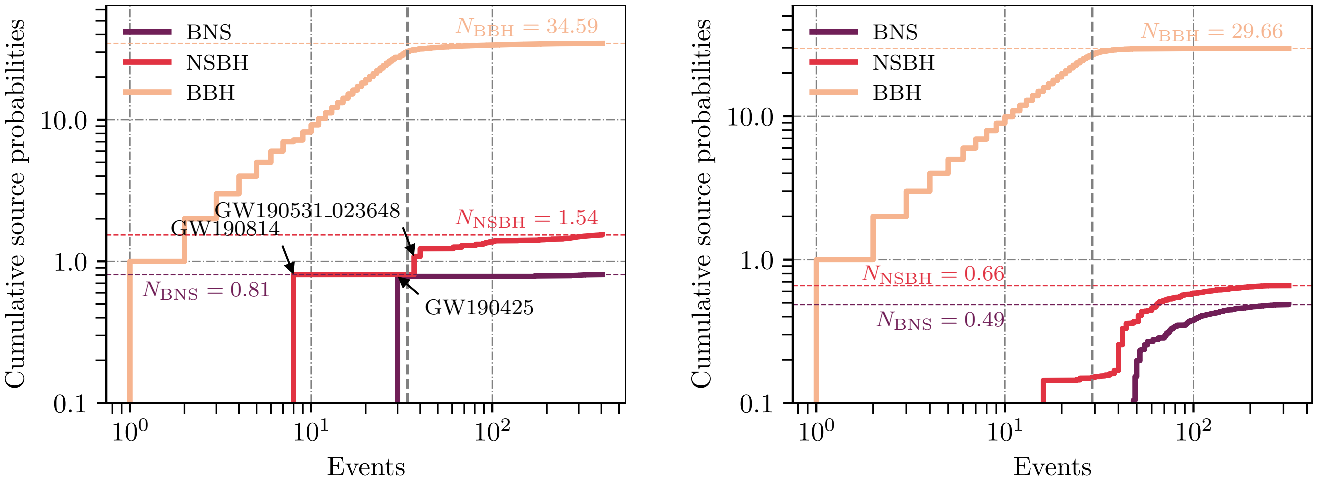
GW190909_114149: This candidate BBH event was found as a coincident event in Hanford and Livingston detectors by GstLAL. It is recovered now with smaller SNR in the Hanford detector and is therefore ranked lower.

C. Marginal-significance candidates

The two GW candidates that satisfy the FAR criteria used by GWTC-2, but do not have $p_{\rm astro}$ greater than 0.5 are listed as marginal candidates in Table III. Both these events were detected by GstLAL with a small FAR, and were assigned to the NSBH class with $p_{\rm astro}$ and $p_{\rm NSBH}$ smaller than 0.5. Since the rate of detectable signals in the NSBH class is smaller than that in the BBH class, the $p_{\rm astro}$ for these are smaller than they would be in the BBH class at the same FAR.

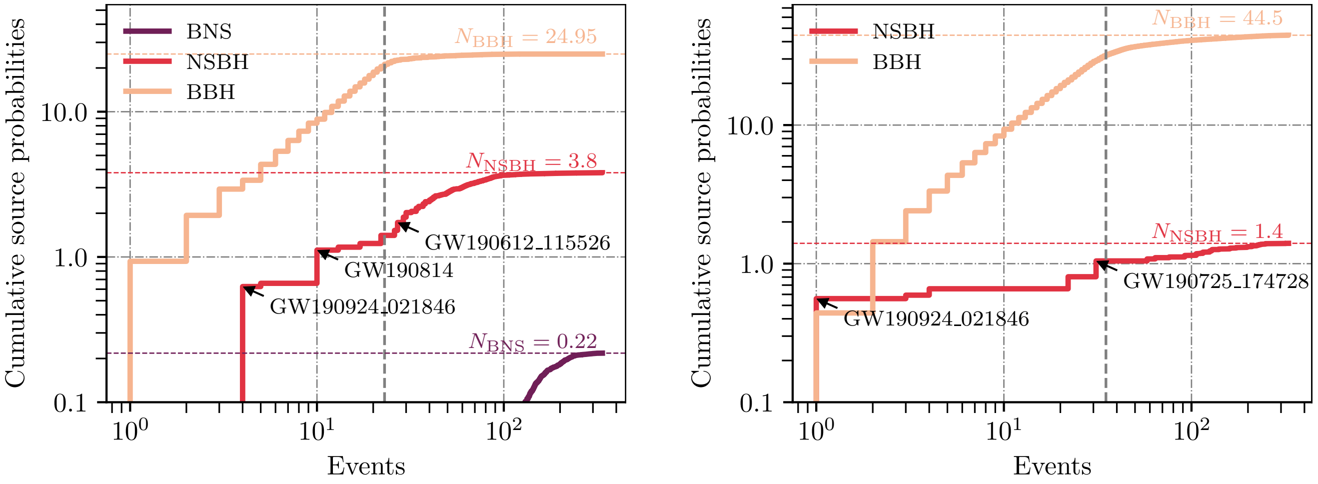
Name	**Inst.**	**MBTA**			**GstLAL**			**PyCBC**			**PyCBC-BBH**		
		FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}
GW190403_051519	HL	−−	−−	−−	−−	−−	−−	−−	−−	−−	7.7	8.0	0.61
GW190408_181802	HLV	8.7×10^{-5}	14.4	1.00	$< 1.0 \times 10^{-5}$	14.7	1.00	2.5×10^{-4}	13.1	1.00	$< 1.2 \times 10^{-4}$	13.7	1.00
GW190412	HLV	$< 1.0 \times 10^{-5}$	18.2	1.00	$< 1.0 \times 10^{-5}$	19.0	1.00	$< 1.1 \times 10^{-4}$	17.4	1.00	$< 1.2 \times 10^{-4}$	17.9	1.00
GW190413_052954	HL	−−	−−	−−	−−	−−	−−	*170*	*8.5*	*0.13*	0.82	8.5	0.93
GW190413_134308	HLV	0.34	10.3	0.99	*39*	*10.1*	*0.04*	*21*	*9.3*	*0.48*	0.18	8.9	0.99
GW190421_213856	HL	1.2	9.7	0.99	0.0028	10.5	1.00	5.9	10.1	0.75	0.014	10.1	1.00
GW190425	LV	−−	−−	−−	$0.034^{\dagger}$	12.9	0.78	−−	−−	−−	−−	−−	−−
GW190426_190642	HL	−−	−−	−−	−−	−−	−−	−−	−−	−−	4.1	9.6	0.75
GW190503_185404	HLV	0.013	12.8	1.00	$< 1.0 \times 10^{-5}$	12.0	1.00	0.038	12.2	1.00	0.0026	12.2	1.00
GW190512_180714	HLV	0.038	11.7	0.99	$< 1.0 \times 10^{-5}$	12.2	1.00	1.1×10^{-4}	12.4	1.00	$< 1.1 \times 10^{-4}$	12.4	1.00
GW190513_205428	HLV	0.11	13.0	0.99	1.3×10^{-5}	12.3	1.00	*19*	*11.6*	*0.49*	0.044	11.8	1.00
GW190514_065416	HL	−−	−−	−−	*450*	*8.3*	*0.00*	−−	−−	−−	2.8	8.4	0.76
GW190517_055101	HLV	0.11	11.3	1.00	0.0045	10.8	1.00	0.0095	10.4	1.00	3.5×10^{-4}	10.3	1.00
GW190519_153544	HLV	7.0×10^{-5}	13.7	1.00	$< 1.0 \times 10^{-5}$	12.4	1.00	$< 1.0 \times 10^{-4}$	13.2	1.00	$< 1.1 \times 10^{-4}$	13.2	1.00
GW190521	HLV	0.042	13.0	0.96	0.20	13.3	0.79	0.44	13.7	0.96	0.0013	13.6	1.00
GW190521_074359	HL	$< 1.0 \times 10^{-5}$	22.2	1.00	$< 1.0 \times 10^{-5}$	24.4	1.00	$< 1.8 \times 10^{-5}$	24.0	1.00	$< 2.3 \times 10^{-5}$	24.0	1.00
GW190527_092055	HL	−−	−−	−−	0.23	8.7	0.85	−−	−−	−−	*19*	*8.4*	*0.33*
GW190602_175927	HLV	3.0×10^{-4}	12.6	1.00	$< 1.0 \times 10^{-5}$	12.3	1.00	0.29	11.9	0.98	0.013	11.9	1.00
GW190620_030421	LV	−−	−−	−−	$0.011^{\dagger}$	10.9	0.99	−−	−−	−−	−−	−−	−−
GW190630_185205	LV	−−	−−	−−	$< 1.0 \times 10^{-5}$	15.2	1.00	−−	−−	−−	0.24	15.1	1.00
GW190701_203306	HLV	35	11.3	0.87	0.0057	11.7	0.99	0.064	11.9	0.99	0.56	11.7	1.00
GW190706_222641	HLV	0.0015	11.9	1.00	5.0×10^{-5}	12.5	1.00	3.7×10^{-4}	11.7	1.00	0.34	12.6	1.00
GW190707_093326	HL	0.032	12.6	1.00	$< 1.0 \times 10^{-5}$	13.2	1.00	$< 1.0 \times 10^{-5}$	13.0	1.00	$< 1.9 \times 10^{-5}$	13.0	1.00
GW190708_232457	LV	−−	−−	−−	$3.1 \times 10^{-4\dagger}$	13.1	1.00	−−	−−	−−	−−	−−	−−
GW190719_215514	HL	−−	−−	−−	−−	−−	−−	−−	−−	−−	0.63	8.0	0.92
GW190720_000836	HLV	0.094	11.6	1.00	$< 1.0 \times 10^{-5}$	11.5	1.00	1.4×10^{-4}	10.6	1.00	$< 7.8 \times 10^{-5}$	11.4	1.00
GW190725_174728*	HLV	3.1	9.8	0.59	−−	−−	−−	0.46	9.1	0.96	2.9	8.8	0.82
GW190727_060333	HLV	0.023	12.0	1.00	$< 1.0 \times 10^{-5}$	12.1	1.00	0.0056	11.4	1.00	2.0×10^{-4}	11.1	1.00
GW190728_064510	HLV	7.5×10^{-4}	13.1	1.00	$< 1.0 \times 10^{-5}$	13.4	1.00	$< 8.2 \times 10^{-5}$	13.0	1.00	$< 7.8 \times 10^{-5}$	13.0	1.00
GW190731_140936	HL	6.1	9.1	0.80	0.33	8.5	0.78	−−	−−	−−	1.9	7.8	0.83
GW190803_022701	HLV	77	9.0	0.96	0.073	9.1	0.94	*81*	*8.7*	*0.17*	0.39	8.7	0.97
GW190805_211137	HL	−−	−−	−−	−−	−−	−−	−−	−−	−−	0.63	8.3	0.95
GW190814	LV	$< 2.0 \times 10^{-4}$	20.4	1.00	$< 1.0 \times 10^{-5}$	22.2	1.00	0.17	19.5	1.00	−−	−−	−−
GW190828_063405	HLV	$< 1.0 \times 10^{-5}$	15.2	1.00	$< 1.0 \times 10^{-5}$	16.3	1.00	$< 8.5 \times 10^{-5}$	13.9	1.00	$< 7.0 \times 10^{-5}$	15.9	1.00
GW190828_065509	HLV	0.16	10.8	0.96	3.5×10^{-5}	11.1	1.00	2.8×10^{-4}	10.5	1.00	1.1×10^{-4}	10.5	1.00
GW190910_112807	LV	−−	−−	−−	$0.0029^{\dagger}$	13.4	1.00	−−	−−	−−	−−	−−	−−
GW190915_235702	HLV	0.0055	12.7	1.00	$< 1.0 \times 10^{-5}$	13.0	1.00	6.8×10^{-4}	13.0	1.00	$< 7.0 \times 10^{-5}$	13.1	1.00
GW190916_200658*	HLV	6.9×10^{3}	8.2	0.66	*12*	*8.2*	*0.09*	−−	−−	−−	4.7	7.9	0.64
GW190917_114630	HLV	−−	−−	−−	0.66	9.5	0.77	−−	−−	−−	−−	−−	−−
GW190924_021846	HLV	0.0049	11.9	0.99	$< 1.0 \times 10^{-5}$	13.0	1.00	$< 8.2 \times 10^{-5}$	12.4	1.00	8.3×10^{-5}	12.5	1.00
GW190925_232845*	HV	*100*	*9.4*	*0.35*	−−	−−	−−	*73*	*9.0*	*0.02*	0.0072	9.9	0.99
GW190926_050336*	HLV	−−	−−	−−	1.1	9.0	0.54	−−	−−	−−	*87*	*7.8*	*0.09*
GW190929_012149	HLV	2.9	10.3	0.64	0.16	10.1	0.87	*120*	*9.4*	*0.14*	*14*	*8.5*	*0.41*
GW190930_133541	HL	0.34	10.0	0.87	0.43	10.1	0.76	0.018	9.8	1.00	0.012	10.0	1.00

TABLE I. Above-threshold GW candidate list. We find 44 events that have p_{astro} in at least one of the searches as greater than 0.5. Bold-faced names indicate the events that were not previously reported in GWTC-2 [8]. The candidates marked with an asterisk were first published in 3-OGC [17]. The second column denotes the observing instruments. Candidate events in GWTC-2.1 which do not meet the p_{astro} threshold but were at the same time as above-threshold events are given in italics. The 4 events marked with a dagger (†) next to their FARs were found only in one detector by the GstLAL search. All four were detected using the data from LIGO Livingston. For the single-detector candidate events, the FAR estimate involves extrapolation. All single-detector candidate events in this list according to the FAR assigned to them are rarer than the background data of about 6 months collected in this analysis. Therefore, a conservative bound on the FAR for triggers denoted by † is $\sim 2\ \mathrm{yr}^{-1}$. GstLAL FARs have been capped at $1 \times 10^{-5}\ \mathrm{yr}^{-1}$ to be consistent with the limiting FARs from other pipelines. Dashes indicate that a pipeline did not find the event with a FAR smaller than the subthreshold FAR threshold of 2 per day.



(a) GstLAL

(b) MBTA



(c) PyCBC

(d) PyCBC-BBH

FIG. 2. Cumulative sum of $p_{\rm BNS}$, $p_{\rm NSBH}$, $p_{\rm BBH}$ as a function of the candidates that pass a FAR threshold of 2 per day. The events are shown in decreasing order of $p_{\rm astro}$. The sum of the source probabilities shown here represents the estimated Poisson rate of sources in each source class per O3a experiment by the different search pipelines. An estimate of the rate of sources in the subthreshold candidate list is obtained by the contribution to the sum from events with $p_{\rm astro}$ less than 0.5. This estimate yields between 2.55–12.40 signals in the BBH class, 0.36–2.39 signals in the NSBH class, and 0.02–0.49 signals in the BNS class in the subthreshold candidates in O3a. The dashed vertical grey line shows where this threshold is for each pipeline. Names are marked for the candidate events with $p_{\rm BNS}$ or $p_{\rm NSBH}$ greater than 20%, since these are of particular interest for cross-correlation studies.

Name	**MBTA**				**GstLAL**				**PyCBC**				**PyCBC-BBH**		
	p_{BBH}	p_{NSBH}	p_{BNS}	p_{astro}	p_{BBH}	p_{NSBH}	p_{BNS}	p_{astro}	p_{BBH}	p_{NSBH}	p_{BNS}	p_{astro}	p_{BBH}	p_{NSBH}	p_{astro}
GW190425_081805	–	–	–	–	0.00	0.00	0.78	0.78	–	–	–	–	–	–	–
GW190707_093326	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.93	0.07	0.00	1.00	0.93	0.07	1.00
GW190720_000836	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.95	0.05	0.00	1.00	1.00	0.00	1.00
GW190725_174728	0.59	0.00	0.00	0.59	–	–	–	–	0.79	0.17	0.00	0.96	0.58	0.24	0.82
GW190728_064510	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.97	0.03	0.00	1.00	0.97	0.03	1.00
GW190814_211039	0.93	0.07	0.00	1.00	0.19	0.81	0.00	1.00	0.54	0.46	0.00	1.00	–	–	–
GW190924_021846	0.92	0.07	0.00	0.99	1.00	0.00	0.00	1.00	0.44	0.56	0.00	1.00	0.44	0.56	1.00
GW190930_133541	0.87	0.00	0.00	0.87	0.76	0.00	0.00	0.76	0.93	0.07	0.00	1.00	0.85	0.15	1.00

TABLE II. Source probabilities (p_{BBH}, p_{BNS}, p_{NSBH}) for the high significance GW candidates listed in Table I for which p_{BNS} or p_{NSBH} is greater than 1%. For other events in the Table I, $p_{\mathrm{astro}} \approx p_{\mathrm{BBH}}$, and therefore we do not list them here. Results are provided from all three matched-filter pipelines. Dashes indicate that a pipeline did not find the event with a FAR smaller than the subthreshold FAR threshold of 2 per day. The classification provided here assumes a boundary of $3\,\mathrm{M}_\odot$ between NSs and BHs in the case of GstLAL and PyCBC, and $2.5\,\mathrm{M}_\odot$ in the case of MBTA.

Name	**Inst.**	**MBTA**			**GstLAL**			**PyCBC**		
		FAR (yr^{-1})	SNR	max p_{astro}	FAR (yr^{-1})	SNR	max p_{astro}	FAR (yr^{-1})	SNR	max p_{astro}
GW190426_152155	HLV	32	9.8	$p_{\mathrm{NSBH}} = 0.01$	0.91	10.1	$p_{\mathrm{NSBH}} = 0.14$	43	8.8	$p_{\mathrm{NSBH}} = 0.01$
GW190531_023648	HLV	8.1	9.8	$p_{\mathrm{BNS}} = 0.05$	0.41	10.0	$p_{\mathrm{NSBH}} = 0.28$	29	9.2	$p_{\mathrm{NSBH}} = 0.01$

TABLE III. Marginal-significance GW event candidate list. There are 2 events that are found in at least one of the searches with a FAR less than 2 per year, but with a p_{astro} smaller than 0.5 in all searches. The event in bold, GW190531_023648, is a new event in GWTC-2.1, not found in GWTC-2. The column max p_{astro} shows the astrophysical class assigned with highest probability. Both events are detected by GstLAL with a small FAR, and are assigned to the NSBH class with p_{astro} and p_{NSBH} smaller than 0.5.

D. Search sensitivity

As in GWTC-2 [8], we quantify the sensitivity of the search via a campaign of simulated signals injected into the O3a data and analyzed by the search pipelines. We use a BBH signal distribution adjusted over that used for GWTC-2 to give more even coverage of the inferred distribution from [115], changing specifically the distributions over binary mass ratio and redshift. In addition to the BBH set, we also inject BNS and NSBH sets of simulated signals into the data. The sets are generated in two stages: first, points are sampled out to the maximum redshift considered for each set, then the samples are reduced to sets of potentially detectable signals by imposing that the expected LIGO Hanford–LIGO Livingston network SNR, calculated using a representative noise power spectral density (PSD), be above a threshold of 6. Although this threshold is below the matched-filter SNRs of events we consider as high-significance candidates, for detection thresholds corresponding to FARs significantly higher than 2 per year (the value used in GWTC-2), the cut may remove a non-negligible fraction of potentially detectable signals, due to random fluctuations in matched-filter SNR. The results of this simulation campaign for all the search pipelines have been made available [124].

The BNS signals are generated using the SpinTaylorT4 waveform model [111, 113], while the BBH and NSBH sets are generated using the SEOBNRv4PHM model [55–57].[5] The component spin magnitudes $|\chi|$ are distributed uniformly up to a maximum of 0.4 for NS components and 0.998 for BBH, with isotropically distributed orientations.

The signal distributions over sky direction and binary orientation are isotropic. The distributions over redshift are proportional to the comoving volume element $\mathrm{d}V_{\mathrm{c}}/\mathrm{d}z$, multiplied by a factor $(1+z)^{-1}$ accounting for time dilation, and by a factor $(1+z)^{\kappa}$ modeling possible evolution of the comoving merger rate density with redshift (as in Appendix E of [115]). A summary of the distributions of the three injection sets is given in Table IV.

Given the merger distribution used for each injection set, the sensitivity of each search over the O3 data is quantified by relating the expected number of detections, at a specified significance threshold, to the local astrophysical merger rate as $N_{\mathrm{det}} = \mathcal{V}R(z=0)$, where $\mathcal{V}$ is an effective sensitive hypervolume with units of volume×time. This effective hypervolume is estimated by counting the number of injected signals that are detected at the given threshold, here a FAR of 2 per year.

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[5] For simulated signals with redshifted total mass below $9\,\mathrm{M}_\odot$, the SEOBNRv4P model without higher-order multipole emission was used, as higher-order multipoles would lie above the data sampling Nyquist frequency.

In addition to assumed merger distributions that follow those used for the injection sets, we also provide $\mathcal{V}$ for a fiducial BBH population model representative of those found to have high posterior probability in our population analysis of GWTC-2 [115]. We choose the POWER LAW + PEAK model (defined in Appendix B.2 of [115]) with parameters $\alpha = 2.5$, $\beta = 1.5$, $m_{\min} = 5\,\mathrm{M}_\odot$, $m_{\max} = 80\,\mathrm{M}_\odot$, $\lambda_{\mathrm{peak}} = 0.1$, $\mu_m = 34\,\mathrm{M}_\odot$, $\sigma_m = 5\,\mathrm{M}_\odot$, $\delta_m = 3.5\,\mathrm{M}_\odot$, setting the redshift evolution to $\kappa = 0$. The sensitivity for this BBH population is evaluated via importance sampling [109, 125] implemented via GWPOPULATION [126]. The effective hypervolume for each search and signal population is given in Table IV.

E. Rates of BBH and BNS events

The rates of BBH and BNS binary mergers in the local Universe were estimated in a companion paper [115] to GWTC-2, using the count of detected events with FAR below 1 per year, combined with estimates of search sensitivity to the respective populations. The BBH rate estimate was marginalized over uncertainties in the parameters of the population models used, while the BNS rate estimate assumed a population uniform in component masses between $1\,\mathrm{M}_\odot$ and $2.5\,\mathrm{M}_\odot$. The merger rate of NSBHs was recently calculated following the discovery of GW200105_162426 and GW200115_042309 [127], and we do not update it here.

Here, we present complementary BBH and BNS rate estimates based solely on the matched filter search pipeline outputs, with methods that allow us to incorporate a large number of likely noise (background) events [23] and thus avoid potential bias due to an arbitrary choice of significance threshold. Such methods allow for both foreground (signal) and background event distributions with a priori unknown rates, considered as independent Poisson processes. Furthermore, for the GstLAL pipeline we employ a multicomponent mixture analysis [108] to estimate the rates of events in several astrophysical classes (BNS, NSBH, and BBH) and terrestrial. Every trigger is assigned probabilities of membership in each class, as described in Section III B 1. For the MBTA and PyCBC rate estimates, only the BBH class is considered.

The merger rate estimate then arises from the number of search events assigned to each class, divided by the estimated search sensitivity obtained via injection campaigns re-weighted to an astrophysical population model [109], as discussed in the previous section. The population models used here to quantify search sensitivity are in general different from those used to obtain source classification probabilities, described in Section III A.

In both the BBH and BNS cases, as for other rate interval estimates derived from search results [7], a Jeffreys ($\propto R^{-1/2}$) prior was used. The choice of prior has little influence on estimated BBH rate due to the large count of signals, but it has a nontrivial effect on the BNS rate estimate as compared to, for instance, a uniform prior.

BBH merger rate estimates are provided by the GstLAL, PyCBC-BBH and MBTA pipelines. The astrophysical population assumed for measuring search sensitivities is given by the POWER LAW + PEAK model of [115] with fiducial parameters as in Section IV D. The resulting merger rates are $25.0^{+7.2}_{-6.1}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ for GstLAL, $26.0^{+8.2}_{-6.8}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ for PyCBC-BBH and $25.6^{+9.6}_{-7.8}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ for MBTA. These estimates are fully consistent with the estimate of $23.9^{+14.3}_{-8.6}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ as derived in [115] using only significant (FAR$<$ 1 yr^{-1}) events, and allowing for uncertainties in the population model parameters. Following [115], we have not included the effect of calibration uncertainties in our rate estimates. A full quantitative analysis of such uncertainties would require accounting for possible frequency- and time-dependent amplitude systematic errors [70]; these are typically $\sim 3\%$ or less, corresponding to a $\lesssim 10\%$ sensitive volume uncertainty which remains subdominant to the Poisson uncertainty in the signal counts [115].

Since the only significant event consistent with BNS merger in O3a, GW190425, was observed in a single detector, it is present only in the GstLAL search results. Hence, we quote a BNS merger rate estimate only from the GstLAL pipeline, as we expect this to be more informative than estimates from pipelines that did not consider single-detector triggers. For measuring the search sensitivity to BNS mergers, we use the injected population described above in Section IV D, yielding an estimated merger rate $286^{+510}_{-237}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. This estimate is fully consistent within uncertainties with the simpler estimate of $320^{+490}_{-240}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ derived using a fixed threshold in expected SNR to determine sensitivity to simulated signals [115].

V. ESTIMATION OF SOURCE PARAMETERS

The physical parameters $\vec{\vartheta}$ describing each GW source binary, corresponding to individual entries from the list of events in Table I, are inferred directly from the data d and represented as a posterior probability distribution $p(\vec{\vartheta}|d)$. This probability distribution is evaluated through Bayes' theorem as

$$p(\vec{\vartheta}|d) \propto p(d|\vec{\vartheta})\pi(\vec{\vartheta})\,, \tag{3}$$

with $p(d|\vec{\vartheta})$ being the likelihood of d given a set of source parameters $\vec{\vartheta}$, and $\pi(\vec{\vartheta})$ being the prior probability distribution assumed for those parameters.

The likelihood itself describes the assumptions of the underlying stochastic process generating the noise present in d from a given detector. This noise is assumed to be Gaussian, stationary and uncorrelated between pairs of detectors [128, 129], as further discussed in Section II B. This yields a Gaussian likelihood [130, 131],

Injection populations						**Sensitive hypervolume $\mathcal{V}$ (Gpc^3 yr)**				
	mass distribution	mass range (M$_\odot$)	spin range	redshift evolution	max. redshift	GstLAL	MBTA	PyCBC	PyCBC BBH	All
BBH (INJ)	$p(m_1) \propto {m_1}^{-2.35}$ $p(m_2\|m_1) \propto m_2$	$2 < m_1 < 100$ $2 < m_2 < 100$	$\|\chi_{1,2}\| < 0.998$	$\kappa = 1$	1.9	0.258	0.196	0.194	0.234	0.308
BBH (POP)	Power Law + Peak	(see text)	$\|\chi_{1,2}\| < 0.998$	$\kappa = 0$	1.9	1.22	0.885	0.914	1.20	1.44
BNS	uniform	$1 < m_1 < 2.5$ $1 < m_2 < 2.5$	$\|\chi_{1,2}\| < 0.4$	$\kappa = 0$	0.15	0.00594	0.00631	0.00657	–	0.00781
NSBH	$p(m_1) \propto {m_1}^{-2.35}$ uniform	$2.5 < m_1 < 60$ $1 < m_2 < 2.5$	$\|\chi_1\| < 0.998$ $\|\chi_2\| < 0.4$	$\kappa = 0$	0.25	0.0174	0.0165	0.0181	–	0.0221

TABLE IV. Measures of sensitivity for the search pipelines. We state the sensitive hypervolume $\mathcal{V}$ for each of four assumed signal populations: a BBH population following the injected distribution, a BBH population given by the Power Law + Peak model of [115], and BNS and NSBH populations following the injected distributions. We give estimates for each search pipeline independently at a FAR threshold of 2 per year, and for all pipelines combined, i.e. counting all injections detected in at least one pipeline at the given threshold.

which for the i^{th} detector used in a given analysis takes the form

$$p(d^i|\vec{\vartheta}) \propto \exp\left[-\frac{1}{2}\left\langle d^i - h^i_{\text{M}}(\vec{\vartheta})\middle| d^i - h^i_{\text{M}}(\vec{\vartheta})\right\rangle\right], \qquad (4)$$

with d^i representing the data from this instrument. $h^i_{\text{M}}(\vec{\vartheta})$ is the binary waveform model $h(\vec{\vartheta})$ calculated for $\vec{\vartheta}$ after being projected onto the detector and adjusted to account for the uncertainty present in the offline calibration (as described in Section II) of d^i [132]. The final likelihood is evaluated coherently across the network of available detectors and is obtained by multiplication of the likelihoods in each detector.

The term from Eq. (4) in angle brackets, $\langle a|b\rangle$, represents a noise-weighted inner product [130, 133]. In addition to d^i and $h^i_M(\vec{\vartheta})$, evaluating this inner product requires specification of the bandwidth to be used in the analysis as well as the PSD characterizing the noise process. The low-frequency cutoff used in our analysis is set at $f_{\text{low}} = 20$ Hz. Time-domain waveform models are generated starting at a frequency f_{start} such that the $(\ell, |m|) = (3, 3)$ spherical harmonic mode of the binary inspiral signal, as estimated from a set of preliminary analyses [7, 8], is present at f_{low}. The high-frequency cutoff f_{high} is selected for each analysis as $f_{\text{high}} = \alpha^{\text{roll-off}} f_{\text{Nyquist}}$ such that the ringdown frequency of the $(\ell, |m|) = (3, 3)$ spherical harmonic mode, inferred from waveforms taken from the same set of preliminary analyses as mentioned above [7, 8], occurs below f_{high}. The parameter $\alpha^{\text{roll-off}}$ in this expression is a scale factor chosen in order to minimize the frequency roll-off effects caused by the application of a tapering window to the time-domain data [134]. The Nyquist frequency f_{Nyquist} is then selected as the smallest power-of-two-valued frequency which together with $\alpha^{\text{roll-off}} = 0.875$ satisfies the constraint on f_{high} specified above. Similarly, the duration of data d used in each analysis is determined from a requirement that the waveforms from previous analyses [7, 8] as evaluated from $f_{\text{low}} = 20$ Hz and rounding up to the next power-of-two number of seconds, are contained in the selected data segment. The PSD for each event is inferred directly from the same data that is to be used in the likelihood, through the parametrized model implemented in BayesWave [135, 136]. From the inferred posterior distribution of PSDs, the median value at each frequency is then used in the final analysis [136, 137].

A GW signal emitted from a binary containing two BHs can be fully characterized by $\vec{\vartheta}$ containing a set of fifteen parameters, as introduced in Section III A, if the binary orbit is assumed to have negligible eccentricity.[6] The mass and spin of the post-merger remnant BH, together with the peak GW luminosity, are calculated from the initial binary parameters using fits to numerical relativity (NR) [138–143].

A. Waveform models

The binary properties of the observed GW events are characterized through matching against a set of waveform models. For the events identified as BBHs, with both components inferred to have masses above $3M_\odot$, we use the independently developed IMRPhenomXPHM [51–54] and SEOBNRv4PHM [55–57] models. Both waveform models capture effects from spin-induced precession of the binary orbit, as well as contributions from both the dominant and sub-dominant multipole moments of the emitted gravitational radiation.

IMRPhenomXPHM [51] describes the GW signal from precessing non-eccentric BBHs and is part of the fourth

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[6] See Table E1 in [134] for precise definitions of all parameters used.

generation of phenomenological frequency domain models. Precession is implemented via a twisting-up procedure, as for its predecessors IMRPhenomPv2 [144, 145] and IMRPhenomPv3HM [146, 147]. For this, an aligned-spin model defined in the co-precessing frame is mapped through a suitable frame rotation to approximate the multipolar emission of a precessing system in the inertial frame. The stationary phase approximation is used to obtain closed form expressions in the frequency domain [148]. The description for the precession dynamics is derived using a multiple scale analysis of the post-Newtonian (PN) equations of motion [149]. The underlying aligned spin model for IMRPhenomXPHM is IMRPhenomXHM [52–54], which calibrates the $(\ell, |m|) = (2,2),(2,1),(3,2),(3,3)$ and (4,4) spherical harmonic modes to hybrid waveforms constructed from NR waveforms and information from the PN and effective-one-body (EOB) descriptions for the inspiral. IMRPhenomXHM represents the amplitudes and phases of spherical or spheroidal harmonic modes in terms of piecewise closed form expressions, with coefficients that vary across the compact binary parameter space, which results in extreme compression of the waveform information and computational efficiency.

SEOBNRv4PHM comes from another waveform family that is primarily based on the EOB formalism where the relativistic two-body problem is mapped to motion of a single body in an effective metric. In this framework, analytical information from several sources, such as PN theory and the test-particle limit, is combined in a resummed form. This is complemented with insights from NR simulations that accurately model the strong-field regime and incorporated into the EOB waveforms via a calibration procedure. We use the SEOBNRv4PHM [55–57] model, which includes precession and modes beyond the dominant quadrupole. This model is based on the aligned-spin model SEOBNRv4HM [58] and is calibrated to NR in that regime. It features full two-spin treatment of the precession equations and relies on a twisting-up procedure to map aligned spin waveforms in the co-precessing frame to the precessing waveforms in the inertial frame [56, 57].

For GW190917_114630, the less massive component is indicated to lie below $3M_\odot$ and hence to have a strong likelihood of being a NS instead of a BH. Following the discussion for GW190814 [38], the nature of the less massive compact object in GW190917_114630 cannot be discerned from the GW data at present. This is primarily dependent on the unequal mass ratio [150–152] which will lead the merger of the binary to occur before an eventual NS component could have been tidally disrupted for any realistic NS equation of state (EoS) [150]. The lack of an observable NS disruption thus removes the potential for the observed signal to contain any additional information above a point-particle baseline. For this reason, we present results for GW190917_114630 with only the two BBH waveform models discussed above.

B. Sampling methods

To represent the continuous posterior probability density functions in $\vec{\vartheta}$, we draw discrete samples from those distributions using three different methods. For analyses using IMRPhenomXPHM we use the Bilby inference package [134, 153], together with the nested sampling [154] method implemented in the Dynesty sampler [155], or the Markov-chain Monte Carlo sampler implemented in the LALInference package [131, 156–158]. For analyses using SEOBNRv4PHM, we use the RIFT package [159–161] which, due to a hybrid exploration of the parameter space split into intrinsic (masses and spins) and extrinsic parameters, is better suited for use with this more computationally expensive waveform model. The results from both analyses are collected and presented in a common format using the PESummary package [162, 163].

C. Priors

The prior probability on $\vec{\vartheta}$ is defined similar to GWTC-2 [8] as uniform in spin magnitudes and redshifted component masses,[7] and isotropic in spin orientations, sky location and orientation of the binary orbit. The prior on the luminosity distance follows a distribution uniform in comoving volume, using a flat ΛCDM cosmology with Hubble constant $H_0 = 67.90\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and matter density $\Omega_\mathrm{m} = 0.3065$ [164]. Masses reported in Section V D are defined in the rest frame of the original binary, and computed by dividing the redshifted masses by $(1+z)$, with z calculated from the same cosmological model.

For analyses performed with the LALInference or Bilby inference packages, we account for uncertainties in the reported strain calibration [70, 165]. The calibration uncertainties are described as frequency-dependent splines, defined separately for the strain amplitude and phase [166]. The coefficients at the spline nodes are allowed to vary alongside the binary signal parameters according to a Gaussian prior distribution set by the measured uncertainty at each node [132].

D. Source properties

In this subsection we report the inferred source properties of the 8 new events reported in Table I. A selection of the one-dimensional marginal posterior distributions are shown in Fig. 3, with two-dimensional projections on the M–q and $\mathcal{M}$–χ_eff planes in Fig. 4 and Fig. 5 respectively. A more detailed set of results are presented

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[7] Specified in the geocenter rest frame.

in Table V in the form of median and 90% credible intervals for the one-dimensional marginal posterior distributions for all 8 events. The complete 15-dimensional posterior distributions are available as part of the public data release accompanying this paper, as detailed further in Section VII.

1. *Masses*

The masses inferred for the 8 events presented in this section are generally comparable to, or higher, than the binaries reported in GWTC-2 [7, 8], as shown in Fig. 4. We find that the most massive BBH in GWTC-2.1 is GW190426_190642 with a total mass of $184.4^{+41.7}_{-36.6}\mathrm{M}_{\odot}$ and a remnant mass of $175.0^{+39.4}_{-34.3}\mathrm{M}_{\odot}$; it probably supersedes the previous most massive BBH GW190521 with total mass of $163.9^{+39.2}_{-23.5}\mathrm{M}_{\odot}$ and remnant mass of $156.3^{+36.8}_{-22.4}\mathrm{M}_{\odot}$ [8]. Both GW190426_190642 and GW190403_051519 join GW190519_153544, GW190521, GW190602_175927 and GW190706_222641 in a population of BBHs with over 50% posterior support for total mass $M > 100\mathrm{M}_{\odot}$ [8].

While the majority of the new events show a preference for mass ratios near unity, following the trend already observed in GWTC-2 [7, 8], both GW190403_051519 and GW190917_114630 recover posteriors with median $q \sim 1/4$ with $q = 0.25^{+0.54}_{-0.11}$ and $q = 0.23^{+0.52}_{-0.09}$ respectively. As shown in Fig. 4, this constraint for unequal masses is robust at the 90% credible level for both GW190403_051519 and GW190917_114630.

2. *Spins*

The best measured spin parameter for CBCs with observable inspiral signals tends to be the effective inspiral spin χ_{eff} [167], introduced in Eq. (2), which is a constant of motion of the binary and approximately conserved under spin-induced precession of the binary orbit [168–171]. The posterior distributions for χ_{eff} for all 8 events are shown in Fig. 3 and Fig. 5. Again, the majority of the binaries are consistent with containing two non-spinning BHs with only GW190403_051519 and GW190805_211137 recovering a non-zero χ_{eff} at 90% credibility. Both binaries report predominantly positive χ_{eff}, further strengthening the pattern of a surplus of events with $\chi_{\mathrm{eff}} > 0$ relative to those with $\chi_{\mathrm{eff}} < 0$ reported in GWTC-2 [8] and investigated further in a companion paper [115].

Similar to the compact objects reported in GWTC-2 [7, 8], the majority of the compact-object spins reported in GWTC-2.1 have magnitudes consistent with zero. Two of the new events show evidence for large BH spins. In the case of GW190403_051519, 89% of the posterior density lies in a region where at least one of the component spin magnitudes is above 0.8 whereas for GW190805_211137 this holds for 57% of the posterior density.

For binaries with very unequal masses, measurements of χ_{eff} can translate into strong measurement constraints of χ_1, the spin magnitude of the more massive object, whose spin angular momentum dominates over the secondary. This is the case for GW190403_051519, whose primary dimensionless spin is measured to be $\chi_1 = 0.92^{+0.07}_{-0.22}$. This represents the most nearly-extremal spin observed using GWs. Similarly, GW190805_211137 is recovered with $\chi_1 = 0.74^{+0.22}_{-0.60}$ and GW190917_114630 with $\chi_1 = 0.31^{+0.59}_{-0.29}$. Both GW190403_051519 and GW190805_211137 are recovered as strongly preferring large χ_1, with the inferred posterior distributions railing against the extremal BH-spin bound at $\chi_1 = 1$. Hence, we also report the 90% lower bounds of $\chi_1 > 0.77$ for GW190403_051519 and $\chi_1 > 0.27$ for GW190805_211137. The posterior distributions for the spin magnitudes and tilt angles for these three events are shown in Fig. 6.

3. *Three-Dimensional Localization*

As the 8 new events are all detected at relatively modest SNRs, together with several identifications as high-mass BBHs, the inferred luminosity distances D_{L} are generally larger than the binaries from GWTC-2 [7, 8]. GW190403_051519 is identified as probably the most distant event, with a recovered $D_{\mathrm{L}} = 8.00^{+5.88}_{-3.99}$ Gpc corresponding to a redshift $z = 1.14^{+0.64}_{-0.49}$ and at nearly twice the median distance compared to GW190413_134308, probably the most distant event reported in GWTC-2 [7, 8]. In addition GW190426_190642, GW190805_211137, GW190916_200658 and GW190926_050336 all have inferred distances comparable to, or larger than, GW190413_134308, further highlighting the access to the distant Universe provided in GWTC-2.1.

Another effect of the modest SNR of the new events is their comparatively poor localization on the sky. The best localized event is GW190925_232845, with a 90% credible region of $\Delta\Omega = 1200\ \mathrm{deg}^2$. The credible intervals for the inferred distances and sky areas are shown in Table V. The inferred localizations for all events are available as part of the accompanying data release to this paper, detailed further in Section VII.

4. *Waveform comparisons – Model systematics*

The use of both the IMRPhenomXPHM [51–54] and SEOBNRv4PHM [55–57] models in the analyses of these events are motivated by the need to capture, and account for, potential differences in the inferred source parameters caused by the different methods used in the constructions of the models themselves. All posterior distributions reported in this section are constructed by combining an equal number of samples drawn from each

Event	M $(M_\odot)$	$\mathcal{M}$ $(M_\odot)$	m_1 $(M_\odot)$	m_2 $(M_\odot)$	χ_{eff}	D_{L} (Gpc)	z	M_{f} $(M_\odot)$	χ_{f}	$\Delta\Omega$ (deg^2)
GW190403_051519	$110.5^{+30.6}_{-24.2}$	$36.3^{+14.4}_{-8.8}$	$88.0^{+28.2}_{-32.9}$	$22.1^{+23.8}_{-9.0}$	$0.70^{+0.15}_{-0.27}$	$8.00^{+5.88}_{-3.99}$	$1.14^{+0.64}_{-0.49}$	$105.2^{+29.1}_{-24.1}$	$0.92^{+0.04}_{-0.11}$	5600
GW190426_190642	$184.4^{+41.7}_{-36.6}$	$77.1^{+19.4}_{-17.1}$	$106.9^{+41.6}_{-25.2}$	$76.6^{+26.2}_{-33.6}$	$0.19^{+0.43}_{-0.40}$	$4.35^{+3.35}_{-2.15}$	$0.70^{+0.41}_{-0.30}$	$175.0^{+39.4}_{-34.3}$	$0.76^{+0.15}_{-0.15}$	8200
GW190725_174728	$18.2^{+4.2}_{-1.8}$	$7.4^{+0.6}_{-0.5}$	$11.5^{+6.2}_{-2.7}$	$6.4^{+2.0}_{-2.0}$	$-0.04^{+0.26}_{-0.14}$	$1.05^{+0.57}_{-0.46}$	$0.21^{+0.10}_{-0.09}$	$17.4^{+4.4}_{-1.8}$	$0.65^{+0.08}_{-0.07}$	2300
GW190805_211137	$80.1^{+22.5}_{-16.1}$	$33.5^{+10.1}_{-7.0}$	$48.2^{+17.5}_{-12.5}$	$32.0^{+13.4}_{-11.4}$	$0.35^{+0.30}_{-0.36}$	$5.31^{+4.10}_{-2.95}$	$0.82^{+0.48}_{-0.40}$	$75.8^{+21.2}_{-15.3}$	$0.81^{+0.09}_{-0.15}$	3900
GW190916_200658	$68.9^{+21.0}_{-14.0}$	$27.3^{+9.3}_{-5.5}$	$44.3^{+21.2}_{-13.3}$	$23.9^{+12.7}_{-10.2}$	$0.18^{+0.33}_{-0.29}$	$4.46^{+3.79}_{-2.52}$	$0.71^{+0.46}_{-0.36}$	$65.7^{+19.8}_{-13.4}$	$0.73^{+0.14}_{-0.23}$	4500
GW190917_114630	$11.4^{+3.0}_{-2.9}$	$3.7^{+0.2}_{-0.2}$	$9.3^{+3.4}_{-4.4}$	$2.1^{+1.5}_{-0.5}$	$-0.11^{+0.24}_{-0.49}$	$0.72^{+0.34}_{-0.31}$	$0.15^{+0.06}_{-0.06}$	$11.2^{+3.0}_{-2.9}$	$0.42^{+0.12}_{-0.06}$	2100
GW190925_232845	$37.0^{+3.8}_{-2.6}$	$15.8^{+1.1}_{-1.0}$	$21.2^{+6.9}_{-3.1}$	$15.6^{+2.6}_{-3.6}$	$0.11^{+0.17}_{-0.14}$	$0.93^{+0.38}_{-0.35}$	$0.19^{+0.07}_{-0.07}$	$35.2^{+3.8}_{-2.4}$	$0.72^{+0.07}_{-0.06}$	1200
GW190926_050336	$62.9^{+22.7}_{-11.9}$	$25.6^{+8.8}_{-5.3}$	$39.8^{+20.6}_{-11.1}$	$23.2^{+10.8}_{-9.7}$	$-0.04^{+0.28}_{-0.33}$	$3.78^{+3.17}_{-2.00}$	$0.62^{+0.40}_{-0.29}$	$60.5^{+21.8}_{-11.6}$	$0.65^{+0.14}_{-0.19}$	2500

TABLE V. Median and 90% symmetric credible intervals for the one-dimensional marginal posterior distributions on selected source parameters for the 8 events that are new to this catalog with $p_{\mathrm{astro}} > 0.5$, highlighted in bold in Table I. The columns show source total mass M, chirp mass $\mathcal{M}$ and component masses m_i, dimensionless effective inspiral spin χ_{eff}, luminosity distance D_{L}, redshift z, final mass M_{f}, final spin χ_{f}, and sky localization $\Delta\Omega$. The sky localization is the area of the 90% credible region. A subset of the one-dimensional posterior distributions are visualized in Fig. 3. Two-dimensional projections of the 90% credible regions in the M–q and $\mathcal{M}$–χ_{eff} planes are shown in Fig. 4 and Fig. 5.

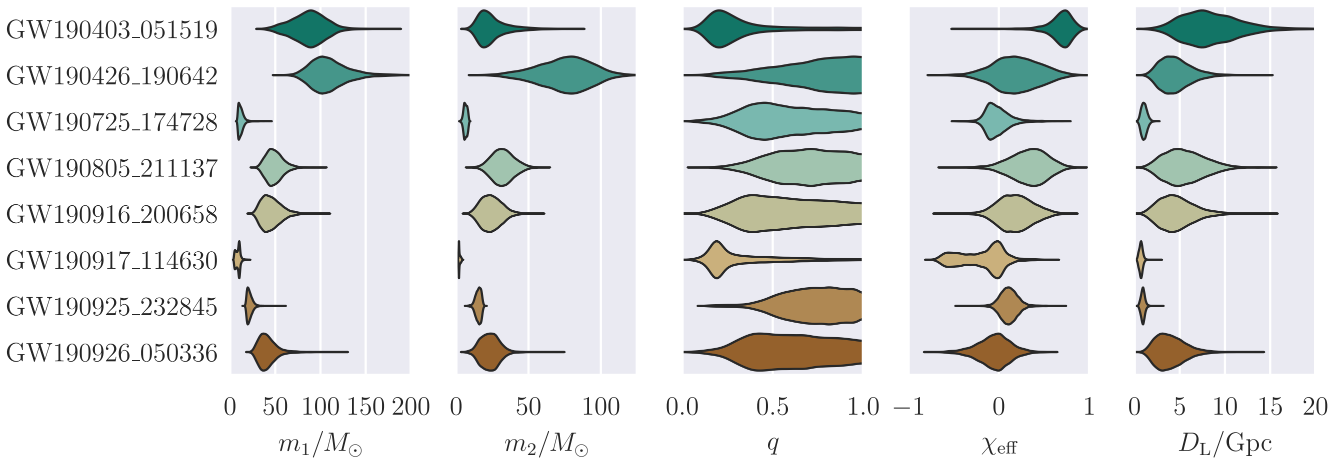

FIG. 3. Marginal posterior distributions on the primary mass m_1, secondary mass m_2, mass ratio q, effective inspiral spin χ_{eff} and luminosity distance D_{L} for the 8 events that are new to this catalog with $p_{\mathrm{astro}} > 0.5$, highlighted in bold in Table I. The vertical span for each region is constructed to be proportional to the one-dimensional marginal posterior distribution at a given parameter value for the corresponding event. The posterior distributions are also represented numerically in terms of their one-dimensional median and 90% credible intervals in Table V.

of the IMRPhenomXPHM and SEOBNRv4PHM analyses [132]. For the majority of the 8 events, the differences between the two single-model analyses, as well as to the combined-model results, are found to be comparable to the impact of model systematics effects identified in GWTC-2 [7, 8] being generally subdominant to the statistical uncertainty caused by the noisy data. For a subset of events, GW190403_051519, GW190426_190642 and GW190917_114630, there are, however, slight differences identified between the IMRPhenomXPHM and SEOBNRv4PHM analyses, most noticeably in the shape and structure of the marginal posterior distribution of some of the recovered mass and spin parameters. In these cases, the differences between analyses using either the the IMRPhenomXPHM or SEOBNRv4PHM models are dominating over the other systematic uncertainties of the analysis, such as the estimation of the noise PSD. A deeper investigation into the broader impact of these model systematic effects, and their impact on the inferred source parameters for the population of GW events presented here, is left for a future study.

5. *Comparison against 3-OGC*

Out of the 8 new events presented in this section, GW190725_174728, GW190916_200658, GW190925_232845 and GW190926_050336 were also independently identified and analyzed as part of 3-OGC [17] using the PyCBC Inference package [172] and the IMRPhenomXPHM waveform model. We compare the inferred source properties for these events as presented in 3-OGC [173] and, to minimize potential model systematic effects, the IMRPhenomXPHM analysis performed for GWTC-2.1 presented here. Overall, we find a broad agreement between the two analyses. While there are differences found in the two sets of posterior distributions, they appear consistent within expectations from the differing choices of the analysis configurations and the assumed prior distributions between the two analyses for low SNR signals [174].

VI. ASTROPHYSICAL IMPLICATIONS

Our analysis reports 8 new candidates with $p_{\rm astro} > 0.5$ in at least one pipeline. None of these candidates have $p_{\rm astro}$ equal to 1 (Table I). Four of them were found only by a single analysis, and none were detected by all the pipelines (Table I). As discussed above in Section III A, $p_{\rm astro}$ values are subject to statistical uncertainties, and are also subject to uncertainties arising from the true rate and distribution of signals. Such uncertainties are larger for events which, if astrophysical, fall within populations with few or zero significant detections. Here, we highlight such uncertainties for specific candidates, and discuss possible astrophysical implications under the hypothesis that the candidates do originate from compact object mergers.

Parameter estimation indicates that two of the new candidates, GW190403_051519 and GW190426_190642, if astrophysical, have sources with a large total mass ($\gtrsim 100\,{\rm M}_\odot$, Table V). Both were found only by the PyCBC-BBH analysis with a low SNR and relatively low $p_{\rm astro}$. They were also not recovered as significant events in the focused search of O3 data for intermediate-mass BH binaries [175]. Since there is only one significant detection to date of a comparable BBH system, GW190521 [176, 177], the calculation of $p_{\rm astro}$ for these candidates is subject to significant potential systematic error. These events are confidently above the break mass in the broken power law mass distribution model, at $39.7^{+20.3}_{-9.1}\,{\rm M}_\odot$, or the Gaussian in the POWER LAW + PEAK model at $33.1^{+4.0}_{-5.6}\,{\rm M}_\odot$ [115, 178, 179]. The estimated primary component masses, assuming astrophysical origin, are both above the lower edge of the pair-instability mass gap $m_{\rm low}$ [180–183], even considering the large uncertainties about its value ($\approx$ 40–70${\rm M}_\odot$, [29–37]). Adopting a rather conservative estimate of $m_{\rm low} = 65{\rm M}_\odot$, the primary component of GW190403_051519 ($m_1 = 88.0^{+28.2}_{-32.9}{\rm M}_\odot$) has a probability 0.12 of being below $m_{\rm low}$ with our standard mass prior, while the primary and secondary components of GW190426_190642 ($m_1 = 106.9^{+41.6}_{-25.2}{\rm M}_\odot$ and $m_2 = 76.6^{+26.2}_{-33.6}{\rm M}_\odot$) are below $m_{\rm low}$ with probabilities of 0.00076 and 0.27, respectively. The upper edge of the mass gap is even more uncertain, with theoretical predictions suggesting $m_{\rm up} \approx 120\,{\rm M}_\odot$ [184, 185]. The primary mass component of GW190403_051519 (GW190426_190642) has a probability 0.033 (0.26) of being above this value of $m_{\rm up}$. Thus, if astrophysical, GW190403_051519 and GW190426_190642 lie in the same group with GW190521: their primary components might be either inside or above the mass gap. Moreover, the estimated final mass of the merger remnant of GW190426_190642 ($M_{\rm f} = 175.0^{+39.4}_{-34.3}{\rm M}_\odot$) is in the intermediate-mass black hole regime (10^2–$10^5{\rm M}_\odot$).

These features might be suggestive of a dynamical formation channel, such as the hierarchical merger of smaller BHs [186–197] or repeated stellar collisions in dense star clusters [198–201]. In active galactic nuclei, the dense gaseous disk surrounding the central BH also triggers the hierarchical assembly of BHs [202–208]. Alternatively, extreme gas accretion from a dense gaseous disk [209–211] or from a stellar companion [212] might assist the growth of BH mass above the pair-instability threshold. Finally, primordial BHs might also have masses in the pair-instability gap [213, 214]. However, even the formation of BHs in this mass range from stellar collapse cannot be excluded, given the large uncertainties in stellar-evolution models [33, 36, 37, 215–217]. For example, very massive ($\gtrsim 230\,{\rm M}_\odot$) extremely metal-poor ($Z < 10^{-4}$) stars might turn into BHs with mass above the pair-instability gap [218–221].

Parameter-estimation analysis indicates a large positive value of the effective inspiral spin $\chi_{\rm eff} = 0.70^{+0.15}_{-0.27}$ and of the primary's spin magnitude $\chi_1 = 0.92^{+0.07}_{-0.22}$ for GW190403_051519. From a theoretical perspective, BH spin magnitudes are highly uncertain [215, 222], with some models [223, 224] predicting very low spins (~ 0.01) for single BHs because of the Tayler–Spruit dynamo [225]. Observations of high-mass X-ray binaries in the local Universe indicate that BH spins can be nearly maximal [226, 227], while the majority of mergers in GWTC-2 are associated with low values of $\chi_{\rm eff}$, with a slight preference for positive values [115]. Even if single stars form BHs with low spins [224], BHs in binaries may still develop high spins because of mass transfer [228], tidal interactions [222, 229, 230], or chemically homogeneous evolution [231, 232]. Alternatively, BHs born from the merger of two smaller BHs are expected to have high natal spins ($\sim$ 0.7–0.9, [139, 140, 142]). This might suggest that the primary component of GW190403_051519 is a second-generation BH, which is also consistent with its large mass [188, 189, 197, 233, 234]. However, the positive effective spin $\chi_{\rm eff}$ of GW190403_051519 indicates a significant alignment of the spin vectors of (any of) the two components with the orbital angular momentum vector of the BBH. Nearly aligned spins are preferentially associated with isolated binary evolution [235, 236], while dynamically formed binaries tend to have an isotropically distributed spin orientations [237, 238].

Finally, GW190403_051519 is associated with a comparatively extreme mass ratio q (Fig. 3). Such low values of the mass ratio are unusual in isolated binary evo-

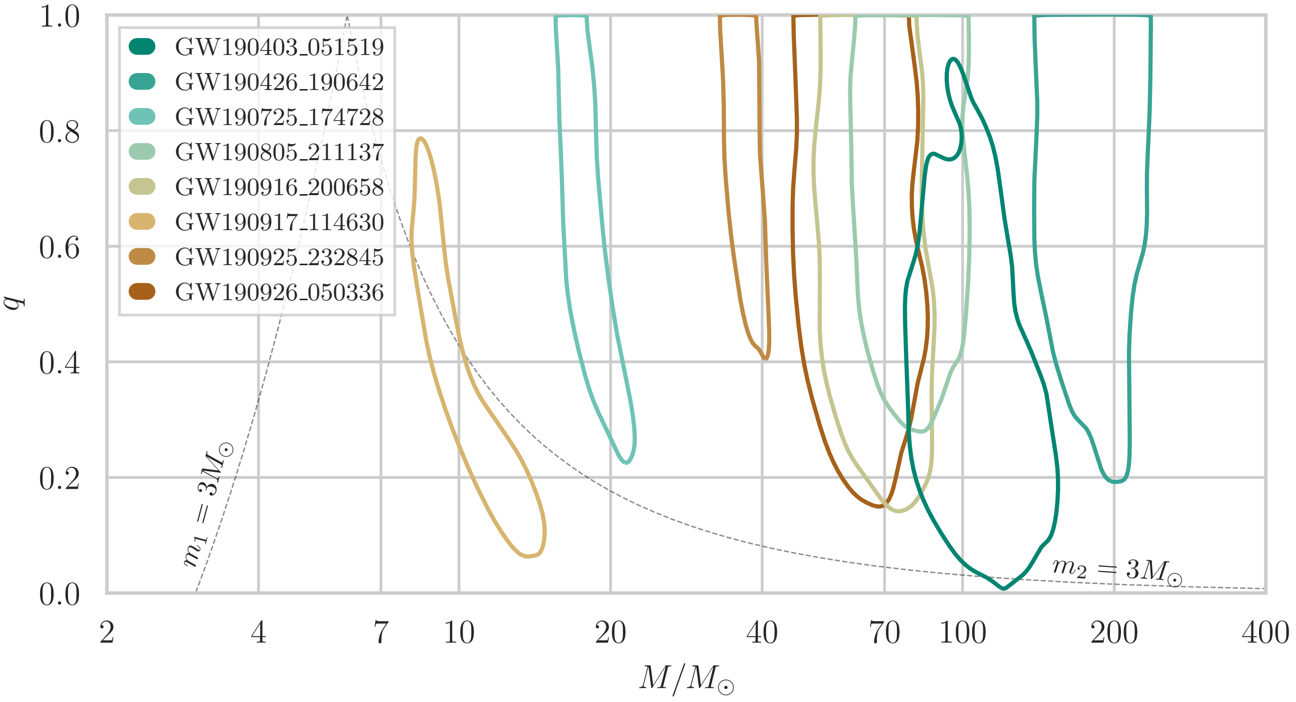

FIG. 4. Contours representing the 90% credible regions in the total mass M and mass ratio q plane for all events new to this catalog with $p_{\rm astro} > 0.5$, highlighted in bold in Table I. The events follow the same color scheme used in Fig. 3. The dashed lines act to separate regions where the primary and secondary binary component can have a mass below $3M_\odot$.

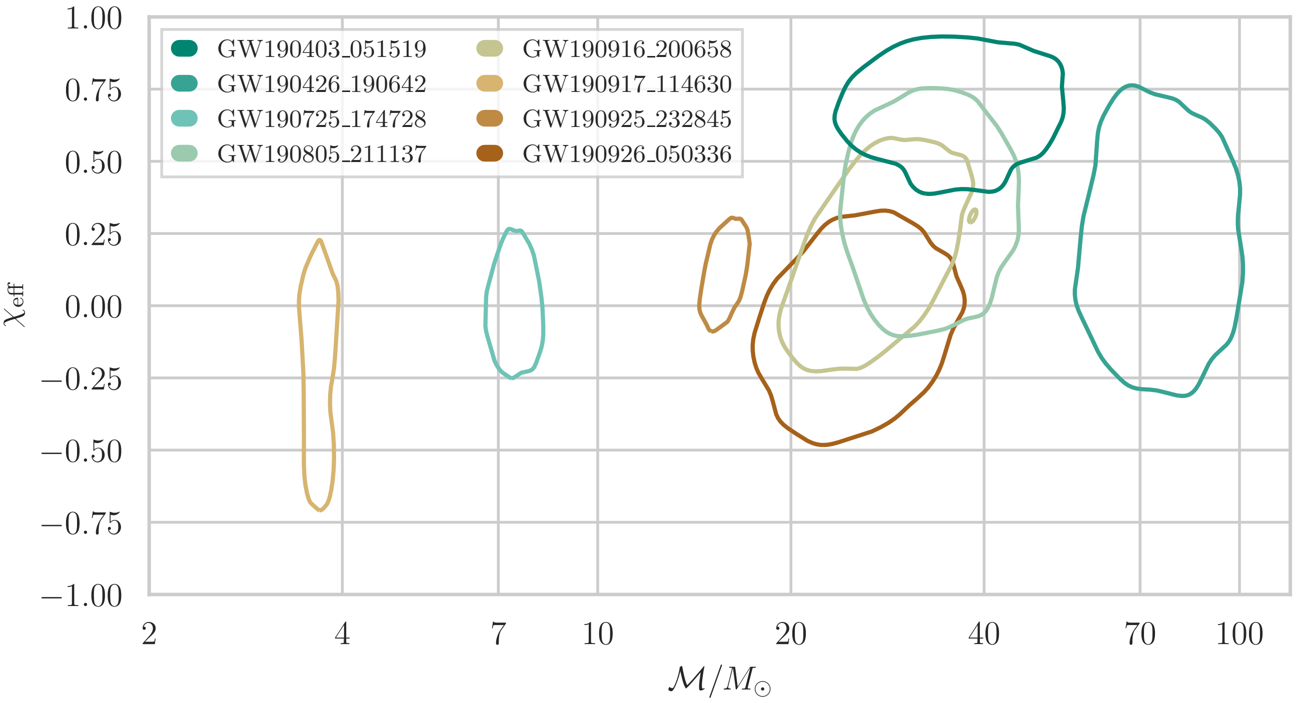

FIG. 5. Contours representing the 90% credible regions in the plane of chirp mass $\mathcal{M}$ and effective inspiral spin $\chi_{\rm eff}$ for all events new to this catalog with $p_{\rm astro} > 0.5$, highlighted in bold in Table I. The events follow the same color scheme used in Figure 3.

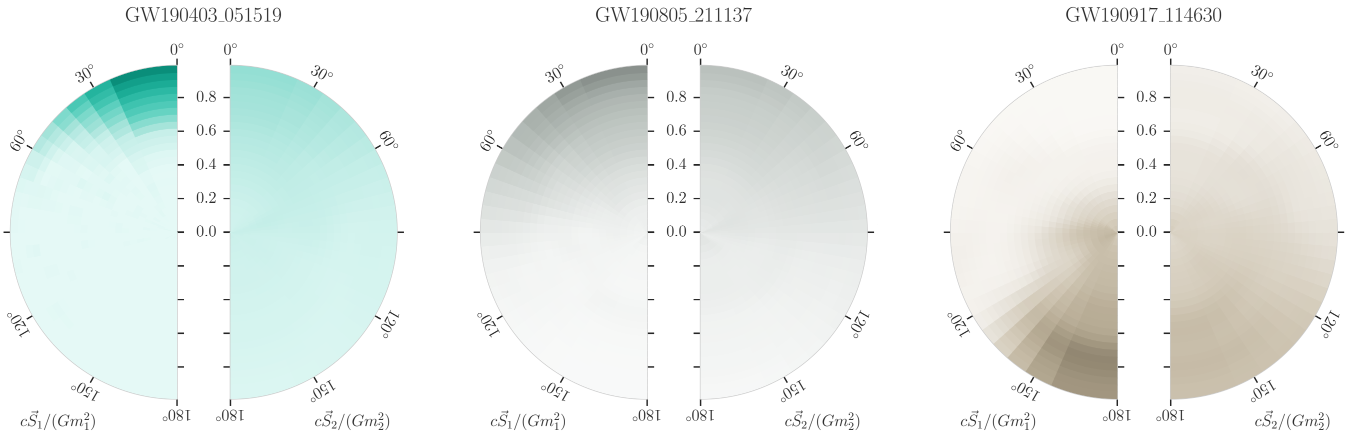

FIG. 6. The dimensionless spin parameters $\vec{\chi}_i = c\vec{S}_i/(Gm_i^2)$ estimated for individual binary components of selected sources. The radial distance of a given pixel on the left (right) of each disk, away from the center of the circle, corresponds to $|\vec{\chi}|$ for the more (less) massive compact object. Each pixel's angle from the vertical axis represents θ_{LS}, the angle between the spin vector $\vec{S}$ and the Newtonian orbital angular momentum. All pixels have equal prior probability with the shading denoting the relative posterior probability of the pixels, after marginalization over azimuthal angles. The events follow the same color scheme used in Figure 3.

lution, especially for the chemically homogeneous evolution [231, 239] but also for the common-envelope scenario [215, 240–243]. In contrast, low mass ratios are expected if the primary and secondary components are a second- and a first-generation BH, respectively [191, 192, 194], or if the primary BH is the result of a stellar merger in a young star cluster [199].

Four of the other new candidates (GW190805_211137, GW190916_200658, GW190925_232845, GW190926_050336) fall in the mass range of the bulk of GWTC-2 BBHs, while the secondary component of GW190725_174728 has a 0.12 probability of lying in the lower mass gap (~ 2–$5\mathrm{M}_{\odot}$). The existence of a lower mass gap was inferred from observations of Galactic X-ray binaries [244–246], but there are a few observations of BHs with mass ≈ 3–$4\mathrm{M}_{\odot}$ in non-interacting binary systems [247, 248] and microlensing surveys find no evidence for a mass gap between NSs and BHs [249, 250]. GWTC-2 BBH observations also suggest a dearth of systems between $2.6\mathrm{M}_{\odot}$ and $6\mathrm{M}_{\odot}$ [115, 251]. The only confirmed GW event with a component in the lower mass gap is GW190814 [38]. Numerical and theoretical models do not exclude the formation of compact objects in this mass range from a core-collapse supernova [252–255]. Other scenarios to explain the formation of binary compact objects in this mass range include mergers in multiple systems [256–259], primordial BHs [213, 260] and mass accretion onto a neutron star [261].

Finally, GW190917_114630 has component masses consistent with an NSBH ($m_1 = 9.3^{+3.4}_{-4.4}\mathrm{M}_{\odot}$, $m_2 = 2.1^{+1.5}_{-0.5}\mathrm{M}_{\odot}$), but was identified only as a BBH candidate, with $p_{\mathrm{NSBH}} = 0$ and $p_{\mathrm{BBH}} = 0.77$, by the pipeline that detected it (GstLAL). Since GW190426_152155 is a marginal event in this catalog, due to its low p_{astro} (Table III), GW190917_114630 is the only high-probability candidate with mass components in the NSBH range. However, as discussed in Section IV A, had it been classified as an NSBH to begin with, its p_{astro} measured by GstLAL would have been smaller due to the lower foreground rate of NSBHs as compared to BBHs in the detection pipelines, and not passed the threshold of 0.5 considered by the follow-up pipelines. As with the unusually high-mass BBH candidates, the assignment of p_{astro} for NSBHs is subject to potential systematic error since no NSBH events have been confidently detected in the data set up to O3a used here, although see [127] for NSBH discoveries in second half of the third observing run (O3b). The masses and effective inspiral spin of this candidate are consistent with prior expectations for NSBH systems [240, 262–268]. Inferring the impact of the new candidates on the global properties of binary compact objects requires a population analysis, which is deferred to future studies.

VII. CONCLUSION

We have presented GWTC-2.1, which includes results from a refined search for CBCs in the first part of the third observing run of the Advanced LIGO and Advanced Virgo detectors. This is an extension to the previous GW catalog, GWTC-2 [8], over the same data, and provides a deeper list of GW candidates. The search we presented here was carried out using three matched-filter pipelines, MBTA, GstLAL, and PyCBC and includes a list of candidates that have a FAR less than 2 per day in any of the pipelines. In addition, we provide detailed source properties of the 8 events that have p_{astro} greater than 0.5 and were not present in GWTC-2.

Out of the 8 new candidates presented here, with the exception of GW190917_114630, whose source masses are consistent with being an NSBH (Section V D), all events have masses consistent with BBHs sources. If astrophysical, these events expand the scope of observed BBHs, with several binaries inferred at larger distances than previous detections and with both a new broader range of recovered BH masses and the addition of two binaries with significantly unequal mass ratio. The primary components of two of the new candidates (GW190403_051519 and GW190426_190642) lie inside or, less likely, above the pair-instability mass gap. GW190403_051519 also shows support for high spin, unequal mass ratio, and remnant mass in the intermeidate-mass BH regime. These features are suggestive of a dynamical formation, by hierarchical BH merger or by stellar collisions in dense stellar clusters or active galactic nuclei. However, we cannot exclude that GW190403_051519 and GW190426_190642 originated from isolated binary systems, because of the large uncertainties in the mass range of the pair-instability mass gap. Among the new candidates, GW190725_174728 shows some support for a secondary component mass in the lower mass gap (2–5$M_\odot$). GW190917_114630, the only candidate with component masses consistent with an NSBH was initially classified as a BBH by the search pipeline, and therefore the $p_{\rm astro}$ assigned to it is subject to systematics due to uncertainty in classification.

The data products associated with GWTC-2.1 include candidate information from relevant search pipeline(s) and localizations for all events that pass a threshold of 2 per day in any search pipeline. The information from search pipeline includes the template mass and spin parameters, the SNR time series, chi-squared values, the time and phase of coalescence in each detector, FAR, and $p_{\rm astro}$ (Section III A). These data can be found at [98]. The source localizations are computed using the rapid localization tool BAYESTAR [269, 270], which was also used to produce the localizations in near real time during the observing runs while sending out GW alerts. We also release the results of the search pipelines running over simulated signal sets classified as BNS, NSBH, and BBH [124] that were used to calculate the sensitivities shown in Table IV. For candidates that have a $p_{\rm astro} > 0.5$, we perform follow-up parameter estimation and also release the posterior samples associated with these events. These are available via [271]. Finally, the strain data for O3a used for the analyses in this paper are also available [41].

The analysis of the O3b data is underway and will be published in the form of GWTC-3, which will build upon this catalog. The LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration (LVK) have already announced the first observations from NSBHs [127] in the data from O3b. Advanced LIGO and Advanced Virgo detectors continue to improve upon their sensitivities and O3a marks the most sensitive GW data published upon so far. The LIGO, Virgo, and KAGRA [272] detectors are currently offline and undergoing commissioning to enhance their sensitivities, and plan to all collect data simultaneously during the fourth observing run (O4) [61]. With further improvement in sensitivities and planning for pre-merger BNS detections [273–275], O4 offers improved prospects for GW and multimessenger astronomy, and promises to build upon our current knowledge of binary populations.

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Analyses in this catalog relied upon the LALSuite software library [276]. The detection of the signals and subsequent significance evaluations were performed with the GstLAL-based inspiral software pipeline [42–44, 277], with the MBTA pipeline [50, 278], and with the PyCBC [48, 49, 96, 279] package. Estimates of the noise spectra and glitch models were obtained using BayesWave [87, 90, 280]. Source parameter estimation was performed with the Bilby library [134, 153] using the `Dynesty` nested sampling package [281], the RIFT library [159–161] and the LALInference library [131]. PESummary was used to post-process and collate parameter-estimation results [162]. The various stages of the parameter-estimation analysis were managed with the Asimov library [282]. Plots were prepared with `Matplotlib` [283], `seaborn` [284] and `GWpy` [81]. `NumPy` [285] and `SciPy` [286] were used in the preparation of the manuscript.

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